Axion/ALPs in Astrophysics and Cosmology.

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SFB Lecture
DESY
Hamburg, D
7 July 2017

Reminder

- At very low energies, axion/ALP interactions with photons, electrons, nucleons described by

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - \frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C_{af}}{f_a}\,\partial_\mu a\, \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f$$

- In case of axion:

$$m_A = 57.0(7)\left(\frac{10^{11}\,\mathrm{GeV}}{f_A}\right)\mu\mathrm{eV}$$

$$C_{A\gamma} = \frac{E}{N} - 1.92(4)$$

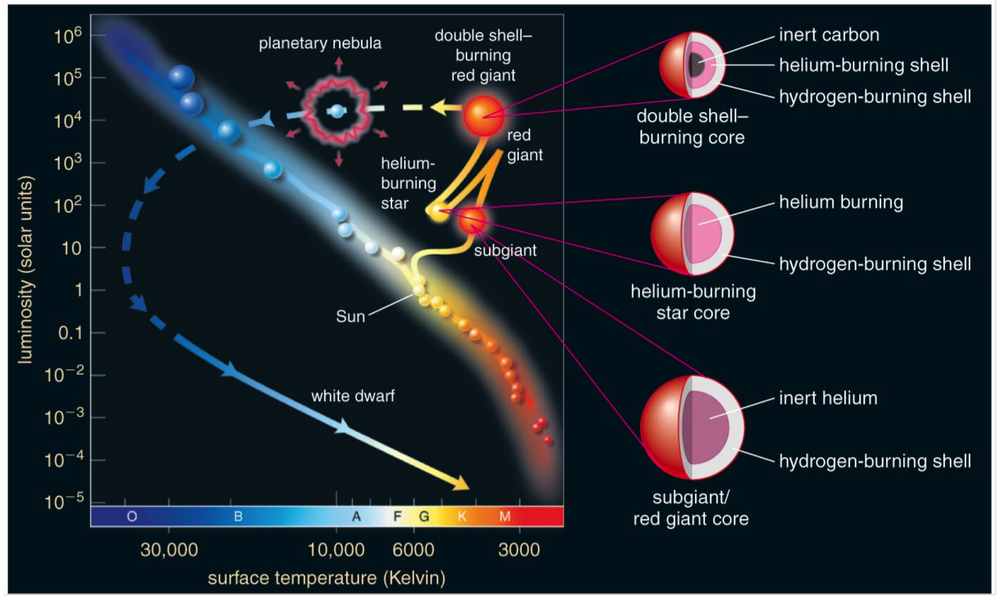
$$\begin{aligned} C_{Ap} &= -0.47(3) + 0.88(3) C_{Au} - 0.39(2) C_{Ad} - 0.038(5) C_{As} \\ &\qquad - 0.012(5) C_{Ac} - 0.009(2) C_{Ab} - 0.0035(4) C_{At}\,, \\ C_{An} &= -0.02(3) + 0.88(3) C_{Ad} - 0.39(2) C_{Au} - 0.038(5) C_{As} \\ &\qquad - 0.012(5) C_{Ac} - 0.009(2) C_{Ab} - 0.0035(4) C_{At} \end{aligned}$$

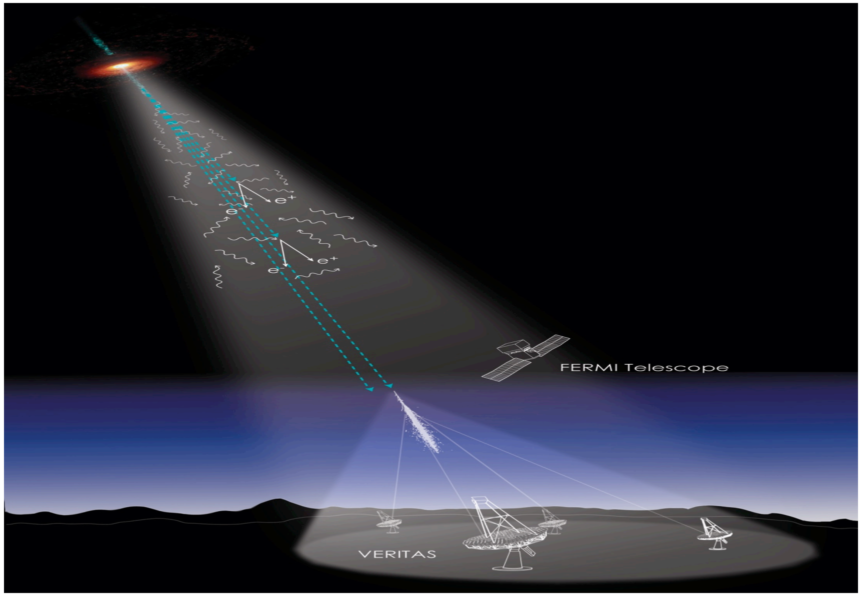
  - Electron coupling very model-dependent

- In case of ALP: mass and couplings very model-dependent

Astrophysical Signatures for Axion/ALPs

- Axion/ALPs may
  - lead to excessive energy losses of stars in various evolutionary stages
  - may convert to photons (or vice-versa) in astrophysical magnetic fields





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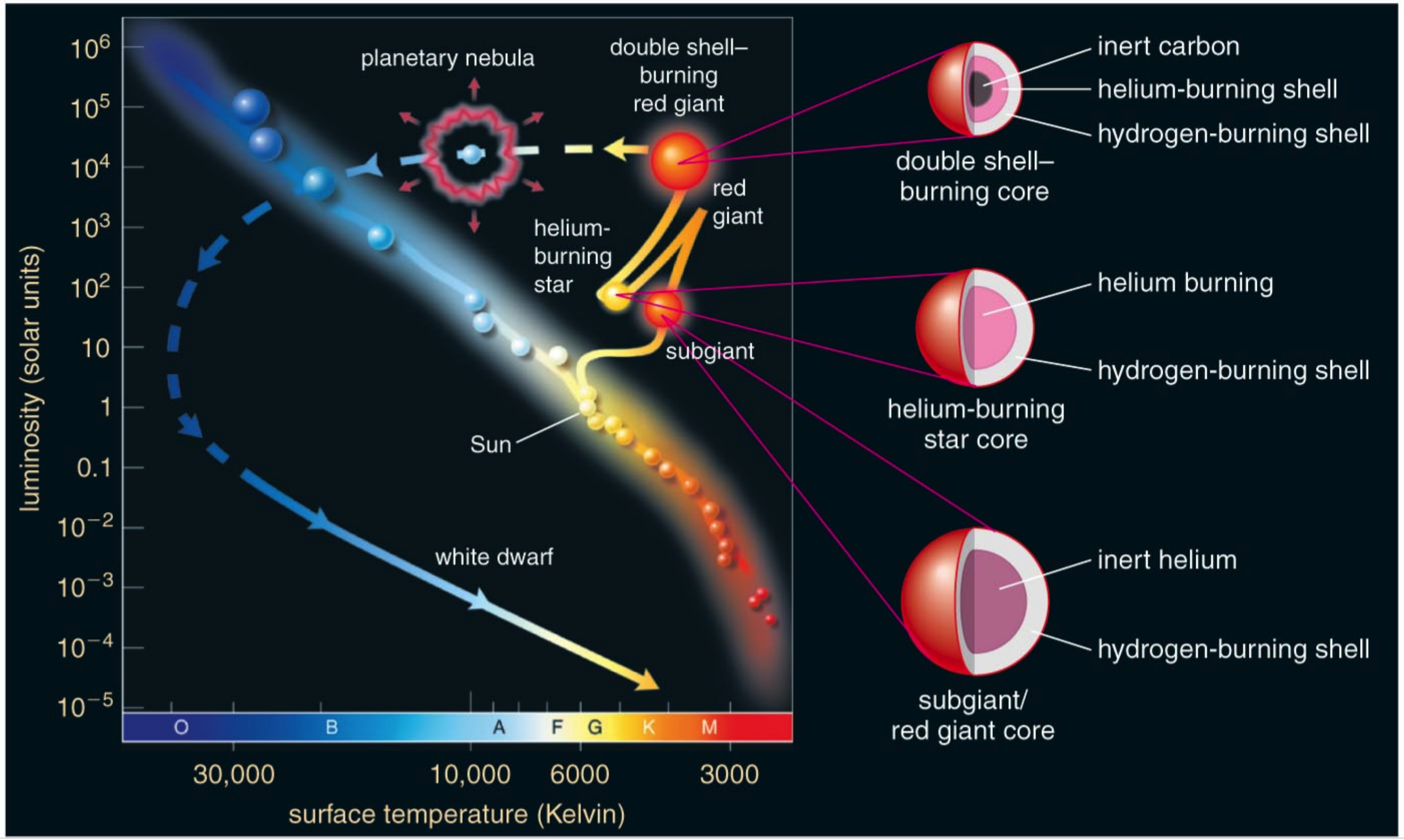
Searching for Axion/ALP Energy Losses of Stars

- Evolution of stars (Main Sequence – Red-Giant (RG) – Helium Burning (HB) – White Dwarf (WD)) sensitive to additional energy losses



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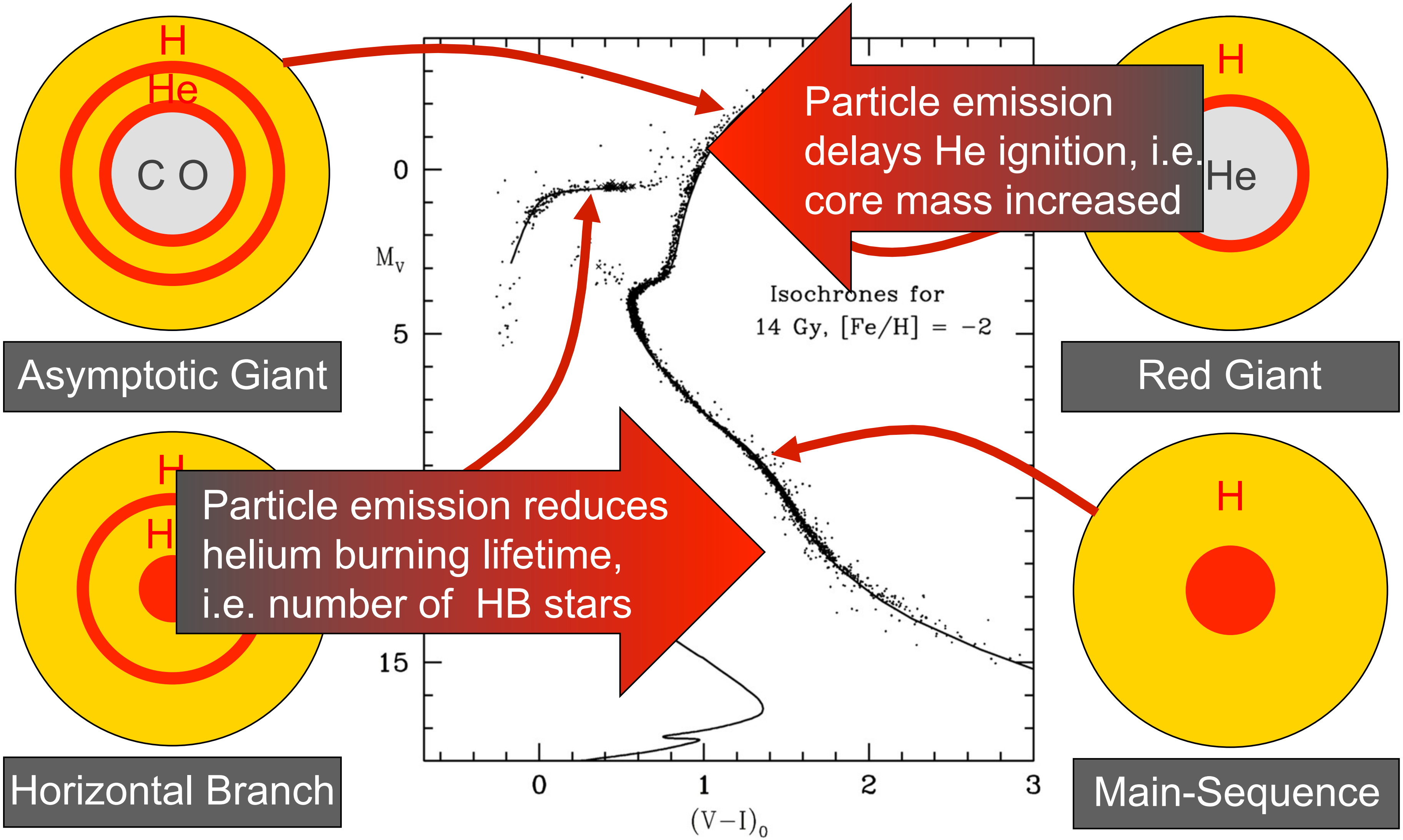
Searching for Axion/ALP Energy Losses of Stars



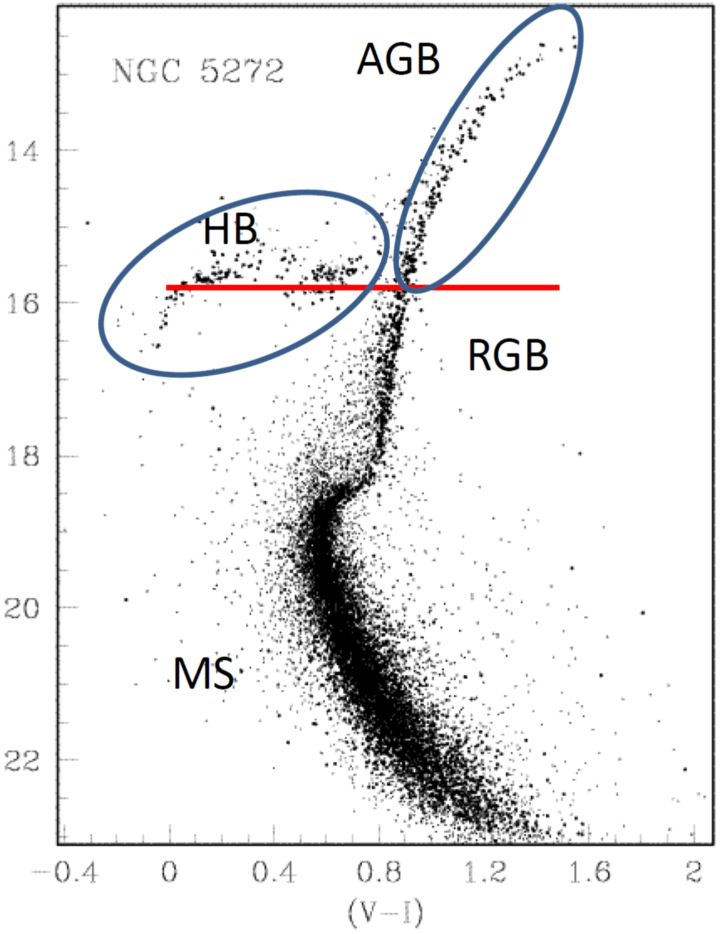
Particle emission delays He ignition, i.e. core mass increased

Particle emission reduces helium burning lifetime, i.e. number of HB stars

[Raffelt 14]

Searching for Axion/ALP Energy Losses of Stars

- RG cooling rate: Brightness of tip of RG branch in color-magnitude diagram of globular cluster [Viaux et al. 13]
- HB cooling rate: Number of HB stars vs. number of RGs in color-magnitude diagram of globular cluster [Ayala et al. 14]



[Giannotti `16]

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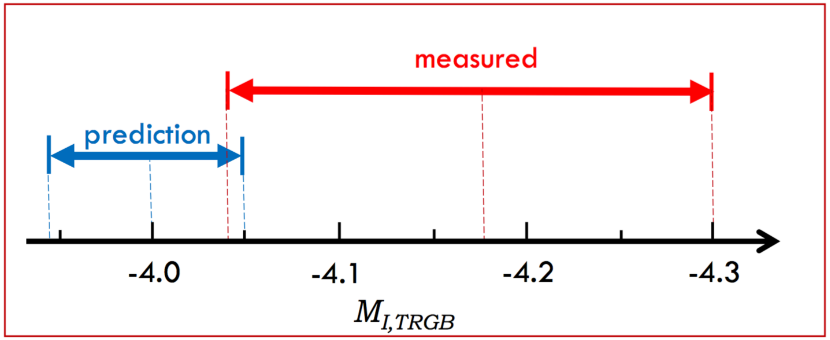

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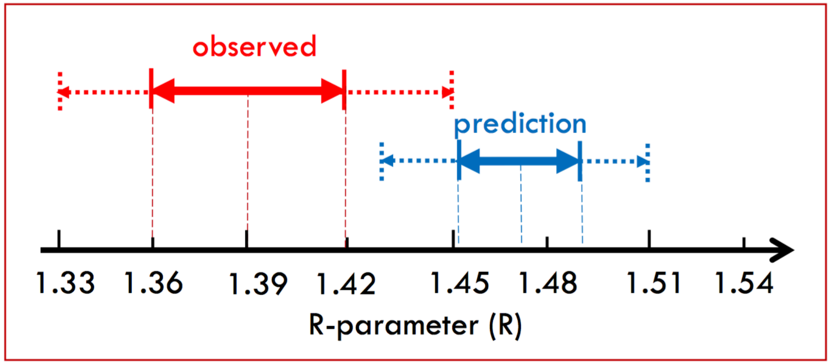
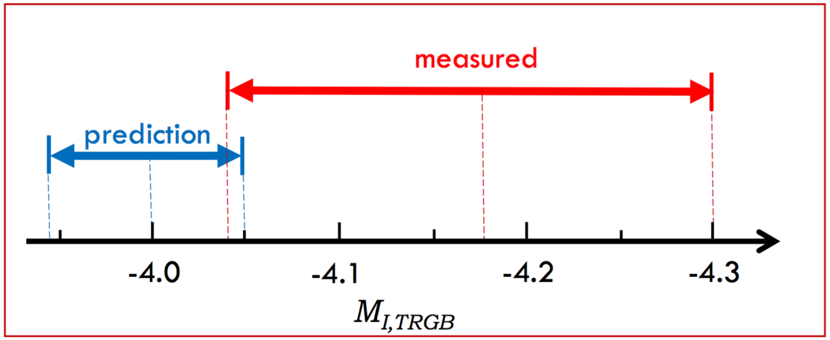


[Giannotti 15]

Searching for Axion/ALP Energy Losses of Stars



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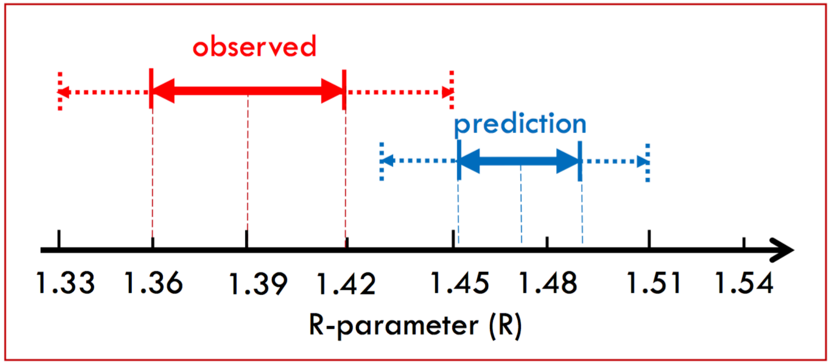

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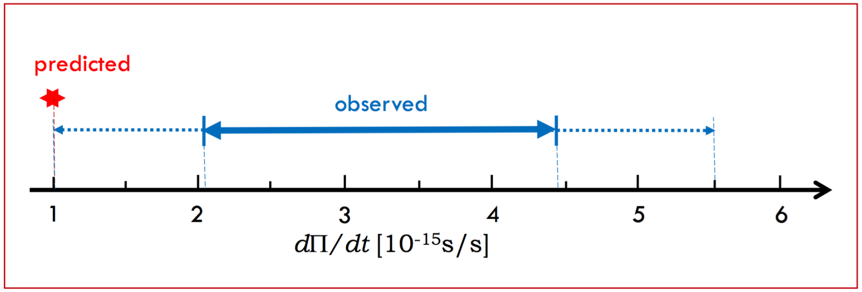

- WD cooling rate:
  - Period decrease of variable WDs [Kepler et al. 91,...]

