

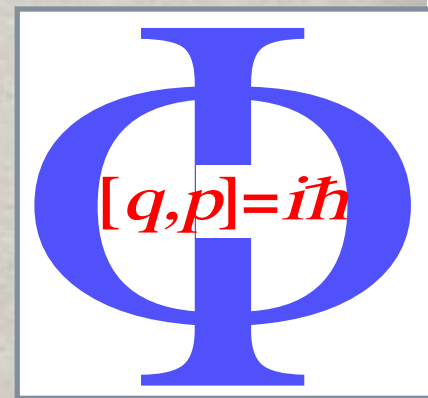
ISSP - 60th Course - News from the Four Interactions
Erice, 18-20th June 2024

ON THE DARK SIDE OF THE UNIVERSE (THEORY)



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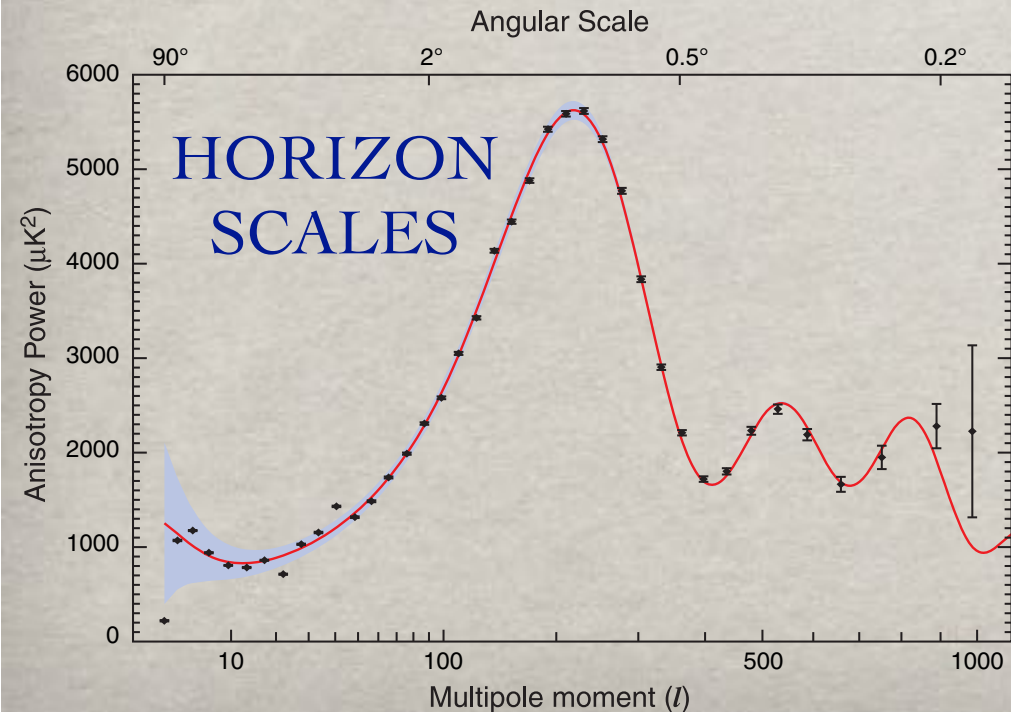
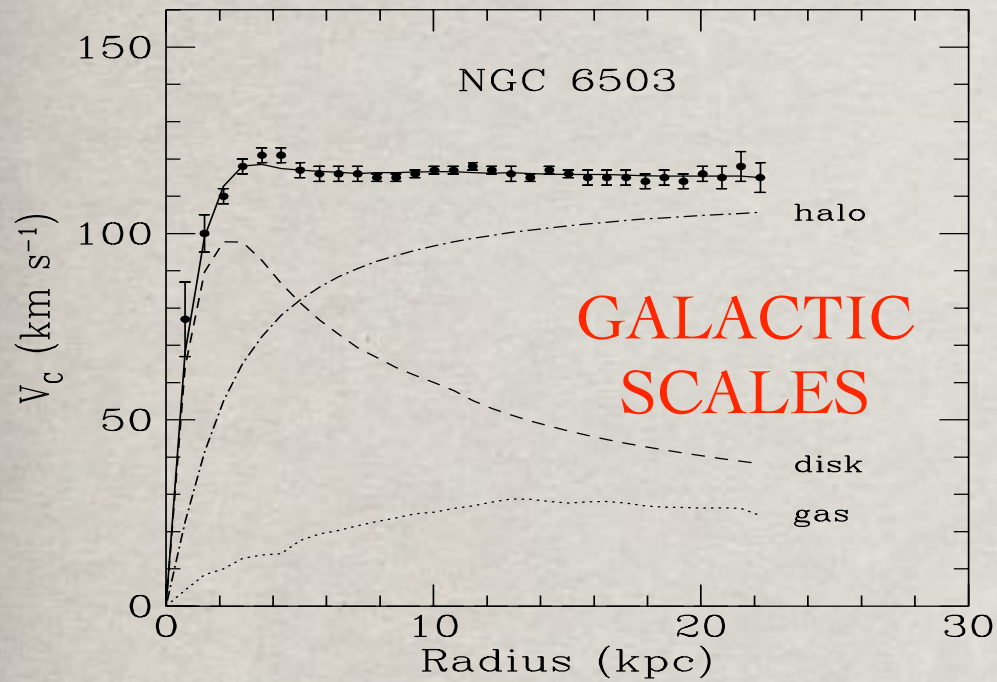


OUTLINE

- Introduction on Dark Matter & Theoretical guiding principles
- Thermal relics:
 - WIMP Dark Matter
 - Asymmetric DM
- Non-thermal relics:
 - FIMP/SuperWIMP/Decaying DM
 - Axion Dark Matter
- Multicomponent DM...
- Outlook

INTRODUCTION

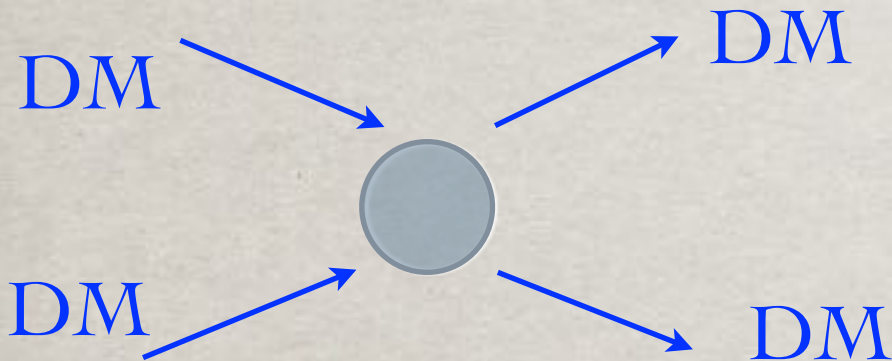
DARK MATTER EVIDENCE



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

DM-DM INTERACTION

Self-interaction:



Bullett cluster bound on
self-interaction:

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

[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]

DARK MATTER EVIDENCE

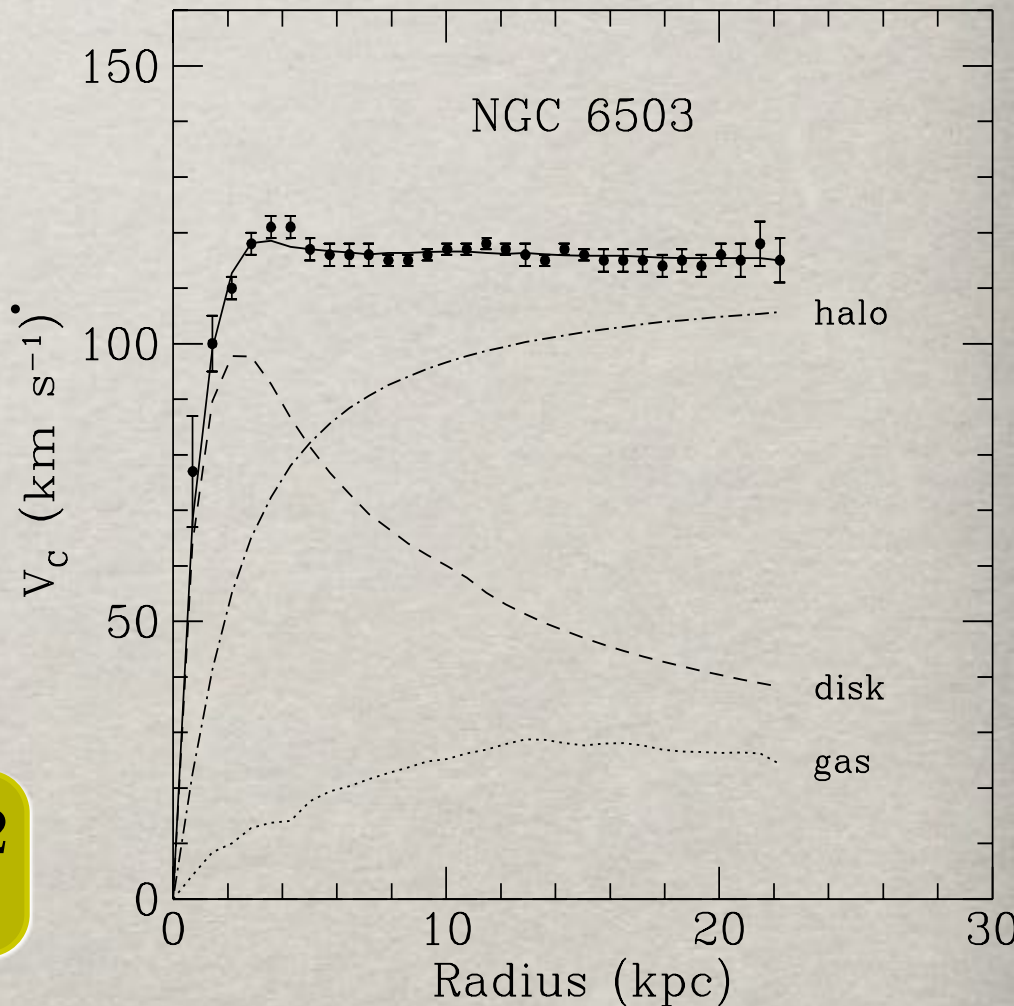
GALACTIC SCALES:

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

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



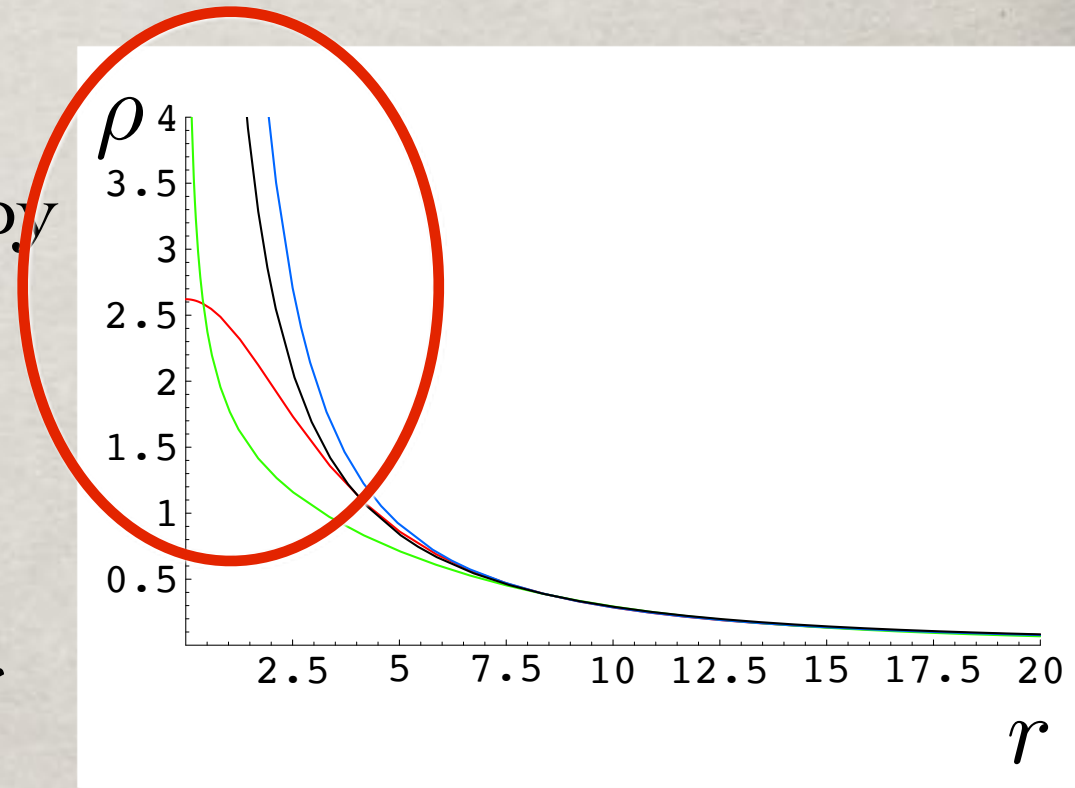
DARK MATTER EVIDENCE

GALACTIC SCALES:

Many density profiles, inspired by data or numerical simulations:

Isothermal, NFW, Moore, Kratsov, Einasto, etc....

They mostly differ in the behaviour at the centre, either cusped or cored !

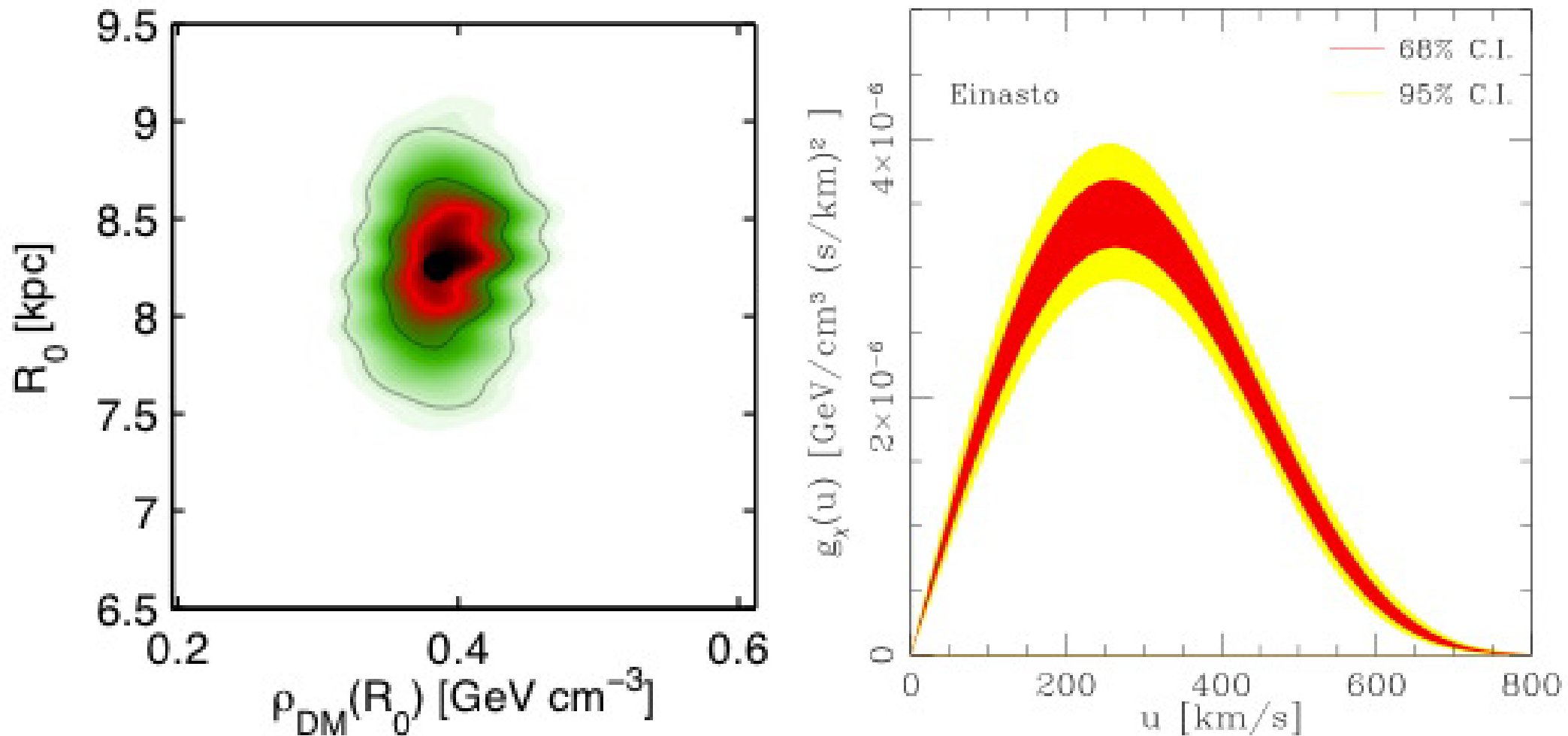


$$\rho(r) = \frac{\rho_0}{(r/R)^\gamma [1 + (r/R)^\alpha]^{(\beta-\gamma)/\alpha}}$$

Critical for indirect detection !

DARK MATTER LOCAL DENSITY & VELOCITY DISTRIBUTION

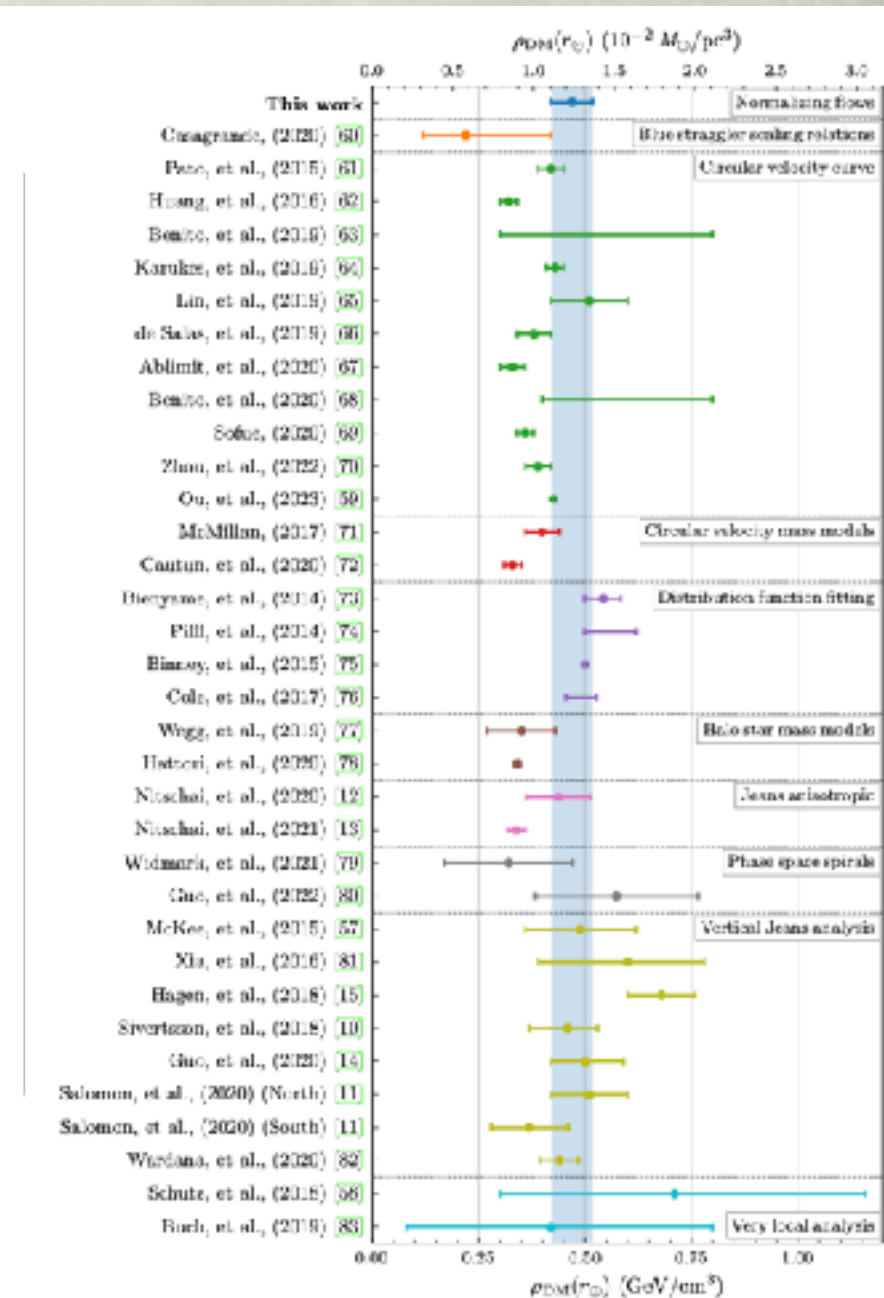
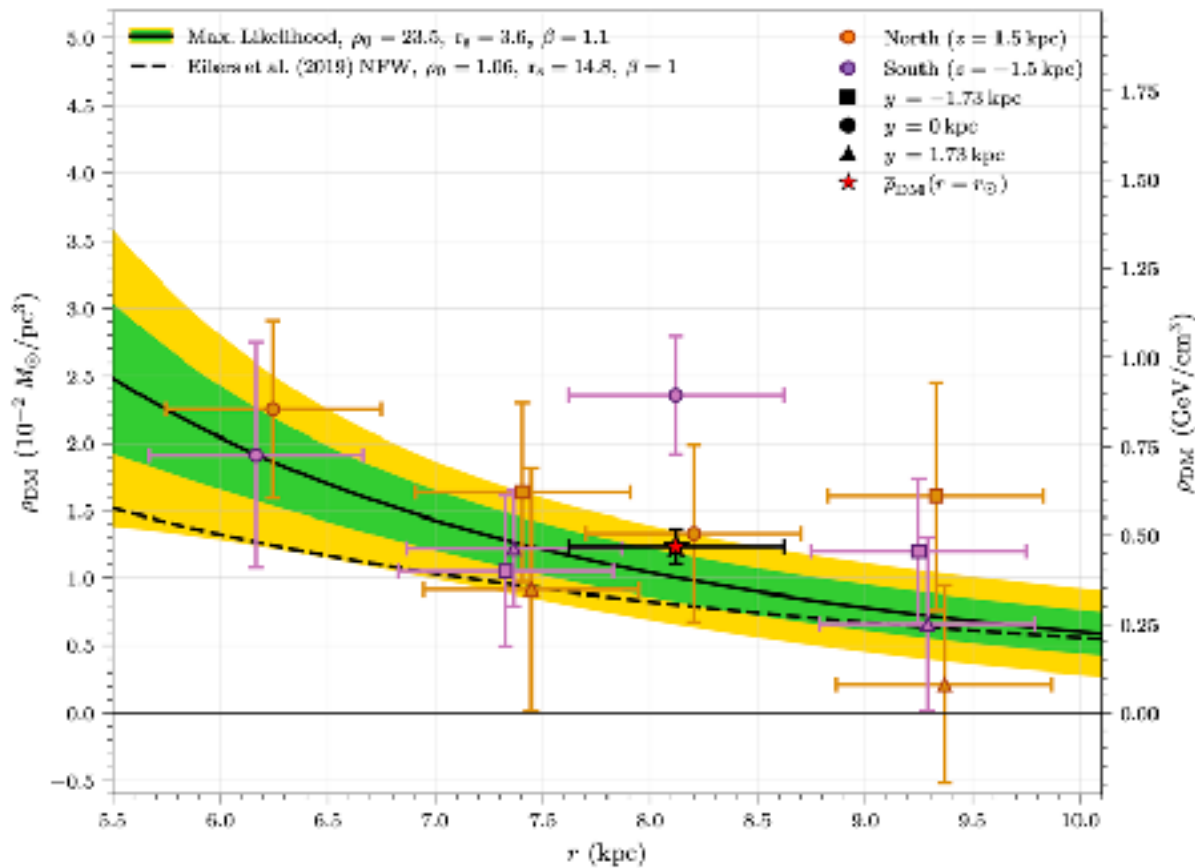
[Catena & Ullio 09, 11]



Critical for Direct Detection !

