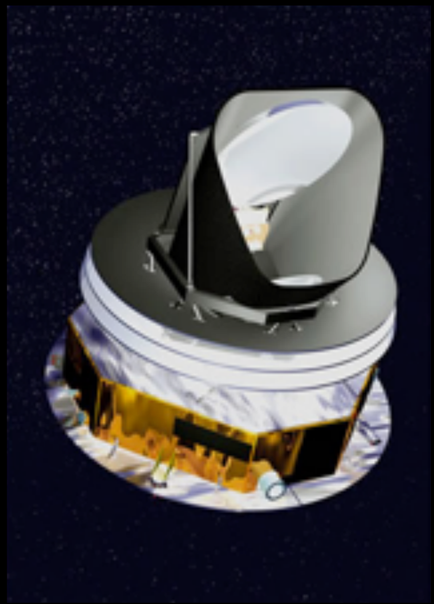
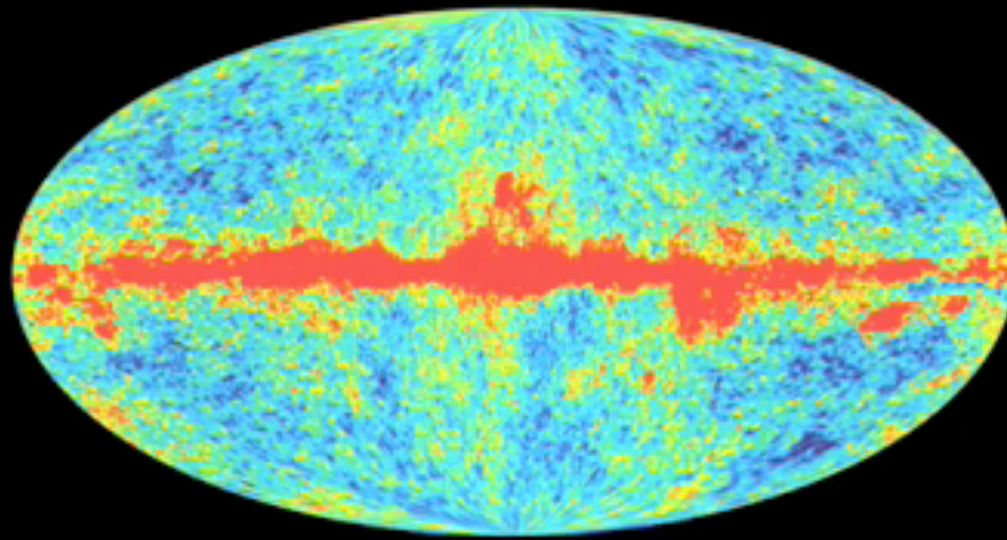
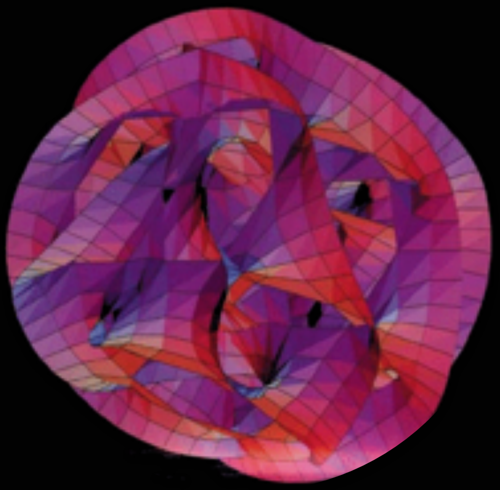




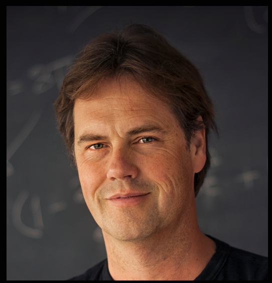
Cosmological tests of ultra-light axions

Daniel Grin

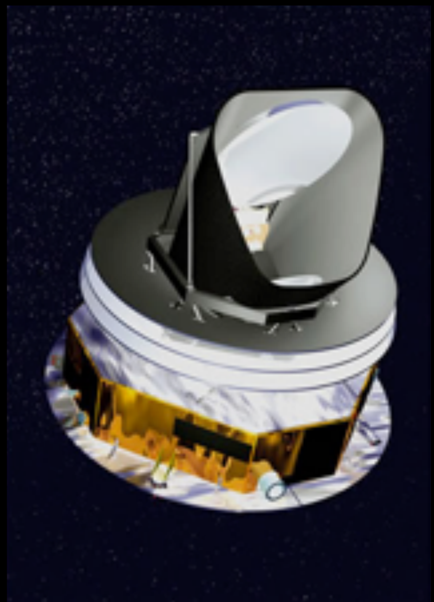
University of Chicago

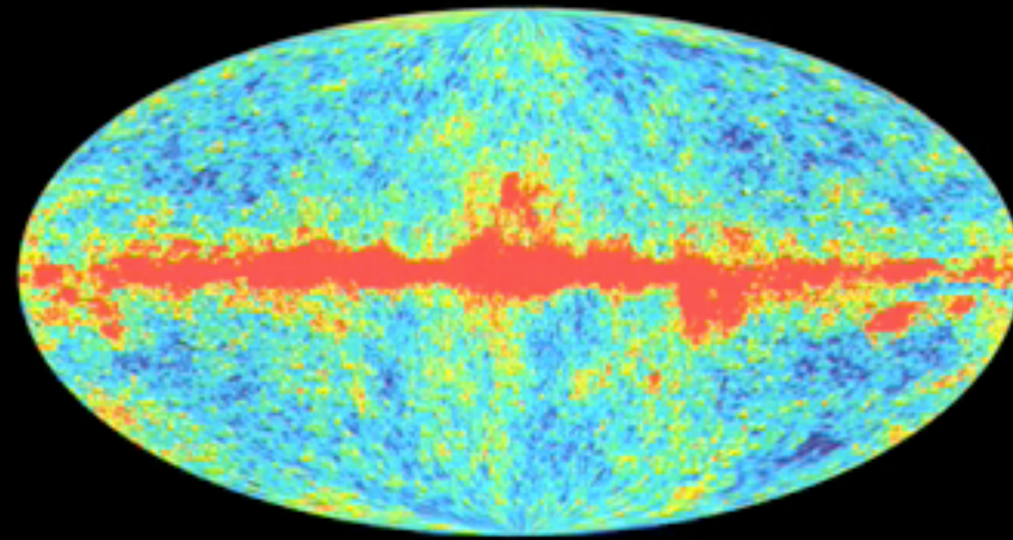
Axion-WIMP 2015 (Zaragoza)

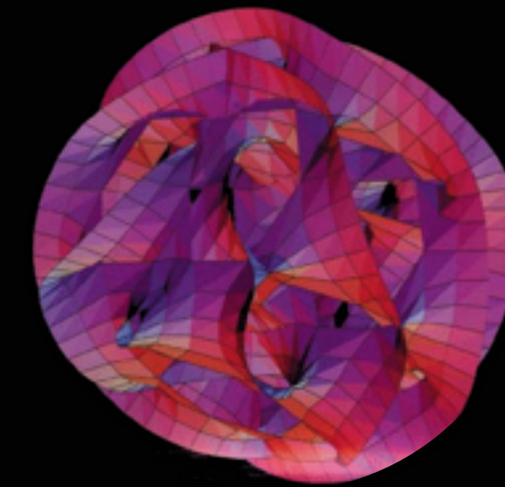




R.Hlozek, DG, D.J. E. Marsh, P.Ferreira, arXiv:1410.2896, PRD 91, 103512







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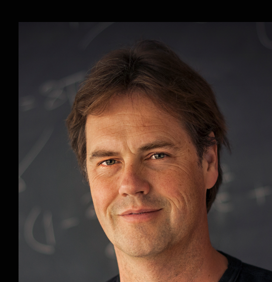

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Strong CP problem

- Strong interaction violates CP through θ-vacuum term

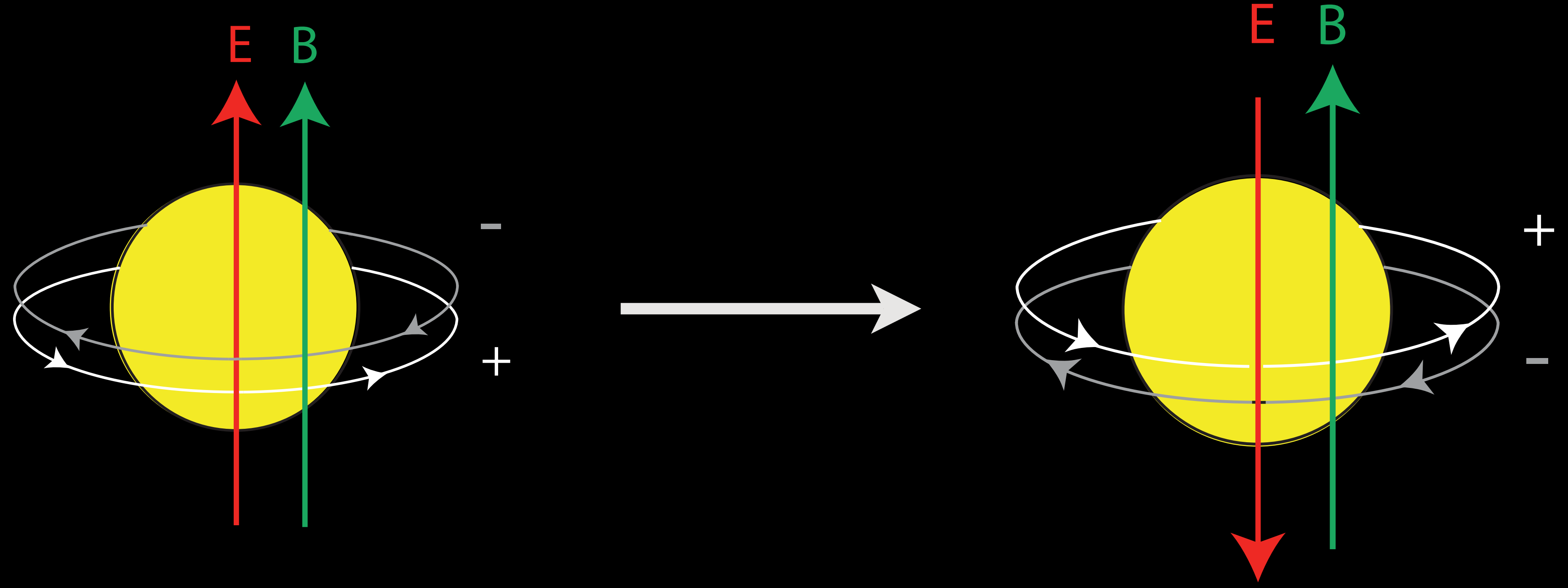
QCD strong-CP problem

$$\mathcal{L}_{\rm CPV} = \frac{\theta g^2}{32\pi^2} G\tilde{G}$$

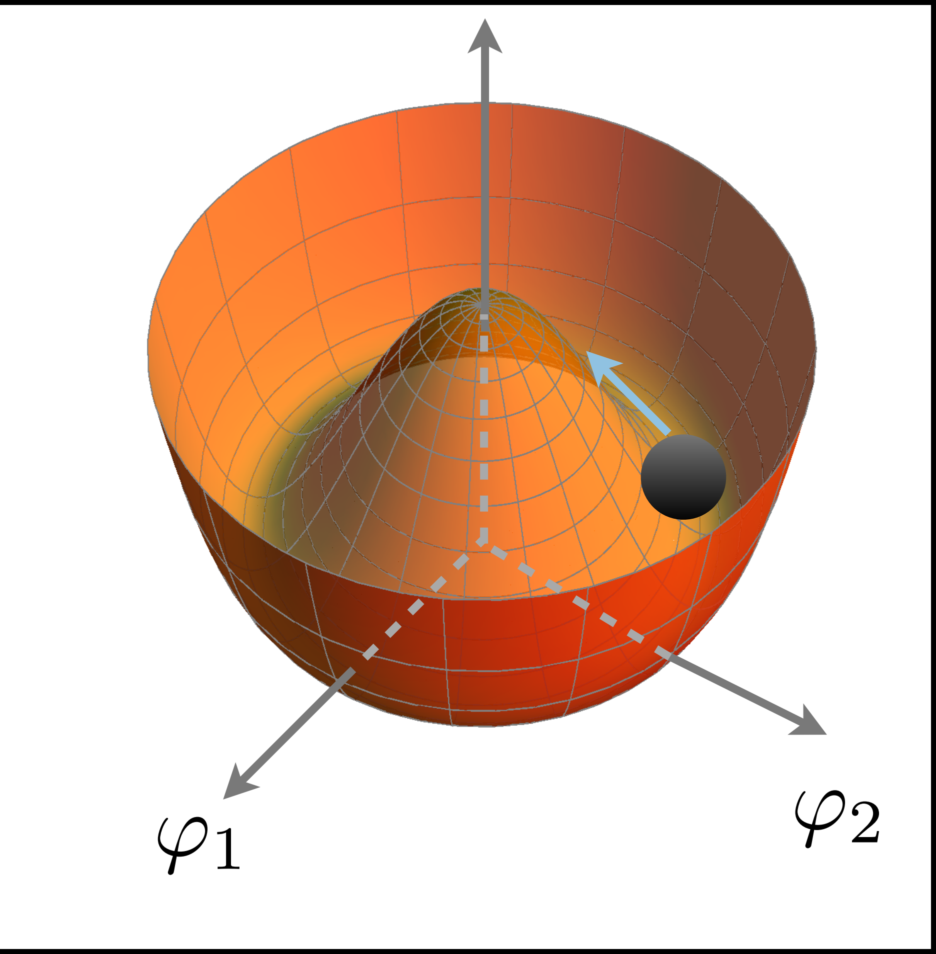
- Limits on the neutron electric dipole moment are strong. Fine tuning?

$$d_n \simeq 10^{-16}\ \theta\ \mathrm{e\ cm}$$

$$\theta \lesssim 10^{-10},$$

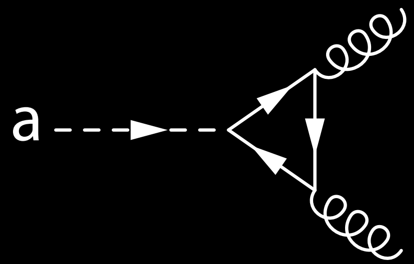


What are axions?



New scalar field with global U(1) symmetry!

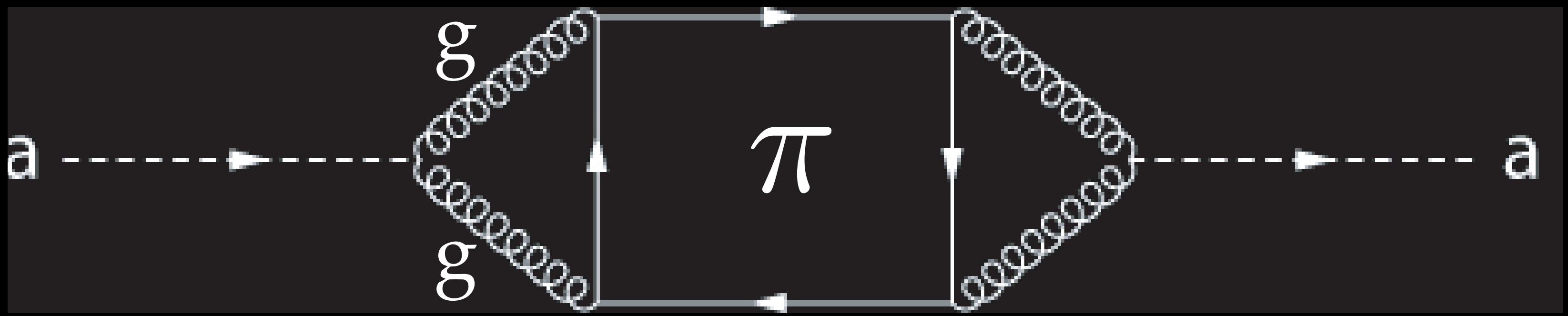
$$\mathcal{L}_{\rm CPV} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \frac{a}{f_{\rm a}} g^2 G\tilde{G}$$



✳ Couples to SM gauge fields (via fermions)

✳ Dynamically erases QCD CP-violation

✳ Mass through pion mixing



Peccei + Quinn (1977), Weinberg +Wilczek (1978), Kim (1979), Shifman et. al (1980), Zhitnitsky (1980), Dine et al. (1981), Sikivie (1983),D.B. Kaplan (1985), A.E Nelson (1985,1990)

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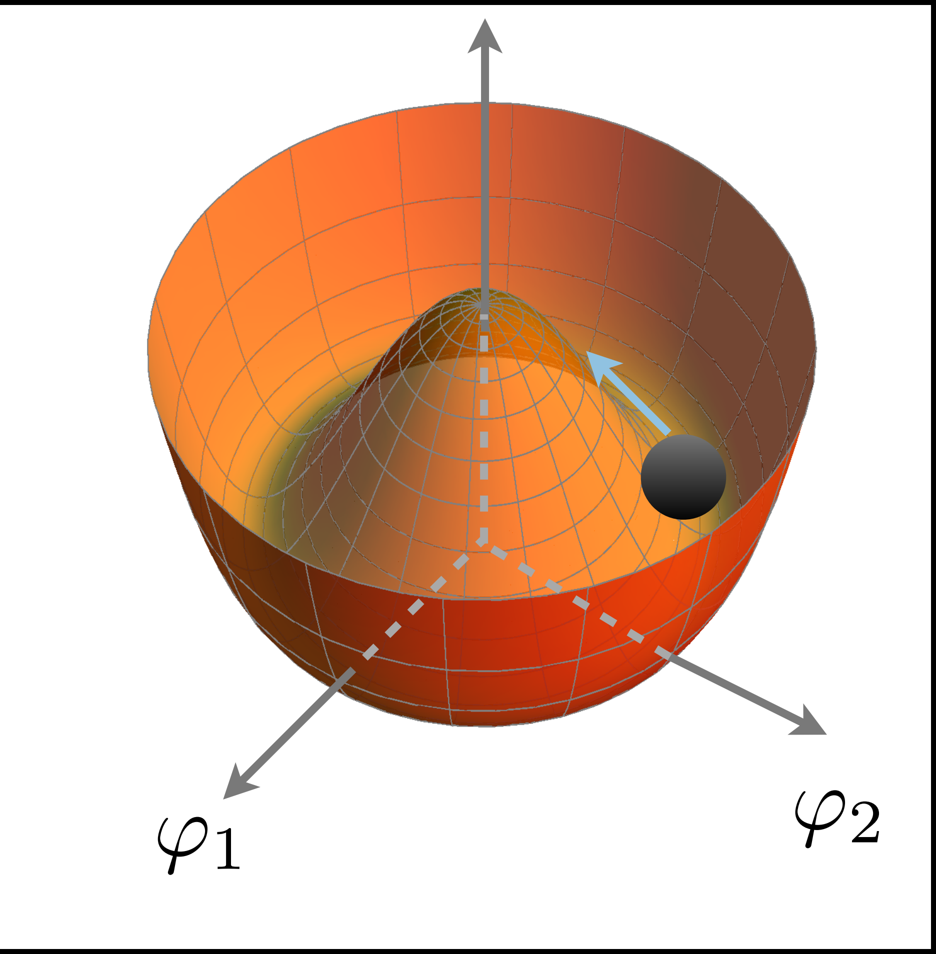

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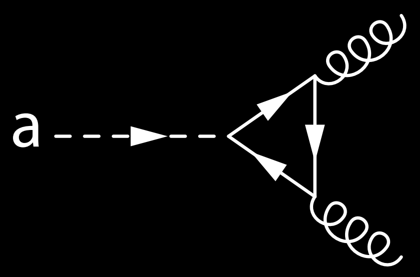

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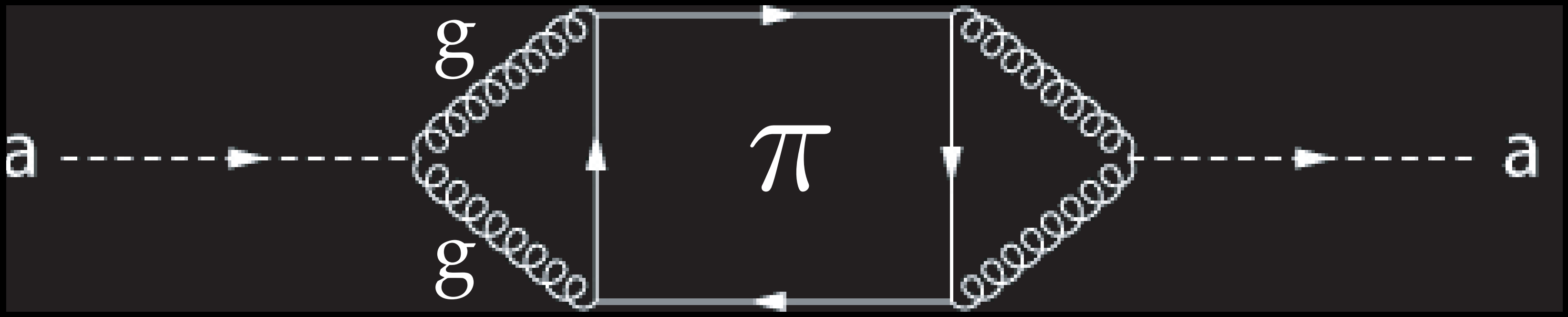

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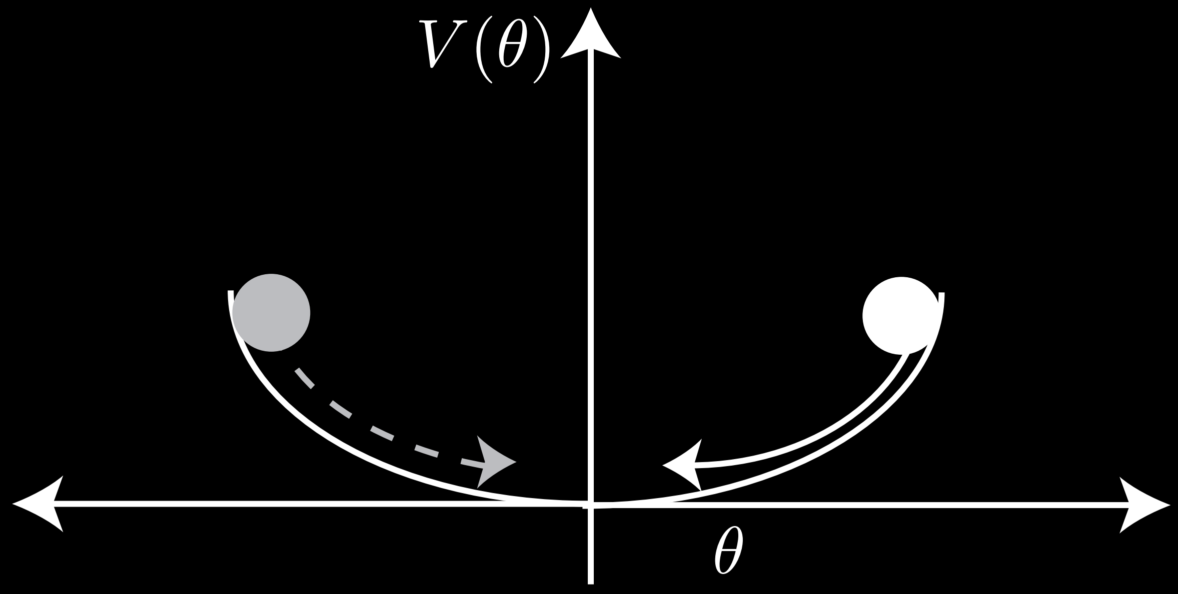
QCD axions are DM candidates

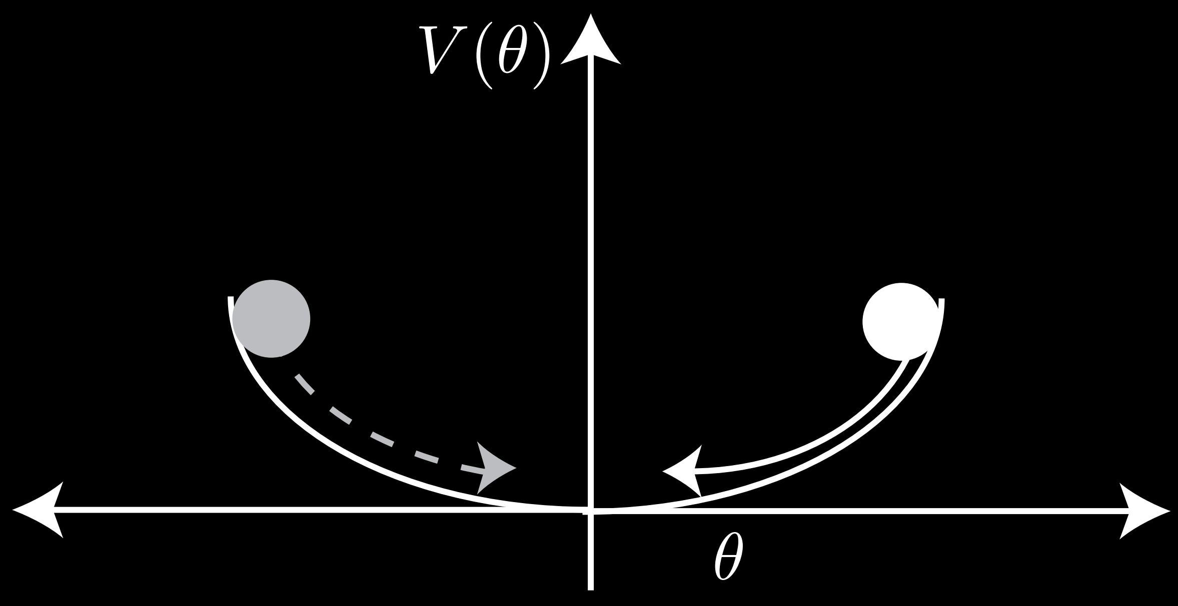
$m_a \lesssim 10^{-2}$ eV



* Field misaligned $m_a \gg 3H \rightarrow$ oscillation
* $\rho_a \propto (1+z)^3$ [as cold dark matter should]
* Axions **ARE** cold
  $v_a/c \lesssim 10^{-13}$ at CMB decoupling timescales

QCD axions are DM candidates

$m_a \lesssim 10^{-2}$ eV



The QCD axion is a cold dark matter candidate

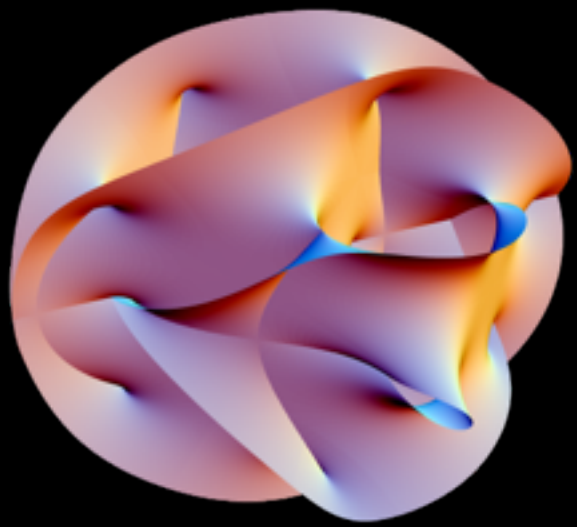
$$\Omega_{\text{mis}} h^2 = 0.236 \left\langle \theta_i^2 f(\theta_i) \right\rangle \left(\frac{m_a}{6.2 \mu\text{eV}} \right)^{-7/6}$$

Solves a problem in particle physics:
Gives us a dark matter candidate for free!

Papers by Turner + Steinhardt, Sikivie, Hagmann, Shellard, Abbott and others

ULTRA-LIGHT AXIONS (ULAS) IN STRING THEORY

* In string theory, extra dimensions compactified: Calabi-Yau manifolds



Ultra-light axions (ULAs) in string theory

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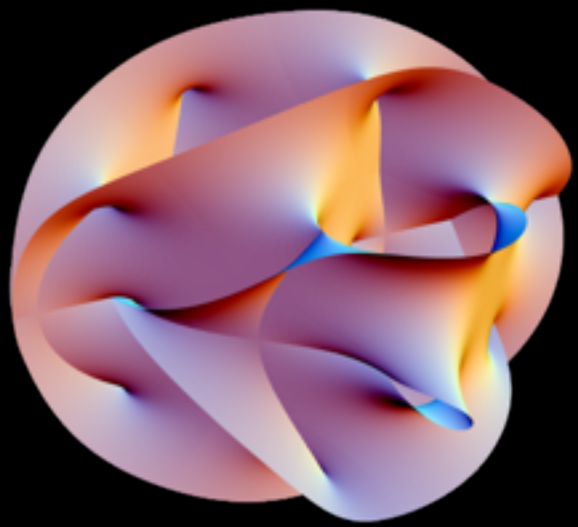
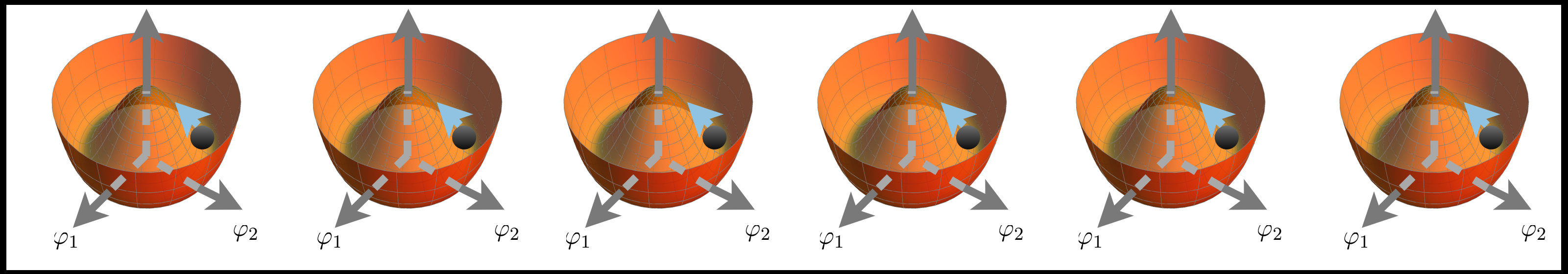


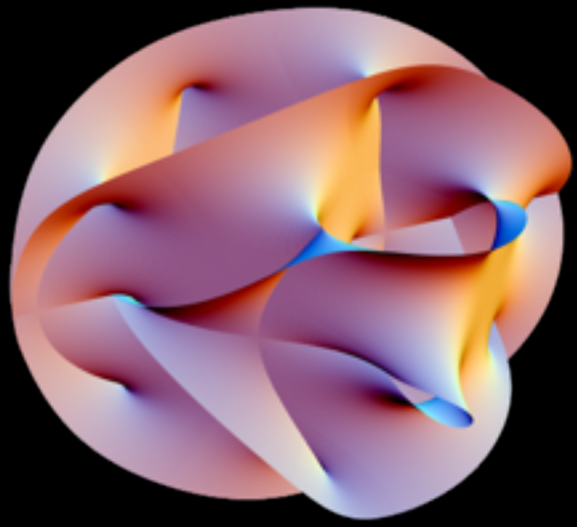


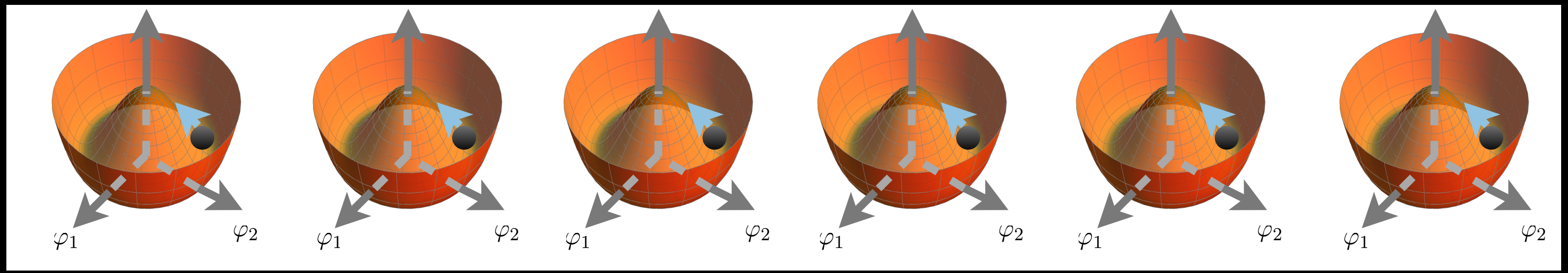
+....

Hundreds of scalars with approx shift symmetry

ULTRA-LIGHT AXIONS (ULAS) IN STRING THEORY

✳ In string theory, extra dimensions compactified: Calabi-Yau manifolds





+....

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Many axions

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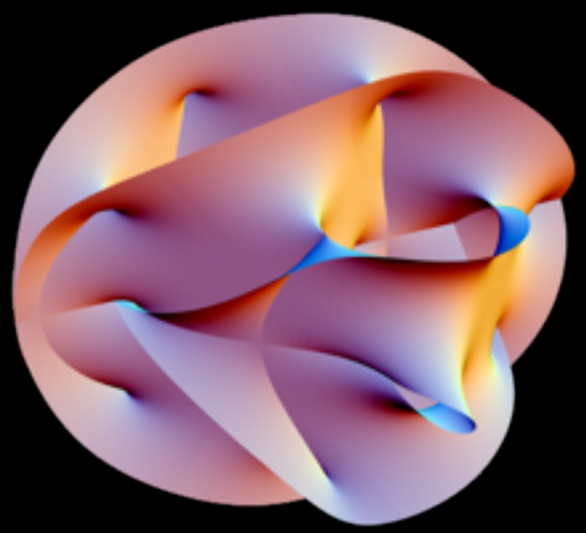
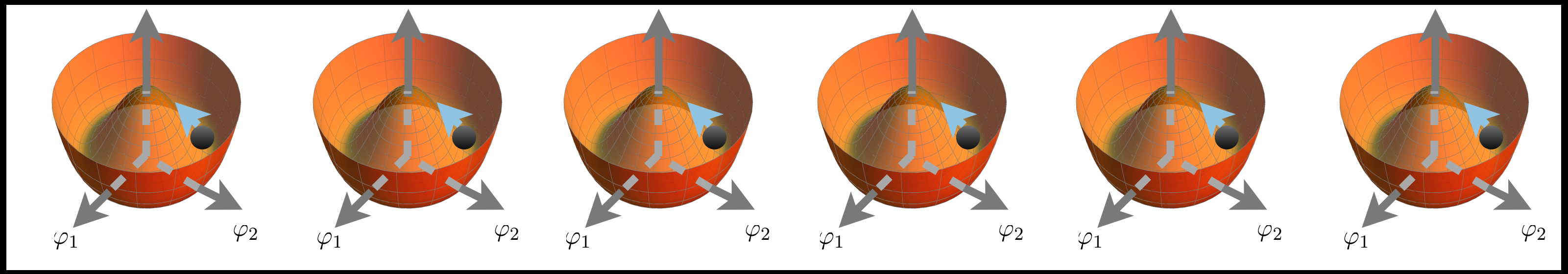




+....

Hundreds of scalars with approx shift symmetry

↓

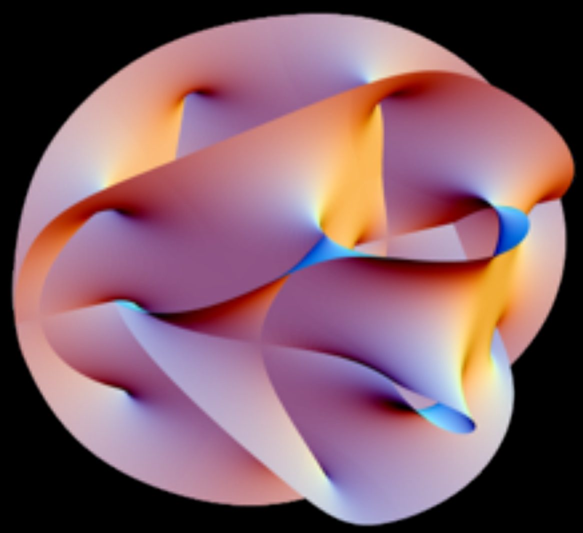
Many axions

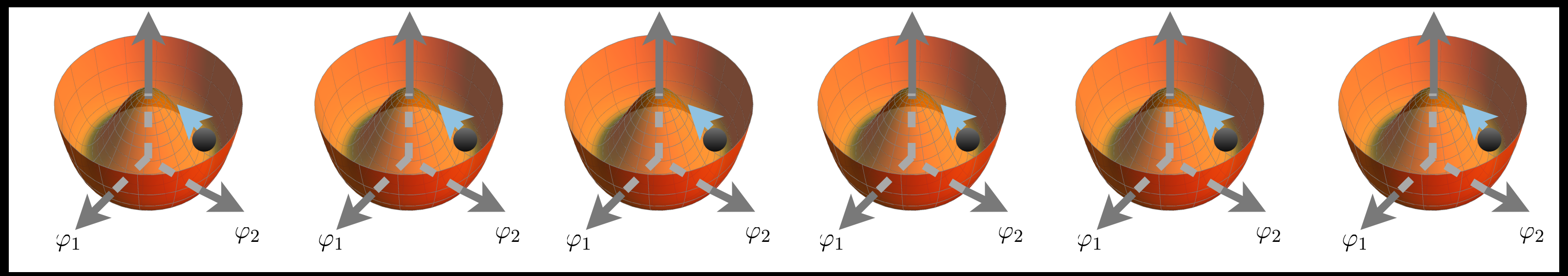
- ✳ Mass acquired non-perturbatively (instantons, D-Branes)

$$\boxed{m_a^2 = \frac{\mu^4}{f_a^2} e^{-\text{Volume}}}$$

ULTRA-LIGHT AXIONS (ULAS) IN STRING THEORY

✳ In string theory, extra dimensions compactified: Calabi-Yau manifolds





+....

Hundreds of scalars with approx shift symmetry

Many axions

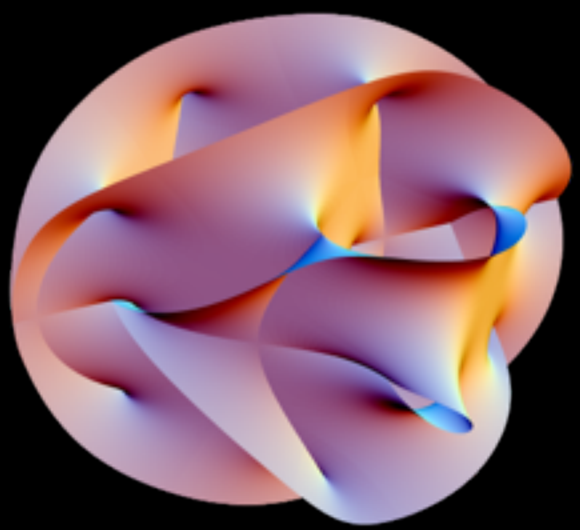
✳ Mass acquired non-perturbatively (instantons, D-Branes)

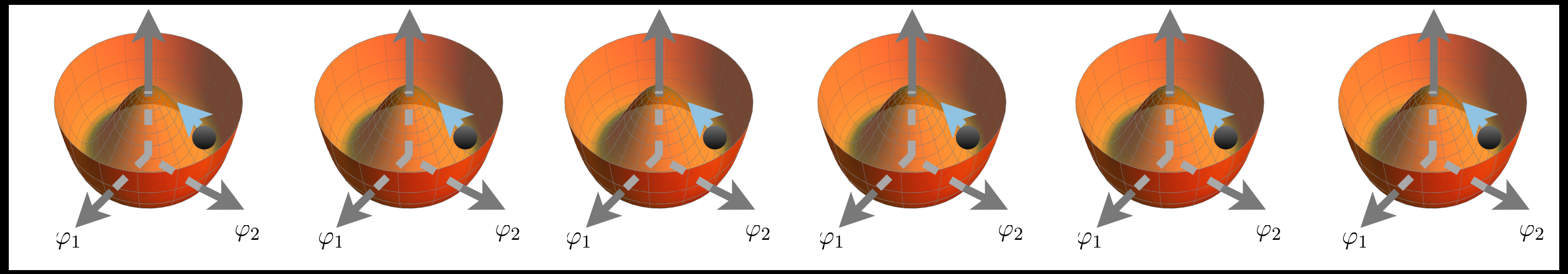
Scale of new ultra-violet physics

$$\boxed{m_a^2 = \frac{\mu^4}{f_a^2} e^{-\text{Volume}}}$$

ULTRA-LIGHT AXIONS (ULAS) IN STRING THEORY

✳ In string theory, extra dimensions compactified: Calabi-Yau manifolds





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↓

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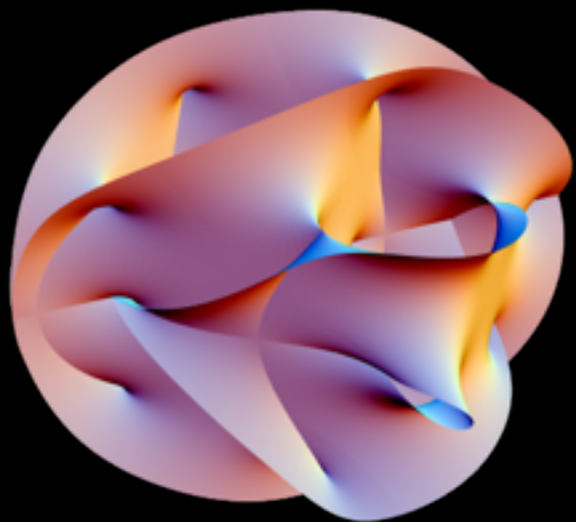
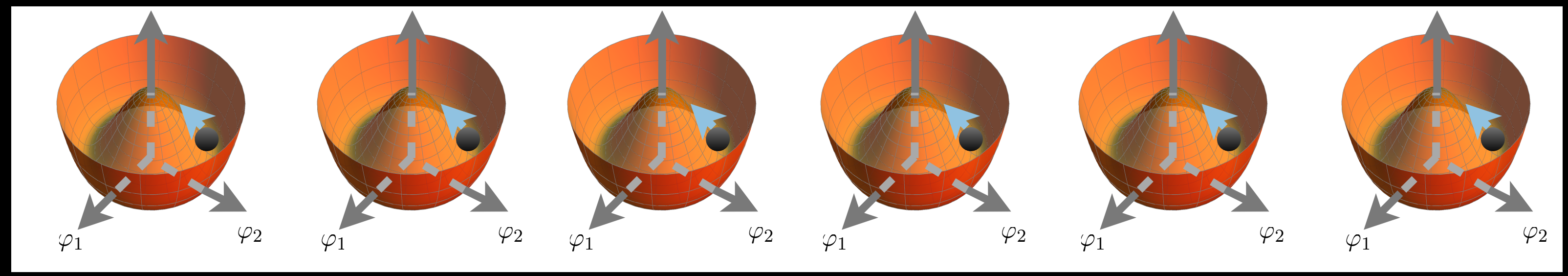
Scale of extra dimensions in Planck units

ULTRA-LIGHT AXIONS (ULAS) IN STRING THEORY

- In string theory, extra dimensions compactified: Calabi-Yau manifolds

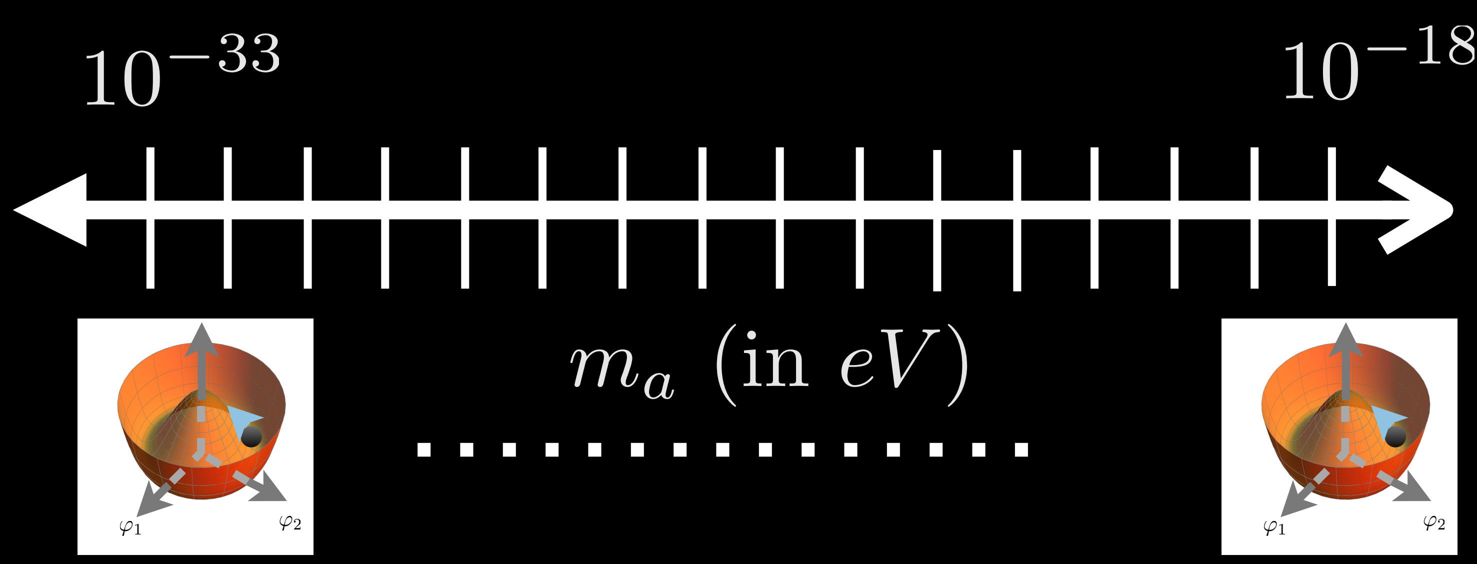




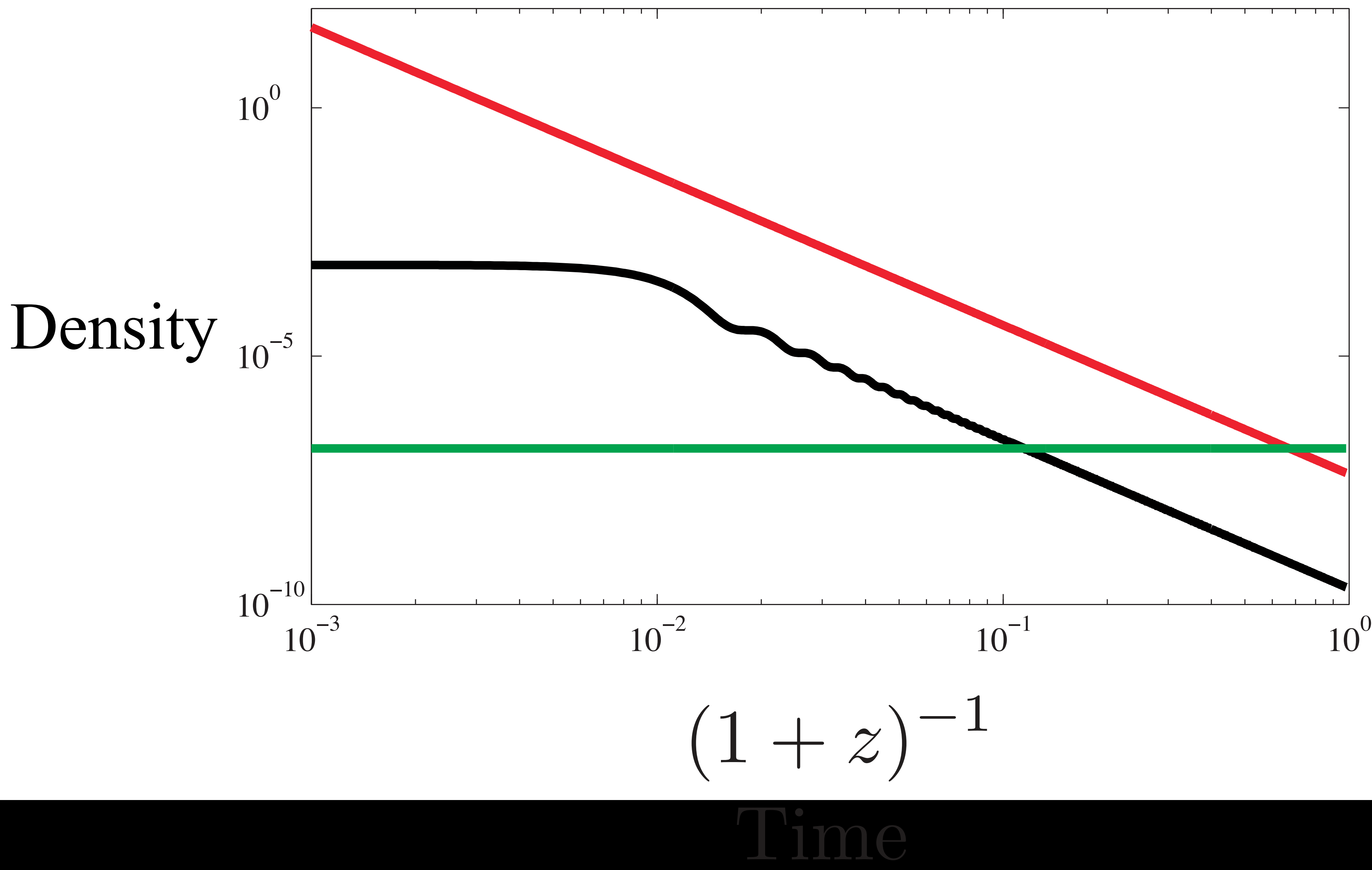
+....

Axiverse! *Arvanitaki+ 2009*

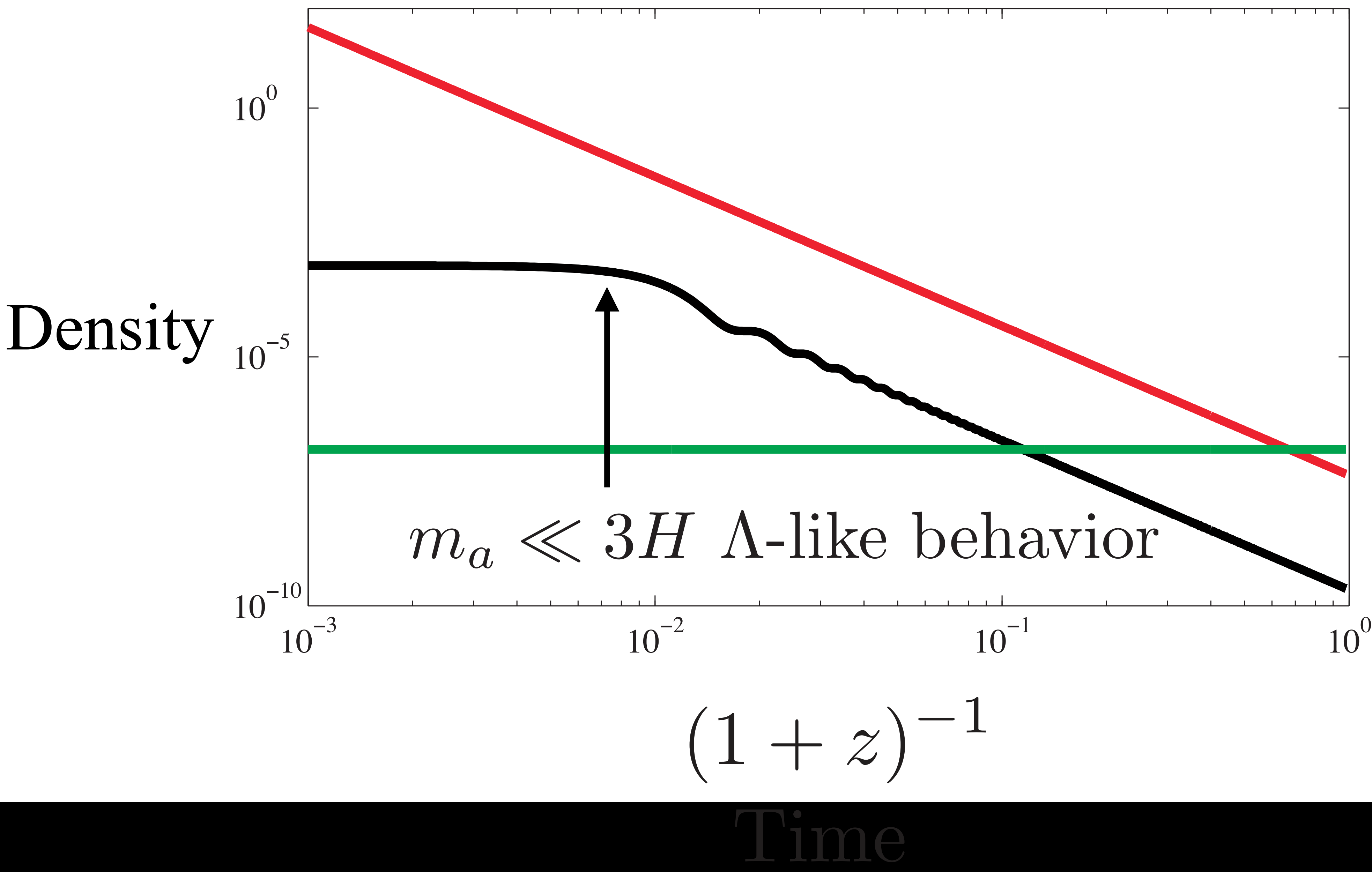
Witten and Srvcek (2006), Acharya et al. (2010), Cicoli (2012)



COSMOLOGY OF ULTRA-LIGHT AXIONS: DARK MATTER AND DARK ENERGY CANDIDATES



Cosmology of ultra-light axions: dark matter and dark energy candidates



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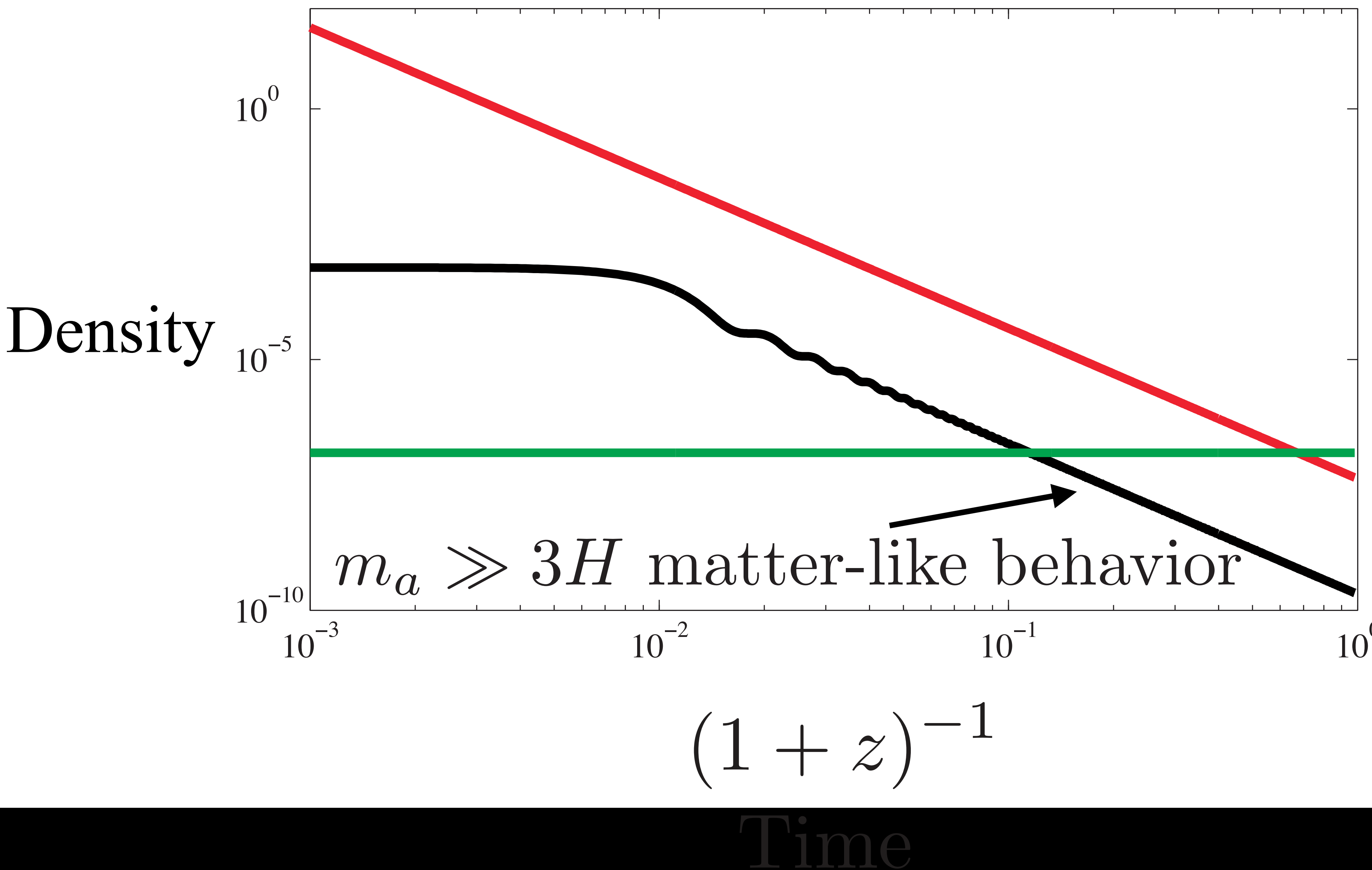
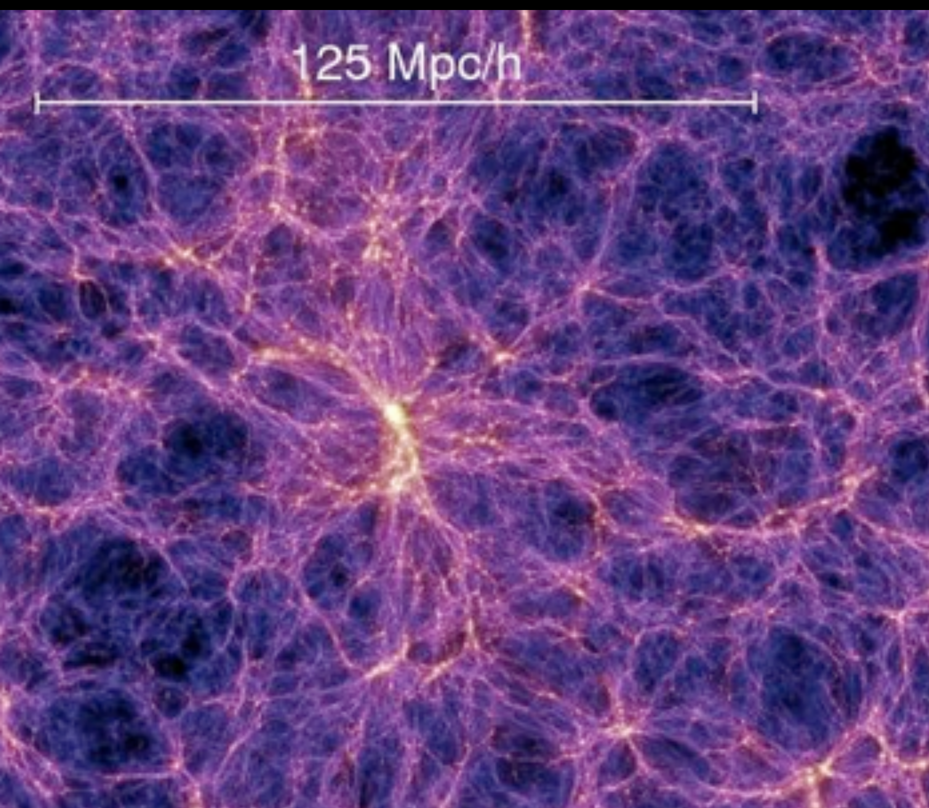
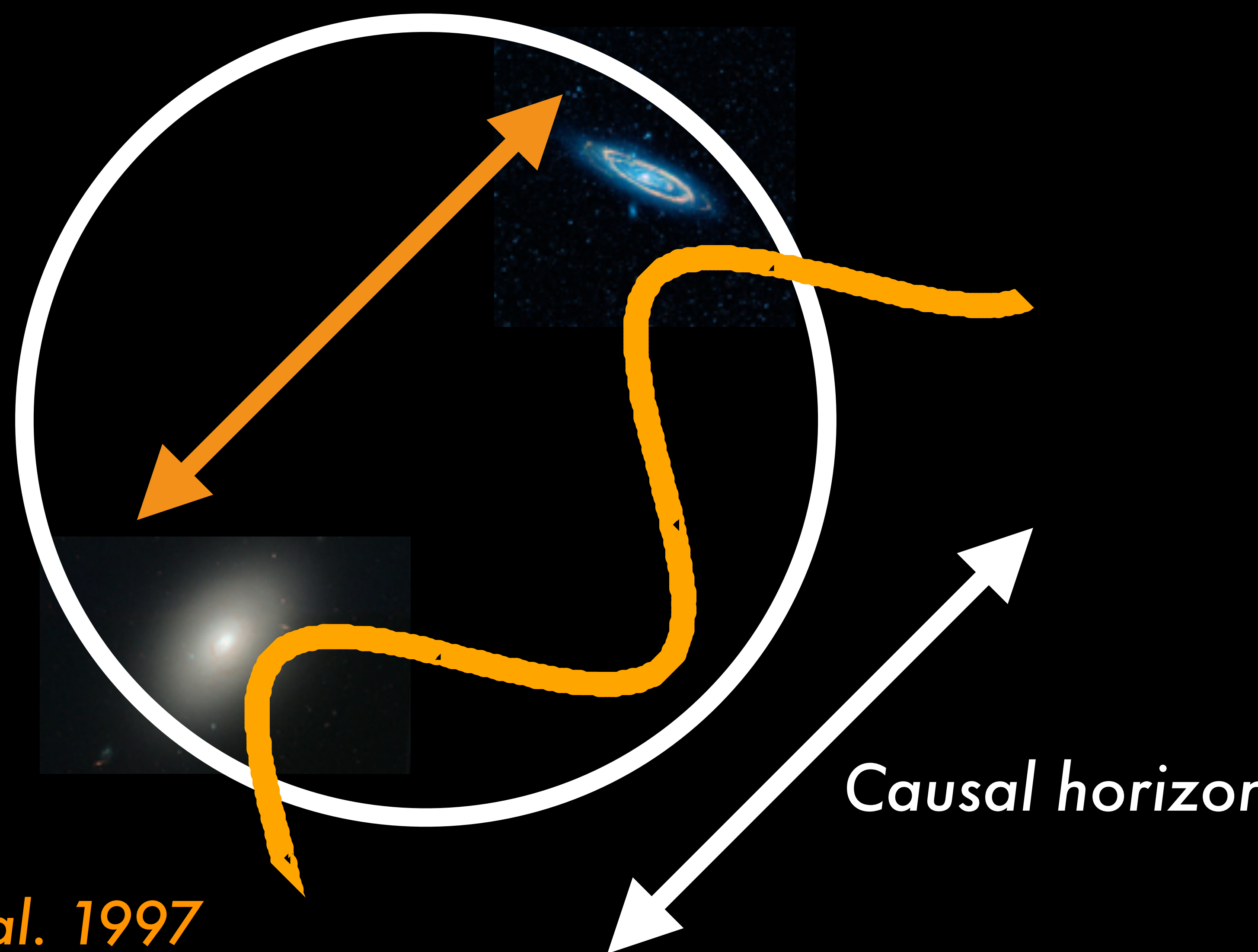


COSMOLOGY OF ULTRA-LIGHT AXIONS: DARK MATTER AND DARK ENERGY CANDIDATES

Scale corresponding to typical galaxy separation today





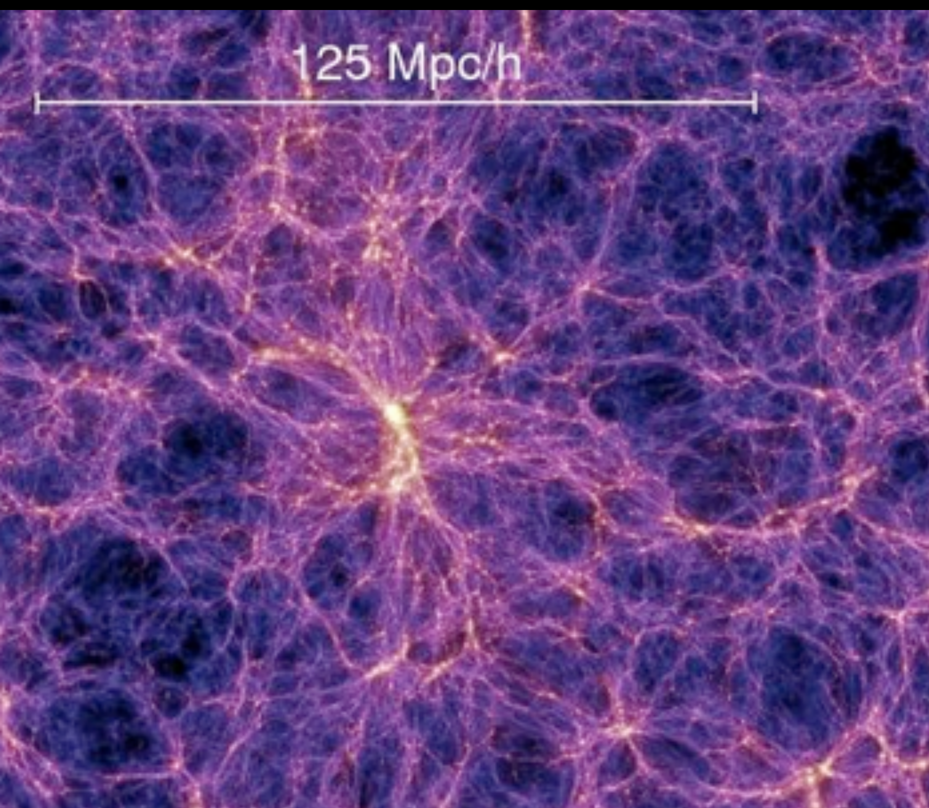
Frieman et al 1995, Coble et al. 1997

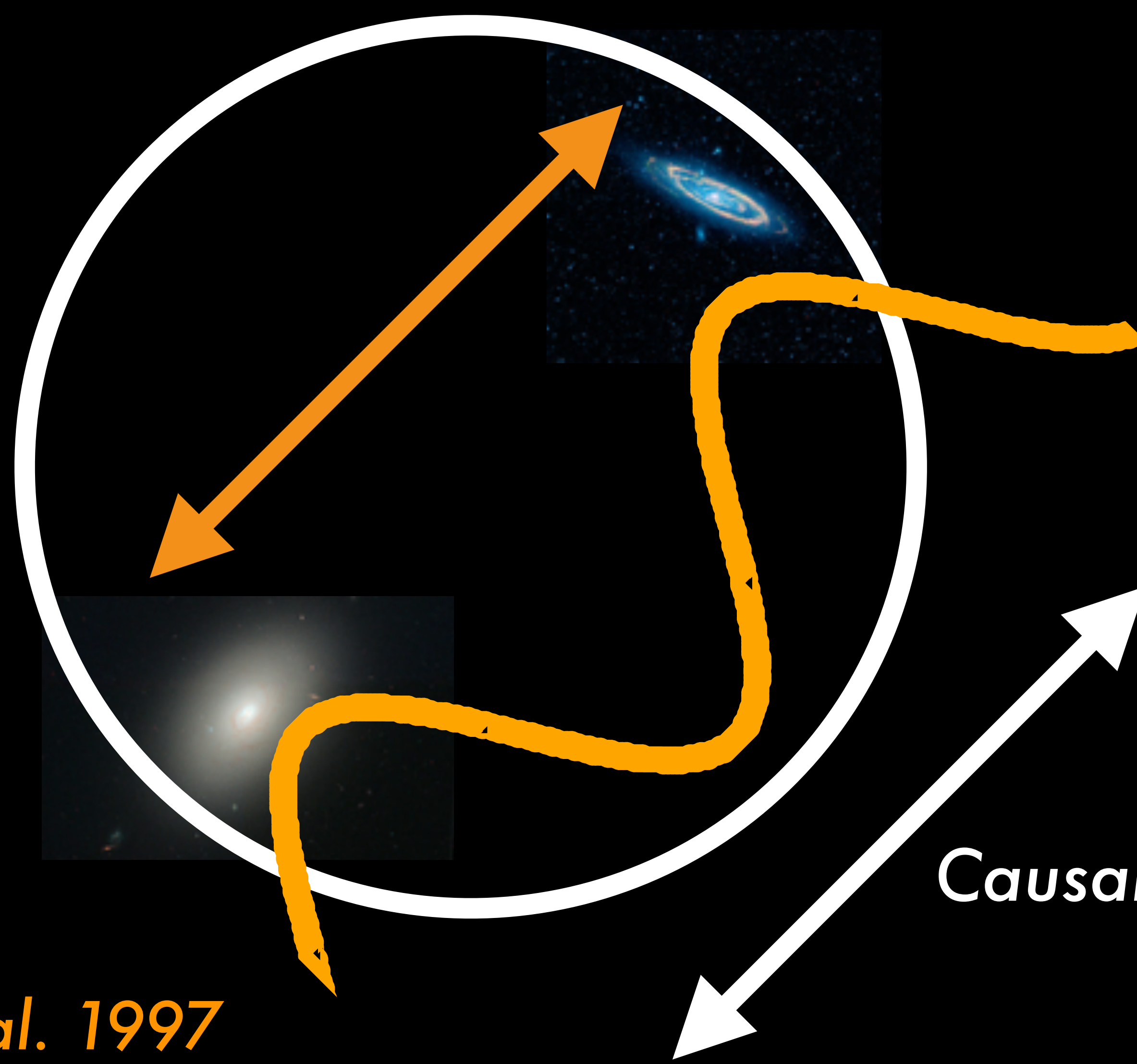
ULA as dark energy with specific w(z)

$m_a \lesssim 10^{-27}$ eV *ULA matter behavior starts too late for struct. formation*

Cosmology of ultra-light axions: dark matter and dark energy candidates

Scale corresponding to typical galaxy separation today





Frieman et al 1995, Coble et al. 1997

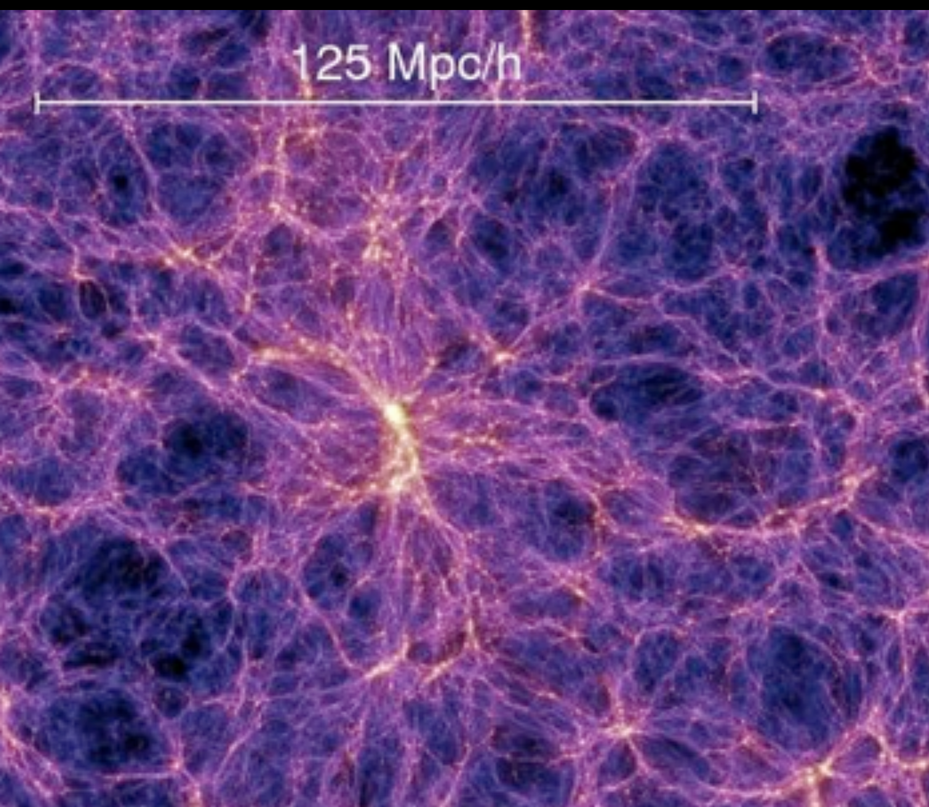
ULA as dark matter

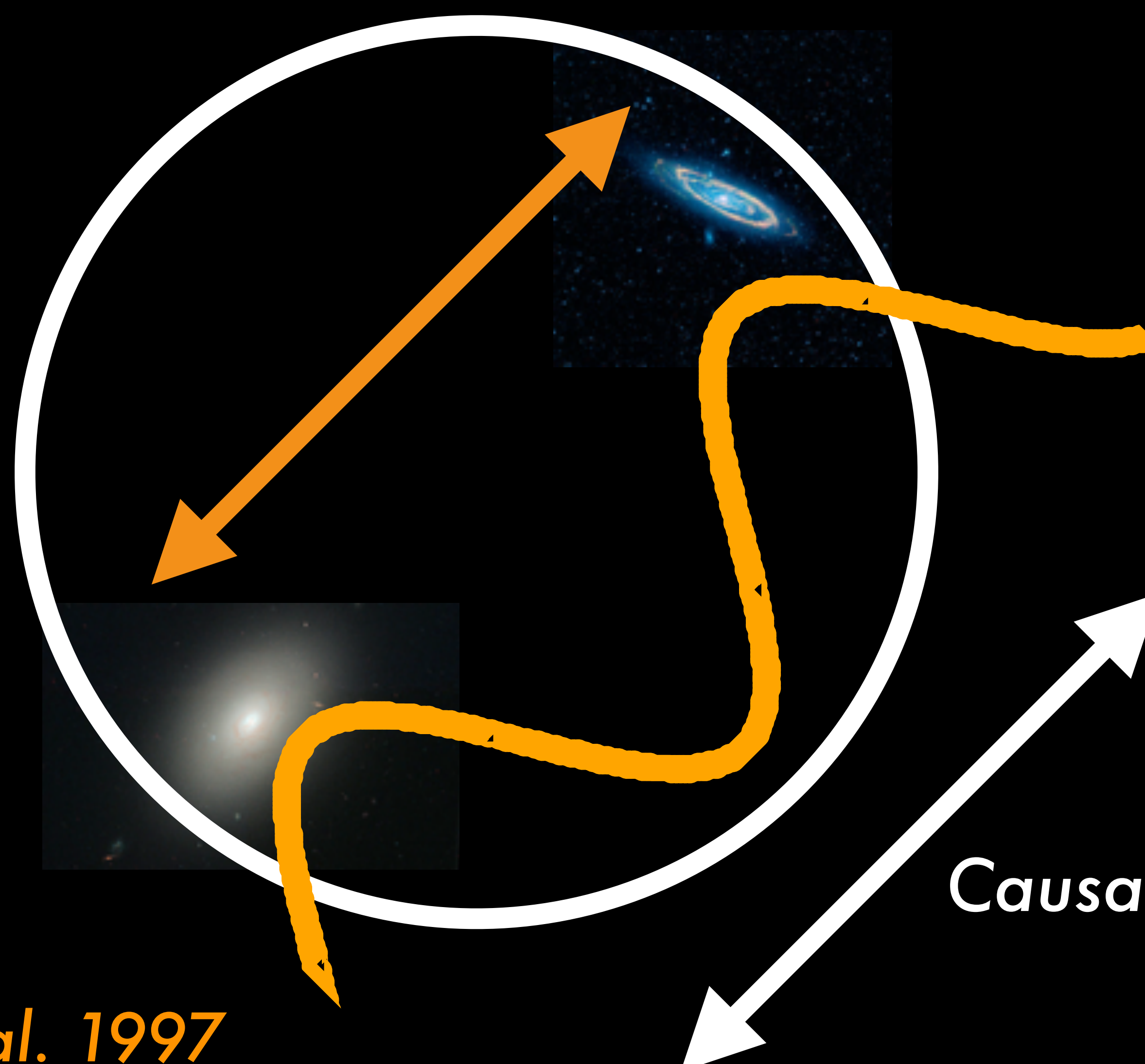
$$m_a \gtrsim 10^{-27}\ \mathrm{eV}$$

ULA matter behavior starts in time for struct. formation

Cosmology of ultra-light axions: dark matter and dark energy candidates

Scale corresponding to typical galaxy separation today





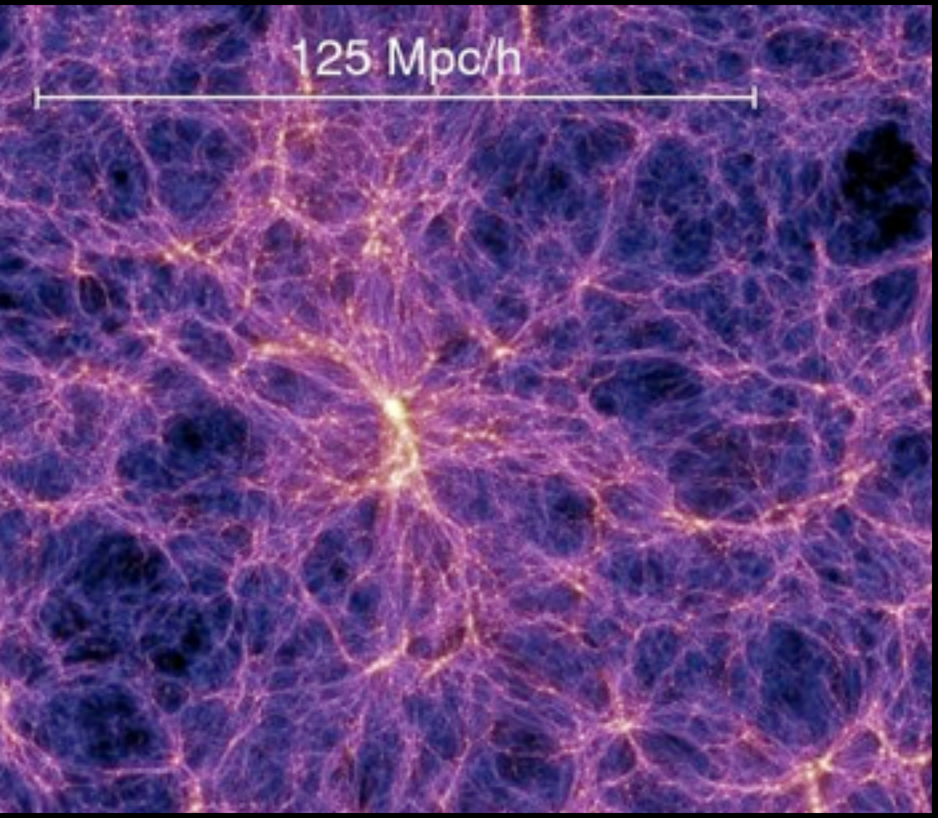
Causal horizon

Frieman et al 1995, Coble et al. 1997

Corresponds to time of matter/radiation equality, when

$$\rho_m = \rho_\gamma + \rho_\nu$$

Cosmology of ultra-light axions: dark matter and dark energy candidates



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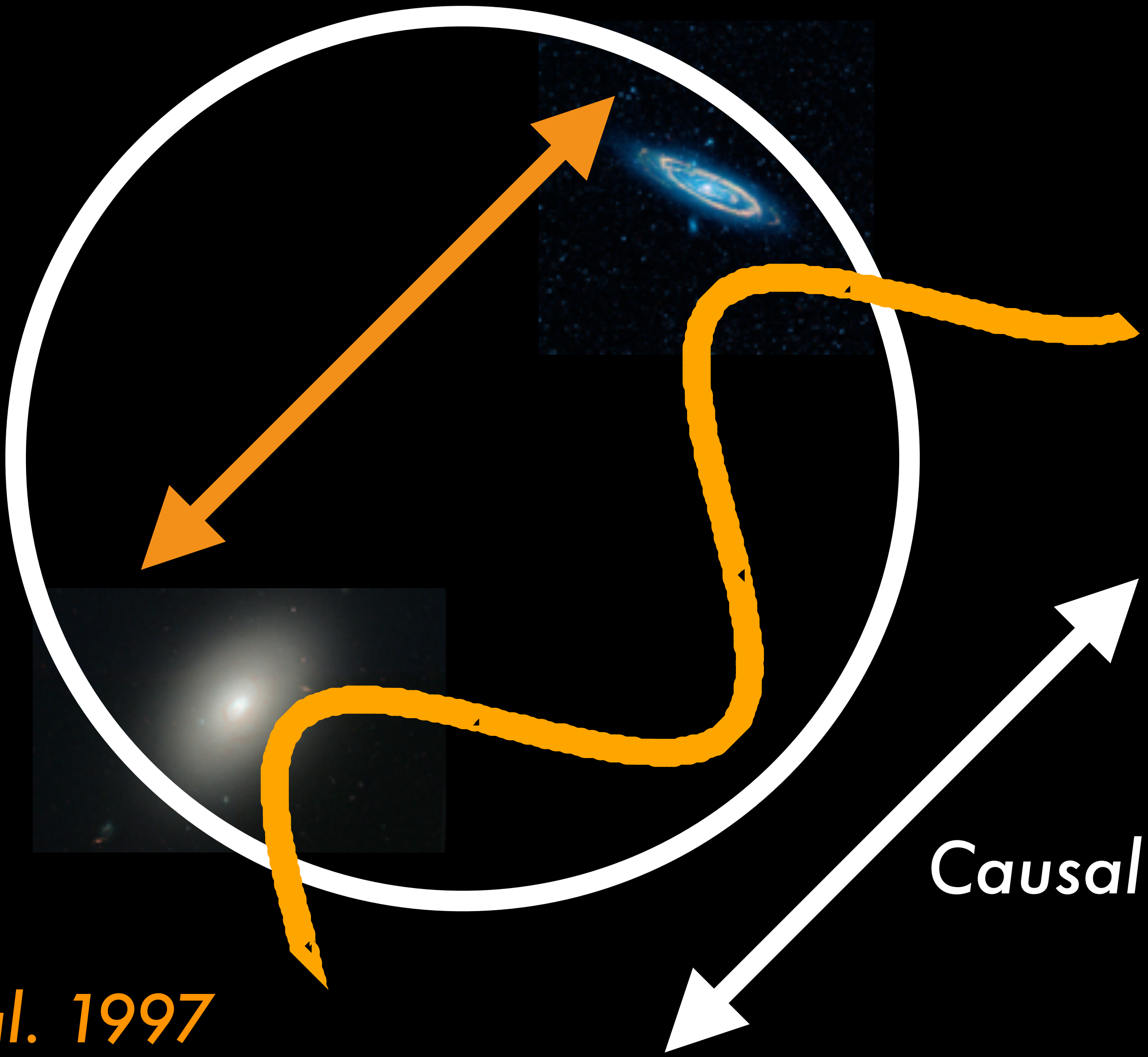


Frieman et al 1995, Coble et al. 1997

Simple relic density constraints: $10^{-33}\ \text{eV} < m_a < 10^{-18}\ \text{eV}$

