ISAPP2024: Particle Candidates for Dark Matter
Scuola Galileiana di Studi Superiori, PD - 25-28th June 2024

WIMP
Dark Matter

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HIDDeN
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

MARIE CURIE ACTIONS

Outline

- Introduction on Dark Matter & Theoretical guiding principles

- Thermal relics:
  - General Boltzmann equation
  - Vanilla WIMP DM

- WIMP Dark Matter

- Non-thermal relics:
  - FIMP/SuperWIMP/Decaying DM

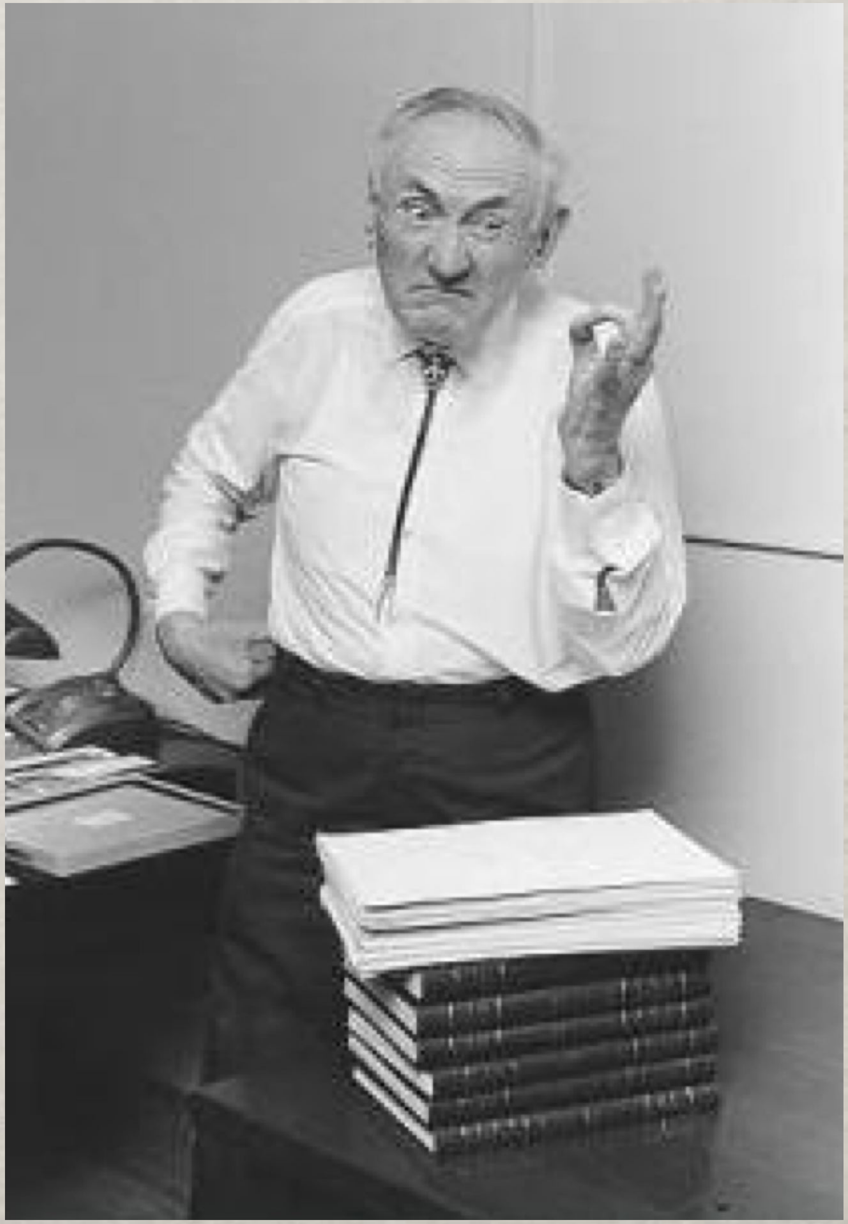
- Outlook

Introduction

DARK MATTER EVIDENCE

CLUSTER SCALES:

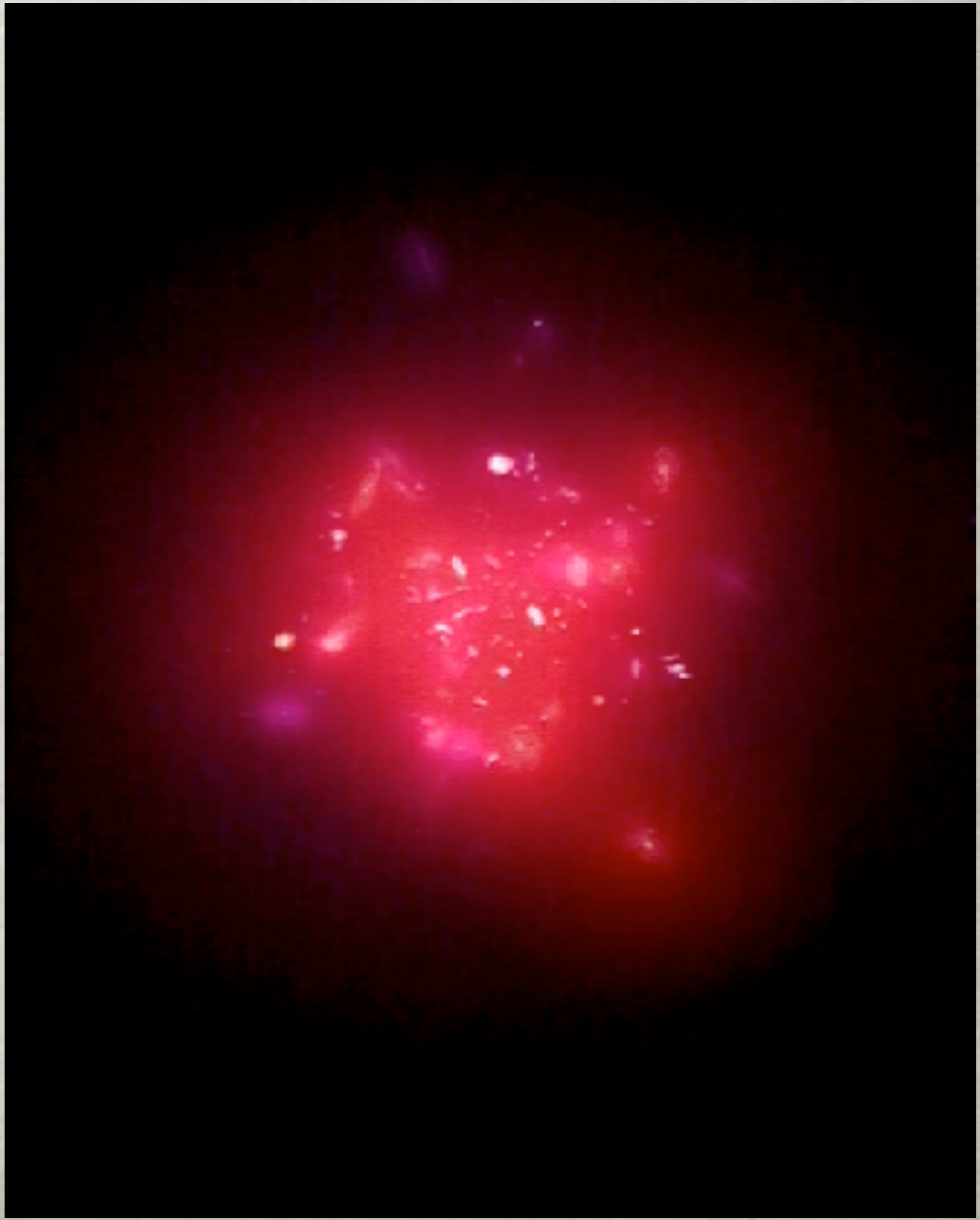
The early history of Dark Matter:
In 1933 F. Zwicky found the first evidence for DM in the velocity dispersion of the galaxies in the COMA cluster...
Already then he called it **DARK MATTER** !



DARK MATTER EVIDENCE

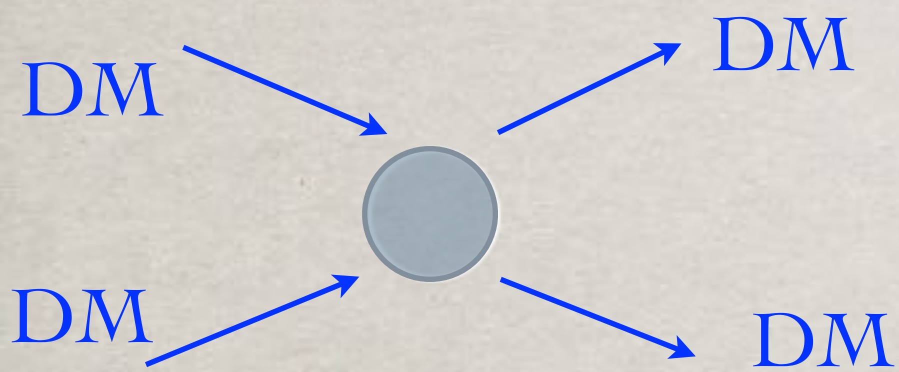
CLUSTER SCALES:

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...



DM-DM INTERACTION

Self-interaction:



Bullett cluster bound on self-interaction:

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

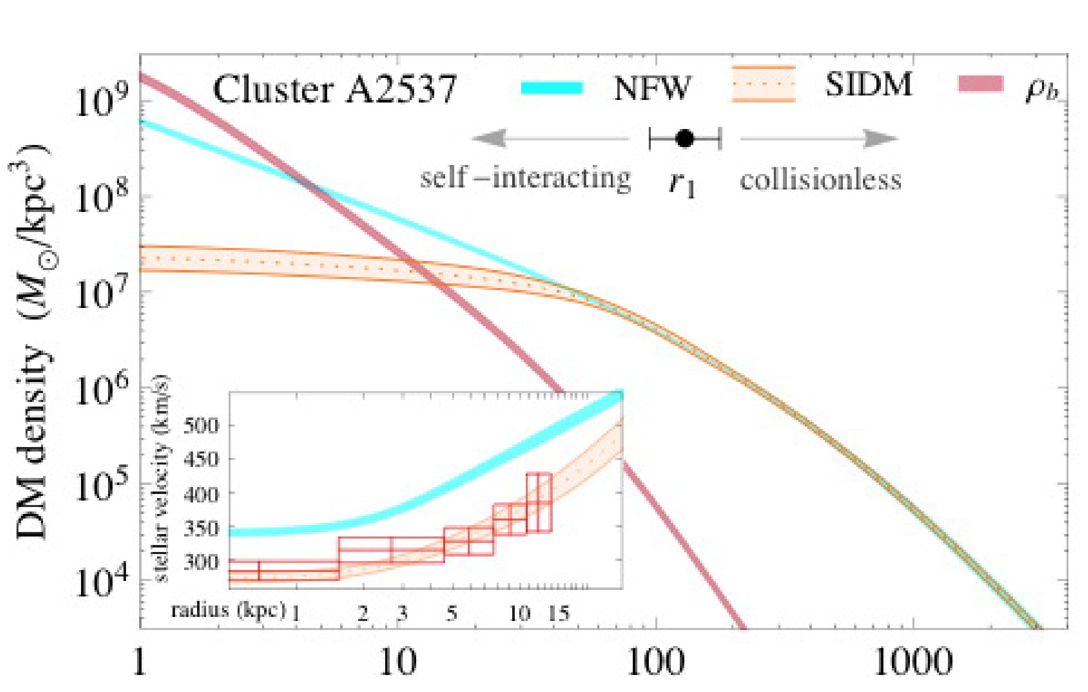
[Markevitch et al 03]

Slightly stronger constraint by requiring a sufficiently large core & from sphericity of halos... [Yoshida, Springer & White 00]

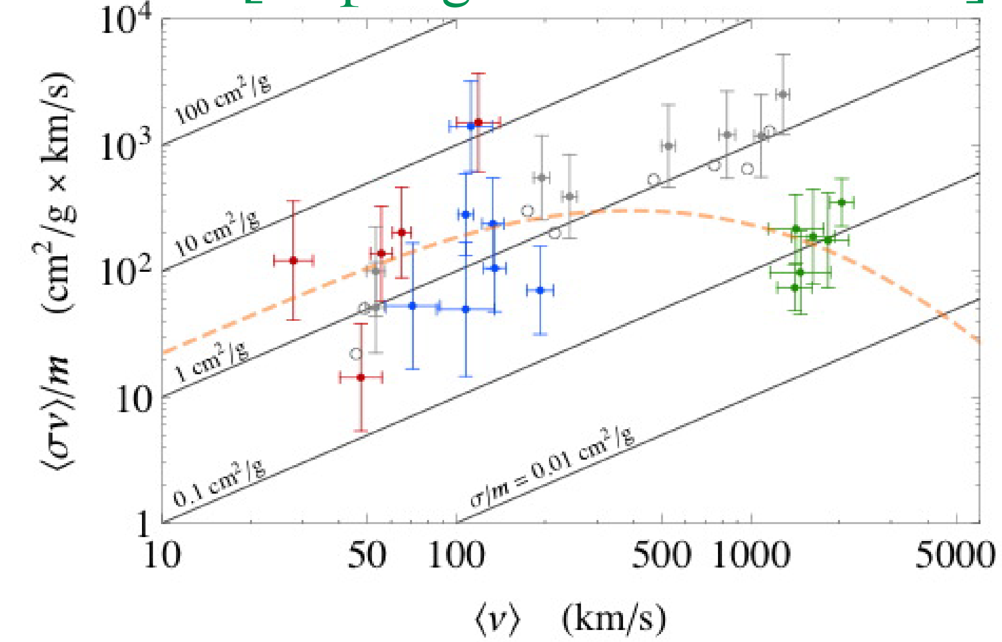
But at the boundary maybe some effect on small scales:
Strongly Interacting Massive Particle [Spergel & Steinhardt 99]

DM-DM INTERACTION

SIMP Dark Matter can relax some of the tensions at small scales and flatten the density in the centre:



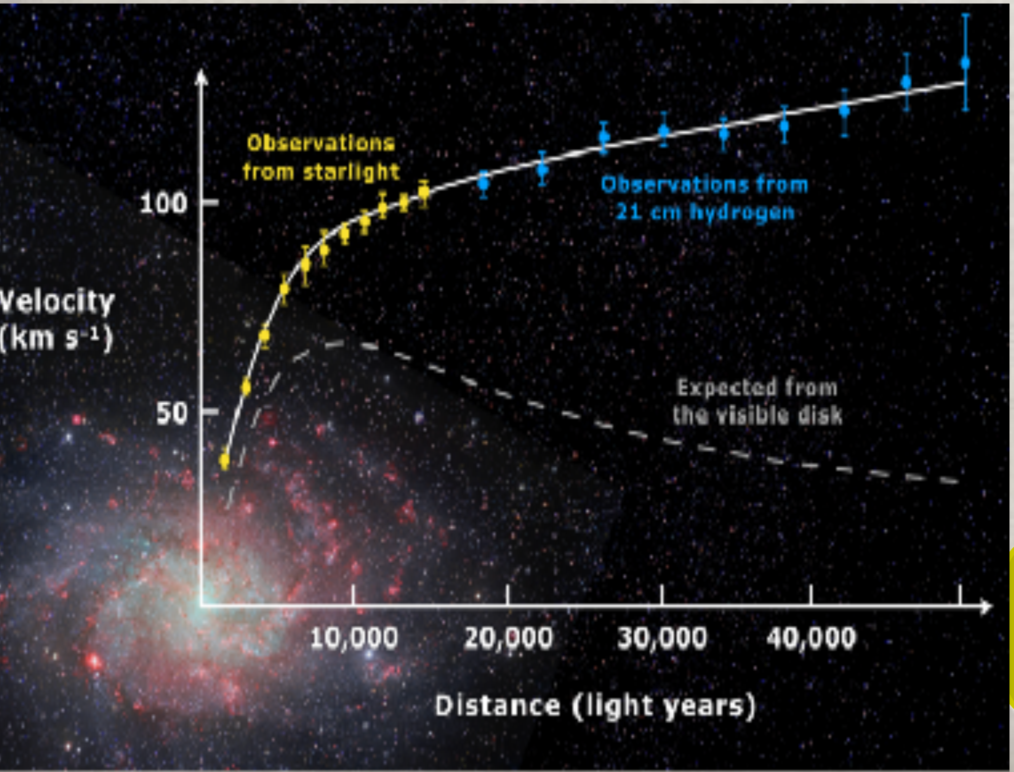
[Kaplinghat, Tulin & Yu 15]



On the other hand it looks that larger cross-sections are needed at dwarves galaxies/low surface brightness galaxies compared to cluster scales...

DARK MATTER
EVIDENCE

GALACTIC SCALES:
Vera Rubin and others noticed that the stars in the outer part of galaxies are faster than expected...



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

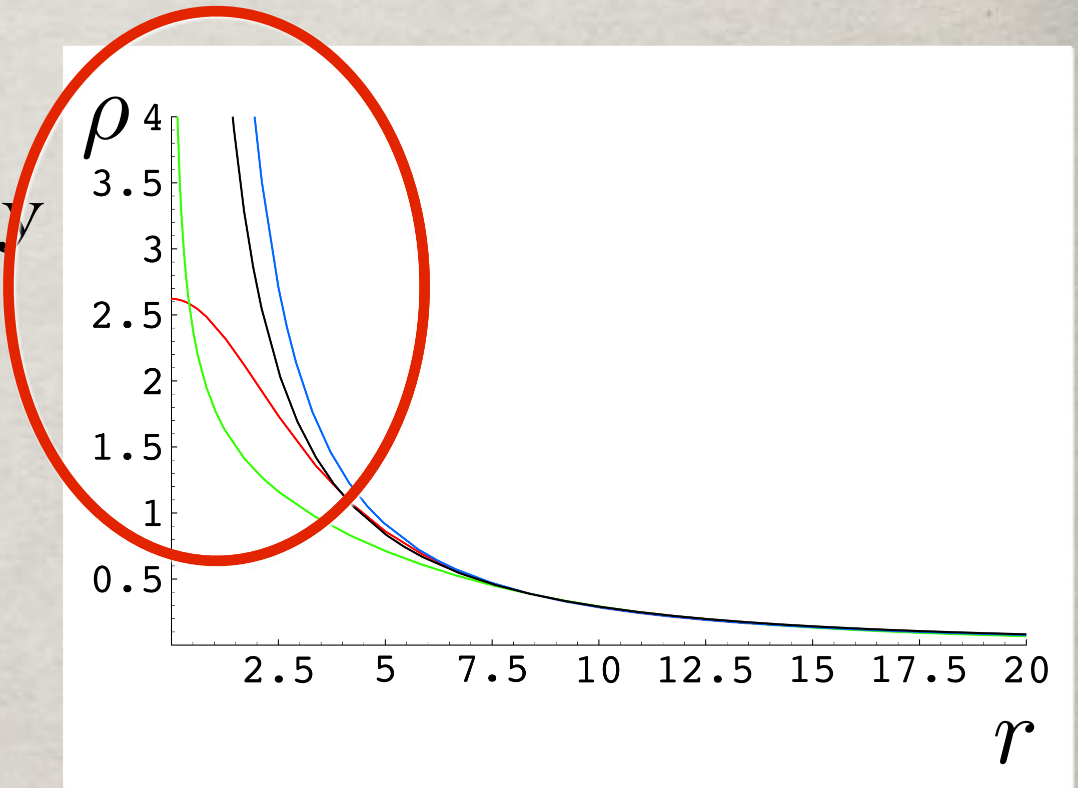
But instead it is constant ! Need

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

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 !