[Giannotti 15]

Searching for Axion/ALP Energy Losses of Stars

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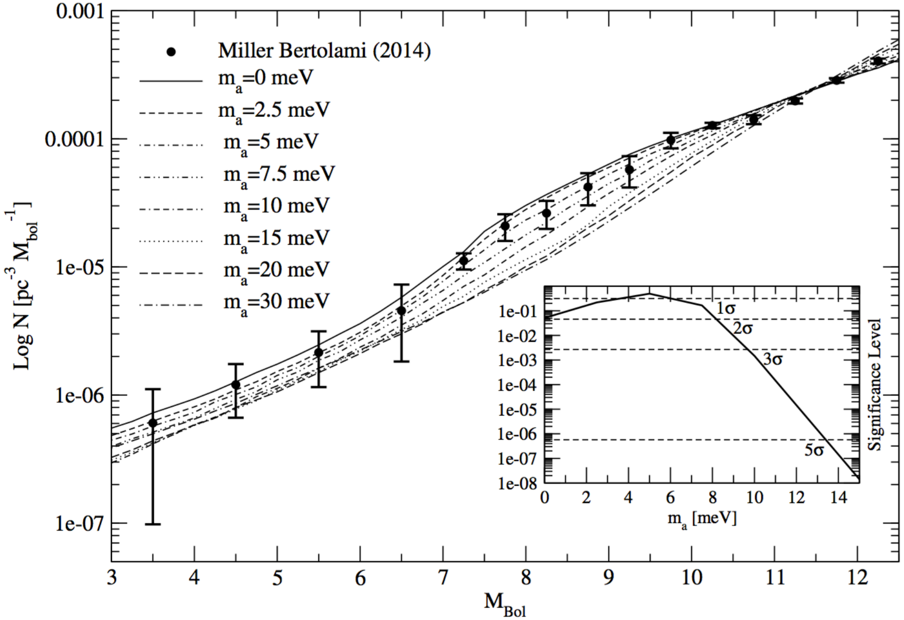
  - White dwarf luminosity function (WDLF) [Isern et al. 08-12]



[Bertolami et al. 15]

Searching for Axion/ALP Energy Losses of Stars

- RG cooling rate: Brightness of tip of RG branch in color-magnitude diagram of globular cluster [Viaux et al. 13]

$$g_{ae} \equiv \frac{m_e}{f_a} |C_{ae}| < 4.3 \times 10^{-13}$$

- HB cooling rate: Number of HB stars vs. number of RGs in color-magnitude diagram of globular cluster [Ayala et al. 14]

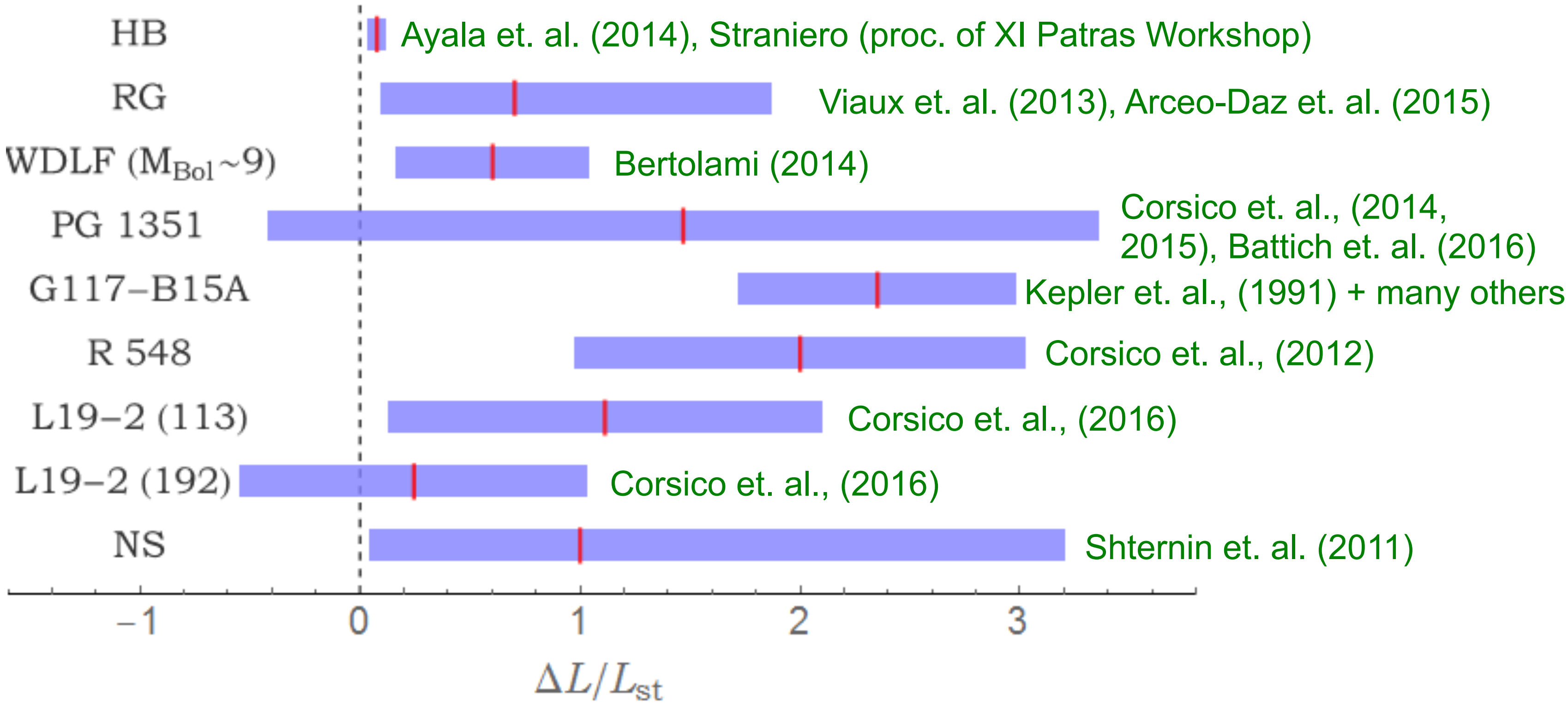
$$g_{a\gamma} \equiv \frac{\alpha}{2\pi f_a} |C_{a\gamma}| < 6.6 \times 10^{-11}\,\mathrm{GeV}^{-1}$$

- WD cooling rate:
  - Period decrease of variable WDs [Kepler et al. 91,...]
  - White dwarf luminosity function (WDLF) [Isern et al. 08-12]

$$g_{ae} \equiv \frac{m_e}{f_a} |C_{ae}| < 2.8 \times 10^{-13}$$

Searching for Axion/ALP Energy Losses of Stars

- However, practically every stellar systems seems to be cooling a bit faster than predicted by models based on SM:



Ayala et. al. (2014), Straniero (proc. of XI Patras Workshop)

Viaux et. al. (2013), Arceo-Daz et. al. (2015)

Bertolami (2014)

Corsico et. al., (2014, 2015), Battich et. al. (2016)

Kepler et. al., (1991) + many others

Corsico et. al., (2012)

Corsico et. al., (2016)

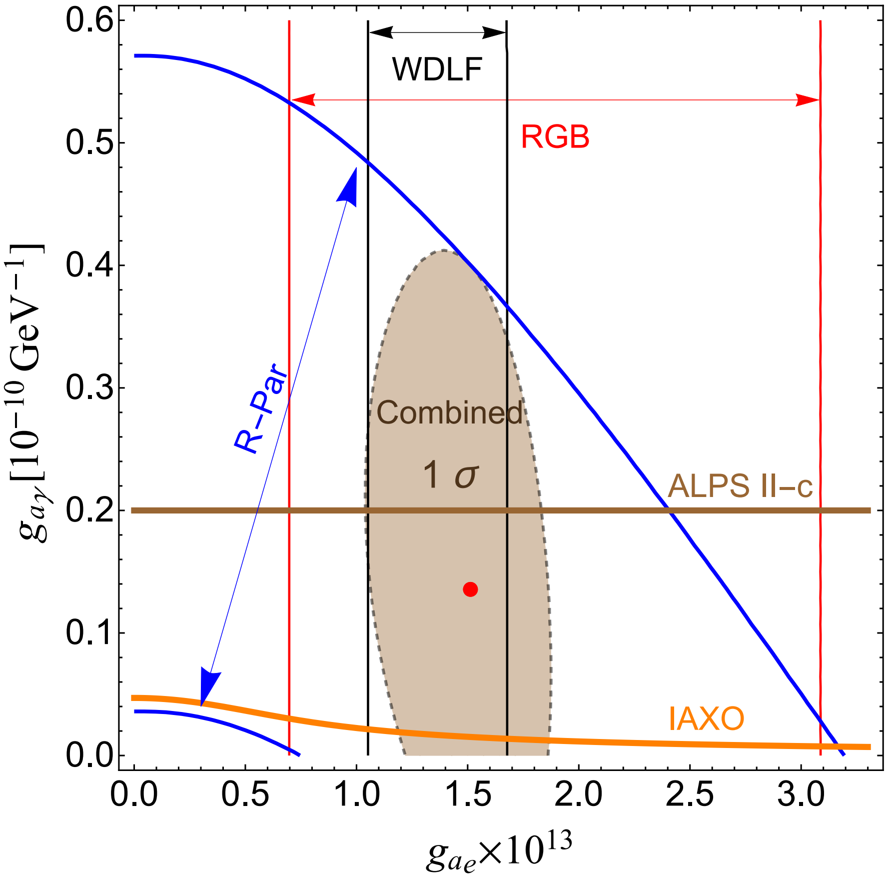
Corsico et. al., (2016)

Shternin et. al. (2011)

[Giannotti, Irastorza, Redondo, AR (2015); Giannotti, Irastorza, Redondo, AR (in preparation)]

Searching for Axion/ALP Energy Losses of Stars

- Excessive energy losses of HBs, RG, WDs can be explained at one stroke by production of axion/ALP with coupling to photons and electrons:



$$g_{a\gamma} = C_{a\gamma}\alpha/(2\pi f_a)$$

$$\gamma + Ze \to Ze + a$$

$$g_{ai} = C_{ai}m_i/f_a$$

$$e + Ze \to Ze + e + a$$

[Giannotti,Irastorza,Redondo,AR,Saikawa (in preparation)]

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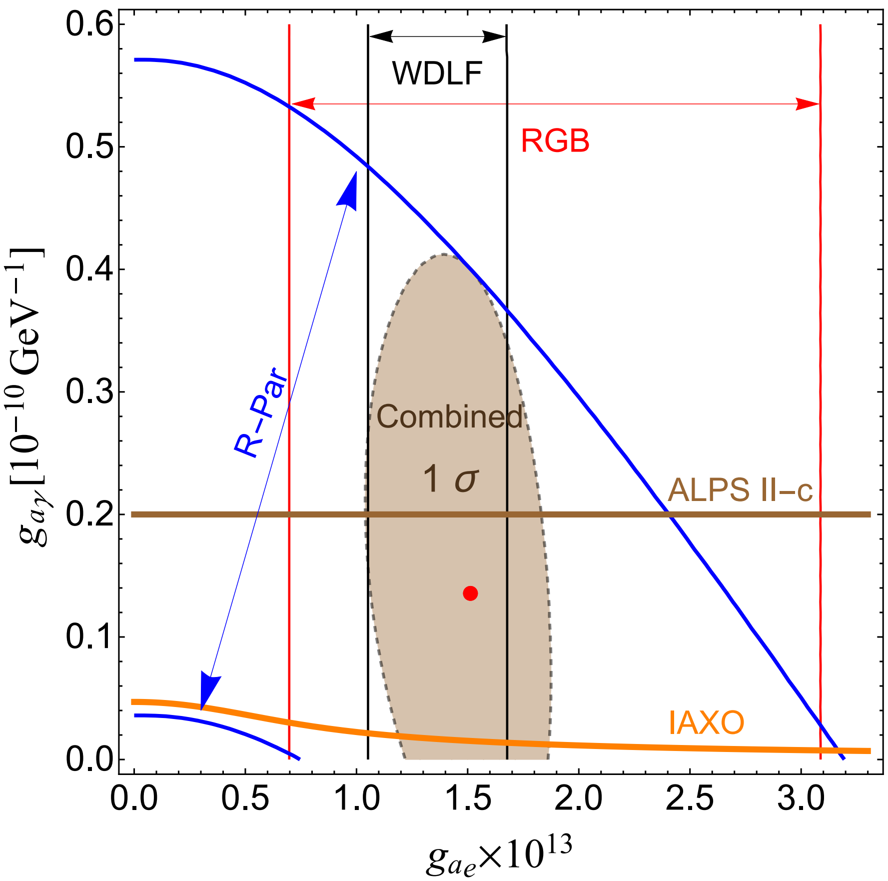
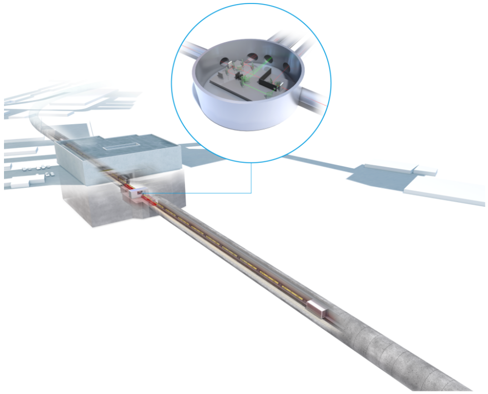
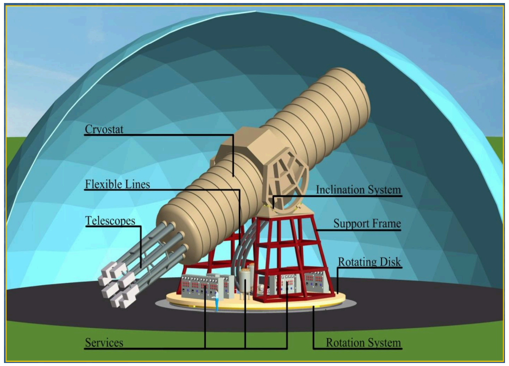


ALPS II



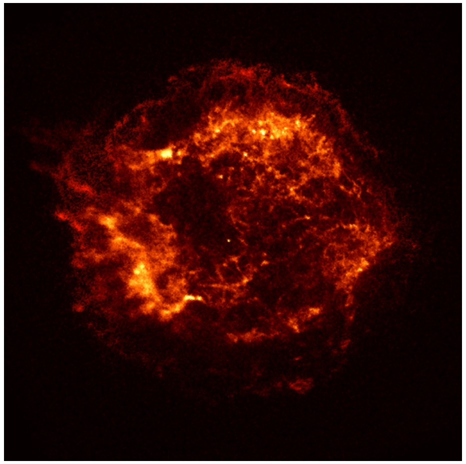
IAXO

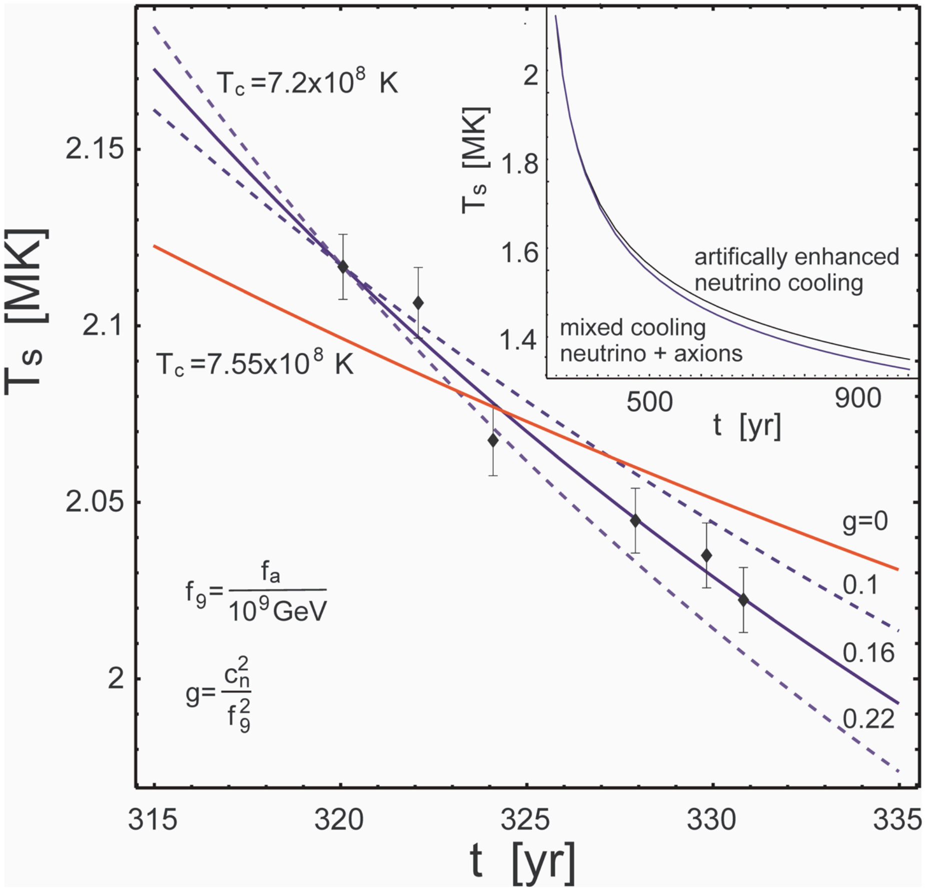


[Giannotti,Irastorza,Redondo,AR,Saikawa (in preparation)]

