**Theoretical Aspects of Astroparticle Physics, Cosmology and Gravitation**
**GGI, Florence, 15-19 March 2021**

# Particle Dark Matter

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# Outline

- Lecture 1:
  Introduction to Dark Matter and cosmology
- Lecture 2 & 3:
  DM as Weakly Interacting Particles
- Lecture 4 & 5:
  Axions and Axionlike particles as DM,
  FIMPs/SuperWIMPs, etc…

# Lecture 1: Outline

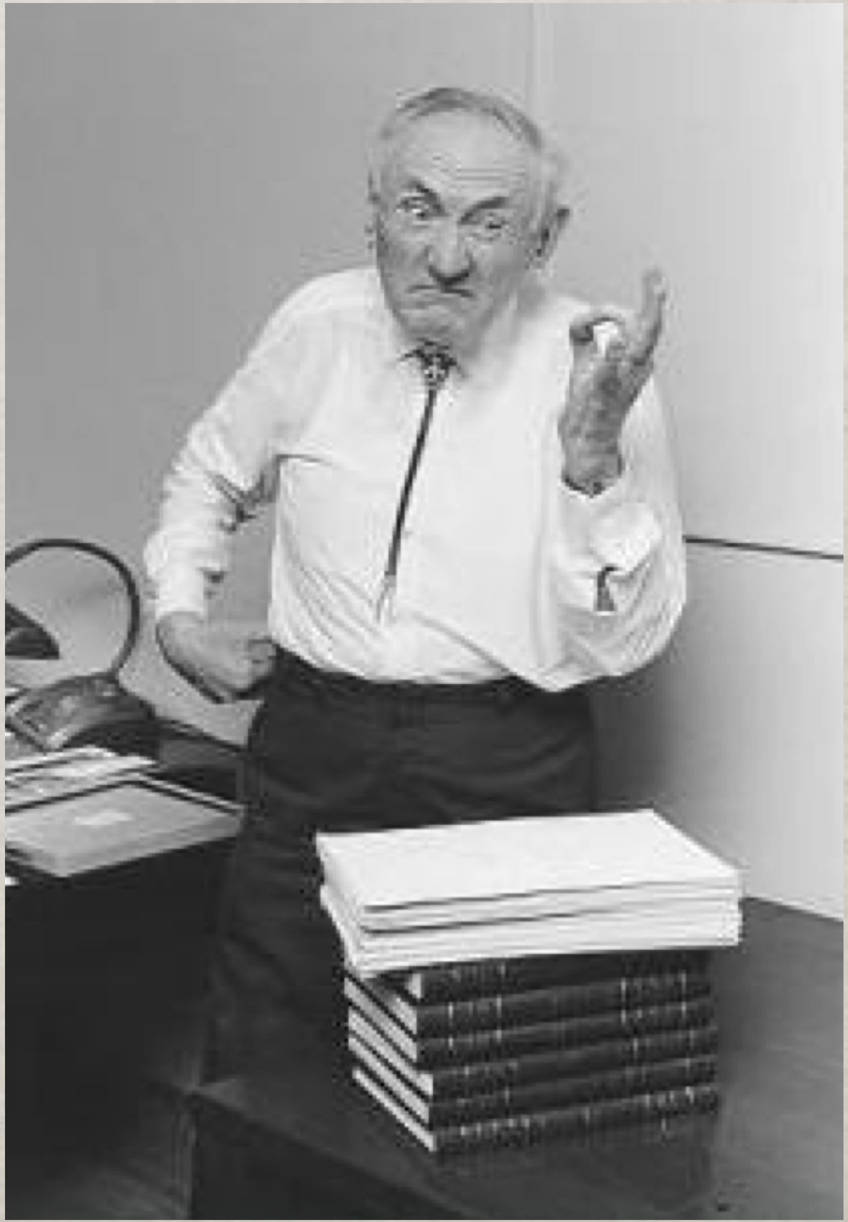
- Dark Matter evidence
- Introduction to Cosmology and global DM evidence
- Structure formation

# 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

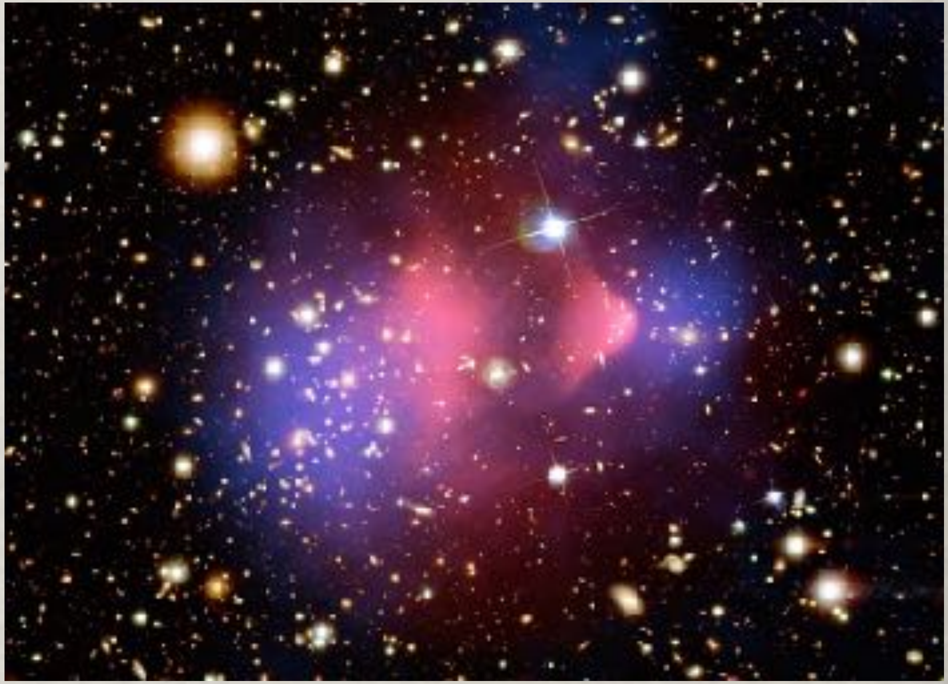
## CLUSTER SCALES:

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

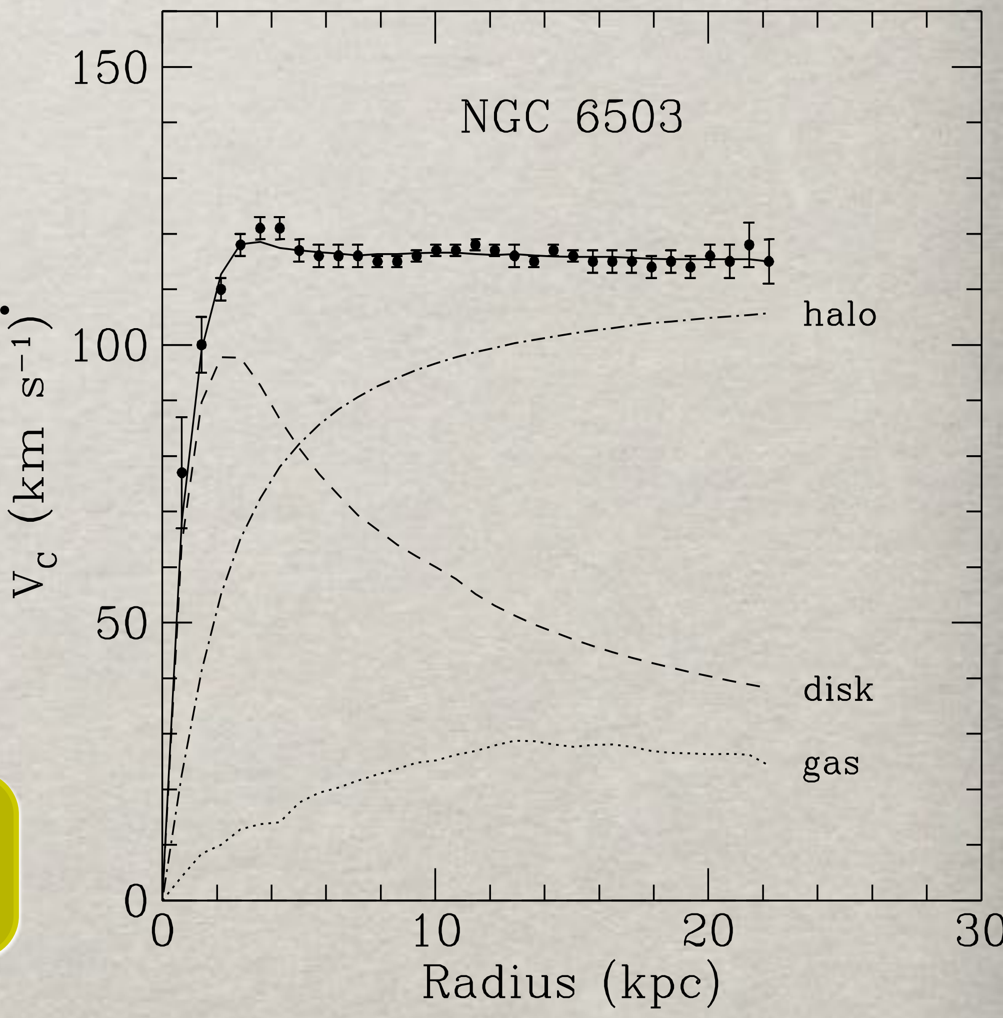
GALACTIC SCALES:

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:

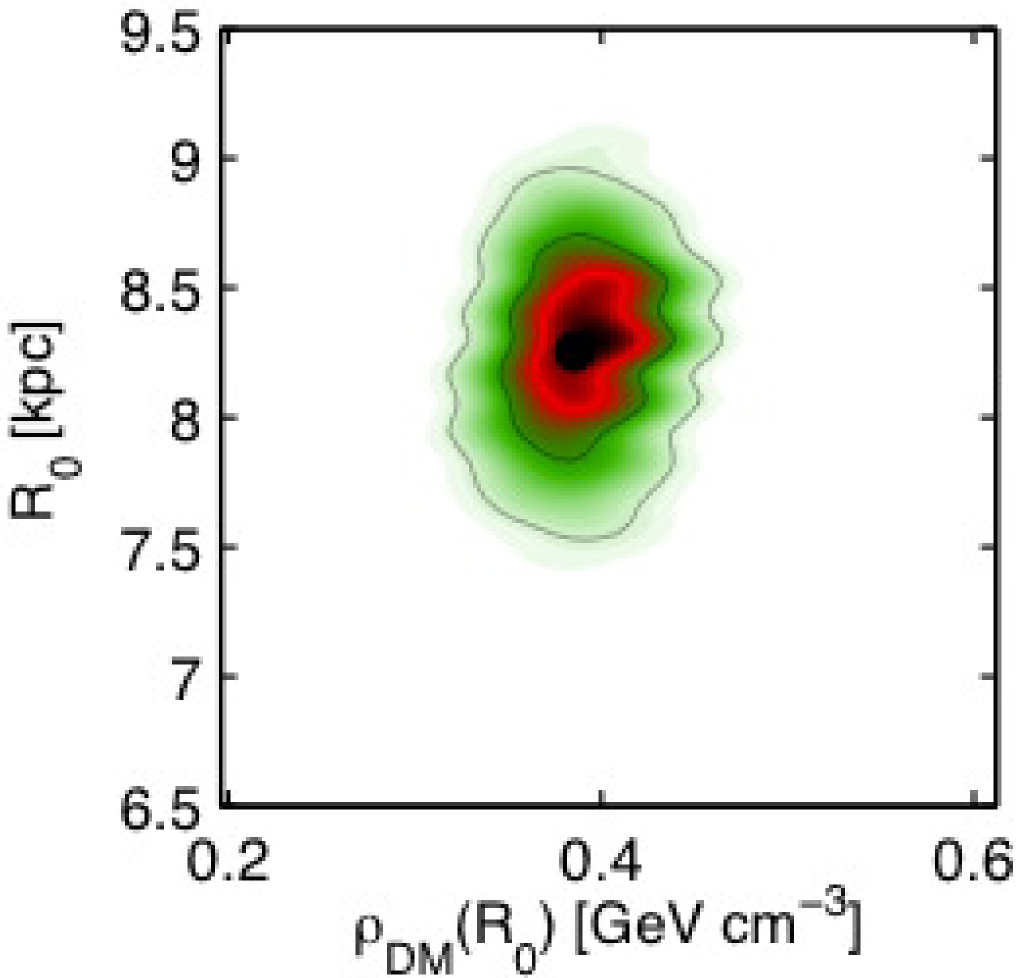
Many density profiles, inpired by data or numerical simulations: Isothermal, NFW, Moore, Kratsov, Einasto, etc.... They mostly differ in the behaviour at the centre, either cusped or cored !

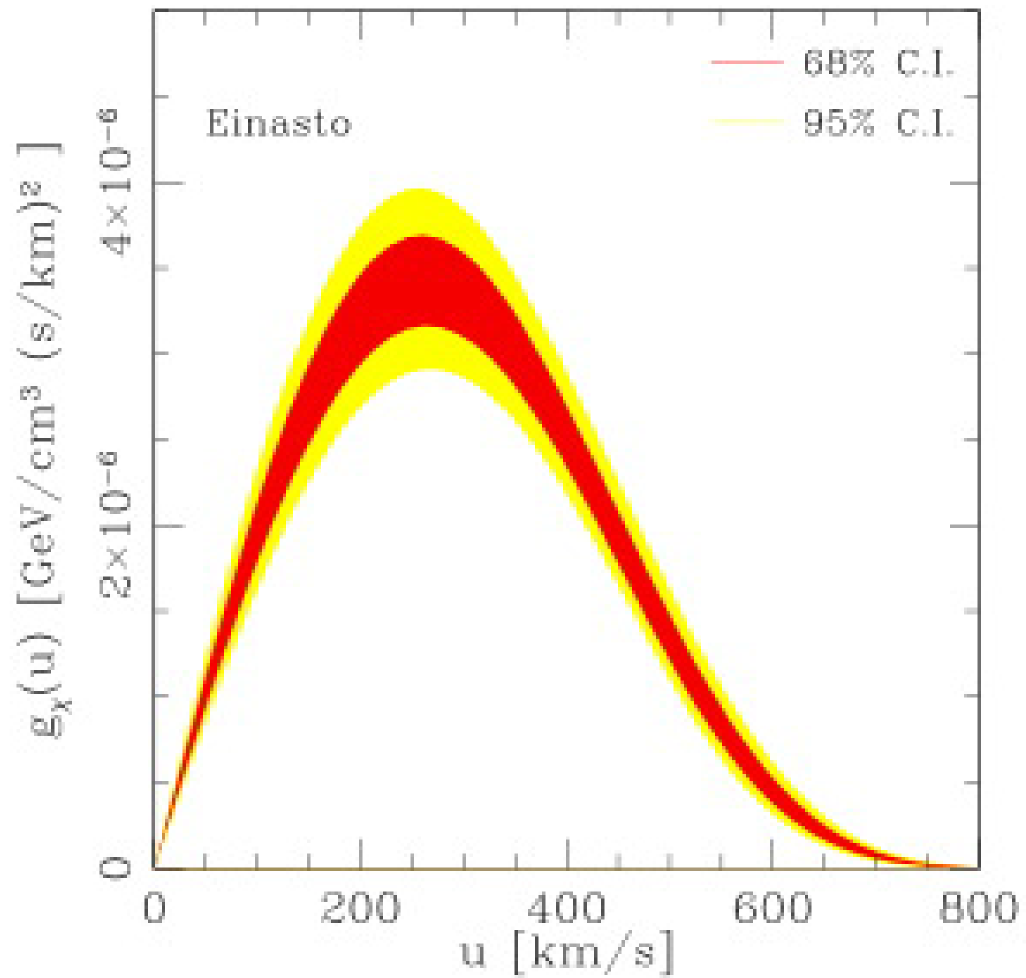

$$\rho(r) = \frac{\rho_0}{(r/R)^\gamma [1 + (r/R)^\alpha]^{(\beta-\gamma)/\alpha}}$$

Critical for indirect detection !

# Dark Matter local density & velocity distribution

[Catena & Ullio 09, 11]

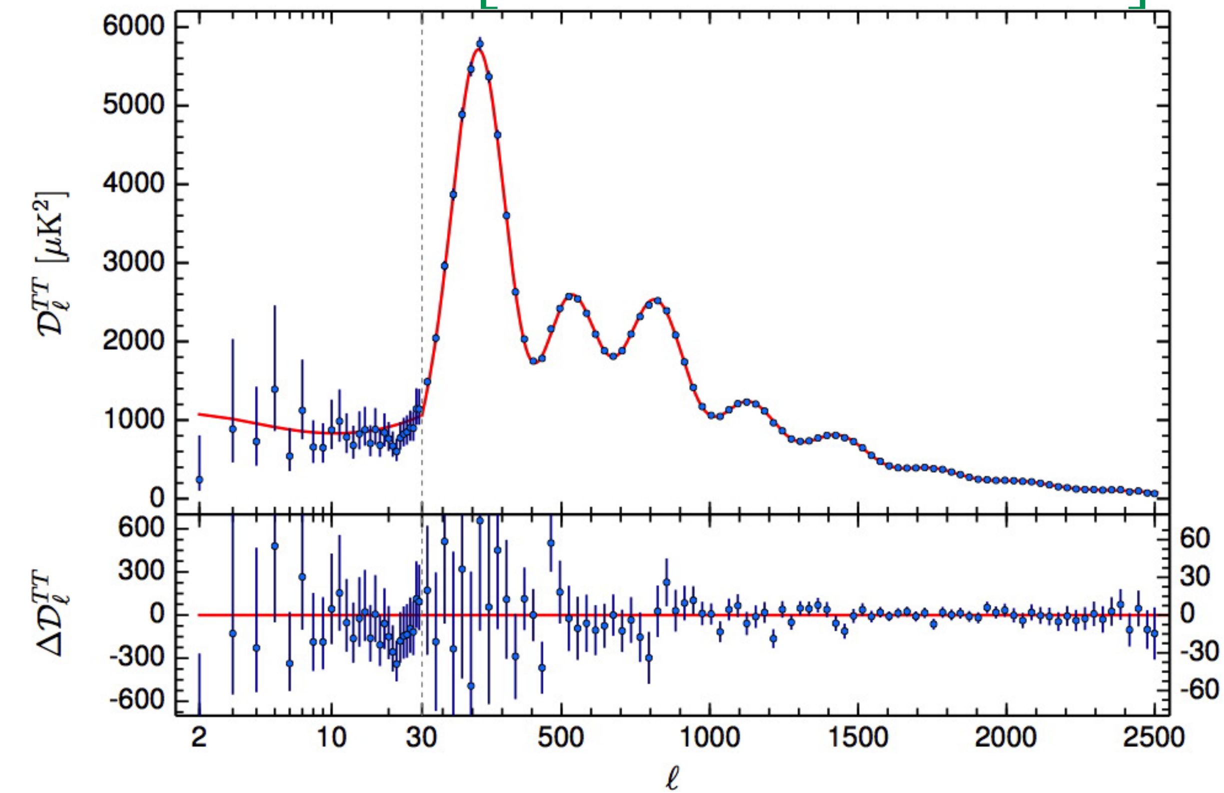



Critical for Direct Detection !

# DARK MATTER EVIDENCE

[Planck coll. 1502.01589]




## HORIZON SCALES:

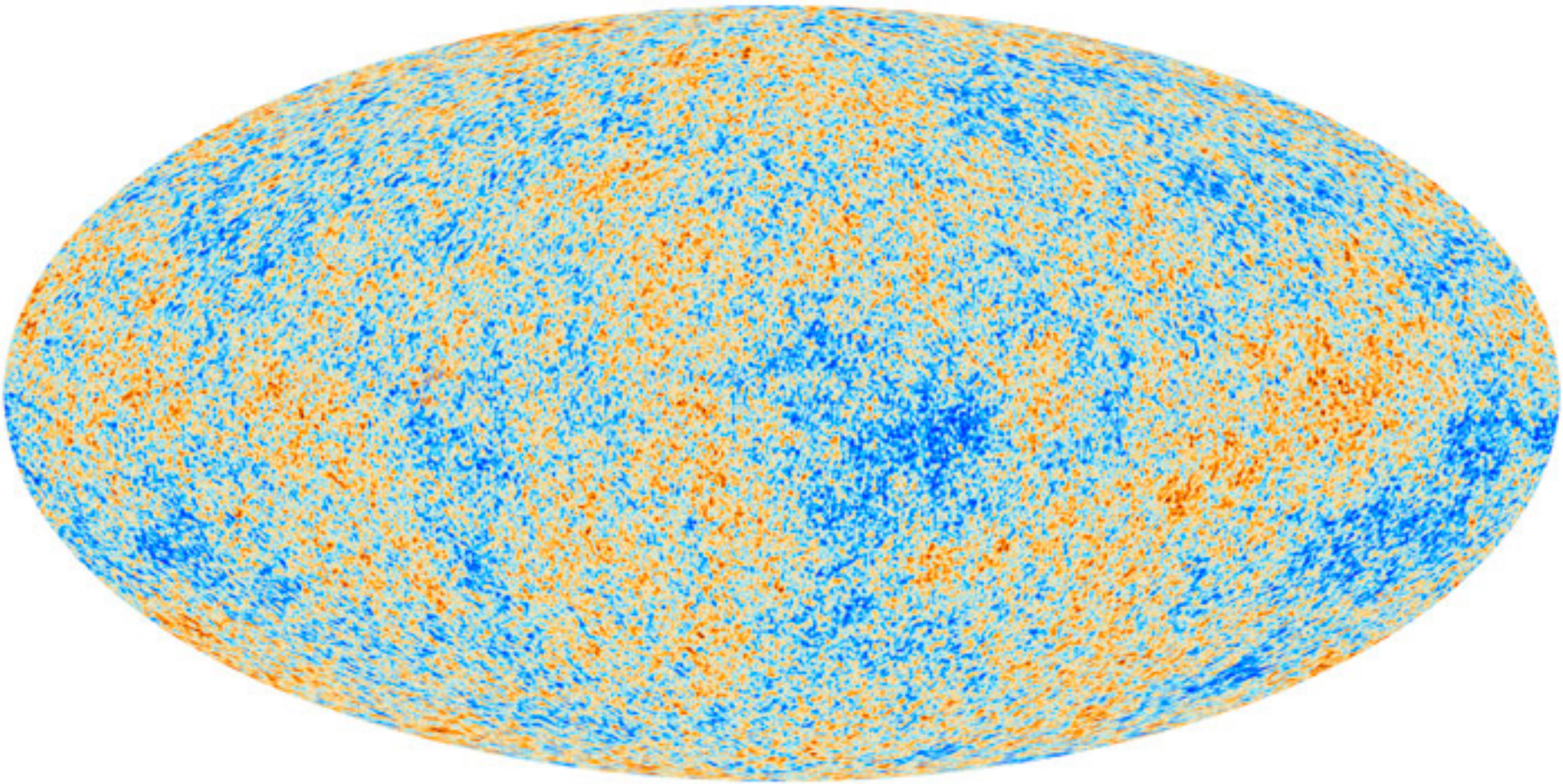
From the position and height of the CMB anisotropy acoustic oscillations peaks we can determine very precisely the curvature of the Universe and other background parameters.

| Particles | $\Omega h^2$ | Type |
|---|---|---|
| Baryons | 0,0224 | Cold |
| Neutrinos | < 0.01 | Hot |
| ??? | 0.11-0.13 | Cold |

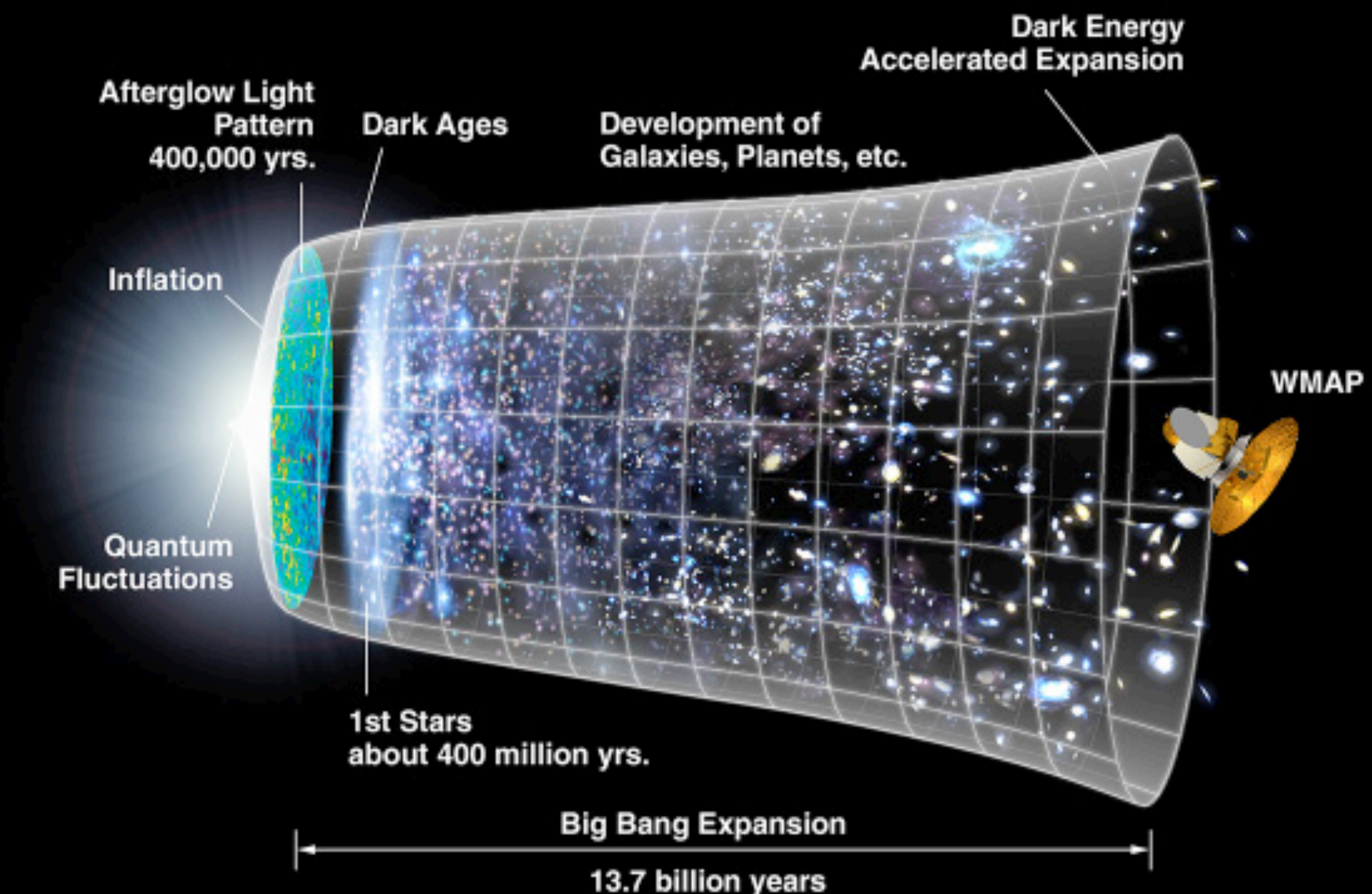
**DARK MATTER** →

# 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 ?

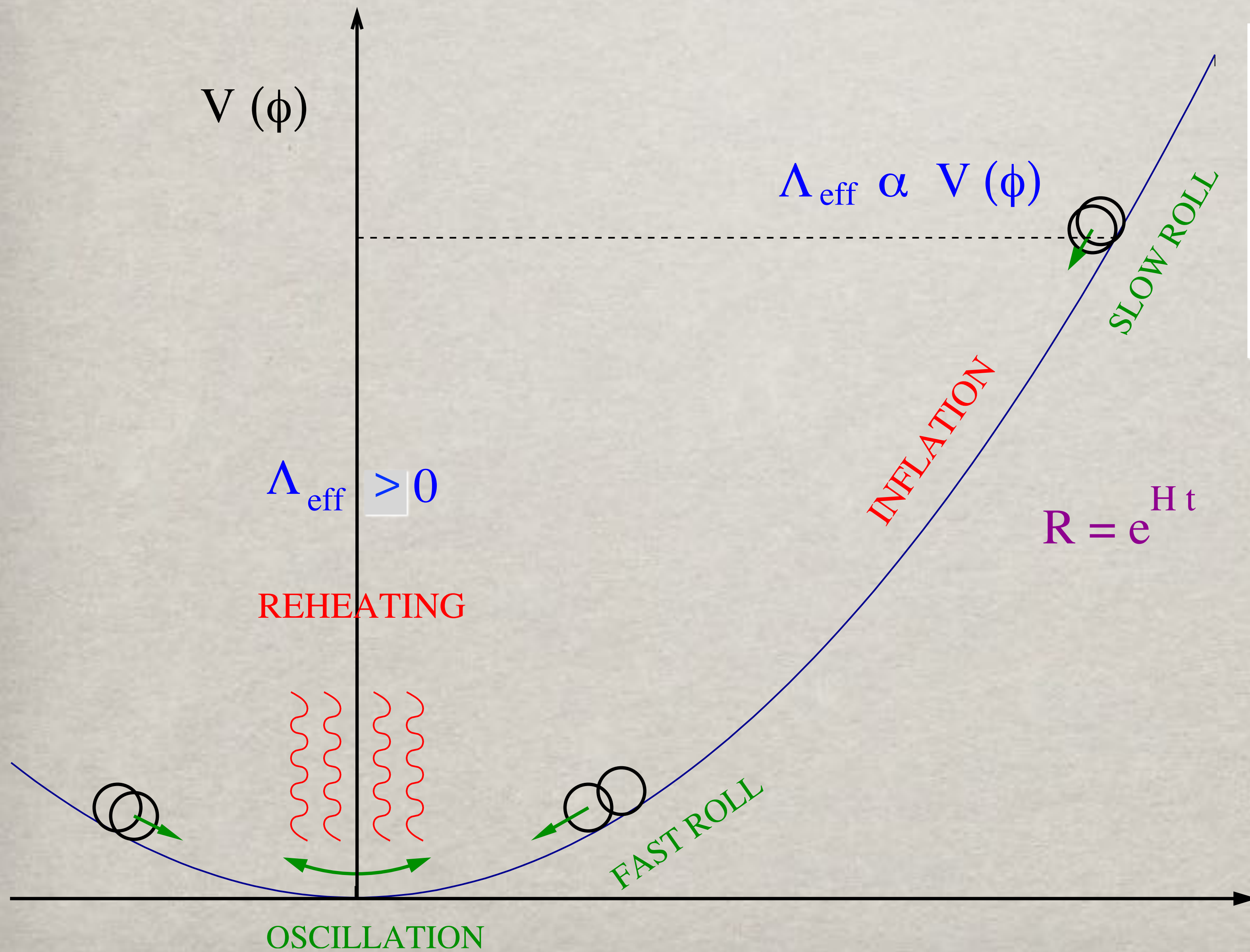


# Following the fluctuations




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

# Inflation: driven by a scalar field $\phi$




$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

$$|\eta| = \left|\frac{V''}{V}\right| \ll 1$$

$R = e^{H t}$ Quasi - de Sitter

de Sitter ?