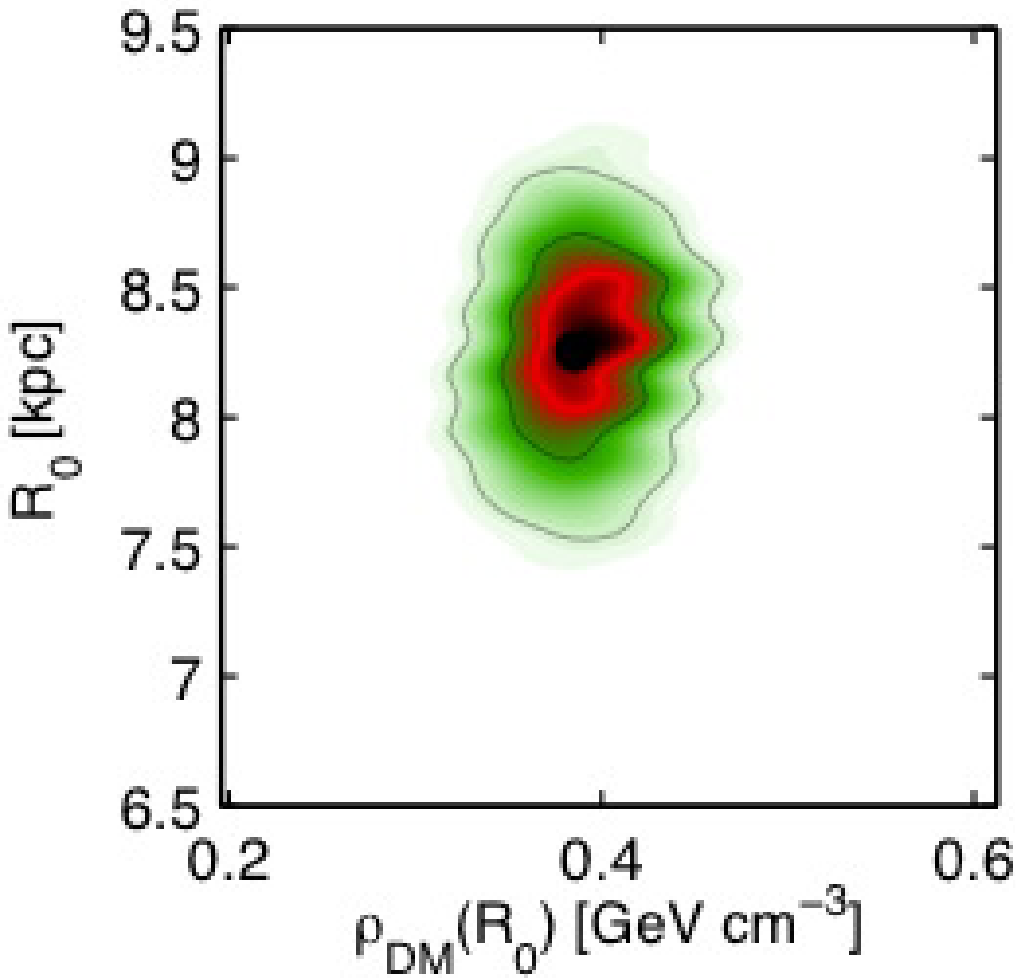


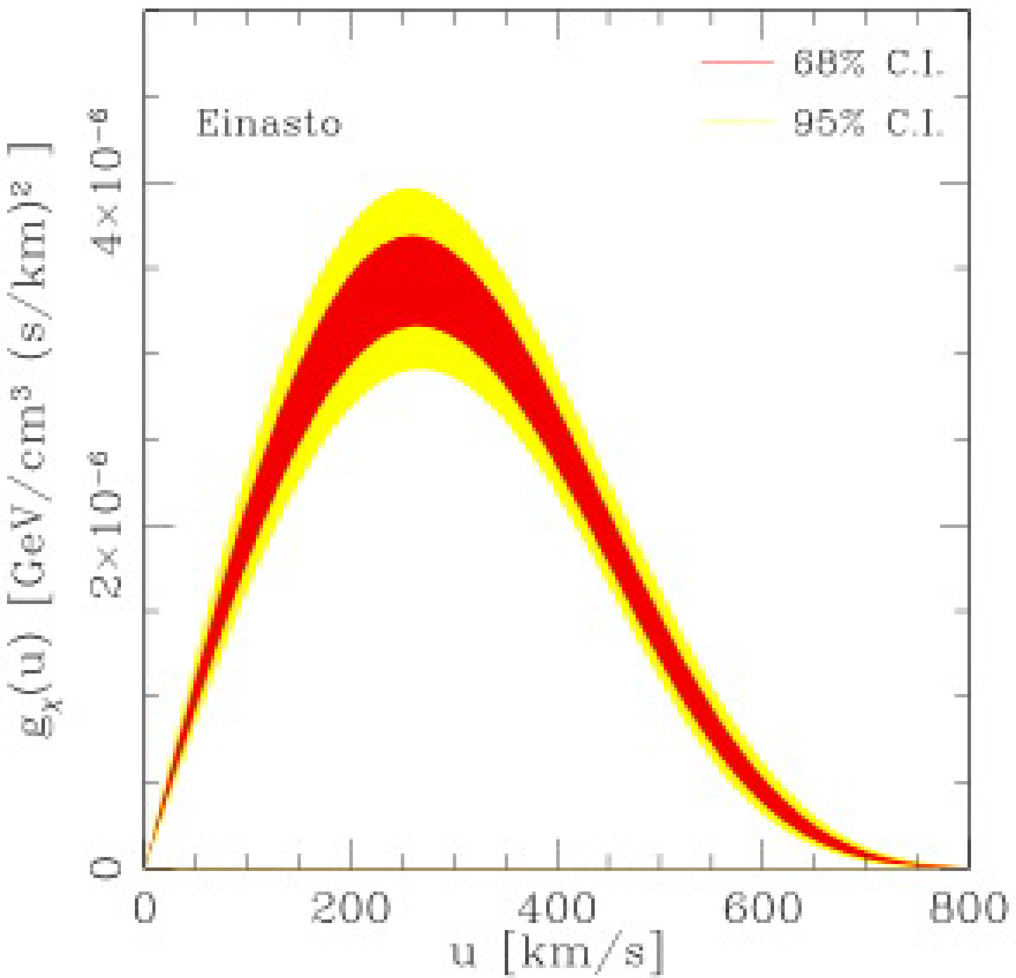
$$\rho(r) = \frac{\rho_0}{(r/R)^\gamma [1 + (r/R)^\alpha]^{(\beta-\gamma)/\alpha}}$$

Critical for indirect detection !

DARK MATTER LOCAL DENSITY & VELOCITY DISTRIBUTION

[Catena & Ullio 09, 11]

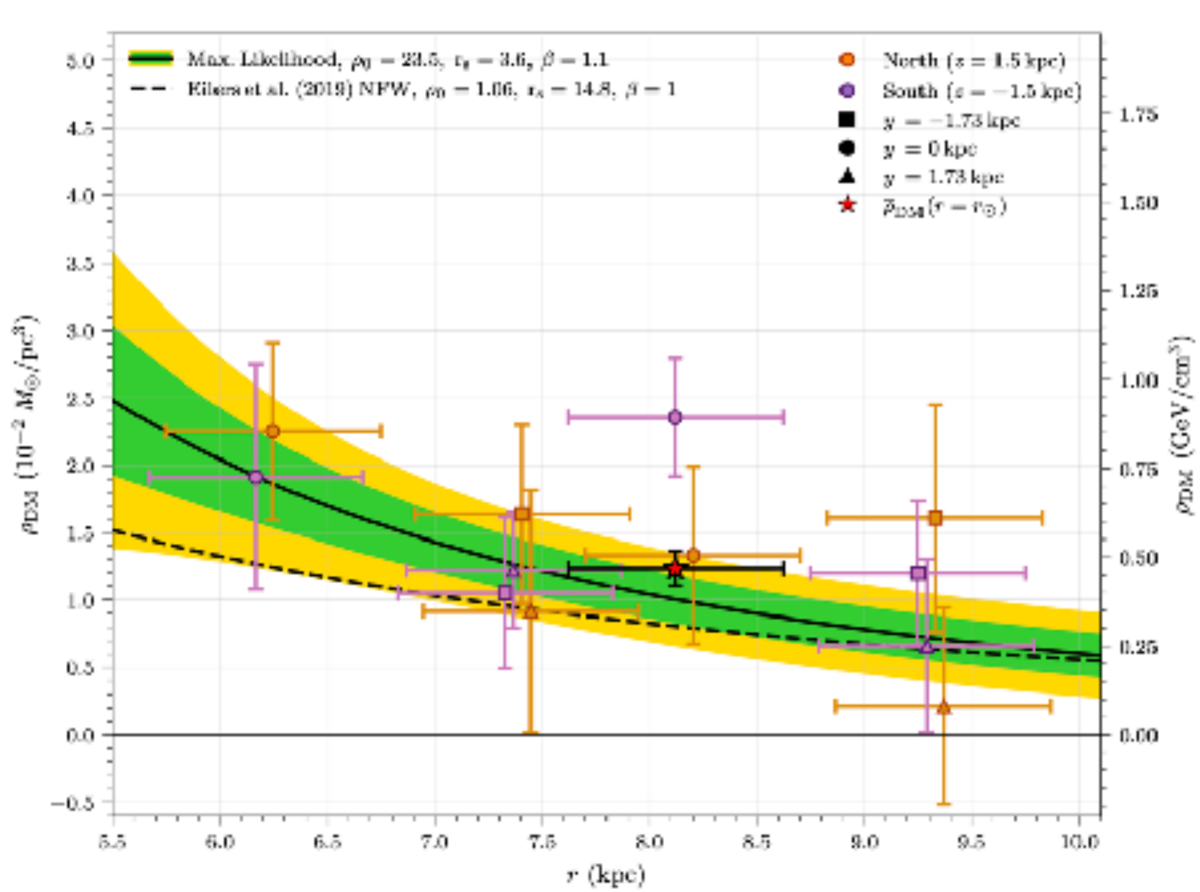


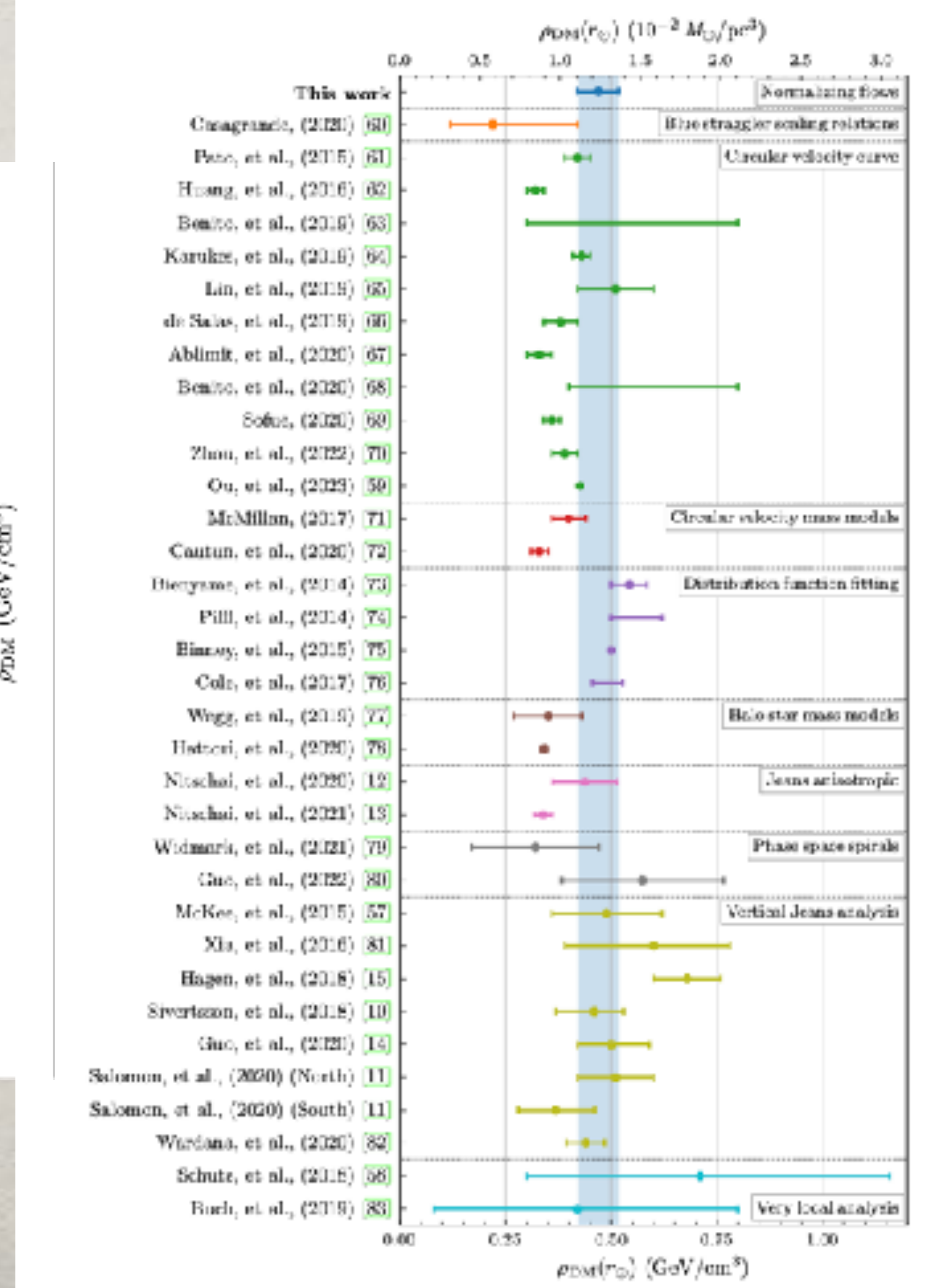


Critical for Direct Detection !

Dark Matter local density from GAIA

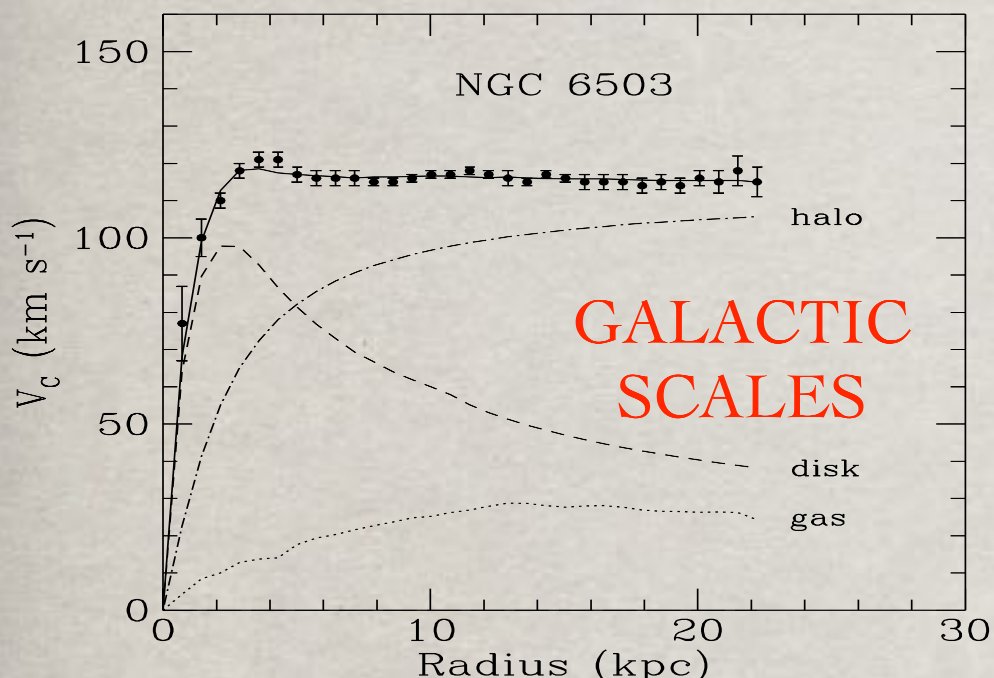
[Lim et al. 2023]

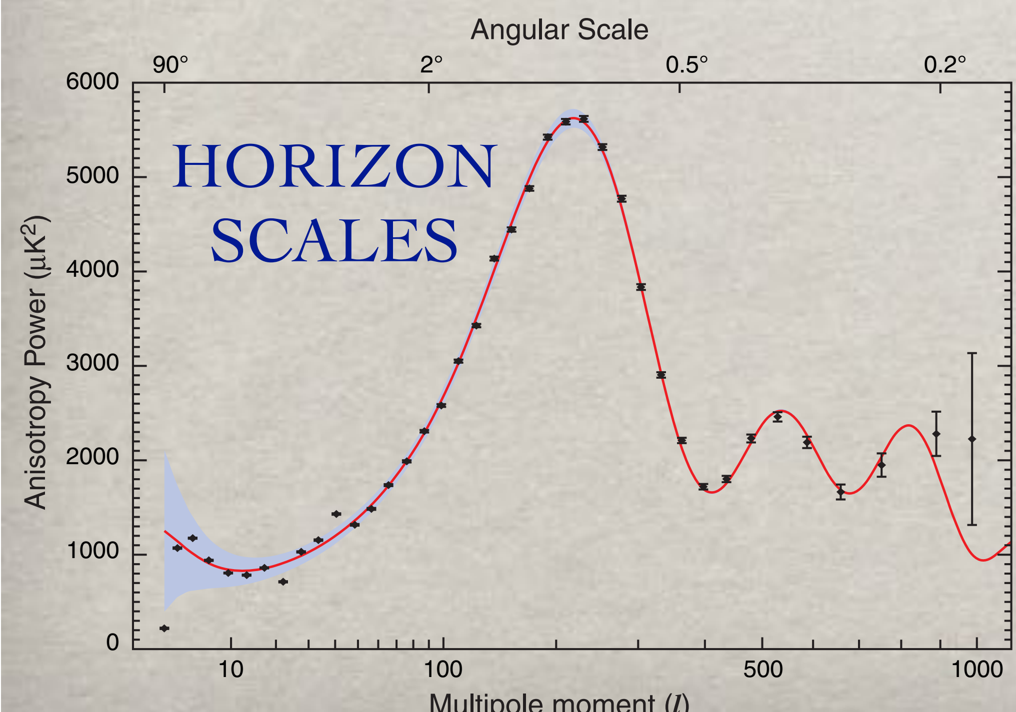




Critical for Direct Detection !