DARK MATTER LOCAL DENSITY FROM GAIA

[Lim et al. 2023]

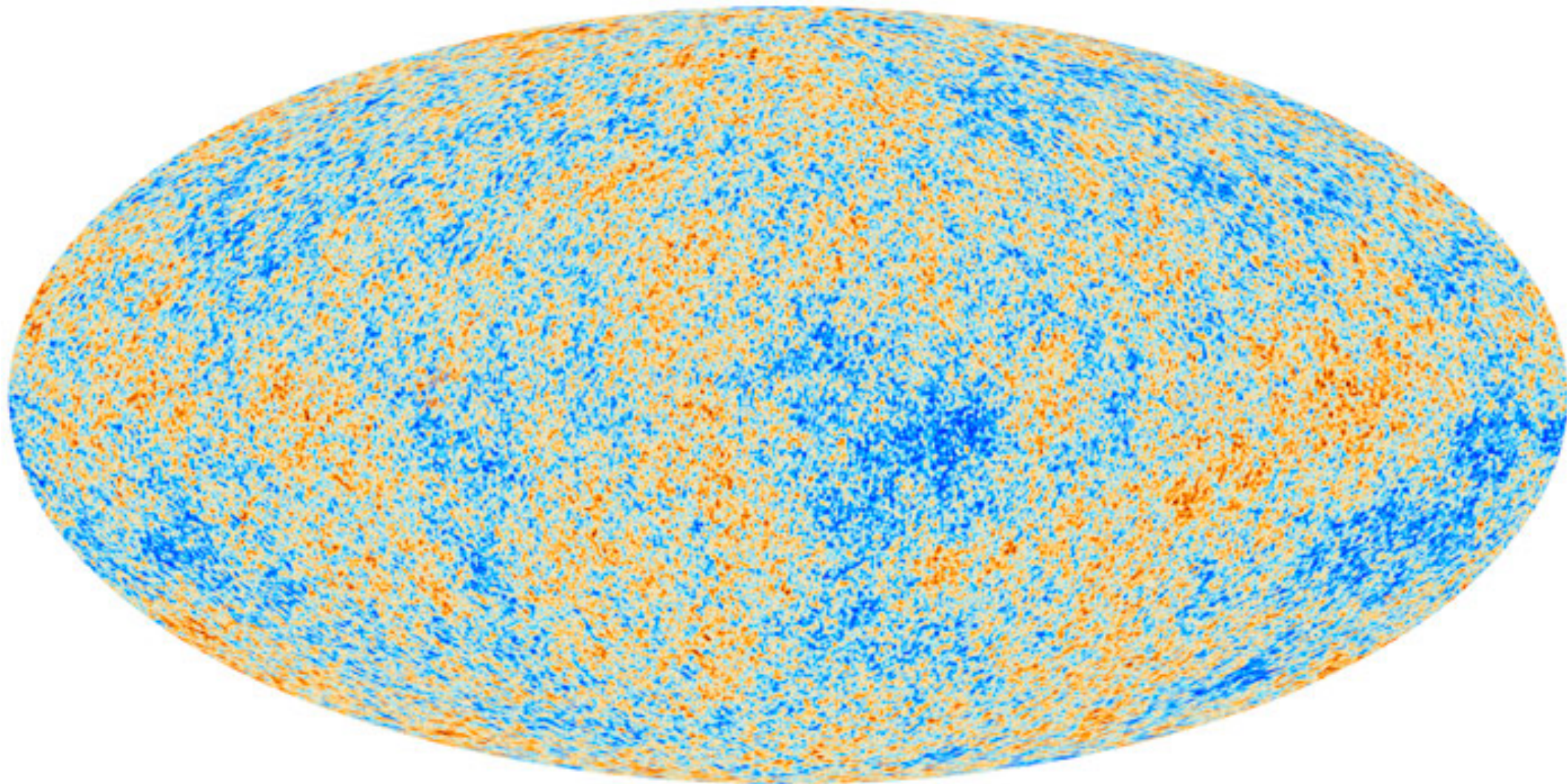


Critical for Direct Detection !

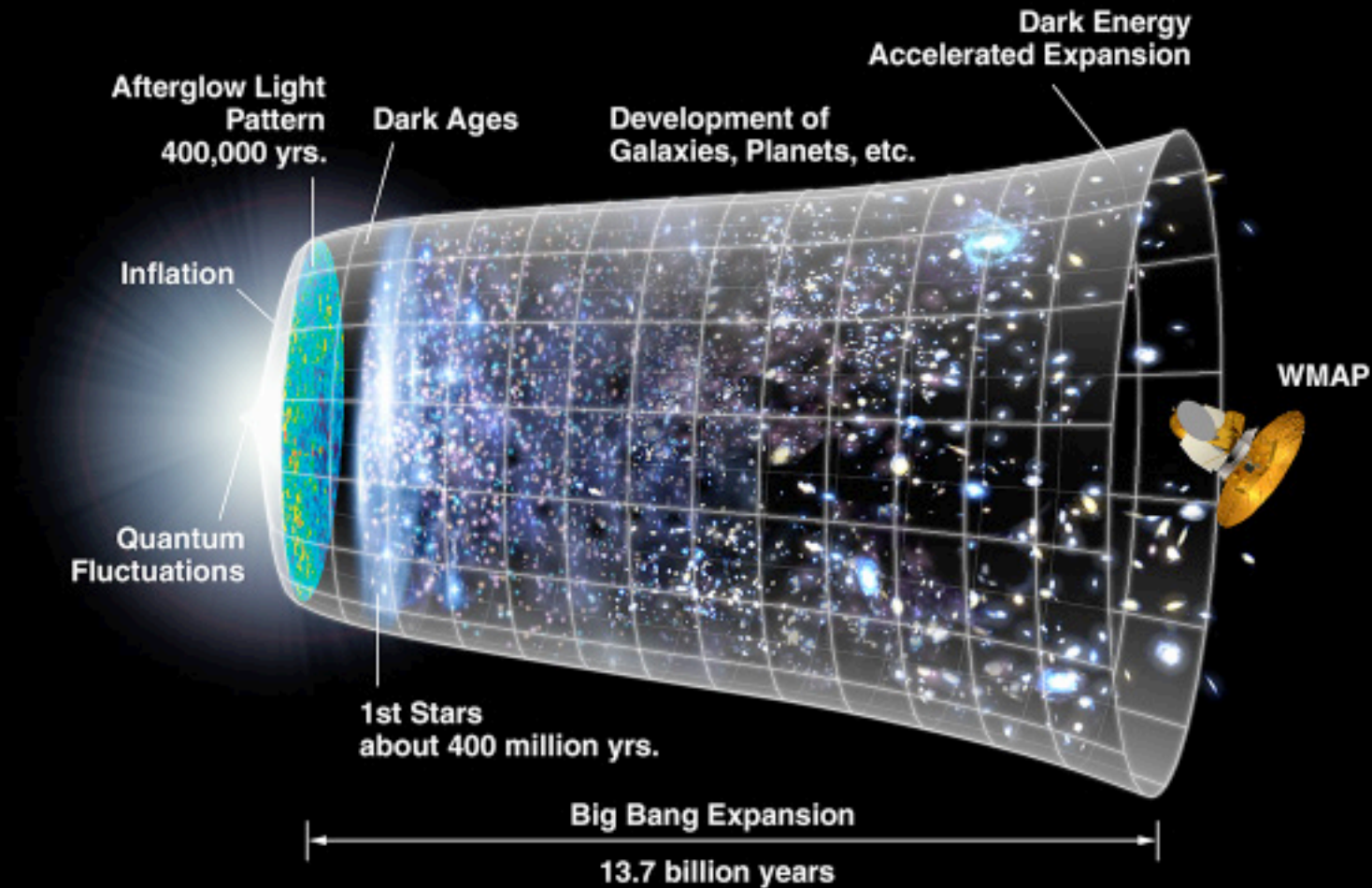
INITIAL CONDITIONS

At recombination $z \sim 1100$ density/temperature fluctuations
were at the order of $1/100000$...

How can they be the seed of structure today ?



FOLLOWING THE FLUCTUATIONS



These small fluctuations are 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

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

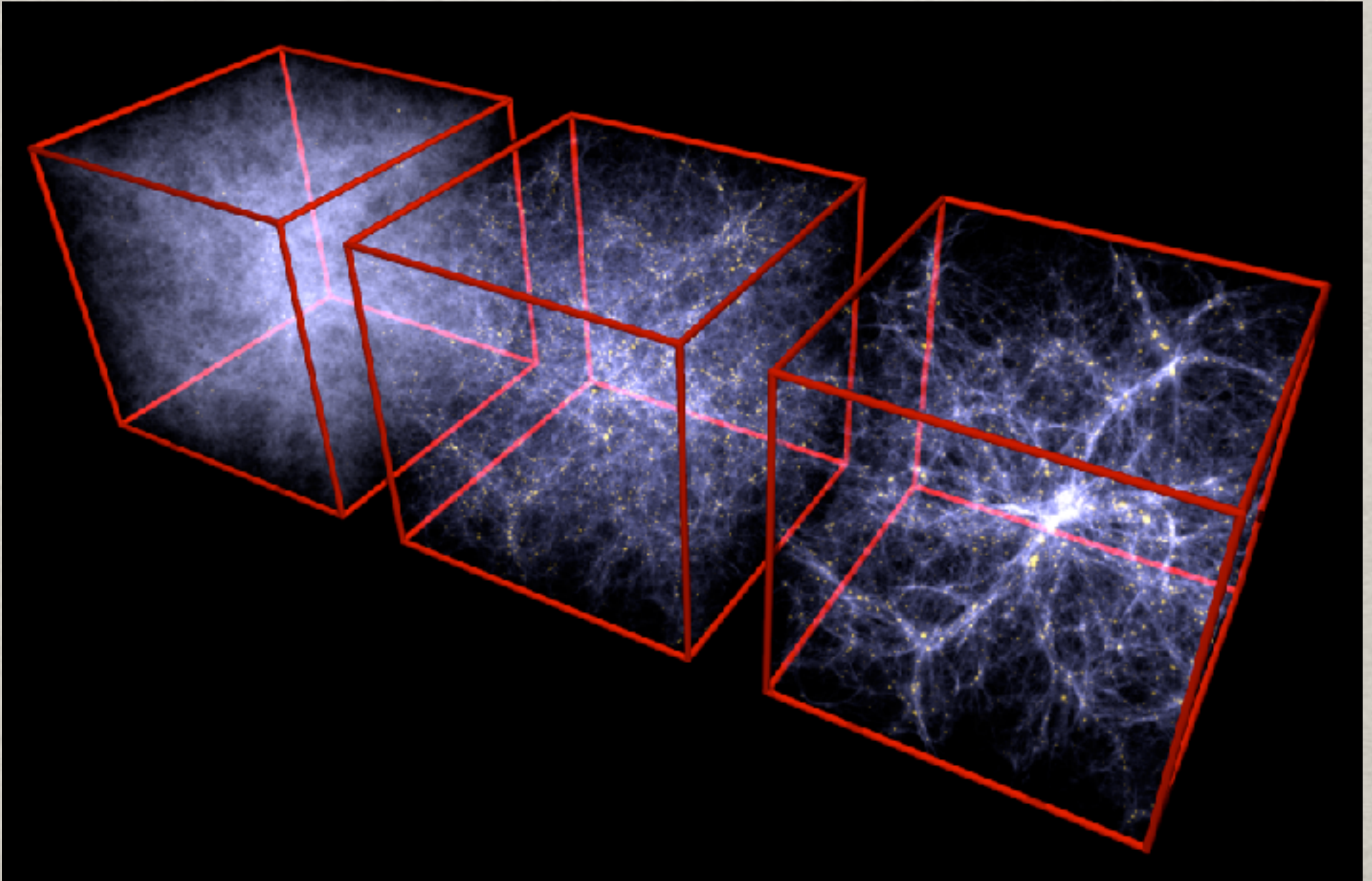
NOTE: much weaker than exponential due to the expansion friction term $\propto H$! Also if the expansion is dominated by radiation, the growth is inhibited and at most only logarithmic in time. We need a long time of matter dominance to make initial fluctuations become large...

Non Linear regime

STRUCTURE FORMATION

V. Springel @MPA Munich

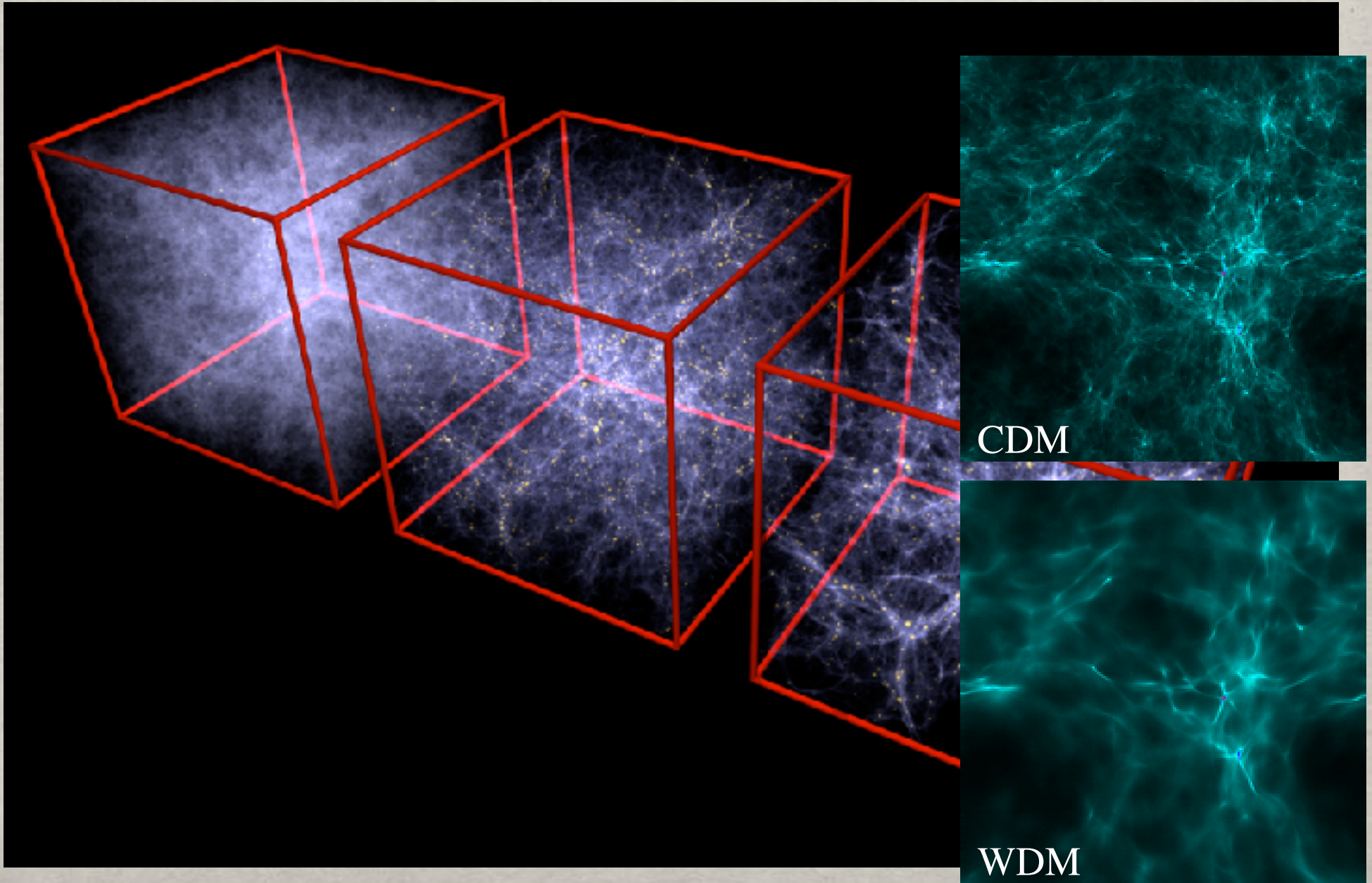
Yoshida et al 03



STRUCTURE FORMATION

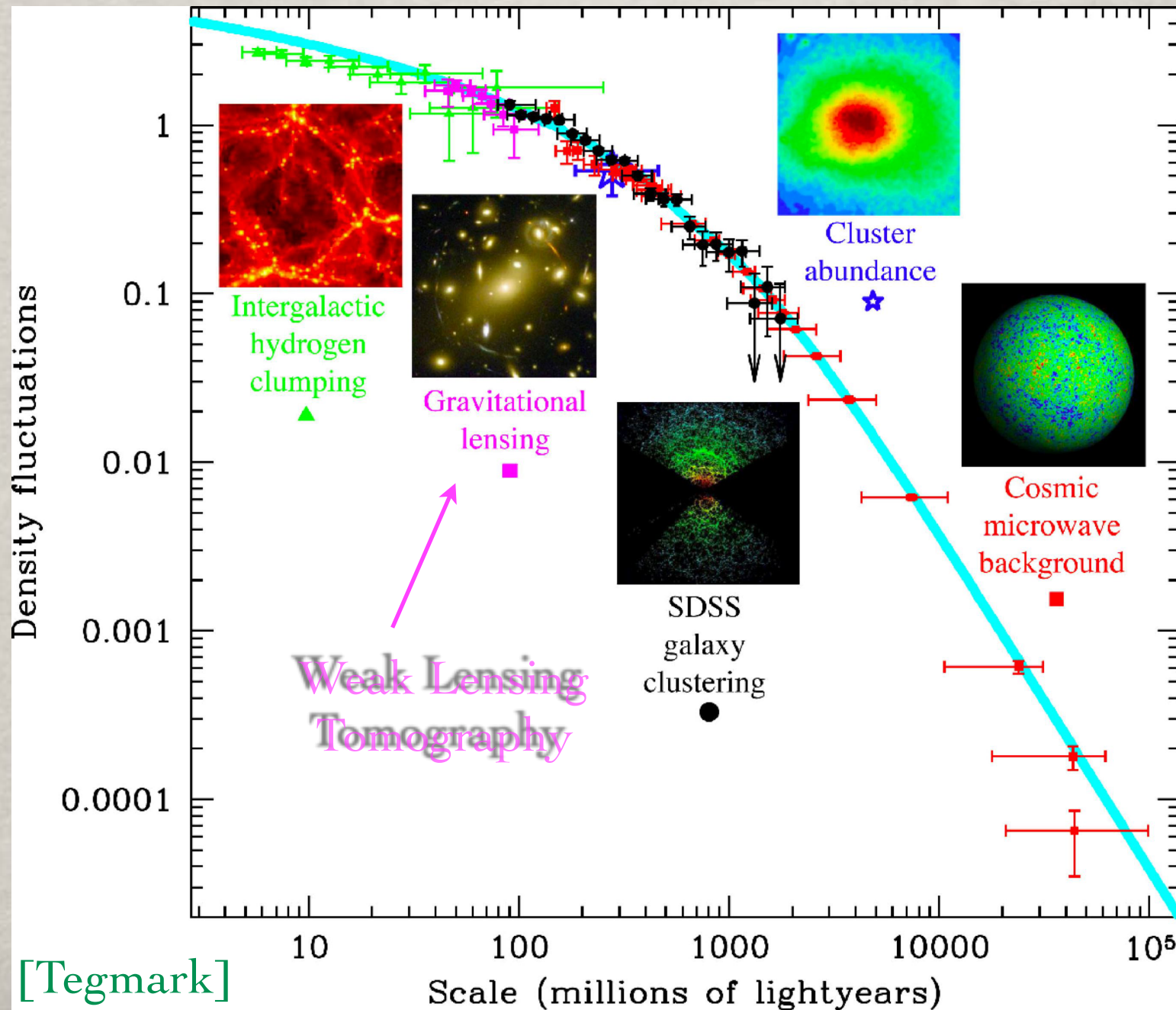
V. Springel @MPA Munich

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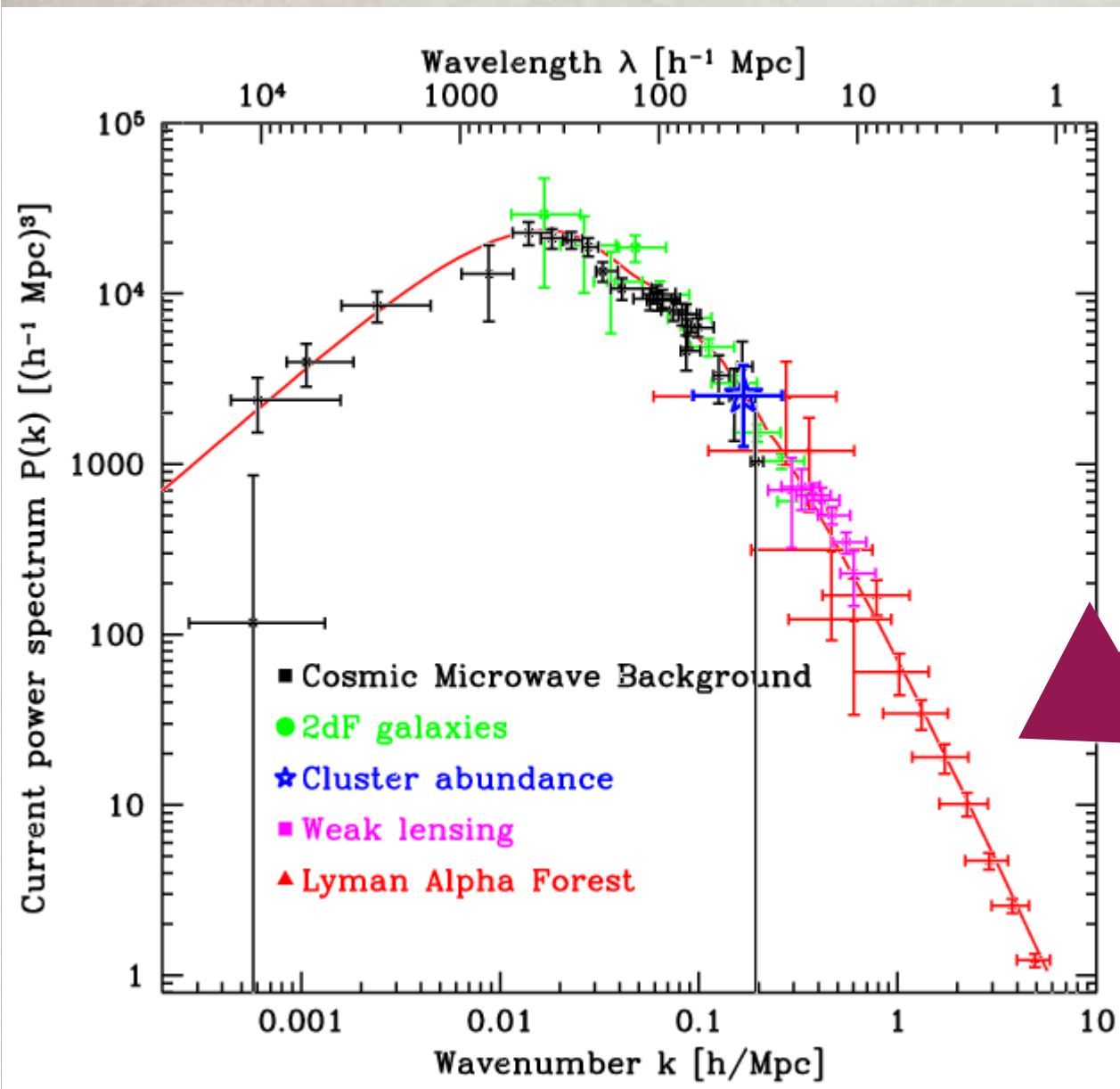
FLUCTUATIONS ON ALL SCALES