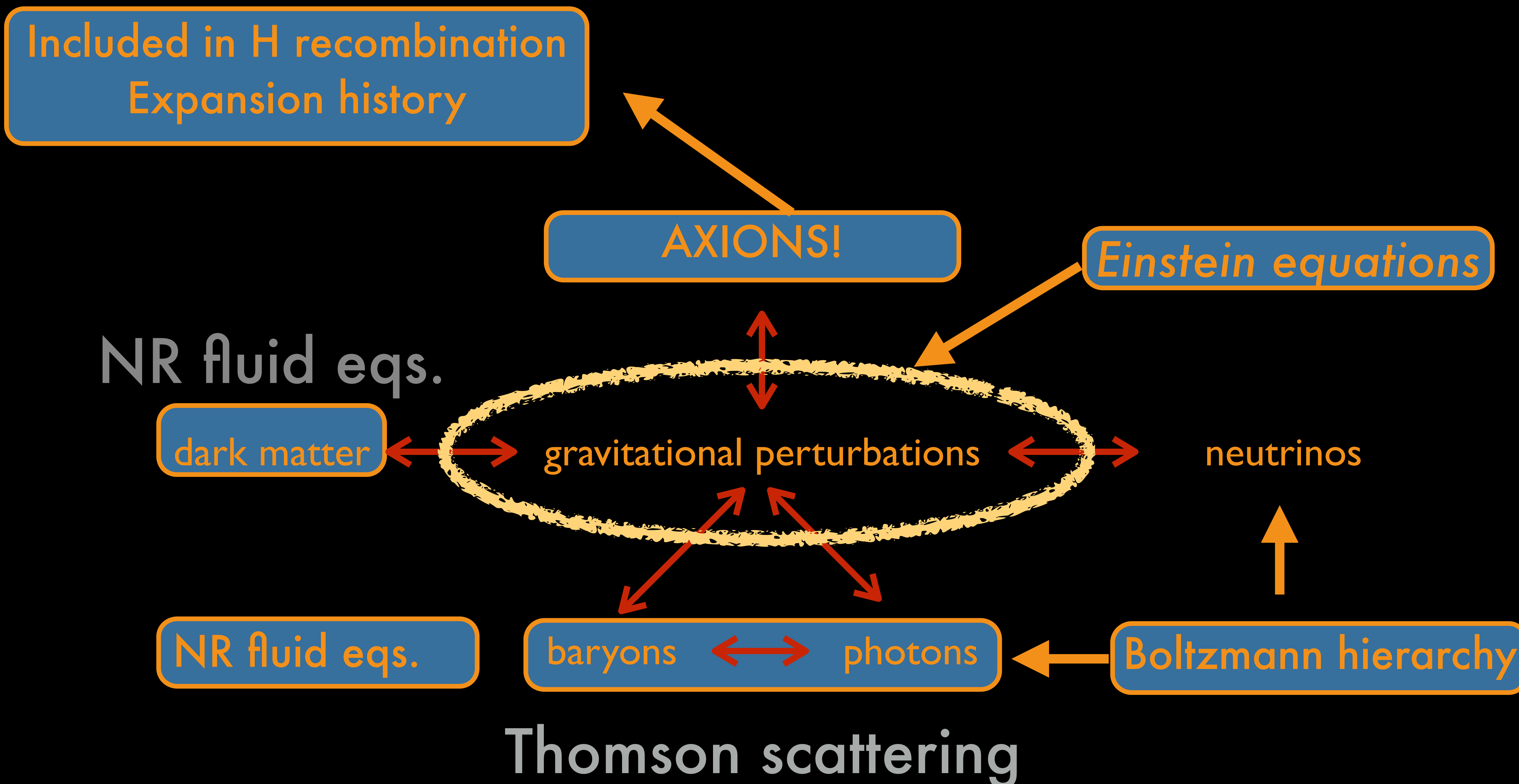
Ultra-light axions are dark matter and dark energy candidates

What about ultra-light axions (ULAs)?
Photon couplings are model-dependent:
Use gravity and cosmological data
to test ULAs

$$10^{-33}\ \mathrm{eV} < m_a < 10^{-18}\ \mathrm{eV}$$

AxiCAMB

CMB and matter perturbation code including ULAs!
Code in prep for public release as part of CosmoSIS package



ULA of any mass is self-consistently followed from DE to DM regime

GROWTH OF ULA PERTURBATIONS

✳ Perturbed Klein-Gordon + Gravity $\;k = 2\pi/\lambda :\;$ wavenumber

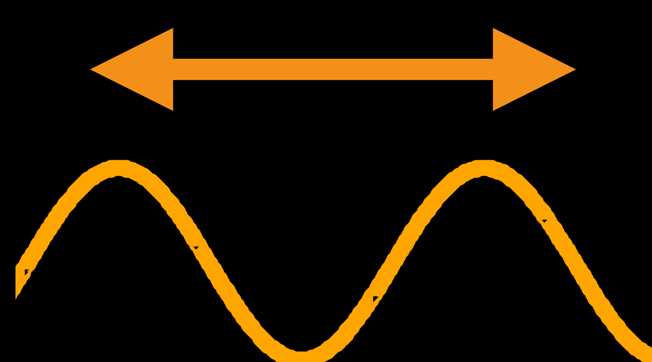
$$\ddot{\delta\phi} + 2\mathcal{H}\delta\dot{\phi} + (k^2 + m_a^2 a^2)\delta\phi = \mathcal{O}(H^2, m^2)\Psi$$

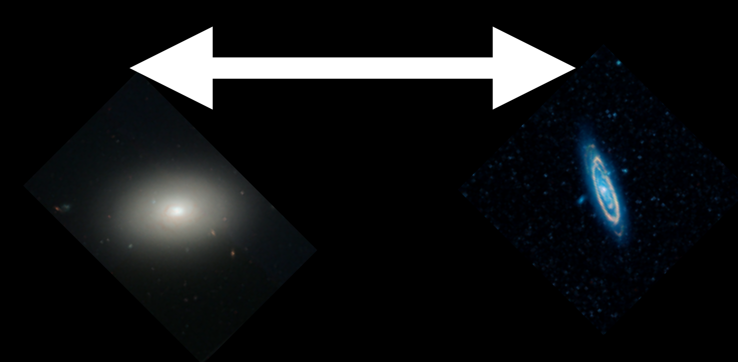
✳ Axionic Jeans Scale is macroscopic [in contrast to QCD axion]:

$$\lambda_J = 2.5\ \mathrm{Mpc}\left(\frac{m_a}{10^{-25}\ \mathrm{eV}}\right)^{-1/2} h^{-1/2}$$

Axion deBroglie wavelength

Macroscopic length scale





GROWTH OF ULA PERTURBATIONS

✳ Perturbed Klein-Gordon + Gravity $k = 2\pi/\lambda$: wavenumber

$$\delta\ddot{\phi} + 2\mathcal{H}\delta\dot{\phi} + (k^2 + m_a^2 a^2)\delta\phi = \mathcal{O}(H^2, m^2)\Psi$$

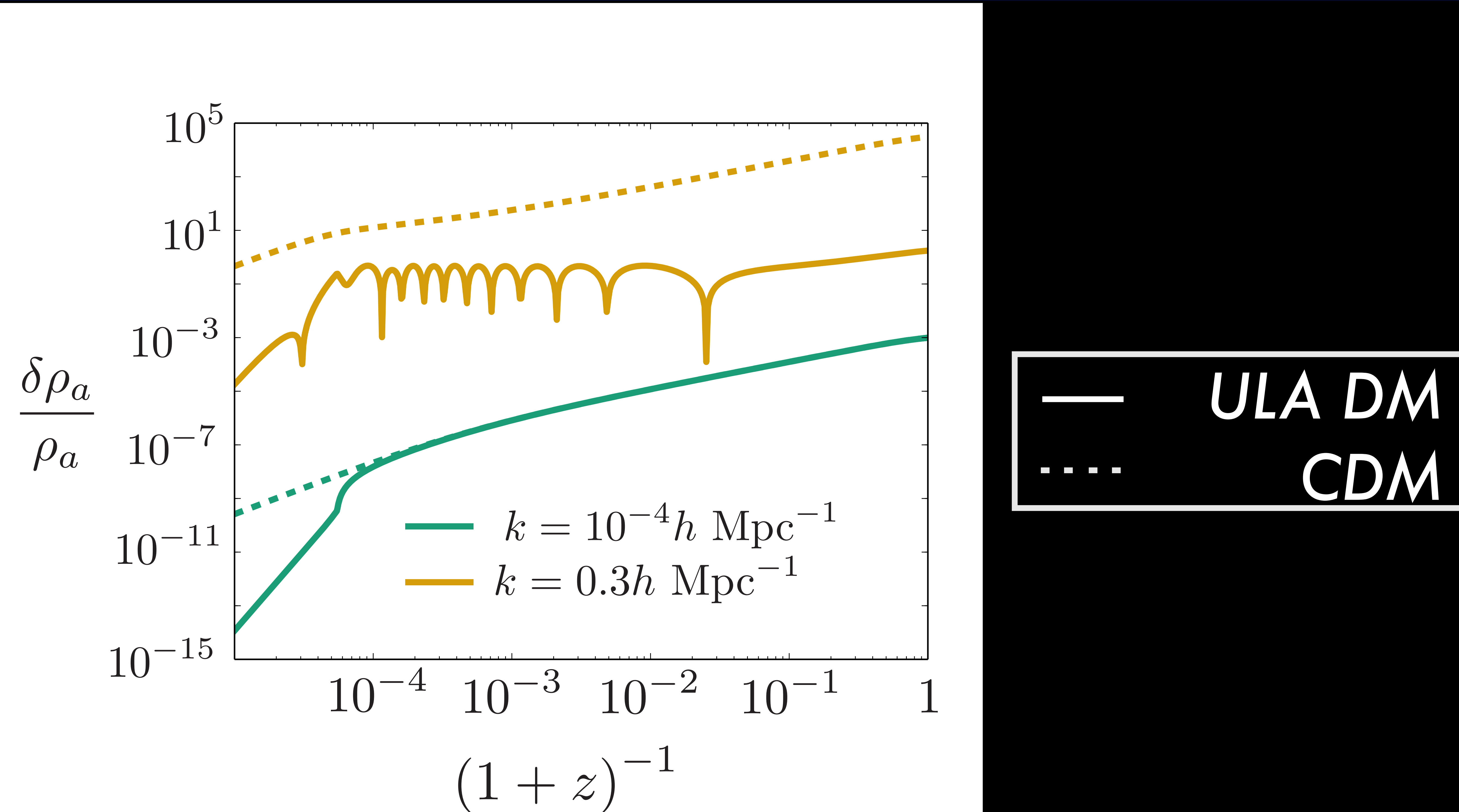
✳ Axionic Jeans Scale is macroscopic [in contrast to QCD axion]:

✳ Computing observables is expensive for $m_a \gg 3H$:

- ✳ Coherent oscillation requires prohibitive time step
- ✳ WKB approximation at late time, exact KG early times

$$\boxed{c_a^2 = \frac{\delta P_a}{\delta \rho_a} = \frac{k^2/m_a^2}{4/(1+z)^2 + k^2/m_a^2}}$$

Growth of ULA perturbations

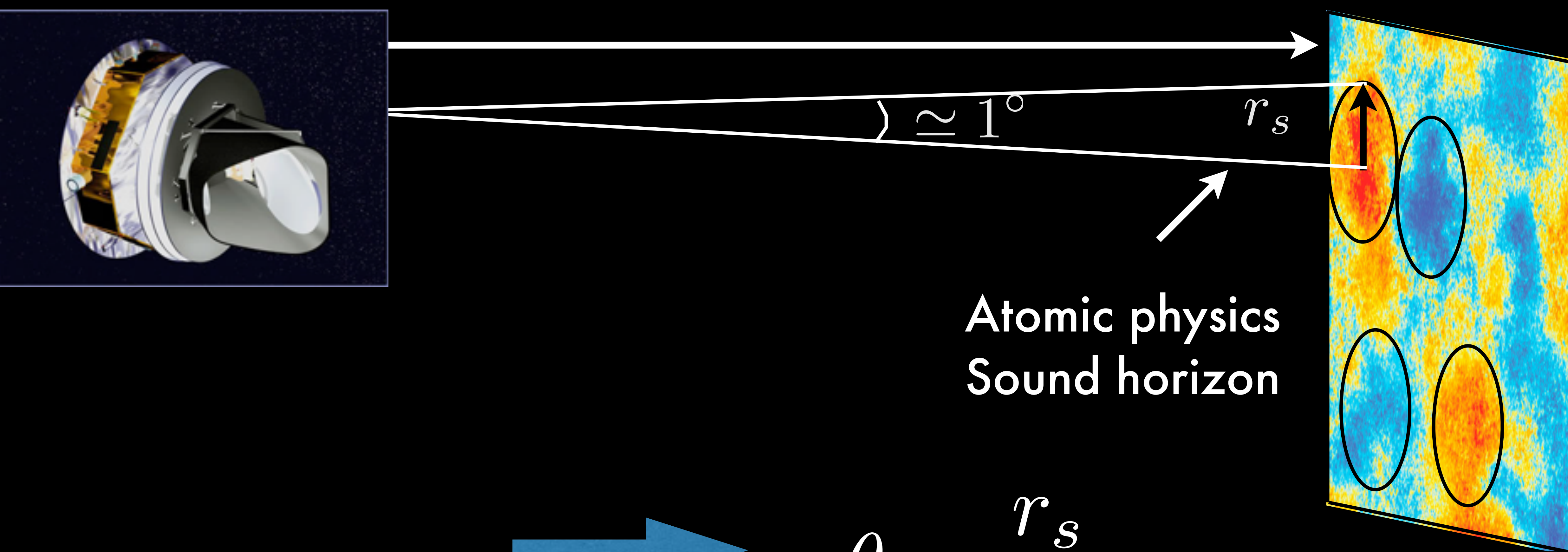


✴Pressure stabilization for modes with $k \gg k_{\mathrm{J}} \sim \sqrt{m\mathcal{H}}$

✴Otherwise ULAs behave like cold dark matter (CDM)

ULAs as dark energy and the angular sound horizon

D (sensitive to any energy source)

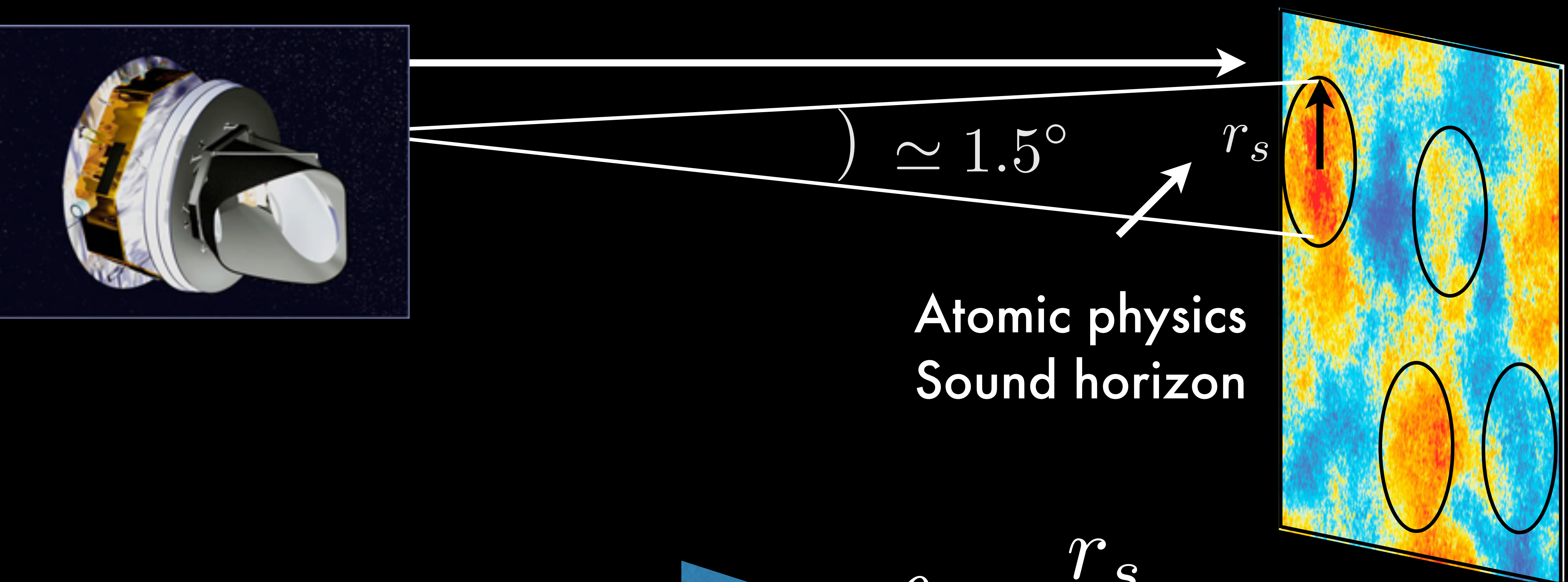


$$\theta = \frac{r_s}{D}$$

Fig. modified from T. Smith with permission

ULAs as dark energy and the angular sound horizon

D (sensitive to any energy source)

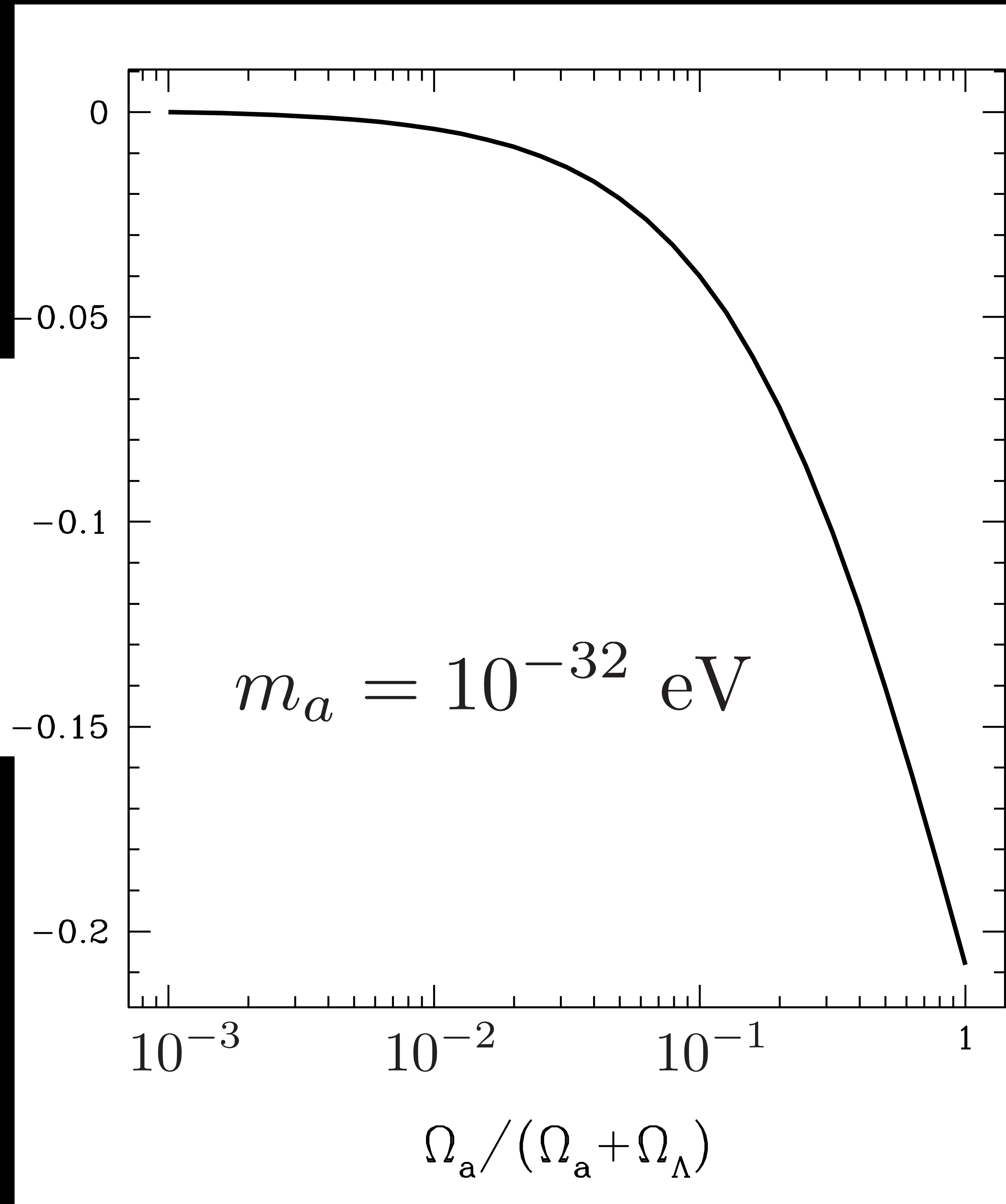


$$\theta = \frac{r_s}{D}$$

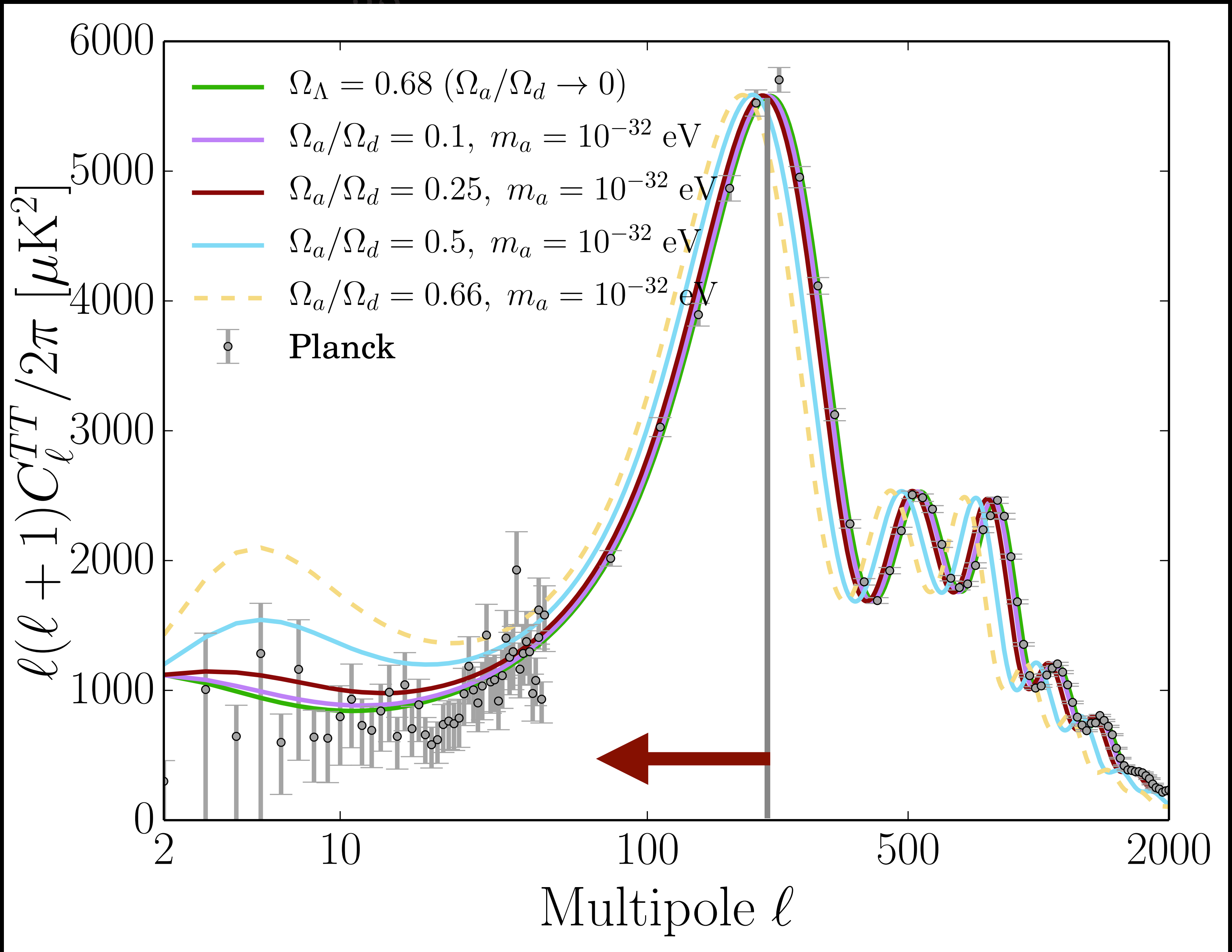
Fig. modified from T. Smith with permission

ULAs as dark energy and the angular sound horizon

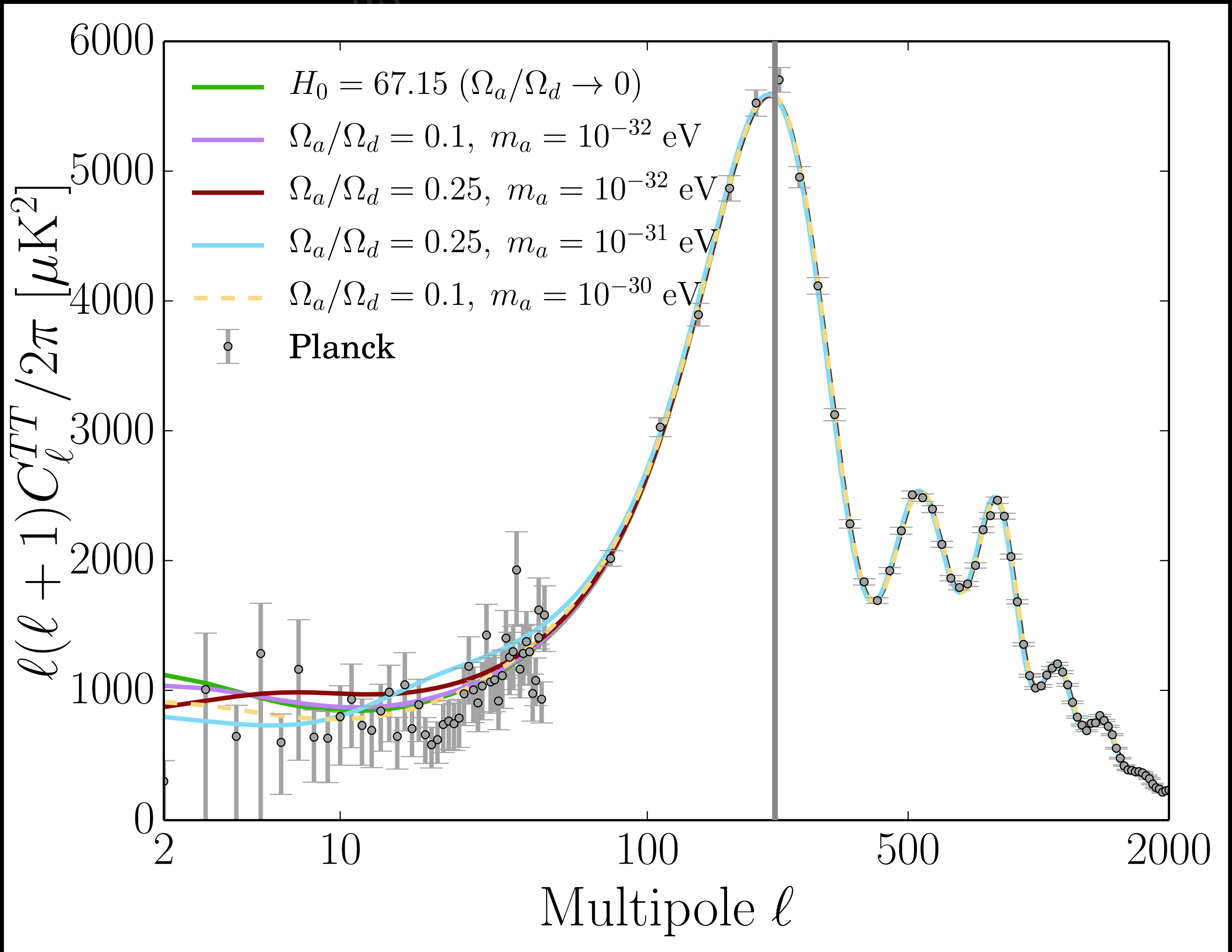
$$\frac{D(z_{\rm decoupling}) - D^{\rm axion}(z^{\rm axion}_{\rm decoupling})}{D(z_{\rm decoupling})}$$



ULAs as dark energy and the angular sound horizon



ULAs as dark energy and the angular sound horizon



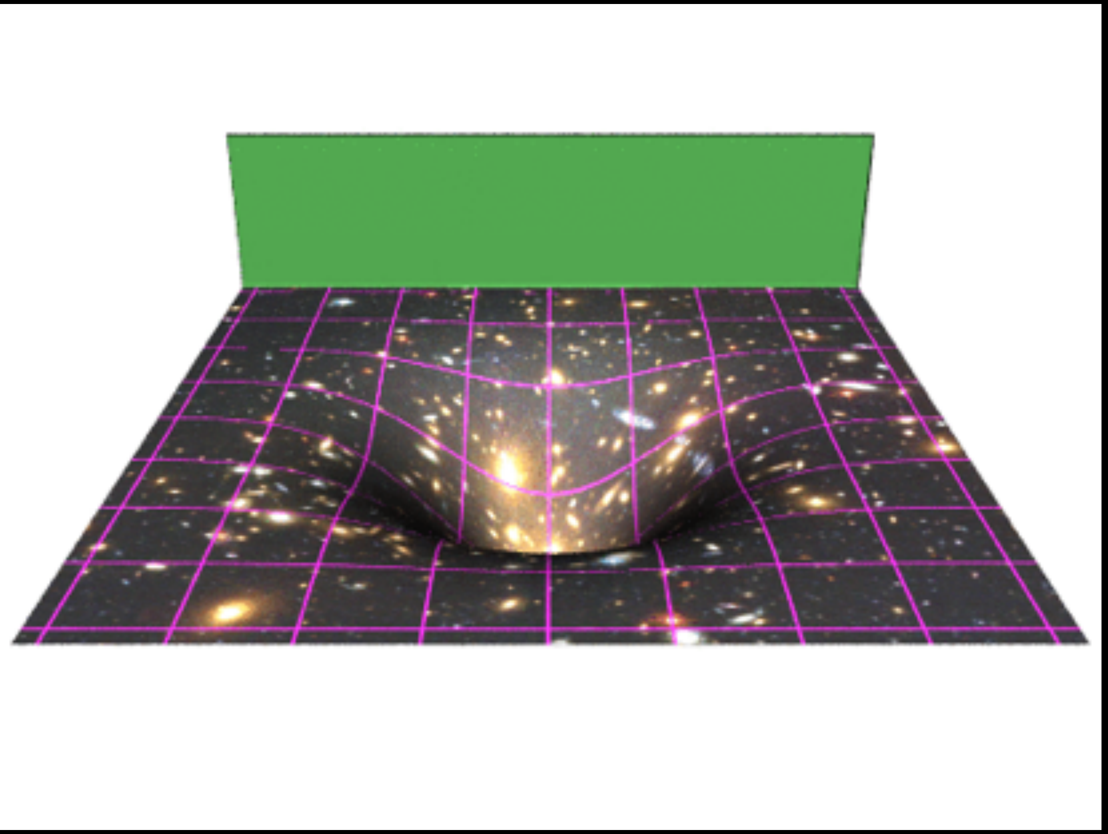
$$\theta_s \equiv \frac{r_s}{d_A(z=1100)} = \left(l_{\rm CMB}^{\rm peak}\right)^{-1}$$

$$d_A \propto \int \frac{dz}{H(z)}$$

Absorb and lock onto usual peaks by lowering H_0

ULAs as dark energy and perturbations in other fluids

Low mass (DE-like) case: late Integrated Sachs-Wolfe Effect

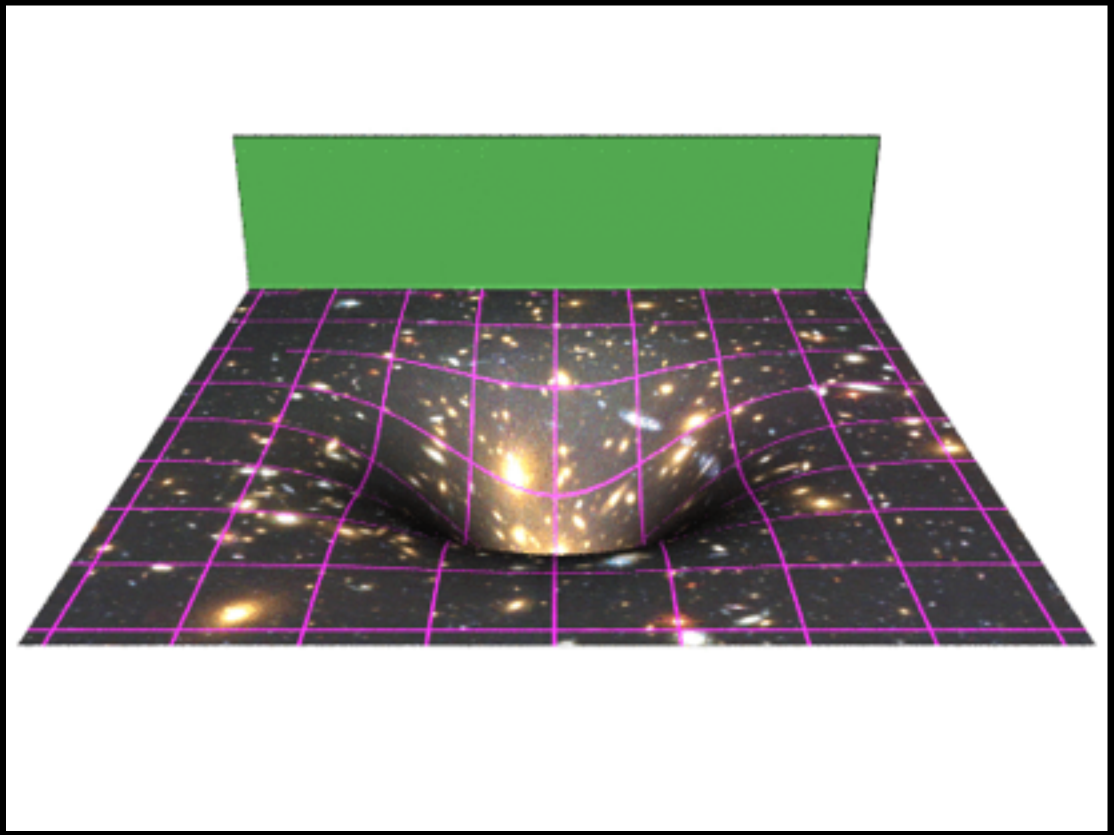


CMB temperature anisotropies from potential decay

$$\Delta T_{\rm ISW} = -2\int_0^{\eta_{\rm dec}} d\eta \dot{\Phi}(\eta, \hat{n}\eta)$$

ULAs as dark energy and perturbations in other fluids

Low mass (DE-like) case: late Integrated Sachs-Wolfe Effect

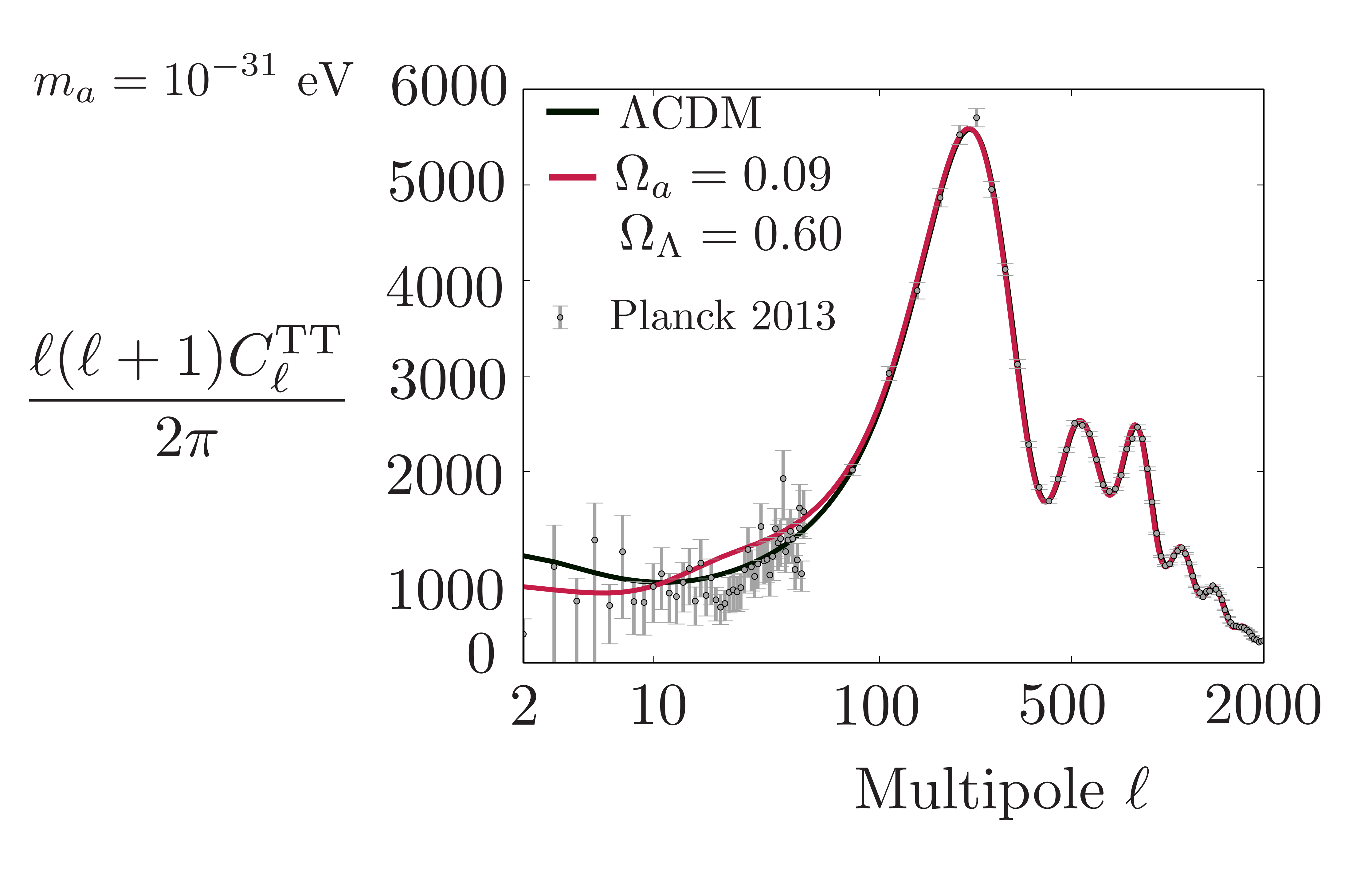


CMB temperature anisotropies from potential decay

$$\Delta T_{\rm ISW} = -2\int_0^{\eta_{\rm dec}} d\eta \dot{\Phi}(\eta, \hat{n}\eta)$$

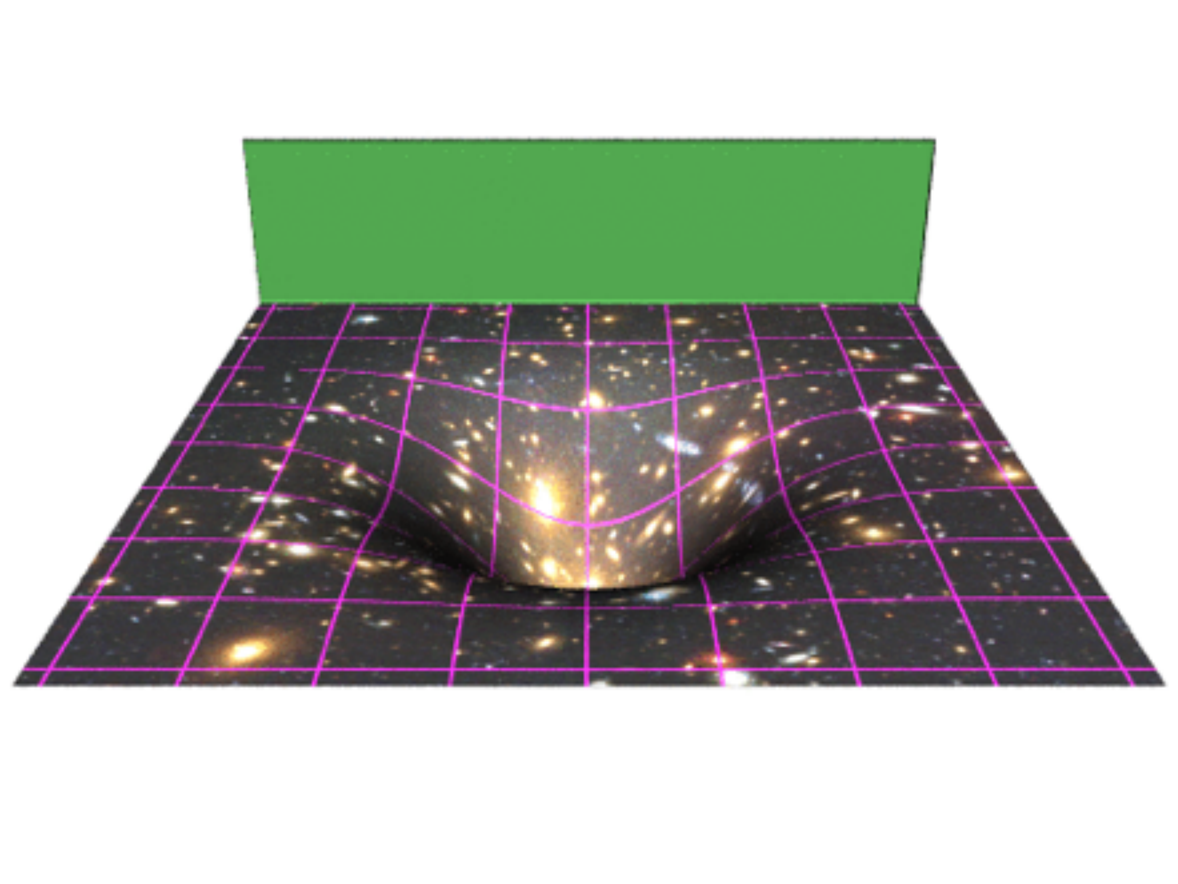
ULAs as dark energy and perturbations in other fluids

Low mass (DE-like) case: late Integrated Sachs-Wolfe Effect



ULAs and the CMB: high mass and early ISW

Higher mass (DM-like) case: high-l ISW



CMB temperature anisotropies from potential decay

$$\Delta T_{\rm ISW} = -2\int_0^{\eta_{\rm dec}} d\eta \dot{\Phi}(\eta, \hat{n}\eta)$$

$$\boxed{\Phi \propto \frac{1}{k^2}\left\{\frac{\Omega_m\delta_m\left(1-\frac{\Omega_a}{\Omega_m}\right)}{a^3}+\frac{\delta_R\Omega_R}{a^4}\right\}}$$

ULAs and the CMB: high mass and early ISW

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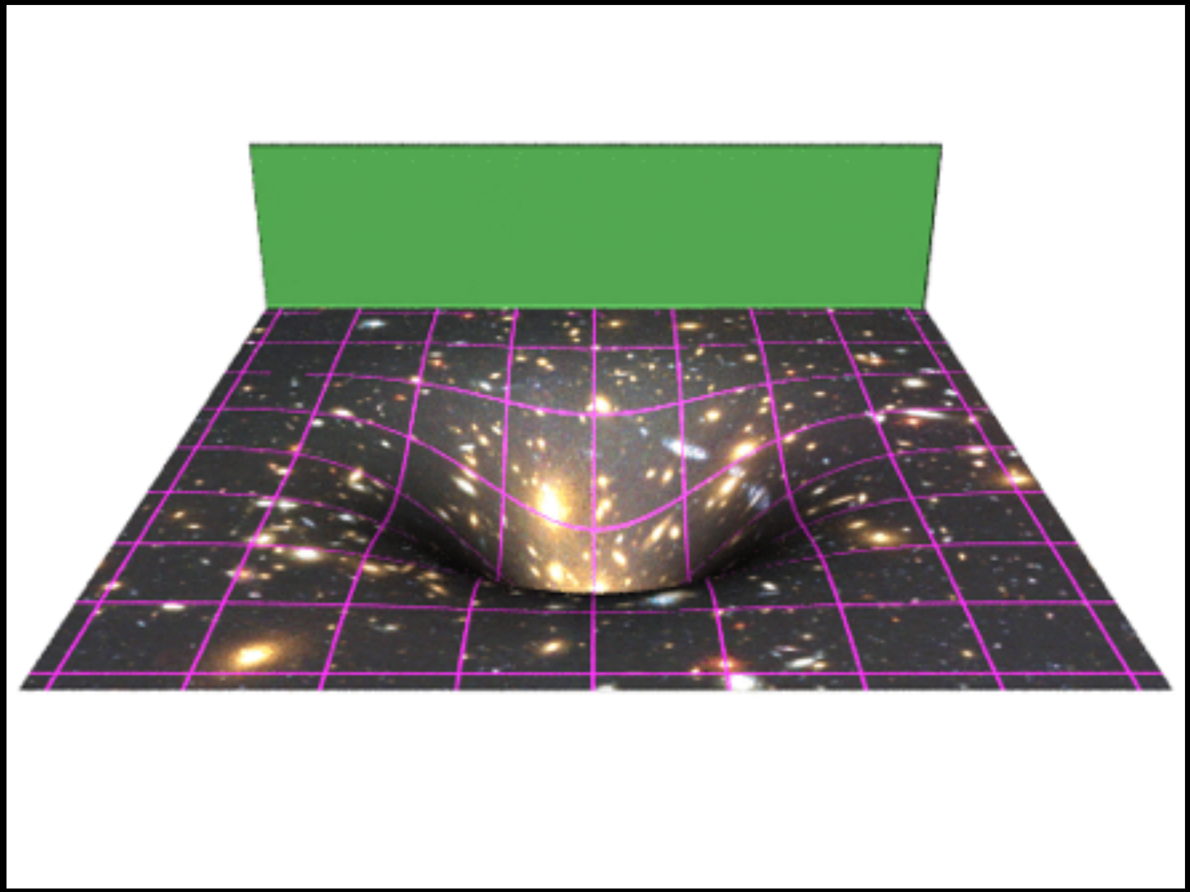

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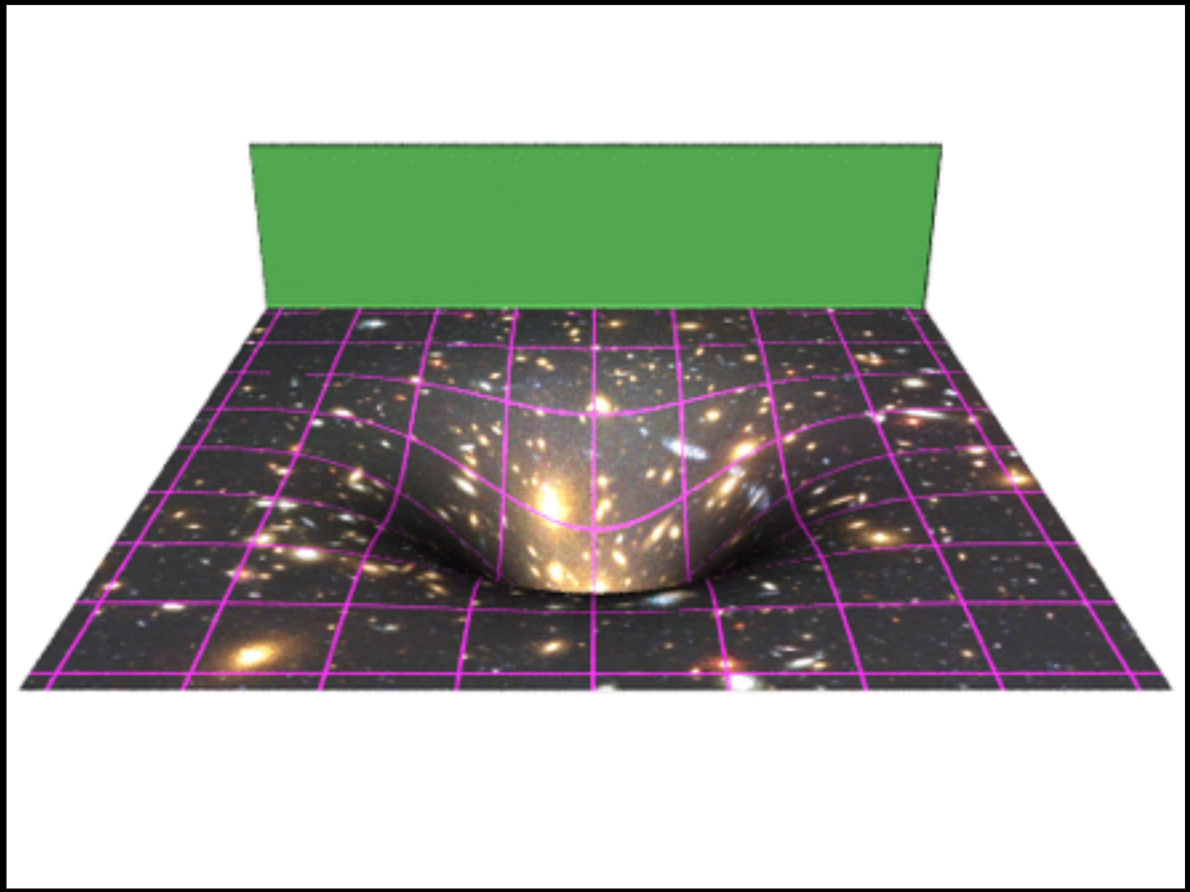
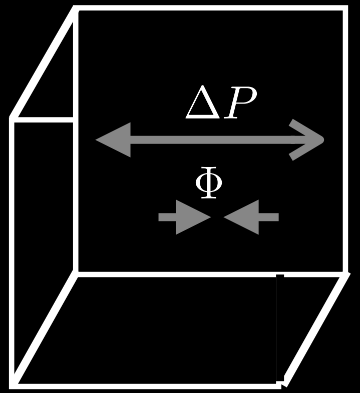




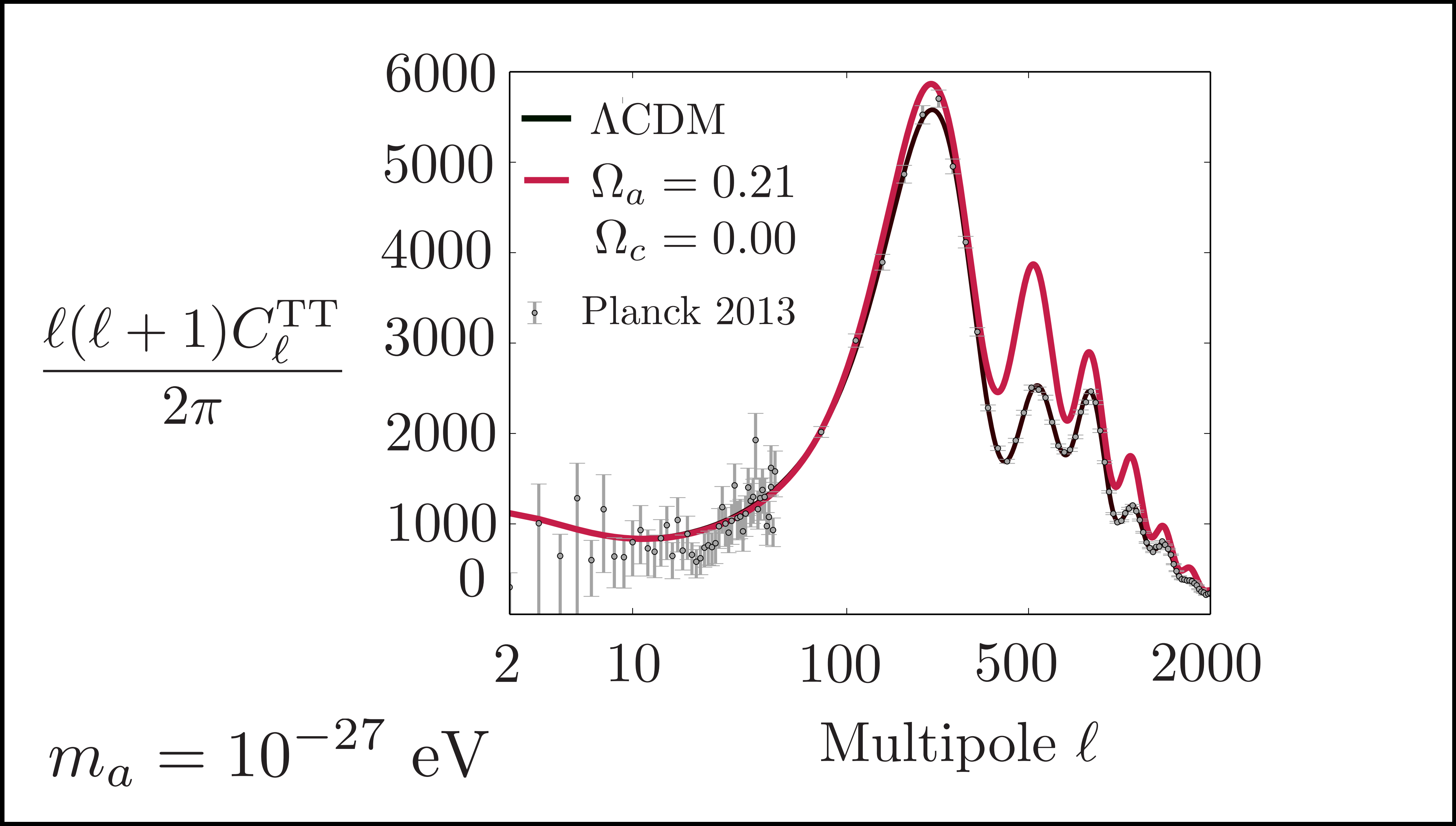
Radiation pressure causes potential decay

$$\Phi \propto \frac{1}{k^2}\left\{\frac{\Omega_m \delta_m \left(1-\frac{\Omega_a}{\Omega_m}\right)}{a^3}+\frac{\delta_R \Omega_R}{a^4}\right\}$$

$$\Delta P \Delta A > \rho \delta V \nabla \Phi$$

ULAs and the CMB: high mass and early ISW

Higher mass (DM-like) case: high-l ISW



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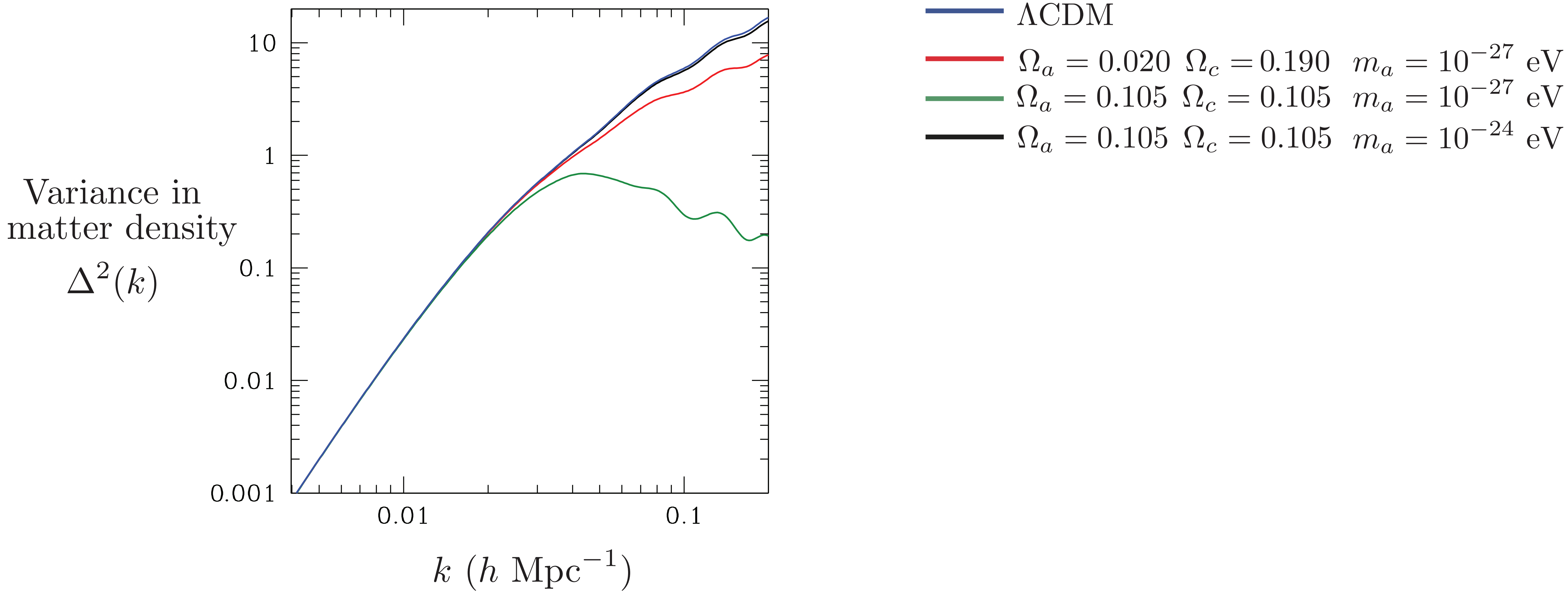
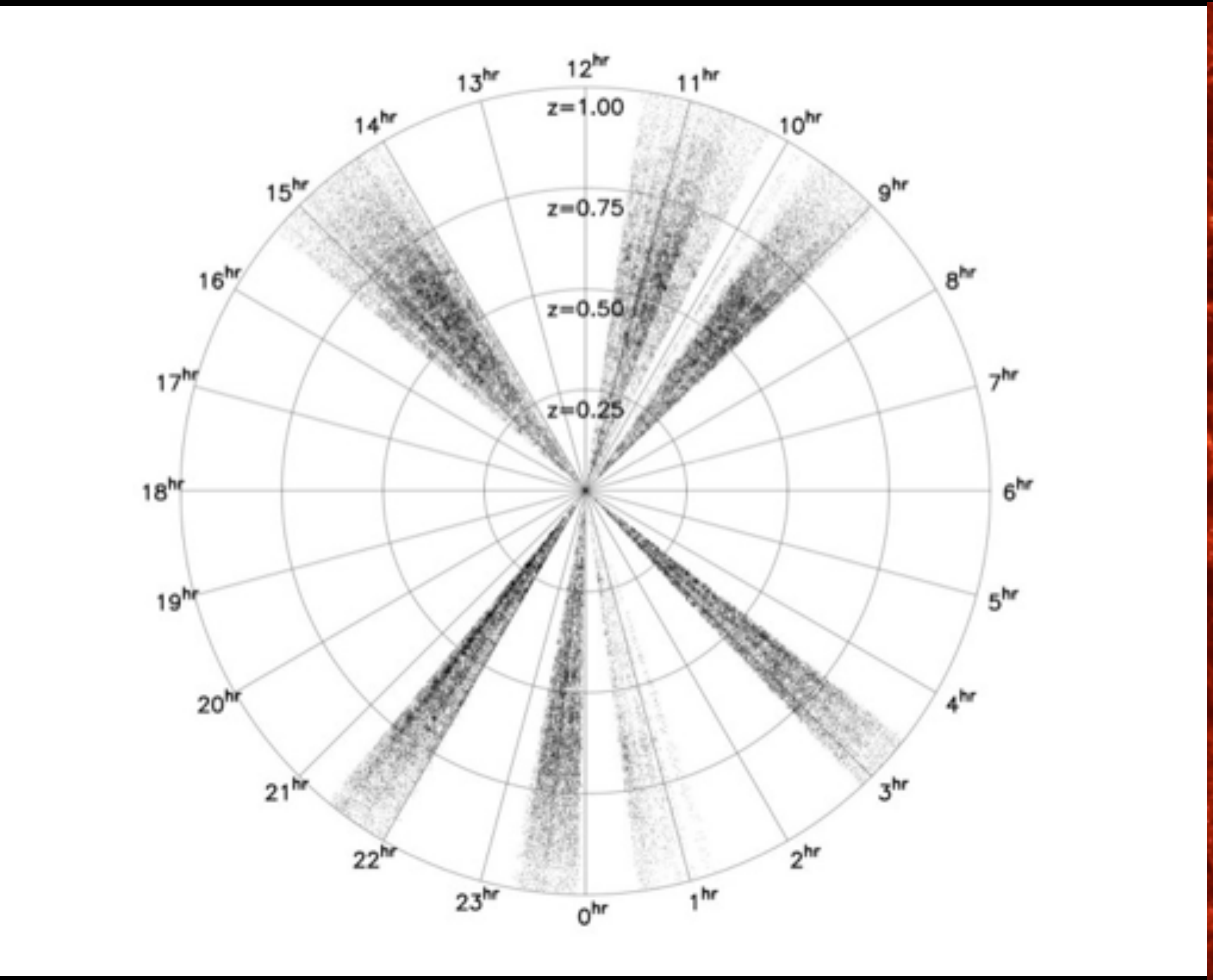
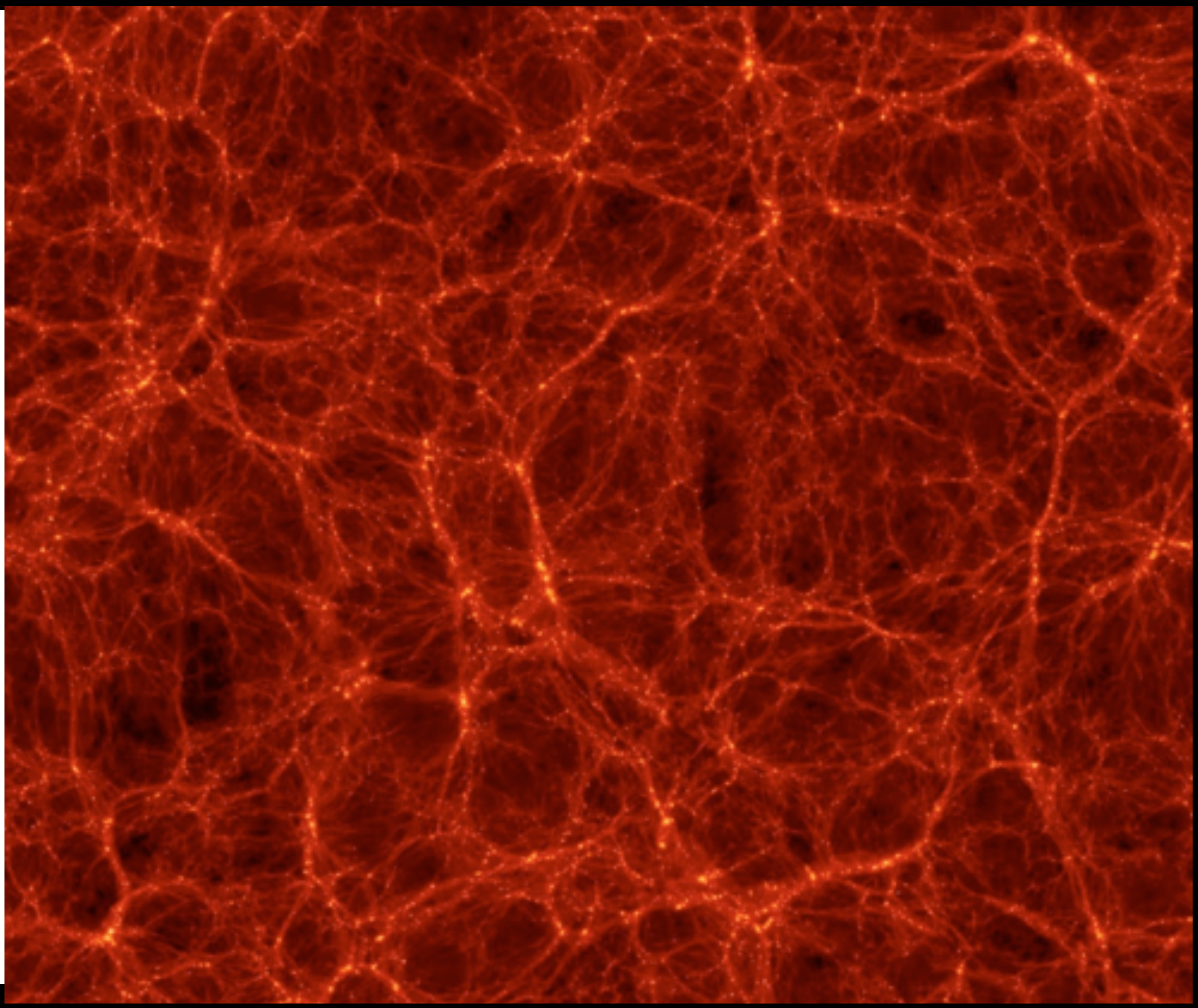
Matter power spectrum for ULA (in DM regime)



- ✳ DM perturbation growth severely suppressed if $k > k_J \simeq \sqrt{m\mathcal{H}}$
- ✳ Suppression grows with $\dfrac{\Omega_a}{\Omega_a + \Omega_c}$
- ✳ Analogous to effect of neutrinos

Matter power spectrum for ULA (in DM regime)





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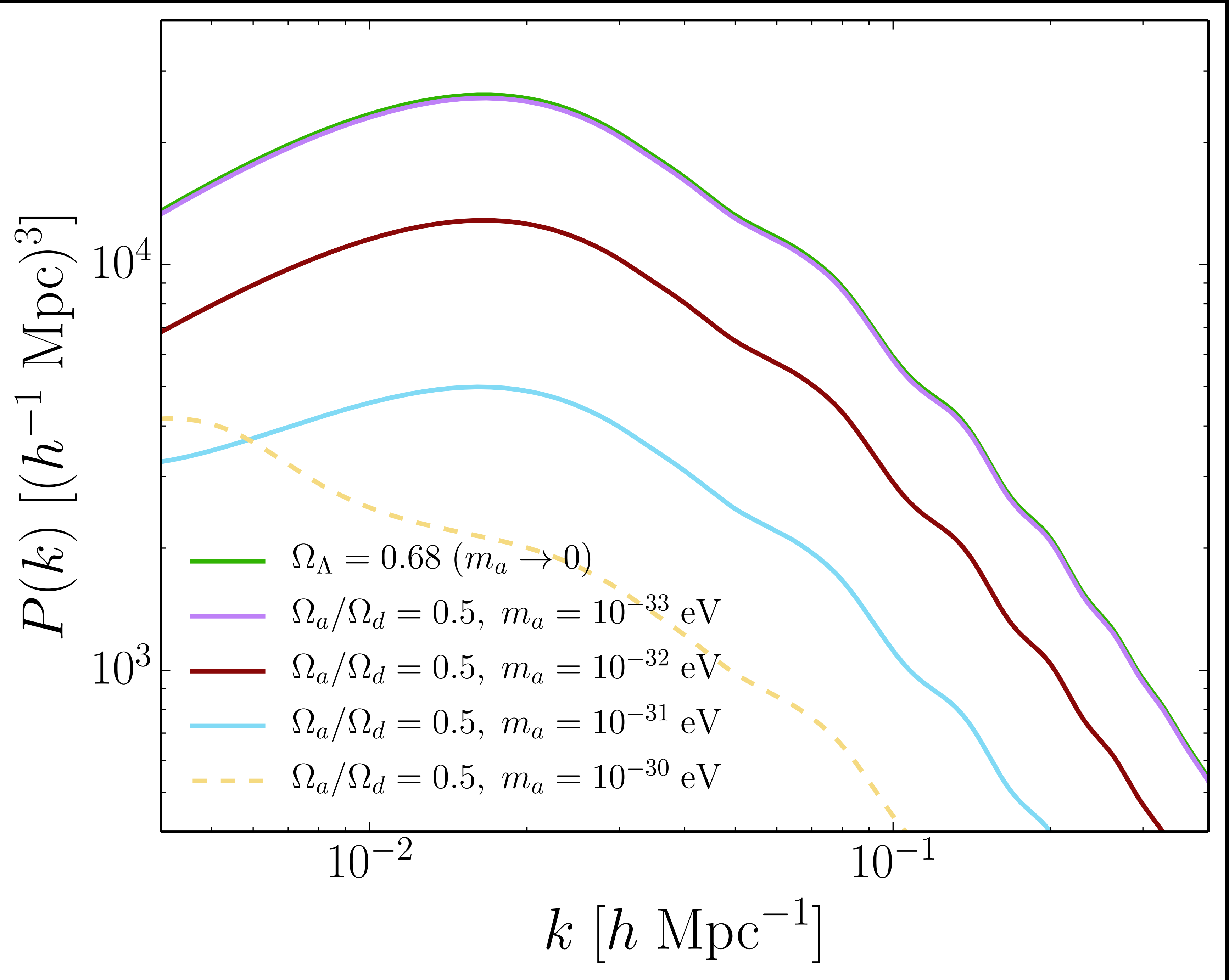
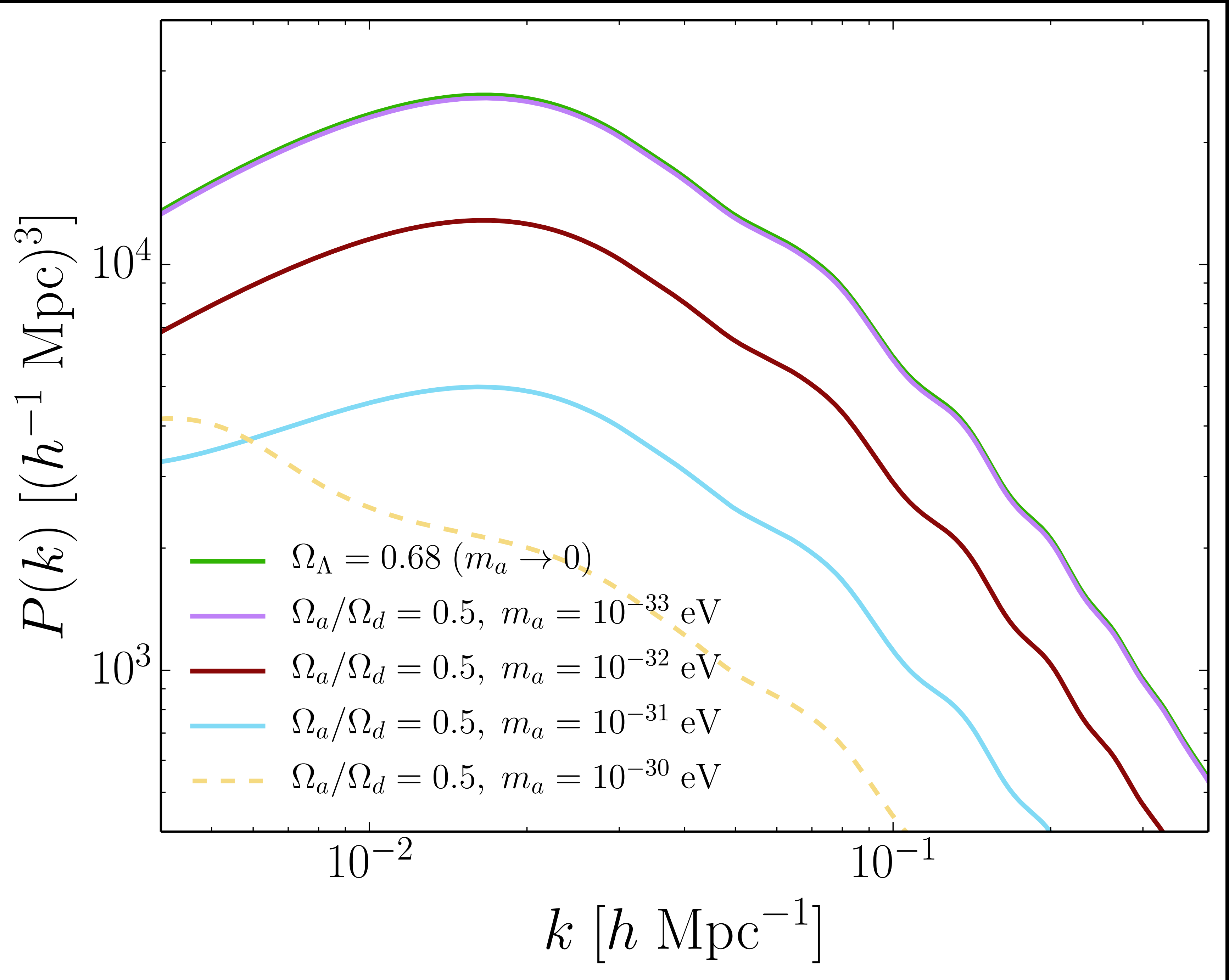


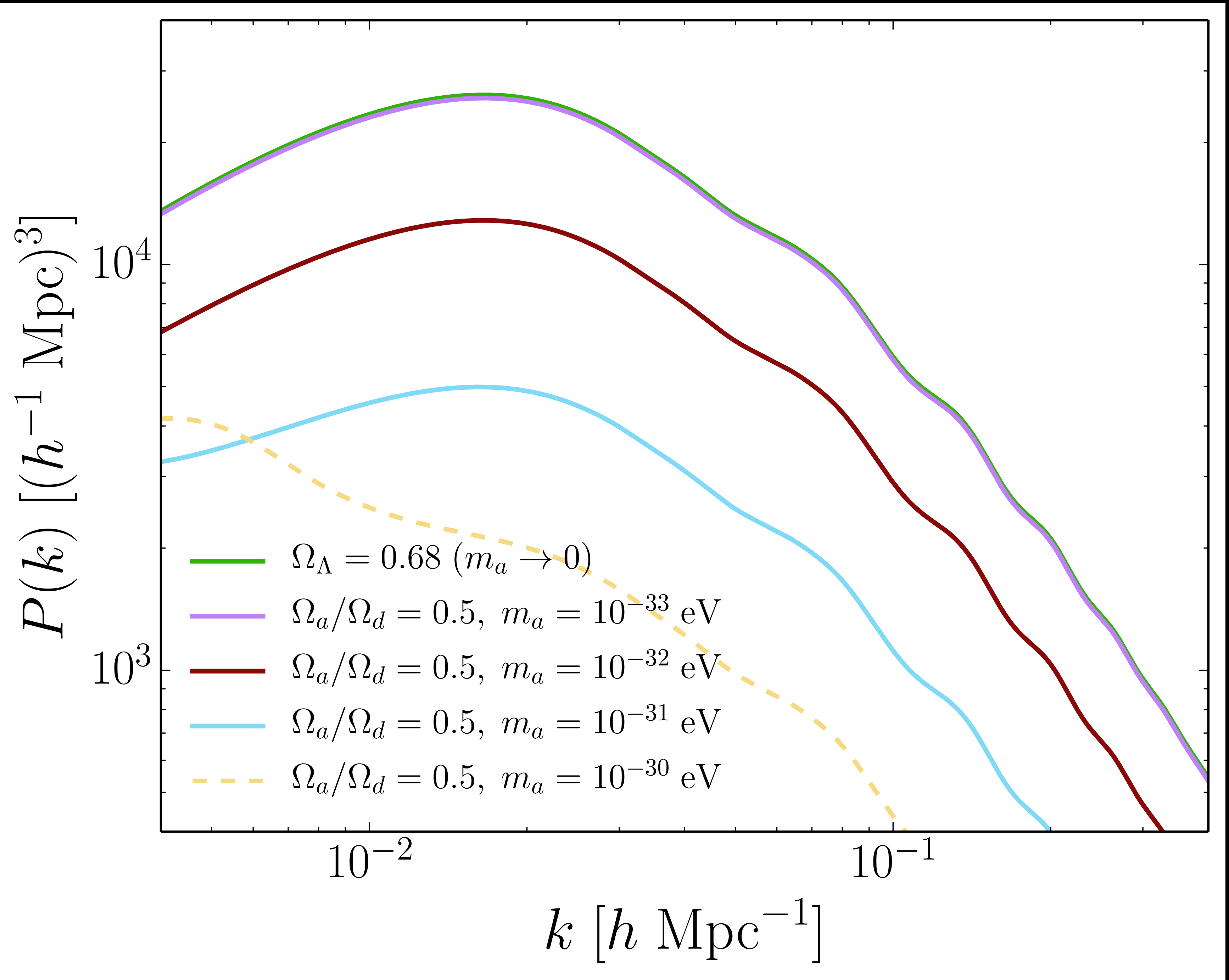
θ_s

Matter power spectrum for ULA (in DE regime)



θ_s fixed to lock CMB

Matter power spectrum for ULA (in DE regime)



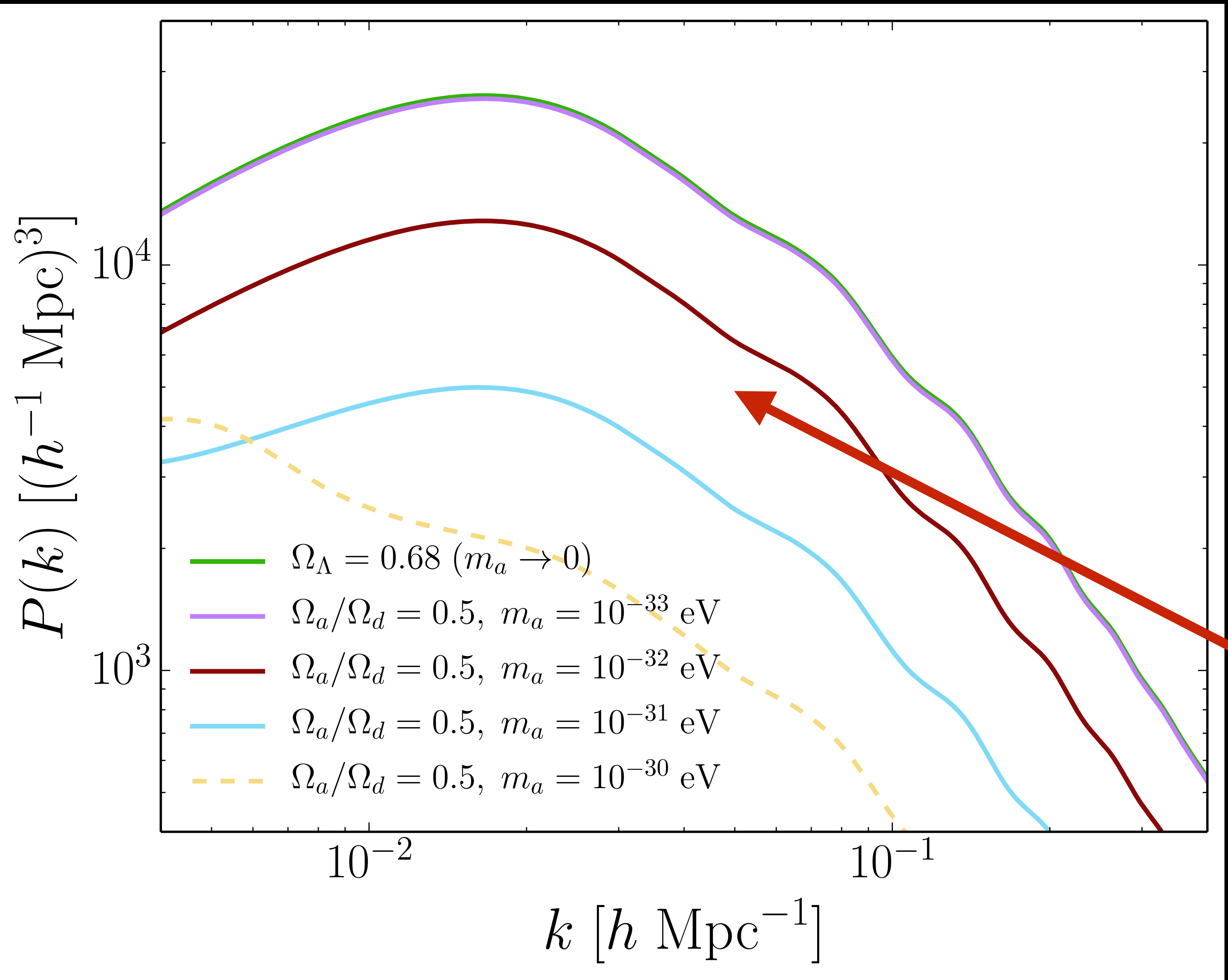
θ_s fixed to lock CMB

H_0 ↓

$$1 + z_{eq} = \frac{\Omega_m h^2}{\rho_{\mathrm{rad}}}$$

Matter-radiation equality delayed

Matter power spectrum for ULA (in DE regime)



θ_s fixed to lock CMB

$H_0 \downarrow$

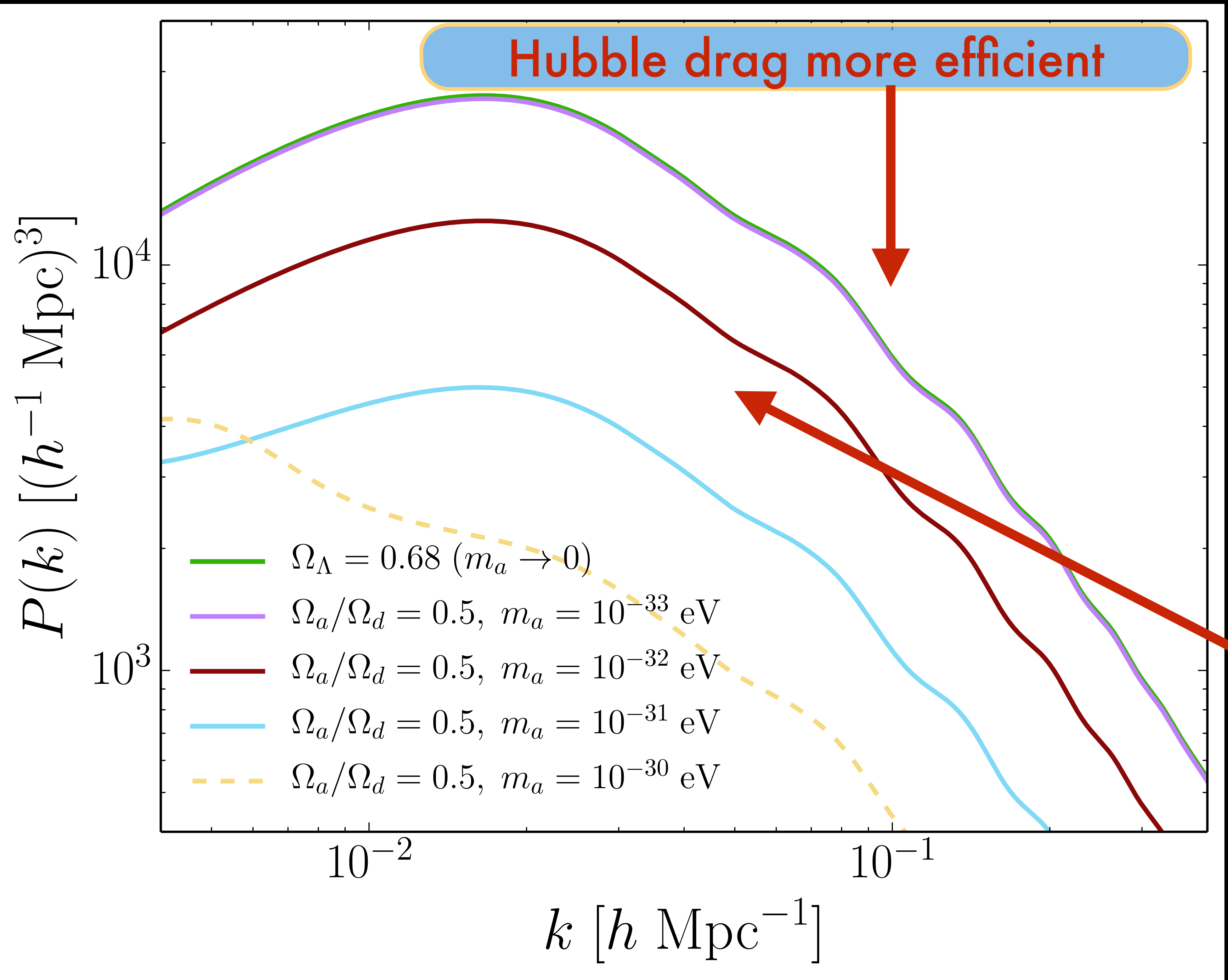
$k_{eq} = \lambda^{-1}_{\mathrm{horizon,eq}} \downarrow$