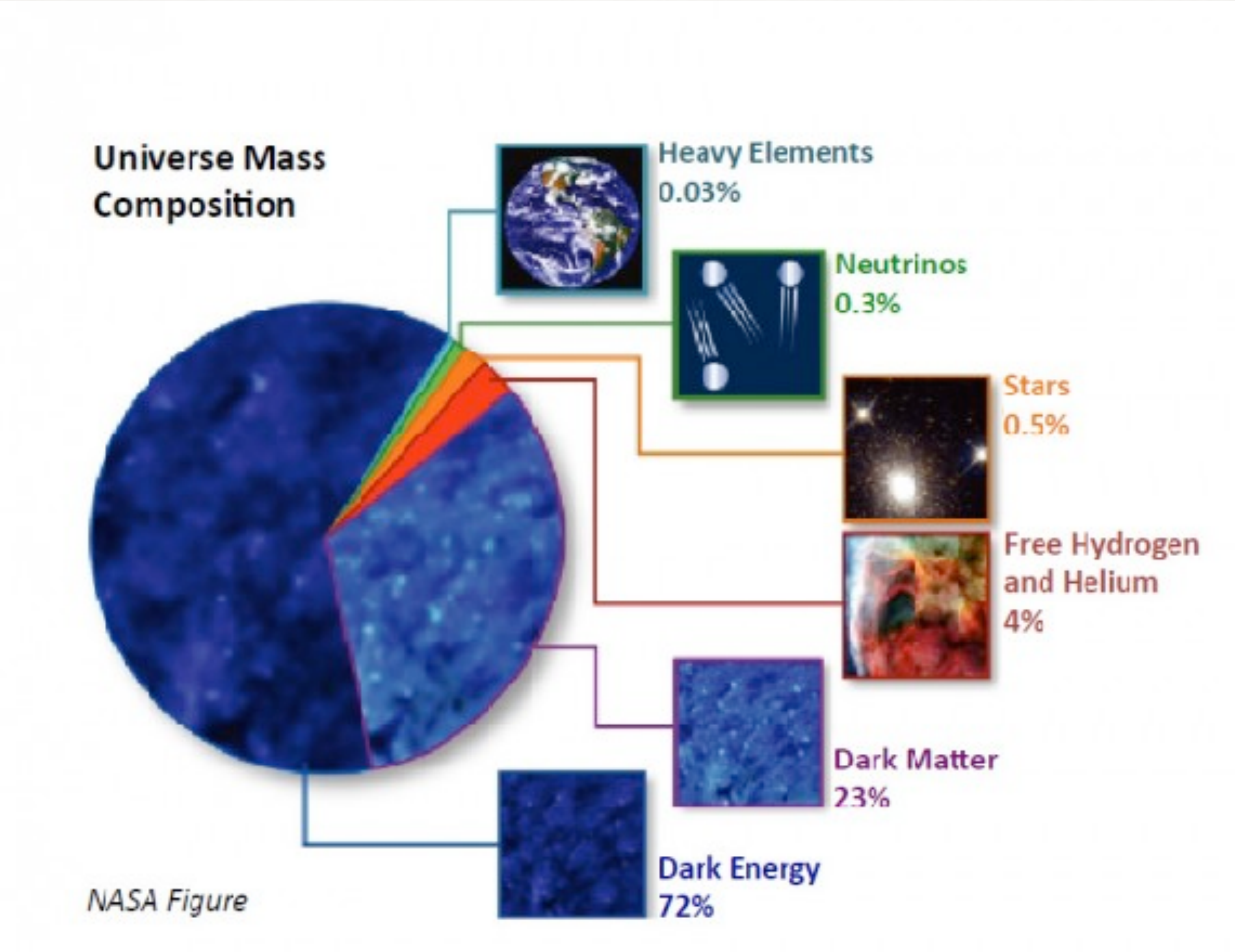
DARK MATTER EVIDENCE





Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	0.1-0.13	Cold

Universe composition

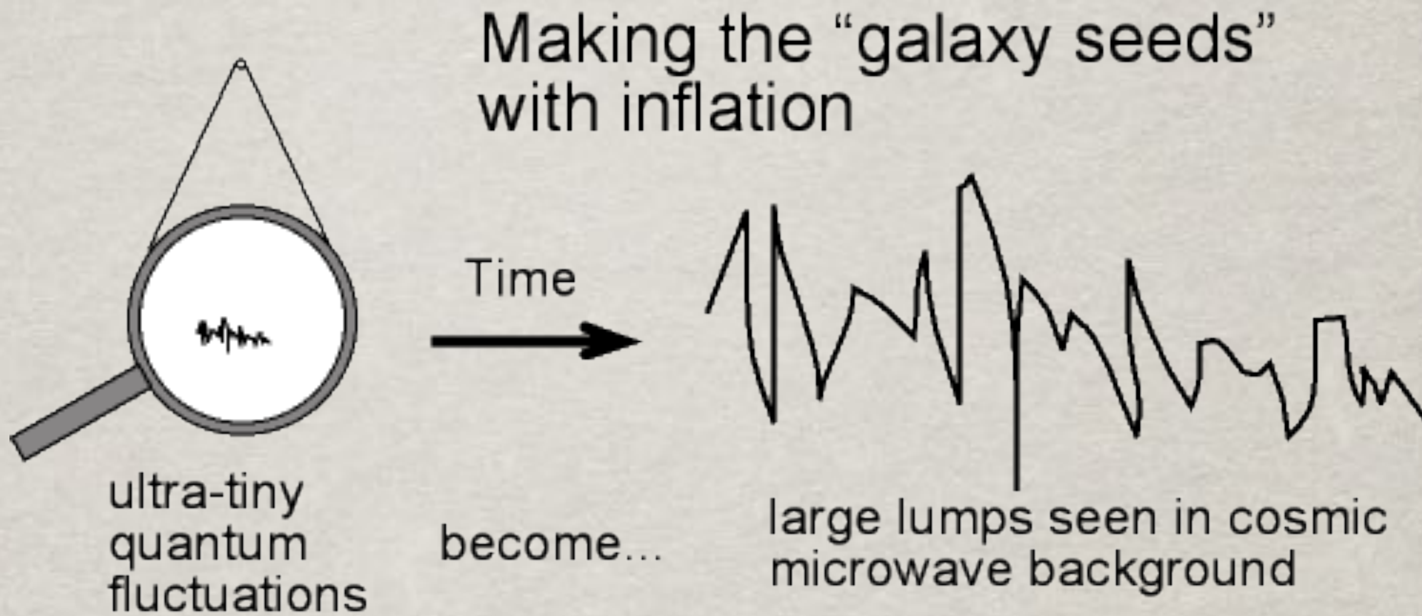


Why $\Omega_{DM}h^2 \sim 5\,\Omega_B h^2$?

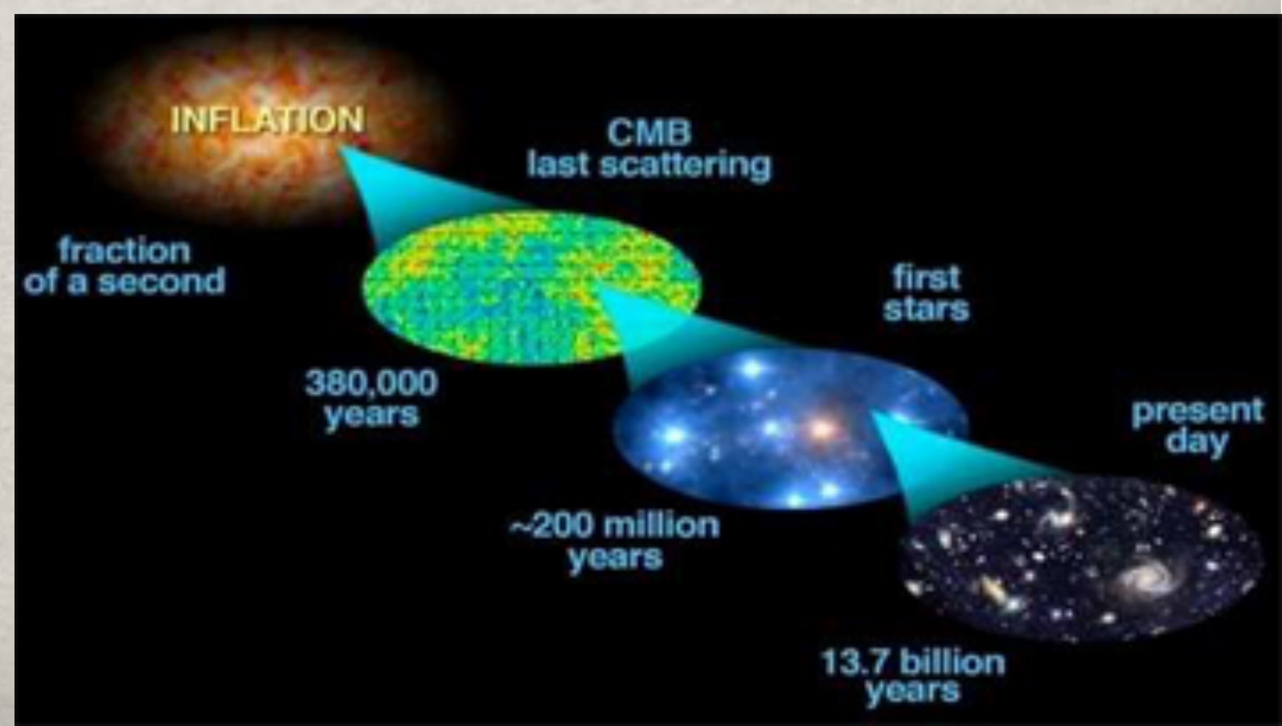
Quantum Fluctuation

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

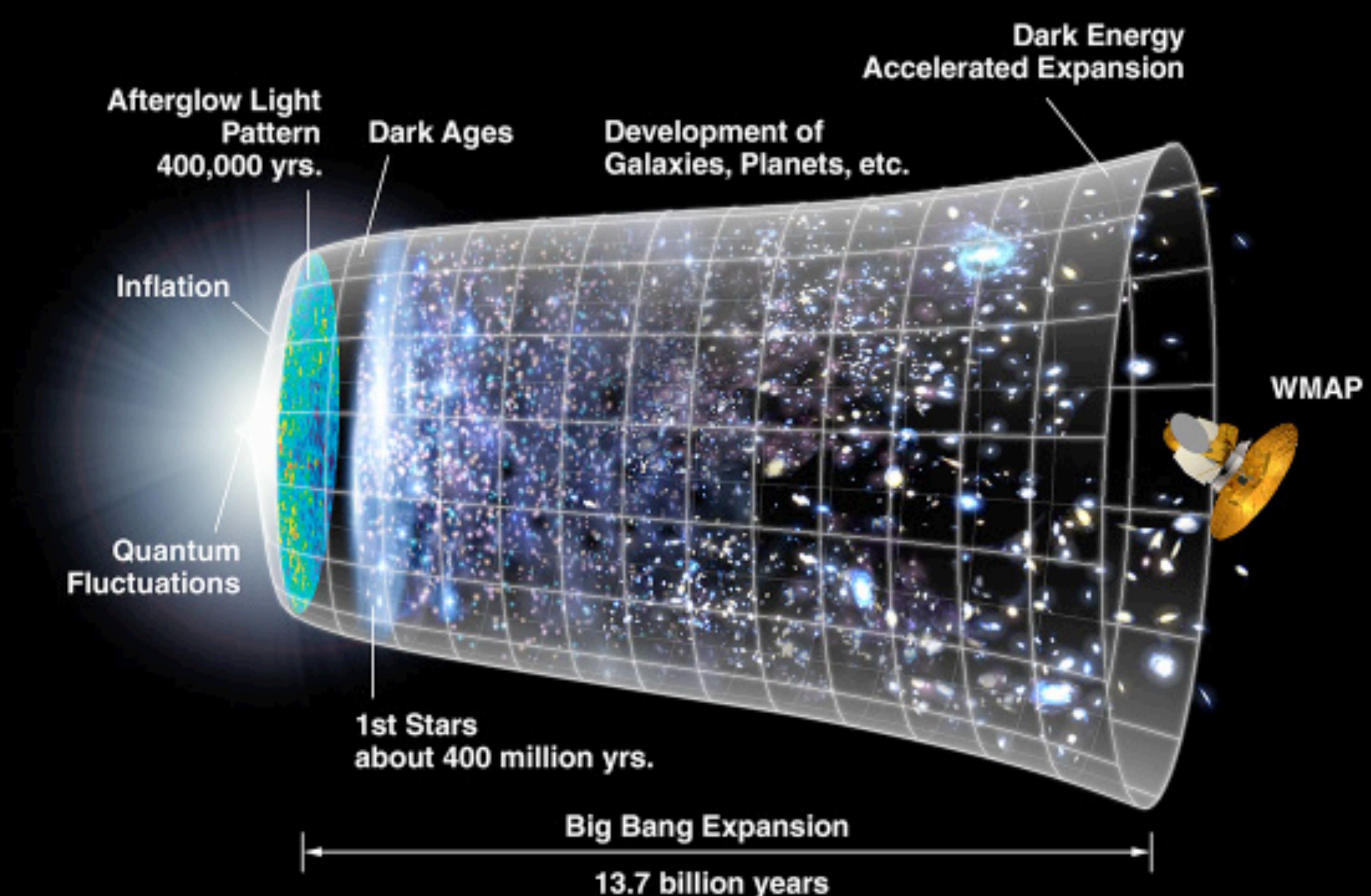
$$\Delta t \Delta E \geq \hbar$$



Gravity stretches
and amplifies
the microscopic
fluctuations to
macroscopic scales !!!



Following the fluctuations



These small fluctuations are amplified by gravity & are the origin of the structure we see today

NASA/WMAP Science Team

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

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

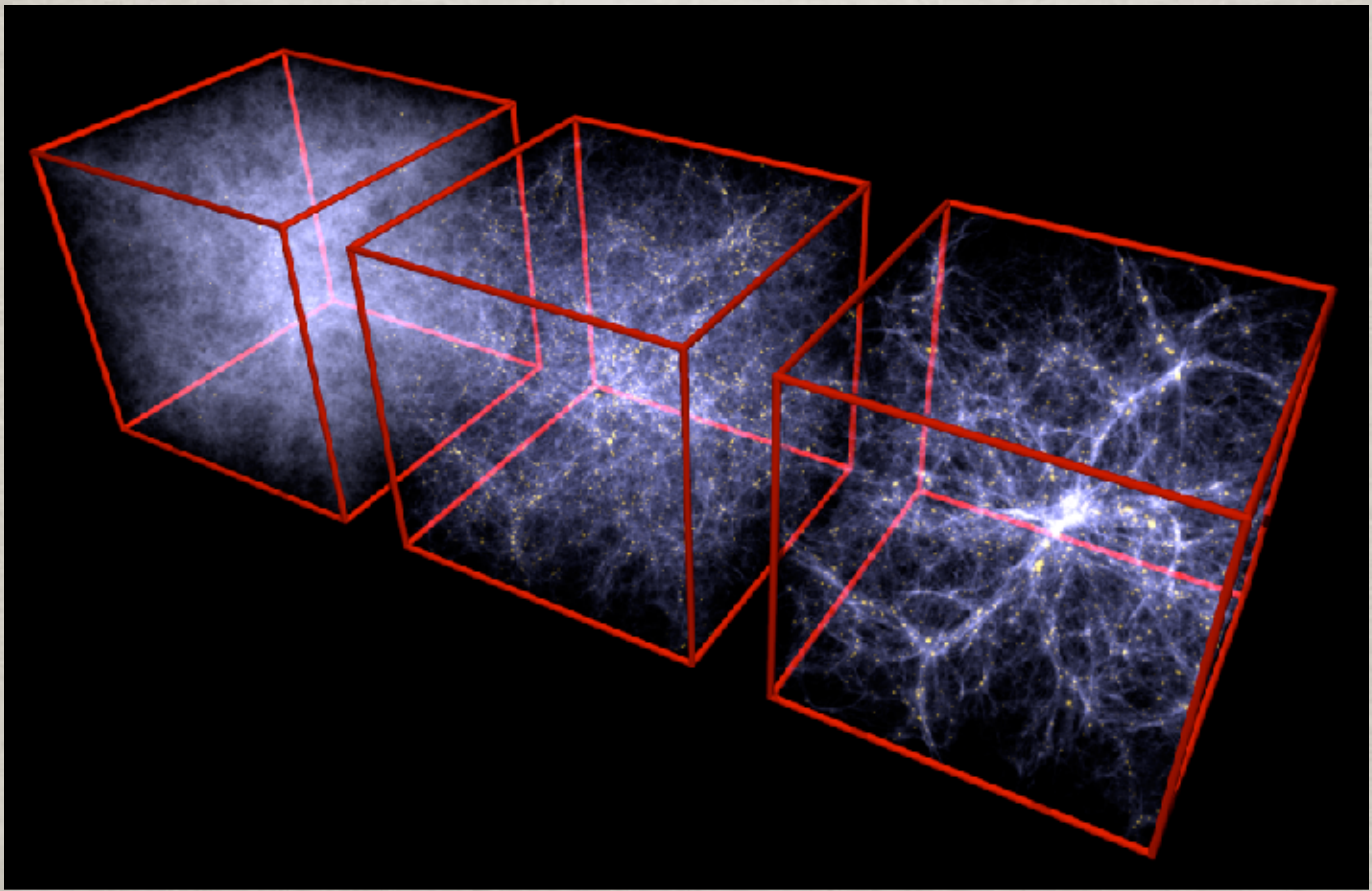
NOTE: much weaker than exponential due to the expansion friction term $\propto H$! Also if the expansion is dominated by radiation, the growth is inhibited and at most only logarithmic in time. We need a long time of matter dominance to make initial fluctuations become large...

Non Linear regime

Structure Formation

V. Springel @MPA Munich

Yoshida et al 03



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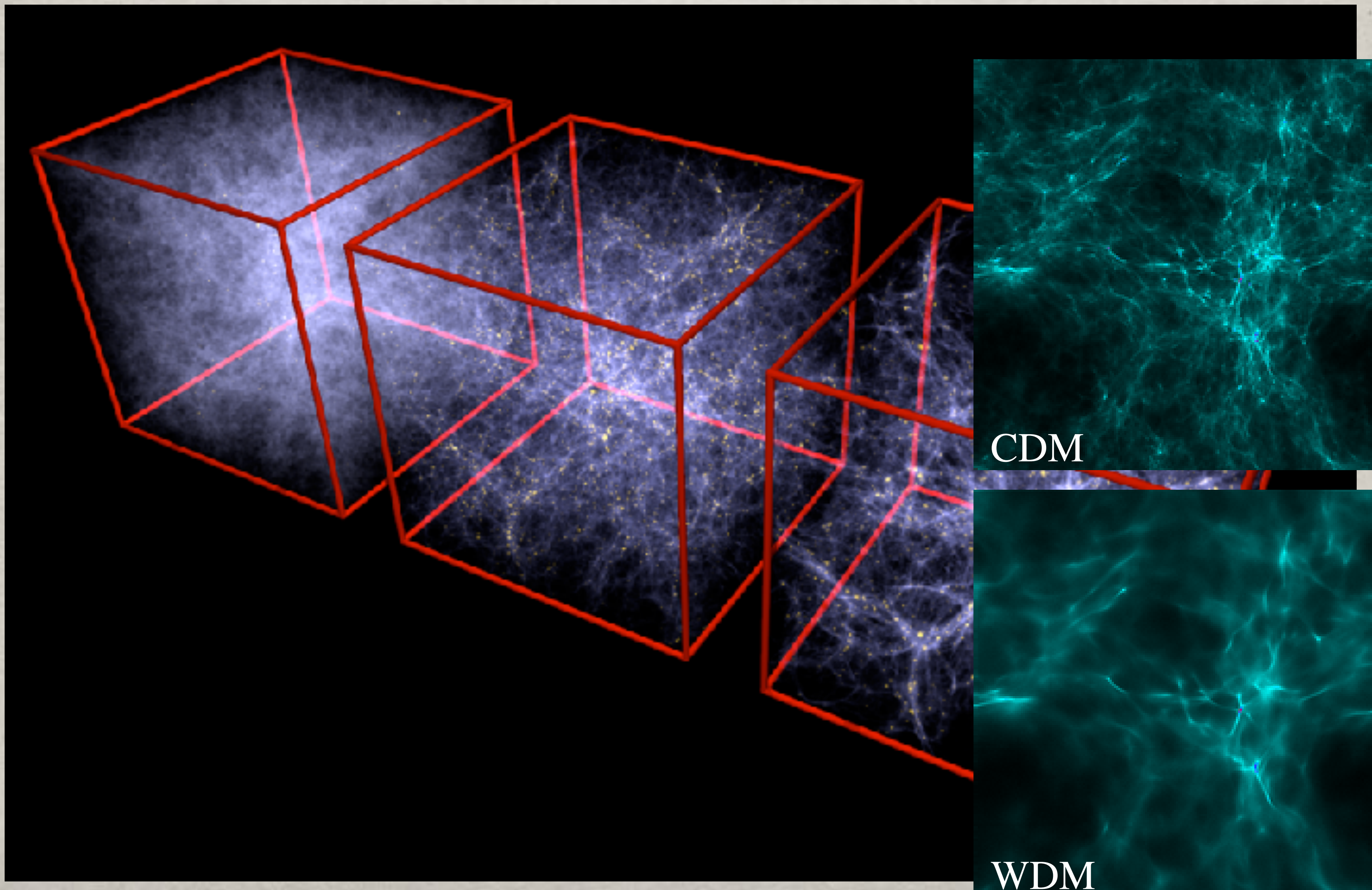
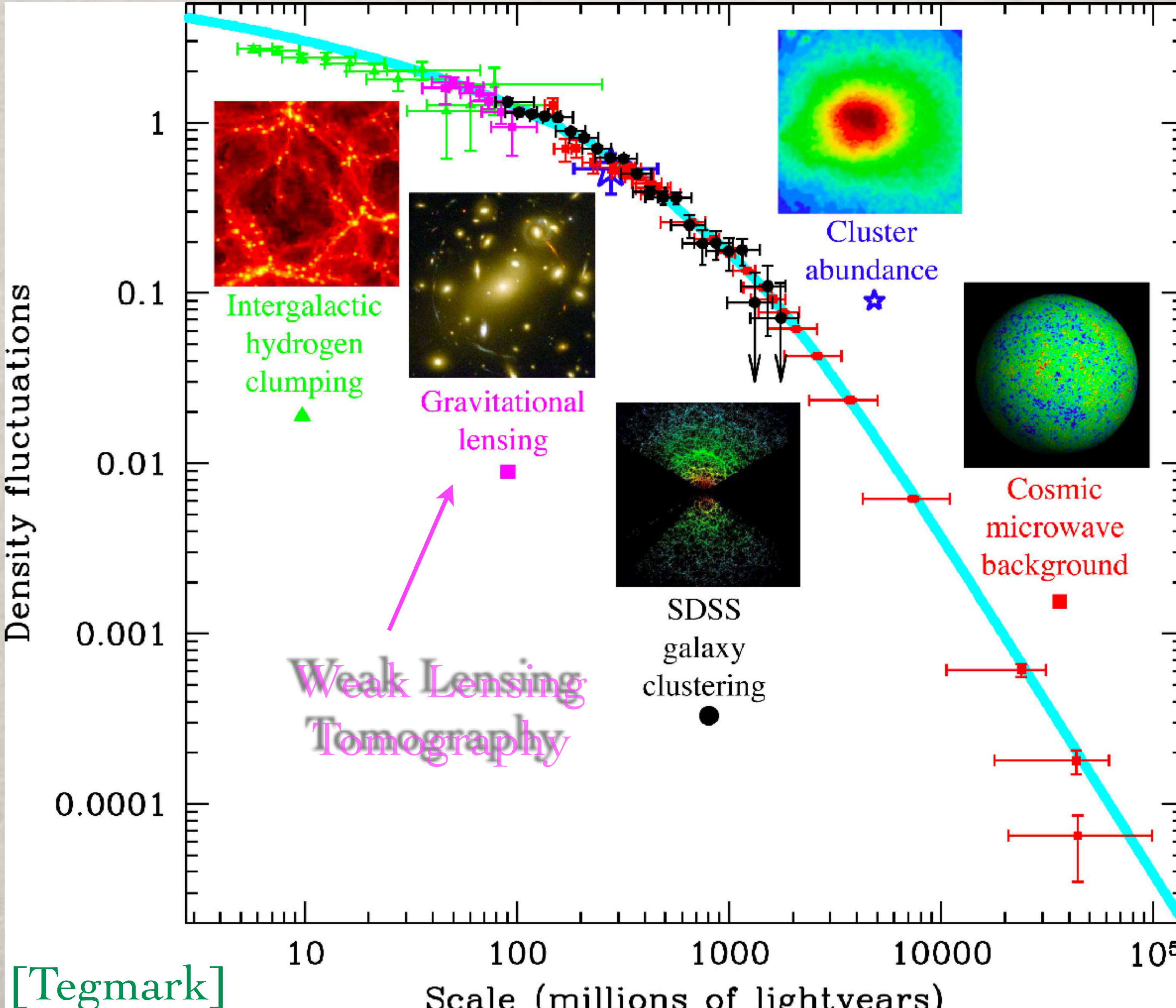