Non-
linear



Linear

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:

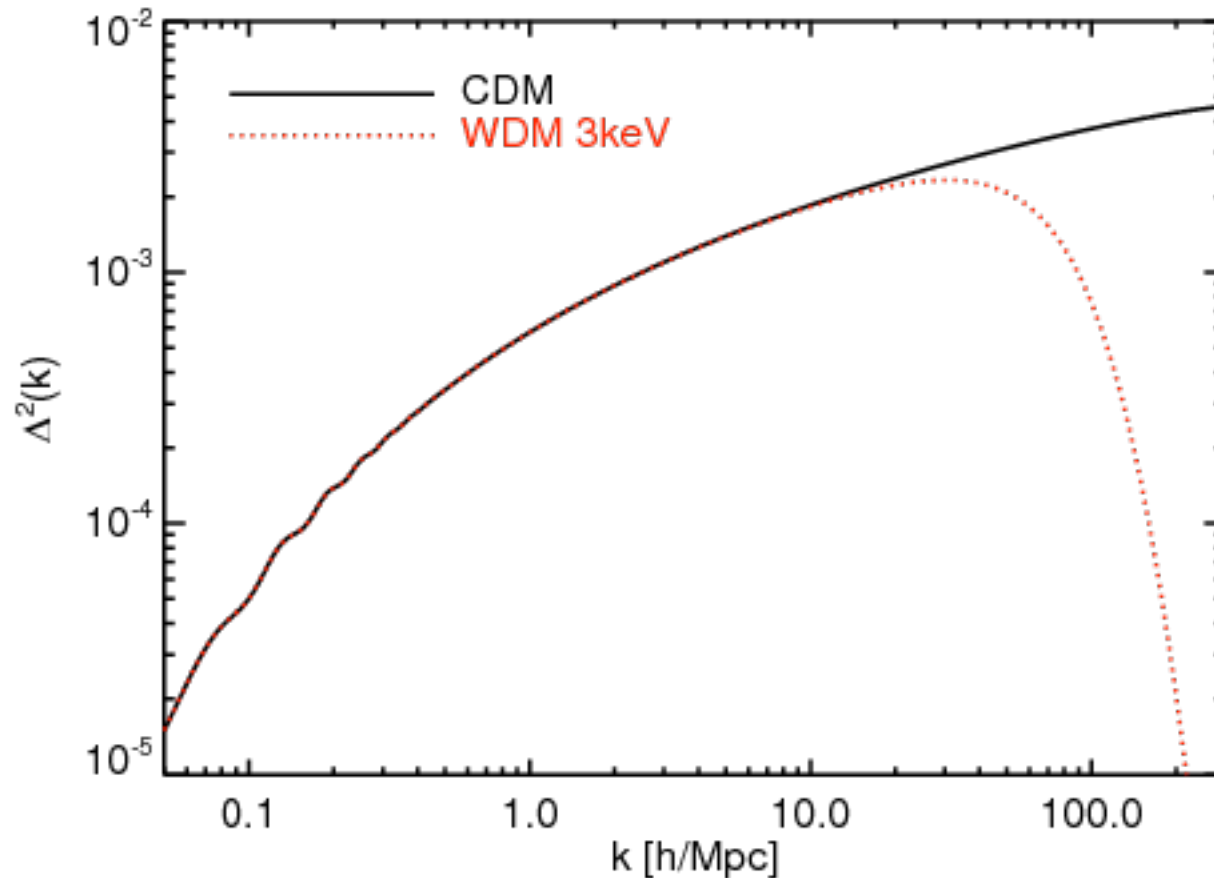
$$m_{WDM} > 4 \text{ keV}$$

[Viel et al. '07]

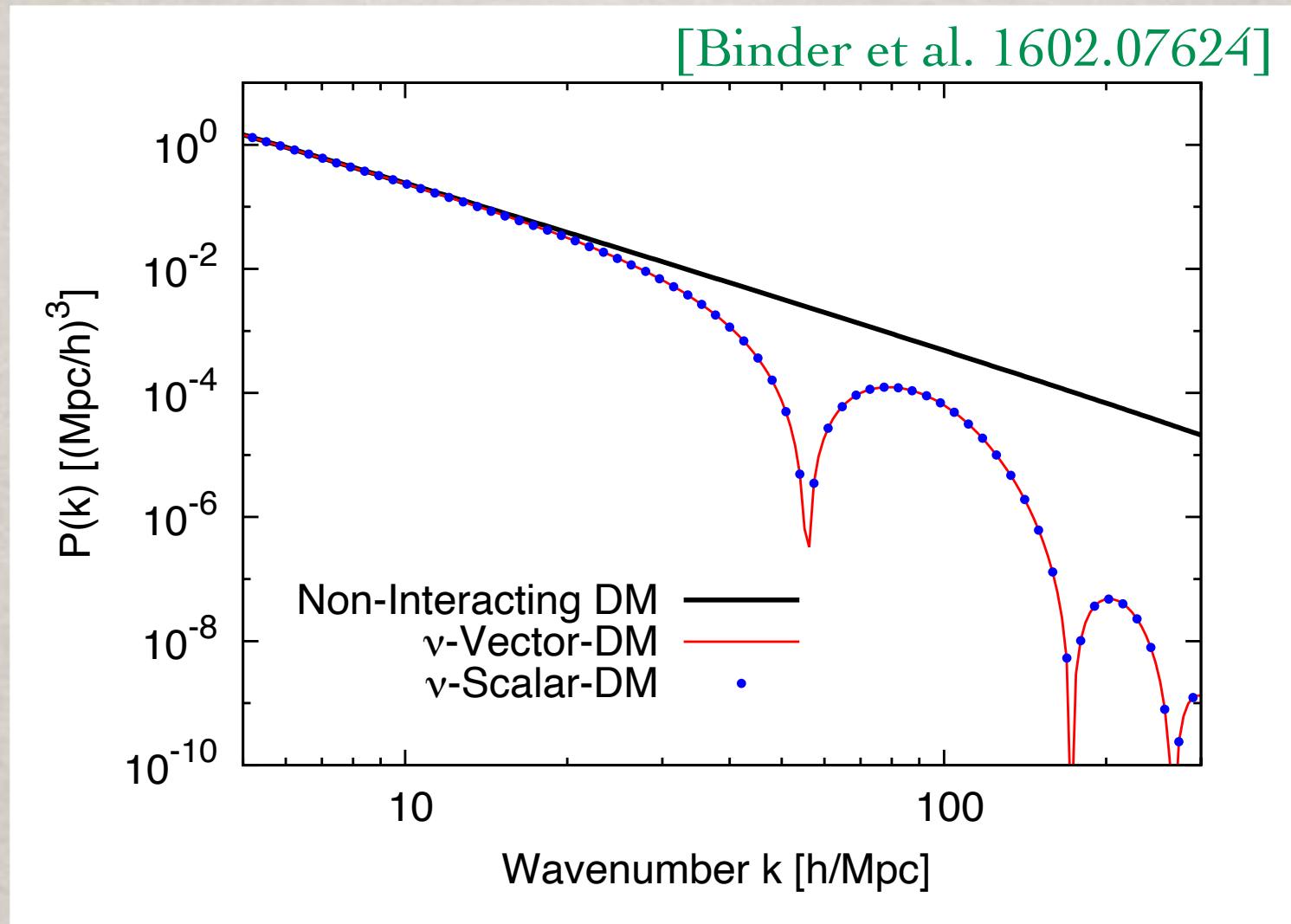
EFFECT FROM WDM

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

[Maio & Viel '15]



INTERACTING DARK MATTER



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

Similar results from ETHOS group

[Bringmann et al. 1603.04884]

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.

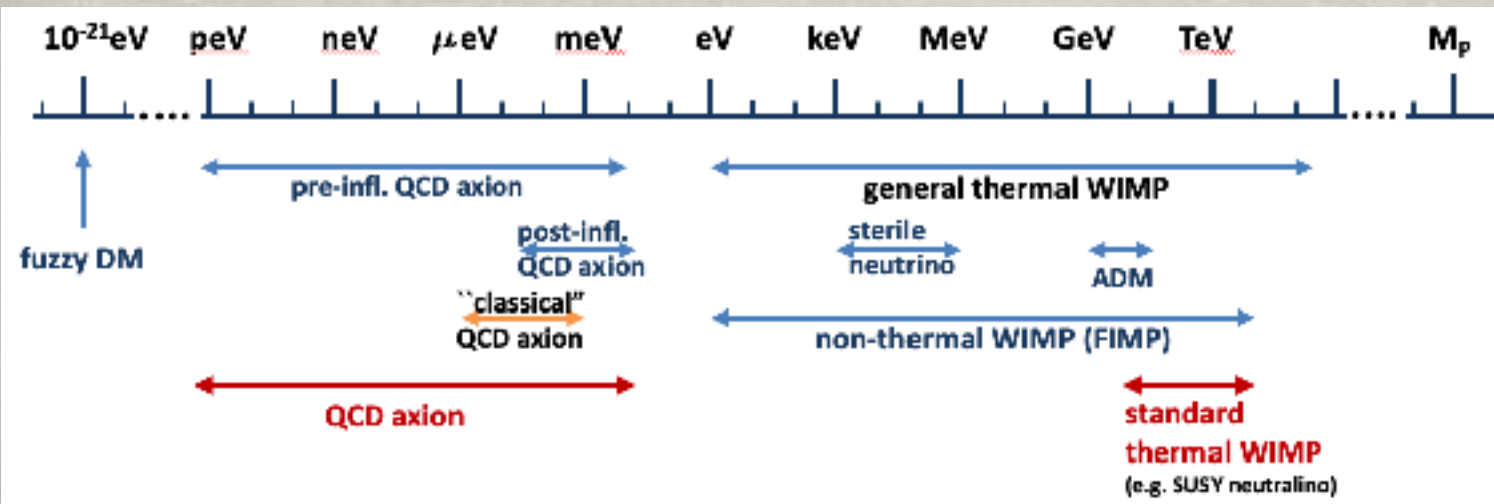


COLD DARK MATTER

But unfortunately too many realizations !

GUIDING PRINCIPLES 4 DM

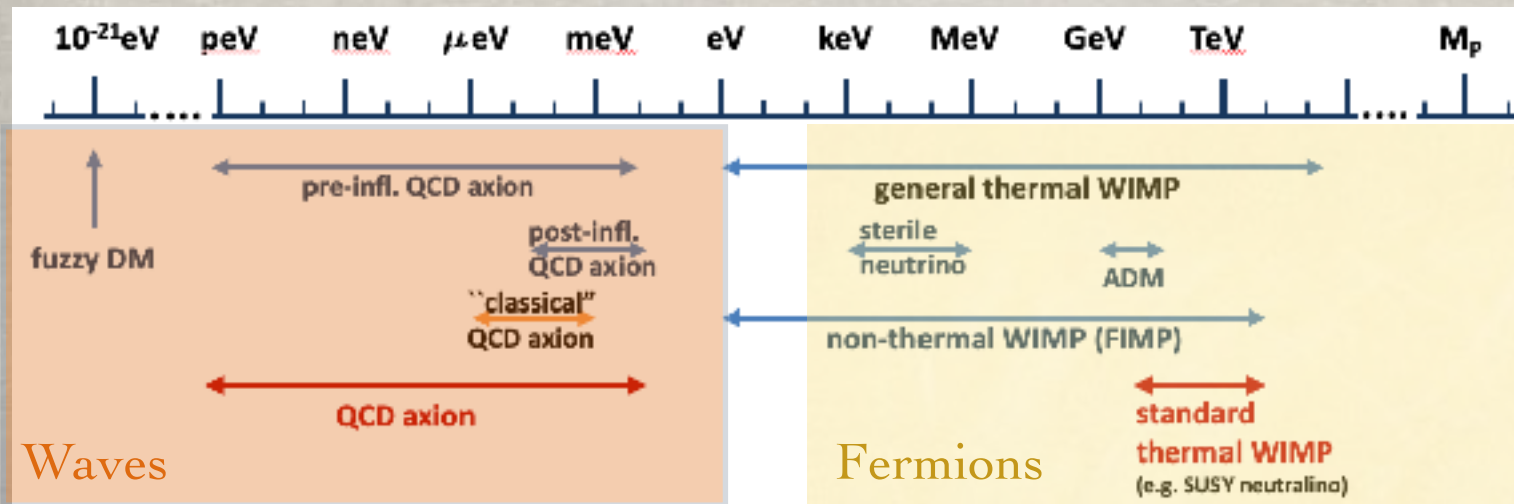
- The DM particle or the DM sector should fit into a BSM model solving more than the DM problem, e.g. hierarchy, neutrino masses, strong CP problem, etc...
- An effective DM production mechanism should be present, possibly independent from initial conditions.
- Possibly detectable Dark sector in the near future.



DARK
MATTER
paradigms

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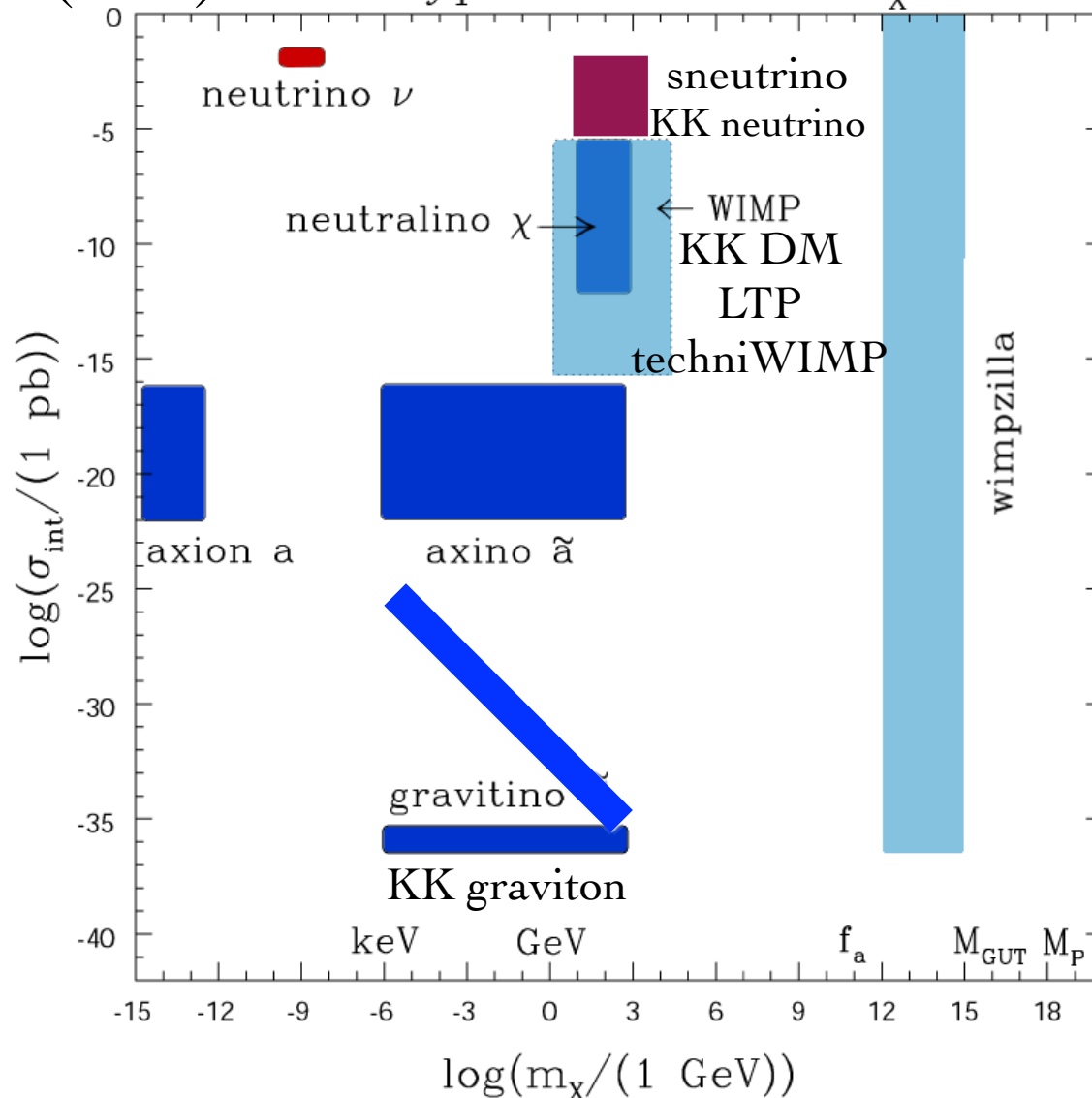


DARK
MATTER
paradigms

DARK MATTER CANDIDATES

[Roszkowski 04]

(non) WIMP-type Candidates $\Omega_{\chi} \sim 1$



Multidimensional
space !

DM production
paradigms:

WIMPs

(e.g. neutralino)

&

“FIMP/SuperWIMPs”

(e.g. axino/gravitino)

&

Misalignment

(e.g. axion/condensate)

THERMAL RELICS: WIMP DARK MATTER

BASIC FORMULAS

Relativistic particles in thermal equilibrium with $p \gg m$:

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

$$\zeta(3) = 1.202$$

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

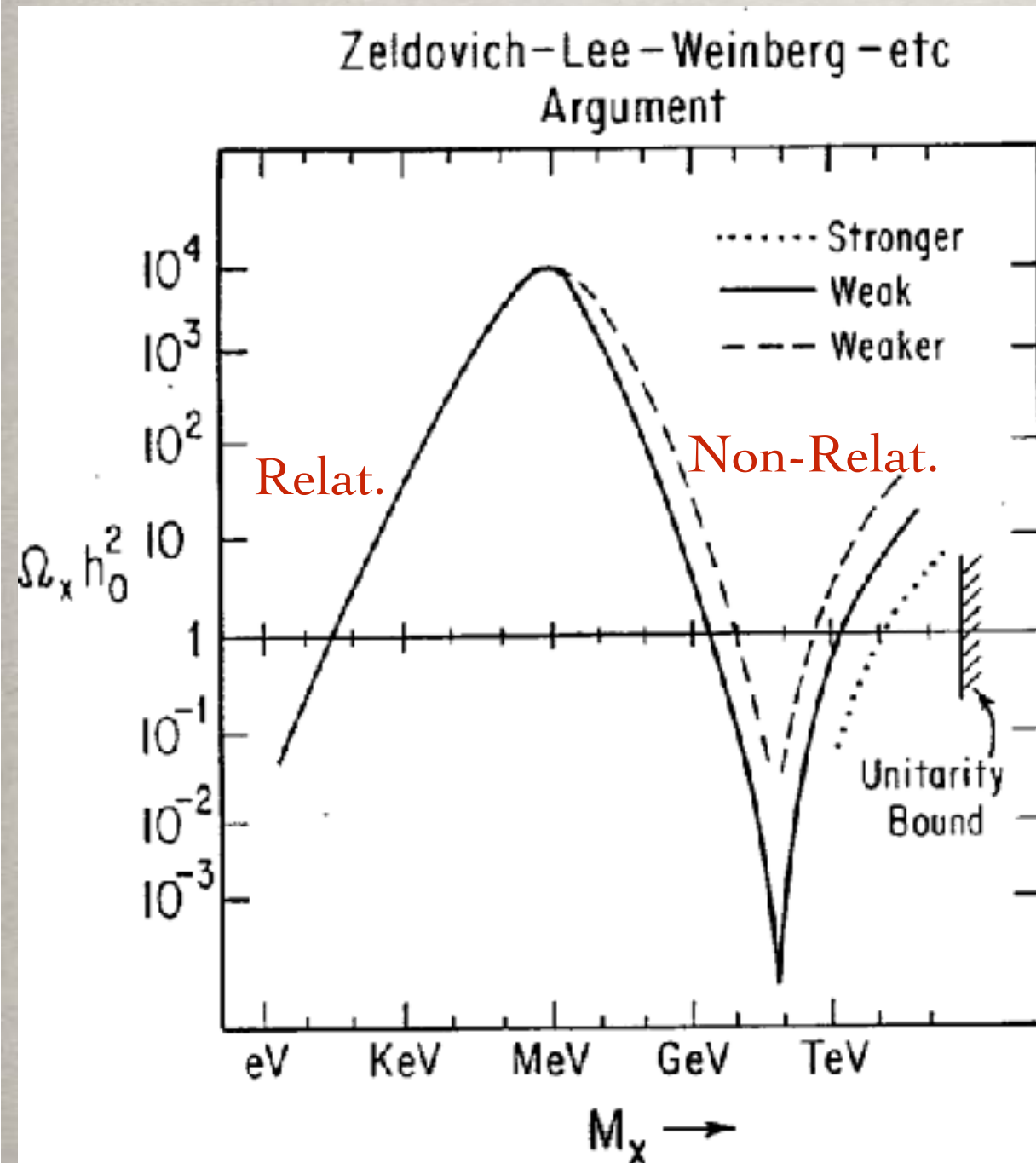
Non-relativistic particles in thermal equilibrium with $m \gg p$:

$$\rho = m n$$

$$n = g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-\frac{m-\mu}{T}} \quad \sim \text{Maxwell-Boltzmann}$$

same for B and F !