Searching for Axion/ALP Energy Losses of Stars

> Neutron star in Cas A:





[Leinson 14]

- Measured surface temperature reveals unusually fast cooling rate
- Hint on extra cooling by axion/ALP due to nucleon bremsstrahlung

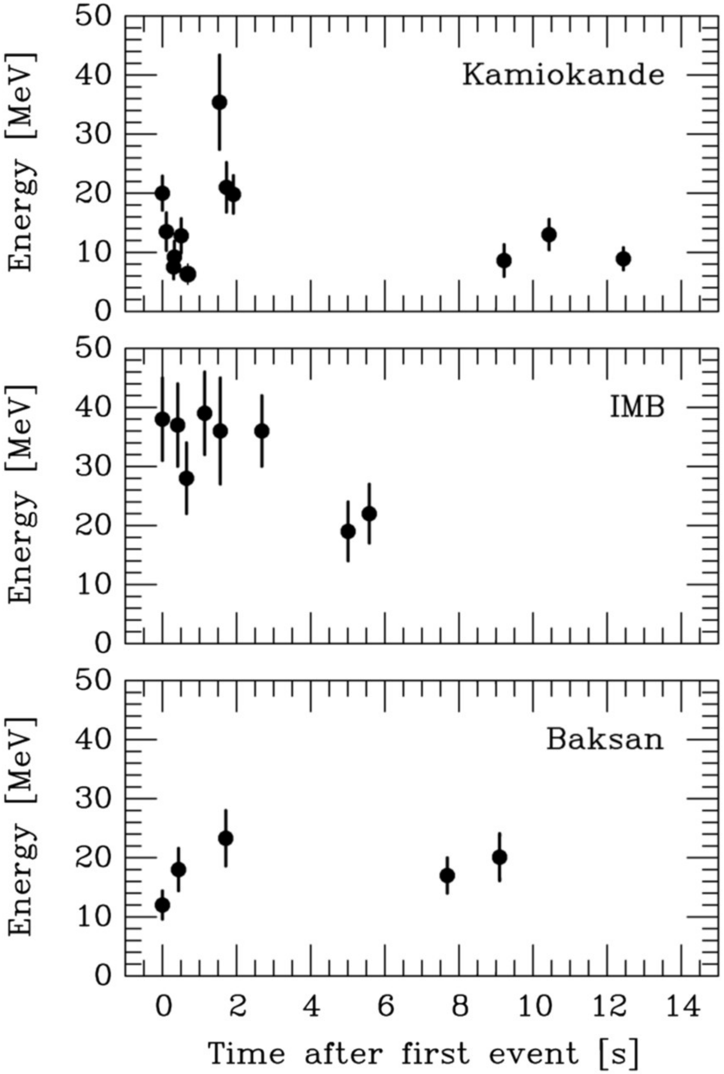
$$N + N \to N + N + a$$

- Required coupling to neutron:

$$g_{an} \equiv \frac{m_n}{f_a} |C_{an}| = (3.8 \pm 3) \times 10^{-10}$$

Searching for Axion/ALP Energy Losses of Stars

- SN 1987 A:



[Raffelt]

- Emission of axion/ALPs would take away energy from neutrino burst and shorten it

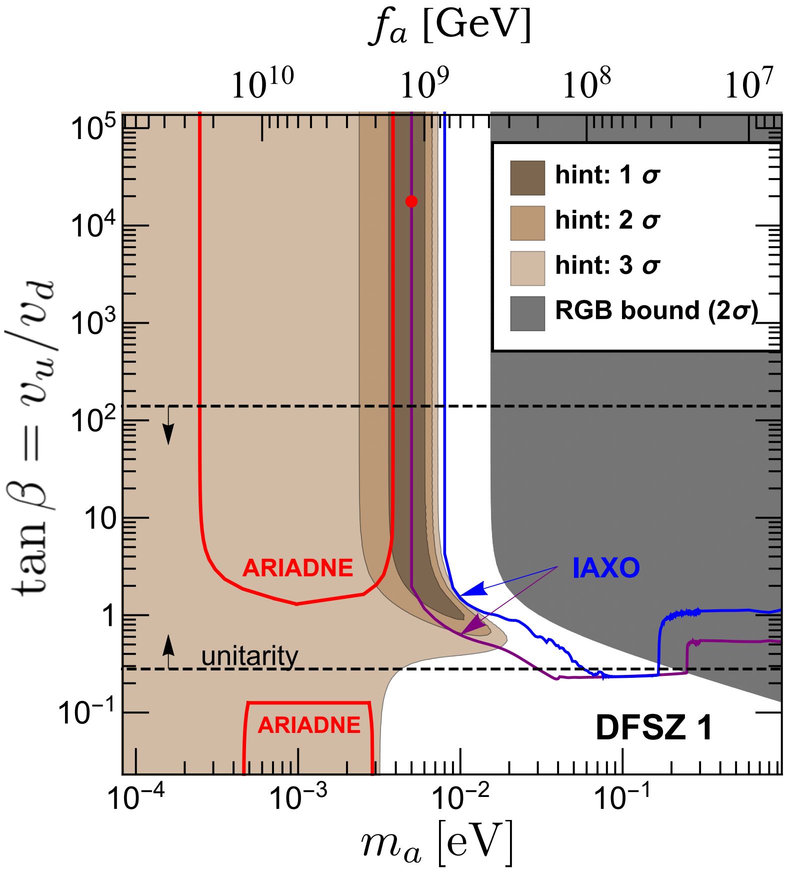
$$g_{ap}^2 + g_{an}^2 < 3.6 \times 10^{-19}$$

[Raffelt 08; Fischer et al. 16; Giannotti et al. (in prep.)]

- Not very solid bound: sparse data and interaction difficult to model

Searching for Axion/ALP Energy Losses of Stars

- Excessive energy losses of HBs, RG, WDs, NS can be explained at one stroke by production of axion with coupling to photons, electrons, nucleons, e.g. for DFSZ axion model:



[Giannotti,Irastorza,Redondo,AR,Saikawa (in preparation)]

$$f_a = \frac{v_{\rm PQ}}{6},$$

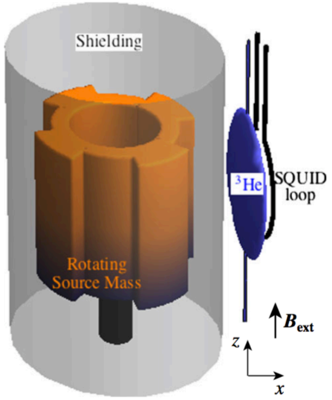
$$C_{ae}^{\rm DFSZ\ I} = \frac{1}{3}\sin^2\beta\,, \qquad C_{ae}^{\rm DFSZ\ II} = \frac{1}{3}(1-\sin^2\beta)$$

$$C_{a\gamma}^{\rm DFSZ\ I} = \frac{8}{3} - 1.92(4)\,, \qquad C_{a\gamma}^{\rm DFSZ\ II} = \frac{2}{3} - 1.92(4)\,,$$

$$C_{Ap} = -0.435\sin^2\beta + (-0.182 \pm 0.025)\,,$$

$$C_{An} = 0.414\sin^2\beta + (-0.16 \pm 0.025)\,.$$

ARIADNE



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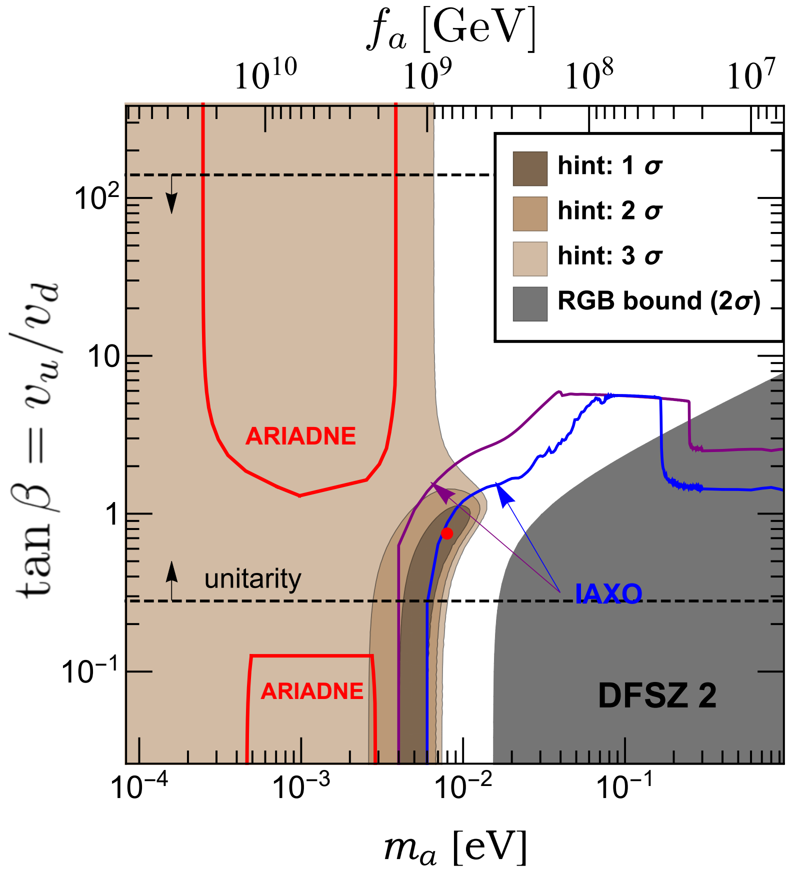

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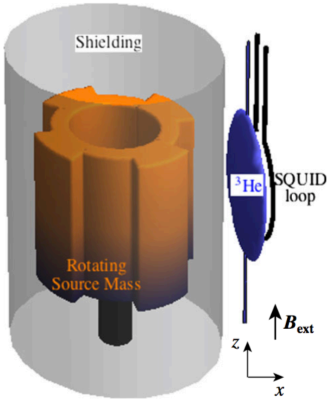

[Giannotti,Irastorza,Redondo,AR,Saikawa (in preparation)]

Searching for Axion/ALP Energy Losses of Stars

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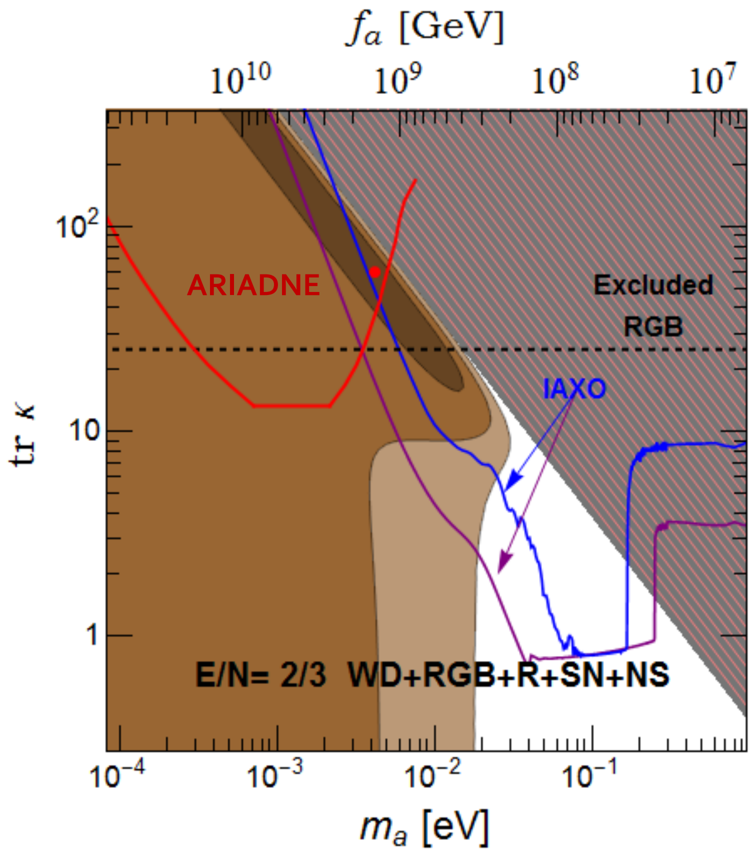


$$\mathcal{L}_Y \supset -\overline{L}_i F_{ij} N_j H - \frac{1}{2}\overline{N_i^c} Y_{ij} N_j \sigma + \text{h.c.}$$

$$C_{ae} \simeq \frac{1}{8\pi^2 N}\left(\kappa_{ee} - \frac{1}{2}\,\text{tr}\kappa\right)$$

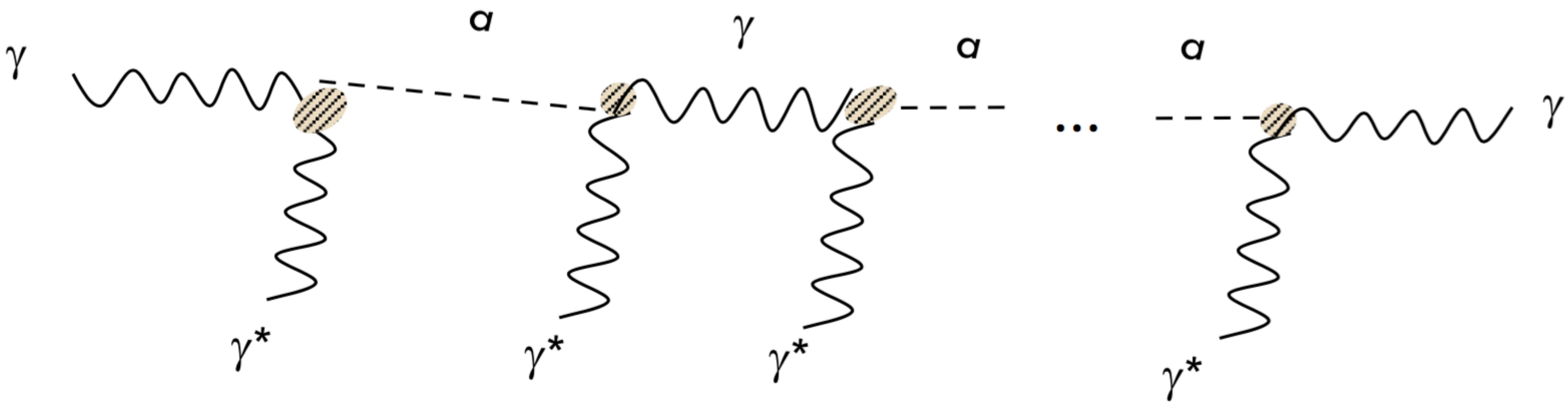
$$C_{aq} \simeq \frac{1}{8\pi^2 N} T_3^q\, \text{tr}\kappa$$

$$\kappa \equiv \frac{m_D m_D^\dagger}{v^2} = \frac{FF^\dagger}{2}$$

[Giannotti,Irastorza,Redondo,AR,Saikawa (in preparation)]

Photon – ALP Conversion in Cosmic Magnetic Fields?

- Photons propagating in magnetic field experience photon-ALP oscillations:



Photon – ALP Conversion in Cosmic Magnetic Fields?

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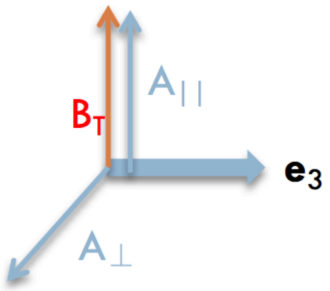
$$\left[E - i\frac{\partial}{\partial x_3} + \begin{pmatrix} \Delta_{\rm pl}+\Delta_{\rm CMB}-\frac{i\Gamma_{\rm abs}}{2} & 0 & 0 \\ 0 & \Delta_{\rm pl}+\Delta_{\rm CMB}-i\frac{i\Gamma_{\rm abs}}{2} & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_{\rm a} \end{pmatrix}\right]\begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix} = 0$$

- $\Delta_{a\gamma} \equiv \frac{g_{a\gamma}B_T}{2} \simeq 1.52\times 10^{-8}\left(\frac{g_{a\gamma}}{10^{-17}\mathrm{GeV}^{-1}}\right)\left(\frac{B_T}{10^{-9}\,\mathrm{G}}\right)\mathrm{Mpc}^{-1}$
- $\Delta_{\rm a} \equiv -\frac{m_{\rm a}^2}{2E} \simeq -7.8\times 10^{5}\left(\frac{m_{\rm a}}{10^{-10}\mathrm{eV}}\right)^2\left(\frac{E}{\mathrm{keV}}\right)^{-1}\mathrm{Mpc}^{-1}$
- $\Delta_{\rm pl} \equiv -\frac{\omega_{\rm pl}^2}{2E} \simeq -1.1\times 10^{-2}\left(\frac{E}{\mathrm{keV}}\right)^{-1}\left(\frac{n_e}{10^{-7}\,\mathrm{cm}^{-3}}\right)\mathrm{Mpc}^{-1}$
- $\Delta_{\rm CMB} \simeq 0.80\times 10^{-10}\left(\frac{E}{\mathrm{keV}}\right)\mathrm{Mpc}^{-1}$



