SAIFR-ICTP Summer School 2018

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Particle Physics & the Early Universe

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elusives-invisiblesPlus
neutrinos, dark matter & dark energy physics

MARIE CURIE ACTIONS

Outline

- Lecture 1: Standard Cosmology & the cosmological parameters
- Lecture 2: Thermal Universe and Big Bang Nucleosynthesis
- Lecture 3: Inflation & the CMB
- Lecture 4: Structure Formation & Dark Matter
- Lecture 5: Baryogenesis

Lecture 4: Outline

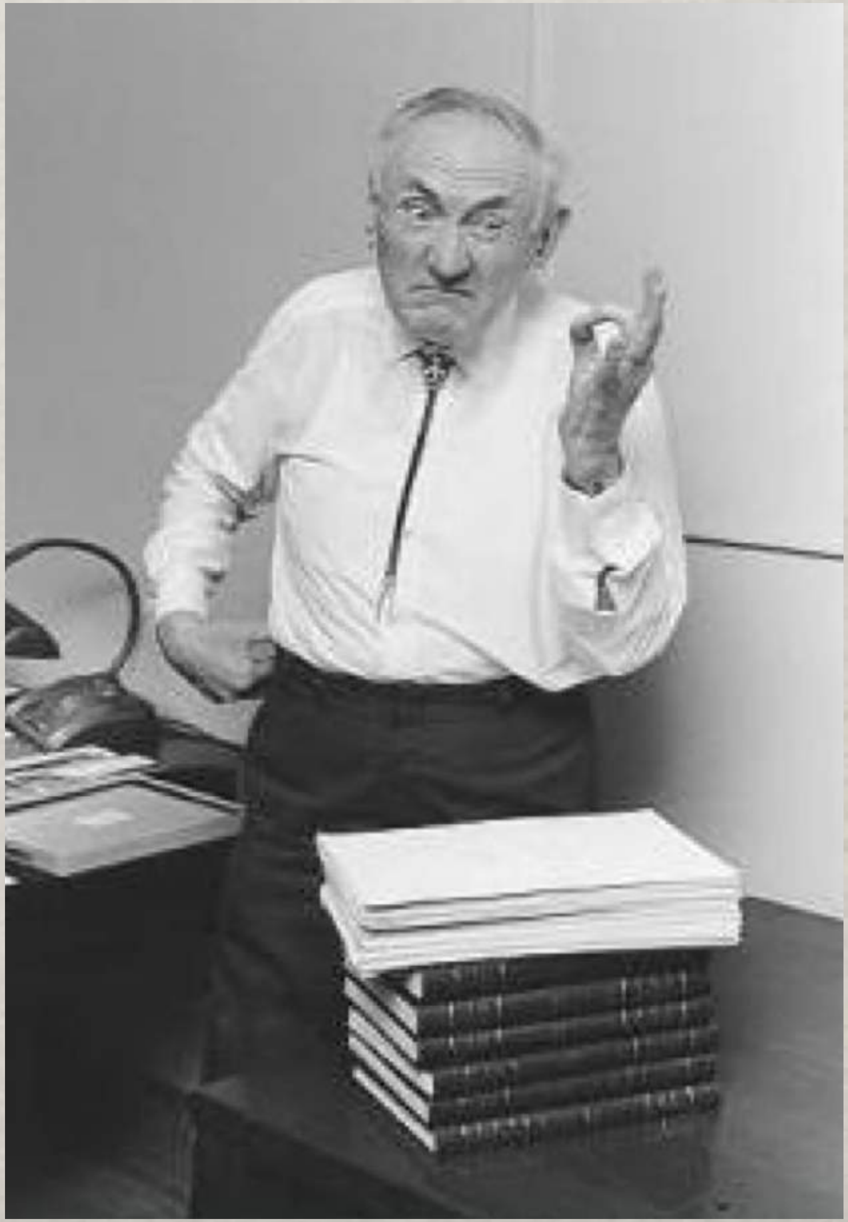
- Dark Matter evidence & Structure Formation
- Neutrinos as Dark Matter
- (Some) Dark Matter Candidates and how to detect them
- Conclusions

Dark Matter and structure formation

DARK MATTER EVIDENCE

CLUSTER SCALES:

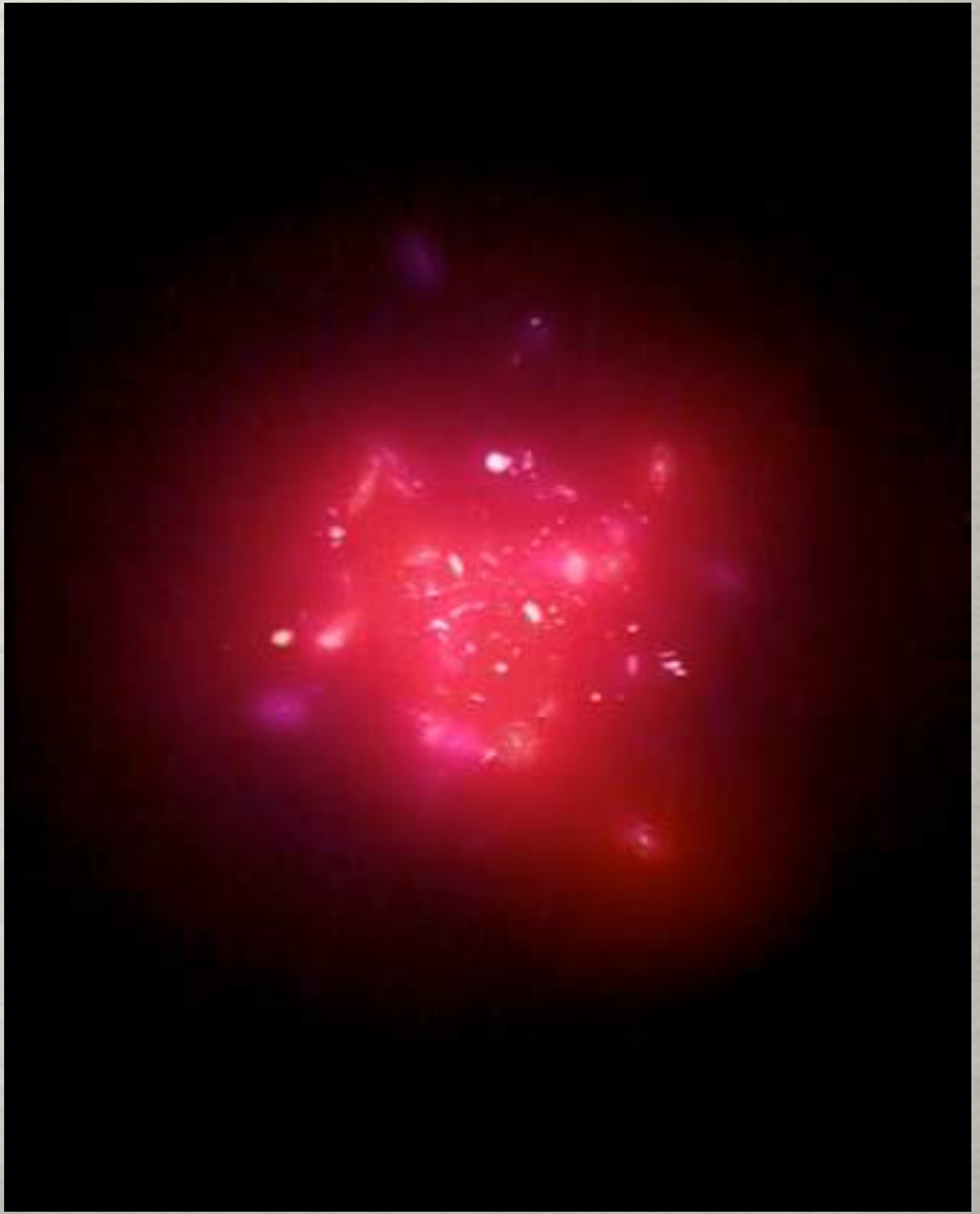
The early history of Dark Matter:
In 1933 F. Zwicky found the first evidence for DM in the velocity dispersion of the galaxies in the COMA cluster...
Already then he called it **DARK MATTER** !



DARK MATTER EVIDENCE

CLUSTER SCALES:

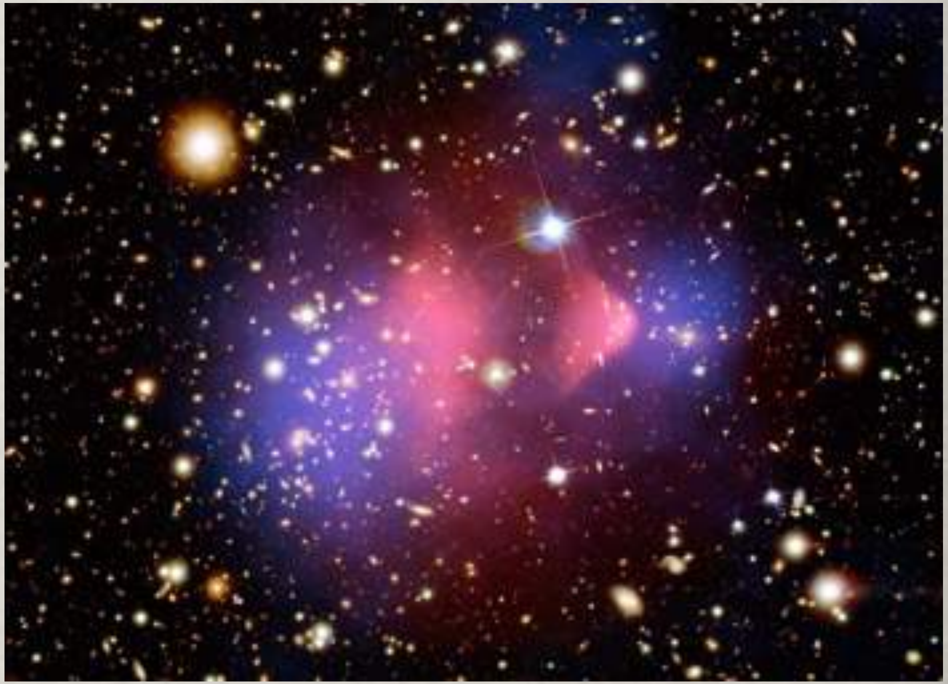
Nowadays even stronger result from X-ray emission: the temperature of the cluster gas is too high, requires a factor 5 more matter than the visible baryonic matter...



DARK MATTER EVIDENCE

CLUSTER SCALES:

Systems like the Bullett cluster allow to restrict the self-interaction cross-section of Dark Matter to be smaller than the gas at the level



$$\sigma \leq 1.7 \times 10^{-24} cm^2 \sim 10^9 pb \quad (m = 1\,\mathrm{GeV})$$

[Markevitch et al 03]

One order of magnitude stronger constraint by requiring a sufficiently large core... [Yoshida, Springer & White 00]

Similar bounds from the sphericity of halos...