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

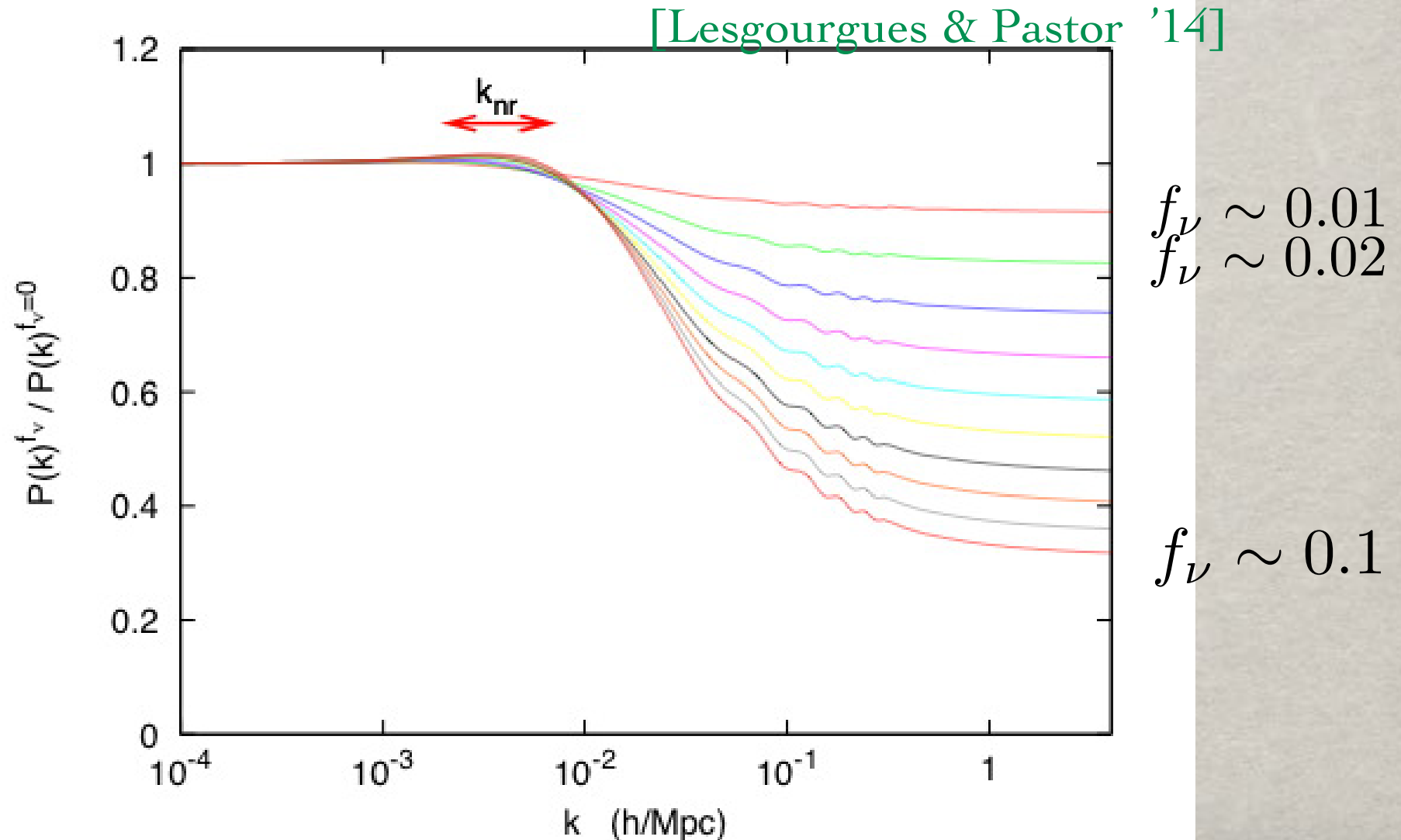
- Unfortunately the small mass also means that neutrinos are **HOT DM...** Their free-streaming is non negligible and the LSS data actually constrain

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

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



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 Boltzmann equation

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

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

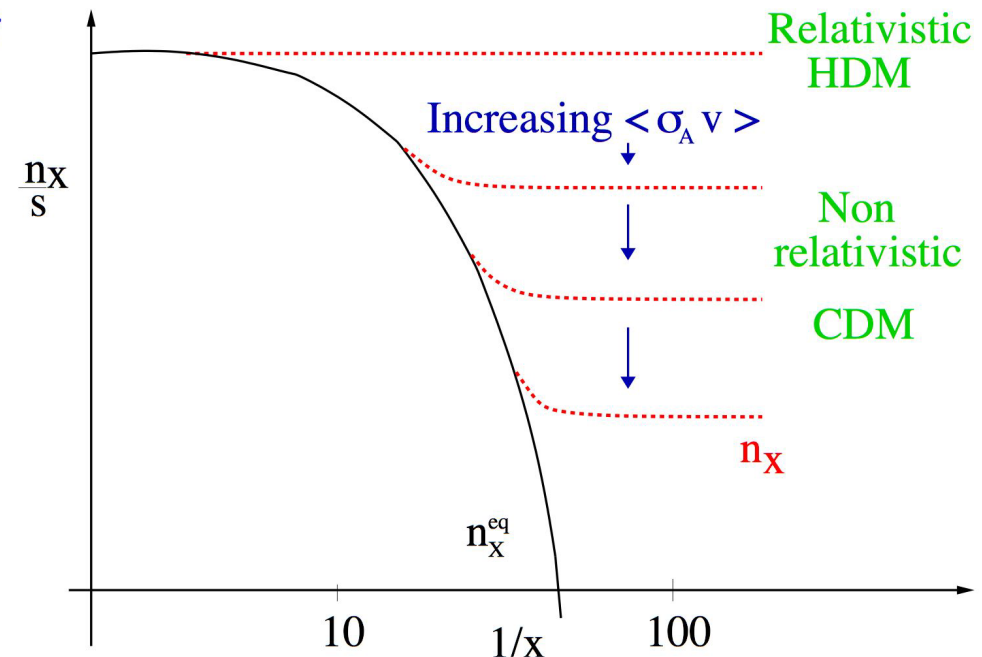
$$\Omega_X = m_X n_X(t_{now}) \propto \frac{1}{\langle \sigma_A v \rangle_{x_f}}$$

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** !



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 $x = \frac{m_X}{T}$:

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

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

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

which has the solution

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

so when σ is sufficiently large after freeze-out

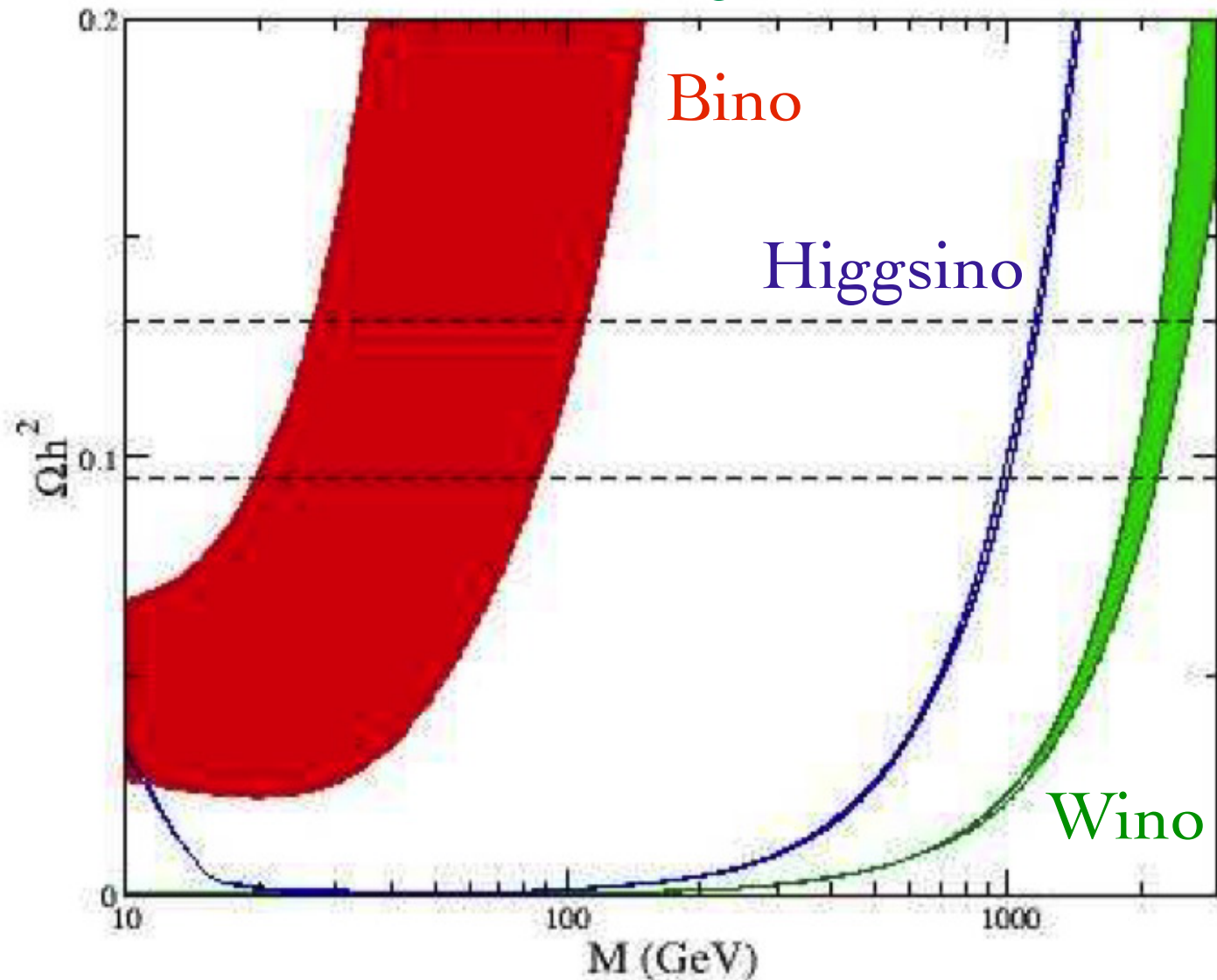
$$Y_X(x) \simeq \frac{1}{\frac{s(m_X)}{H(m_X)} \int_{x_f}^x \frac{dx}{x^2} \langle \sigma(X + X \rightarrow \text{anything}) v \rangle(x)}$$

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

WELL-TEMPERED NEUTRALINO

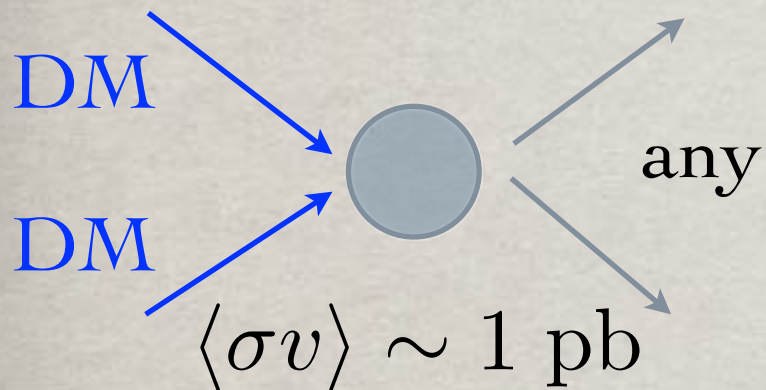
Relic density strongly dependent on neutralino nature !!!

[Arkani-Hamed, Delgado & Giudice 0601041]

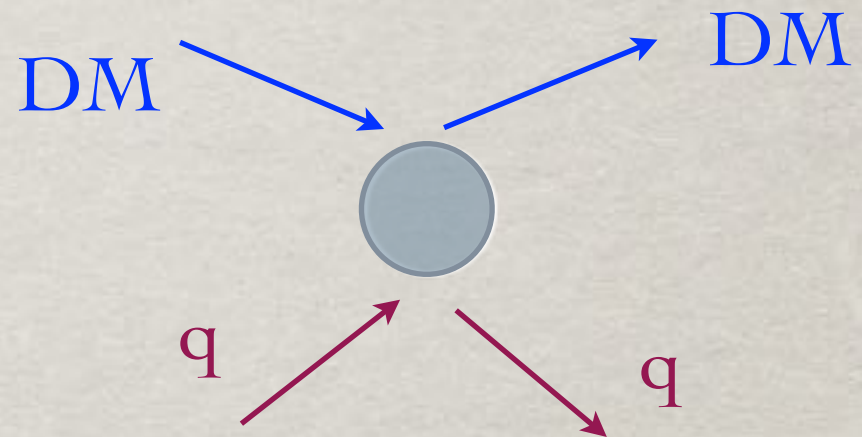


THE WIMP CONNECTION

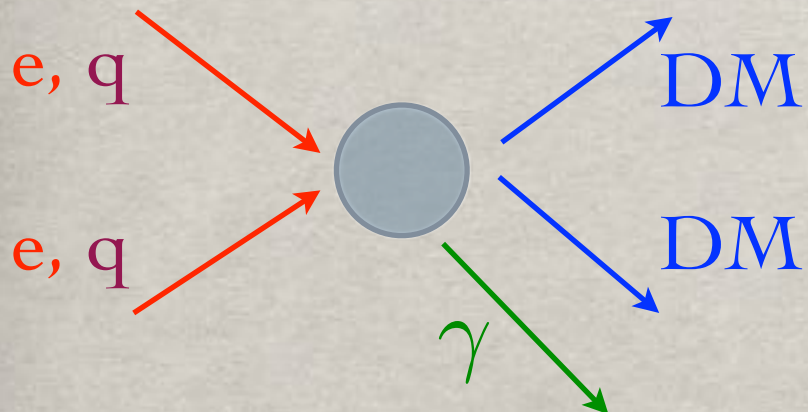
Early Universe: $\Omega_{CDM} h^2$



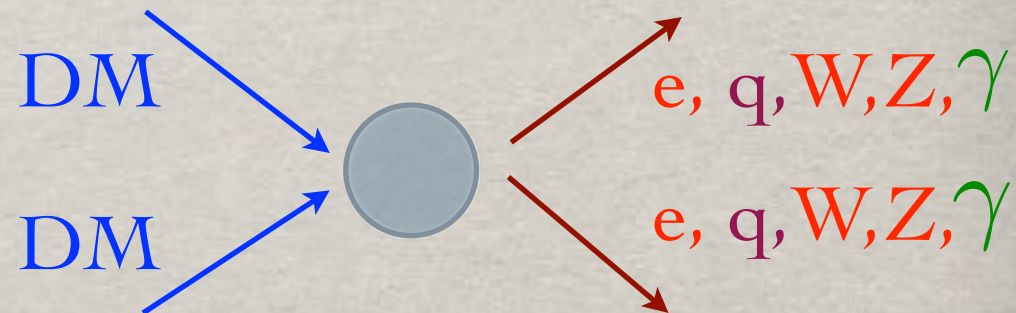
Direct Detection:



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

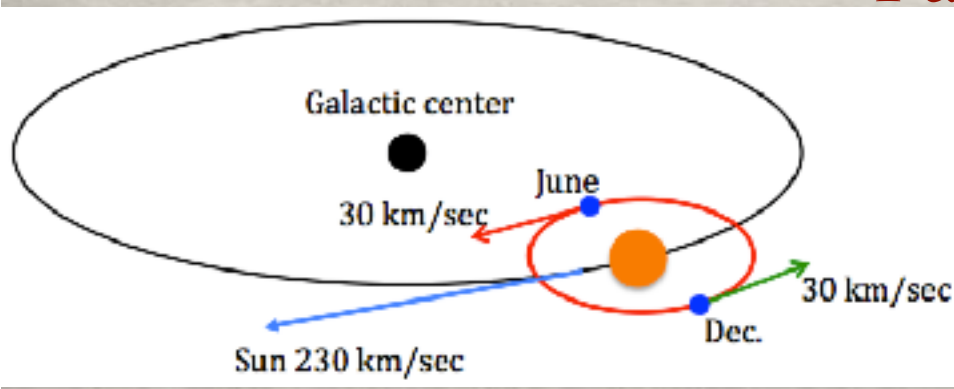
$$E_{kin}^{DM} \sim \frac{1}{2} m_{DM} v^2 \sim 50 \text{ keV} \frac{m_{DM}}{100 \text{ GeV}}$$

Need very low threshold !

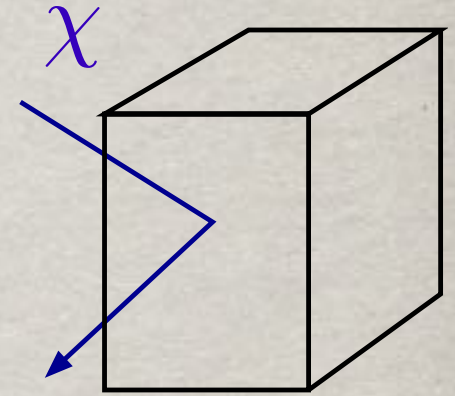
- The rate is
$$\frac{dR}{dE_R} \propto \sigma_n F^2(E_R) \frac{\rho_{DM}}{m_{DM}} \int_{v_{min}}^{\infty} \frac{dv}{v} f(v)$$

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 $\Omega_{DM} h^2 \sim 0.1$
 $\langle \sigma v \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s} \rightarrow \sigma \sim 10^{-36} \text{ cm}^2 = 1 \text{ pb}$

- Exchange of Z boson:

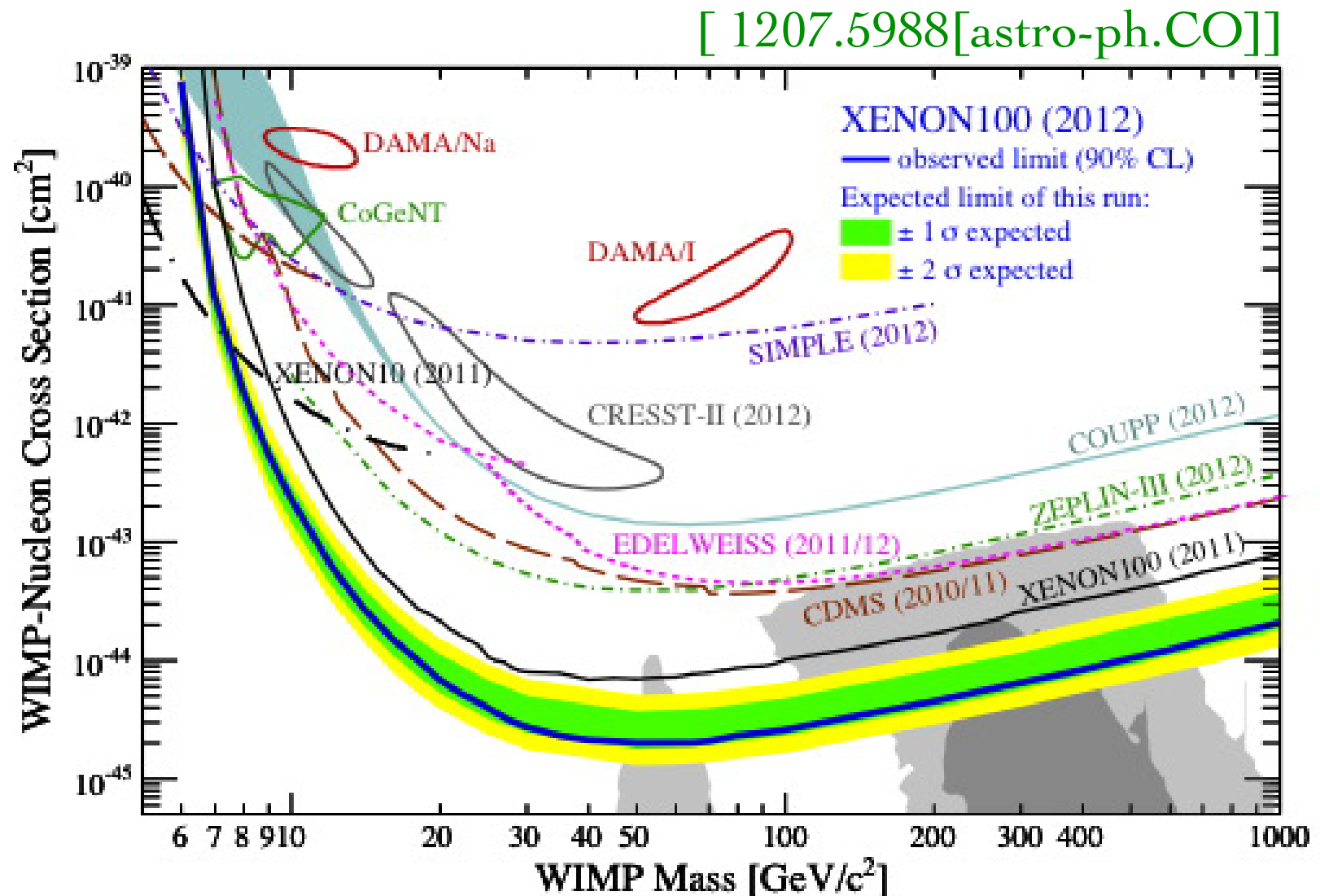
$$\sigma \sim \lambda_{Z\chi}^2 G_F^2 m_p^2 \sim 10^{-38} \lambda_{Z\chi}^2 \text{ cm}^2 = 10^{-2} \lambda_{Z\chi}^2 \text{ pb}$$

- Exchange of Higgs boson:

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

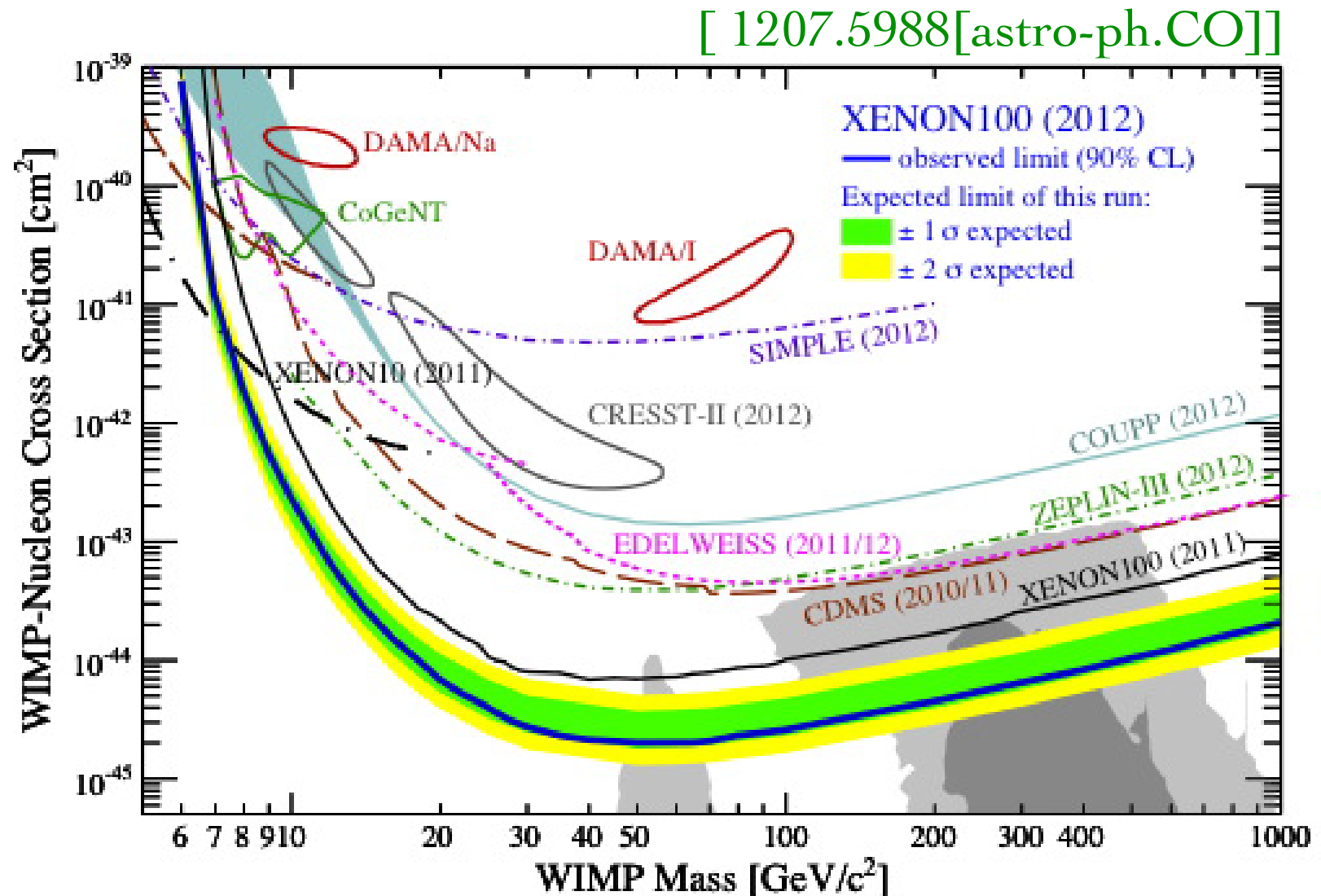
DIRECT DETECTION OF DM

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



DIRECT DETECTION OF DM

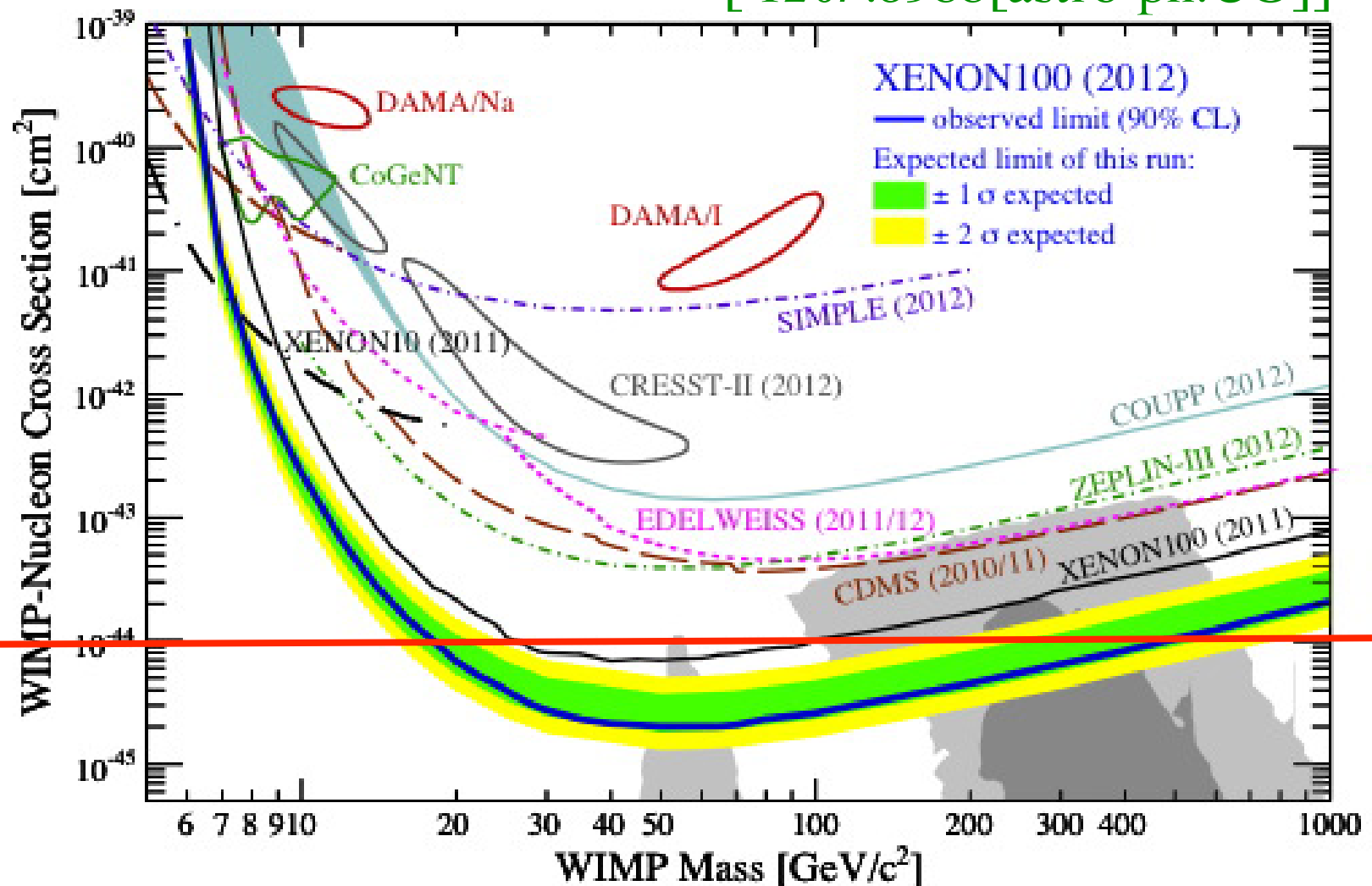
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Z



