Dark Matter

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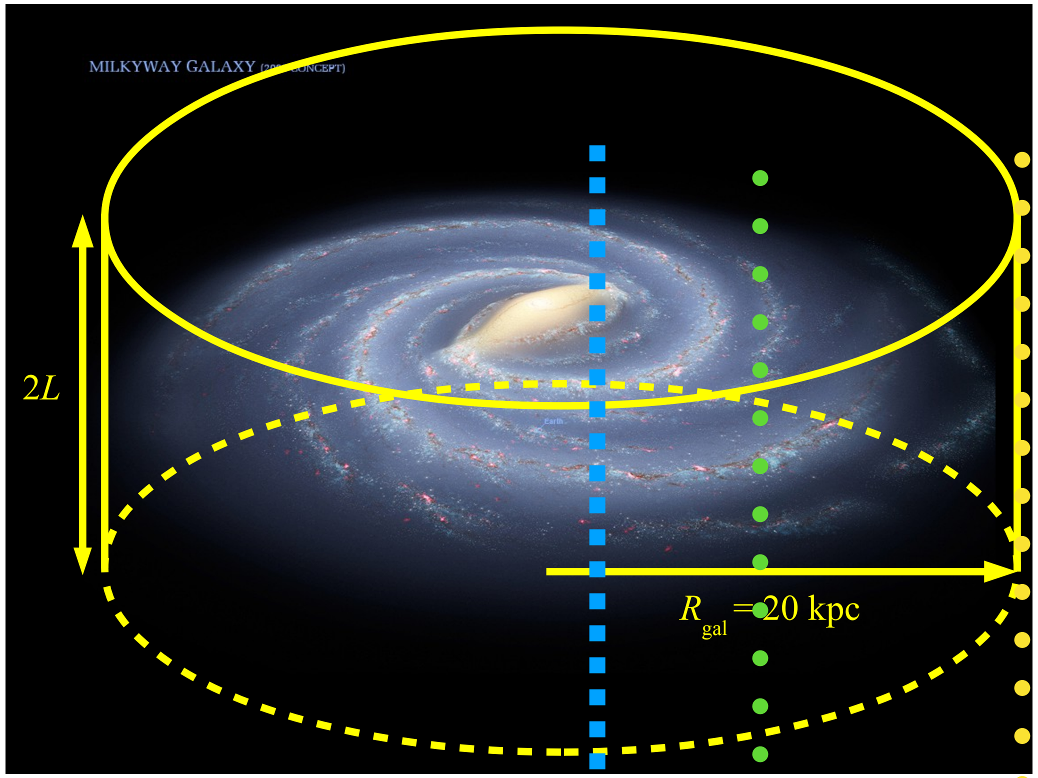
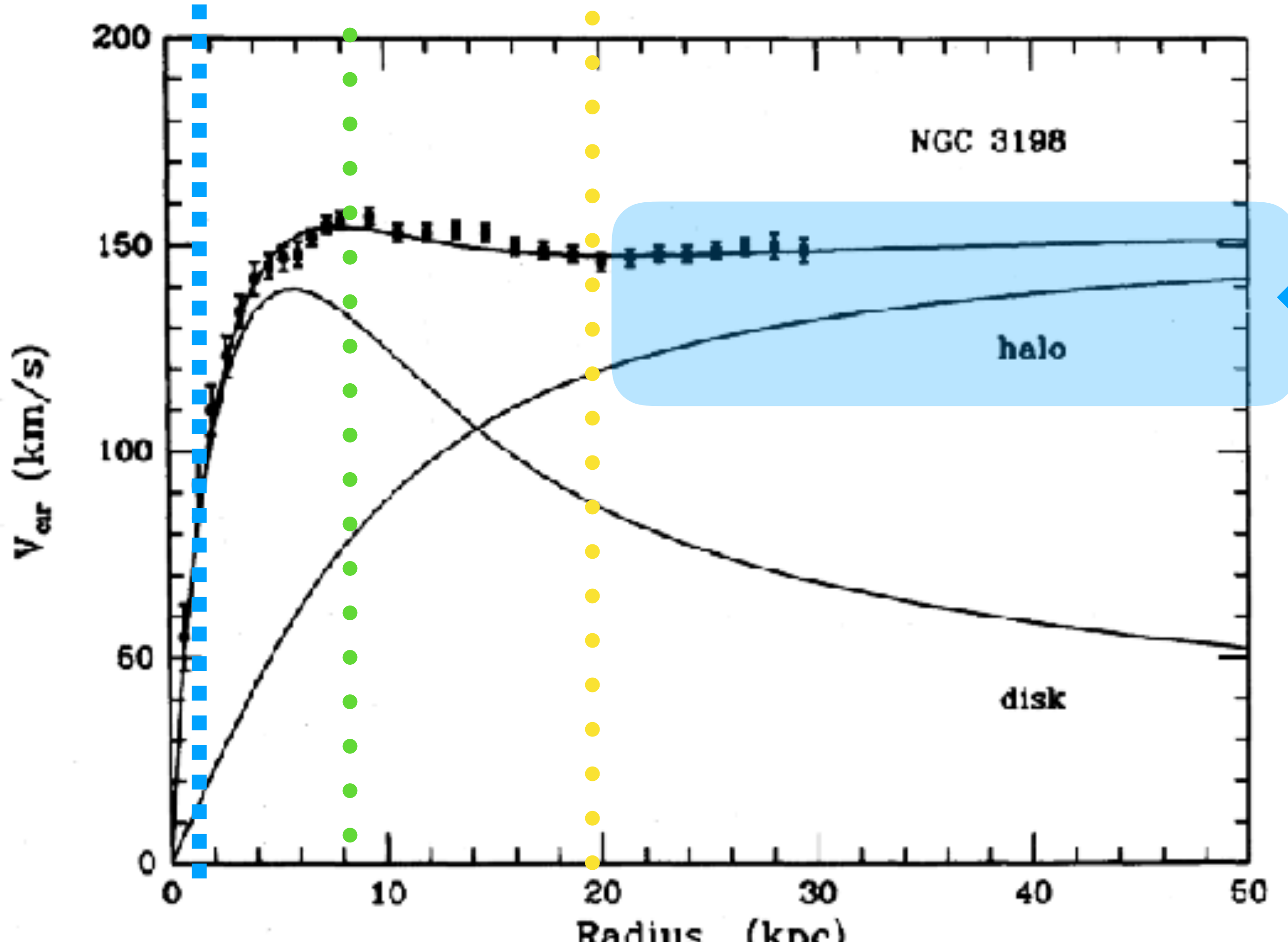
LAPTH, Annecy

DESY, Oct 2017

Recap of previous lecture

There is a halo of dark matter all around us





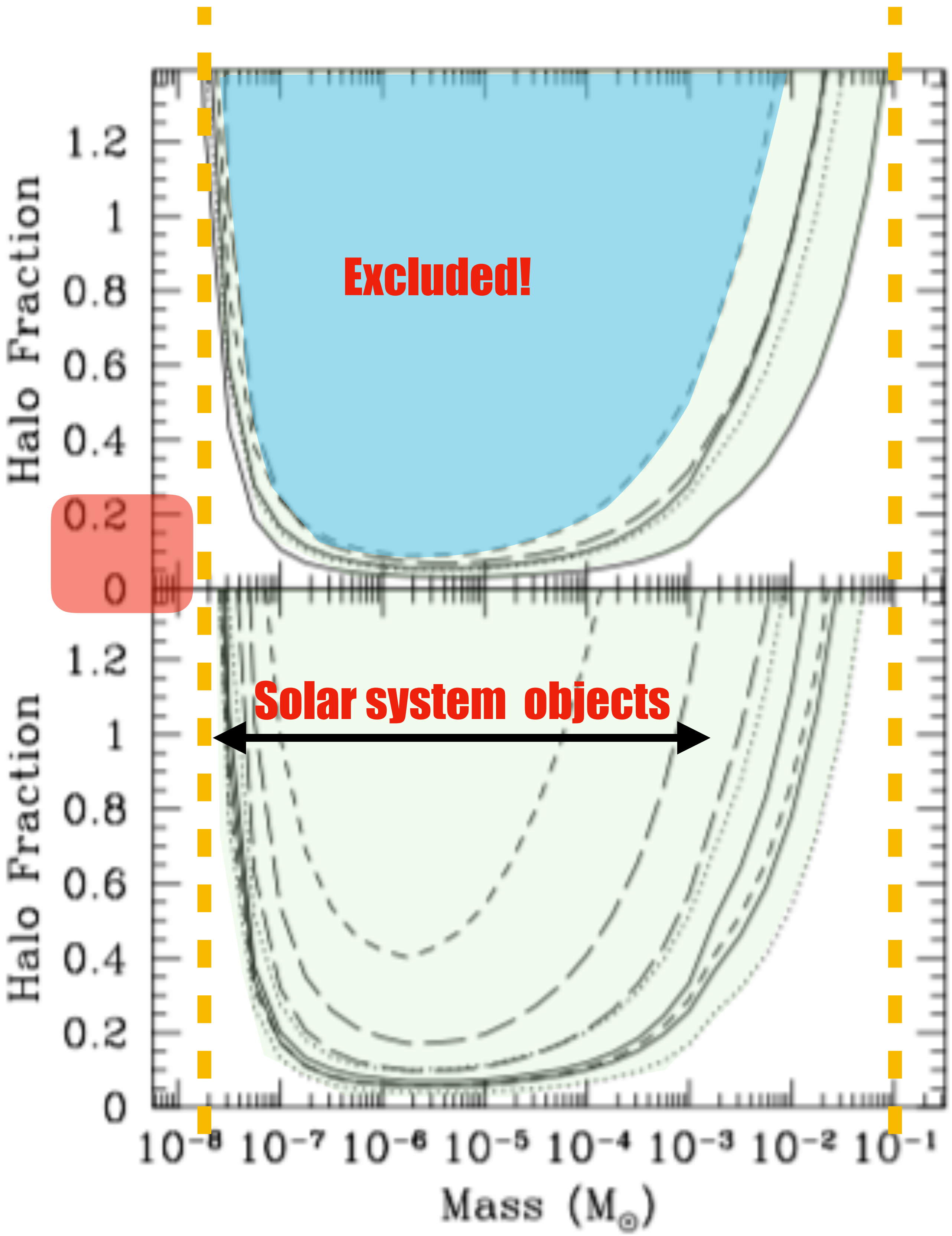
$$v_c^{\,2} = \frac{G\,M(r)}{r}$$

$$v \simeq 10^{-3}\ c$$

Galactic Dark Matter

What is the halo made of?

Is the dark matter made of compact objects?



EROS and MACHO

(La Silla vs Mount Stromlo Observatory, Australia)

Earth $3\ 10^{-6}\ M_\odot$

Jupiter $\simeq\ 10^{-3}\ M_\odot$

Pluto $\simeq 6\ 10^{-8}\ M_\odot$

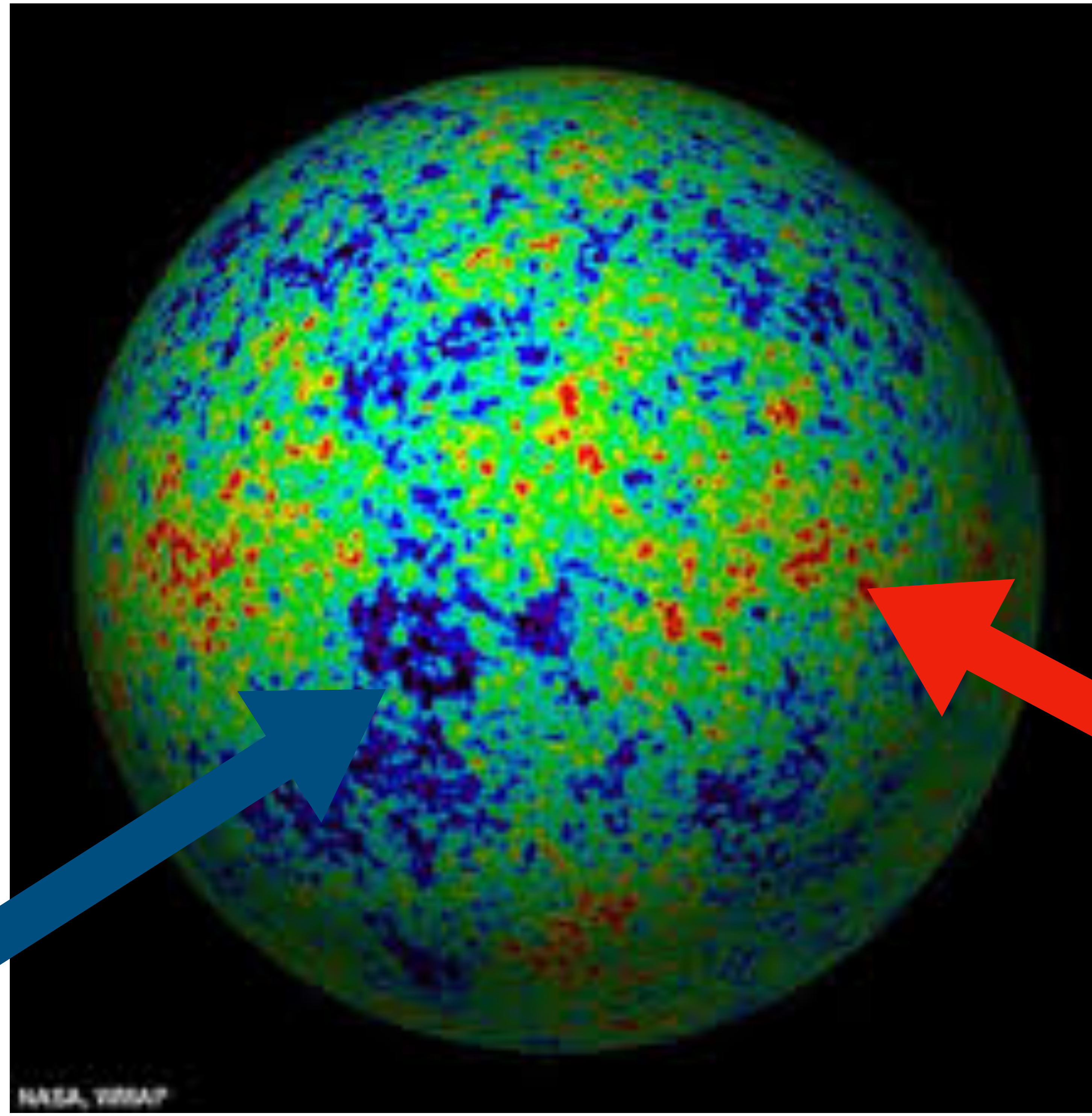
MACHO fraction < 10%

Fig. 3.— Halo fraction upper limit (95% c.l.) versus lens mass for the five EROS models (top) and the eight MACHO models (bottom). The line coding is the same as in Figure 2.