Peak of P(k) to lower k

$$1 + z_{eq} = \frac{\Omega_m h^2}{\rho_{\mathrm{rad}}}$$

Matter-radiation equality delayed

Matter power spectrum for ULA (in DE regime)



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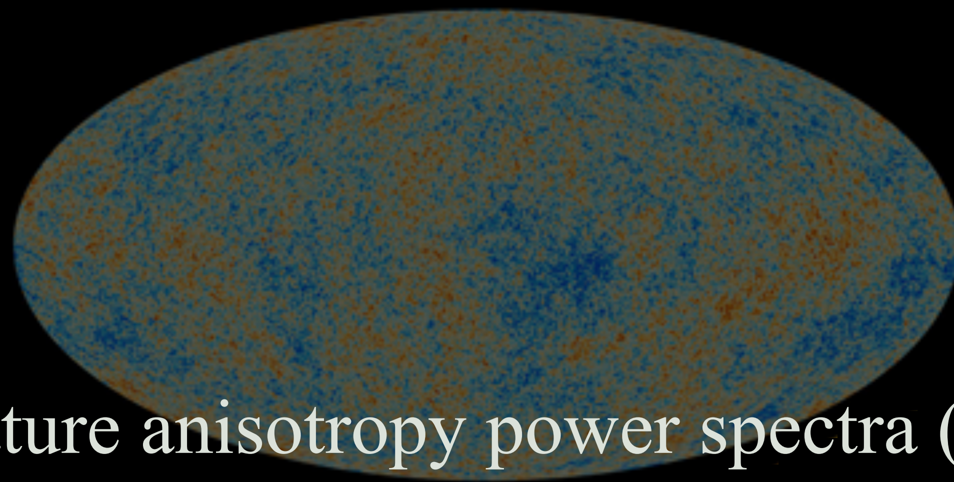
Matter-radiation equality delayed

DATA



✳Planck 2013 temperature anisotropy power spectra (+SPT+ACT)

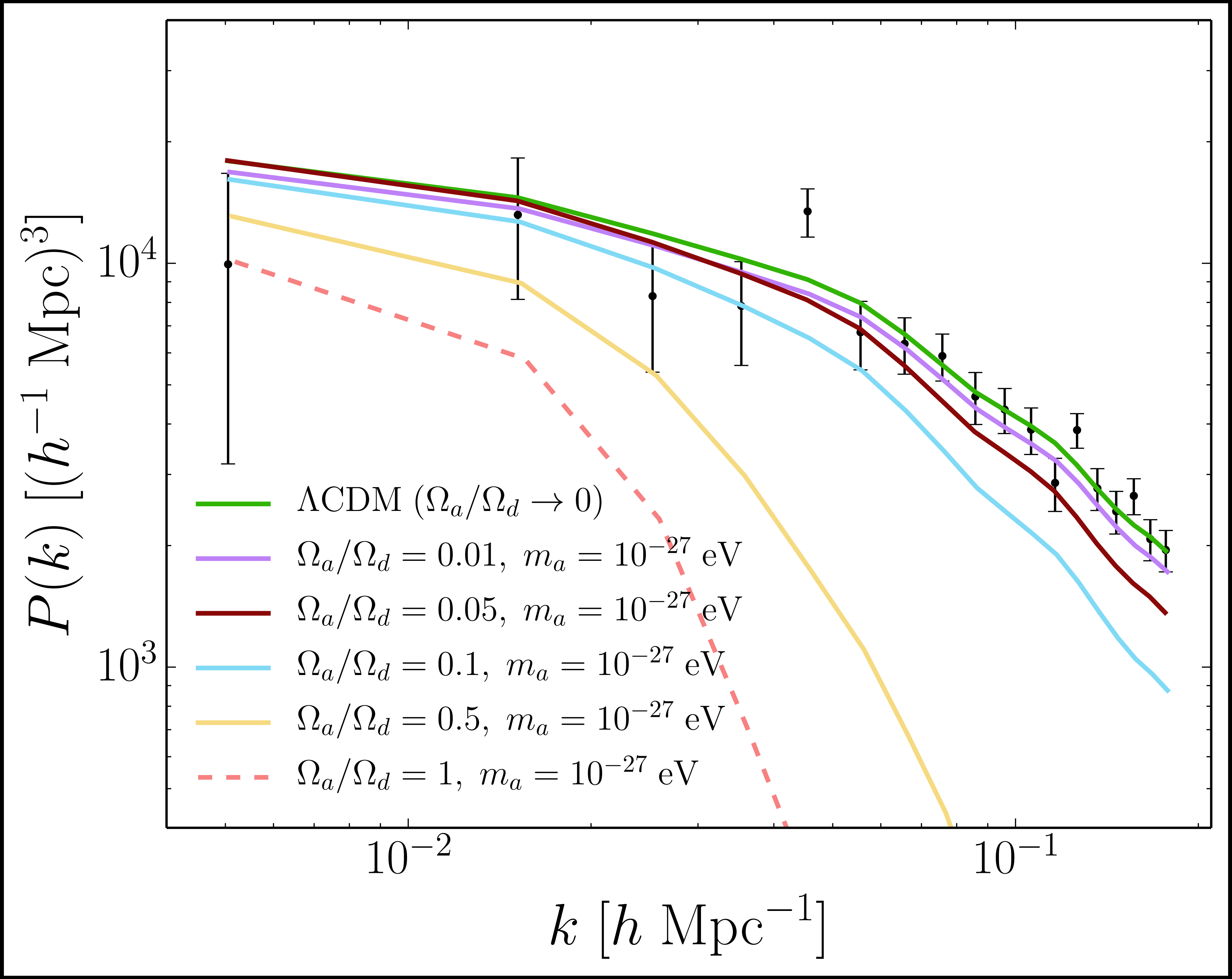
✳Cosmic variance limited to $\ell \sim 1500$

✳WiggleZ galaxy survey (linear scales only $k \lesssim 0.2h\ \mathrm{Mpc}^{-1}$)

✳240,000 emission line galaxies at z<1

✳3.9 m Anglo-Australian Telescope (AAT)

DATA



Convolve with WiggleZ window function

Difficult parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$

Difficult parameter space

$$\boxed{m_a, \Omega_a h^2}, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$

ULA parameters

Difficult parameter space

$$m_a, \Omega_a h^2, \boxed{\Omega_c h^2, \Omega_b h^2, \Omega_\Lambda}, n_s, A_s, \tau_{\rm reion}$$

Densities of standard species

Difficult parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\text{reion}}$$

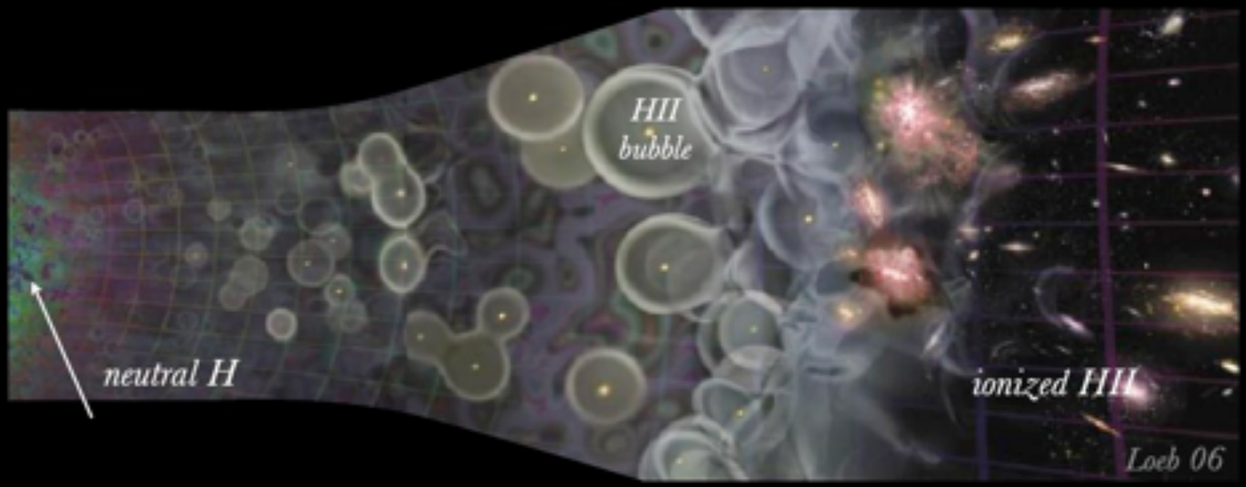
$$\Delta^2_{\mathcal{R}}(k) \equiv A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

Initial conditions

Difficult parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$

$$\tau_{\rm reion} = \int dl n_e \sigma_T$$



Difficult parameter space

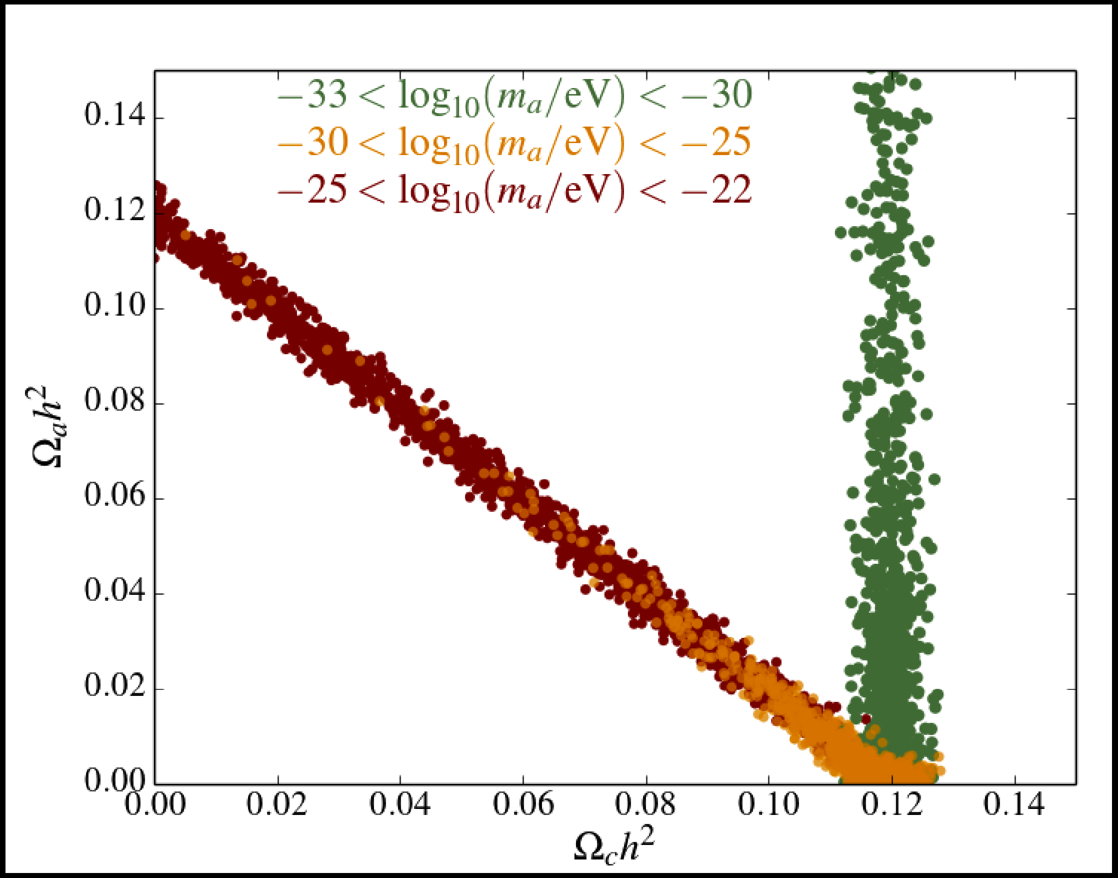
$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$

AxiCAMB

Compare with data
Explore posterior using Monte Carlo Markov Chain (MCMC)

Difficult parameter space

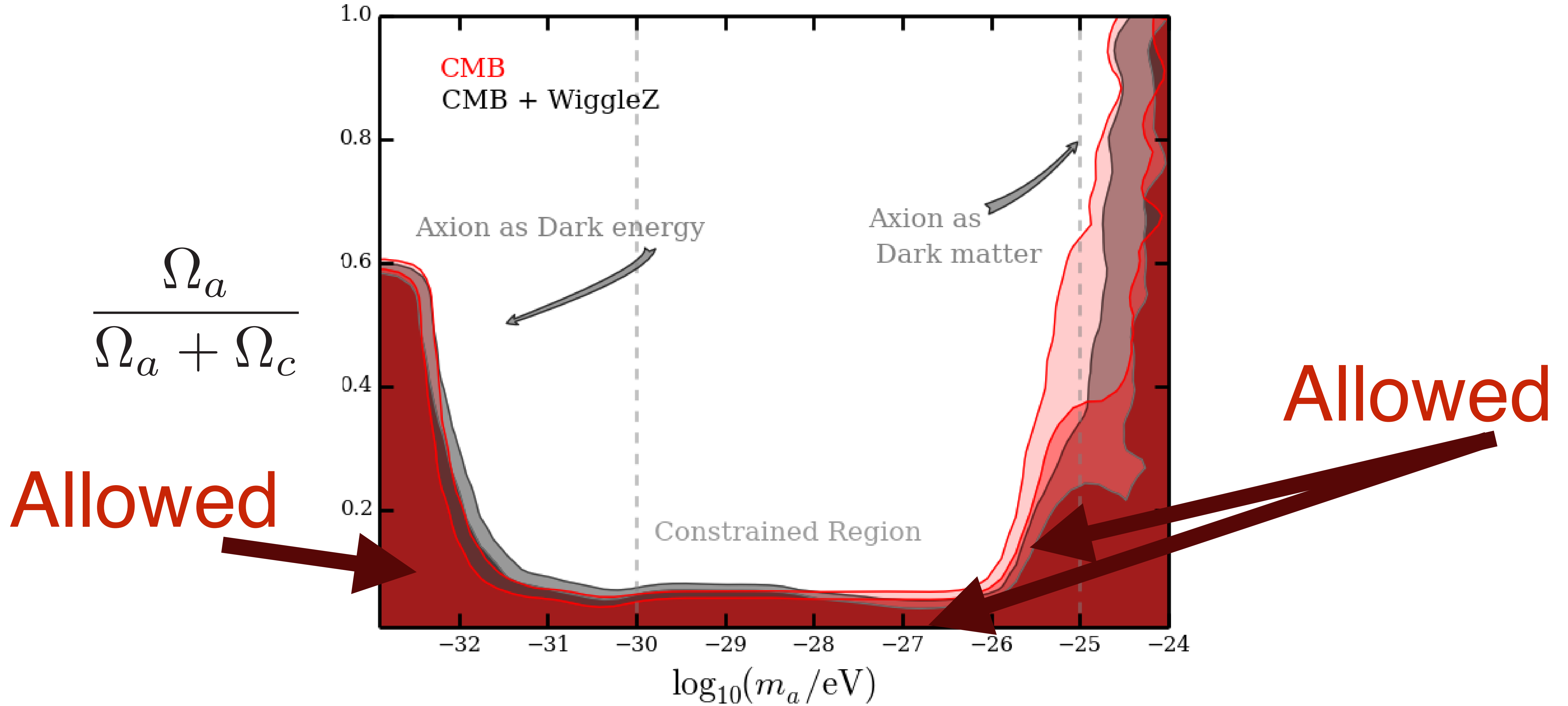
$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$



Addressed using nested sampling

MULTINEST (Hobson, Feroz, others 2008)

CONSTRAINTS



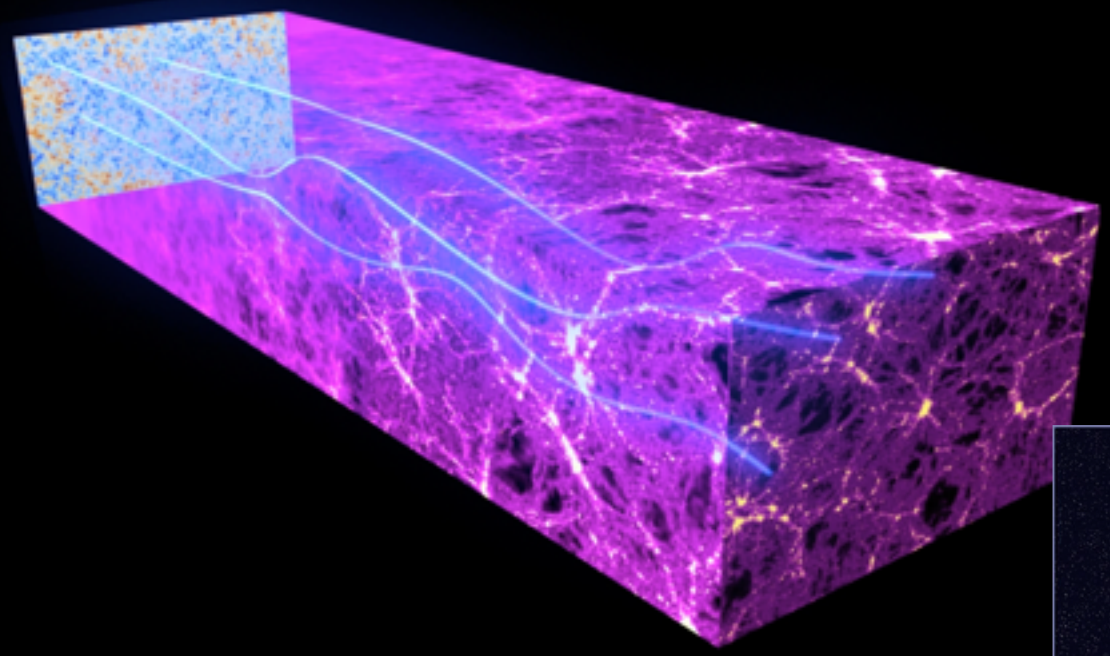
- ✳Interesting constraints over 7 orders of magnitude in mass:

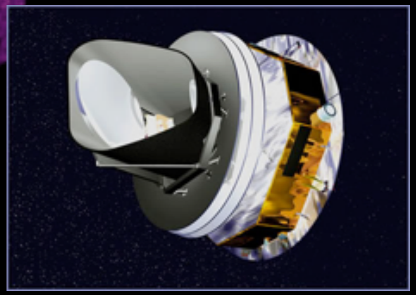
  Thanks to AxiCAMB and MultiNest

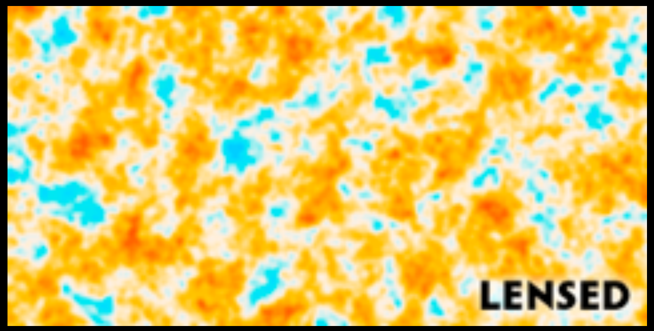
- ✳ULAs highly constrained if $10^{-32}\ \mathrm{eV} \lesssim m_a \lesssim 10^{-25.5}\ \mathrm{eV}$
- ✳ULAs are viable DM/DE candidates in linear theory outside ``belly''

ONGOING WORK: CMB LENSING

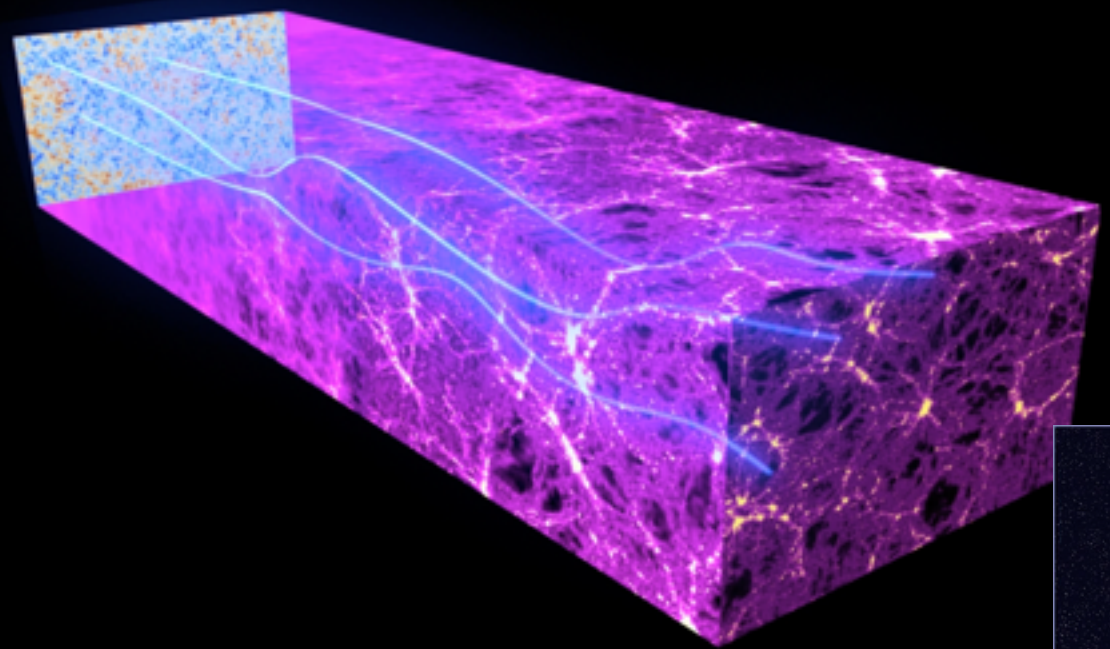
A slice of (dark matter) life at z~1



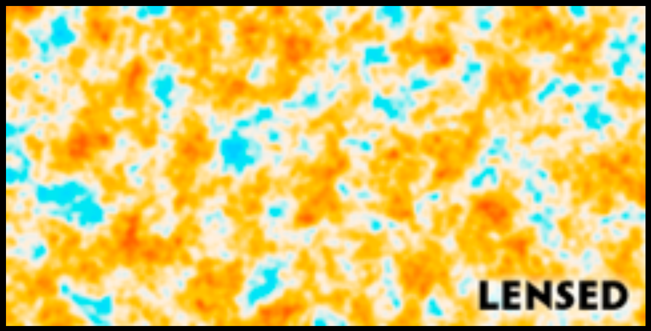


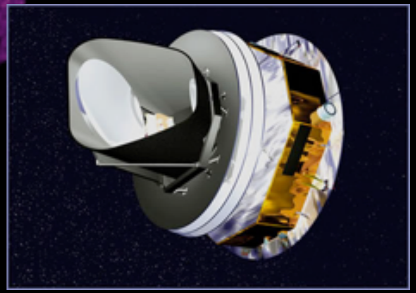


ONGOING WORK: CMB LENSING



A slice of (dark matter) life at z~1

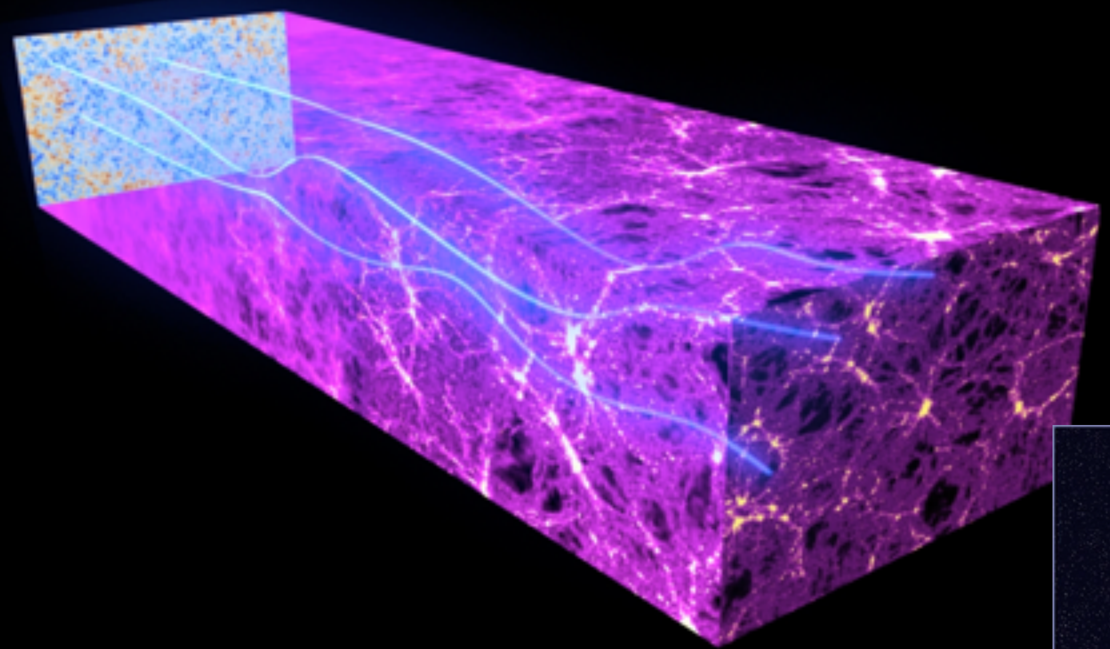




$$\kappa(\vec{\theta}) = \frac{1}{2}\nabla^2_{\vec{\theta}}\psi(\vec{\theta}) = \frac{1}{2}\vec{\nabla}\cdot\vec{\alpha}$$

$$\psi(\vec{\theta}) = \frac{2d_c(\eta_{ls})}{d_c(\eta_l)d_c(\eta_s)}\int \Phi(d_c(\eta)\theta, \eta)d\eta$$

ONGOING WORK: CMB LENSING



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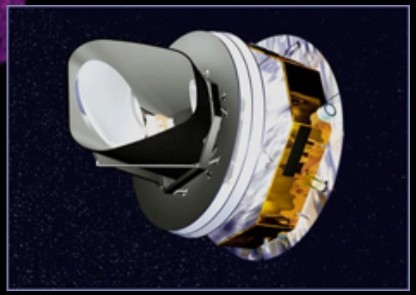
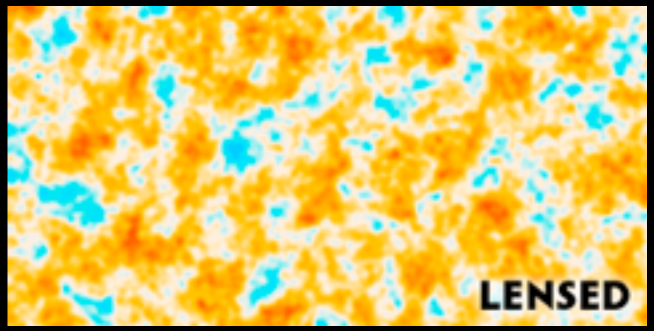




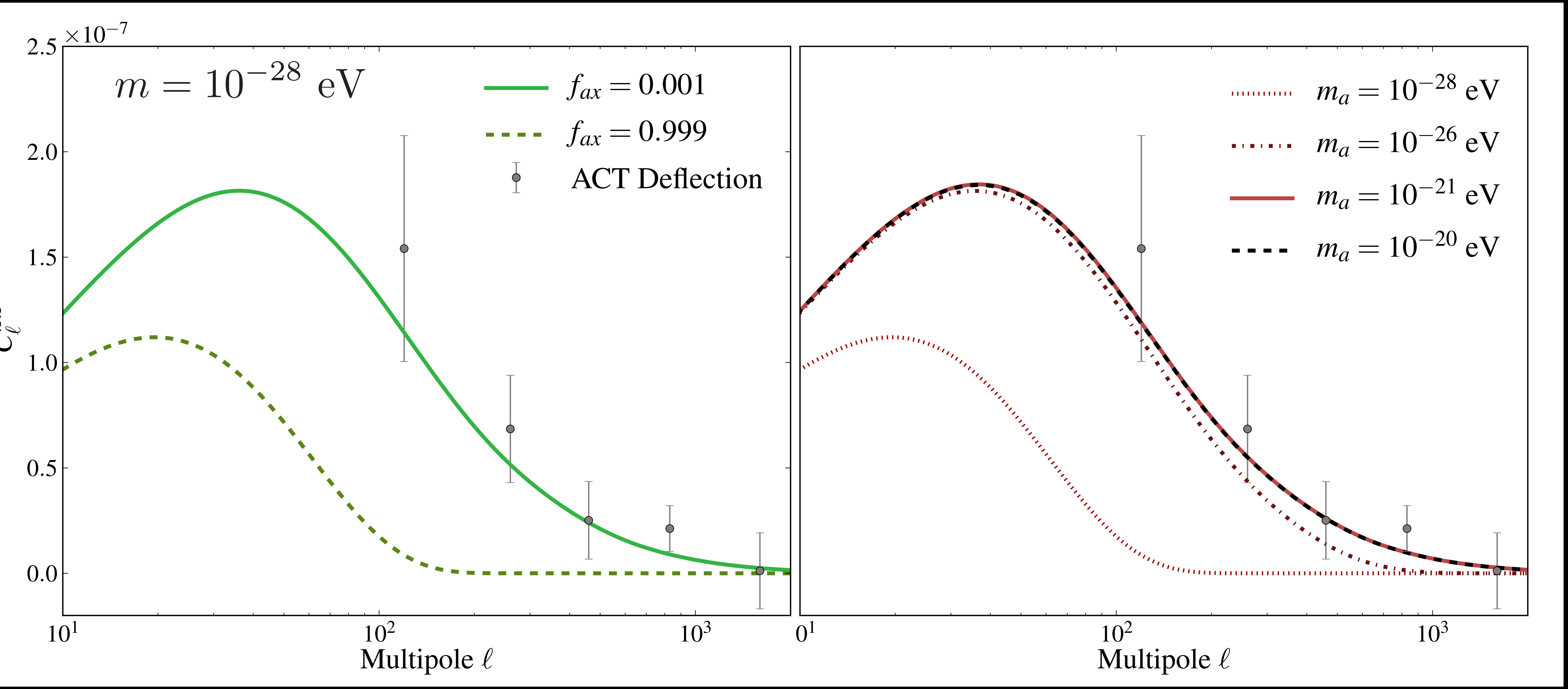
$$\kappa(\vec{\theta}) = \frac{1}{2}\nabla^2_{\vec{\theta}}\psi(\vec{\theta}) = \frac{1}{2}\vec{\nabla}\cdot\boxed{\vec{\alpha}}$$

Deflection angle

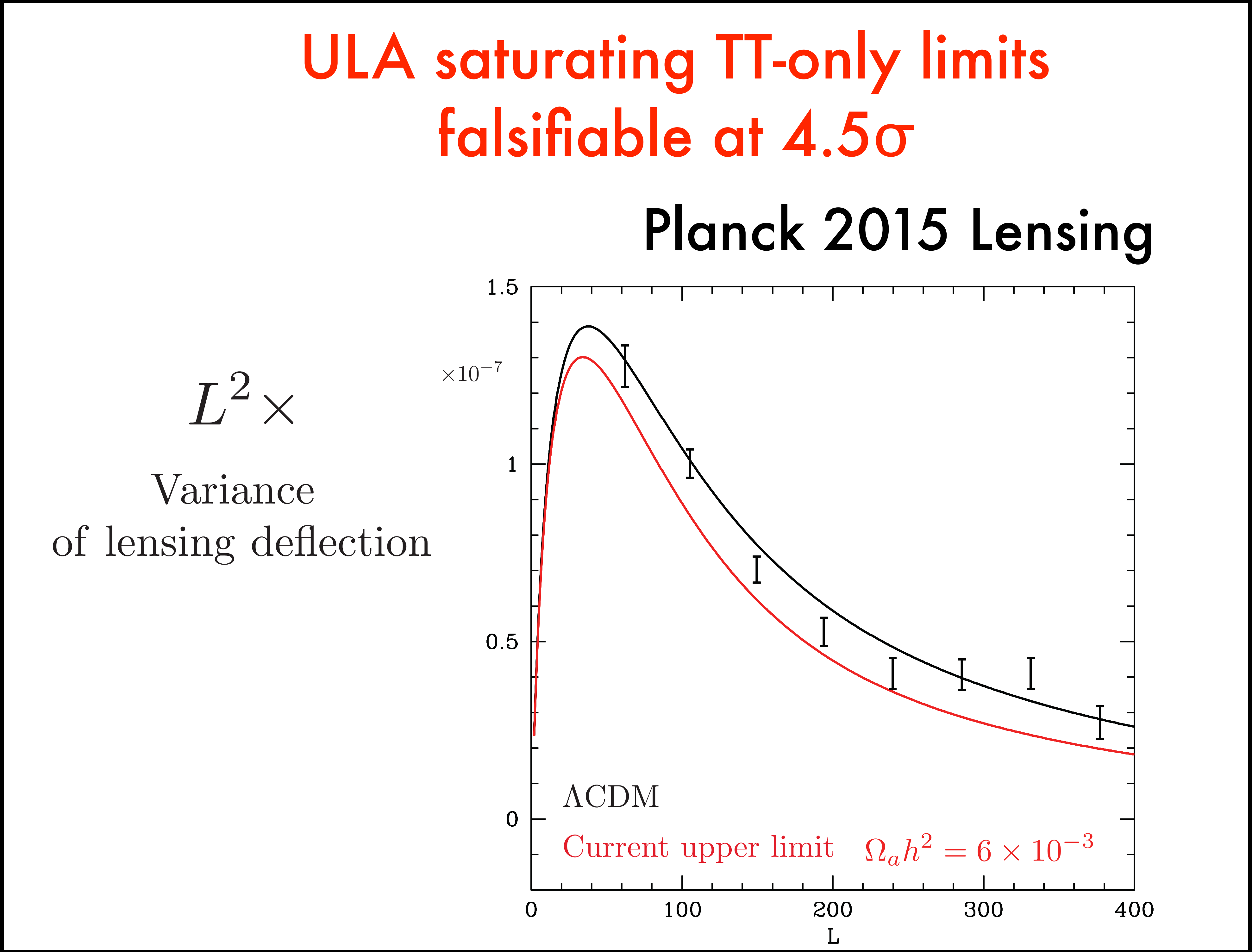
$$\psi(\vec{\theta}) = \frac{2d_c(\eta_{ls})}{d_c(\eta_l)d_c(\eta_s)}\int \Phi(d_c(\eta)\theta,\eta)d\eta$$

ULAs change

ONGOING WORK: CMB LENSING



ONGOING WORK: CMB LENSING



ULAs change lens geometry and growth of structure

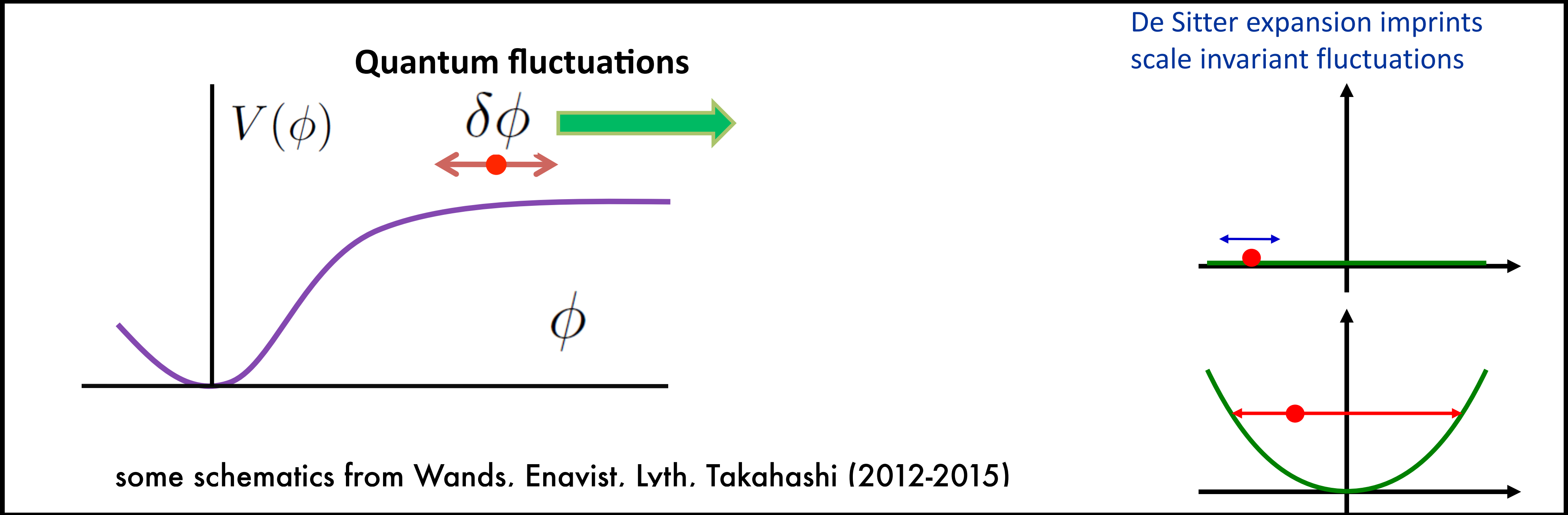
ONGOING WORK: PREPARING AXICAMB FOR PUBLIC RELEASE

- CosmoSIS (Zuntz, Paterno, Jennings, Rudd, Manzotti, Dodelson+) allows
  - Easy and modular use of power spectra codes
  - Comparison with many different data sets/likelihoods
  - Variety of cross-correlation studies
  - Clever samplers for difficult parameter spaces
- We are packaging AxiCAMB in a wrapper to allow use in CosmoSIS
  - Added self-consistent treatment of Ω_K and m_ν

Axions and isocurvature fluctuations

Axions and isocurvature fluctuations

✳ If $f_a > H_I$



$$\sqrt{\langle a^2 \rangle} = \frac{H_\mathrm{I}}{2\pi}$$

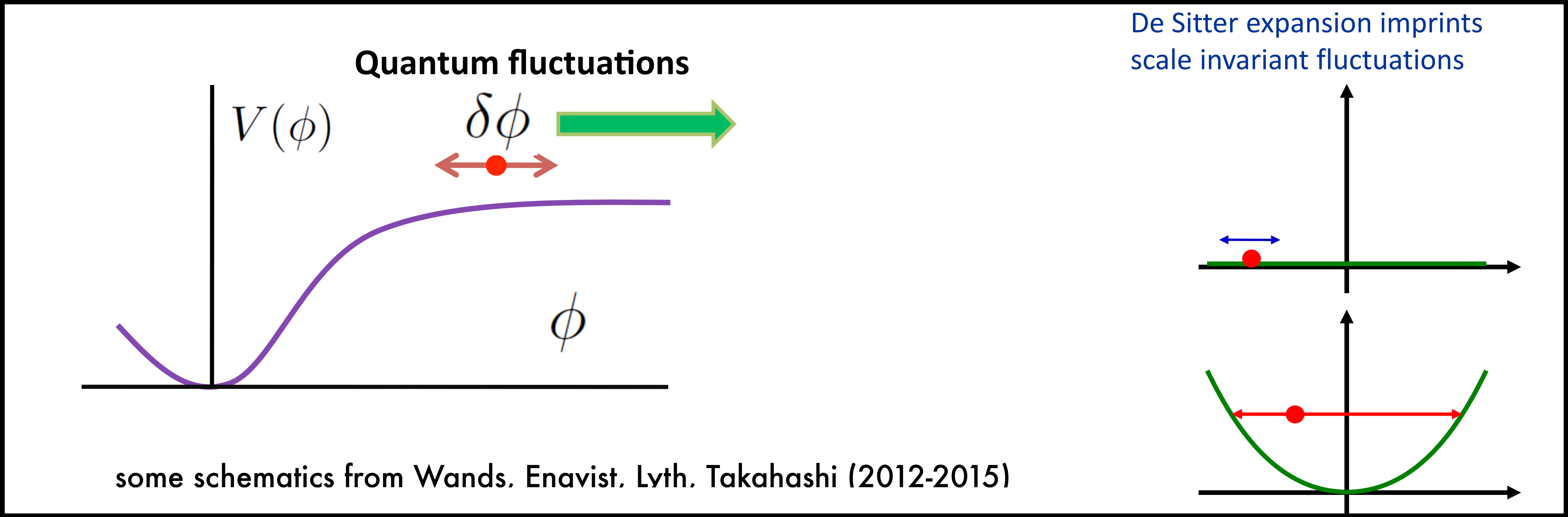
Quantum zero-point fluctuations!

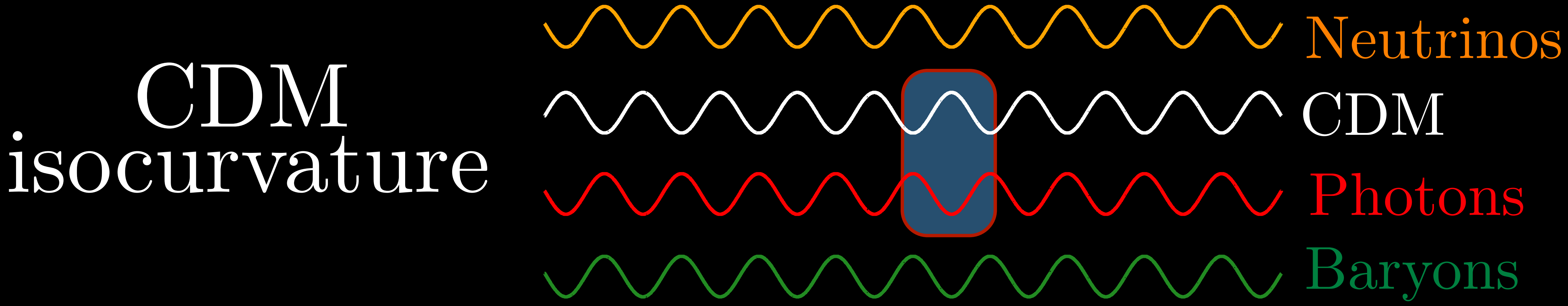
$$\rho_a \ll \rho_{\rm tot} \to \Phi_a \ll 10^{-5}$$

$$S_{a\gamma} = \frac{\delta n_a}{n_a} - \frac{\delta n_\gamma}{n_\gamma} = \frac{\delta \rho_a}{\rho_a} - \frac{3}{4}\frac{\delta\rho_\gamma}{\rho_\gamma} \sim 10^{-5}$$

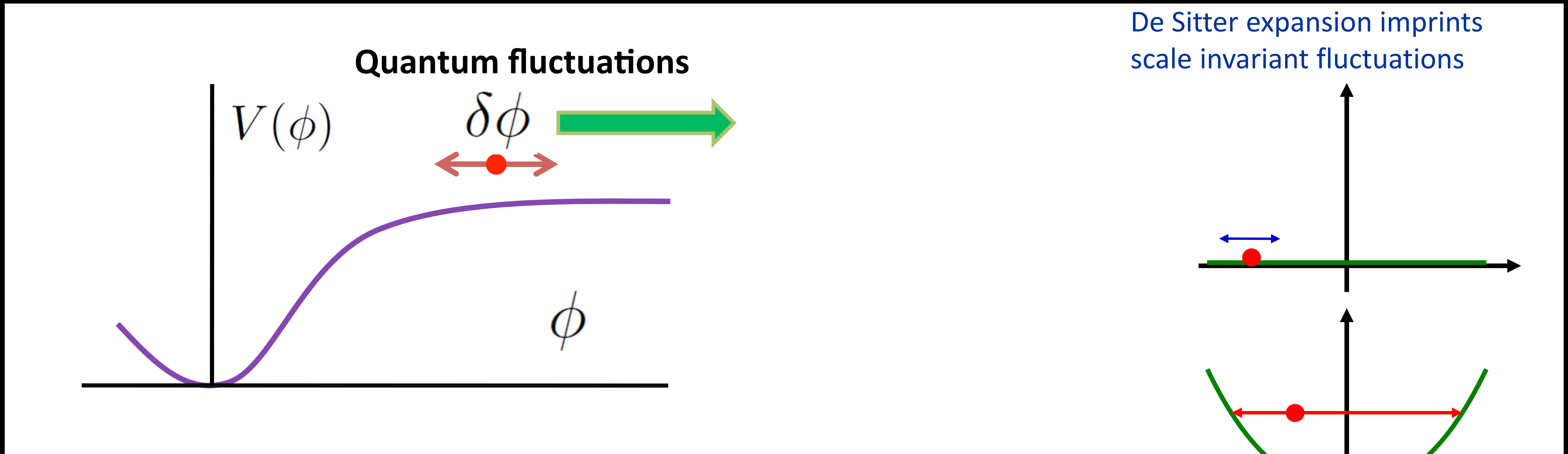
AXIONS AND ISOCURVATURE FLUCTUATIONS

✴ If $f_a > H_I$



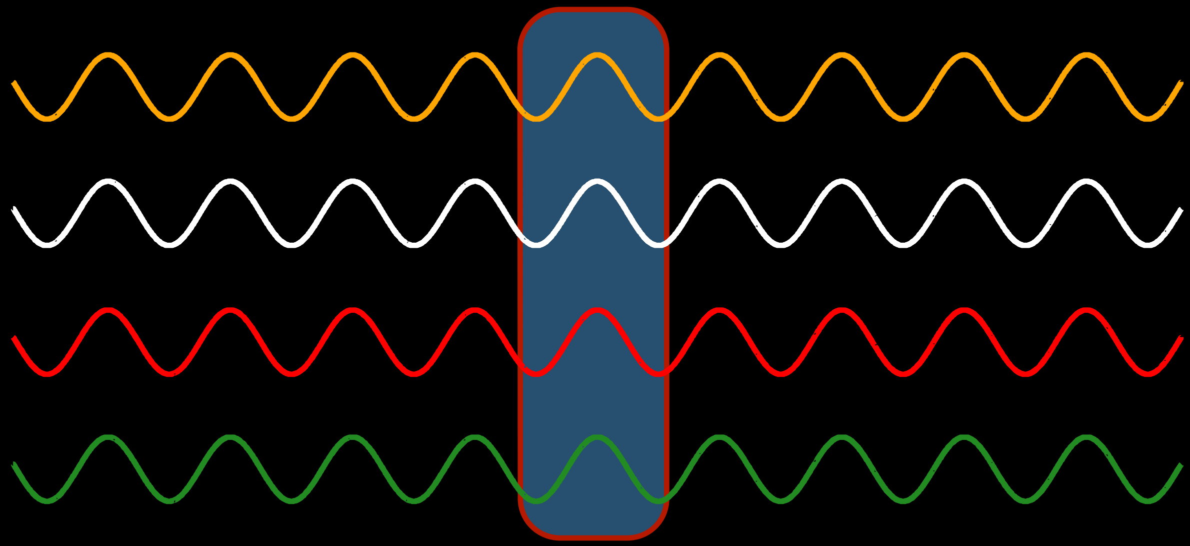


- If $f_a > H_I$

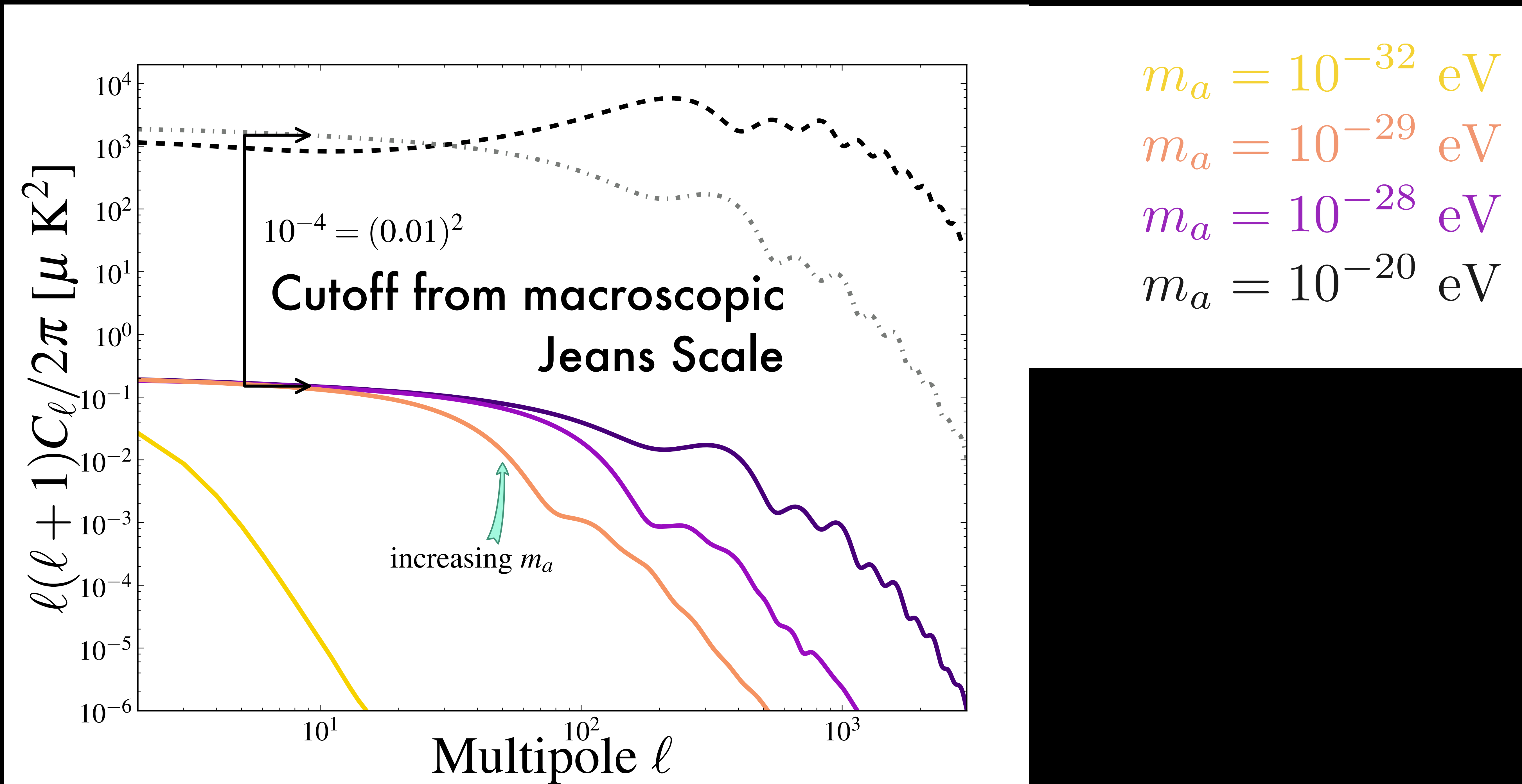


some schematics from Wands, Enqvist, Lyth, Takahashi (2012-2015)

Adiabatic fluctuations

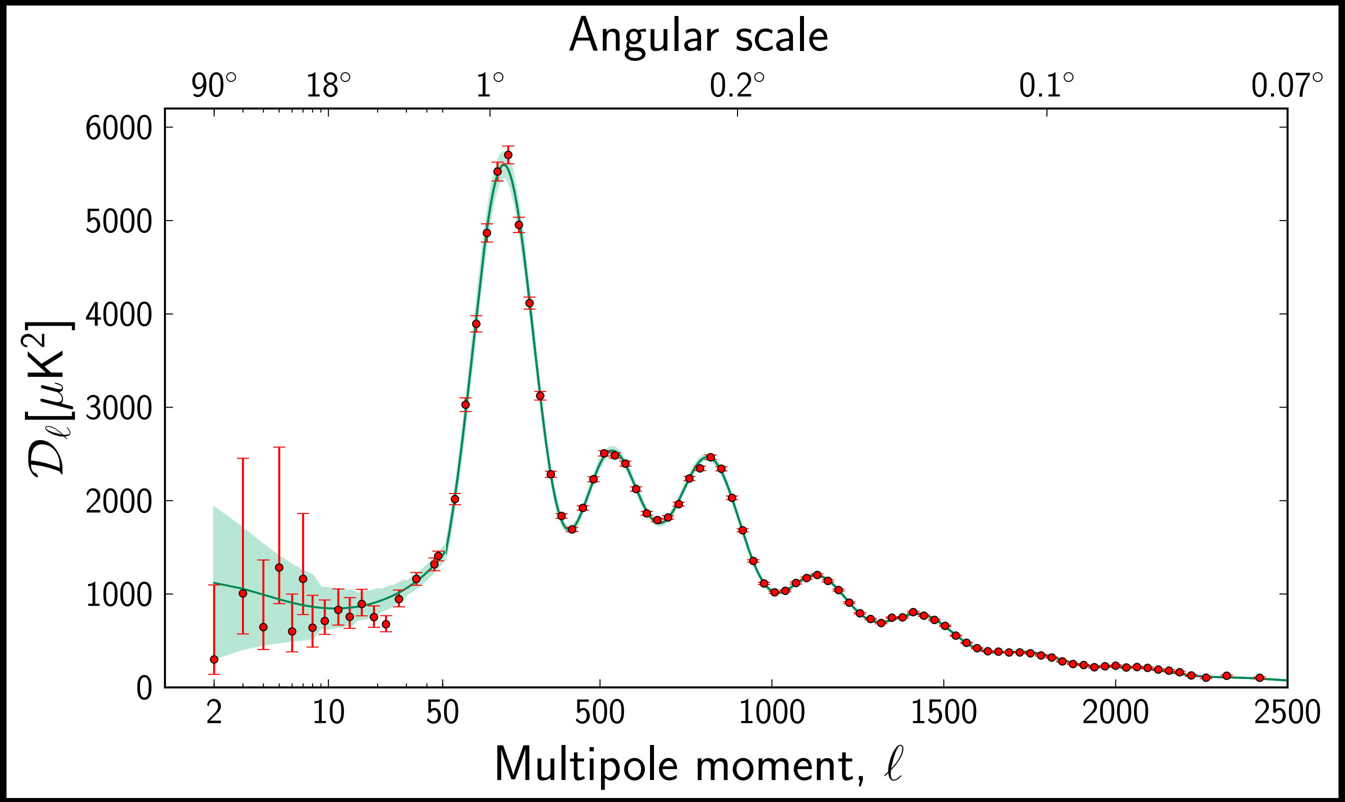


ULAS AND ISOCURVATURE FLUCTUATIONS



Isocurvature spectra have distinct phase structure from adiabatic fluctuations
Spectra from AxiCAMB using initial conditions obtained in DG+ (2015 in prep)

Planck 2013 TT



$$\alpha \equiv \frac{P_{S_{c\gamma}}(k)}{P_{S_{c\gamma}(k)} + P_{\mathcal{R}}(k)} \leq 0.039$$

$$\frac{H_I}{f_a \bar{\theta}} \frac{\Omega_a}{\Omega_{\rm d}} \lesssim 4 \times 10^{-5}$$

ULAS AND ISOCURVATURE FLUCTUATIONS

QCD axion

$$\frac{\Omega_a}{\Omega_a + \Omega_c} \lesssim 10^{-12} \left(\frac{10^{14}\mathrm{GeV}}{H_I} \right)^{7/2}$$

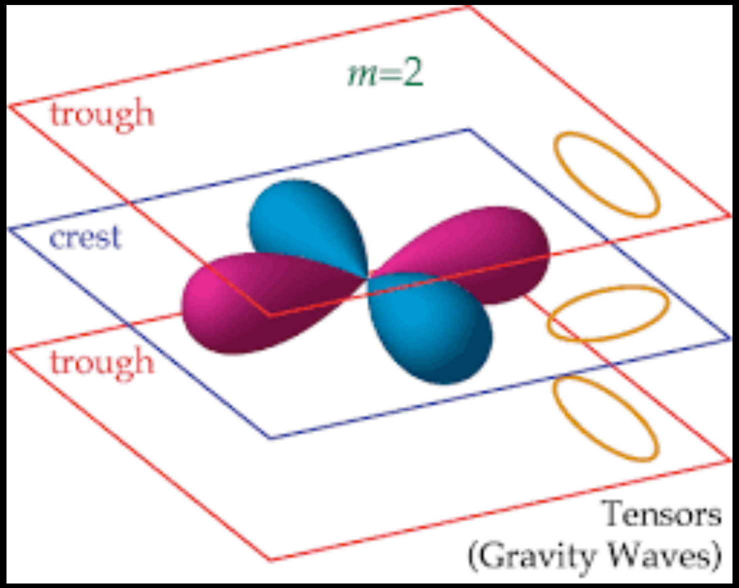
ULAs

$$\frac{\Omega_a}{\Omega_a + \Omega_c} \lesssim 10^{-3} \left(\frac{10^{14}\mathrm{GeV}}{H_I} \right)$$

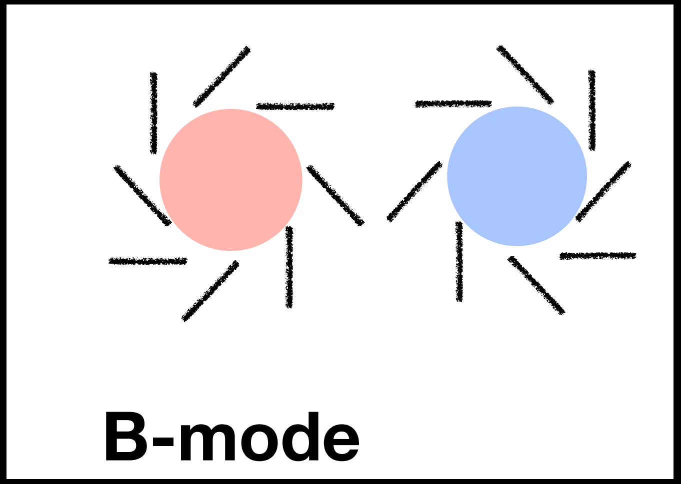
D.J.E. Marsh, DG , R. Hlozek, P.Ferreira:
arXiv:1403.4216, Phys. Rev. Lett. 113, 011801
arXiv:1303.3008, Phys. Rev. D 87, 121701(R)
Also see Gondolo and Visinelli 2012,2013

Forecast/future work: Tensors and ULAs

✳ Primordial gravitational waves are sensitive to H_I



Potentially observable CMB polarization signature



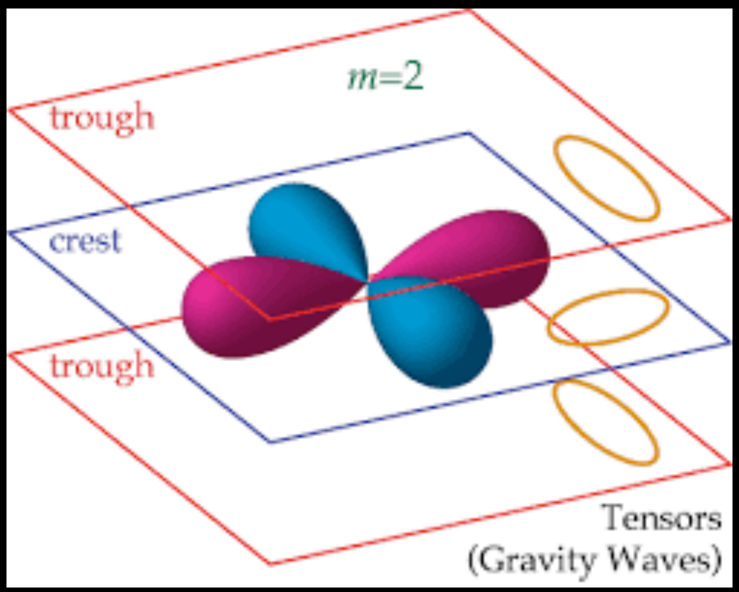
✳ Current limits are $H_I \lesssim 10^{14}$ GeV . If saturated by a detection:

$$\frac{\Omega_a}{\Omega_a + \Omega_c} \lesssim 10^{-12}$$

$$\frac{\Omega_a}{\Omega_a + \Omega_c} \lesssim 10^{-3}$$

FORECAST/FUTURE WORK: TENSORS AND ULAS

✳ Primordial gravitational waves are sensitive to H_I



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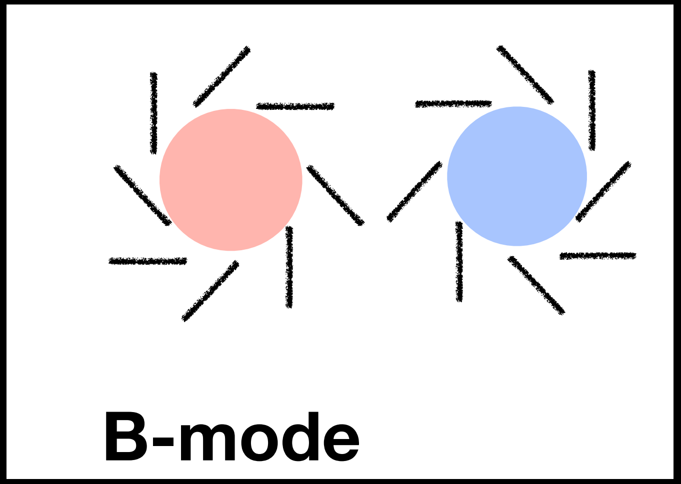


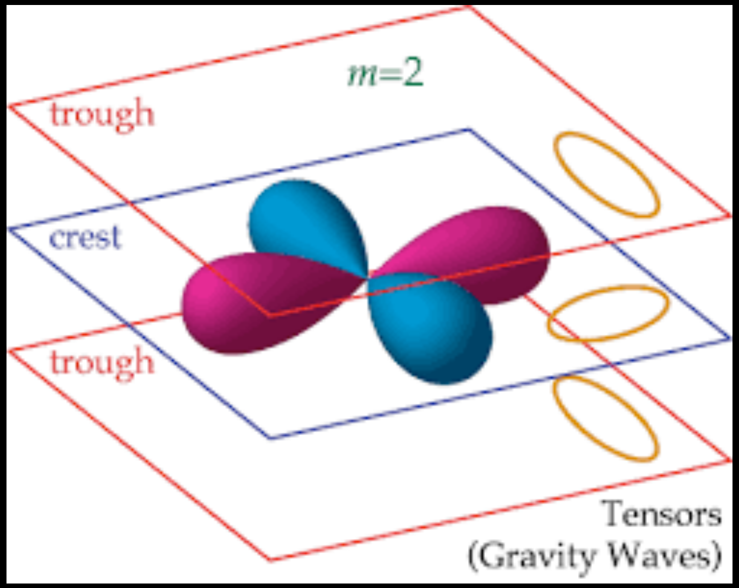
✳ Current limits are $H_I \lesssim 10^{14}\ \mathrm{GeV}$. If saturated by a detection:

QCD axion $\frac{\Omega_a}{\Omega_a + \Omega_c} \lesssim 10^{-12}$

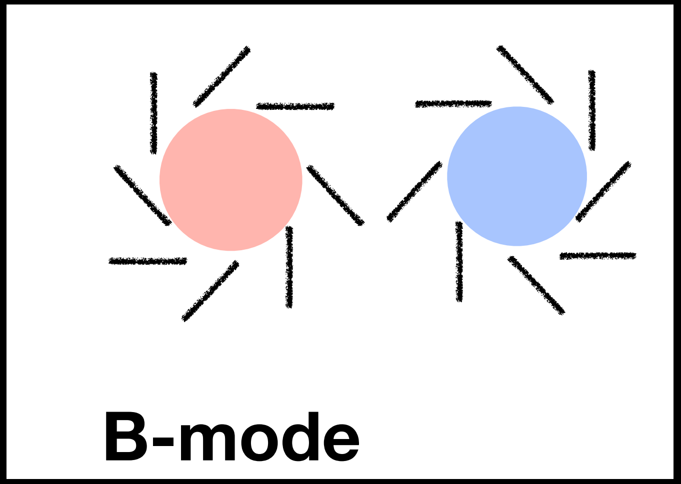
ULA $\frac{\Omega_a}{\Omega_a + \Omega_c} \lesssim 10^{-3}$

Forecast/future work: Tensors and ULAs

- Primordial gravitational waves are sensitive to H_I



Potentially observable CMB polarization signature



- Current limits are $H_I \lesssim 10^{14}\ \mathrm{GeV}$. If saturated by a detection:

$$\frac{\Omega_a}{\Omega_a+\Omega_c} \lesssim 10^{-12}\left(\frac{0.2}{r}\right)$$

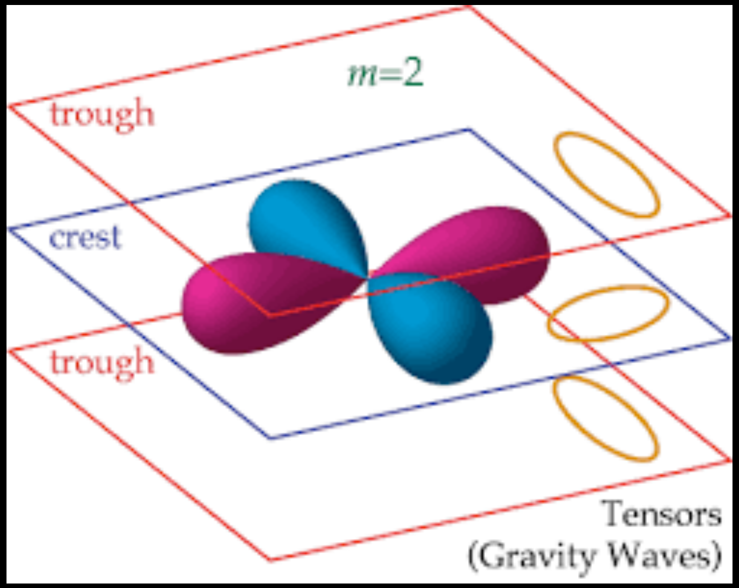
QCD axion

$$\frac{\Omega_a}{\Omega_a+\Omega_c} \lesssim 10^{-3}\left(\frac{0.2}{r}\right)$$

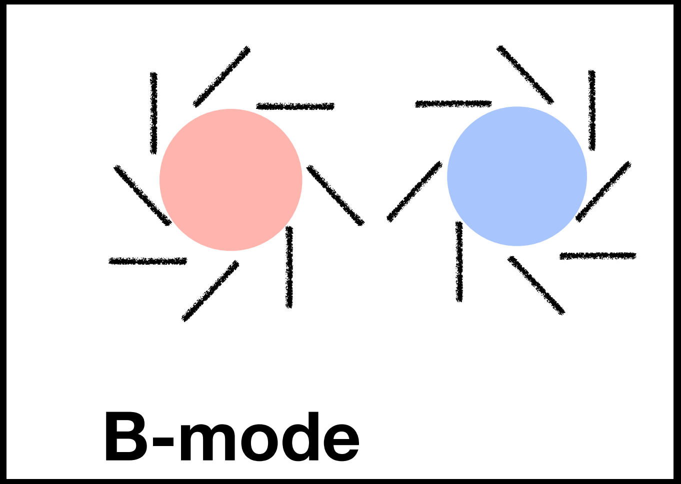
ULAs

FORECAST/FUTURE WORK: TENSORS AND ULAS

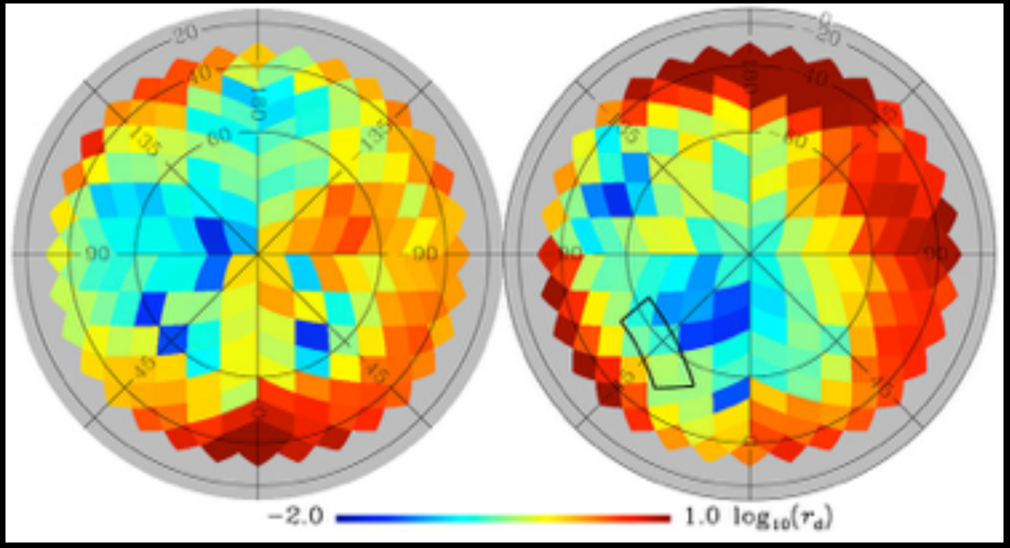
- Primordial gravitational waves are sensitive to H_I



Potentially observable CMB polarization signature

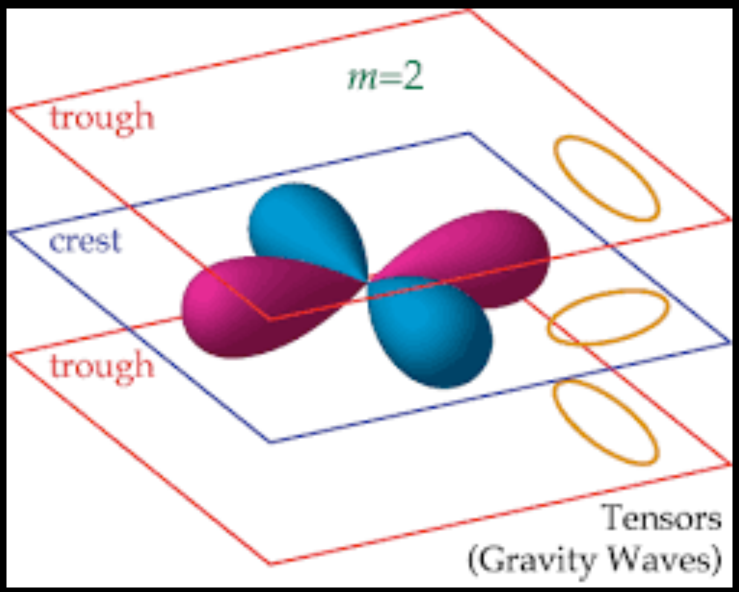


- Current limits are $H_I \lesssim 10^{14}\ \mathrm{GeV}$. If saturated by a detection:
- *Warning!* Polarized foregrounds are challenging [e.g. BICEP2+Planck 2015]

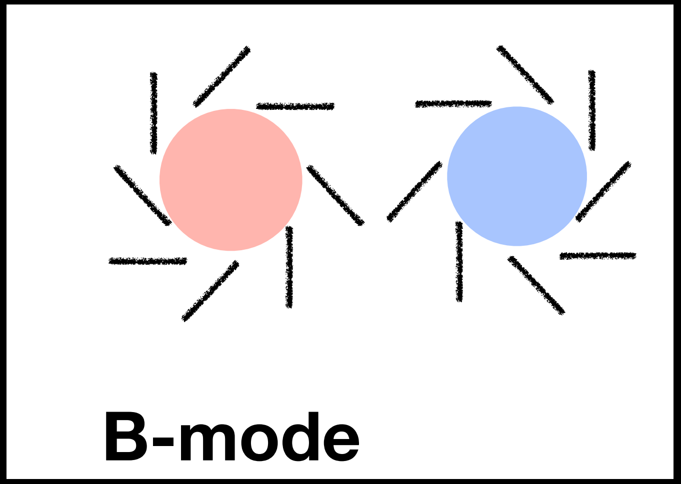


Forecast/future work: Tensors and ULAs

* Primordial gravitational waves are sensitive to H_I



Potentially observable CMB polarization signature



* Current limits are $H_I \lesssim 10^{14}\ \mathrm{GeV}$. If saturated by a detection:
* *Warning!* Polarized foregrounds are challenging [e.g. BICEP2+Planck 2015]
* Limits may be evaded with non-trivial PQ breaking or moduli-decay thermal history (see talks by Rajendra 2014)

ULAs as an inflationary probe

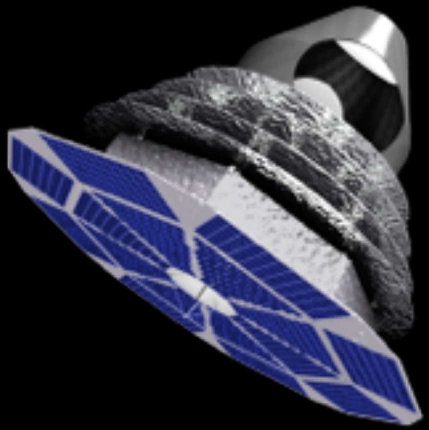
- Discovery of QCD axion/ULA dark matter $\longrightarrow$ trouble for
  - GUT-scale inflation

QCD axion $H_I \sim 10 \text{ GeV}$ ULA $H_I \sim 10^5 \text{ GeV}$

  - Null prediction for primordial B-mode searches

SPT/BICEP2-3/KECK

Spider

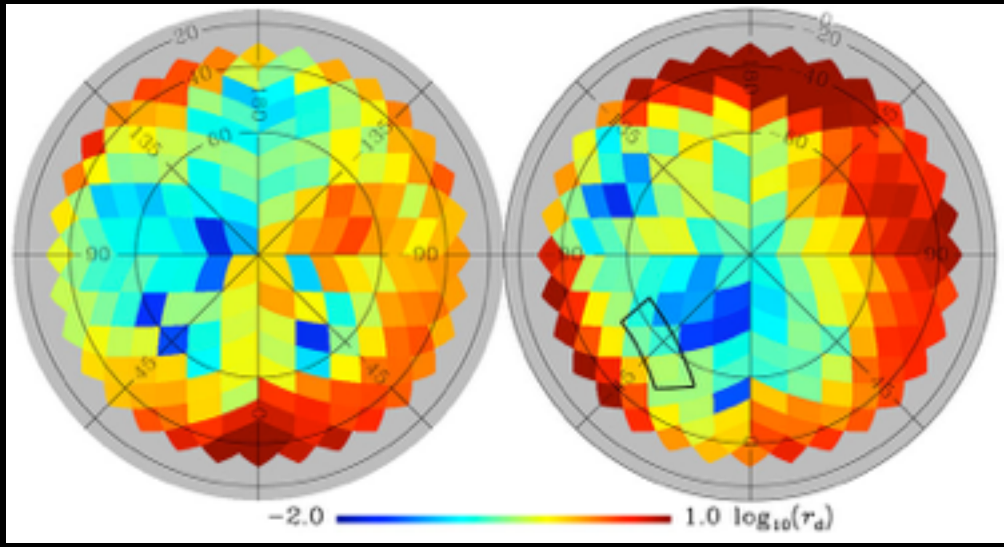


CORE

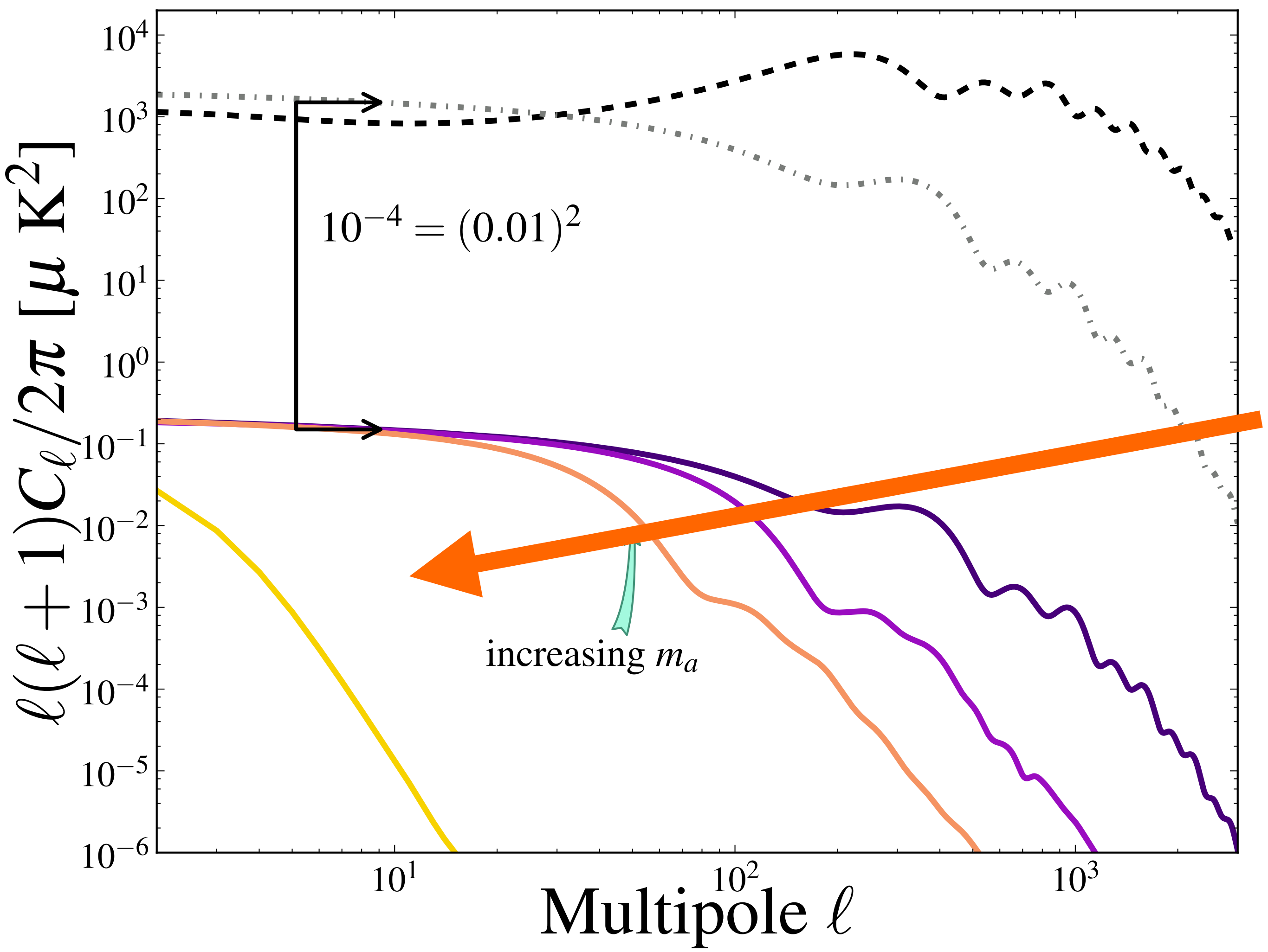
  - Avoidable with non-trivial thermal history/richer PQ symmetry breaking story (see Rajendran 2014)

Forecast/future work: Tensors and ULAs

- Polarized foregrounds are tricky: e.g. BICEP2+Planck



Forecast/future work: Tensors and ULAs



- ✳ Low-l plateau disappears
- ✳ Information lost
- ✳ Planck limits assume CDM isocurvature

✳ For $m_a \leq 10^{-27}$ eV, constraints cannot be simply remapped.