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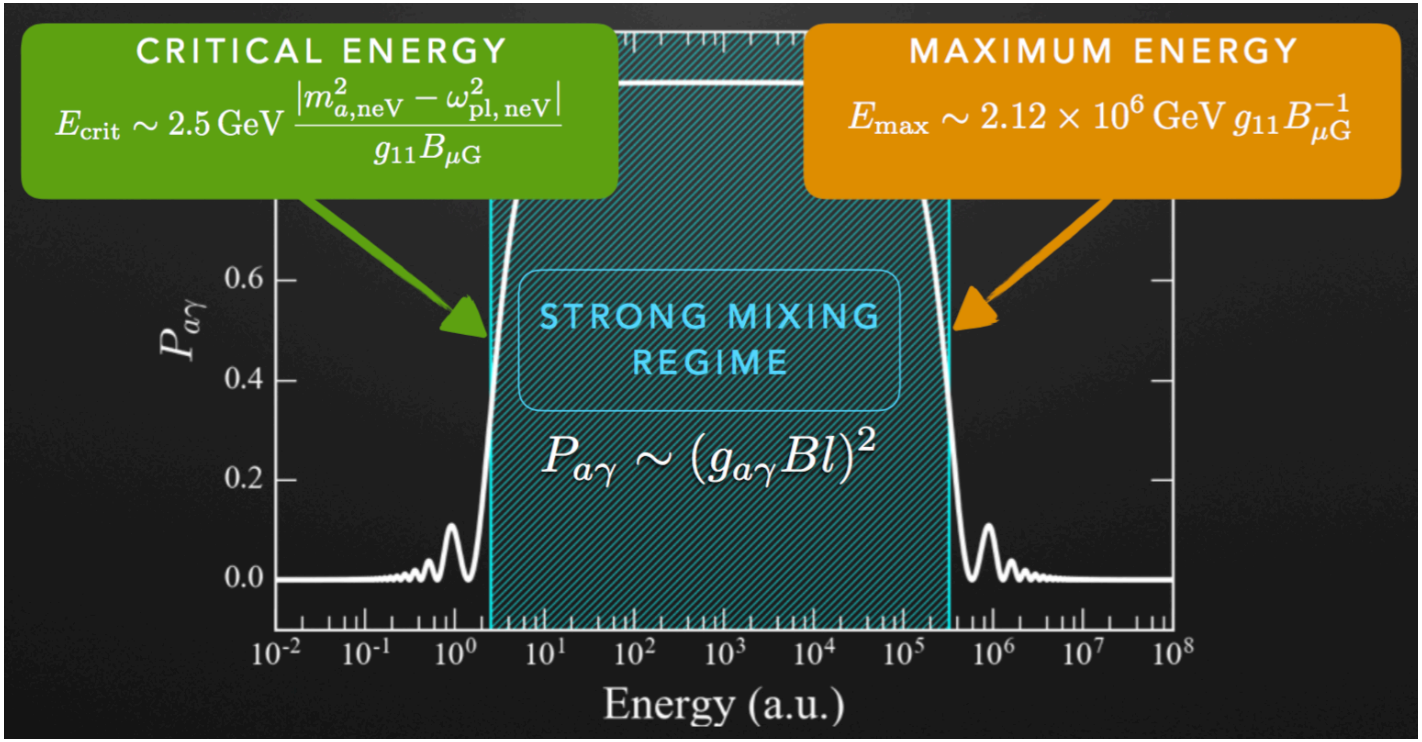
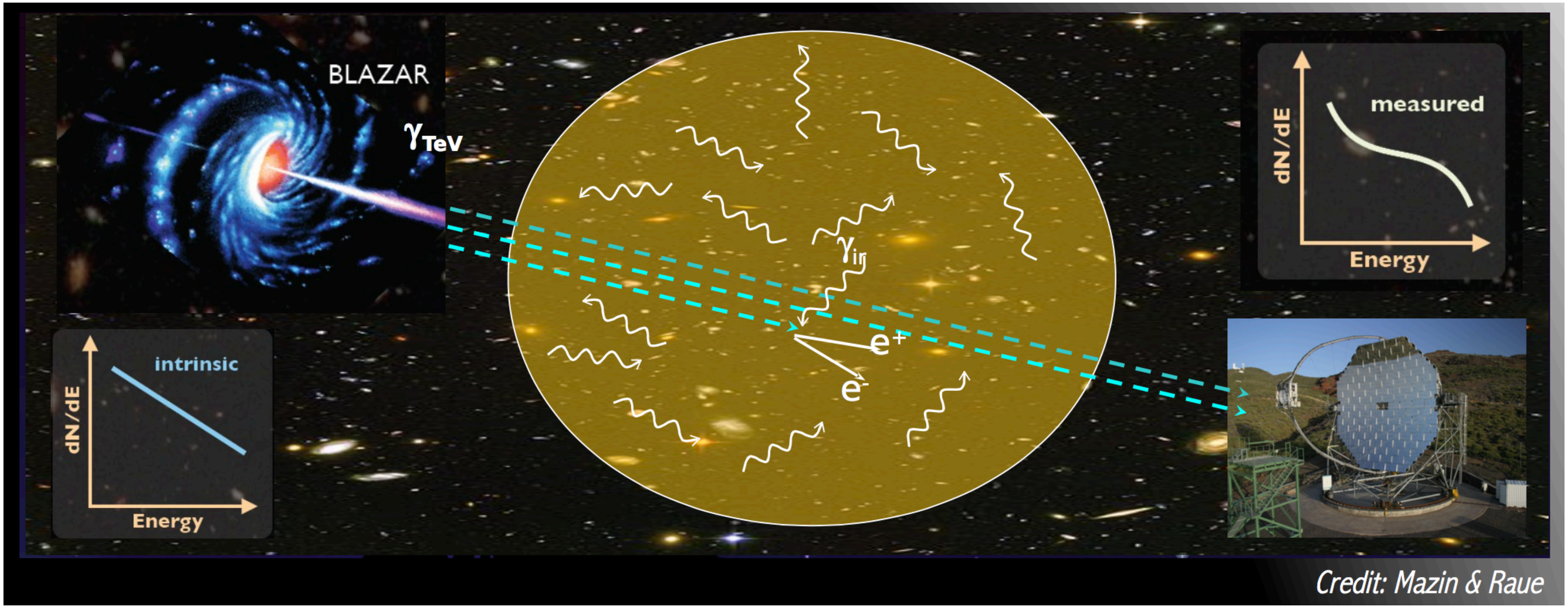


- Signatures for ALPs in AGN spectra:
  - Apparent boost in photon flux (reduced opacity of Universe)
  - Apparent spectral irregularities

Photon – ALP Conversion in Cosmic Magnetic Fields?

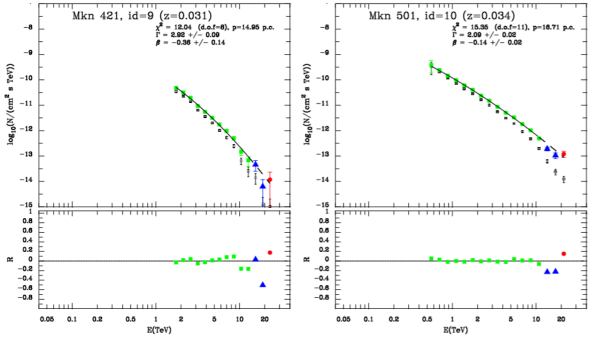
- Gamma ray spectra from distant AGNs should show an energy and red-shift dependent exponential attenuation, due to pair production at Extragalactic Background Light (EBL)



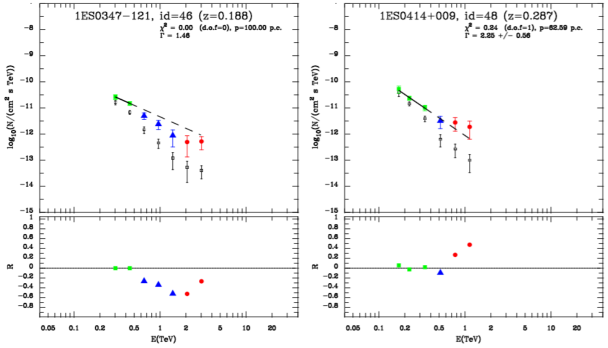
Credit: Mazin & Raue

Photon – ALP Conversion in Cosmic Magnetic Fields?

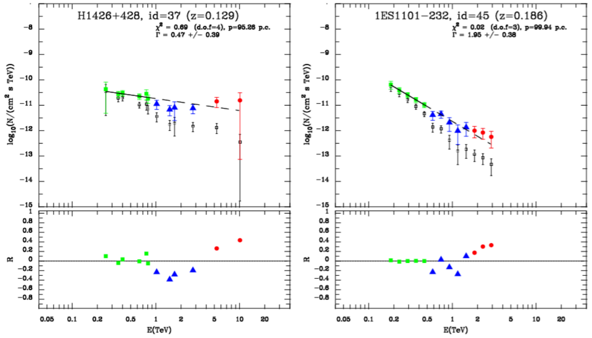
- Gamma ray spectra from distant AGNs should show an energy and red-shift dependent exponential attenuation, due to pair production at Extragalactic Background Light (EBL)
- Indication of anomalous gamma transparency: attenuation observed by IACT and Fermi-LAT too small [Aharonian et al. 07; de Angelis,Roncadelli et al. 07;...;Horns,Meyer 12;Meyer,Horns,Raue 13;Rubtsov,Troitsky 14;Kohri,Kodama 17]



(a) (b)

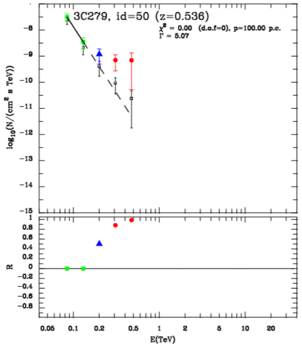


(e) (f)



(c) (d)

[Horns,Meyer 12]

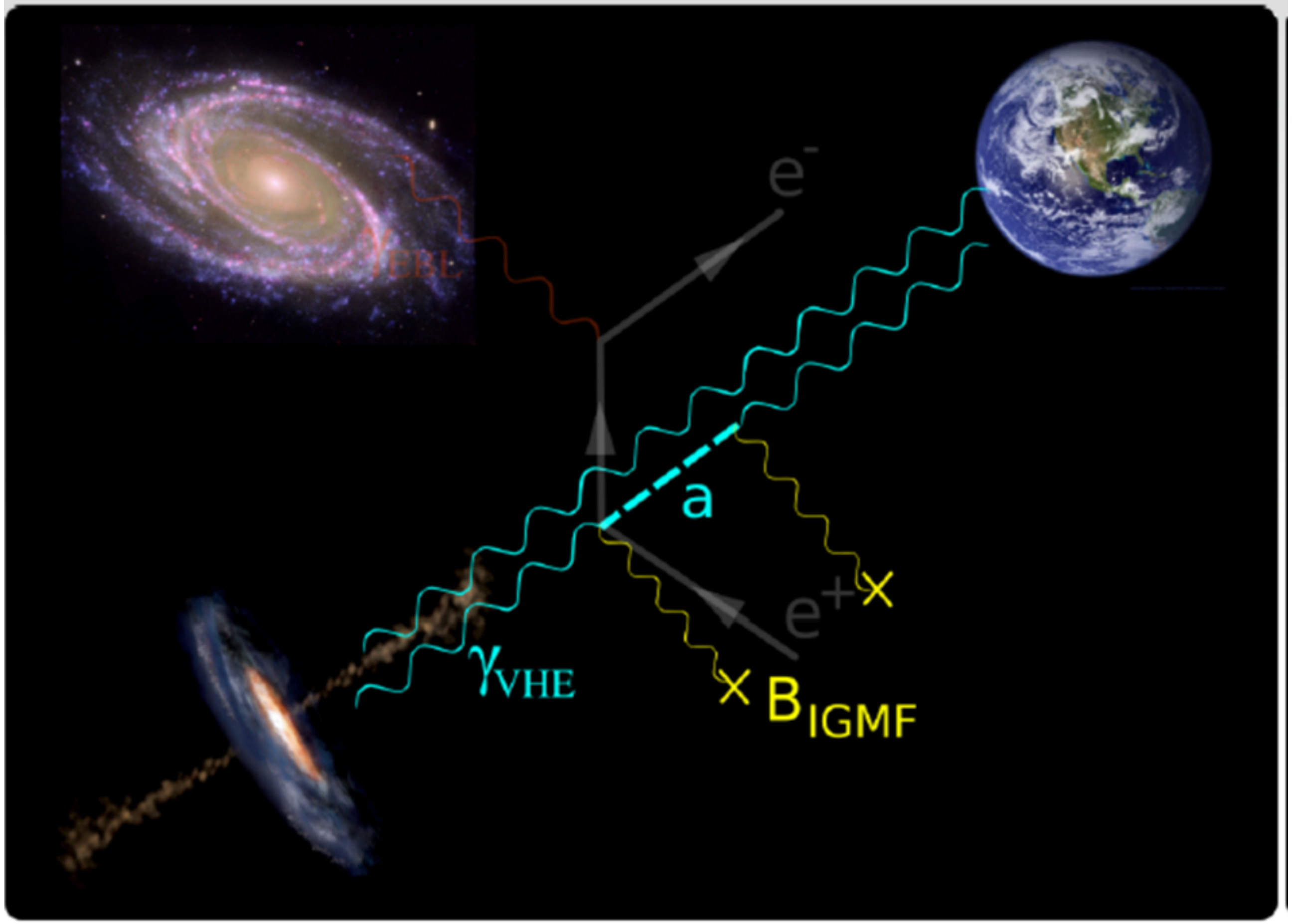


(g)

Photon – ALP Conversion in Cosmic Magnetic Fields?

- Possible explanation: photon <-> ALP conversions in magnetic fields

  [De Angelis et al 07; Simet et al 08; Sanchez-Conde et al 09; Meyer,Horns,Raue 13; Rubtsov,Troitsky 14; Kohri,Kodama 17]



[Manuel Meyer 12]

Photon – ALP Conversion in Cosmic Magnetic Fields?

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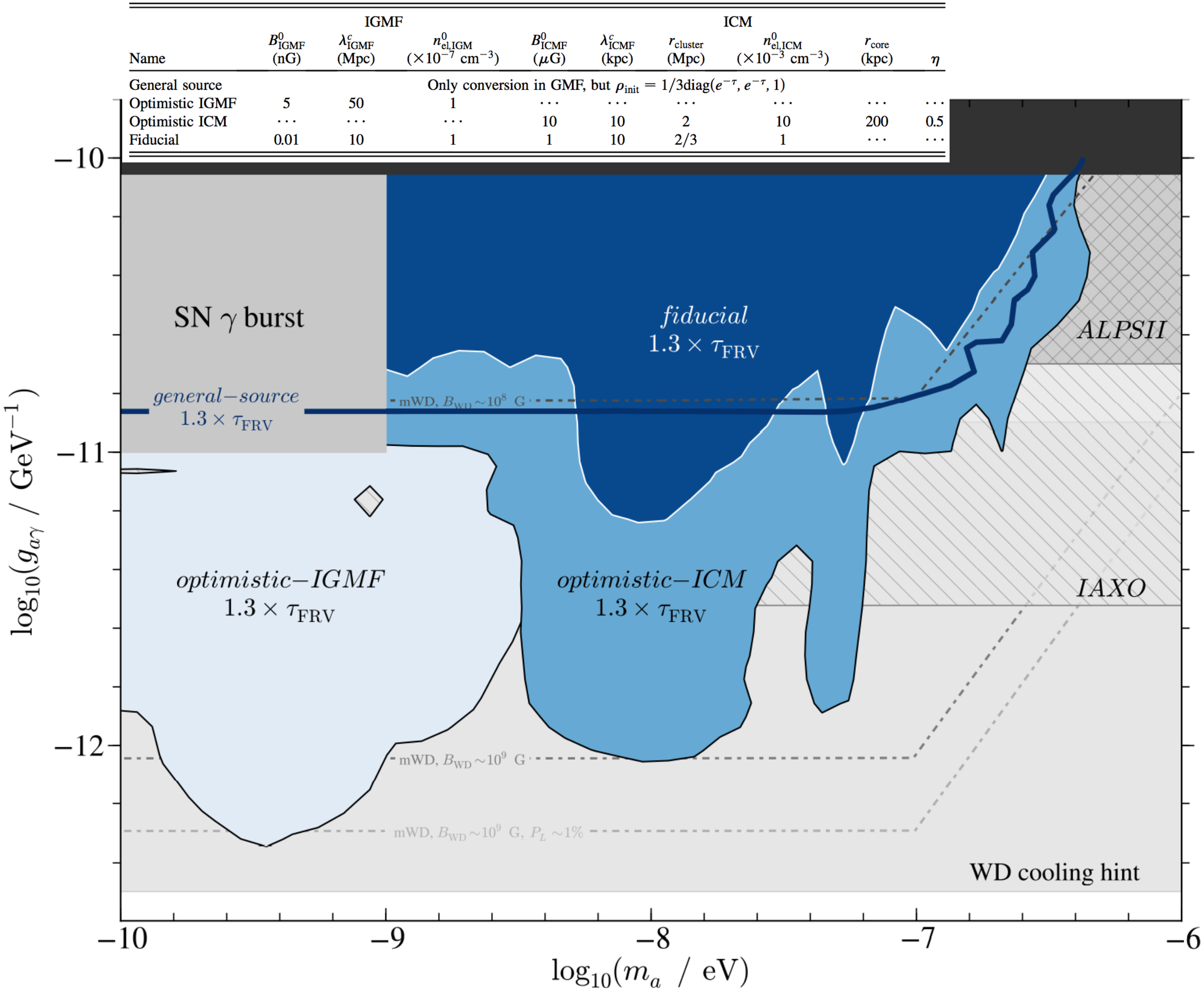
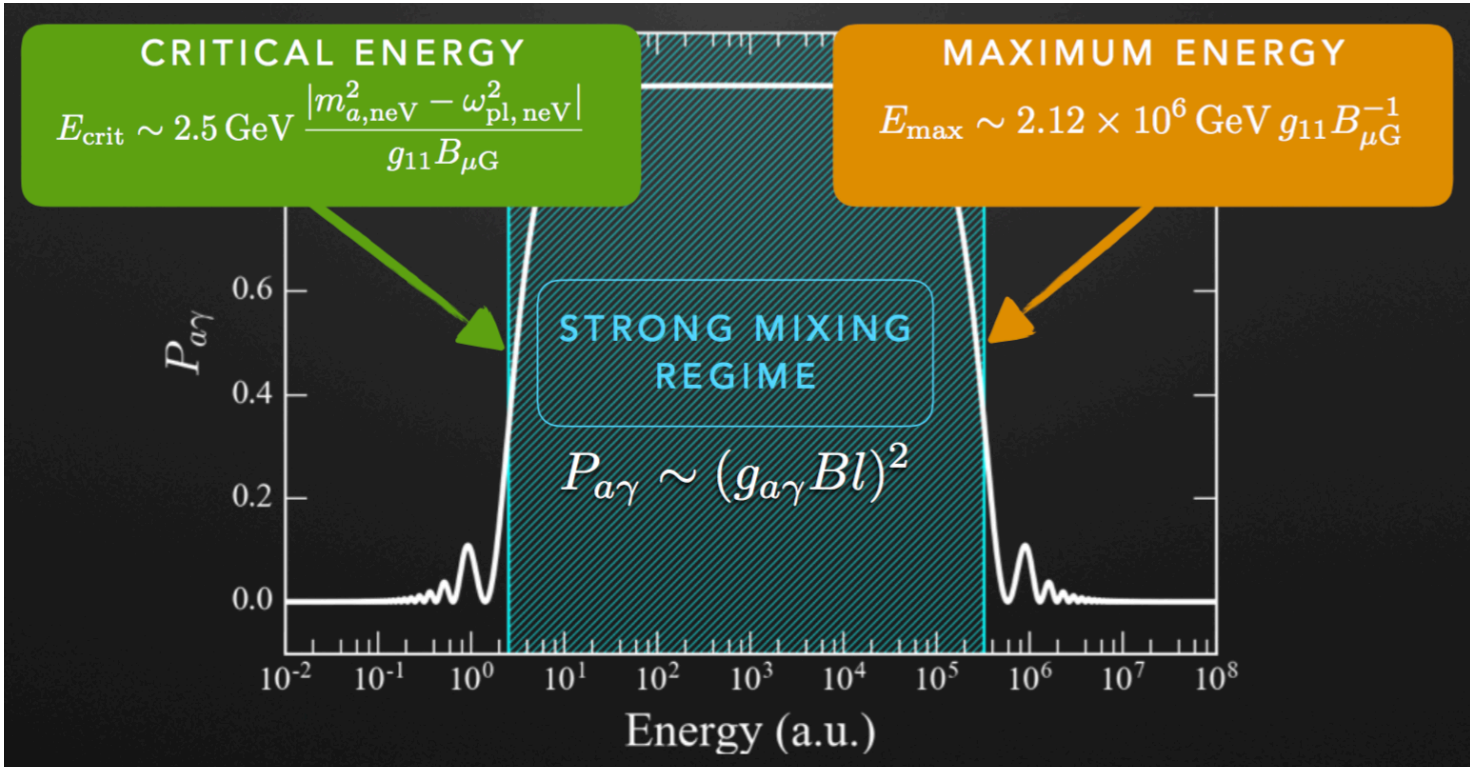