Anisotropies of temperature

$$\bar{T} = 2.7K$$

2003, WMAP



hotter regions

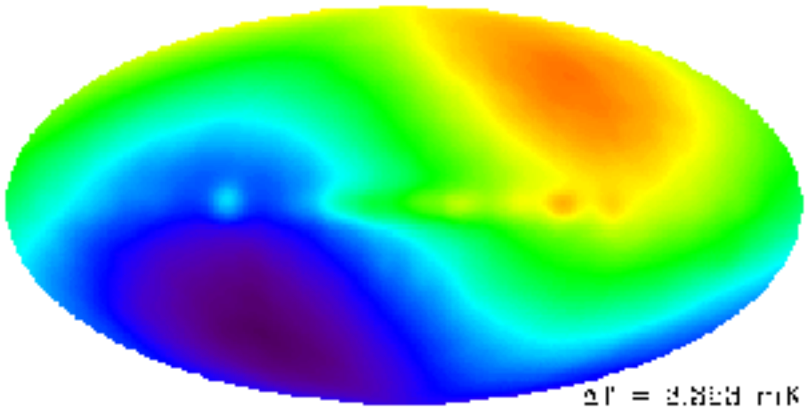
colder regions

$$\frac{\delta T}{T} \simeq 10^{-5}$$

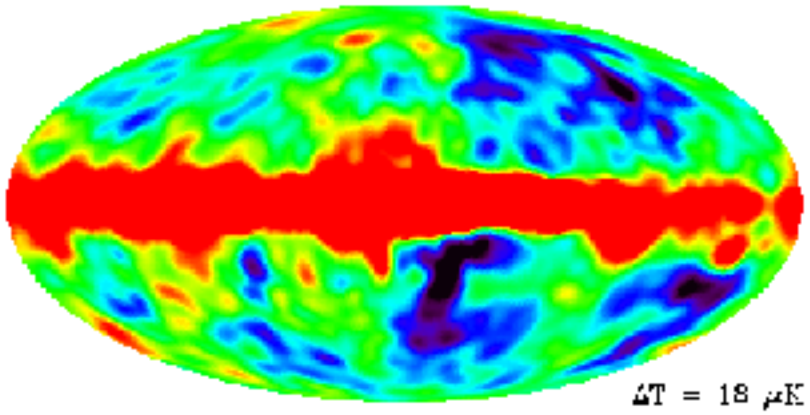
Anisotropies of temperature

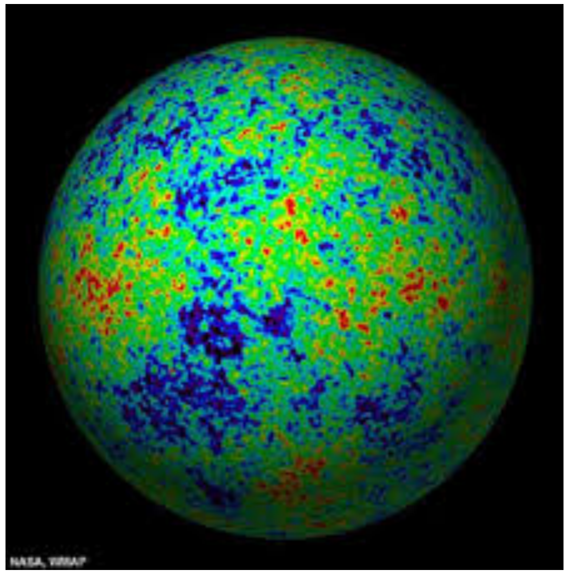
$$Y_0^0 = cst$$

$$Y_1^0 = \cos\theta$$



$$Y_l^m$$

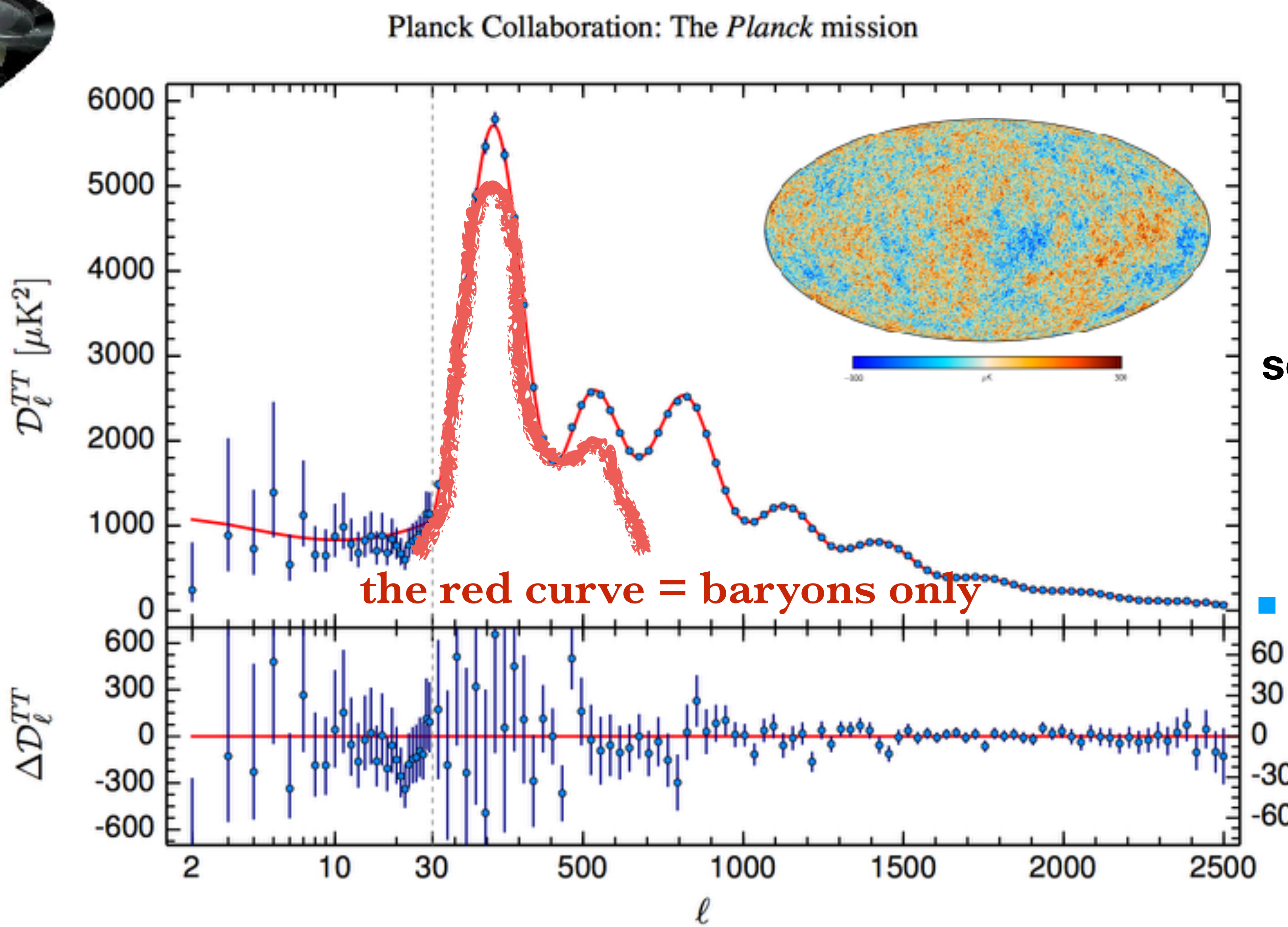




l > 2000

The higher l, the more details you get

Anisotropies of temperature

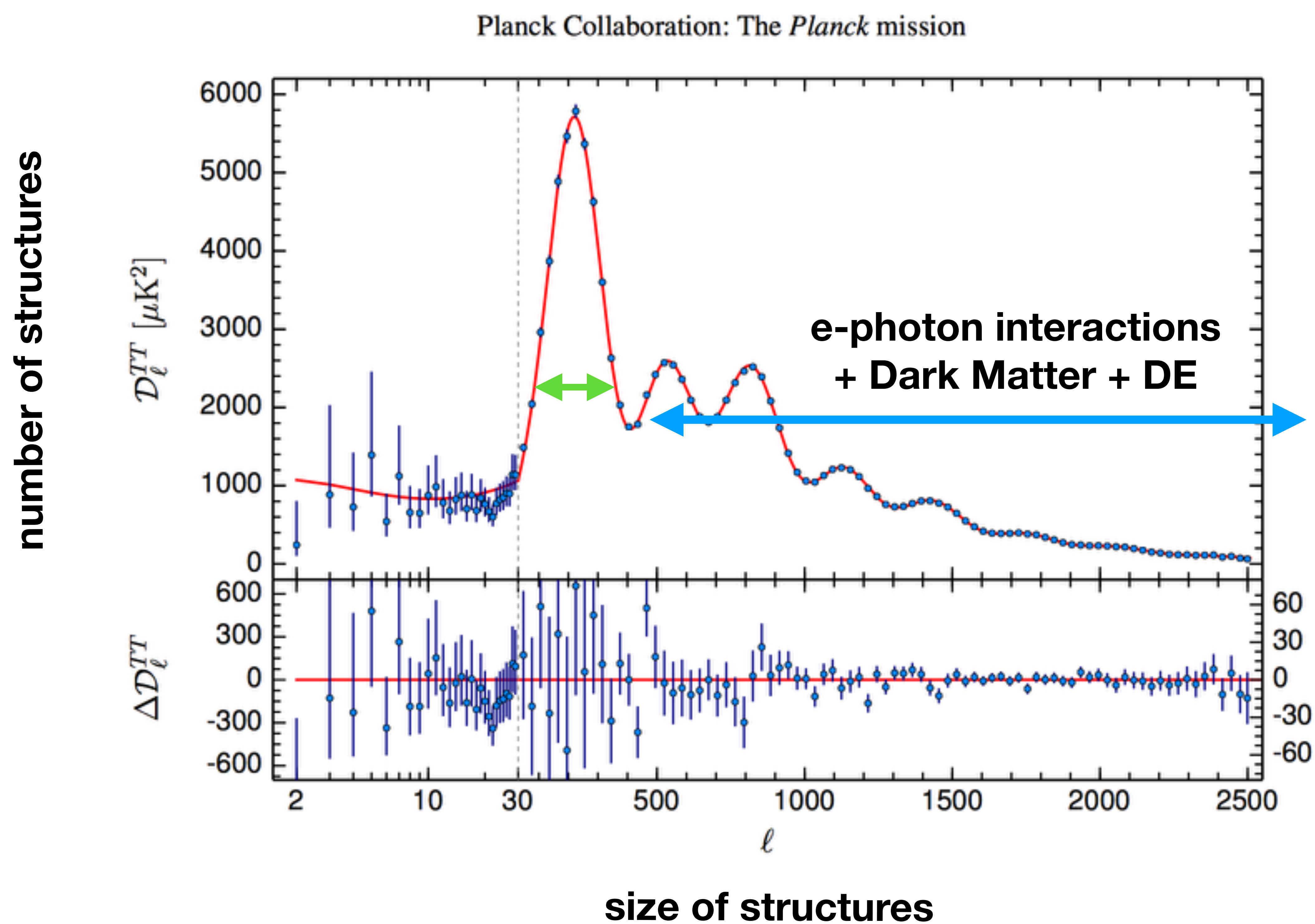


scale of galaxies

No large-scale fluctuations if “baryons” dominate the matter density

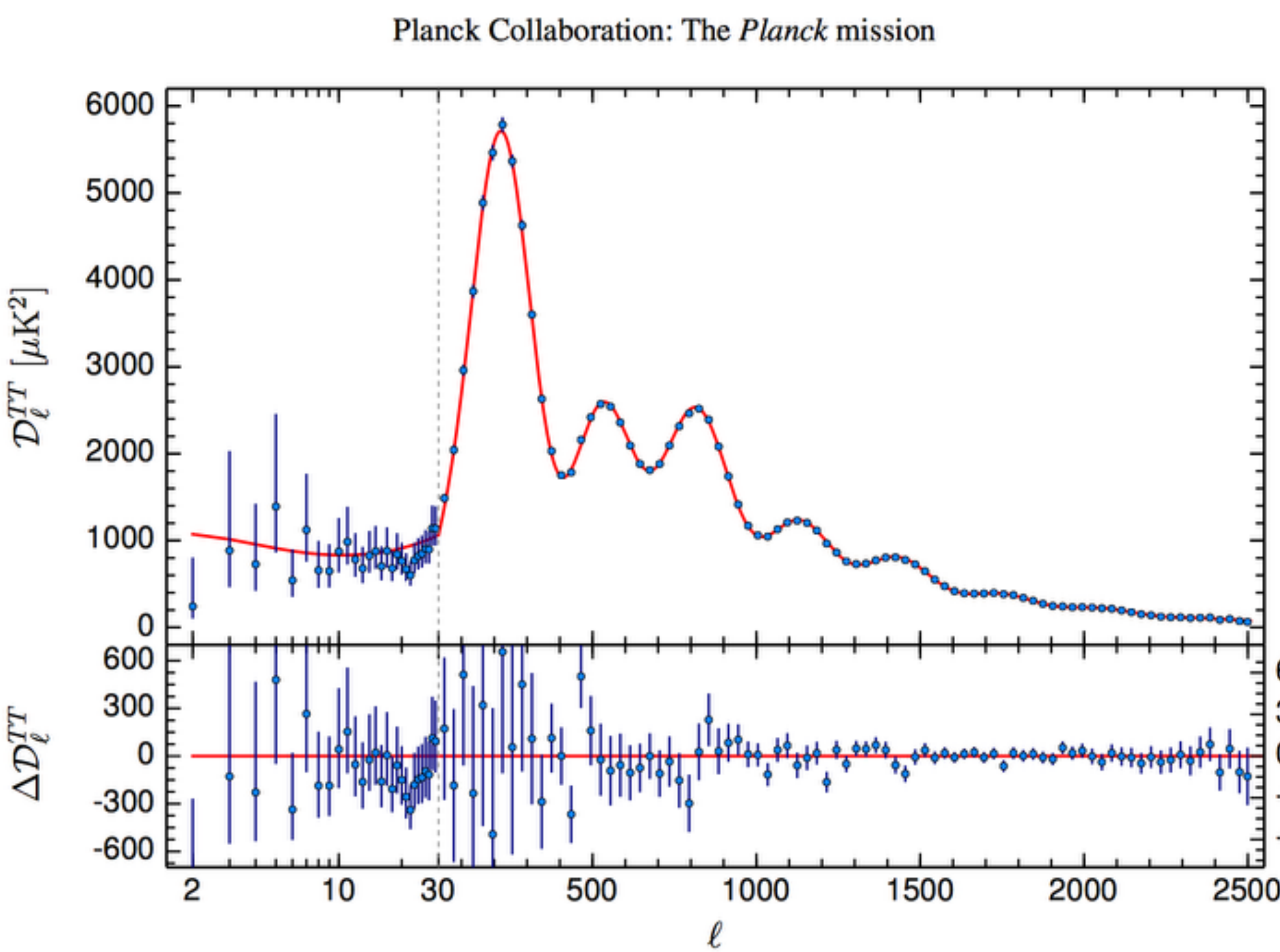
Therefore there must be more dark matter than baryons

Anisotropies of temperature



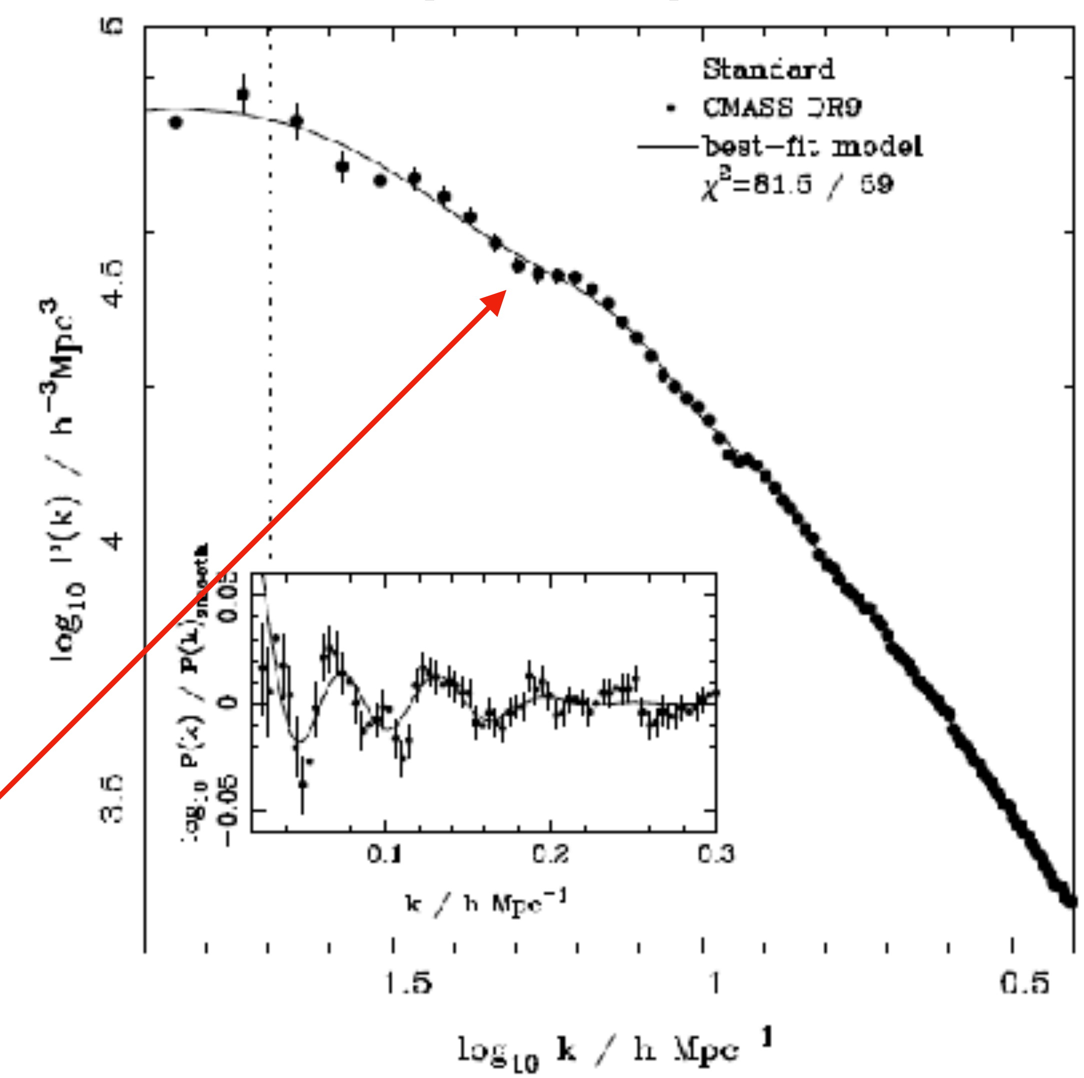
the suppression of small-scales is indicative of the presence of baryons

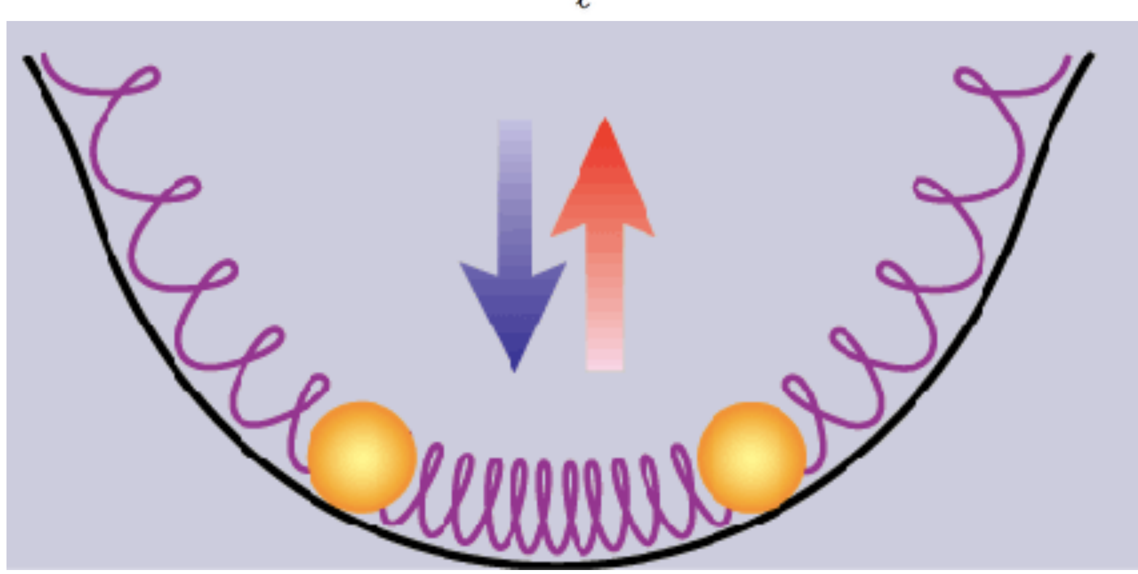
Anisotropies of temperature



scale of galaxies

matter power spectrum





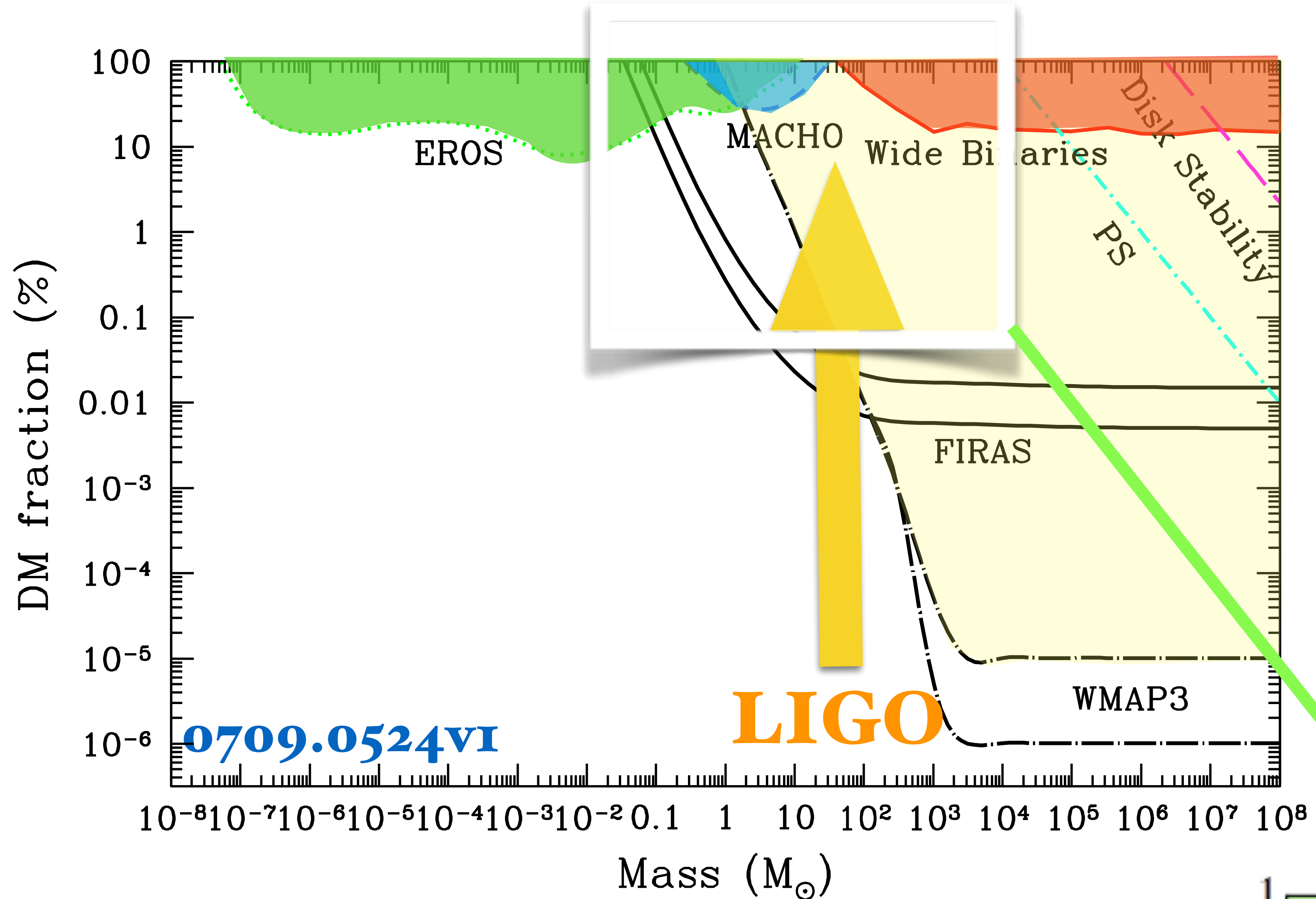
baryonic acoustic oscillations

II. Candidates

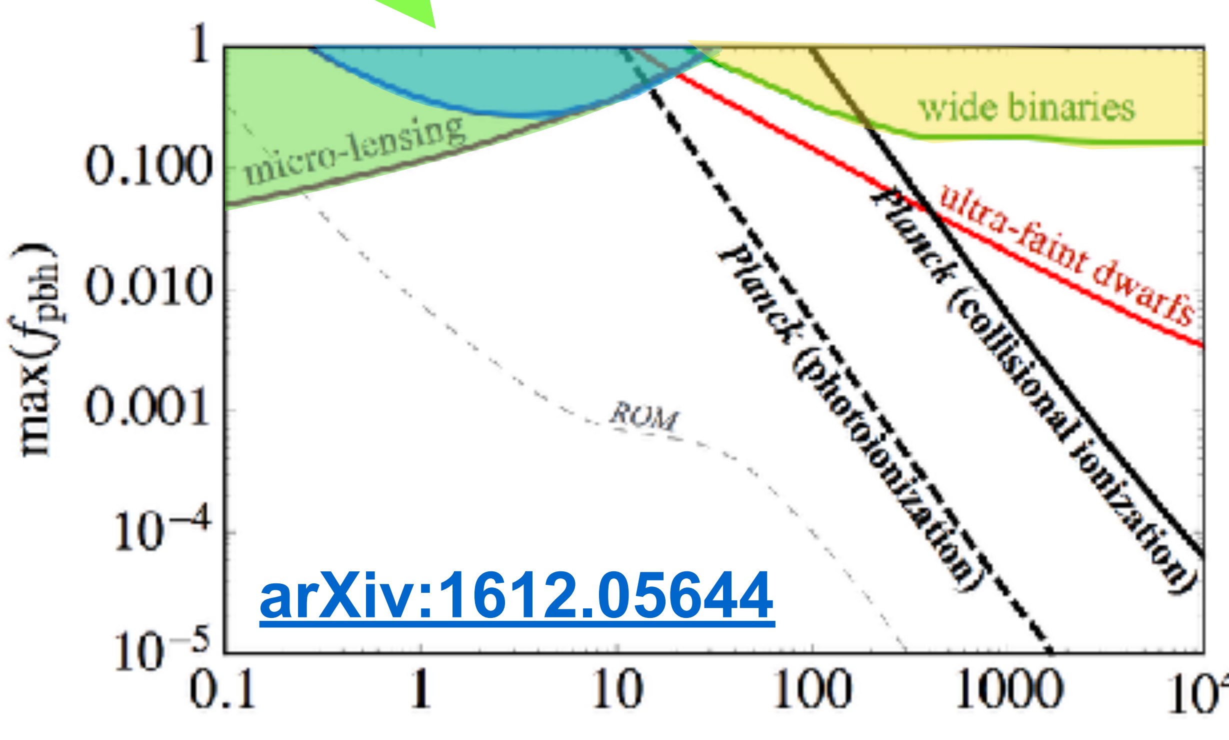
- Primordial Black Holes
- Modified gravity
- Particles (Relic density)

II. A. Primordial Black Holes

Can Primordial Black Holes be the DM?



arXiv:1603.00464
arXiv:1501.07565
arXiv:1607.06077

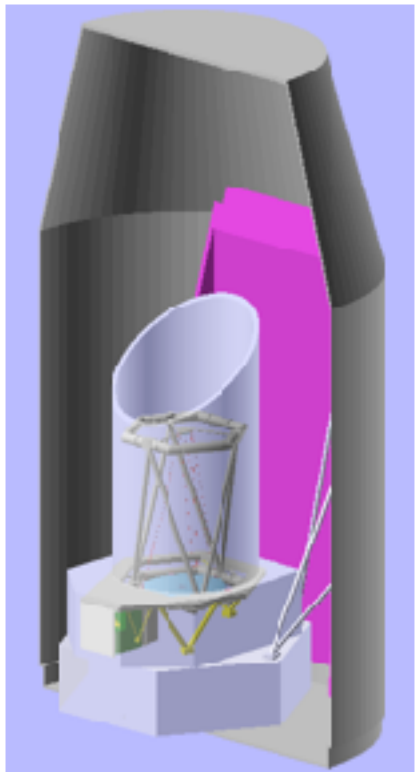


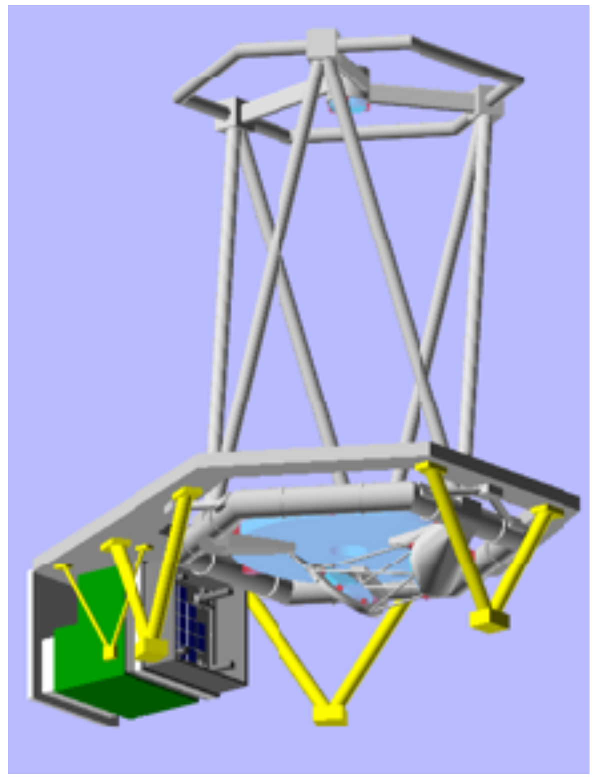
arXiv:1612.05644

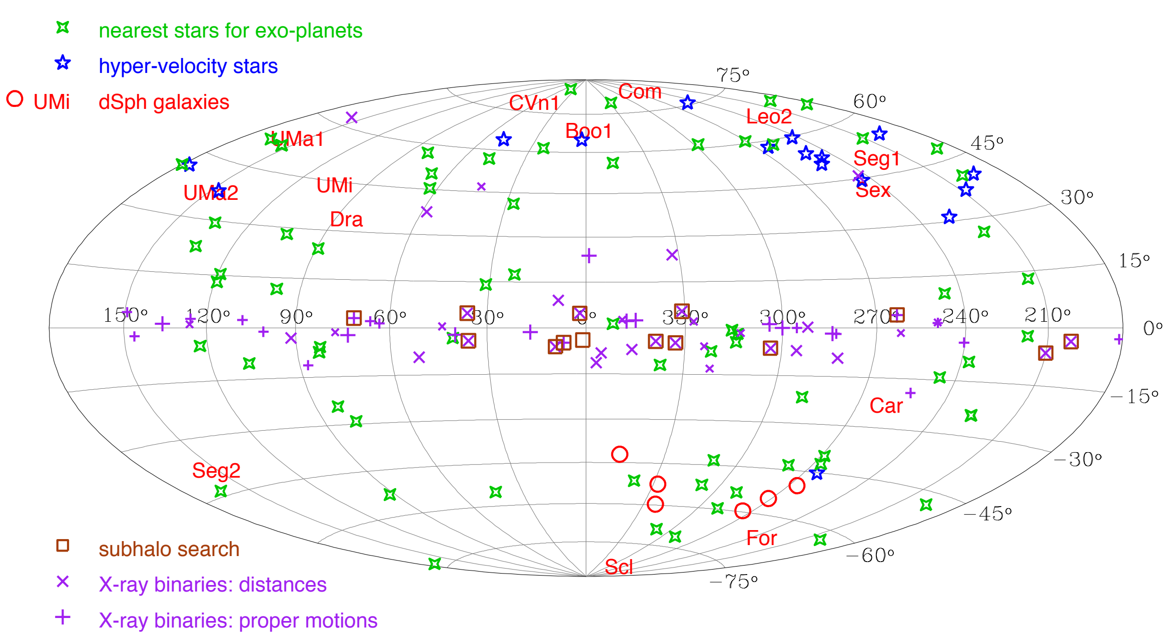
An ensemble of PBH in the 1-100 Msun range might be allowed.

Can Primordial Black Holes be the DM?