DARK MATTER EVIDENCE

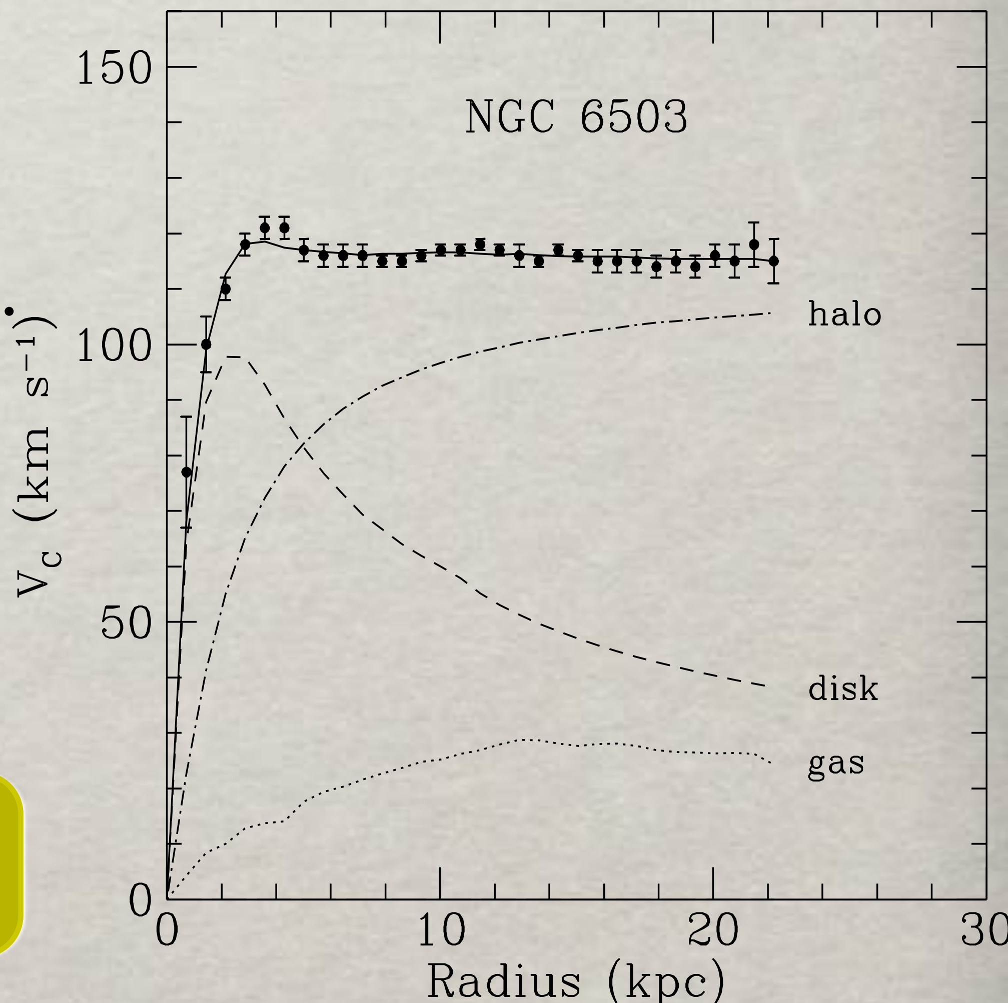
GALACTIC SCALES:

the stars in the outer part of galaxies are faster than expected...

$$v_c^2 \propto G_N \frac{M(r)}{r} \propto \frac{M_{tot}}{r}$$

But instead it is constant ! Need

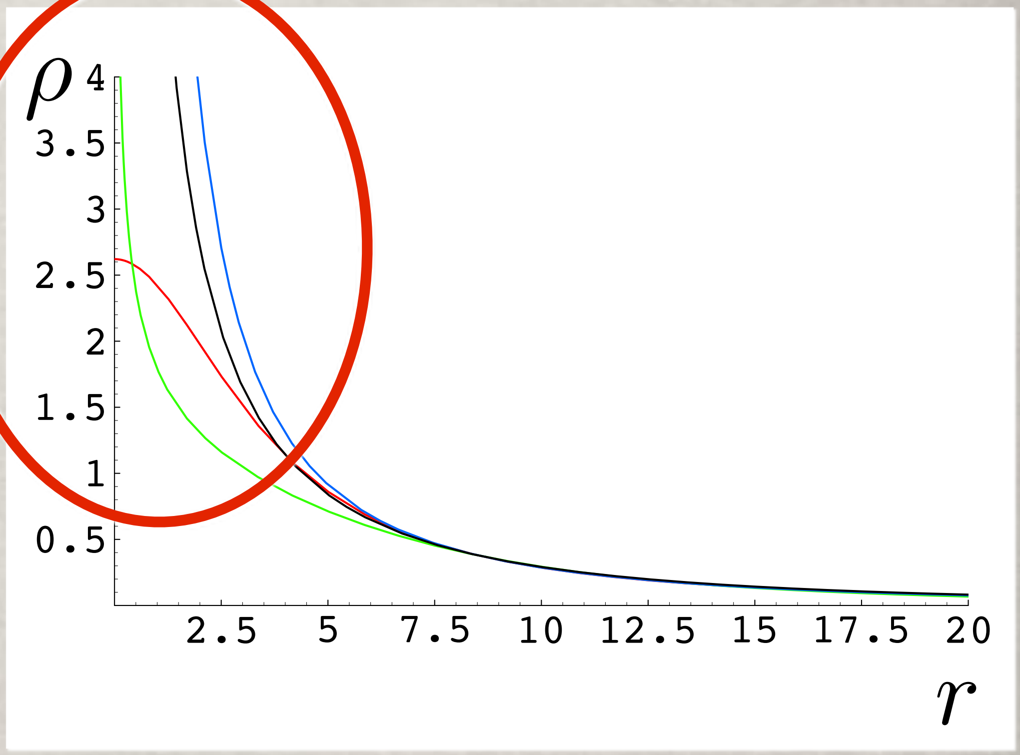
$$M(r) \propto r, \text{ i.e. } \rho_{DM} \propto r^{-2}$$



DARK MATTER EVIDENCE

GALACTIC SCALES:

Many density profiles, inpired by data or numerical simulations: Isothermal, NFW, Moore, Kratsov, Einasto, etc.... They mostly differ in the behaviour at the centre, either cusped or cored !

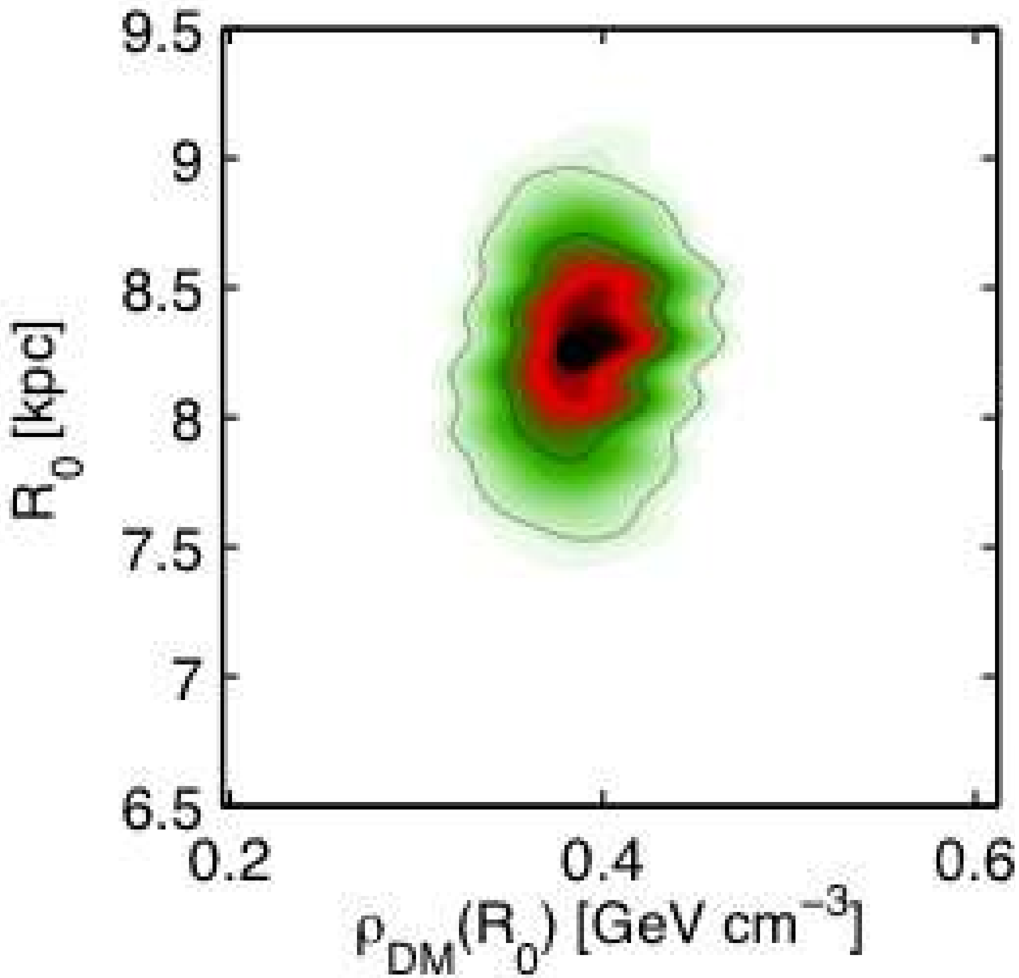


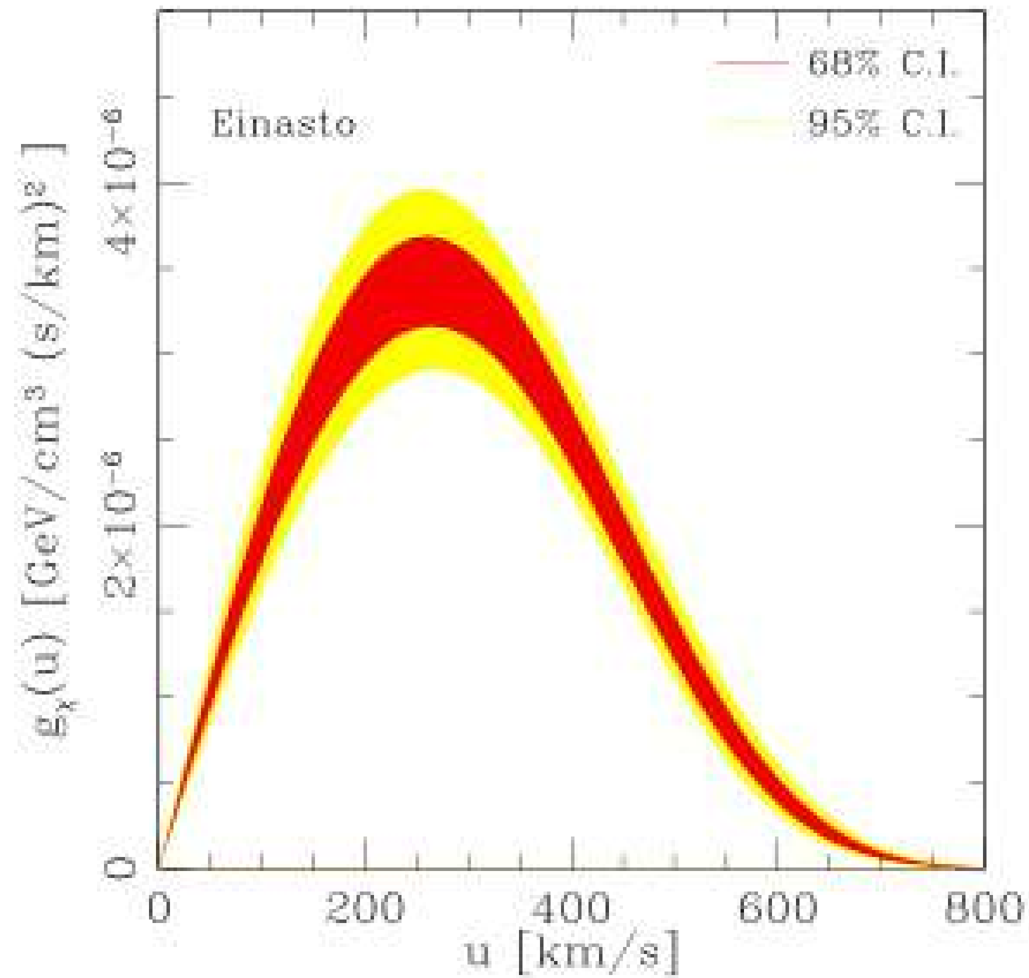
$$\rho(r) = \frac{\rho_0}{(r/R)^\gamma[1+(r/R)^\alpha]^{(\beta-\gamma)/\alpha}}$$

Critical for indirect detection !