	IGMF			ICM					
Name	$B^0_{\rm IGMF}$ (nG)	$\lambda^c_{\rm IGMF}$ (Mpc)	$n^0_{\rm el,IGM}$ ($\times 10^{-7}$ cm^{-3})	$B^0_{\rm ICMF}$ (μG)	$\lambda^c_{\rm ICMF}$ (kpc)	$r_{\rm cluster}$ (Mpc)	$n^0_{\rm el,ICM}$ ($\times 10^{-3}$ cm^{-3})	$r_{\rm core}$ (kpc)	η
General source	Only conversion in GMF, but $\rho_{\rm init} = 1/3{\rm diag}(e^{-\tau}, e^{-\tau}, 1)$								
Optimistic IGMF	5	50	1	⋯	⋯	⋯	⋯	⋯	⋯
Optimistic ICM	⋯	⋯	⋯	10	10	2	10	200	0.5
Fiducial	0.01	10	1	1	10	2/3	1	⋯	⋯

[Meyer,Horns,Raue 13]

Photon – ALP Conversion in Cosmic Magnetic Fields?

- Part of parameter space of interest ruled out by
  - non-observation of gamma-ray signal from SN 1987 A due to ALP-photon conversion in galactic magnetic field [Brockway et al. 96; Grifols et al. 96; Payez et al. 15]
  - non-observation of spectral irregularities in AGN, due to photon-ALP conversions [Abramowski 13; Ajello et al. 16; Berg et al. 16]


CRITICAL ENERGY

$$E_{\rm crit} \sim 2.5\,{\rm GeV}\,\frac{|m^2_{a,{\rm neV}} - \omega^2_{\rm pl,\,neV}|}{g_{11} B_{\mu{\rm G}}}$$

MAXIMUM ENERGY

$$E_{\rm max} \sim 2.12 \times 10^6\,{\rm GeV}\,g_{11} B^{-1}_{\mu{\rm G}}$$

STRONG MIXING REGIME

$$P_{a\gamma} \sim (g_{a\gamma} B l)^2$$

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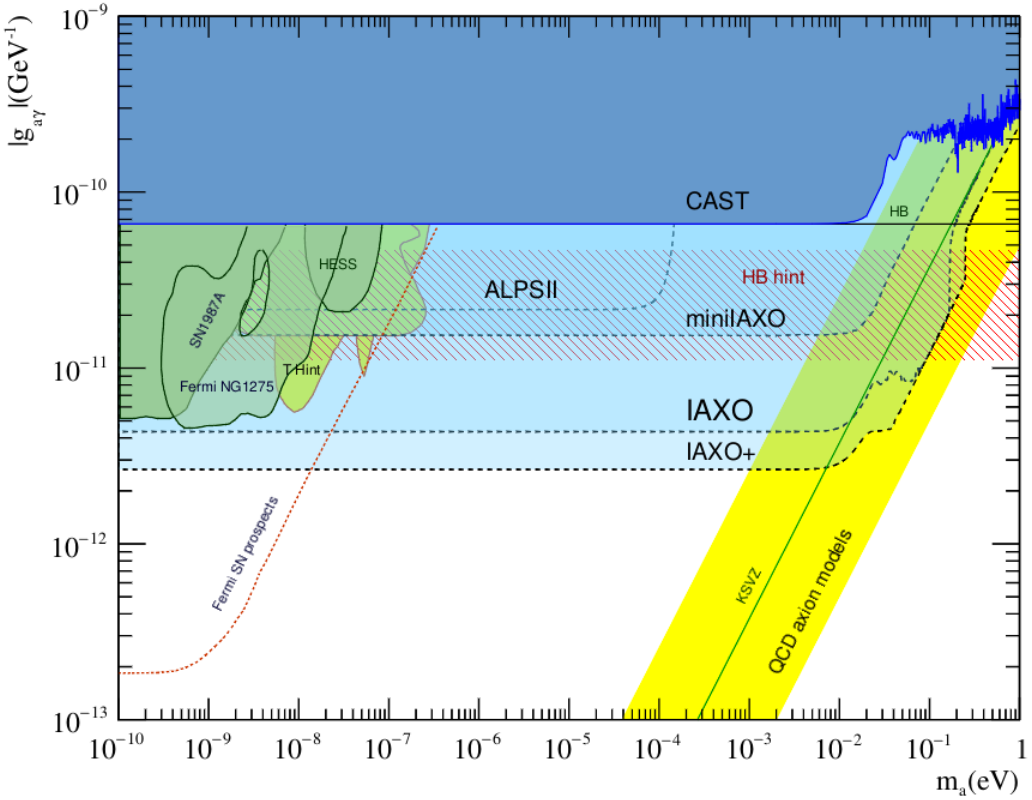
  - non-observation of gamma-ray signal from SN 1987 A due to ALP-photon conversion in galactic magnetic field [Brockway et al. 96; Grifols et al. 96; Payez et al. 15]
  - non-observation of spectral irregularities in AGN, due to photon-ALP conversions [Abramowski 13; Ajello et al. 16; Berg et al. 16]



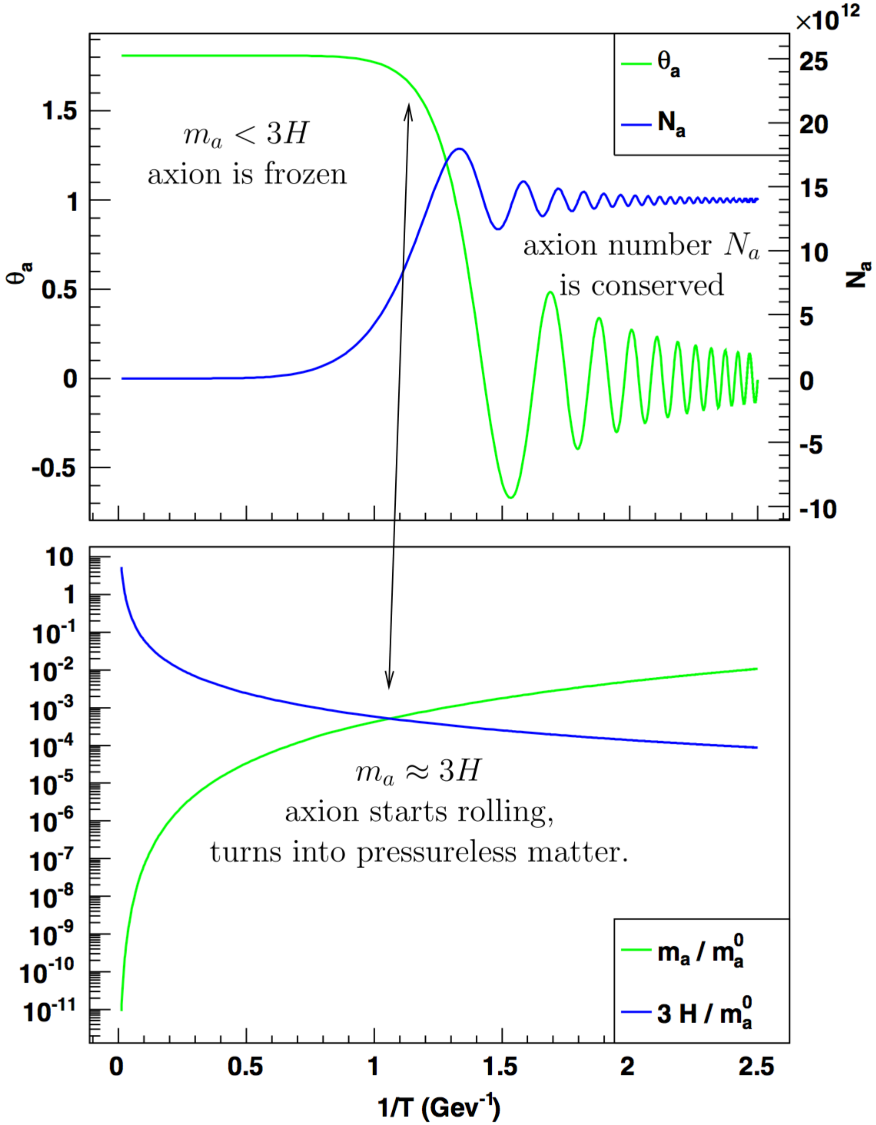
[Irastorza 17]

Axion Cold Dark Matter

> DM from vacuum realignment:

[Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]

- In early universe, axion frozen at random initial value
- Later, field feels pull of mass towards zero and oscillates around it
- Spatially uniform oscillating classical field = coherent state of many, extremely non-relativistic particles = CDM



[Wantz,Shellard `09]

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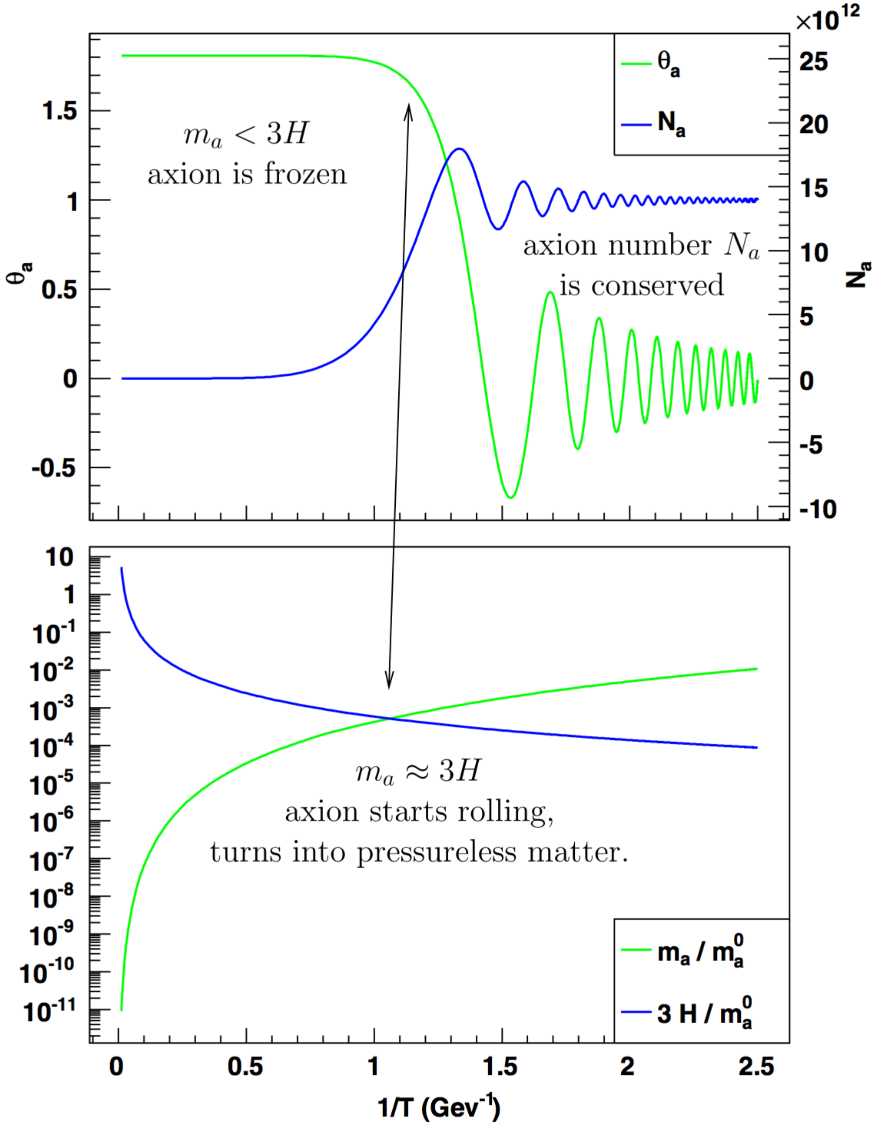
Crucial QCD input for prediction of axion DM abundance:

- Equation of state at temperatures around 1 GeV: determines $H(T)$
- Topological susceptibility:

$$\chi(T) \equiv \int d^4x \langle q(x) q(0) \rangle_T$$

determines $m_A^2(T) = \chi(T)/f_A^2$



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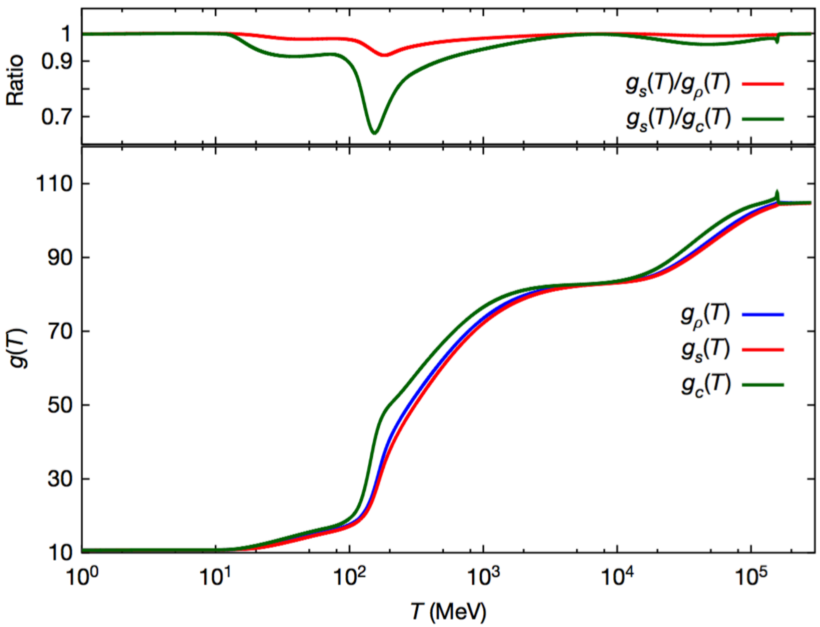
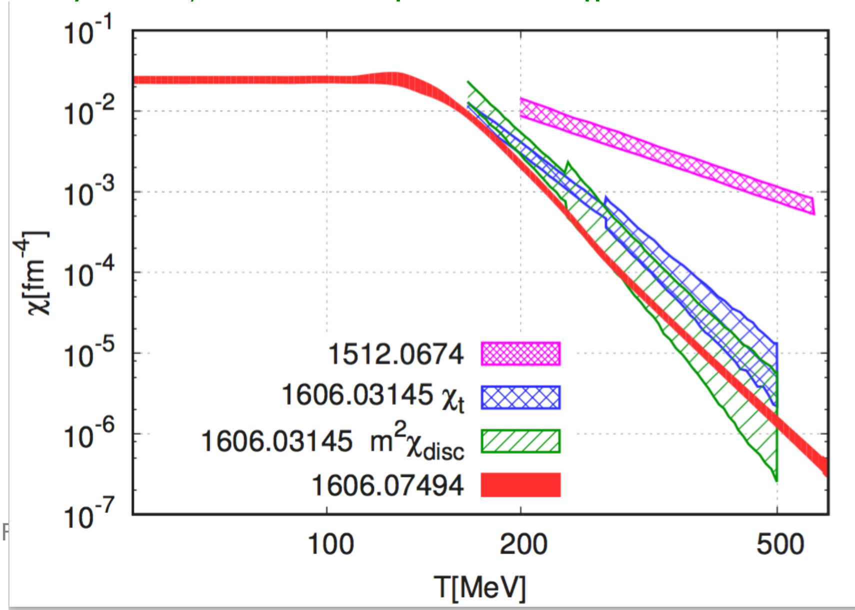
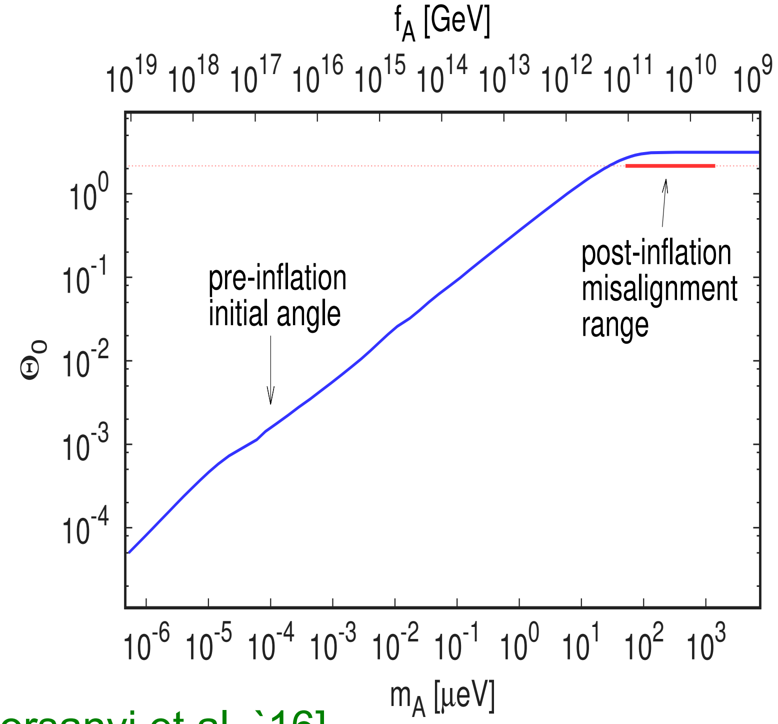