Theia (optical) Small-Jasmine (IR)







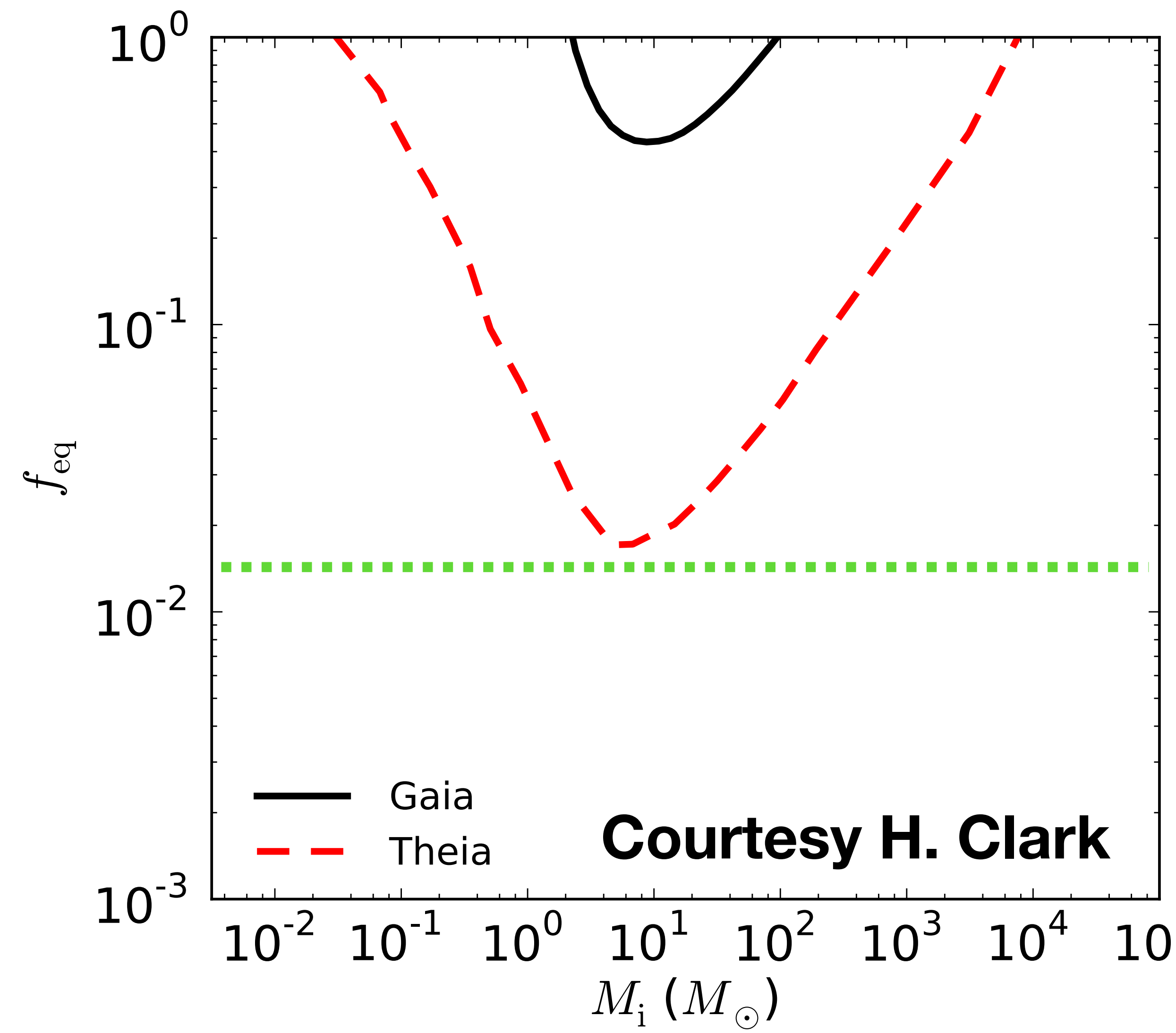


Fig. 2.8: Projected sensitivity of *Theia* to the fraction of dark matter in the form of ultracompact minihalos (UCMHs) of mass M_i at the time of matter-radiation equality. Smaller masses probe smaller scales, which correspond to earlier formation times (and therefore to *later* stages of inflation). A UCMH mass of 0.1 $M_\odot$ corresponds to a scale of just 700 pc. Expected constraints from *Gaia* are given for comparison, showing that *Theia* will provide much stronger sensitivity, as well as probe smaller scales and earlier formation times than ever reached before.

II. B. Modified gravity

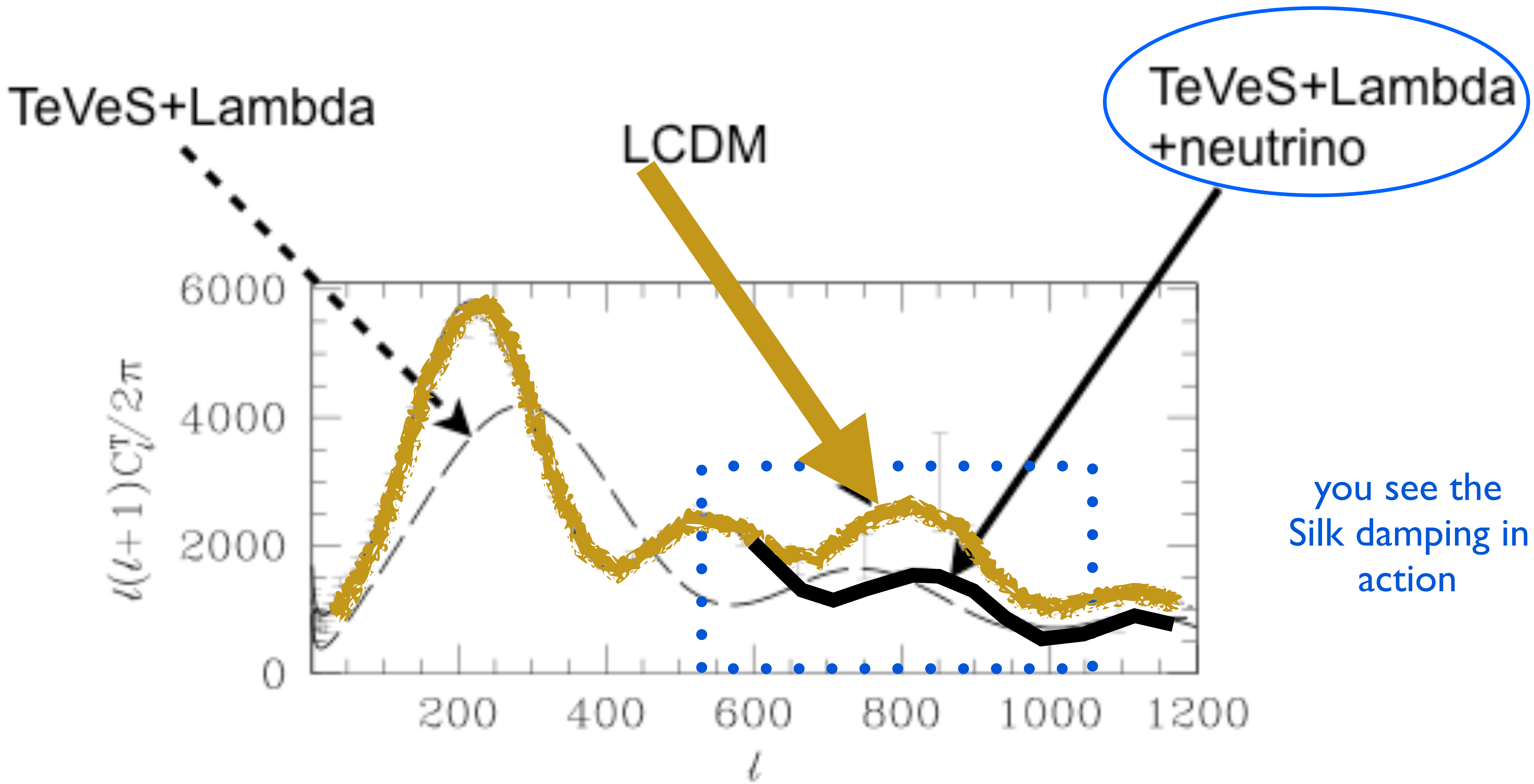
One possible theory : TeVeS (baryons only)

Bekenstein astro-ph/0403694

Relativistic (covariant) version of MOND

$$\mu\left(\frac{|\vec{a}|}{a_0}\right)\vec{a} = -\nabla\Phi$$

$$\mu(x) = 1 \text{ if x} > 1 \quad \mu(x) \simeq x \text{ if x} < 1$$



you see the Silk damping in action

astro-ph/0505519

II. C. Particles

gravity

matter

massive particles

stable

neutral

not in atoms

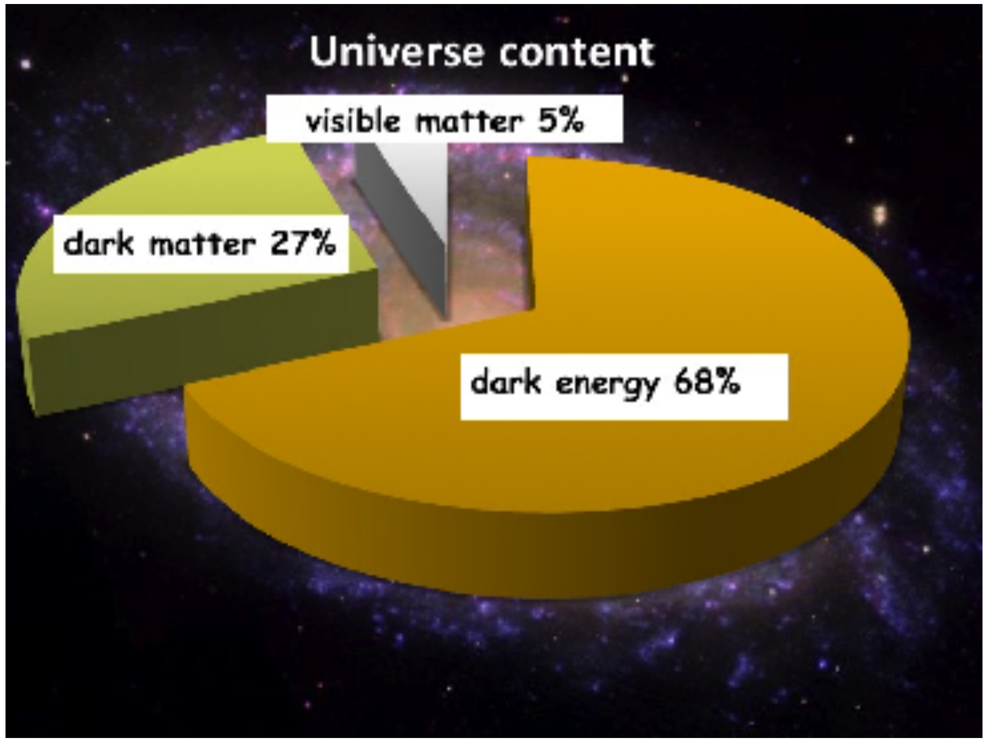
long lifetime

no electrical charge

no strong force

Weakly interacting

Relic density



Why 27%?

How many DM particles were produced in the Early Universe?

How much should there be today if DM was made of particles?

Does it match observations?

Relic density

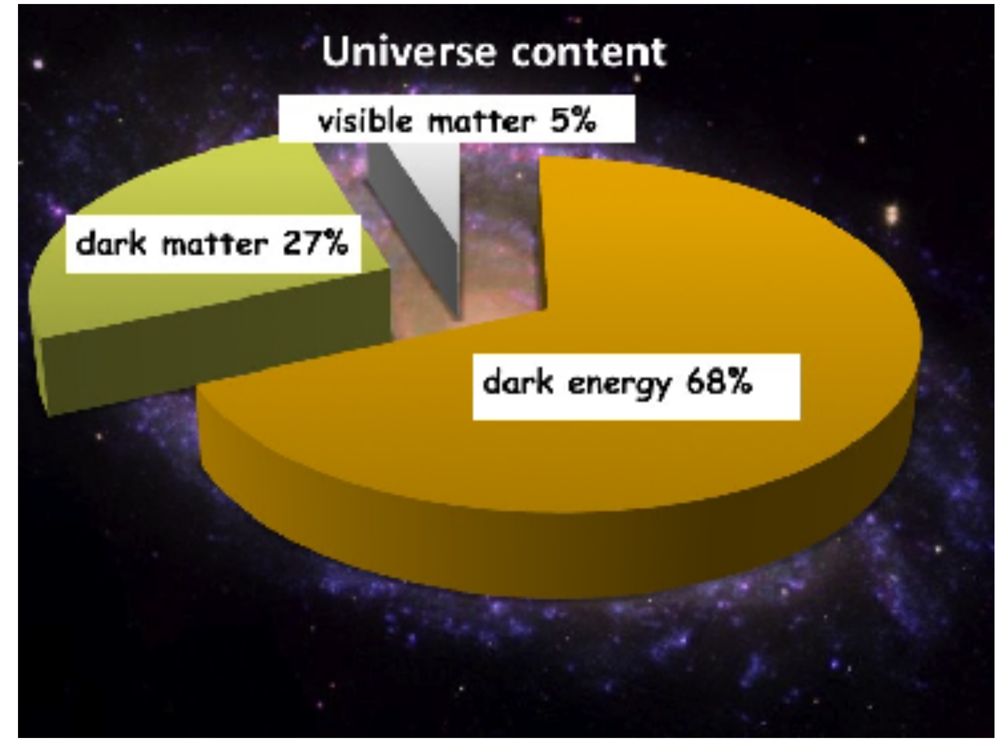
For the “baryons”

Thermal production

$$e^+e^- \to \gamma\gamma$$

$$\sigma_T \sim 6\ 10^{-25}\ \text{cm}^2$$

The annihilation process is so efficient
that there would be no electrons left at all



Asymmetry

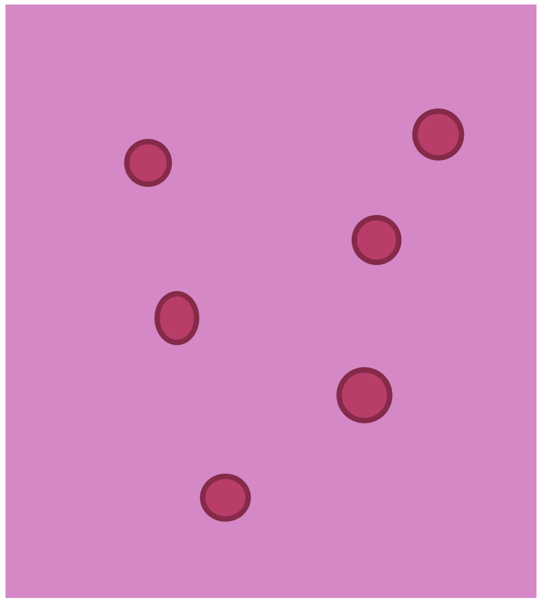
For the Dark Matter

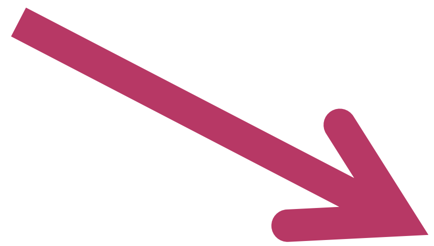
Thermal production but … non-thermal,freeze-in

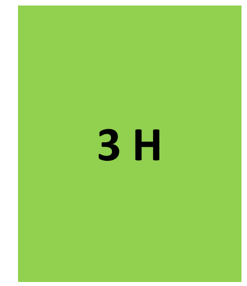
No asymmetry! but …

Relic density

Expansion of the Universe

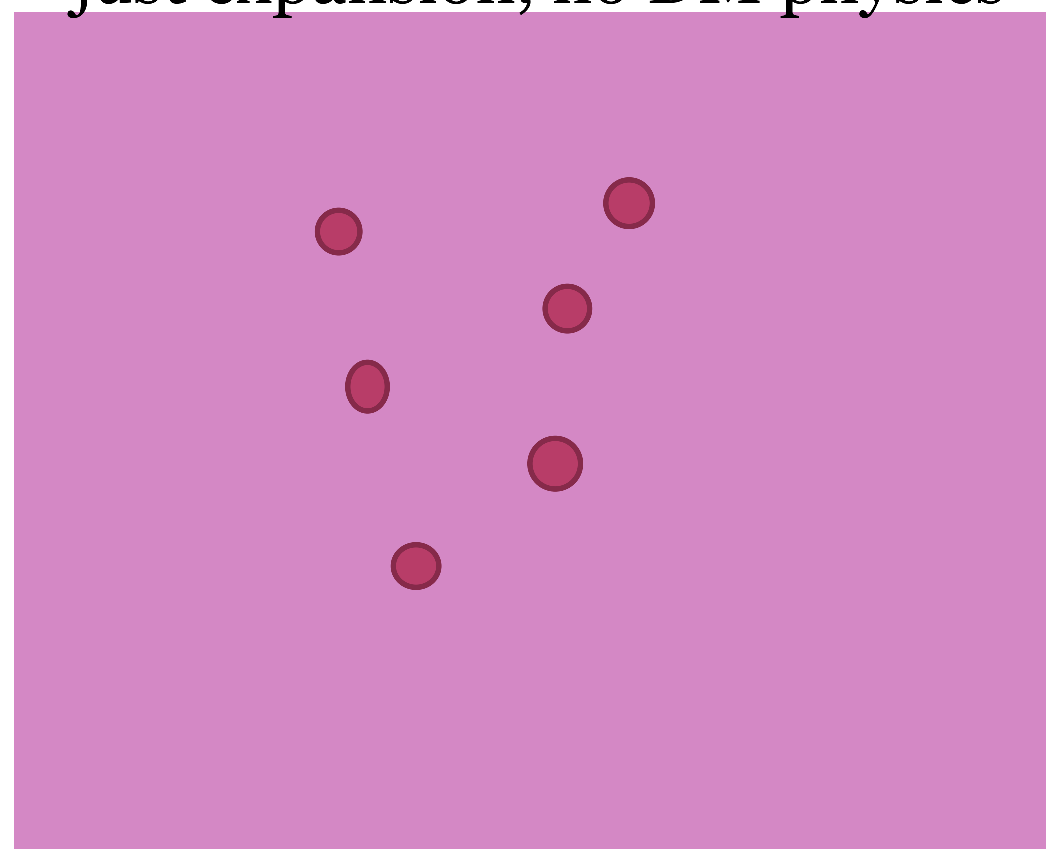






Early Universe

just expansion, no DM physics

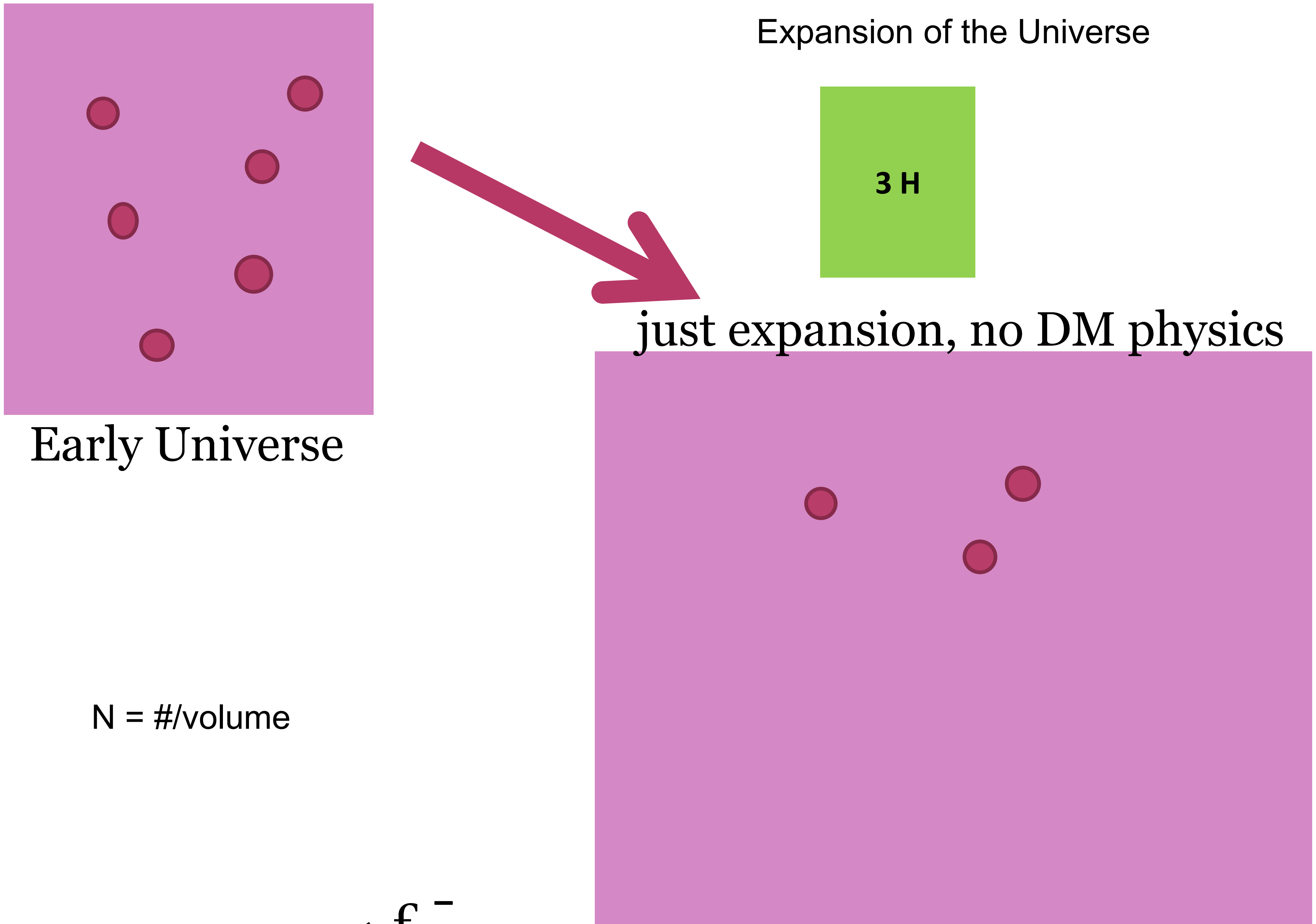


Late Universe

N = #/volume

Massive DM particles can overclose the Universe!