FLUCTUATIONS ON ALL SCALES

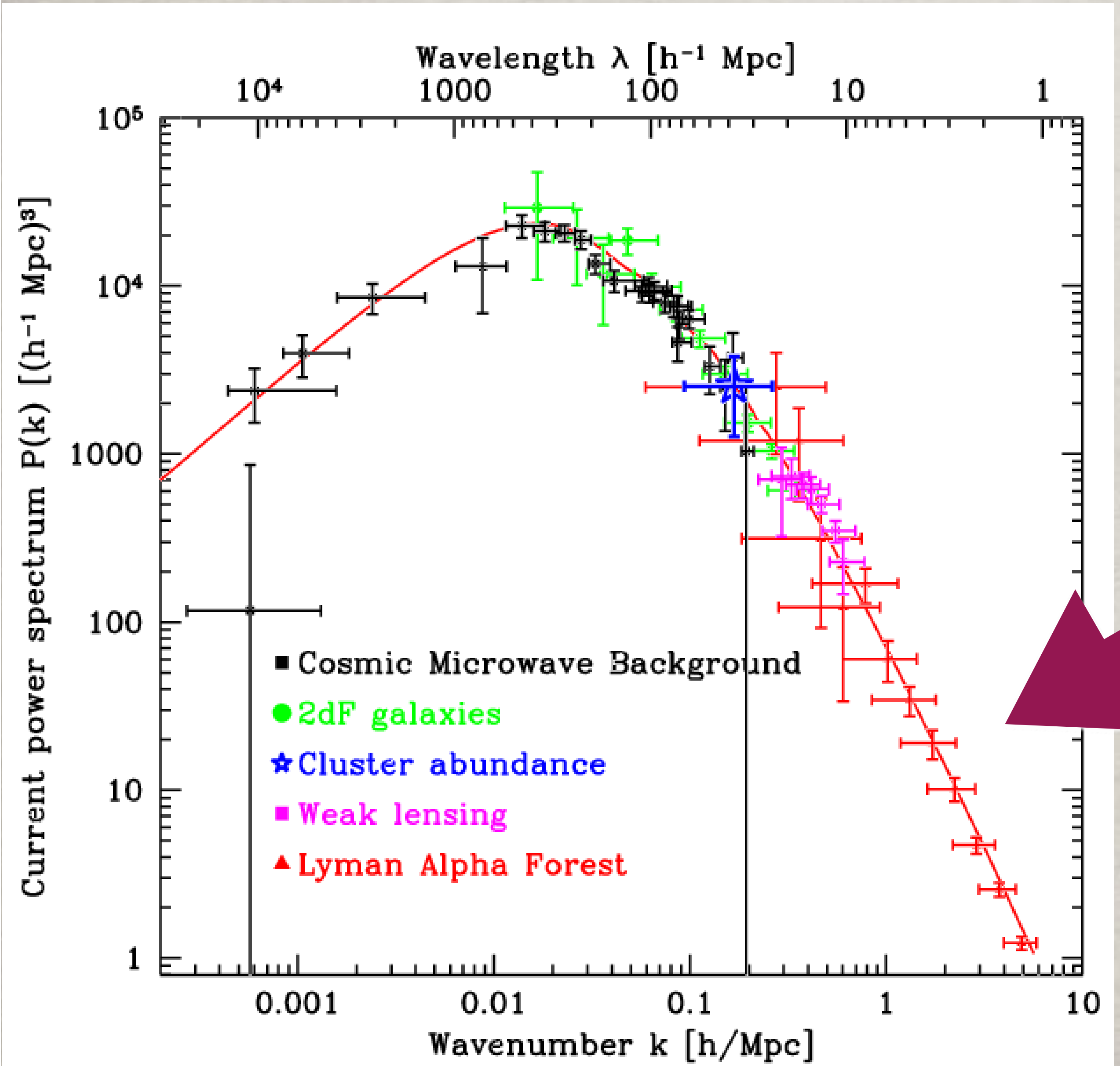
Non-linear



Linear

[Tegmark]

WDM & the Power spectrum



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

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

Compare with the data:

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

[Viel et al. '07]

DARK MATTER PROPERTIES

- Interacts very weakly, but surely gravitationally (electrically neutral, non-baryonic and decoupled from the primordial plasma !!!)

- It must have the right density profile to “fill in” the galaxy rotation curves, i.e. non-dissipative.

- No pressure and negligible free-streaming velocity, it must cluster & cause structure formation.

⬇

COLD DARK MATTER

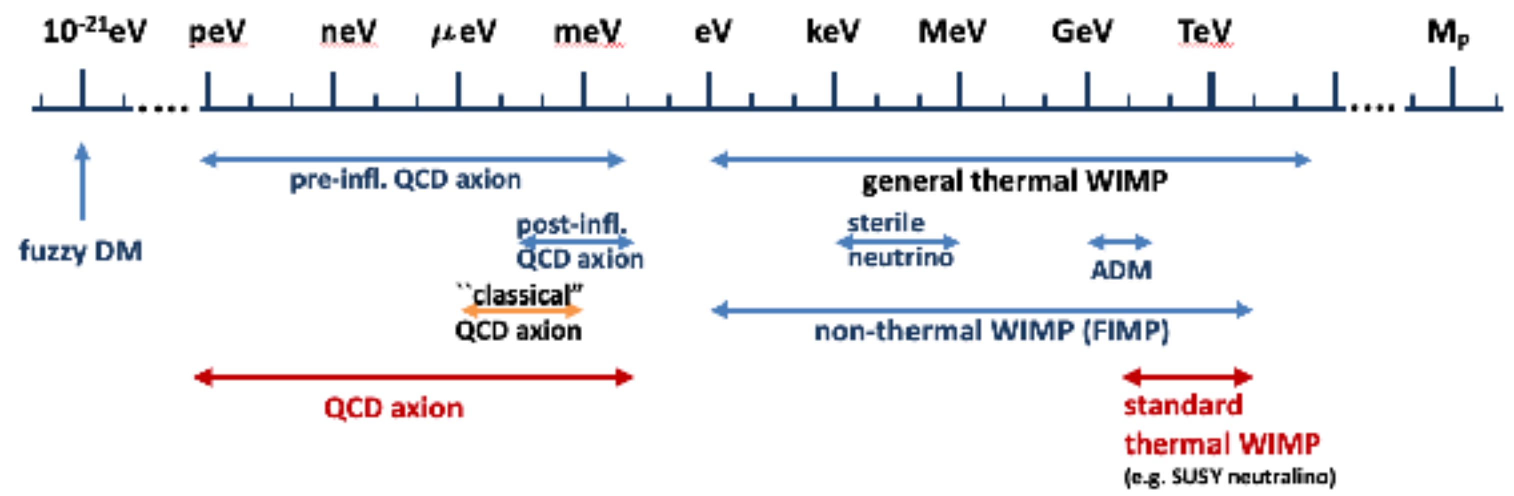
But unfortunately too many realizations !

Guiding principles 4 DM

- The DM particle or the DM sector should fit into a BSM model solving more than the DM problem, e.g. hierarchy, neutrino masses, strong CP problem, etc…

- An effective DM production mechanism should be present, possibly independent from initial conditions.

- Possibly detectable Dark sector in the near future.



DARK MATTER paradigms

GUIDING PRINCIPLES 4 **DM**

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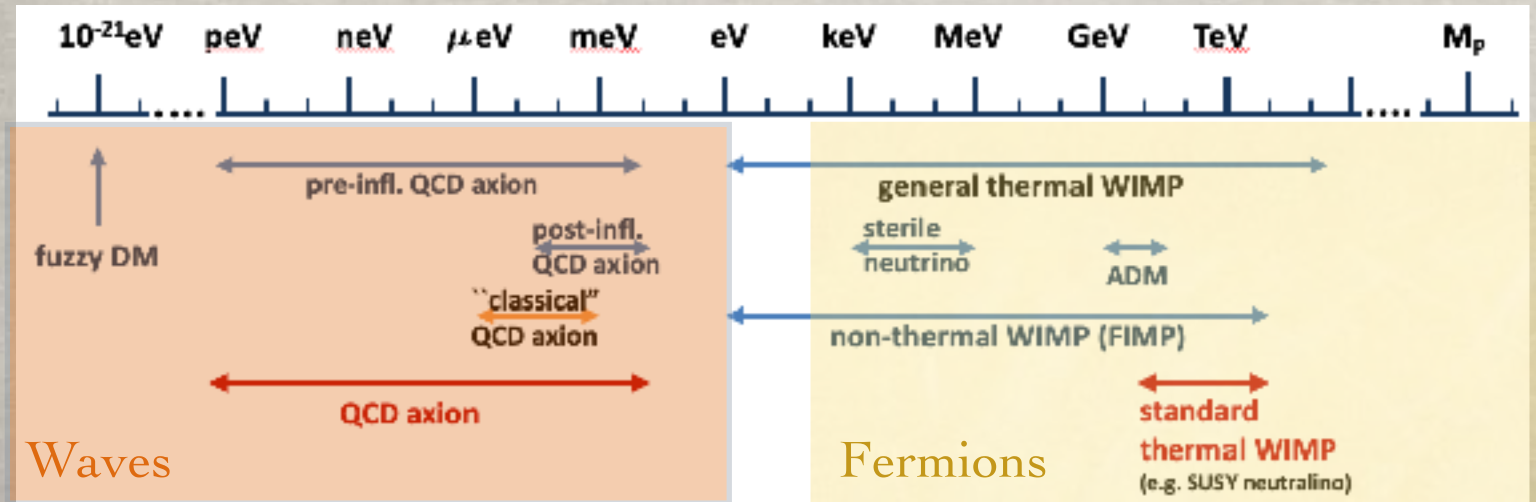
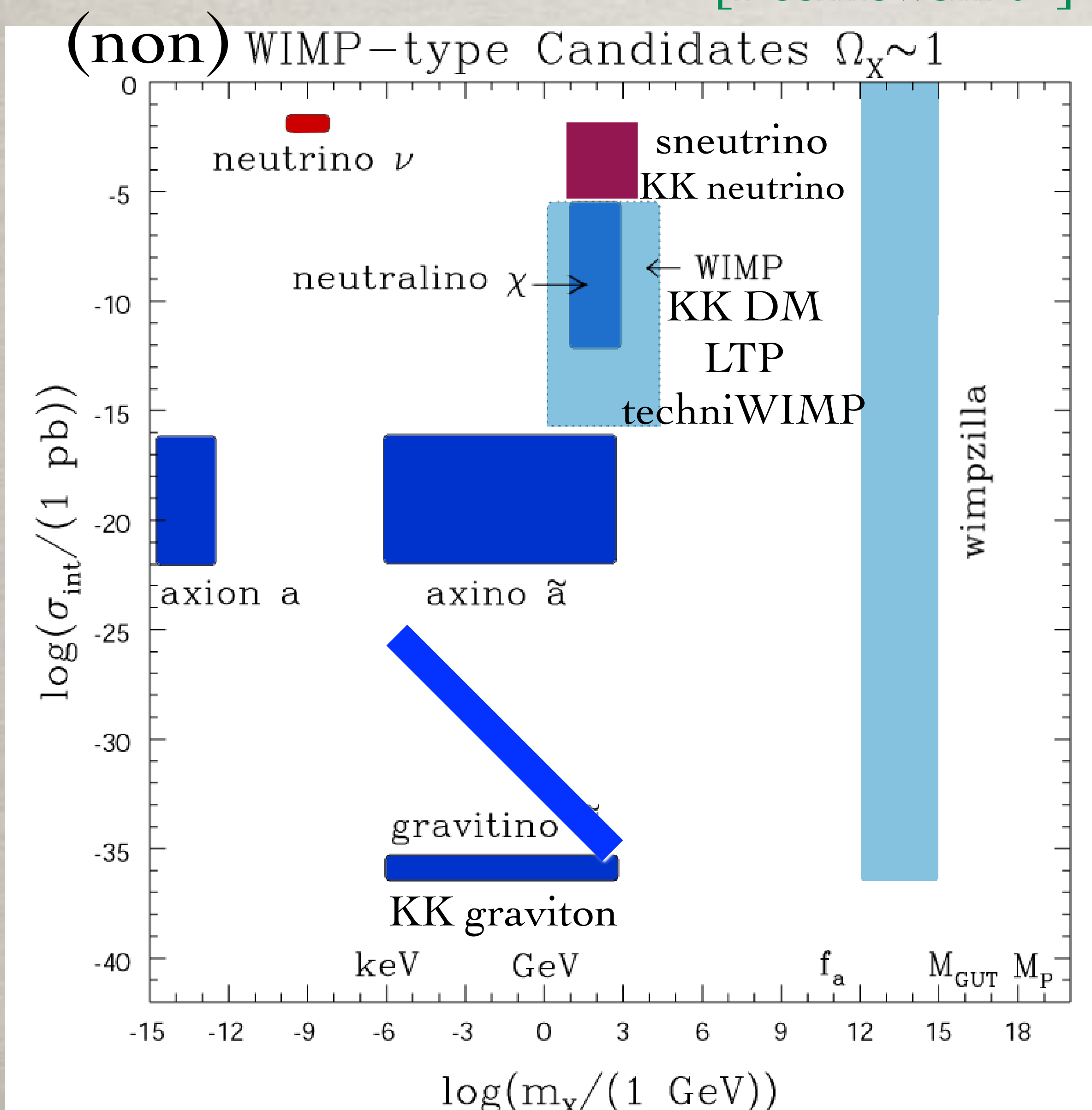


DARK MATTER paradigms

DARK MATTER CANDIDATES

[Roszkowski 04]



Multidimensional space !

DM production paradigms:

WIMPs
(e.g. neutralino)
&
"FIMP/SuperWIMPs"
(e.g. axino/gravitino)
&
Misalignment
(e.g. axion/condensate)

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, DM, etc... ???

Thermal relics: WIMP Dark Matter

Basic formulas

Relativistic particles in thermal equilibrium with p >> m:

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

$$\zeta(3) = 1.202$$

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

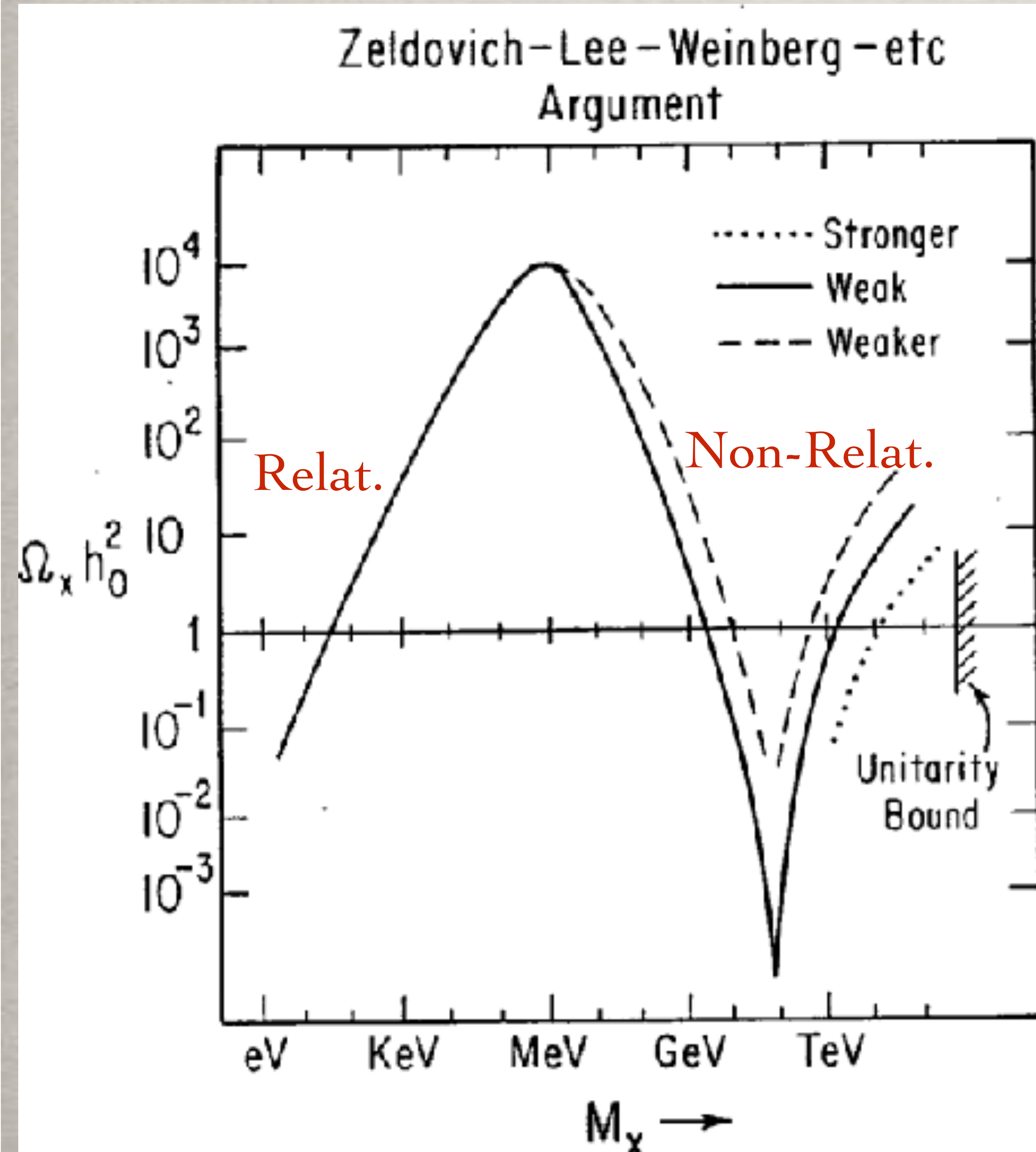
Non-relativistic particles in thermal equilibrium with m >> p:

$$\rho = m \, n$$

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

~ Maxwell-Boltzmann
same for B and F !

Hut-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 !