[Borsanyi et al., Nature `16 [1606.0794]]

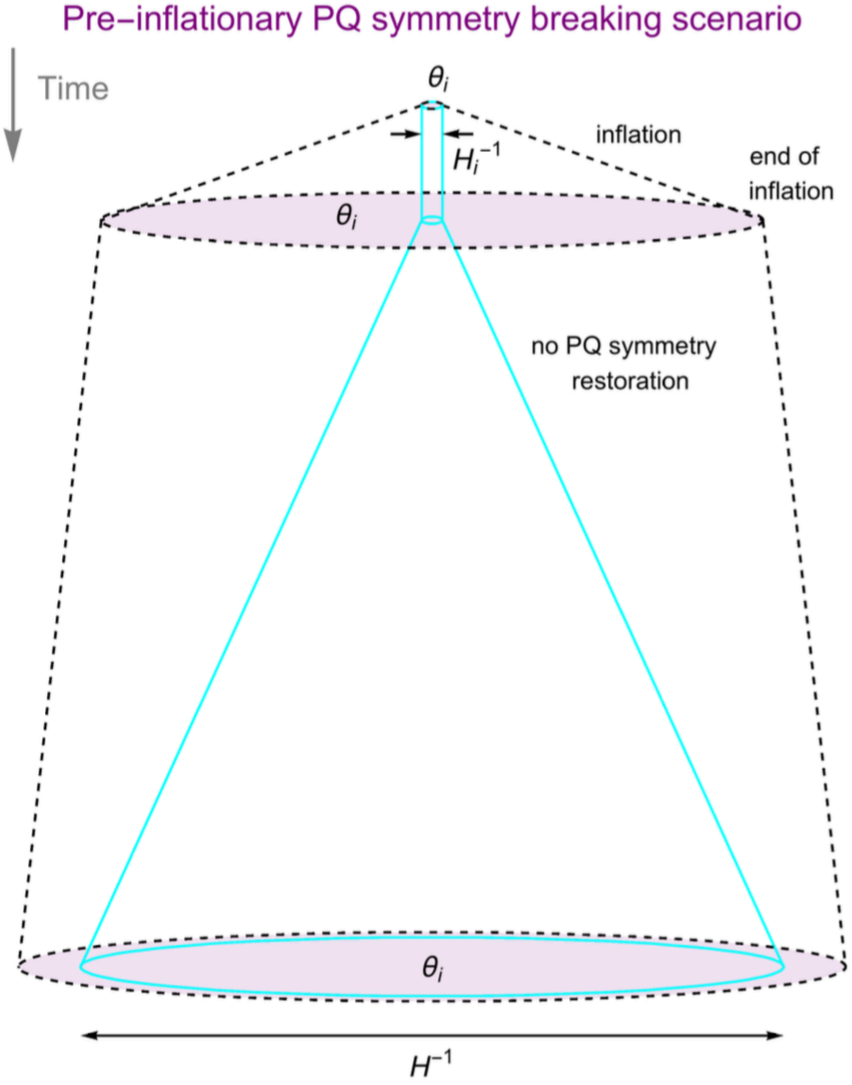


Axion Cold Dark Matter

- If PQ symmetry broken during inflation and not restored afterwards (pre-inflationary PQ breaking scenario)
  - Axion CDM density depends on single initial angle during inflation and f_A



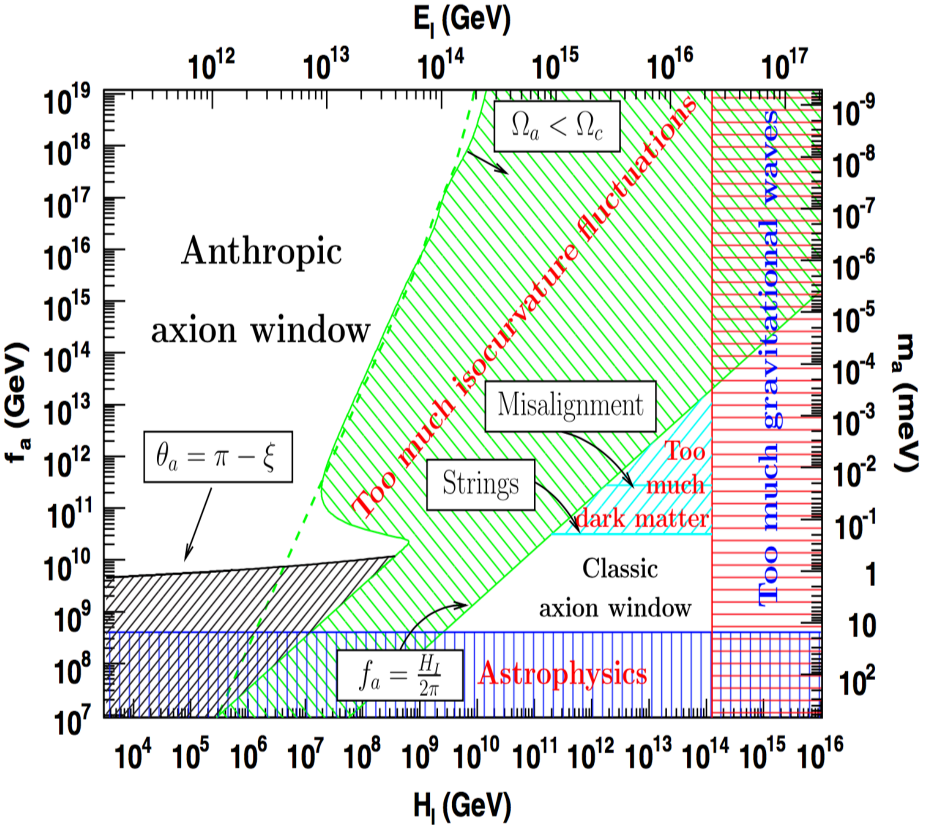
[Borsanyi et al. `16]



[Saikawa]

Axion Cold Dark Matter

- If PQ symmetry broken during inflation and not restored afterwards (pre-inflationary PQ breaking scenario)
  - Axion CDM density depends on single initial angle during inflation and f_A
  - Axion is present during inflation and creates isocurvature fluctuations which are not erased after inflation



[Wilczek,Turner `91; Beltran et al. 06; Hertzberg,Tegmark,Wilczek 08; Visinelli,Gondolo 09; Hamann et al. 09; **Wantz,Shellard 09**]

Axion Cold Dark Matter

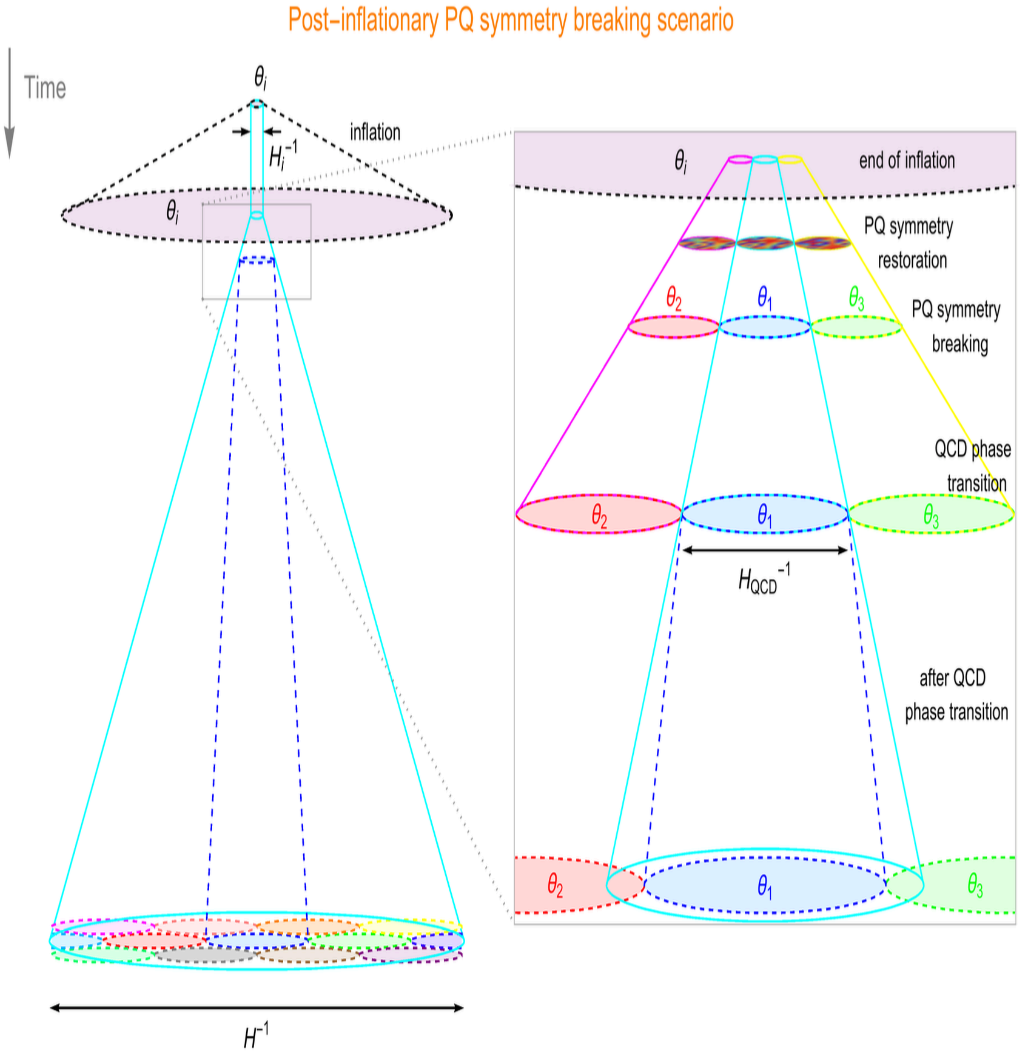
- If Peccei-Quinn symmetry restored after inflation (post-inflationary PQ breaking scenario)
  - Vacuum realignment contribution depends on spatially averaged initial misalignment angle and f_A

$$\Omega_{A,\mathrm{real}} h^2 = (3.8 \pm 0.6) \times 10^{-3} \times \left(\frac{f_A}{10^{10}\,\mathrm{GeV}} \right)^{1.165}$$

  - Upper limit on f_A from requirement that realignment contribution should not exceed DM abundance gives lower limit on axion mass:

$$m_A > 28(2)\ \mu\mathrm{eV}$$

[Borsanyi et al. `16]



[Saikawa]

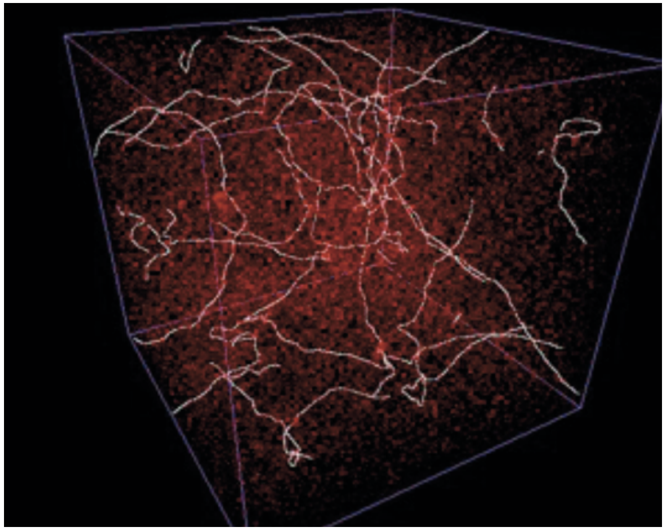
Axion Cold Dark Matter

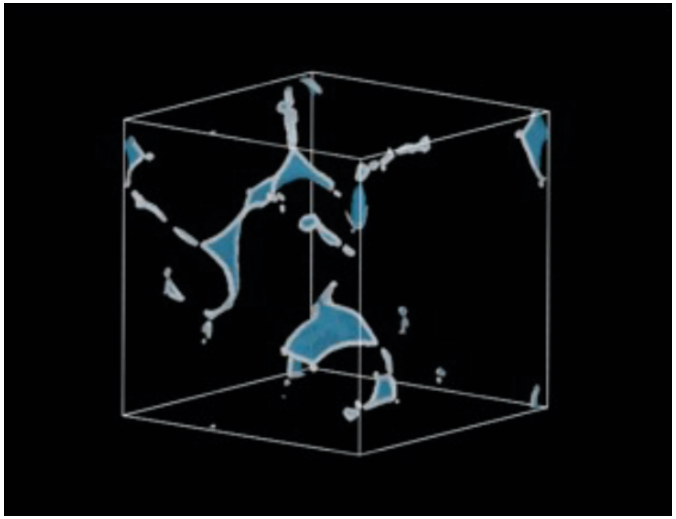
- If Peccei-Quinn symmetry restored after inflation (post-inflationary PQ breaking scenario)
  - Additional contributions arise from decay of topological defects (axion strings and axion domain walls)

$$\Omega_{A,\mathrm{tot}}h^2 = \Omega_{A,\mathrm{real}}h^2 + \Omega_{A,\mathrm{string}}h^2 + \Omega_{A,\mathrm{wall}}h^2$$

  - Latter determined by lattice simulations of cosmic string and wall networks

    [Hiramatsu et al. 12; Kawasaki et al. 15]





[Hiramatsu et al. 12]

Axion Cold Dark Matter

> If Peccei-Quinn symmetry restored after inflation (post-inflationary PQ breaking scenario)

- For $N_{\rm DW}=1$, string-wall systems short lived, leading to

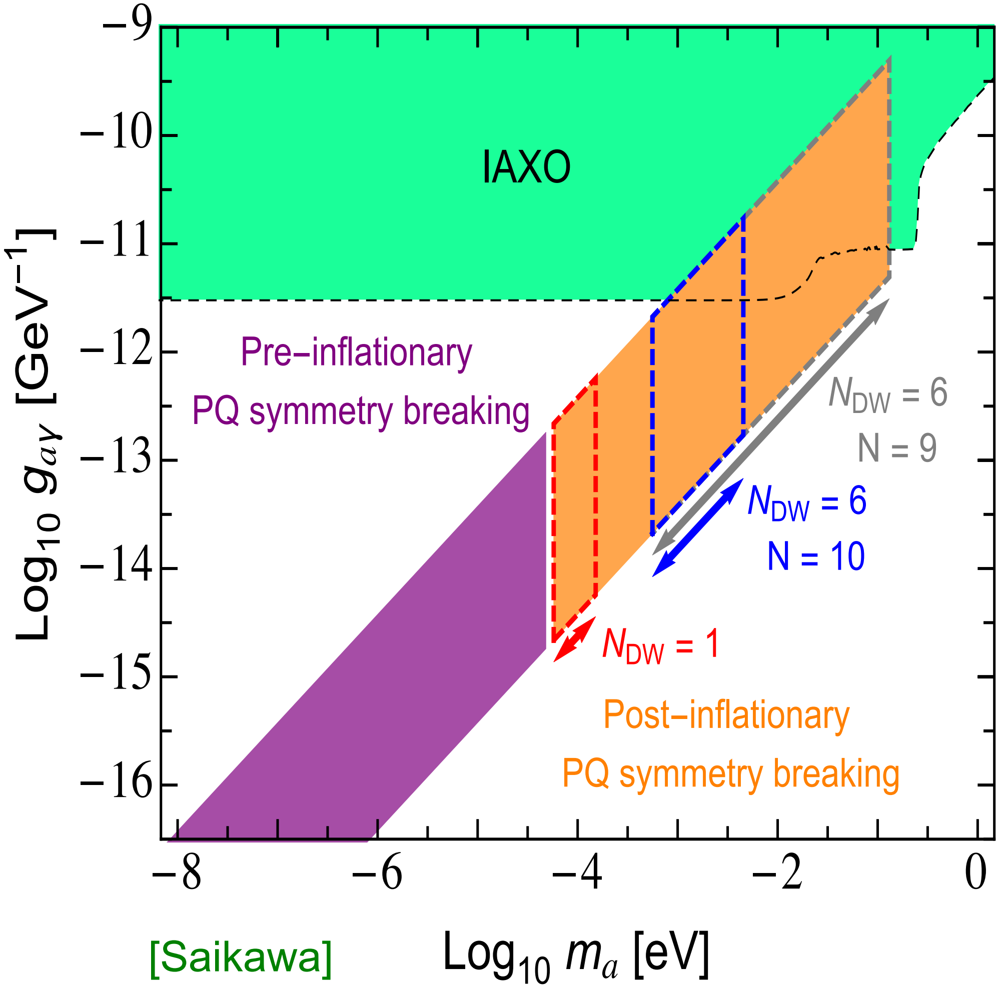
$$\Omega_{A,{\rm tot}}h^2 \approx 1.6^{+1.0}_{-0.7}\times 10^{-2}\times\left(\frac{f_A}{10^{10}\,{\rm GeV}}\right)^{1.165}$$

CDM explained for

$$m_A \approx (50\text{–}200)\,\mu{\rm eV}$$

- For $N_{\rm DW}>1$, string-wall systems absolutely stable, eventually overclosing Universe, unless PQ symmetry explicitely broken e.g. by Planck suppressed operators $\Delta V = g\sigma^N/M_{\rm P}^{N-4}$