Dark Matter local density & velocity distribution

[Catena & Ullio 09, 11]

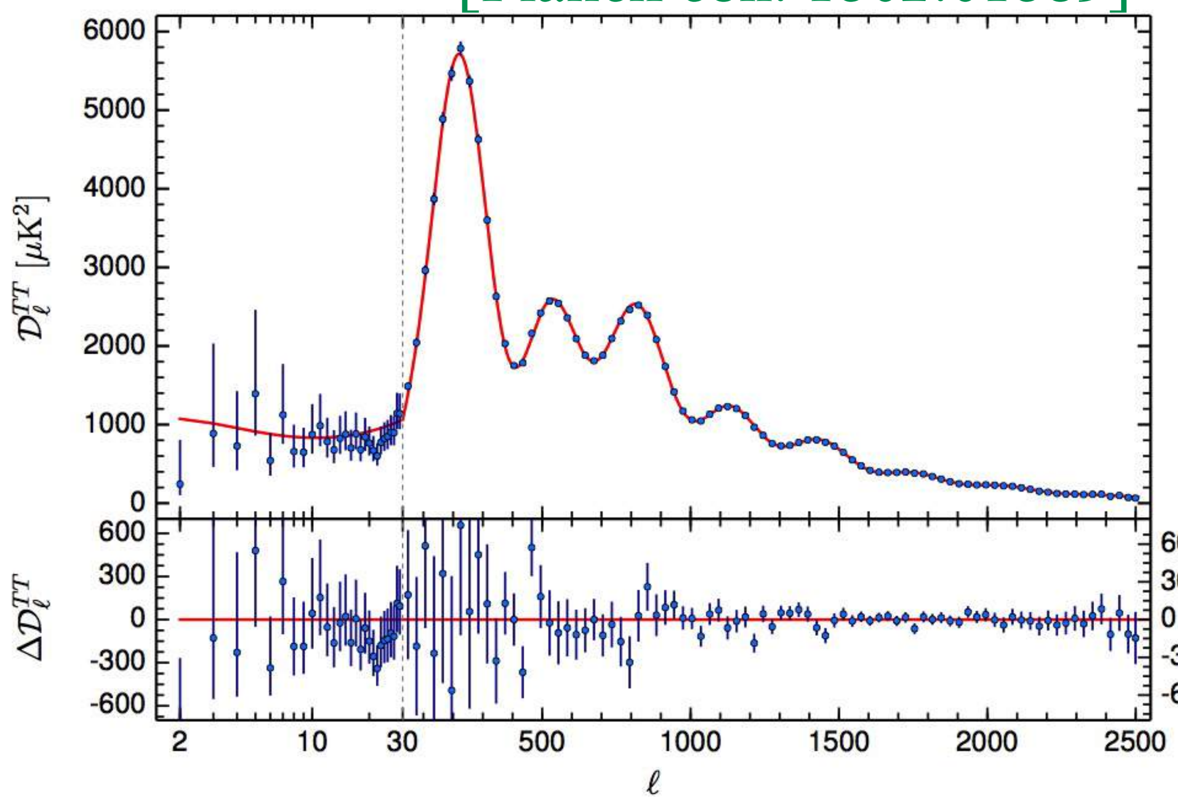




Critical for Direct Detection !

DARK MATTER EVIDENCE

[Planck coll. 1502.01589]



HORIZON SCALES:

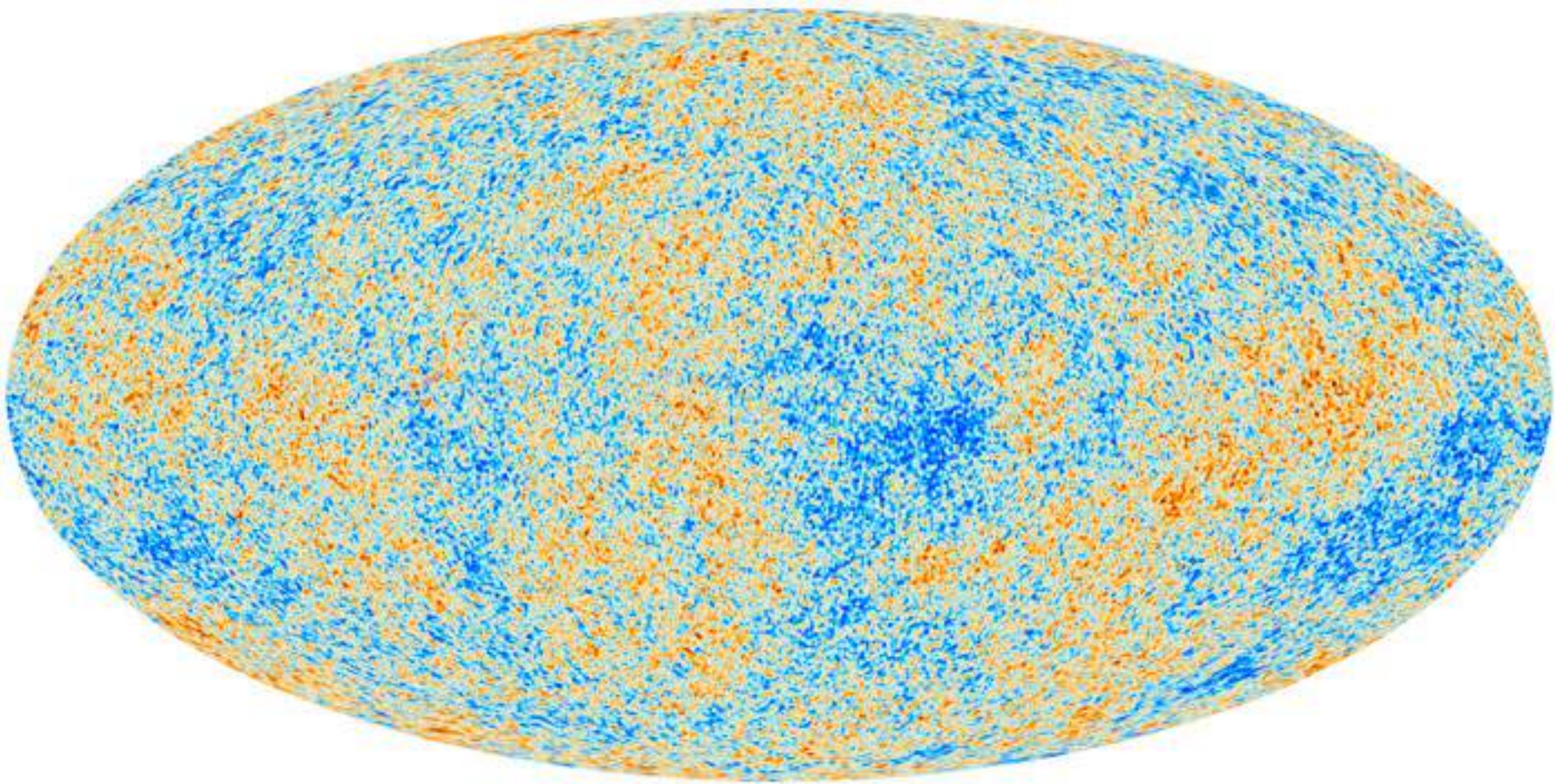
From the position and height of the CMB anisotropy acoustic oscillations peaks we can determine very precisely the curvature of the Universe and other background parameters.

Particles	Ωh^2	Type
Baryons	0,0224	Cold
Neutrinos	< 0.01	Hot
???	0.11-0.13	Cold

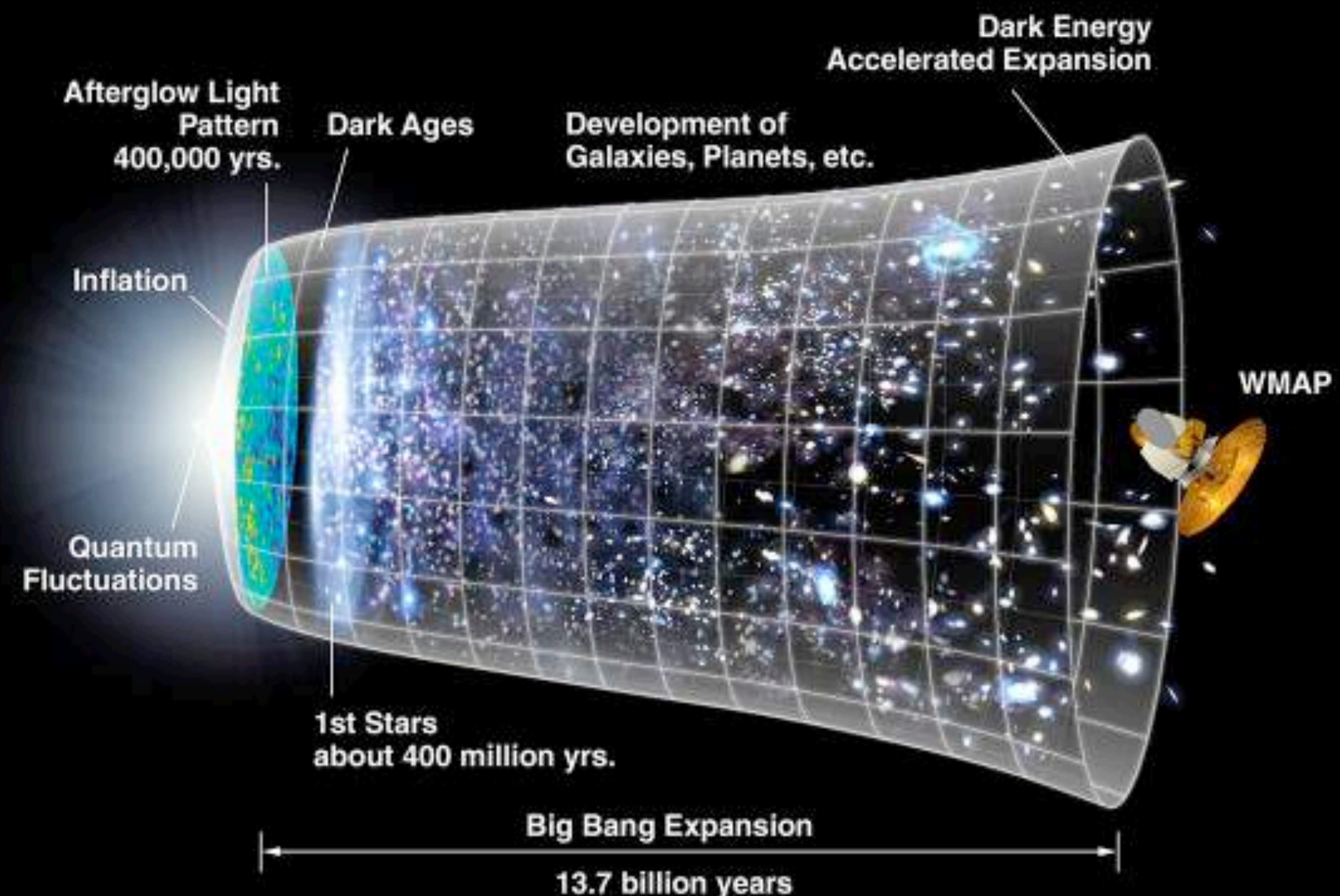
DARK MATTER →

Initial conditions

At recombination z ~ 1100 density/temperature fluctuations were at the order of 1/100000...
How can they be the seed of structure today ?



Following the fluctuations



We need seeds of small fluctuations, that were amplified by gravity & are the origin of the structure we see today

How do fluctuations grow ?

What happens after such perturbations "re-enter" the horizon ?