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

for Dirac (Majorana)

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

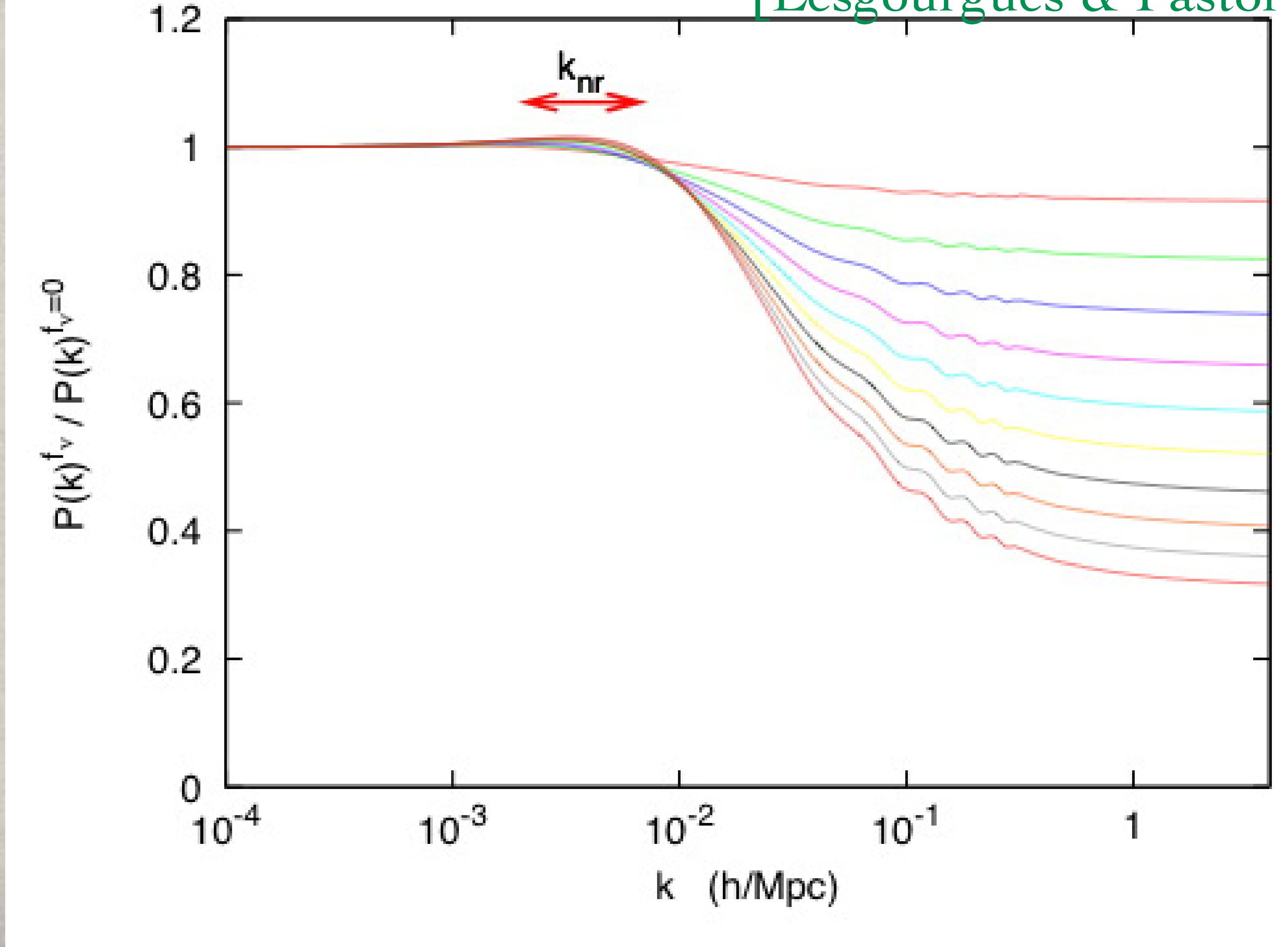
$m_\nu \leq 0.27 \sim 1$ eV → $\Omega_\nu \ll \Omega_{DM}$

NEED to go beyond the Standard Model !

Neutrino as HDM

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

[Lesgourgues & Pastor '14]



$f_\nu \sim 0.01$

$f_\nu \sim 0.02$

$f_\nu \sim 0.1$

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

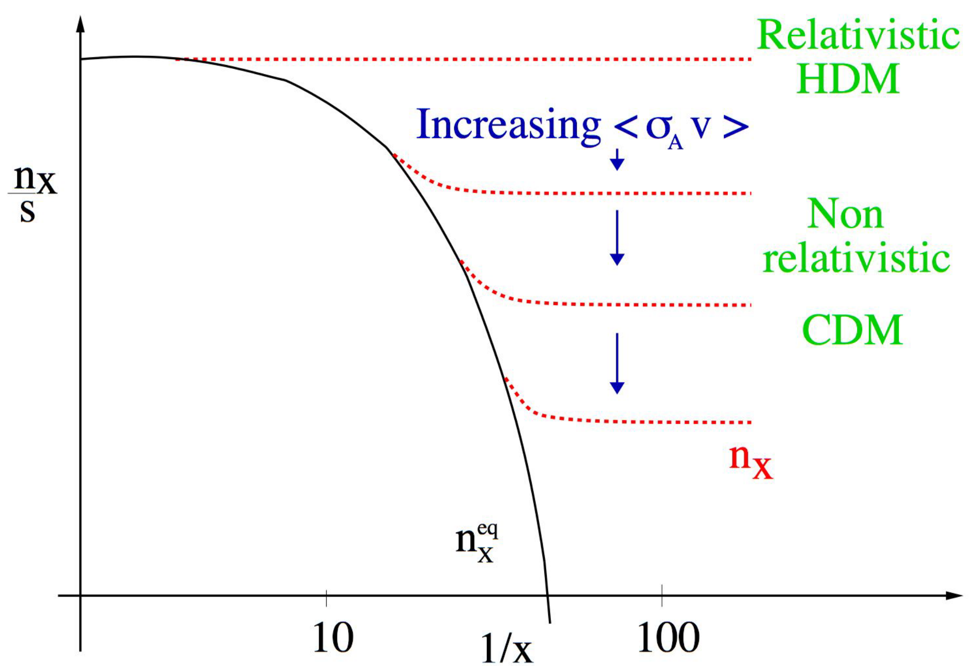
$$\Omega_X = m_X n_X(t_{now}) \quad \propto \quad \frac{1}{\langle \sigma_A v \rangle_{x_f}}$$

Abundance ⇔ Particle properties

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

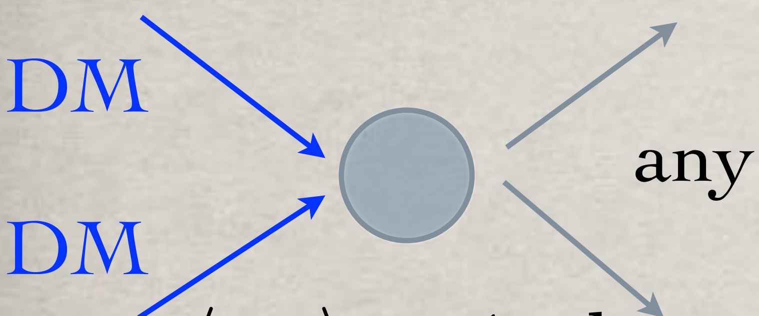
Weakly Interacting Massive Particle

For weaker interactions need lighter masses HOT DM !



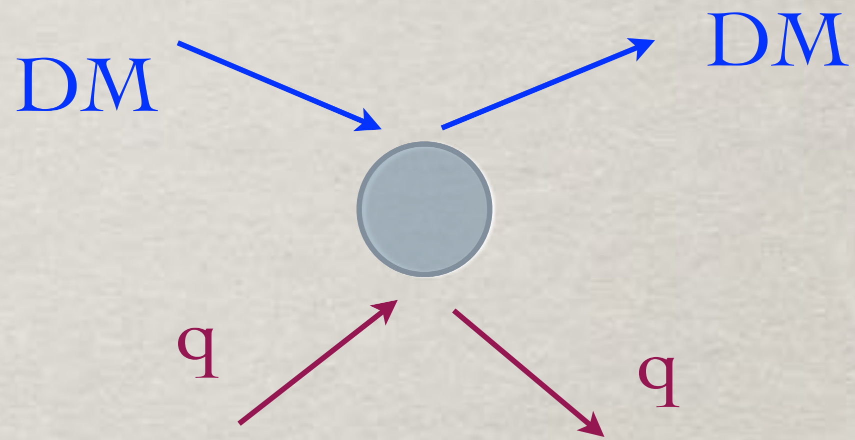
THE WIMP CONNECTION

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

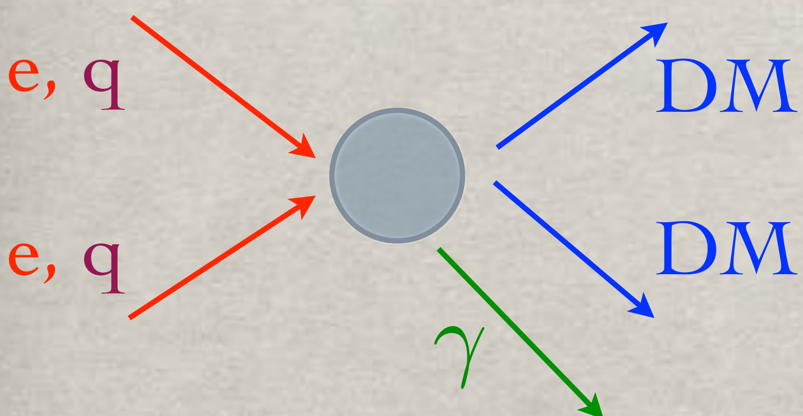


$\langle \sigma v \rangle \sim 1 \text{ pb}$

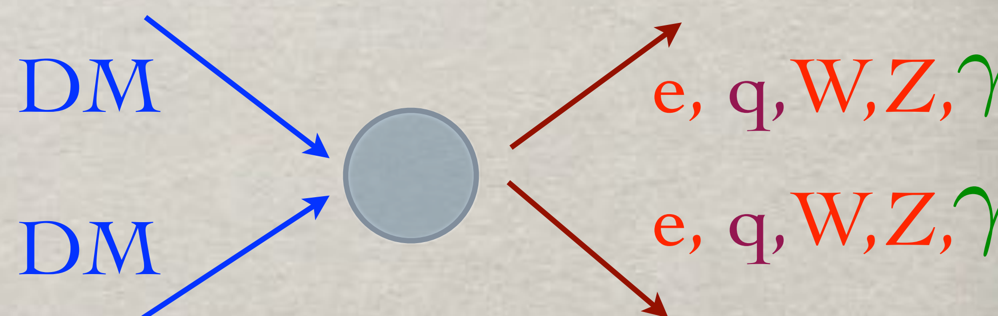
Direct Detection:



Colliders: LHC/ILC



Indirect Detection:

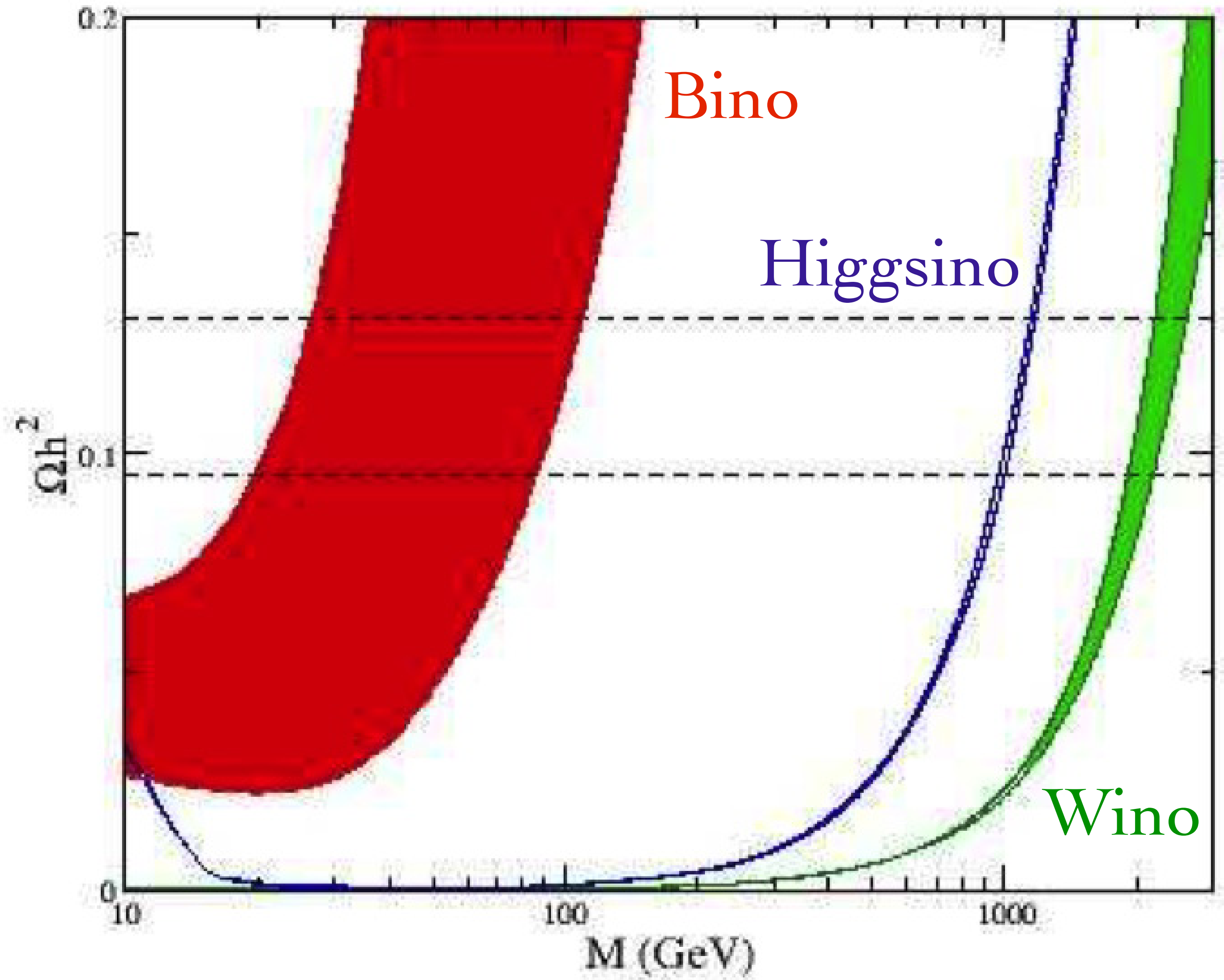


3 different ways to check this hypothesis !!!

Well-tempered neutralino

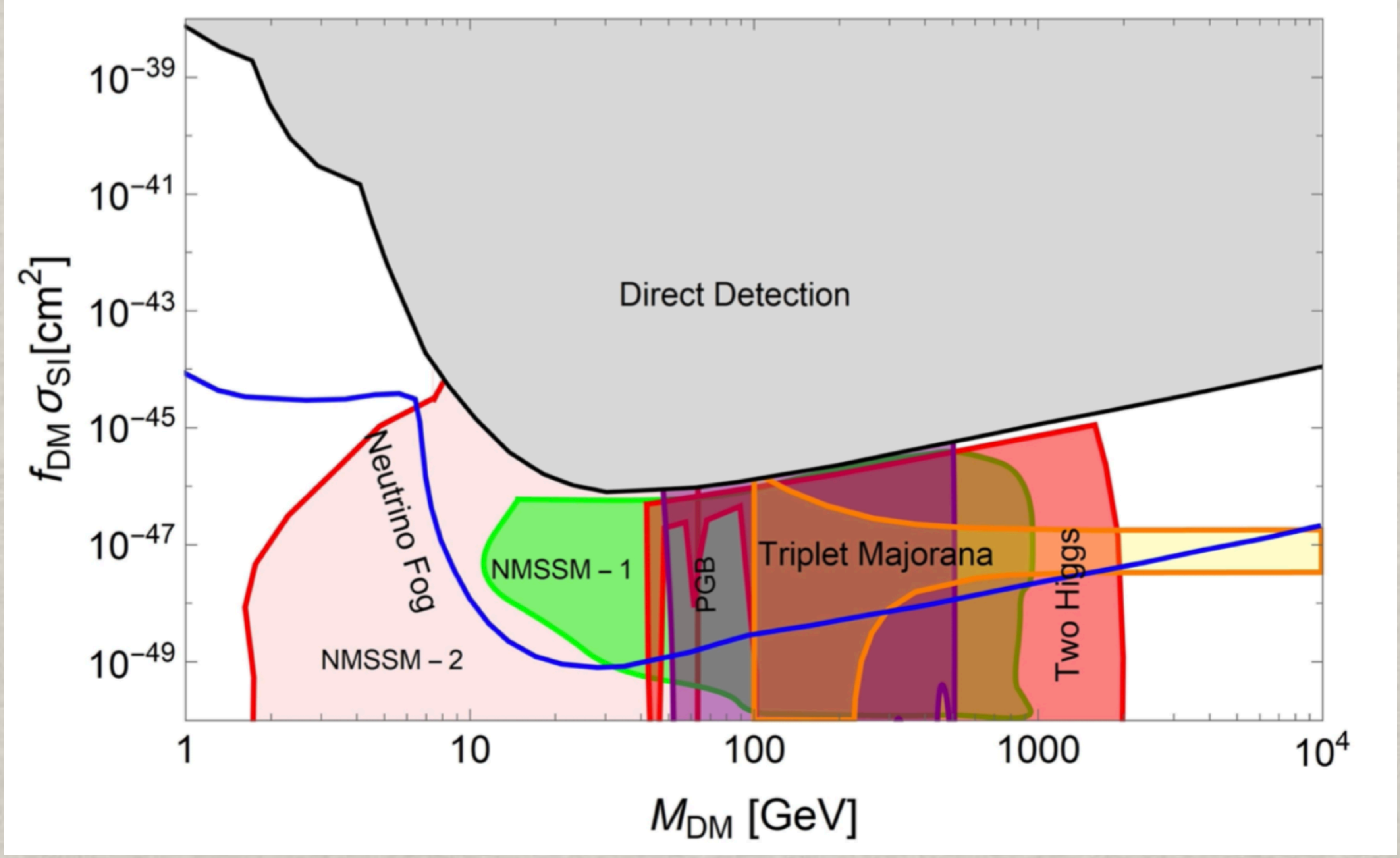
Relic density strongly dependent on neutralino nature !!!

[Arkani-Hamed, Delgado & Giudice 0601041]



WIMP Models...
...not yet excluded !

[Snowmass 2021 Cosmic Frontier ArXiv:2203.08084]

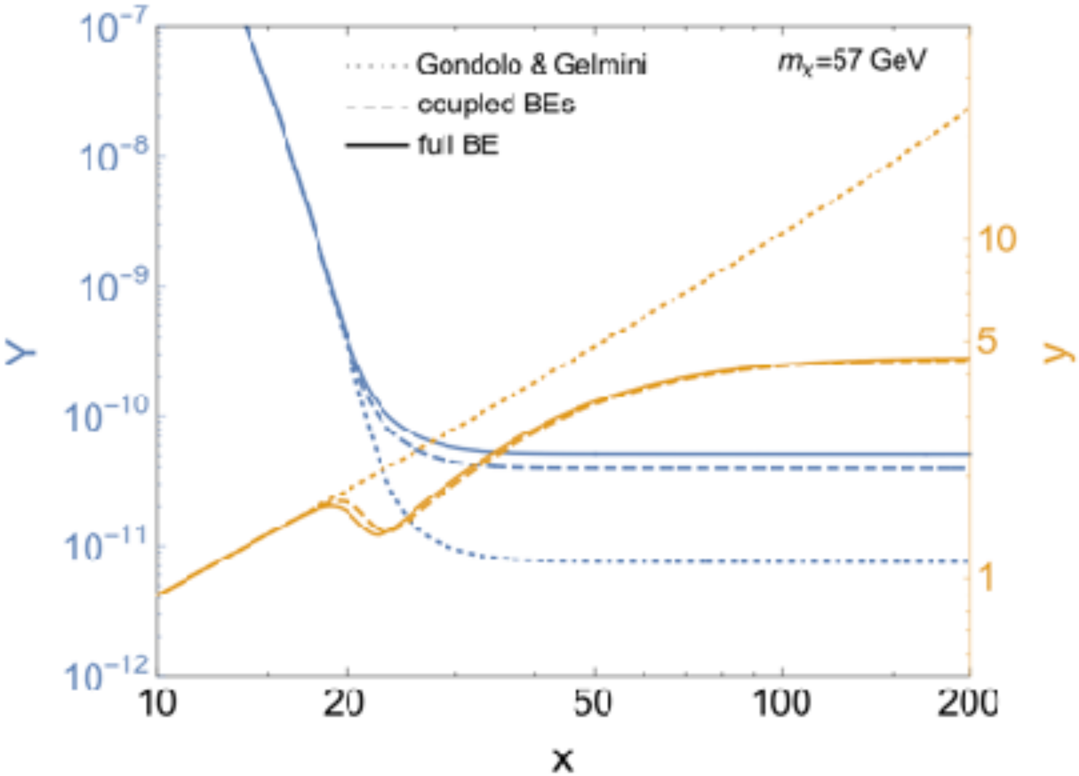


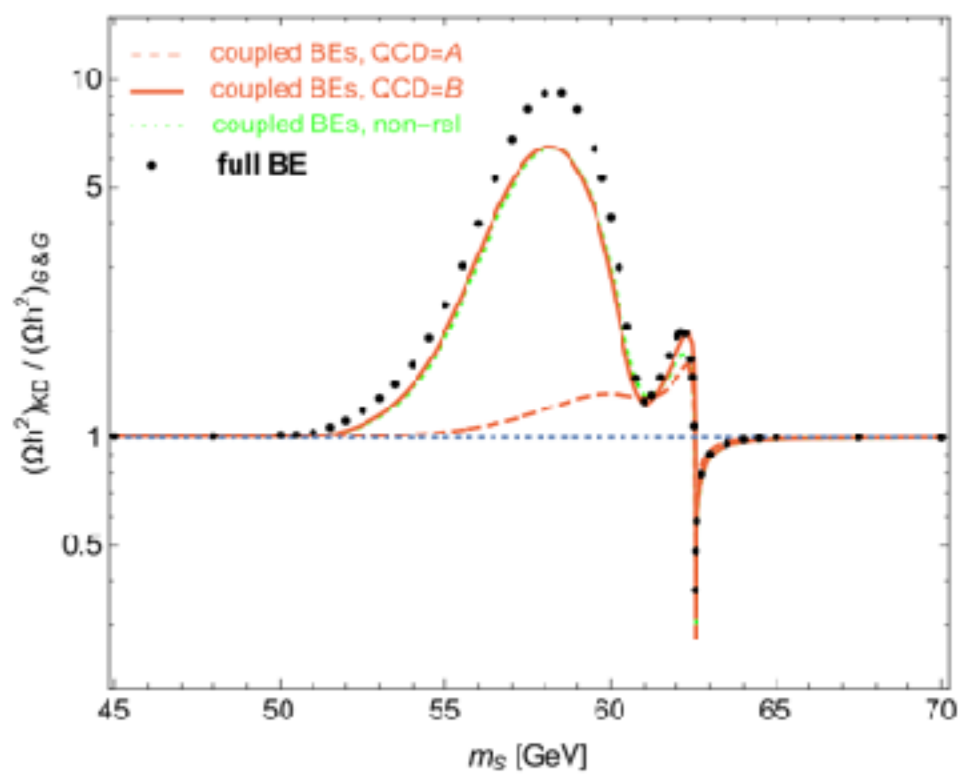
Disentangle production & DD via coannihilation, mixing, etc!