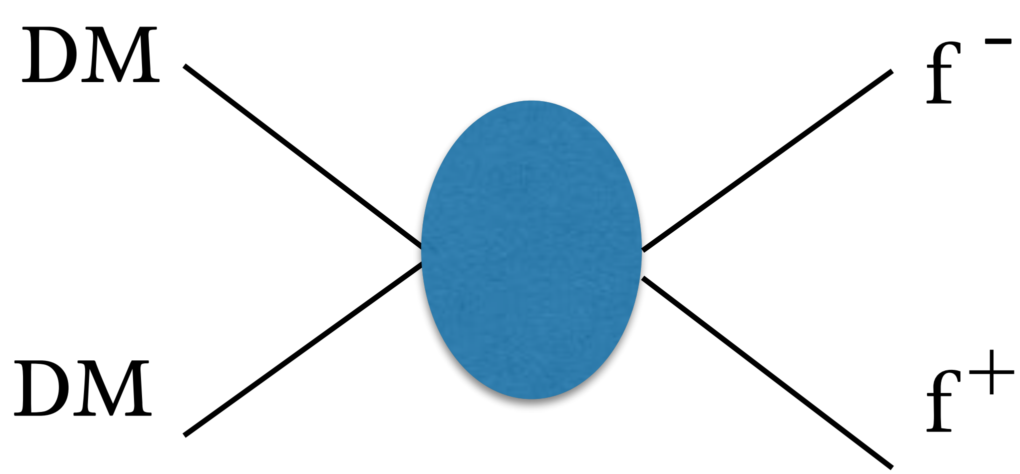
Relic density



Early Universe

Late Universe

N = #/volume



Number is reduced due to annihilations

The Boltzmann equation

Expansion of the Universe

number density of DM

(#/V)

$$\frac{dn}{dt} = -3Hn - \sigma v(n^2 - n_0^2)$$

Time evolution of
the number density

Annihilations change
the number density

Deriving the Boltzmann equation

$$\frac{df}{d\lambda} = C(f).$$

$$\frac{df}{d\lambda} = \frac{\partial f}{\partial x^\mu}\frac{dx^\mu}{d\lambda} + \frac{\partial f}{\partial p^\nu}\frac{dp^\nu}{d\lambda} = p^\mu \frac{\partial f}{\partial x^\mu} - \Gamma^\nu{}_{\alpha\beta}\, p^\alpha p^\beta \frac{\partial f}{\partial p^\nu}$$

using $\quad \dfrac{dp^\nu}{d\lambda} + \Gamma^\nu{}_{\alpha\beta}\, p^\alpha p^\beta = 0$

Isotropic Universe $\quad p^i \dfrac{\partial f}{\partial x^i} = 0$

$$\frac{df}{d\lambda} = E\frac{\partial f}{\partial t} - \Gamma^0{}_{\alpha\beta}\, p^\alpha p^\beta \frac{\partial f}{\partial E}$$

$$E\frac{\partial f}{\partial t} - \Gamma^0{}_{\alpha\beta}\, p^\alpha p^\beta \frac{\partial f}{\partial E} = C(f)$$

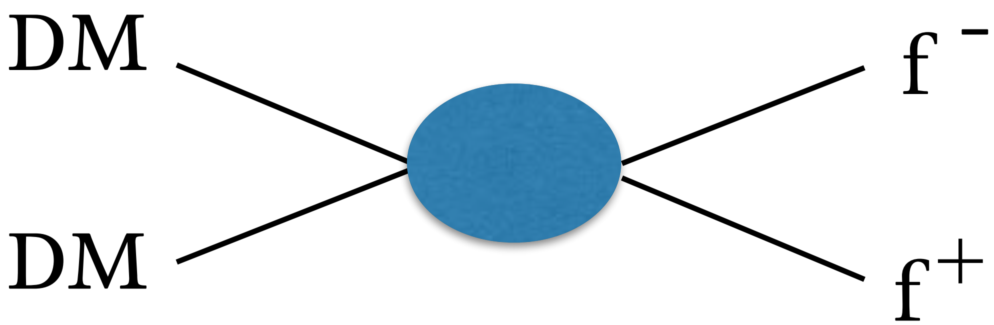
$$\frac{\partial f}{\partial t} - H\frac{E^2 - m^2}{E}\frac{\partial f}{\partial E} = \frac{1}{E}C(f)$$

$$\frac{g}{(2\pi)^3}\int \left(\frac{\partial f}{\partial t} - H\frac{E^2 - m^2}{E}\frac{\partial f}{\partial E}\right) d^3p = \frac{g}{(2\pi)^3}\int \frac{1}{E}C(f)\, d^3p.$$

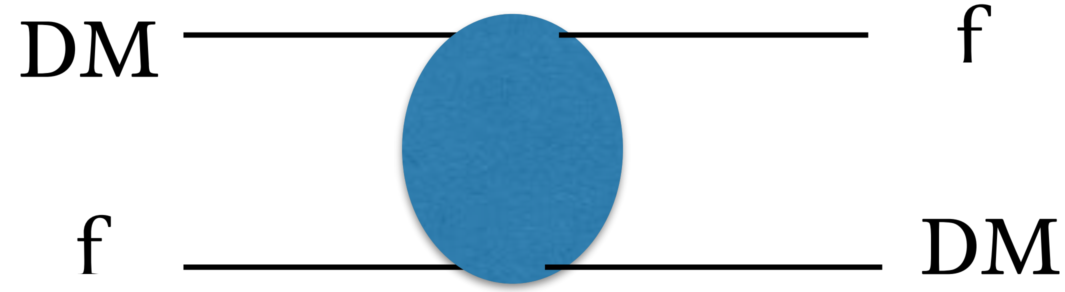
$$\frac{\partial n}{\partial t} + 3Hn = \frac{g}{(2\pi)^3}\int \frac{1}{E}C(f)\, d^3p.$$

Deriving the Boltzmann equation

$$\frac{\partial n}{\partial t} + 3Hn = \frac{g}{(2\pi)^3} \int \frac{1}{E} C(f) d^3 p.$$



annihilations; change the number density



elastic scattering; do not change density

$$\mathrm{DM\ DM} \to \mathrm{f\ \bar{f}}$$
$$f\ \bar{f} \to \mathrm{DM\ DM}$$

$$\mathrm{DM\ DM} \to \mathrm{f\ \bar{f}}$$

Non-relativistic transition

expansion won

$$C(f) = -\frac{1}{2} \sum_{spins} \int \left[f f_2 (1 \pm f_3)(1 \pm f_4) \left| \mathcal{M}_{12\to34} \right|^2 - f_3 f_4 (1 \pm f)(1 \pm f_2) \left| \mathcal{M}_{34\to12} \right|^2 \right]$$
$$(2\pi)^4 \delta^4 (p + p_2 - p_3 - p_4) \frac{d^3 p_2}{(2\pi)^3 2E_2} \frac{d^3 p_3}{(2\pi)^3 2E_3} \frac{d^3 p_4}{(2\pi)^3 2E_4}$$

$$\dot{n} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right)$$

Boltzmann equation caught in the act

number of particles

(reverse) annihilation
expansion

$$\mathrm{DM\ DM} \rightarrow \mathrm{f\ \bar{f}}$$
$$f\ \bar{f} \rightarrow \mathrm{DM\ DM}$$

1-way annihilation
$$\mathrm{DM\ DM} \rightarrow \mathrm{f\ \bar{f}}$$

Expansion wins but
annihilations were too efficient

Non-relativistic
transition

today

number of particles

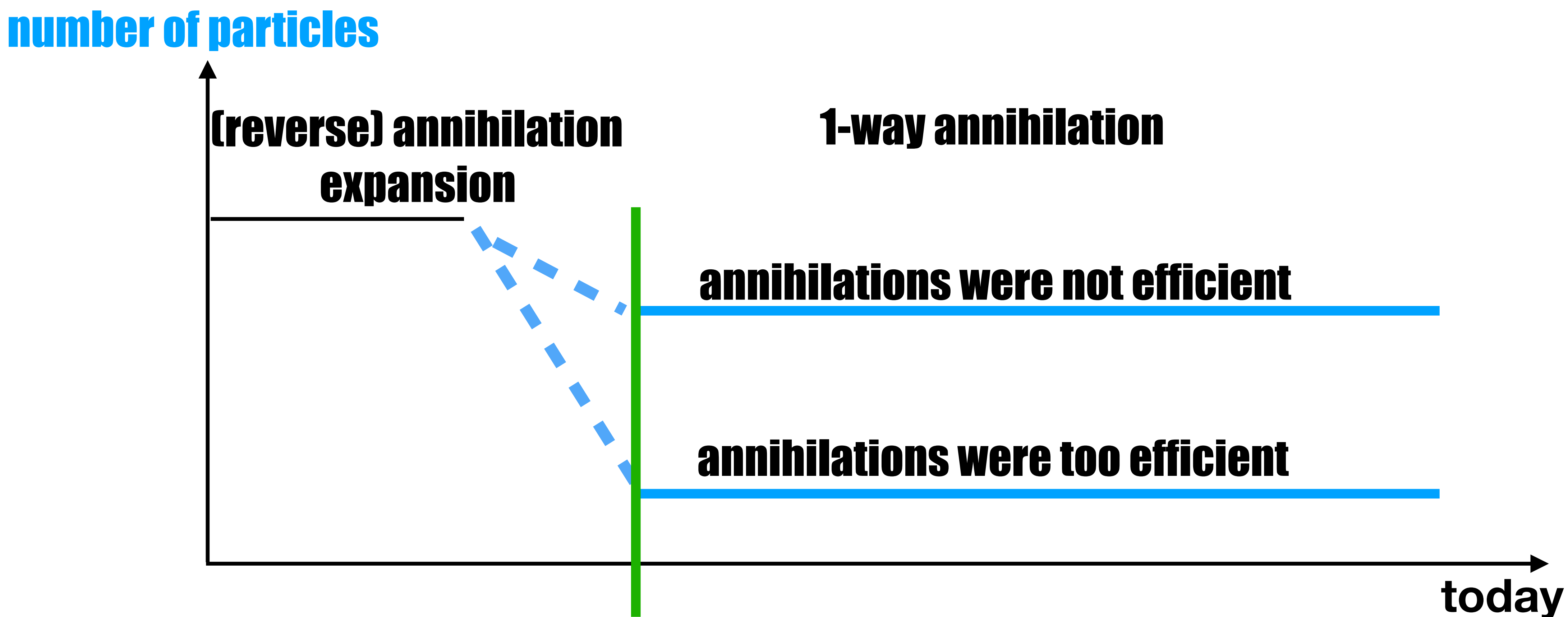
(reverse) annihilation
expansion

Expansion wins but annihilations
were not efficient

Non-relativistic
transition

today

Boltzmann equation caught in the act



Chemical decoupling
Freeze-out

Only one cross section gives the observed number of DM particles!

Interactions maintaining the thermal equilibrium can continue

$$\frac{dn}{dt} = -3Hn - \sigma v(n^2 - n_0^2) \qquad \sigma v\ n_{DM}^2 \simeq H\ n_{DM} \Rightarrow \sigma v\ n_{DM} \simeq H$$

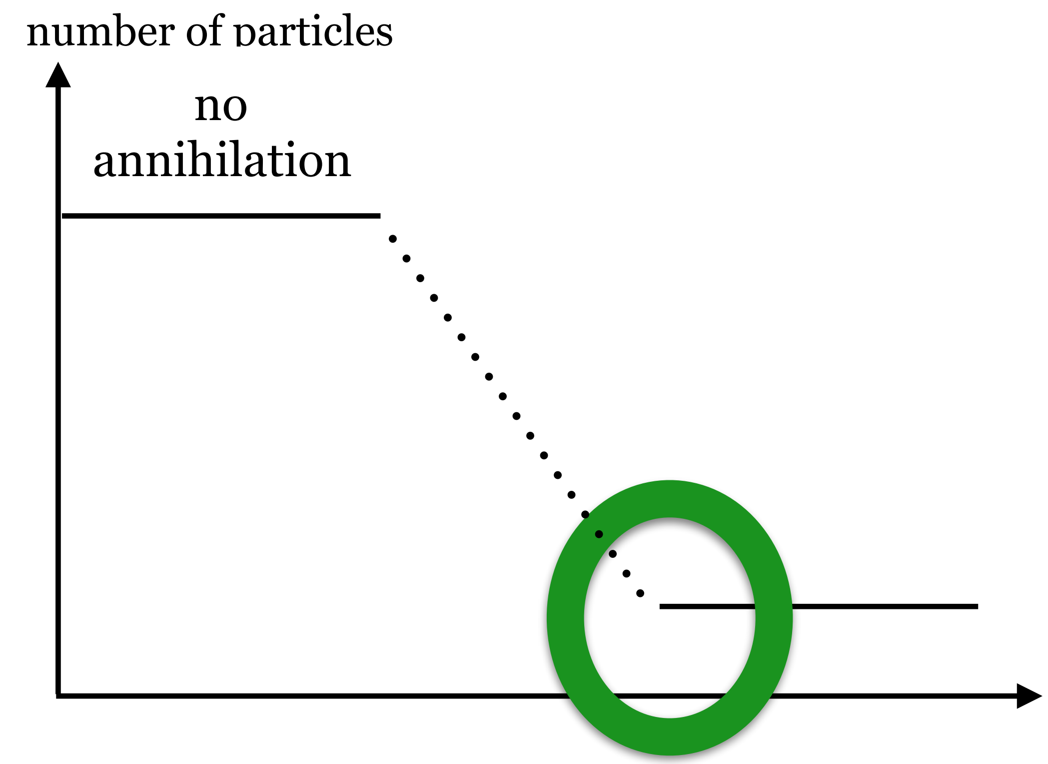
Analytical solution

$$\langle \sigma v \rangle n_{\rm DM} = H$$

$$n_{\rm DM} a^3 = n_{\rm DM,0}\ a_0^3$$

$$a(T) = \frac{T_0}{T} \quad \text{and} \quad H = H_r T^2$$

$$n_{\rm DM,0} = \frac{H_r}{\langle \sigma v \rangle} \frac{T_0}{T_{fo}}$$



$$\Omega_0 = \frac{\rho_{\rm DM,0}}{\rho_{c,0}} \rightarrow \Omega_0 = \frac{n_{\rm DM,0}}{\rho_{c,0}} m_{\rm DM} \rightarrow \boxed{\Omega_0 = \frac{H_r}{\rho_{c,0}} \frac{T_0}{\langle \sigma v \rangle} \frac{m_{\rm DM}}{T_{fo}}}$$

x_{fo}

At freeze-out, the density obeys Boltzmann statistics

$$n(T) \propto (m_{\rm DM} T)^{3/2}\ e^{-\frac{m_{\rm DM}}{T}} \qquad n_{\rm DM,0} = \frac{H_r}{\langle \sigma v \rangle} \frac{T_0}{T_{fo}} \qquad x_{fo}^{-1} \simeq \ln \frac{\langle \sigma\ v \rangle\ T_0^2\ m}{H_\alpha\ (2\pi)^{3/2}\ \sqrt{x_{fo}}}.$$

$$x_{fo} \approx 12 + (\approx 2) \log\left(\frac{m_{dm}}{MeV} \times \frac{\sigma v}{3.10^{-26} cm^3 / s} \right)$$

Numerical solution

Numerically: ★ re-write Boltzmann to remove T^3 factors in number density by using $n = y\, T^3$

$$\frac{dy}{dt} = -\sigma v \times (y^2 - y_0^2) \times T^3$$

★ solve dy/dT instead of dy/dt

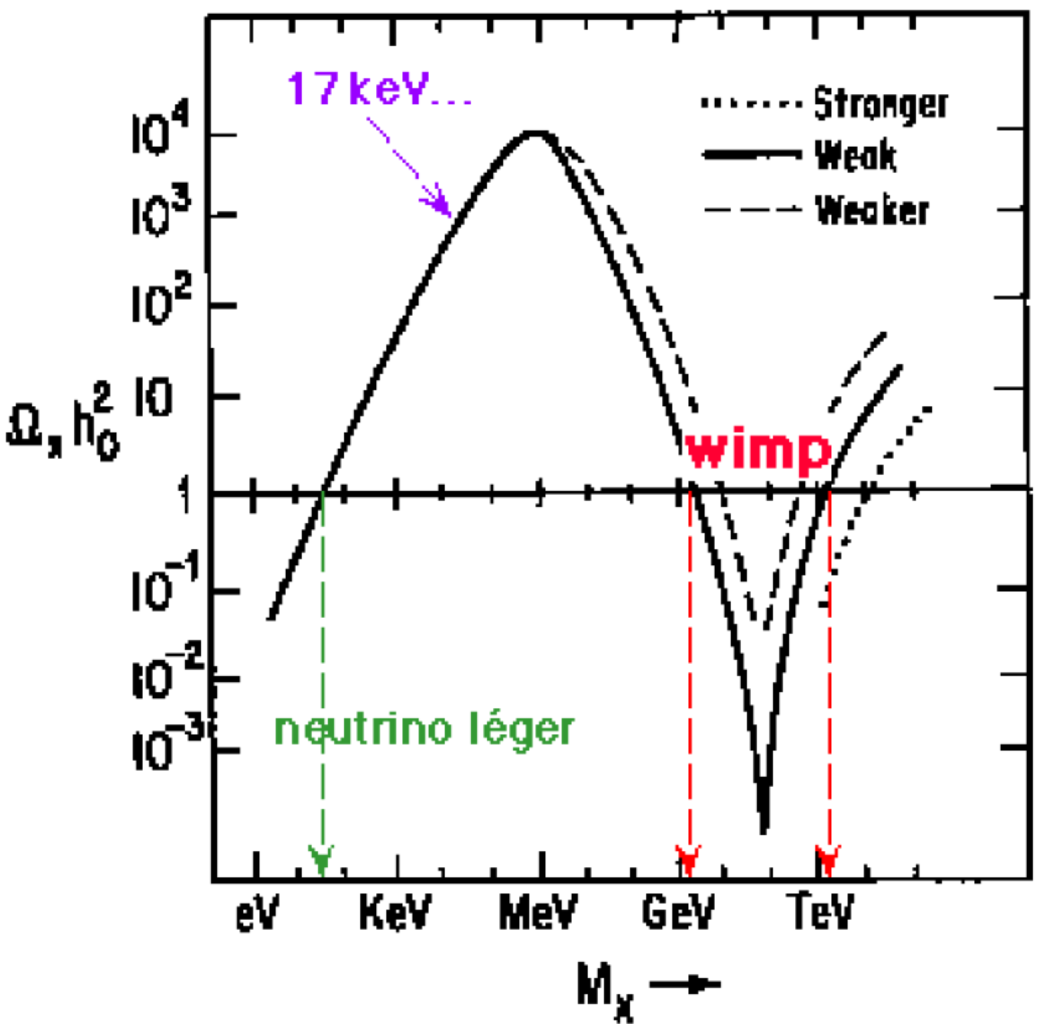
$$\frac{dy}{dT} = \frac{\sigma v}{2 t_r T_0^2} \times (y^2 - {y_0}^2)$$

Tempted to use: $$\frac{y_{i+1} - y_i}{\Delta T} = \Lambda \times (y^2 - {y_0}^2)$$???

$$\frac{y_{i+1} - y_i}{\Delta T} = \frac{\Lambda}{2} \times \left[({y_i}^2 - {y_{0_i}}^2) + ({y_{i+1}}^2 - {y_{0_{i+1}}}^2) \right]$$

The Hut, Lee&Weinberg argument

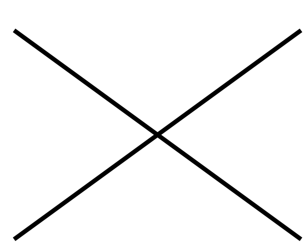
Can we have light thermal DM? no! (well...)



$$\frac{dn}{dt} = -3Hn - \sigma v (n^2 - n_0^2)$$

$$\Omega h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}$$

$$\sigma v \sim 3\ 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$



$$\sigma\ \mathrm{v} \propto \frac{\mathrm{m_{dm}}^2}{\mathrm{m_w}^4} \Rightarrow \Omega_{\mathrm{DM}} h^2 \propto m_{\mathrm{DM}}^{-2}$$

Particle physics examples

The supersymmetric case

N=1 : 1 operator of supersymmetry
Each operator change the spin of particles by 1/2
SUSY operator applied on SM spectrum leads to new particles with different spin

~ double SM spectrum

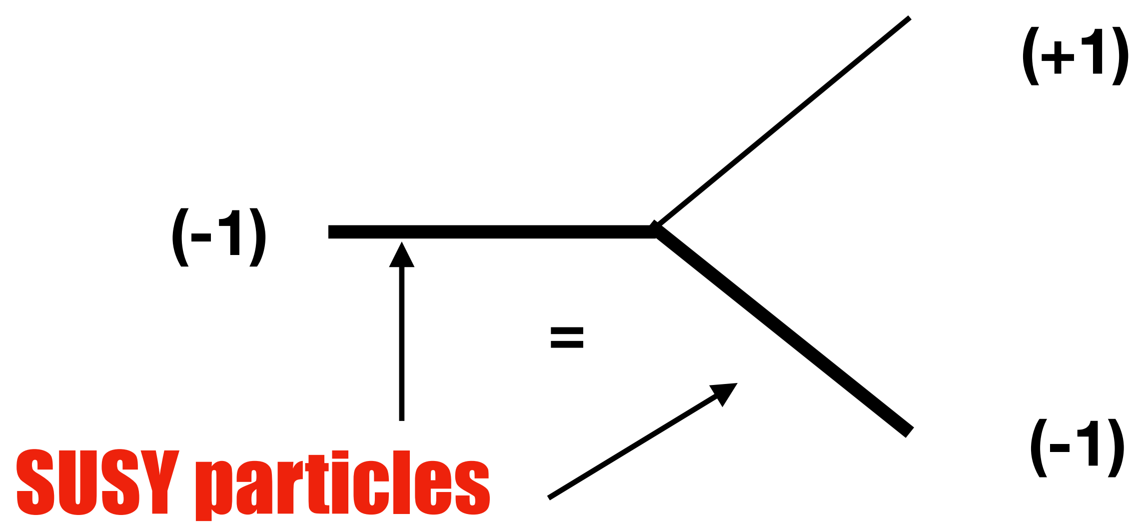
- **SM fermions + spin-0 particles** **sfermions**
- **Higgs/Gauge boson spin-1/2 particles** **fermions neutralinos**

R-parity

$$R_p = (-1)^{3B+L+2s}$$

Initial realisation:
all masses the same as SM

Nothing at LEP, LHC
so masses can't be the same!



The supersymmetric case

SUSY

photon	$\rightarrow$	photino
$s = 1$		$s = \frac{1}{2}$
Z^0	$\rightarrow$	Zino
$s = 1$		$s = \frac{1}{2}$
2 Higgs	$\rightarrow$	2Higgsinos
$s = 0$		$s = \frac{1}{2}$

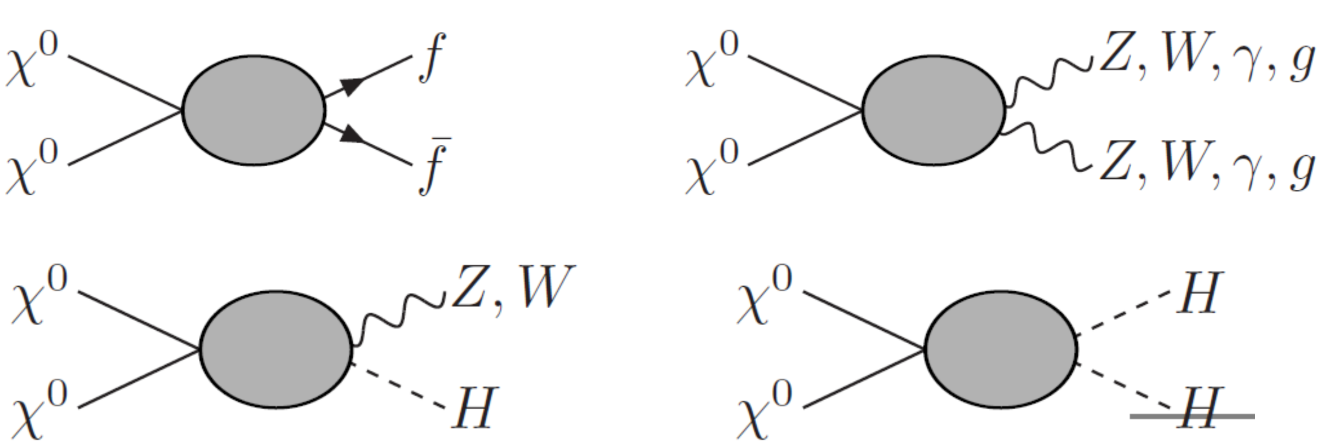
NEUTRALINOS

+R-parity = stable DM

$W^{\pm}$	$\rightarrow$	Wino
$s = 1$		$s = \frac{1}{2}$
H^+	$\rightarrow$	Higgsinos
$s = 0$		$s = \frac{1}{2}$

CHARGINOS

gluon	$\rightarrow$	gluino
$s = 1$		$s = \frac{1}{2}$



All cross sections are

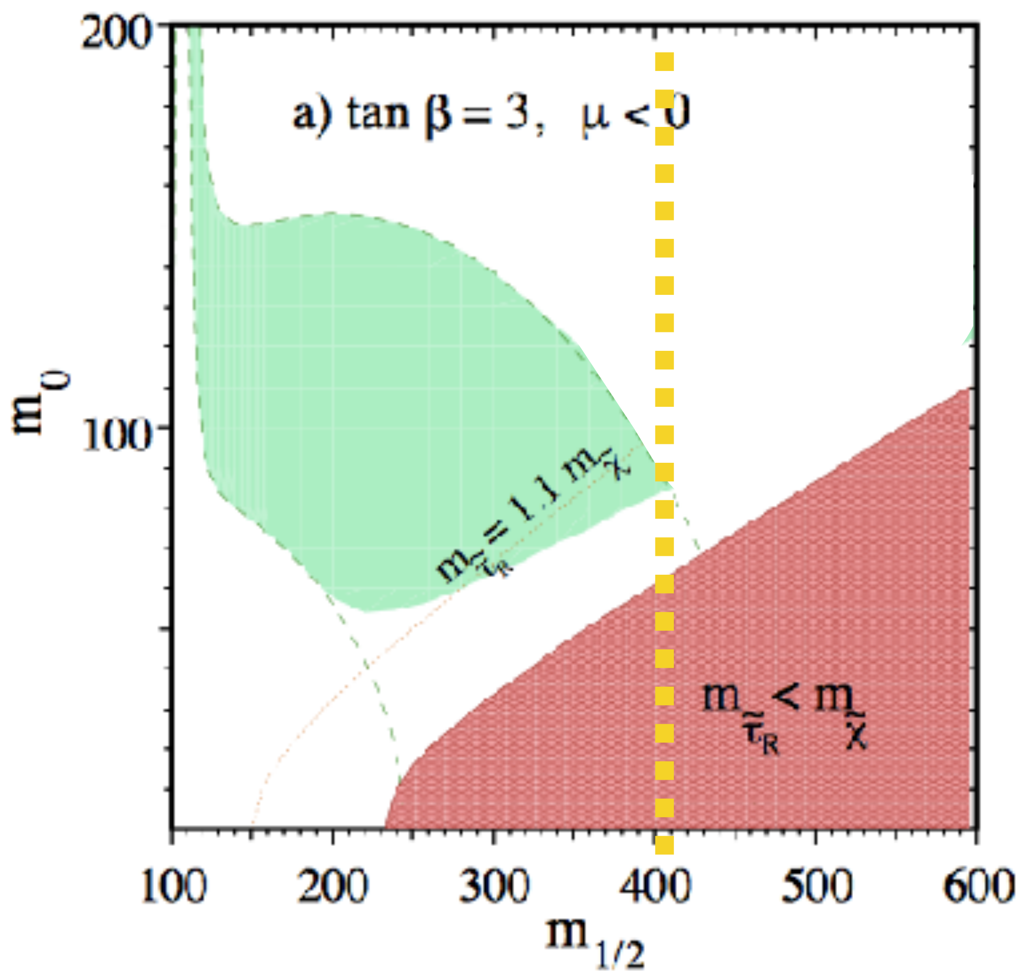
$$\sigma v \propto m_\chi^2$$

Lee-Weinberg limit applies!