In the Newtonian limit we have for the density perturbations of a matter fluid $\delta = \frac{\delta\rho}{\rho}$

$$\ddot{\delta}_k + 2H\dot{\delta}_k + \left(\frac{{c_s}^2 k^2}{a^2} - 4\pi G\rho\right)\delta_k = 0,$$

where $c_s = \delta p/\delta\rho$ is the sound speed in the plasma. Again a linear equation with a negative "mass" term... The fluctuations with negative mass grow and those have k below k_J ,i.e. a physical wavelength larger than the Jeans length:

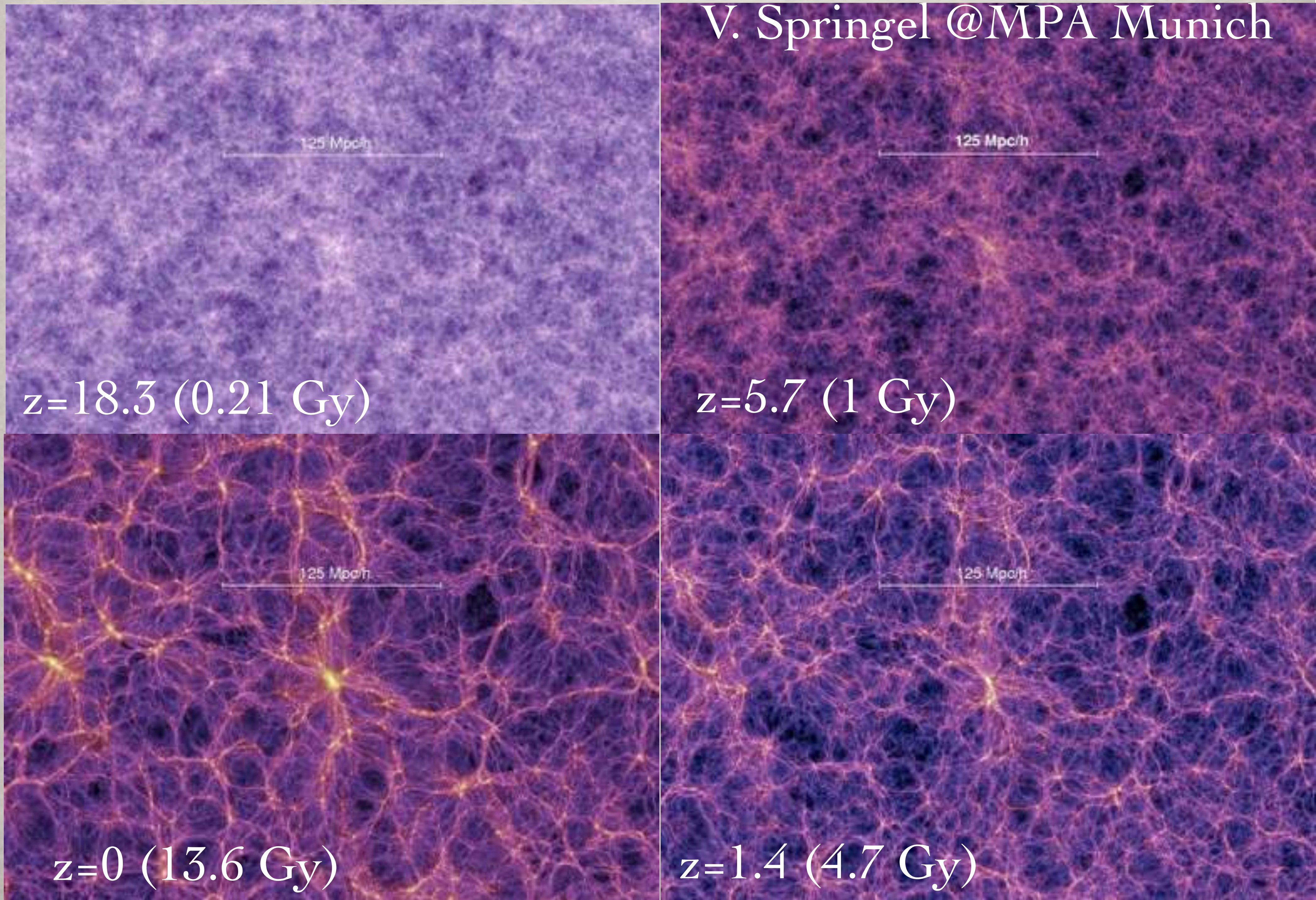
$$\lambda_J = \frac{2\pi a}{k} = c_s\sqrt{\frac{\pi}{G\rho}} \simeq \frac{c_s}{H} \quad \text{sound horizon}$$

How strongly do they grow ? The growing solution is

$$\delta_k \sim C_1 H \int \frac{dt}{a^2 H^2} + C_2 H \sim C_1 t^{2/3} + C_2 t^{-1} \quad \text{for matter dominance}$$

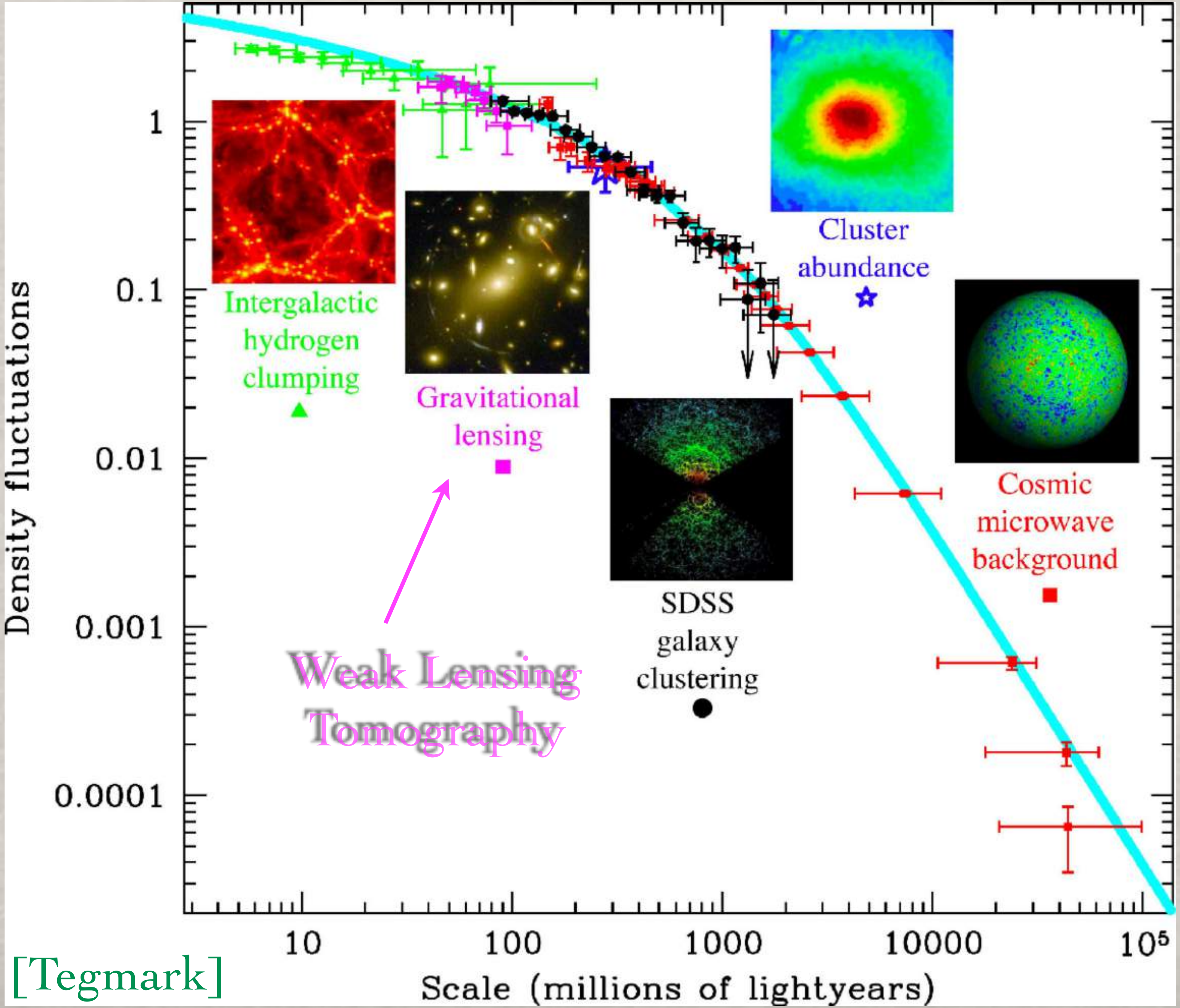
NOTE: much weaker than exponential due to the expansion friction term $\propto H$! Also if the expansion is dominated by radiation, the growth is inhibited and at most only logarithmic in time. We need a long time of matter dominance to make initial fluctuations become large... Non Linear regime

Structure Formation



FLUCTUATIONS ON ALL SCALES

Non-linear



Linear

Neutrinos as Hot Dark Matter

Neutrino as (prototype) DM

- Massive neutrino is one of the first candidates for DM discussed; for thermal SM neutrinos:

$$\Omega_\nu h^2 \sim \frac{\sum_i m_{\nu_i}}{93 \text{ eV}}$$

but $m_\nu \leq 2$ eV (Tritium β decay) so $\Omega_\nu h^2 \leq 0.07$

- Unfortunately the small mass also means that neutrinos are HOT DM... Their free-streaming is non negligible and the LSS data actually constrain

$m_\nu \leq 0.27 \sim 1$ eV $\Rightarrow$ $\Omega_\nu \ll \Omega_{DM}$

NEED to go beyond the Standard Model !

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$m_\nu \leq 0.27 \sim 1$ eV ➡ $\Omega_\nu \ll \Omega_{DM}$

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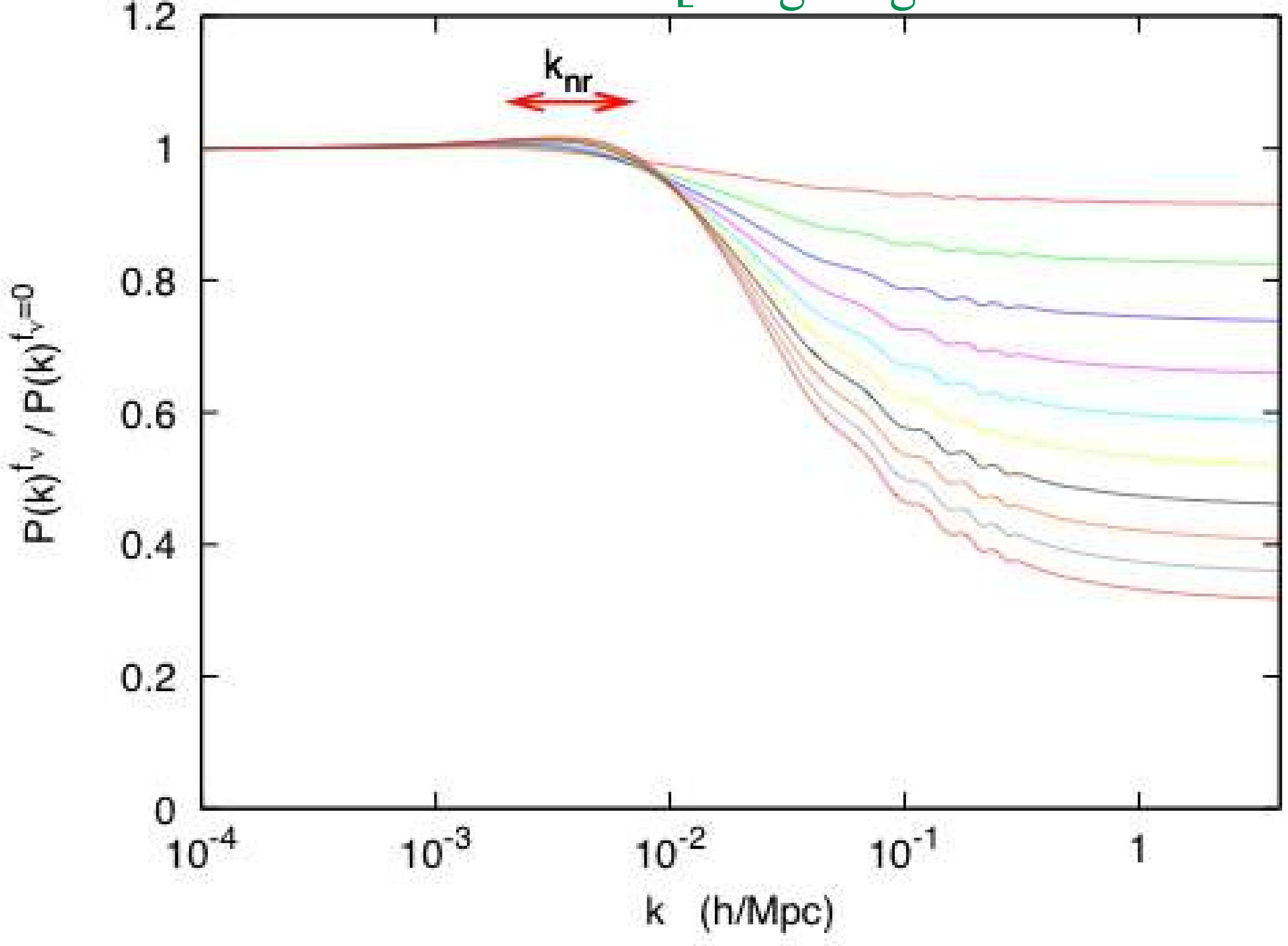
Neutrino as HDM