# INFLATON AS QUANTUM FIELD

Apart for the classical motion, there are fluctuations:

$$\boxed{\phi = \varphi_c + \delta\varphi}$$

In an inflationary (de Sitter) phase these are given by

$$\boxed{\delta\varphi = \frac{H}{2\pi}}$$

**THEY REMAIN IMPRINTED IN THE METRIC AND ARE STRETCHED TO COSMOLOGICAL SCALES !!!**

$\Rightarrow$ $\delta g_{\mu\nu}, \delta\rho, \delta p \sim 10^{-5}$ PRIMORDIAL FLUCTUATIONS

# 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:

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

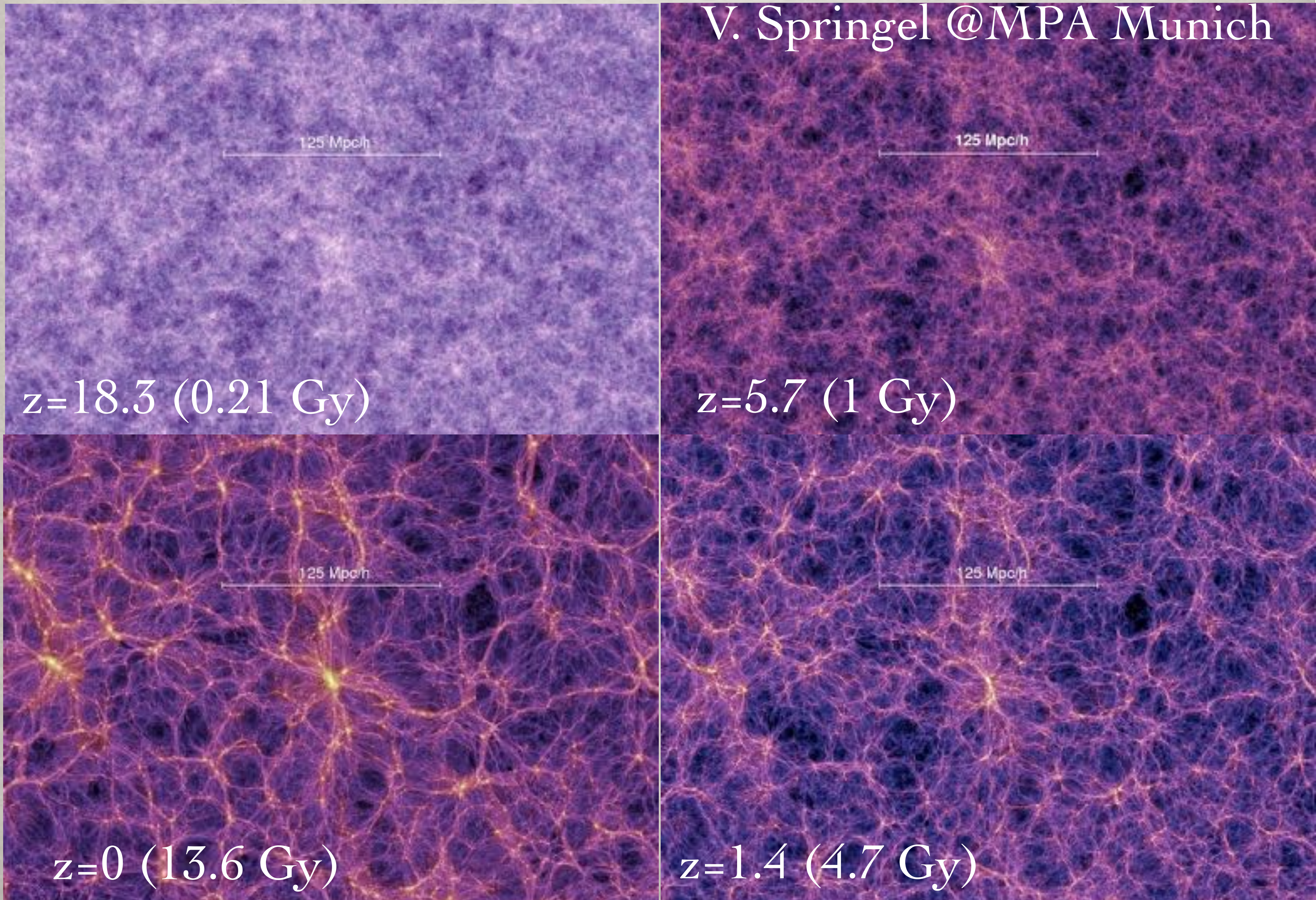
How strongly do they grow ? The growing solution is

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

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...

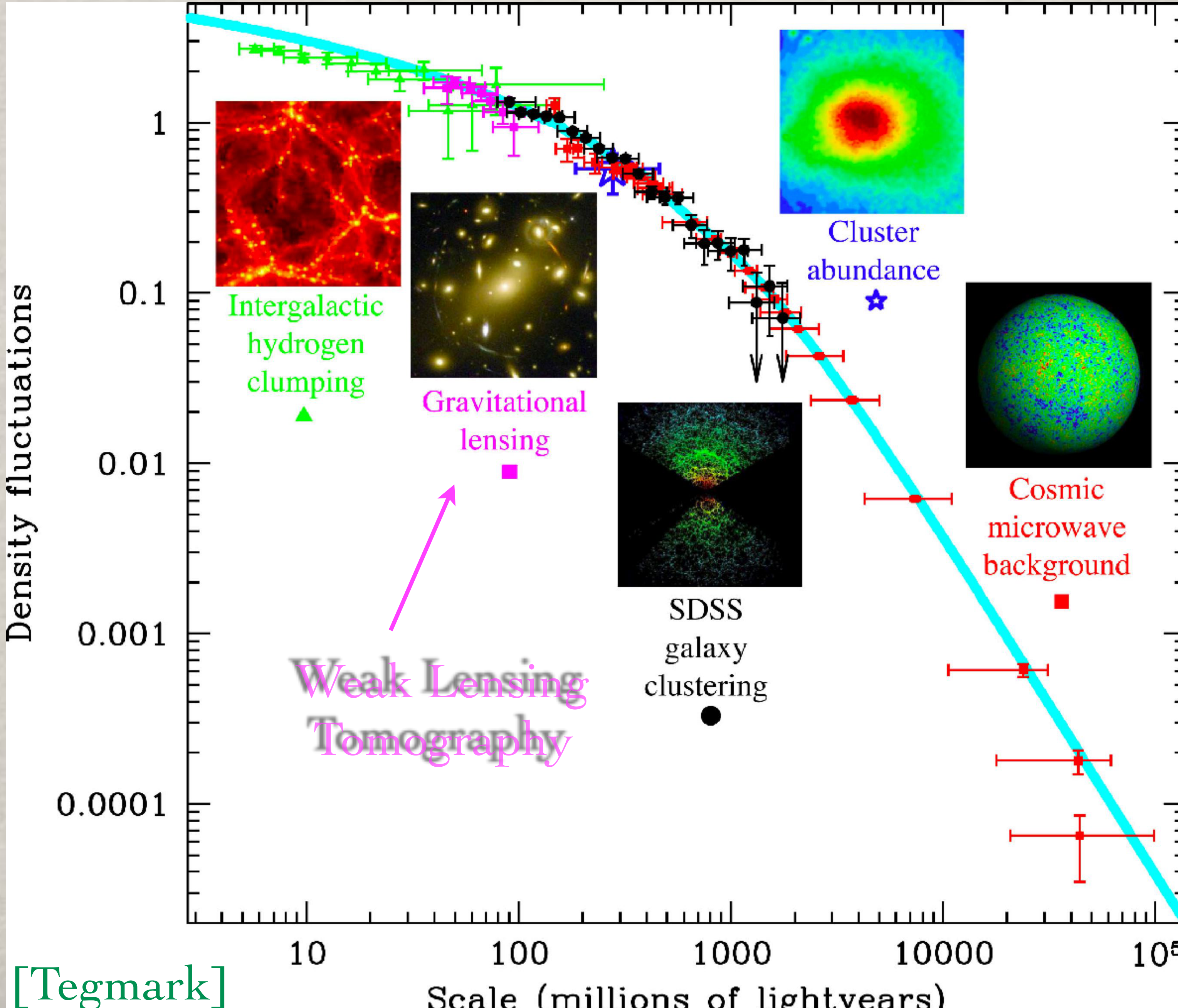
Non Linear regime

# Structure Formation



# FLUCTUATIONS ON ALL SCALES

Non-linear




Linear

[Tegmark]

# Introduction to Cosmology

# Einstein's equation: Energy is Geometry

$$\boxed{\mathcal{R}_\mu^\nu - \frac{1}{2}\delta_\mu^\nu \mathcal{R} \;=\; 8\pi G_N \, T_\mu^\nu + \Lambda \delta_\mu^\nu}$$

Einstein's Tensor:
Geometry of Space-time

Energy-momentum Tensor:
ALL the Physics content

Classical so far...

Quantum

The birth of Cosmology as a science:
the Universe's dynamics and fate is determined by its Energy (Particle) content,
both the known and the unknown....

# The Standard Model

Our present understanding of the forces and particles is based on the symmetry group $SU(3)_c \times SU(2)_L \times U(1)_Y$ .

| Standard Model | | | |
|---|---|---|---|
| Matter | | | Forces |
| $e$ | $\mu$ | $\tau$ | $\gamma$ |
| $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ | $W^\pm, Z$ |
| $u$ | $c$ | $t$ | $g$ |
| $d$ | $s$ | $b$ | $G$ |

$+ \; h$

It describes perfectly the data so far, but it is incomplete:

- theoretically it does not explain flavour and the presence of 3 generations, nor why the Higgs is light...
- it lacks a Dark Matter and inflaton candidate and also a mechanism to generate the baryon number...

# Which model Beyond the SM ?

weakly coupled ⟷ strongly coupled

Cosmology

(Collider-based) Particle Physics

To pinpoint the completion of the SM, exploit the complementarity between Cosmology and Particle Physics to explore all the sectors of the theory: the more weakly coupled and the more strongly coupled to the Standard Model fields...

Best results if one has information from both sides, e.g. neutrinos, axions, etc... ???

# Standard Cosmology

Cosmological Principle (nowadays also experimental result...):
The Universe is homogeneous and isotropic
on large scales (i.e. larger than ~100 Mpc)

⬇

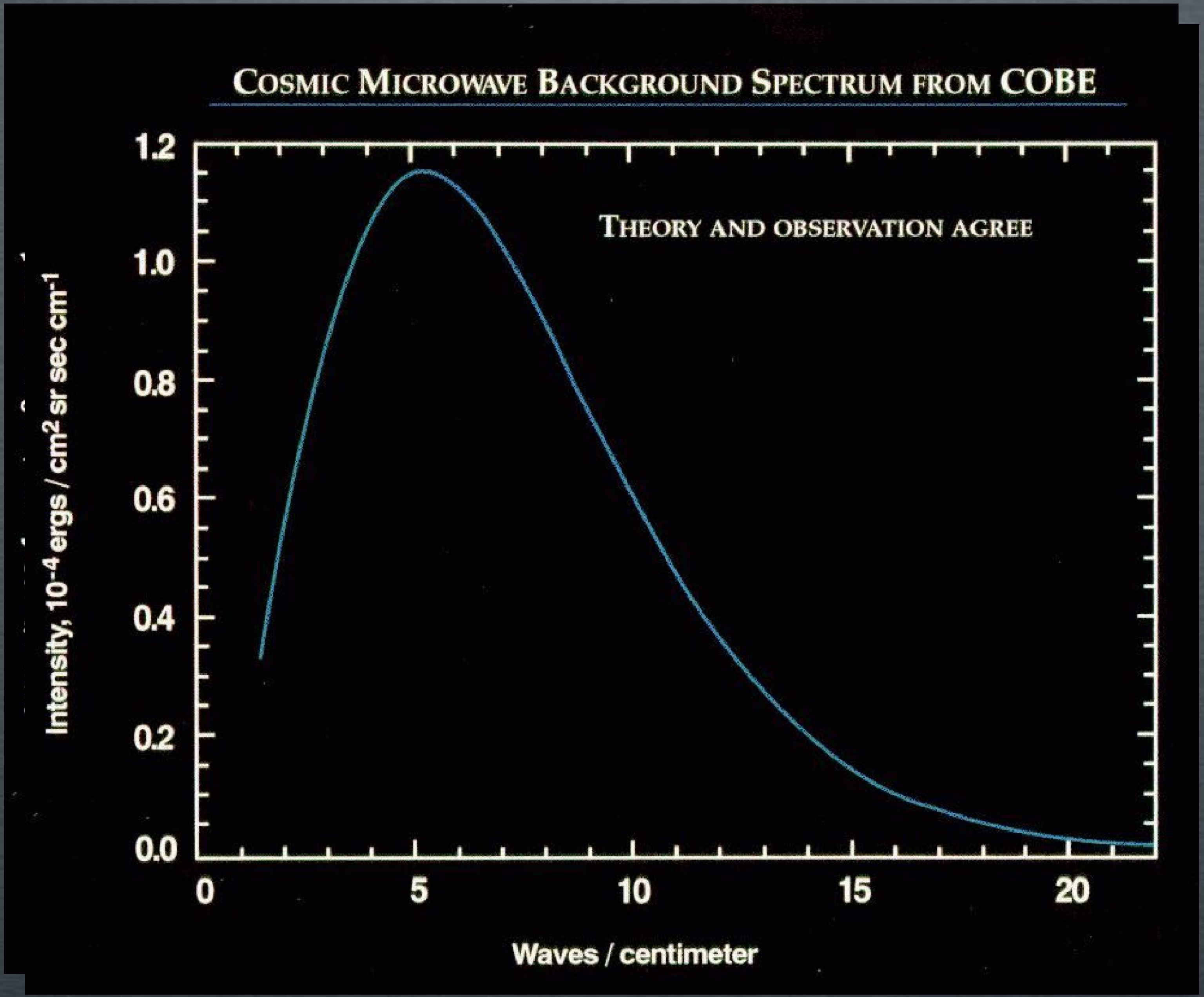
It is described by the Friedmann-Robertson-Walker Metric:

$$\boxed{ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-\kappa r^2} + r^2 d\Omega\right)}$$

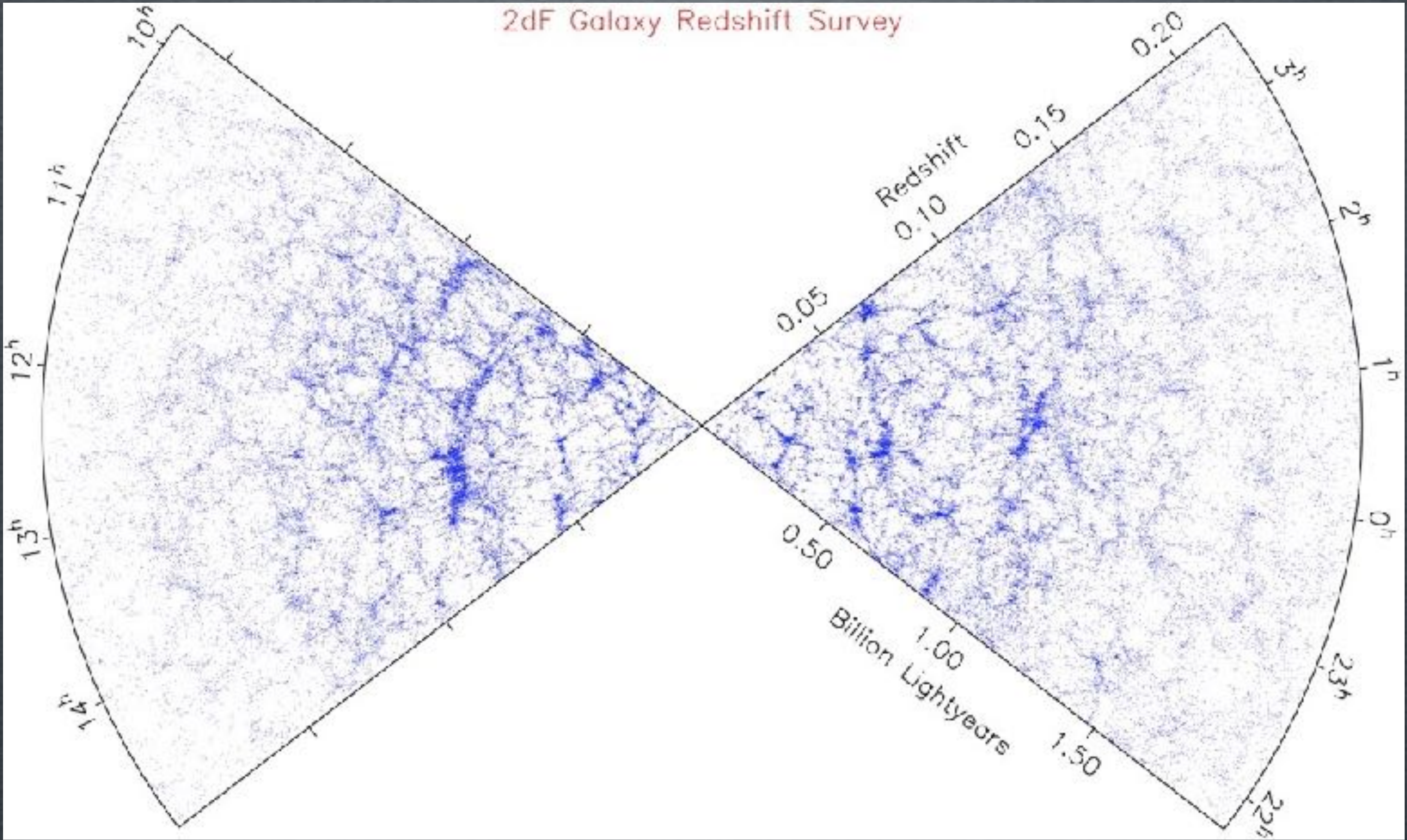
conformal to Minkowski for $dt^2 = a^2(\eta)d\eta^2$ $\quad \kappa = 0$

- Only one dynamical variable: the scale factor $a(t)$
- One constant parameter: the spatial curvature $\kappa$

# 1/2 Physics Nobel Prize 2006 to J. Mather for COBE: ISOTROPY: Perfect Black Body in all directions !



# HOMOGENEITY: less structure at large redshifts !



# Energy momentum tensor

Perfect fluid approximation $T^{\mu}_{\nu} = (\rho + p)u^{\mu}u_{\nu} - p\delta^{\mu}_{\nu}$

where $\rho$ and $p$ are the fluid density and pressure, while $u$ is the fluid 4-velocity. So in the rest-frame of the fluid, where $u = (1, \vec{0})$, i.e. assuming that the fluid is at rest in the Universe, we have

$$T^{\mu}_{\nu} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & -p & 0 & 0 \\ 0 & 0 & -p & 0 \\ 0 & 0 & 0 & -p \end{pmatrix}$$

Moreover the energy-momentum tensor is covariantly conserved:

$$\mathcal{D}_{\mu} T^{\mu\nu} = 0 \quad \rightarrow \quad \dot{\rho} + 3H(\rho + p) = 0$$

continuity equation

This can be solved if we know the equation of state $p(\rho) = w\rho$ then

$$\frac{\dot{\rho}}{\rho} = -3(1+w)H \quad \Rightarrow \quad \rho \propto a^{-3(1+w)}$$

So the different energy types are modeled by perfect fluids with equation of state $w_i = p_i / \rho_i$ .

# Friedmann equation:

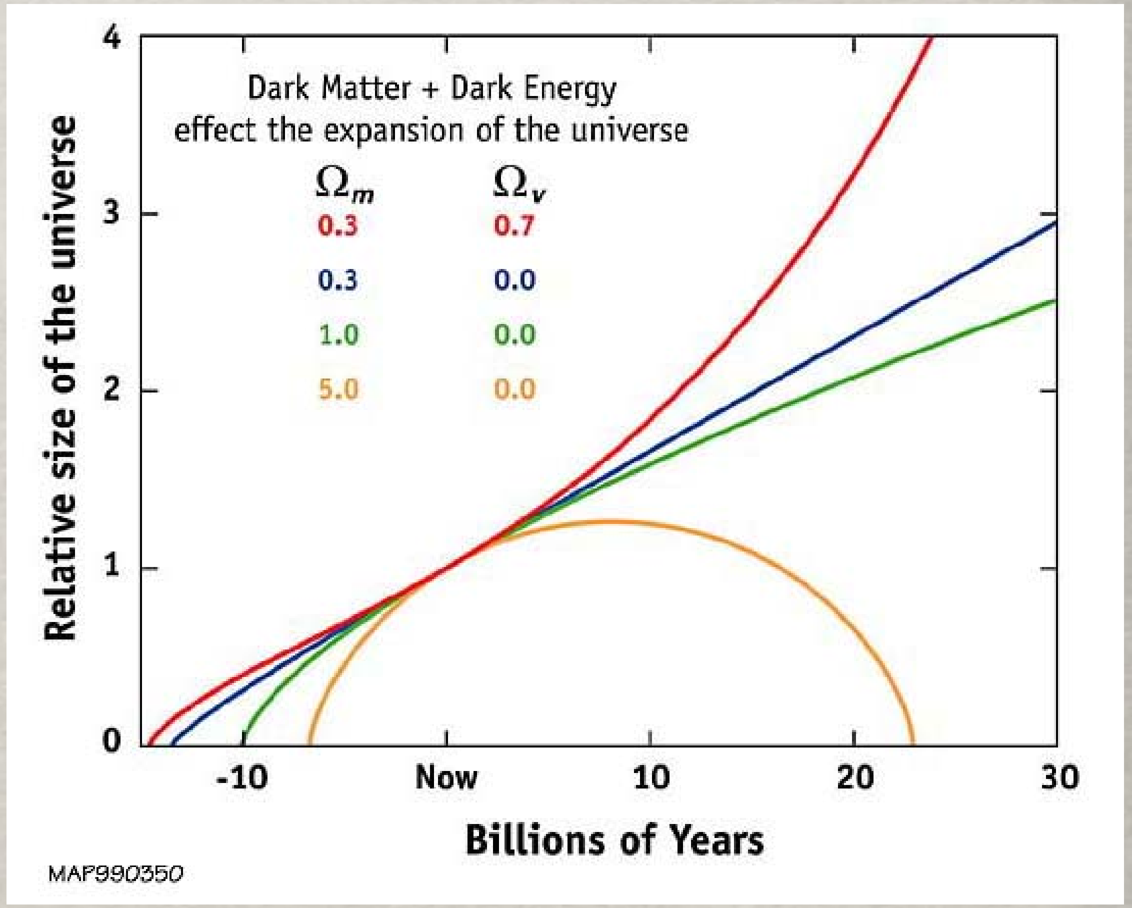
$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\rho + \Lambda - \frac{\kappa}{a^2}$$

- The energy density & curvature decree the time evolution of the scale factor
- Key parameter is the critical density:

$$\rho_c = \frac{3H^2}{8\pi G_N} \qquad \Omega_i = \frac{\rho_i}{\rho_c}$$

$\Omega_i$ :density in $\sim 10^4 \mathrm{eV/cm}^3$

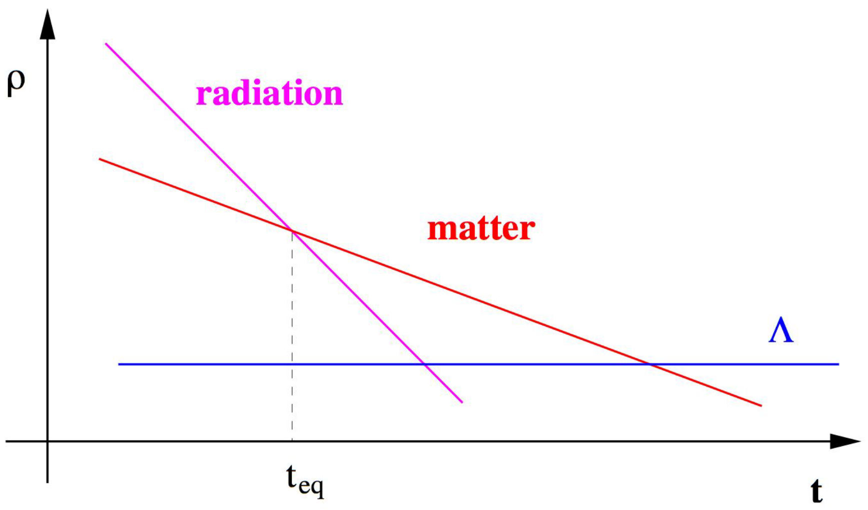
~ 10 protons/m3



# Different energy types

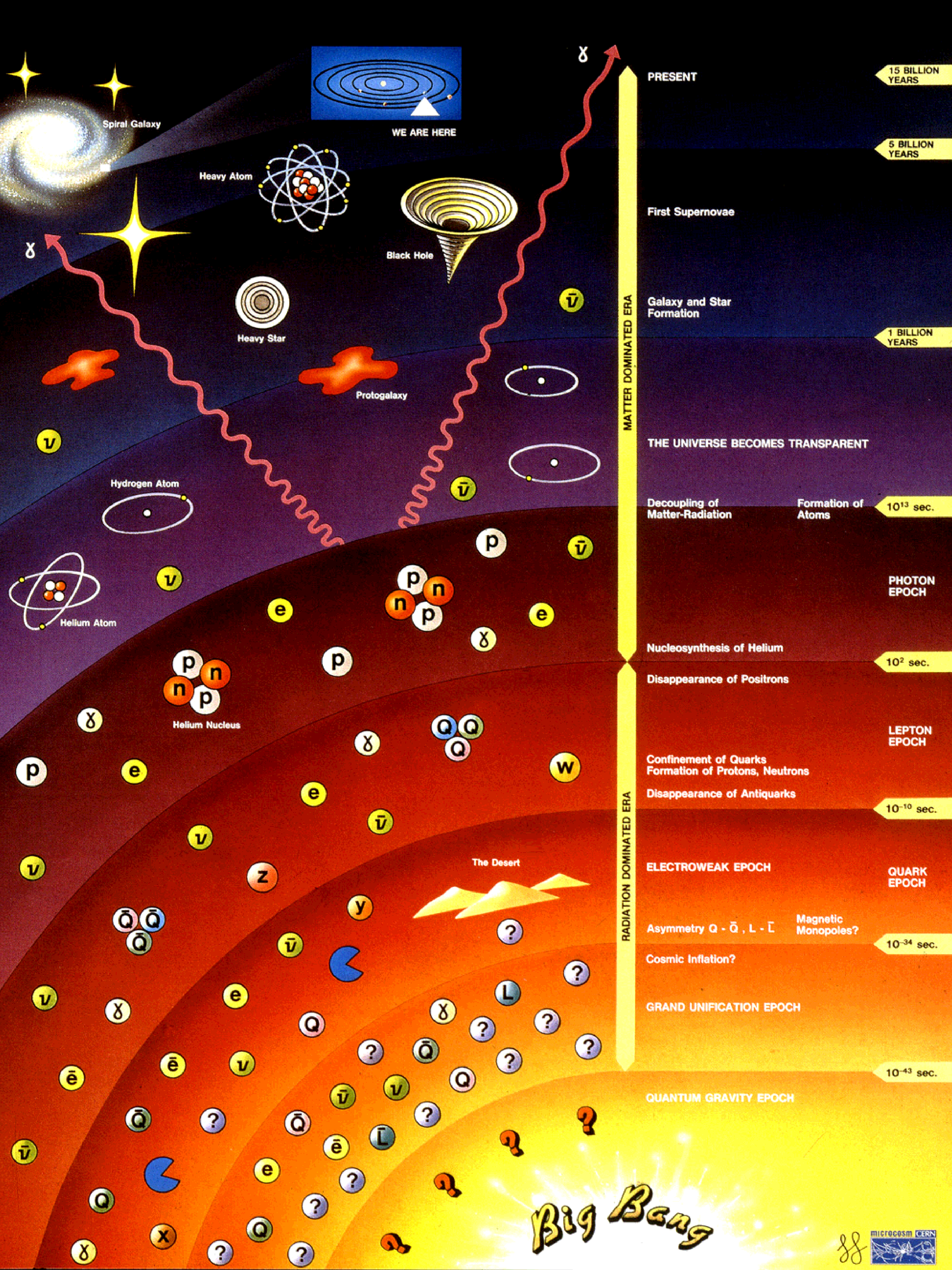
Depending on the pressure and the equation of state, the energy densities give different expansion rates:

| Type | $p/\rho$ | $\rho(a)$ | $a(t)$ |
|---|---|---|---|
| Generic | $w$ | $a^{-3(1+w)}$ | $t^{2/(3(1+w))}$ |
| Radiation | $1/3$ | $\propto a^{-4}$ | $\propto t^{1/2}$ |
| Matter | $0$ | $\propto a^{-3}$ | $\propto t^{2/3}$ |
| $\Lambda$ | $-1$ | const. | $e^{Ht}$ |
| Curvature | $-1/3$ | $\propto a^{-2}$ | $\propto t^{1}$ |




Always decelerating apart for the cosmological constant !

Different epochs of the Universe history


Spiral Galaxy
WE ARE HERE
Heavy Atom
Black Hole
Heavy Star
Protogalaxy
Hydrogen Atom
Helium Atom
Helium Nucleus
The Desert
MATTER DOMINATED ERA
RADIATION DOMINATED ERA
PRESENT
15 BILLION YEARS
5 BILLION YEARS
First Supernovae
Galaxy and Star Formation
1 BILLION YEARS
THE UNIVERSE BECOMES TRANSPARENT
Decoupling of Matter-Radiation
Formation of Atoms
$10^{13}$ sec.
PHOTON EPOCH
Nucleosynthesis of Helium
$10^{2}$ sec.
Disappearance of Positrons
LEPTON EPOCH
Confinement of Quarks
Formation of Protons, Neutrons
Disappearance of Antiquarks
$10^{-10}$ sec.
ELECTROWEAK EPOCH
QUARK EPOCH
Asymmetry $Q - \bar{Q}$ , $L - \bar{L}$
Magnetic Monopoles?
$10^{-34}$ sec.
Cosmic Inflation?
GRAND UNIFICATION EPOCH
$10^{-43}$ sec.
QUANTUM GRAVITY EPOCH
Big Bang
microcosm CERN

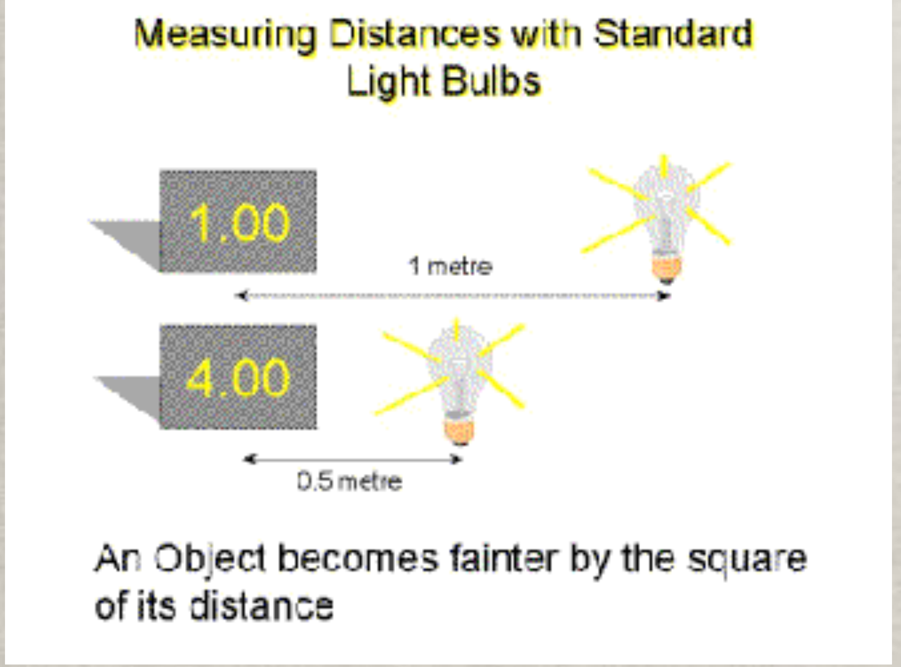
# Important Epochs

- Today: $T = 2.7K \sim 10^{-4}$ eV $\quad z = 0$
- First stars: $T \sim 10^{-3} \quad z \sim 15 - 20$
- Photon decoupling: CMB $T = 0.4$ eV $\quad z = 1100$
- Matter and Radiation equality: $T = 1$ eV $\quad z \sim 1300$
- Nucleosynthesis: $T = 0.1$ MeV
- Neutrino decoupling: C$\nu$B $T \sim 1$ MeV
- QCD phase transition $T \sim 0.3$ GeV
- EW phase transition $T \sim 100$ GeV
- ????