Higgs portal DM

On the Higgs resonance the DM is not in kinetic equilibrium !

[Binder, Bringmann, Gustafsson & Hryczuk 1706.07433]



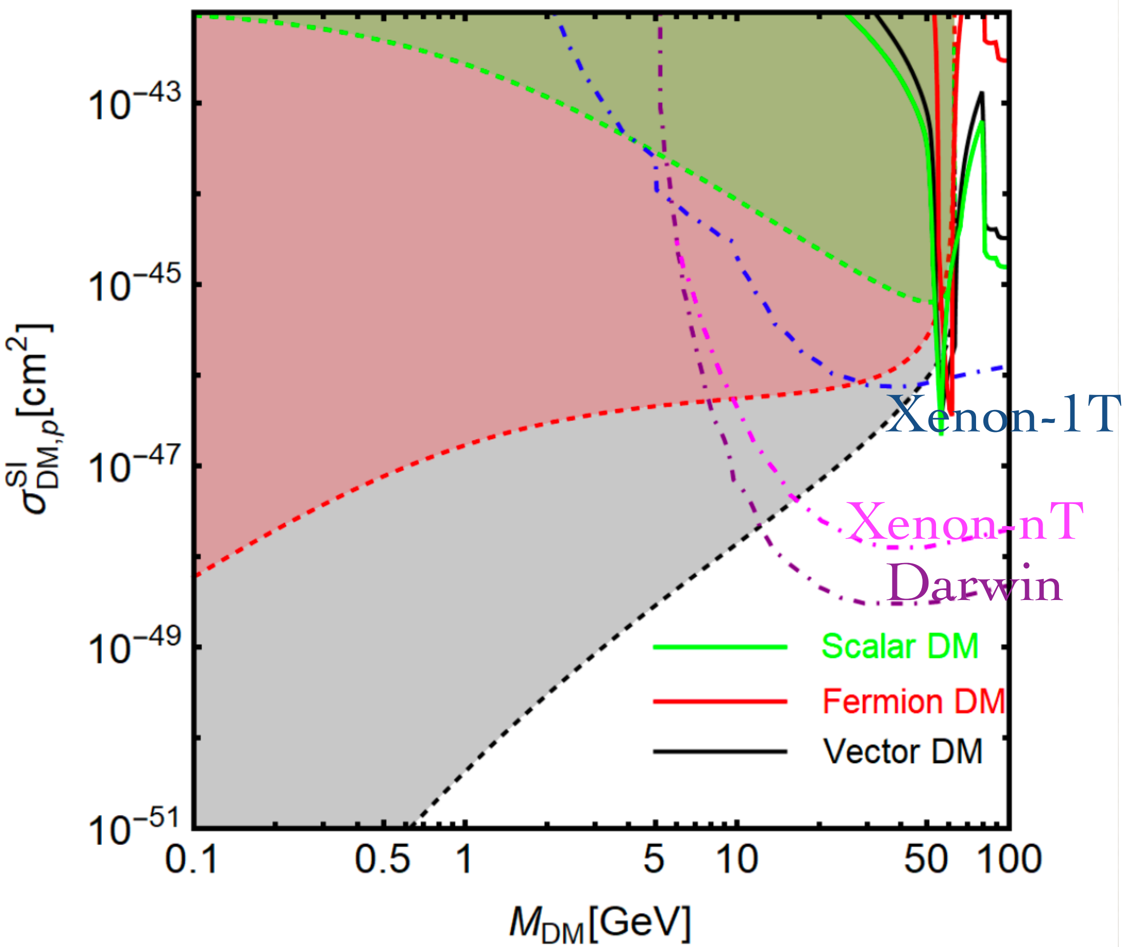


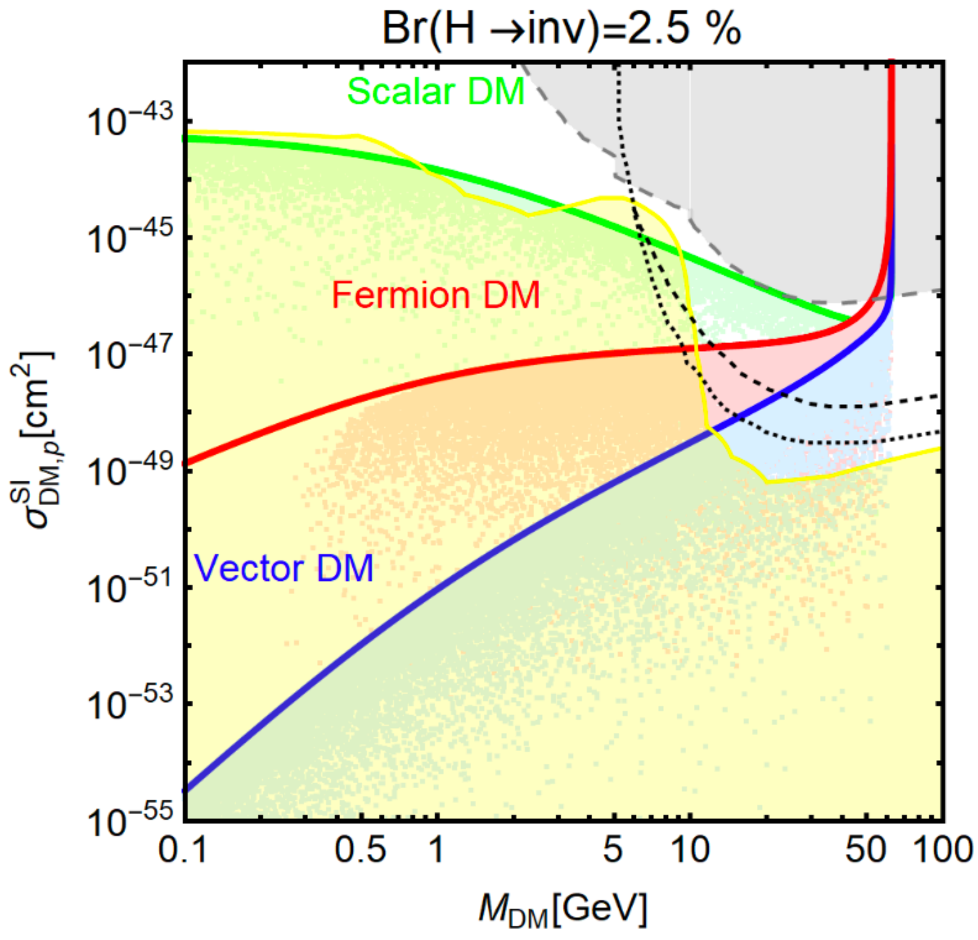
Prediction for DM density strongly modified !

Higgs portal DM

Careful when using EFTs, sometime results change in the full model, e.g. simple example the Higgs portal !

[Arcadi, Djouadi & Kado 2101.02507]



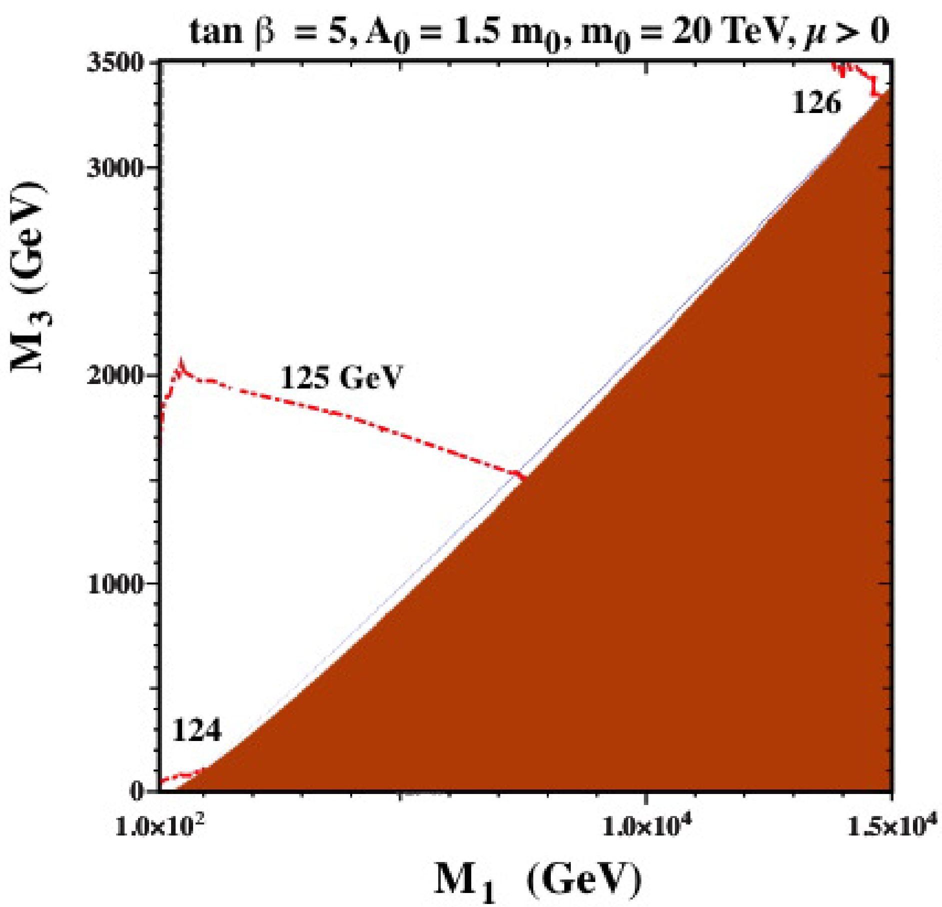


Interference effects can reduce the DD cross-sections !

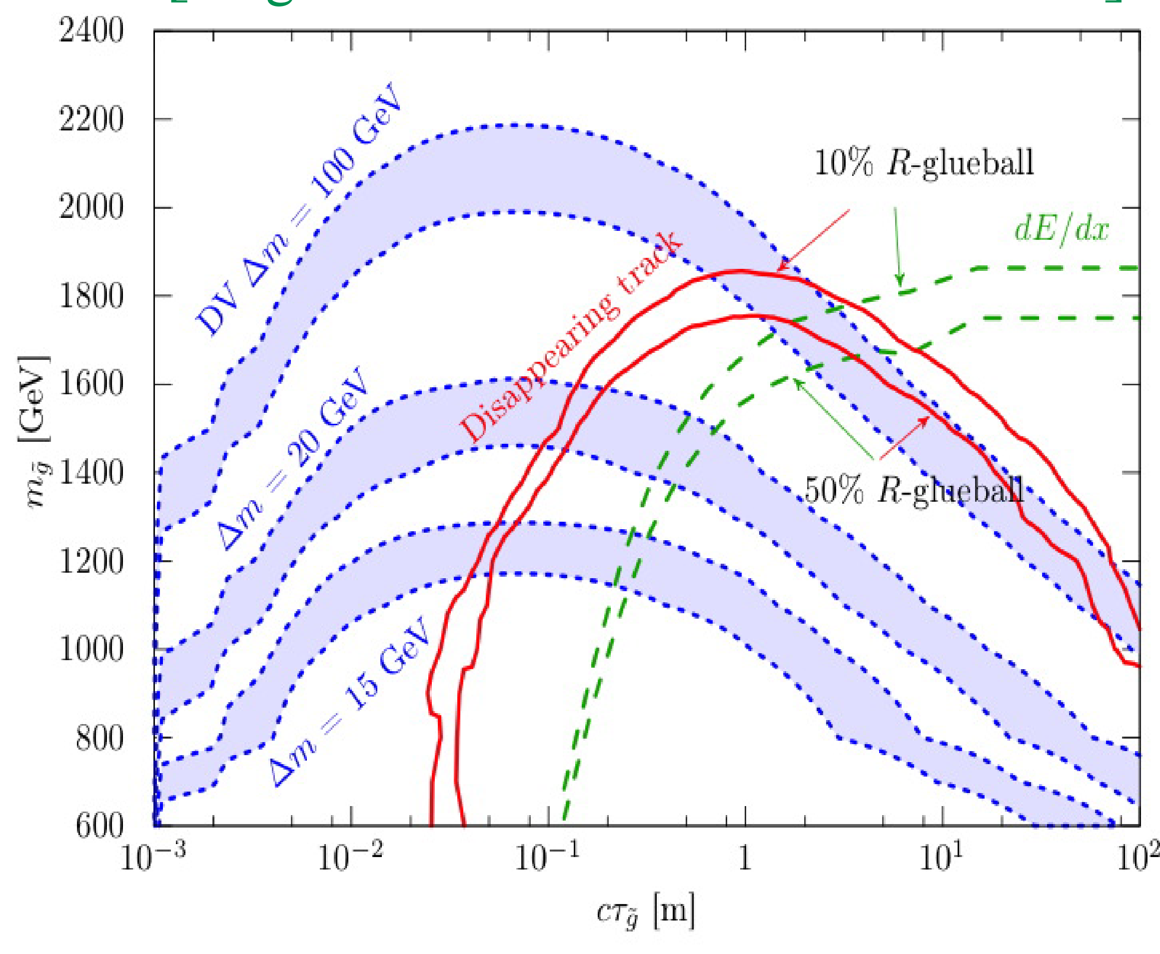
Bino-gluino coannihilation

For non-universal gaugino masses also the gluino plays a role and extends the mass to the multiTeVs !

[Ellis, Evans, Luo & Olive 1510.03498]

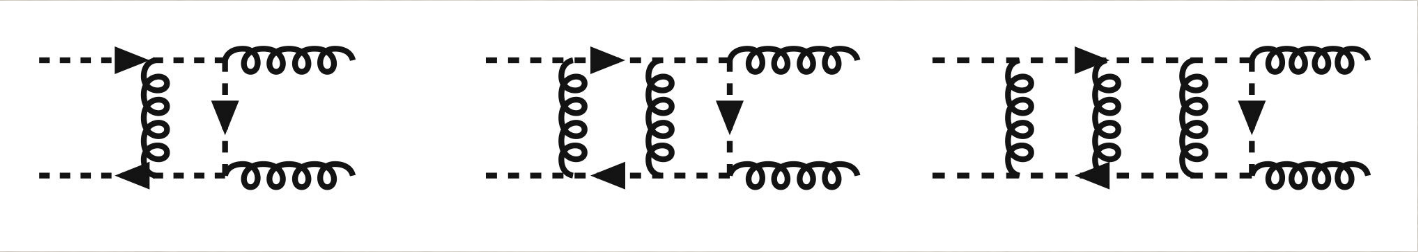


[Nagata, Otono & Shirai 1701.07664]



Sommerfeld Factor

[Sommerfeld 39, Sakharov 48]



- Consider one particle moving in the Coulomb field produced by the other... In Feynman diagrams it correspond to resumming over all ladder diagrams with soft gluons. The effect arises from the long-range nature of the force !
- The cross-section factorizes for a massless gauge boson:

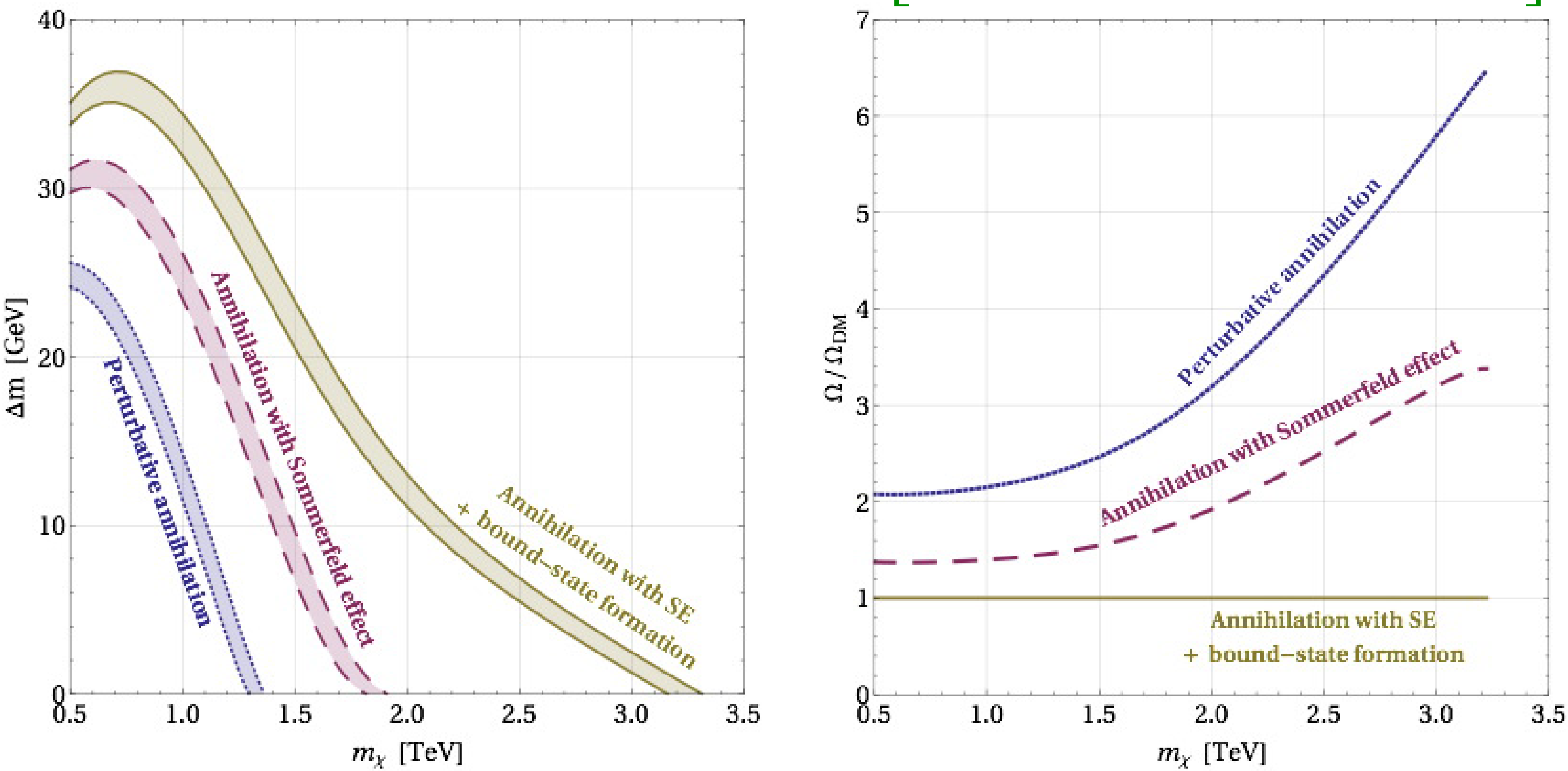
$$\sigma_S = \sigma_0 \times E_S(\beta) \qquad E_S(\beta) = \frac{z}{1 - e^{-z}} \quad \text{with} \quad z = \frac{C\pi\alpha_N}{\beta}$$

- Dominant correction for small velocity !!!