DIRECT DETECTION OF DM

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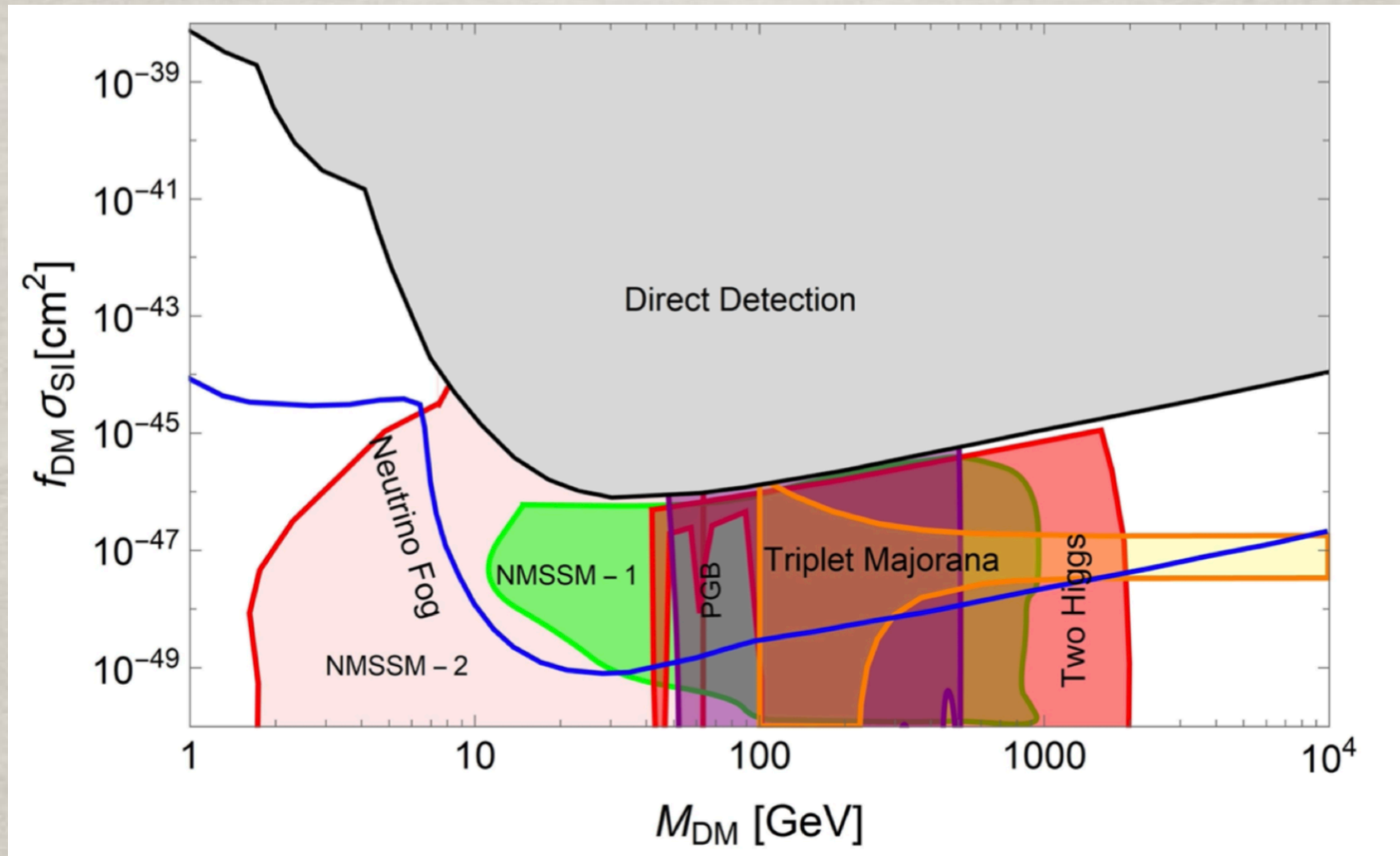
[1207.5988[astro-ph.CO]]



WIMP MODELS...

...NOT YET EXCLUDED !

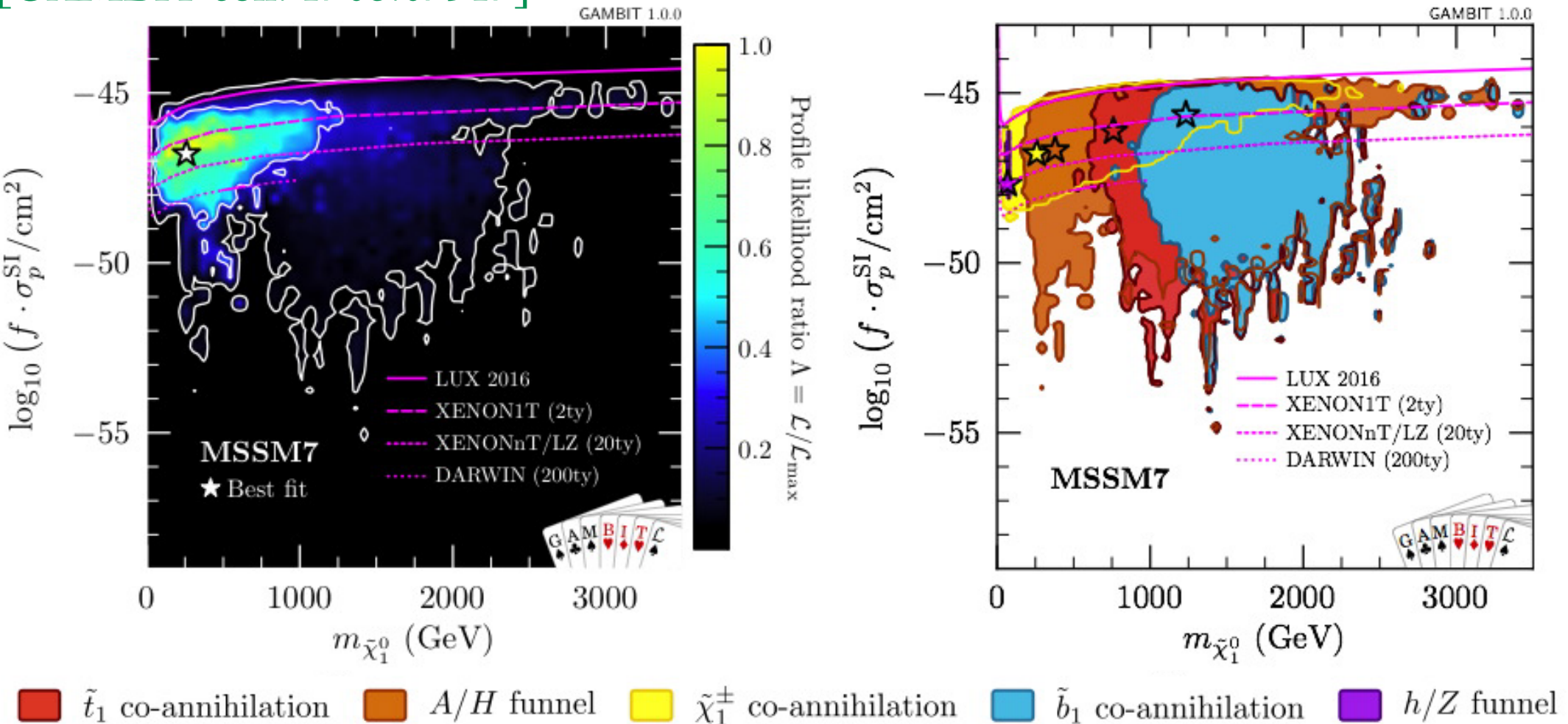
[Snowmass 2021 Cosmic Frontier ArXiv:2203.08084]



Disentangle production & DD via coannihilation, mixing, etc!

HIGGSINO DARK MATTER

The Higgsino DM region mostly covered by Direct Detection:
 [GAMBIT coll. 1705.07917]

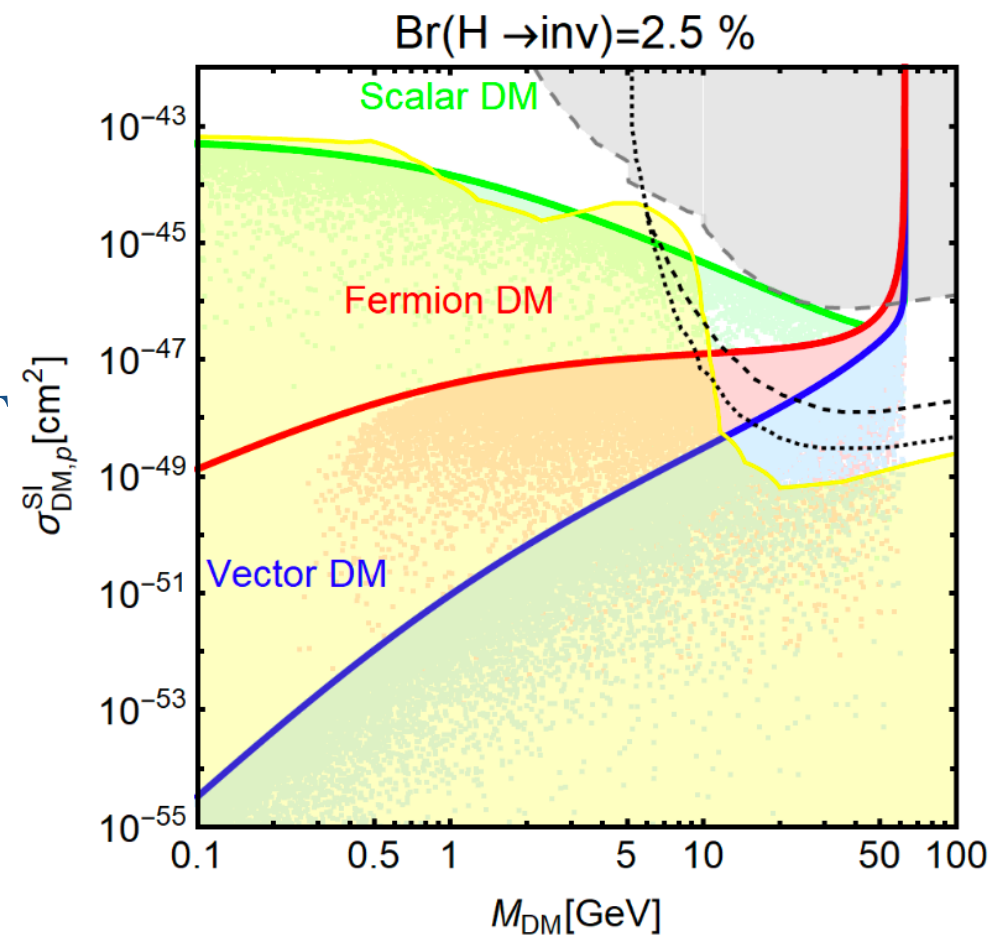
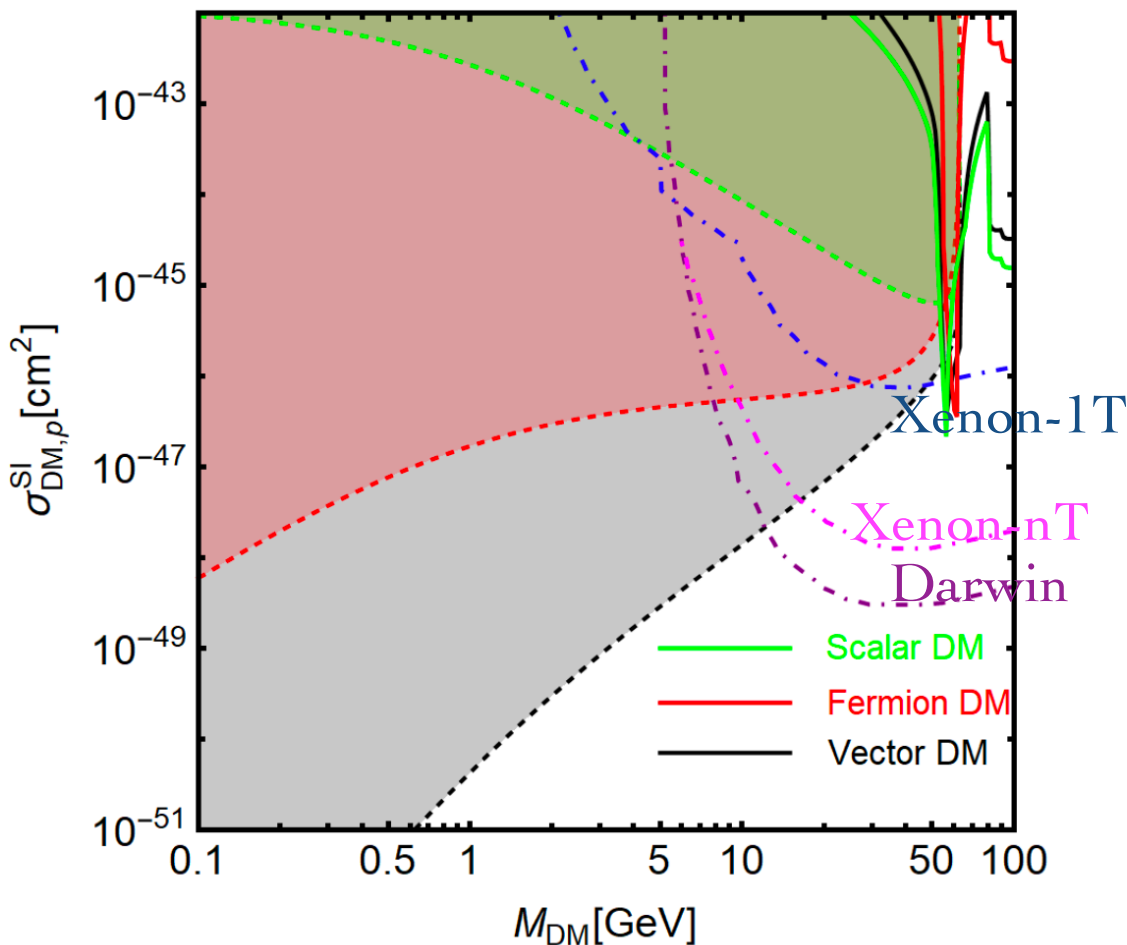


Nevertheless for other compositions low cross-section is possible

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]

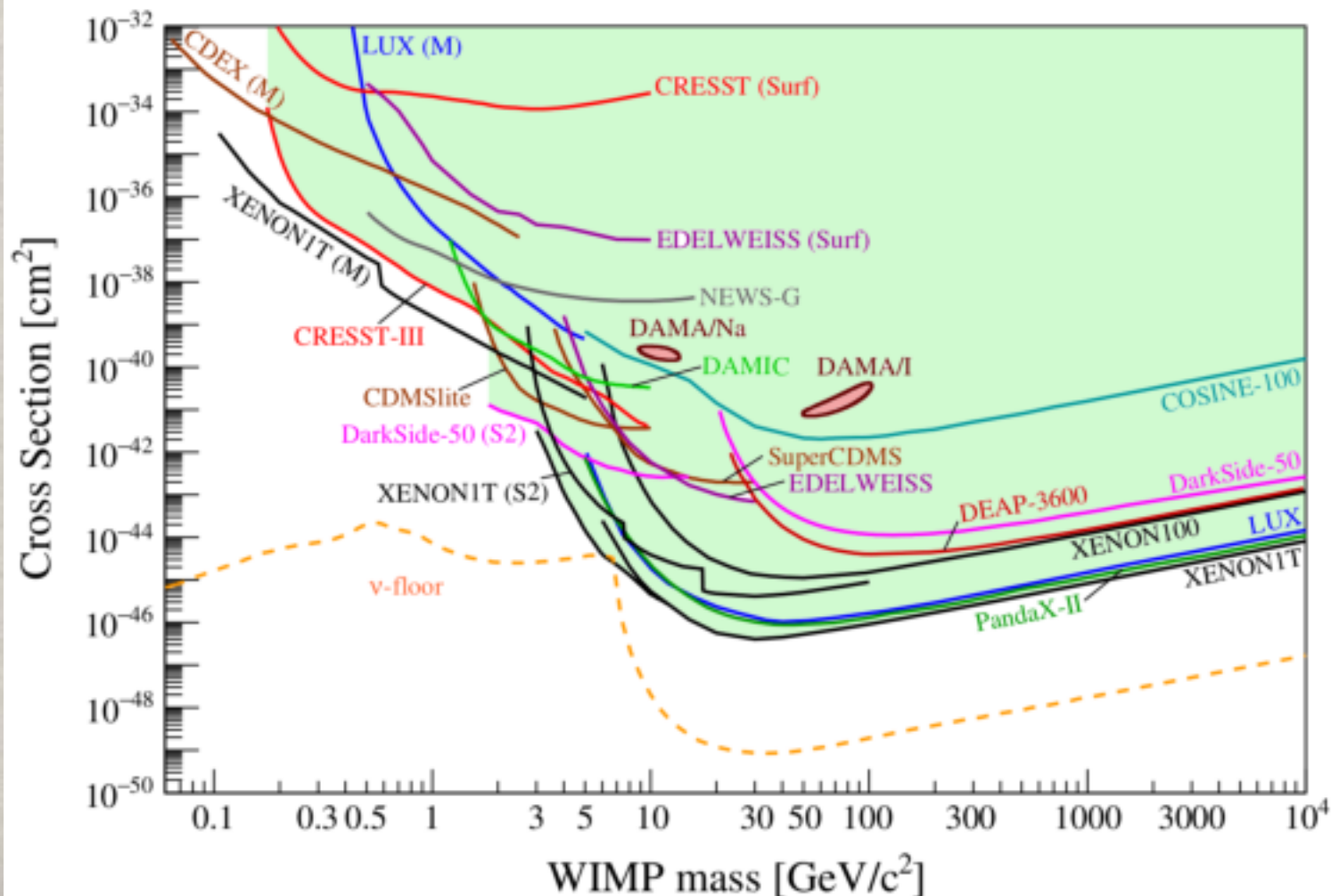


Interference effects can reduce the DD cross-sections !