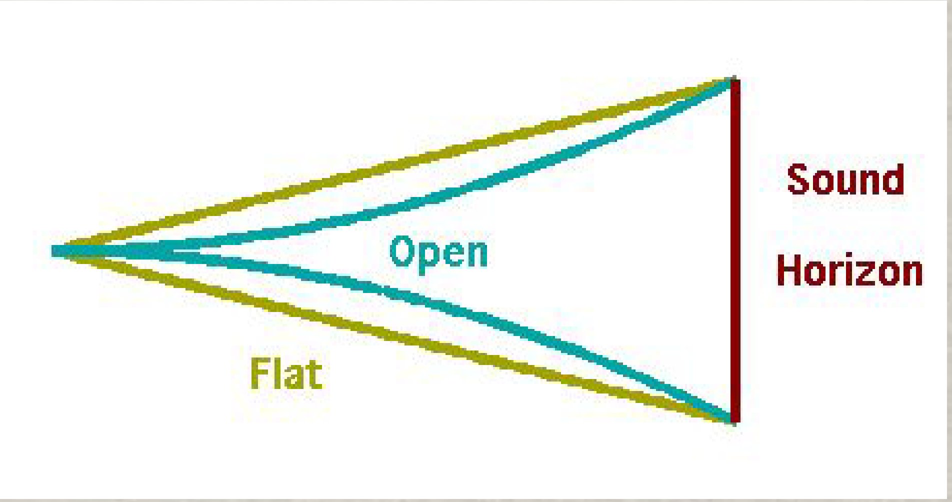
# Standard candles and rulers

# How can we measure the expansion of the Universe ?

Standard Candle




Standard Ruler



# Luminosity distance

$$D_L^2 = \frac{L}{4\pi\Phi}$$

Intrinsic Luminosity

Measured Flux

For a FRW universe it is given simply by

$$D_L^2 = (1+z)\int_0^z \frac{dz}{H(z)}$$

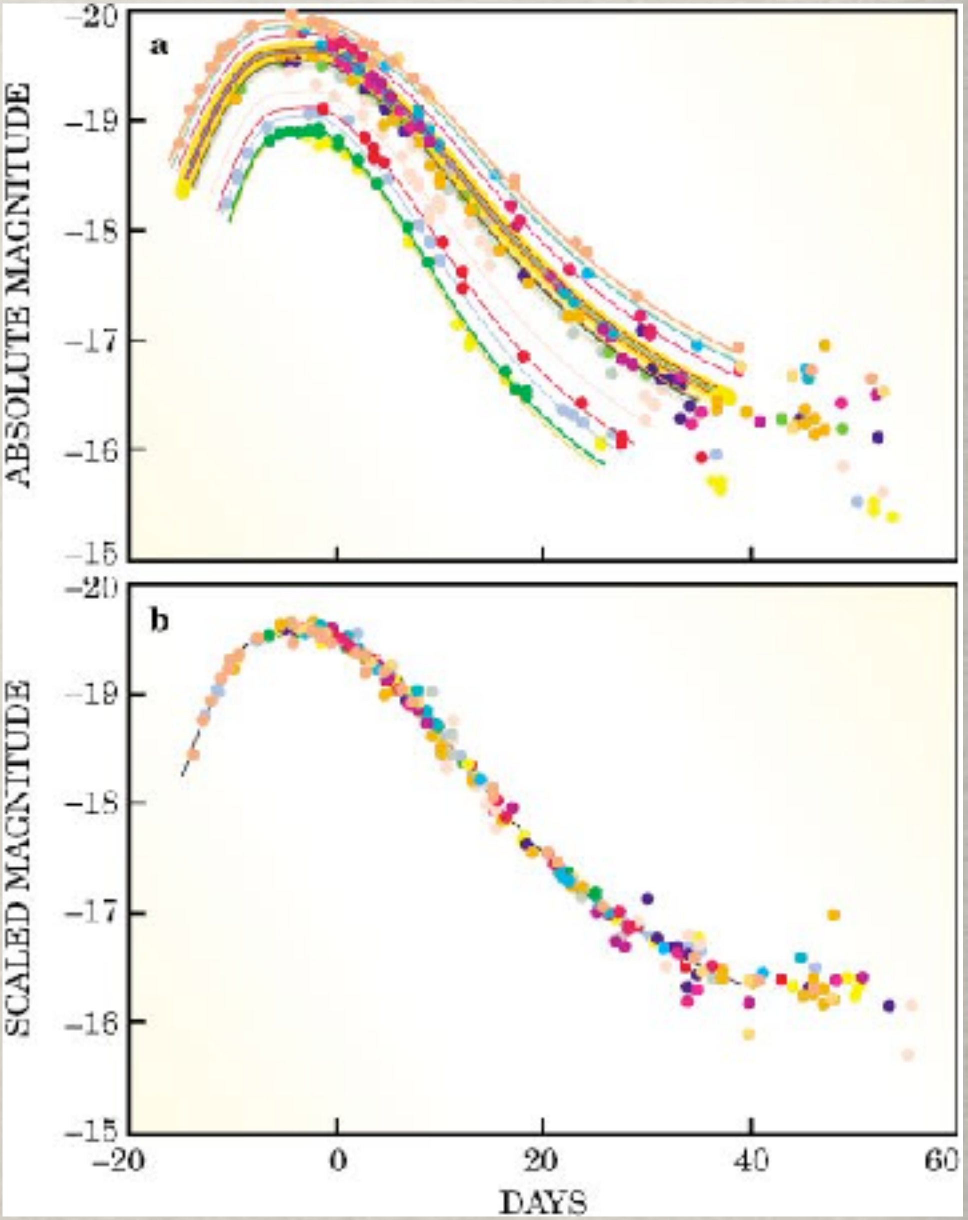
where $$H^2(z) = H_0^2 \sum_i \Omega_{i,0}(1+z)^{3(1+w_i)}$$

→ determination of the cosmological parameters

$$\Omega_{DM}(w=0), \Omega_\Lambda(w=-1), ...$$

# SN-IA AS STANDARD CANDLES

Type Ia supernova is the explosion of a white dwarf star in a binary star system. Material from a companion red giant star is dumped on the white dwarf until the smaller star reaches a precise mass limit.



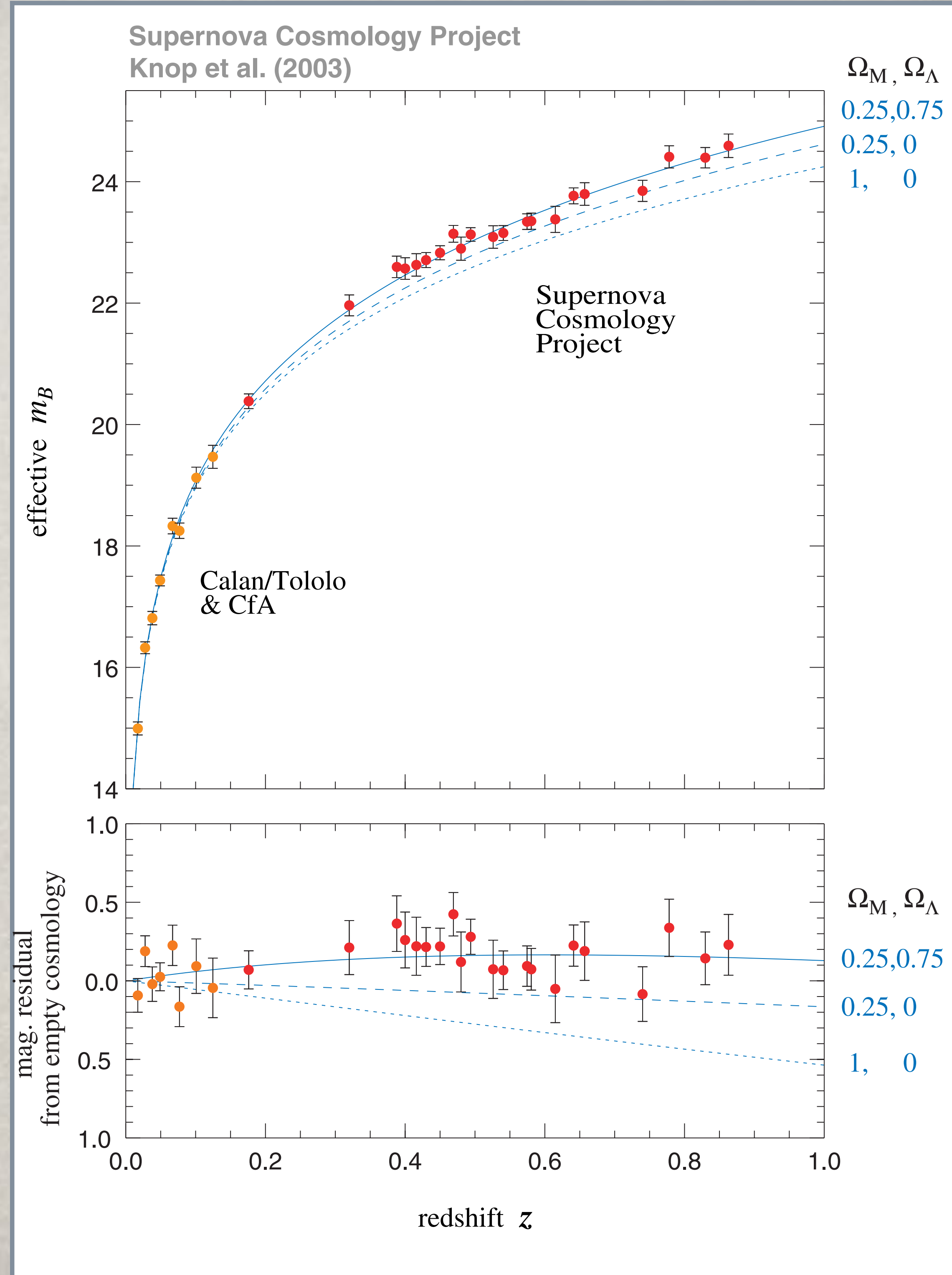

The spectra can be corrected to lie on the same line and follow a relation between peak luminosity and width of the light curve...

# Supernovae Ia as Standard Candles

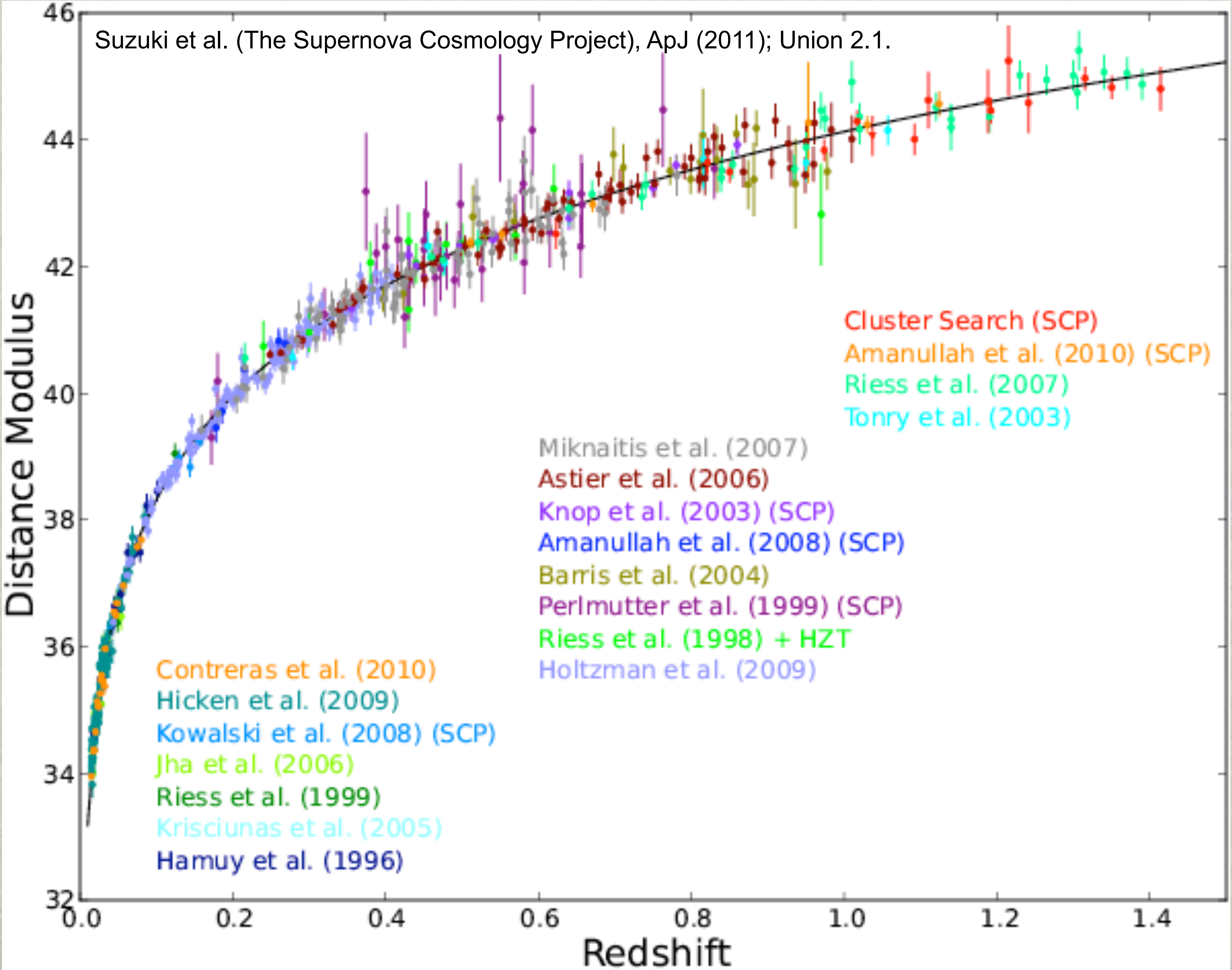
- Measure the apparent magnitude as a function of the redshift $z$ and test the first correction to the Hubble flow

- The Universe is accelerating !

$$\Lambda > 0$$



# SN-IA AS STANDARD CANDLES



# ANGULAR DISTANCE

$$D_A = \frac{R}{d}$$

Standard Ruler

Distance to the Ruler

For a FRW universe it is given simply by

$$D_A = (1+z)R\left(\int_0^z \frac{dz}{H(z)}\right)^{-1}$$

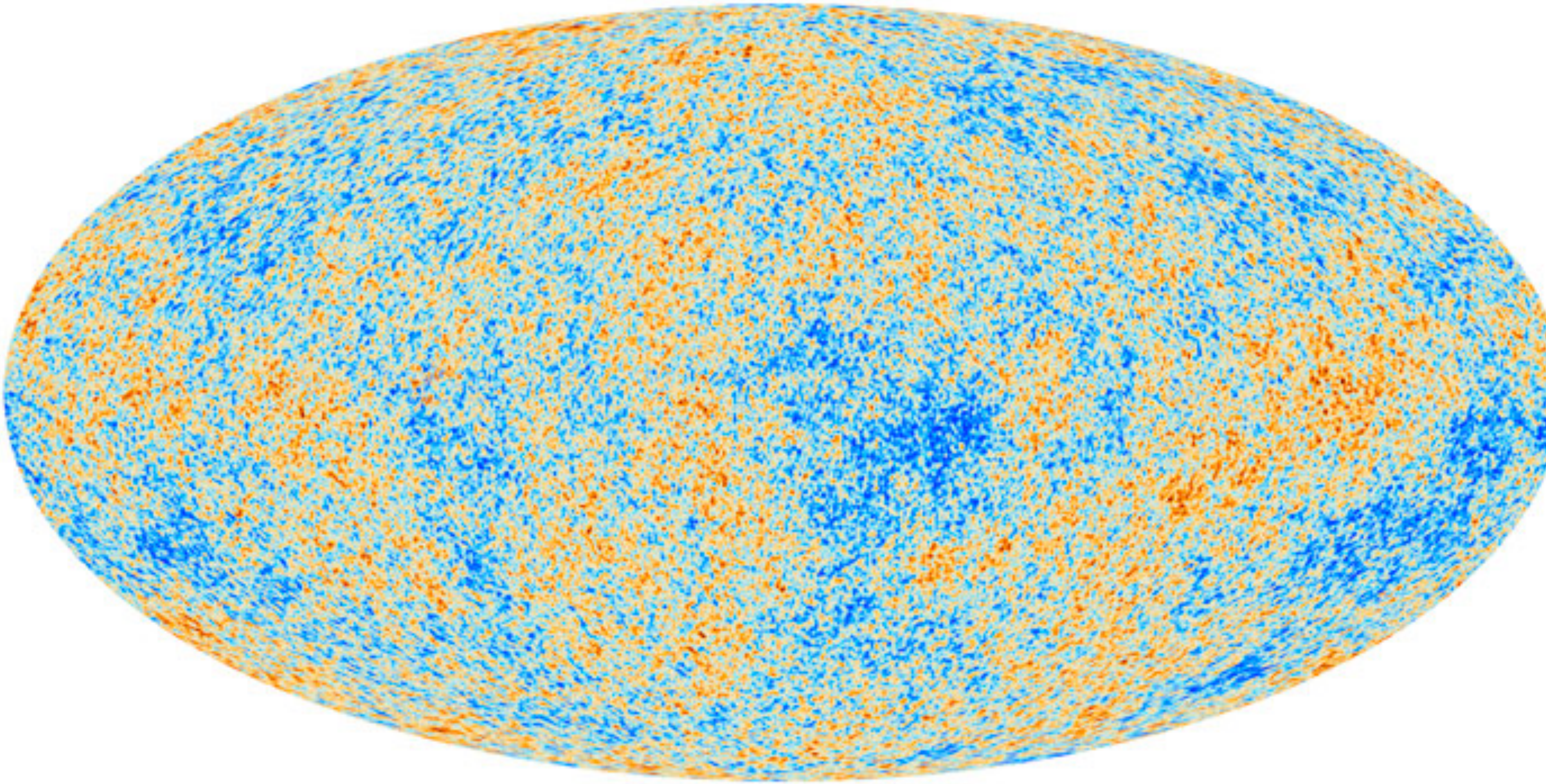
where $H(z) \sim H_0 \Omega_{D,0}^{1/2} (1+z)^{3/2(1+w_D)}$ for a dominant component

e.g. for the sound horizon at decoupling for MD

$$\frac{D_{A,CMB}}{(1+z_{CMB})} \sim \frac{2}{H_0 \Omega_{M,0}^{1/2}}$$

# CMB ANISOTROPIES

Physics of the fluctuations on the homogeneous background !



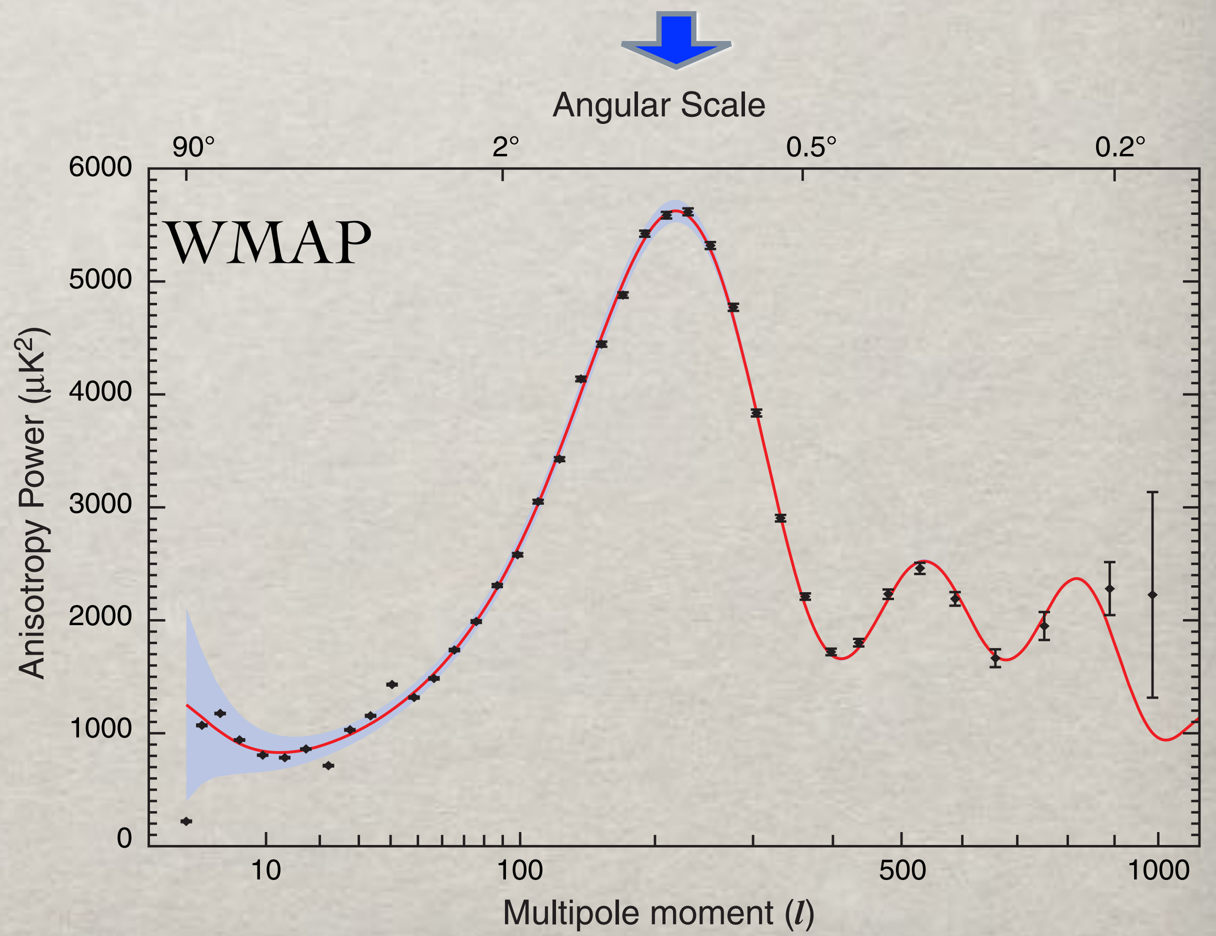
$$\langle T(\theta)T(0)\rangle = \sum_{\ell,m} a_{\ell m} Y^{\ell}_{m}(\theta)$$

# The sound horizon in the baryon-photon plasma as standard ruler

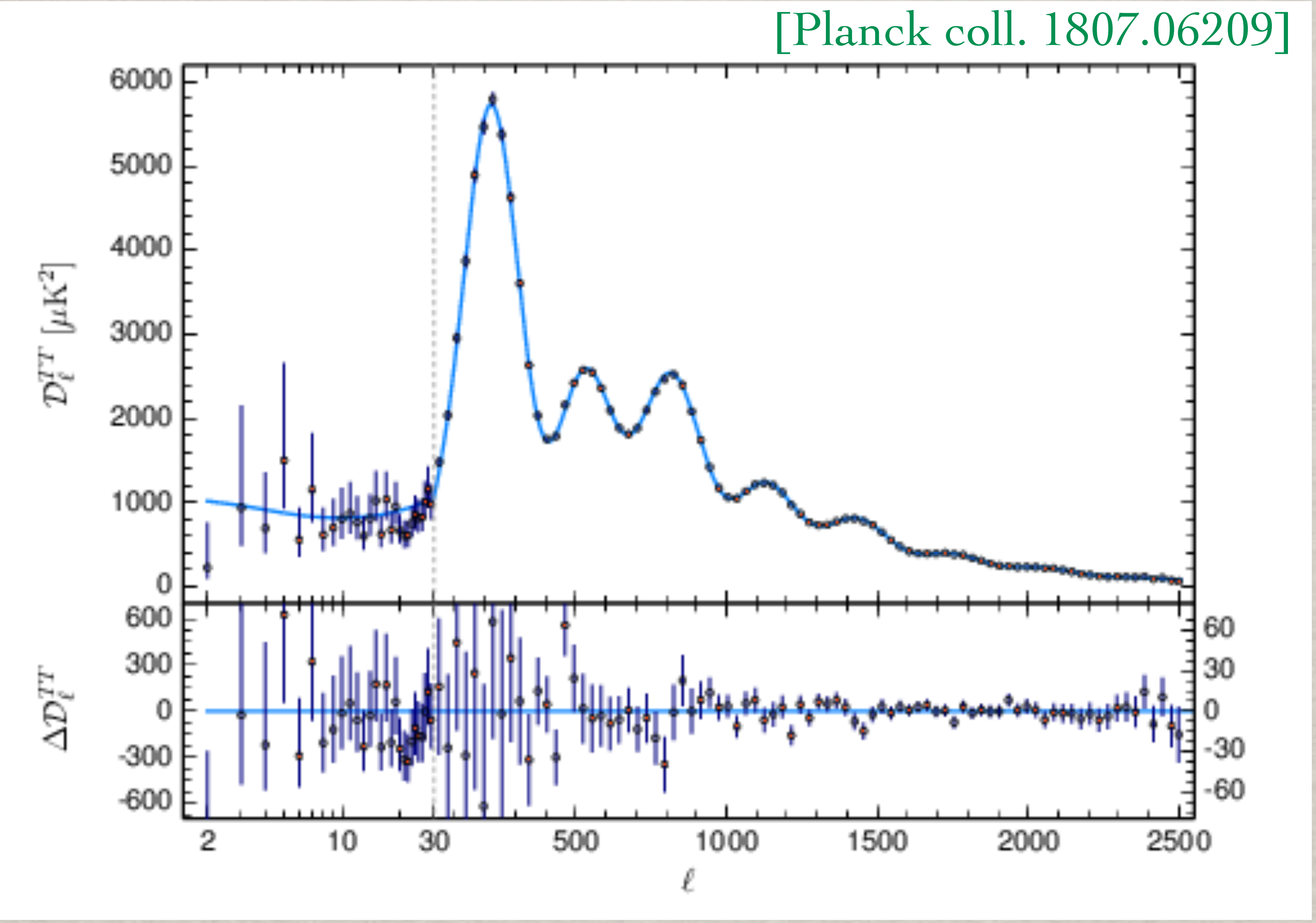
- Measure the angle corresponding to the first peak in the CMB anisotropies
- The Universe is **FLAT**

$$\Omega_{tot} = 1.014 \pm 0.017$$
$$\Rightarrow \kappa \simeq 0$$

Sound Horizon



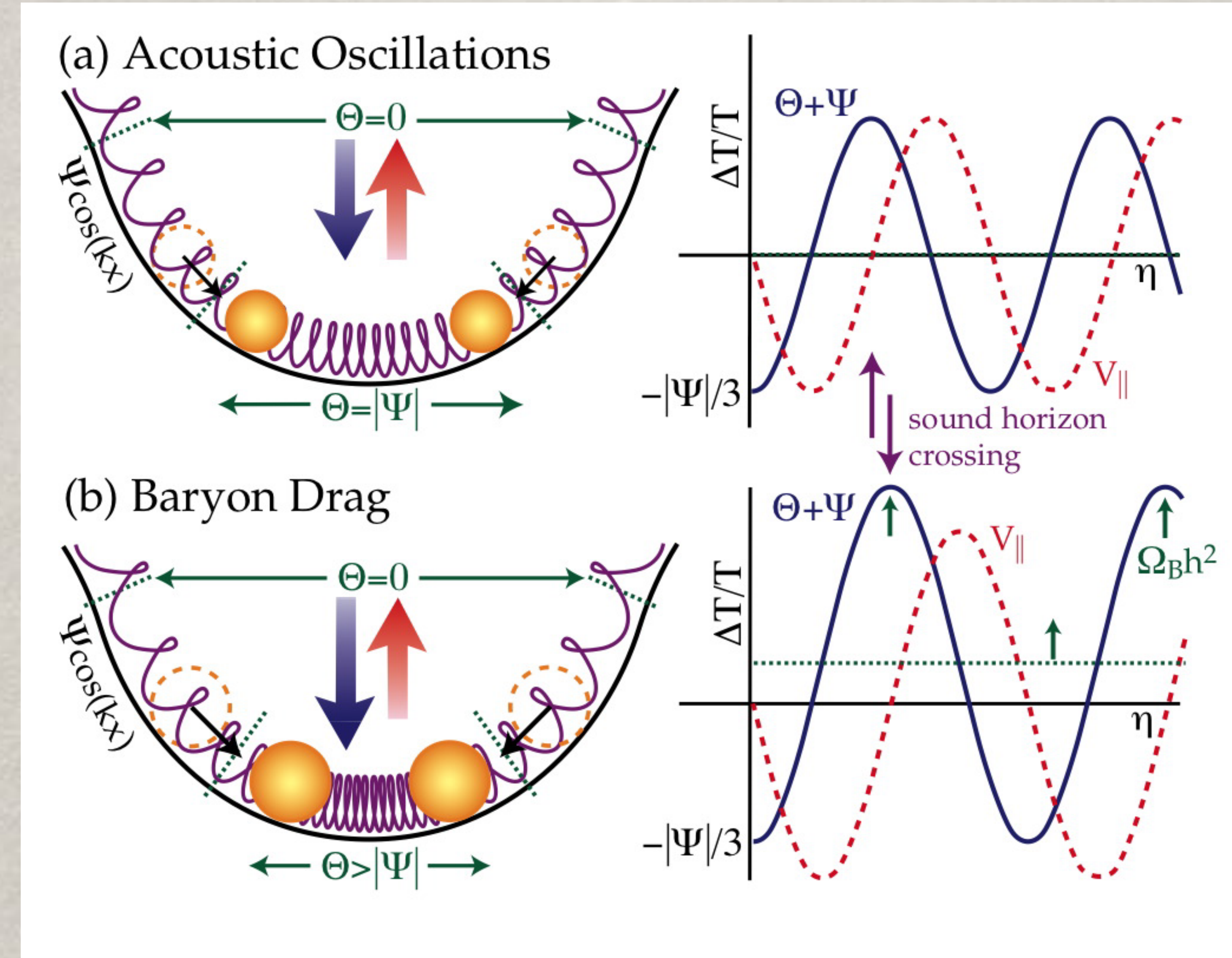
# Planck TT spectrum




Perfect agreement with 6-parameter $\Lambda CDM$ model!