  RELEVANT AT FREEZE-OUT and TODAY !

Sommerfeld Factor for coannihilation

[J. Harz & K. Petraki 2018]



Coannihilation with a colored state:bound states are important !

The stronger annihilation makes higher masses preferred.

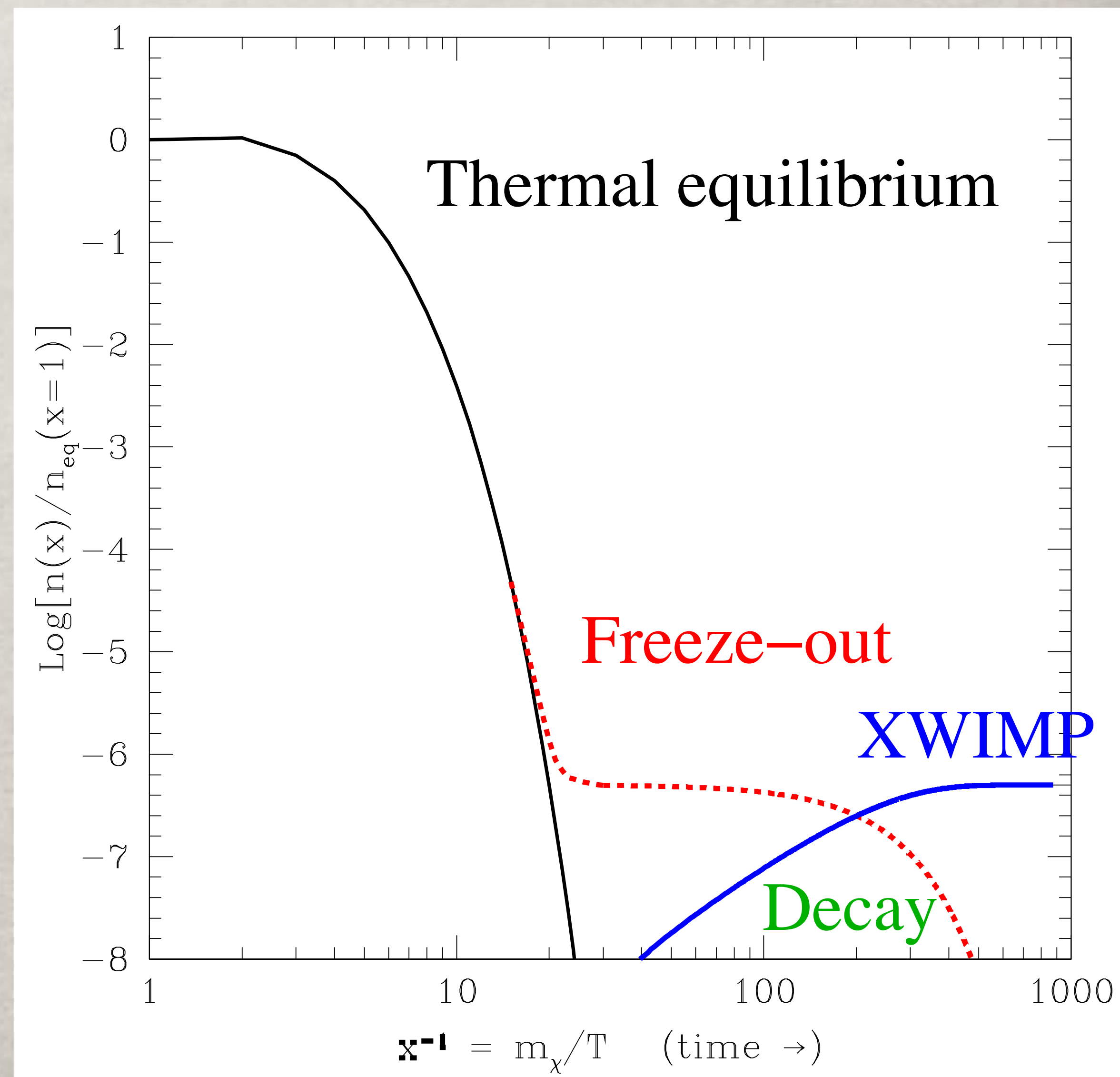
SuperWIMP mechanism

[JE Kim, A.Masiero, D.Nanopoulos *Phys.Lett.B* 139 (1984) 346-350]
[LC, JE Kim, L. Roszkowski *Phys.Rev.Lett.* 82 (1999) 4180-4183]
[J.L. Feng et al. *Phys.Rev.D* 68 (2003)063504]

- A long-lived WIMP particle can decay after decoupling and produce the DM population:

$$\Omega_X^{NT} = \frac{m_X}{m_{NLSP}} \Omega_{NLSP}$$

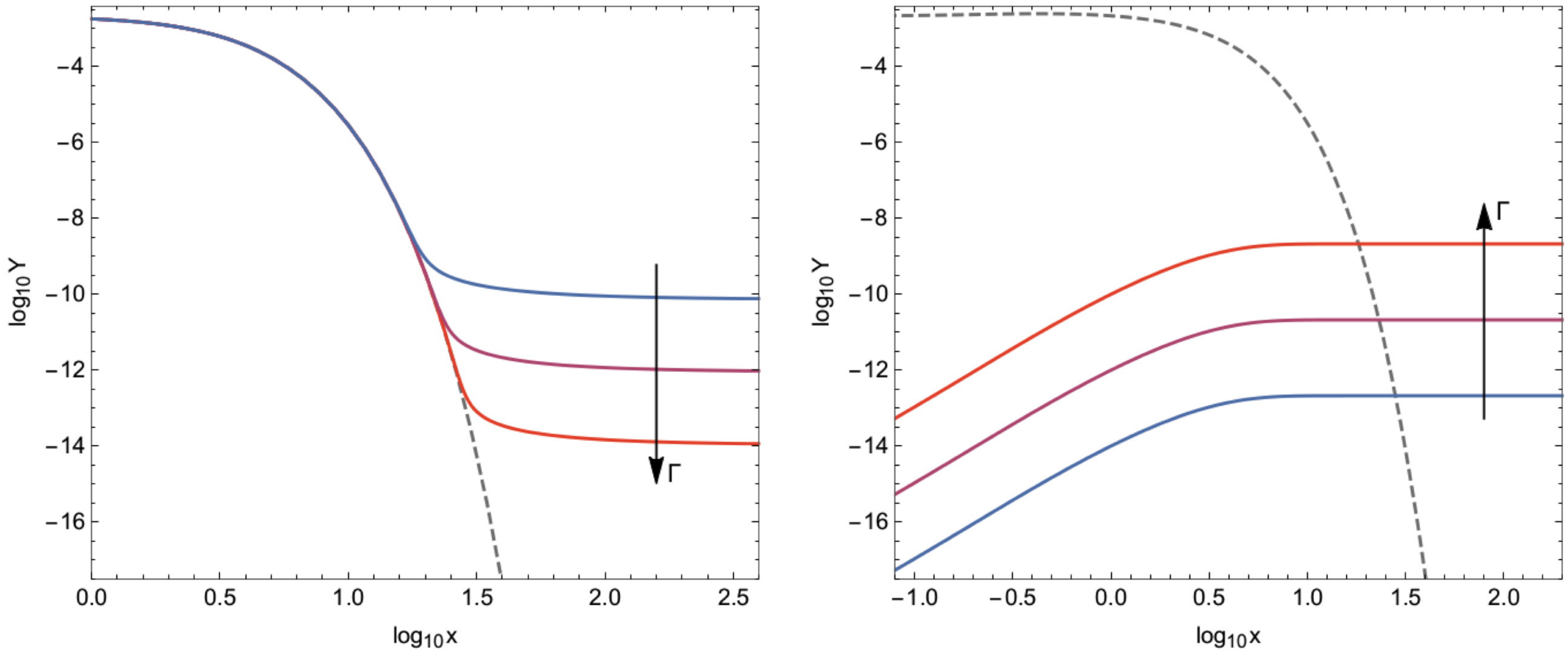
- In the decay also other particles are produced, but they should not disrupt BBN or any other cosmological observable…



SuperWIMP/FIMP paradigms

WIMP vs FIMP Dark Matter

$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$



[Figure from N. Bernal's talk at Invisibles18]

Instead of starting from thermal equilibrium, consider the opposite case: a particle so weakly interacting that is not initially in equilibrium, but it is driven towards it by the interaction with particles in the thermal bath.

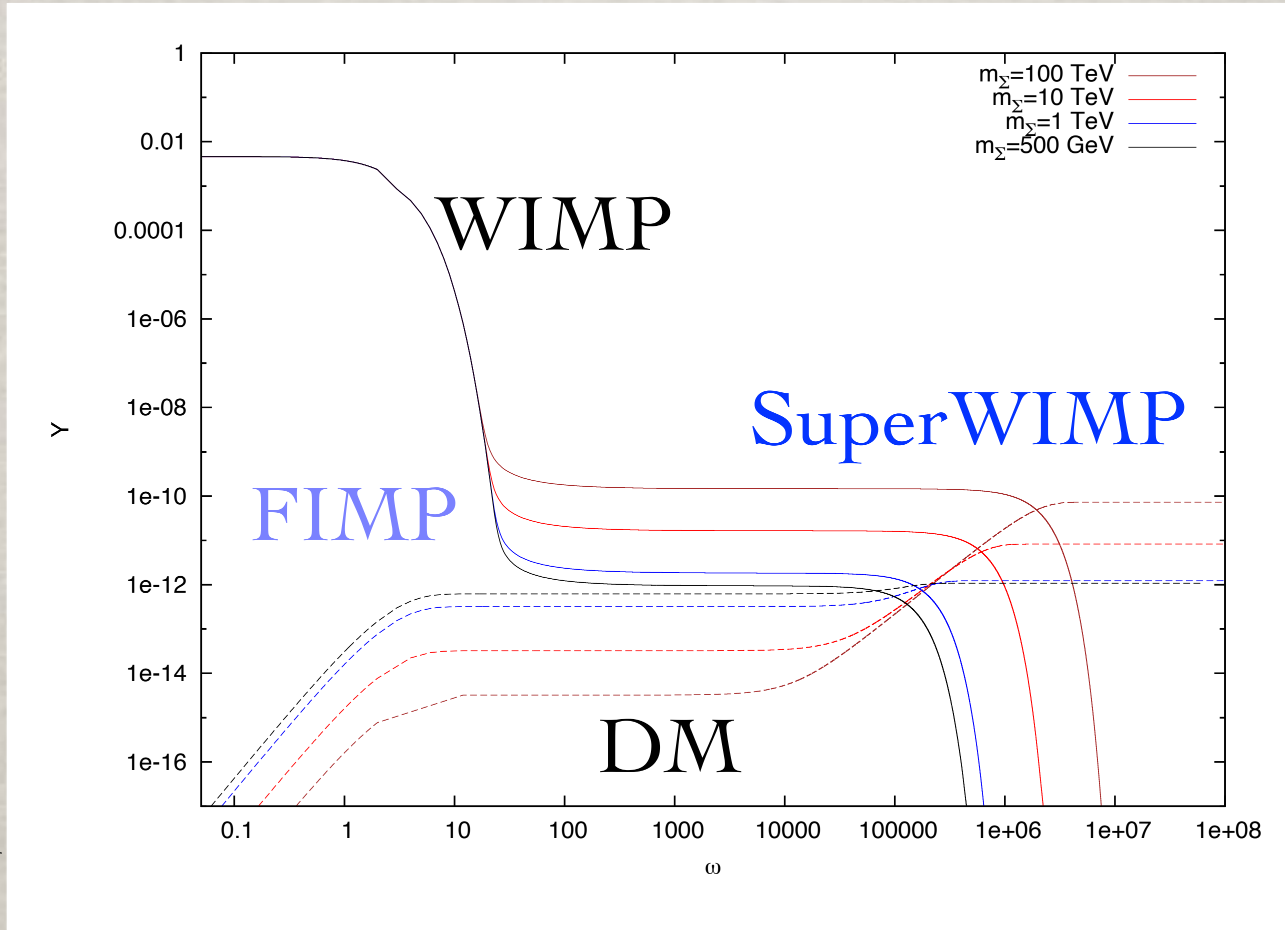
Same Boltzmann equation, but different dynamics !

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:

[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

SuperWIMP / FIMP

- The FIMP/SuperWIMP type of Dark Matter production is effective for any mass of the mother and daughter particle !
- Indeed if the mass ratio is large the WIMP-like density of the mother particle gets diluted:

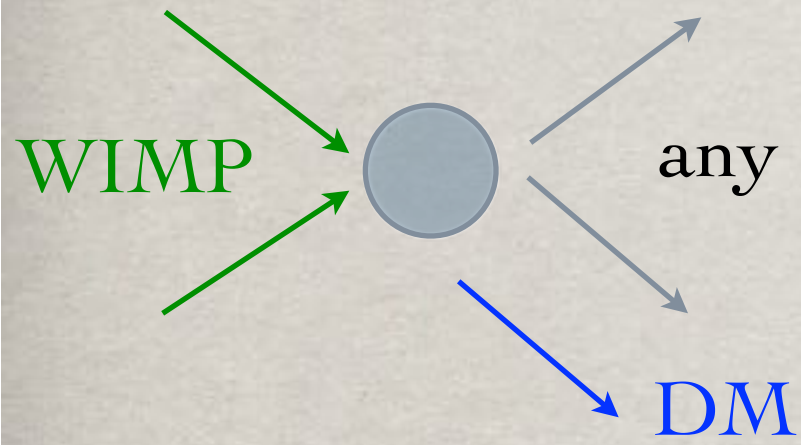
$$\Omega^{SW} h^2 = \frac{m_\psi}{m_\Sigma} \, BR(\Sigma \to \psi) \, \Omega_\Sigma h^2$$

- Moreover the FIMP production is dependent on the decay rate of the mother particle not just the mass and can work also in different parameter regions…

$$\Omega^{FI} h^2 = 10^{27} \frac{g_\Sigma}{g_*^{3/2}} \, \frac{m_\psi \Gamma(\Sigma \to \psi)}{m_\Sigma^2}$$

F/SWIMP CONNECTION

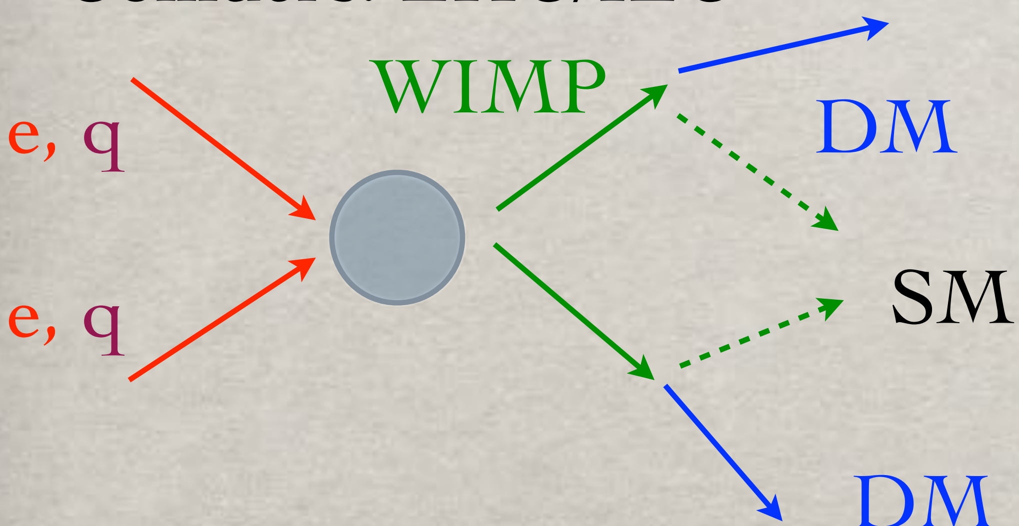
Early Universe: $\Omega_{CDM} h^2$



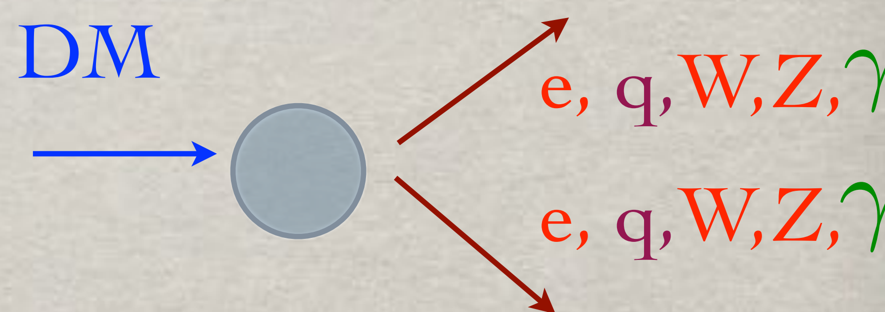
Direct Detection:

NONE...

Colliders: LHC/ILC



Indirect Detection:



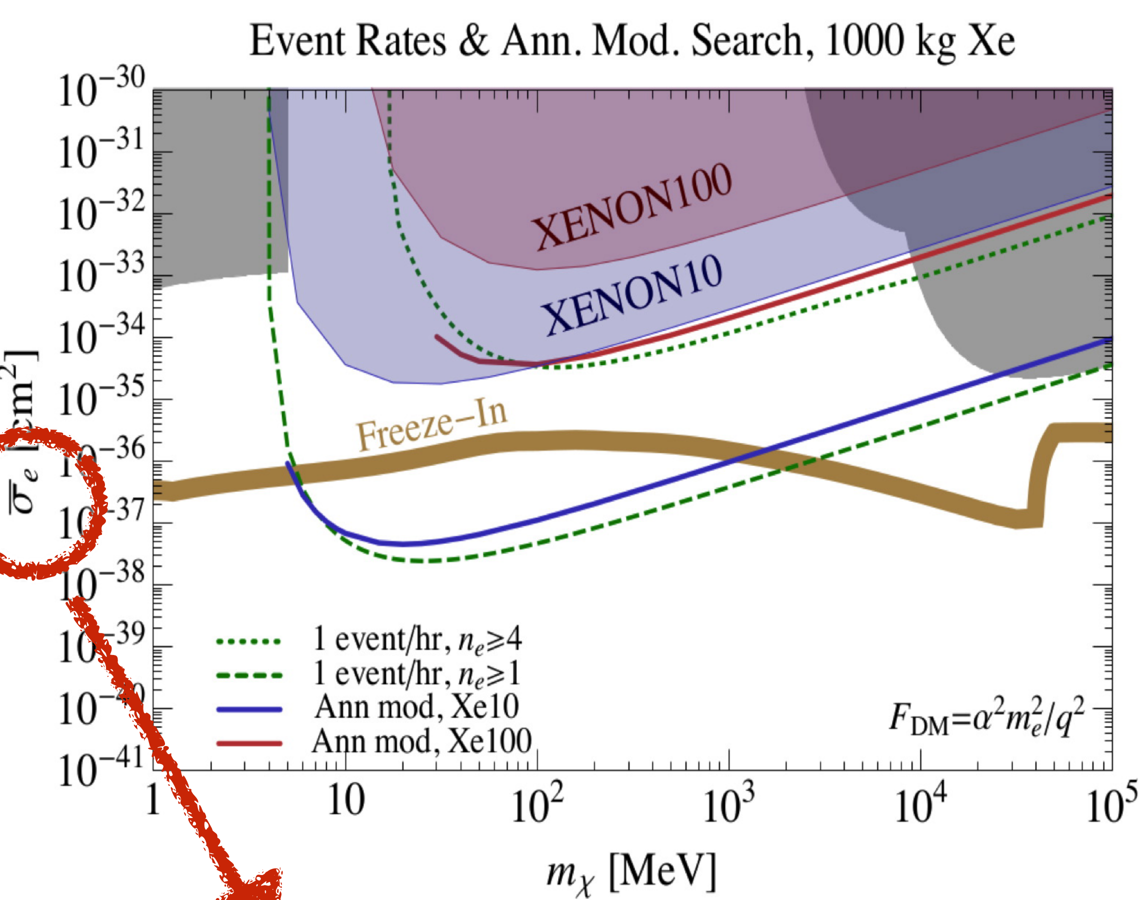
decaying DM !