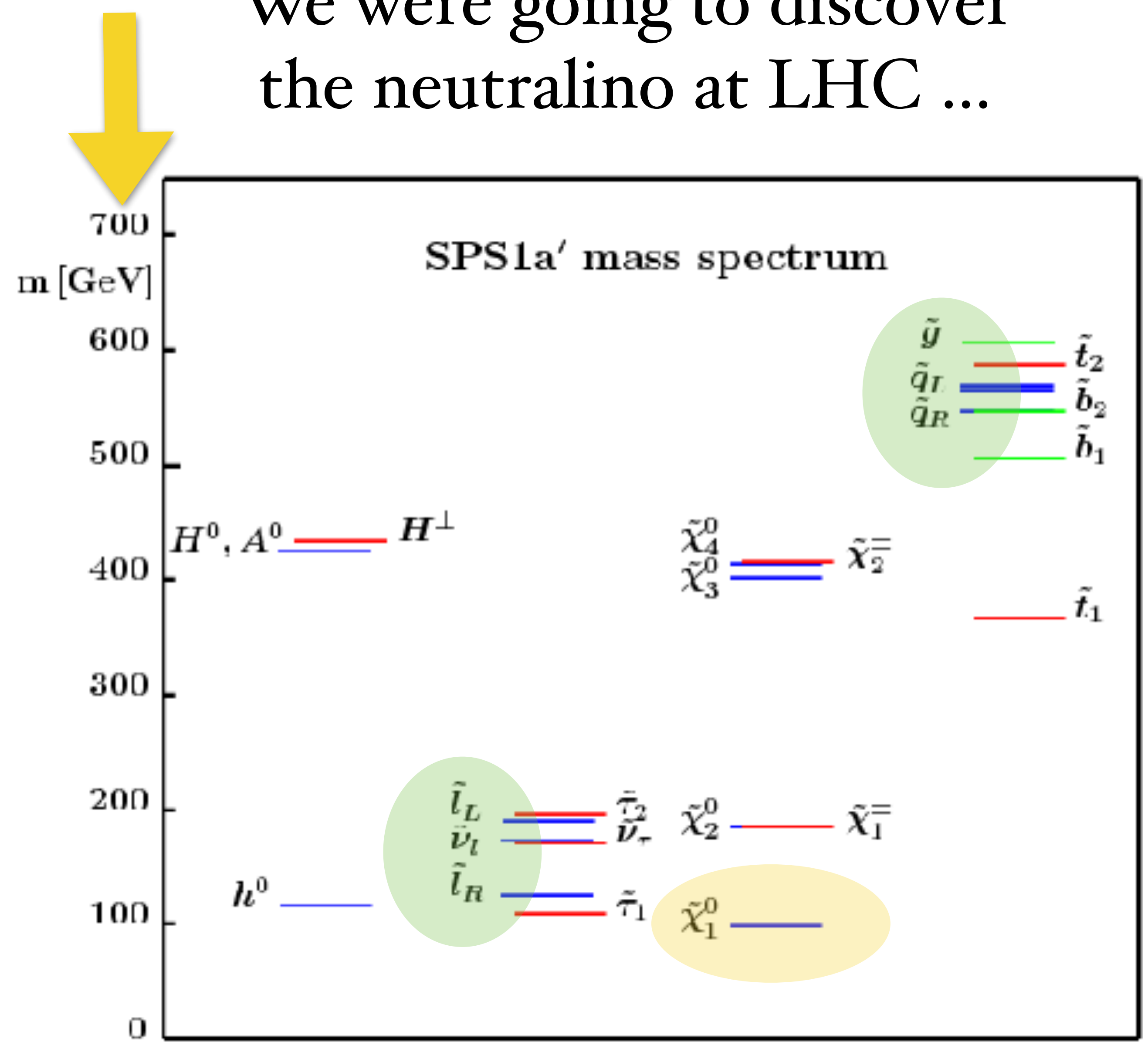
Supersymmetric and relic density

Before 1998

mDM <200 GeV



We were going to discover the neutralino at LHC ...



Exceptions to relic calculations

Nucl.Phys. B237 (1984) 285-306 Phys.Rev. D43 (1991) 3191-3203

Coannihilations

$$\frac{dn_i}{dt} = -3Hn_i - \sigma v_{ann}(n_i^2 - n_{i,0}^2) - \sigma v_{co-ann}(n_i n_j - n_{i,0} n_{j,0})$$

$$\frac{dn_j}{dt} = -3Hn_j - \sigma v_{ann}(n_j^2 - n_{j,0}^2) - \sigma v_{co-ann}(n_i n_j - n_{i,0} n_{j,0}) - \Gamma_j (n_j - n_{j,0})$$

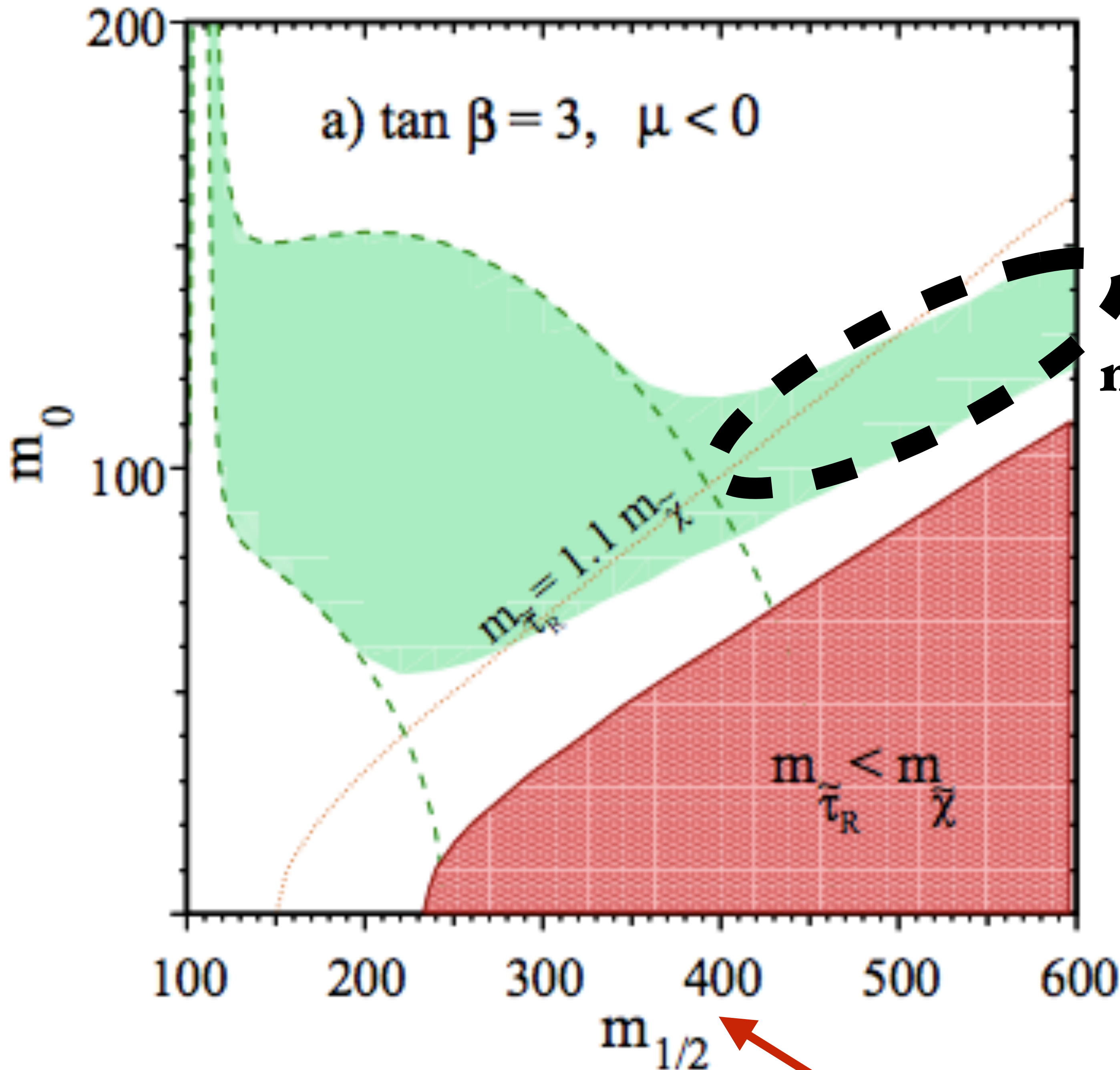
$$\frac{\Gamma_{ann}}{\Gamma_{coann}} = \frac{\langle \sigma v \rangle_{ann}}{\langle \sigma v \rangle_{coa}} \frac{n_1}{n_2} = \frac{\langle \sigma v \rangle_{ann}}{\langle \sigma v \rangle_{coa}} \frac{m_{d_1}}{m_{d_2}} e^{-\beta(m_{d_2} - m_{d_1})}$$

The mass difference is critical

Exceptions to relic calculations

hep-ph/9810360

Neutralino relic abundance?



coannihilations

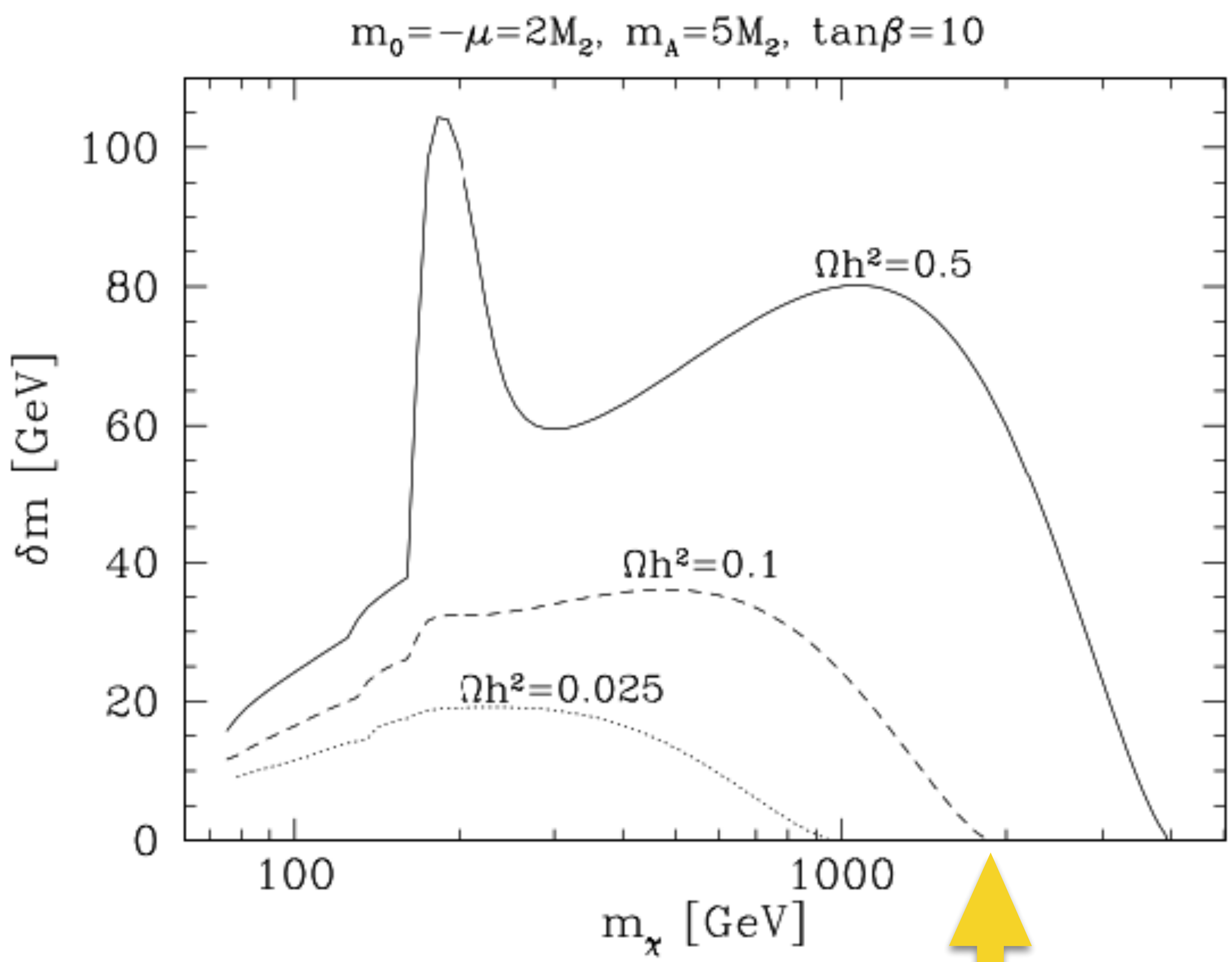
mDM > 200 GeV

neutralino mass < 200 GeV

Exceptions to relic calculations

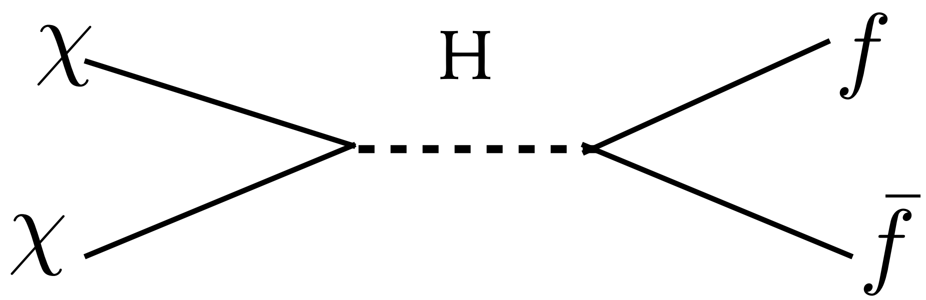
hep-ph/9911496

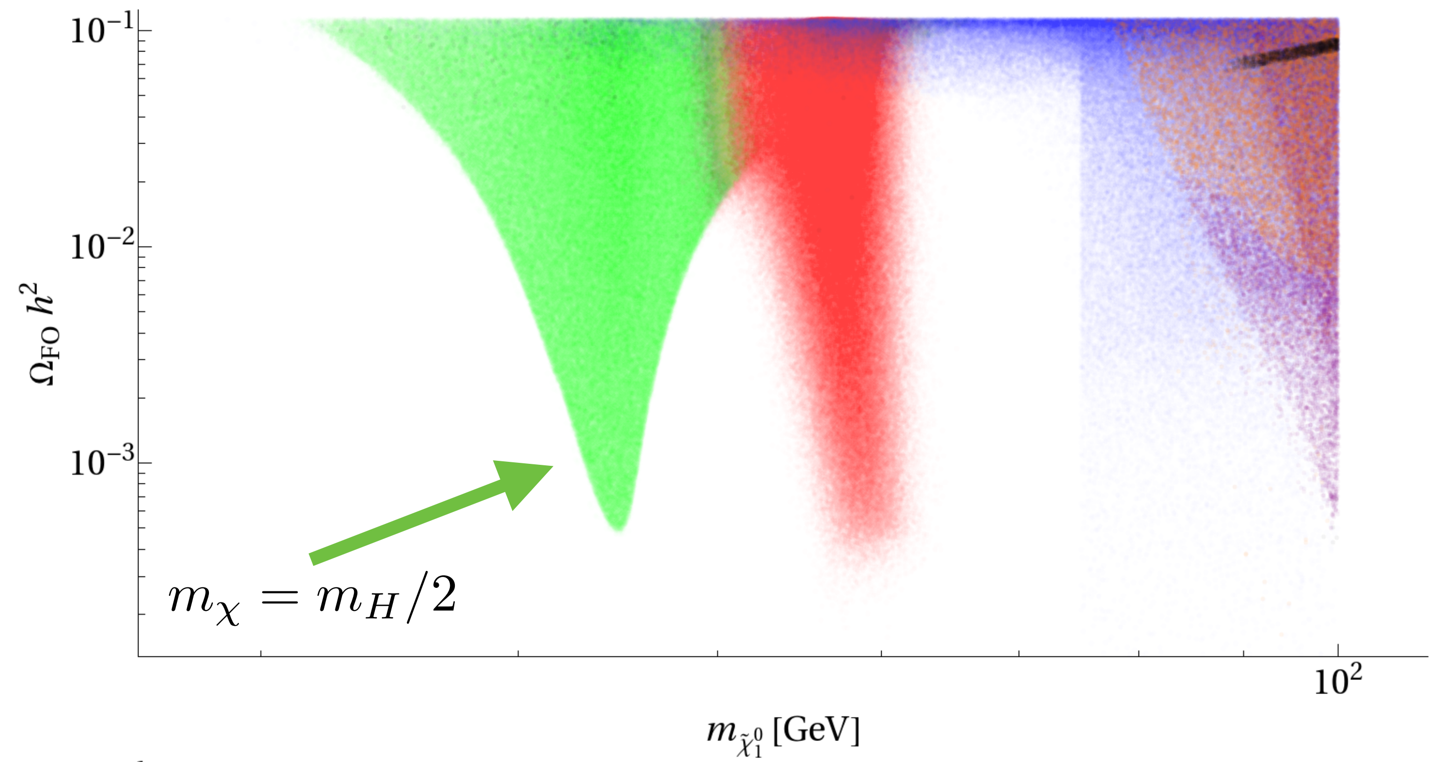
DM co-annihilations with “stops”

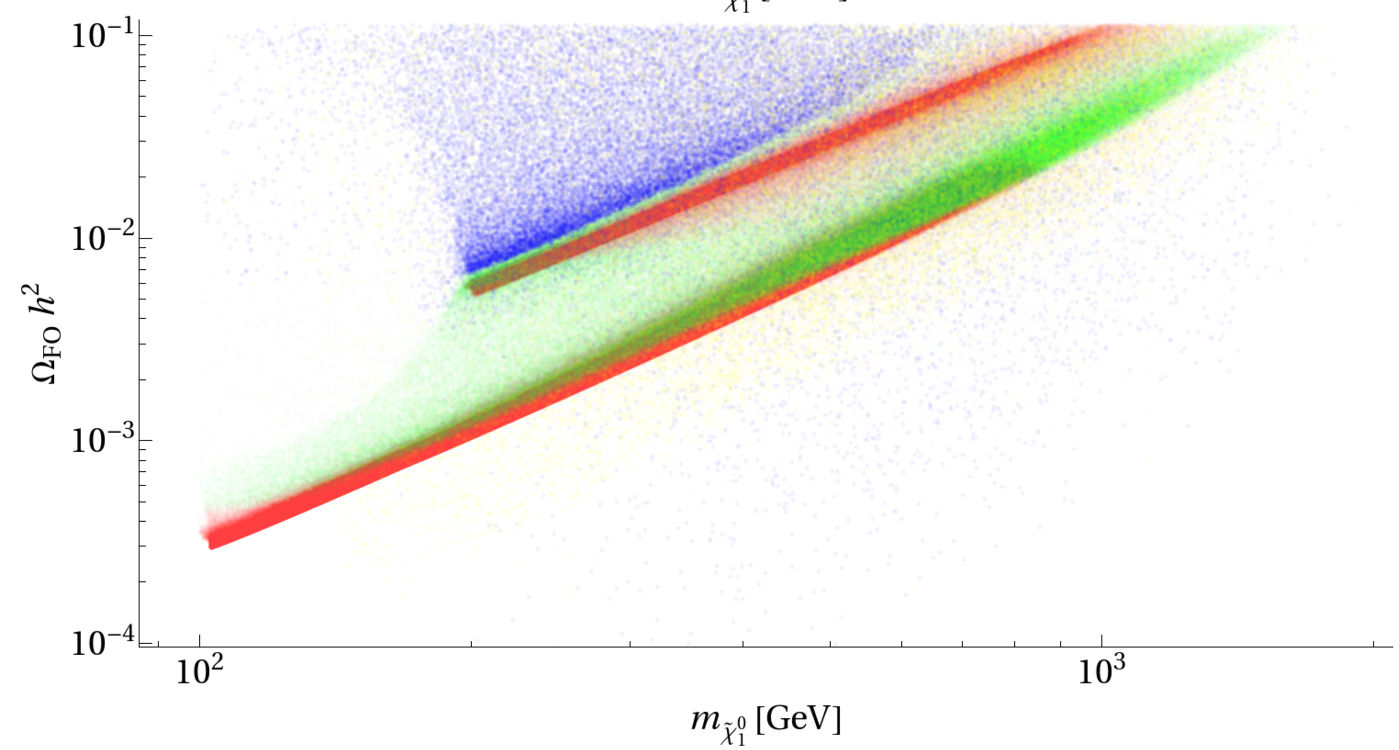


mDM > TeV

Exceptions to relic calculations







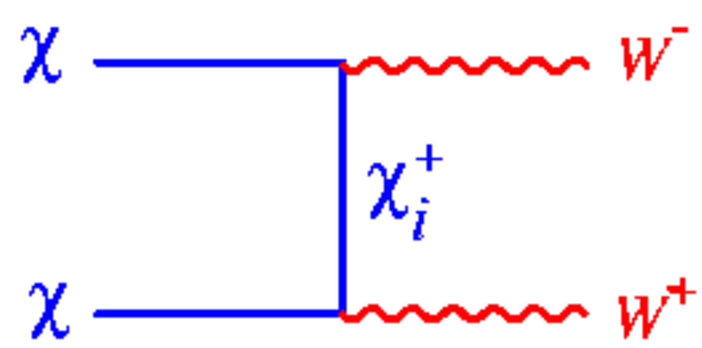
Different couplings probe different nature of the neutralino

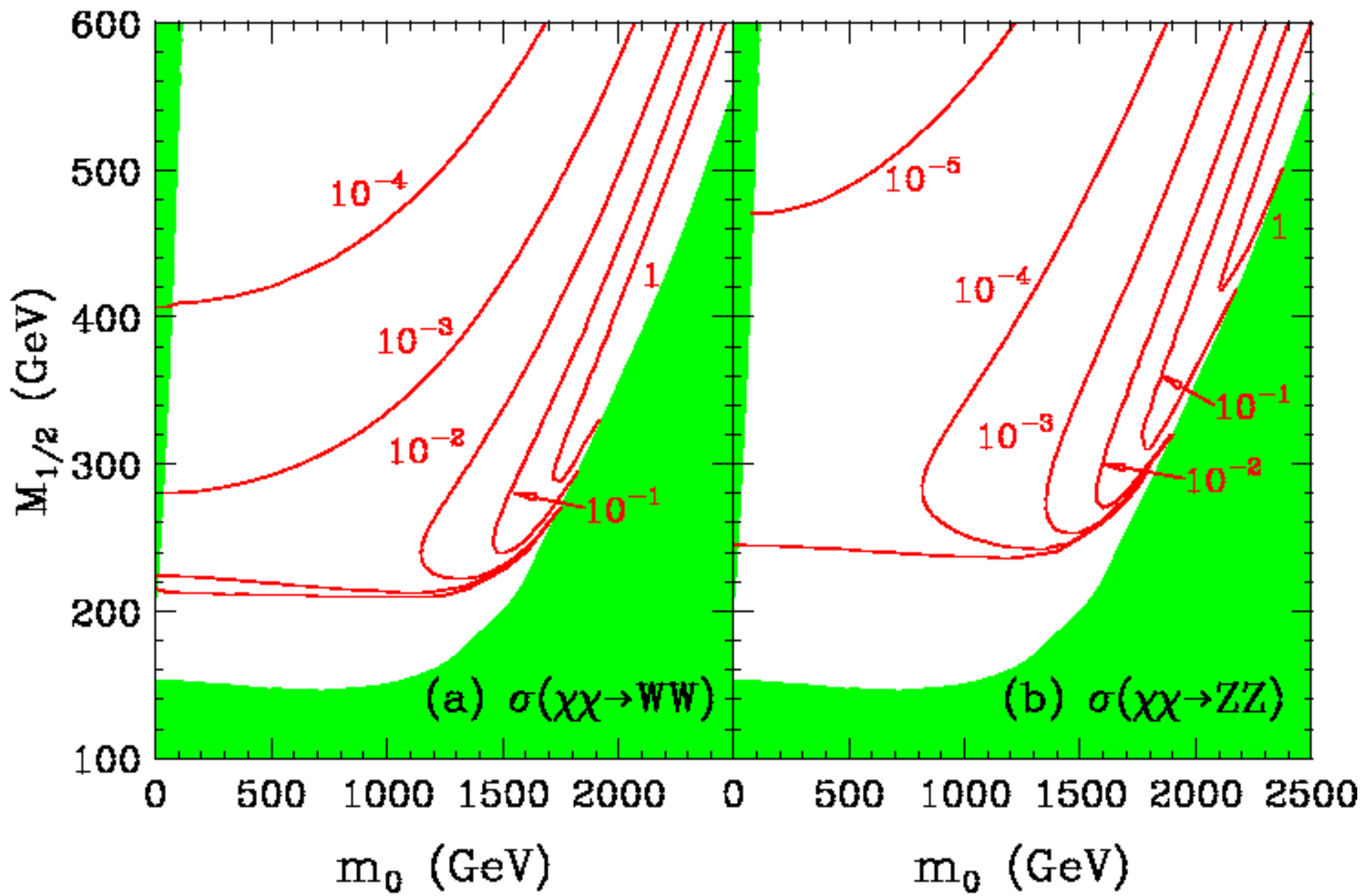
$$\chi_i^0 = N_{i1}\tilde{B}^0 + N_{i2}\tilde{W}^3 + N_{i3}\tilde{H}_1^0 + N_{i4}\tilde{H}_2^0$$
$$i = 1, \ldots, 4$$