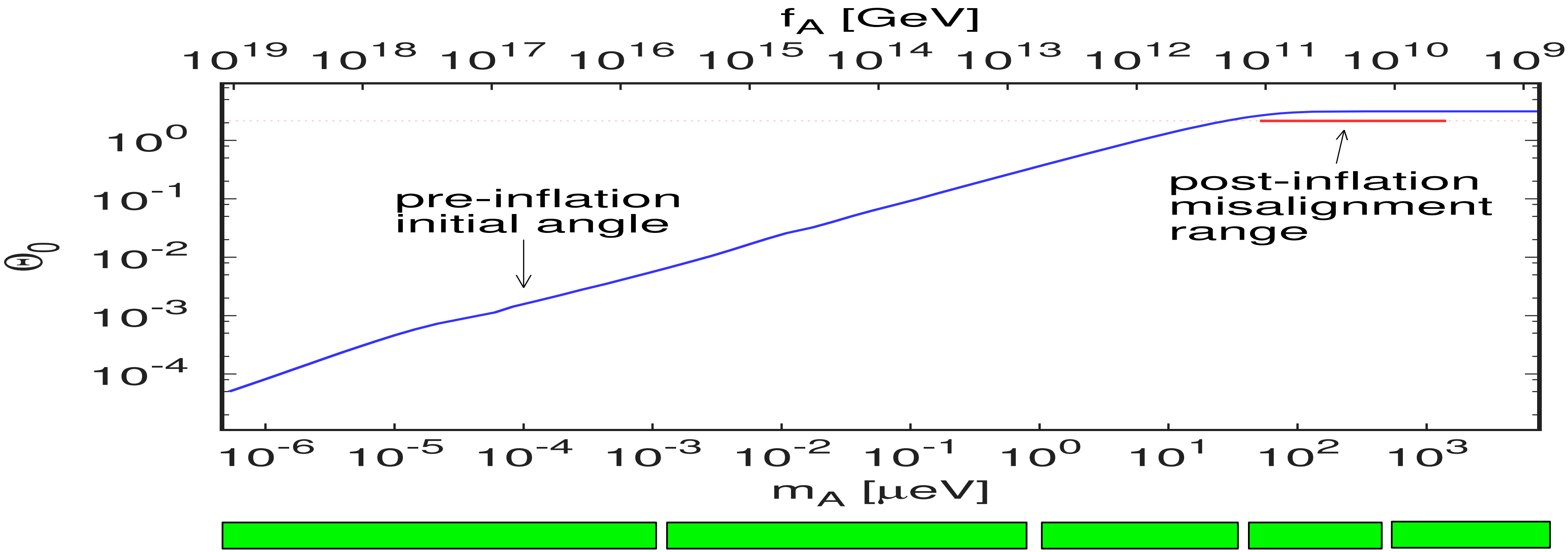
[AR,Saikawa `16]



[Saikawa]

Axion Dark Matter Direct Detection Experiments

- Upcoming generation of axion dark matter direct detection experiments can probe entire mass range:



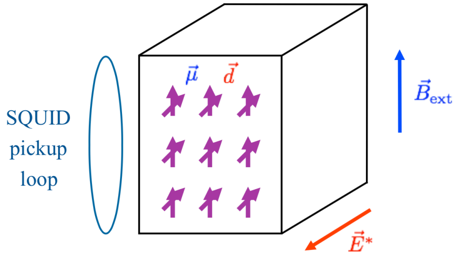
CASPEr

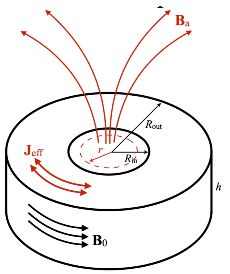
ABRACADABRA

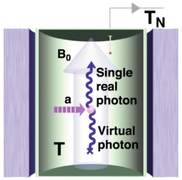
ADMX
HAYSTACK
CULTASK

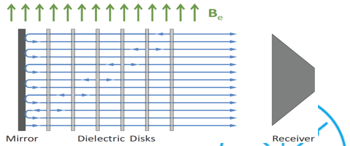
MADMAX
ORPHEUS
ORGAN
QUAX

BRASS







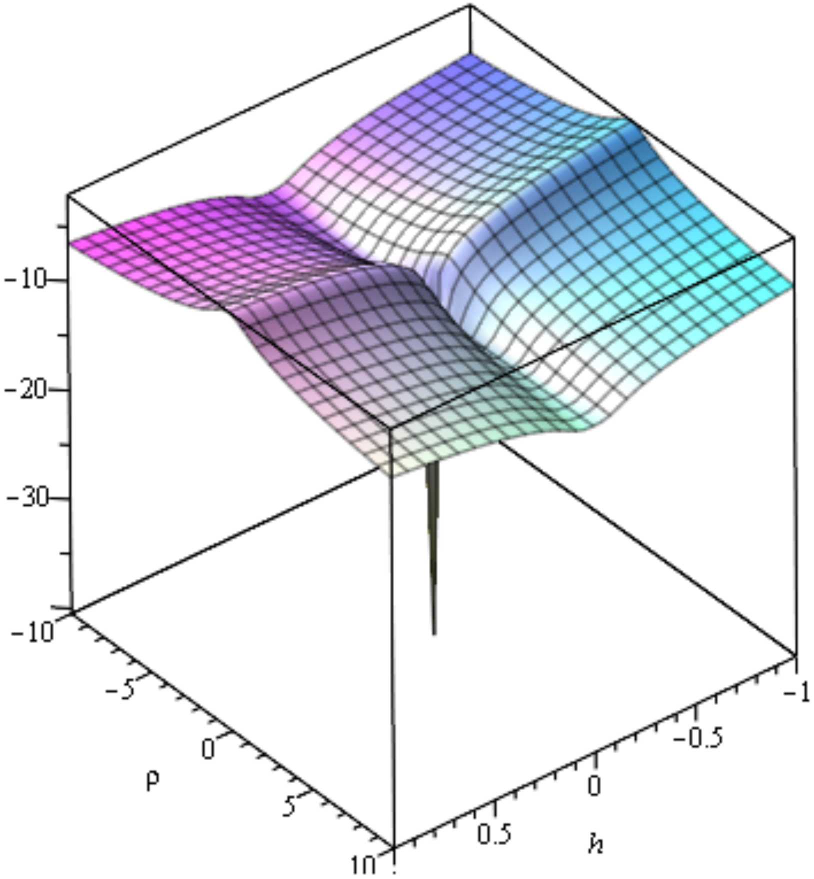


Unifying Inflation and Dark Matter with PQ Field

- $\mid \sigma \mid = \rho/\sqrt{2}$ or mixture with Higgs modulus may play role of inflaton, if it has non-minimal coupling to gravity,

$$S \supset - \int d^4x \sqrt{-g} \left[\frac{M^2}{2} + \xi_\sigma \, \sigma^* \sigma \right] R$$

[Fairbairn,Hogan,Marsh `14]



[Ballesteros,Redondo, AR,Tamarit `16]

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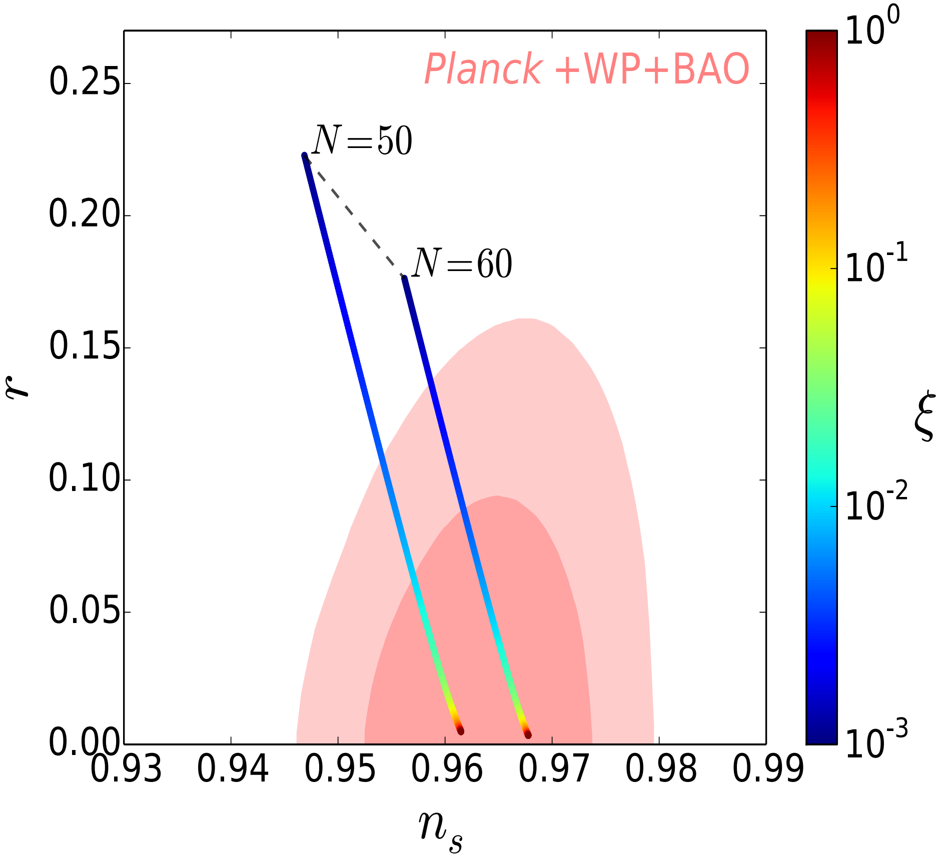
[Fairbairn,Hogan,Marsh `14]

- CMB observables

$$A_s = (2.20 \pm 0.08) \times 10^{-9}\,,$$
$$n_s = 0.967 \pm 0.004\,,$$
$$r < 0.07$$

fit by

$$\xi \simeq 2 \times 10^5 \sqrt{\lambda} \gtrsim 10^{-3}$$



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Unifying Inflation and Dark Matter with PQ Field

- PQ symmetry restored after inflation already in preheating stage when PQ field undergoes Hubble damped oscillations in quartic potential

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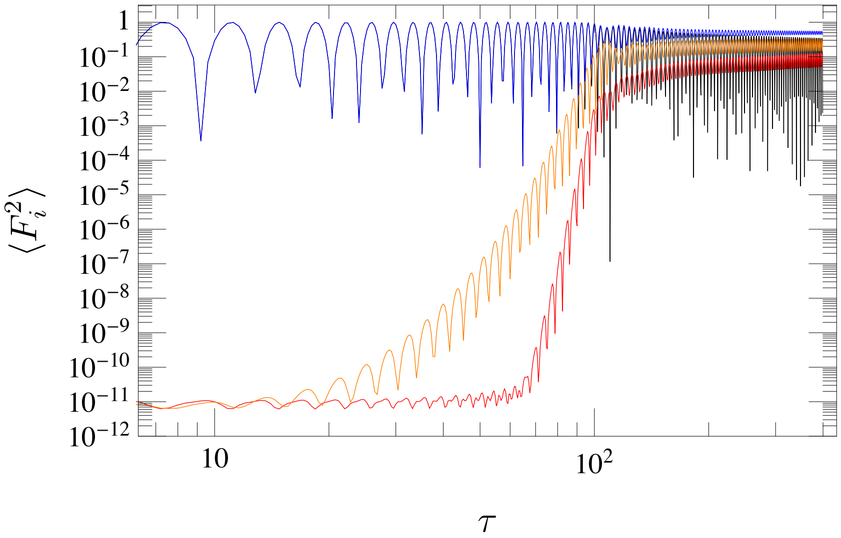

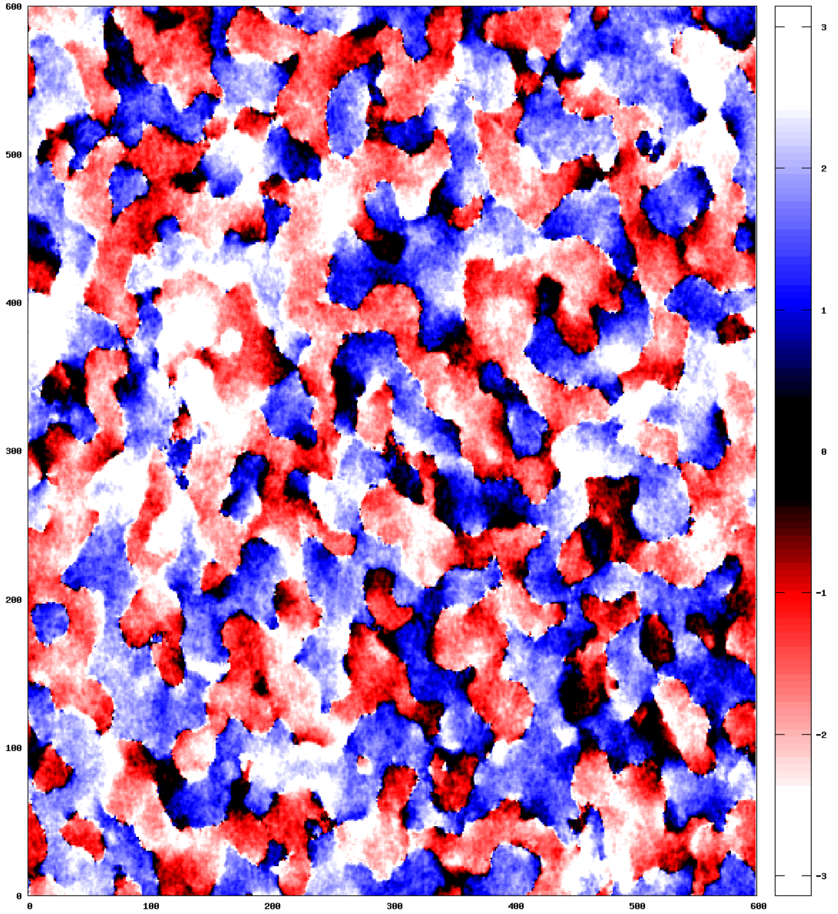

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- PQ symmetry restored after inflation already in preheating stage when PQ field undergoes Hubble damped oscillations in quartic potential

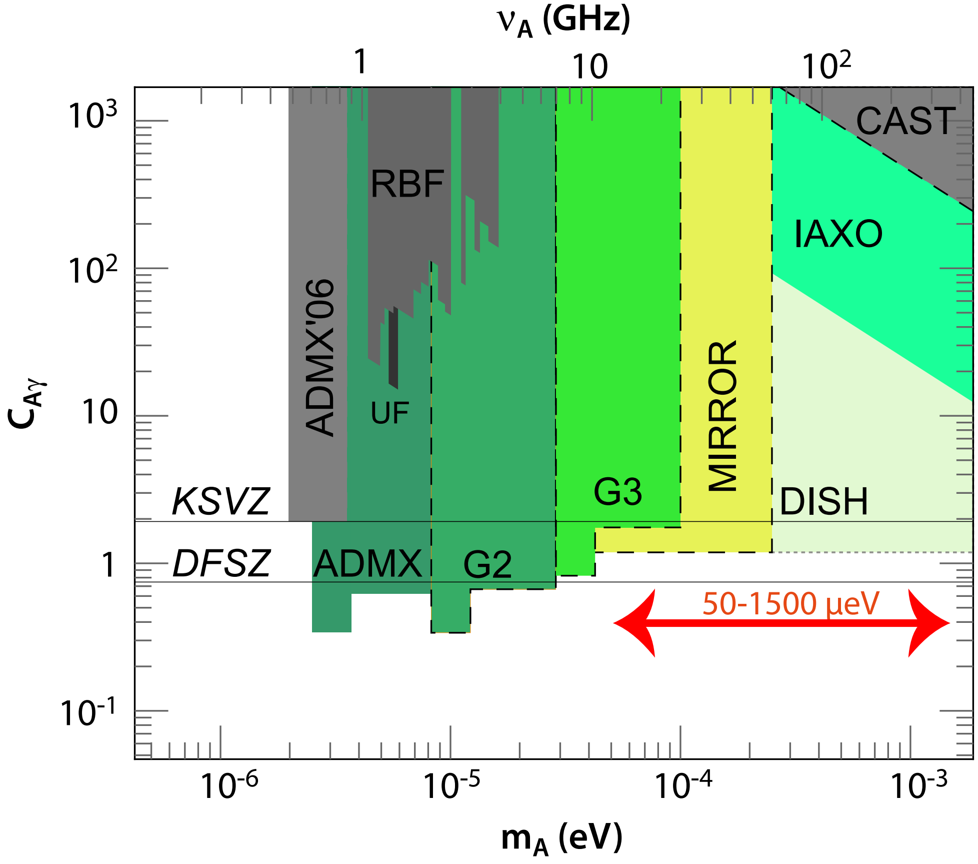
  [Ballesteros,Redondo, AR,Tamarit `16]

- Axion mass predicted
  - For $N_{\rm DW} = 1$:

    $$50\,\mu{\rm eV} \lesssim m_A \lesssim 200\,\mu{\rm eV}$$

  - For $N_{\rm DW} > 1$:

    $$100\,\mu{\rm eV} \lesssim m_A \lesssim 10\,{\rm meV}$$



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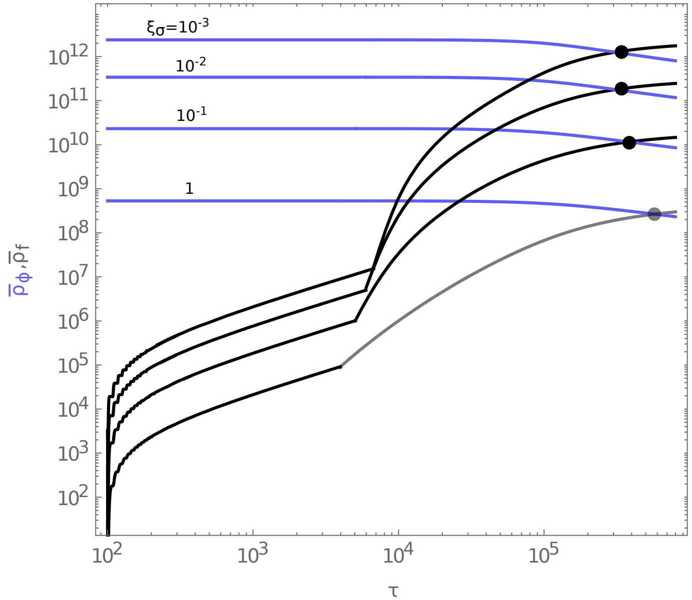
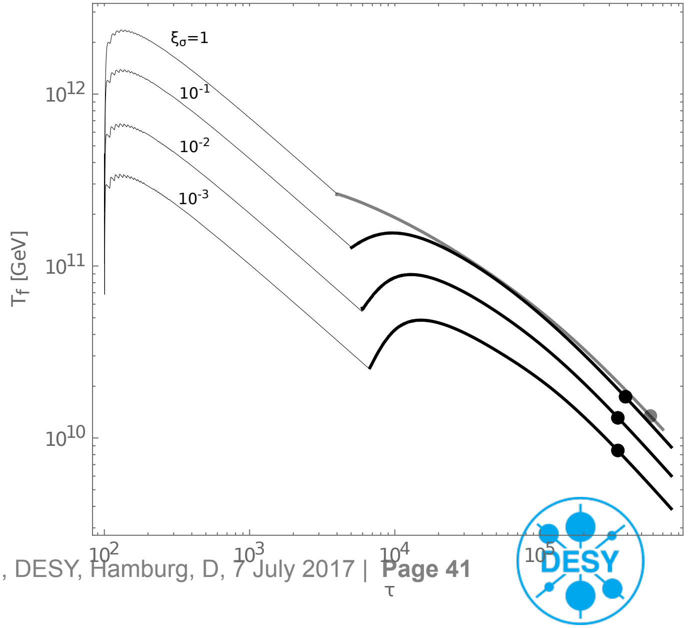