- ✳ MCMC in progress

CONCLUSIONS AND TAKE-AWAY

- Ultra-light axions may be probed at the 0.5% level using current cosmological data
- Entropy fluctuations and tensor perturbations are a powerful ULA probe
- Public AxiCAMB will be available later this summer

Additional slides for question time

FUTURE WORK: ULAS AND GALAXIES

✳ULA with $m_a \sim 10^{-22}$ eV have $\lambda_J \sim 100$ kpc

possibly helping with two challenges for ΛCDM

Cusp/core problem

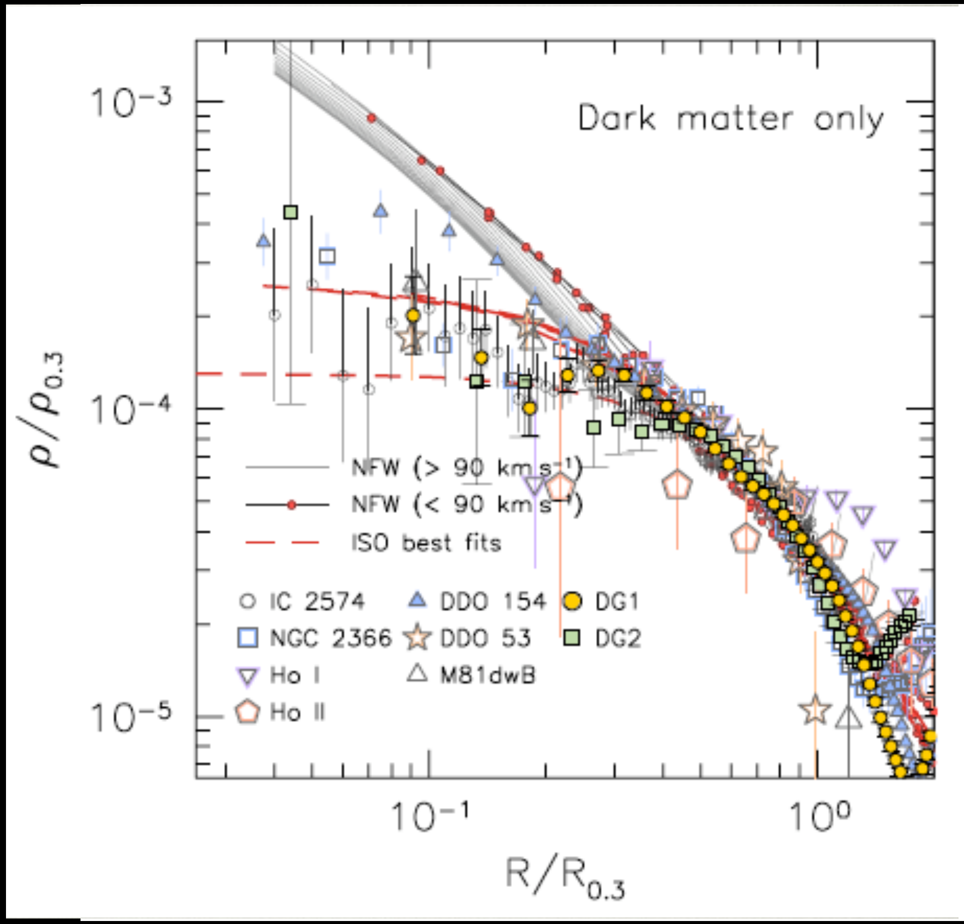


Figure from Brooks 2014/Oh 2011

Missing satellites Problem

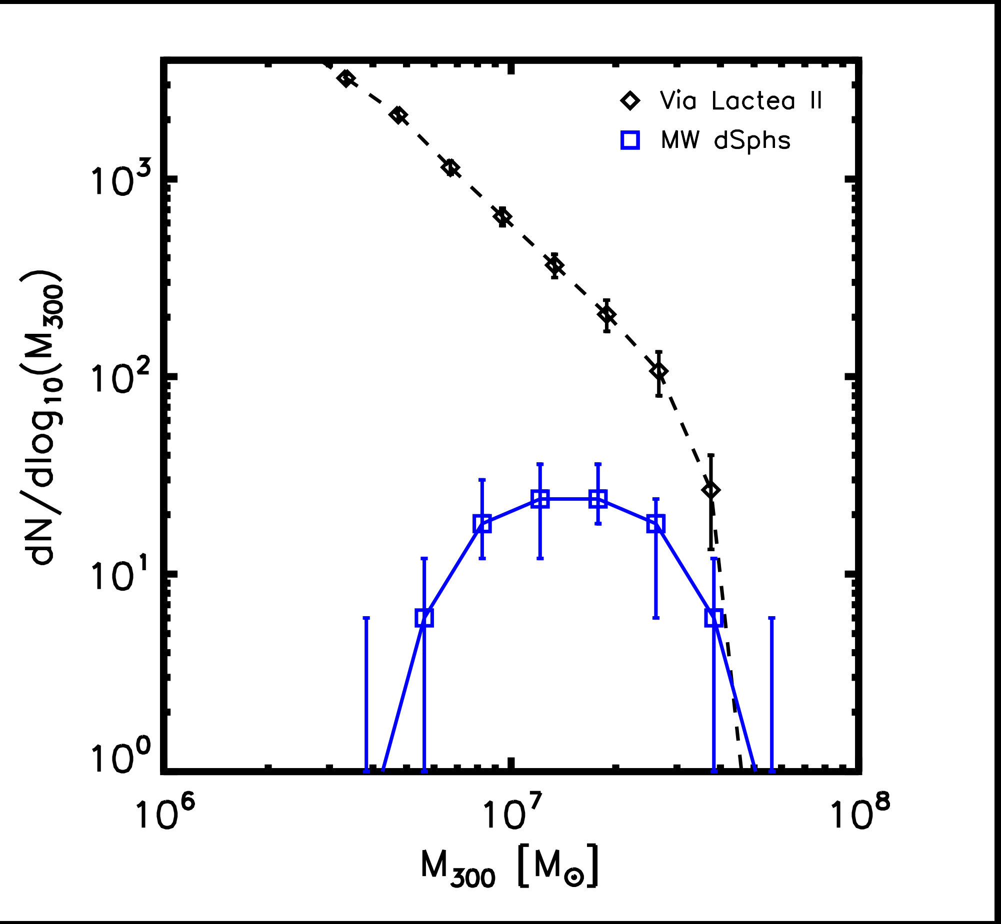


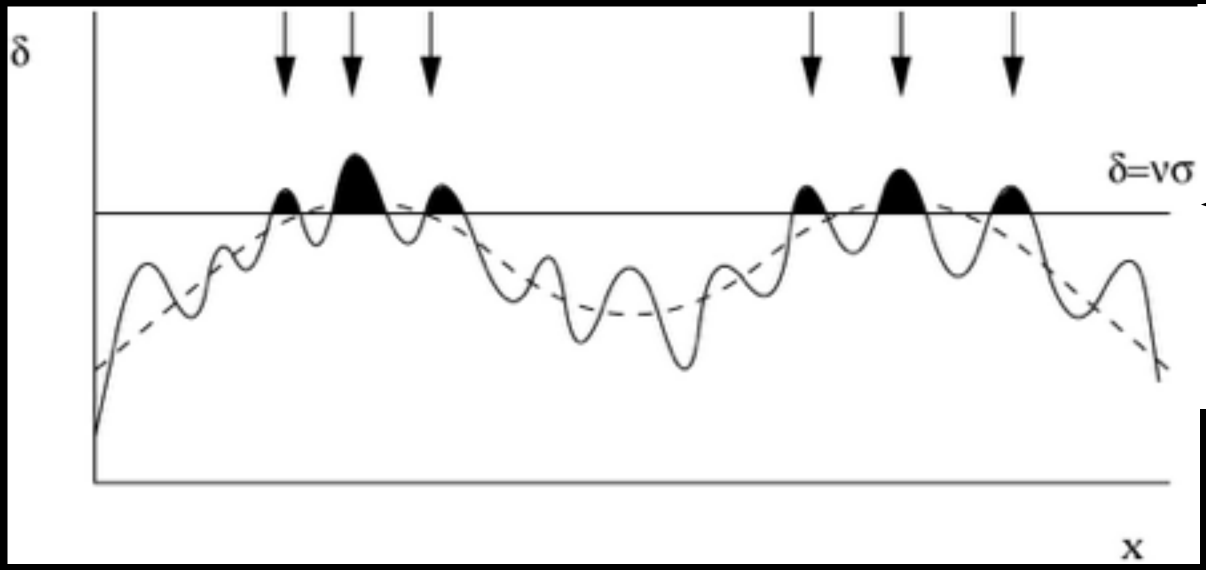
Figure from Bullock 2010

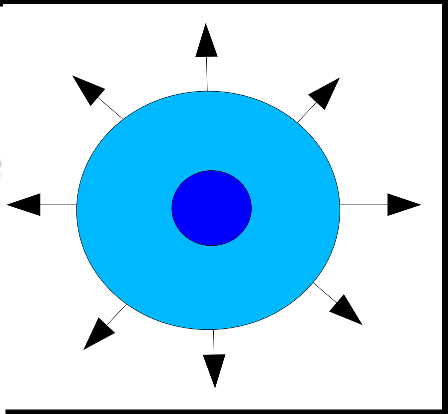
FUTURE WORK: ULAs AND GALAXIES

- ✳ULA with $m_a \sim 10^{-22}$ eV have $\lambda_J \sim 100$ kpc

  possibly helping with two challenges for ΛCDM

- ✳Elegant analytic arguments that ULA can help with both problems (Marsh et al. 2013 and 2014)





$$\delta_c^{\Lambda\mathrm{CDM}} = 1.686$$

$$\delta_c^{\Lambda\mathrm{ULA}} = ????$$

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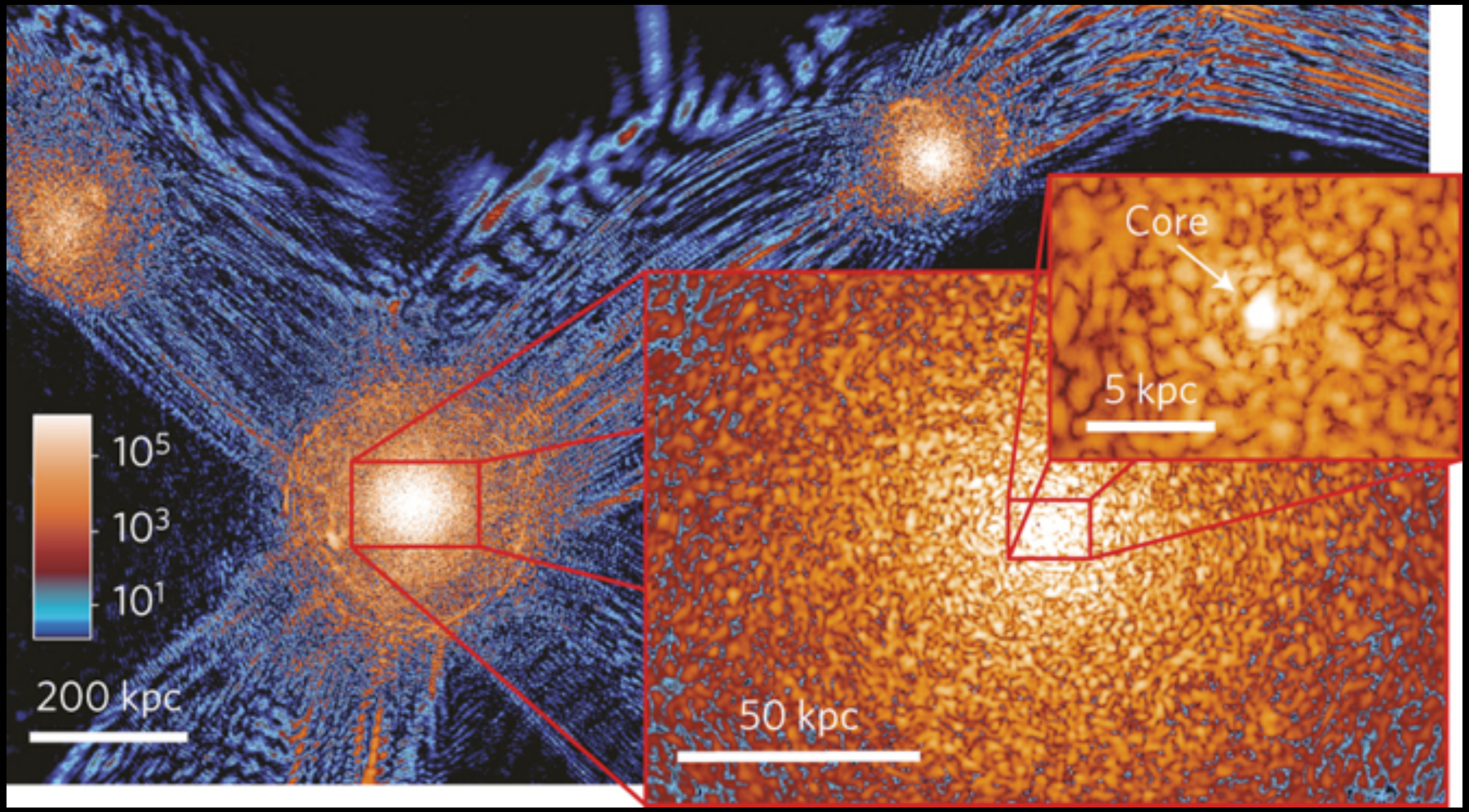


- Scant simulation work (N-body not appropriate for ULA) (Schive 2014)

ULAS AND GALAXIES

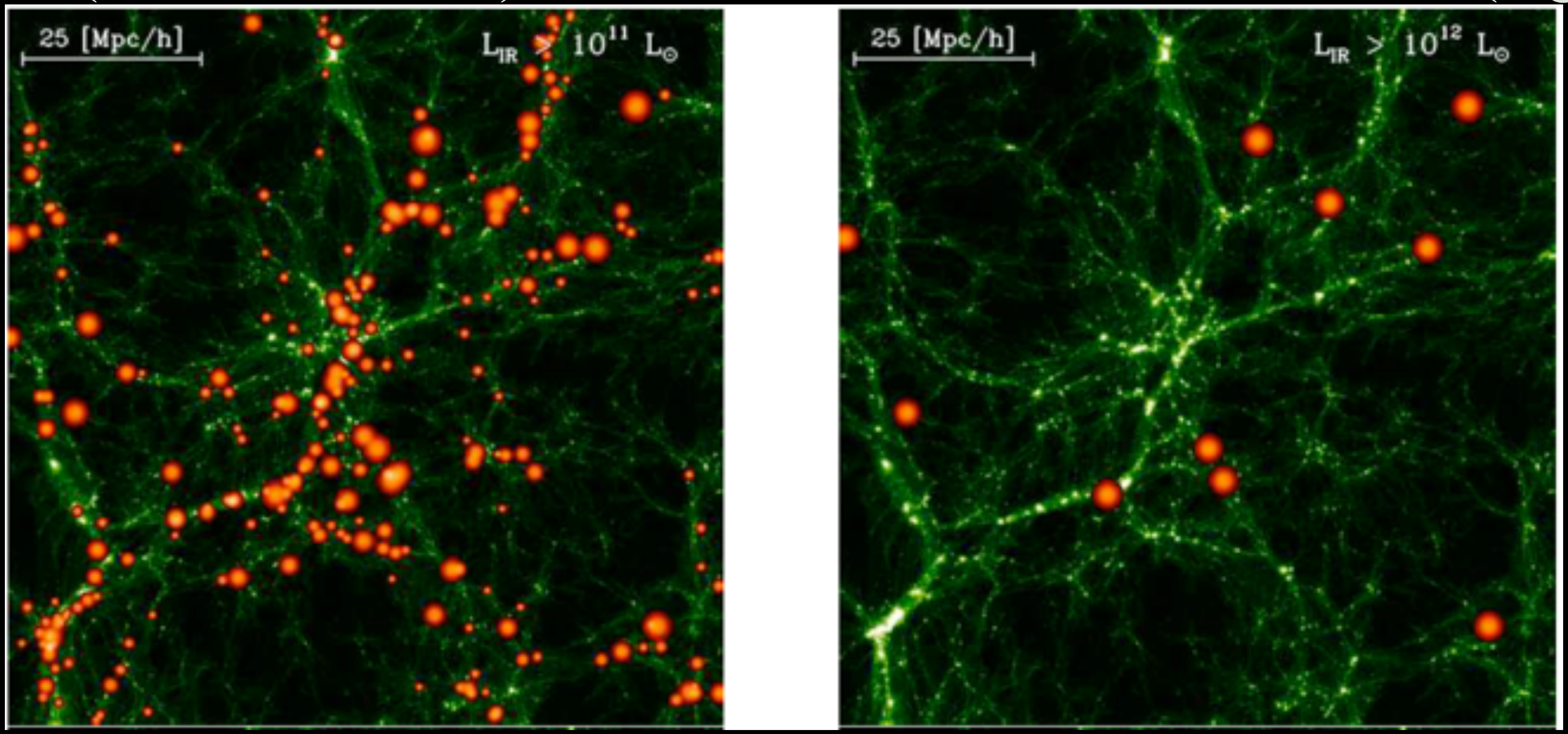
- Future growth in mode number driven by galaxy surveys

DARK ENERGY SURVEY

WFIRST
Wide-Field Infrared Survey Telescope

LSST

- Galaxies (and DM halos) are biased tracers of matter field (e.g. Baugh 2013)



- Generally bias scale-dependent for structure suppressing species (LoVerde 2013)

ULAs and galaxies

- Future growth in mode number driven by galaxy surveys

DARK ENERGY SURVEY

WFIRST
Wide-Field Infrared Survey Telescope

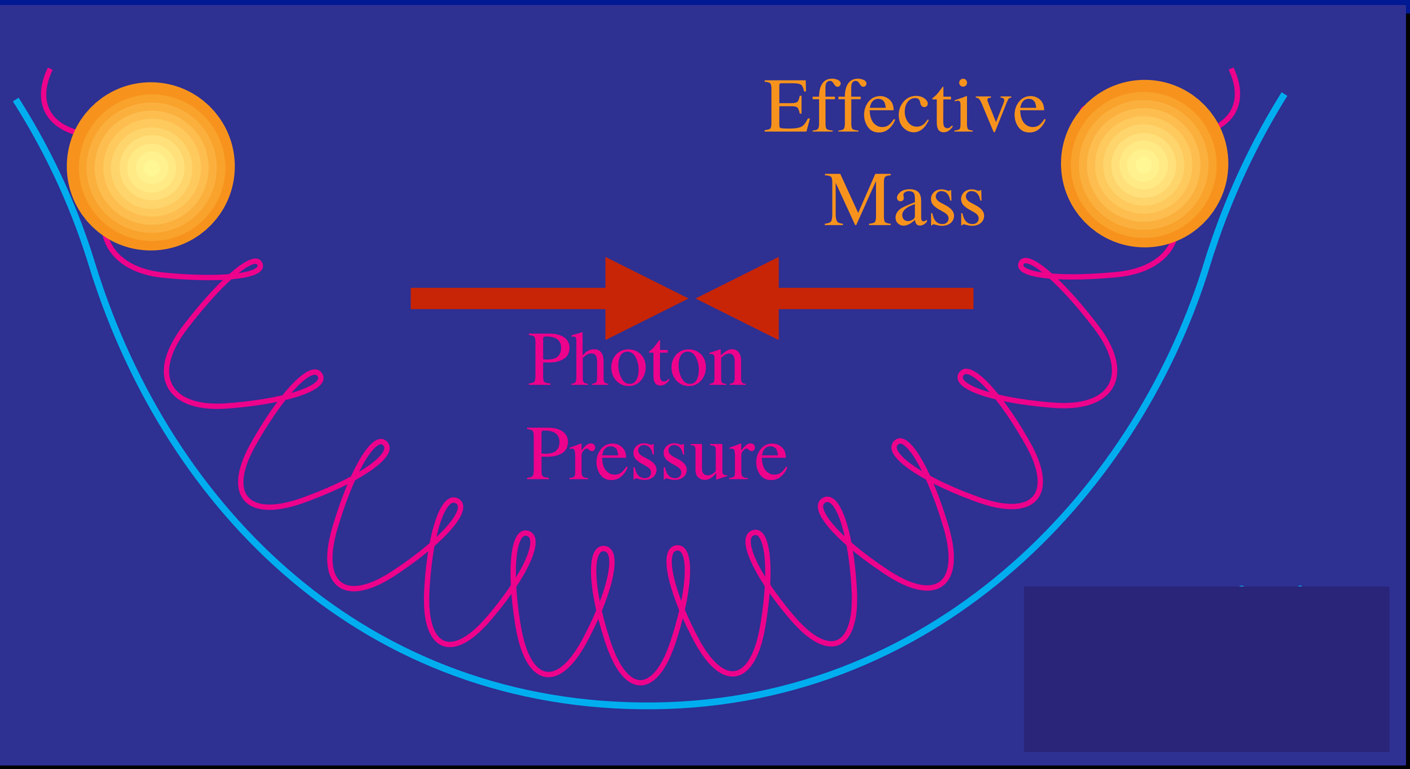
LSST

- Galaxies (and DM halos) are biased tracers of matter field (e.g. Baugh 2013)
- Future surveys will revolutionize:
  - Weak lensing
  - Strong lensing
  - Substructure [via timing]
  - MW dwarf population

Essential to understand how (or if) ULAs populate halos

Additional slides: Introduction

Acoustic oscillations in the CMB

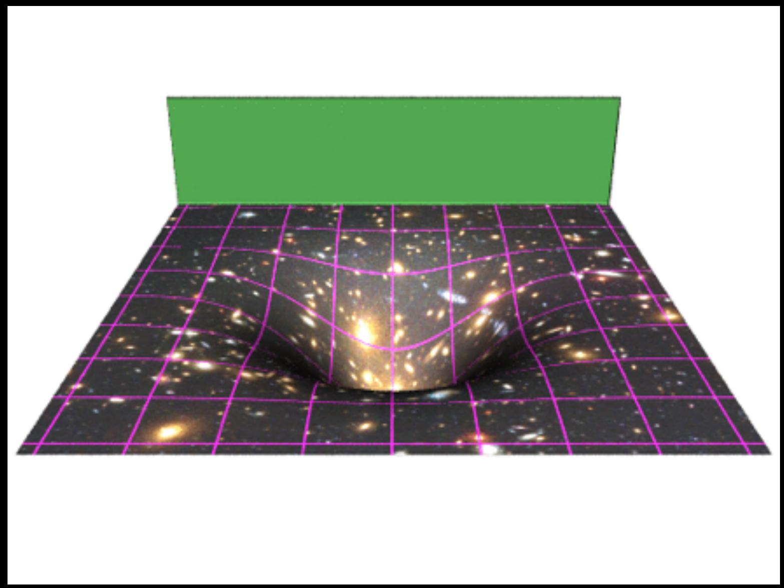


Gravity compresses

Ψ

and drives

$\dot{\Psi}$



- Baryons: Inertia $p_b \propto \frac{1}{a}$
- $e^- \ \gamma$ coupled through Thomson scattering $\Gamma \propto n_e \sigma_T$
- Restoring force: Radiation Pressure

$$\delta P_\gamma = c_s^2 \delta\rho_\gamma \qquad c_s^2 = \frac{1}{3}\left[1 + 3\rho_{\rm b}/4\rho_\gamma\right]^{-1}$$

Acoustic oscillations in the CMB

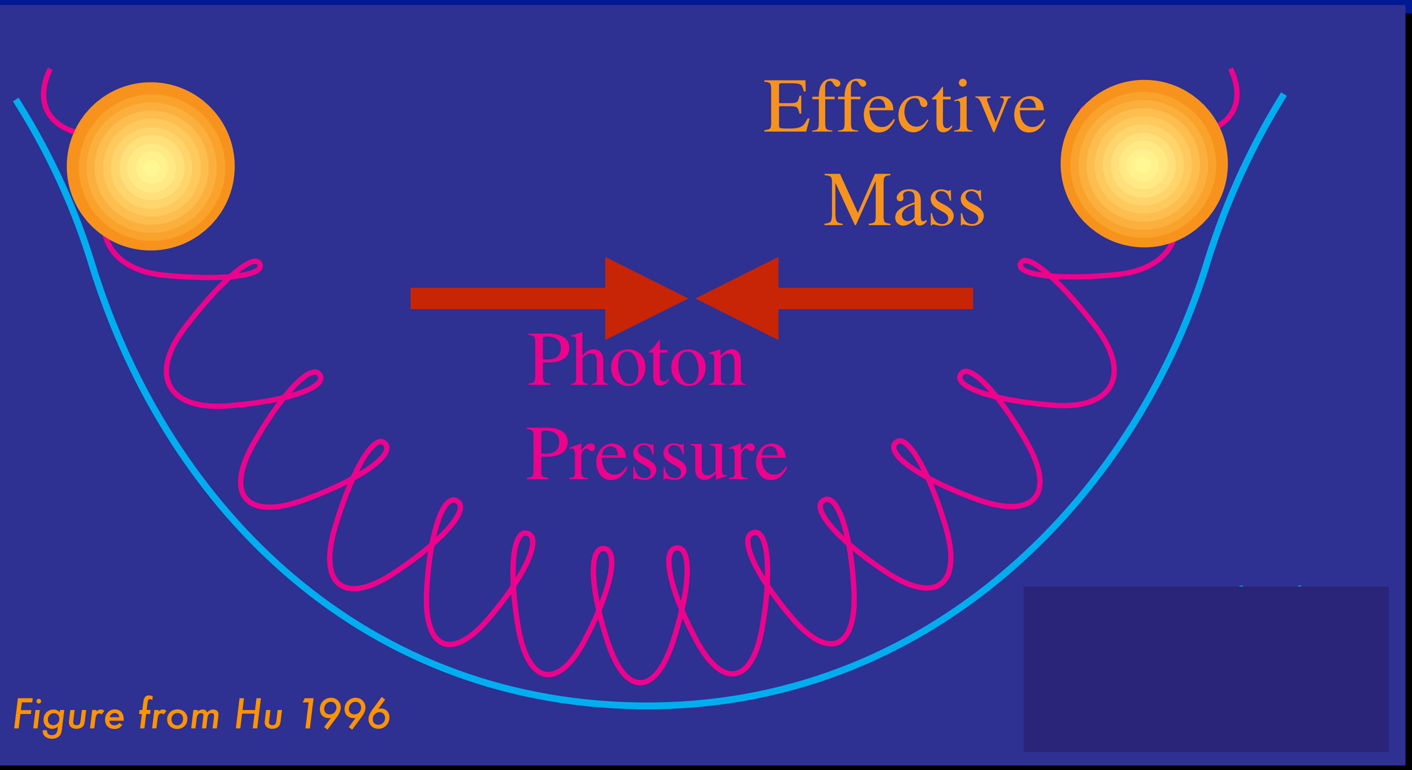


Figure from Hu 1996

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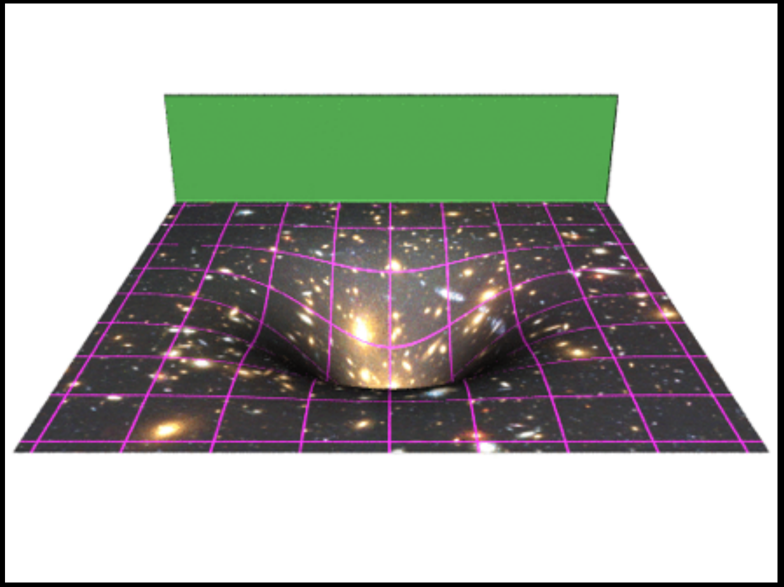

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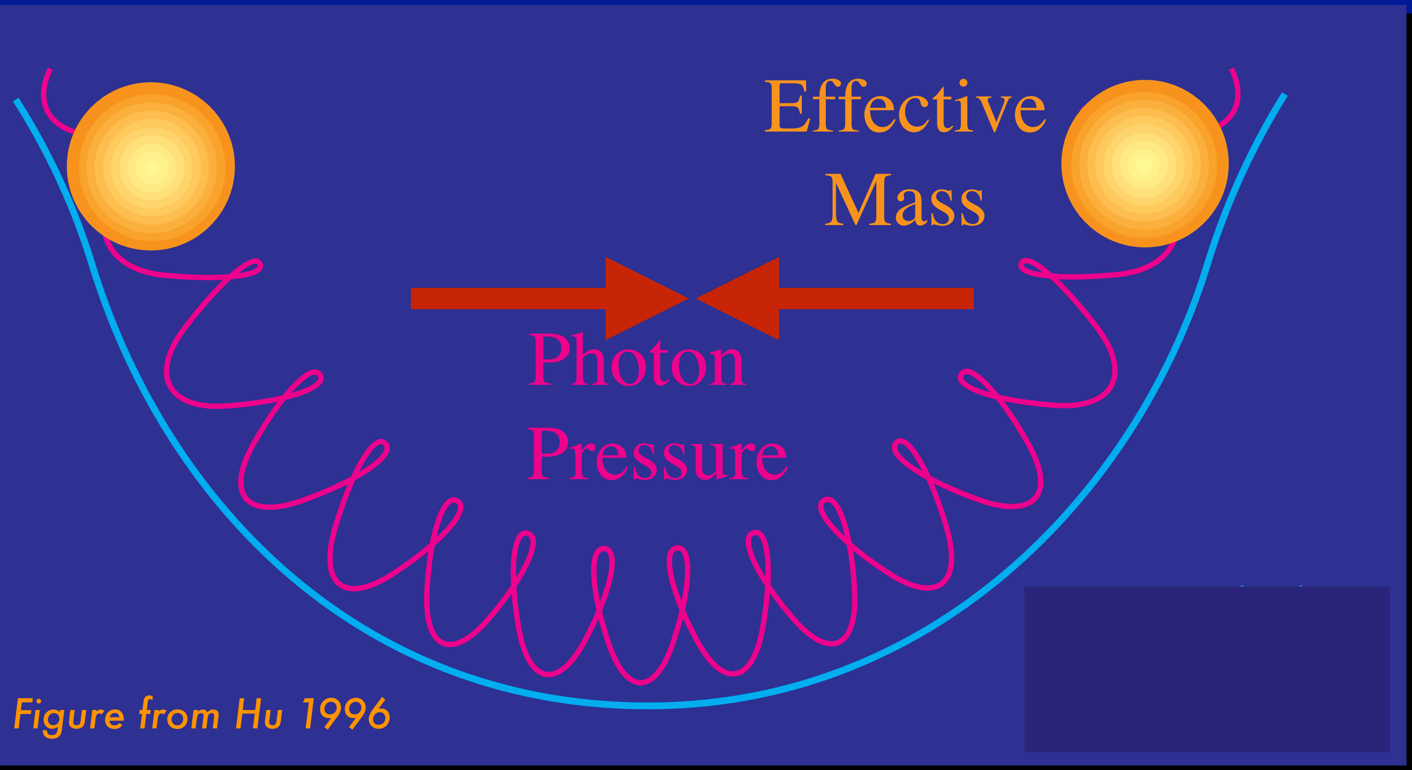

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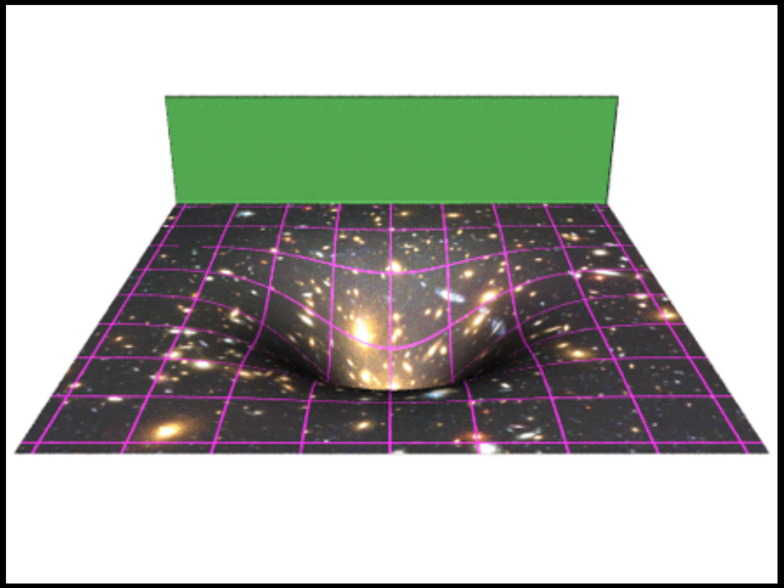

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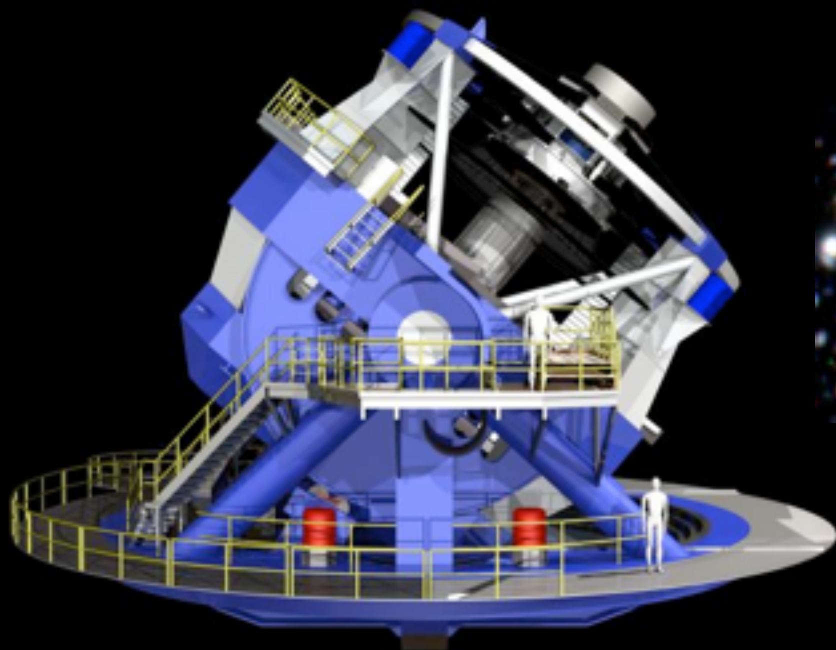
ONGOING/FUTURE OBSERVATIONS

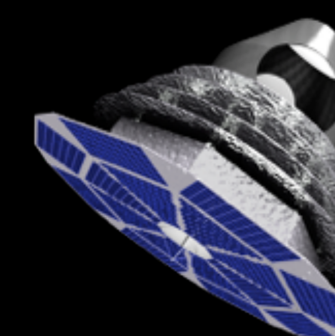


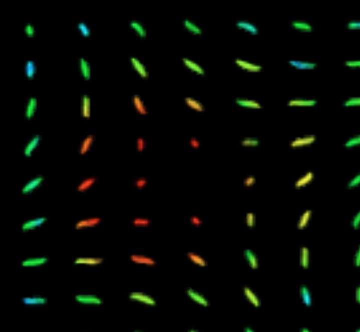
LSST

Scientific targets:
Modified Gravity
Neutrino hierarchy
Dark energy equation of state
Substructure in halos (via lensing)

SPT/BICEP2-3/KECK

SPIDER



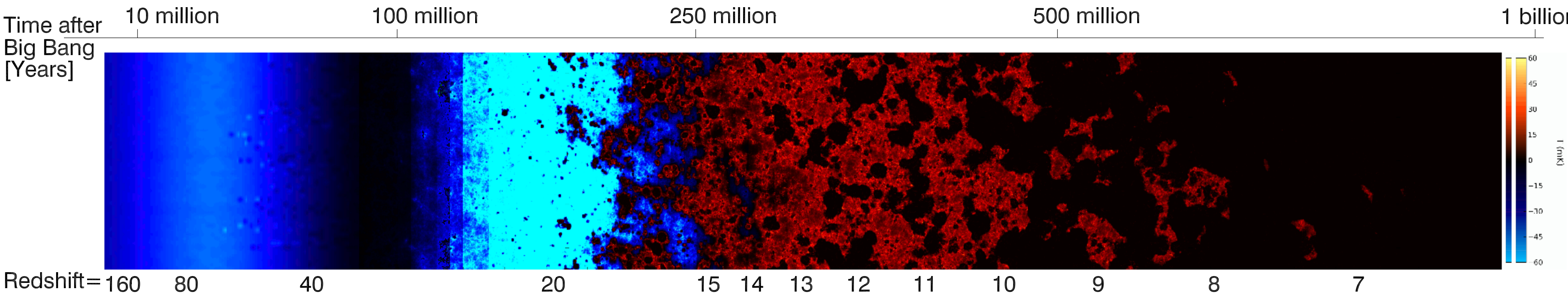


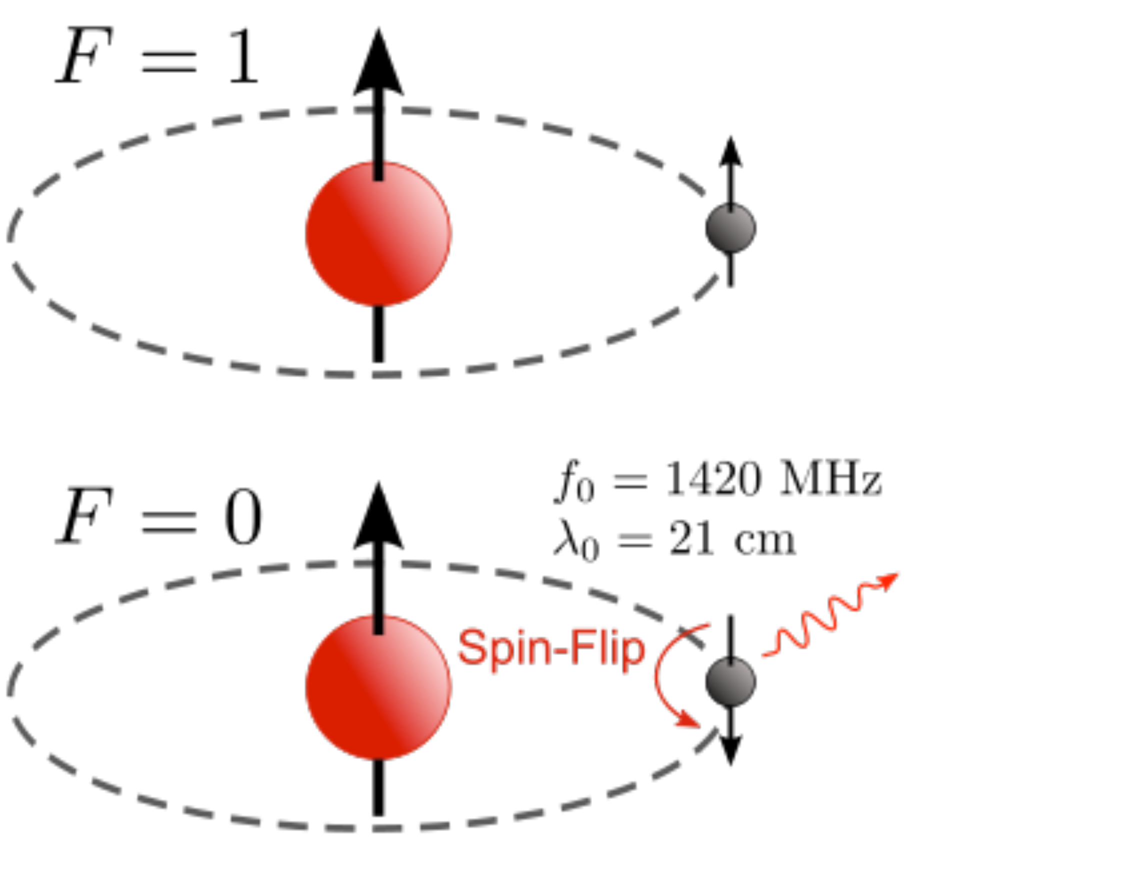
COrE
Cosmic Origins Explorer

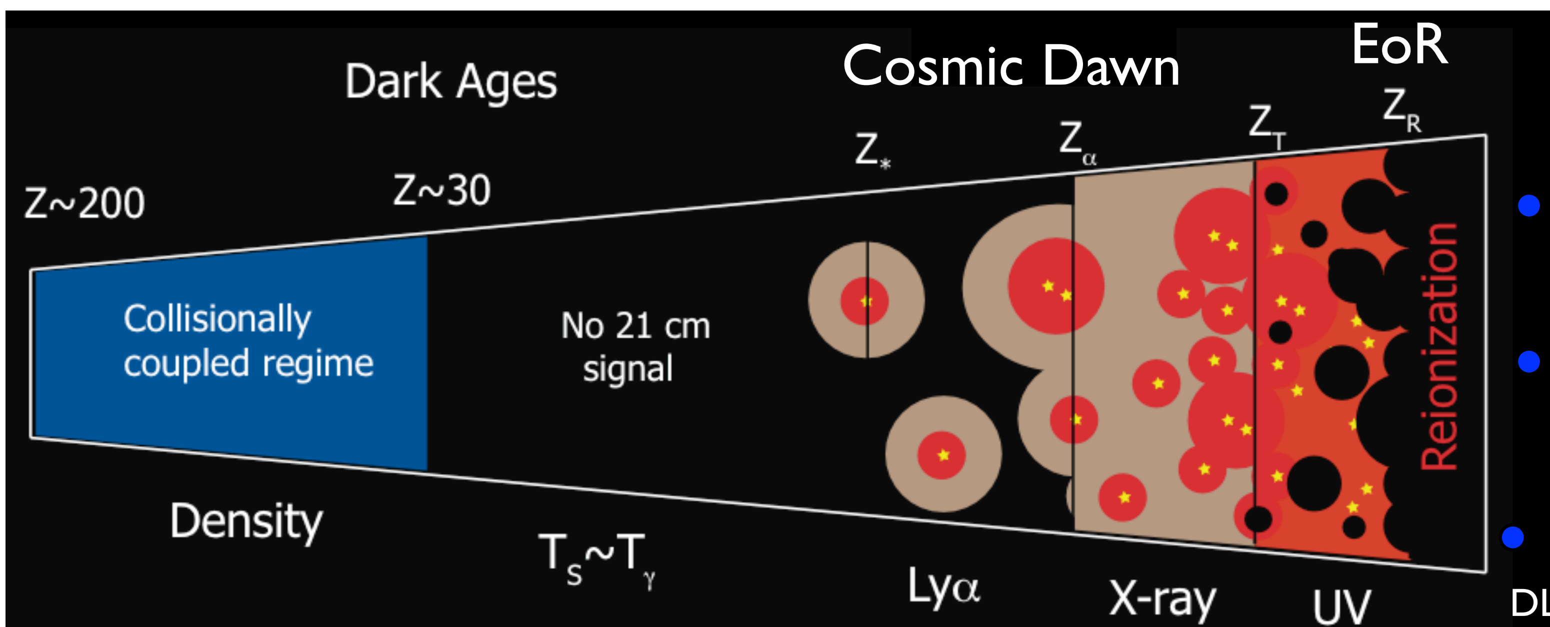
WFIRST
Wide-Field Infrared Survey Telescope

ongoing/Future observations [21-cm line]

21-cm cosmology [probes of structure on small scales and early times]







ONGOING/FUTURE OBSERVATIONS [21-CM LINE]

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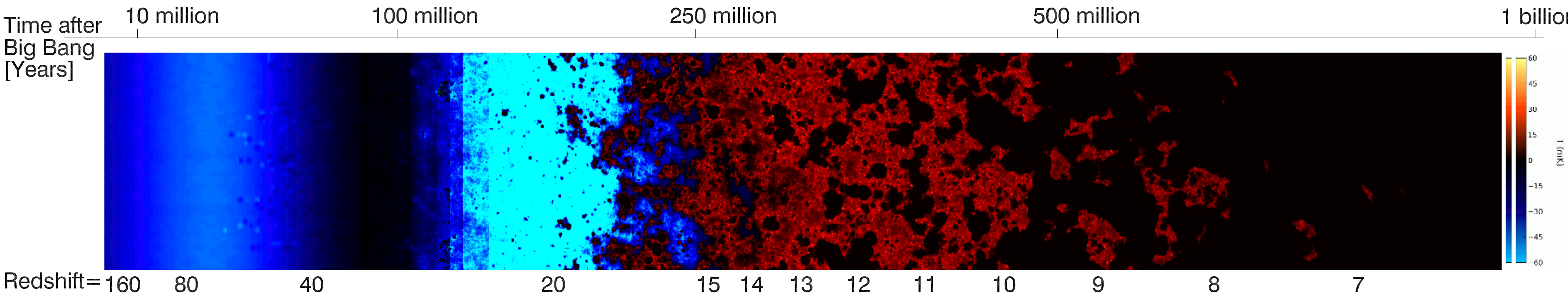
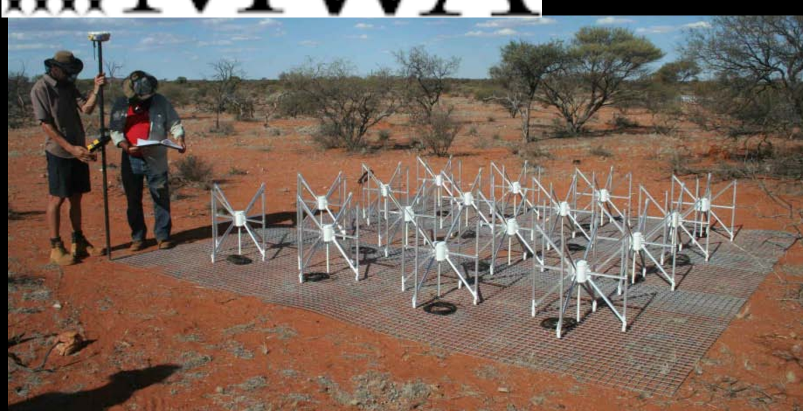


MWA



LOFAR

SKA
SQUARE KILOMETRE ARRAY

Additional slides:
QCD Axion theory/experiment

in collaboration with R. Hložek (Princeton), D. J. E. Marsh (Perimeter Institute), P. Ferreira (Oxford):

arXiv:1303.3008, Phys. Rev. D 87, 121701 (2013)
arXiv:1403.4216, Phys. Rev. Lett. 113, 011801 (2014)
arXiv:1410.2896, submitted to Phys, Rev. D

Strong CP problem

- Strong interaction violates CP through θ -vacuum term

QCD strong-CP problem

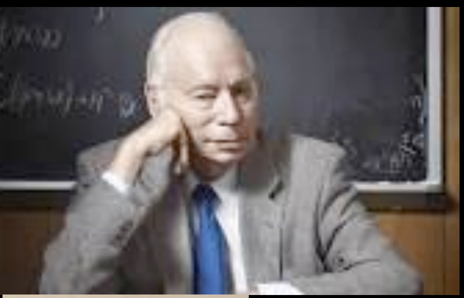
$$\mathcal{L}_{\mathrm{CPV}} = \frac{\theta g^2}{32\pi^2} G\tilde{G}$$

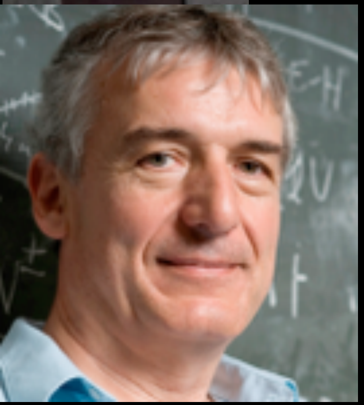
- Limits on the neutron electric dipole moment are strong. Fine tuning?

$$d_n \simeq 10^{-16}\ \theta\ \mathrm{e\ cm}$$

$$\theta \lesssim 10^{-10},$$

Cleaning up the dark matter mess?





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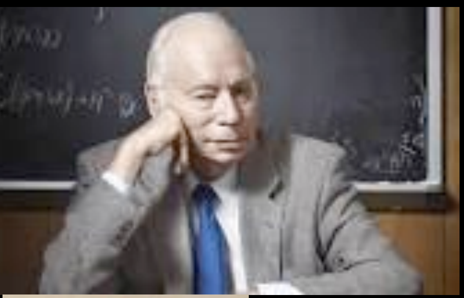

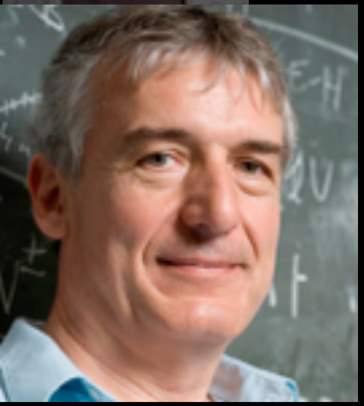

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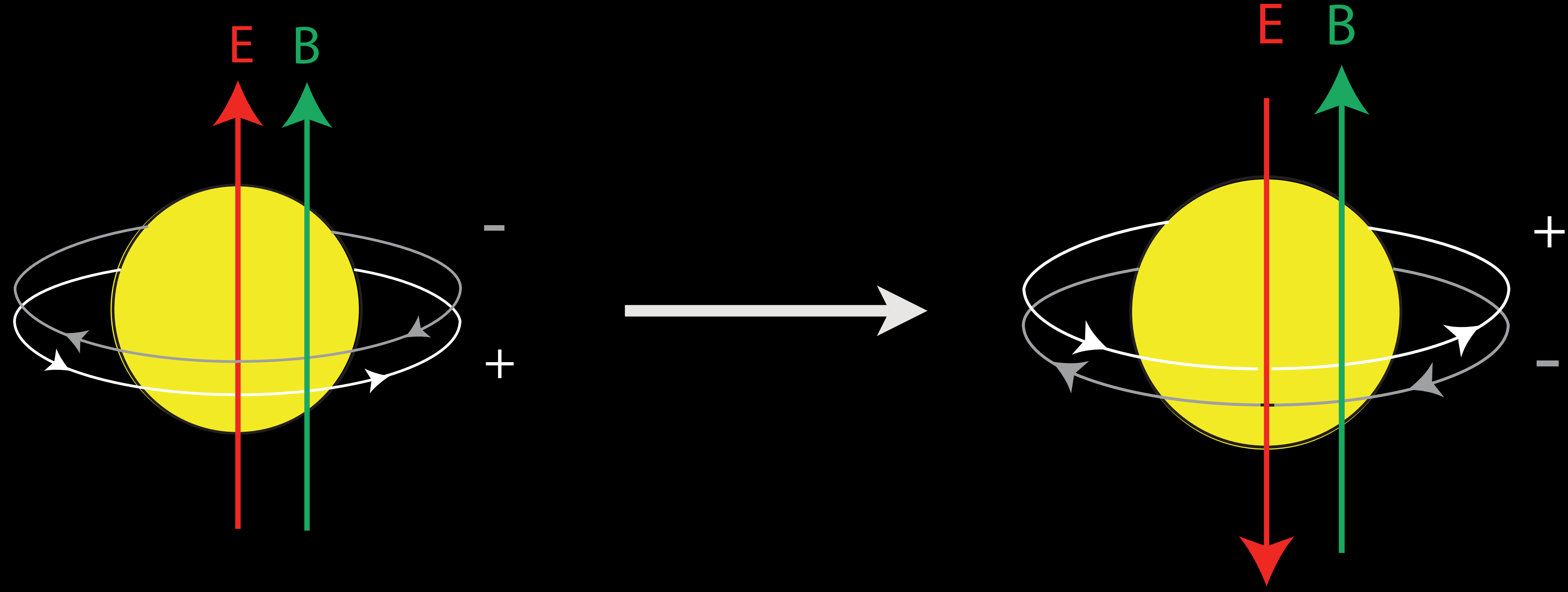

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KEY QUESTIONS:

- **Can the *dark matter* or *dark energy* be an ultra-light boson, like an axion?**

- What is the connection between the physics of inflation and the physics of the dark sector? Are initial fluctuations in different species spatially locked?

- What new probes of the dark sector could we soon have at our disposal?

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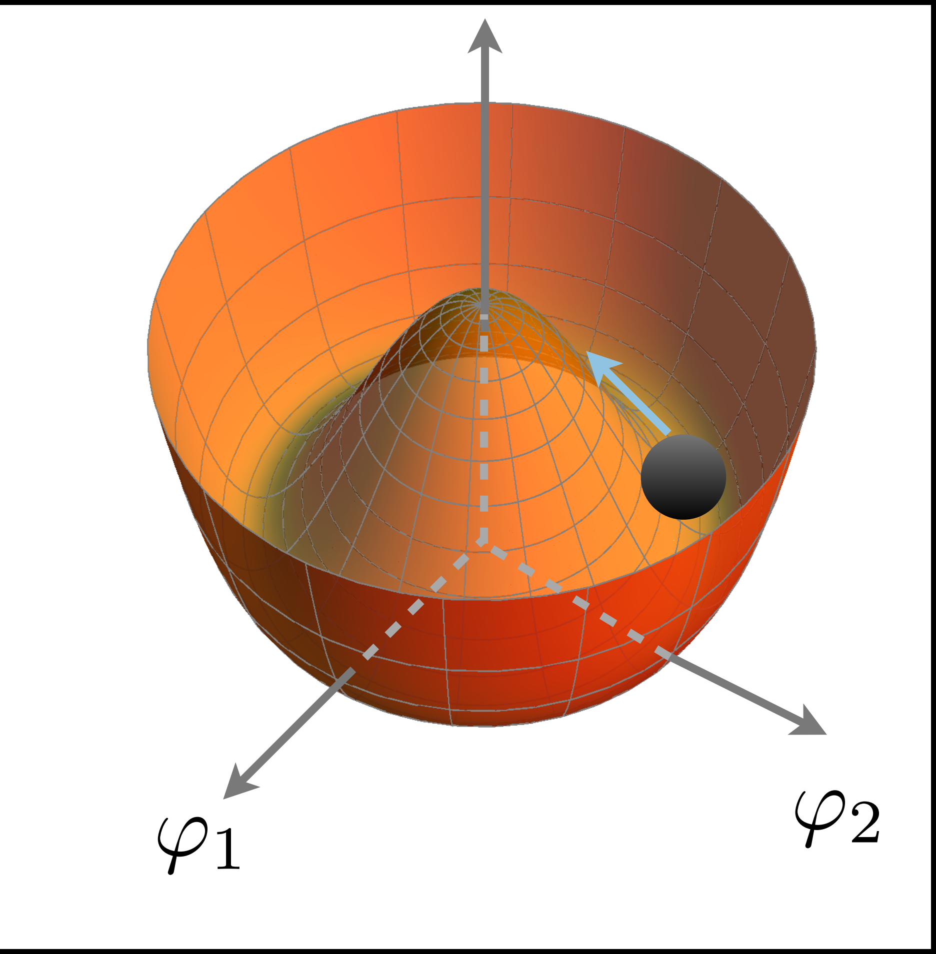
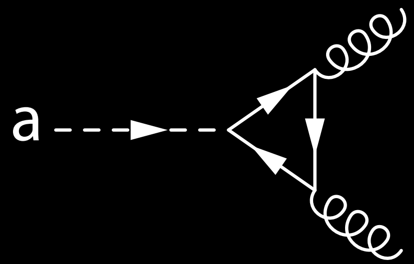
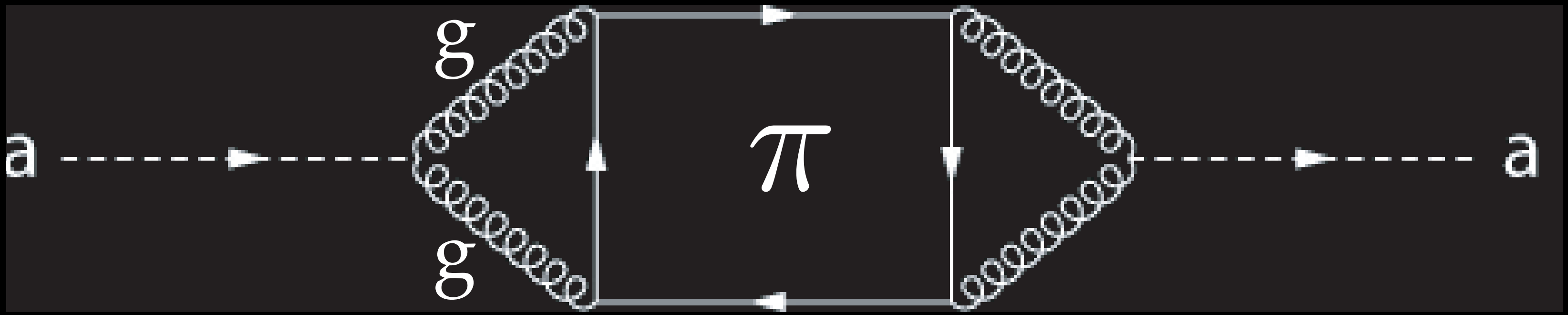


New scalar field with global U(1) symmetry!

$$\mathcal{L}_{\mathrm{CPV}} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \frac{a}{f_{\mathrm{a}}} g^2 G\tilde{G}$$

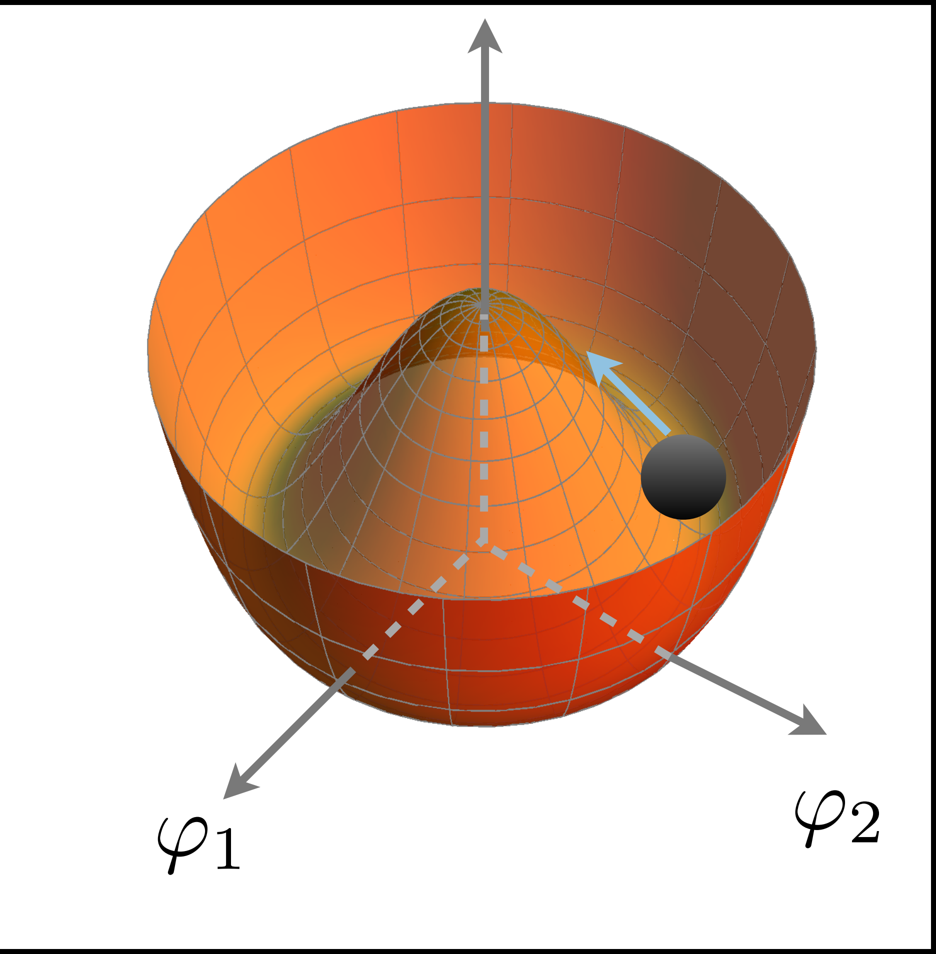


- ✳ Couples to SM gauge fields (via fermions)
- ✳ Dynamically erases QCD CP-violation
- ✳ Mass through pion mixing



Peccei + Quinn (1977), Weinberg +Wilczek (1978), Kim (1979), Shifman et. al (1980), Zhitnitsky (1980), Dine et al. (1981), D.B. Kaplan (1985), A.E Nelson (1985,1990)

WHAT ARE AXIONS?



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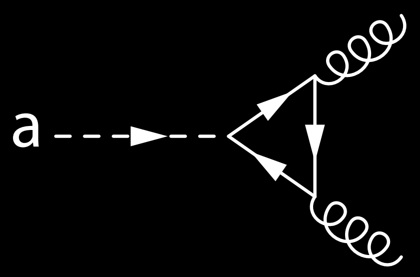

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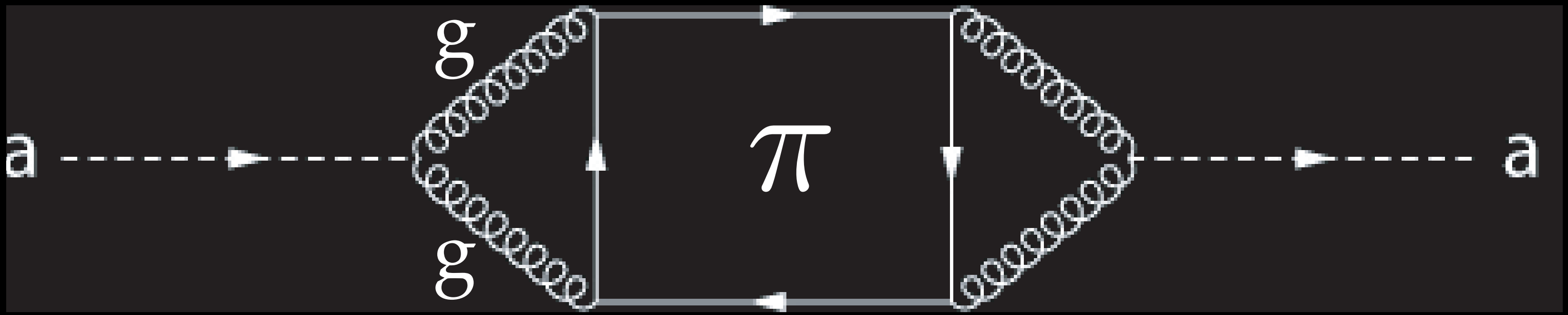

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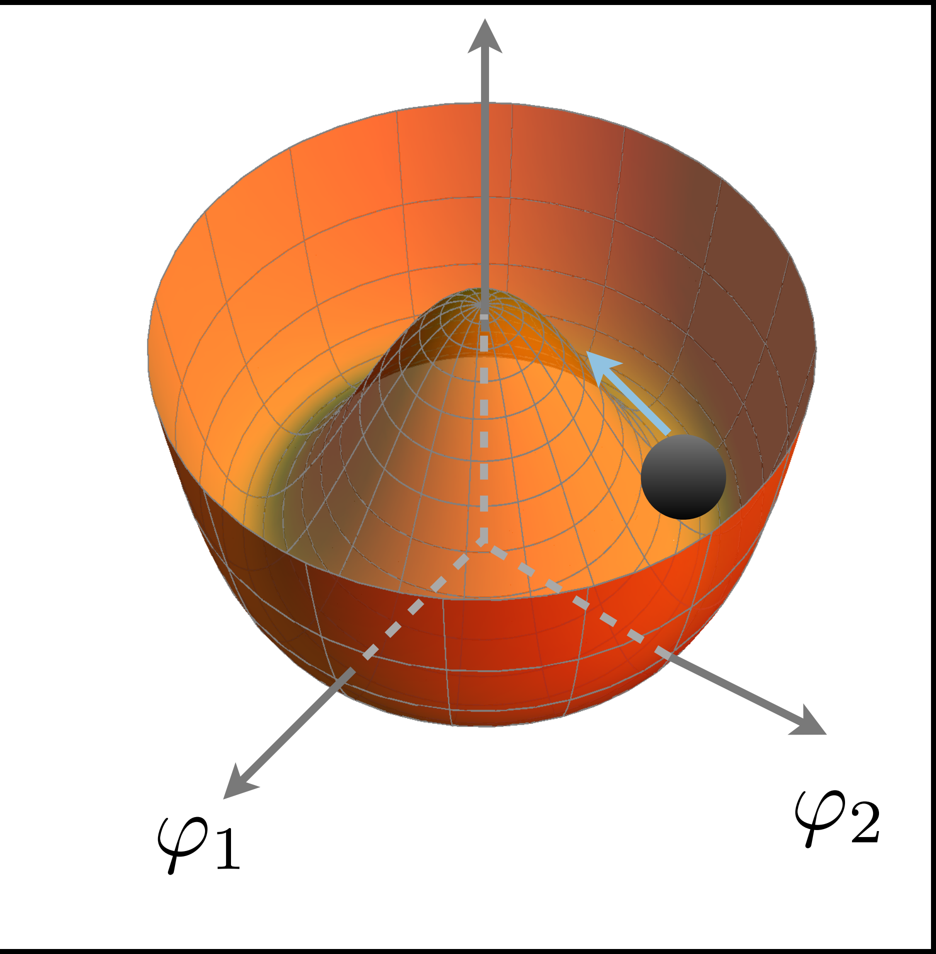

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Broken at scale f_a

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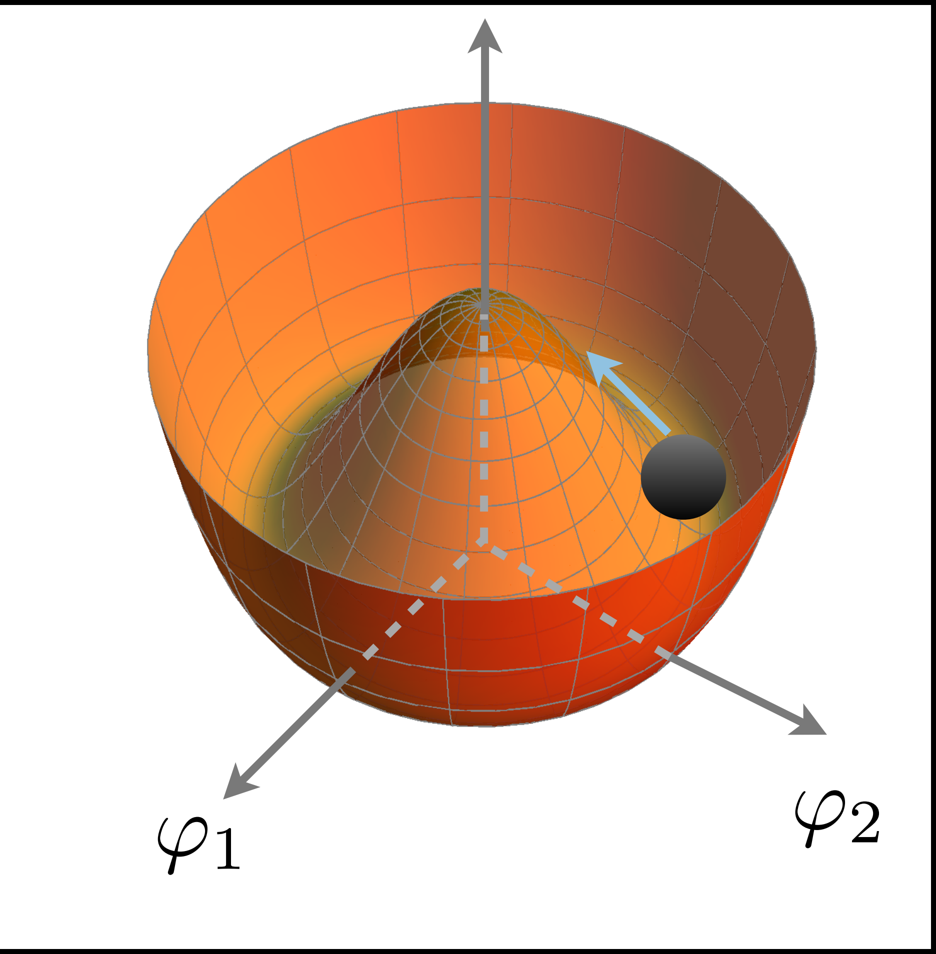

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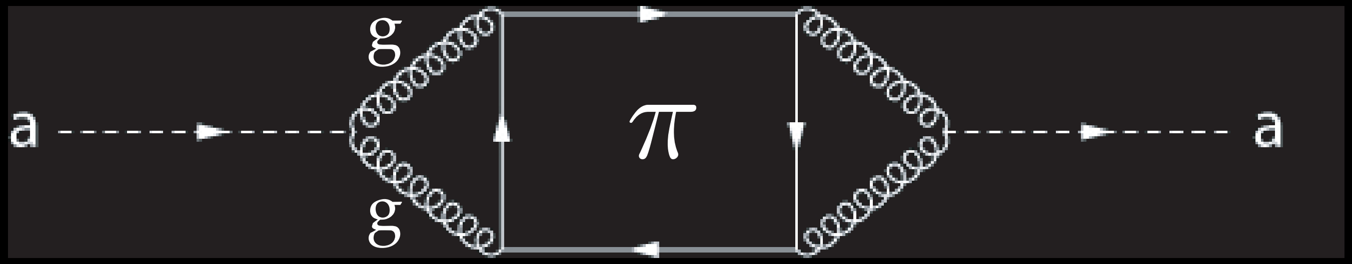
Axions solve the strong CP problem

- New field (axion) and U(1) symmetry dynamically drive net CP-violating term to 0

$$\mathcal{L}_{\rm CPV} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \frac{a}{f_{\rm a}} g^2 G\tilde{G}$$

- Through coupling to pions, axions pick up a mass



$$\boxed{m_a \simeq \frac{\Lambda_{\rm QCD}^2}{f_a}}$$

$$\Lambda_{\rm QCD} \simeq 200\ \mathrm{MeV}$$

Axions solve the strong CP problem

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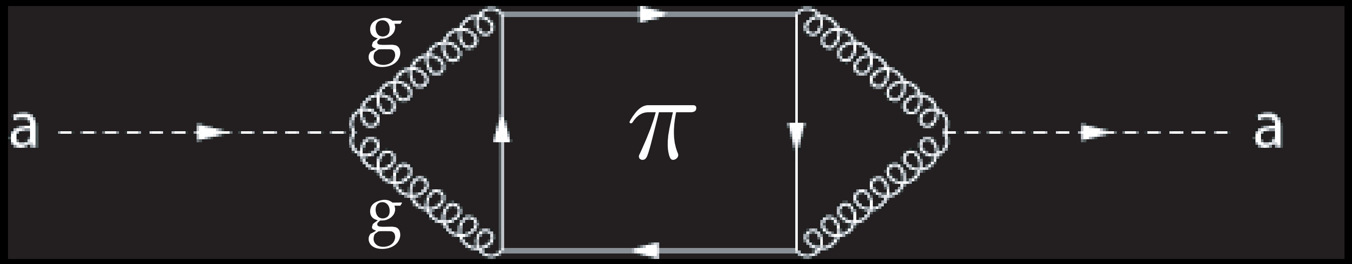
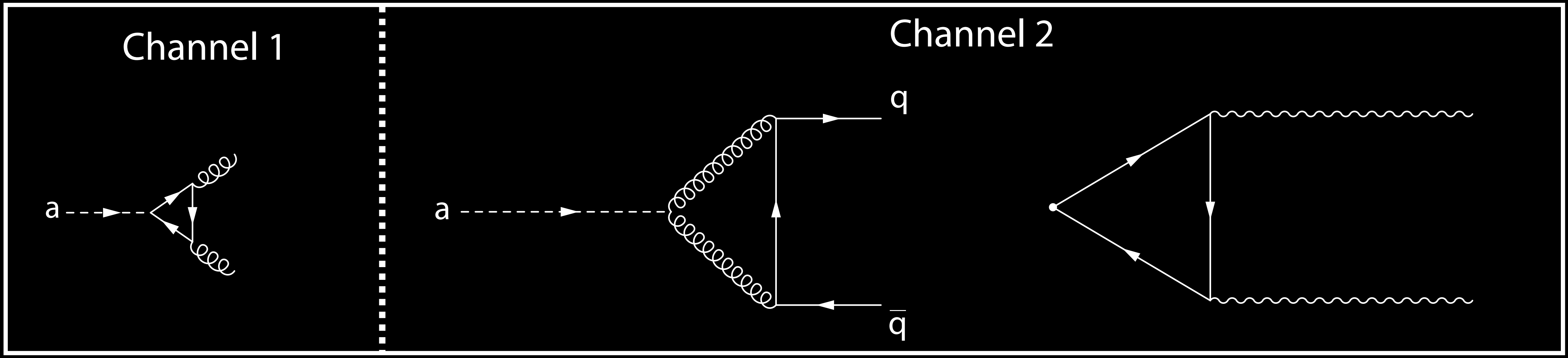


$$m_a = 6.2\mu \text{ eV} \left(\frac{10^{12} \text{ GeV}}{f_{\mathrm{a}}} \right)$$

Two-photon coupling of axion



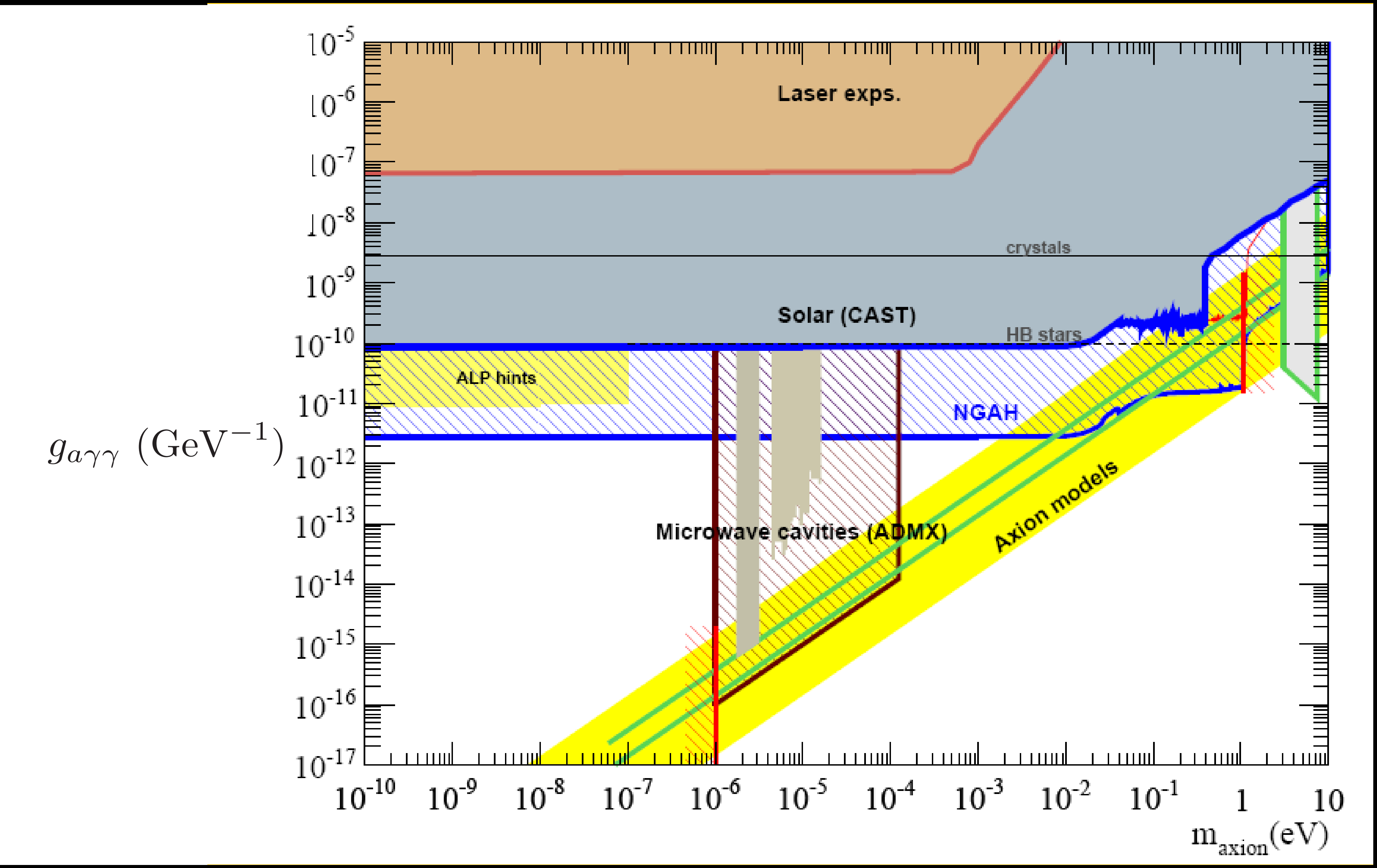
* Axions interact weakly with SM particles $\Gamma, \sigma \sim \alpha^2$

* Axions have a two-photon coupling

$$g_{a\gamma\gamma} = -\frac{3\alpha}{8\pi f_a}\xi \qquad \mathcal{L} \propto g_{a\gamma\gamma}\vec{E}\cdot\vec{B}$$

* Very little freedom once f_a specified

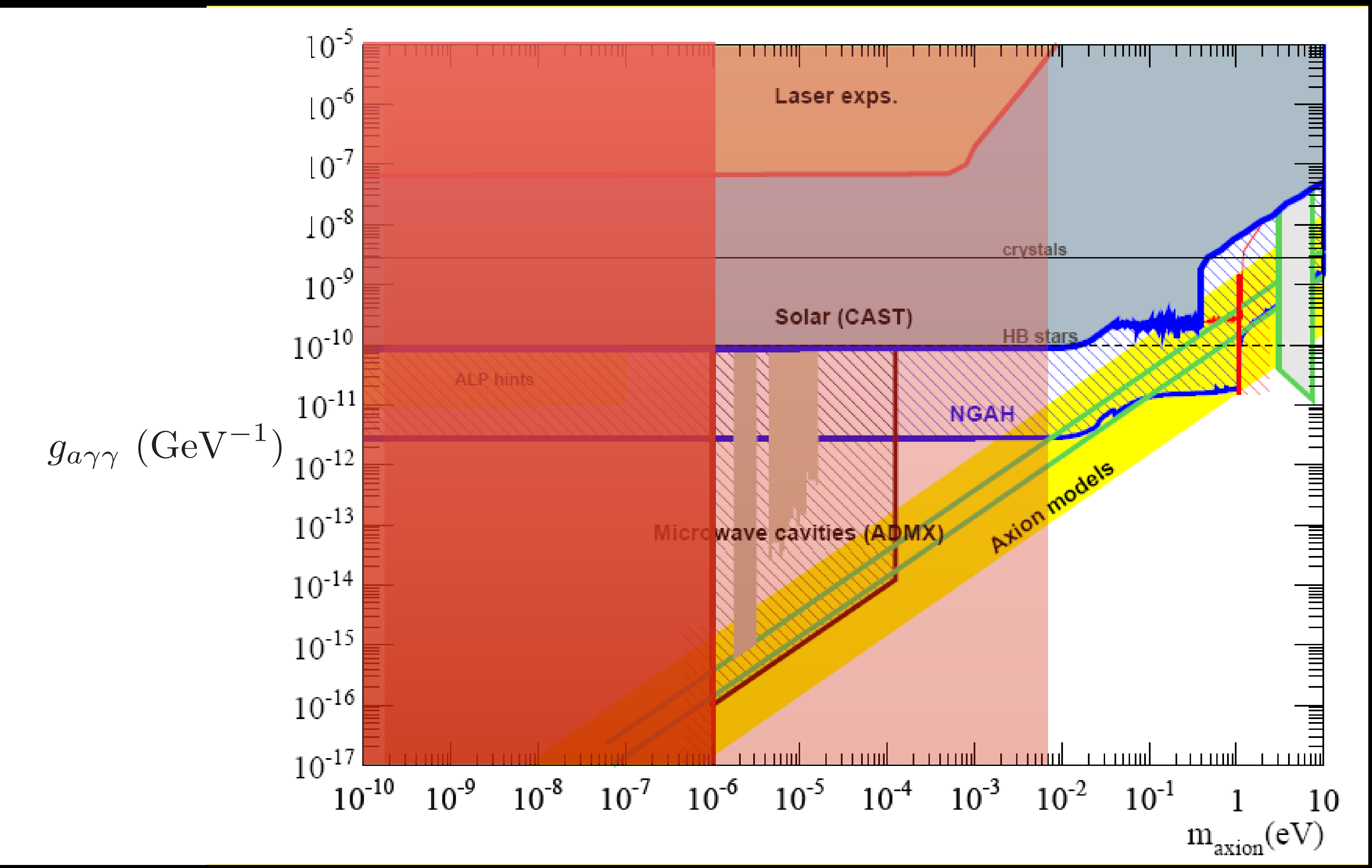
LIMITS



$$\mathcal{L} \propto g_{a\gamma\gamma} a \vec{E} \cdot \vec{B} \quad g_{a\gamma\gamma} \propto 1/f_a$$

LIMITS

Cosmoloaical abundance



$$\mathcal{L} \propto g_{a\gamma\gamma} a \vec{E} \cdot \vec{B} \quad g_{a\gamma\gamma} \propto 1/f_a$$

Dark matter axion abundance

- QCD axion couples to quarks/pions, temp-dependent mass
  - High-temp regime

$$m_{\rm a} = 0.02 m_{\rm a}^{(T=0)} \left(\frac{\Lambda_{\rm QCD}}{T}\right)^4 \text{ if } T \gg \Lambda_{\rm QCD}$$

  - Low-temp regime $m_{\rm a} = m_{\rm a}^{(T=0)}$ if $T \lesssim \Lambda_{\rm QCD}$

$$\boxed{\Omega_{\rm mis} h^2 = 0.236 \left\langle \theta_i^2 f(\theta_i) \right\rangle \left(\frac{f_a}{10^{12}\ \text{GeV}}\right)^{7/6}} \quad \text{if } f_a \lesssim 10^{18}\ \text{GeV}$$

$$\boxed{\Omega_{\rm mis} h^2 = 0.005 \left\langle \theta_i^2 f(\theta_i) \right\rangle \left(\frac{f_a}{10^{12}\ \text{GeV}}\right)^{3/2}} \quad \text{if } f_a \gtrsim 10^{18}\ \text{GeV}$$

Anthropic axion window: $f_a > \max\{T_{\mathrm{RH}}, H_{\mathrm{I}}\}$

- Axion field is relatively homogeneous

$$\langle\theta^2\rangle = \overline{\theta}^2 + \left(\frac{H_I}{2\pi f_a}\right)^2$$

- Abundance

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Misalignment in our Hubble Patch

- Abundance

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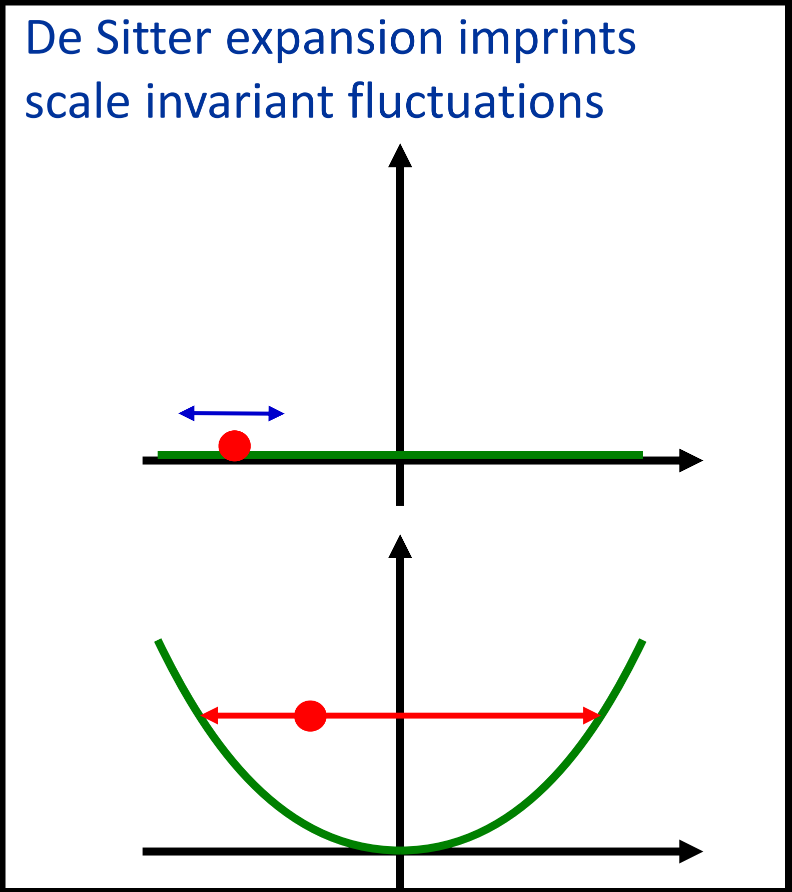
Vacuum fluctuations from inflation



- Abundance

From Raffelt 2012

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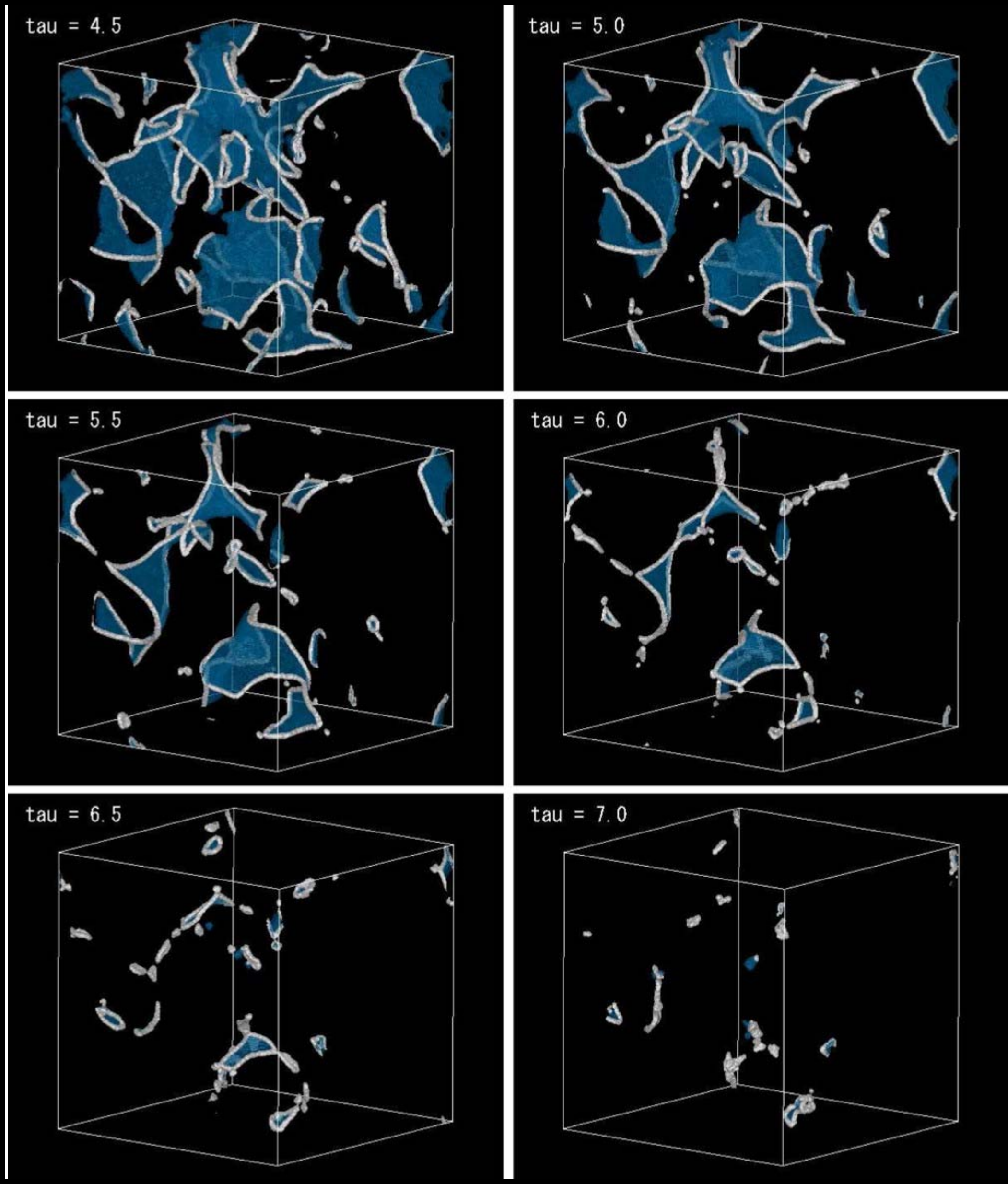
- Abundance

$$\Omega_a h^2 \simeq 0.43 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6} \theta_i^2$$

$$\Omega_a h^2 \simeq 0.005 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{3/2} \theta_i^2$$