The resonance implies smaller couplings are needed for the neutrinos to be the DM

Exceptions to relic calculations

Focus points





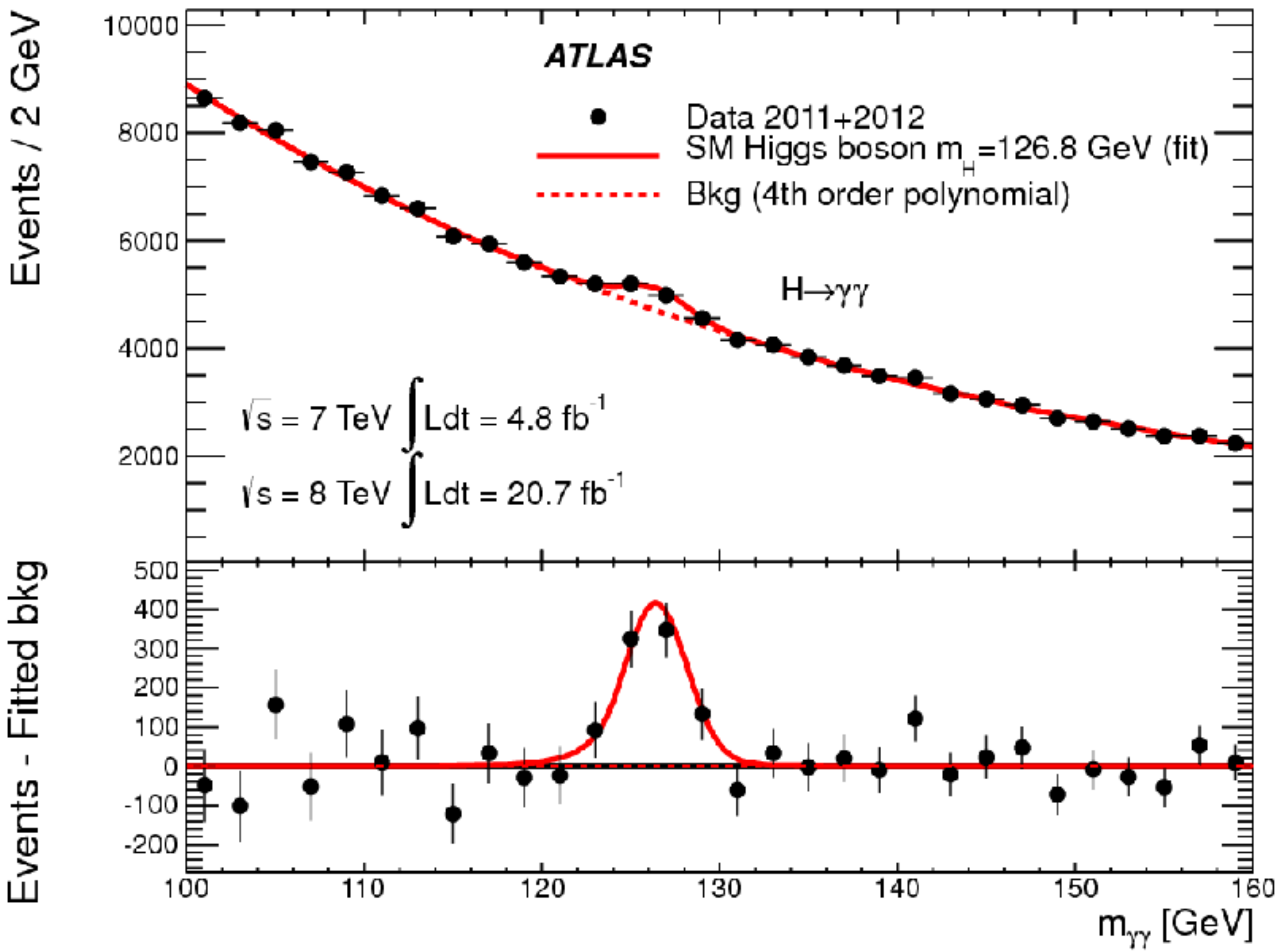
SUSY survival mode

10. **The last refuge of mixed wino-Higgsino dark matter**
Martin Beneke (Munich, Tech. U.), Aoife Bharucha (Marseille, CPT), Andrzej Hryczuk (Oslo U. & Warsaw, Inst. Nucl. Studies), Stefan Recksiegel (Munich, Tech. U.), Pedro Ruiz-Femenia (Madrid, Autonoma U. & Munich, Tech. U. & Madrid, IFT). Nov 2, 2016. 30 pp.
Published in **JHEP 1701 (2017) 002**
TUM-HEP-1065-16, FTUAM-16-38, IFT-UAM-CSIC-16-106
DOI: 10.1007/JHEP01(2017)002
e-Print: **arXiv:1611.00804 [hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Link to Article from SCOAP3
Detailed record - Cited by 5 records

11. **Very Degenerate Higgsino Dark Matter**
Eung Jin Chun (Korea Inst. Advanced Study, Seoul), Sunghoon Jung (SLAC & Santa Barbara, KITP), Jong-Chul Park (Chungnam Natl. U.). Jul 14, 2016. 19 pp.
Published in **JHEP 1701 (2017) 009**
DOI: 10.1007/JHEP01(2017)009
e-Print: **arXiv:1607.04288 [hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Link to Article from SCOAP3
Detailed record - Cited by 4 records

12. **Light Higgsino Dark Matter from Non-thermal Cosmology**
Luis Aparicio (ICTP, Trieste), Michele Cicoli (ICTP, Trieste & Bologna U. & INFN, Bologna), Bhaskar Dutta (TAMU, College Station), Francesco Muia (Bologna U. & INFN, Bologna), Fernando Quevedo (ICTP, Trieste & Cambridge U., DAMTP). Jun 30, 2016. 22 pp.
Published in **JHEP 1611 (2016) 038**
DOI: 10.1007/JHEP11(2016)038
e-Print: **arXiv:1607.00004 [hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Link to Article from SCOAP3
Detailed record - Cited by 3 records

Remember discoveries are not easy …

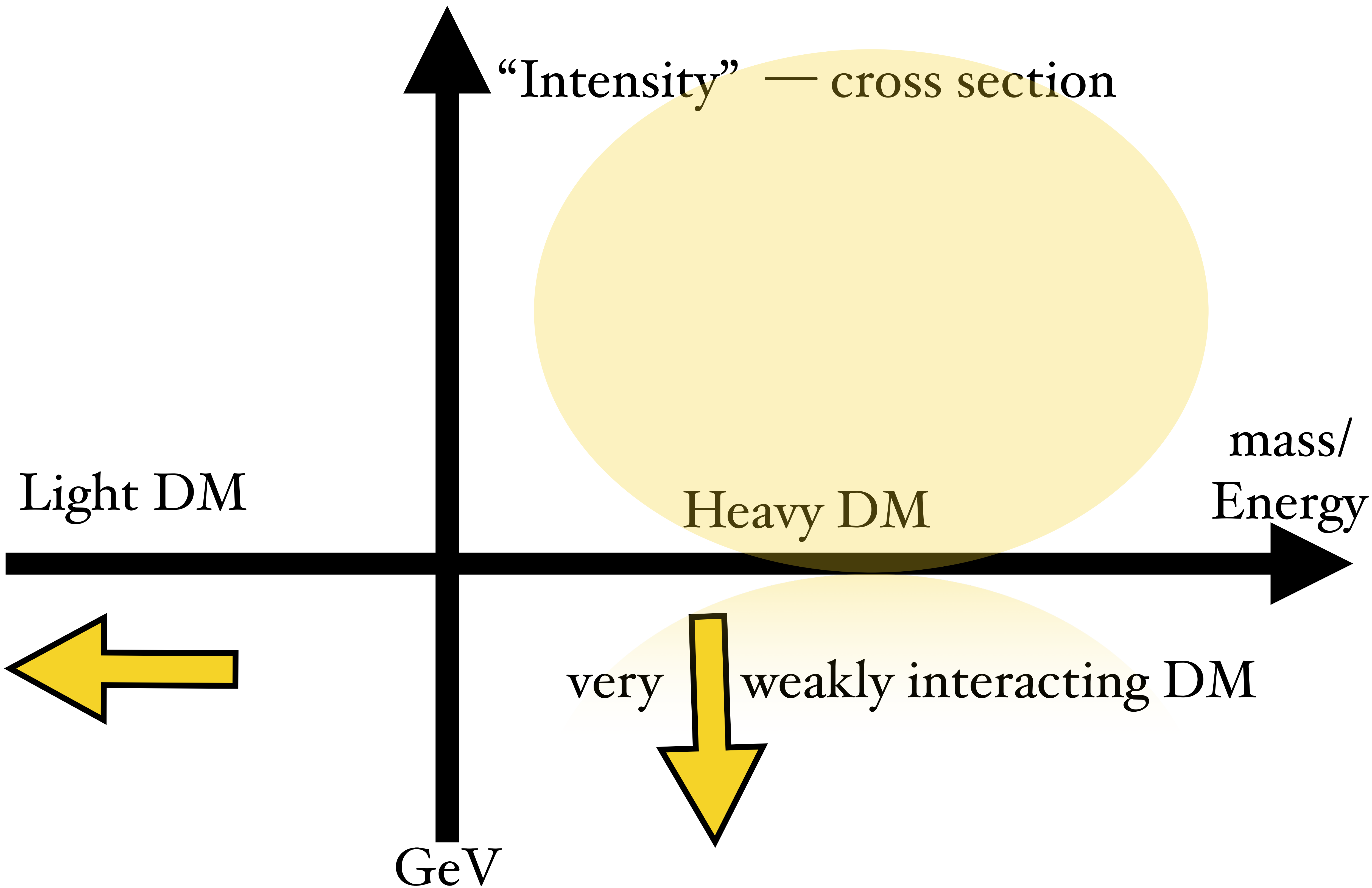


Particle physics examples

Beyond SUSY

Where else could DM particles be?

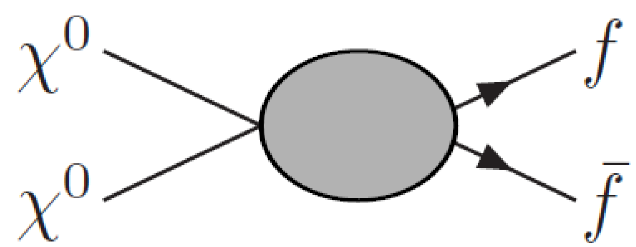
following the dark matter path



Light Dark Matter

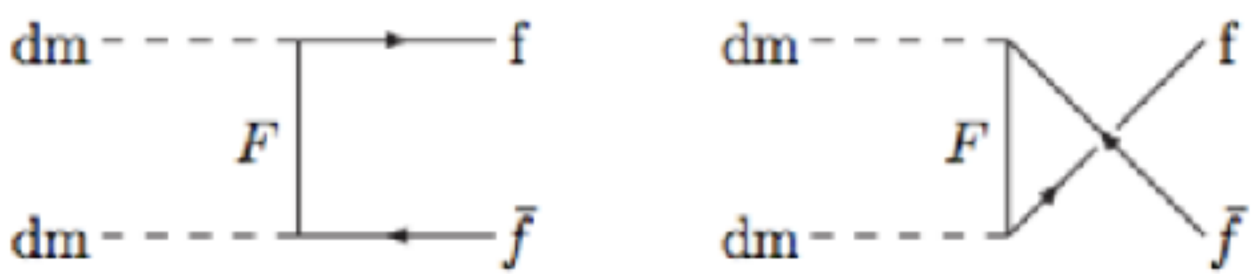
astro-ph/0208458v3   hep-ph/0305261

$$\frac{dn}{dt} = -3Hn - \sigma v(n^2 - n_0^2)$$



What kind of mediator?

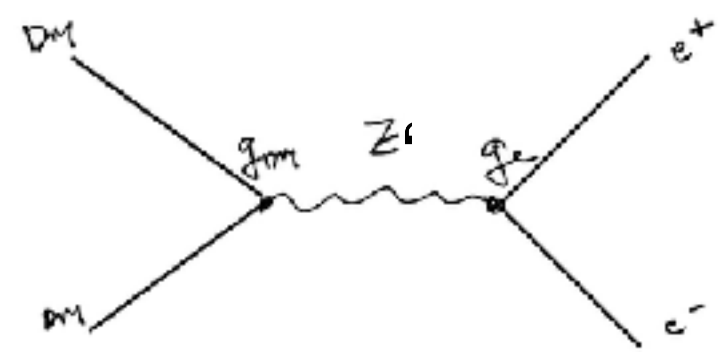
vector-like fermions



$$\sigma v \propto \frac{1}{m_F^4} \left((C_l^2 + C_r^2)\ m_f + 2 C_l\ C_r\ m_F \right)^2$$

$$\sigma v \propto \frac{1}{m_F^2}$$

dark photons/Z'

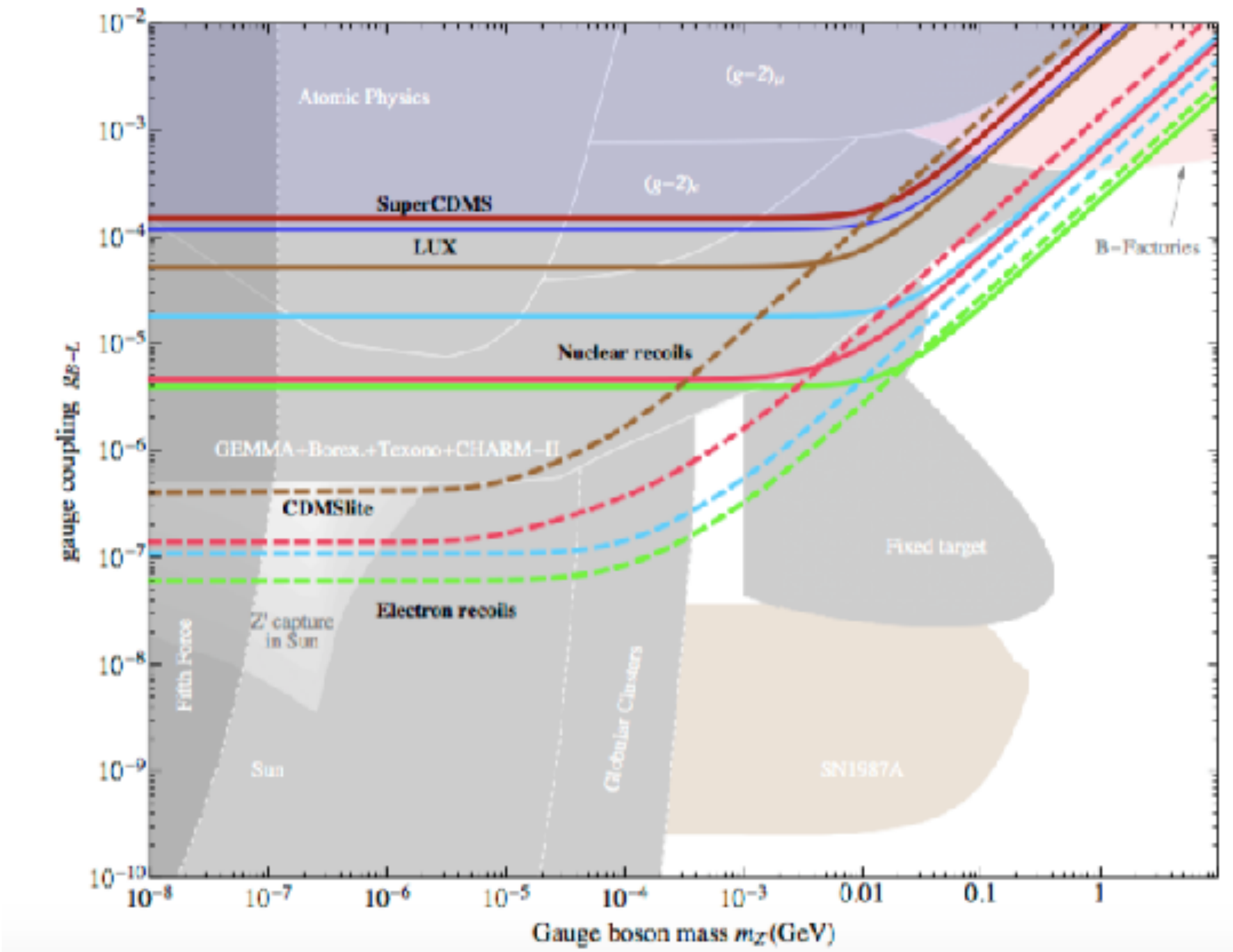


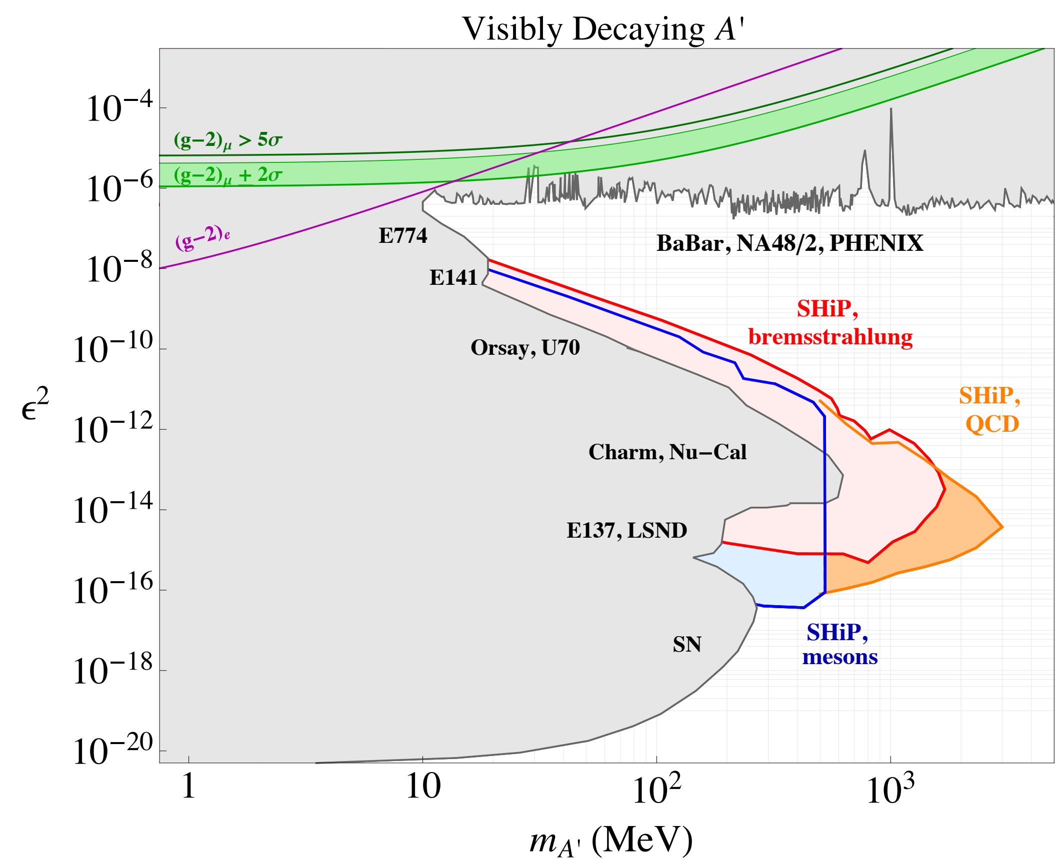
$$\sigma v \propto v^2 \frac{m_{\rm DM}^2}{m_{Z'}^4}\ g_{\rm DM}^2\, g_e^2$$

$$m_{\rm DM} \simeq m_{Z'}$$

DM can be light!