- Axion mass predicted

- Large reheating temperature
  - $10^7\,\mathrm{GeV}$ for pure PQ scalar inflation $(\lambda_{H\sigma} > 0)$
  - $10^{10}\,\mathrm{GeV}$ for mixed PQ scalar/ Higgs inflation $(\lambda_{H\sigma} < 0)$



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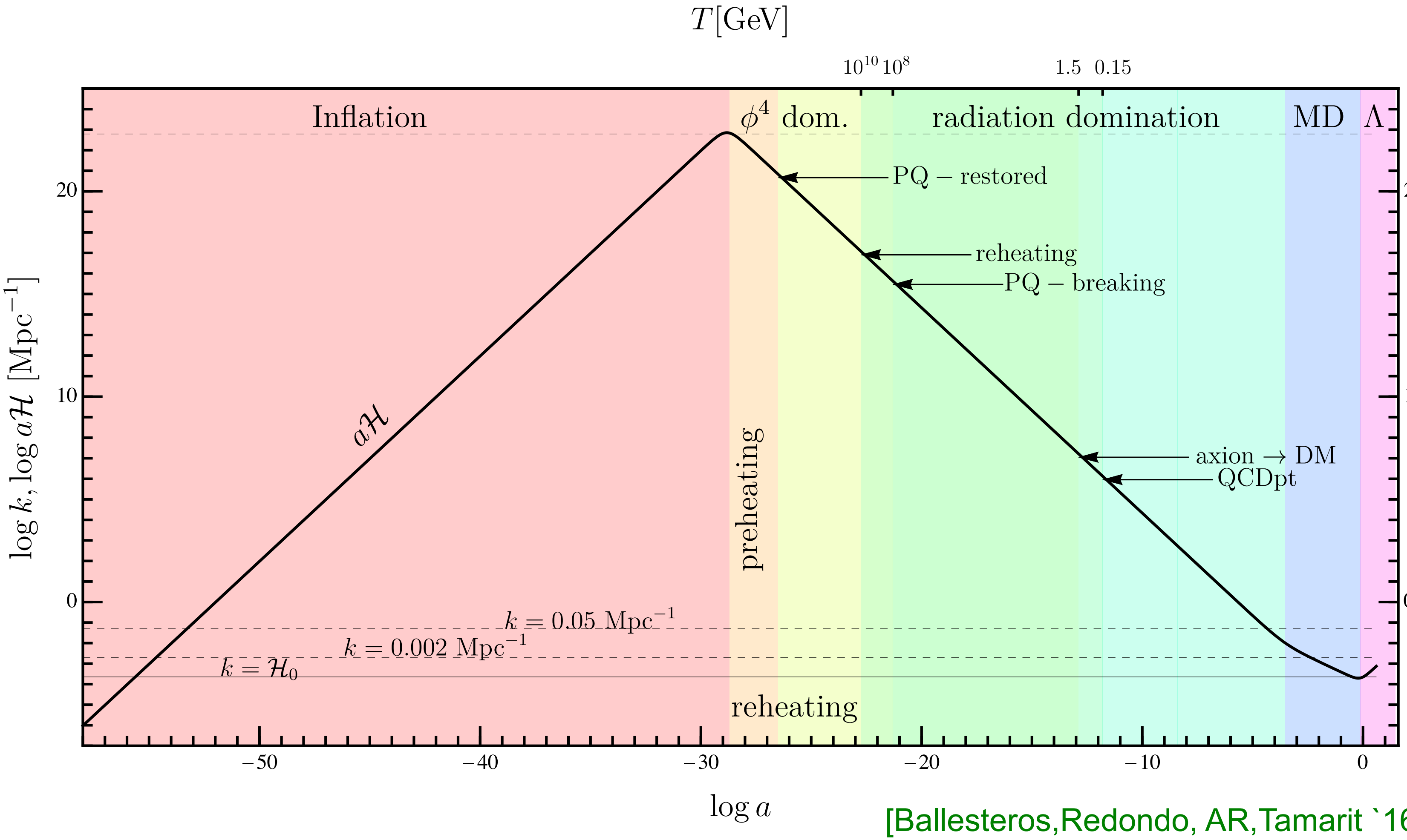
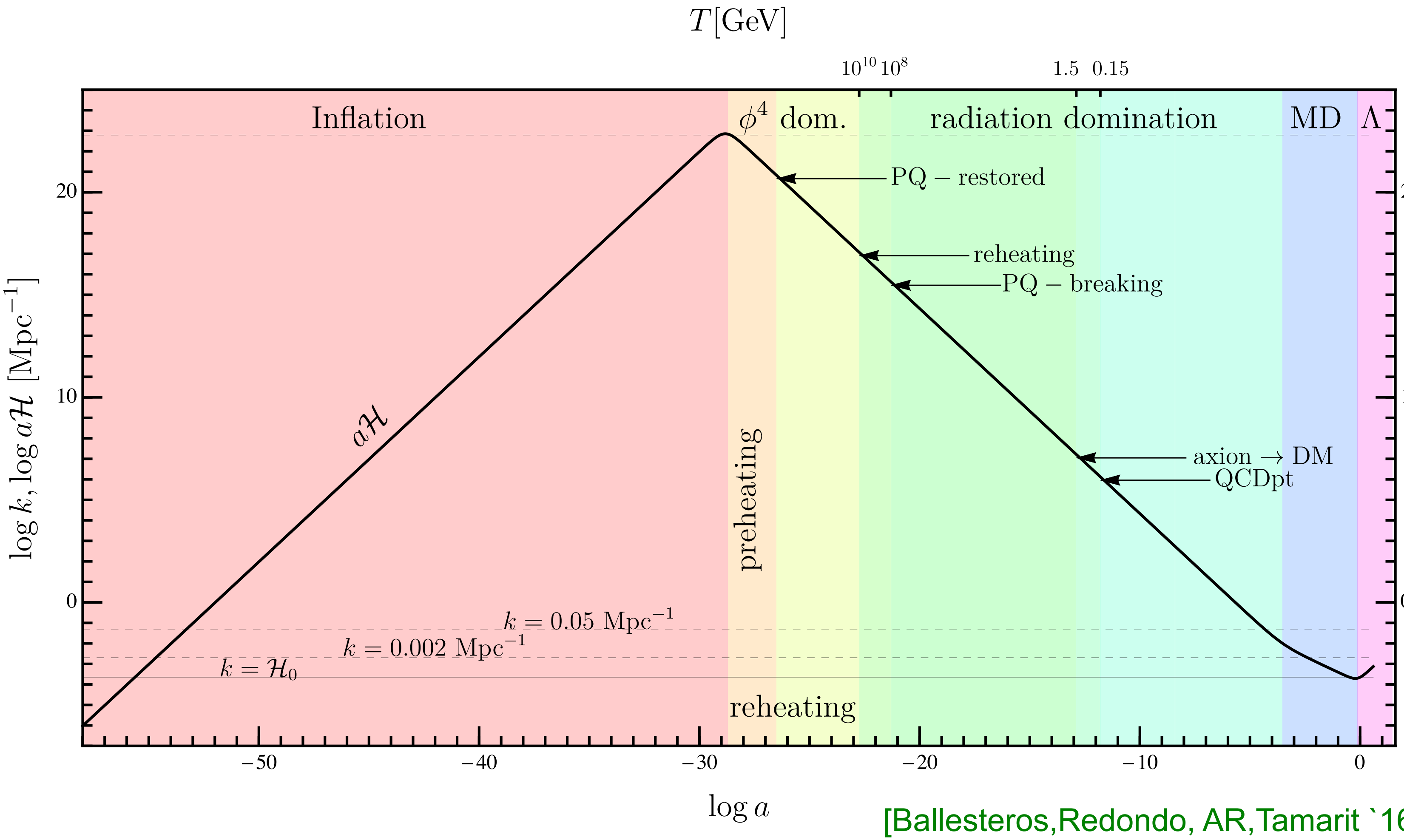


[Ballesteros,Redondo, AR,Tamarit `16]

- Universe expands as in a radiation-dominated era ($w = 1/3$) from the end of inflation until matter-radiation equality

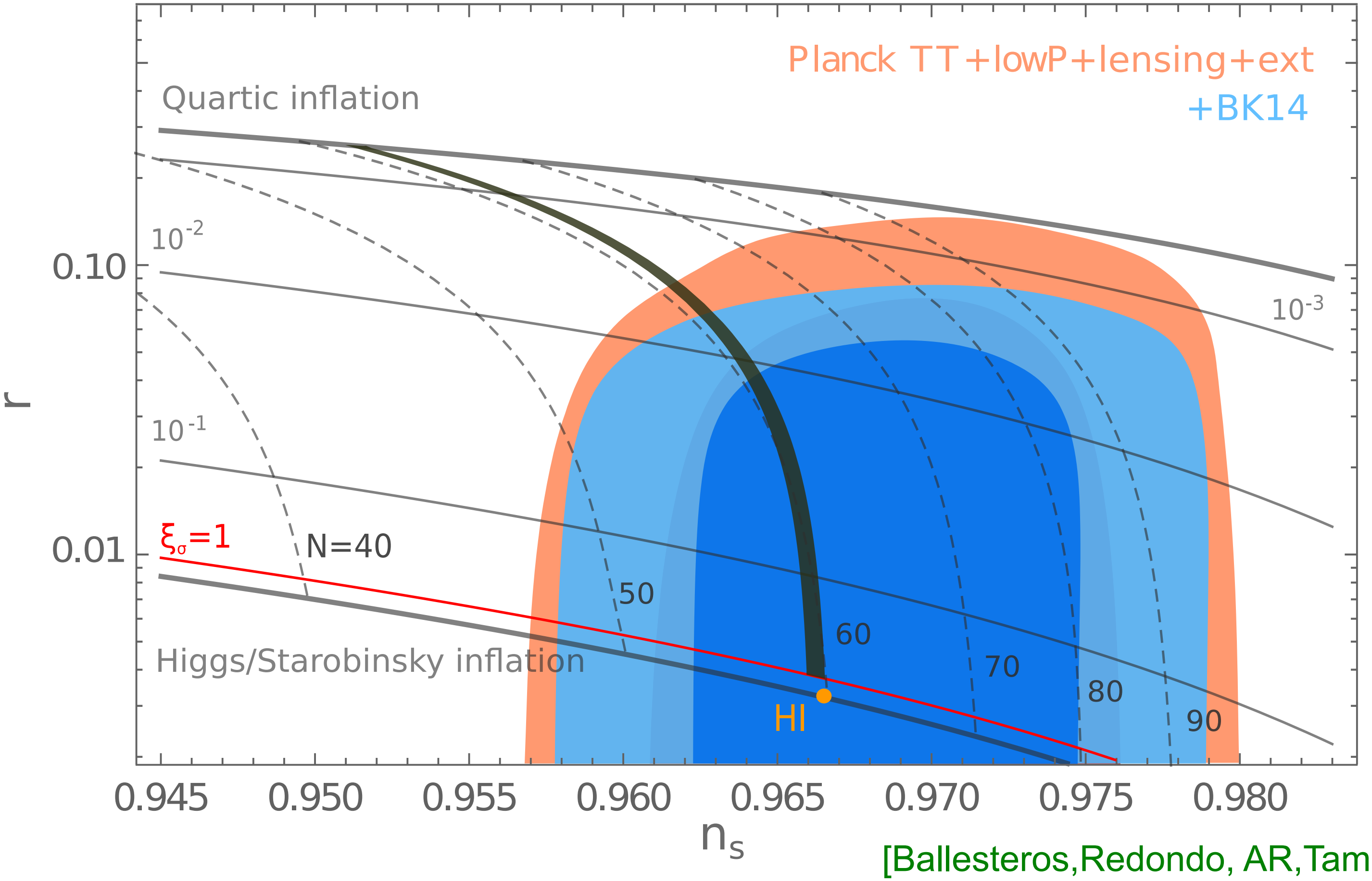
Unifying Inflation and Dark Matter with PQ Field



[Ballesteros,Redondo, AR,Tamarit `16]

- Allows to calculate number of e-folds $N(k) = \ln\left(a_{\mathrm{end}}/a(k)\right)$ from the time a given comoving scale k leaves horizon until end of inflation [Liddle,Leach 03]

Unifying Inflation and Dark Matter with PQ Field



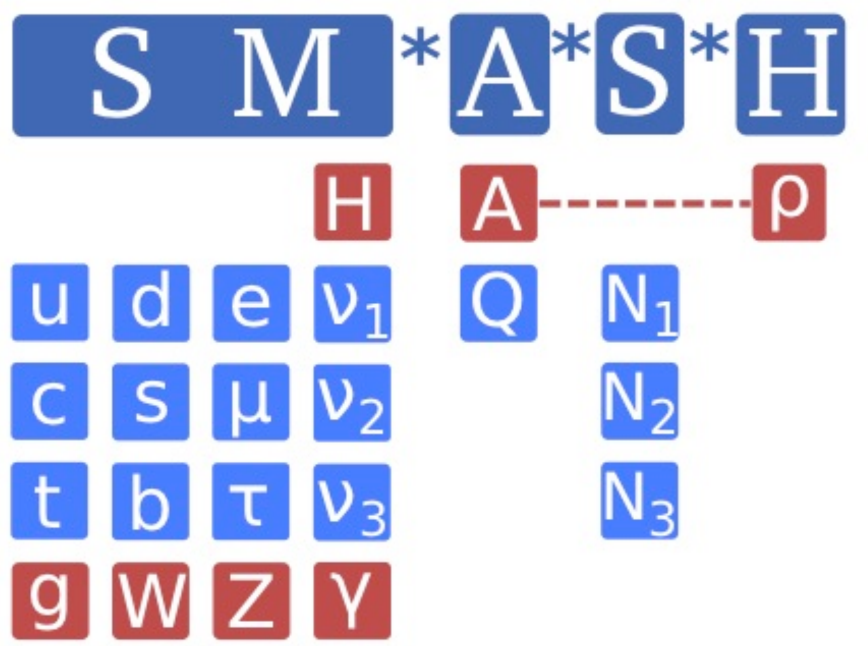
[Ballesteros,Redondo, AR,Tamarit `16]

- Sharp prediction of r vs n_s for fixed pivot scale, e.g. $k_0 = 0.002\ \mathrm{Mpc}^{-1}$
- Can be probed decisively by next generation CMB experiments (e.g. LiteBIRD, PRISM)

Unifying Inflation, Dark Matter, and Seesaw with PQ Field

- Augmenting axion models with three SM singlet neutrinos, getting their Majorana masses also through the vev $v_\sigma = N_{\rm DW} f_A$
  - no strong CP problem
  - dark matter
  - inflation
  - neutrino masses and mixing
  - baryogenesis via leptogenesis

[Dias et al. `14; Ballesteros et al. `16]



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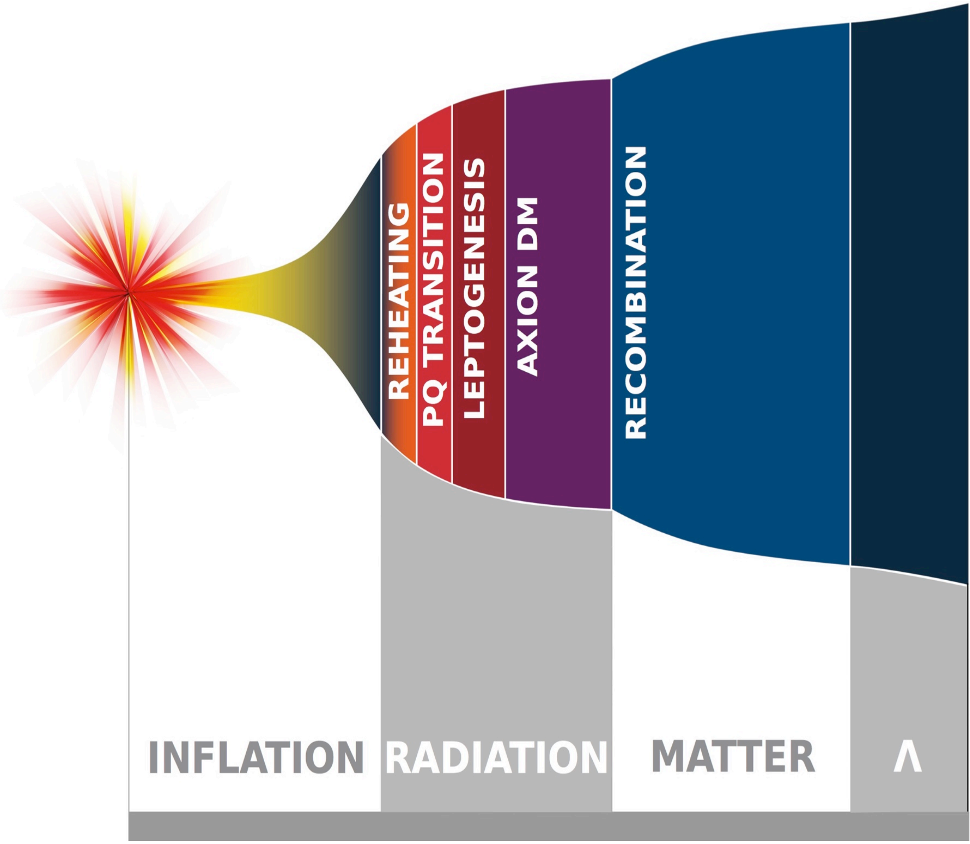
[Dias et al. \`14; Ballesteros et al. \`16]

- Complete and consistent history of the universe from inflation to now



[desy.de]

Summary

- Axion/ALPs may explain puzzles from astrophysics and cosmology:
    - Dark matter
    - Stellar energy losses
    - Anomalous transparency of the universy for gamma rays

- Relevant parameter range can will be probed decisively by next generation experiments