- $\overline{\theta}$ can be tuned to get DM abundance for many axion masses

Classic axion window: $f_a < \max\{T_{\rm RH}, H_{\rm I}\}$



- ✳ Axion field is very inhomogeneous

$$\left\langle \overline{\theta}_i^2 \right\rangle = \frac{\pi^2}{6}$$

- ✳ Defects [domain walls, strings, etc..]

$$\mathcal{O}(1) \lesssim \alpha_{\rm defect} \lesssim \mathcal{O}(10^2)$$

- ✳ Abundance

$$\Omega_a h^2 \simeq 2.0\,\{1 + f_{\rm defect}\} \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6}$$

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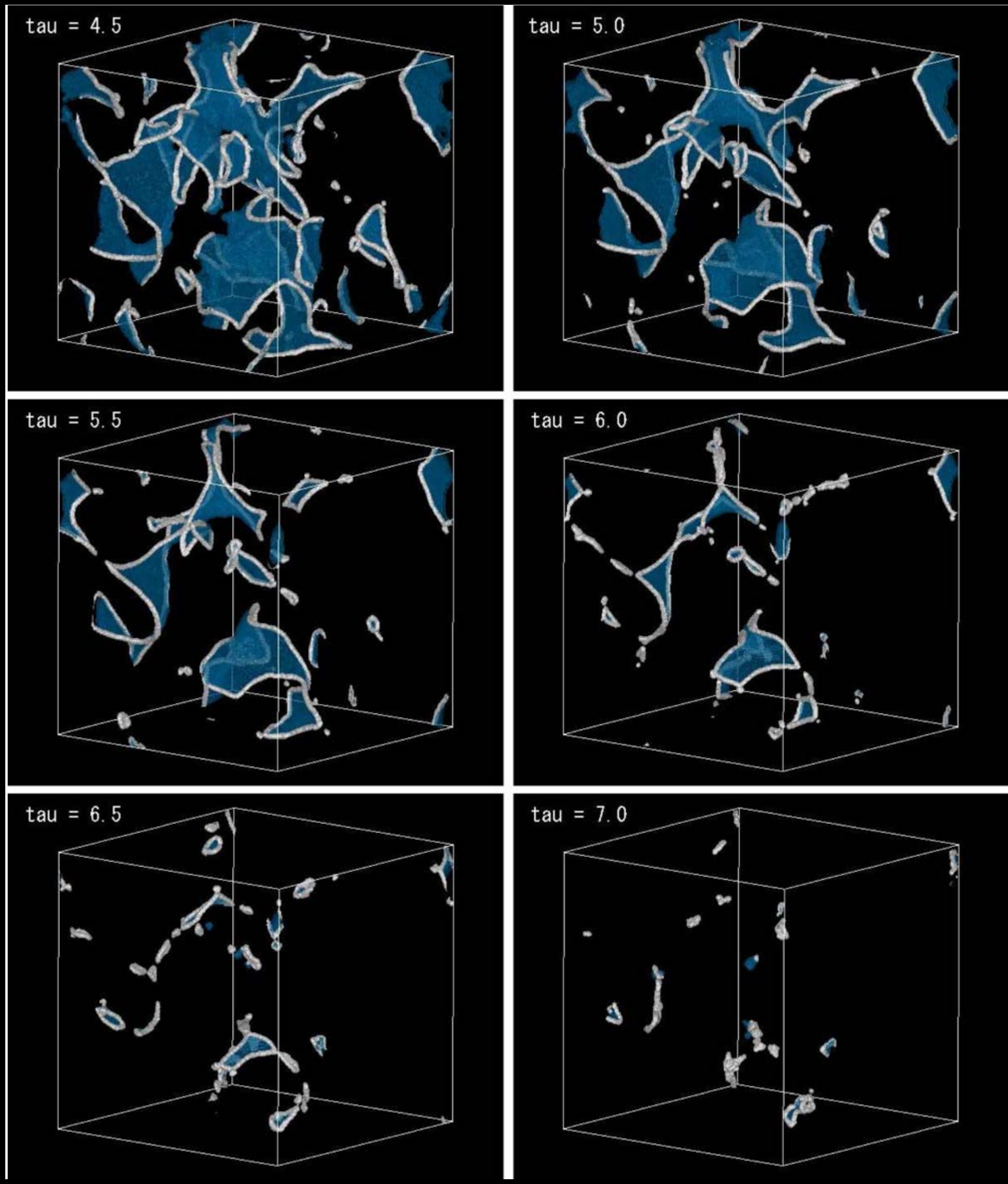

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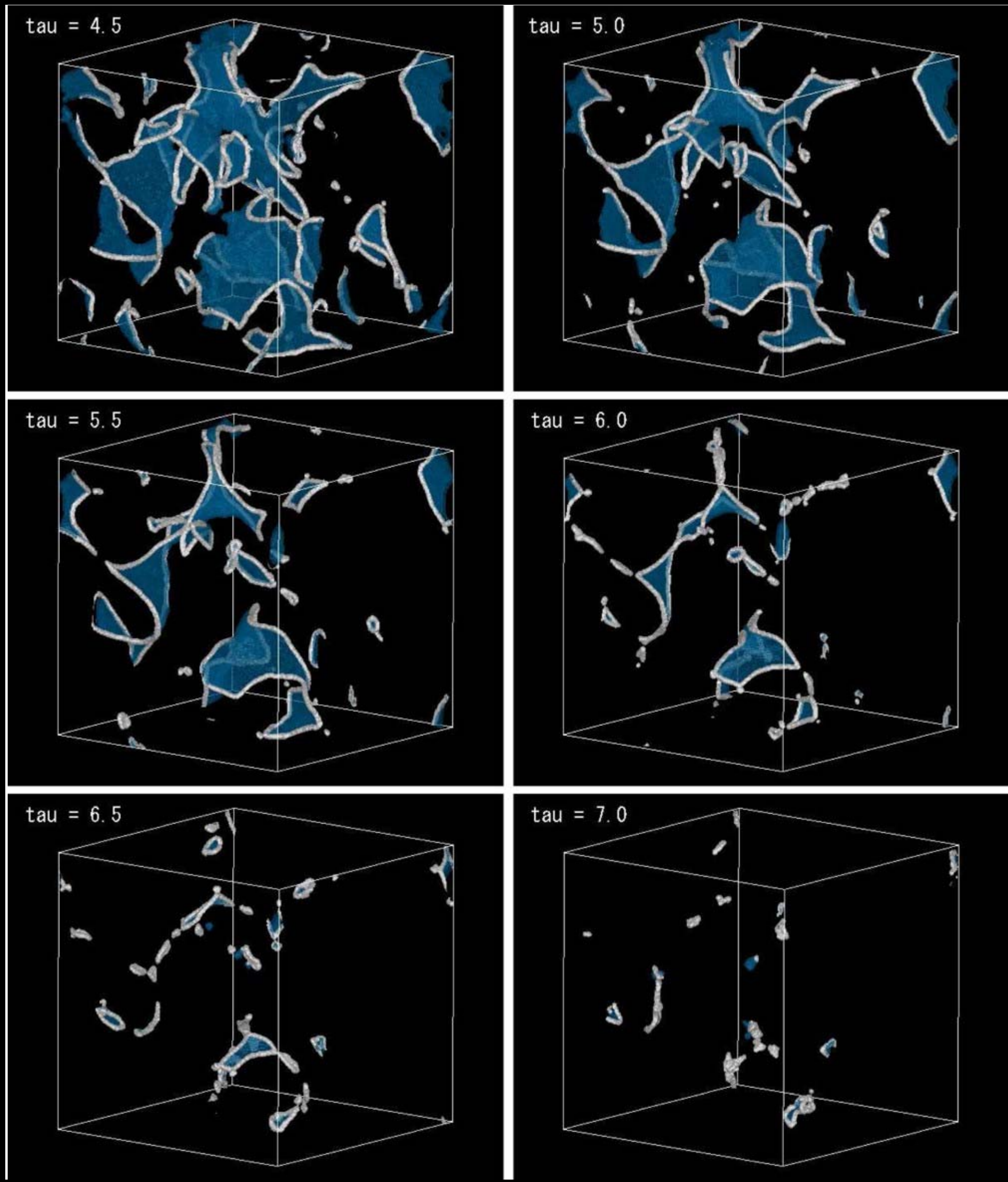

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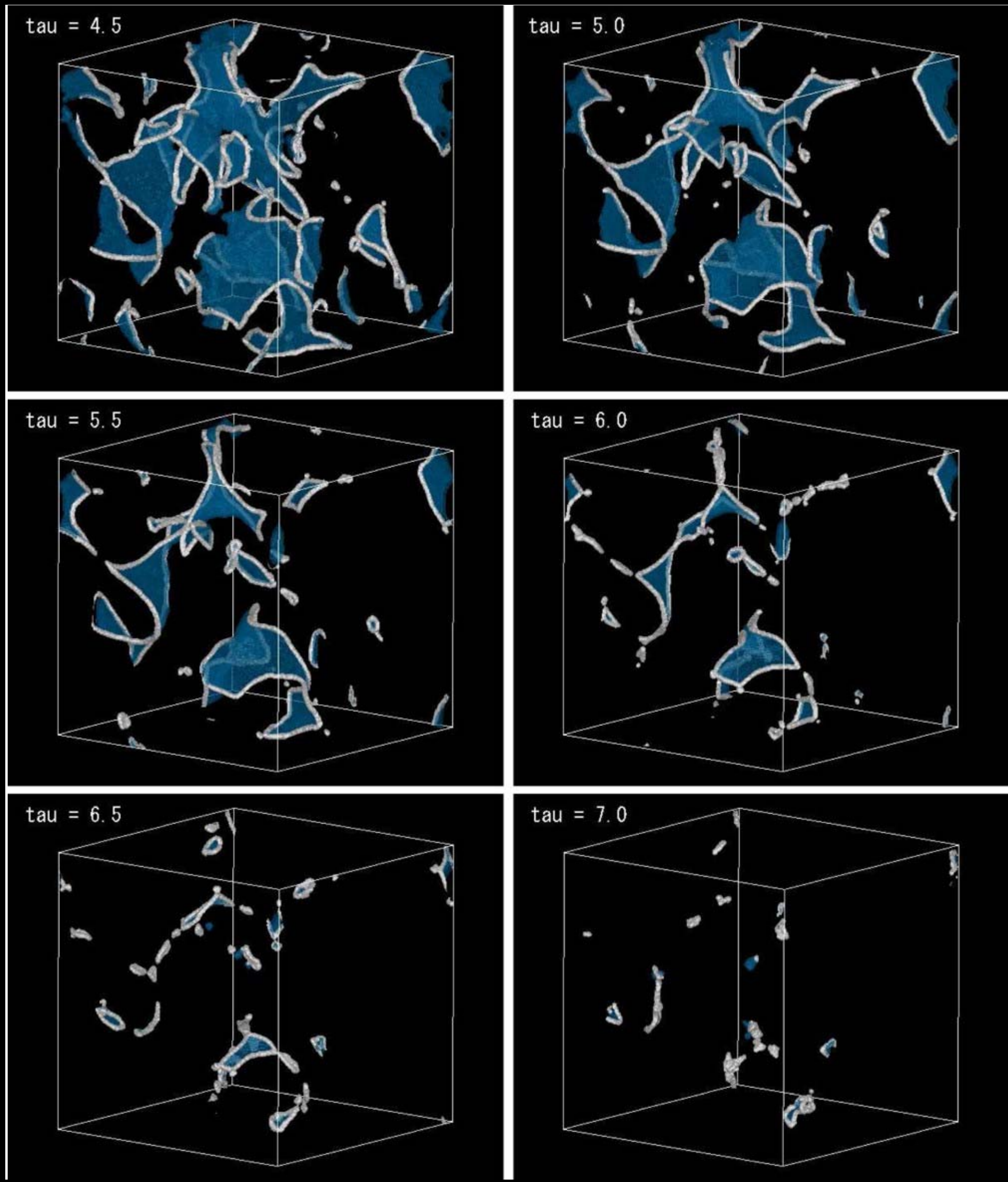

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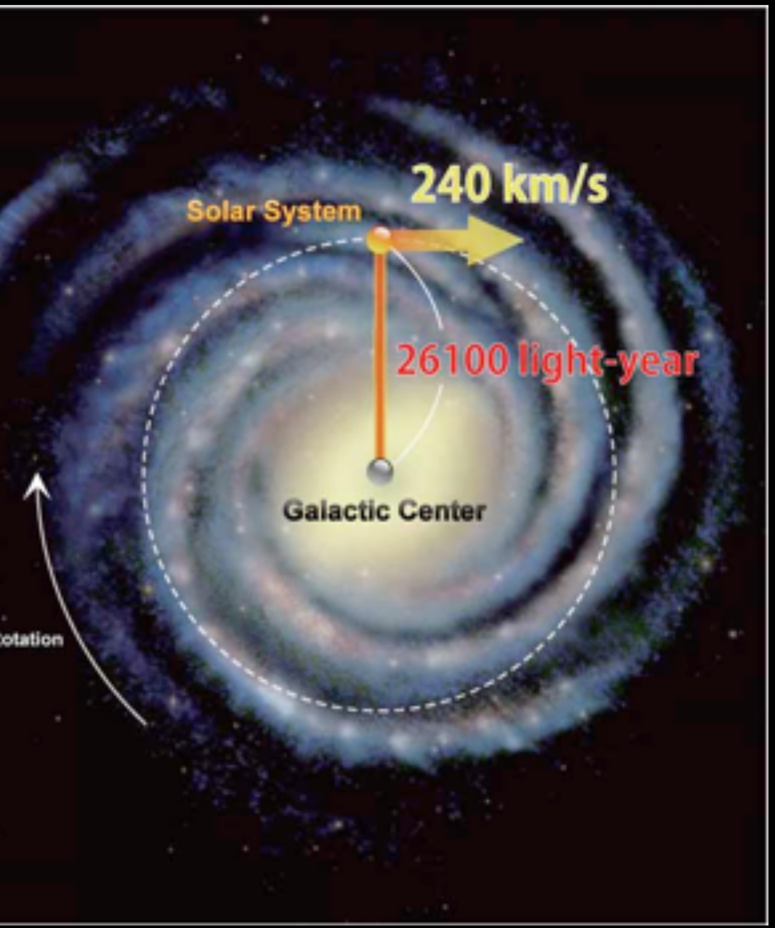
How to look for a QCD axion

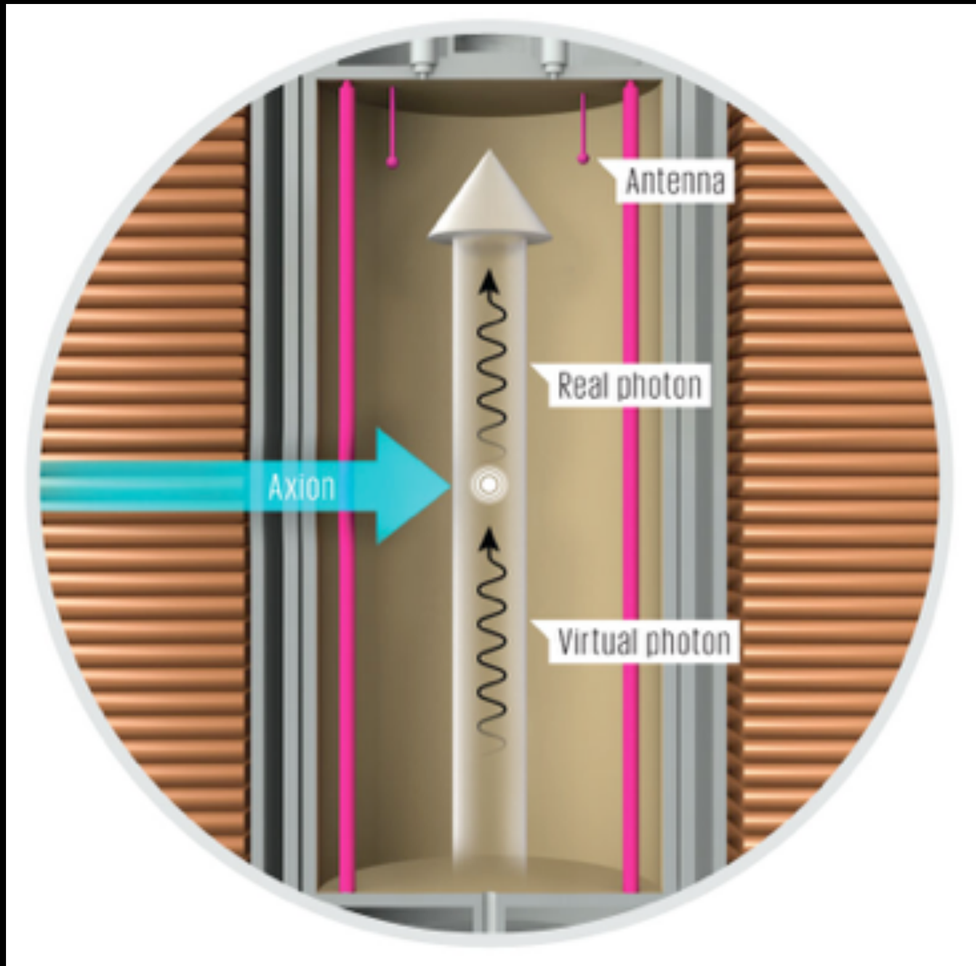
✳ADMX: Use the DM axions the universe gives you

$$\mathcal{L} \propto g_{a\gamma\gamma} a \vec{E} \cdot \vec{B} \quad g_{a\gamma\gamma} \propto 1/f_a$$

P. Sikivie 1983

$E_\gamma = m_a c^2$ → *Excite cavity TEM modes*





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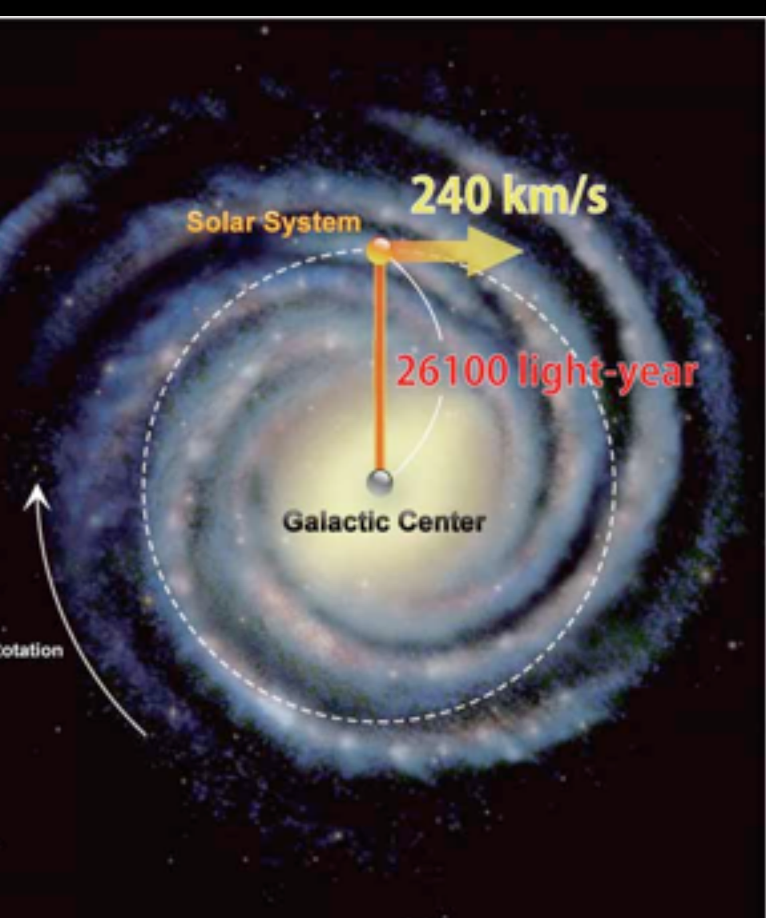
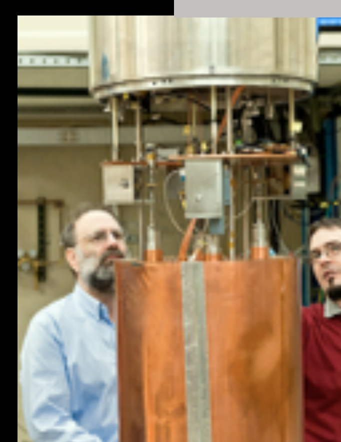
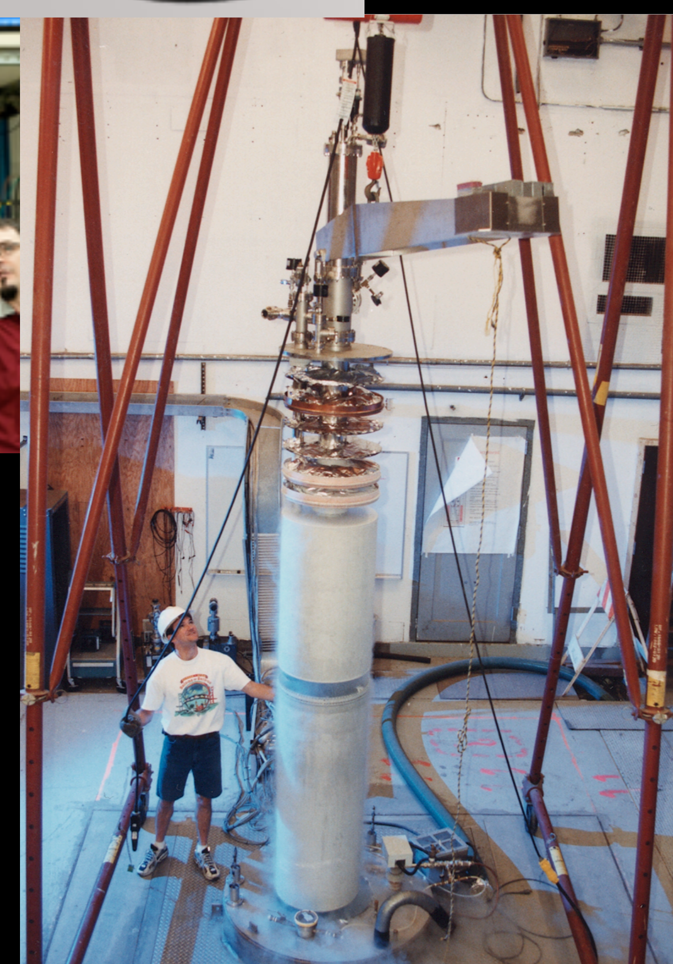
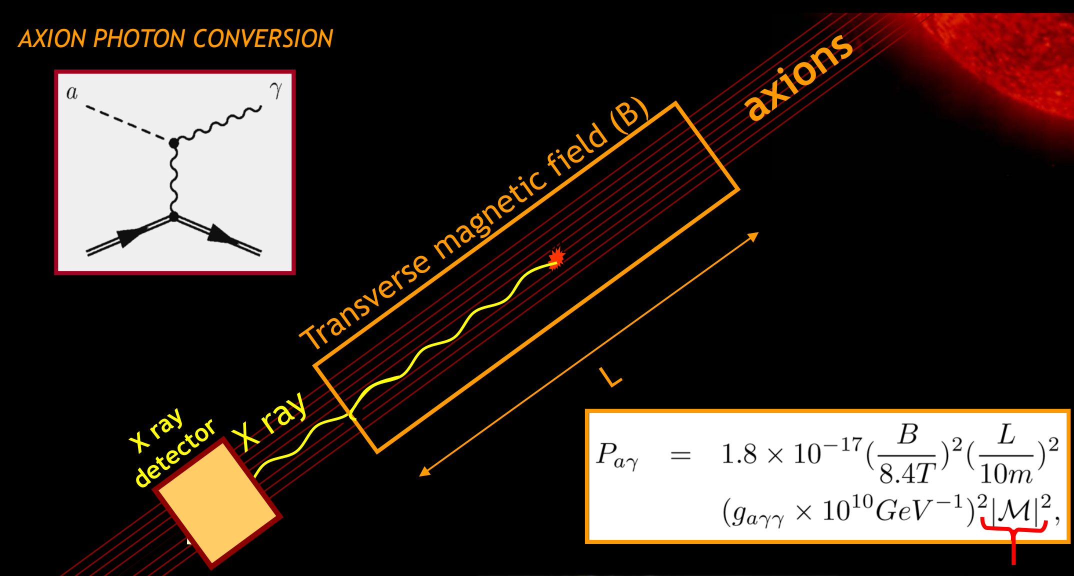
L. Rosenberg and G. Rybka +....

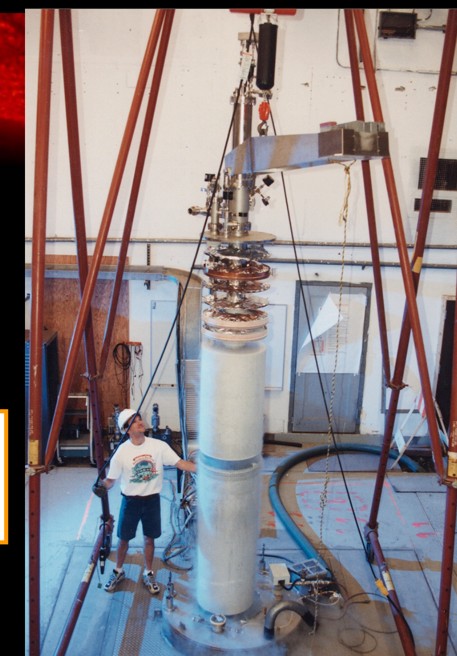


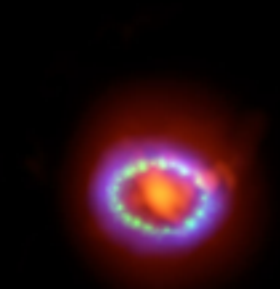


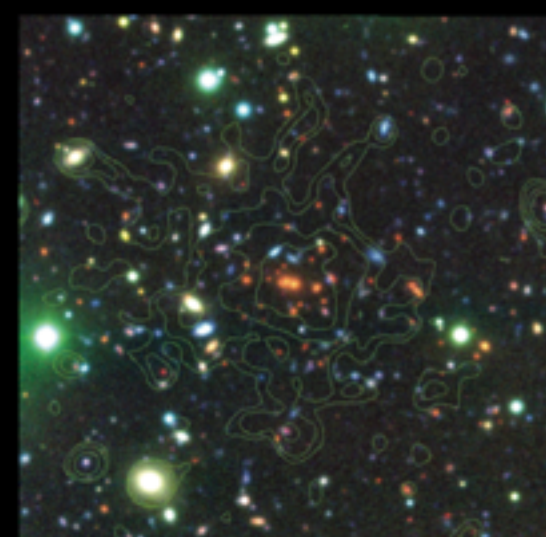


Limits and horizon

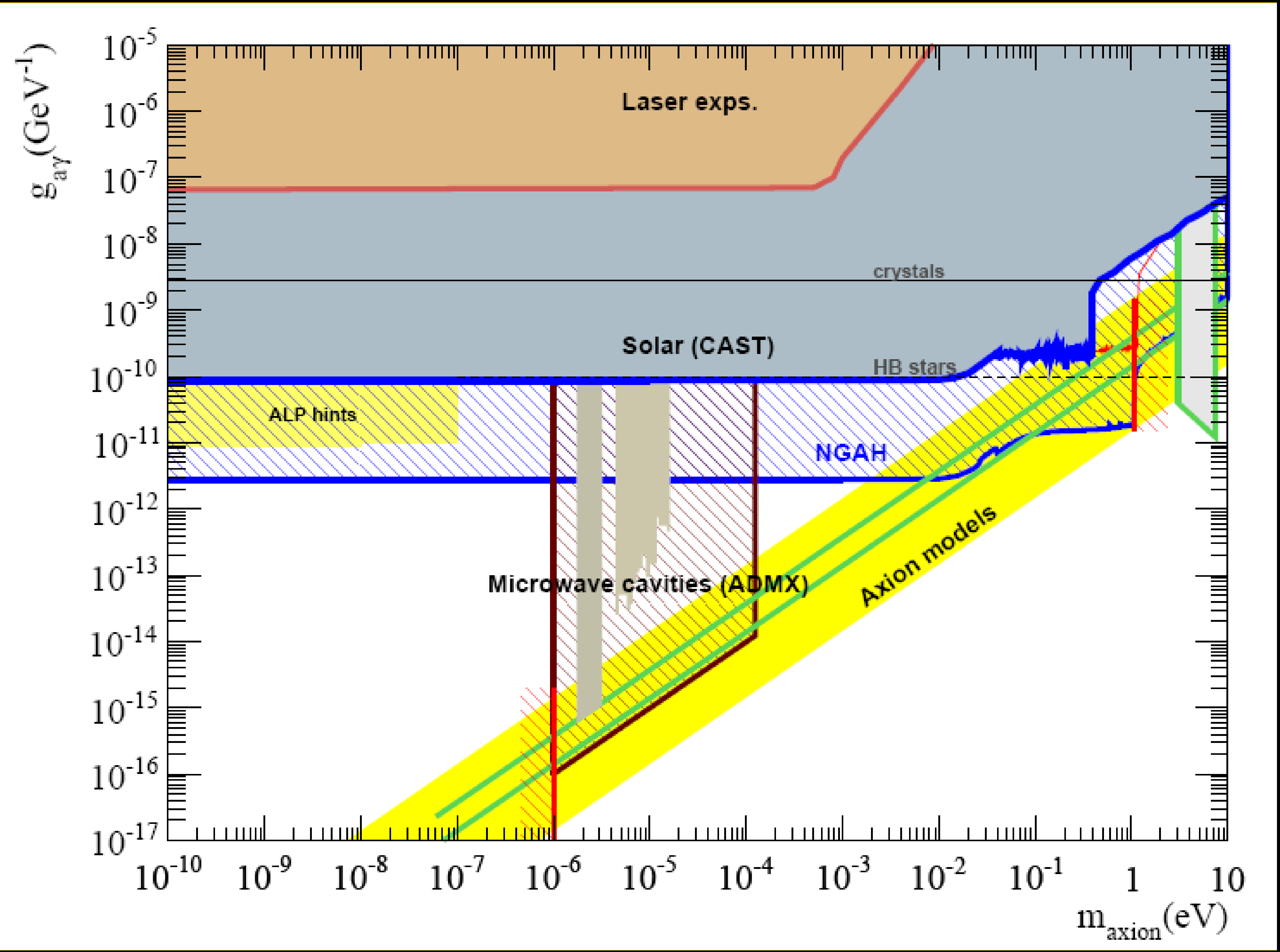






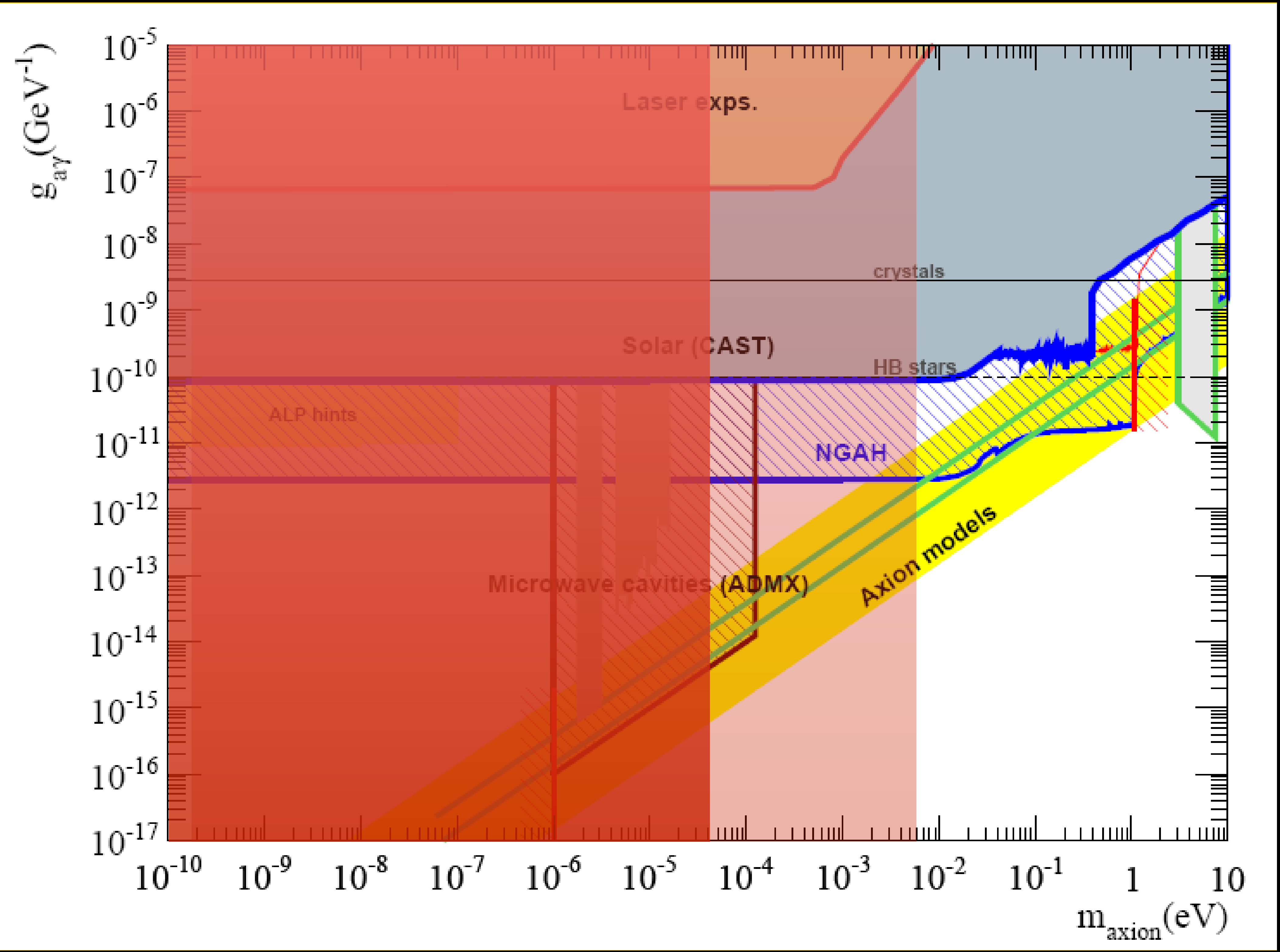


Limits and horizon

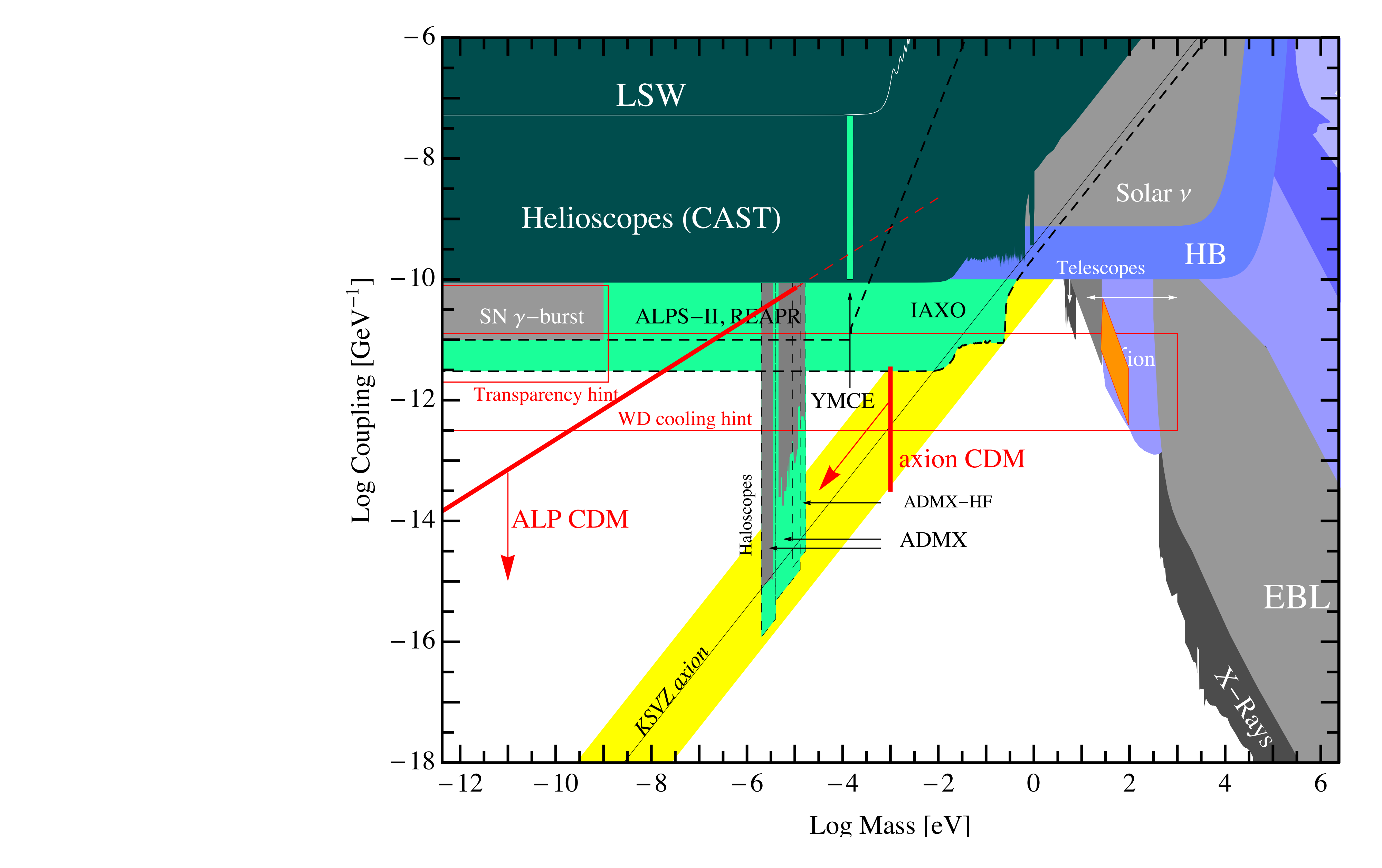


Limits and horizon

Cosmological abundance limits (more soon...)



Experimental constraints
ULA and axion-like particles (ALPs)



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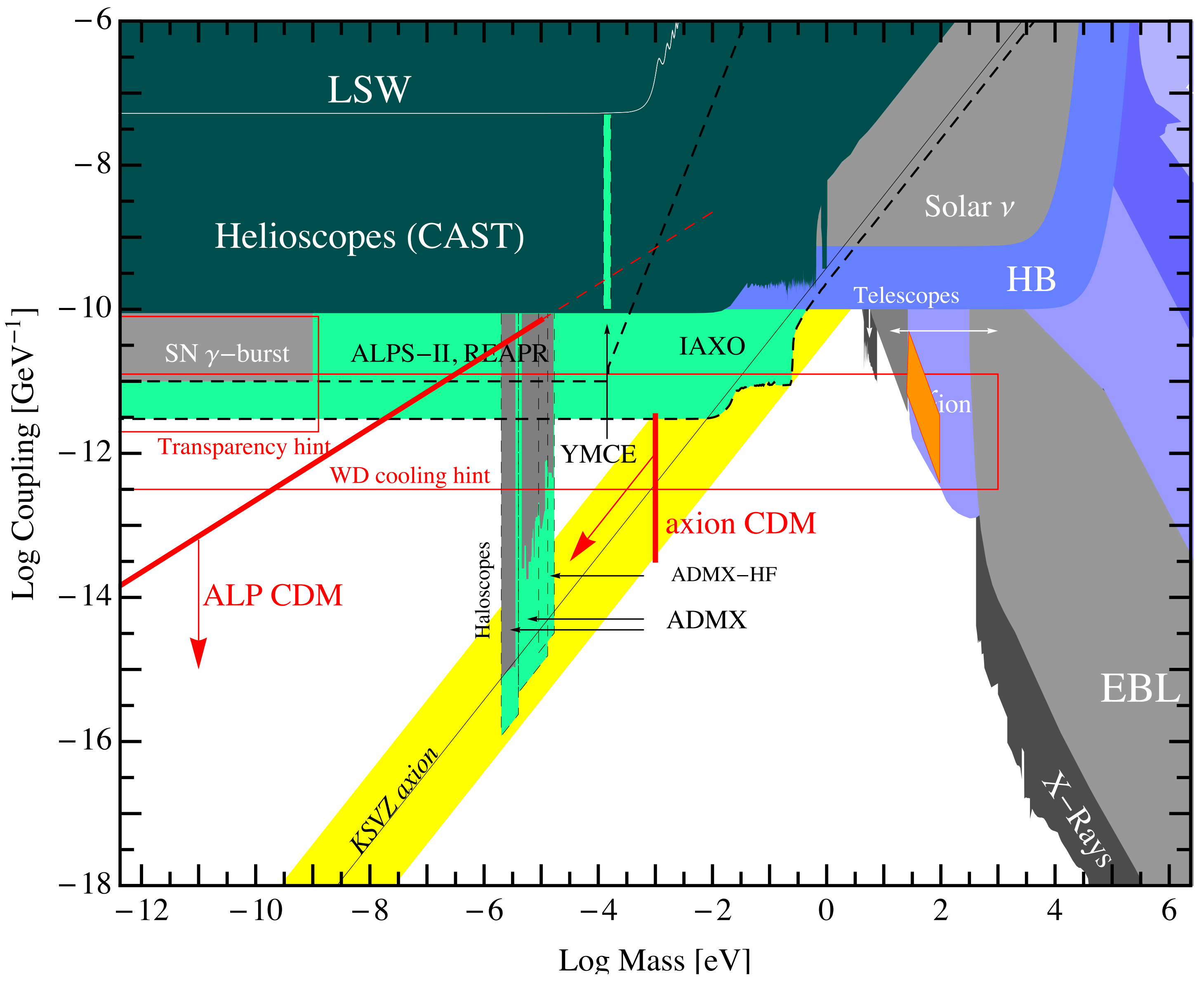
Experimental constraints
ULA and axion-like particles (ALPs)

Experimental desert: Gravitational constraints essential



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From arXiv: 1205.2671

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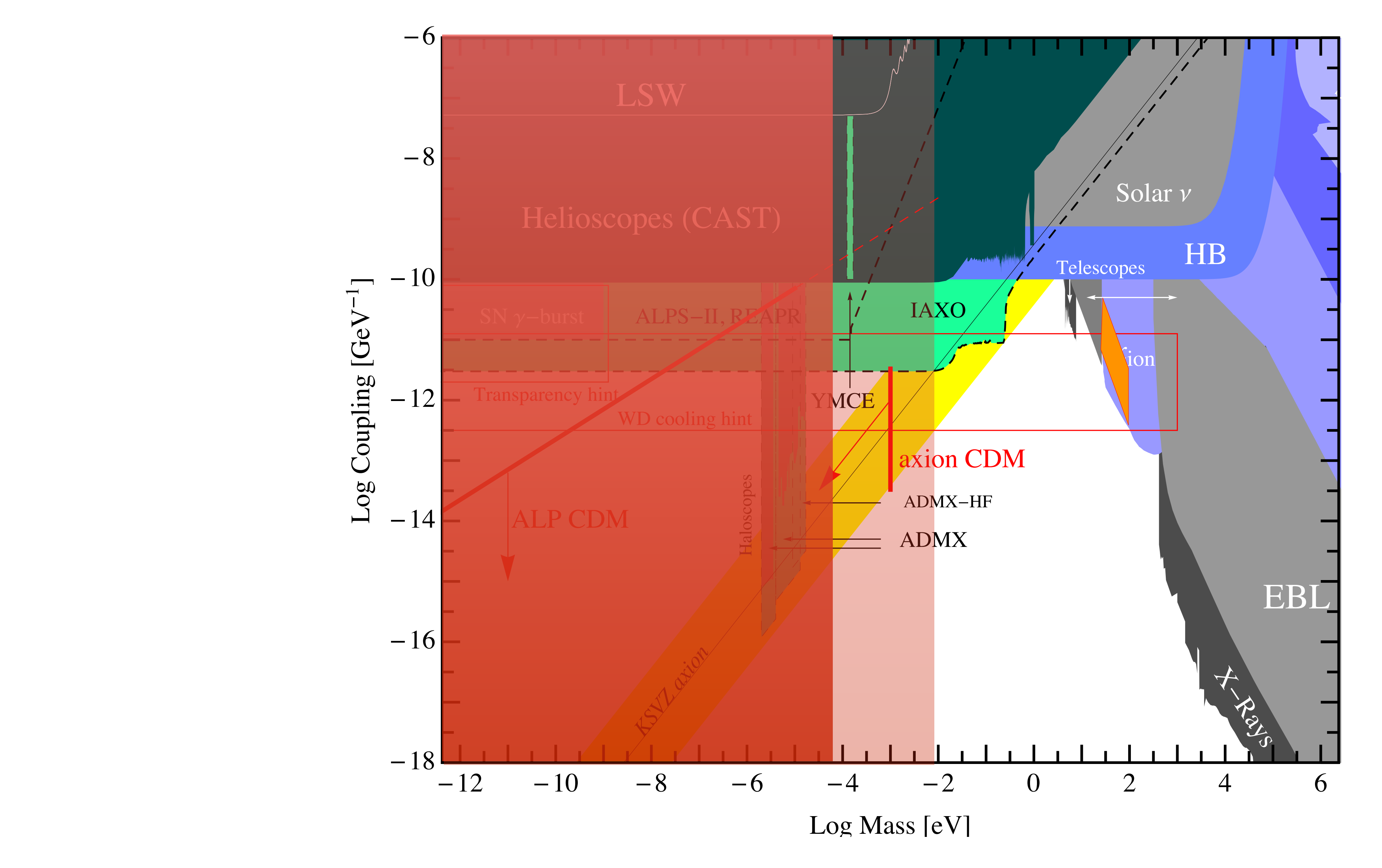

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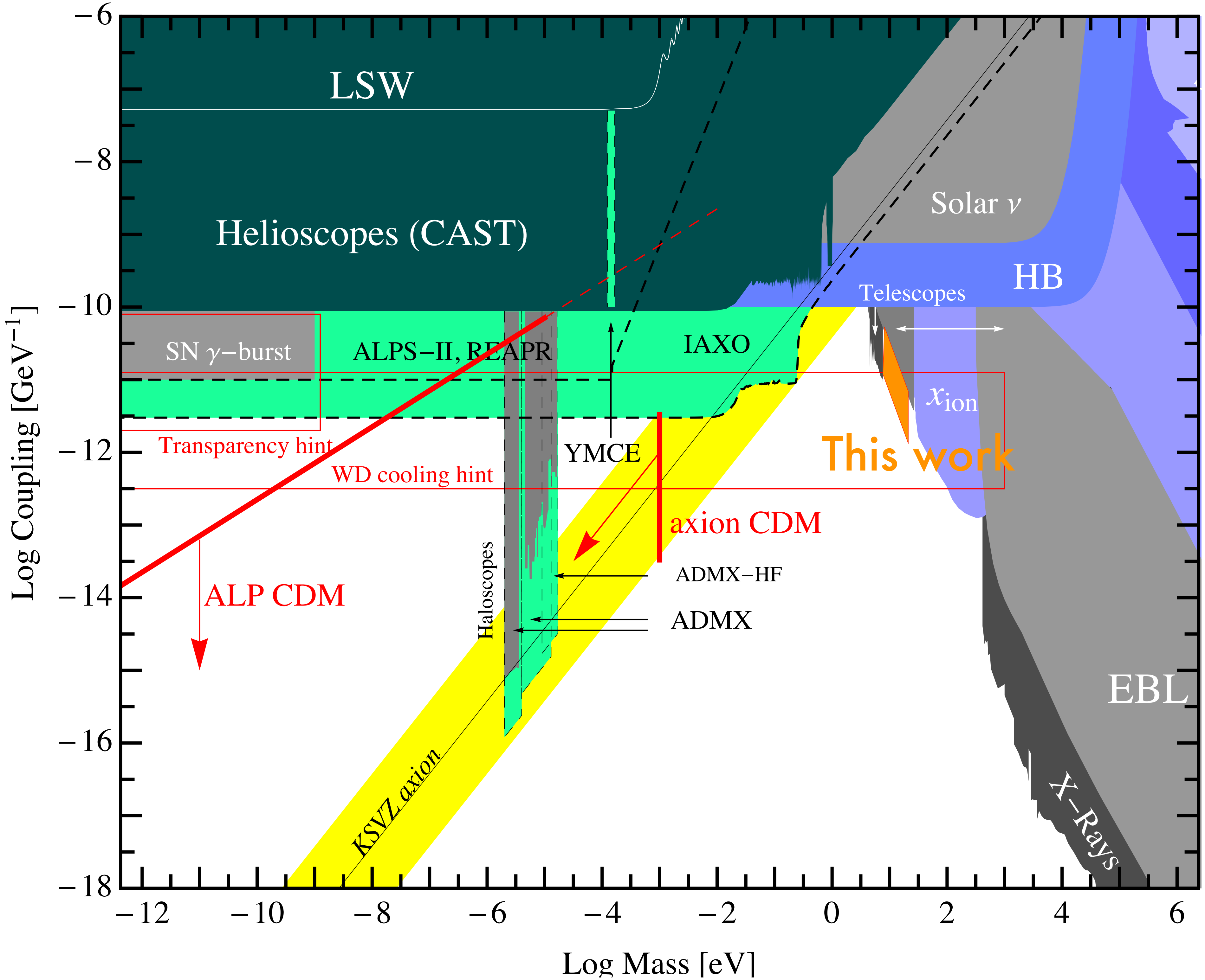
Lay of the land

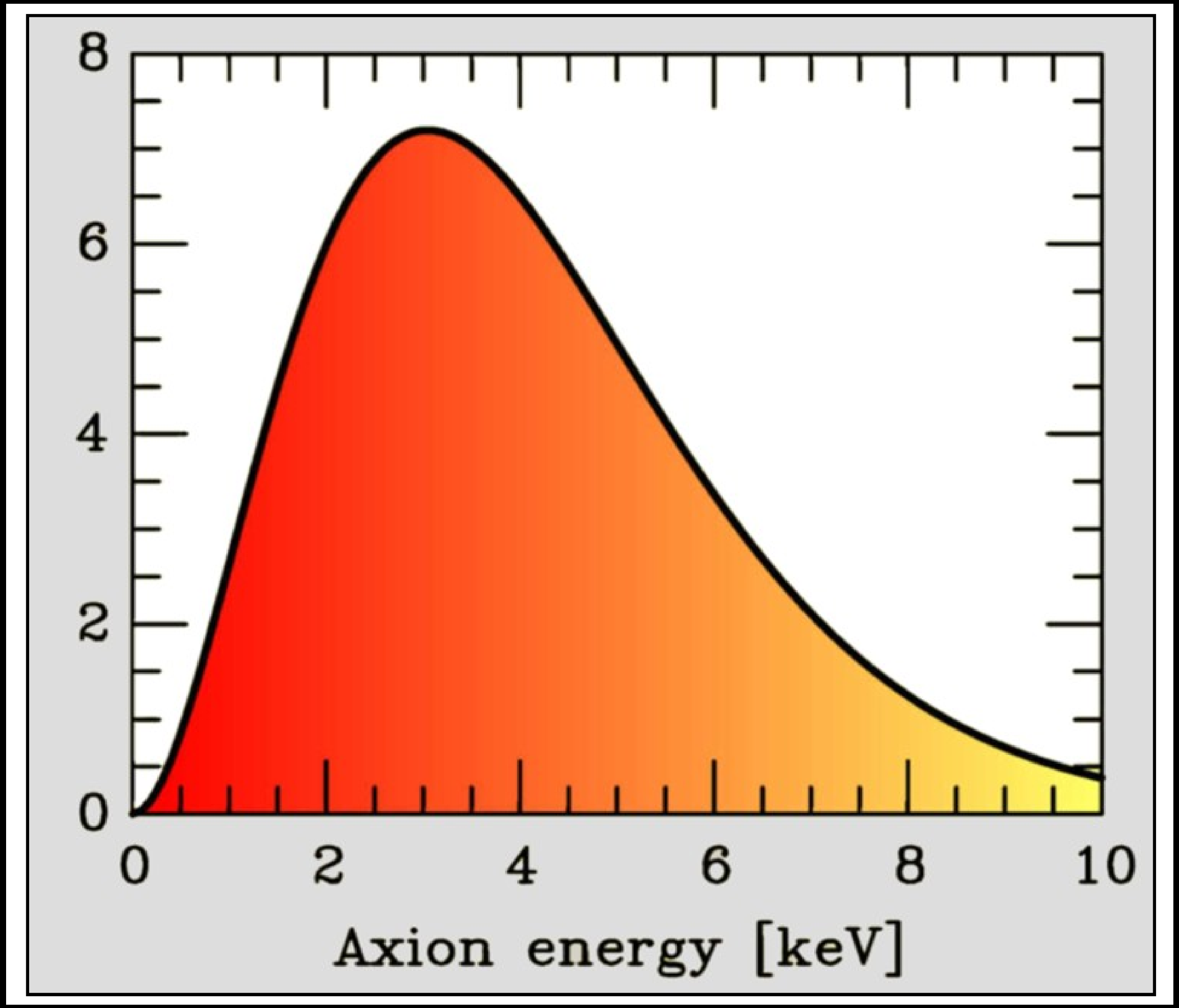


Axion helioscopes

- Resonance condition

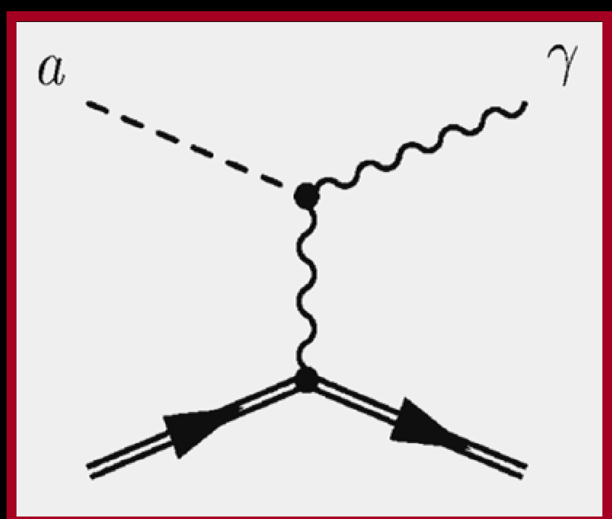
$$qL < \pi \quad \Rightarrow \quad \sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{2\pi E_a}{L}}$$

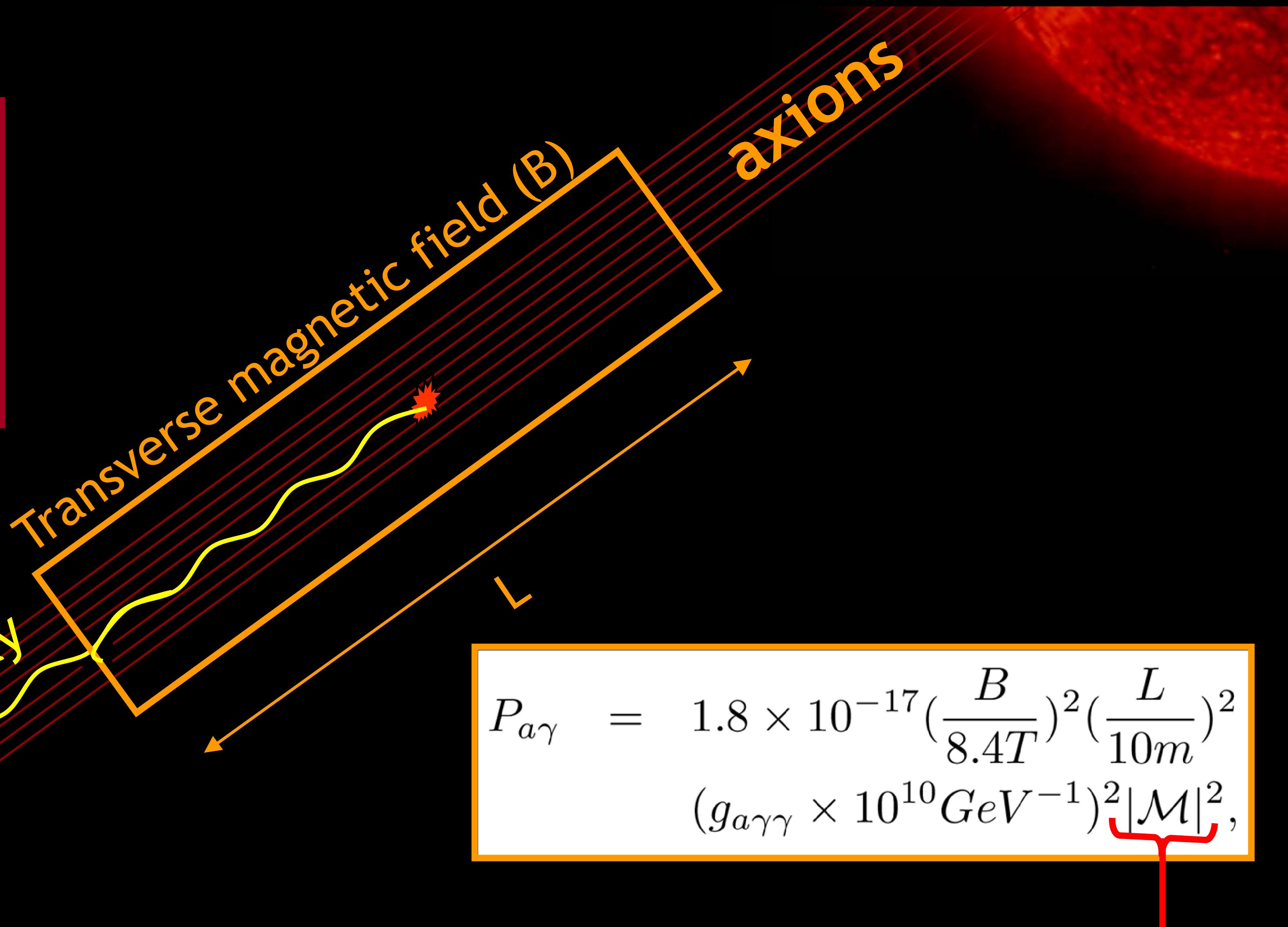
- Broad axion energy spectrum



Axion helioscopes

* Backwards Primakoff process (Sikivie, Zioutas, and many others)





$$P_{a\gamma} = 1.8 \times 10^{-17} \left(\frac{B}{8.4T}\right)^2 \left(\frac{L}{10m}\right)^2 (g_{a\gamma\gamma} \times 10^{10} GeV^{-1})^2 \underbrace{|\mathcal{M}|^2}_{},$$

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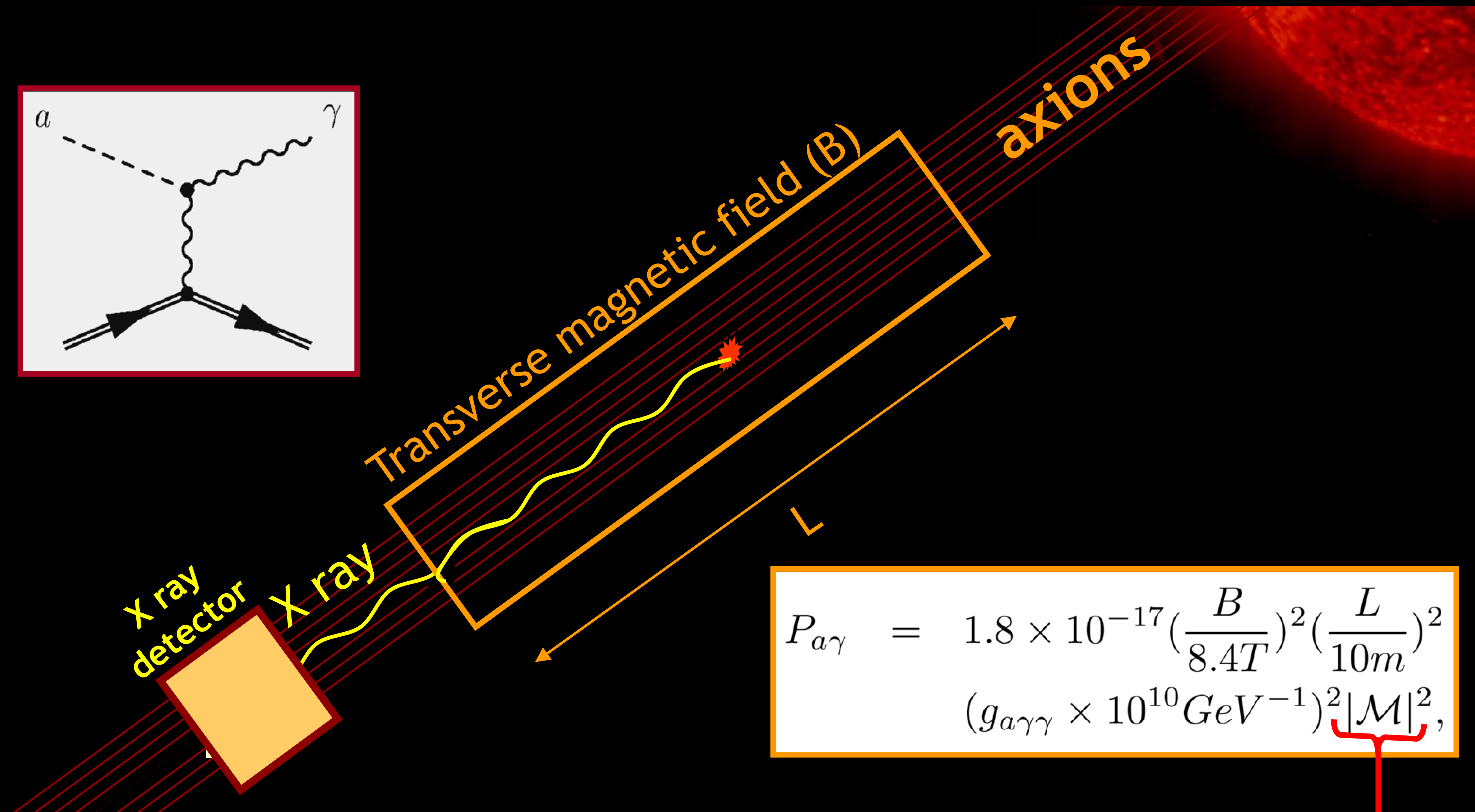

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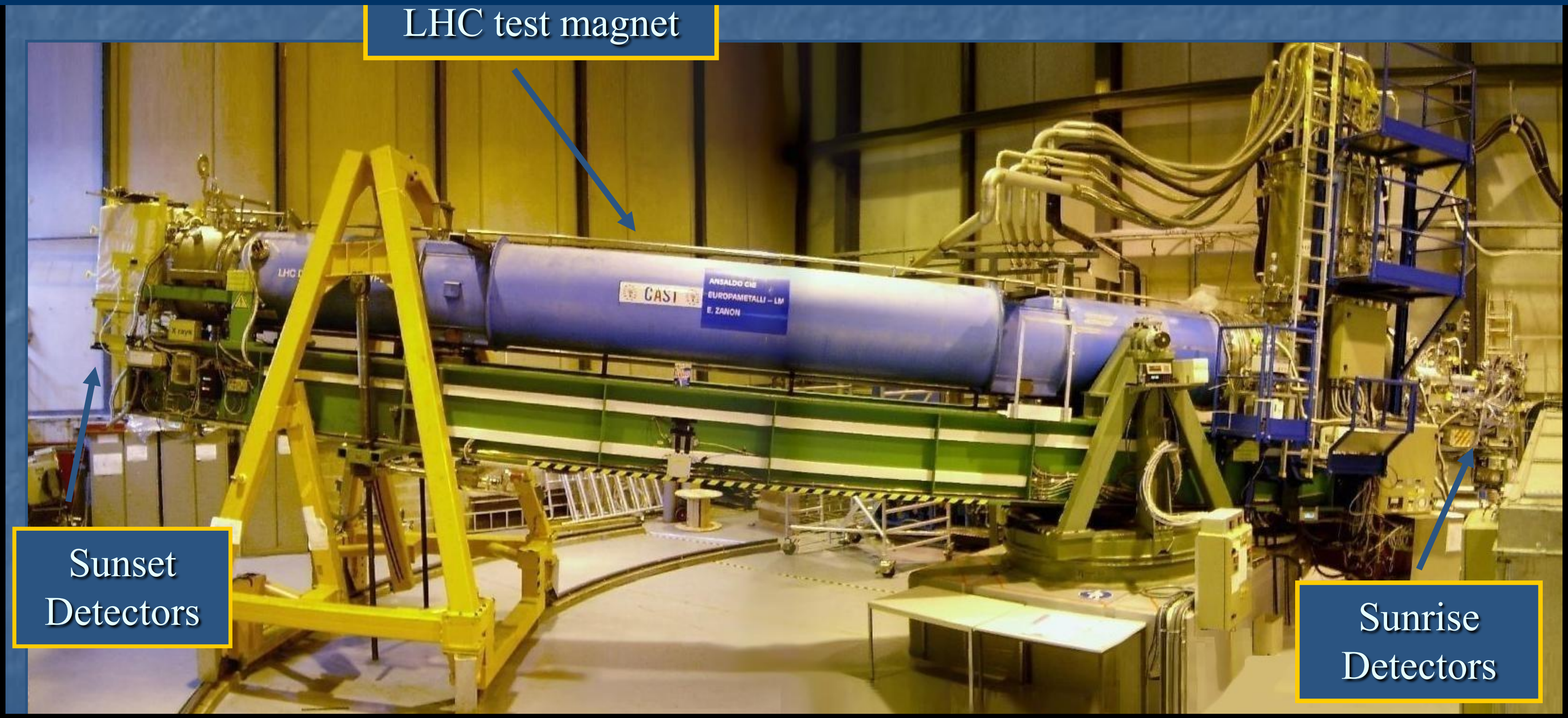
CAST/IAXO

- ✴ CAST
  - ➢ LHC test magnet (B=9 T, L=9.26 m)



- ✴ IAXO proposal: 15-20m length magnet, optimized shape [not LHC DUD]

CAST/IAXO

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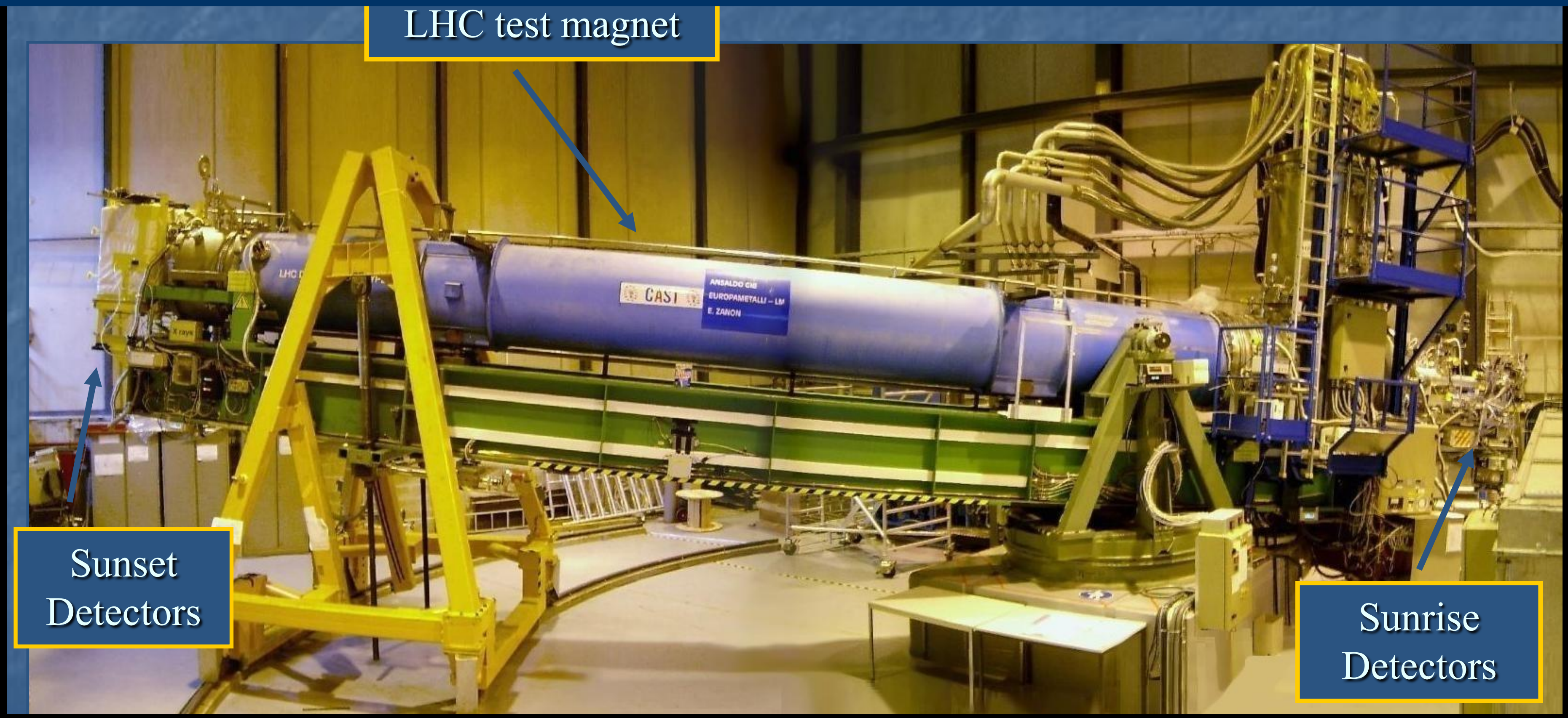
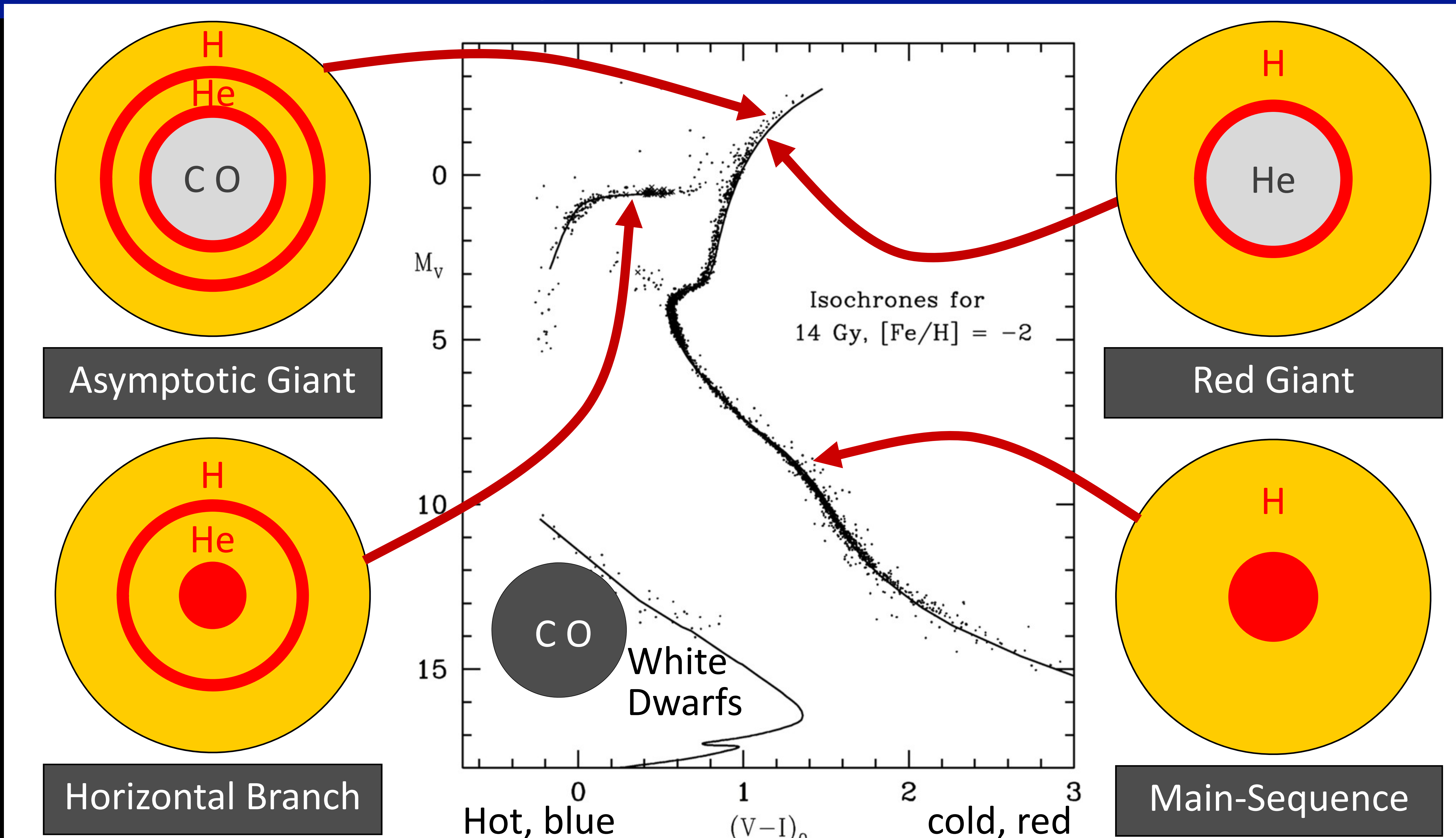


- IAXO proposal: 15-20m length magnet, optimized shape [not LHC DUD]

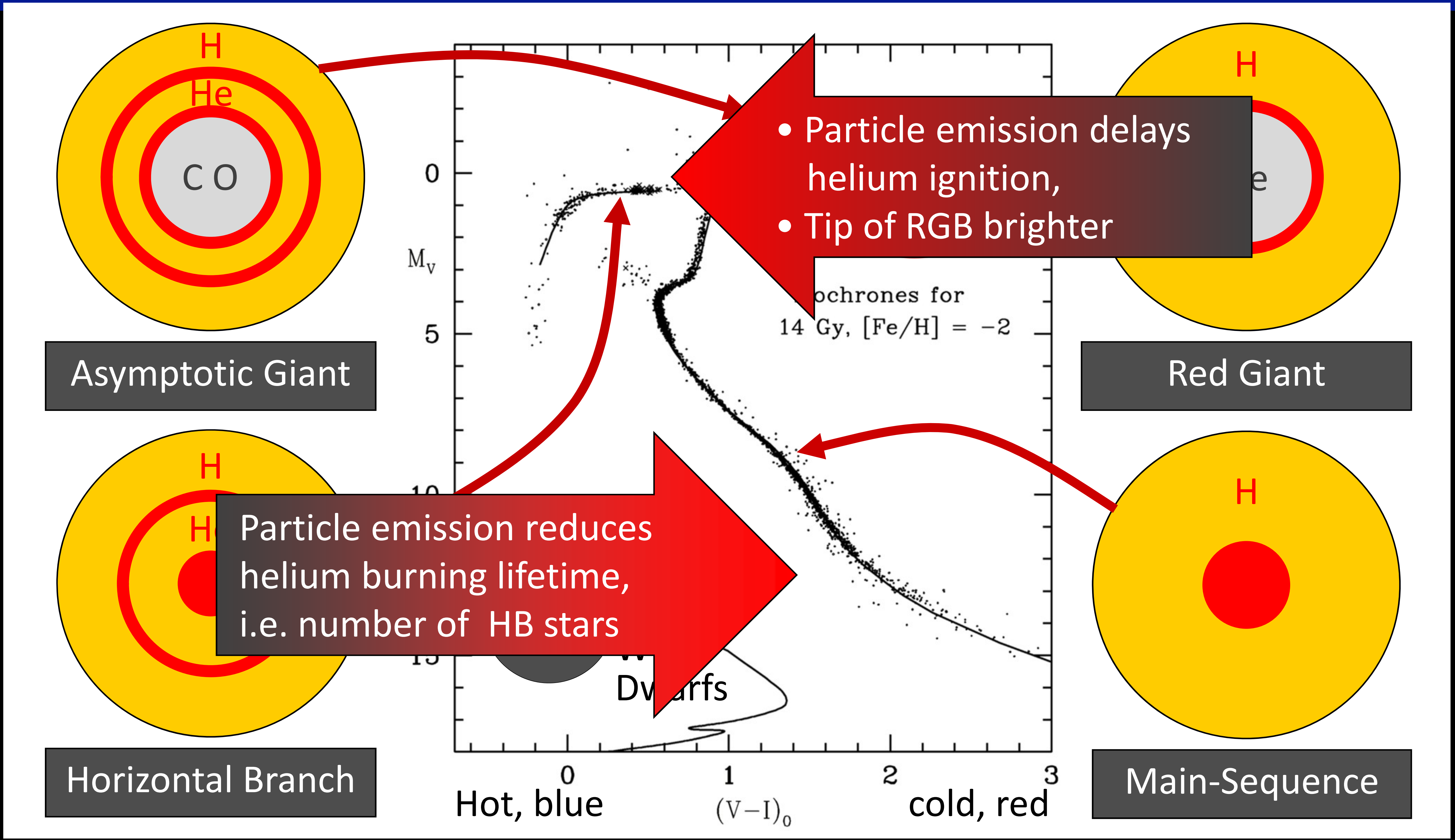
Making axions in stars, II



From Raffelt 2012

$$g_{a\gamma\gamma} \lesssim 10^{-10}\ \mathrm{GeV}^{-1}$$

Making axions in stars, II



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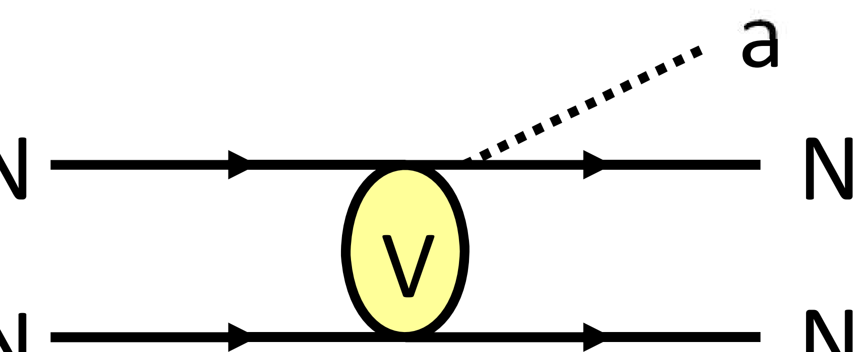
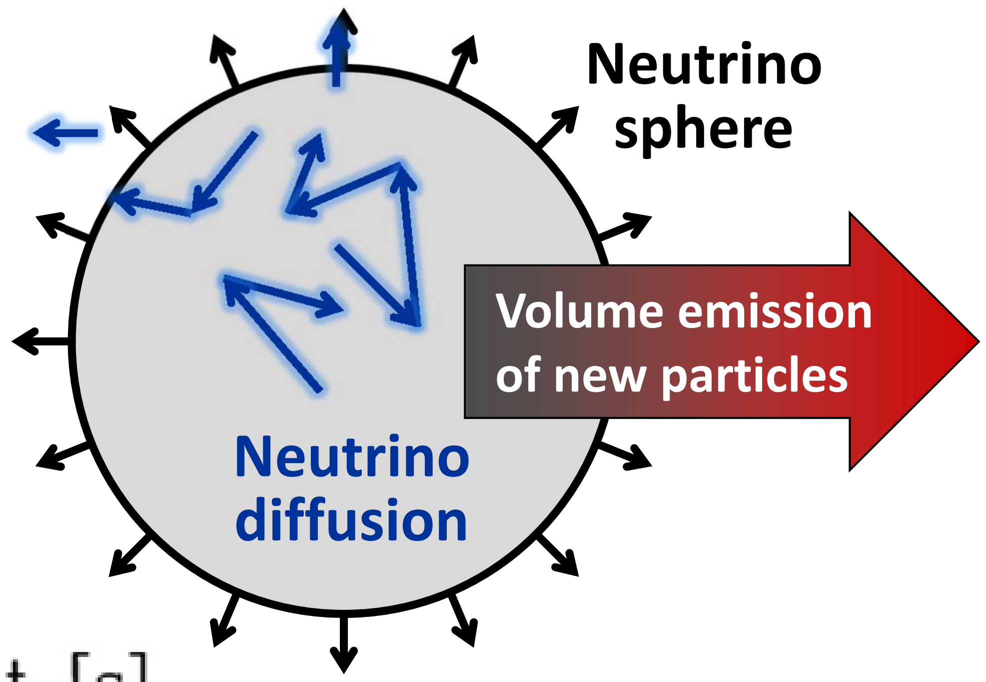
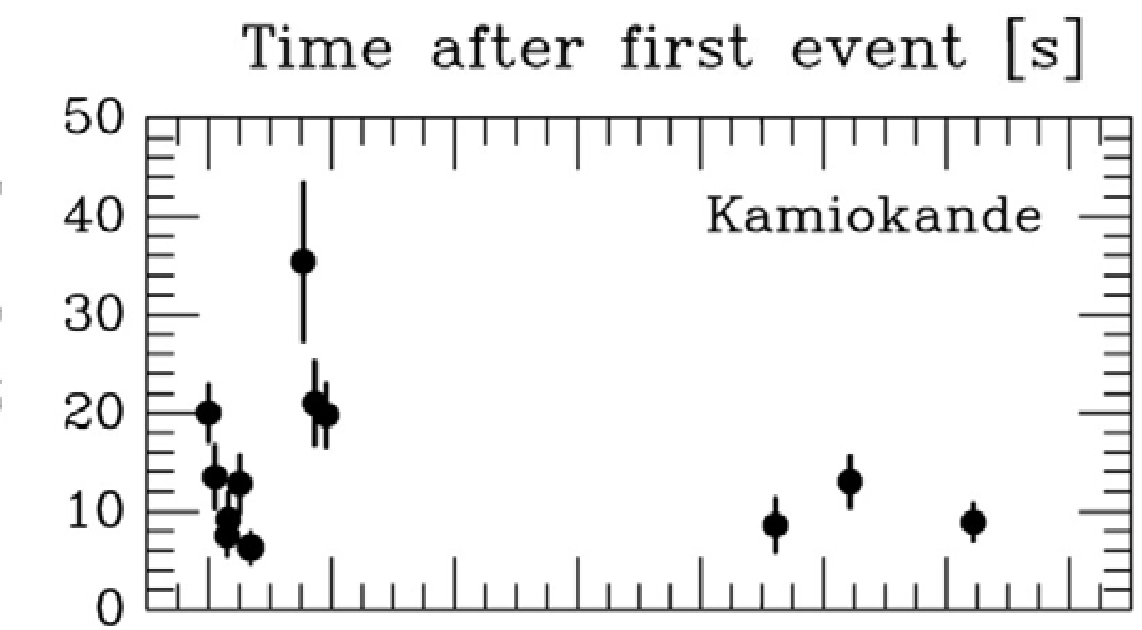
Making axions in (exploding) stars, III