Searching for Z'/dark photons





Effects of Weakly Interacting Slim Particles in Cavities with a Moving Boundary Condition

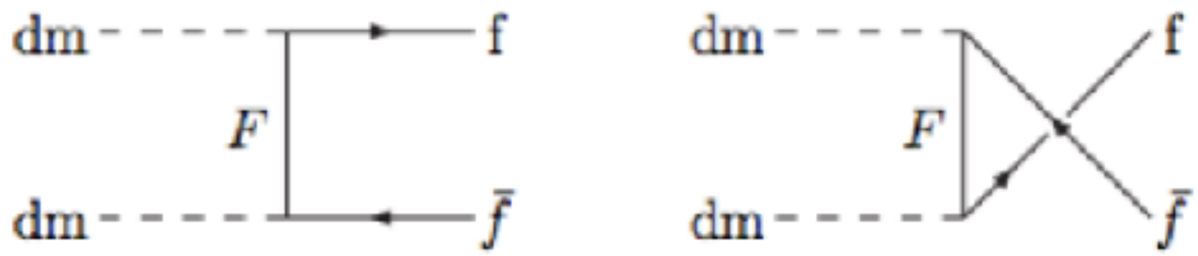
Ariel Arza

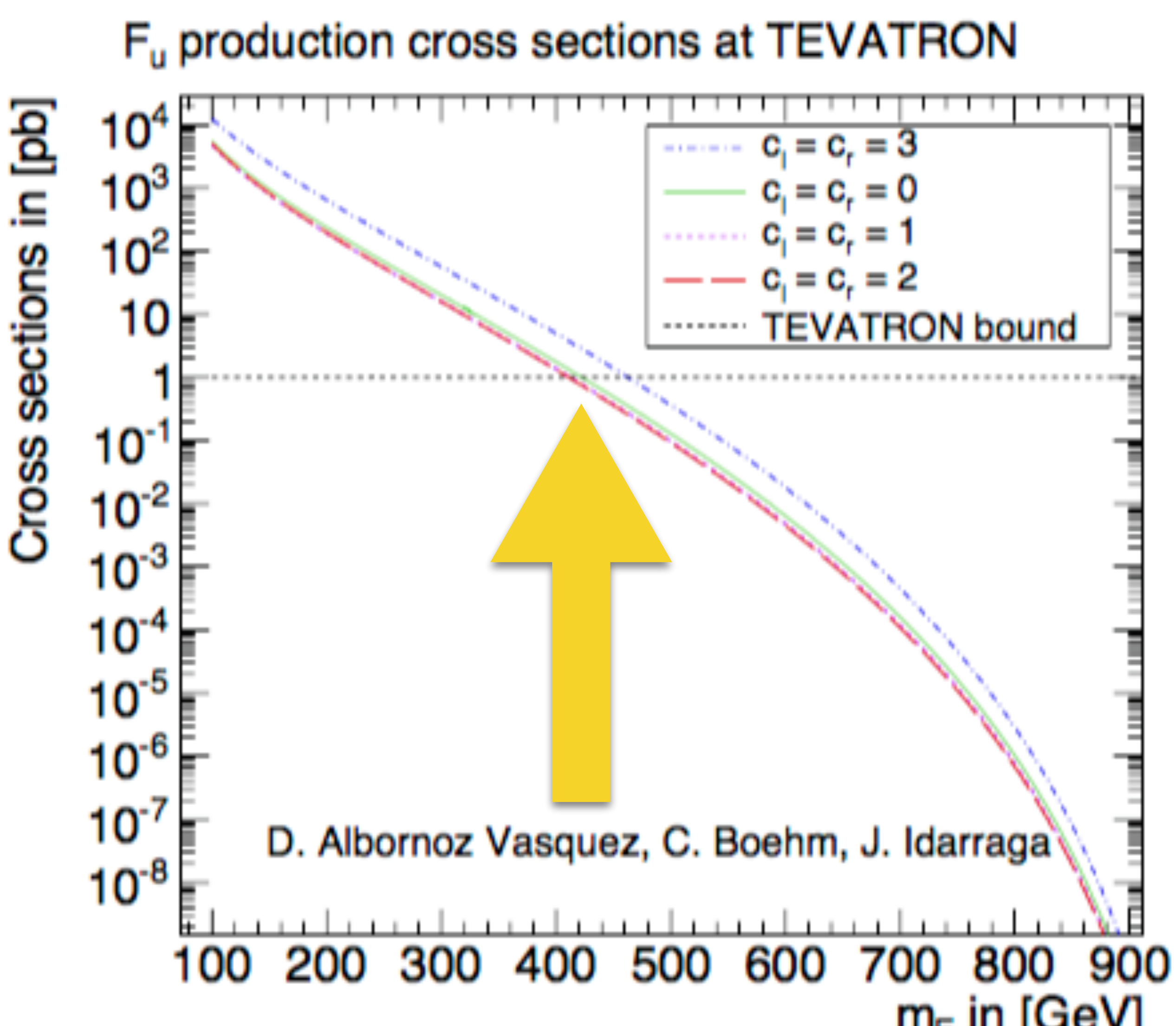
May 10, 2017

e-Print: arXiv:1705.03906 [hep-ph] | PDF

T-channel mediators at LHC

first example of simplified models at LHC



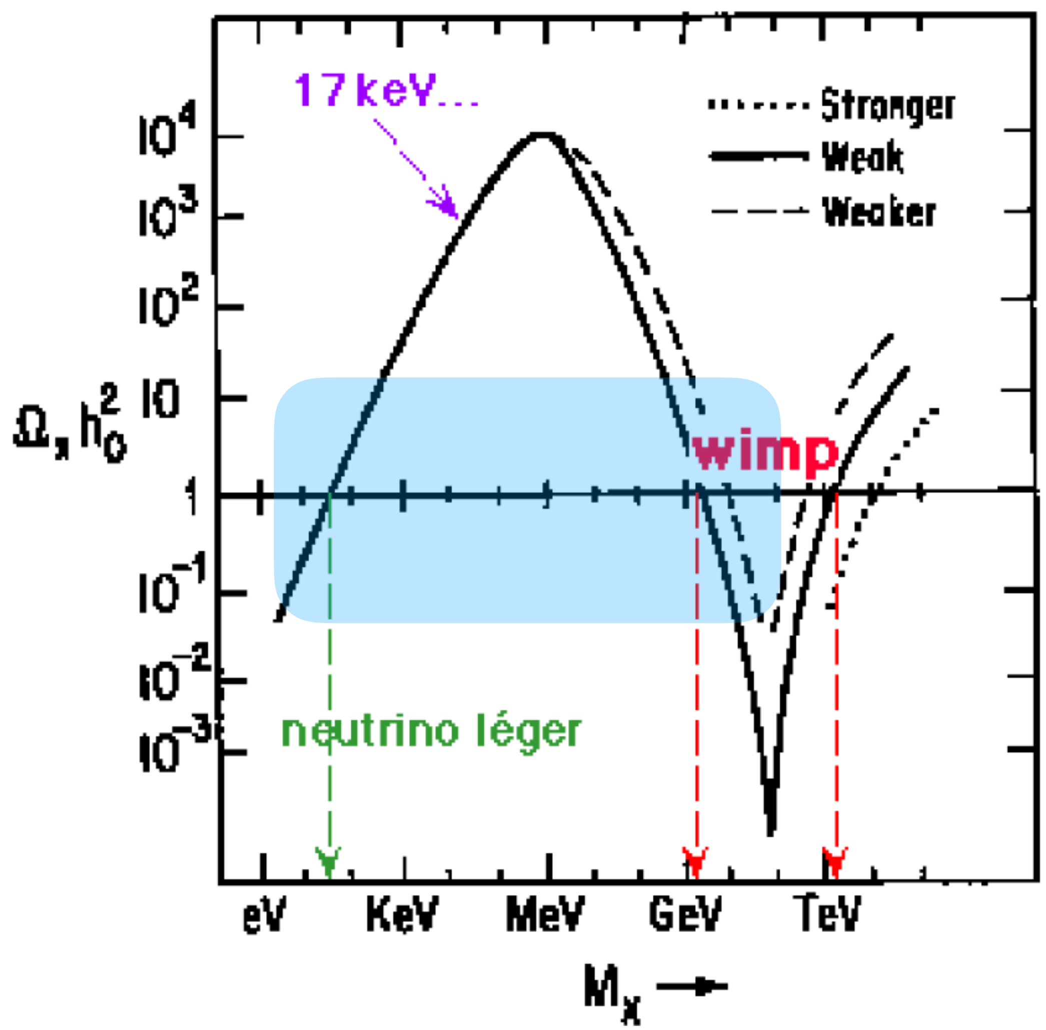


0912.5373

The mediator can be produced through the exchange of DM

Ruled out (now) up to TeV

Another exception to Hut, Lee&Weinberg

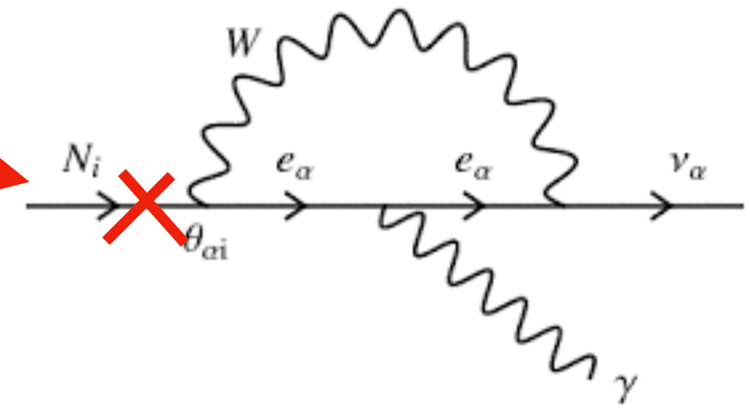


Why not considering MeV, keV, eV etc DM??

Non-thermal DM candidates

sterile neutrinos

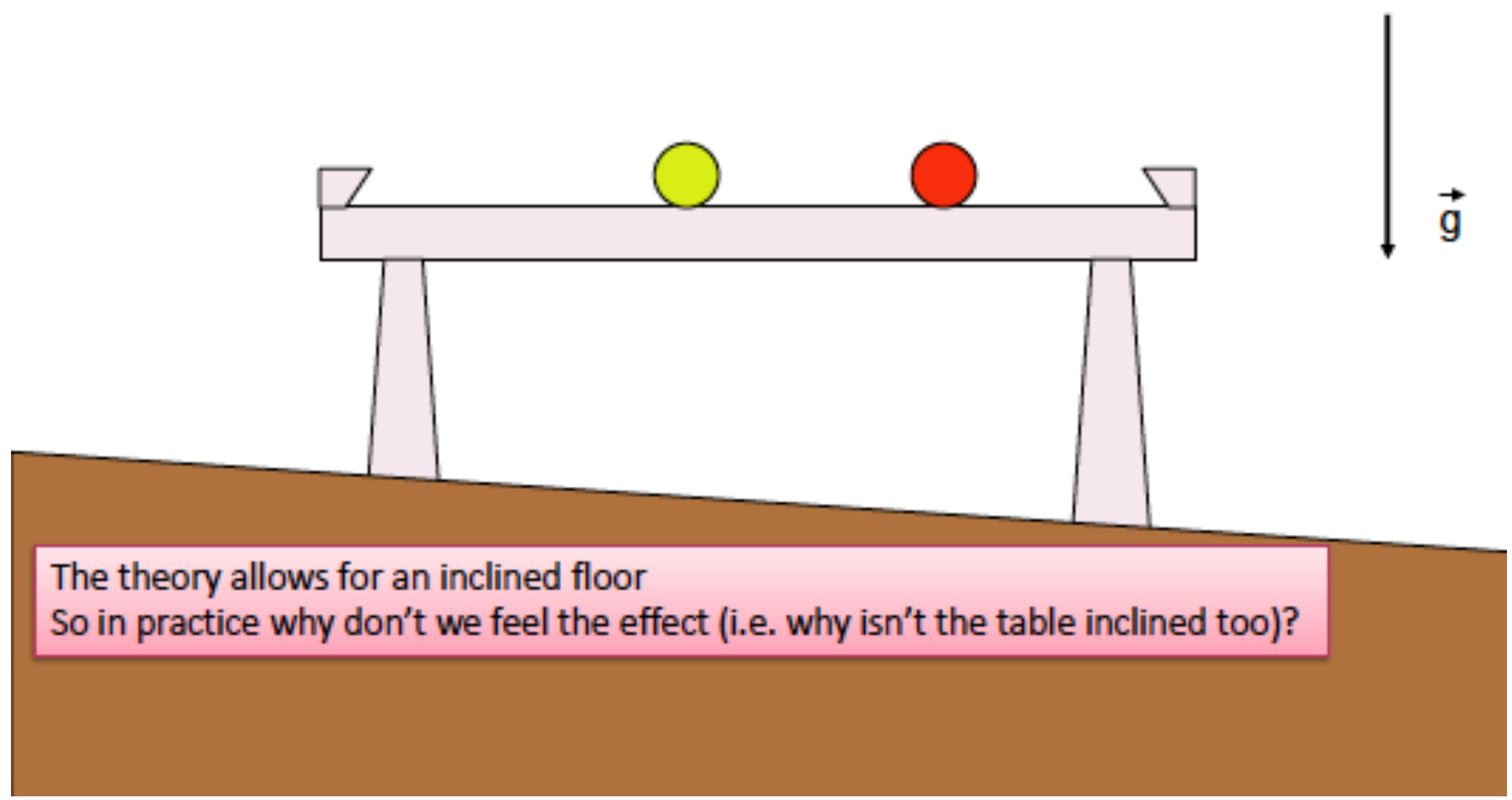
mixing angle



axions

$$L_{\text{QCD}} = \ \ldots + \boxed{\theta \frac{g^2}{32\pi^2} G^a{}_{\mu\nu} \tilde{G}^{a\mu\nu}}$$

QCD field strength

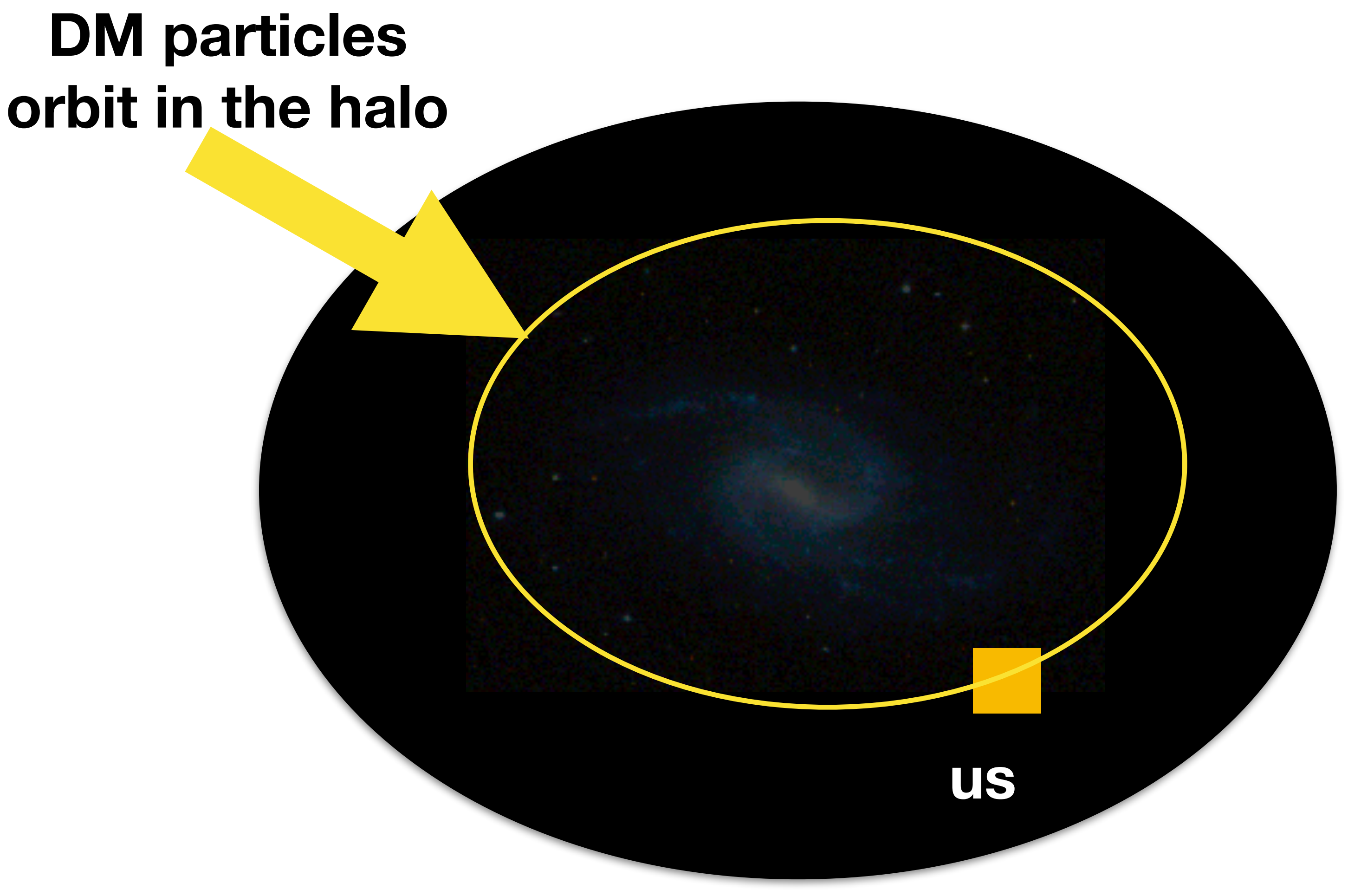


Courtesy P. Sikivie

III. Signatures

* Direct Detection
* Indirect Detection
* LHC

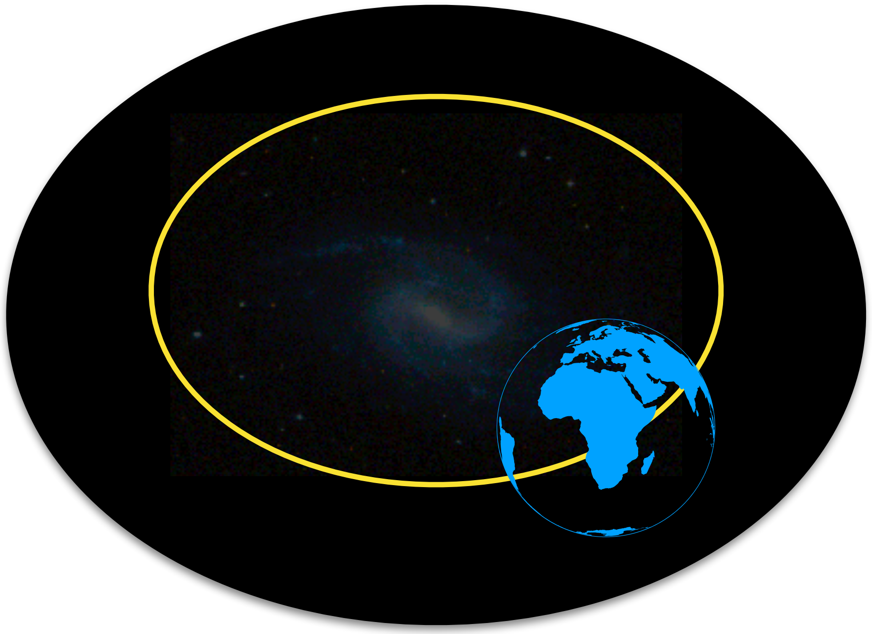
III. A. Direct detection



DM particles cross through the Earth

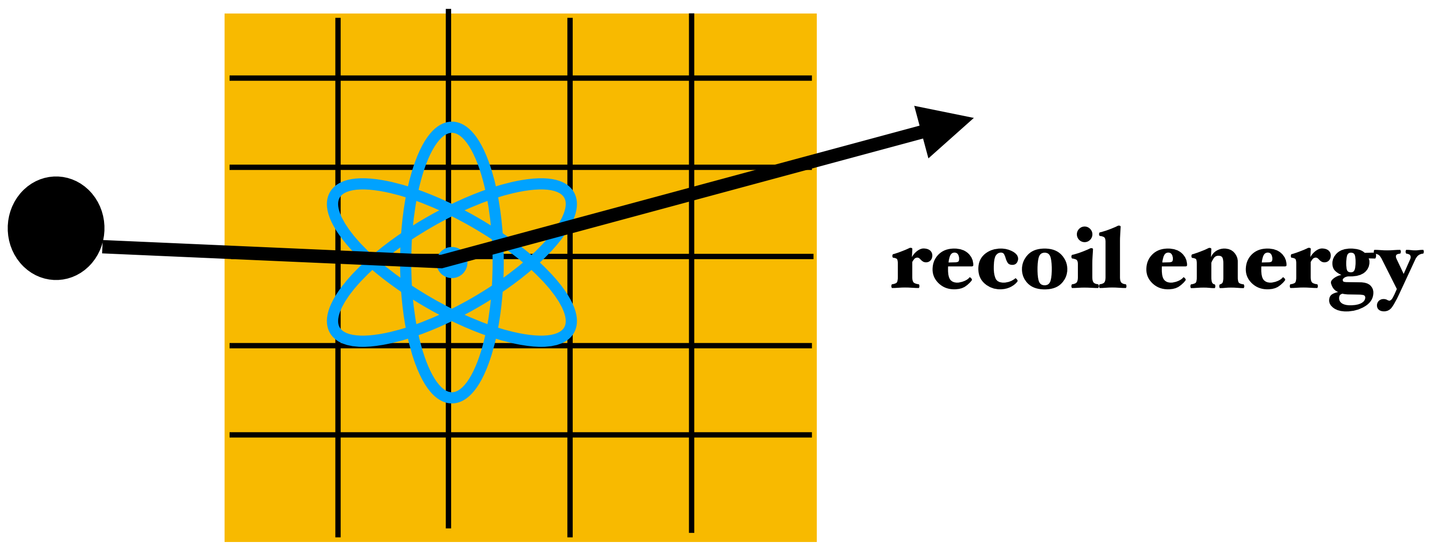
Principle of direct detection

Make a detector, wait, hope for an interaction within



Assuming that

DM interacts with SM particles
We are able to detect the interaction

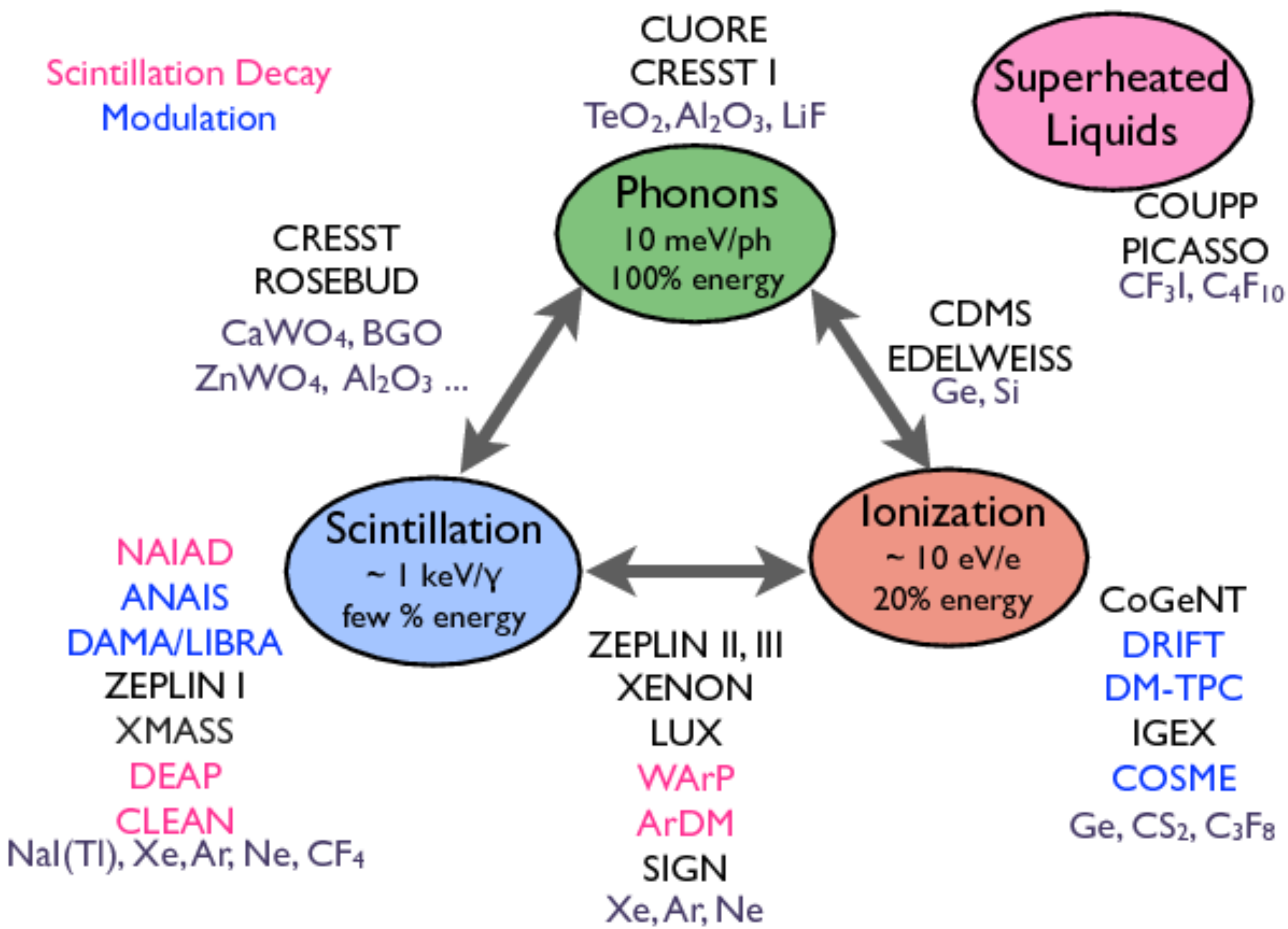


What kind of signatures do we expect?

ionisation
scintillation
phonons
heat

Principle of direct detection

arXiv:1203.2566 **+ many presentations**

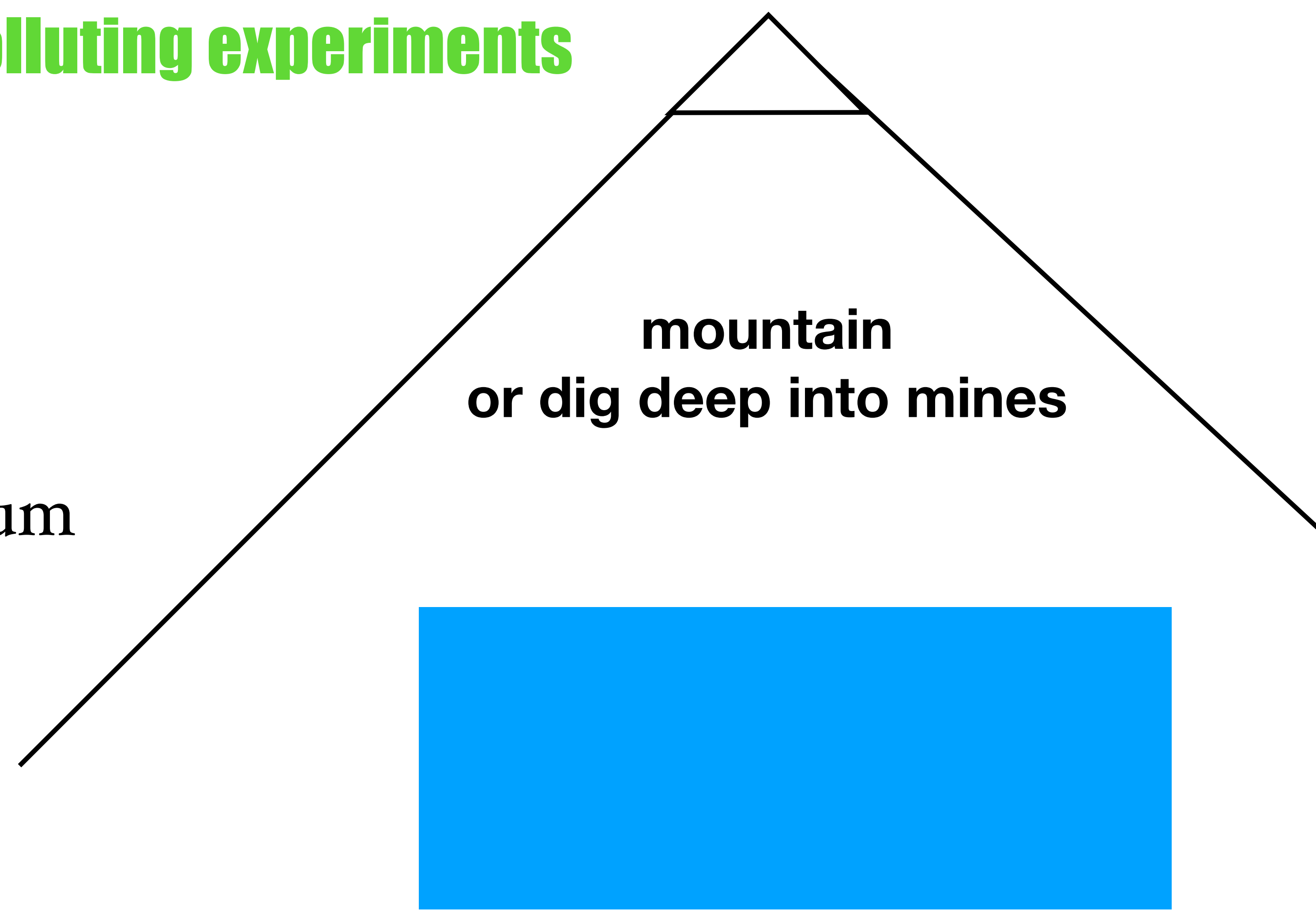


Principle of direct detection

How do we know we have detected DM?