DIRECT DETECTION

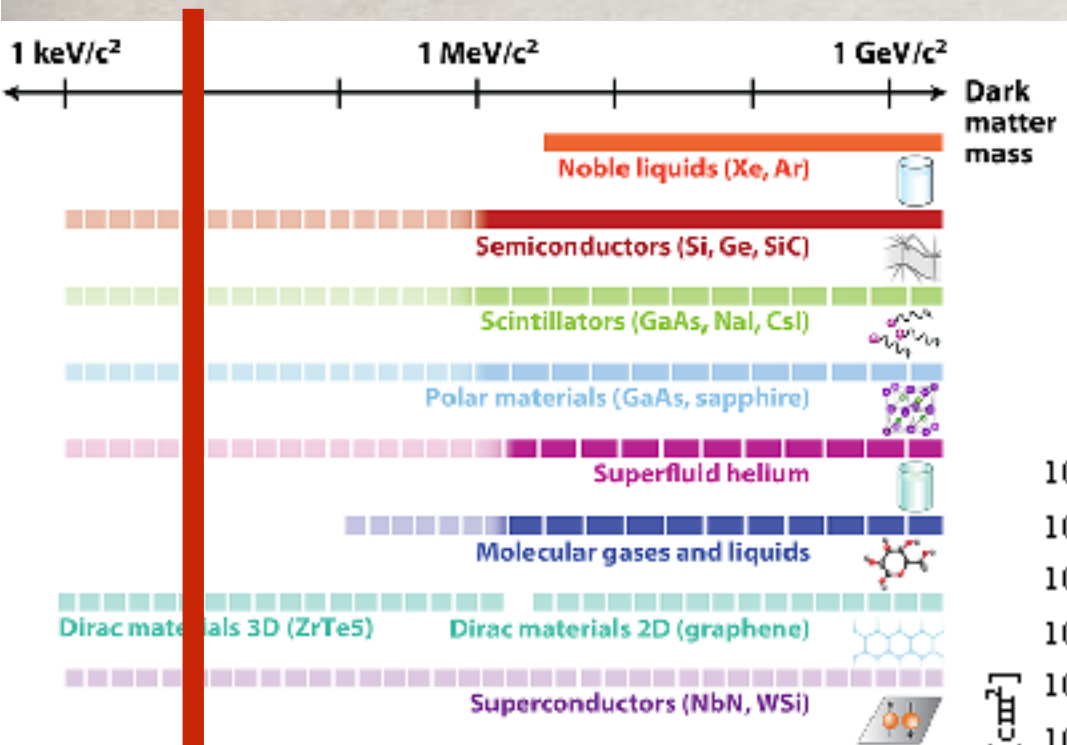
The constraints are moving towards the neutrino floor, with new frontiers at low masses:

[Billard et al. 2104.07634]



LOW MASS WIMPs

The DD searches are being extended to low masses via new technologies and sensitivity to electron scatterings:

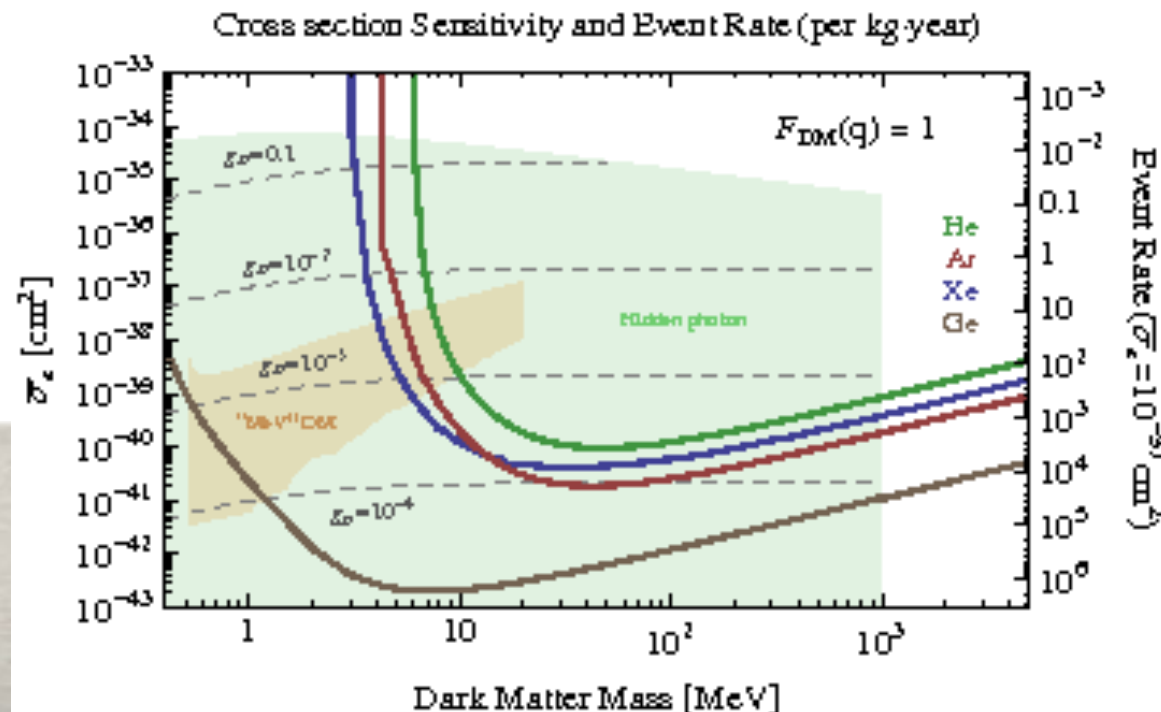


[R. Essig 2104.07634]

Warm
DM

Cold Dark Matter

[Essig, Mardon & Volansky 1108.5383]

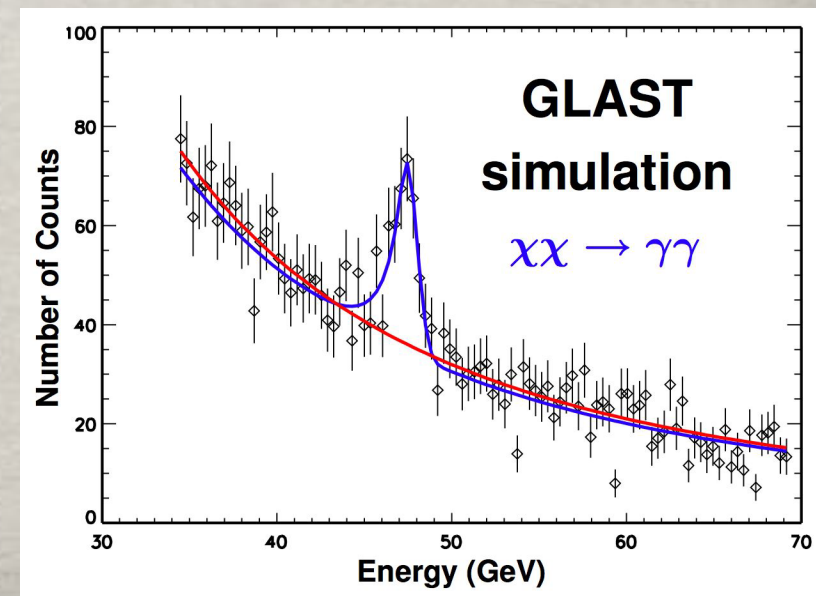


THE HOPE: DETECT DM !

- The flux in a species i is given by

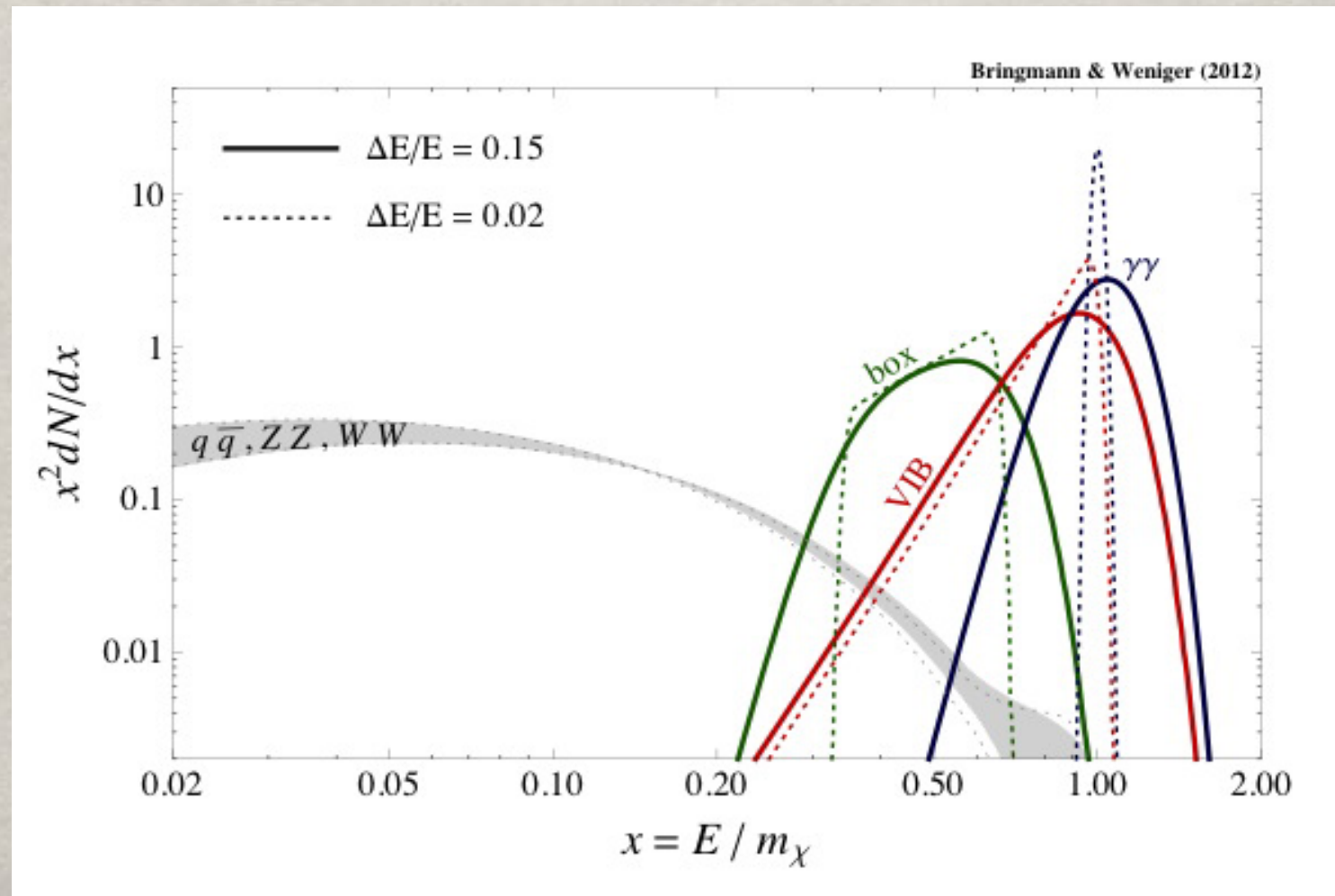
$$\Phi(\theta, E) = \underbrace{\sigma v}_{\text{Particle Physics}} \underbrace{\frac{dN_i}{dE}}_{\text{Particle Physics}} \underbrace{\frac{1}{4\pi m_{DM}^2}}_{\text{Particle Physics}} \underbrace{\int_{l.o.s.} ds \rho^2(r(s, \theta))}_{\text{Halo property } J(\theta)}$$

- 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.



DM SPECTRAL FEATURES

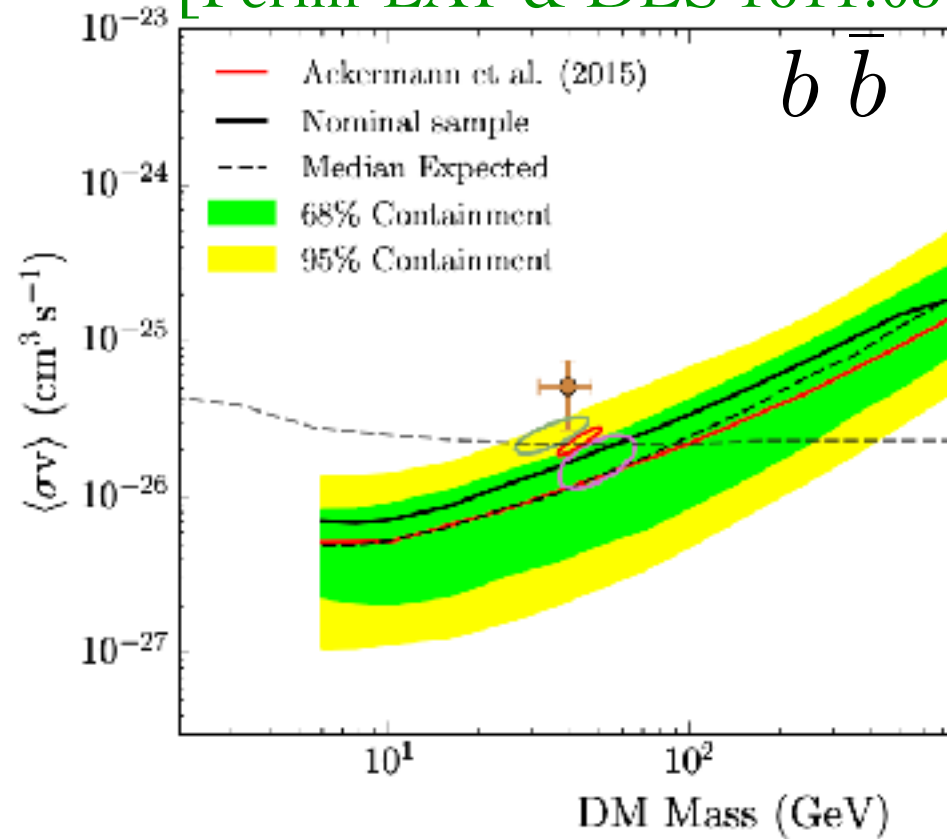
Depending on the model, different features could appear and stick out from the continuum spectrum, helping to see the signal and disentangle the model ! **Smoking guns !**



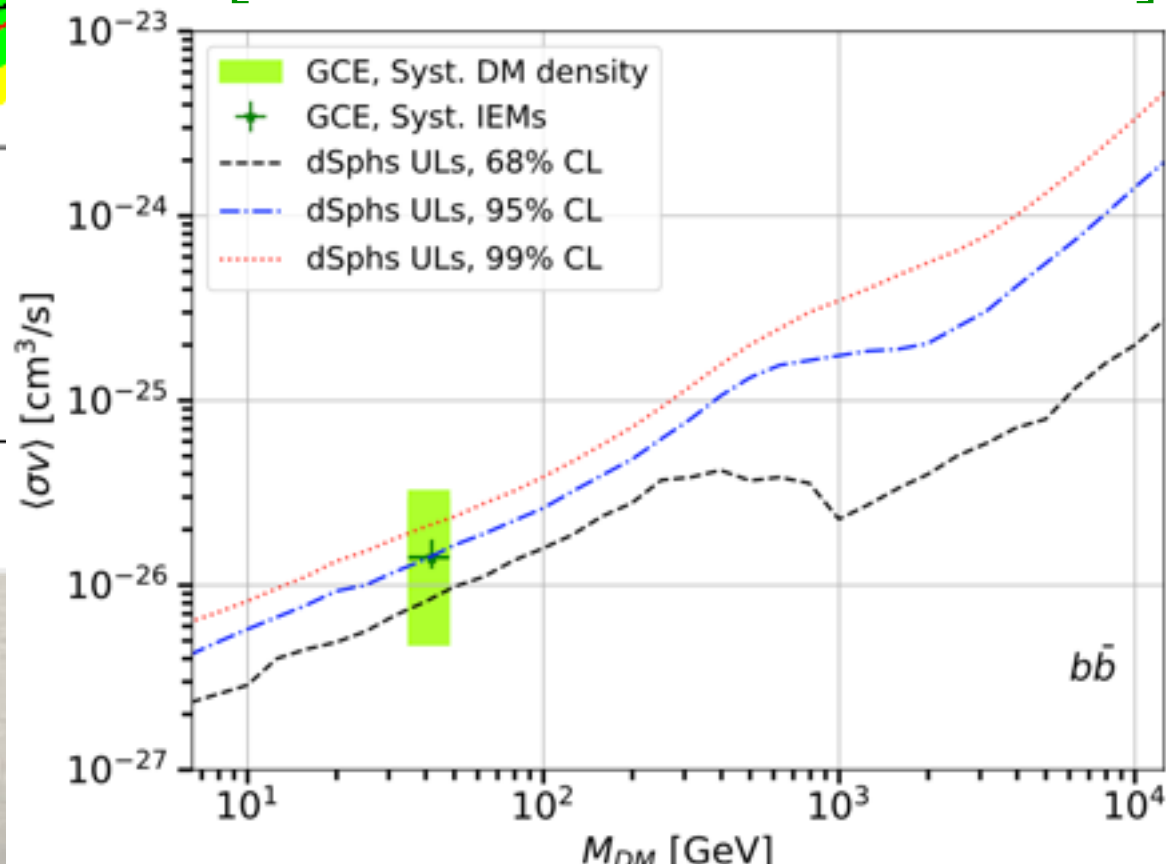
BOUNDS ON WIMP DM

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

[Fermi-LAT & DES 1611.03184]



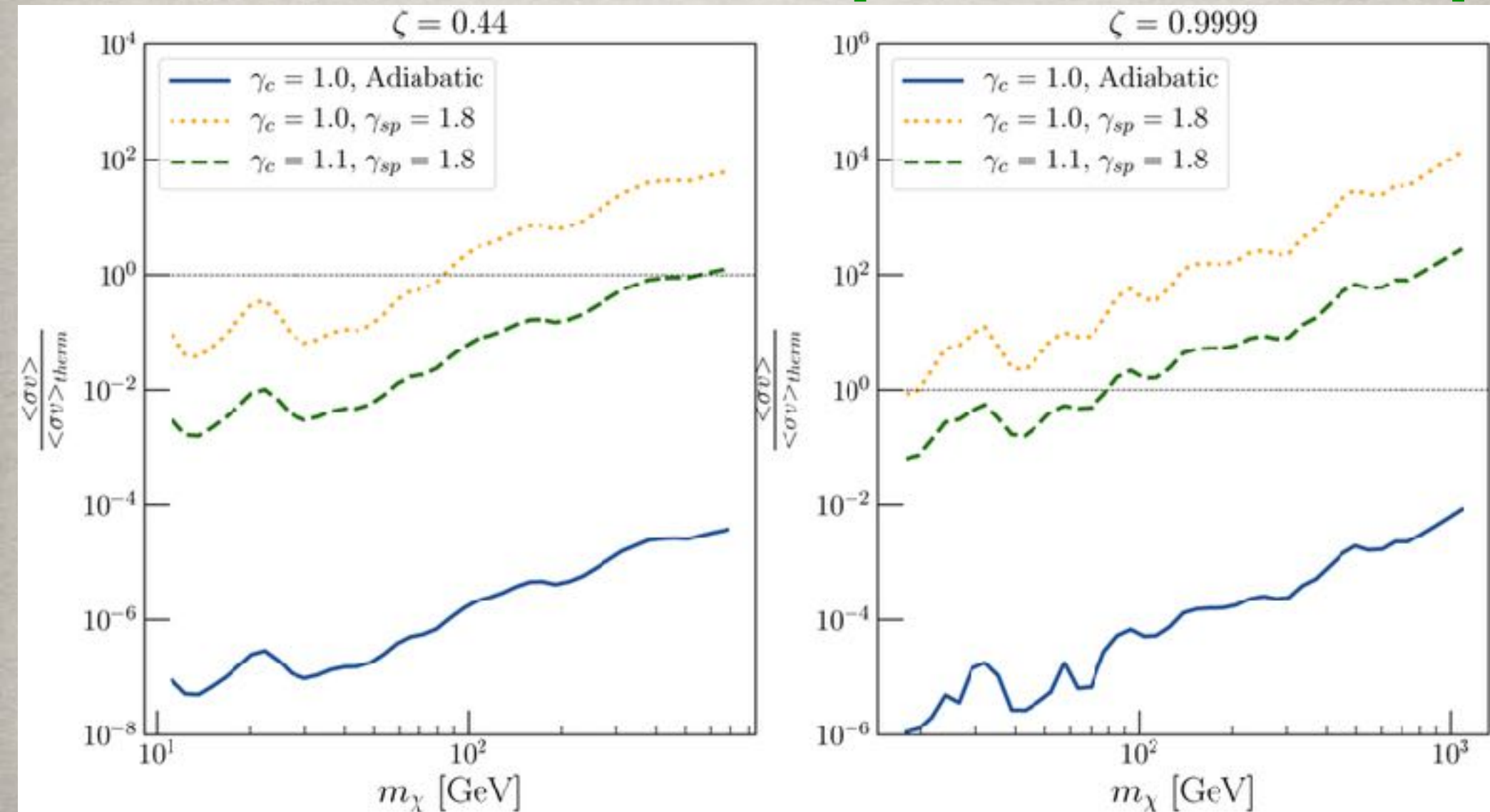
[Di Mauro & Winkler 2101.11027]



WIMP DM ID: P-WAVE

For a cuspy profile the centre of the galaxy can constrain also p-wave annihilation:

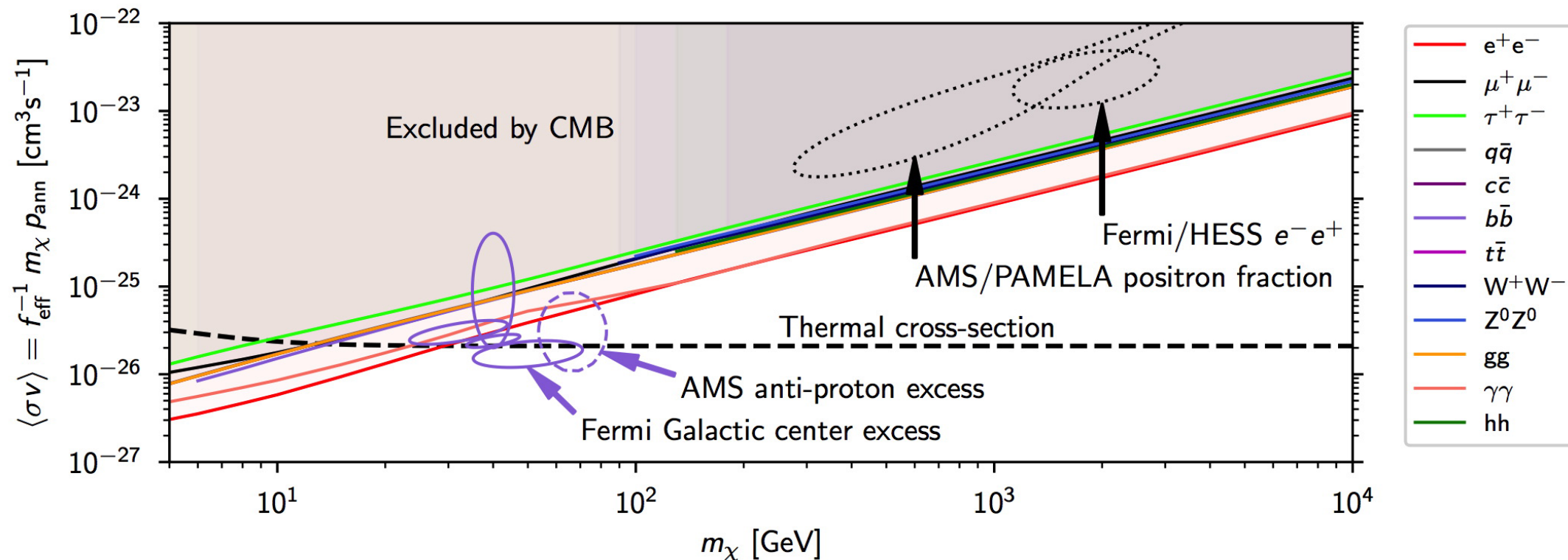
[FERMI-lat arXive:1904.06261]



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:

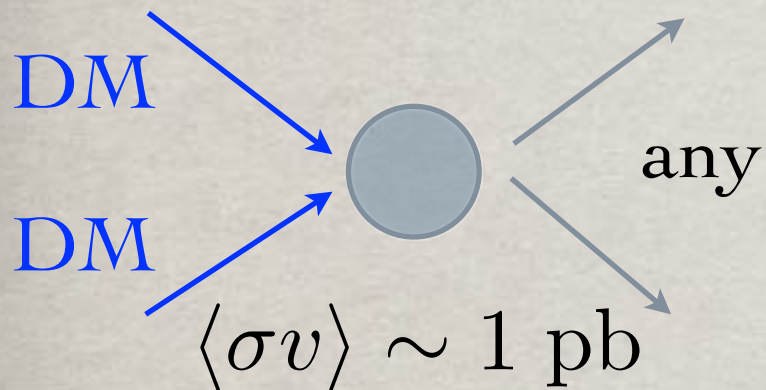
[Planck 1807.06209]



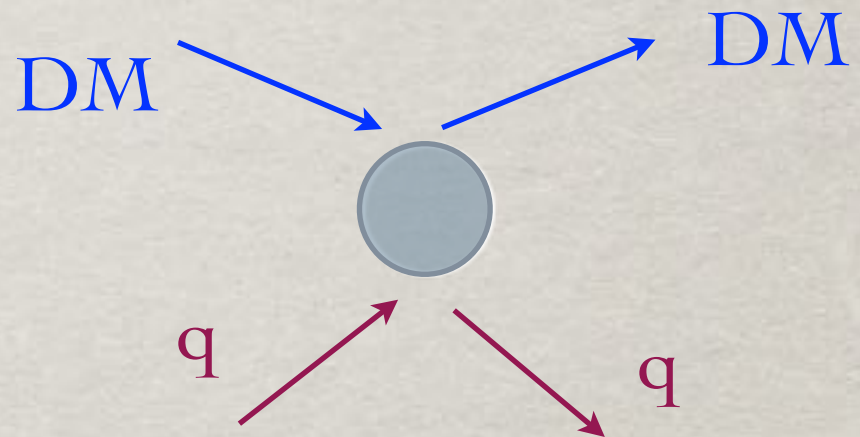
but not the models explaining the Galactic centre excess...