Nucleon-Nucleon
Bremsstrahlung





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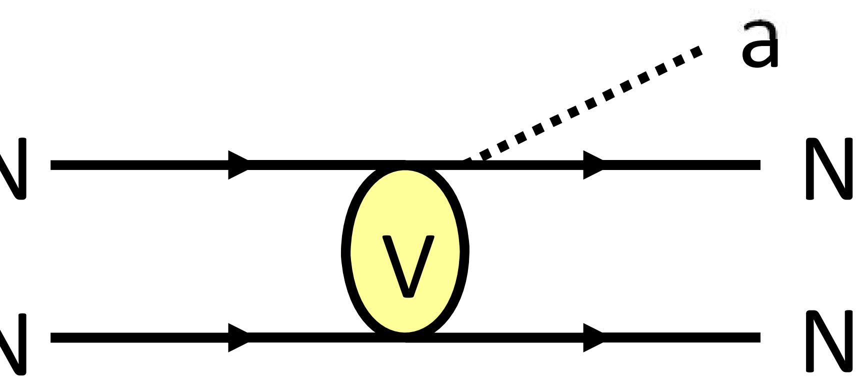

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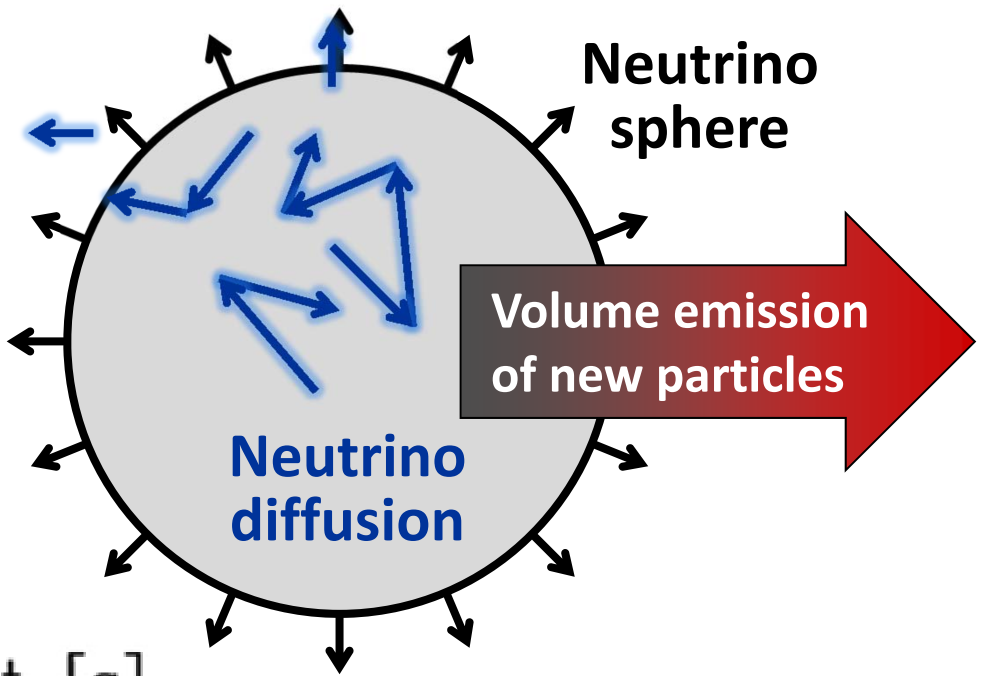

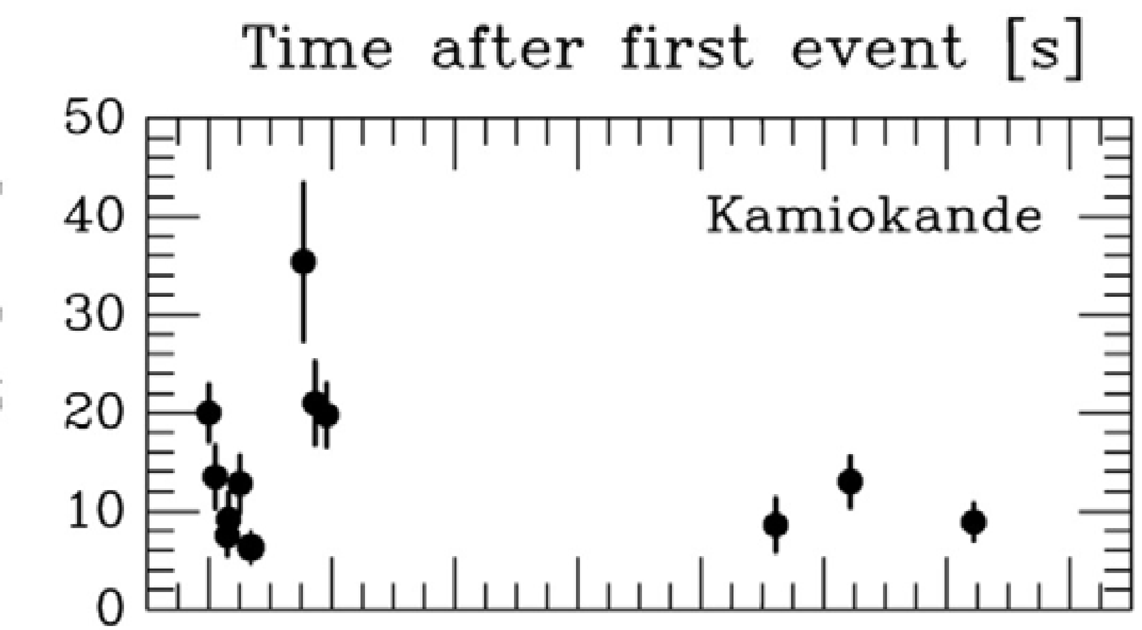

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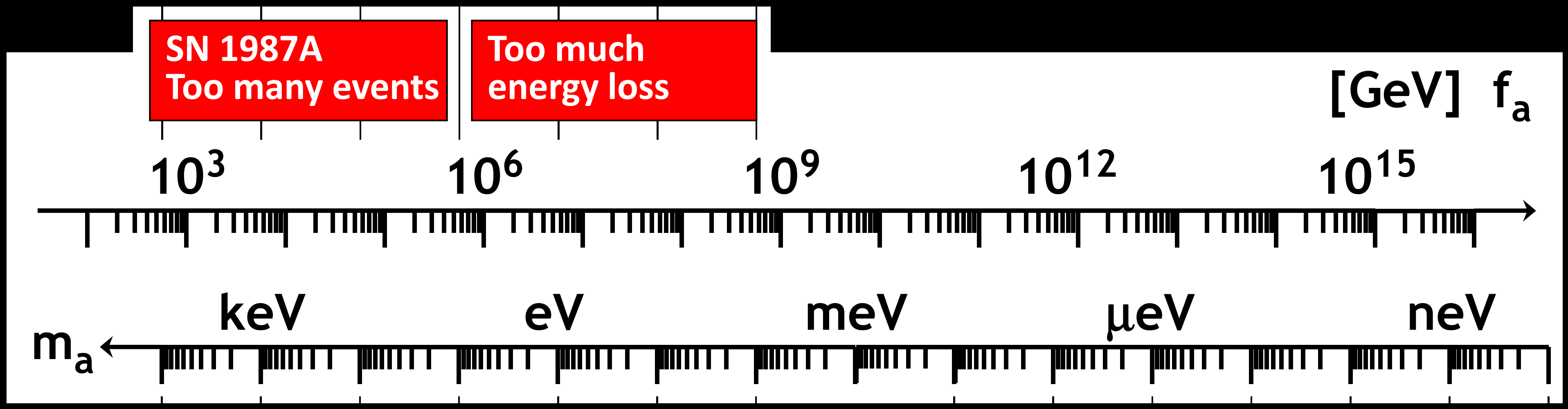
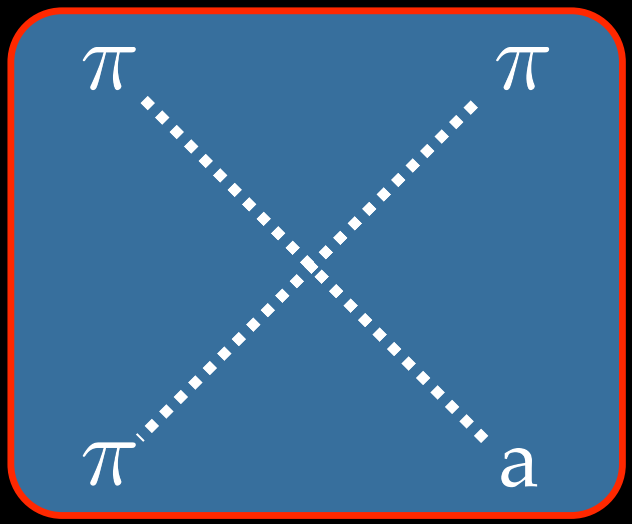
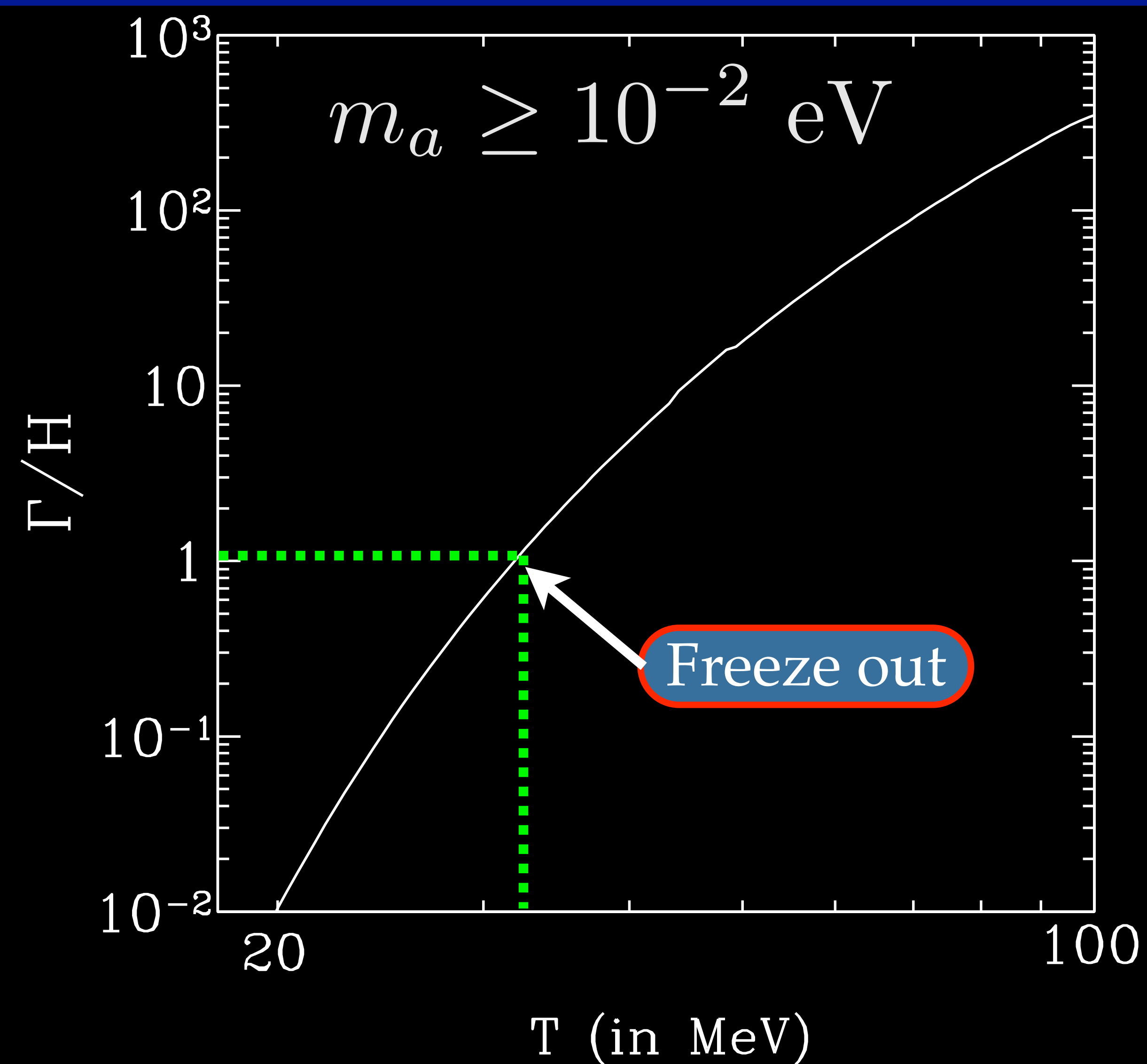


Hot axion production at early times

Axion Production:



$$\Omega_{\rm a} h^2 = \frac{m_{\rm a,eV}}{130}\left(\frac{10}{g_{*,\rm F}}\right)$$



- ✴ Axions produced through interactions between non-relativistic pions in chemical equilibrium with rate

Axion hot dark matter

* Axion free-streaming length

$$\lambda_{\rm fs} \simeq \frac{196\ {\rm Mpc}}{m_{\rm a,eV}}$$

* Entropy generation, e.g. modulus decay

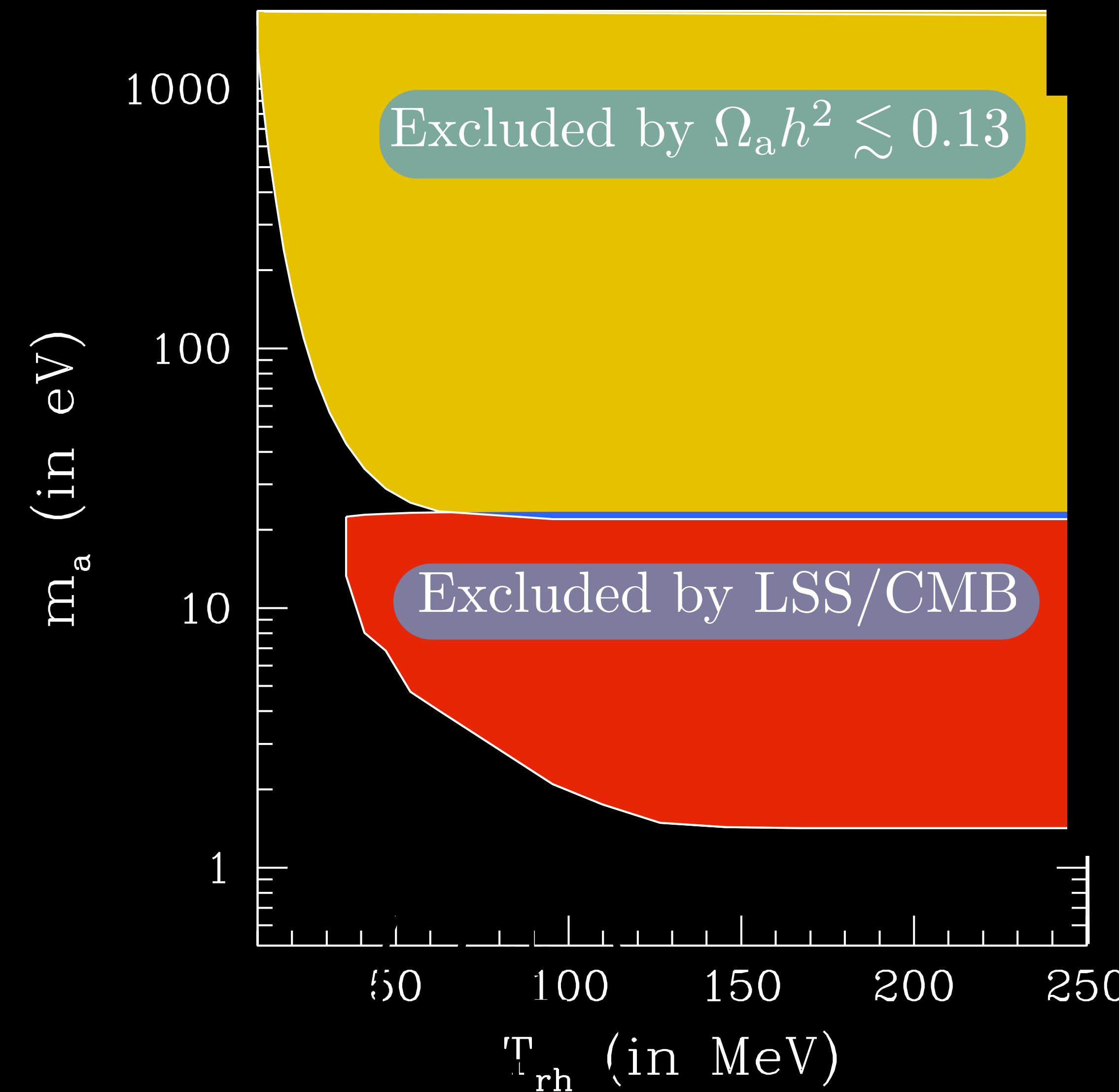
$$T_{\rm rh} \sim 10\ {\rm MeV} \left(\frac{m_\phi}{\rm TeV}\right)^{3/2}$$

* Axion temperature lowered

$$\frac{T_{\rm a}}{T_\nu} \propto \left(\frac{T_{\rm rh}}{T_{\rm F}}\right)^{5/3}$$

* Free streaming-length modified

$$\lambda_{\rm fs} \simeq \frac{196\ {\rm Mpc}}{m_{\rm a,eV}} \left(\frac{T_{\rm a}}{T_\nu}\right)$$

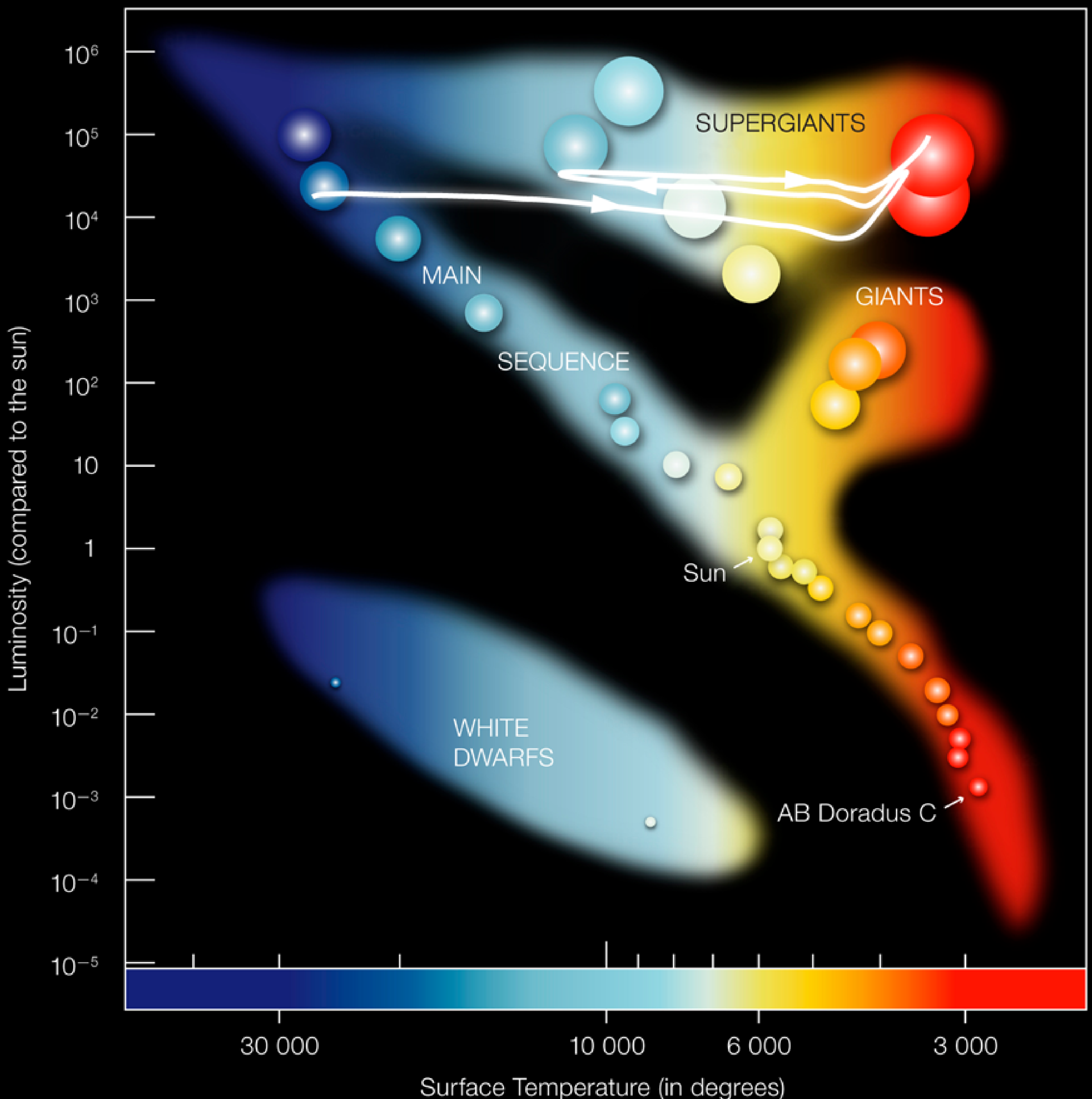


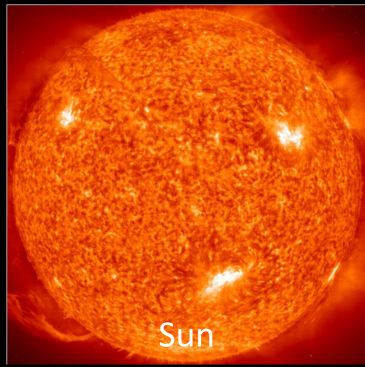
with T.L. Smith and M. Kamionkowski
Phys. Rev. D77 085020, 0711.1342

$$\Omega_a \rightarrow \Omega_a \left(\frac{T_{\rm rh}}{T_{\rm F}}\right)^5$$

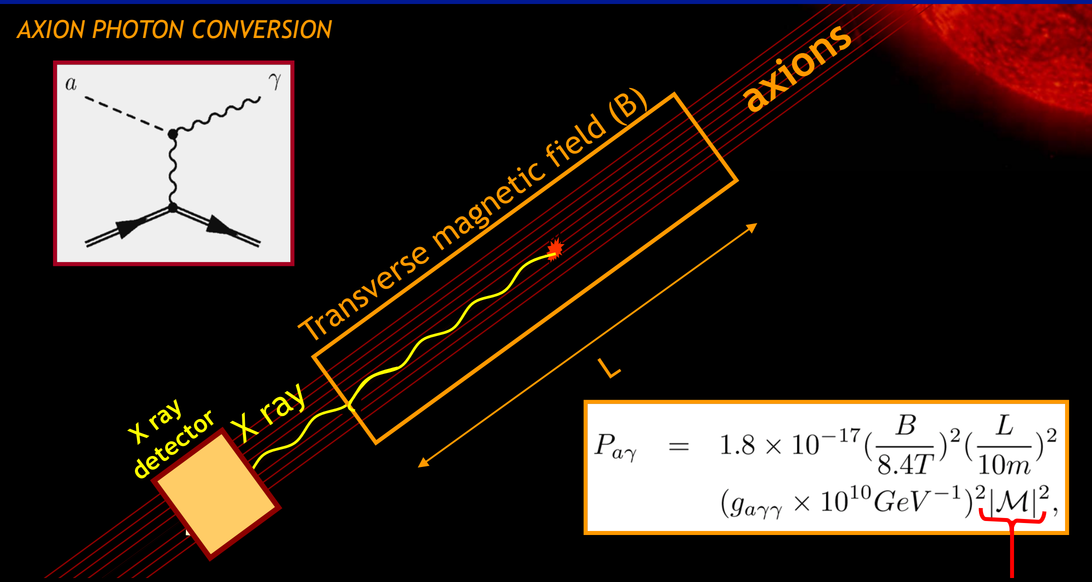
How to look for a QCD axion

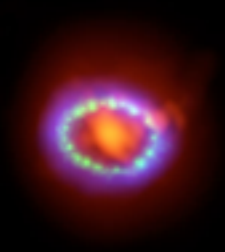
* Helioscopes (CAST) or stellar evolution

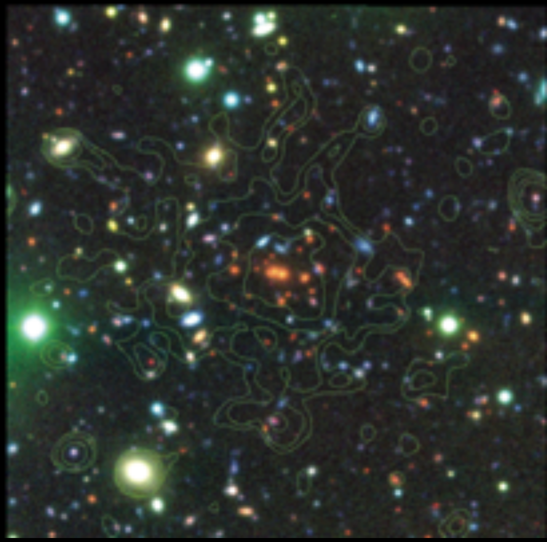


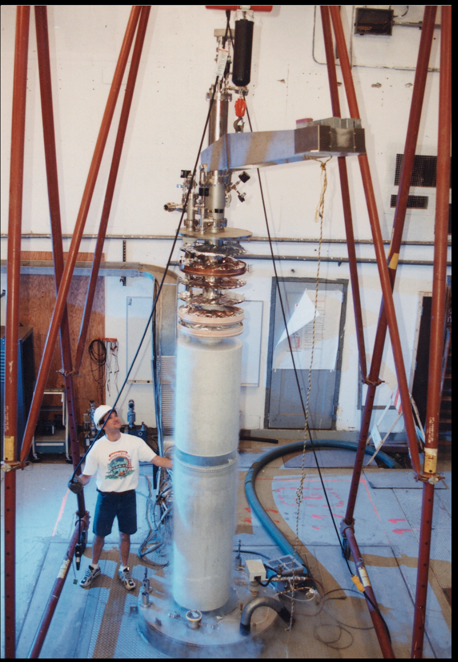


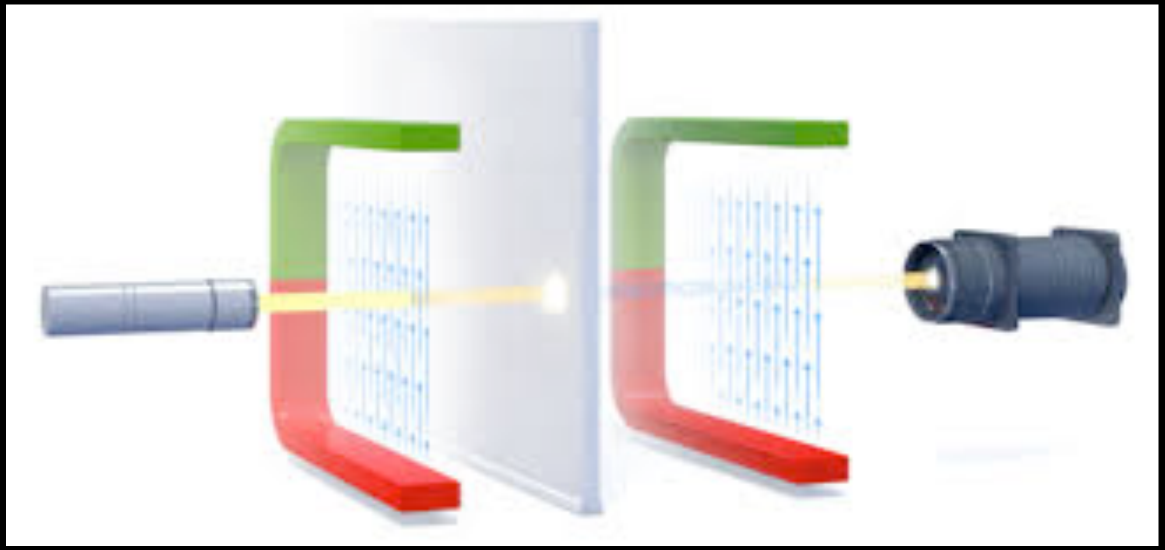
Experimental constraints
Axions and other axion-like particles (ALPS)







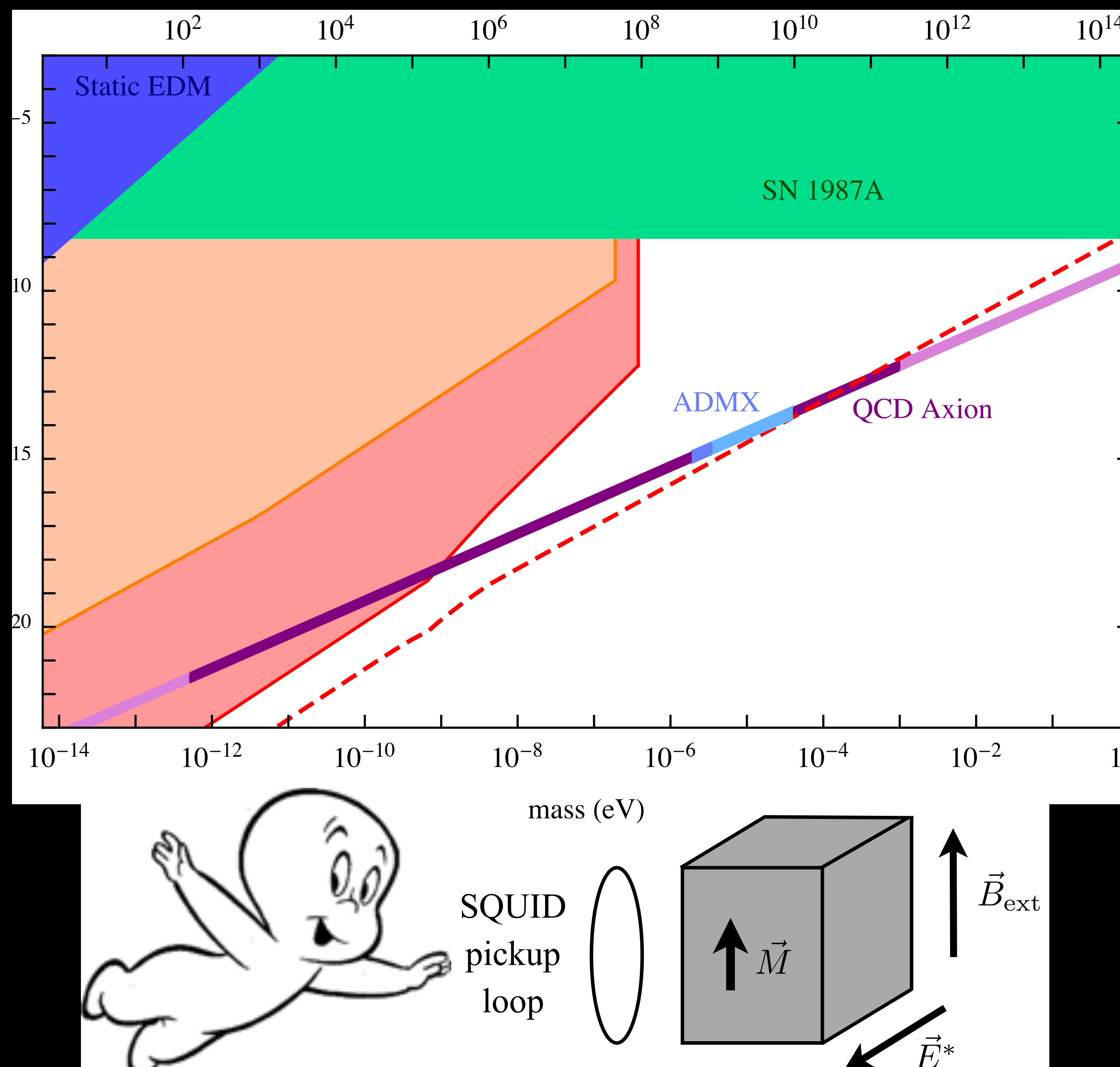




From arXiv: 1205.2671

Experimental constraints
Axions and other axion-like particles (ALPS)

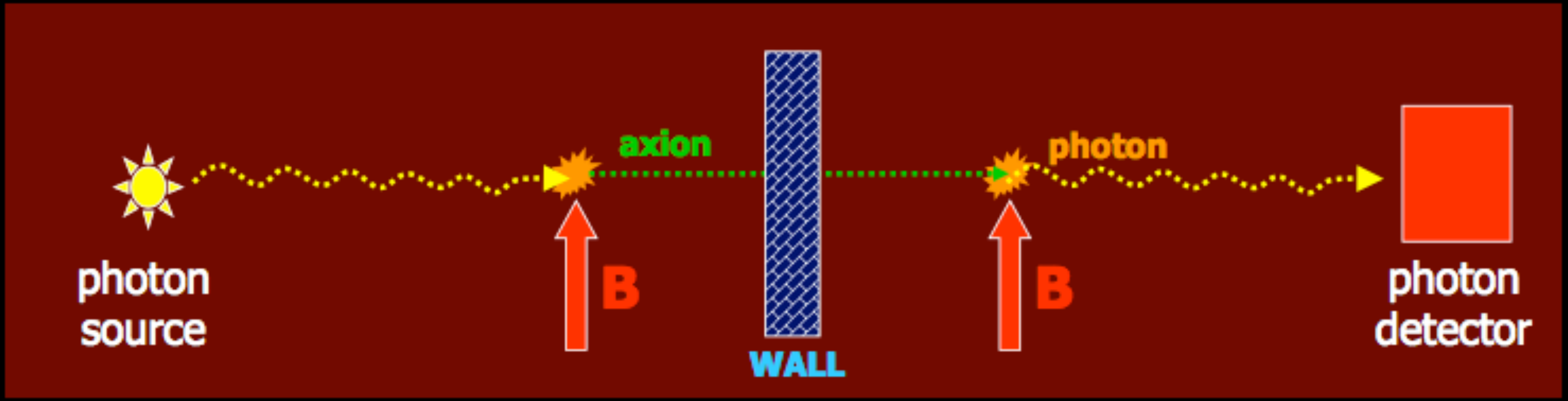
CASPer



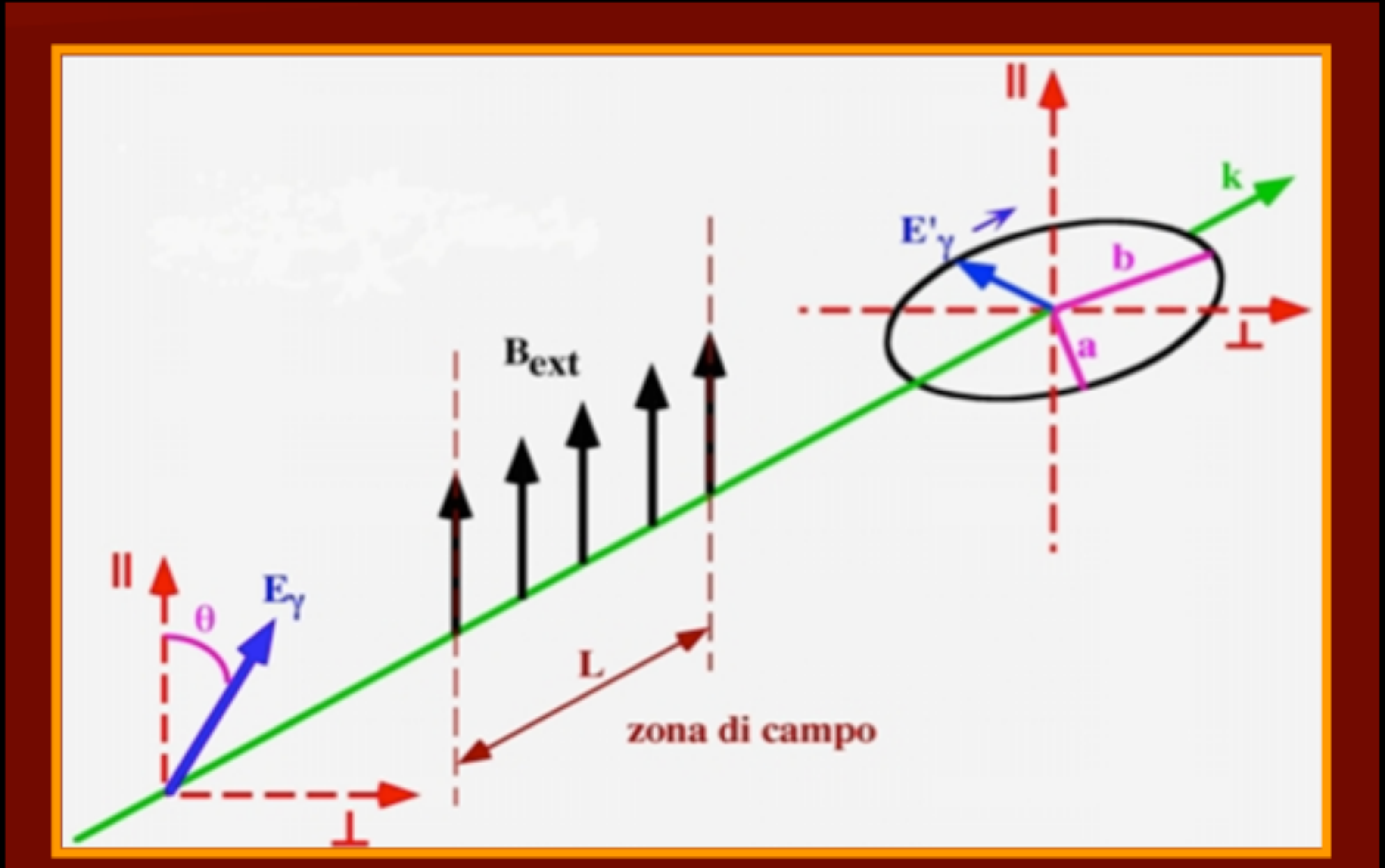
From arXiv: 1205.2671

Laser experiments

Light shining through walls (e.g. GammeV)

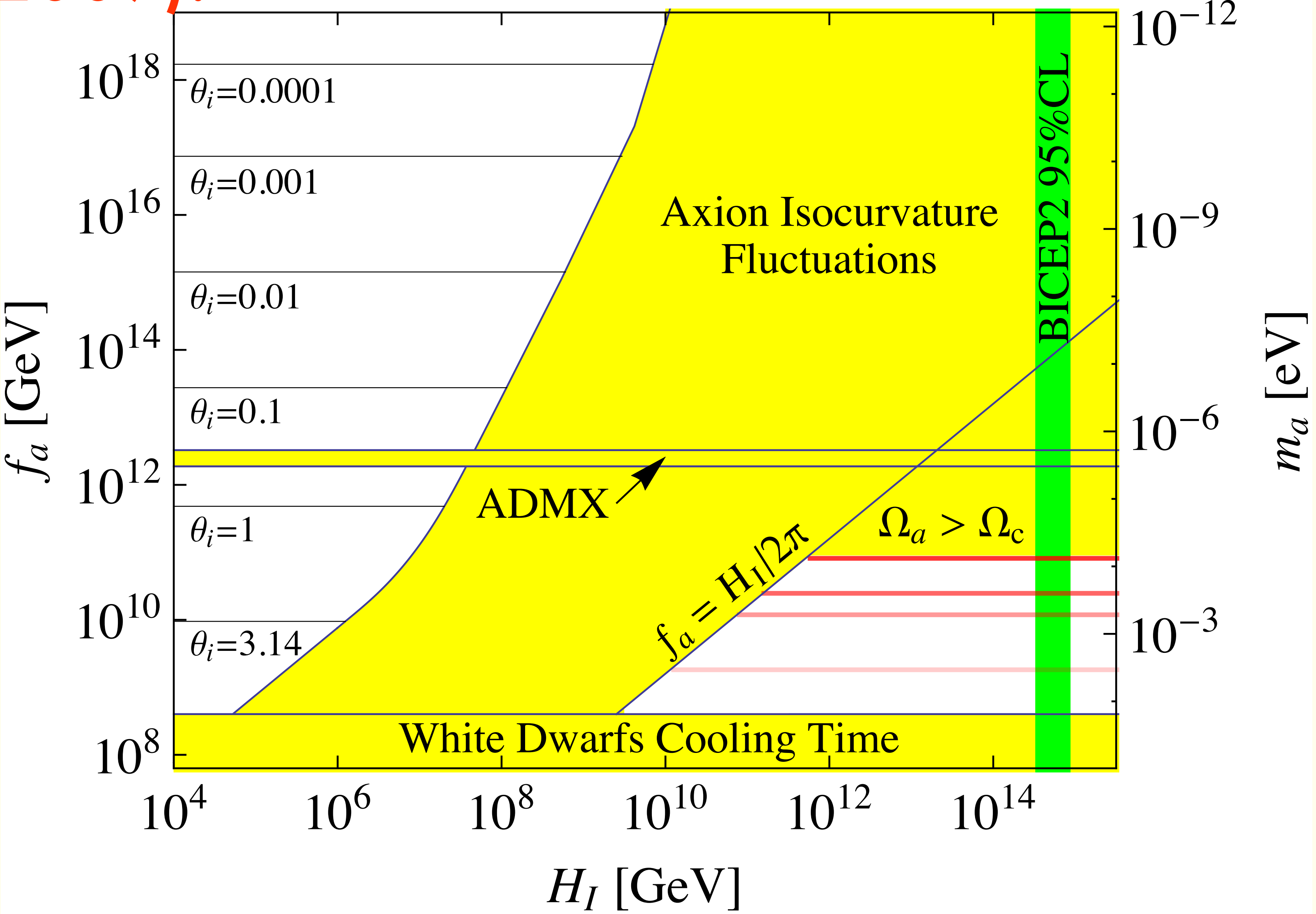


Polarization experiments (e.g. PVLAS)



BICEP2 [inflationary energy scale detected?]

(Gondolo 2009):



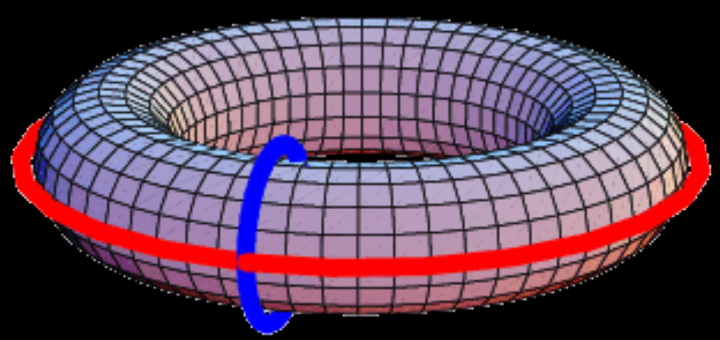
✳ Hard to accomodate QCD axion DM w/o classical window (defects)! [Marsh +yours truly+others 1403.4216 (2014), Gondolo et al. 2014 1403.4594]

$$\frac{\Omega_a}{\Omega_d} \lesssim 5 \times 10^{-12} \left(\frac{f_a}{10^{16}\ \mathrm{GeV}} \right)^{5/6}$$

More on ULA motivations

Light axions and string theory

- String theory has extra dimensions: *compactify (6)!*
- Form fields and gauge fields: `Axion' is KK zero-mode of form field



$$\mathcal{L} \propto \frac{aG\tilde{G}}{f_{\mathrm{a}}}$$

ULAs: gravitational constraints

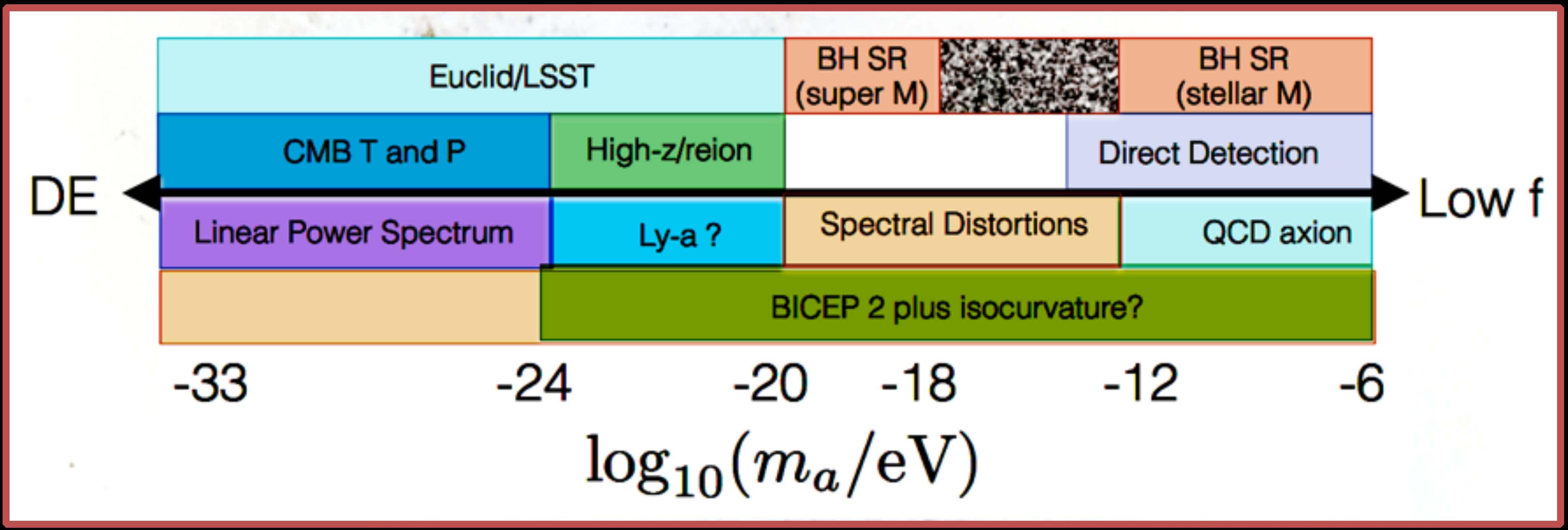


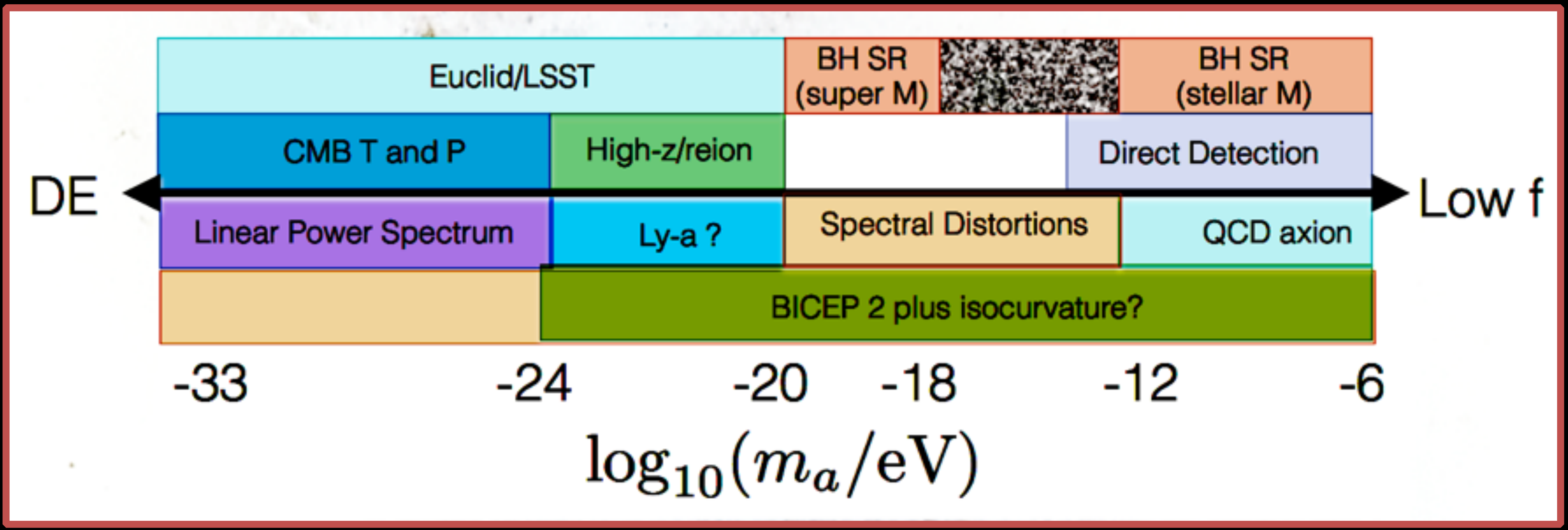
figure adapted from DJEM 2014

$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-\mathrm{Volume}}$$

Flat logarithmic mass distribution:
Very low axion masses natural!

ULAs: gravitational constraints

Independent of axion SM couplings: uncertainties astrophysical!



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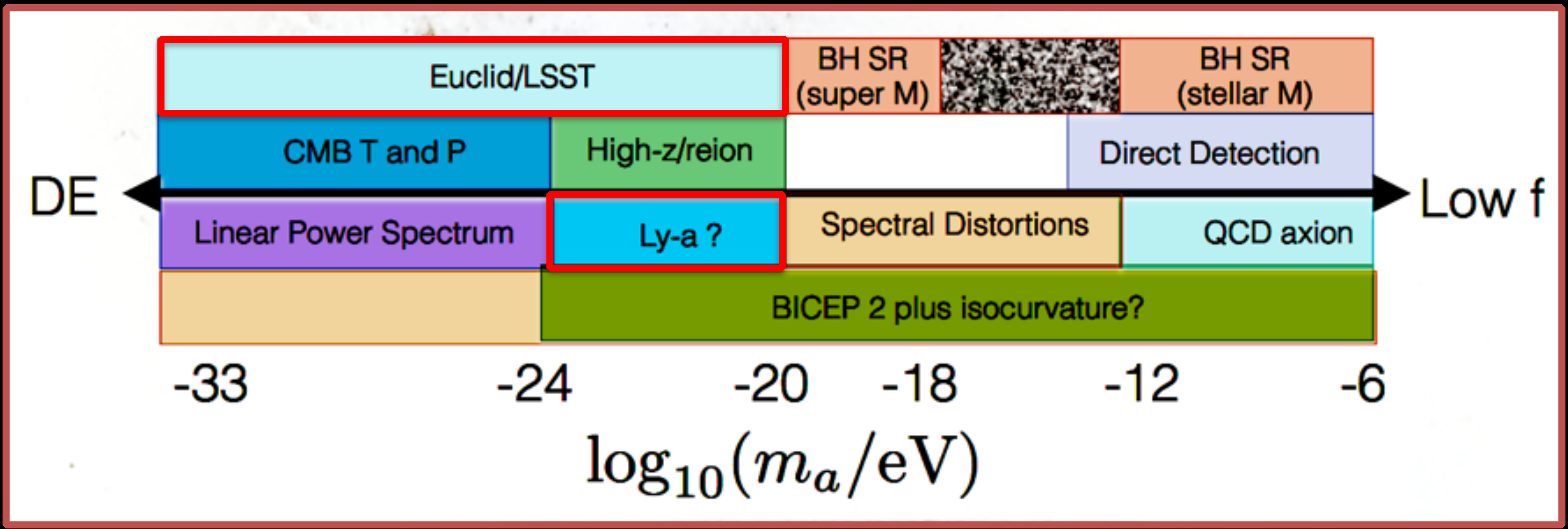
Forecast: uncertain scales



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Constraint: astrophysical uncertainties

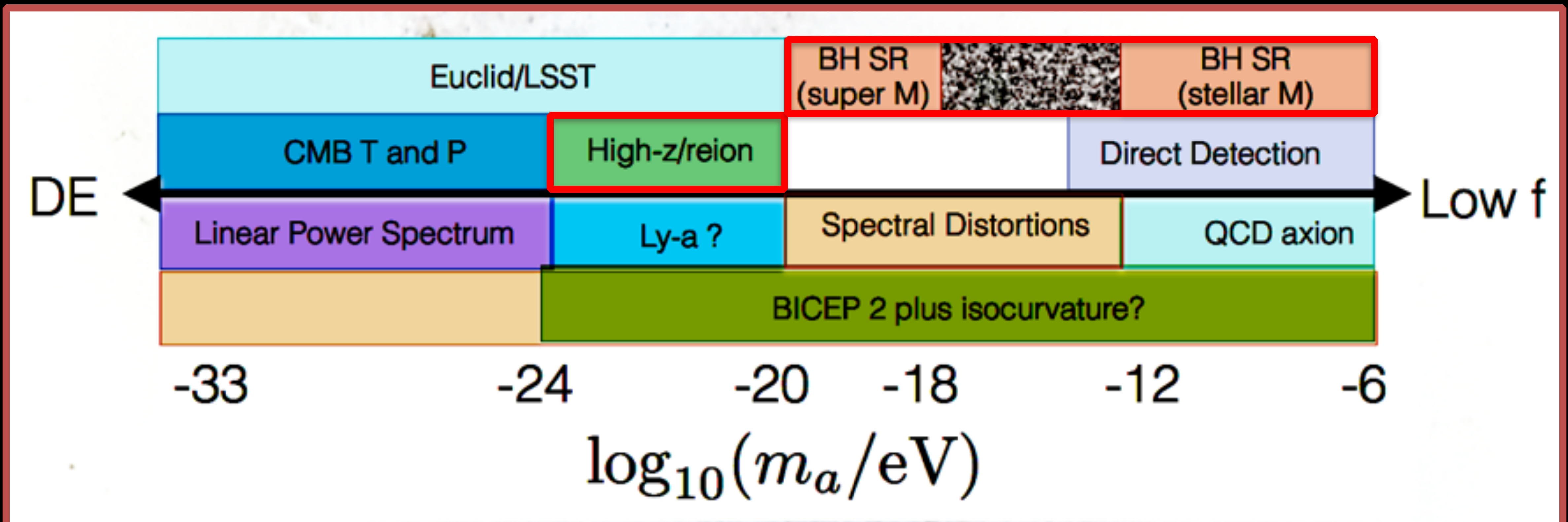

figure adapted from DJEM 2014

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Forecast

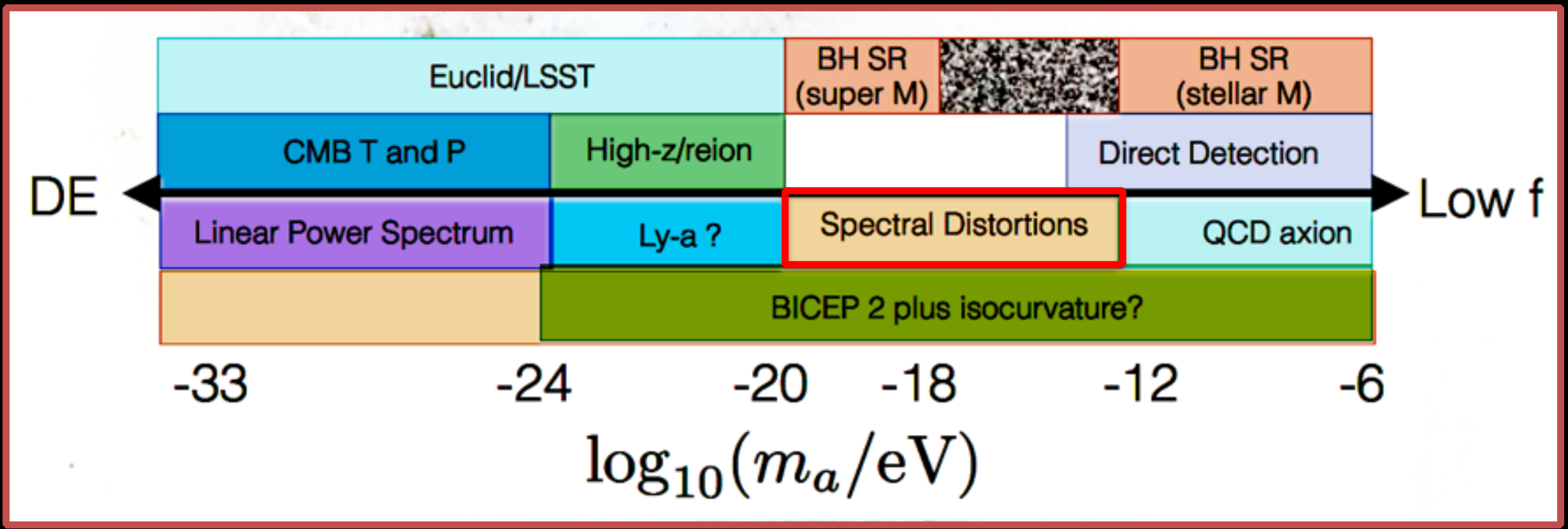

figure adapted from DJEM 2014

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$\longrightarrow$ Flat logarithmic mass distribution: Very low axion masses natural!

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Underway

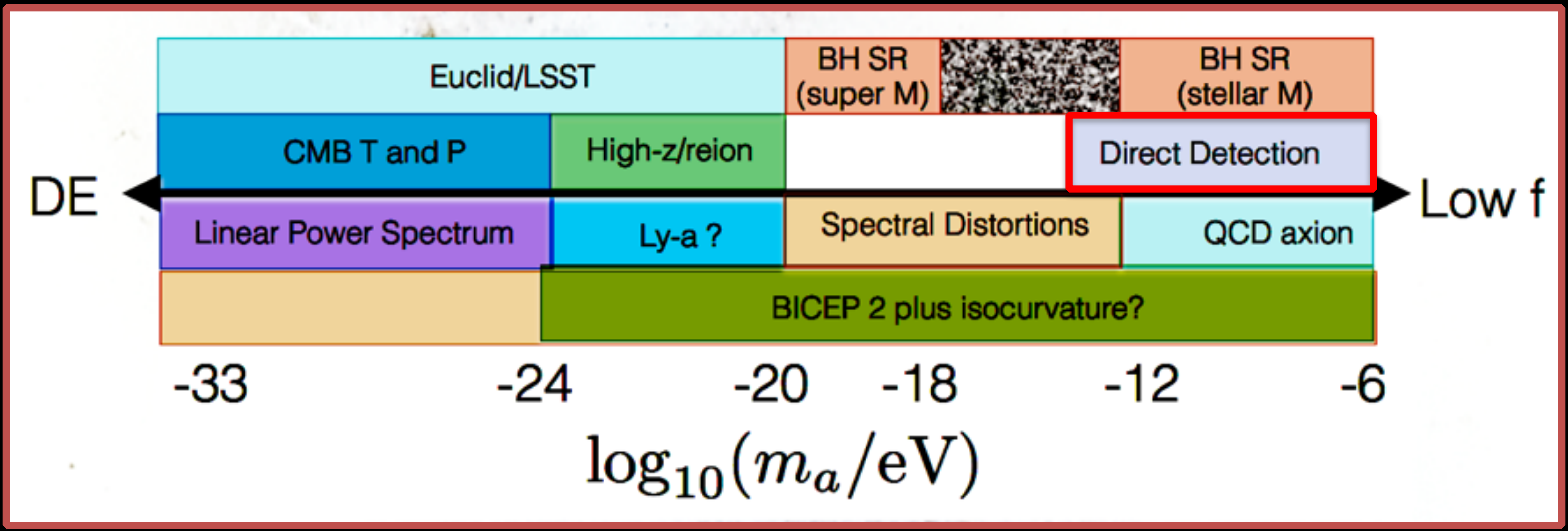

figure adapted from DJEM 2014

$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-\mathrm{Volume}} \longrightarrow$$

Flat logarithmic mass distribution:
Very low axion masses natural!

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Independent of axion SM couplings: uncertainties astrophysical!

DUST!

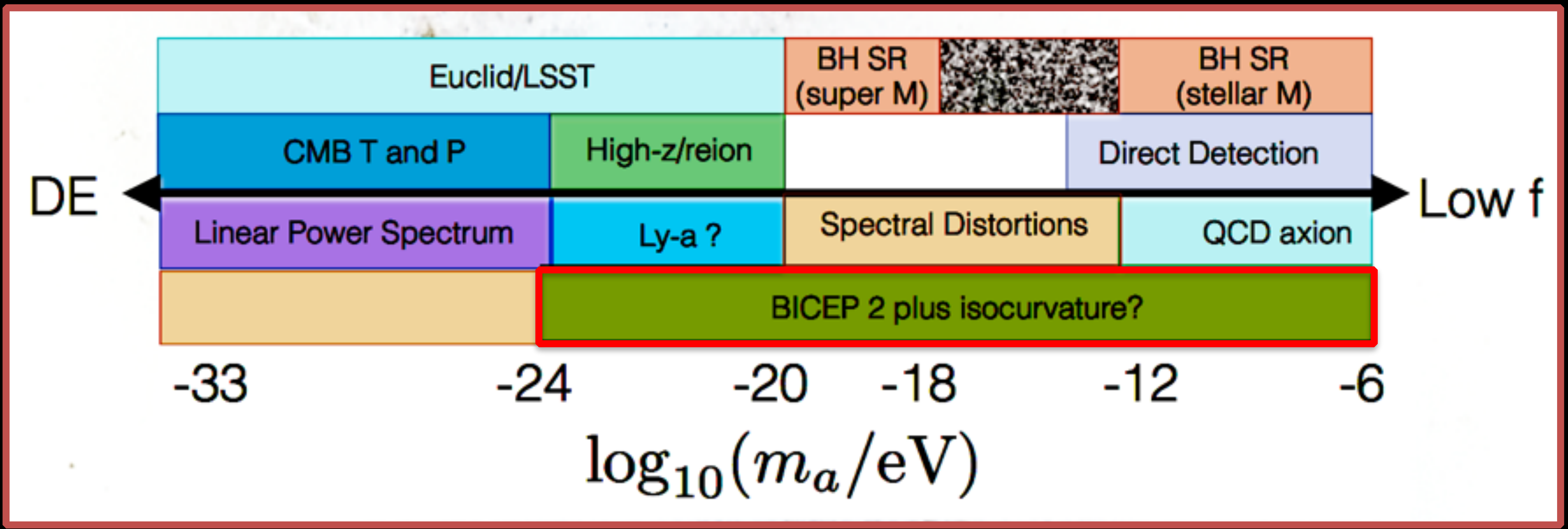

figure adapted from DJEM 2014

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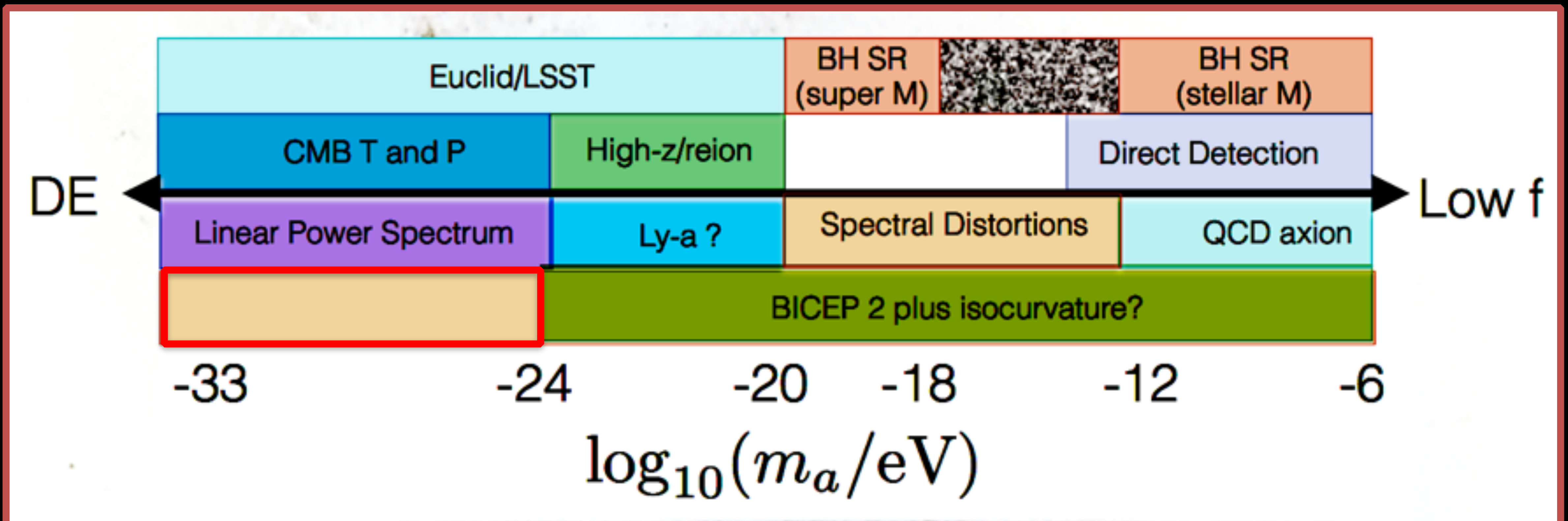
Rough forecast



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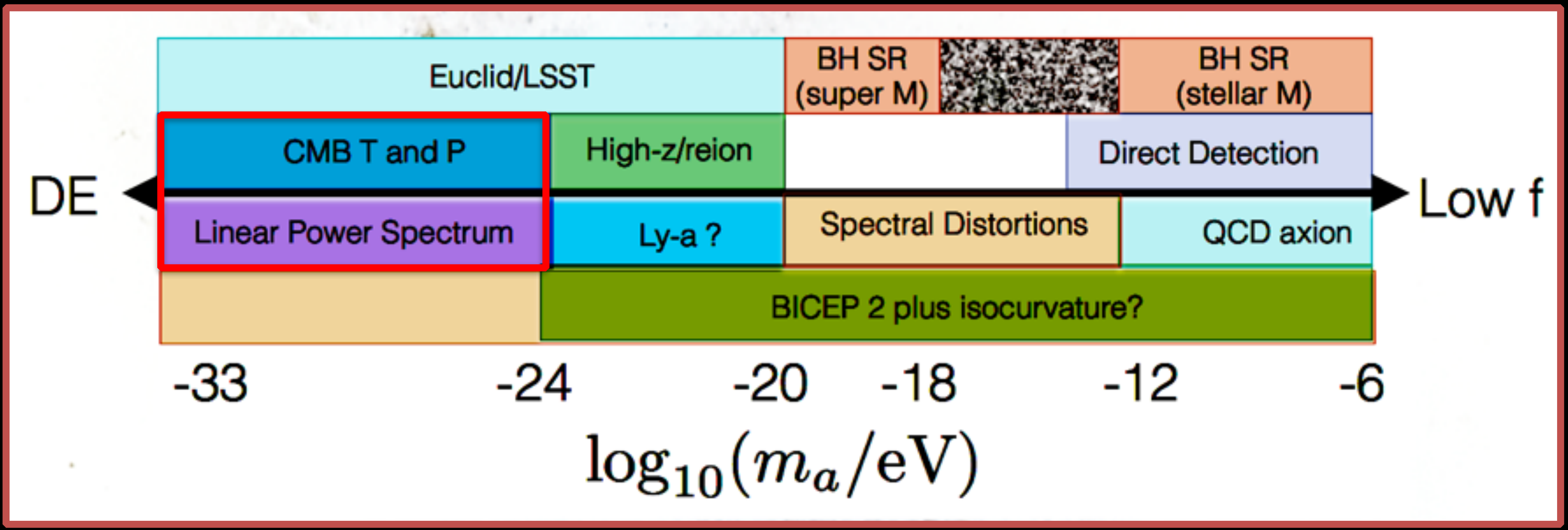
IRONCLAD: this work



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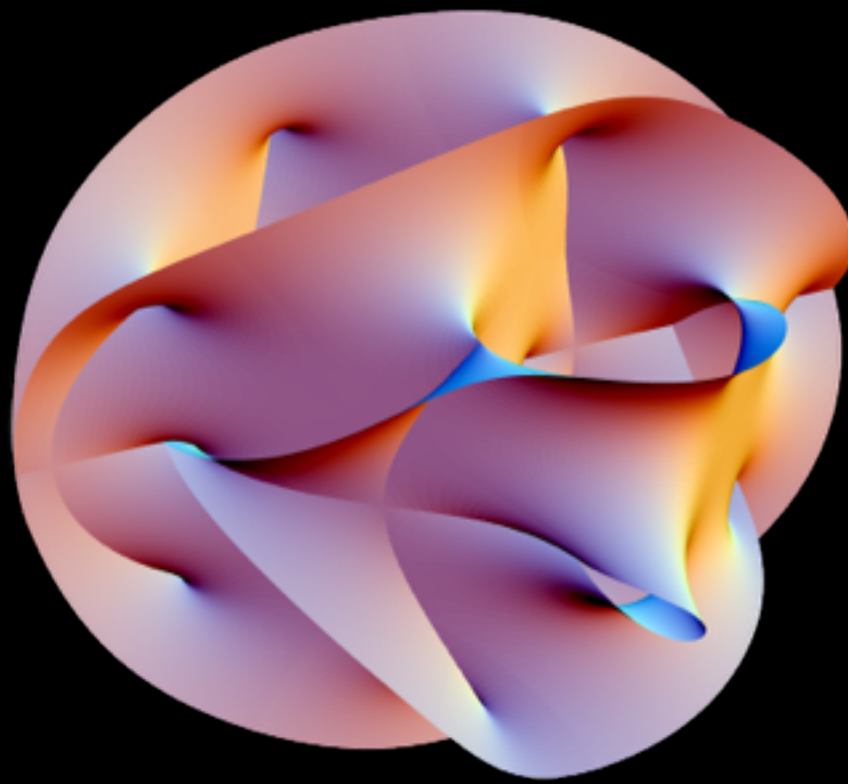
The axiverse: ultra-light axions (ULAs)

- Calabi-Yau manifolds

Many 2-cycles $\longrightarrow$ Many axions

Hundreds!



- Mass from non-perturbative physics (instantons, D-branes)

$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-\mathrm{Volume}}$$

$$f_a \propto \frac{M_{\mathrm{pl}}}{\mathrm{Volume}}$$

$$\mathcal{L} \propto g_{a\gamma\gamma} \vec{E}_{\mathrm{gauge}} \cdot \vec{B}_{\mathrm{gauge}}$$
$$g_{a\gamma\gamma} \propto \frac{1}{f_a}$$

Also Witten and Srvcek (2006), Acharya et al. (2010), Cicoli (2012)

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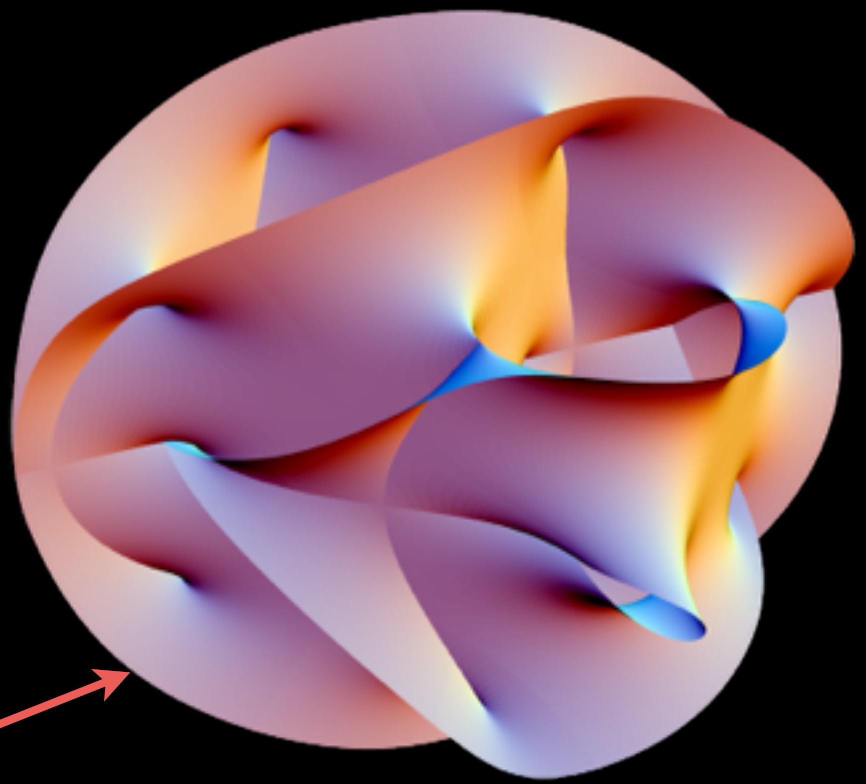

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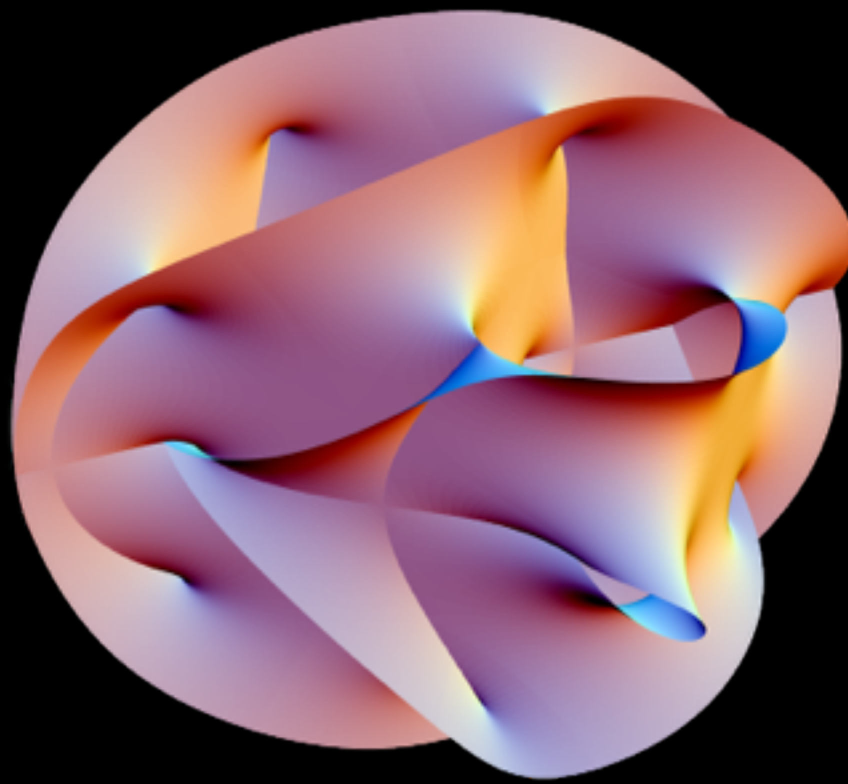

* Mass from non-perturbative physics (instantons, D-branes)

New UV scale: not QCD scale

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$$f_a \propto \frac{M_{\rm pl}}{\text{Volume}}$$

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THE AXIVERSE: ULTRA-LIGHT AXIONS (ULAS)

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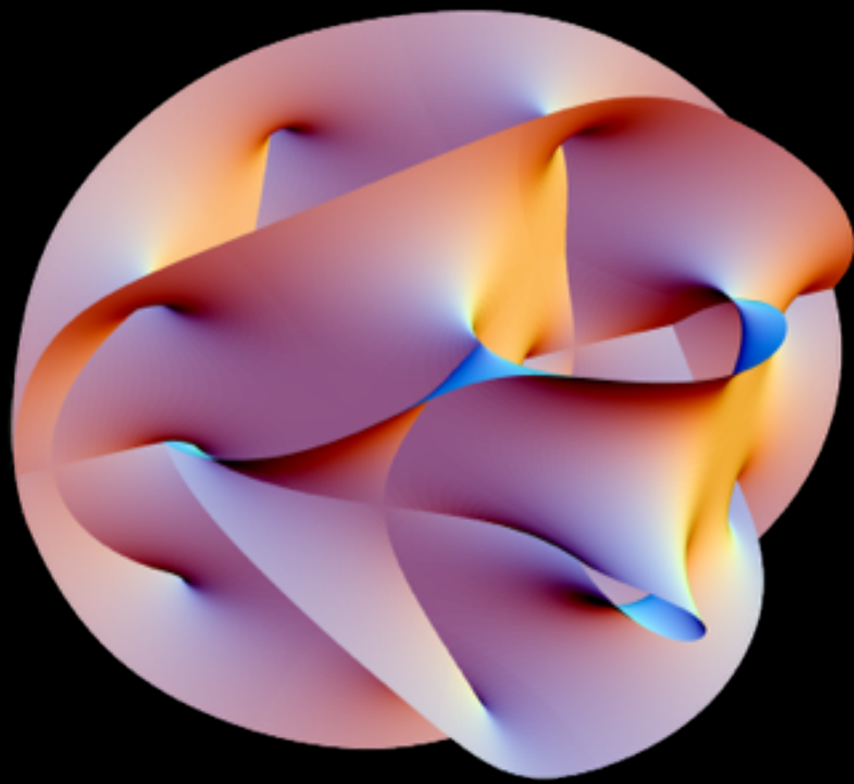
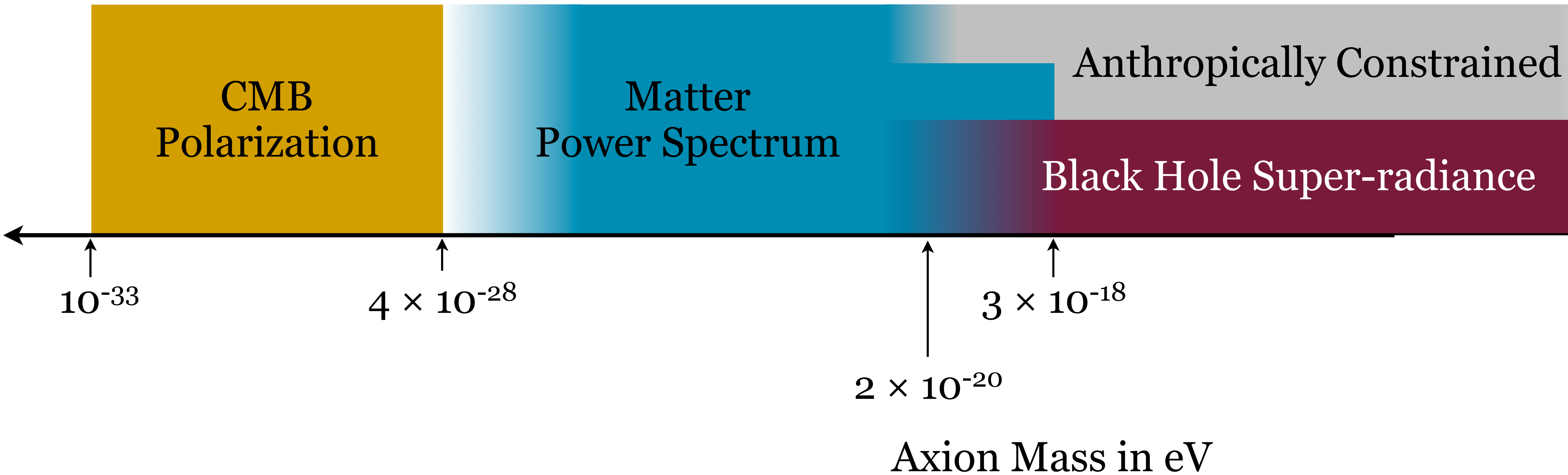


Scalars with approximate shift symmetry ⟶ "Axion"

Also Witten and Srvcek (2006), Acharya et al. (2010), Cicoli (2012)

The axiverse: ultra-light axions (ULAs)



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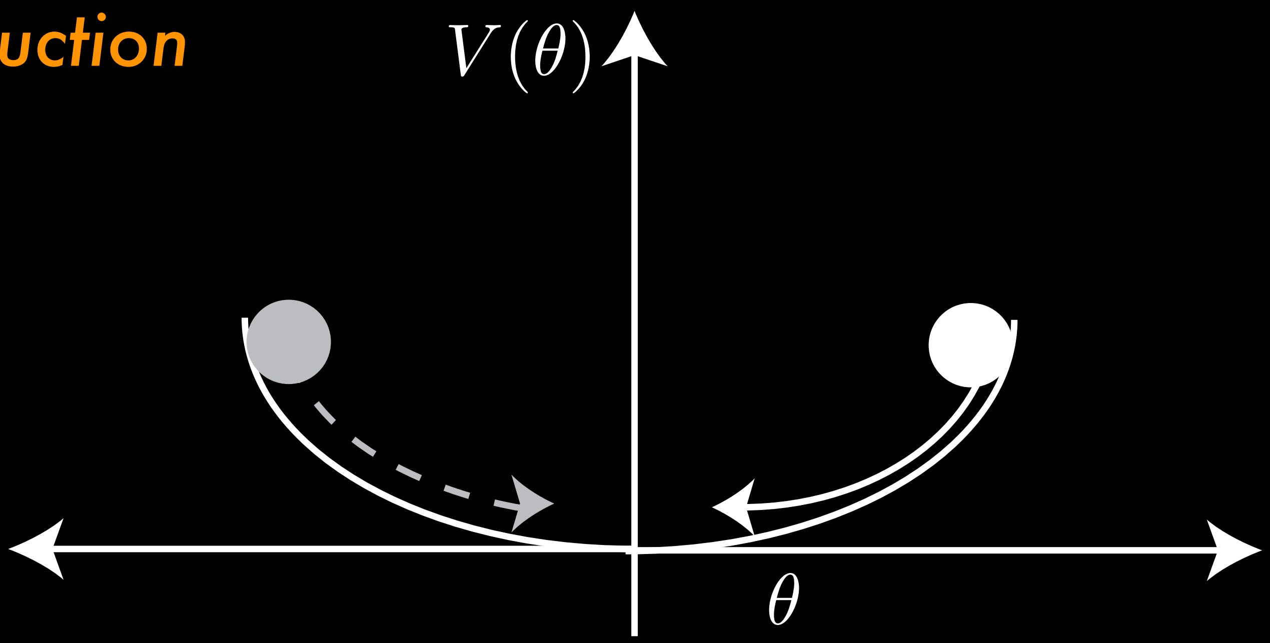
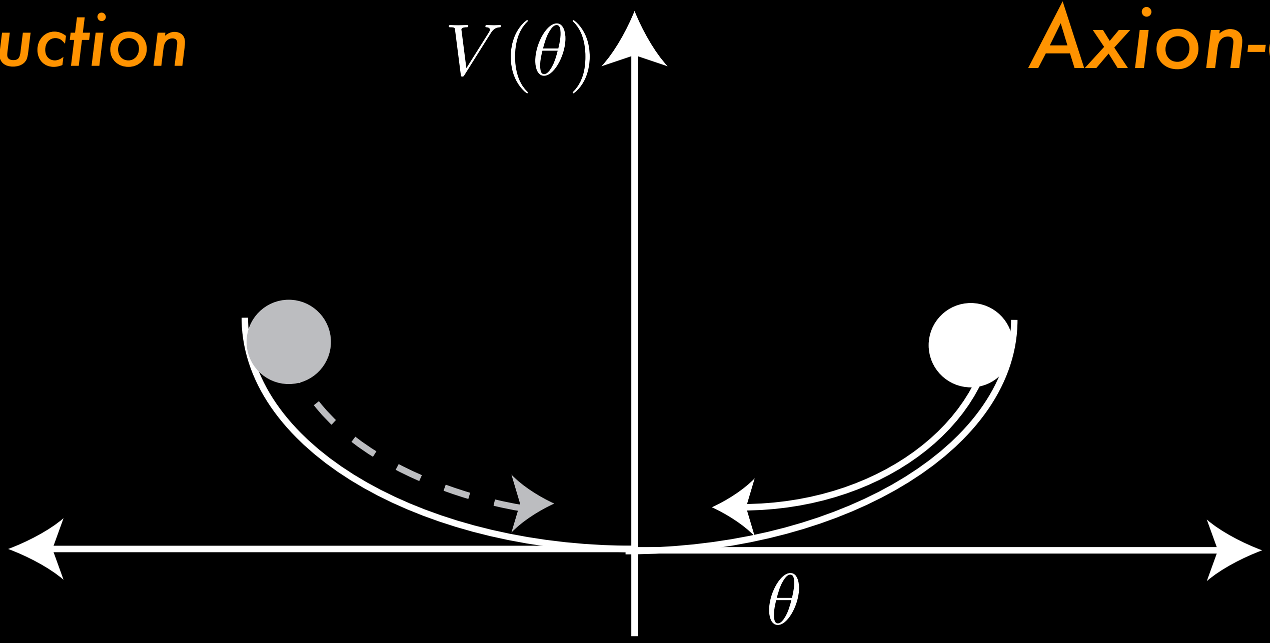
Misalignment production