We **don't** know unless we understand the background sources!

* radioactivity produces neutrons
* neutrons behave like WIMPs
* electrons, photons are also polluting experiments



To understand the background,
we need to reduce it to its minimum

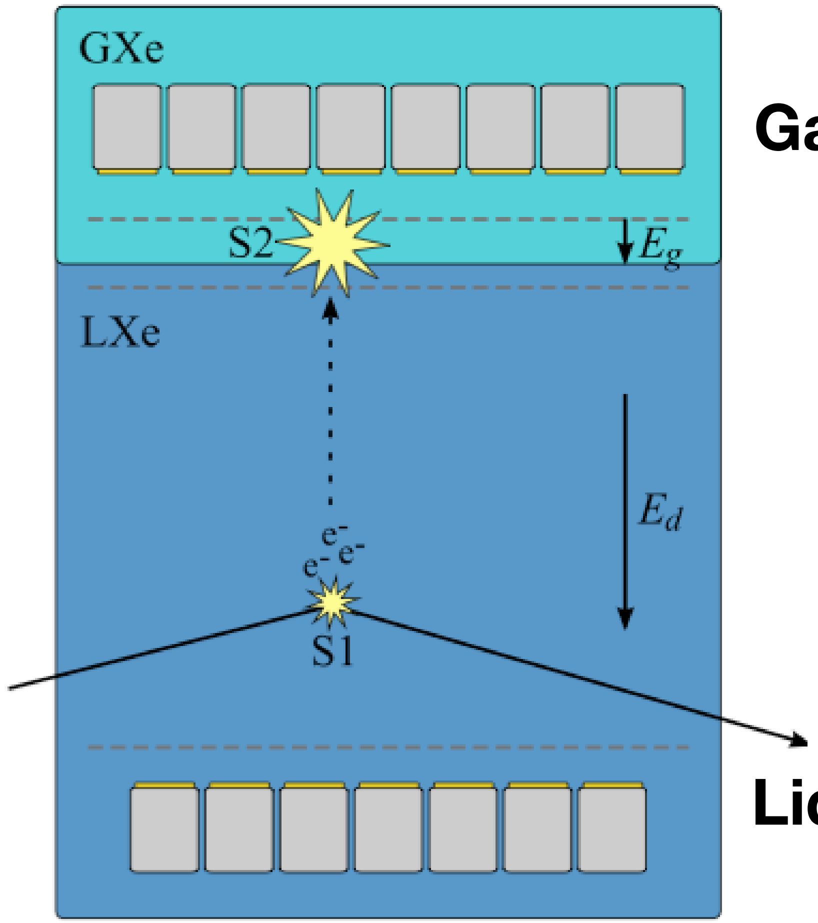
We need shielding

No dark matter direct detection experiments **in the Southern Hemisphere !**

Principle of direct detection

Principle of direct detection

XENON100 experiment now 1T and nT



Gas Xenon

Liquid Xenon

S1 = primary scintillation signal

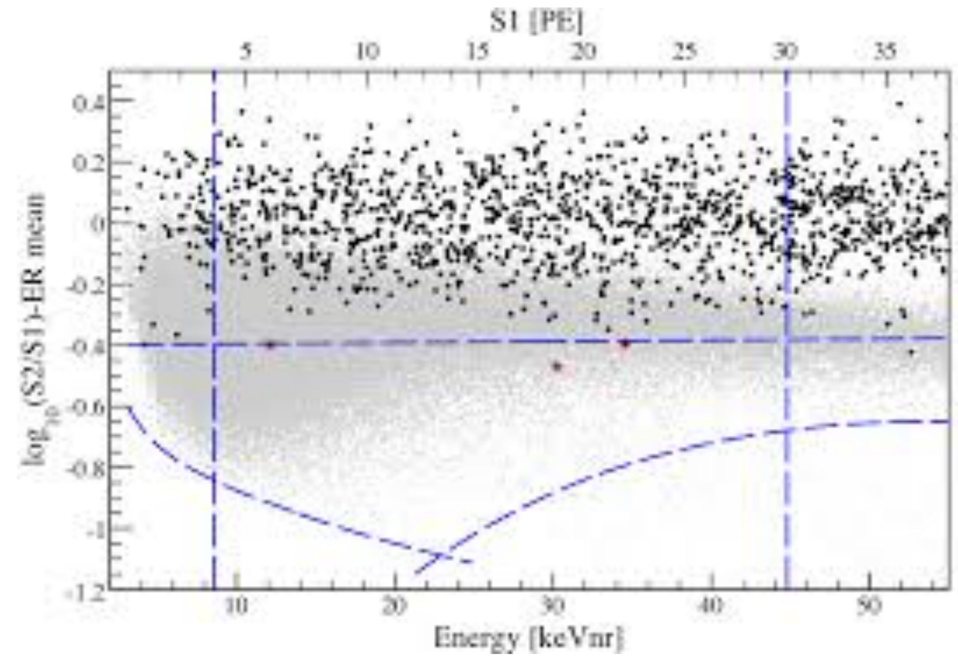
S2 = secondary scintillation signal (from the drift of electrons from ionised Xenon)

Xenon 10 (10 kg Xenon)

Principle of direct detection

How do we separate DM from background?

The Xenon experiment

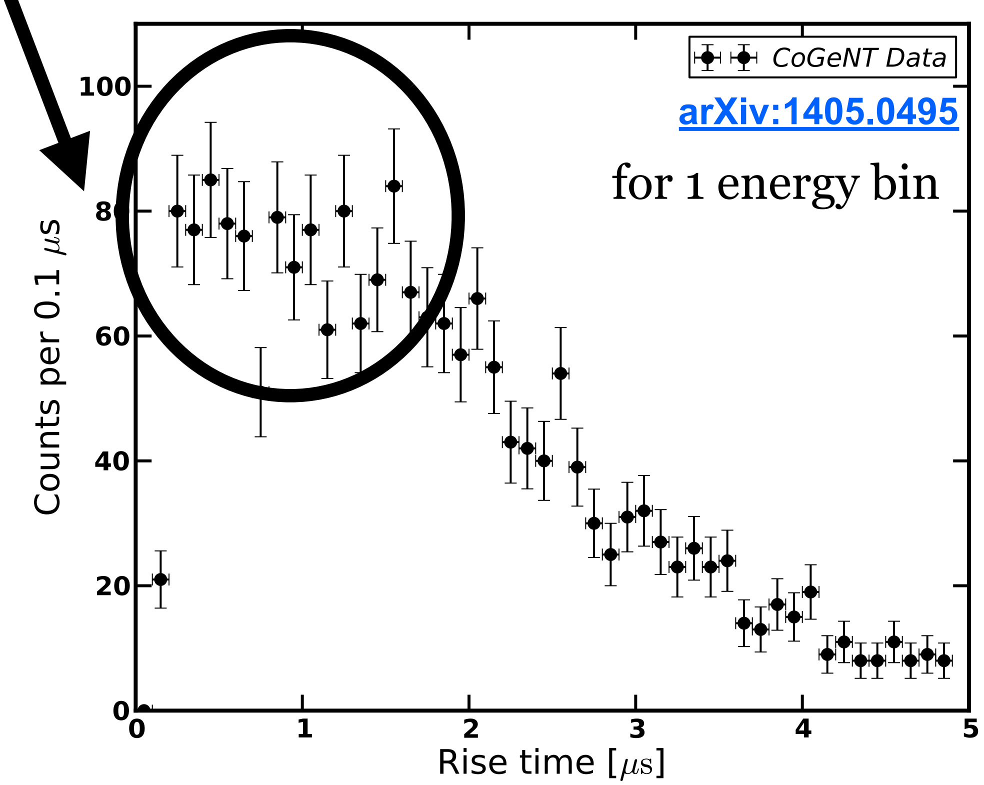


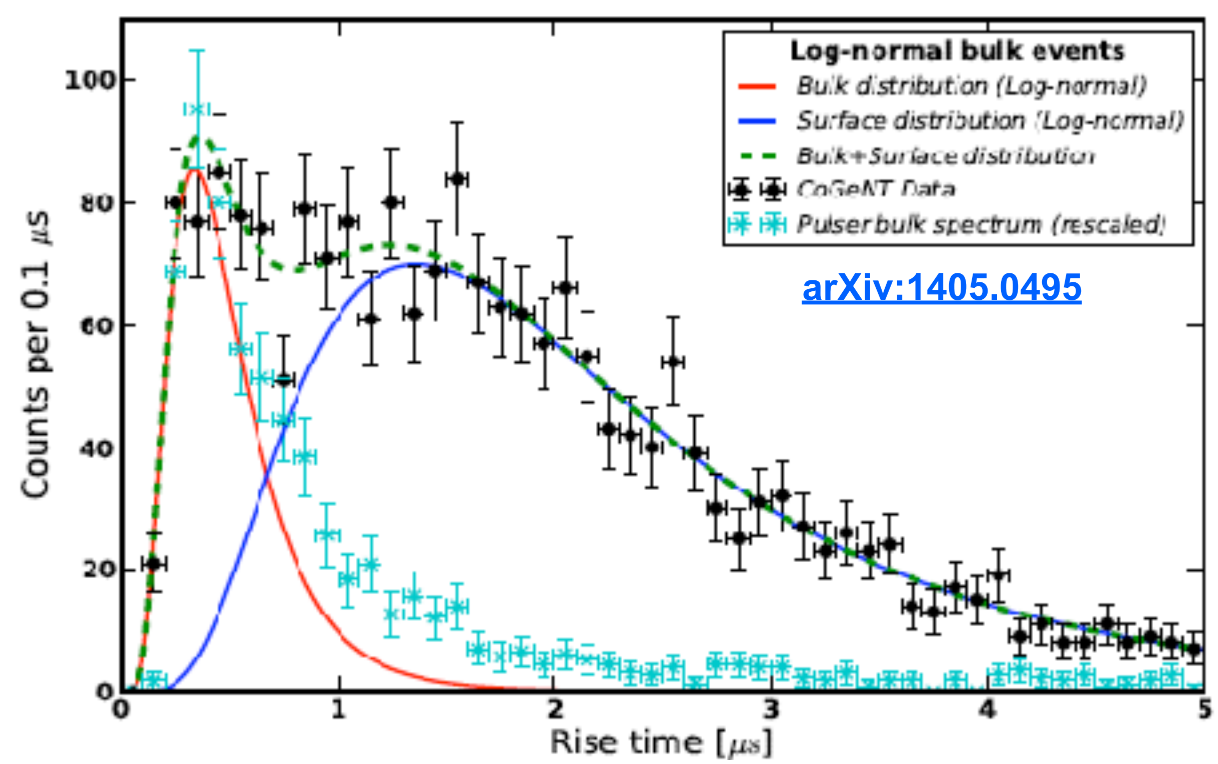
The CoGeNT experiment

collect ionisation charge signal+background

Only way: rise time of events

Where DM lies





Principle of direct detection

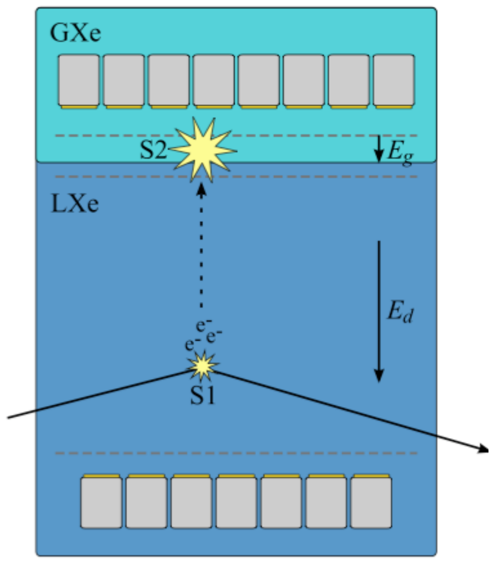
<u>Recoil energy</u>

$$E_{nr} = \frac{S_1}{L_y \, \mathcal{L}_{\mathrm{eff}}} \boxed{\frac{S_{er}}{S_{nr}}},$$

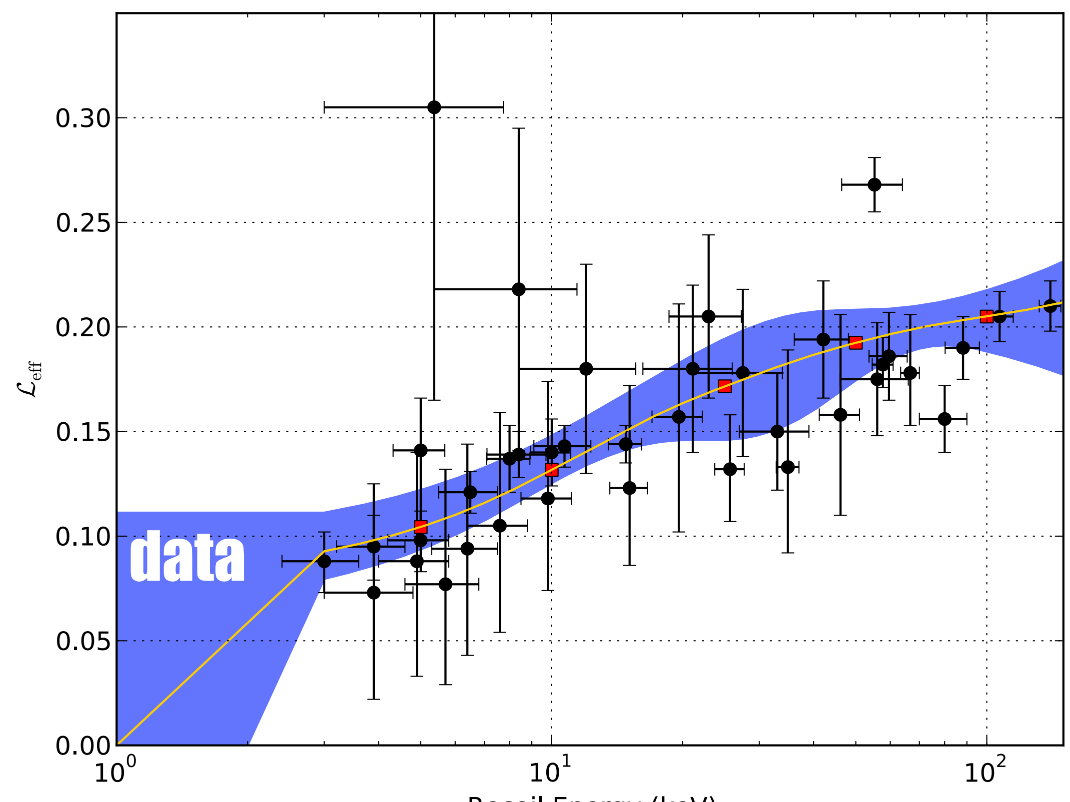
Recoil energy depends crucially on Leff

Light yield for the calibration source emitting gammas

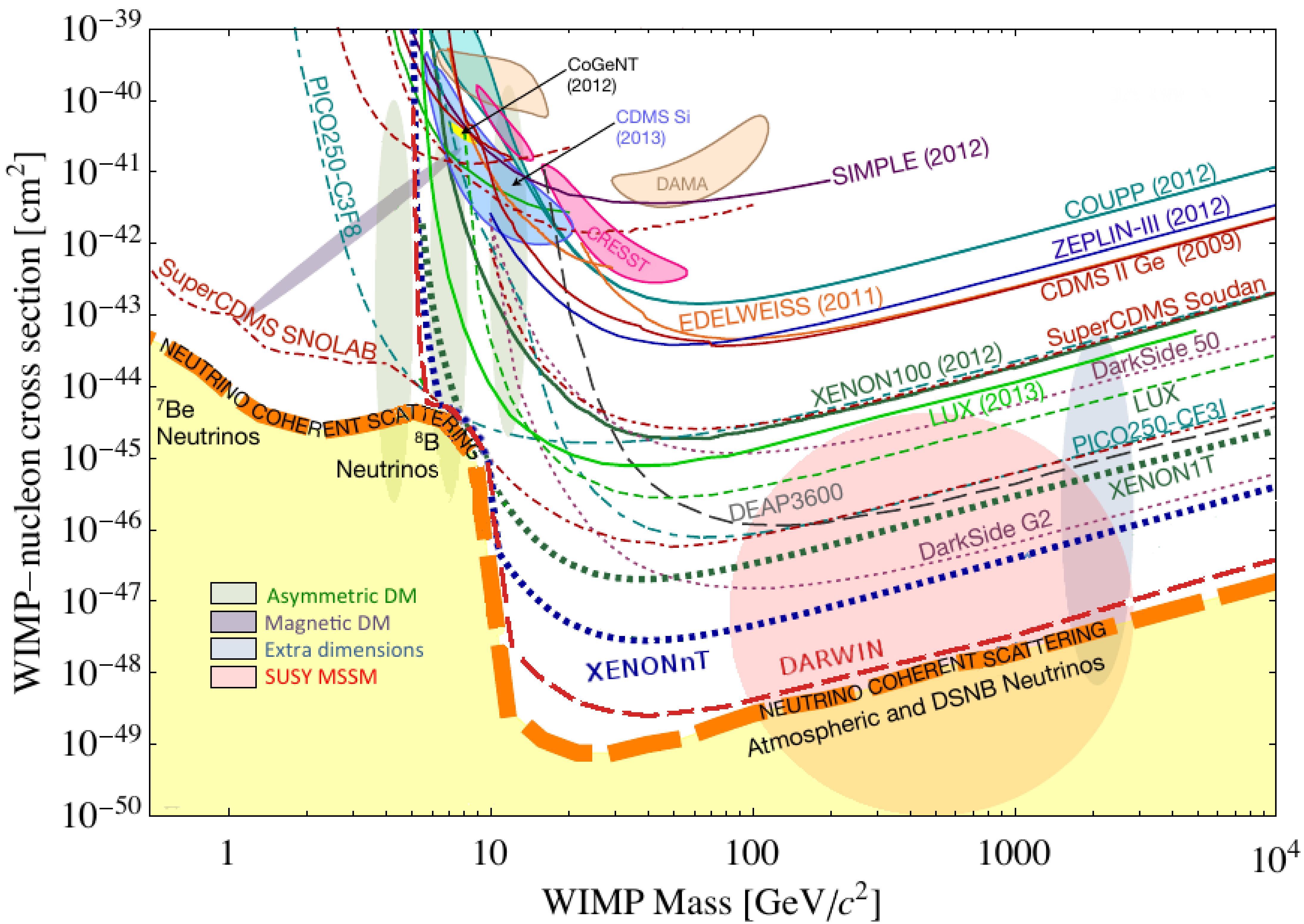
quenching factors, related to the electric field



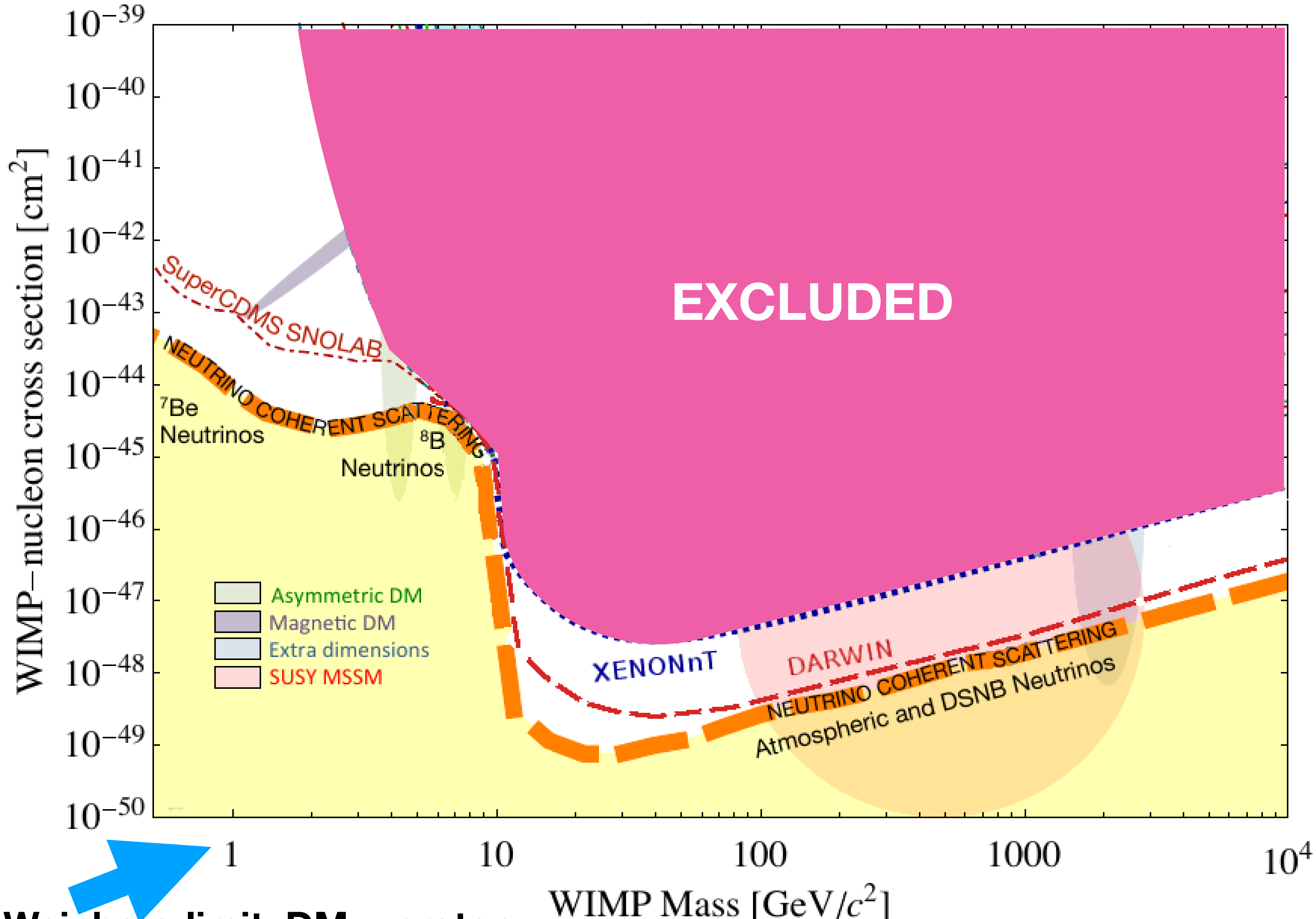
One needs to measure Leff



Principle of direct detection



Principle of direct detection



Lee&Weinberg limit: DM > proton but light DM OK so experiments need to be extended.