Even massive neutrinos remain relativistic for a long time and their free-streaming suppresses fluctuations on small scales

[Lesgourgues & Pastor '14]



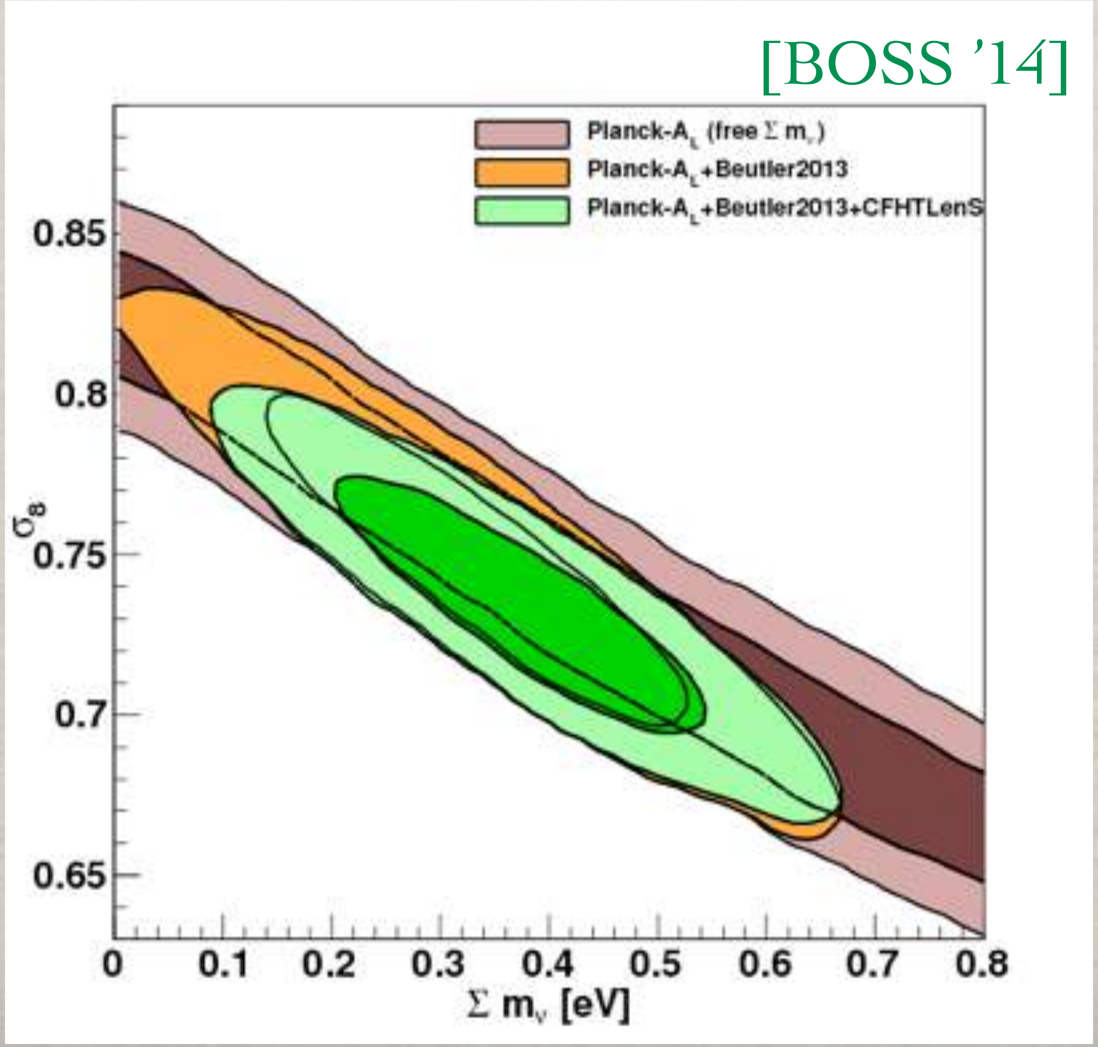
$f_\nu \sim 0.01$

$f_\nu \sim 0.02$

$f_\nu \sim 0.1$

Neutrino as HDM

The suppression at small scales reduces the lensing potential at such scales and modifies the lensing signal in the CMB and the LSS & BAO as measured by galaxies surveys.

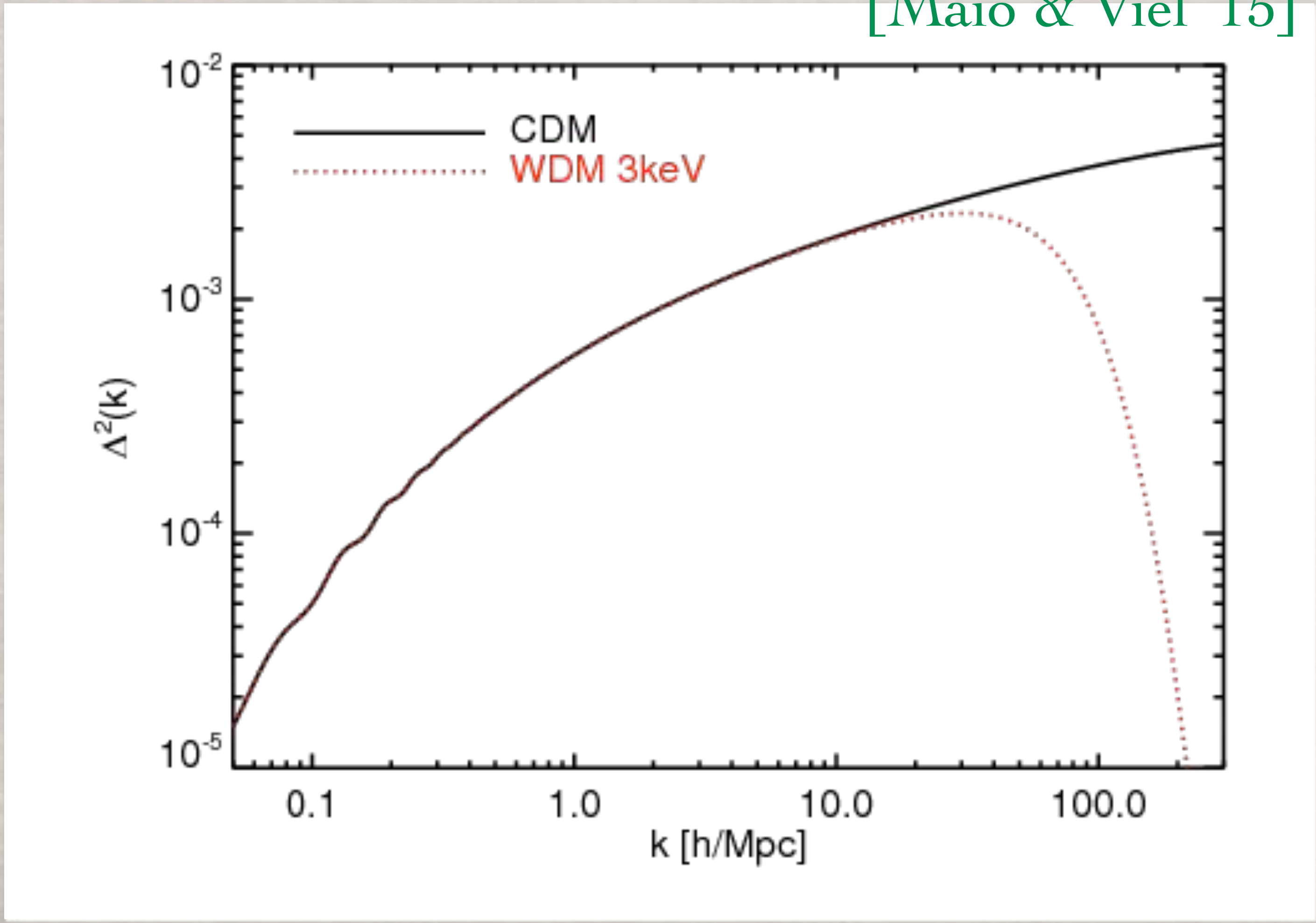


Degeneracy with sigma_8

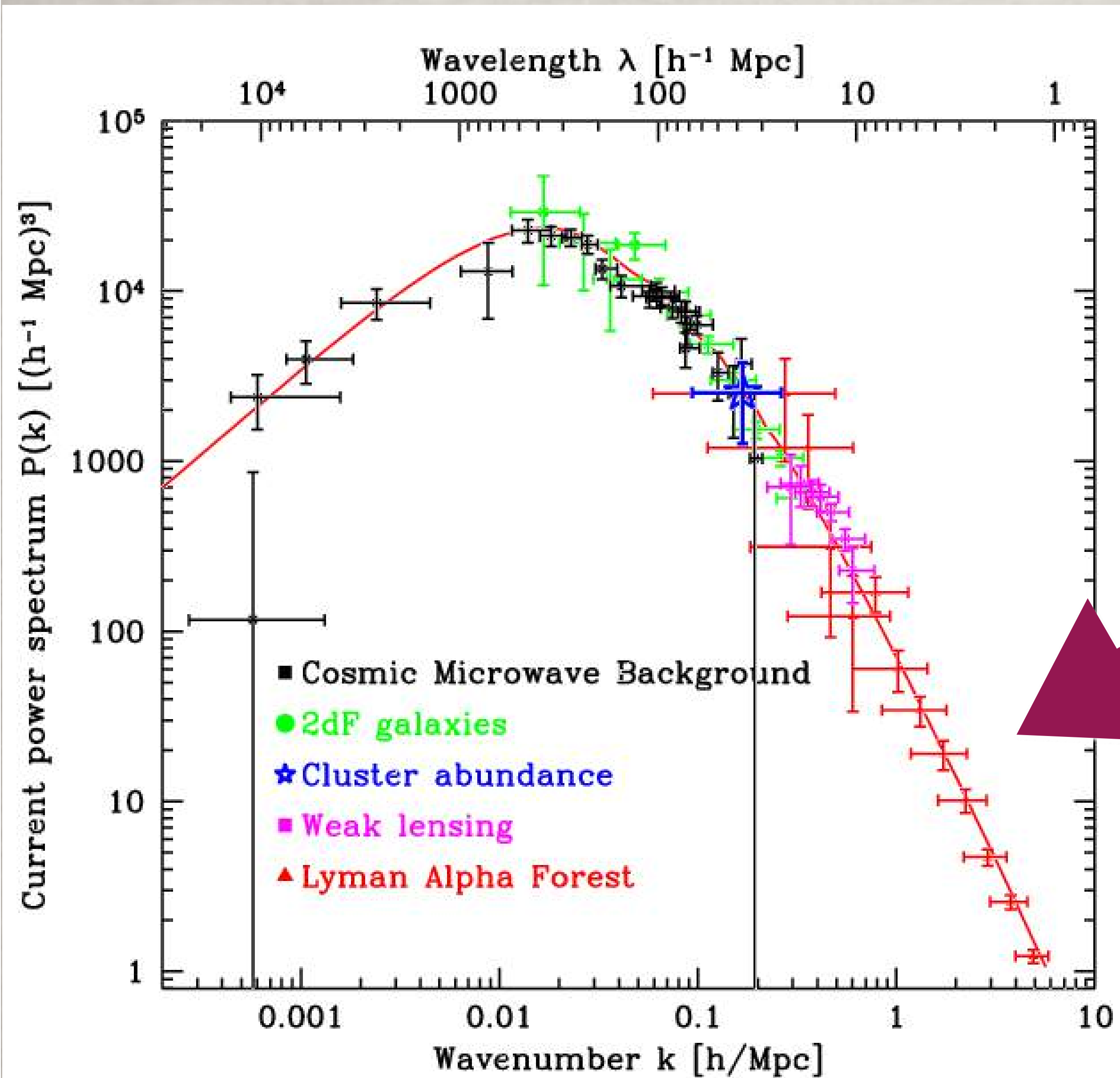
Effect from WDM

Also heavier/less relativistic particles can have an effect & their free-streaming suppresses fluctuations on smaller scales