Cosmological axion evolution

Misalignment production

Axion-driven acceleration



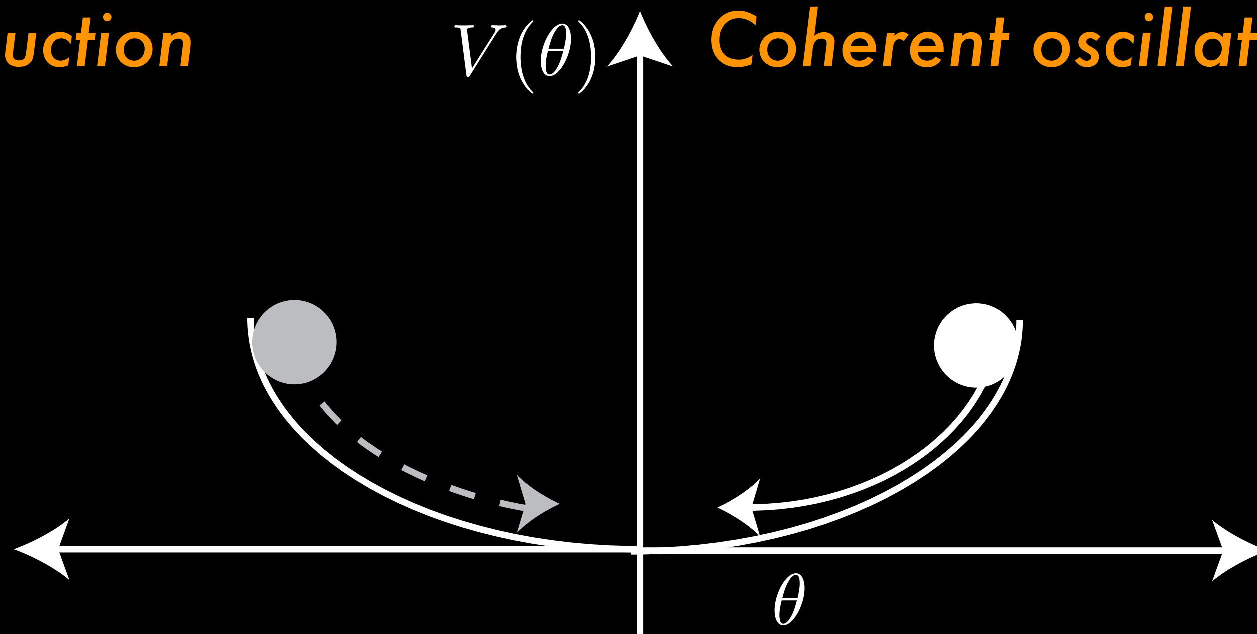
$$m \ll 3H \rightarrow n_a \propto \ \mathrm{const}, w_a \equiv \frac{P_a}{\rho_a}, w_a \simeq -1$$

$$m \gg 3H \rightarrow n_a \propto a^{-3}, \langle w_a \rangle_{T=2\pi/m_a} = 0$$

Cosmological axion evolution

Misalignment production

Coherent oscillation, Axions act like CDM



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Cosmological axion evolution

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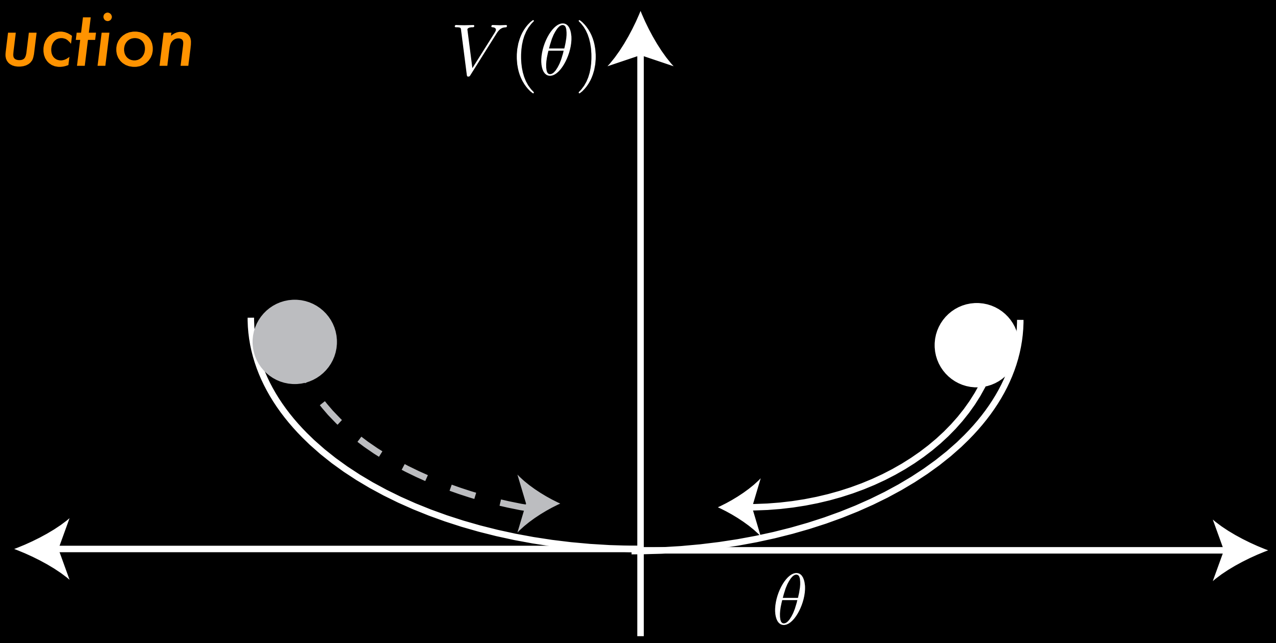
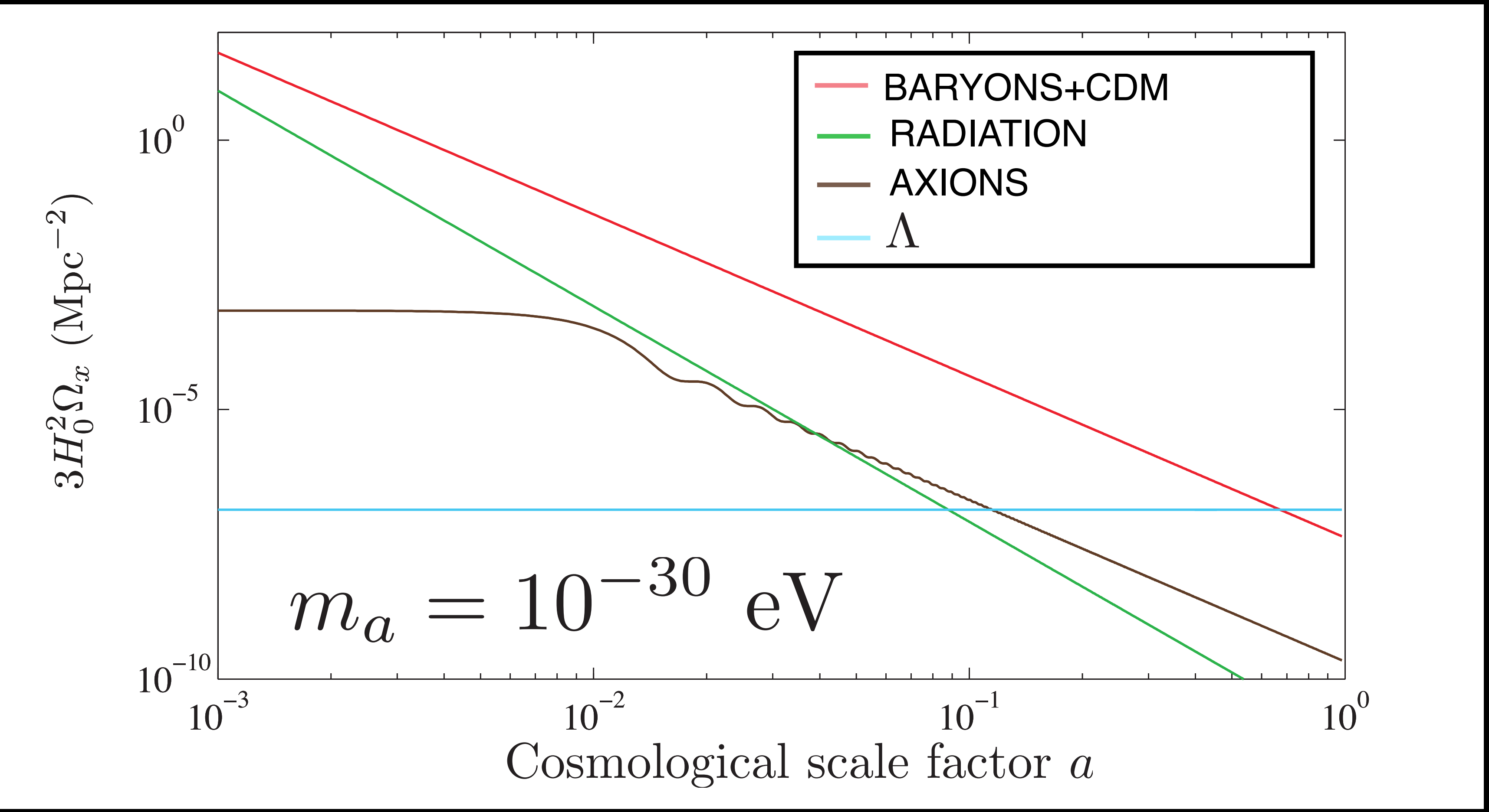


For QCD axion, we have a CDM candidate!

$$\Omega_{\rm mis}h^2 = 0.236\,\langle\theta_i^2 f(\theta_i)\rangle\left(\frac{m_a}{6.2\mu{\rm eV}}\right)^{-7/6}$$

Cosmological axion evolution

Different parameter space for non-QCD axion(Frieman et al 1995, Coble et al. 2007)



10^{-33} eV $< m_a < 10^{-18}$ eV

Cosmological axion evolution

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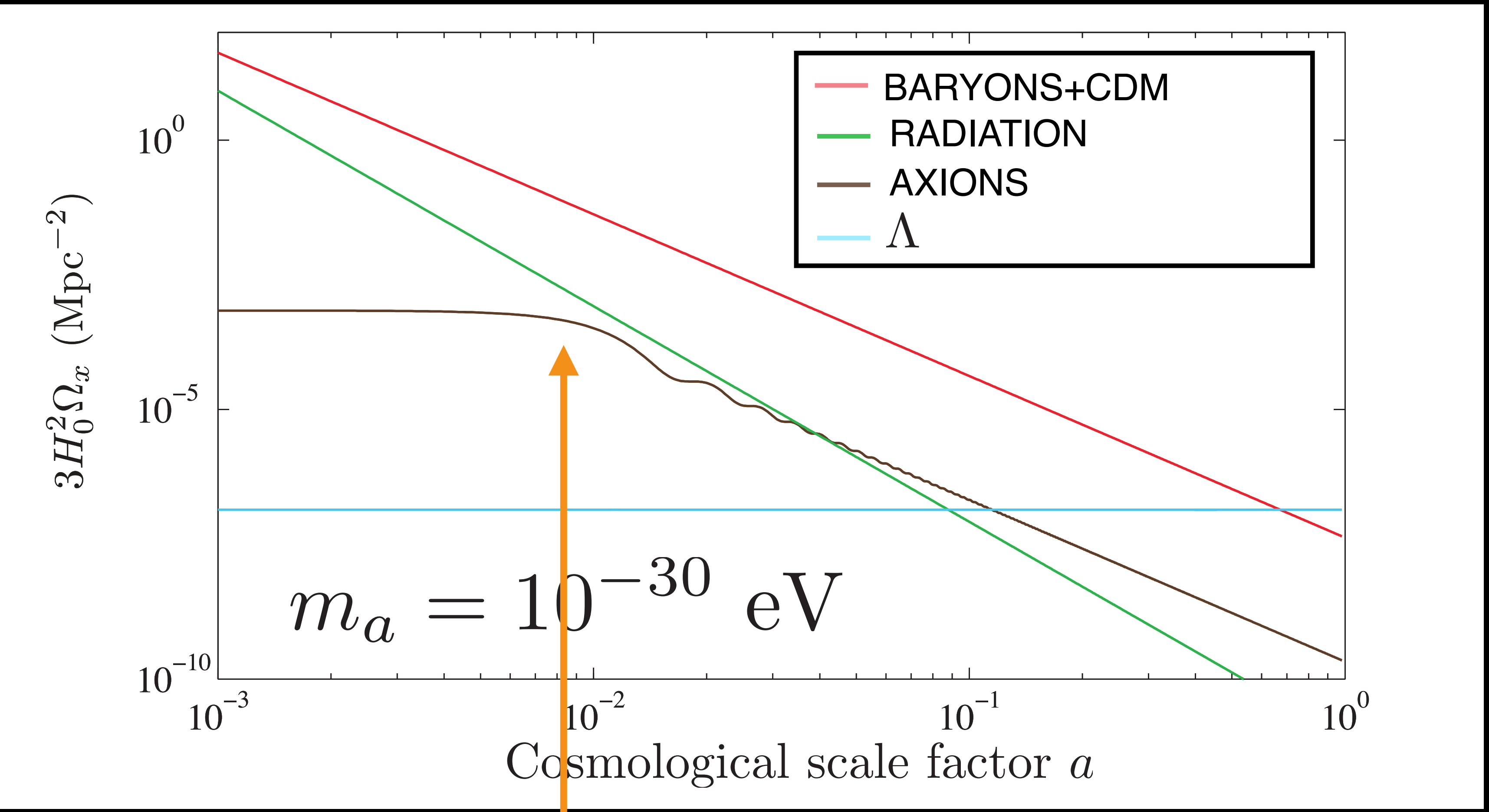
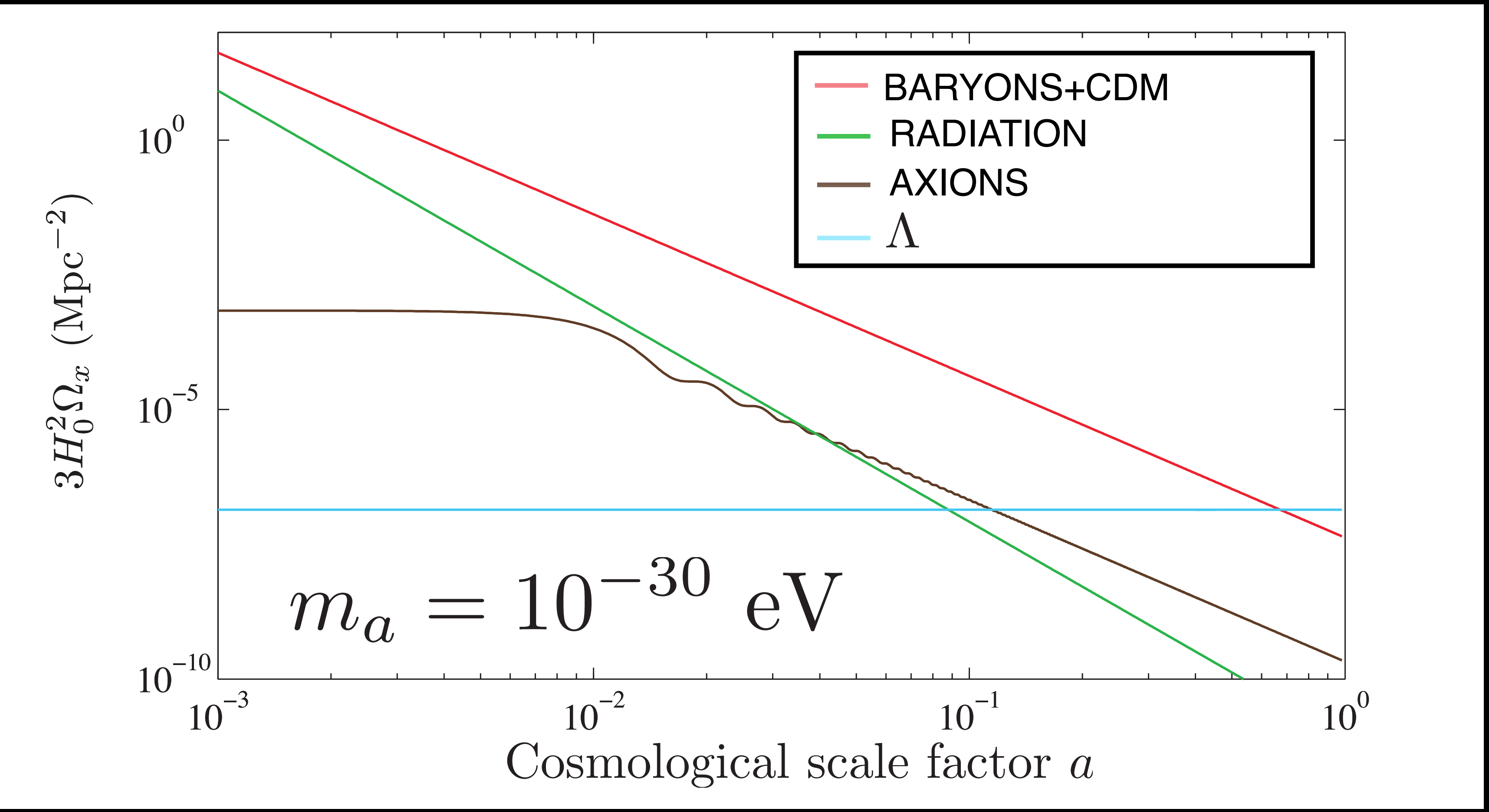


$$10^{-33}\ \mathrm{eV} < m_a < 10^{-18}\ \mathrm{eV}$$

$$a \equiv a_{\rm osc} \quad m_a = 3H(a)$$

Cosmological axion evolution

Different parameter space for non-QCD axion(Frieman et al 1995, Coble et al. 2007)



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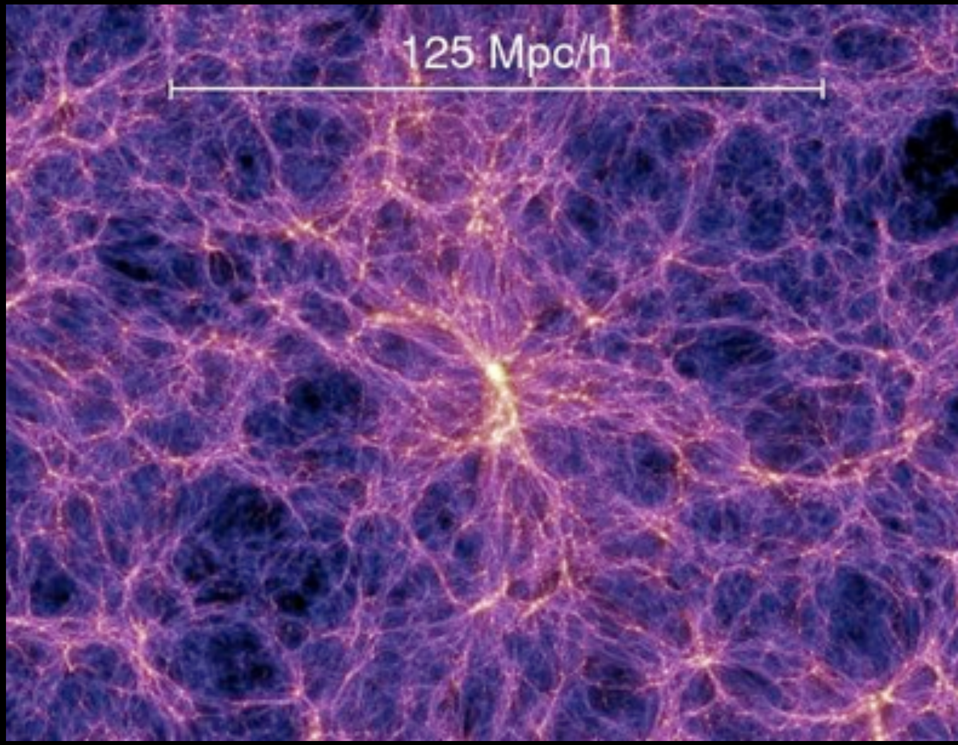


'DM' axions $\quad a_{\rm osc} < a_{\rm eq}$ $\quad$ Oscillation starts in time for struct. formation

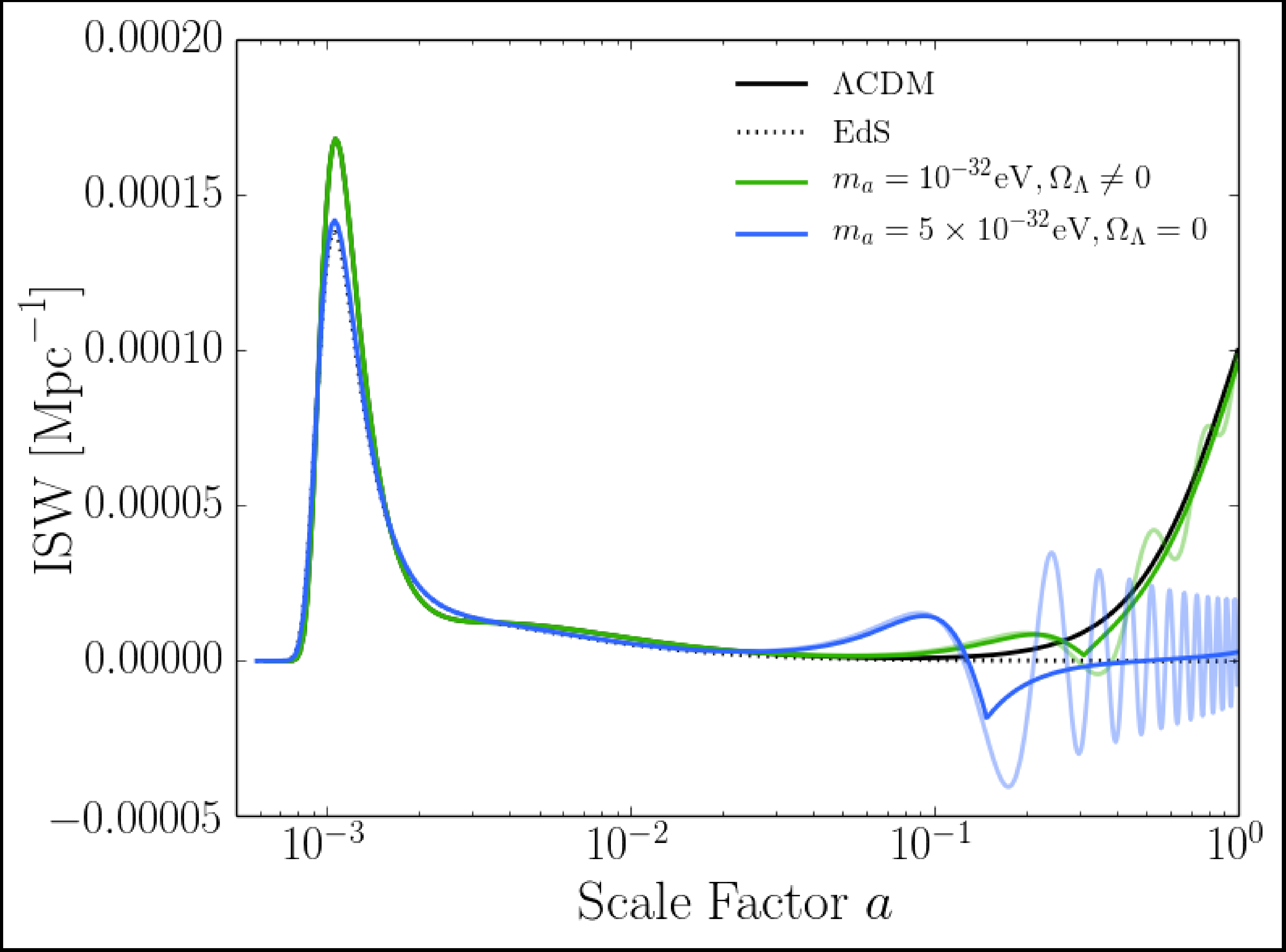
$$m_a > 10^{-27}\ {\rm eV}$$

DE axions $\quad a_{\rm osc} > a_{\rm eq}$ $\quad$ Oscillation starts too late for struct. formation

$$m_a < 10^{-27}\ {\rm eV}$$

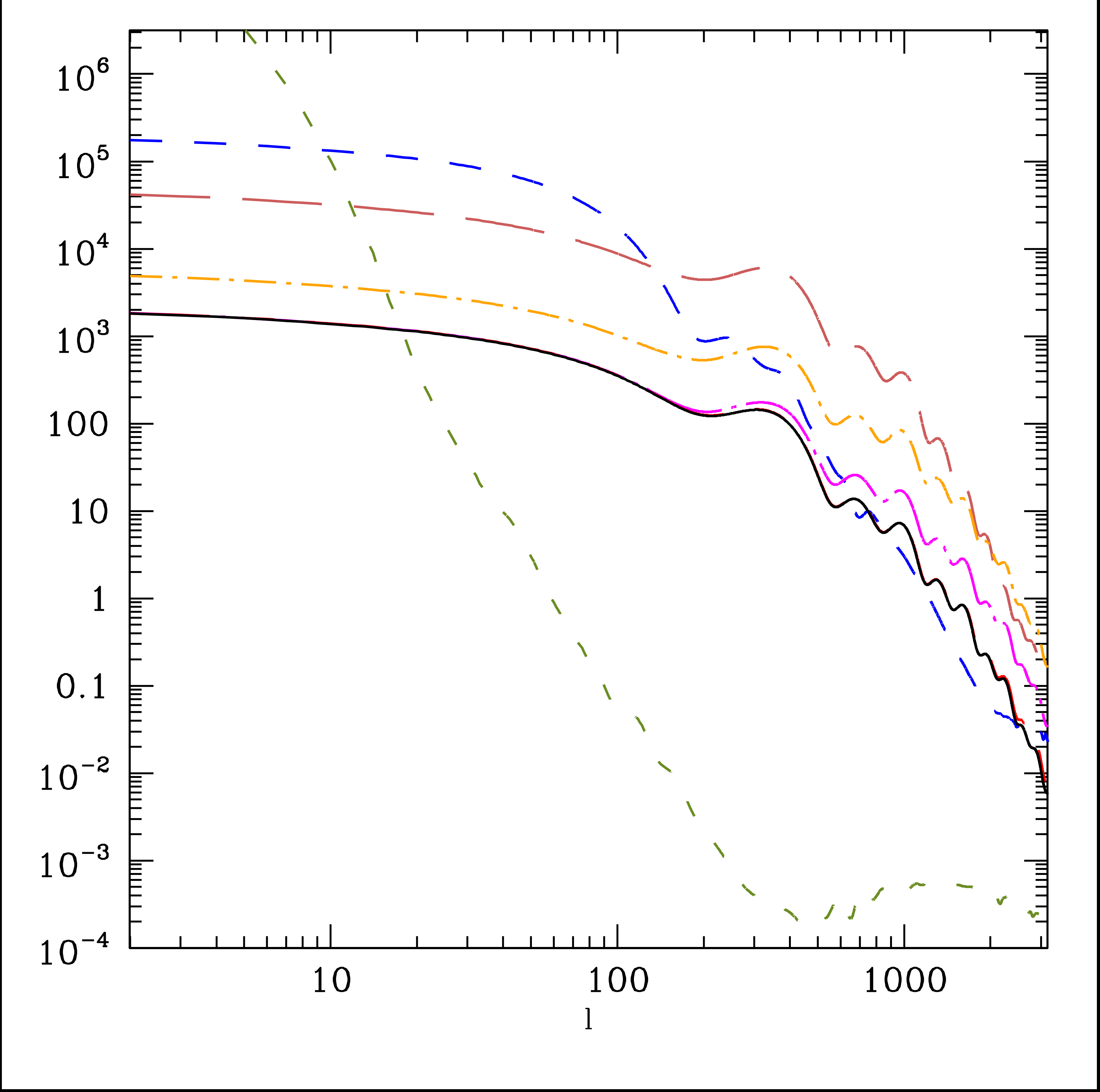
Additional slides:
ULA search details

ISW TEST



0.00020
0.00015
0.00010
0.00005
0.00000
−0.00005
ISW [Mpc^{-1}]
10^{-3}
10^{-2}
10^{-1}
10^{0}
Scale Factor a
ΛCDM
EdS
$m_a = 10^{-32}\mathrm{eV}, \Omega_\Lambda \neq 0$
$m_a = 5 \times 10^{-32}\mathrm{eV}, \Omega_\Lambda = 0$

Getting under the hood: The need for numerical care



Getting under the hood: The need for numerical care

$$\dot{\delta}_a = 3\mathcal{H}\left[w_a - 1\right]\delta_a - (1 + w_a)\left(kv_a + \dot{h}\right)$$

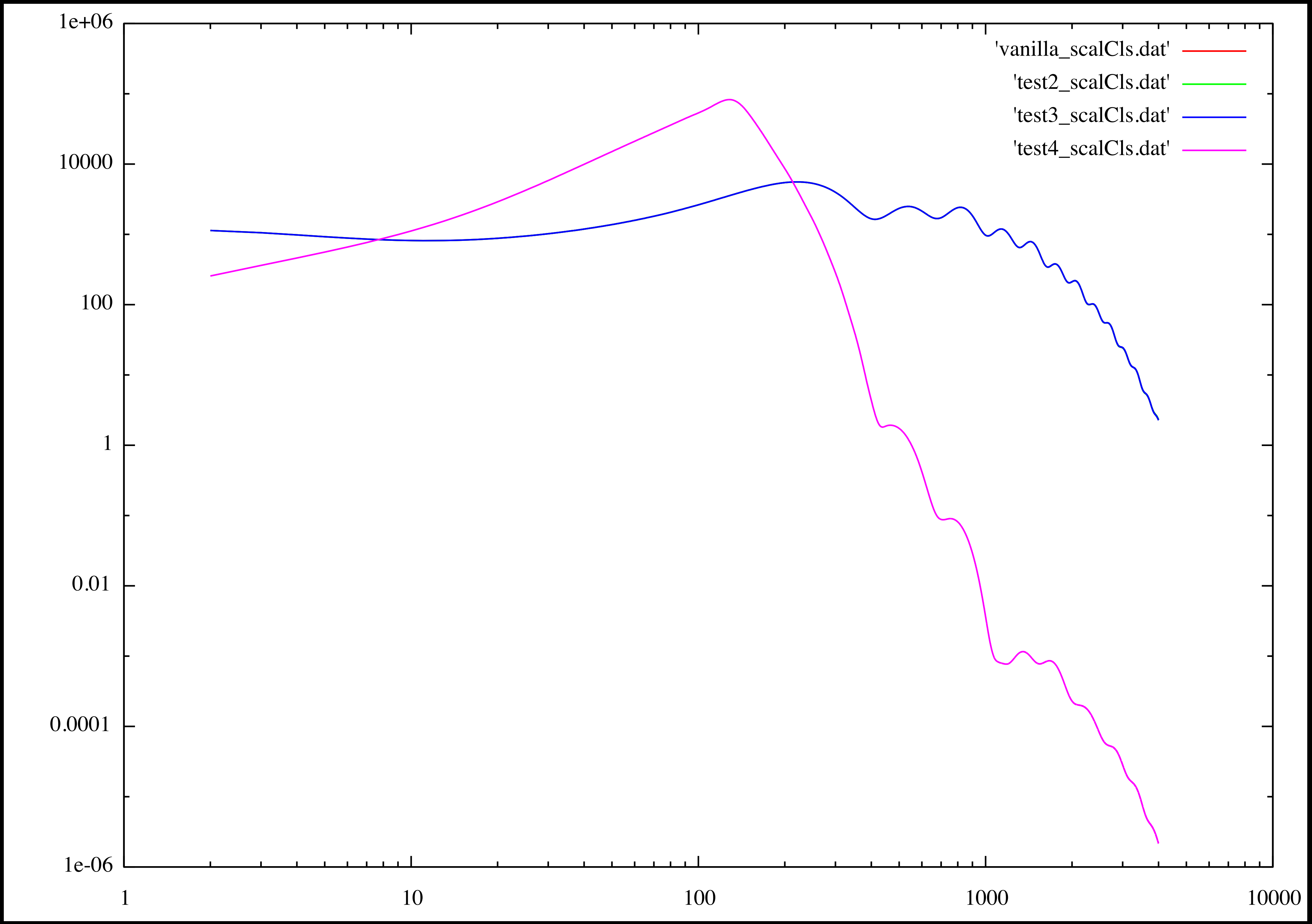
$$\dot{v}_a = -3\mathcal{H}\left[1 - 3w_a\right]v_a - \frac{\dot{w}_a}{(1 + w_w)}v_a + \frac{k\delta_a}{(1 + w_a)}$$

$$\dot{w}_a = -3\mathcal{H}\left(1 + w_a\right)\left[c_{\rm ad}^2 - w_a\right]$$

$$c_{\rm ad}^2 = \frac{\dot{P}_a}{\dot{\rho}_a} = -1 + \frac{2m_a a}{\mathcal{H}}\sqrt{\frac{(1 - w_a)}{(1 + w_a)}}$$

$$\dot{\rho}_a = -3\mathcal{H}\rho_a\left(1 + w_a\right)$$

Getting under the hood: The need for correct (super-horizon) initial conditions



Getting under the hood: The need for correct (super-horizon) initial conditions

Synchronous gauge 00-Einstein $\dot{h} \propto \eta \left[\frac{3\delta_{\mathrm{R}}}{a^2} + 3a^2 \mathcal{A} \delta_a \right]$

Getting under the hood: The need for correct (super-horizon) initial conditions

Synchronous gauge 00-Einstein

$$\dot{h} \propto \eta \left[\cancel{\frac{3\delta_{\rm R}}{a^2}} + 3a^2 \mathcal{A} \delta_a \right]$$

Perrotta and Baccigalupi, astro-ph/9811156

Getting under the hood: The need for correct (super-horizon) initial conditions

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Perrotta and Baccigalupi, astro-ph/9811156

$$\dot{\delta}_\gamma \simeq -\frac{\dot{h}}{2}$$

NOT KOSHER!

Getting under the hood: The need for correct (super-horizon) initial conditions

Synchronous gauge 00-Einstein

$$\dot{h} \propto \eta \left[\cancel{\frac{3\delta_{\mathrm{R}}}{a^2}} + 3a^2 \mathcal{A}\delta_a \right]$$

Perrotta and Baccigalupi, astro-ph/9811156

$$\dot{\delta}_\gamma \simeq -\frac{\dot{h}}{2}$$

NOT KOSHER!

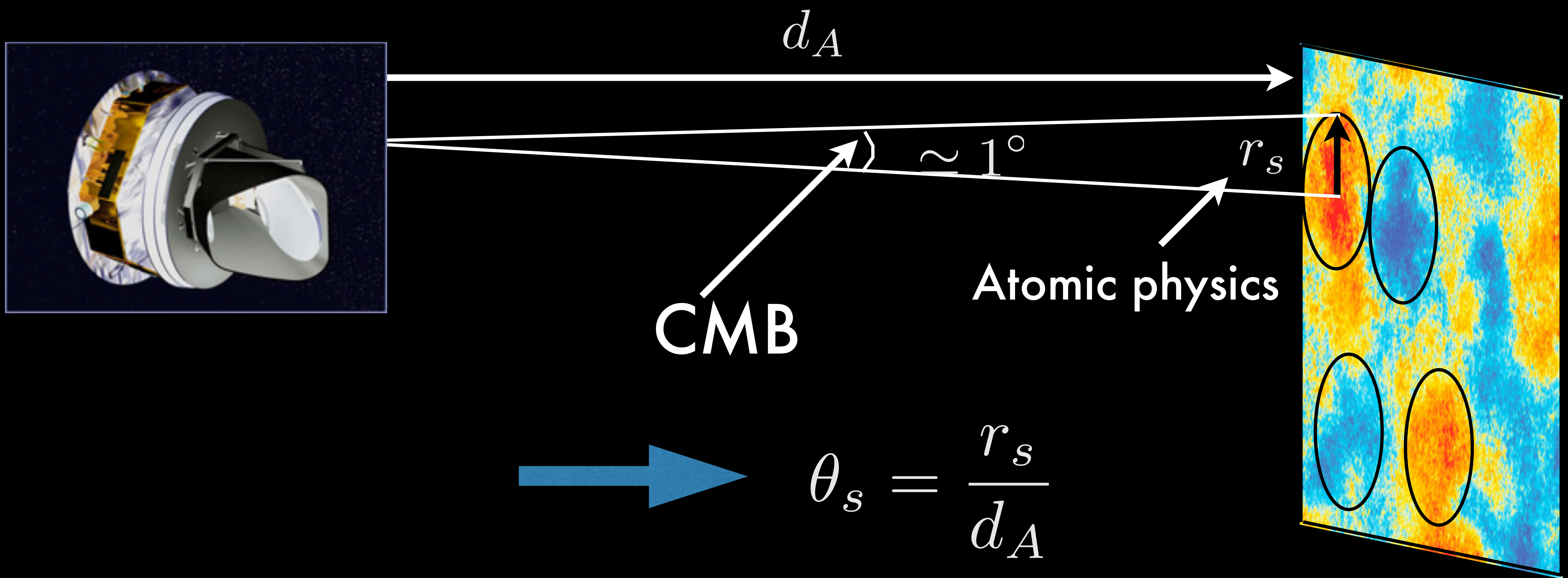
Solve Eigensystem and expand systematically

$$\frac{d\vec{U}_{\vec{k}}}{d\ln x} = \left(\underline{A}_0 + \underline{A}_1 x + \ldots \underline{A}_n x^n\right) \vec{U}_{\vec{k}}$$

Bucher, Moodley, and Turok, PRD62, 083508, sol'ns can be obtained using this technique, outlined in Doran et al. , astro-ph/0304212

ULAs and the angular sound horizon

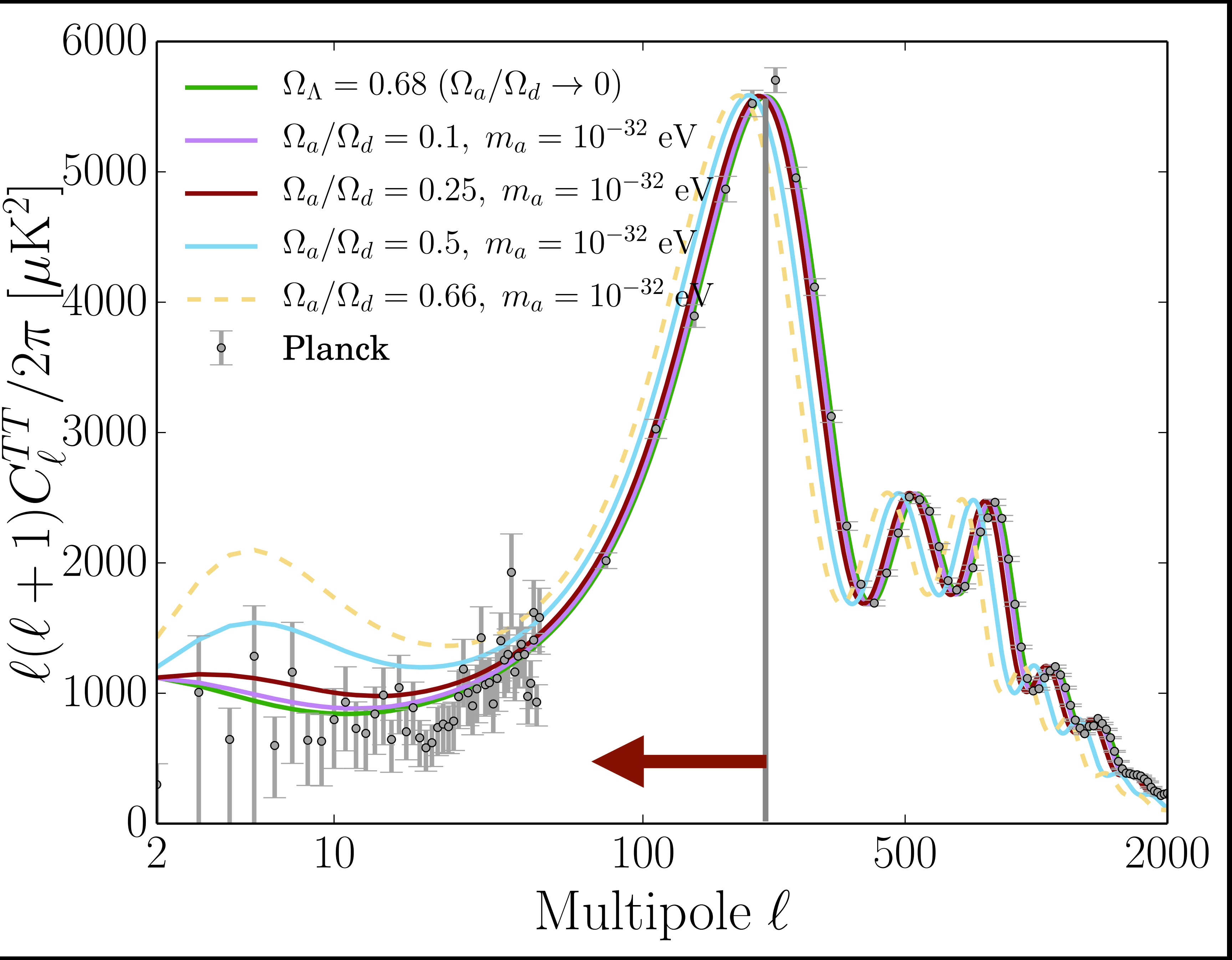
$$\theta_s \equiv \frac{r_s}{d_A(z=1100)} = \left(l_{\rm CMB}^{\rm peak}\right)^{-1}$$



$$\theta_s = \frac{r_s}{d_A}$$

Diagram by T. Smith (used with permission)

ULAs and the angular sound horizon



$$\theta_s \equiv \frac{r_s}{d_A(z=1100)} = \left(l_{\mathrm{CMB}}^{\mathrm{peak}}\right)^{-1}$$

$$d_A \propto \int \frac{dz}{H(z)}$$

$$H(z) = H_0 \left\{ \frac{\Omega_m}{a^3} + \frac{\Omega_{\mathrm{axion}}}{a^{3\int[1+w(\eta)]d\eta}} \right\}^{1/2}$$

Faster early expansion brings LSS closer

ULAs and the angular sound horizon

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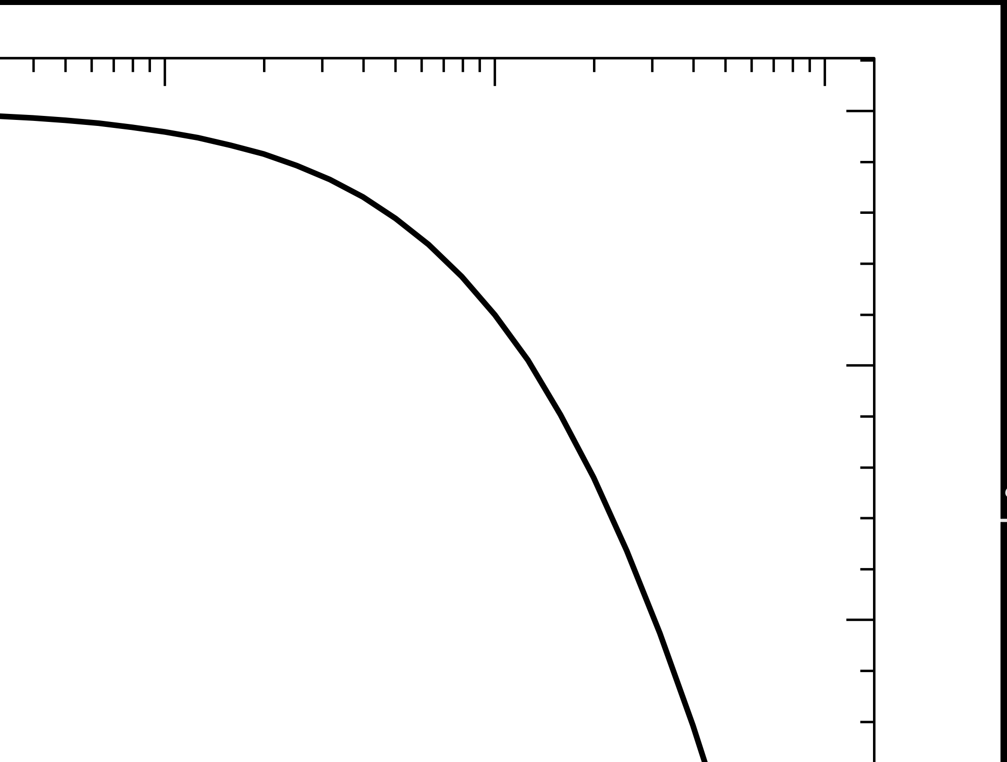

$$\ldots \frac{\ldots \text{axion}}{\ldots + w(\eta)]d\eta} \Bigg\}^{1/2}$$

Faster early expansion brings LSS closer

ULAs and the angular sound horizon

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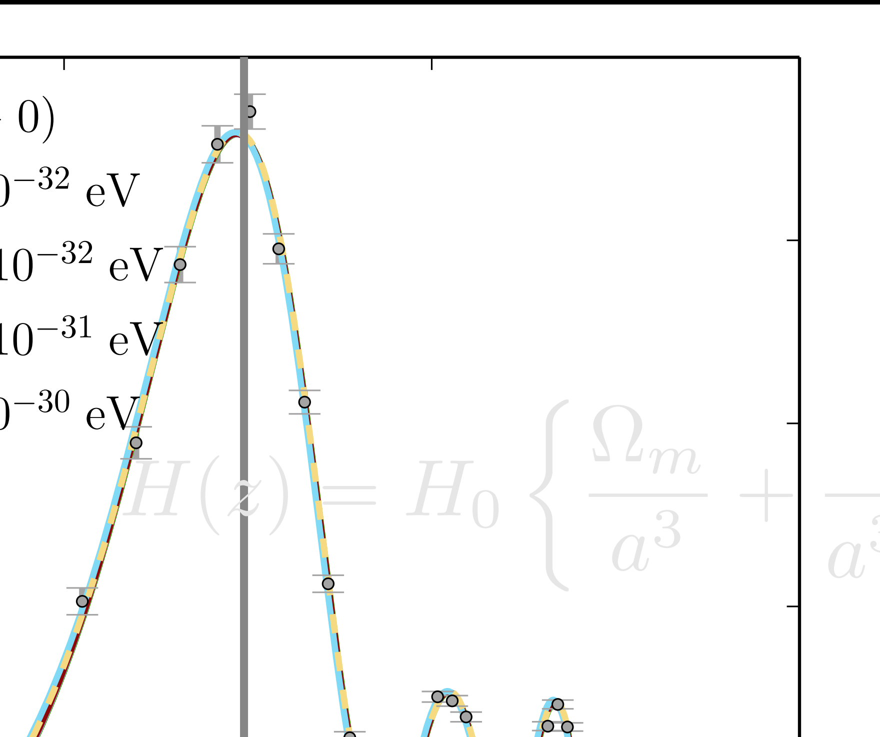
$$d_A \propto \int \frac{dz}{H(z)}$$

Absorb and lock onto usual peaks by lowering

$$H_0$$



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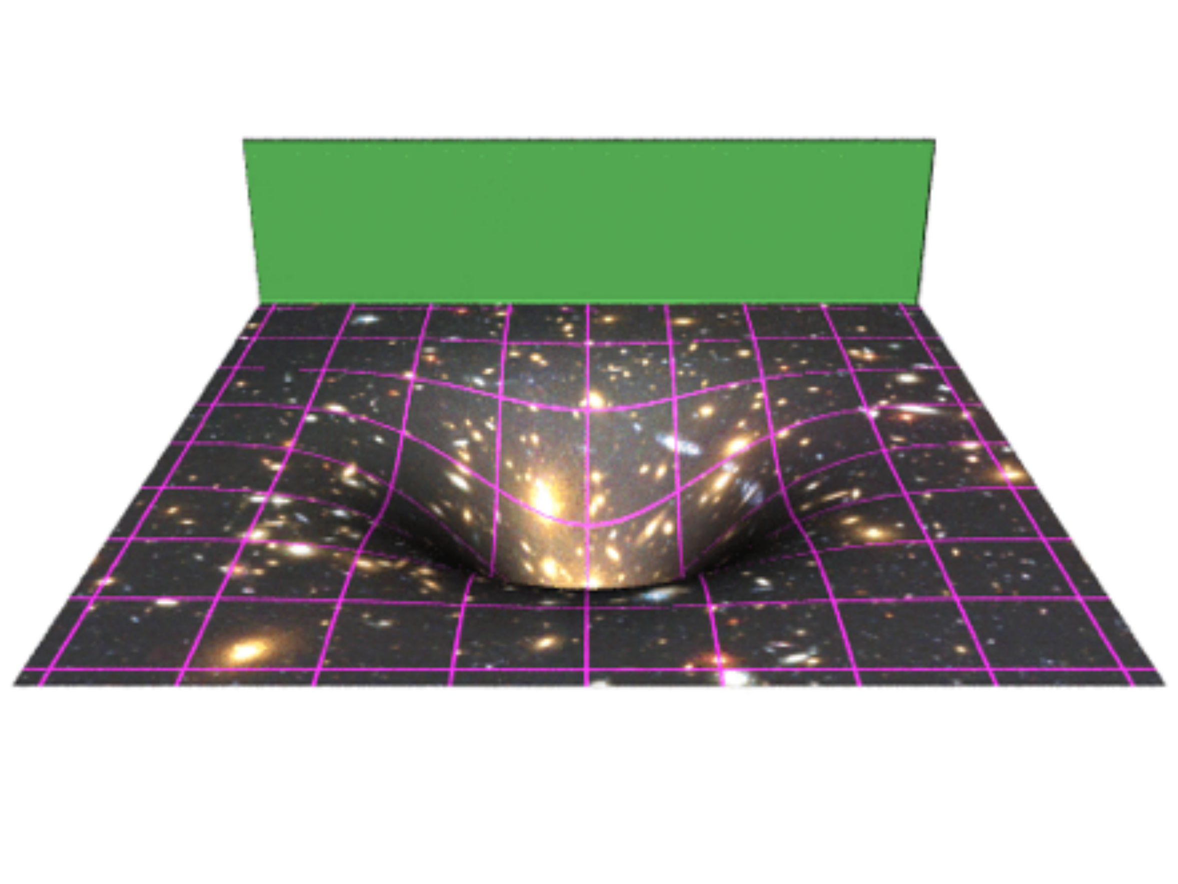
Faster early expansion brings LSS closer

ULAs and the CMB: high mass and early ISW

Higher mass (DM-like) case: high-l ISW



CMB temperature anisotropies from potential decay

$$\Delta T_{\rm ISW} = -2\int_0^{\eta_{\rm dec}} d\eta \dot{\Phi}(\eta, \hat{n}\eta)$$

$$\Phi \propto \frac{1}{k^2}\left\{\frac{\Omega_m \delta_m \left(1-\frac{\Omega_a}{\Omega_m}\right)}{a^3} + \frac{\delta_R \Omega_R}{a^4}\right\}$$

ULAs and the CMB: high mass and early ISW

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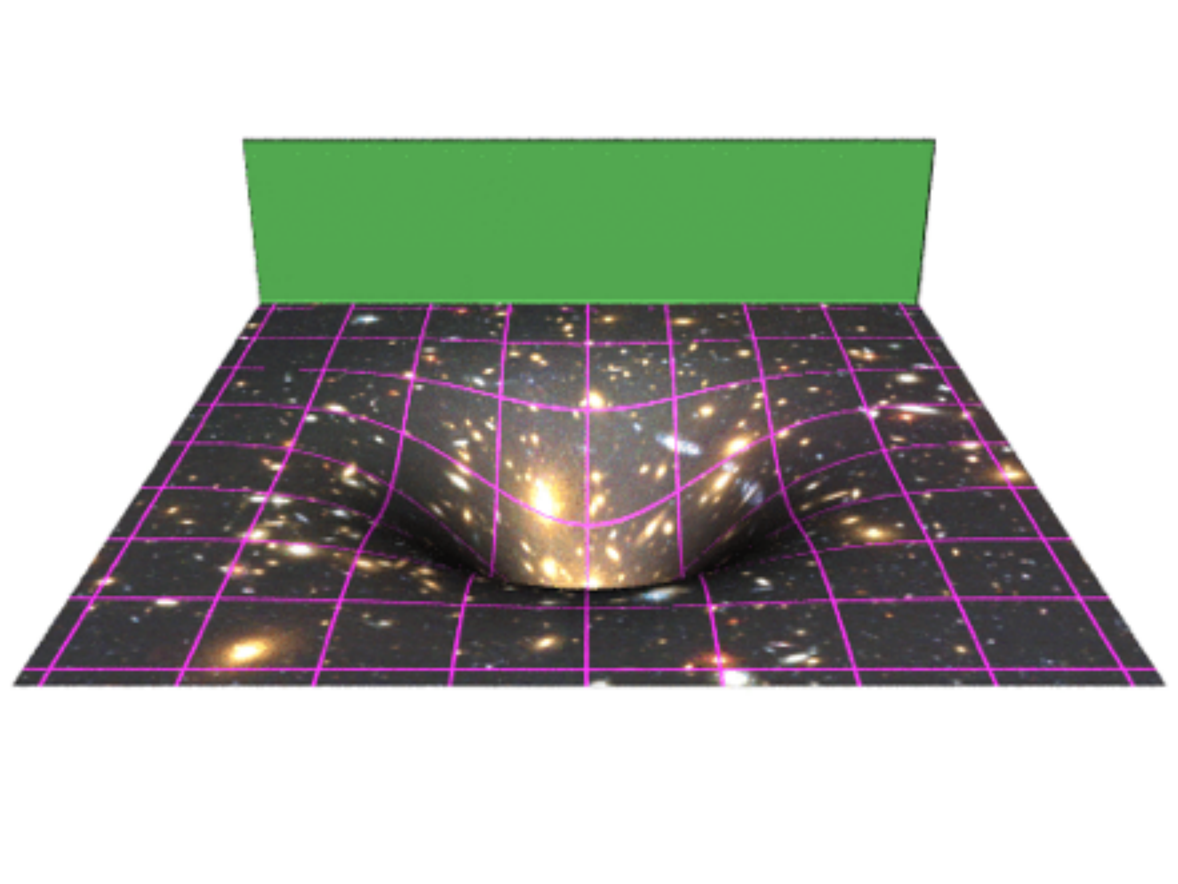

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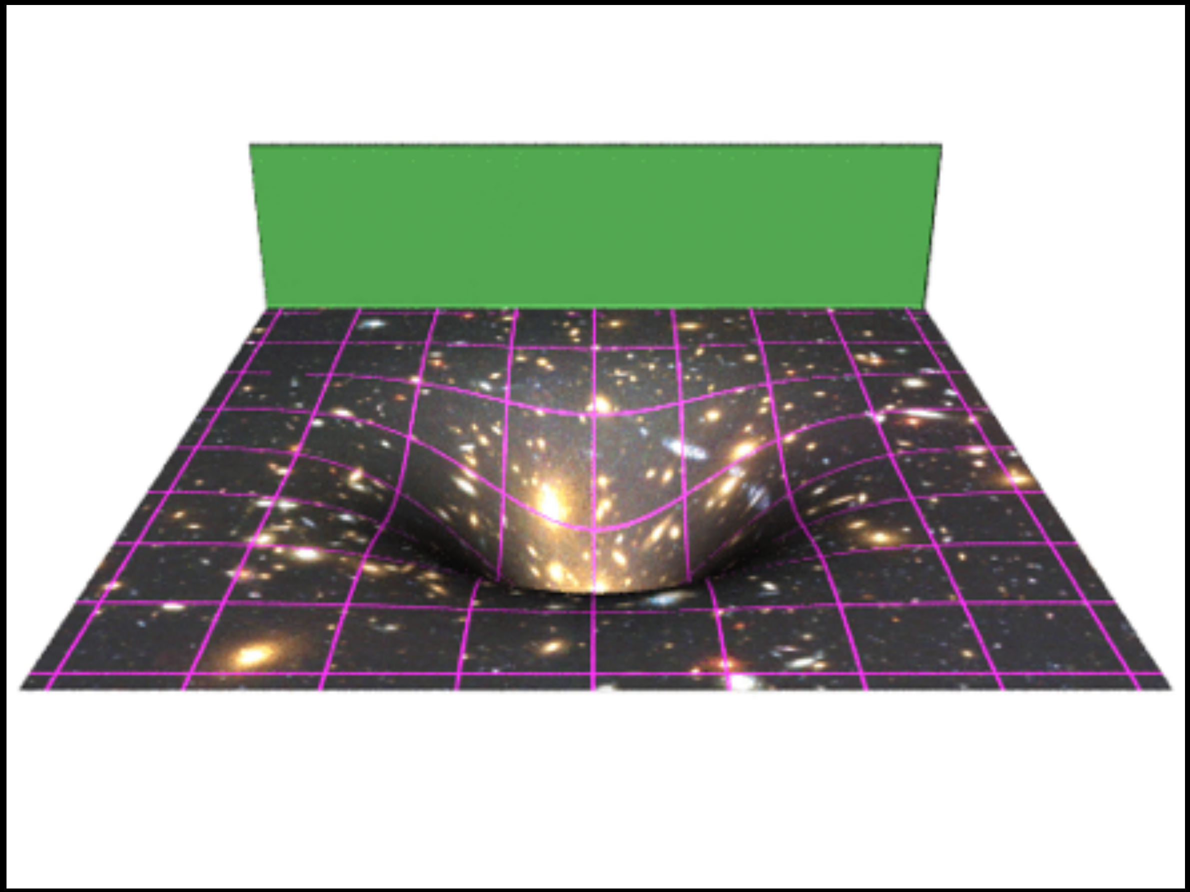
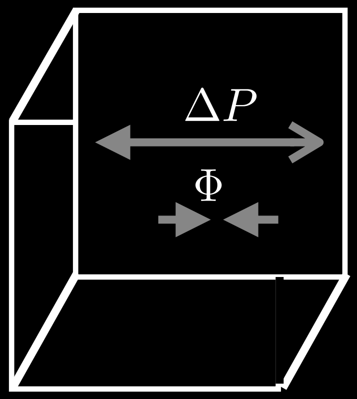




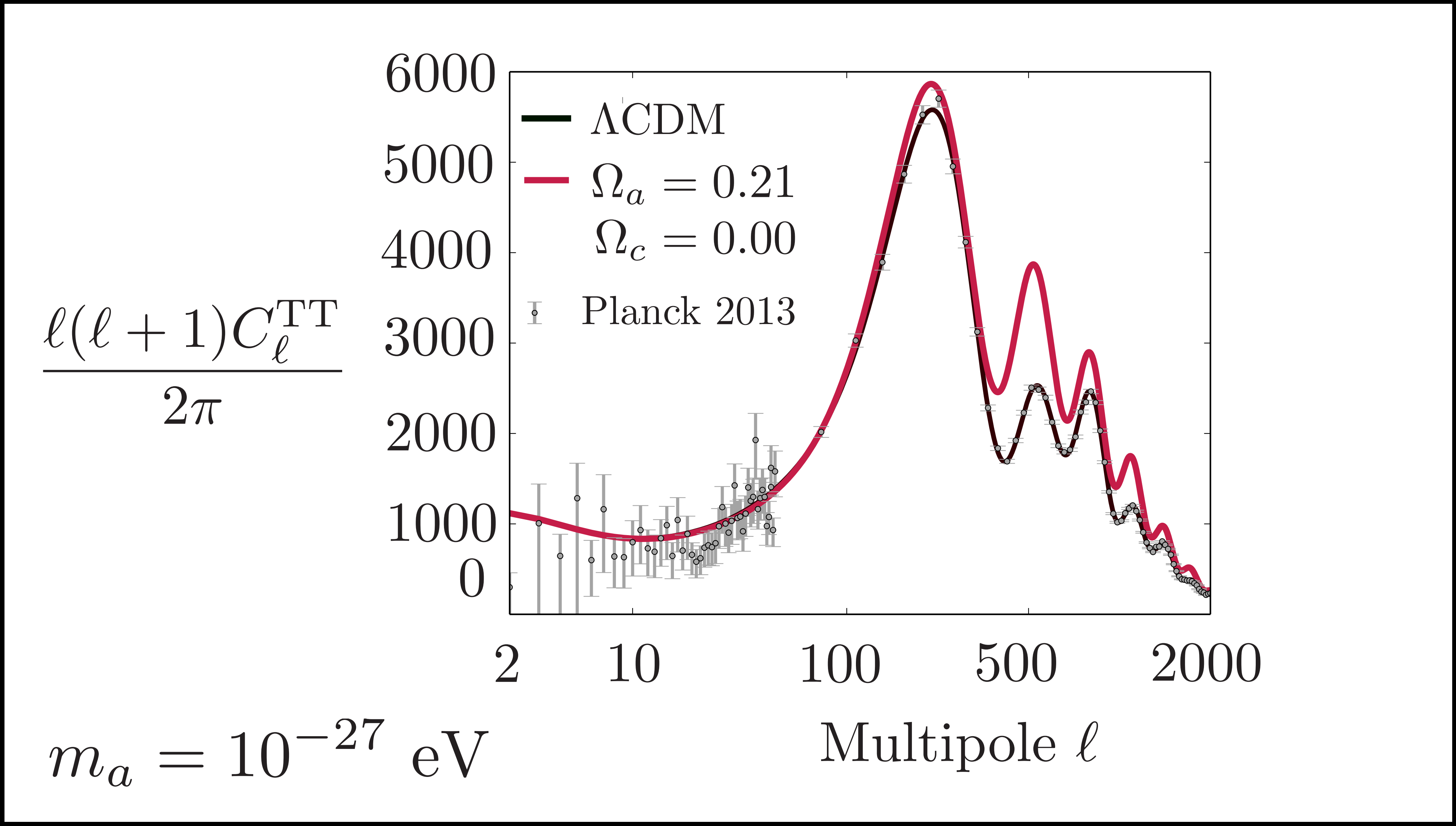
Radiation pressure causes potential decay

$$\Phi \propto \frac{1}{k^2}\left\{\frac{\Omega_m\delta_m\left(1-\frac{\Omega_a}{\Omega_m}\right)}{a^3}+\frac{\delta_R\Omega_R}{a^4}\right\}$$

$$\Delta P \Delta A > \rho \delta V \nabla \Phi$$

ULAs and the CMB: high mass and early ISW

Higher mass (DM-like) case: high-l ISW



Growth of ULA perturbations

- Perturbed Klein-Gordon + Gravity

$$\ddot{\delta\phi} + 2\mathcal{H}\dot{\delta\phi} + (k^2 + m_a^2 a^2)\delta\phi = 4\dot{\Psi}\dot{\phi}_0 - \Psi a^2 m_a^2 \phi_0$$

- Axionic Jeans Scale is macroscopic [in contrast to QCD axion]:

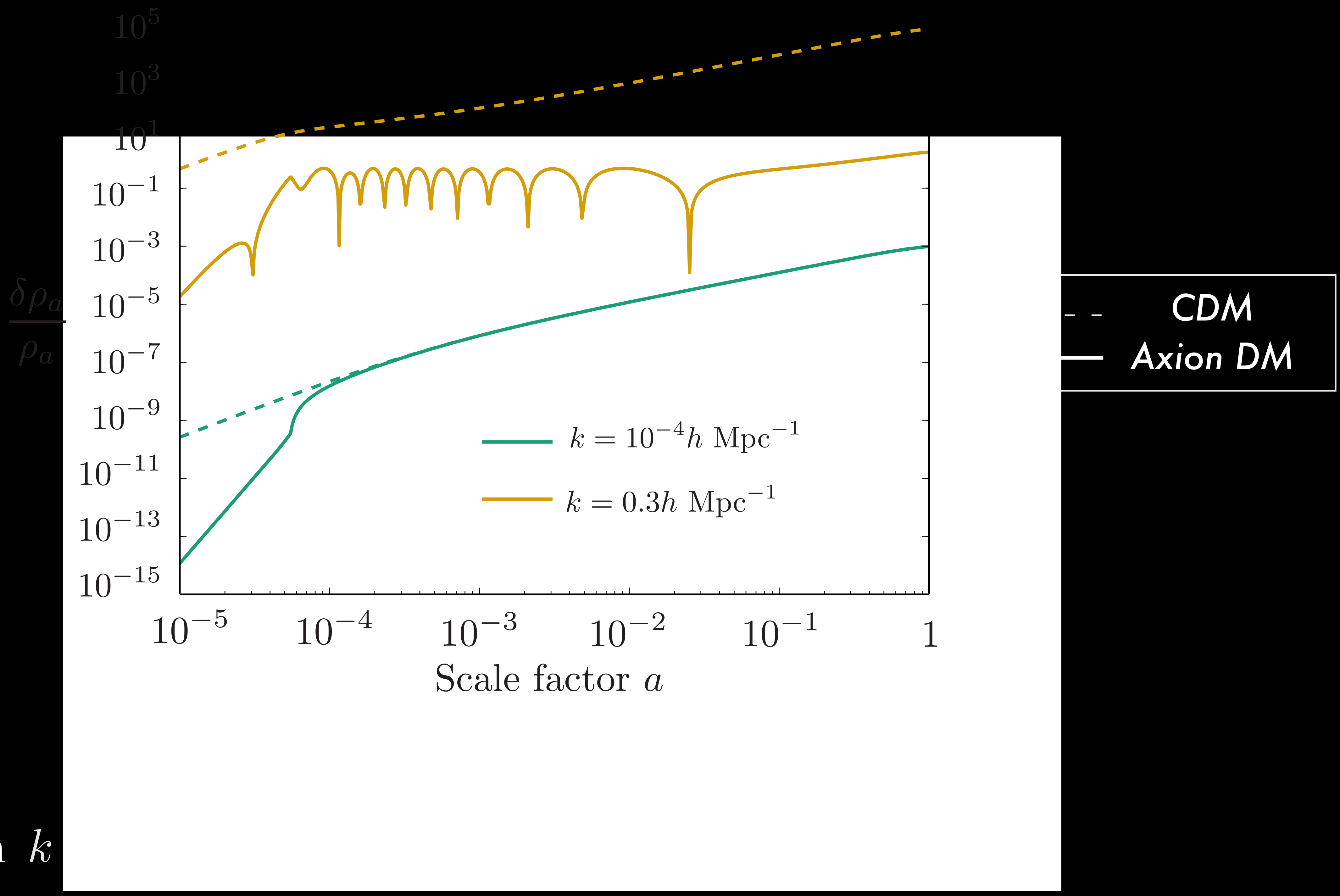
$$\boxed{\lambda_J = 2.4 h^{-1/2} \left(\frac{m}{10^{-25}\ \mathrm{eV}}\right)^{-1/2} \mathrm{Mpc}}$$

- Computing observables is expensive for $m \gg 3\mathcal{H}$:
  - Coherent oscillation time scale $\Delta\eta \sim (ma)^{-1} \ll \Delta\eta_{\mathrm{CAMB}}$
  - WKB approximation

$$\delta\phi = A_c \Delta_c(k,\eta) \cos(m\eta) + A_s \Delta(k,\eta) \sin(m\eta)$$

$$\boxed{c_a^2 = \frac{\delta P}{\delta\rho} = \frac{k^2/(4m^2a^2)}{1 + k^2/(4m^2a^2})}$$

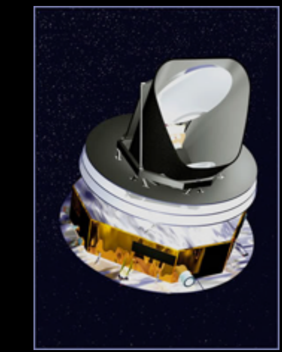
GROWTH OF ULA PERTURBATIONS

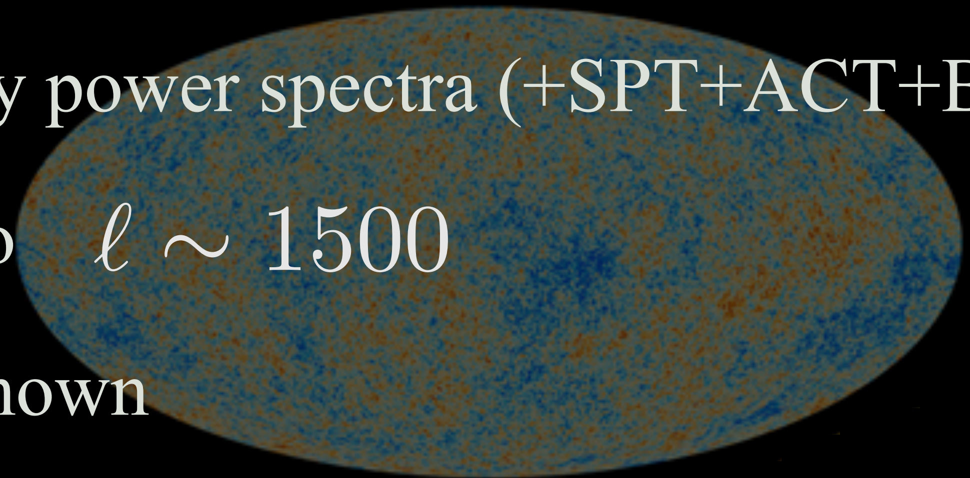


✳ Modes with k

✳ "Pressure" stabilization

DATA

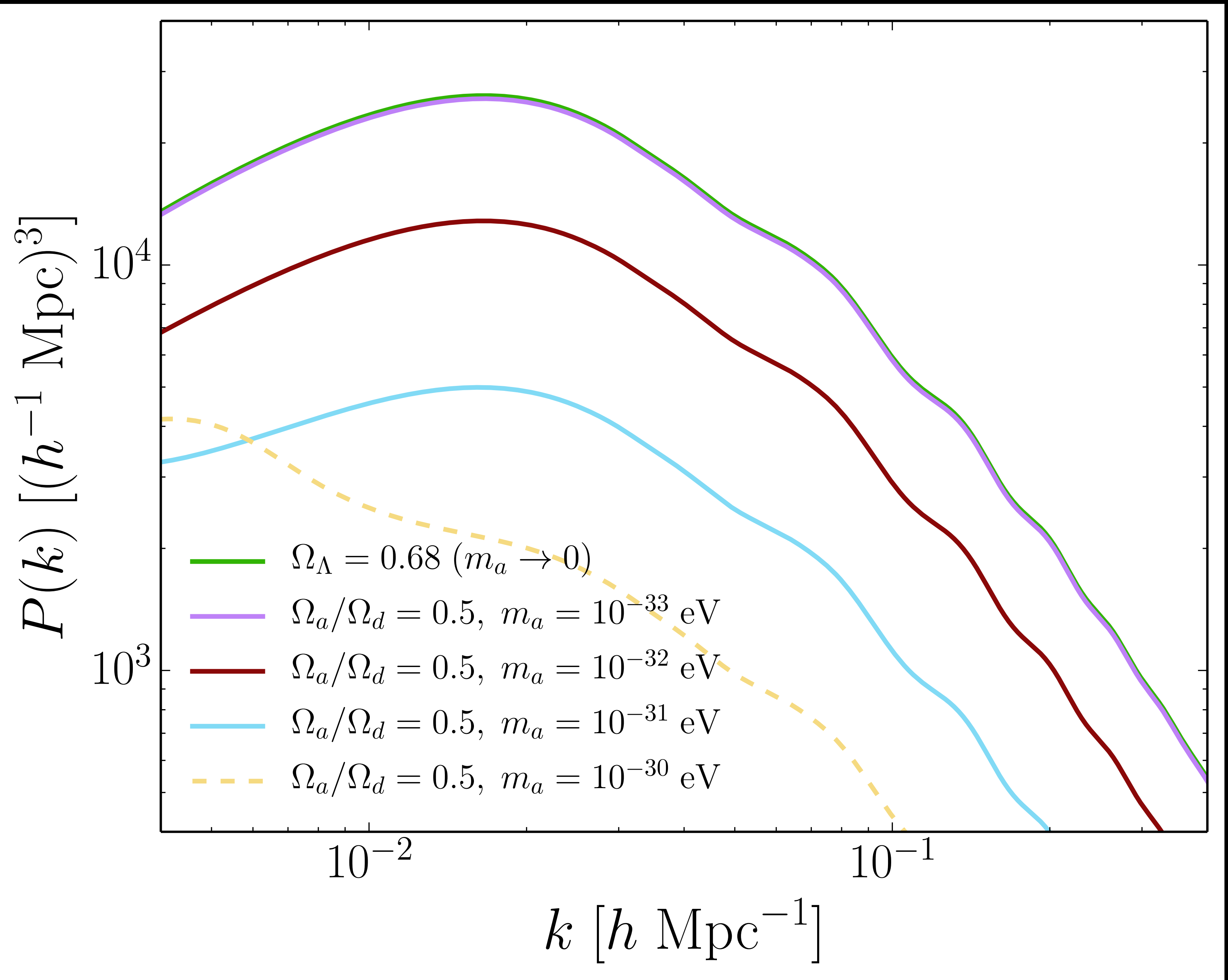




- ✳Planck 2013 temperature anisotropy power spectra (+SPT+ACT+BAO)
  - ✳Cosmic variance limited to $\ell \sim 1500$
  - ✳Power spectrum already shown

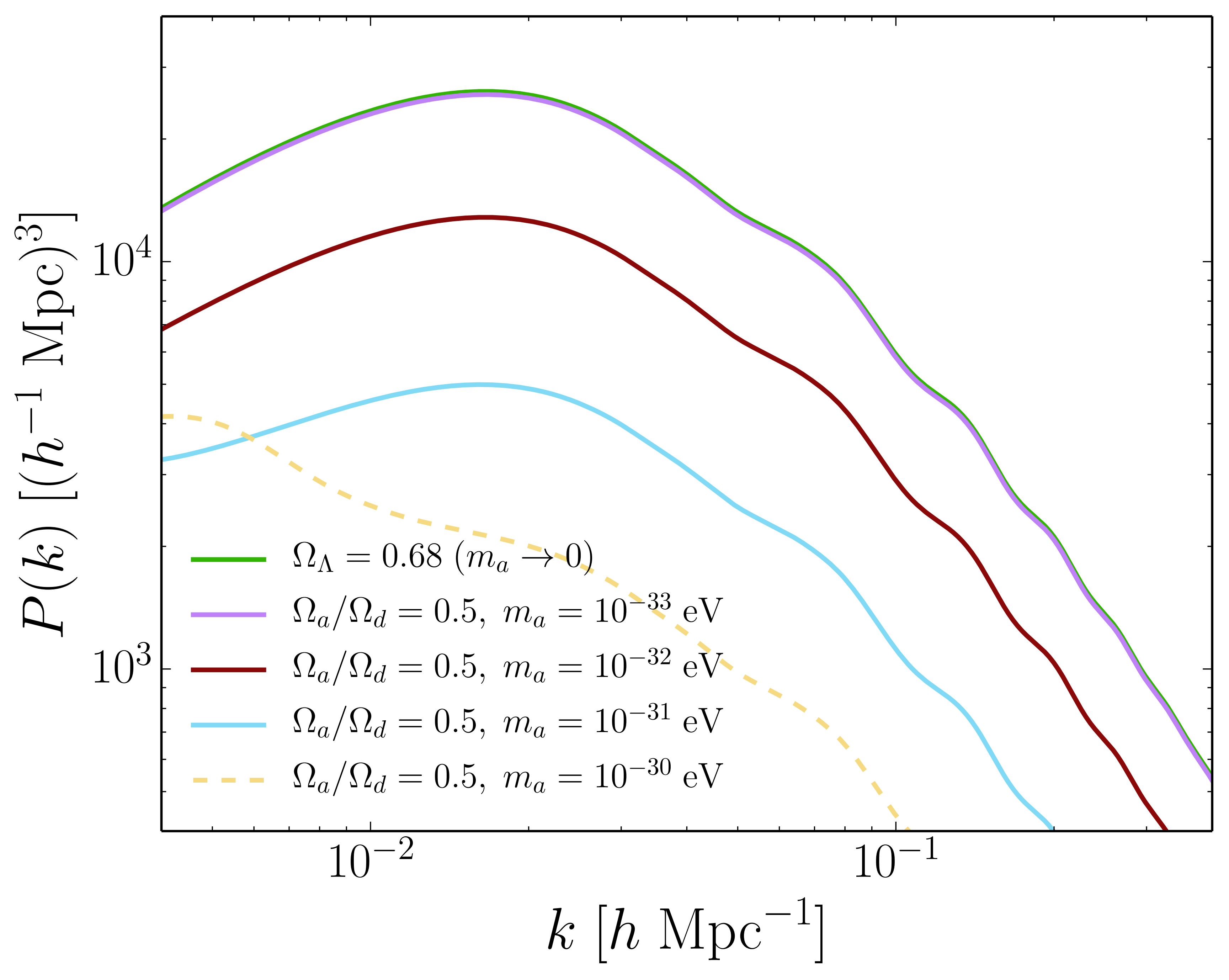
- ✳WiggleZ galaxy survey (linear scales only $k \lesssim 0.2h\ \mathrm{Mpc}^{-1}$)
  - ✳Galaxy bias marginalized over
  - ✳Theory P(k) convolved with survey window function
  - ✳240,000 emission line galaxies at z<1
  - ✳3.9 m Anglo-Australian Telescope (AAT)

Matter power spectrum for ULA (in DE regime)



θ_s

Matter power spectrum for ULA (in DE regime)



θ_s fixed to lock CMB

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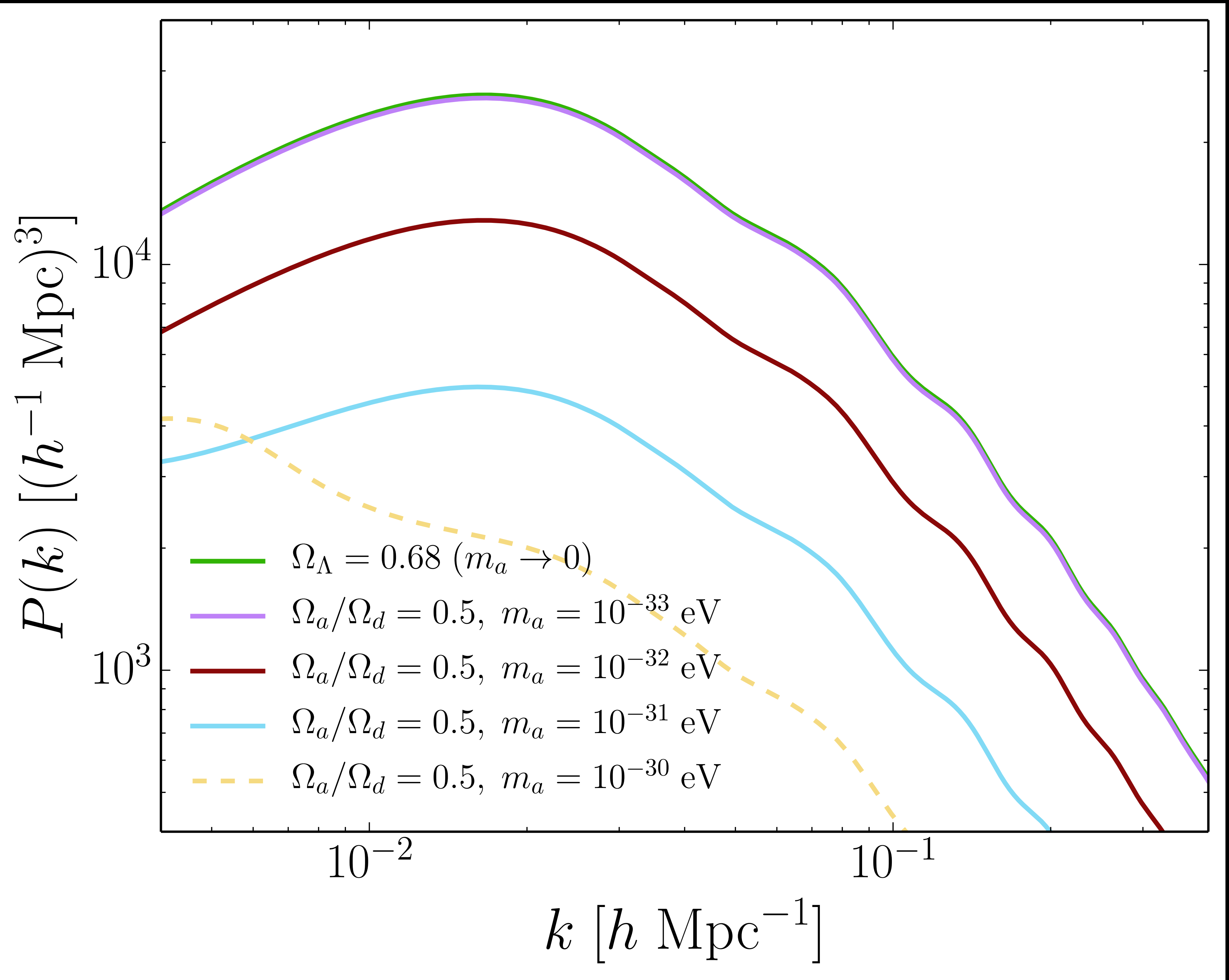


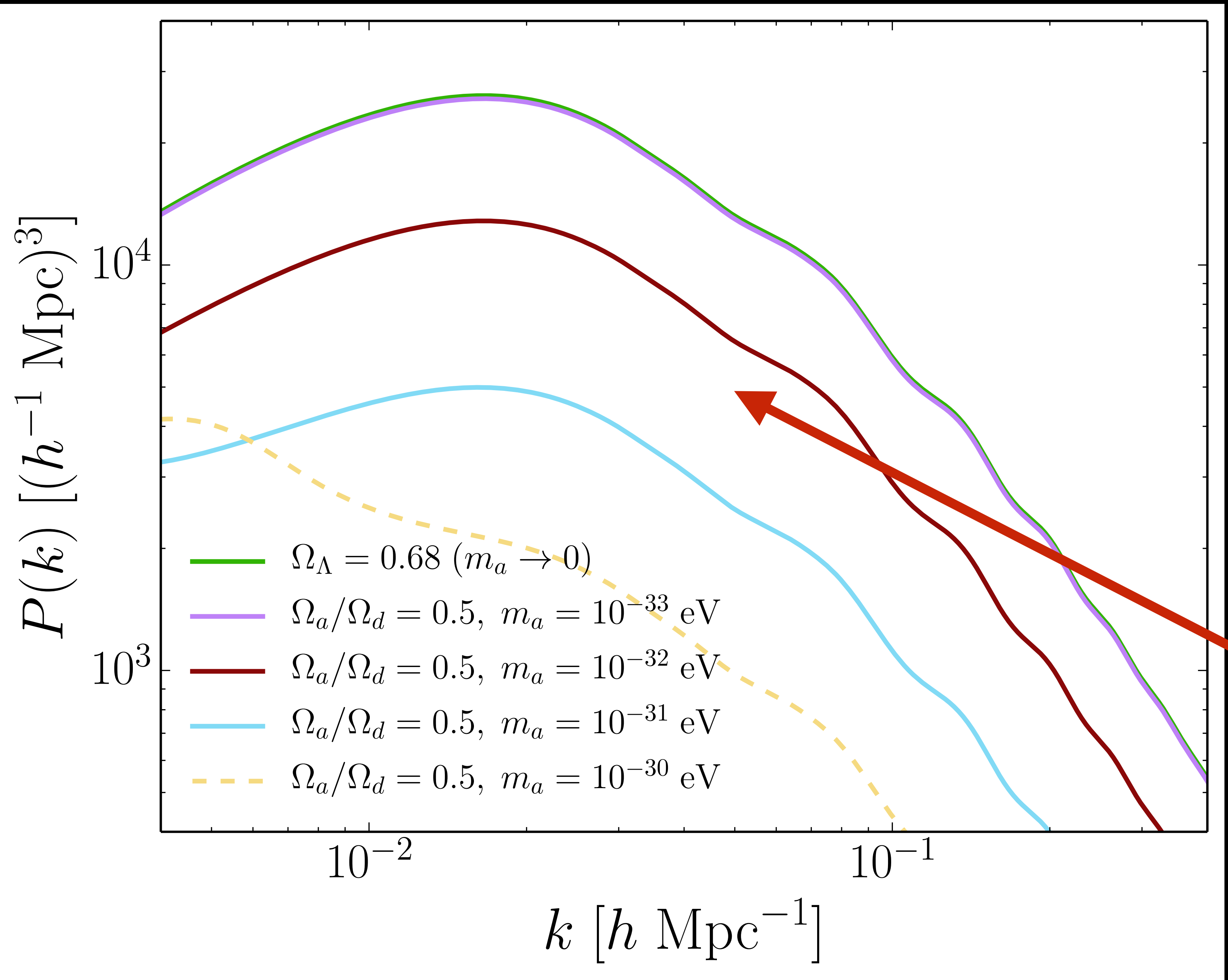
θ_s fixed to lock CMB

$H_0 \downarrow$

$$\boxed{1 + z_{eq} = \frac{\Omega_m h^2}{\rho_{\mathrm{rad}}}}$$

Matter-radiation equality delayed

Matter power spectrum for ULA (in DE regime)