3 different ways to check this hypothesis !!!

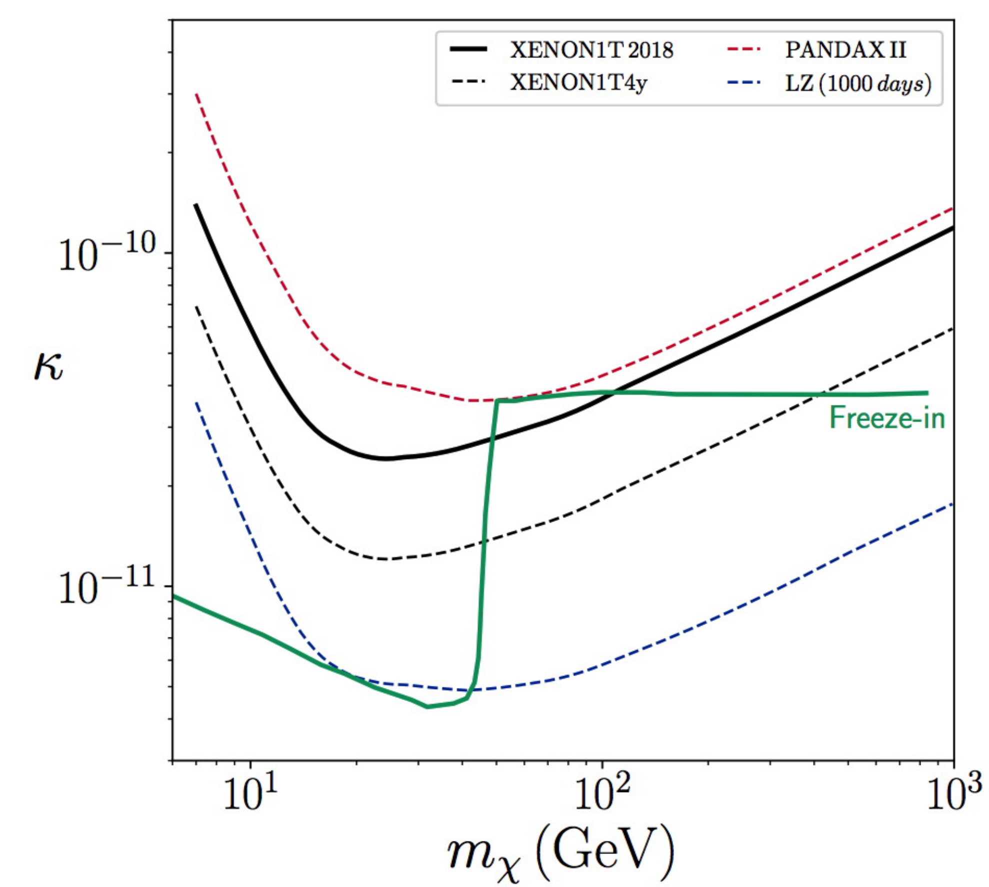
Direct detection of FIMPs

Direct detection experiment start to become sensitive even to tiny couplings, if there is a sufficient enhancement by the number density or a light mediator/Dark Matter !

[Essig, Volansky & Yu 2017]



[Hambye et al. 1807.05022]



Note: here electron scattering !!!

But also low T_RH !

A simple WIMP/SWIMP model

[G. Arcadi & LC 1305.6587]

Consider a simple model where the Dark Matter, a Majorana SM singlet fermion, is coupled to the colored sector via a renormalizable interaction and a new colored scalar Σ :

$$\lambda_\psi \bar{\psi} d_R \Sigma + \lambda_\Sigma \bar{u}^c_R d_R \Sigma^\dagger$$

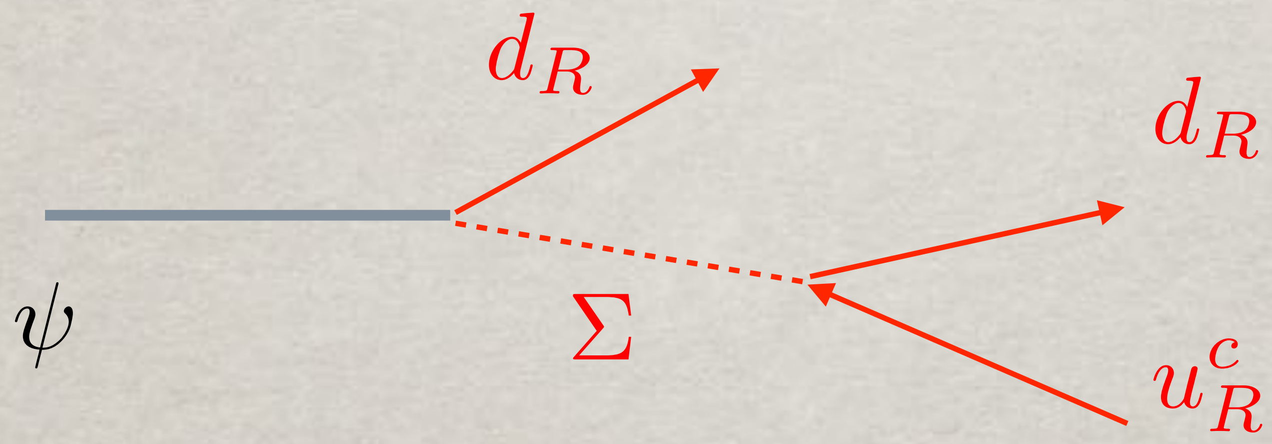
Try to find a cosmologically interesting scenario where the scalar particle is produced at the LHC and DM decays with a lifetime observable by indirect detection.
Then the possibility would arise to measure the parameters of the model in two ways !

→ FIMP/SWIMP connection

A simple WIMP/SWIMP model

[G. Arcadi & LC 1305.6587]

No symmetry is imposed to keep DM stable, but the decay is required to be sufficiently suppressed. For $m_\Sigma \gg m_\psi$:

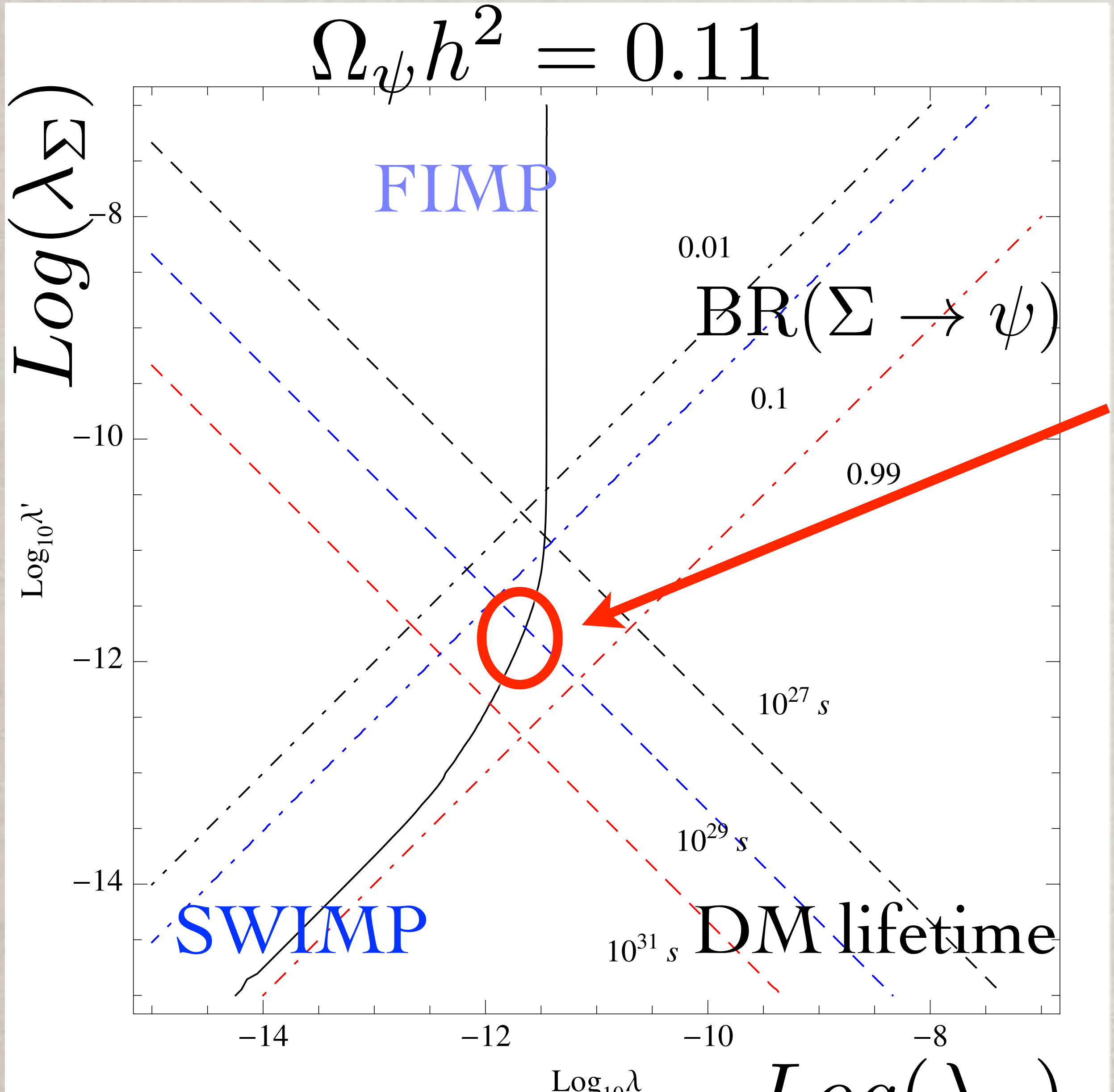


Decay into 3 quarks via both couplings !

To avoid bounds from the antiproton flux require then

$$\tau_\psi \propto \lambda_\psi^{-2} \lambda_\Sigma^{-2} \frac{m_\Sigma^4}{m_\psi^5} \sim 10^{28} s$$

A simple WIMP/SWIMP model



[G. Arcadi & LC 1305.6587]

DM decay observable
in indirect detection
& right abundance
& sizable BR in DM

$\lambda_\psi \sim \lambda_\Sigma$

But unfortunately
Σ decays outside
the detector @ LHC!
Perhaps visible
decays with a bit of
hierarchy...

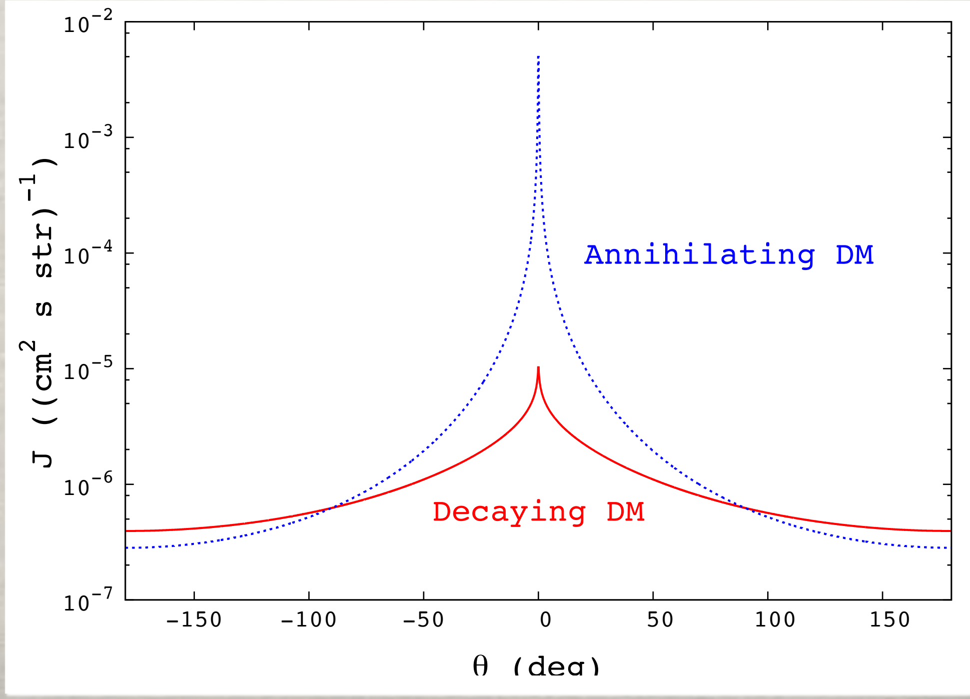
DECAYING DM

- 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...



FIMP/SWIMP at LHC

At the LHC we expect to produce the heavy charged scalar Σ, as long as the mass is not too large... In principle the particle has two channels of decay with very long lifetimes.
Fixing the density by FIMP mechanism we have:

$$l_{\Sigma,DM} = 2.1 \times 10^5 \mathrm{m}\, g_\Sigma x \left(\frac{m_{\Sigma_f}}{1\mathrm{TeV}}\right)^{-1} \left(\frac{\Omega_{CDM}h^2}{0.11}\right)^{-1} \left(\frac{g_*}{100}\right)^{-3/2}$$

Very long apart for small DM mass, i.e. $x = \dfrac{m_{DM}}{m_{\Sigma_f}} \ll 1$

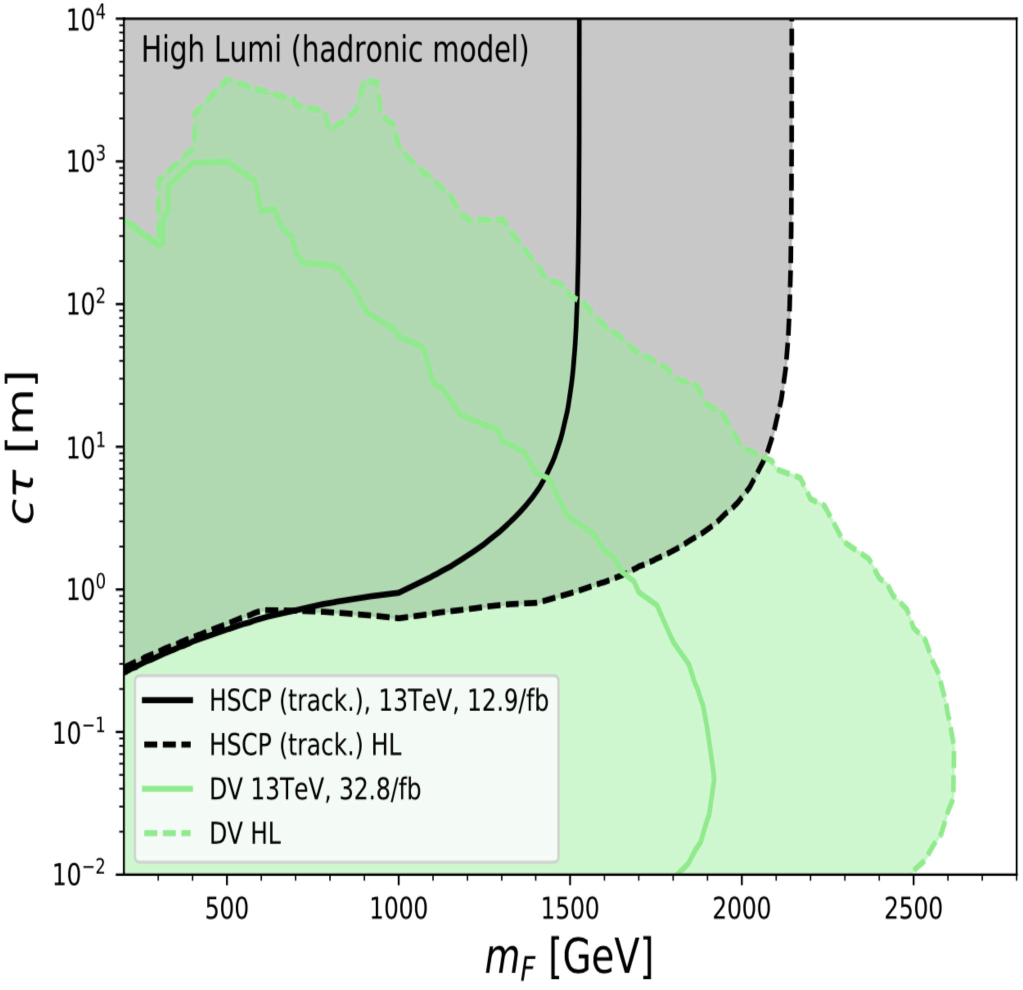
Moreover imposing ID "around the corner" gives

$$l_{\Sigma,SM} \simeq 55\,\mathrm{m}\, \frac{1}{g_\Sigma} \left(\frac{m_{\Sigma_f}}{1\mathrm{TeV}}\right)^{-4} \left(\frac{m_\psi}{10\mathrm{GeV}}\right)^{4} \left(\frac{\tau_\psi}{10^{27}\mathrm{s}}\right) \left(\frac{\Omega_{CDM}h^2}{0.11}\right) \left(\frac{g_*}{100}\right)^{3/2}$$

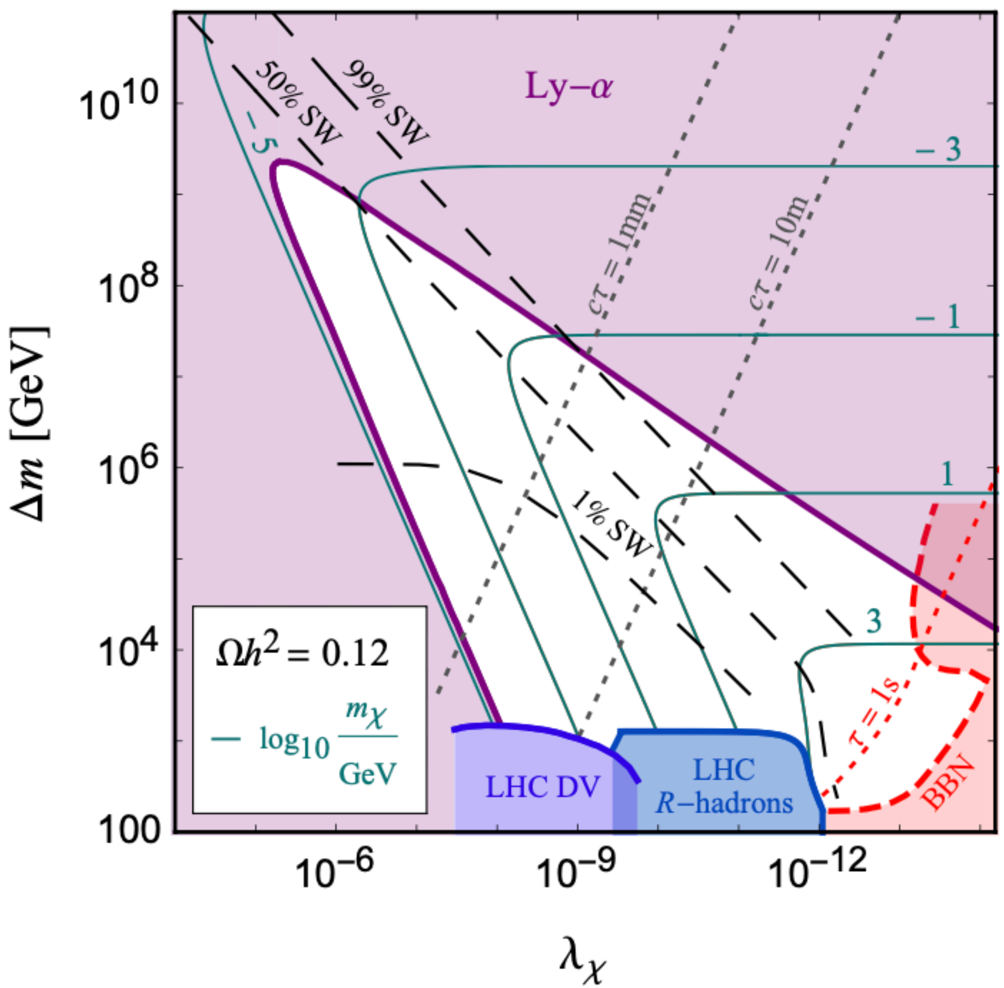
At least one decay could be visible !!!

LHC and Cosmo bounds

[G. Belanger et al. 1811.05478]



[Q. Decant et al. 2111.09321]



Here DM is the scalar and the Fermion is charged under QCD