[Maio & Viel '15]



WDM & the Power spectrum



WARM DM suppresses perturbations on scales smaller than its free-streaming length:

$$\lambda_{FS} \sim \mathrm{Mpc} \left(\frac{m_{WDM}}{1\mathrm{keV}} \right)$$

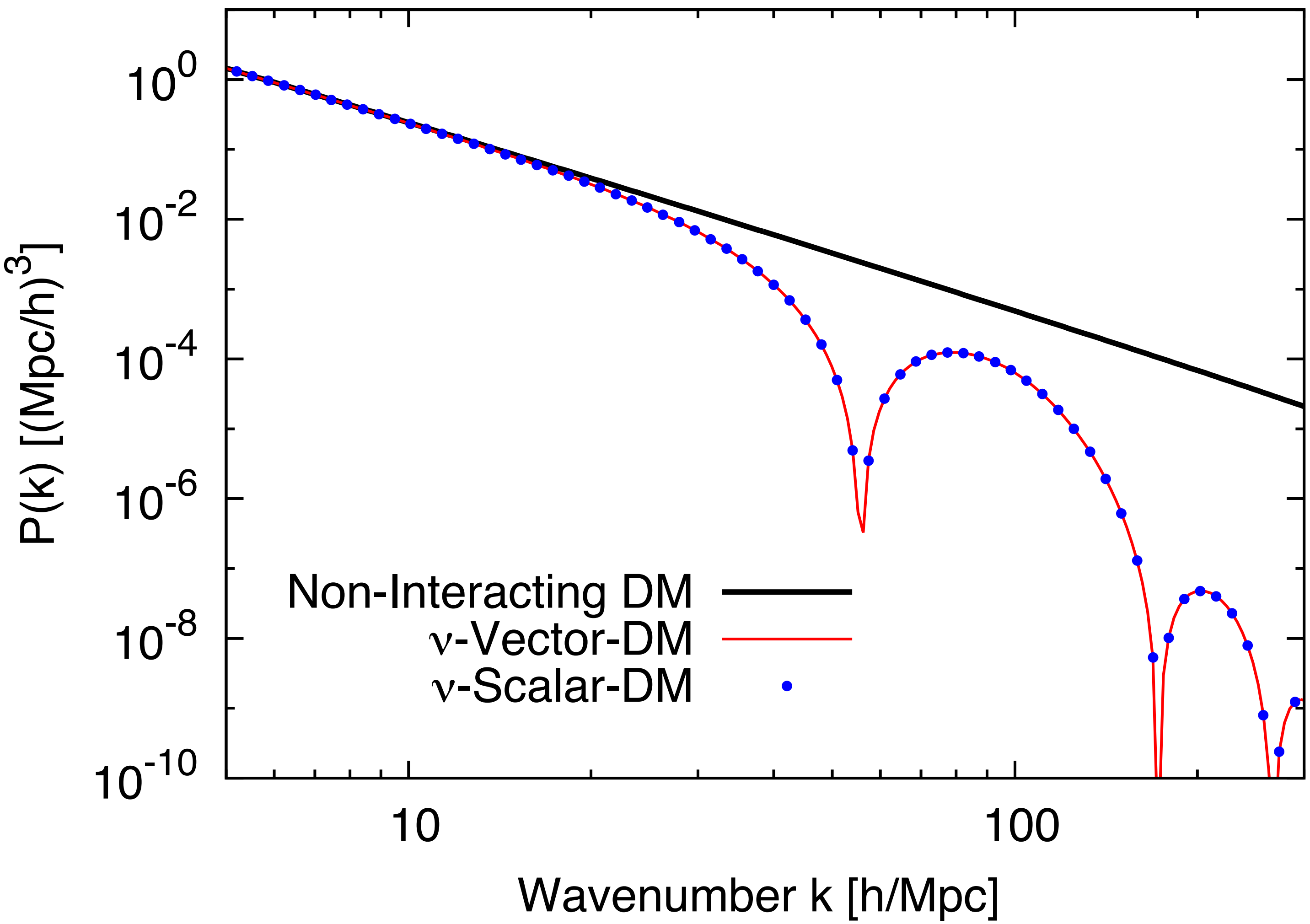
Compare with the data:

$$m_{WDM} > 4\ \mathrm{keV}$$

[Viel et al. '07]

Interacting Dark Matter

[Binder, LC et al. 1602.07624]



$$M^{\rm cut}\ 10^9 M_\odot \left(\frac{N_\nu \alpha_\nu \alpha_\chi}{2\times 10^{-4}}\right)\left(\frac{m_\chi}{1TeV}\right)^{-3/4}\left(\frac{m_\phi}{1MeV}\right)^{-3}$$

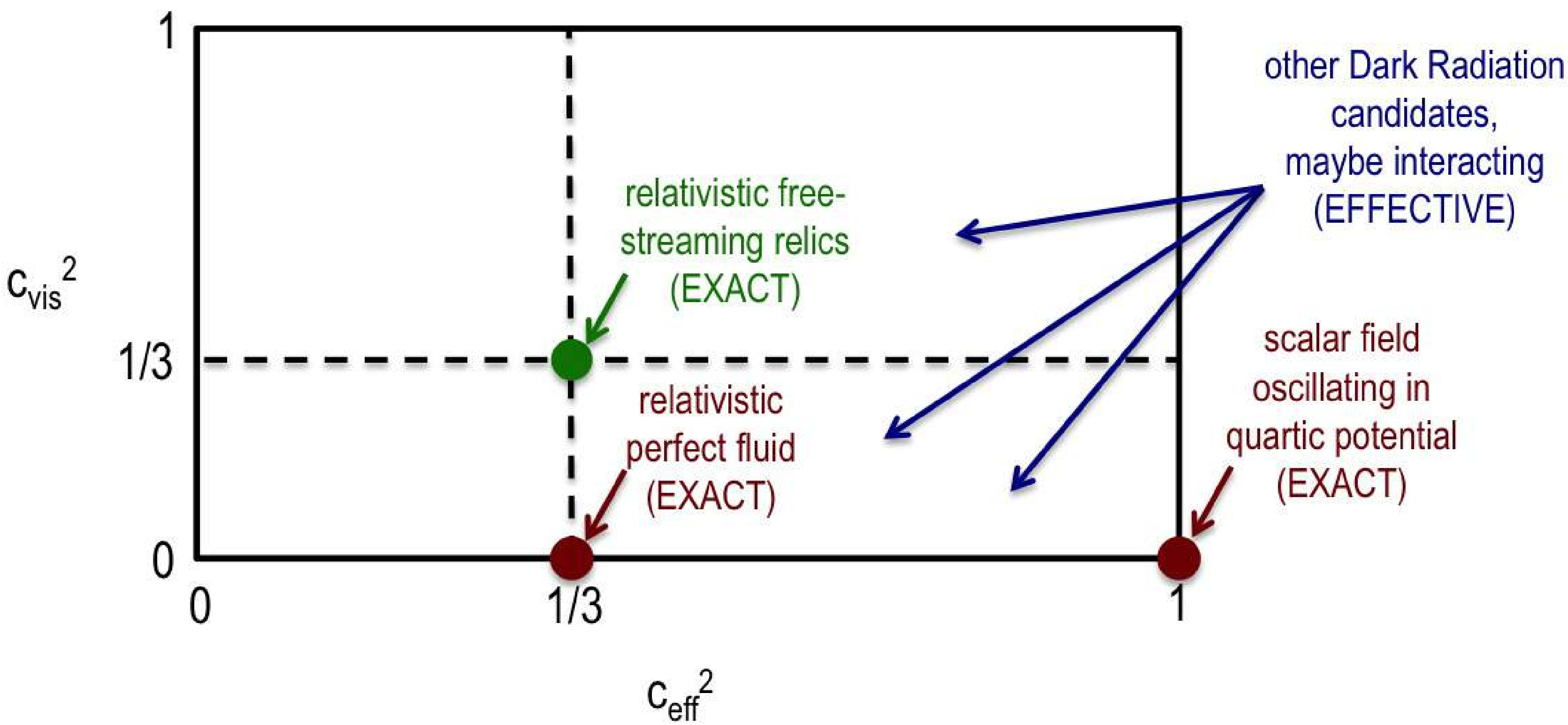
Neutrino as DR

[Lesgourgues @ Ferrara Meeting '14]

Define two phenomenological parameters changing the perturbation equations:

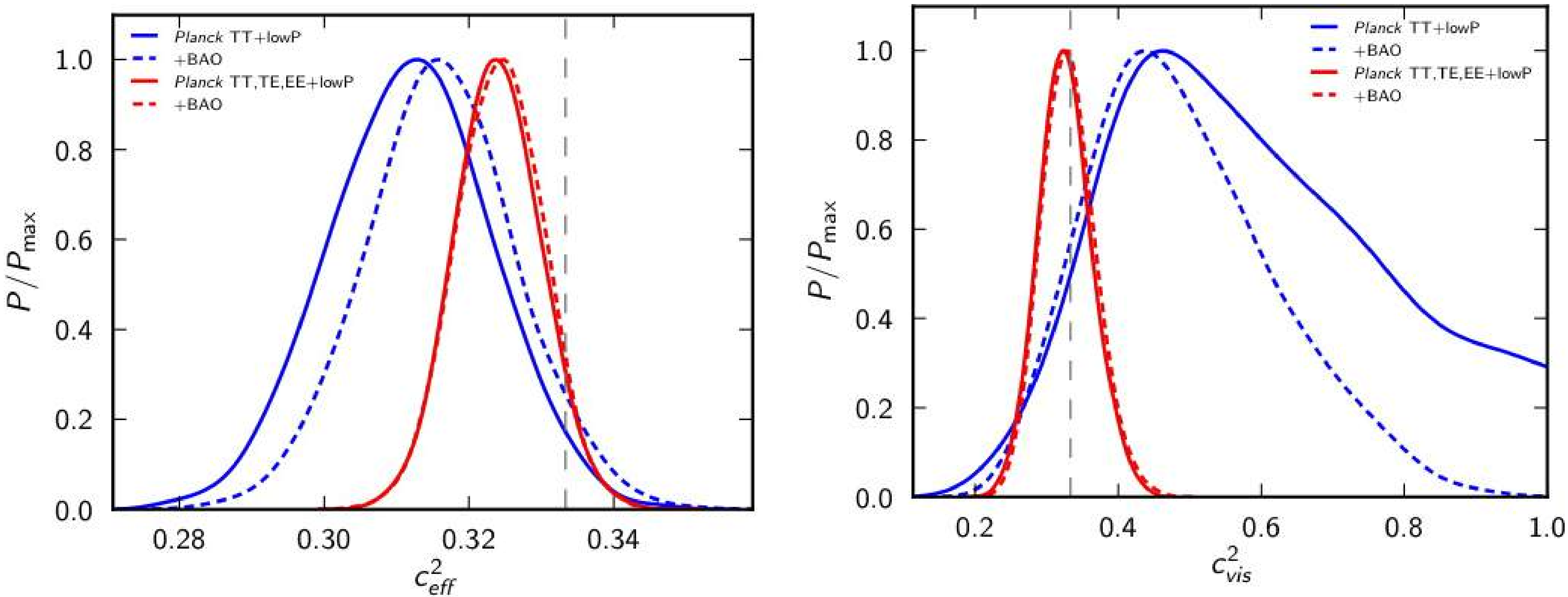
1) Effective *sound speed* : $\delta p = c_{eff}^2 \, \delta\rho$
2) Effective *viscosity speed* c_{vis} controlling the amount of anisotropic pressure / shear