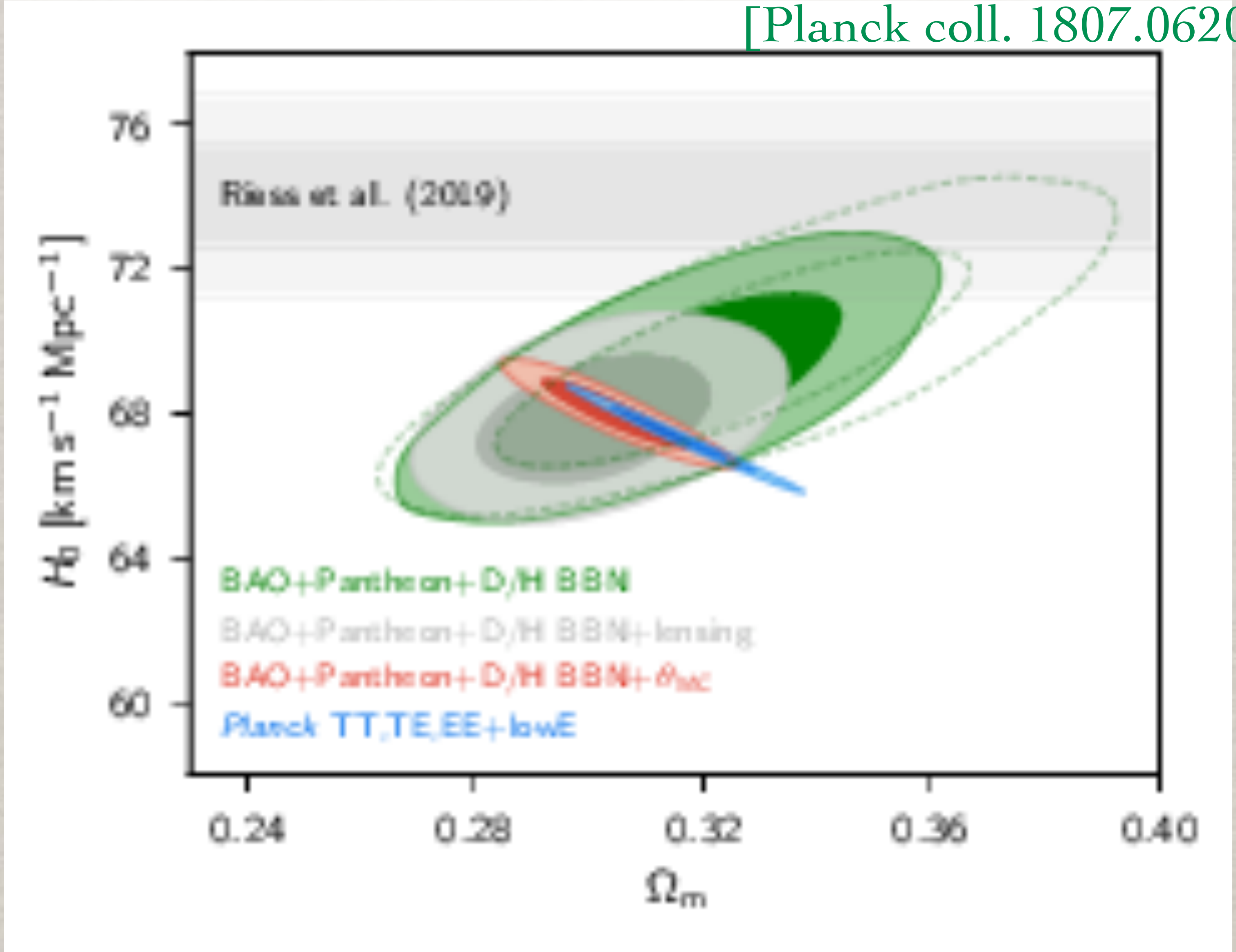
# CMB PRIMER

[Wayne Hu's CMB primer at http://background.uchicago.edu/~whu/]




Baryons increase the mass in the plasma and the drag force...

# Planck cosmo parameters

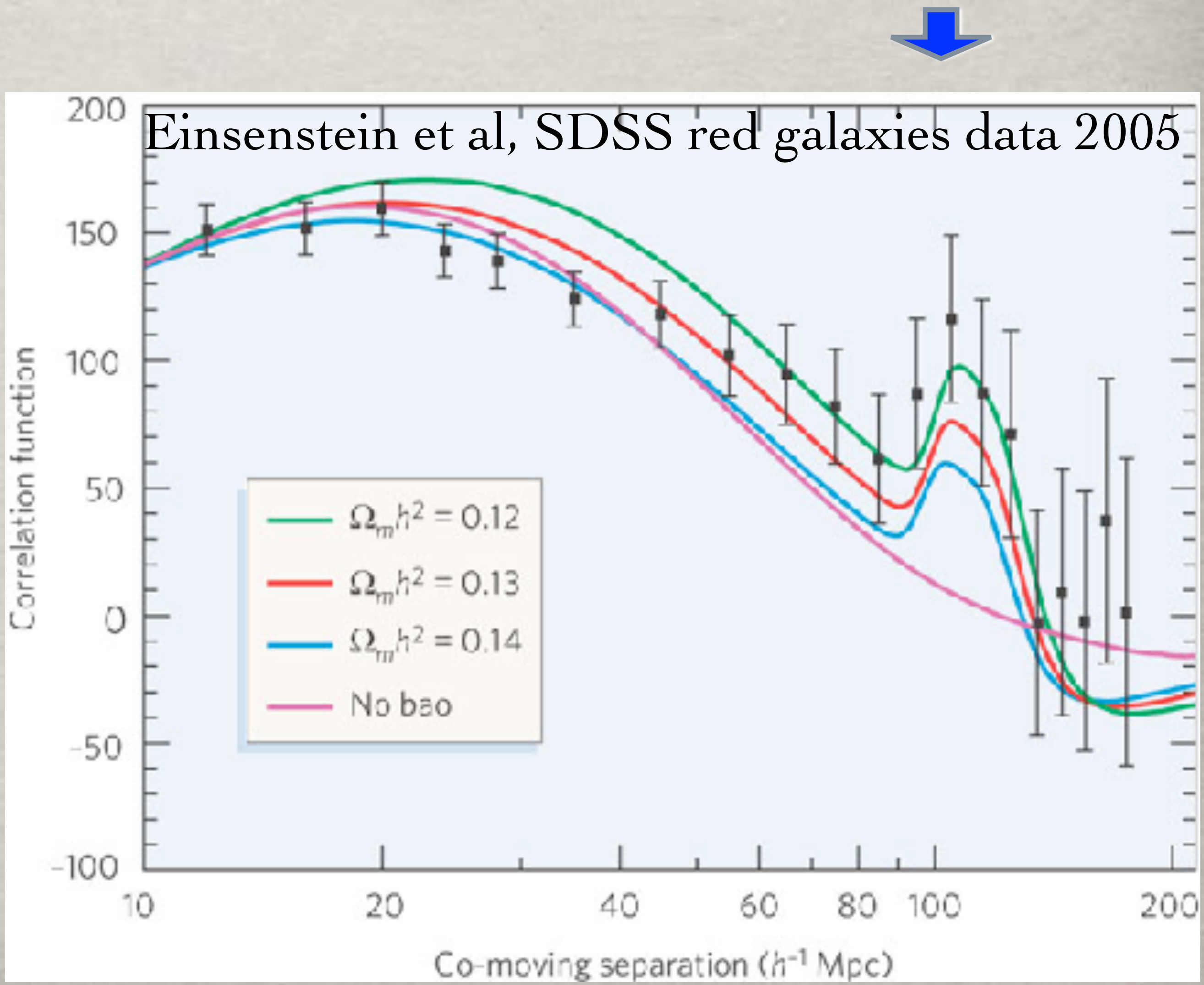



Discrepancy in the H_0 measurement depending on $\Omega_m$.

# The sound horizon in the baryon-photon plasma as standard ruler

Sound Horizon

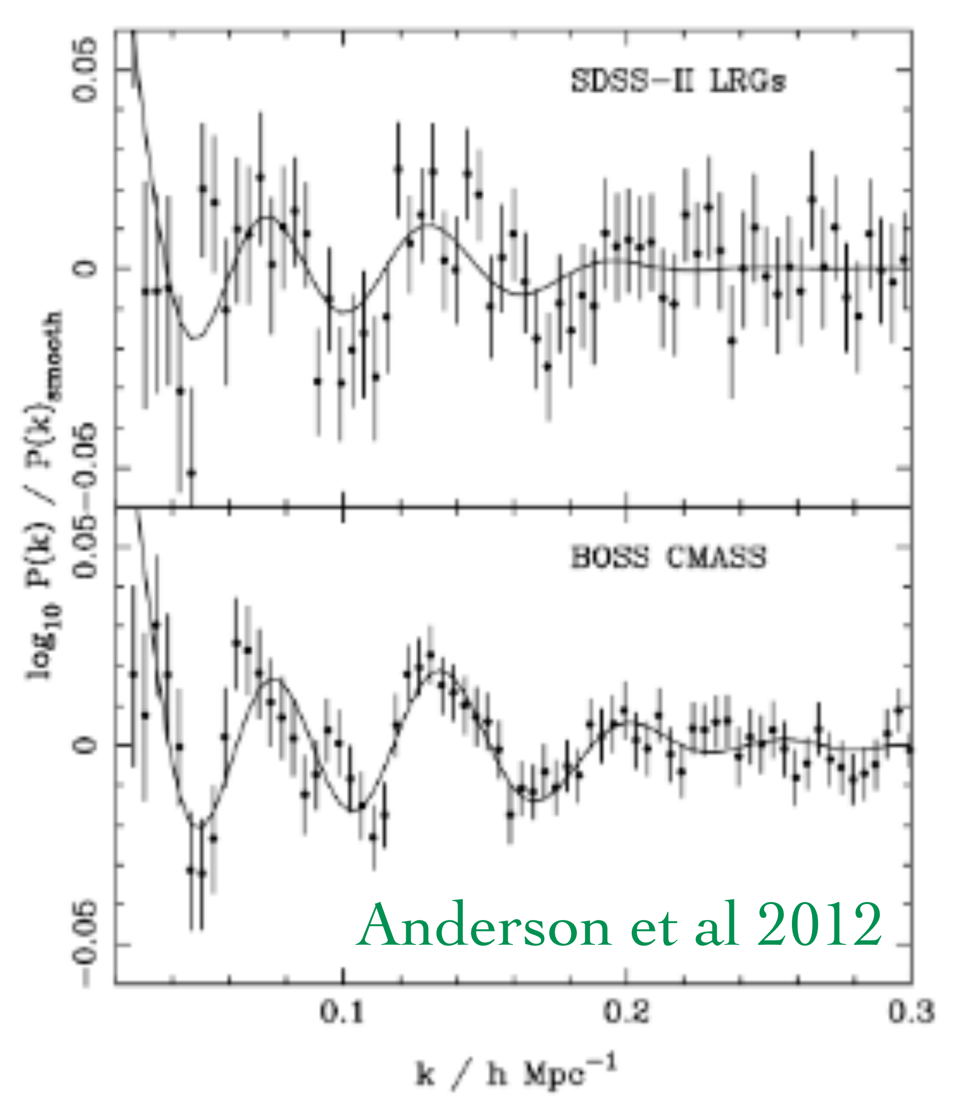
- The same scale is visible in the (baryonic) matter distribution (BAO)
- The more baryons (less CDM), the stronger the signal !



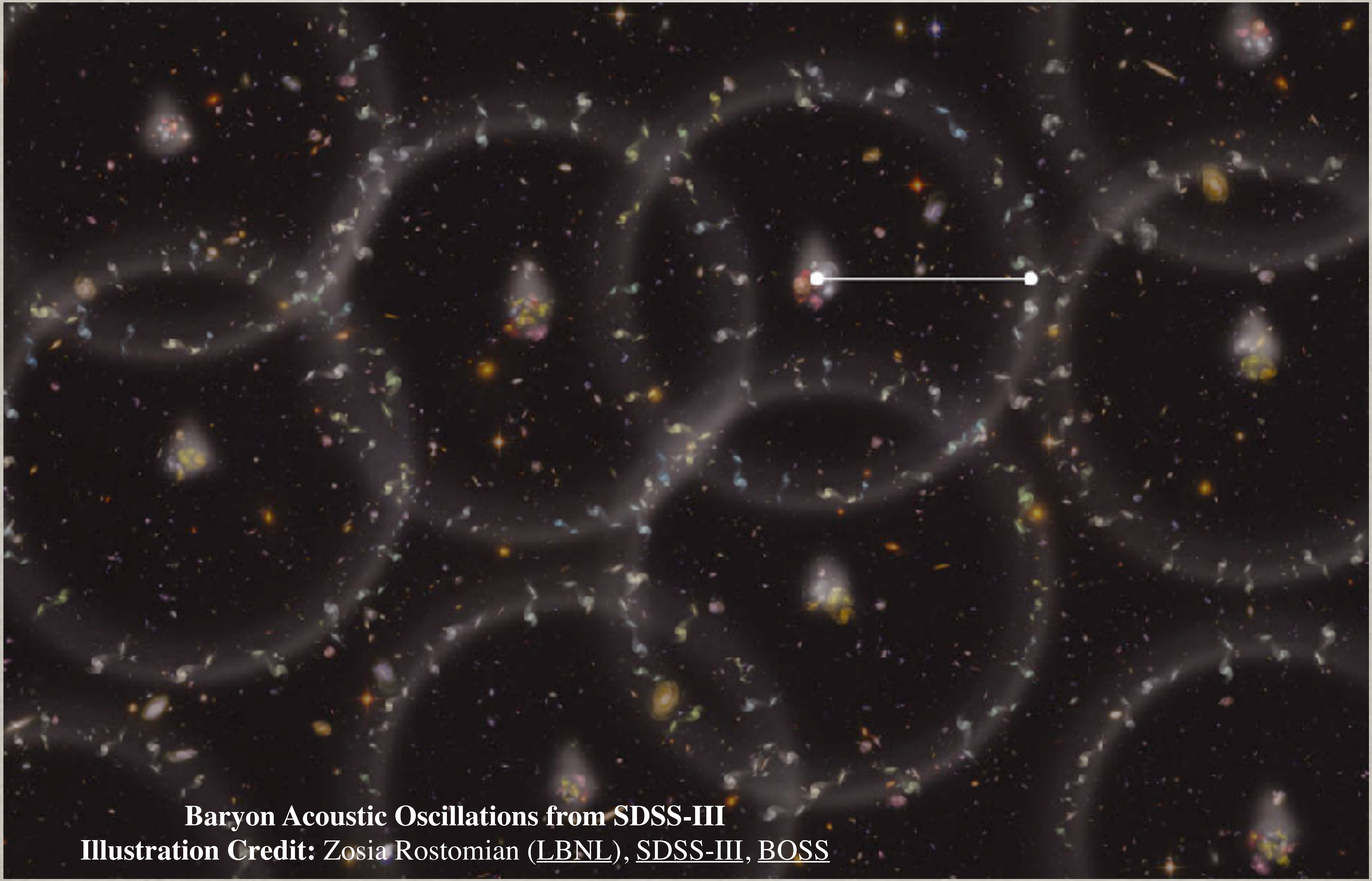
# THE SOUND HORIZON IN THE BARYON-PHOTON PLASMA AS STANDARD RULER

- The signal has been now detected in the galaxy power spectrum (two-point correlation !) with high precision.

- All measurement are consistent !



# BAO: an artistic view



# Lecture 3: Outline

- Basics of thermodynamics
- WIMP mechanism
- How to detect a WIMP

# Basics of thermodynamics

# Basic formulas

Relativistic particles with p >> m

$$\rho = \xi_\rho \; g \frac{\pi^2}{30} \; T^4 \qquad \xi_\rho = 1 \; (B) \text{ or } 7/8 \; (F)$$

$$\zeta(3) = 1.202$$

$$n = \xi \; g \frac{\zeta(3)}{\pi^2} \; T^3 \qquad \xi = 1 \; (B) \text{ or } 3/4 \; (F)$$

Non-relativistic particles with m >> p

$$\rho = m \; n$$

$$n = g \left( \frac{mT}{2\pi} \right)^{3/2} \; e^{-\frac{m-\mu}{T}}$$

Maxwell Boltzmann
same for B and F !

# Basic formulas II

Entropy density for relativistic species:

$$s = \frac{\rho + p}{T} = \frac{4\rho}{3T} = \frac{2\pi^2}{45} g_S \, T^3$$

$$g_S = \sum_B g_B \left(\frac{T_B}{T}\right)^3 + \sum_F g_F \frac{7}{8} \left(\frac{T_F}{T}\right)^3$$

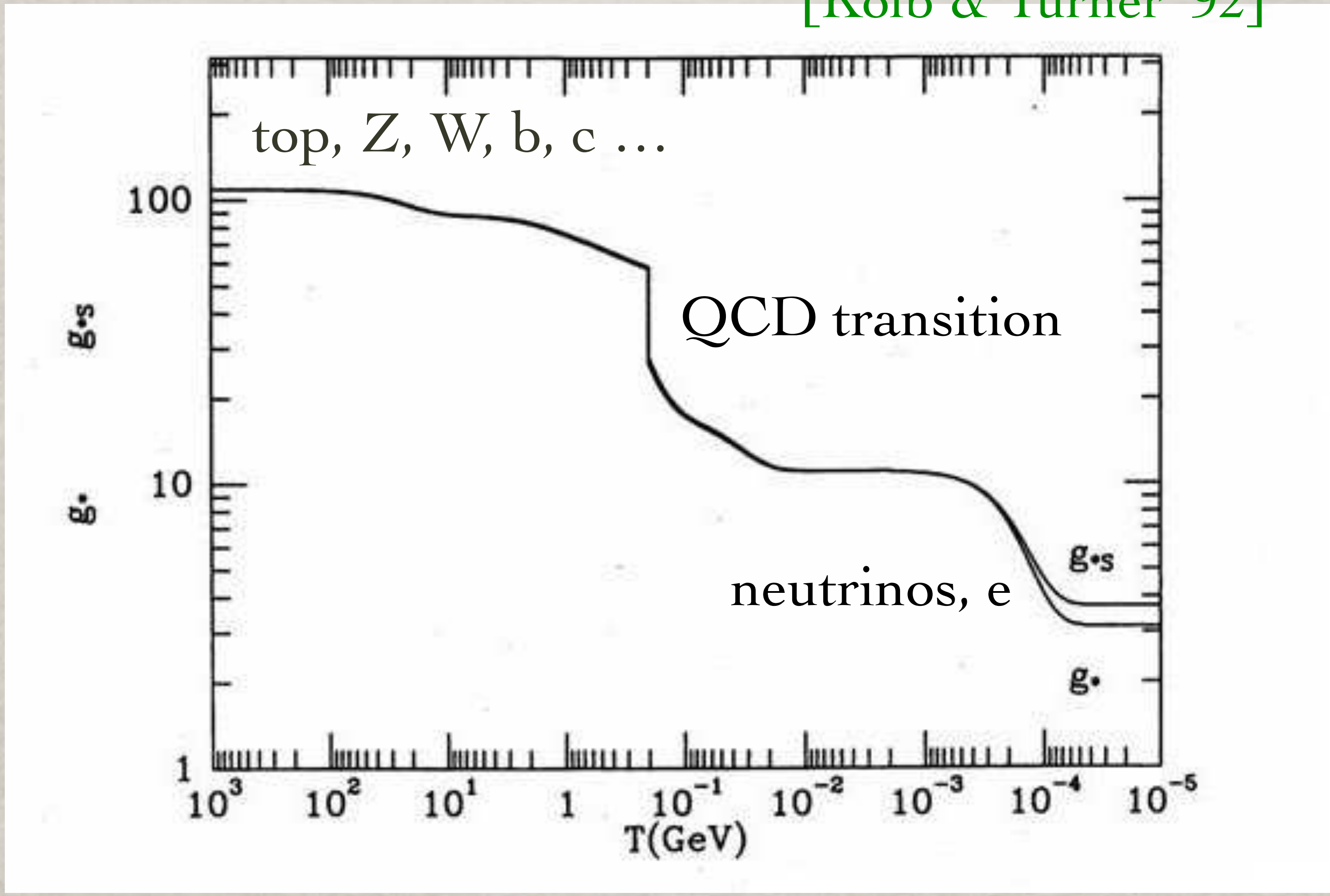
Non-relativistic particles:

$$s = \frac{mn}{T} = g \, m \left(\frac{m}{2\pi T}\right)^{3/2} e^{-\frac{m-\mu}{T}} \sim 0$$

The entropy is stored practically into radiation !

# Degrees of freedom

[Kolb & Turner '92]



# Dark Matter production mechanism

# Neutrino as (prototype) DM

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

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

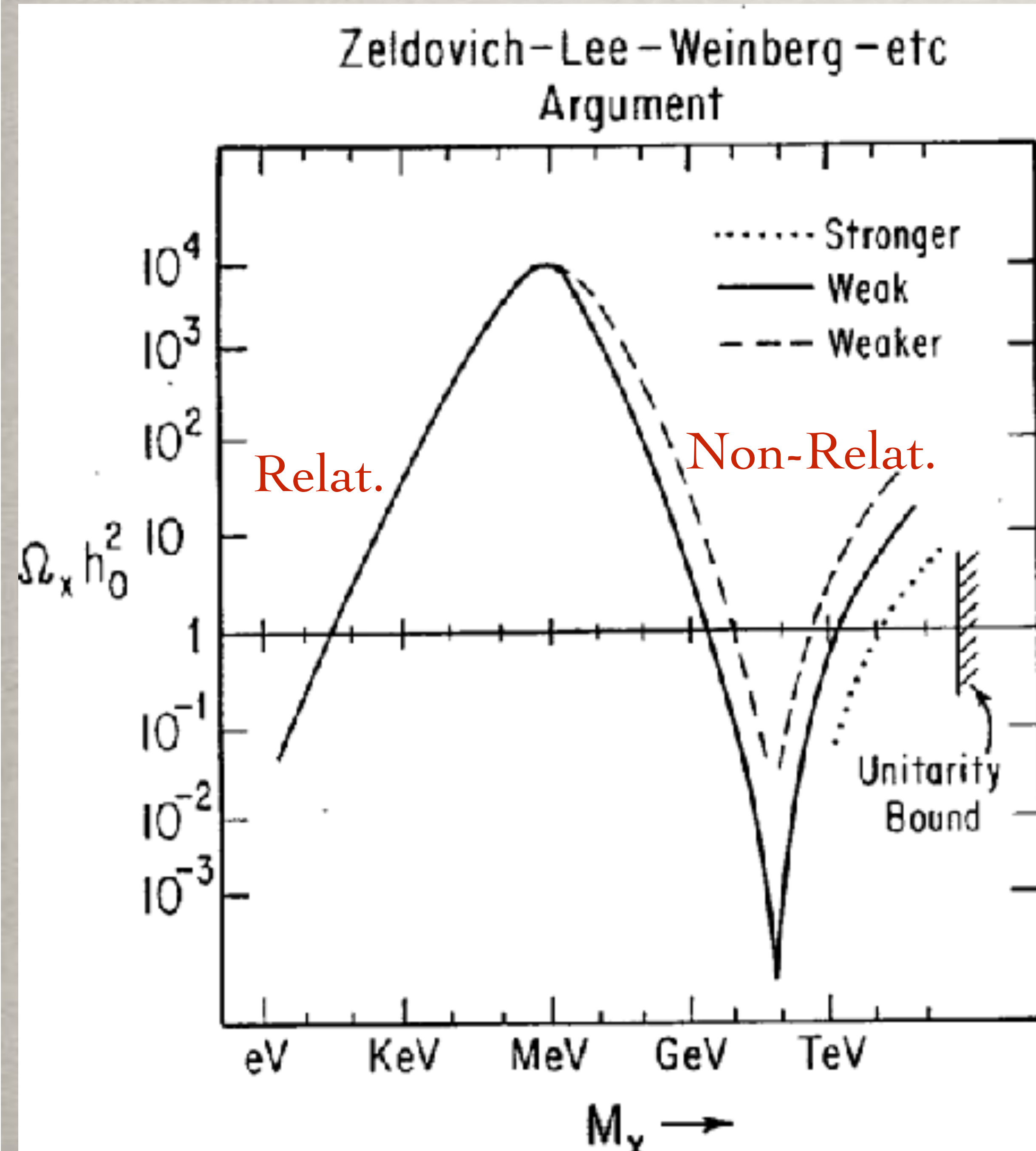
but $m_\nu \leq 2\ \mathrm{eV}$ (Tritium $\beta$ decay) so $\Omega_\nu h^2 \leq 0.07$

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

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

NEED to go beyond the Standard Model !

# 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

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

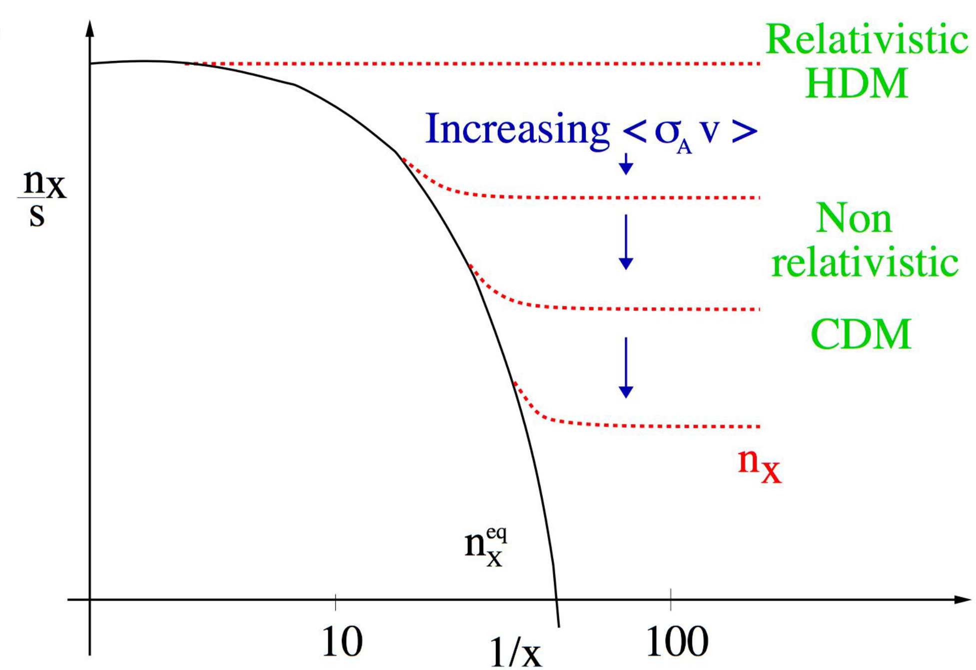
Hubble expansion     Collision integral

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

# THE WIMP MECHANISM II

## Approximate solution of the Boltzmann equation

Rewrite the equation in terms of $Y = \frac{n}{s}$ and $\frac{d}{dt} = Hx\frac{d}{dx}$ for $x = \frac{m_X}{T}$:

$$\frac{dY_X}{dx} = -\frac{s\langle\sigma(X+X \to \text{anything})v\rangle}{xH}\left(Y_X^2 - Y_{eq}^2\right)$$

Until $x_f$ we have $Y_X = Y_{eq}$, after that we can neglect $Y_{eq}$ that decreases exponentially and then

$$\frac{dY_X}{Y_X^2} = -\frac{s(x)\langle\sigma(X+X \to \text{anything})v\rangle(x)}{xH(x)}dx$$

which has the solution

$$Y_X(x) = \frac{Y_X(x_f)}{1 + Y_X(x_f)\frac{s(m_X)}{H(m_X)}\int_{x_f}^{x}\frac{dx}{x^2}\langle\sigma(X+X \to \text{anything})v\rangle(x)}$$

so when $\sigma$ is sufficiently large after freeze-out

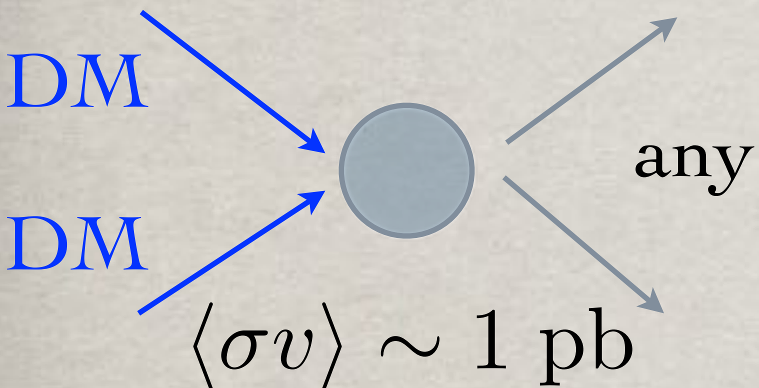
$$Y_X(x) \simeq \frac{1}{\frac{s(m_X)}{H(m_X)}\int_{x_f}^{x}\frac{dx}{x^2}\langle\sigma(X+X \to \text{anything})v\rangle(x)}$$

very weakly dependent on $x_f$; otherwise $Y_X(x) = Y_X(x_f)$.

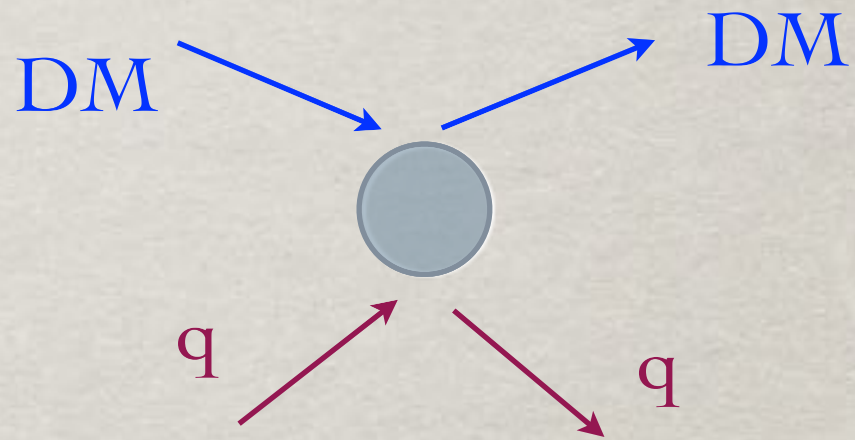
# How to detect a WIMP

# THE WIMP CONNECTION

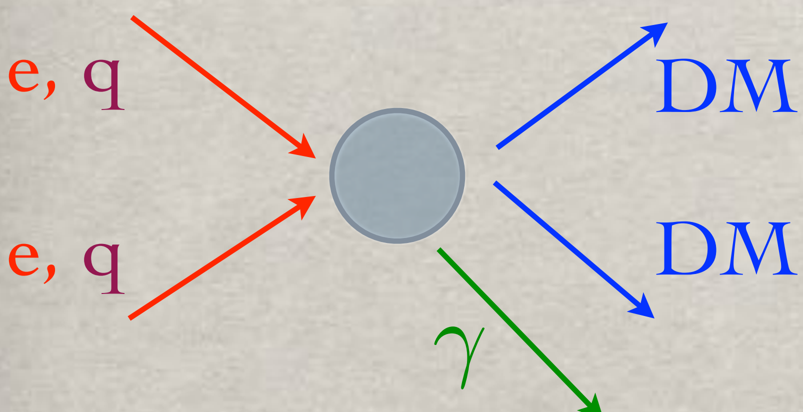
Early Universe: $\Omega_{CDM} h^2$



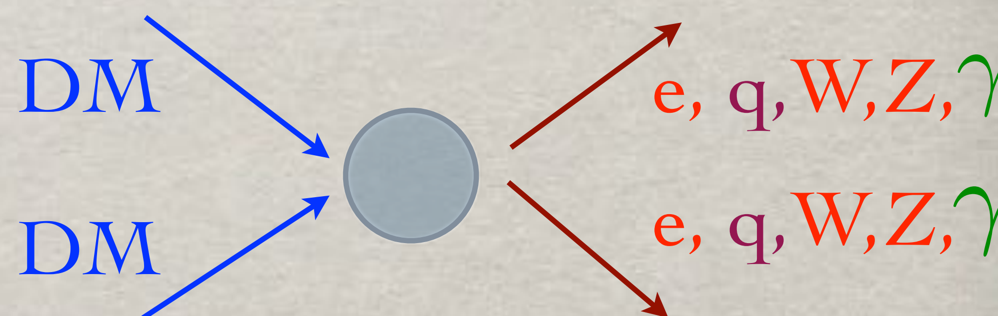

Direct Detection:




Colliders: LHC/ILC




Indirect Detection:




3 different ways to check this hypothesis !!!