THE WIMP CONNECTION

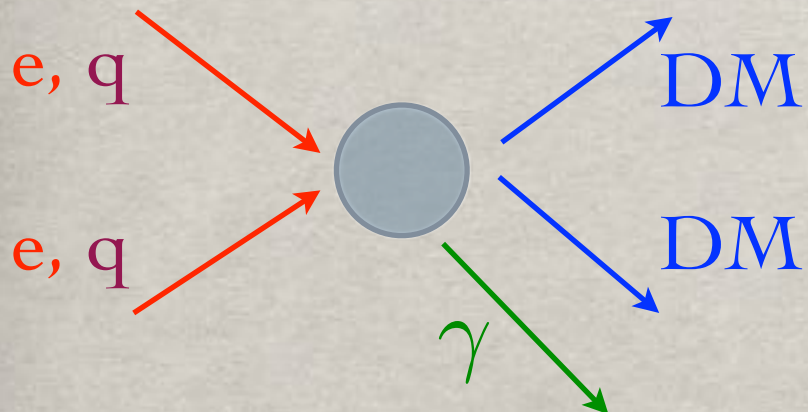
Early Universe: $\Omega_{CDM} h^2$



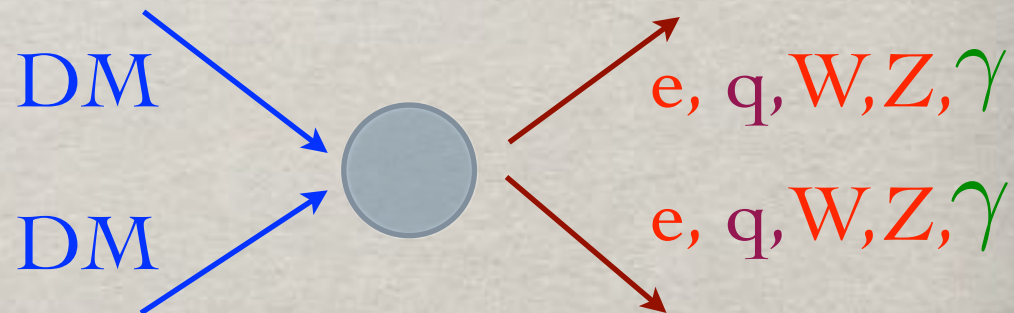
Direct Detection:



Colliders: LHC/ILC



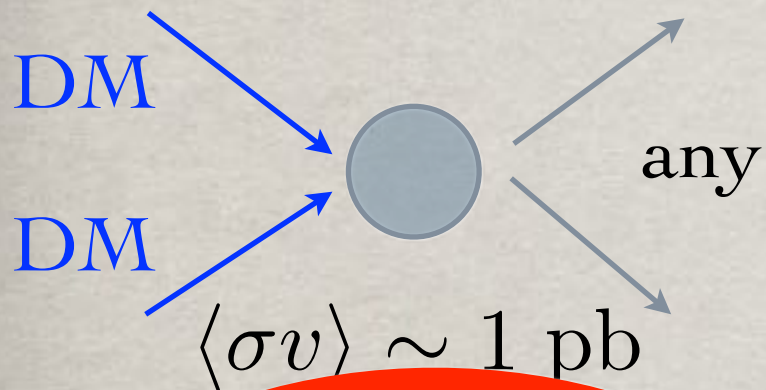
Indirect Detection:



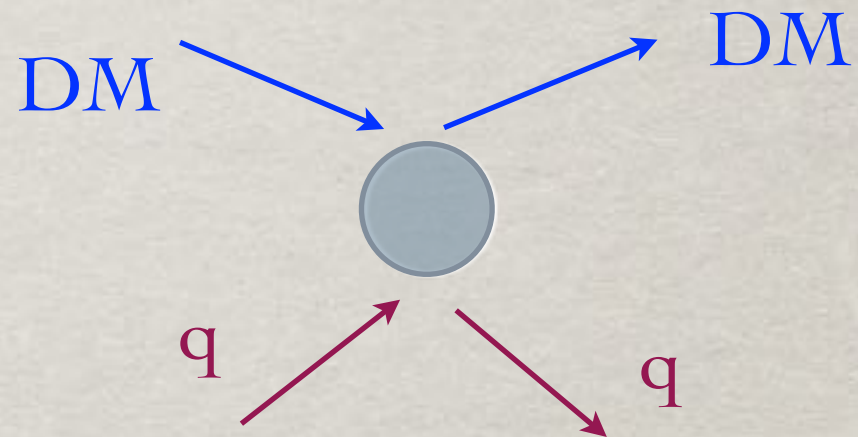
3 different ways to check this hypothesis !!!

THE WIMP CONNECTION

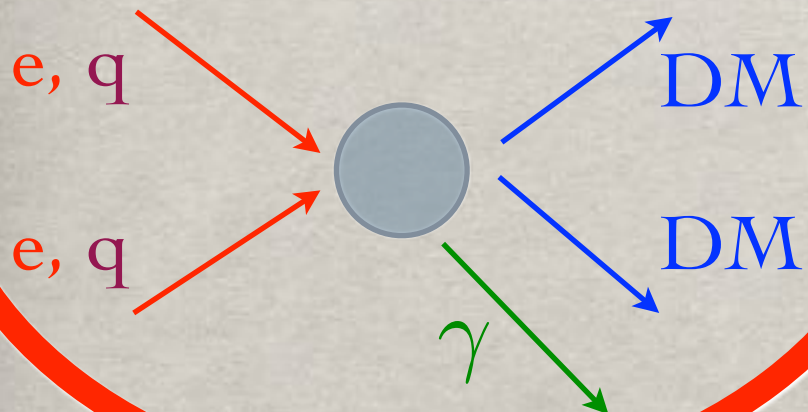
Early Universe: $\Omega_{CDM} h^2$



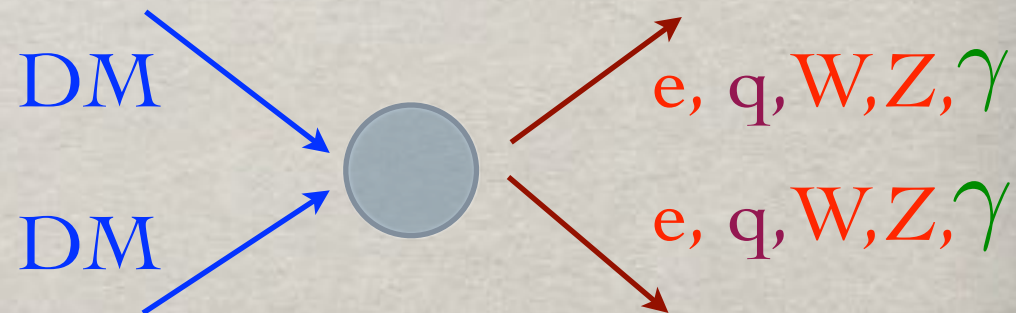
Direct Detection:



Colliders: LHC/ILC



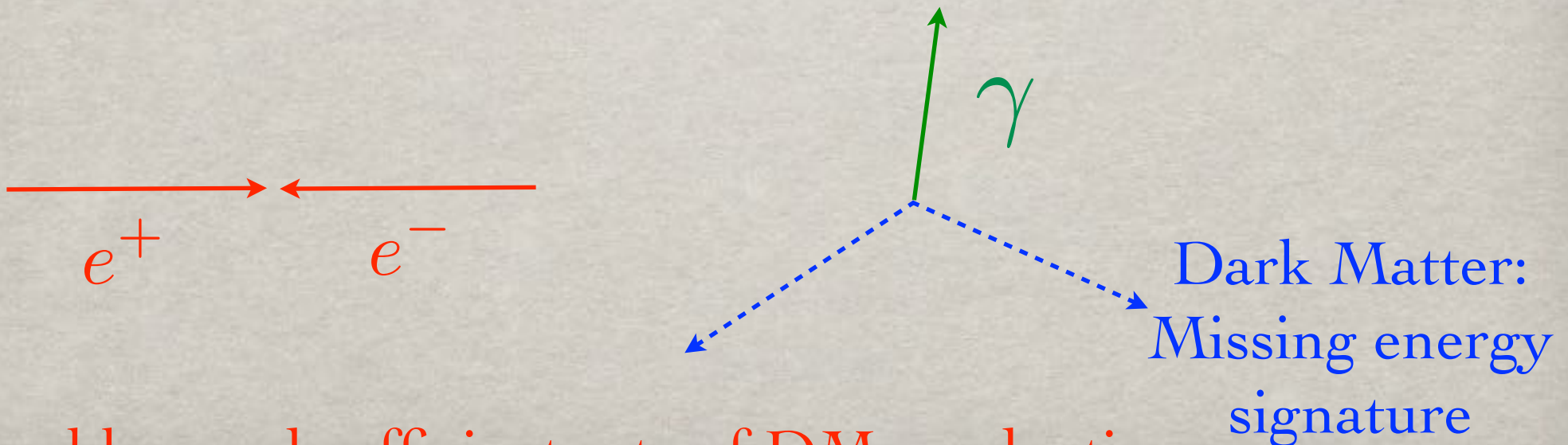
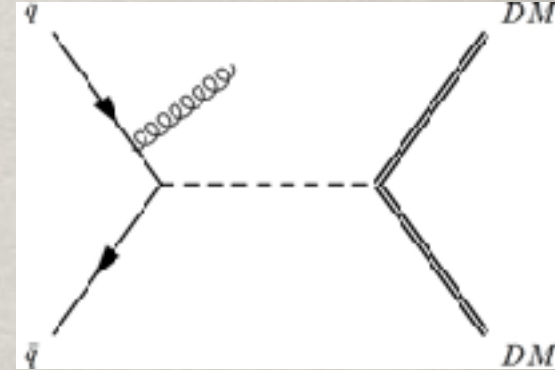
Indirect Detection:



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)



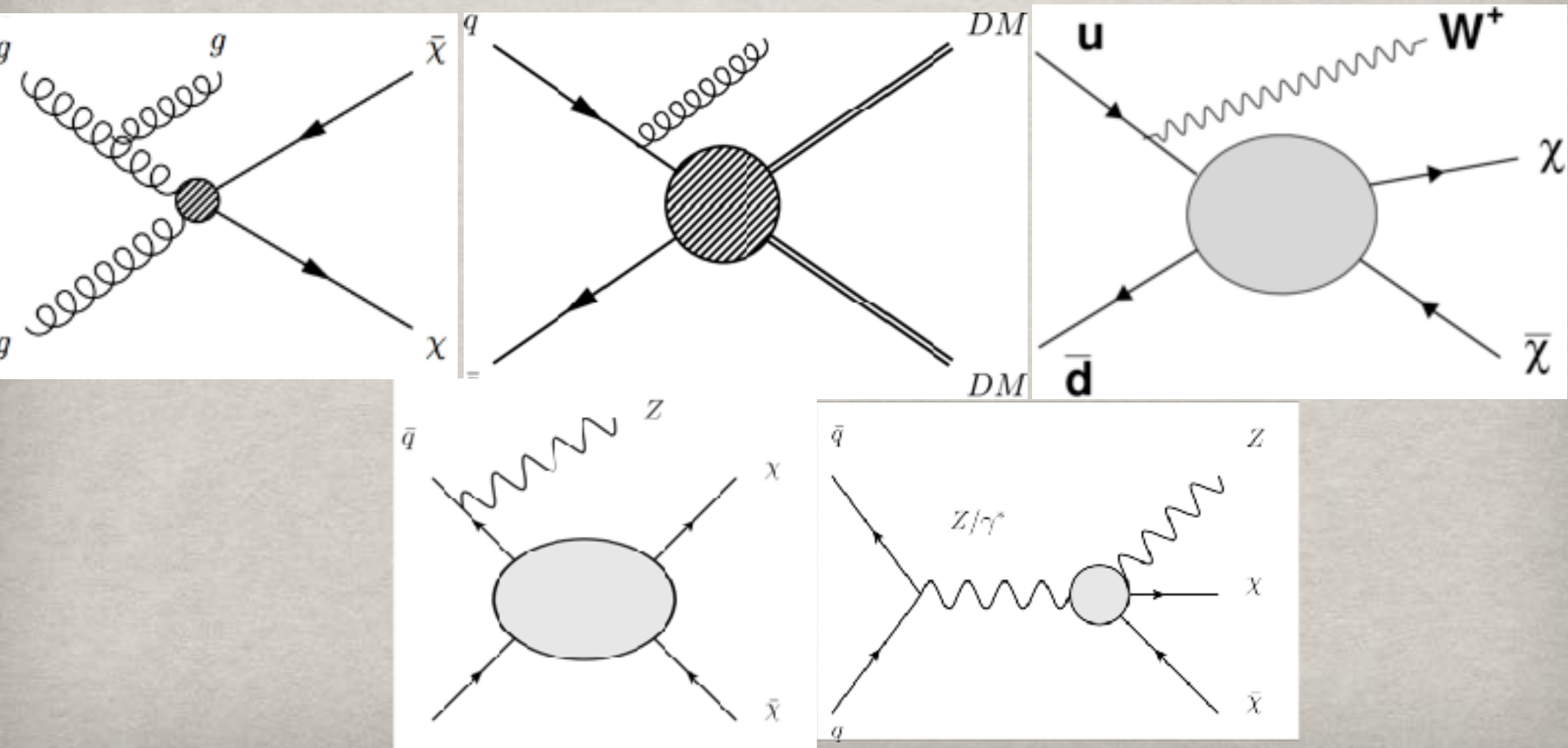
Trouble: need sufficient rate of DM production...

EFT FOR DARK MATTER

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

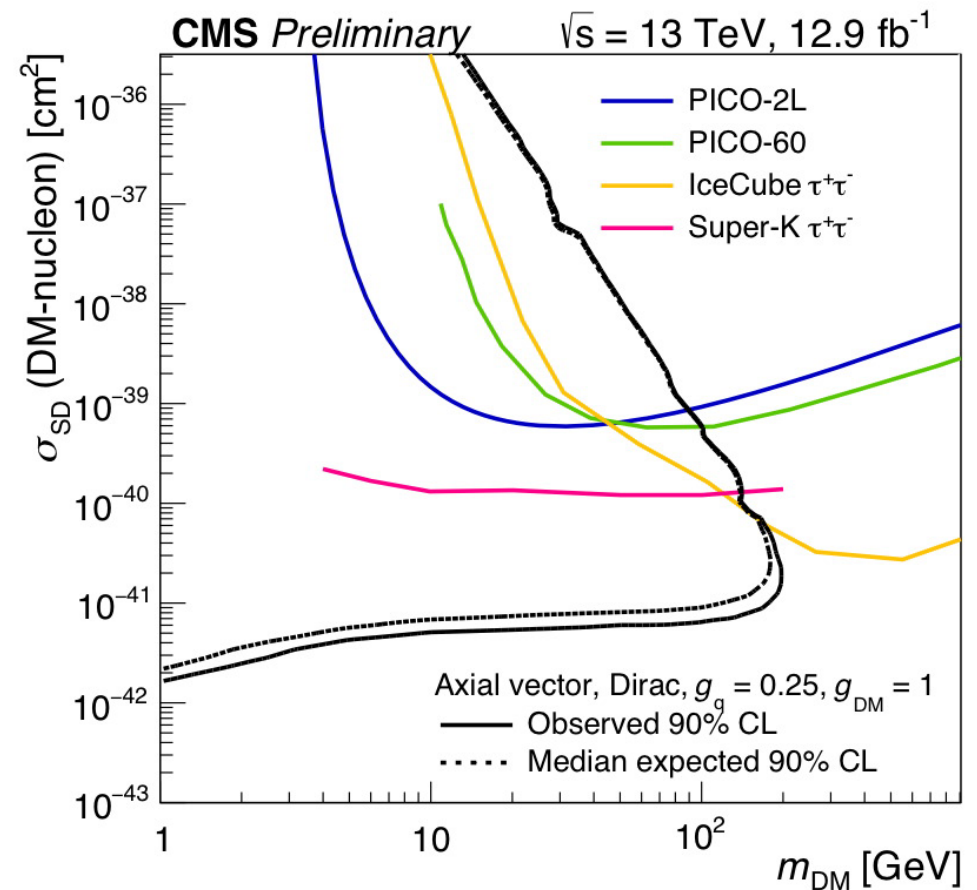
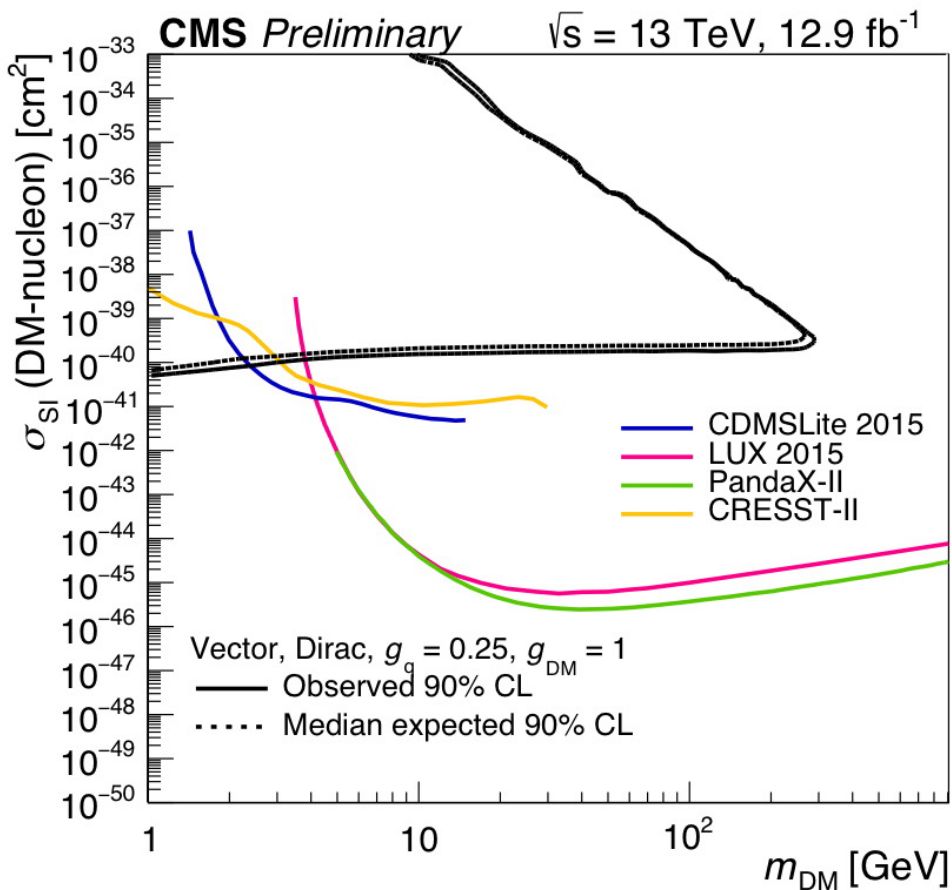
Consider the production of a pair of DM particles together with ISR of a SM particle: gluon, photon, W/Z, top, etc...

EFT: Many different effective operators are possible !



LHC: SIMPLIFIED MODELS

[CMS, EXO-16-039-pas]



Very strong bounds for the axial vector case !

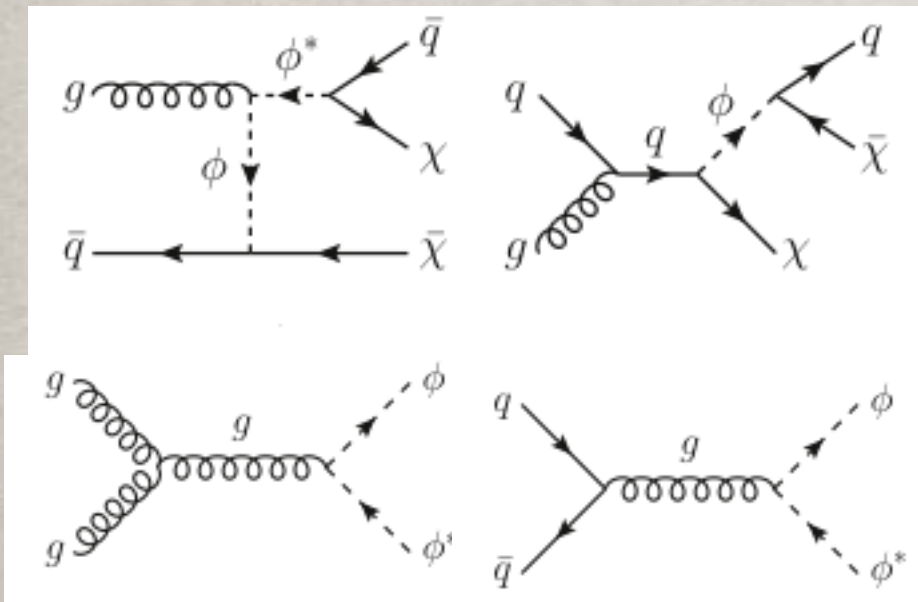
CAVEAT FOR THE EFT: T

In the case of t-channel mediation, there is no resonant enhancement, but instead more channels for monojets as well as dijets show up, e.g. for scalar mediator:

[An et al. 2013, Papucci et al 2014]

Mono-jet without ISR

Dijet and MET



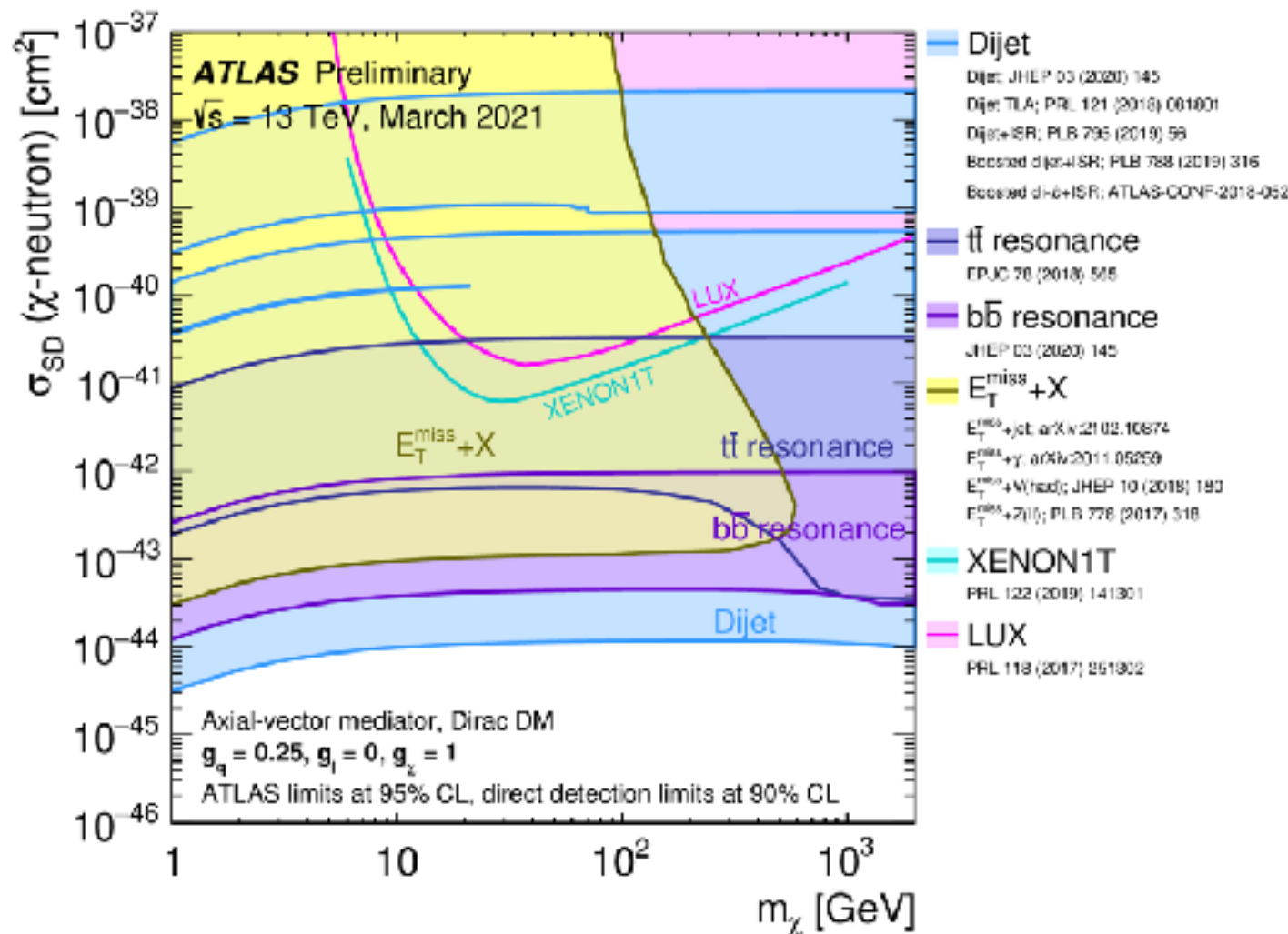
Complementary limits from Mono-jets & Di-jets !