Archidiacono et al. 2011
inspired from *Hu 1998,*
Trotta & Melchiorri 2004…



Neutrinos as DR

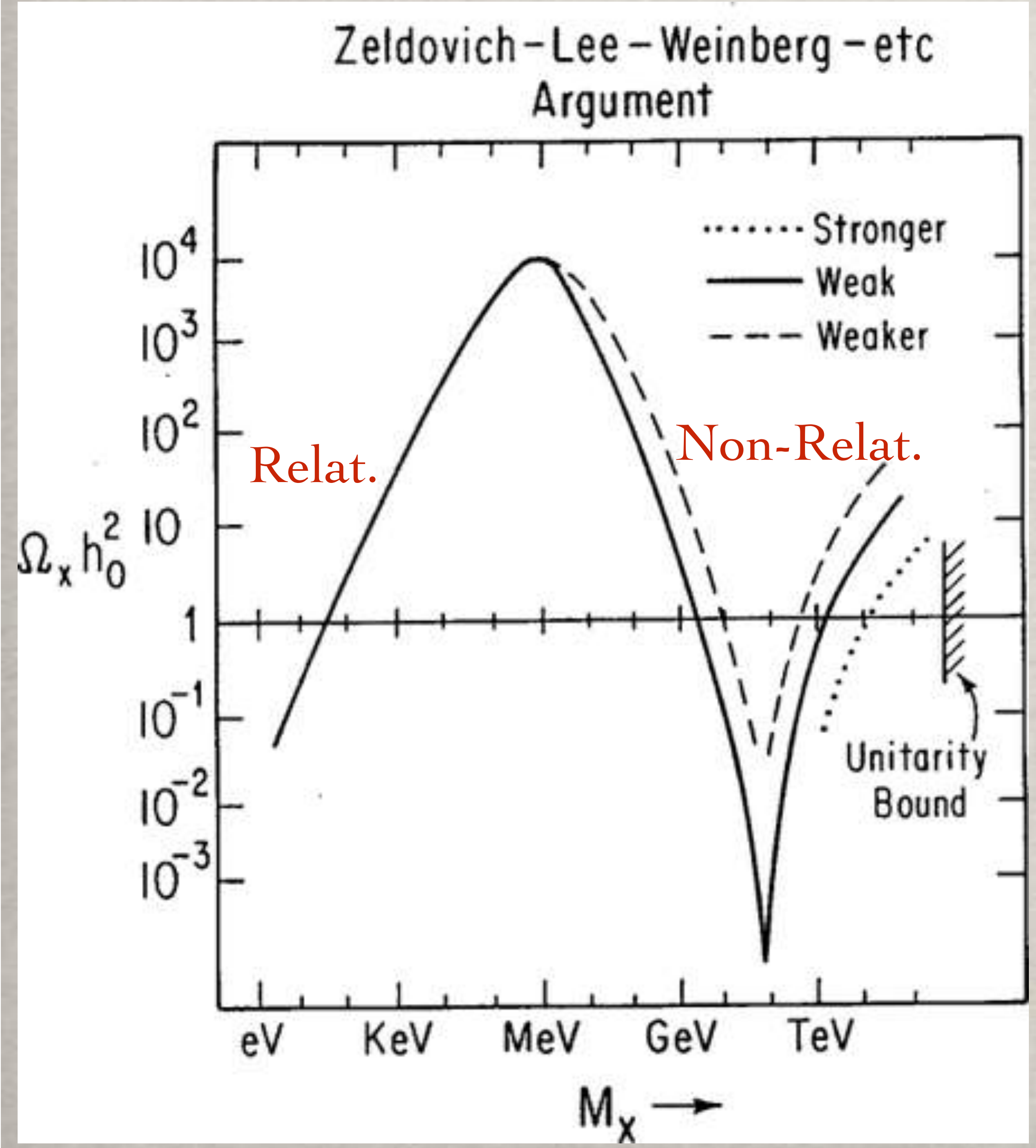
[Planck 1502.01589]



Parameter	TT+lowP	TT+lowP+BAO	TT,TE,EE+lowP	TT,TE,EE+lowP+BAO
c^2_{vis}	$0.47^{+0.26}_{-0.12}$	$0.44^{+0.15}_{-0.10}$	0.327 ± 0.037	0.331 ± 0.037
c^2_{eff}	0.312 ± 0.011	0.316 ± 0.010	0.3240 ± 0.0060	0.3242 ± 0.0059

Dark Matter production mechanisms

Zeldovich-Lee-Weinberg bound



Two possibilities for obtaining the "right" value of $\Omega_\nu h^2$: decoupling as relativistic species or as non-relativistic ! In-between the density is too large !

$m_\nu > 4(12)\mathrm{GeV}$

for Dirac (Majorana)

THE WIMP MECHANISM

Primordial abundance of stable massive species

[see e.g. Kolb & Turner '90]

The number density of a stable particle X in an expanding Universe is given by the Bolzmann equation

$$\frac{dn_X}{dt} + 3Hn_X = \langle\sigma(X + X \to \text{anything})v\rangle \left(n_{eq}^2 - n_X^2\right)$$

Hubble expansion Collision integral

The particles stay in thermal equilibrium until the interactions are fast enough, then they freeze-out at $x_f = m_X/T_f$

defined by $n_{eq}\,\langle\sigma_A v\rangle_{x_f} = H(x_f)$ and that gives

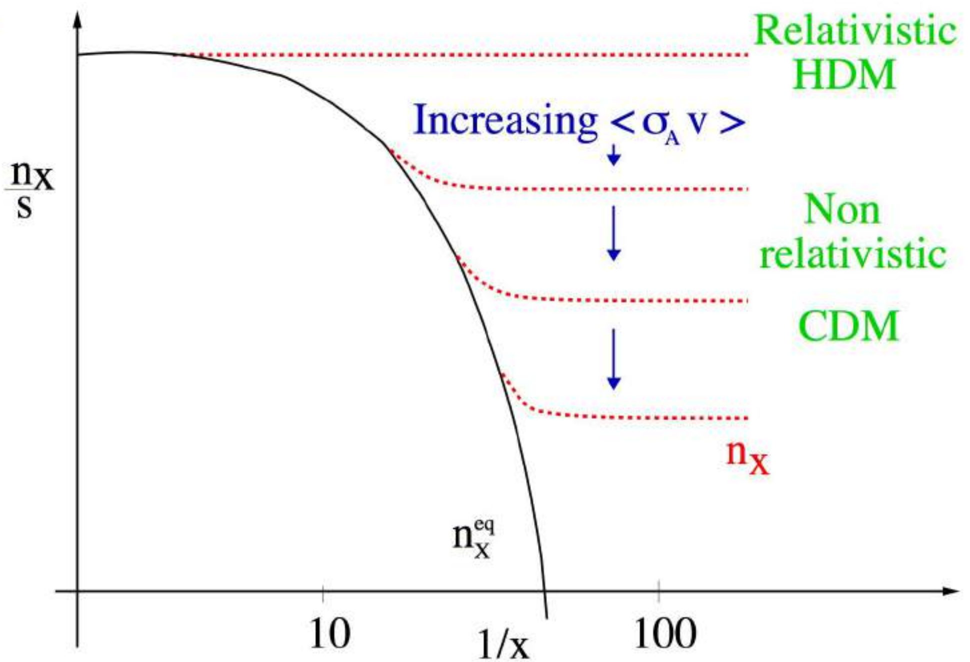
$$\Omega_X = m_X n_X(t_{now}) \quad \propto \quad \frac{1}{\langle\sigma_A v\rangle_{x_f}}$$

Abundance $\Leftrightarrow$ Particle properties

For $m_X \simeq 100$ GeV a WEAK cross-section is needed !

Weakly Interacting Massive Particle

For weaker interactions need lighter masses HOT DM !



Boltzmann equation

[Gondolo & Gelmini 91]

$$\frac{dY}{dx} = -\frac{2\pi g_S}{15}\left(\frac{10}{g_\rho}\right)^{1/2}\frac{M_P}{m}\langle\sigma v\rangle_x\left(Y^2 - Y_{eq}^2\right)$$

where Y = n/s, x = m/T, g_rho denote the number of degrees of freedom for entropy and energy density and

$$\langle\sigma v\rangle_x = \frac{1}{4x^4K_2^2(x)}\int_{2x}^{\infty} dz z^2\tilde{\sigma}\left(\frac{x}{z}\right)K_1(z)$$

where we defined

$$\tilde{\sigma}\left(\frac{m}{\sqrt{s}}\right) = (s - 4m^2)\sigma(m, s) = s\beta^2\sigma(\beta)$$

and K_i (x) are modified Bessel functions coming from Maxwell-Boltzmann statistics

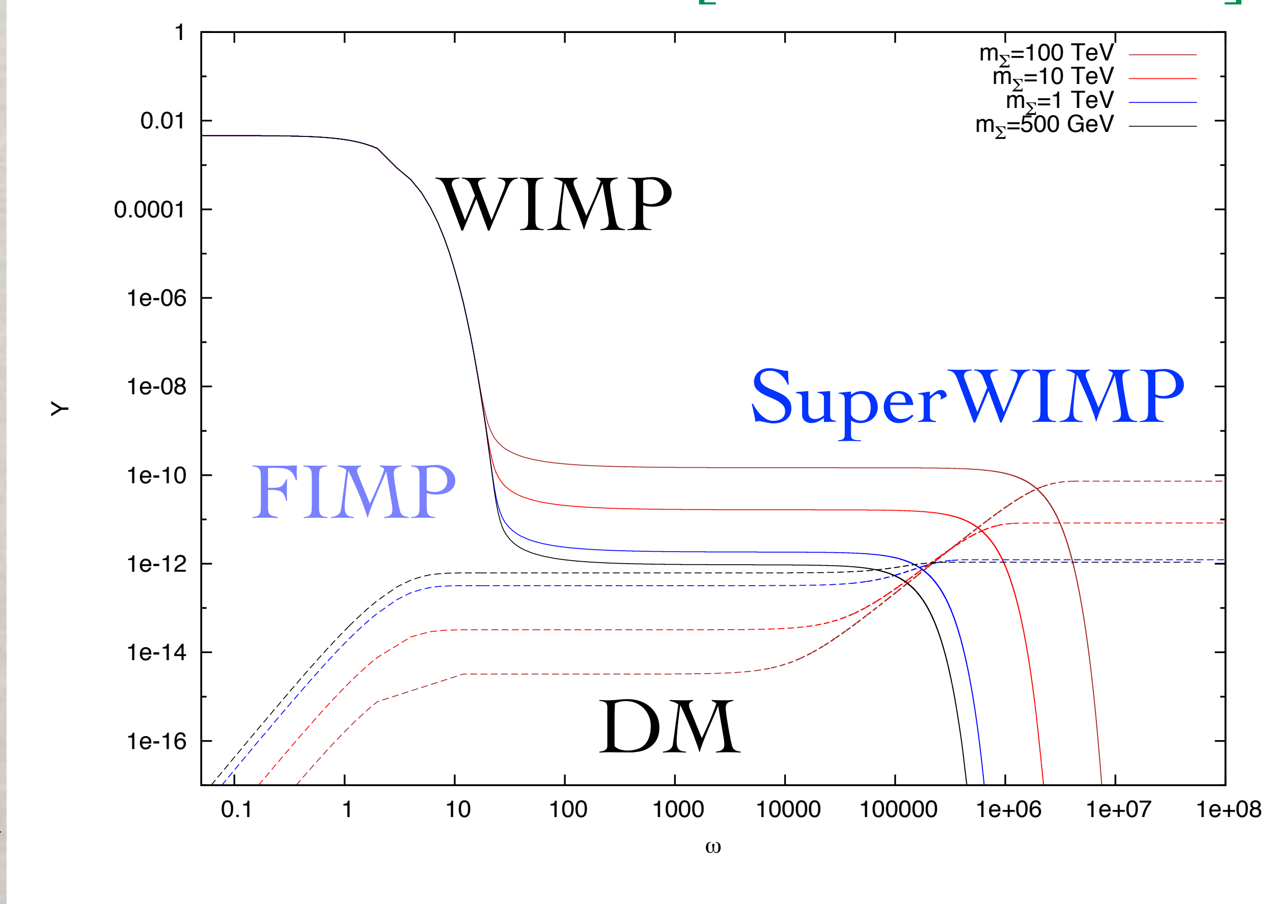
SuperWIMP/FIMP paradigms

Add to the BE a small decaying rate for the WIMP into a much more weakly interacting (i.e. decaying !) DM particle:

[G. Arcadi & LC 13]

[Hall et al 10]