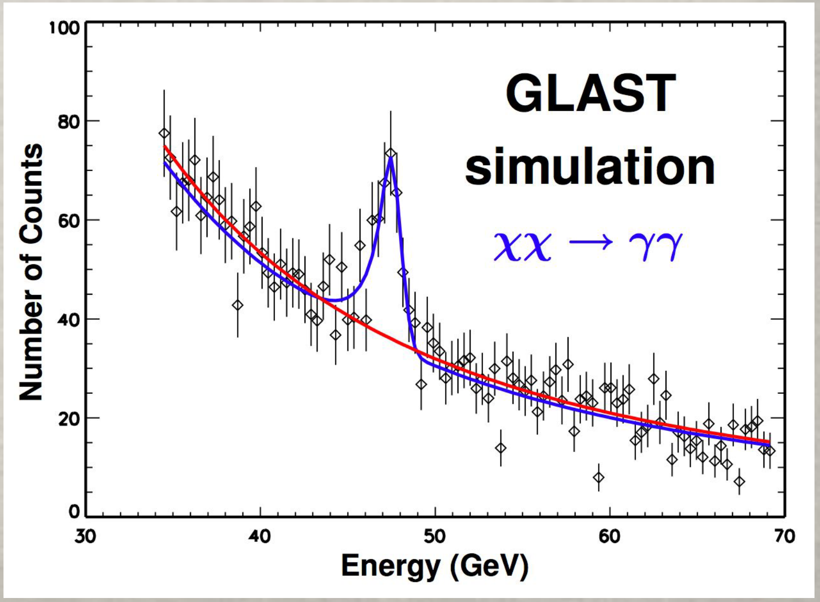
# THE HOPE: DETECT DM !

- The flux in a species i is given by

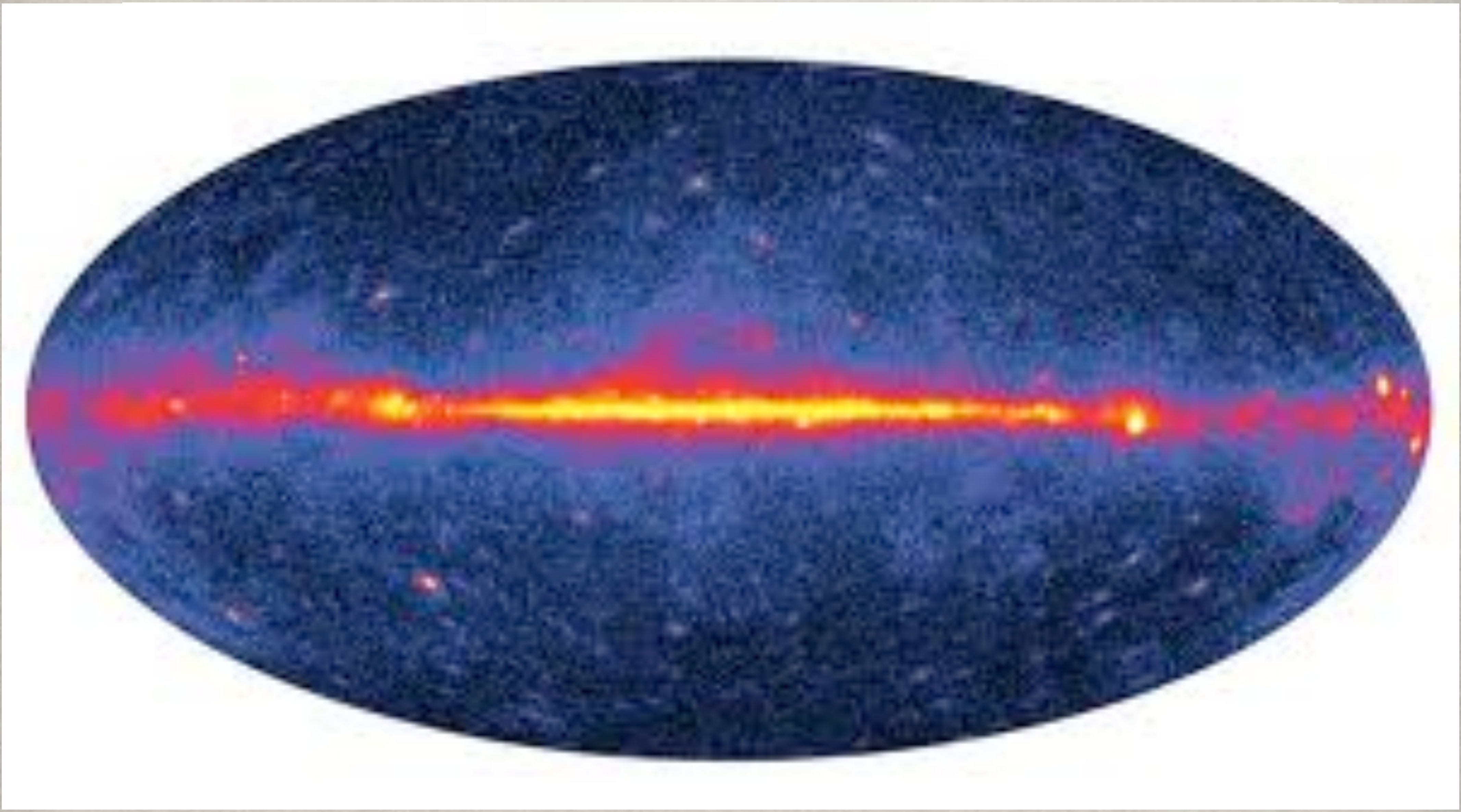
$$\Phi(\theta, E) = \sigma v \frac{dN_i}{dE} \frac{1}{4\pi m_{DM}^2} \int_{l.o.s.} ds\, \rho^2(r(s,\theta))$$

Particle Physics　　　Halo property J( $\theta$ )

- Strongly dependent on the halo model/density via J and the DM clumping: BOOST factor !
- Spectrum in gamma-rays determined by particle physics ! Smoking gun: gamma line...
- For other species also the propagation plays a role.



# THE HOPE: DETECT DM !



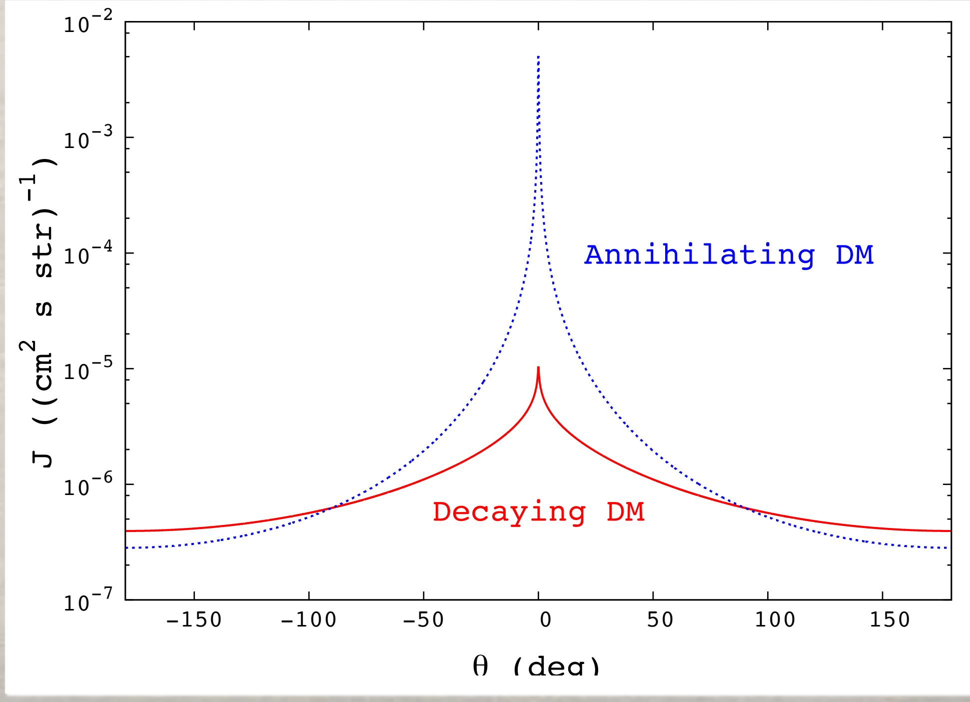
# DECAYING DM

- The flux from DM decay in a species i is given by

$$\Phi(\theta, E) = \frac{1}{\tau_{DM}} \frac{dN_i}{dE} \frac{1}{4\pi m_{DM}} \int_{l.o.s.} ds\ \rho(r(s,\theta))$$

Particle Physics  Halo property $J(\theta)$

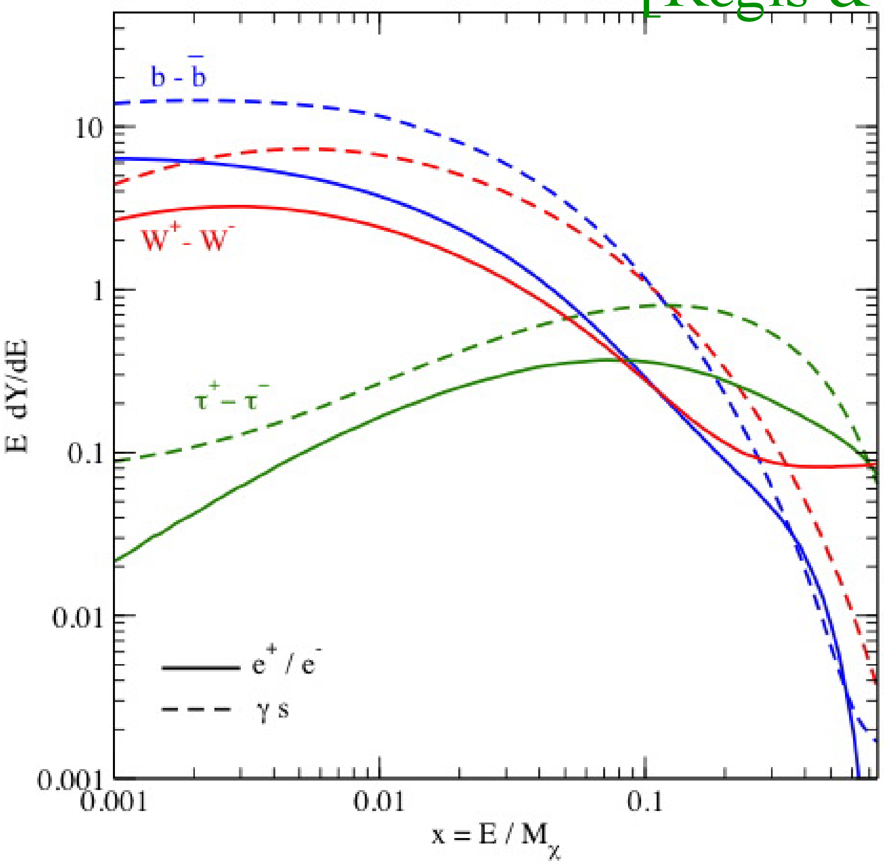
- Very weak dependence on the Halo profile; what matters is the DM lifetime...
- Galactic & extragalactic signals are comparable...
- Spectrum in gamma-rays given by the decay channel! Smoking gun: gamma line...

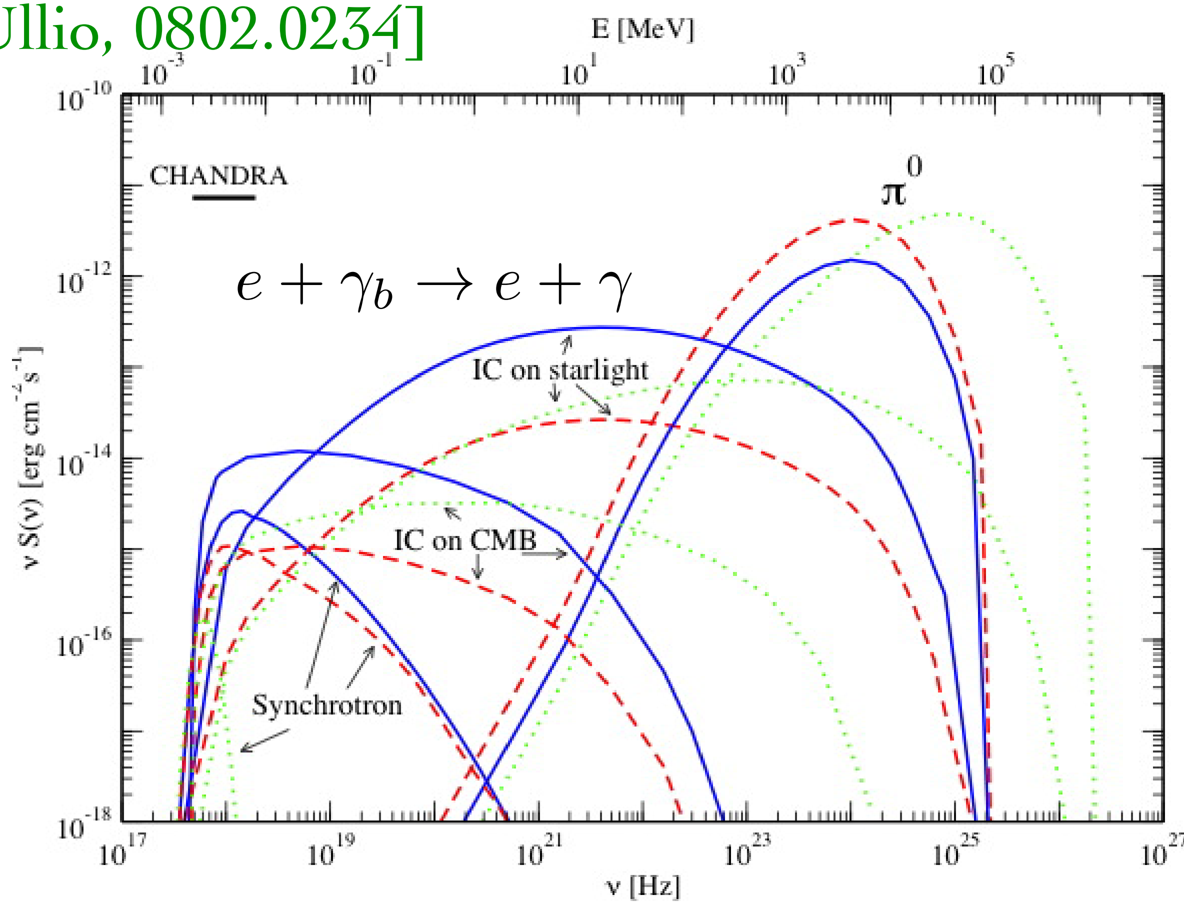


# EM Spectrum from DM

Dark Matter annihilation (or decay) can give photons not only directly from the annihilation, but also by many secondary processes, especially if stable charged particles are produced: Synchrotron emission, Inverse Compton scattering

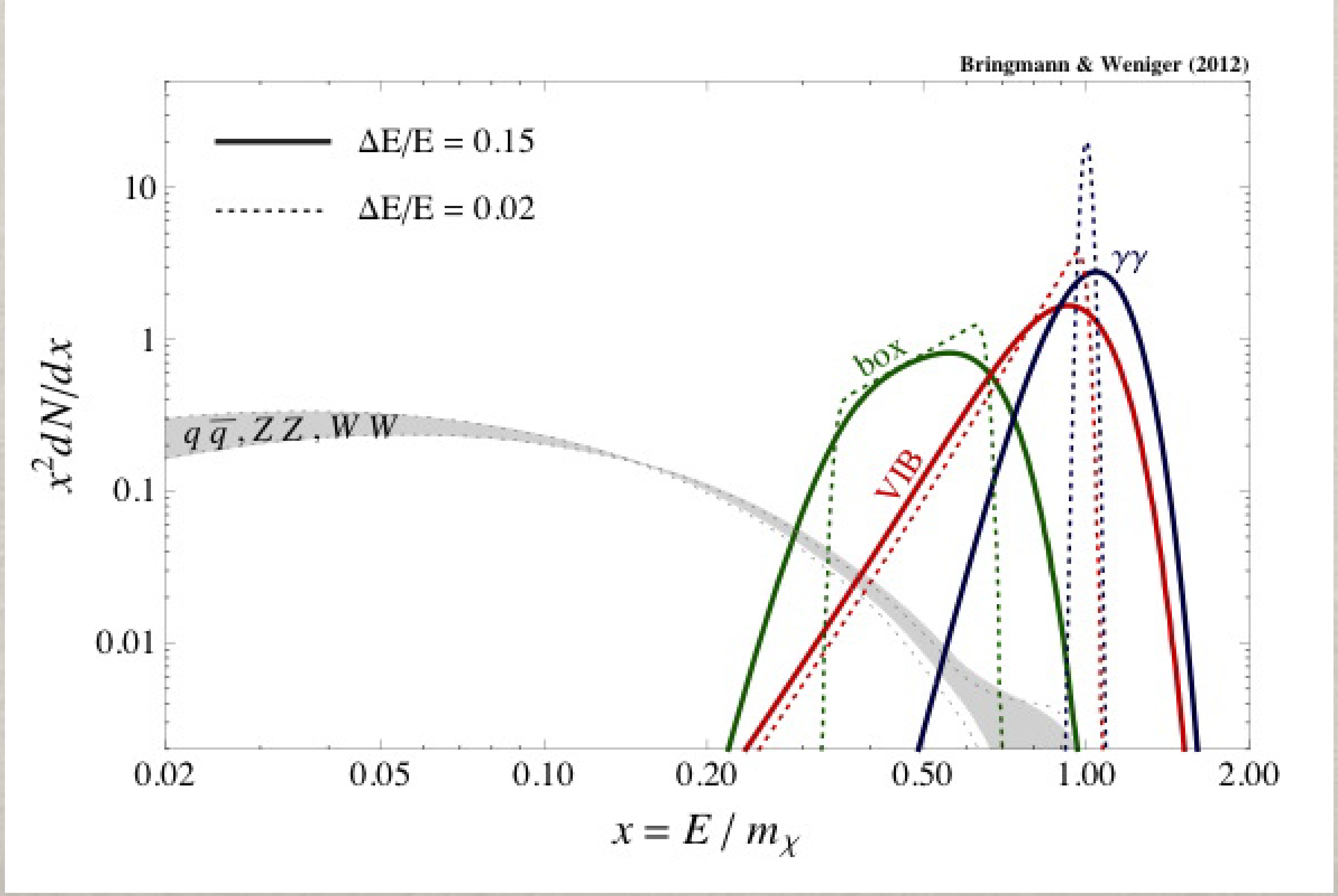
[Regis & Ullio, 0802.0234]



# DM Spectral features

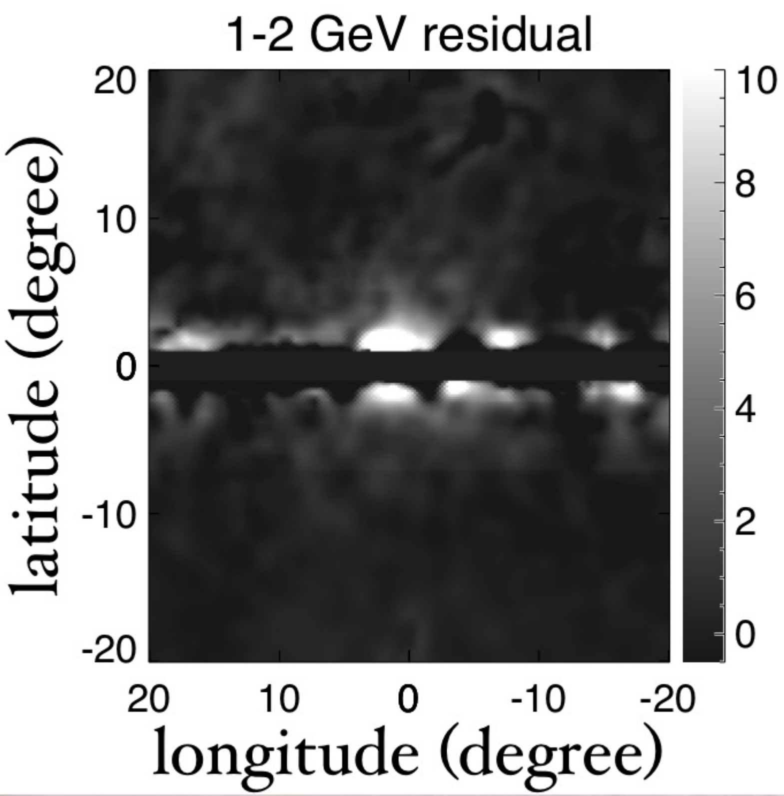
Depending on the model, different features could appear and stick out from the continuum spectrum, helping to see the signal and disentangle the model ! Smoking guns !

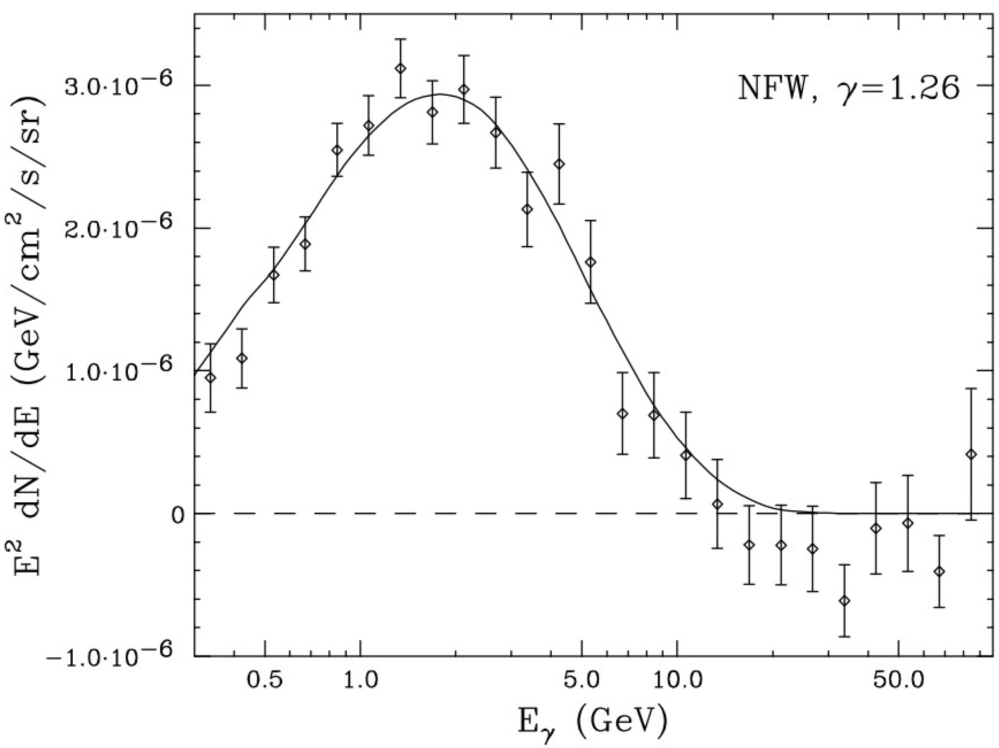


# Galactic centre excess

An excess has been found since some years in the FERMI-lat data by Hooper & al. in the direction of the Galactic centre:

[Daylan & al 1402.6703]



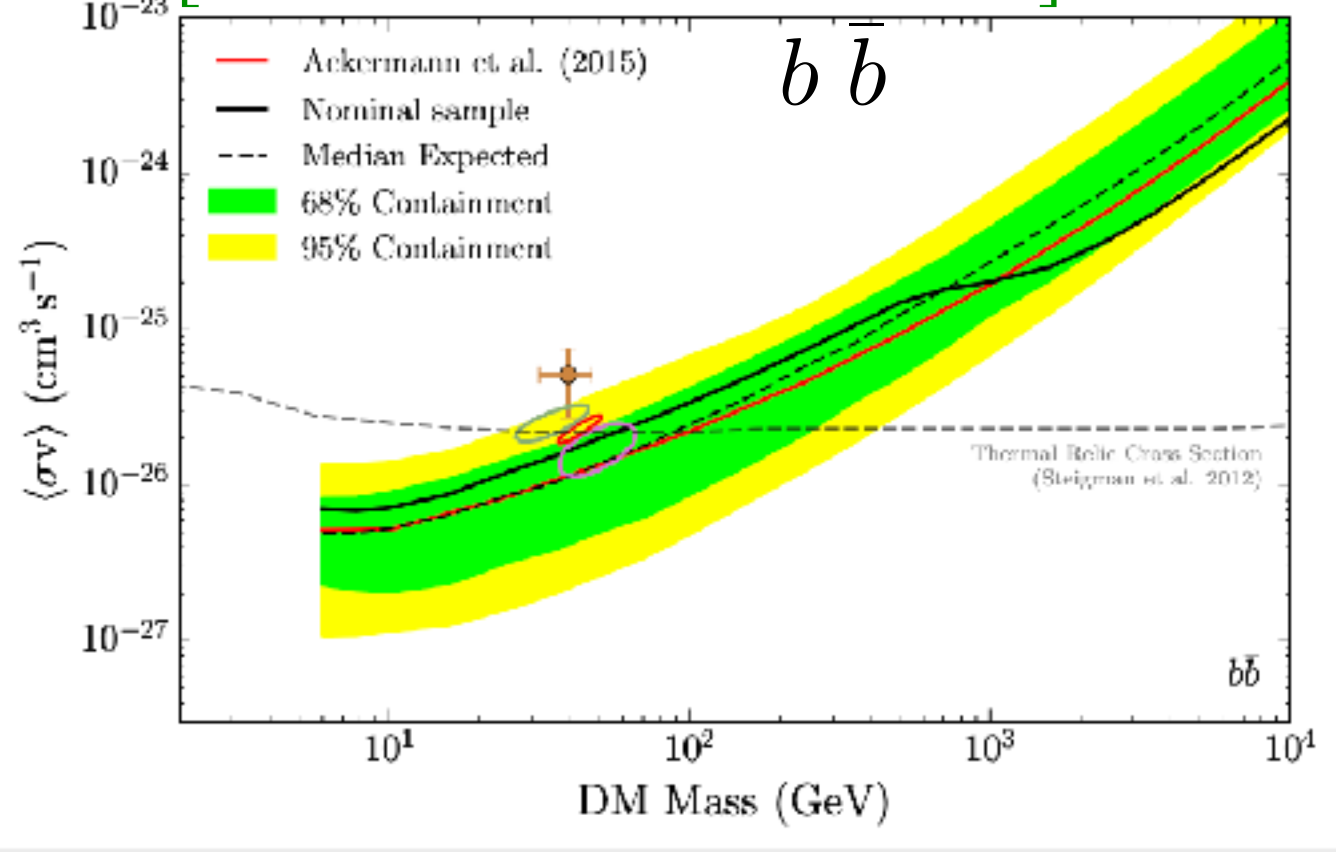

Compatible with a thermal relic annihilating into $b\,\bar{b}, \tau^+\,\tau^-$

# Bounds on WIMP DM

Strong limits are obtained from dwarf satellite galaxies, considering measured J-factors:

[Fermi-LAT & DES 1611.03184]