θ_s fixed to lock CMB

$H_0 \downarrow$

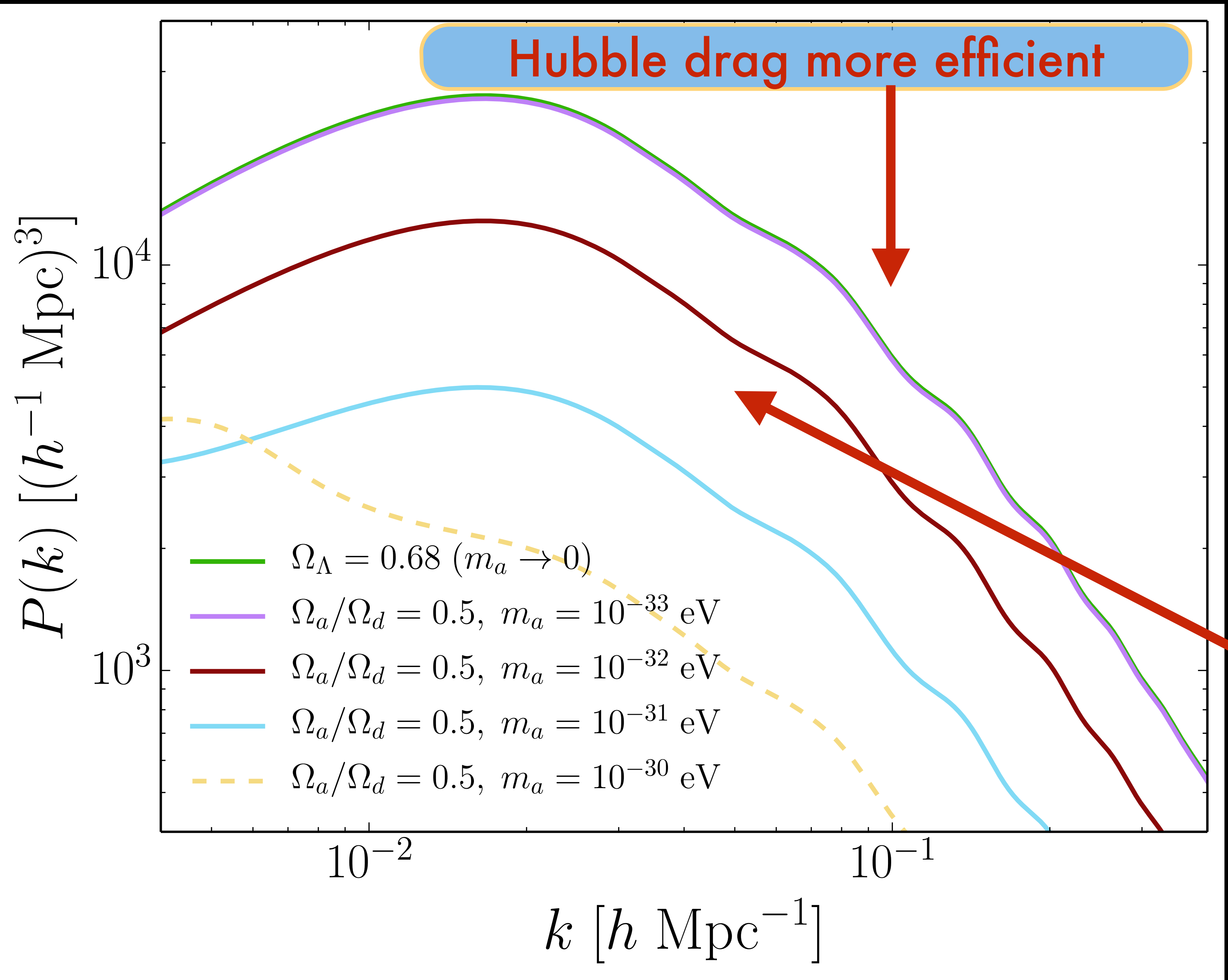
$k_{eq} = \lambda^{-1}_{\mathrm{horizon,eq}} \downarrow$

Peak of P(k) to lower k

$$1 + z_{eq} = \frac{\Omega_m h^2}{\rho_{\mathrm{rad}}}$$

Matter-radiation equality delayed

Matter power spectrum for ULA (in DE regime)



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Data

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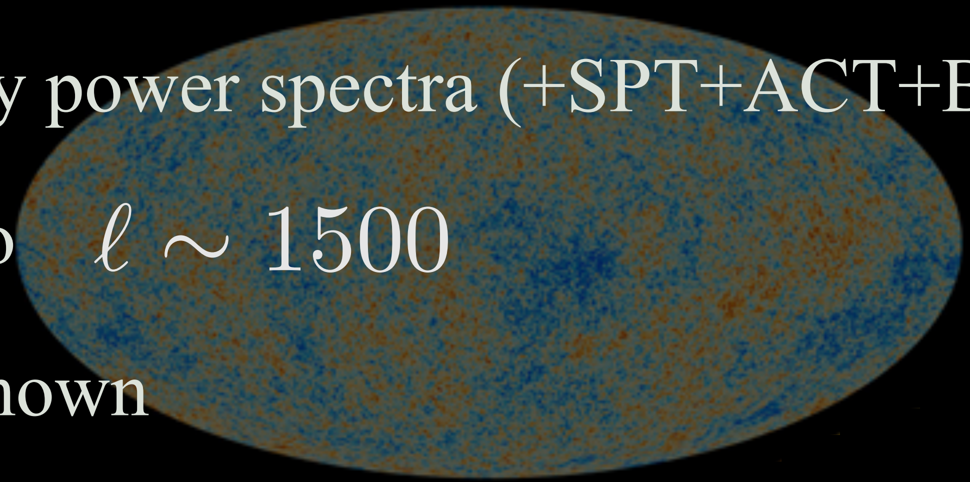

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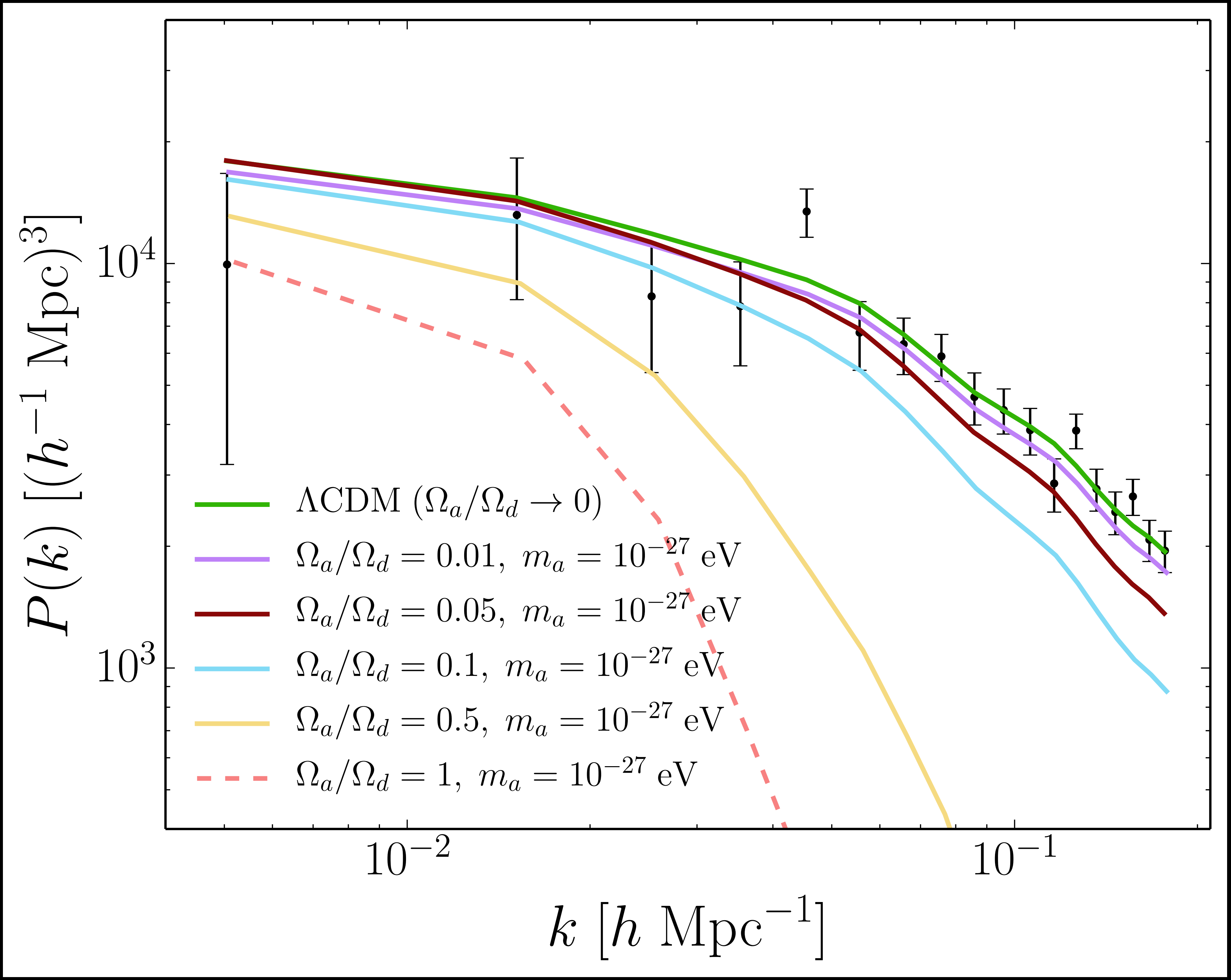

$P(k)\ [(h^{-1}\ \mathrm{Mpc})^3]$
10^4
10^3
10^{-2}
10^{-1}
$k\ [h\ \mathrm{Mpc}^{-1}]$
ΛCDM $(\Omega_a/\Omega_d \to 0)$
$\Omega_a/\Omega_d = 0.01,\ m_a = 10^{-27}$ eV
$\Omega_a/\Omega_d = 0.05,\ m_a = 10^{-27}$ eV
$\Omega_a/\Omega_d = 0.1,\ m_a = 10^{-27}$ eV
$\Omega_a/\Omega_d = 0.5,\ m_a = 10^{-27}$ eV
$\Omega_a/\Omega_d = 1,\ m_a = 10^{-27}$ eV

Difficult parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\mathrm{reion}}$$

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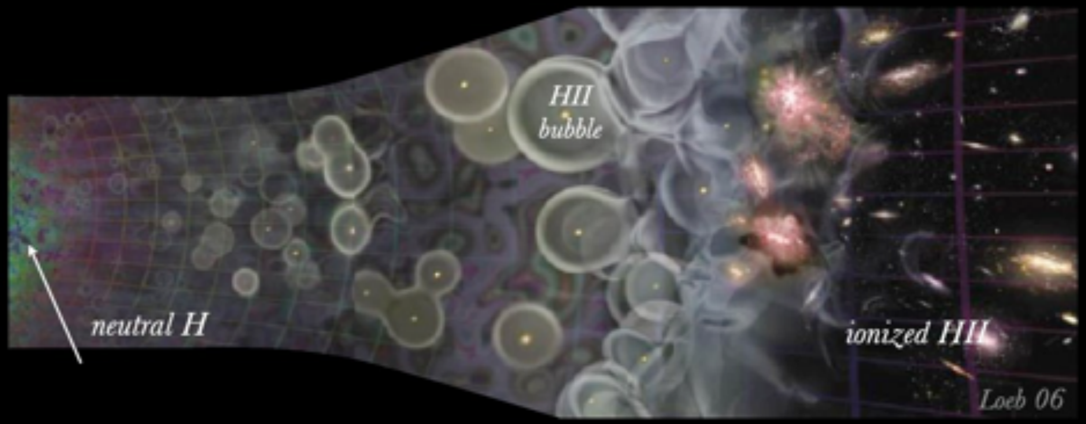
$$\Delta^2_{\mathcal{R}}(k) \equiv A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

Initial conditions

Difficult parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$

$$\tau_{\rm reion} = \int dl n_e \sigma_T$$



Difficult parameter space

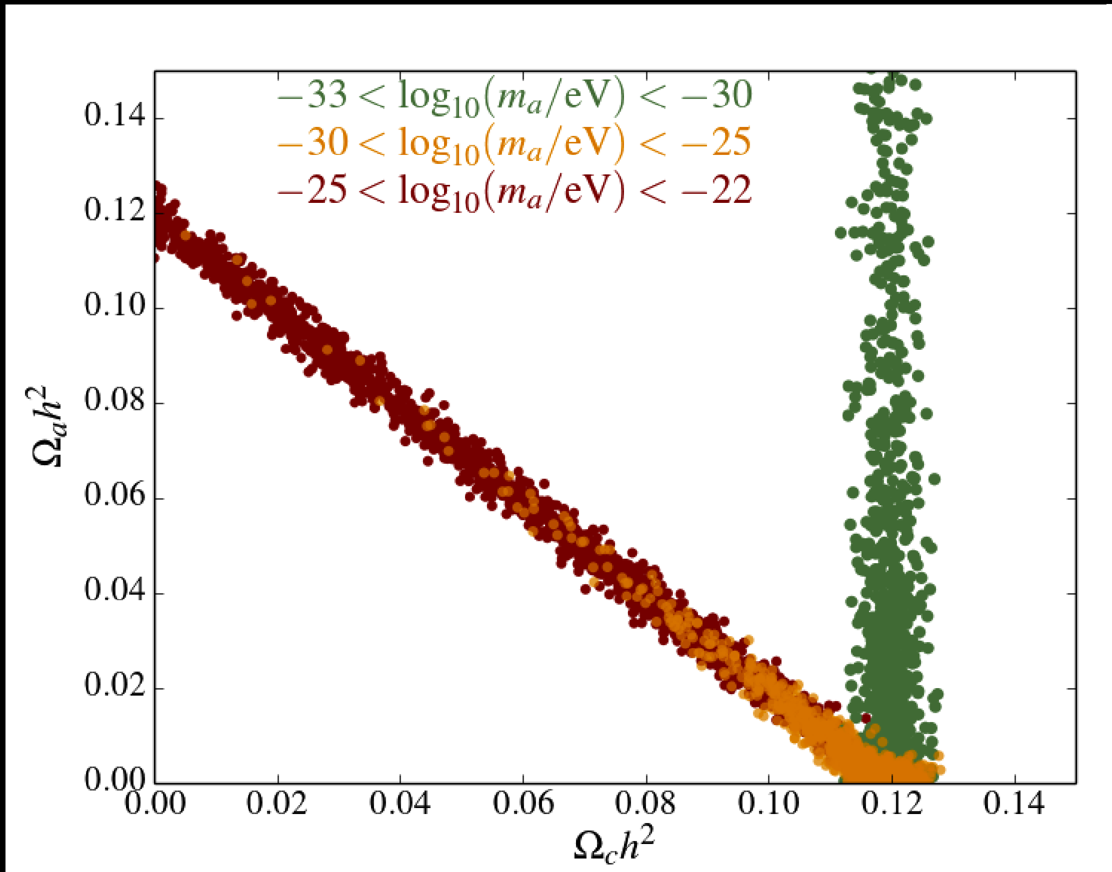
$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$

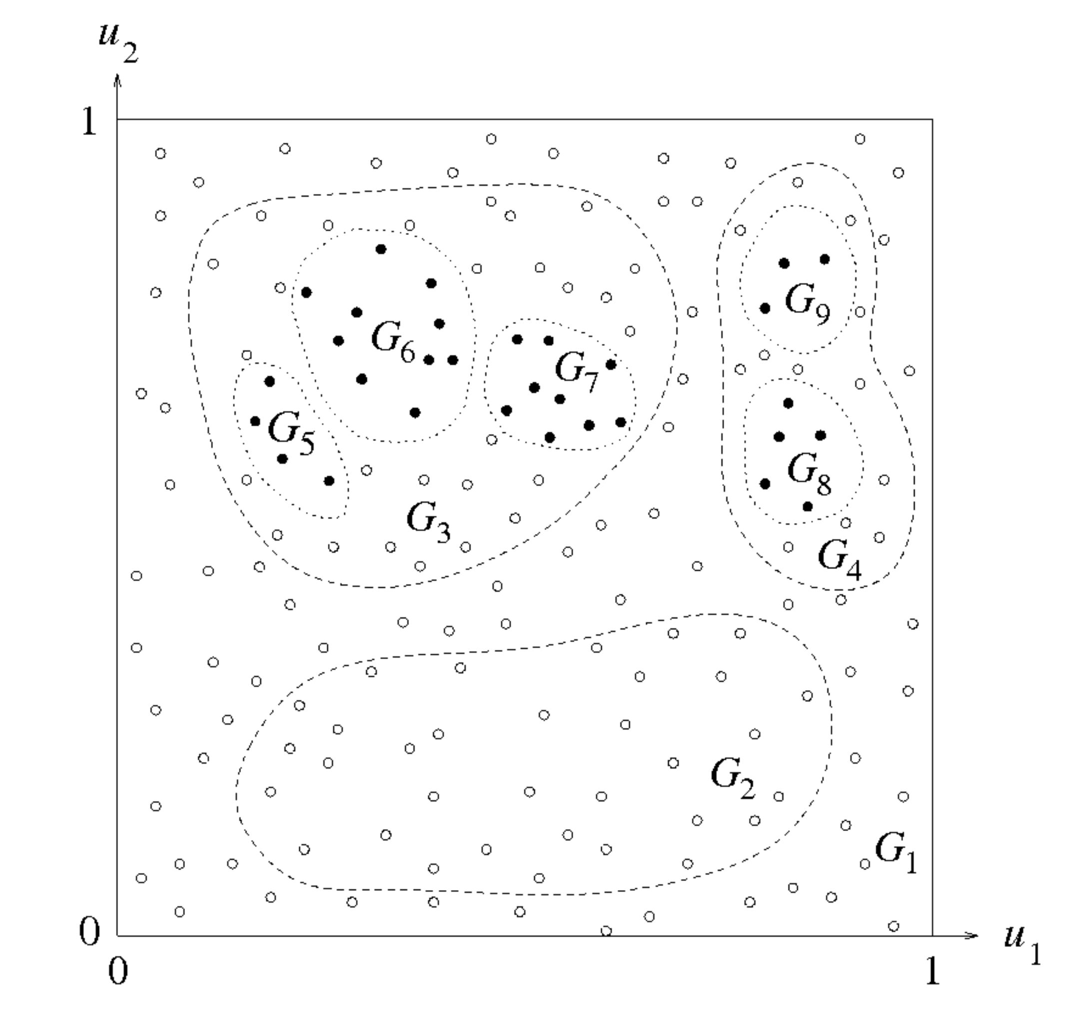
AxiCAMB

Compare with data
Explore posterior using Monte Carlo Markov Chain (MCMC)

Difficult parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$





Addressed using nested sampling

MULTINEST (Hobson, Feroz, others 2008)

Difficult parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$

Difficult parameter space

$$\boxed{m_a, \Omega_a h^2,} \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$

ULA parameters

Difficult parameter space

$$m_a, \Omega_a h^2, \boxed{\Omega_c h^2, \Omega_b h^2, \Omega_\Lambda}, n_s, A_s, \tau_{\rm reion}$$

Densities of standard species

Difficult parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\text{reion}}$$

$$\Delta^2_{\mathcal{R}}(k) \equiv A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

Initial conditions

Difficult parameter space

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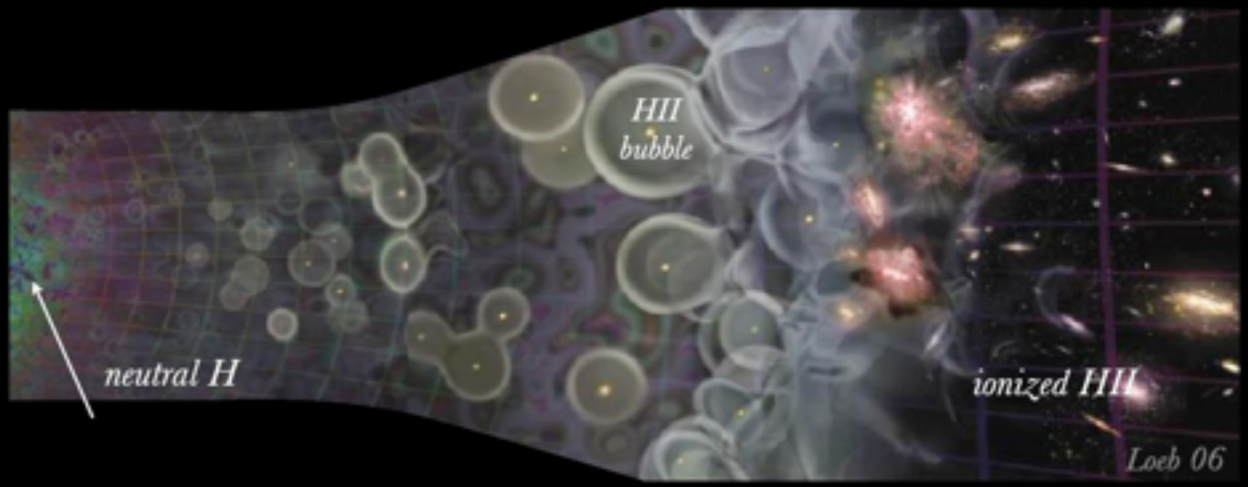

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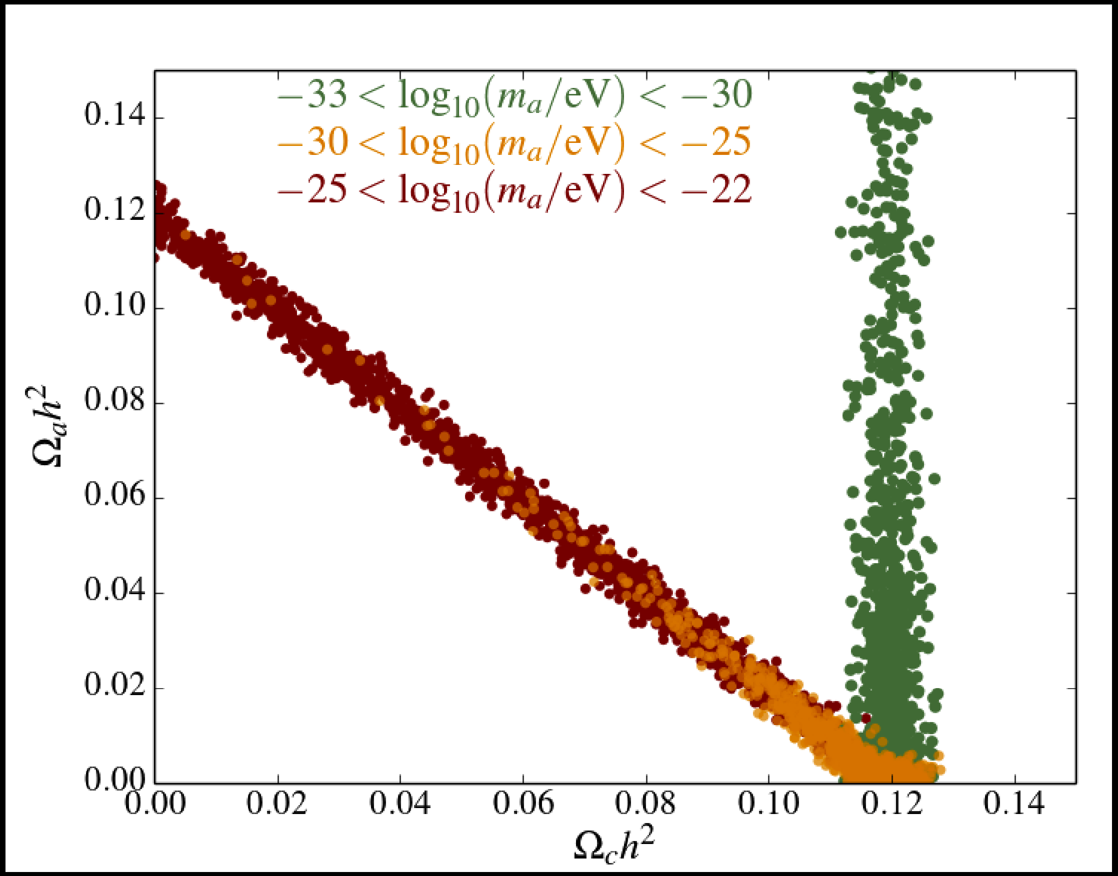

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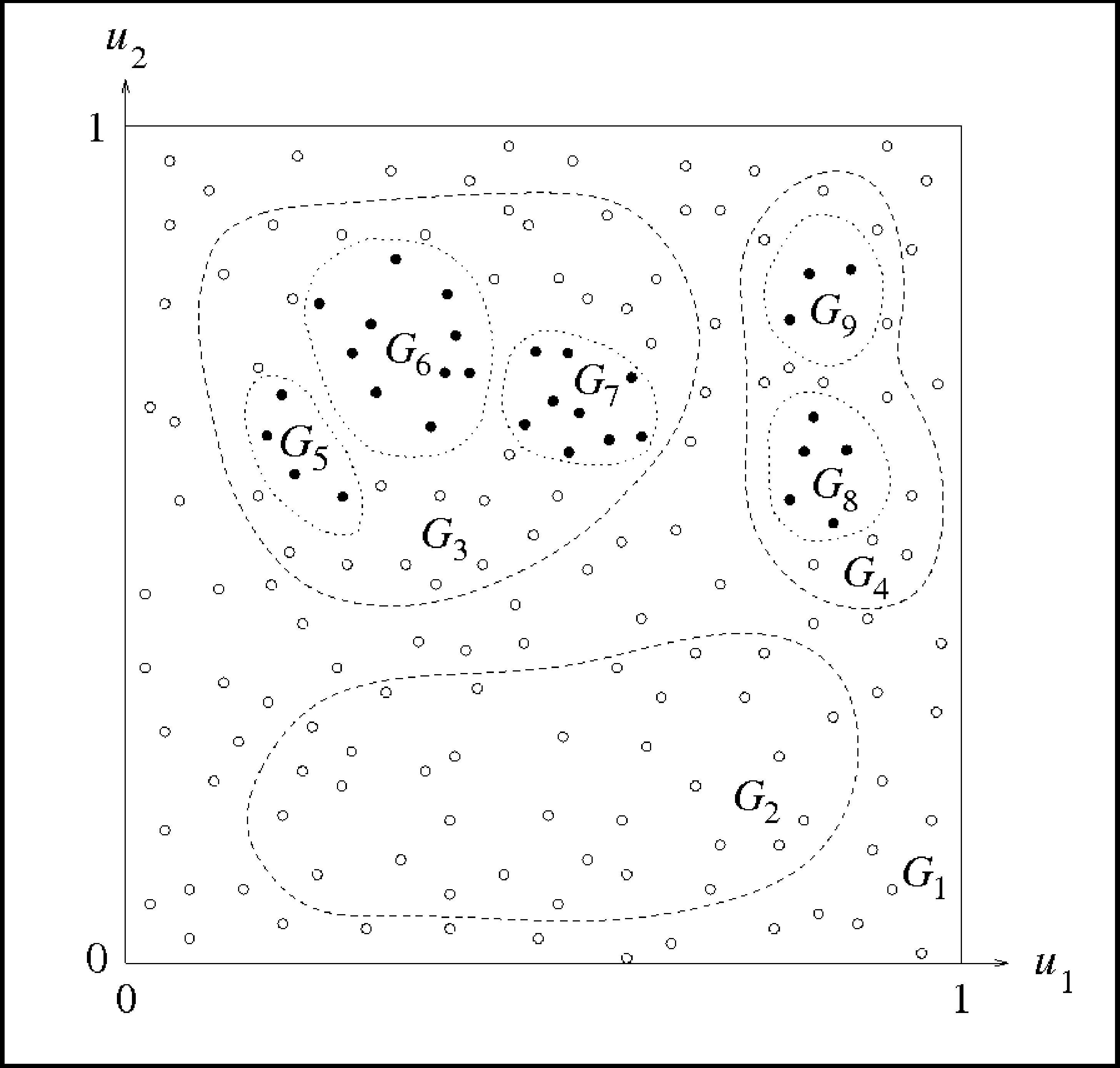
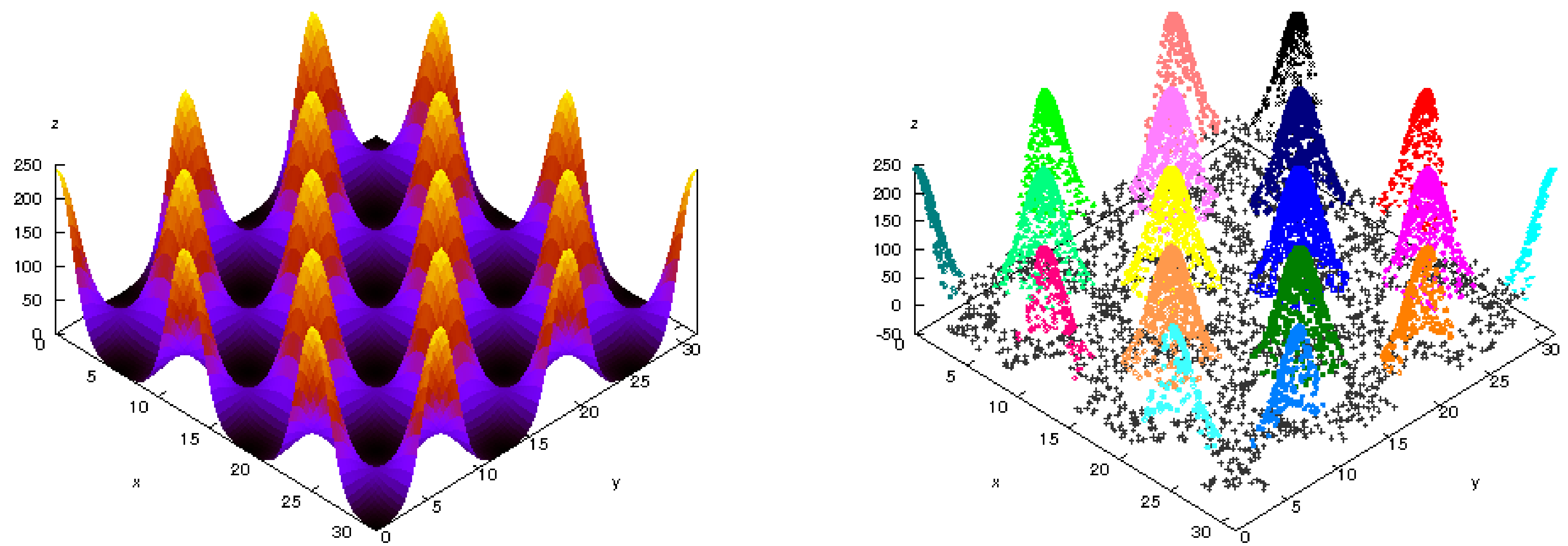


Difficult parameter space

$$m_a, \Omega_a h^2, \Omega_c h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau_{\rm reion}$$

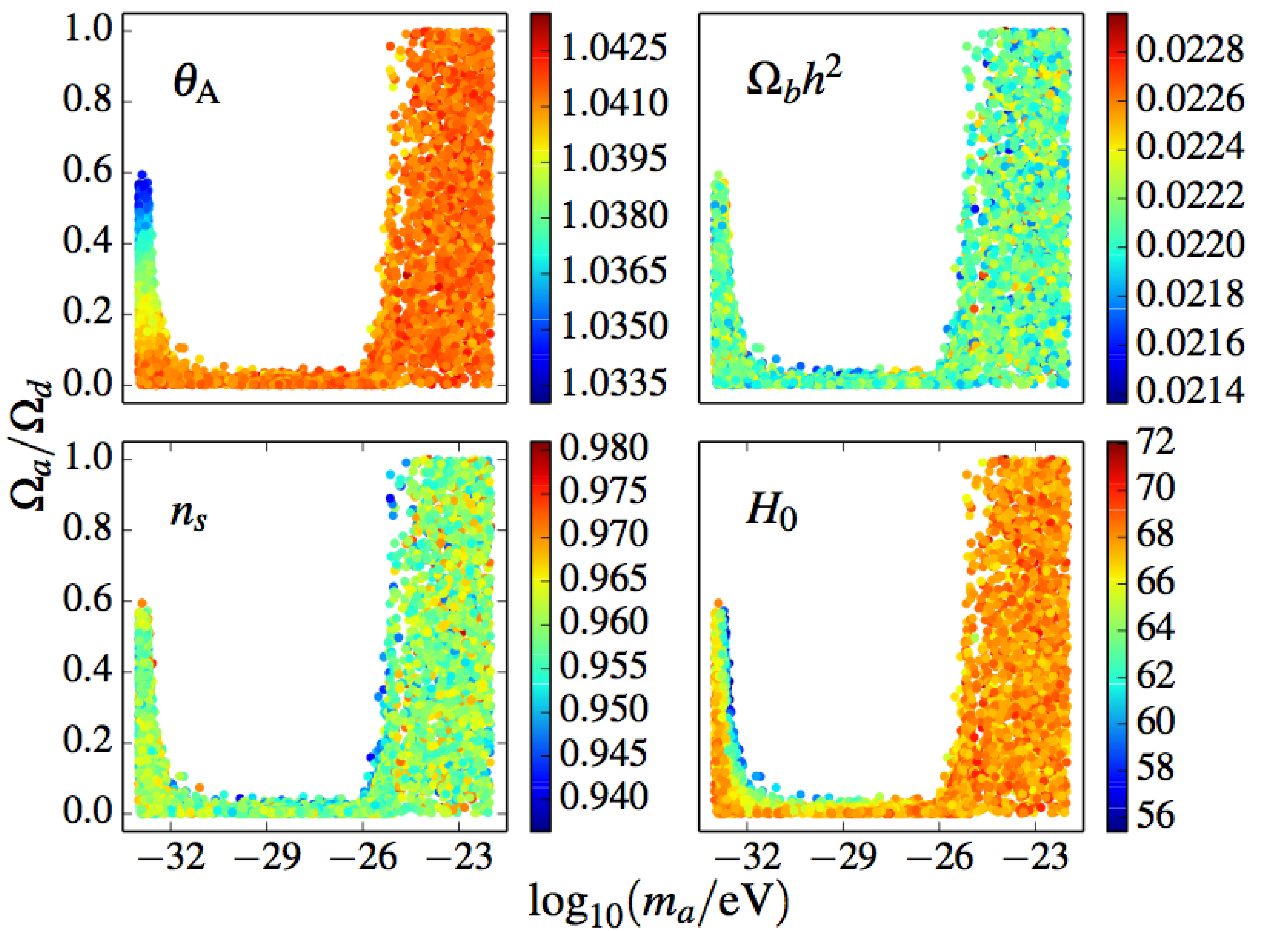
TOY PROBLEM: EGG-BOX LIKELIHOOD

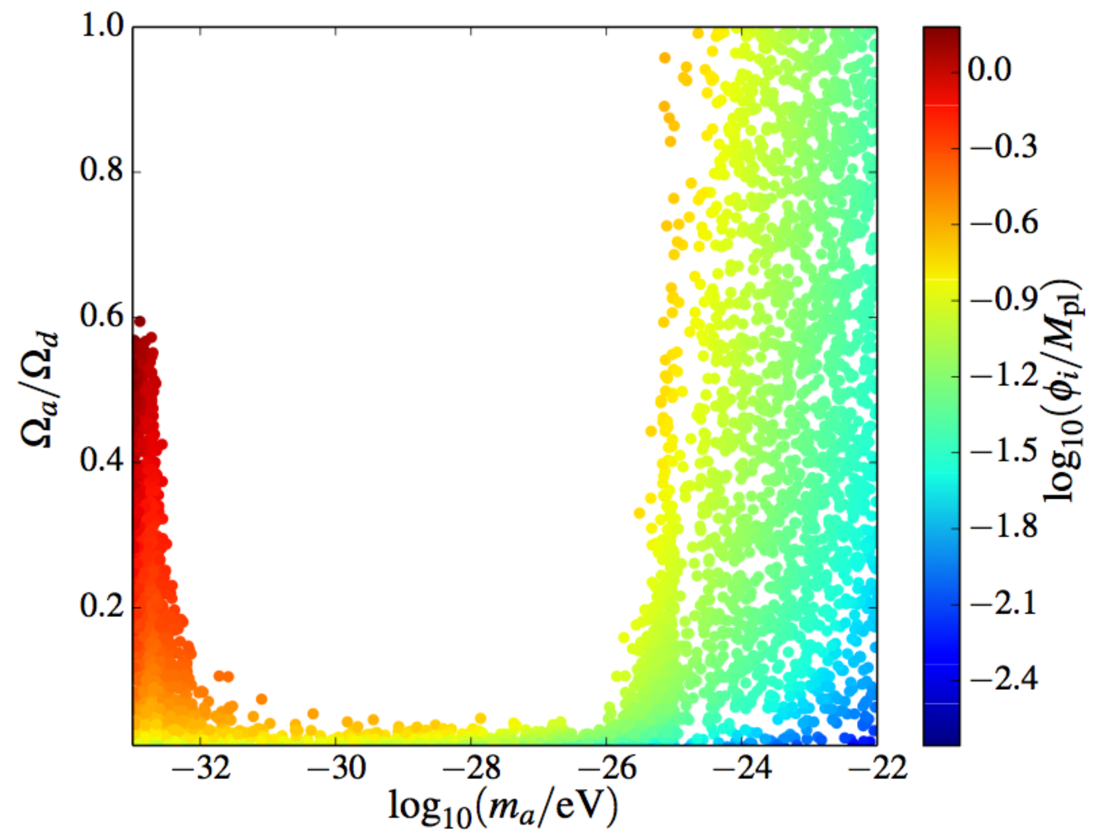


Addressed using nested sampling

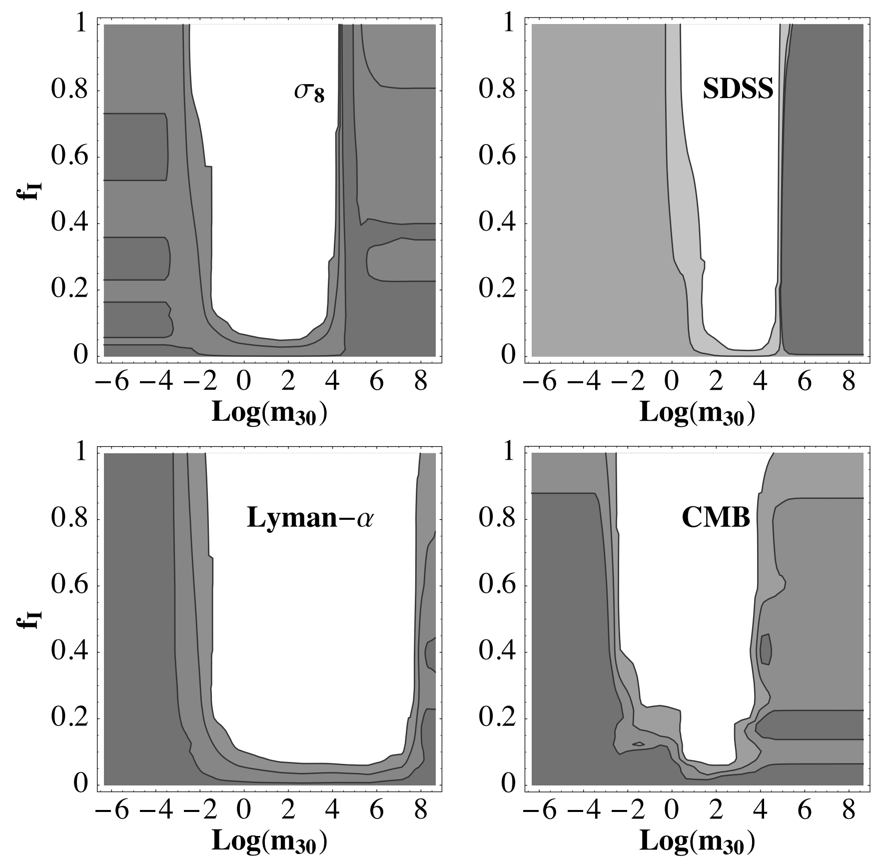
MULTINEST (Hobson, Feroz, others 2008)

Degeneracies/Weak gravity conjecture





Amendola and Barbieri



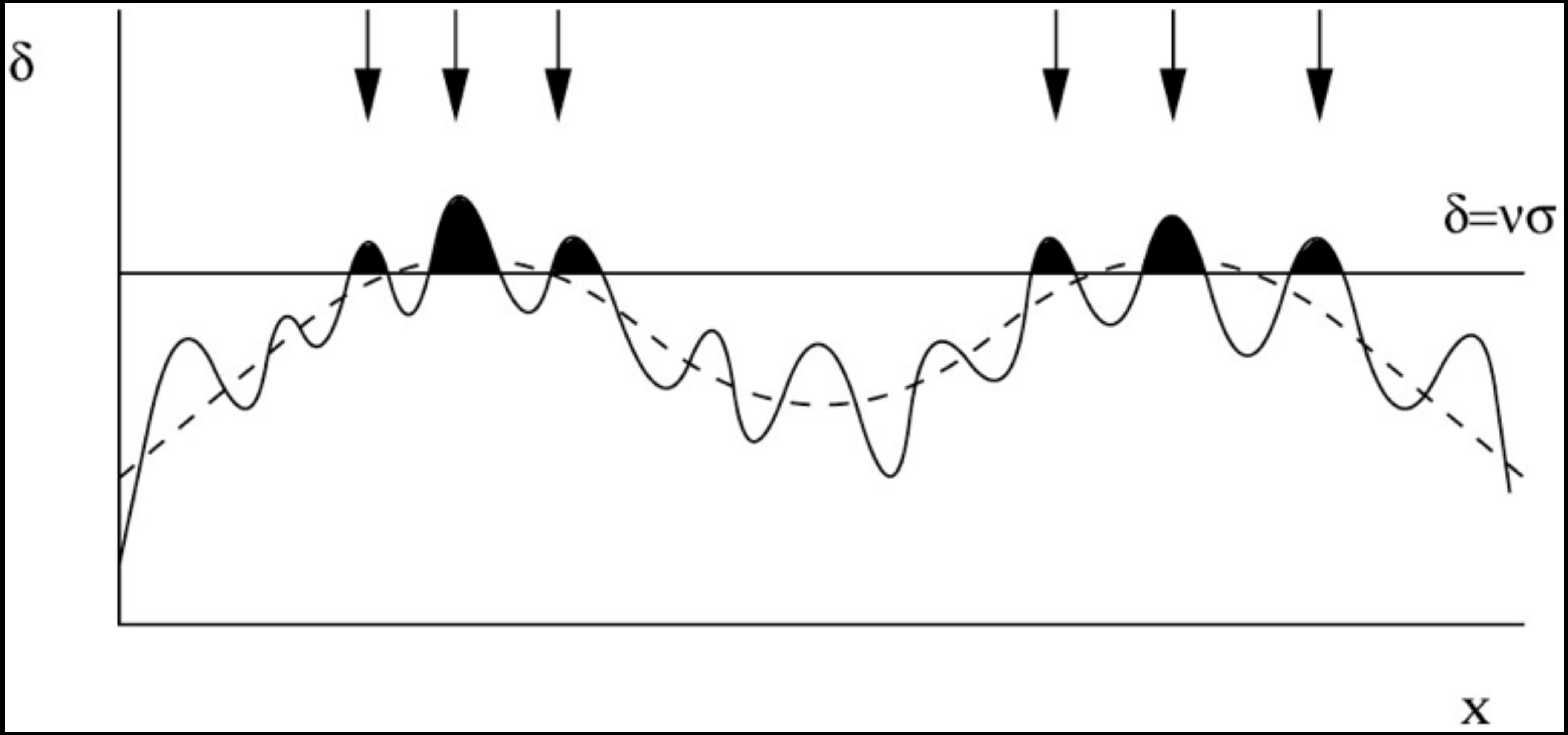
Old power spectrum constraints from Amendola and Barbieri, arXiv:hep-ph/0509257

1) *Grid search*
2) *No isocurvature*
3) *No marginalization over foregrounds*
4) *No lensing, no polarization*
5) *No real Boltzmann code [step in power spectrum, or unclustered DE at low m]*

Additional slides:
ULAs and galaxies

Future work: ULAs and galaxies

- Galaxies are biased tracers



Future work: ULAs and galaxies

✳ Galaxies are biased tracers

$$\delta_g = b\left(\frac{\delta\rho_m}{\rho_m}\right) \quad \textbf{vs.} \quad \boxed{\delta_g = b\left(\frac{\delta\rho_m + \delta\rho_a}{\rho_m + \rho_a}\right)}$$

Unfair penalty on scales where axions don't cluster

✴ Galaxies are biased tracers

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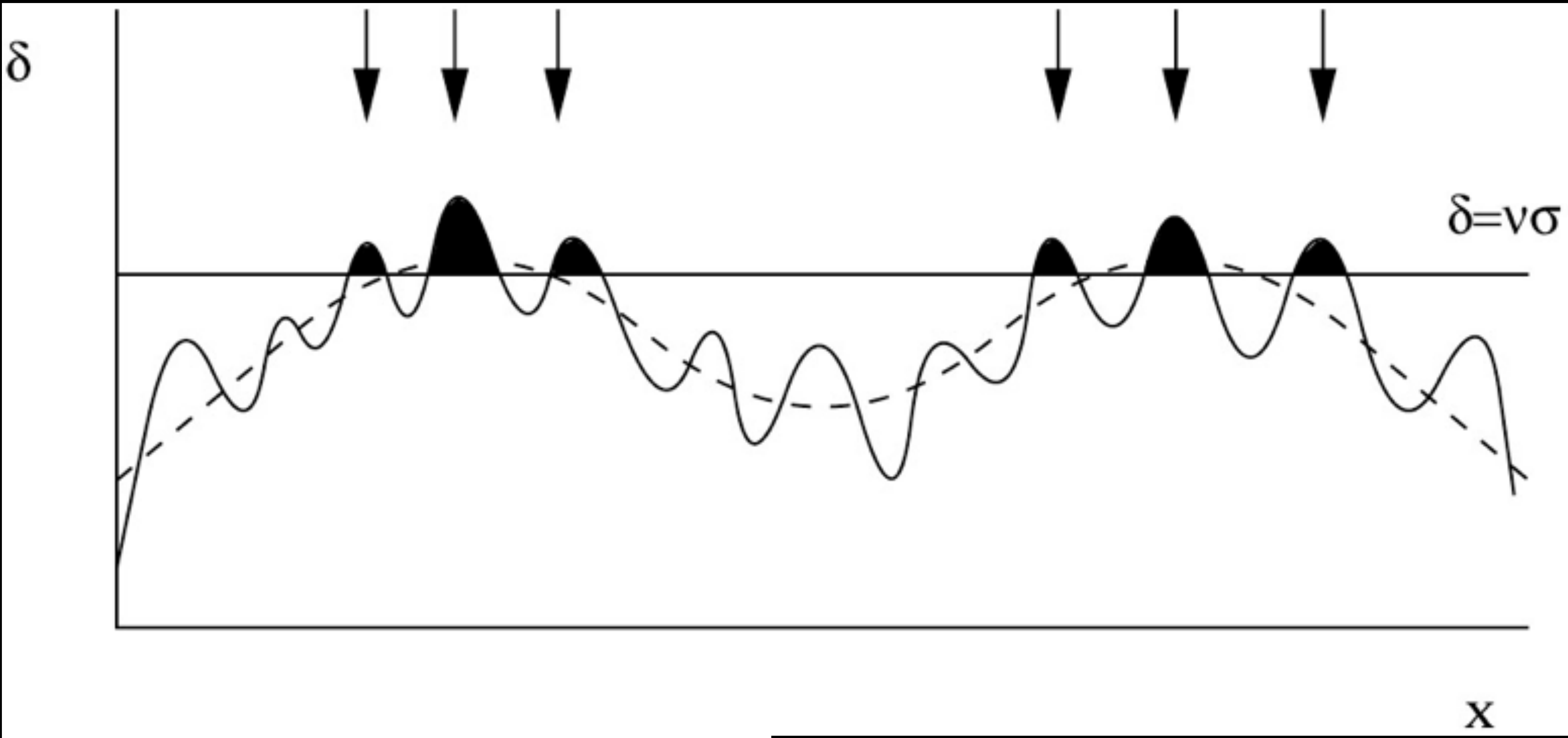
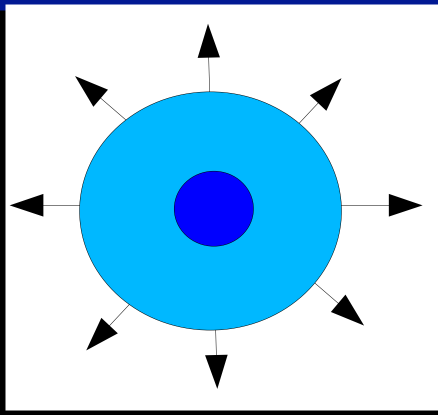
Doesn't include ULAs as matter component on scales where they cluster

Future work: ULAs and galaxies

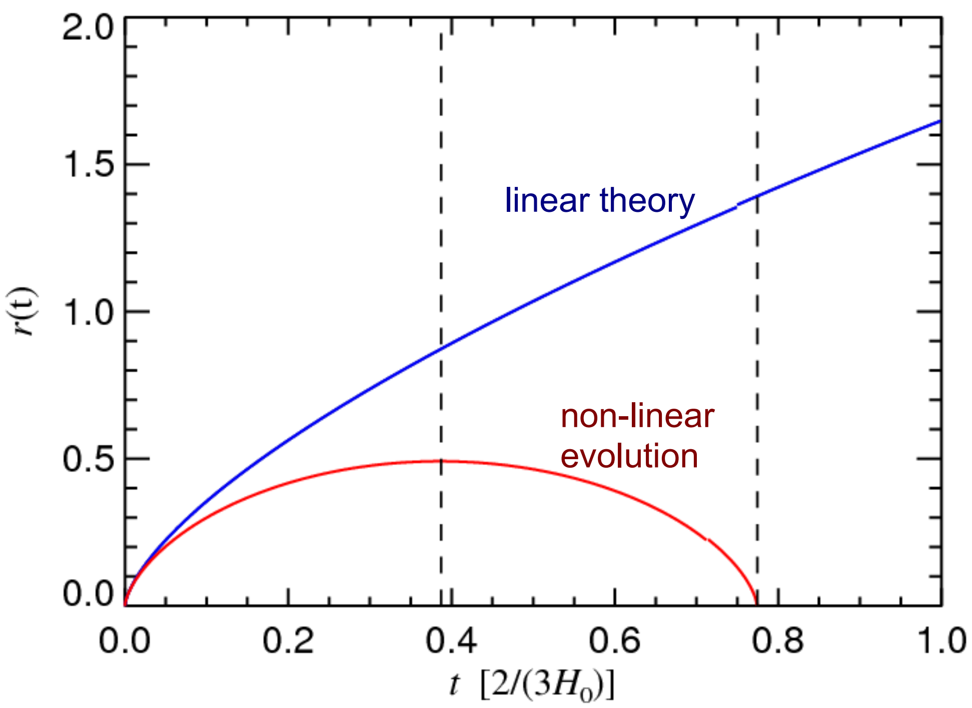
Collapse threshold for ULA DM unknown



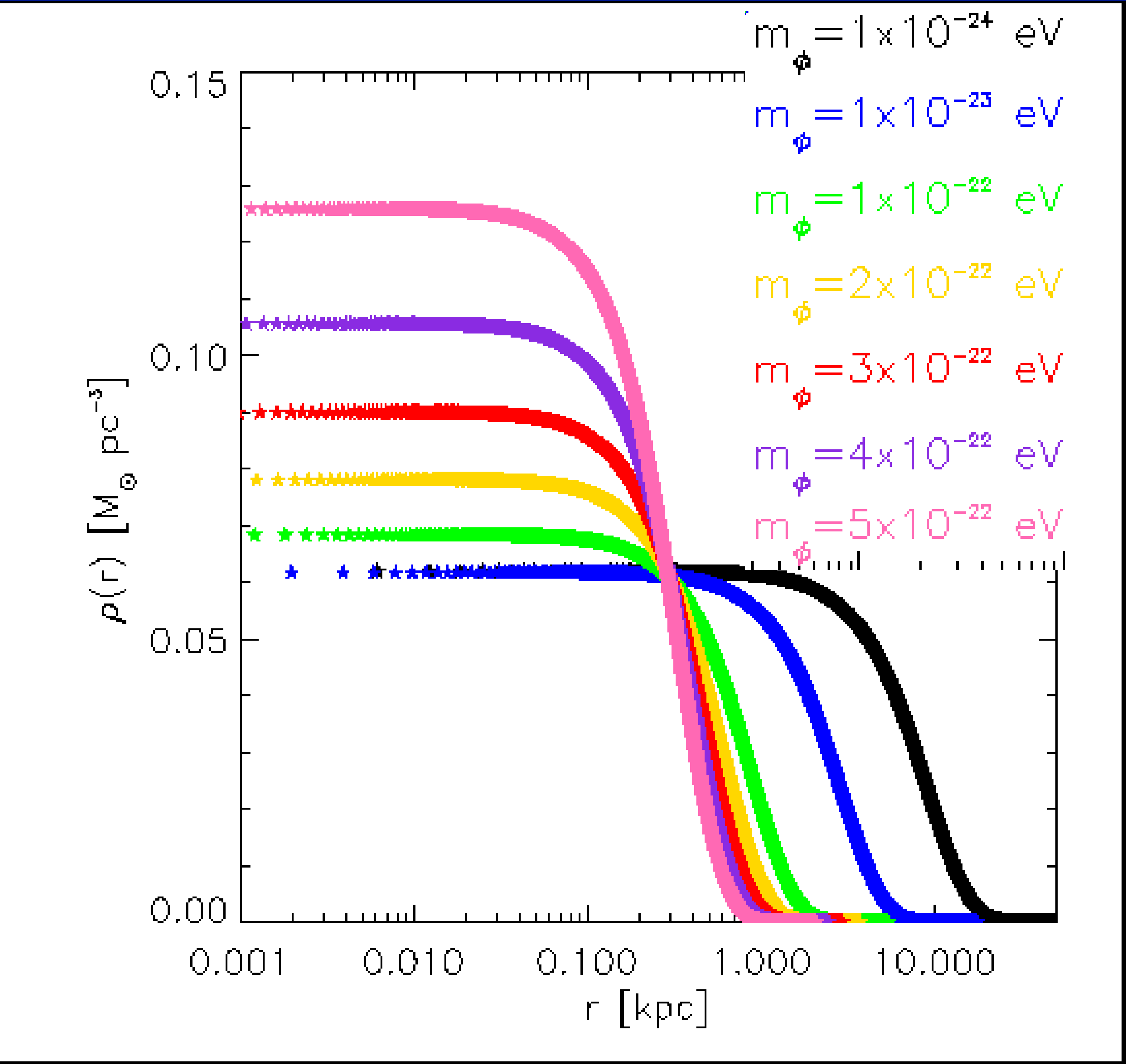


$$\delta_c^{\Lambda\mathrm{CDM}} = 1.686$$

$$\delta_c^{\Lambda\mathrm{ULA}} = ????$$

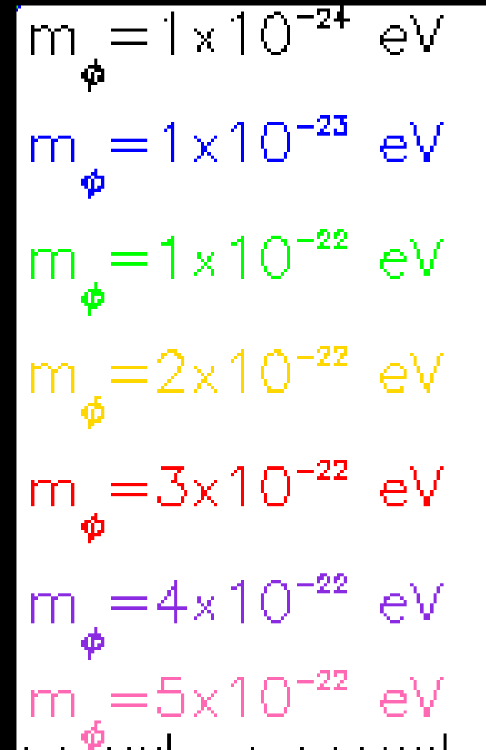


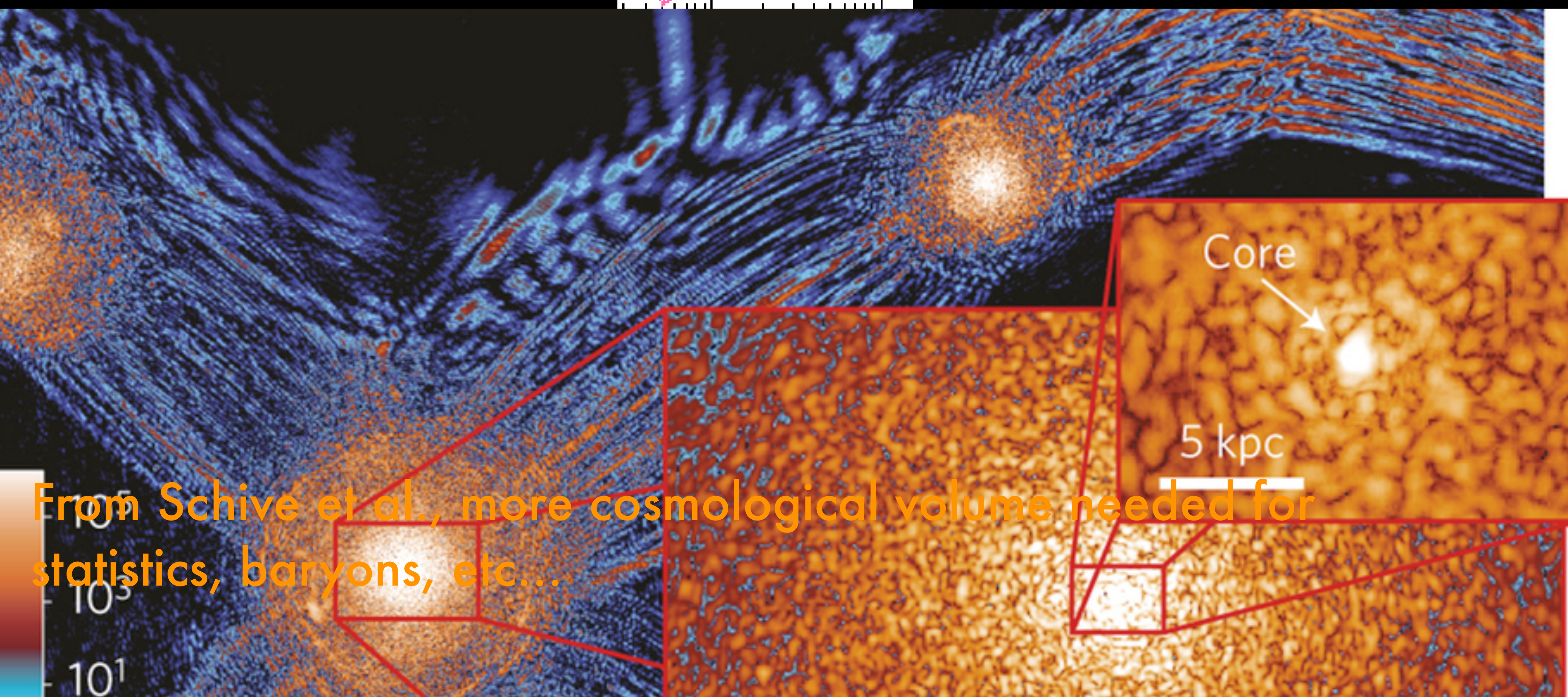
FUTURE WORK: ULAS CORES + CUSPS?



Cores! (Hu/Gruzinov/Barkana 2001, see also Marsh and Silk 2013, Marsh and Pop 2015, Matos 2012, Schive 2014, and others)

FUTURE WORK: ULAs CORES + CUSPS?

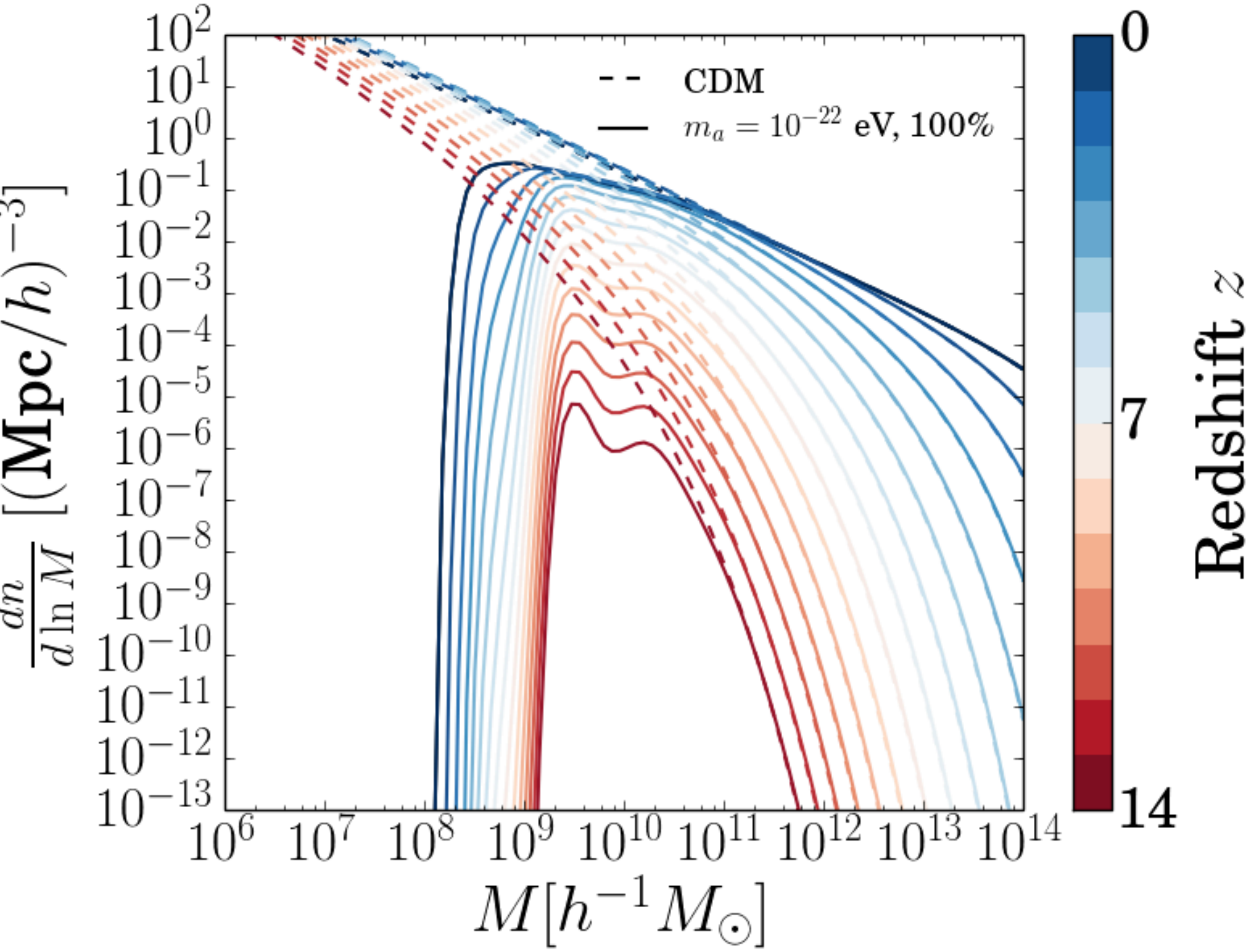


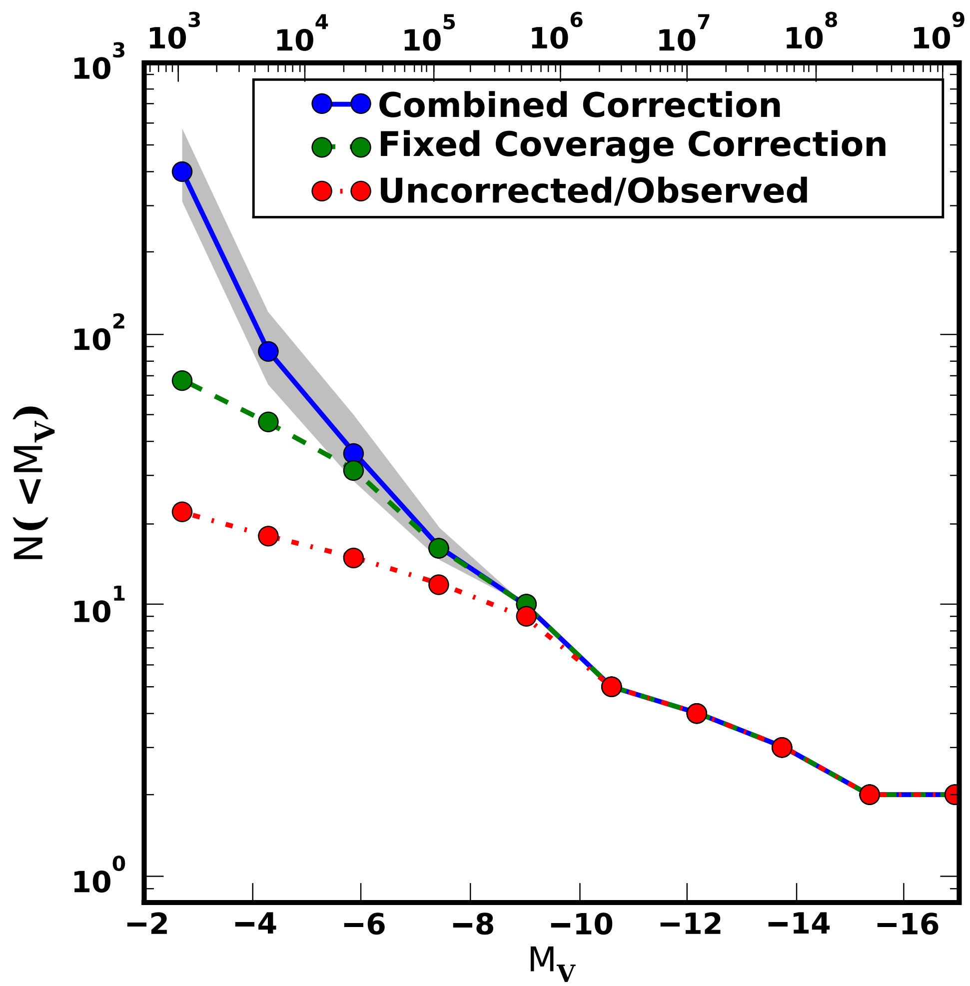


From Schive et al., more cosmological volume needed for statistics, baryons, etc…

Future work: ULAs and galaxies

Missing satellite problem?



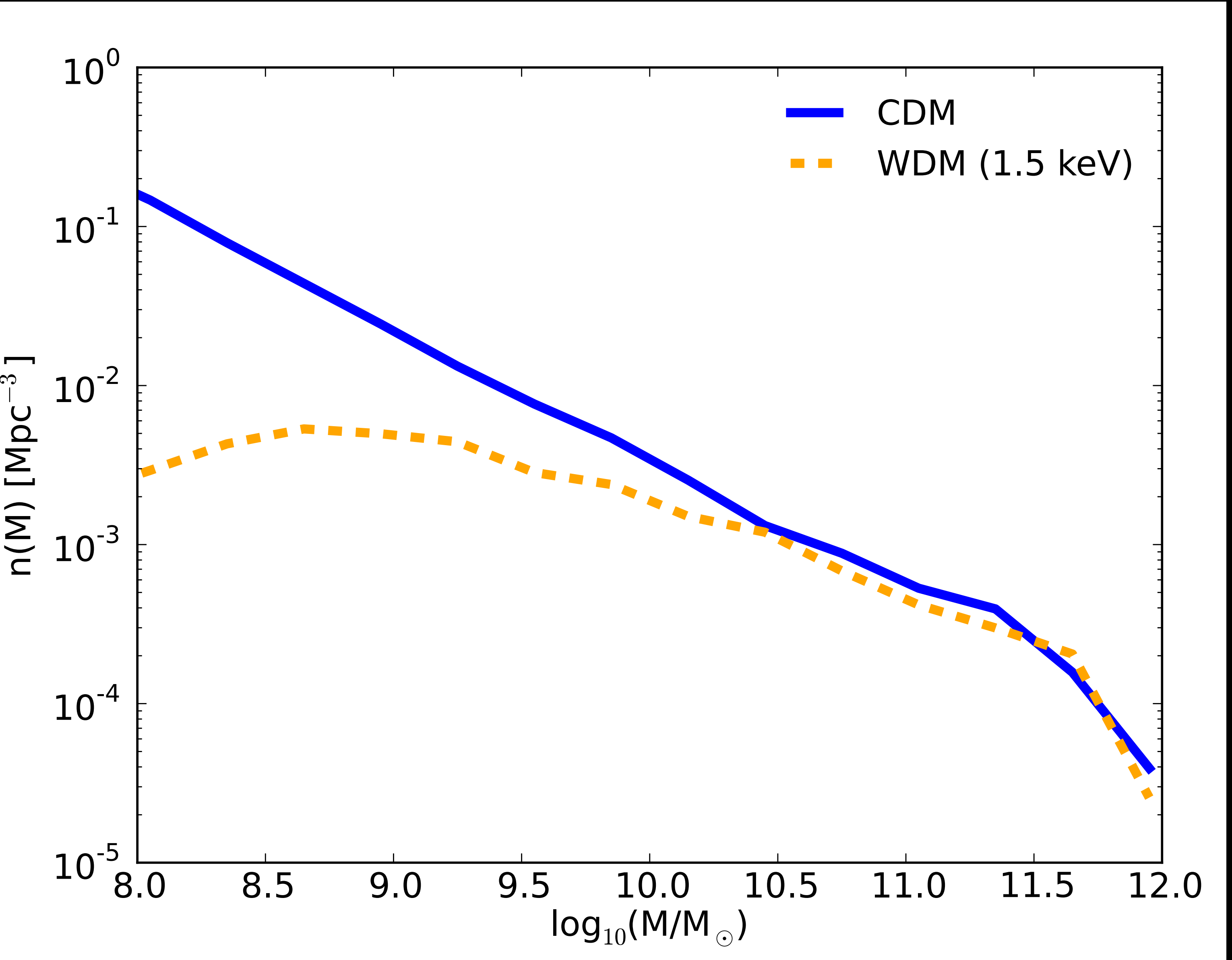


Marsh et al 2014, Klypin 1999, Bullock 2010

Future work: ULAs and galaxies

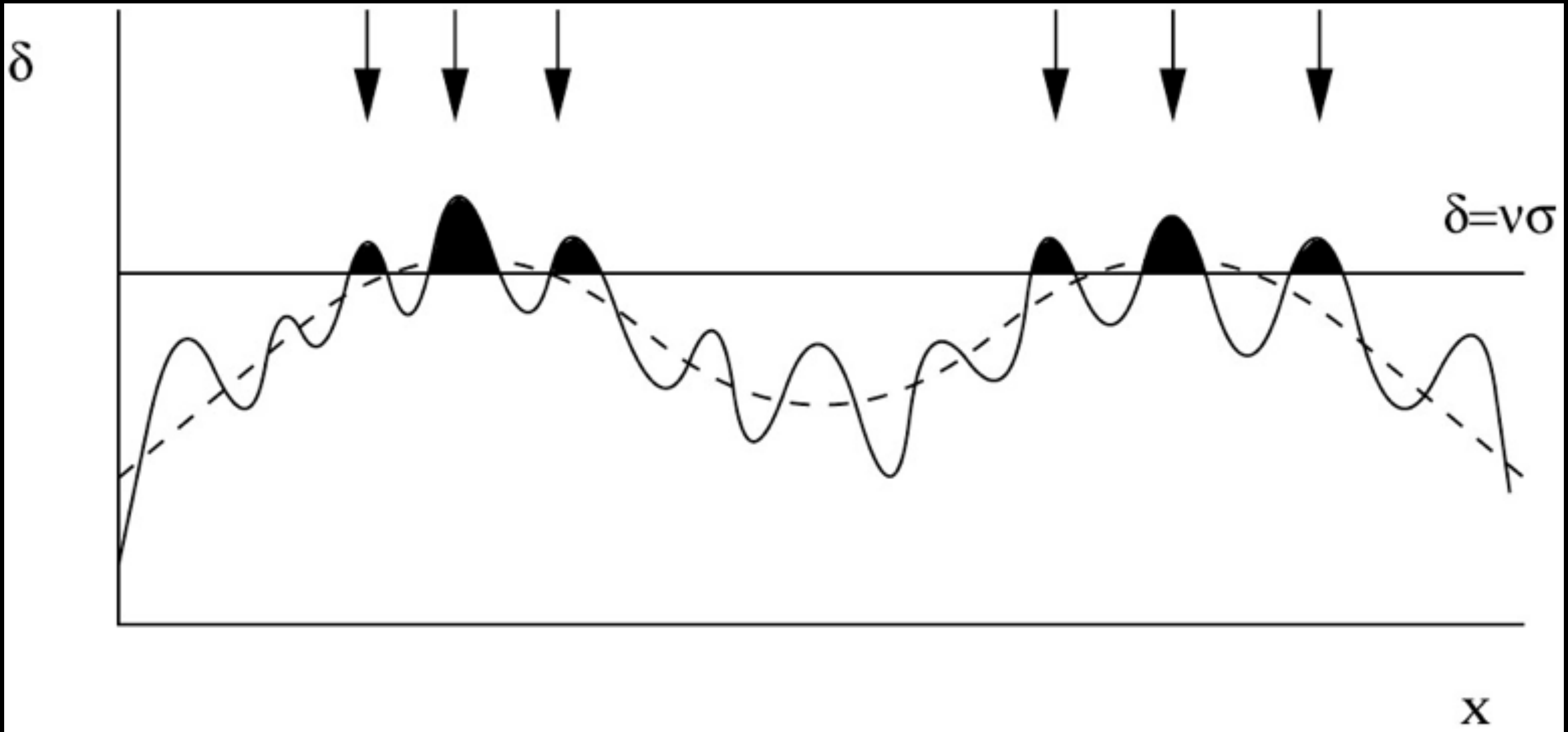
- ✳Galaxy correlation function (counts, bias)
- ✳Galaxy lensing
- ✳Substructure in halos [flux ratio anomalies in multiply lensed]

ULA substructure?



Future work: ULAs and galaxies

* Galaxies are biased tracers



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Unfair penalty on scales where axions don't cluster

✴ We use hard switch at $k_{osc} = k_{eq}; k_{\rm osc} \equiv a_{\rm osc} H_{\rm osc}$

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Doesn't include ULAs as matter component on scales where they cluster

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FUTURE WORK: ULAS AND GALAXIES

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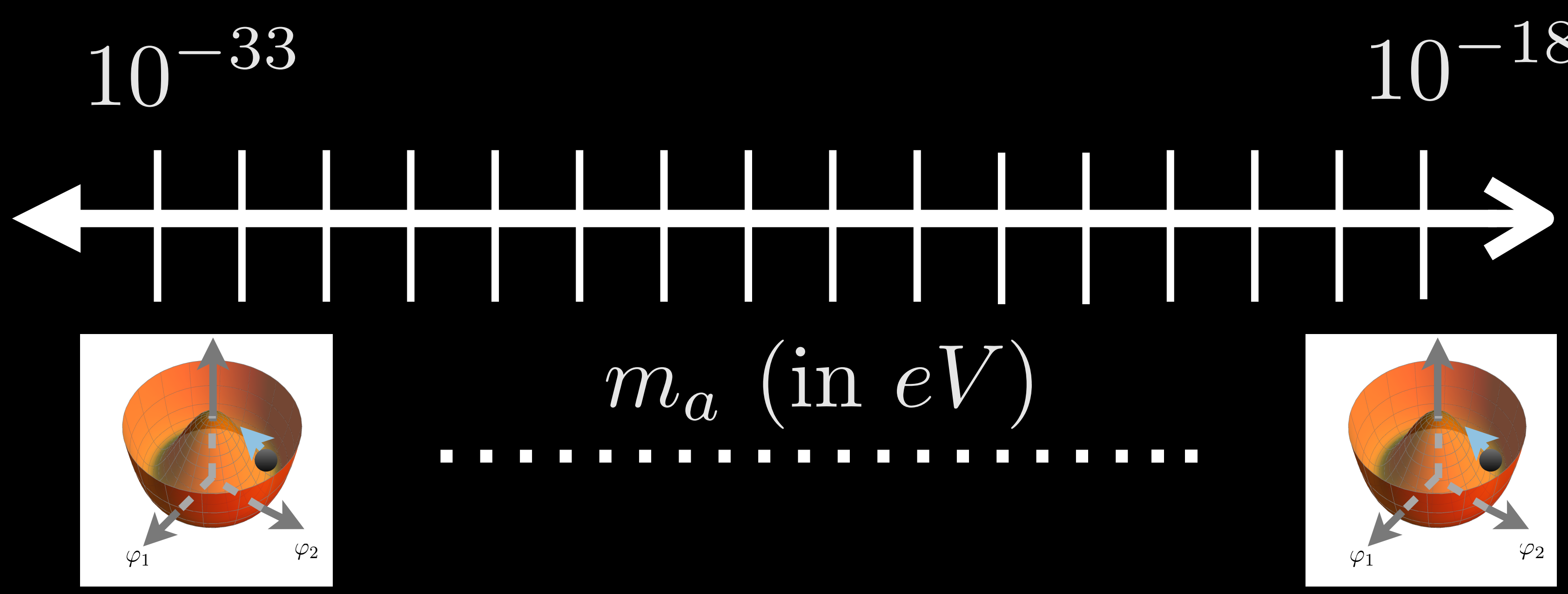
Doesn't include ULAs as matter component on scales where they cluster

- We use hard switch at $k_{osc} = k_{eq}; k_{\rm osc} \equiv a_{\rm osc} H_{\rm osc}$
- Realistic [smooth] treatment of scale-dependent bias needed (incorporating physics of ULA formation in halos)
  - Often neglected (but shouldn't be) for neutrinos (LoVerde 2013)

Future work: richer modeling and axiverse

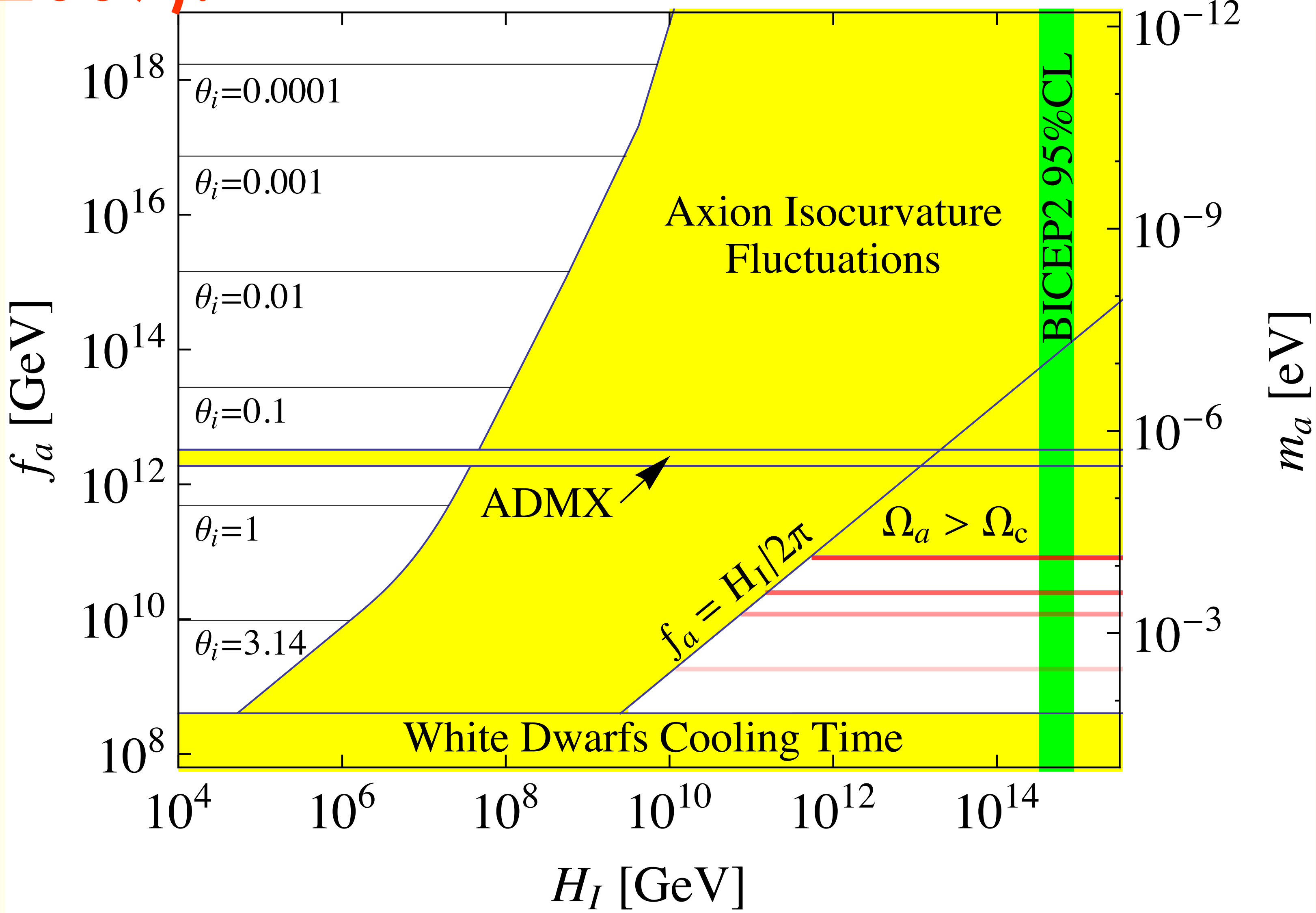
- Include spectrum of N axions (and interactions) in AXICAMB

$$\frac{dn}{d\ln m_a} \propto \mathrm{const}$$



BICEP2 [inflationary energy scale detected?]

(Gondolo 2009):



✳ Hard to accomodate QCD axion DM w/o classical window (defects)! [Marsh +yours truly+others 1403.4216 (2014), Gondolo et al. 2014 1403.4594]

$$\frac{\Omega_a}{\Omega_d} \lesssim 5 \times 10^{-12} \left(\frac{f_a}{10^{16}\ \mathrm{GeV}} \right)^{5/6}$$