FIMP DM produced by WIMP decay in equilibrium



[Feng et al 04]

SuperWIMP DM produced by WIMP decay after freeze-out

Two mechanism naturally giving "right" DM density depending on WIMP/DM mass & DM couplings

Strong CP & the Axion

The QCD vacuum has a non trivial structure, as a superposition of different topological configurations, giving rise to strong CP problem from the term:

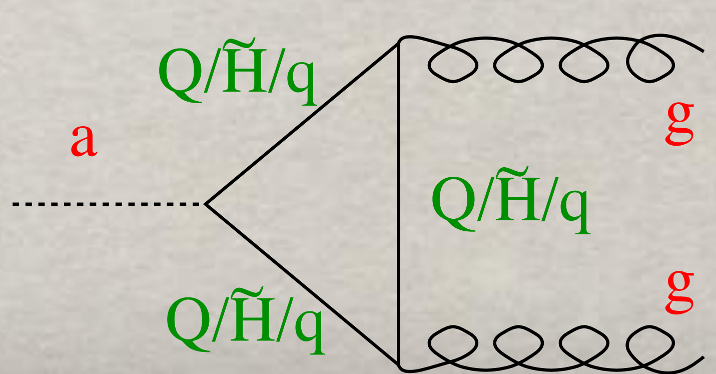
['t Hooft 76]

$$\mathcal{L} = \theta \; \frac{\alpha_s}{8\pi} F^b_{\mu\nu} \tilde{F}^{\mu\nu}_b$$

But from the bounds on neutron el. dipole moment $\theta < 10^{-9}$

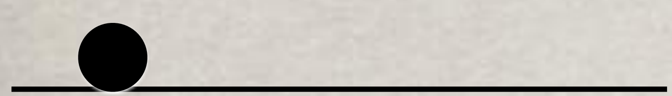
Peccei-Quinn solution: add a chiral global U(1) and break it spontaneously at f_a , leaving the axion, a pseudo-Goldstone boson, interacting as

$$\mathcal{L}_{PQ} = \frac{\alpha_s}{8\pi f_a} a F^b_{\mu\nu} \tilde{F}^{\mu\nu}_b$$



Axions as Dark Matter

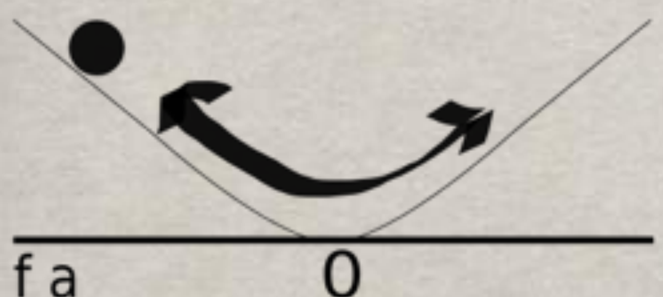
The axion is also a very natural DM candidate, but in this case in the form of a condensate, e.g. generated by the misalignment mechanism:



Before the QCD phase transition the potential for the axion is flat

After the QCD phase transition a potential is generated

$$V(a) = \Lambda_{QCD}^4 \left(1 - \cos\left(\theta + \frac{a}{f_a}\right)\right)$$



by instantons effects and the axion starts to oscillate coherently around the minimum:

zero momentum particles >> CDM !

Axions as Dark Matter

Their energy density by misalignment is

$$\Omega_a h^2 = 0.5 \left(\frac{f_a}{10^{12}\text{GeV}} \right)^{7/6} \theta_i^2$$

Axions can contribute to star/SN cooling and so

$$0.5 \times 10^{10}\text{GeV} \leq f_a \leq 10^{12}\text{GeV}$$

[Raffelt 98]

Therefore the mass for axion DM is very small:

$$m_a = \Lambda_{QCD}^2 / f_a \sim 6 \times 10^{-5}\text{eV} \left(\frac{f_a}{10^{11}\text{GeV}} \right)^{-1}$$

AXION DM SEARCHES

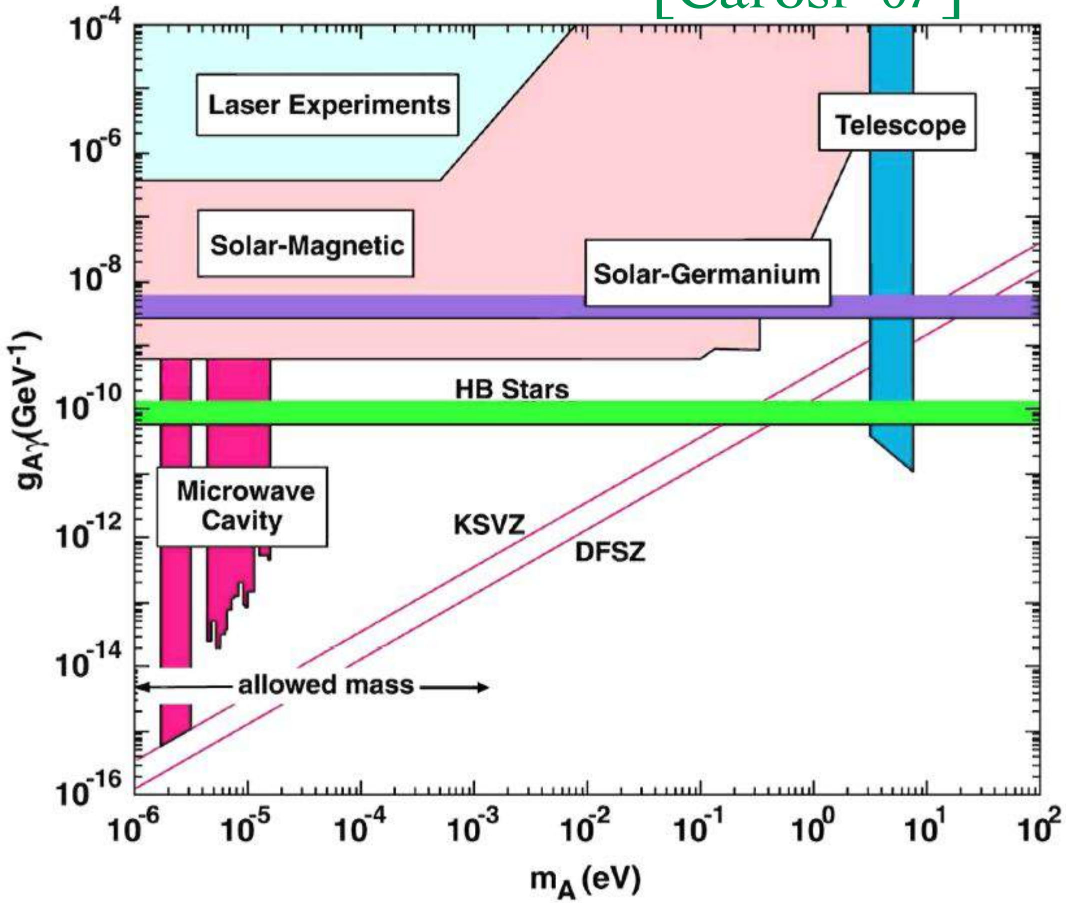
The right abundance can be obtained if the Peccei-Quinn scale is of the order of 10^{11-12} GeV and the mass in the μeV.

ADMX is finally touching the expected region.

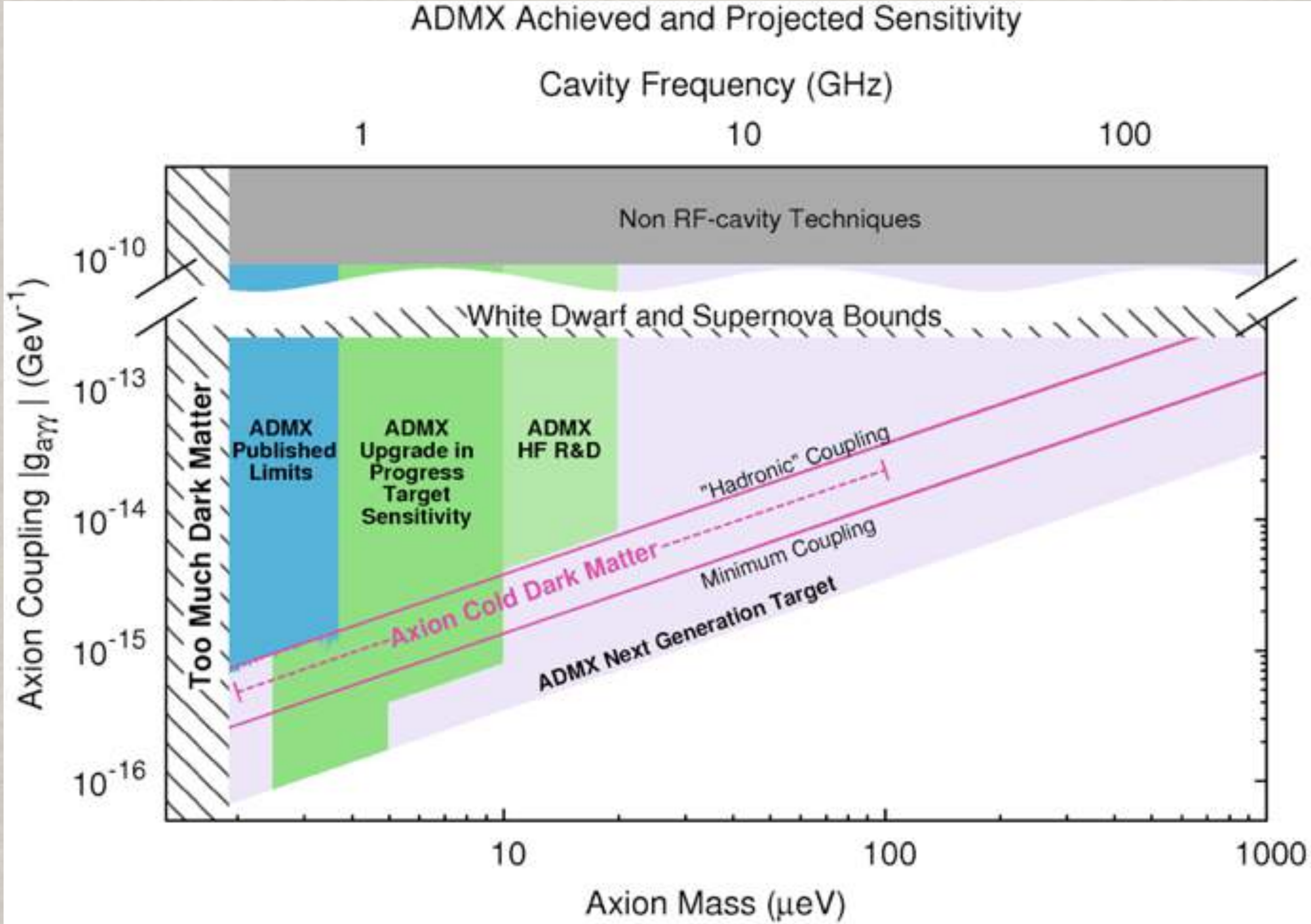
But it could be much wider for non-standard cosmologies...

[Gondolo et al 09]

[Carosi '07]



AXION DM SEARCHES



http://www.phys.washington.edu/groups/admx/home.html

Conclusions & Outlook

- We have strong evidence for DM from gravity, but the nature of Dark Matter is still unclear… It requires to go Beyond the Standard Model, probably most "natural" candidates are WIMPs, SuperWIMPs, axions!
- The WIMP mechanism is being probed already by astrophysical observations and particle physics experiments. Some hints were found, but no confirmation so far…
- Keep looking and doing model-building !

References

- Review on neutrinos in cosmology:
  Julien Lesgourgues & Sergio Pastor,
  "Neutrino cosmology and Planck" ,
  New J. Phys. 16(2014) 065002 (arXiv:1404.1740)

- Reviews on Dark Matter, especially Indirect Detection:
  - G. Bertone, D. Hooper, J. Silk
  Phys.Rept. 405 (2005) 279 (hep-ph/9404175)
  - A. Ibarra, D. Tran, C. Weniger
  Int.J.Mod.Phys.A28 (2013)1330040 (arXiv:1307.6434)