$b\,\bar{b}$



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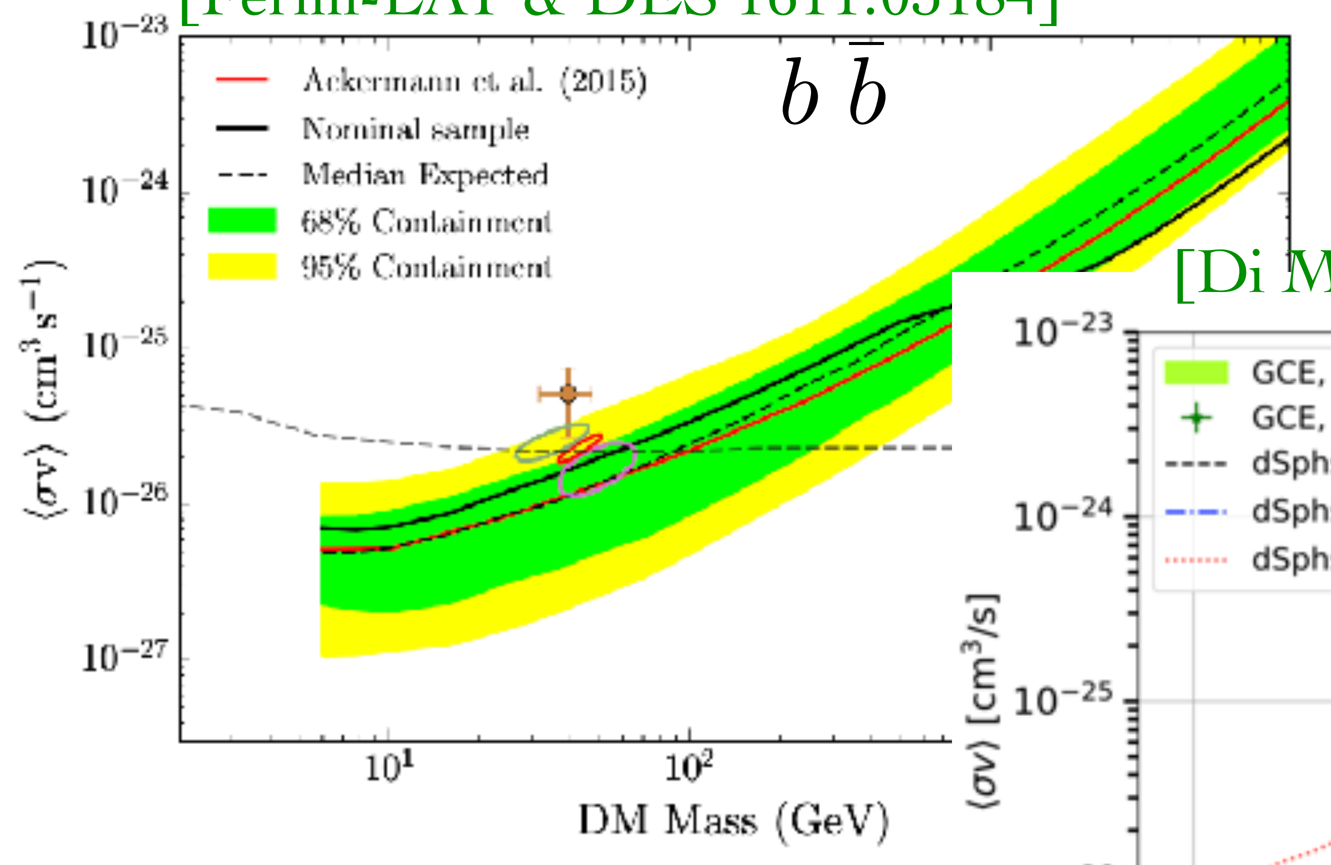
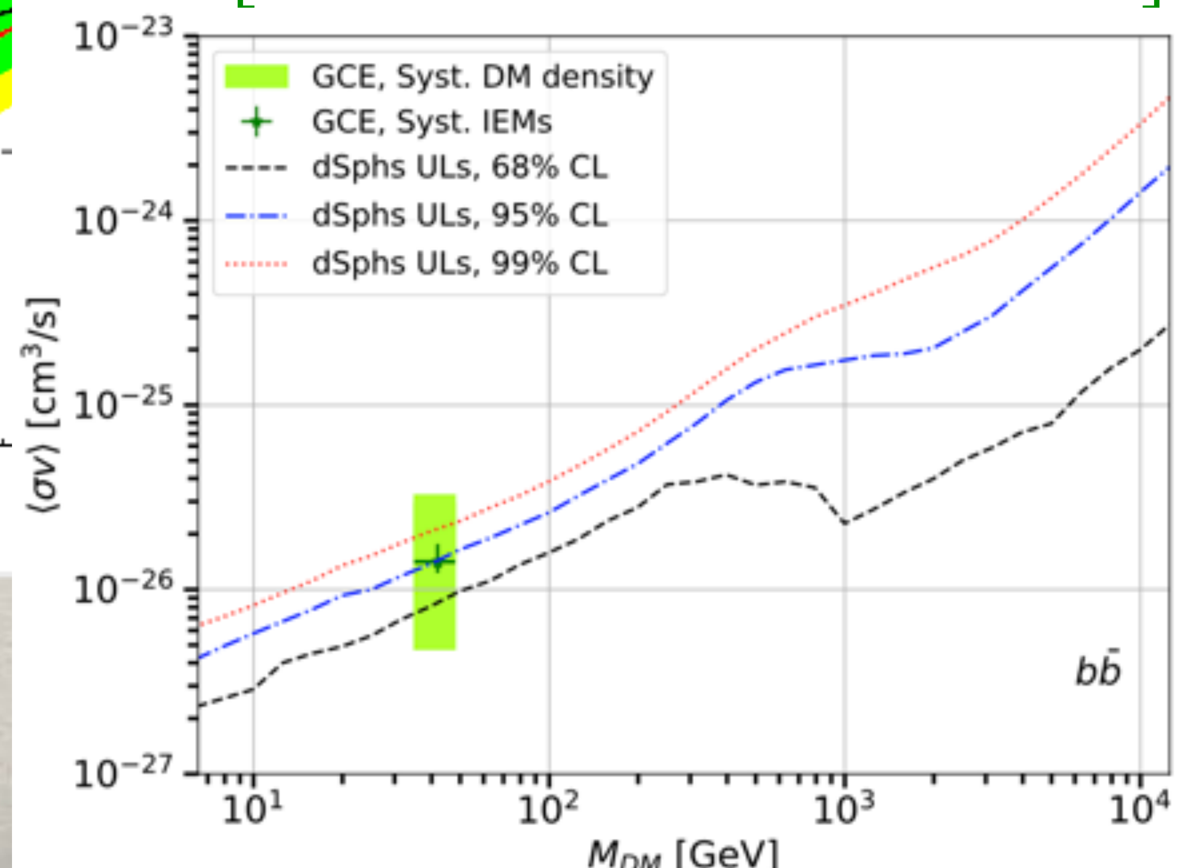
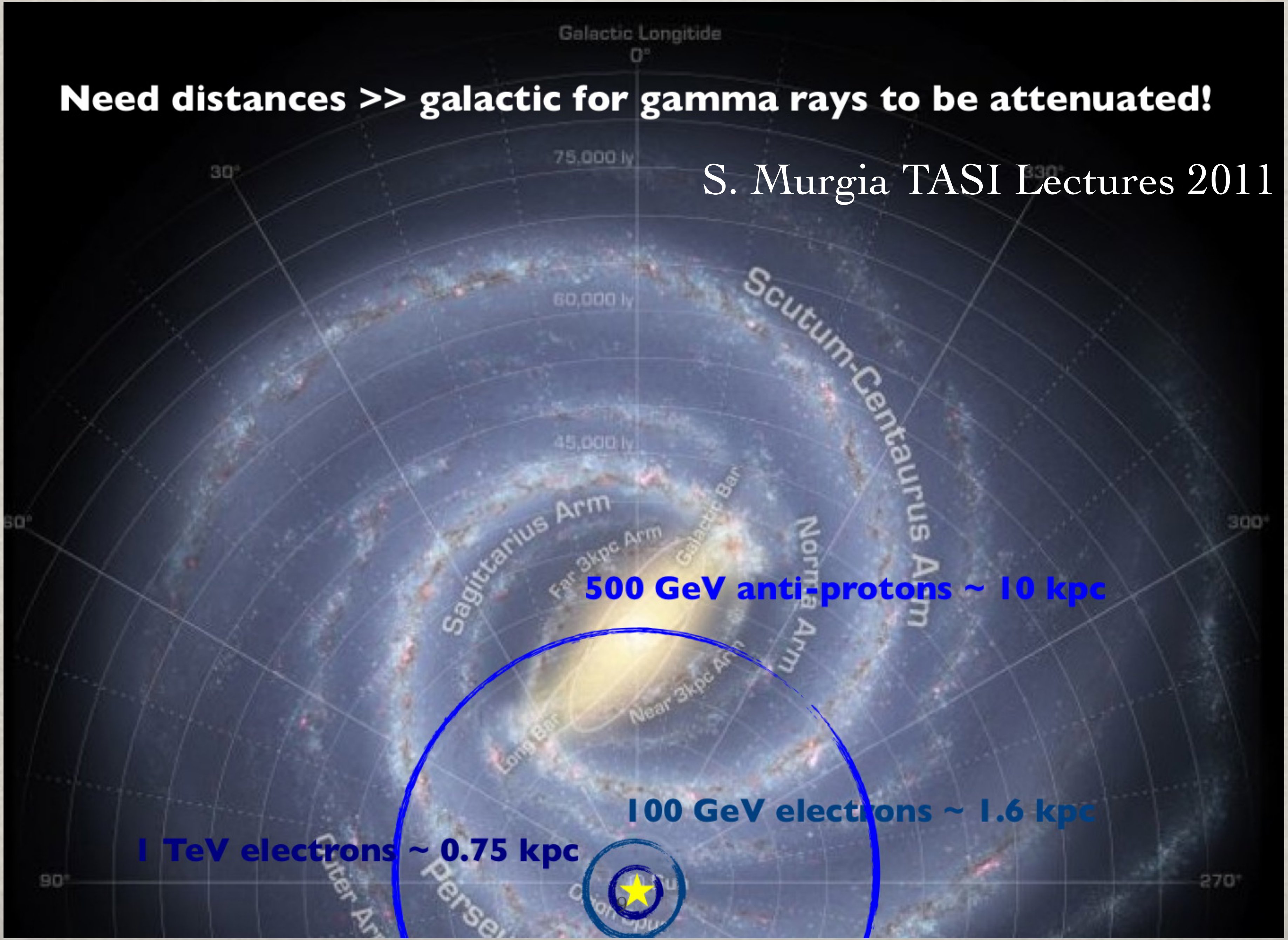



[Di Mauro & Winkler 2101.11027]

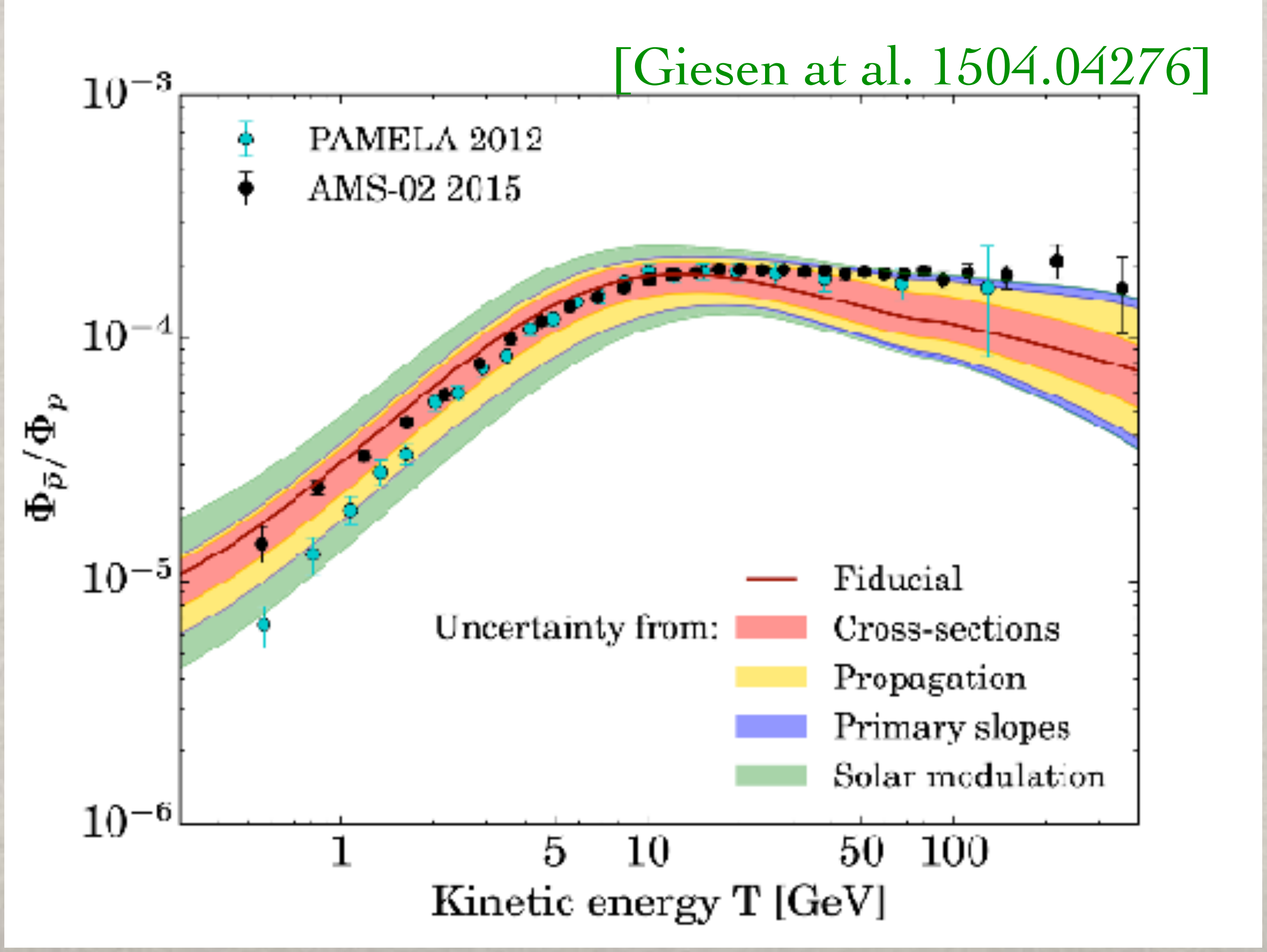


# GALACTIC PARTICLE'S RANGES



# Antimatter in CR: antiprotons

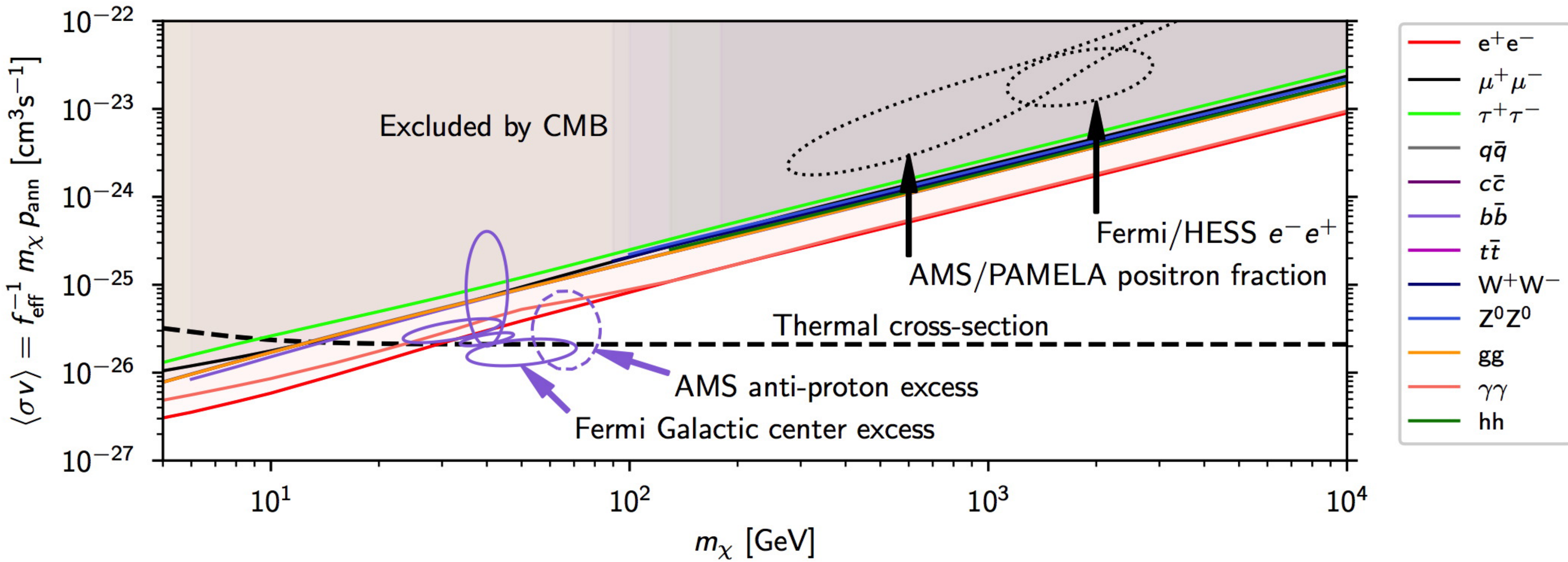
Latest data from AMS-02 for antiprotons: is there an excess ???



# PLANCK: DM ANNIHILATION

WIMP annihilation also modifies the epoch of recombination due to the release of energy in the primordial plasma and leaves imprints into the CMB ! Planck can now exclude cross-sections as those needed by PAMELA and AMS-02:

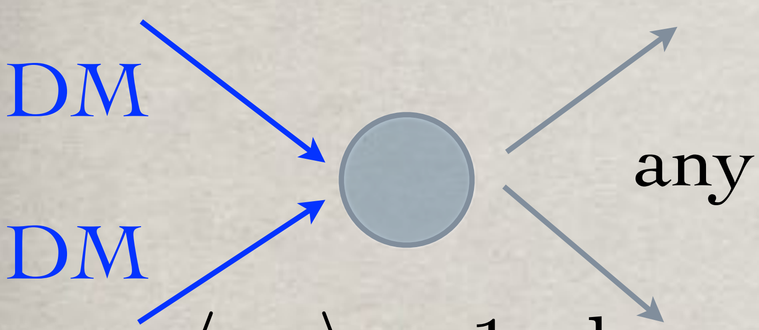
[Planck 1807.06209]




but not the models explaining the Galactic centre excess…

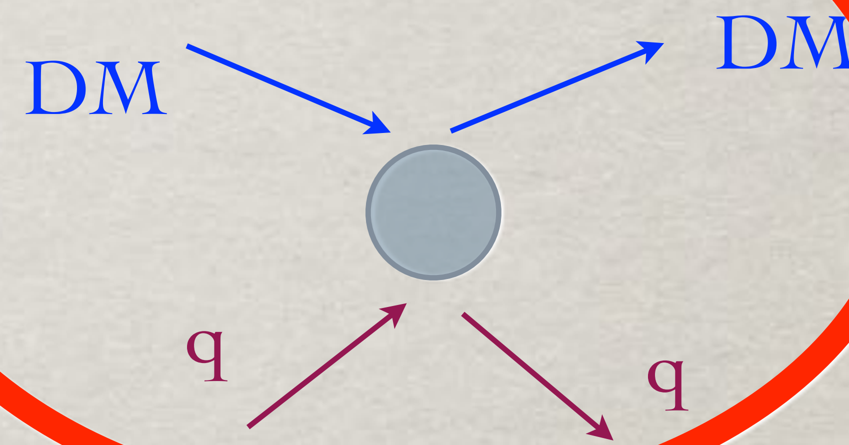
# THE WIMP CONNECTION

Early Universe: $\Omega_{CDM}h^2$

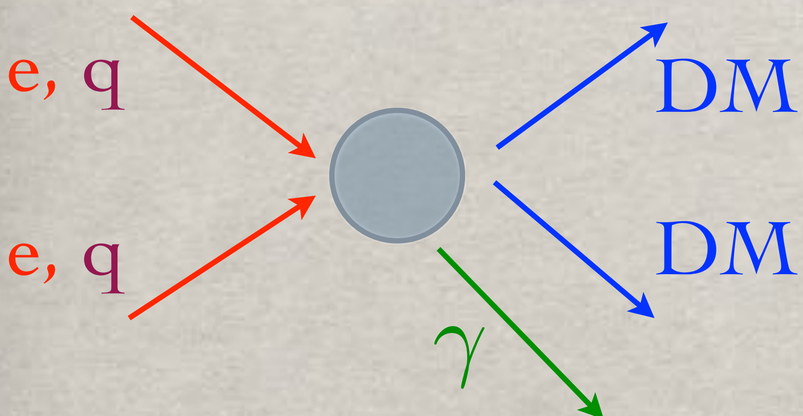



$\langle \sigma v \rangle \sim 1$ pb

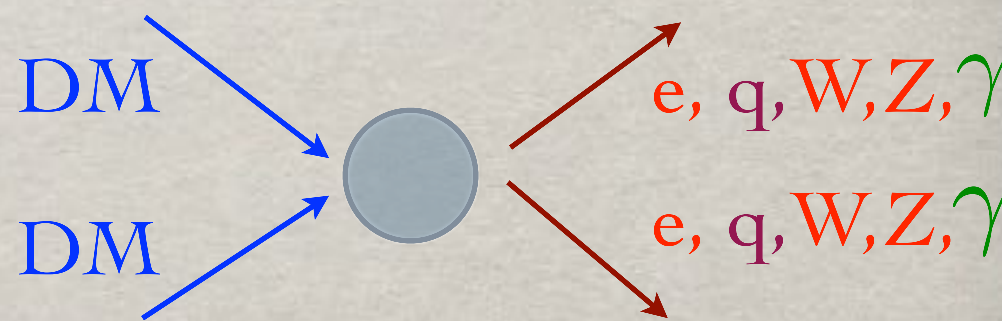
Direct Detection:




Colliders: LHC/ILC

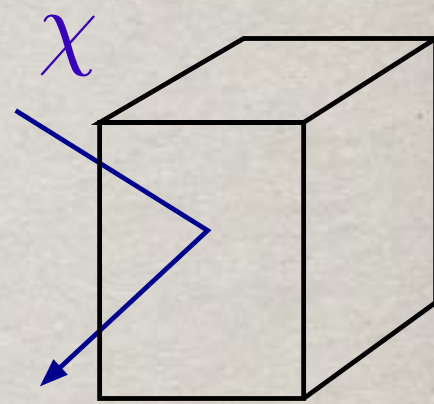



Indirect Detection:




3 different ways to check this hypothesis !!!

# Direct WIMP detection




- Elastic scattering of a WIMP on nuclei. The recoil energy is in the keV range:

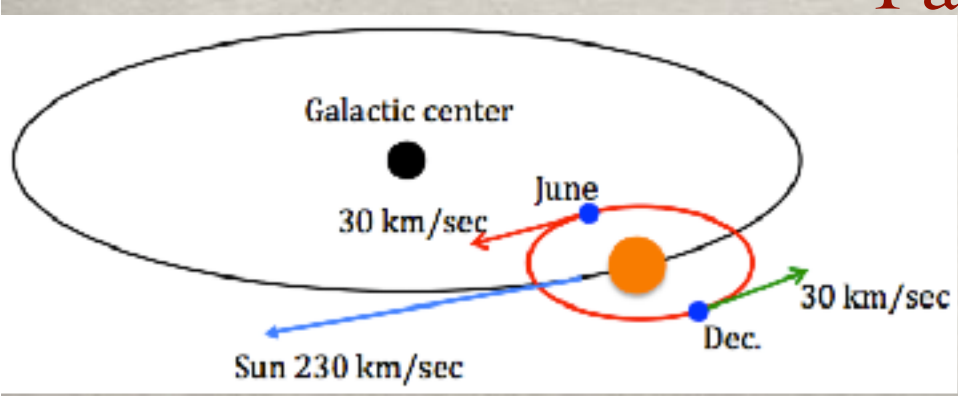
with $$\Delta E = \frac{4 m_{DM} m_N}{(m_{DM}+m_N)^2}\, E_{kin}^{DM}$$

$$E_{kin}^{DM} \sim \frac{1}{2} m_{DM} v^2 \sim 50 \text{ keV} \frac{m_{DM}}{100\text{GeV}}$$

Need very low threshold !

- The rate is $$\frac{dR}{dE_R} \propto \sigma_n F^2(E_R)\ \frac{\rho_{DM}}{m_{DM}} \int_{v_{min}}^{\infty} \frac{dv}{v} f(v)$$

Particle Physics Halo physics




Rate depends on $v$ in lab frame

→ annual modulation !

# Direct WIMP detection

How large are the cross-sections that we expect from thermal consideration or the exchange of (known) EW particles ?

- Thermal relic cross-section to give $\Omega_{DM} h^2 \sim 0.1$

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} cm^3/s \rightarrow \sigma \sim 10^{-36} cm^2 = 1 \text{ pb}$$

- Exchange of Z boson:

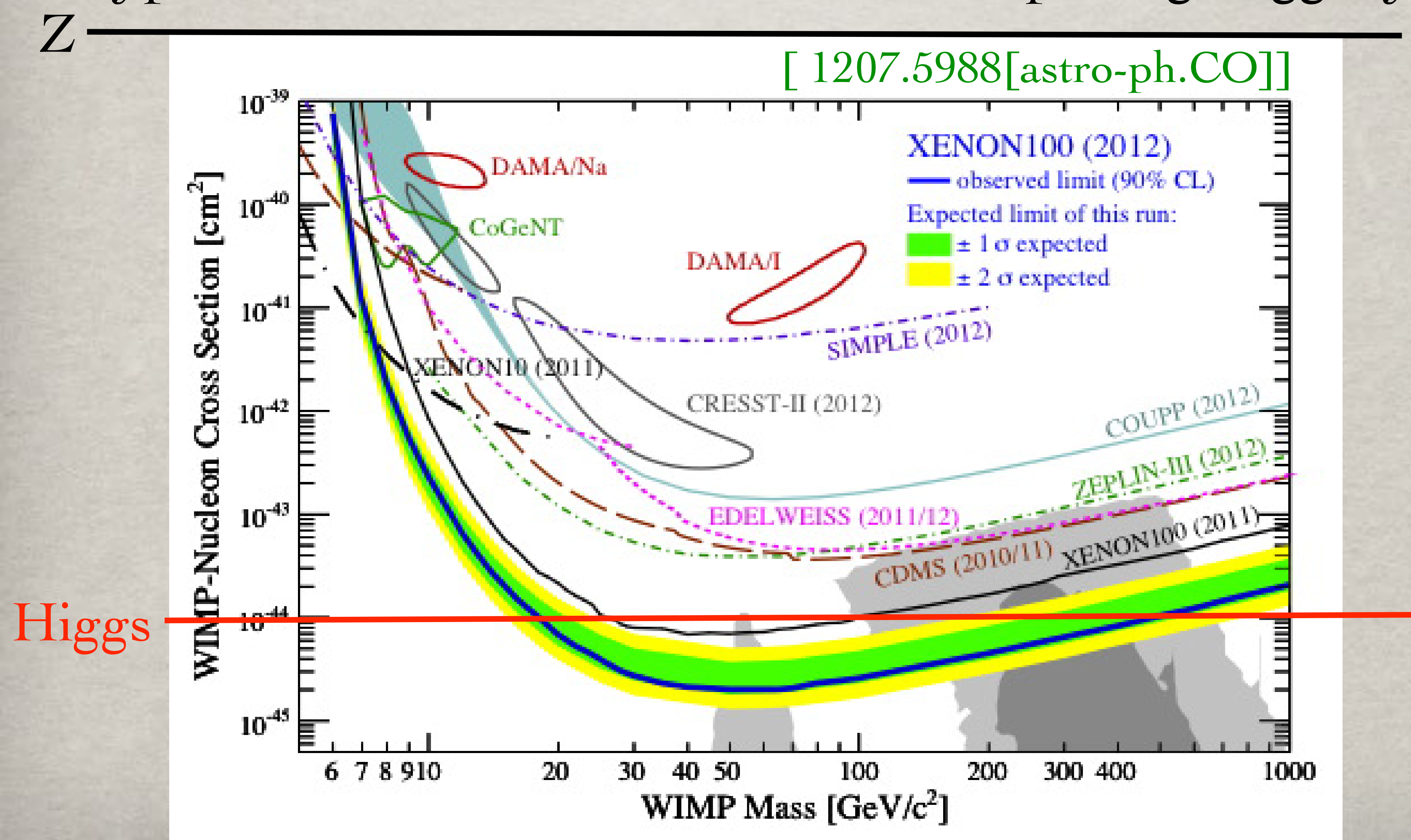
$$\sigma \sim \lambda_{Z\chi}^2 G_F^2 m_p^2 \sim 10^{-38} \lambda_{Z\chi}^2 cm^2 = 10^{-2}\ \lambda_{Z\chi}^2 \text{ pb}$$

- Exchange of Higgs boson:

$$\sigma_p \sim \lambda_{h\chi}^2 m_p^2 / m_h^4 \sim 10^{-44} \lambda_{h\chi}^2 cm^2 = 10^{-8}\ \lambda_{h\chi}^2 \text{ pb}$$

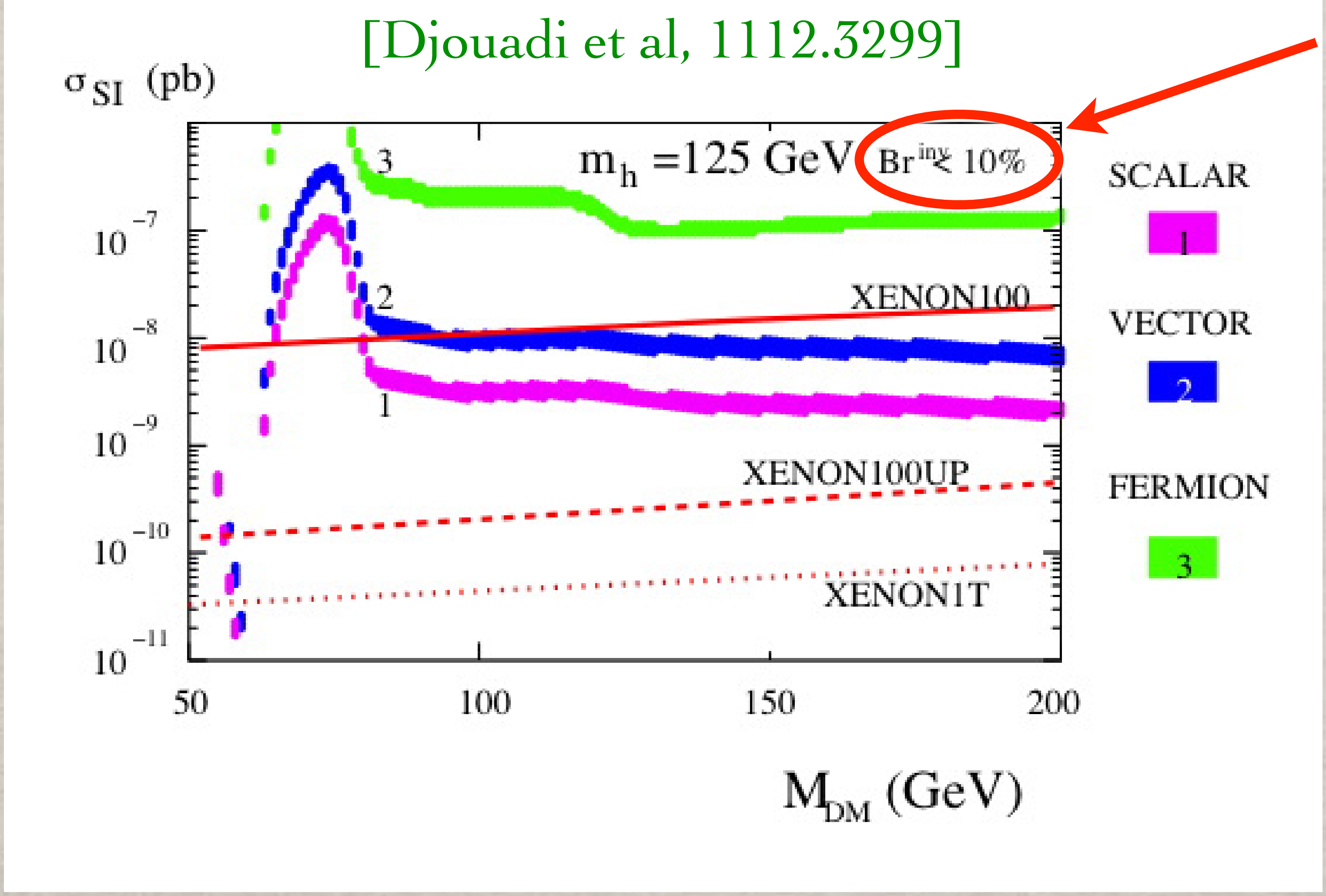
# Direct detection of DM

A large part of parameter space already excluded by searches: Z-type cross-section is out, now we are exploring Higgs-type



# Higgs portal DM

If the DM interacts with Higgs via portal interaction,
it is already under siege by DD & LHC:

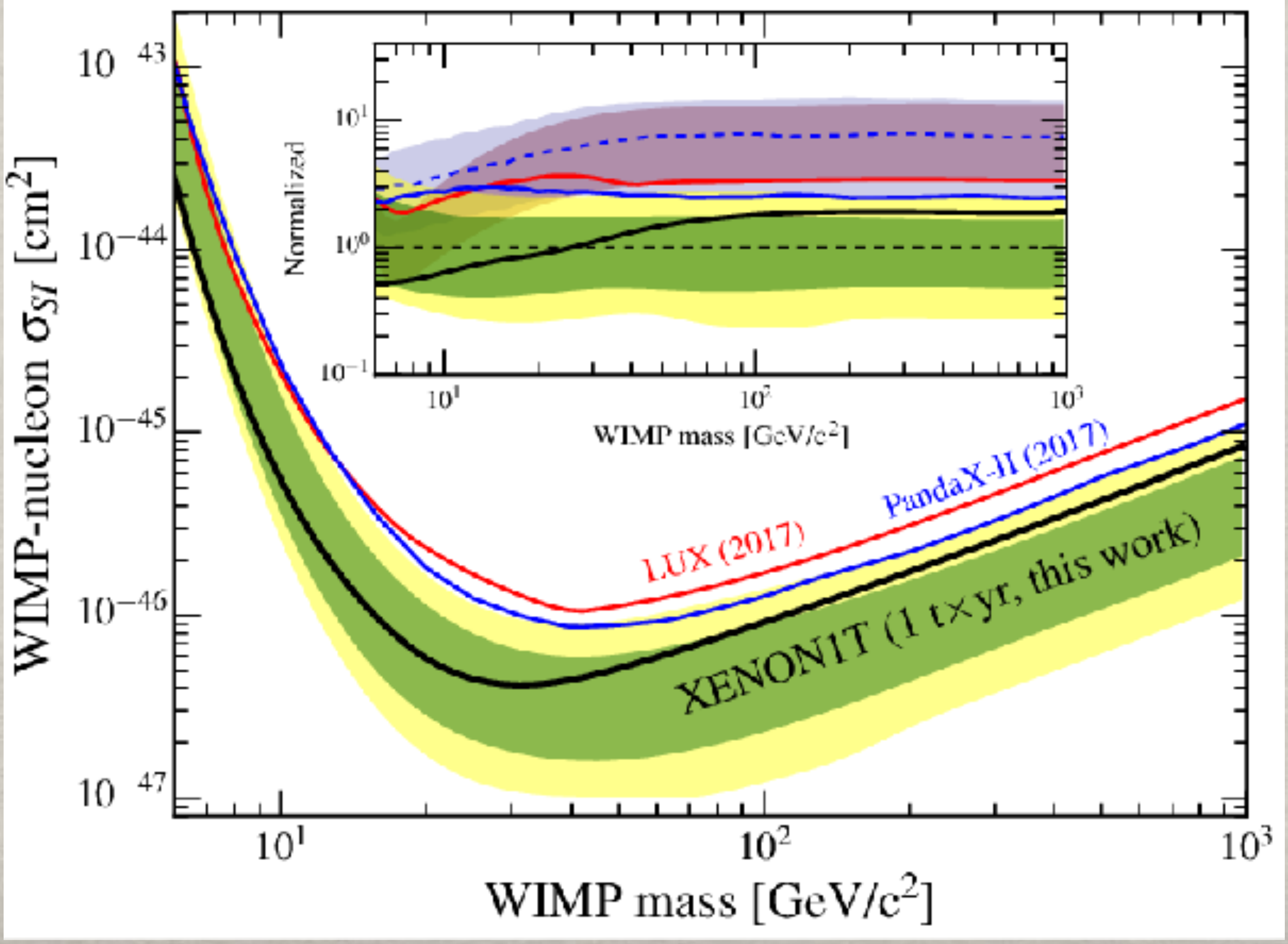



Invisible Higgs decay

# NOW STRONGER BOUNDS

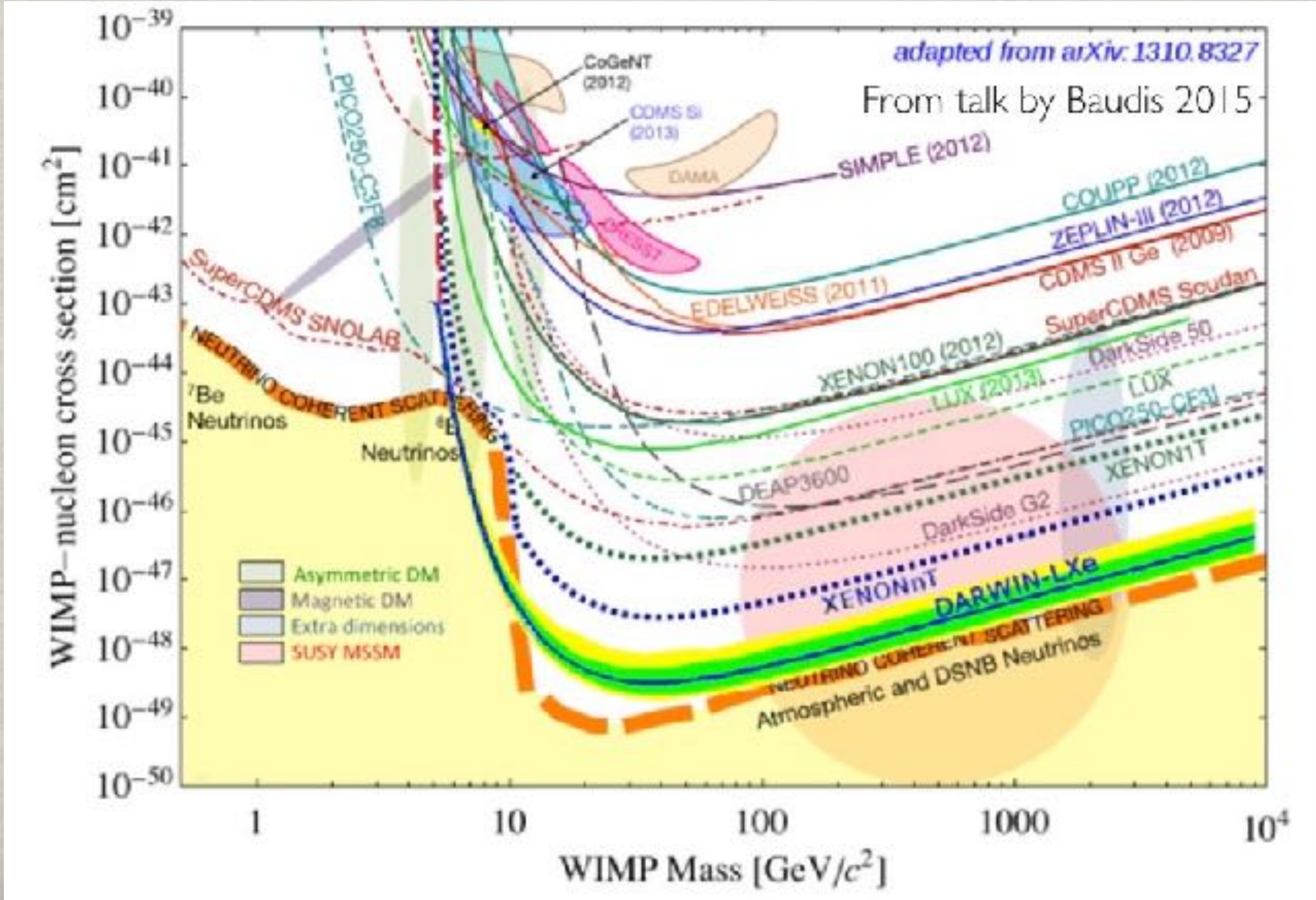
The XENON1T experiment latest results:

[arXiv: 1805.12562]



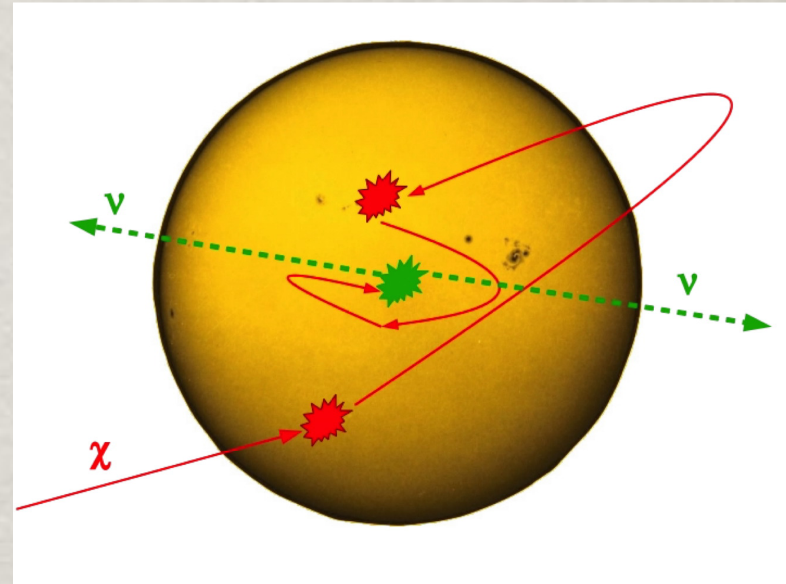
# Future of DM DD

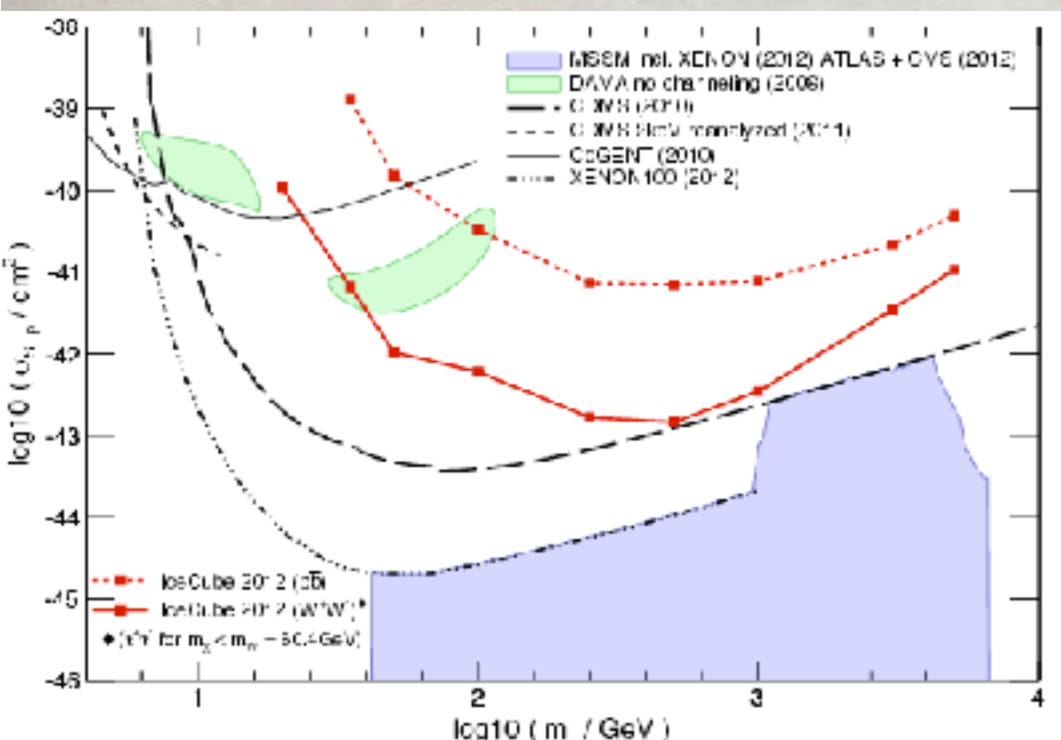
Neutrino background limits how far one can go. But there are already ideas on ways to suppress this background...

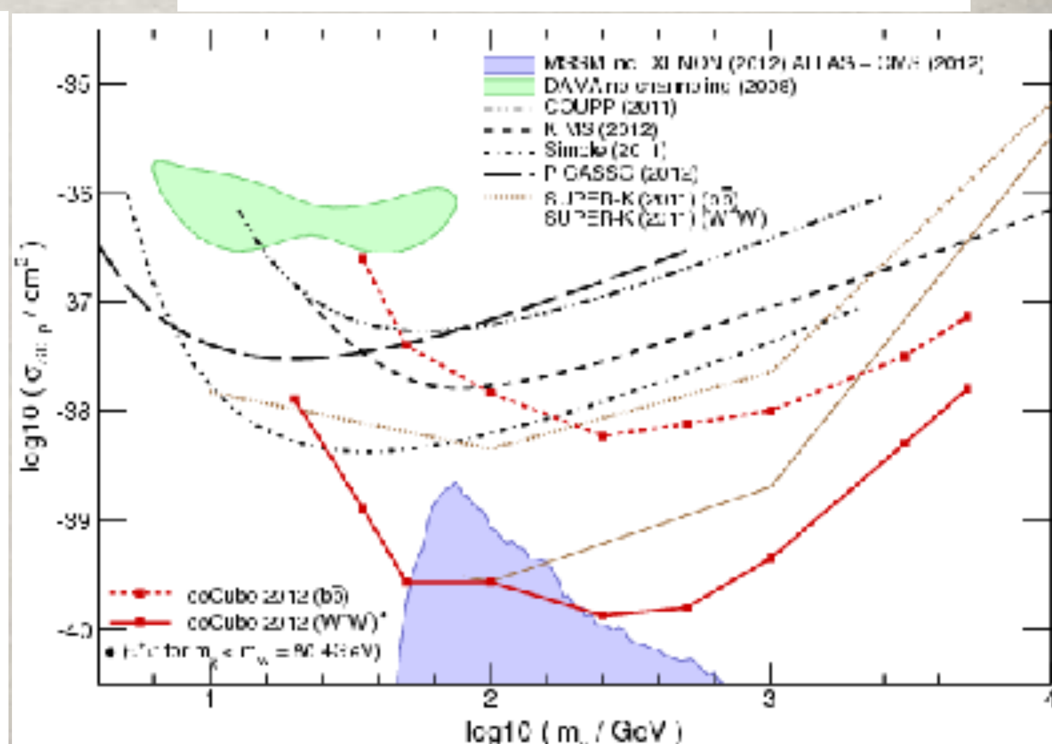


# DM signal in neutrinos

DM can accumulate and annihilate in the sun, if it interacts sufficiently strongly with protons; the only particles that can escape the sun environment are neutrinos: Limits from neutrino detectors

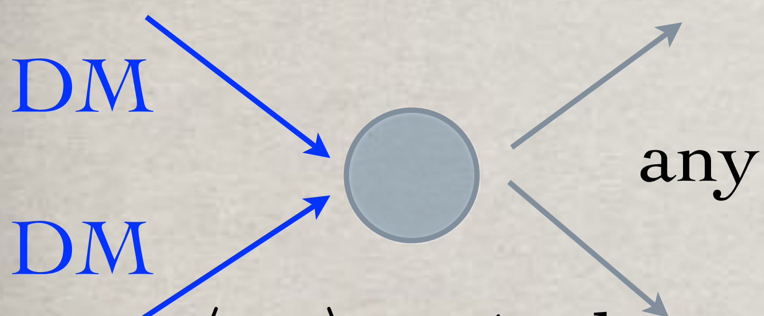


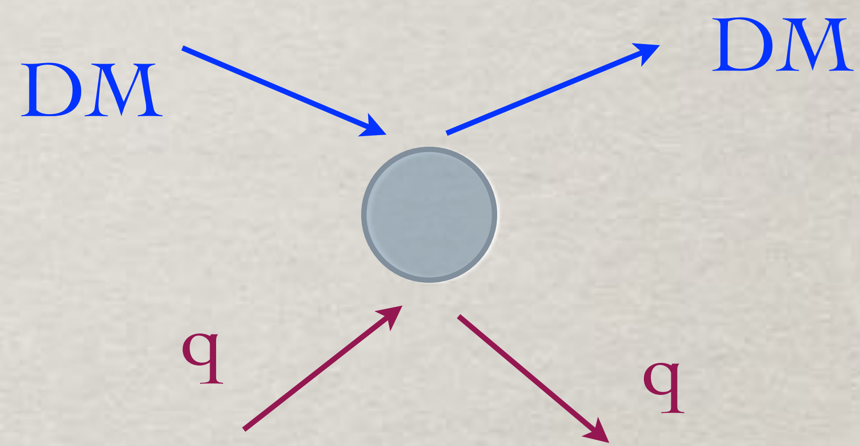
# THE WIMP CONNECTION

Early Universe: $\Omega_{CDM} h^2$

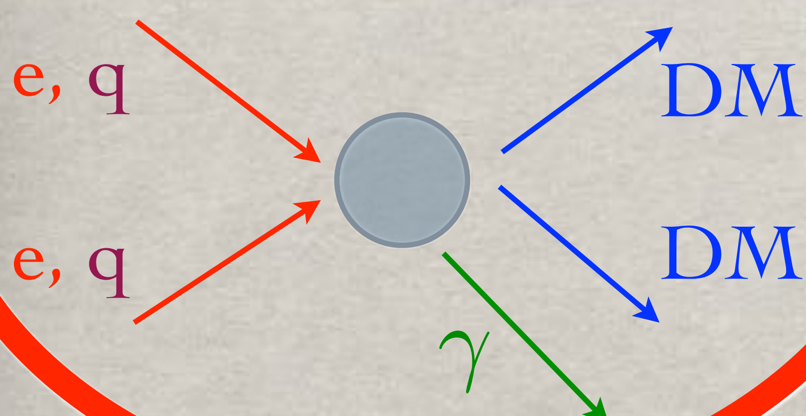



$\langle \sigma v \rangle \sim 1$ pb

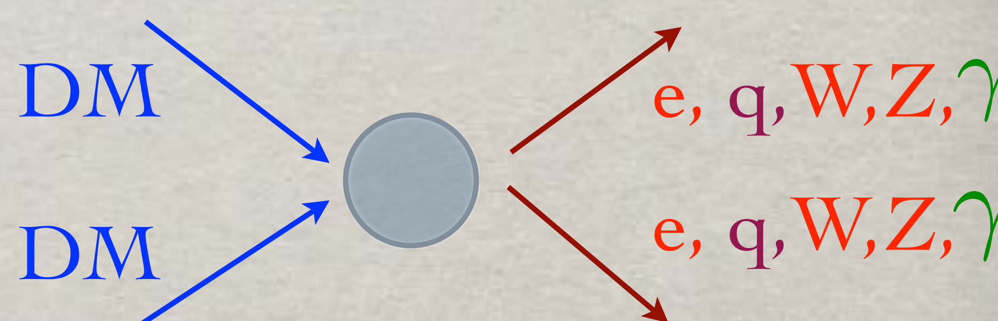
Direct Detection:




Colliders: LHC/ILC



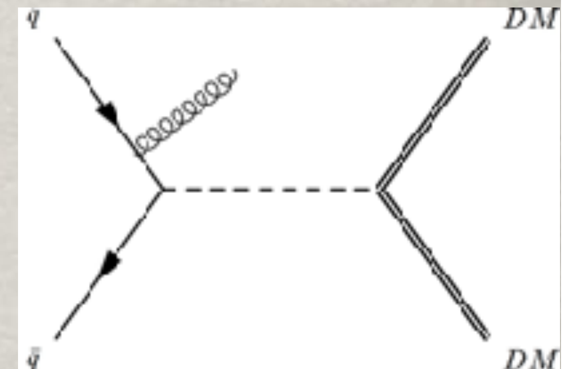

Indirect Detection:




3 different ways to check this hypothesis !!!

# Missing energy signature

- The direct production of two DM particles in a collider gives unfortunately no signal ! The energy just disappears...



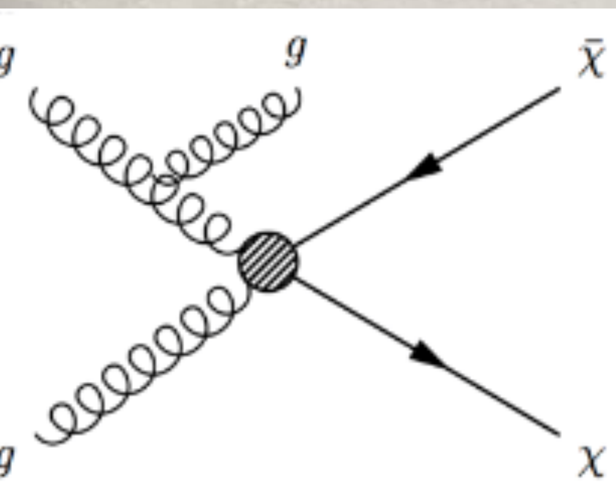

- How is it possible to tag such events: Thanks to Initial State Radiation !
 i.e. either a single photon or gluon emitted by the initial parton, recoiling against the DM particle(s)

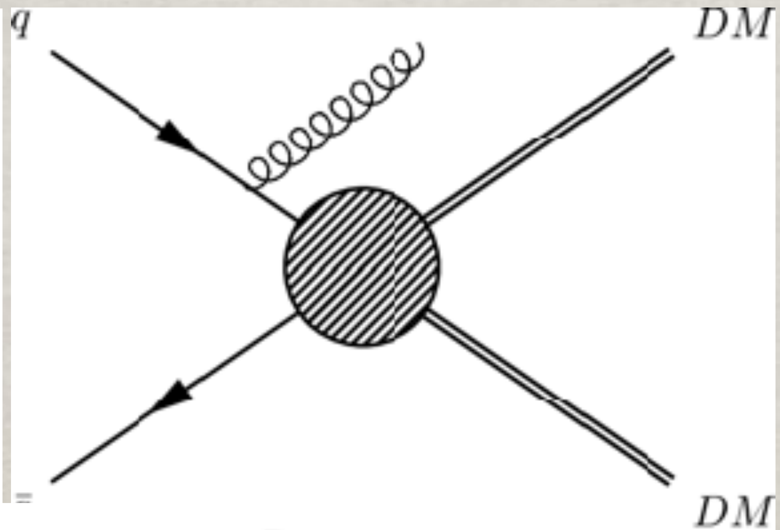

Trouble: need sufficient rate of DM production...

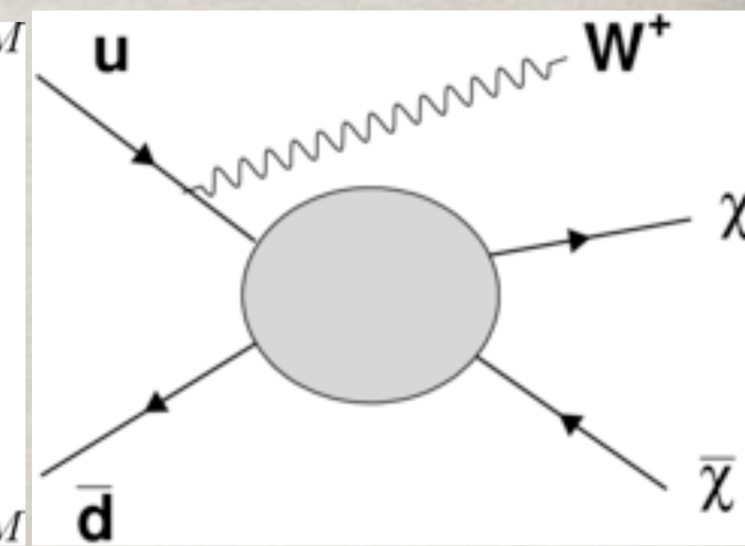
# EFT for Dark Matter

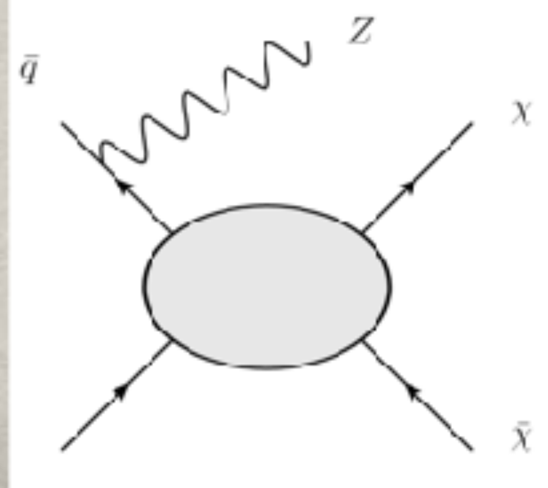
[ Beltram et al 2000, Goodman et al 2000 & 2001, Bai et al 2001,....]

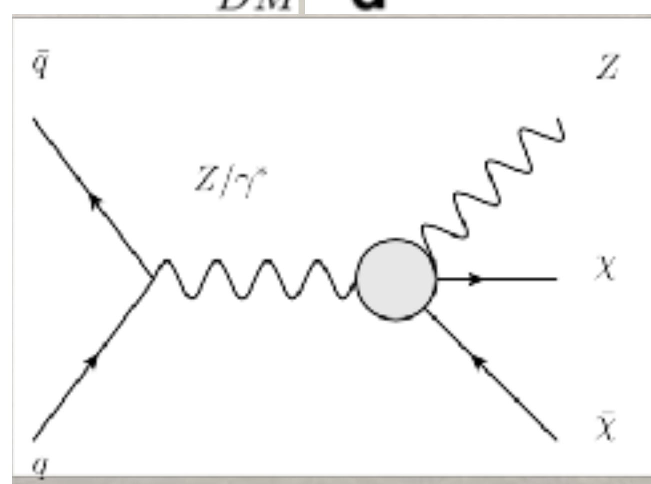
Consider the production of a pair of DM particles together with ISR of a SM particle: gluon, photon, W/Z, top, etc...
EFT: Many different effective operators are possible !



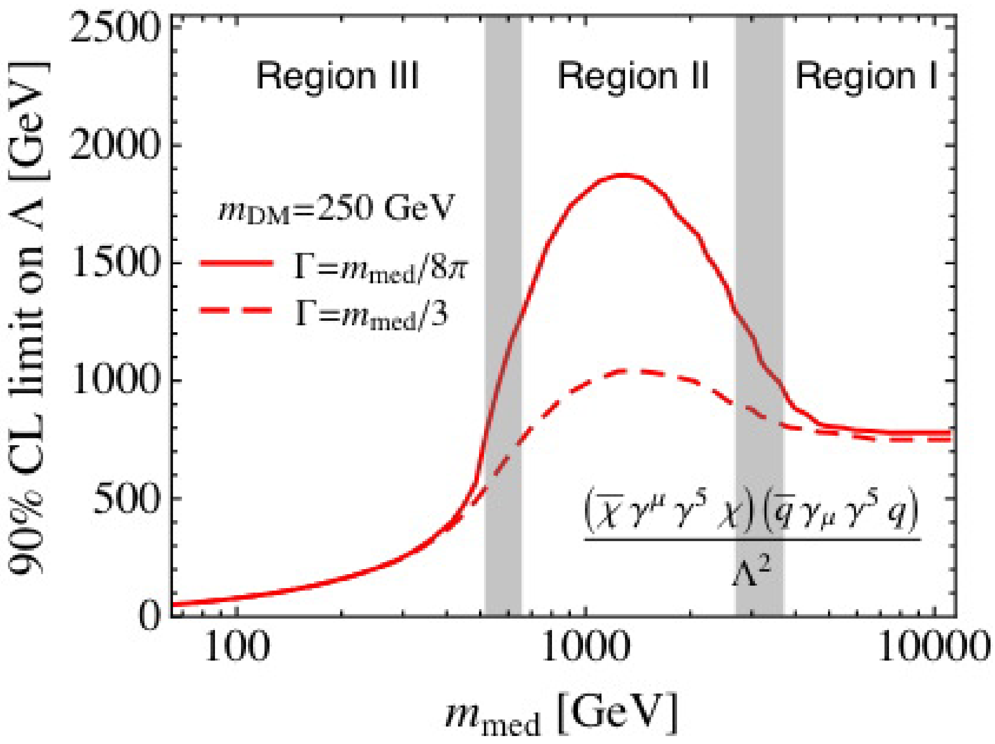



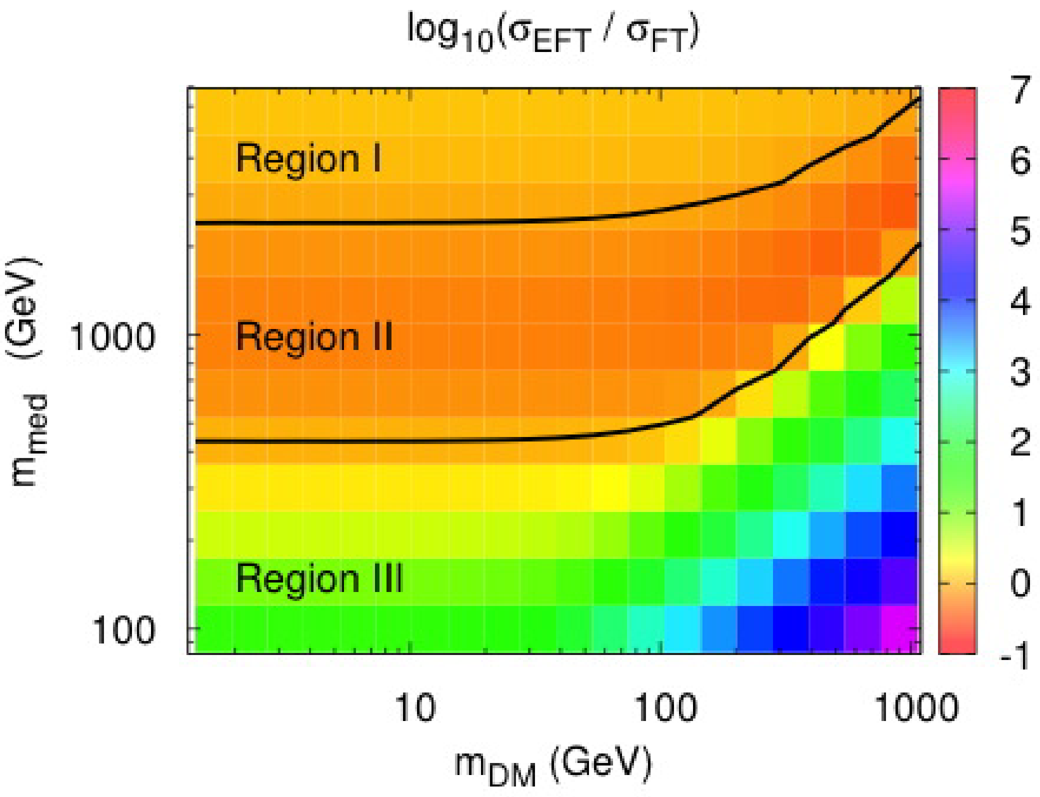
# Caveat for the EFT: s

While the use of EFT for the case of non-relativistic scattering with matter in DM direct detection is well-justified, at LHC energies one has to be more careful...

[Fox et al 11, Busoni et al 13, O.Buchmuller et al 13, ...]

[O.Buchmuller et al 1308.6799]

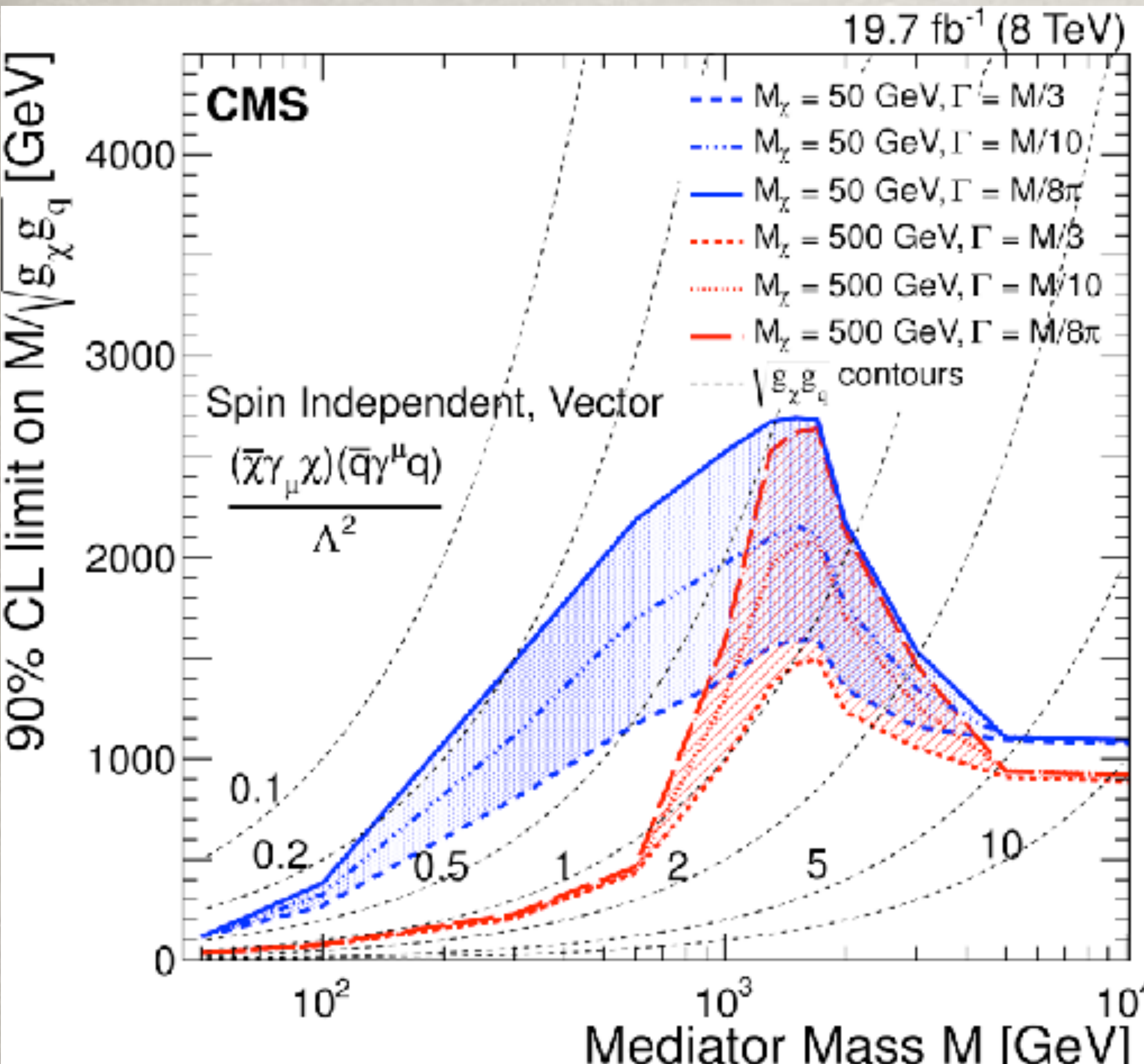


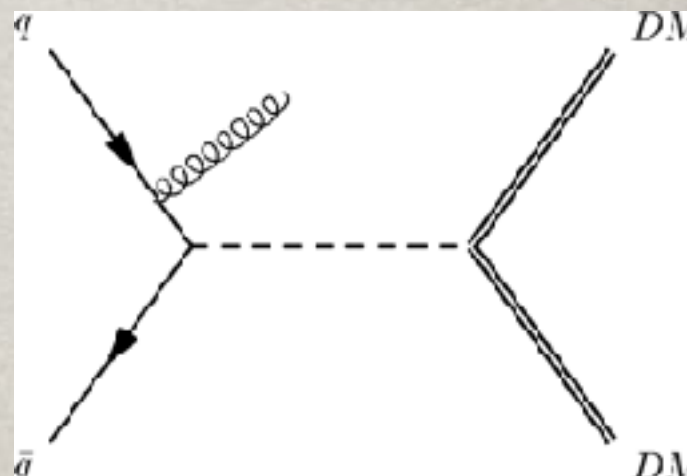

The bound is valid only for large mediator mass !

# LHC: SIMPLIFIED MODELS

[ CMS collaboration, EPJC 75 (2015) 235]

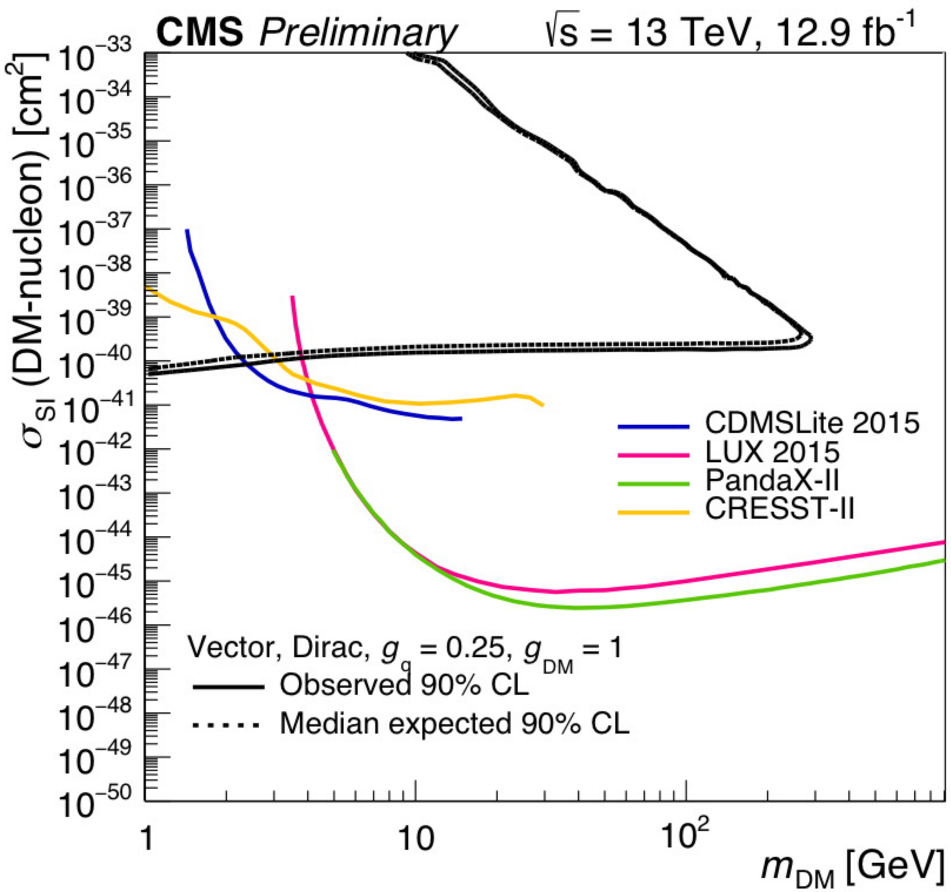


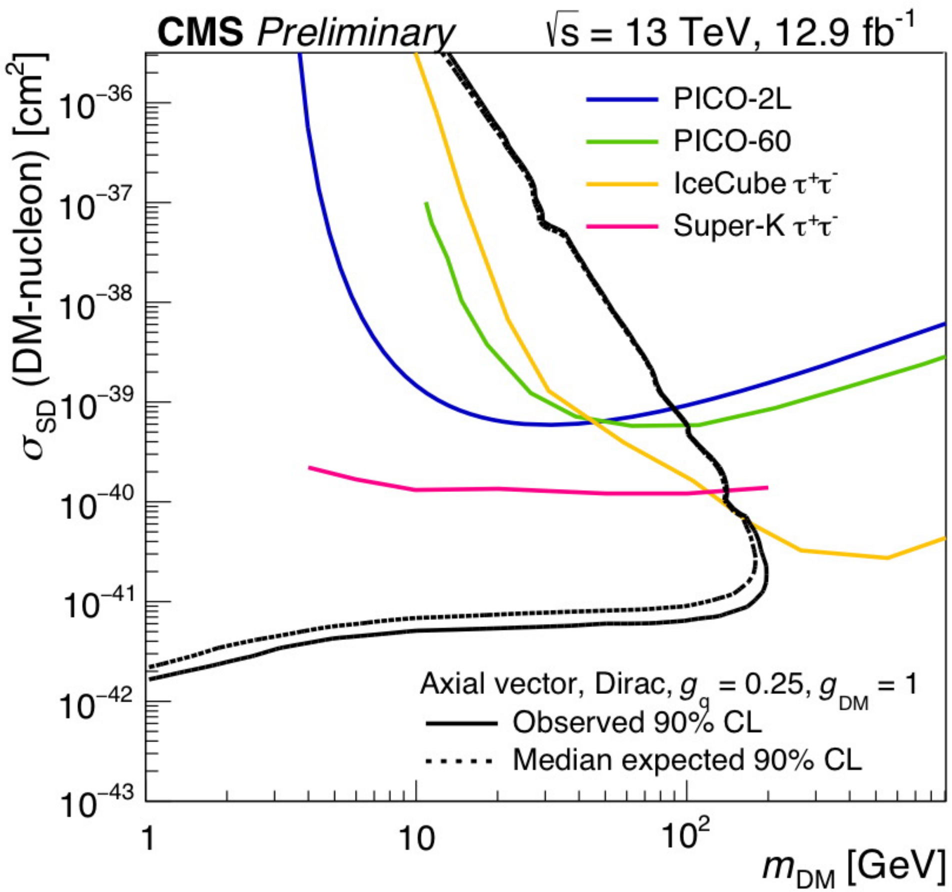

Vector mediator



# LHC: SIMPLIFIED MODELS II

[CMS, EXO-16-039-pas]

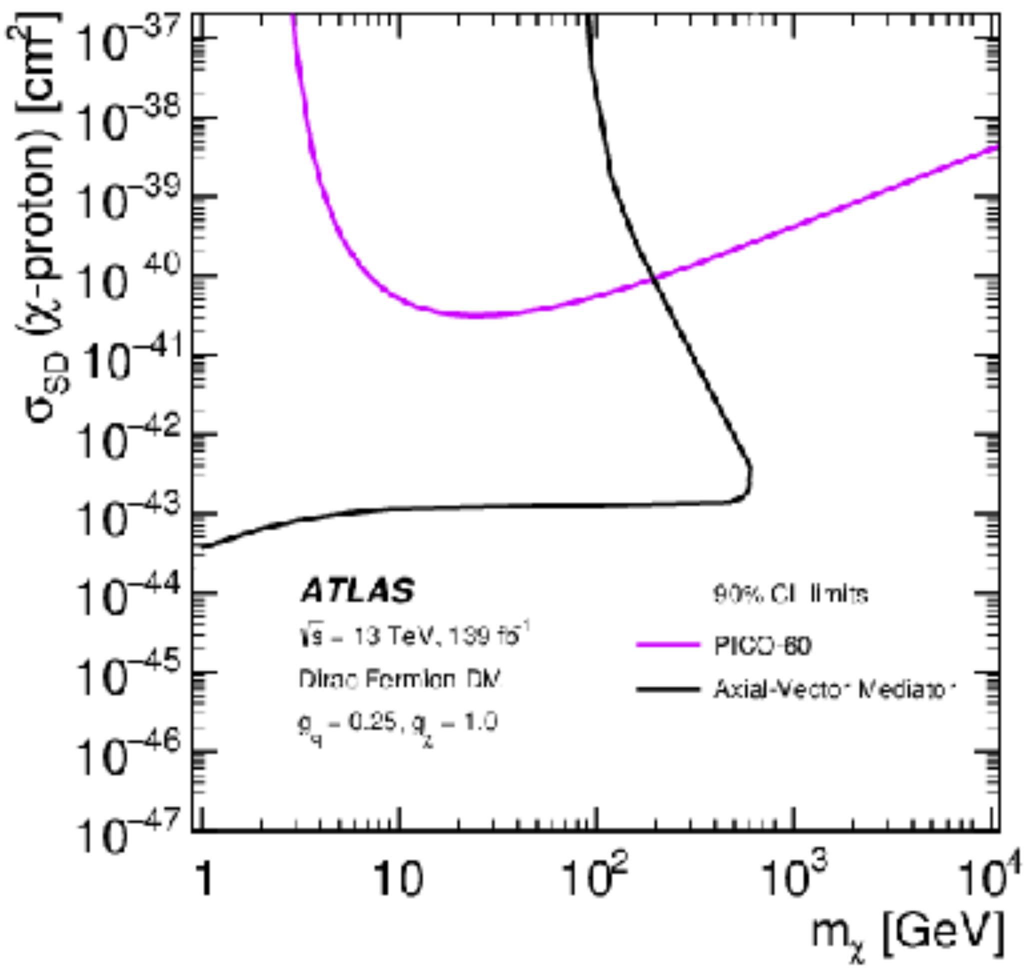


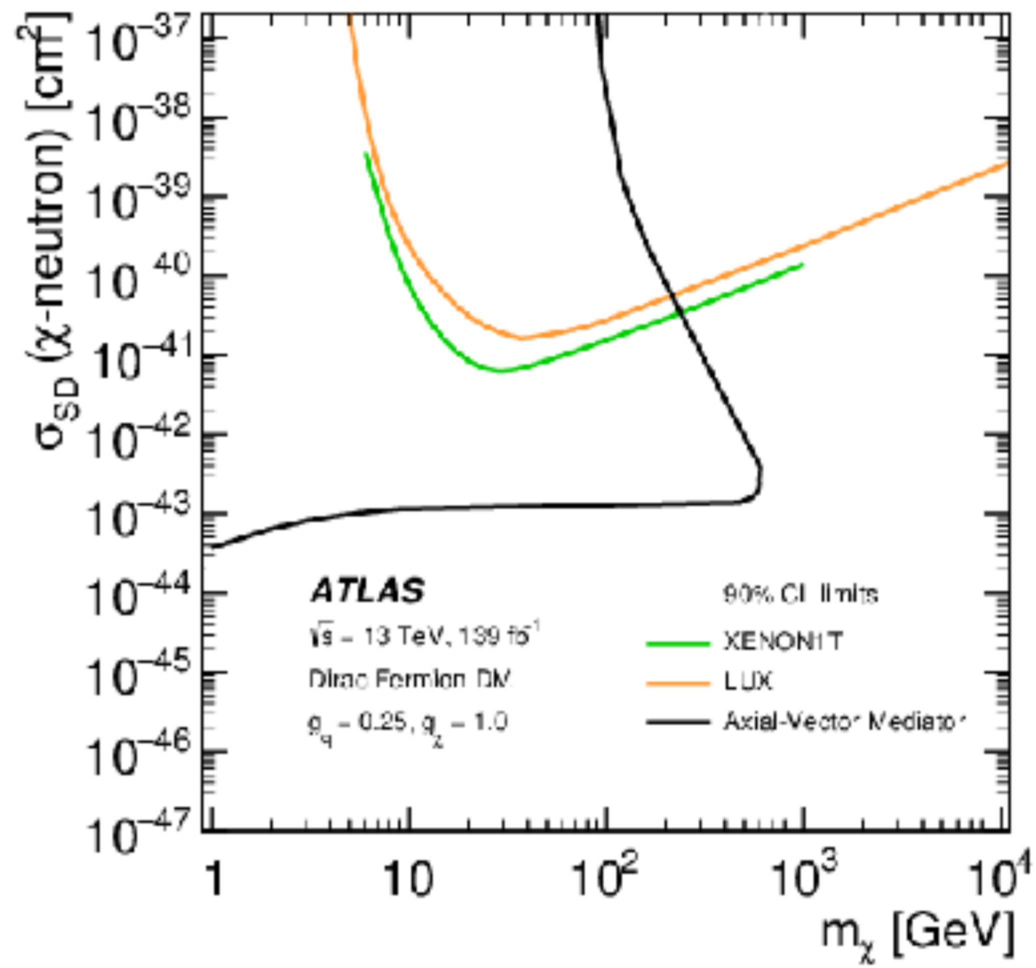




Very strong bounds for the axial vector case, which gives spin dependent scattering !

# LHC: SIMPLIFIED MODELS III

[ATLAS 2102.10874 hep-ex]

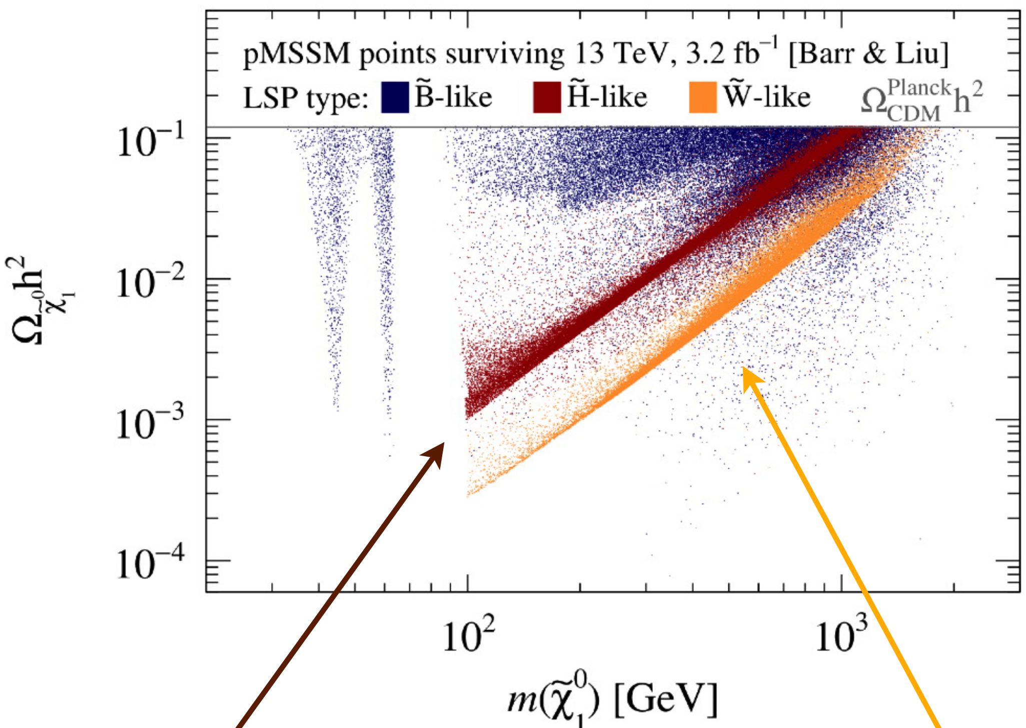


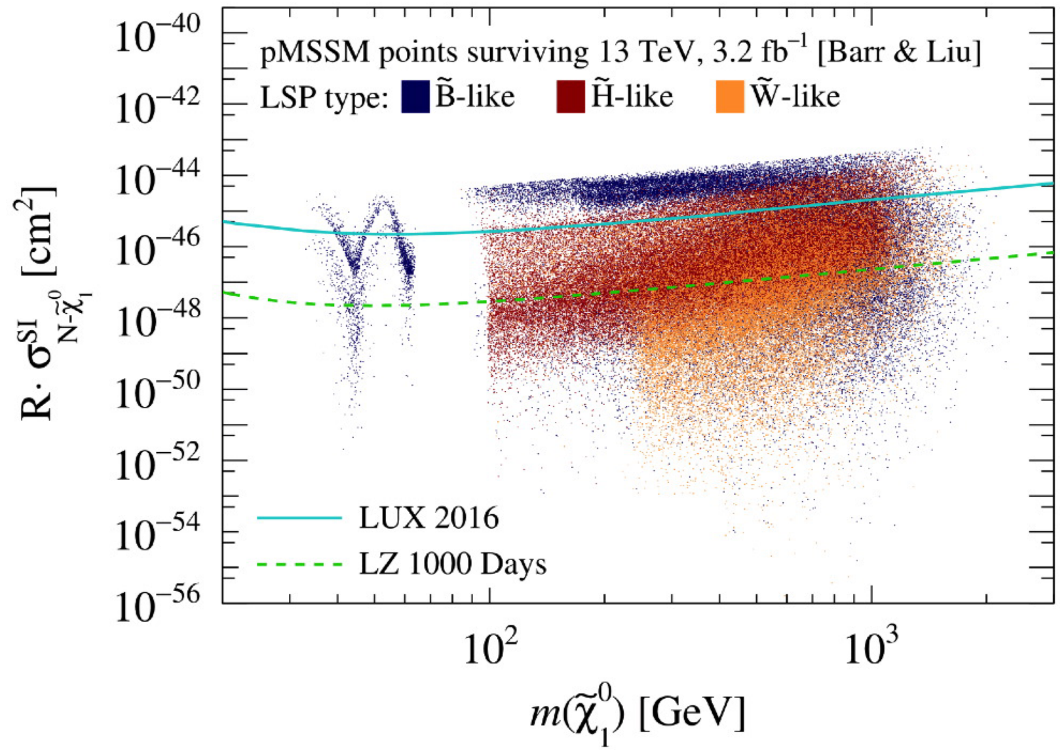




Very strong bounds for the axial vector case !

# SUSY MODELS STILL ALIVE

pMSSM points surviving after LHC-13 data [Barr & Liu 2016]



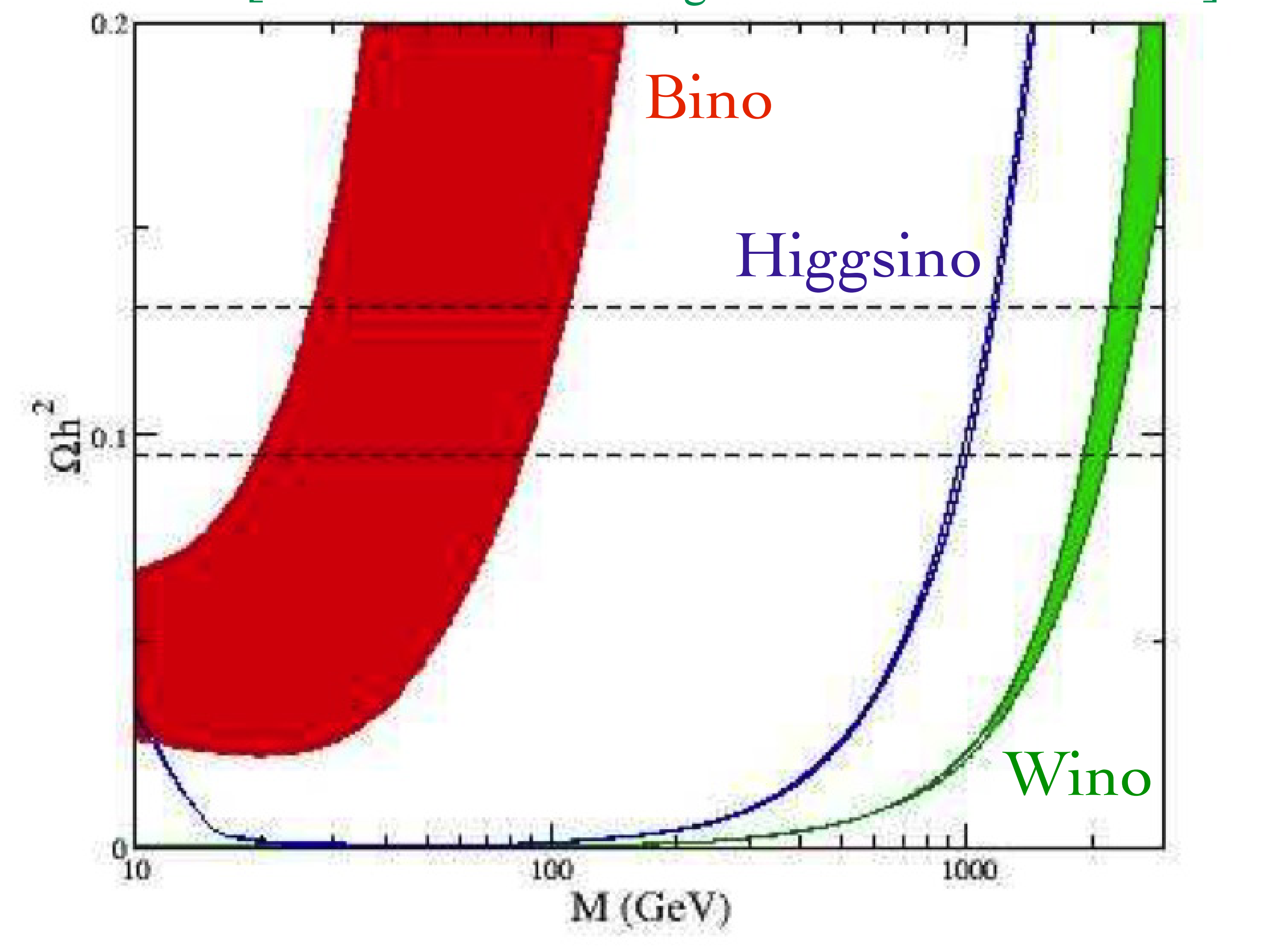

Higgsino band Wino band

Wino DM challenged by Indirect Detection, but Higgsino parameter space still viable (and also some Bino-like...)

# Well-tempered neutralino

Relic density strongly dependent on neutralino nature !!!

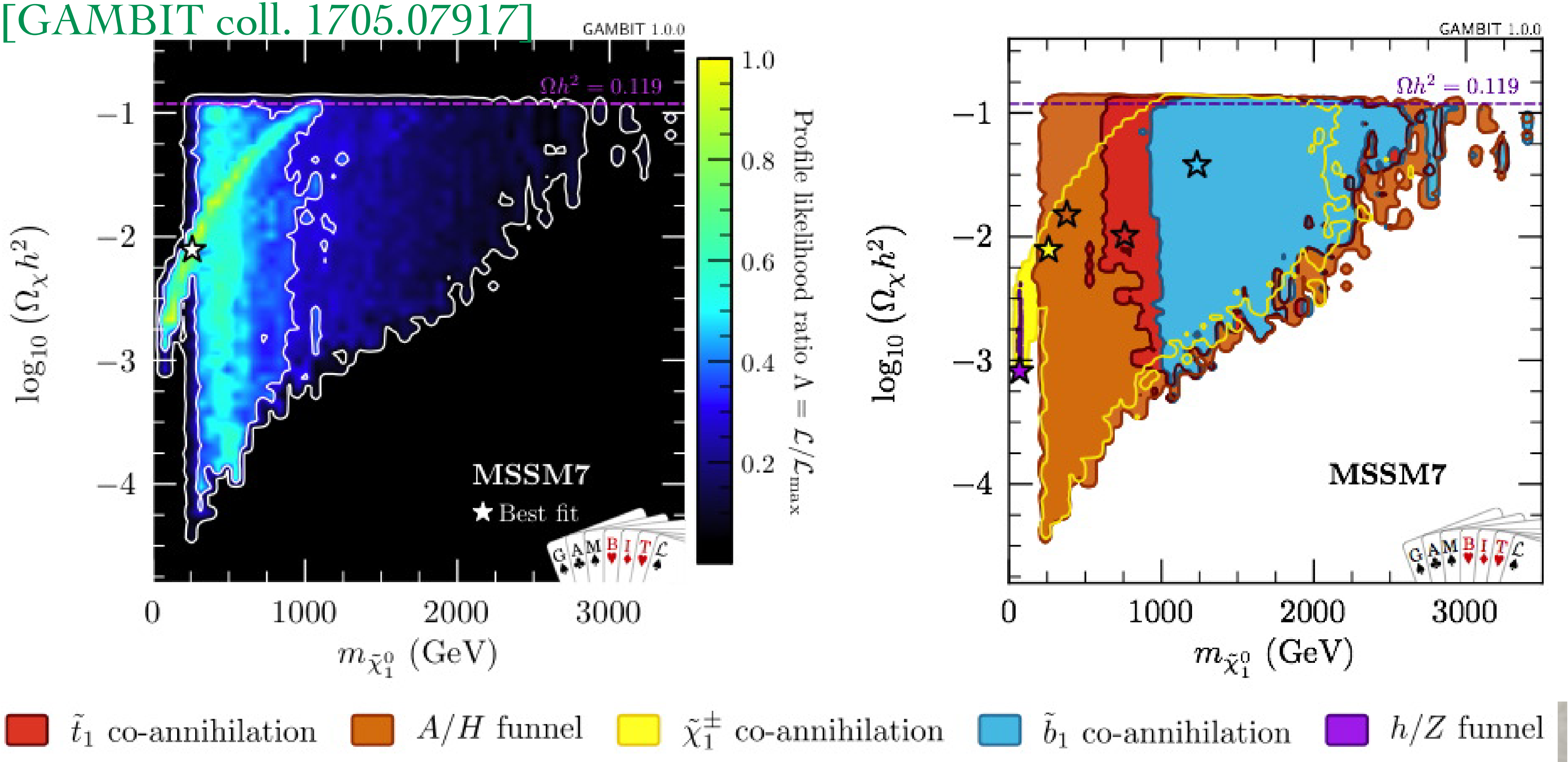
[Arkani-Hamed, Delgado & Giudice 0601041]



# MSSM-7 Dark Matter

With more parameters, more mechanism are possible, i.e. in the MSSM with 7 parameters: both Bino & Higgsino DM !

[GAMBIT coll. 1705.07917]

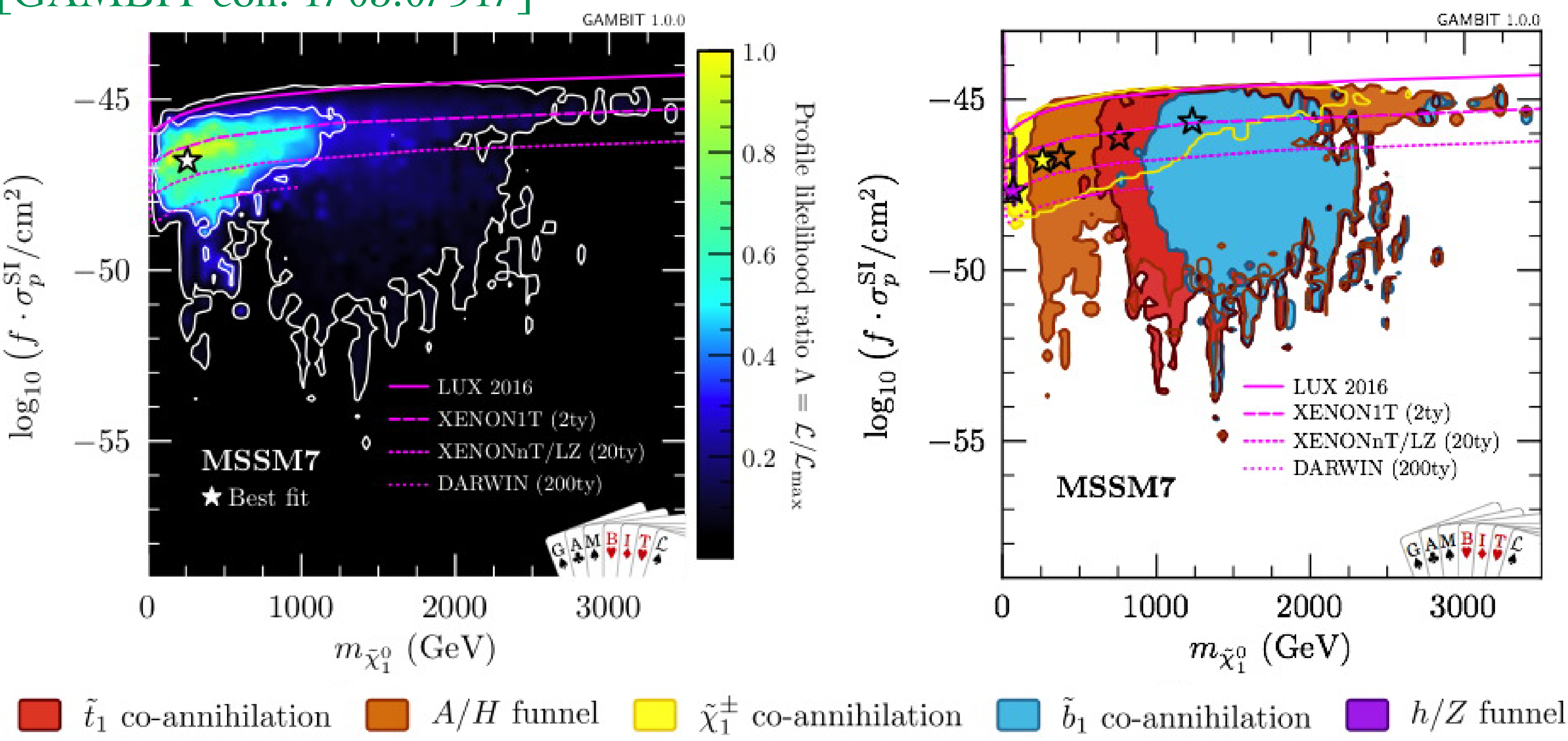



For Higgsino coannihilation with charginos is always present !

# Higgsino Dark Matter

The Higgsino DM region mostly covered by Direct Detection:

[GAMBIT coll. 1705.07917]




Nevertheless for other compositions low cross-section is possible