In some cases direct searches for the mediator or di-jets can be more effective than monojets (i.e. also for Z').

[Fradsen et al. 2012, Chala et al. 2015]

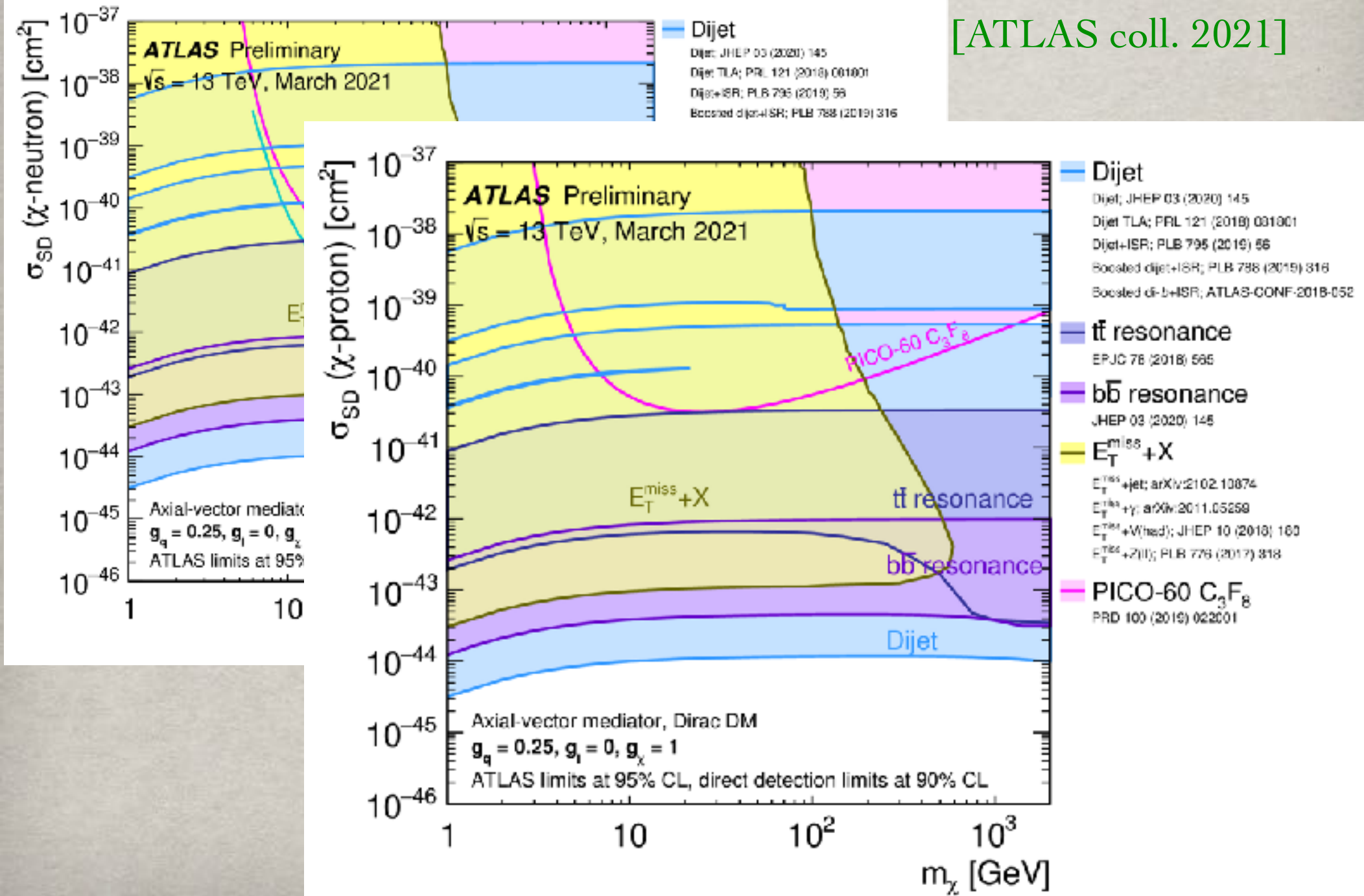
LHC LIMITS FROM DIJETS

[ATLAS coll. 2021]



LHC LIMITS FROM DIJETS

[ATLAS coll. 2021]

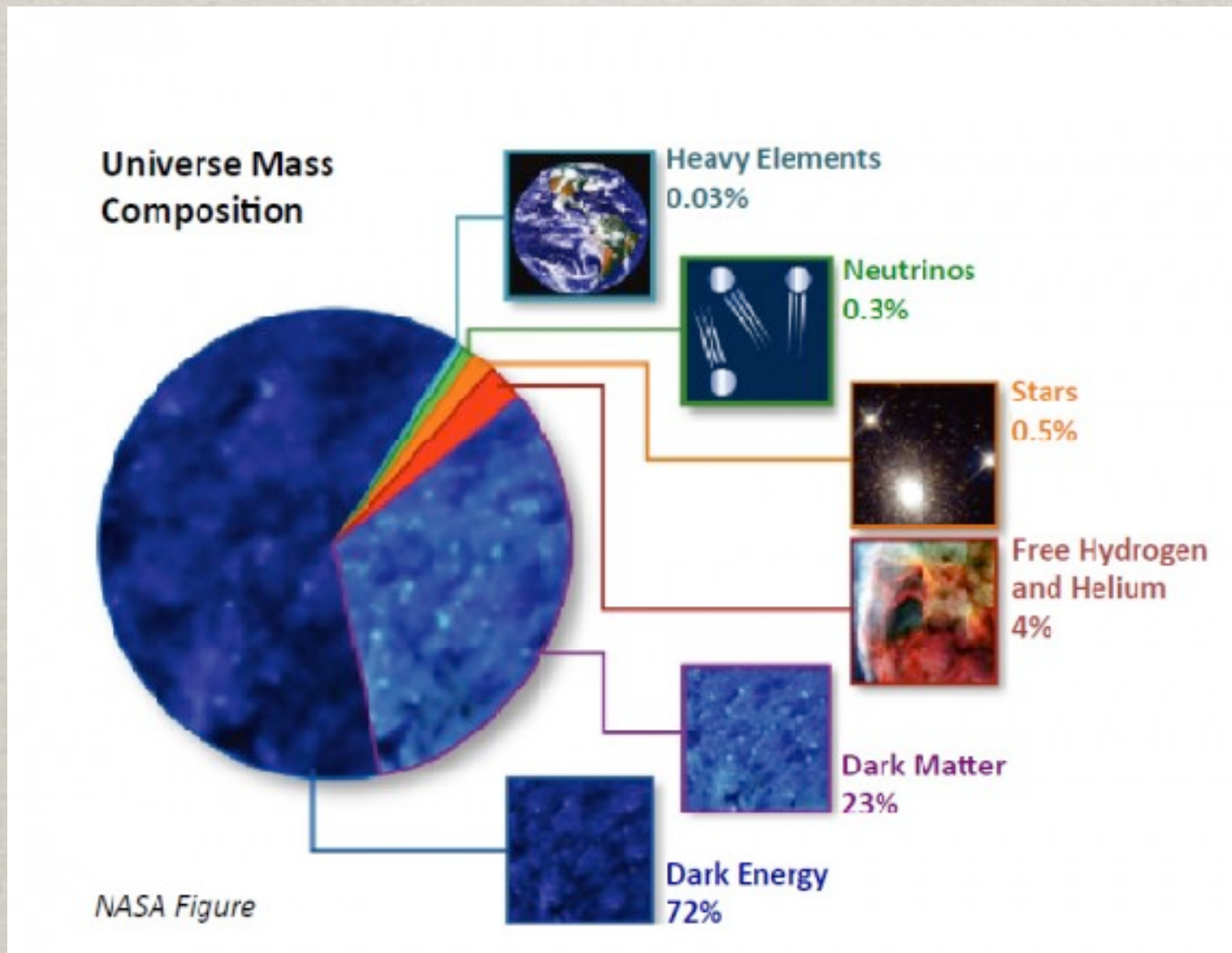


LHC-D/ID COMPLEMENTARITY

- DD and especially ID have a much more extended mass reach than a collider, even if the sensitivity decreases for large masses since the number density becomes lower...
- A missing energy signal at LHC does not guarantee that the escaping particle is DM or even a thermal relic. We need also a detection signal at ID or DD to be sure that we are seeing the DM particle !
- Goal is also checking the consistency with the WIMP mechanism from measures @ collider (not so simple).

THERMAL RELICS: ASYMMETRIC DARK MATTER

UNIVERSE COMPOSITION



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

SAKHAROV CONDITIONS

Sakharov studied already in 1967 the necessary conditions for generating a baryon asymmetry from a symmetric state:

- **B violation:** trivial condition since otherwise B remains zero...
- **C and CP violation:** otherwise matter and antimatter would still be annihilated/created at the same rate
- **Departure from thermal equilibrium:** the maximal entropy state is for $B = 0$, or for conserved CPT, no B generated without time-arrow...

Now exactly the same conditions have to hold also for the generation of a Dark Matter Asymmetry !

ASYMMETRIC DARK MATTER

[Griest & Seckel '87, Kaplan, Luty & Zurek 90, ...]

Assume instead that there is an asymmetry stored in DM as in baryons: DM asymmetry generated in the same way as the baryon asymmetry..
It may also be generated together with the baryon asymmetry and then it is natural to expect the **SAME** asymmetry in both sectors.

$$\Psi \rightarrow B + X$$

$$n_{DM} \sim n_b \rightarrow \Omega_{DM} \sim 5 \Omega_b$$

$$\text{for } m_{DM} \sim 5 m_p = 5 \text{ GeV}$$

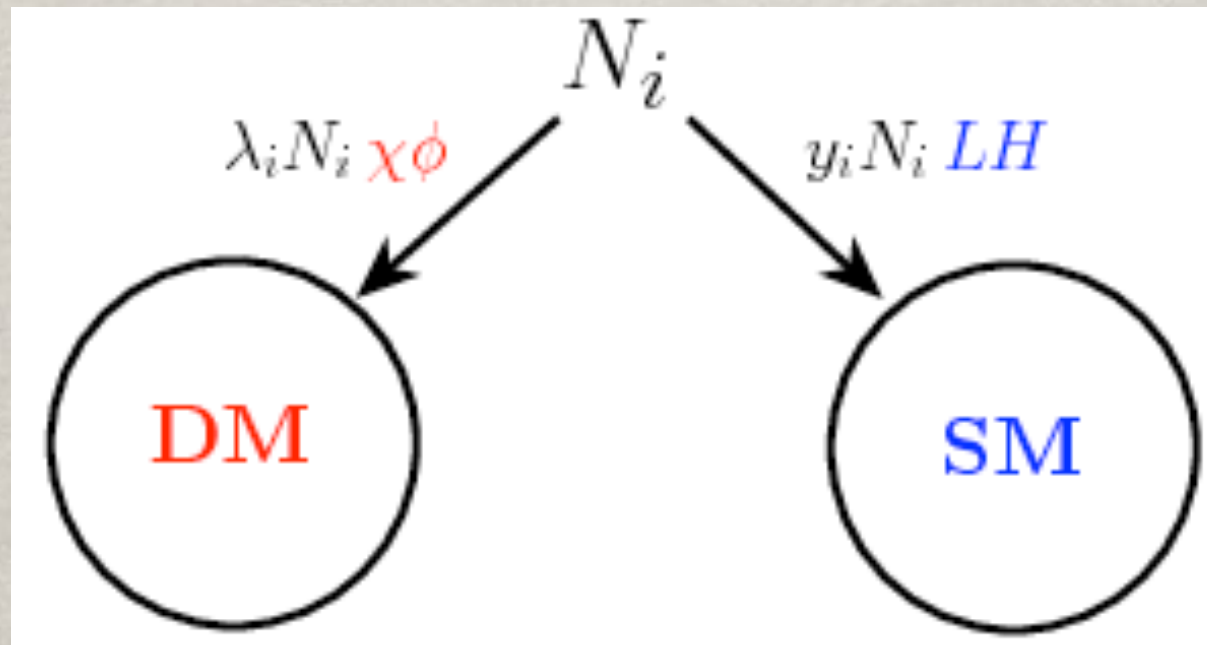
The puzzle of similar densities can be given by
similar masses !

ASYMMETRIC DARK MATTER

[Griest & Seckel '87, Kaplan, Luty & Zurek 90, ...

Falkowski, Ruderman & Volansky 2011]

Simple mechanism to generate such case:
out-of-equilibrium decay of a particle producing
both B-L and DM, e.g. even decay of a RH neutrino

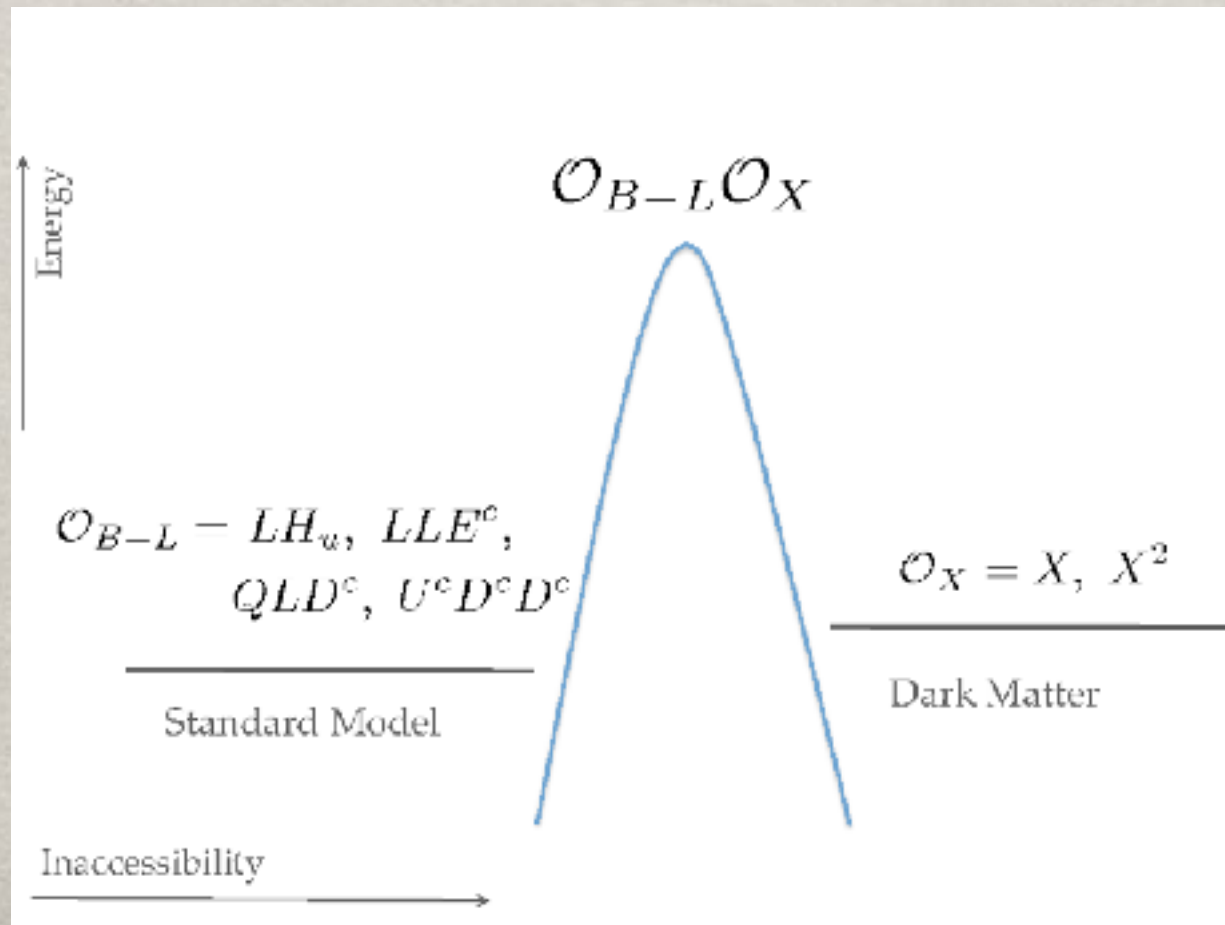


Need similar CP violation in both sectors !

ASYMMETRIC DARK MATTER

[Griest & Seckel '87, Kaplan, Luty & Zurek 90, ...]

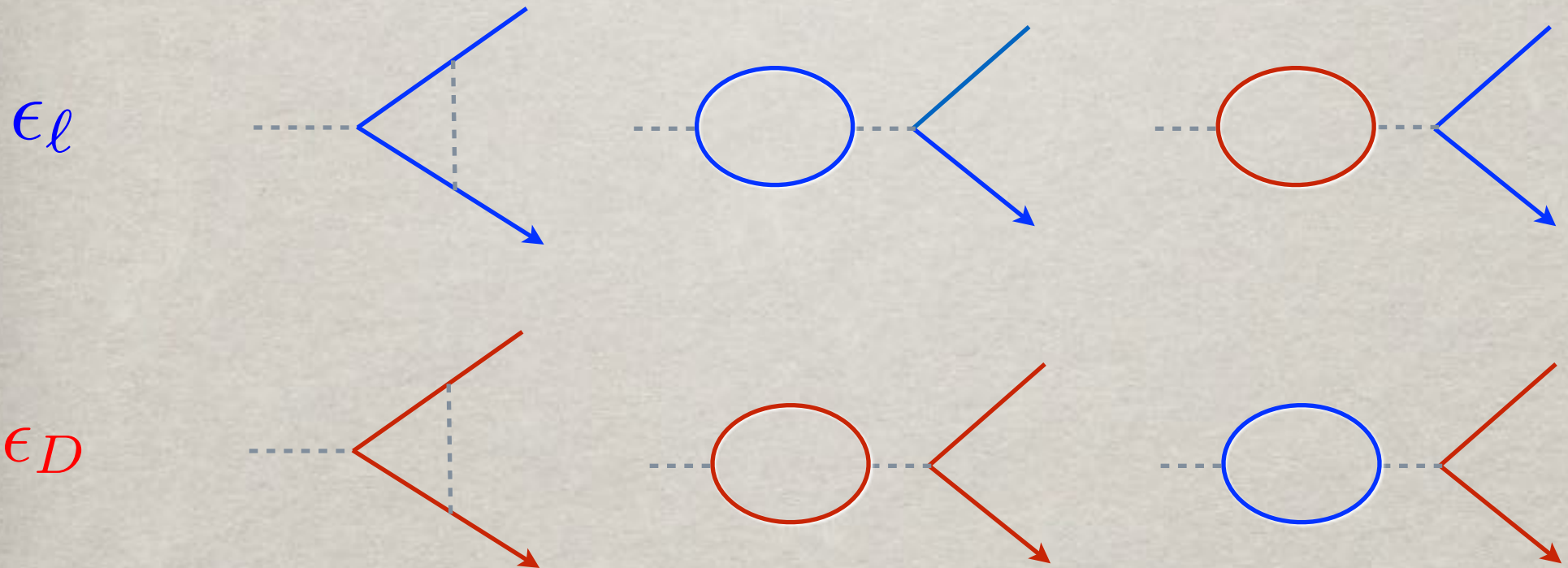
Otherwise B-L can be produced and then reprocessed into DM/B/L by sphaleron processes. All other coupling exchanging DM/B frozen out !



CP VIOLATION FOR ADM

[A. Biswas, S. Choubey, LC & S. Khan 2018]

The CP asymmetry in the decay has generally contributions from both lepton/DM sectors:

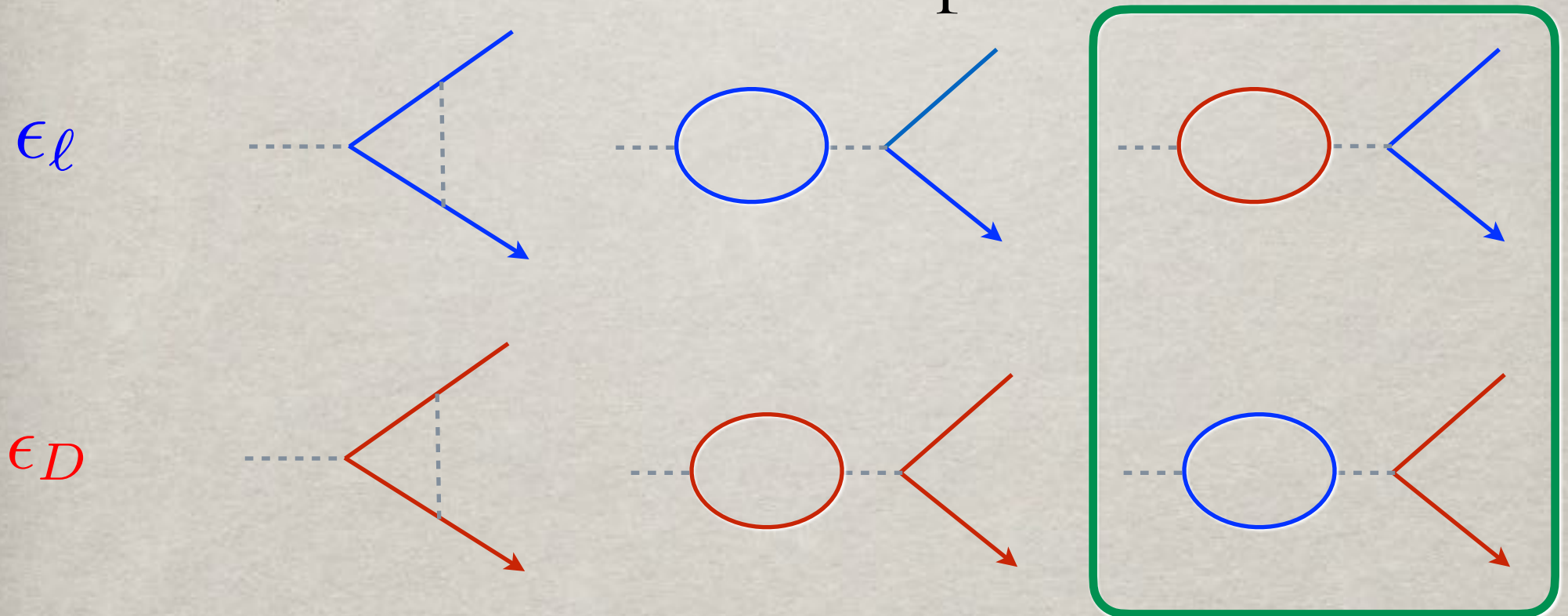


$$\epsilon_\ell = \epsilon_D$$

CP VIOLATION FOR ADM

[A. Biswas, S. Choubey, LC & S. Khan 2018]

The CP asymmetry in the decay has generally contributions from both lepton/DM sectors:



But the wave-function contribution with virtual leptons/DM can dominate both asymmetries and give $\epsilon_\ell = \epsilon_D$!

CP VIOLATION FOR ADM

[A. Biswas, S. Choubey, LC & S. Khan 2018]

The CP asymmetry in both decays comes from the same phases, contained in the neutrino sector, since the DM couplings can be chosen real:

$$\frac{\epsilon_{\ell}}{\epsilon_D} = 1 + \frac{\text{Im} [3((y^{\dagger}y)_{12}^*)^2]}{2\alpha_1\alpha_2\text{Im} [3(y^{\dagger}y)_{12}^*]}$$

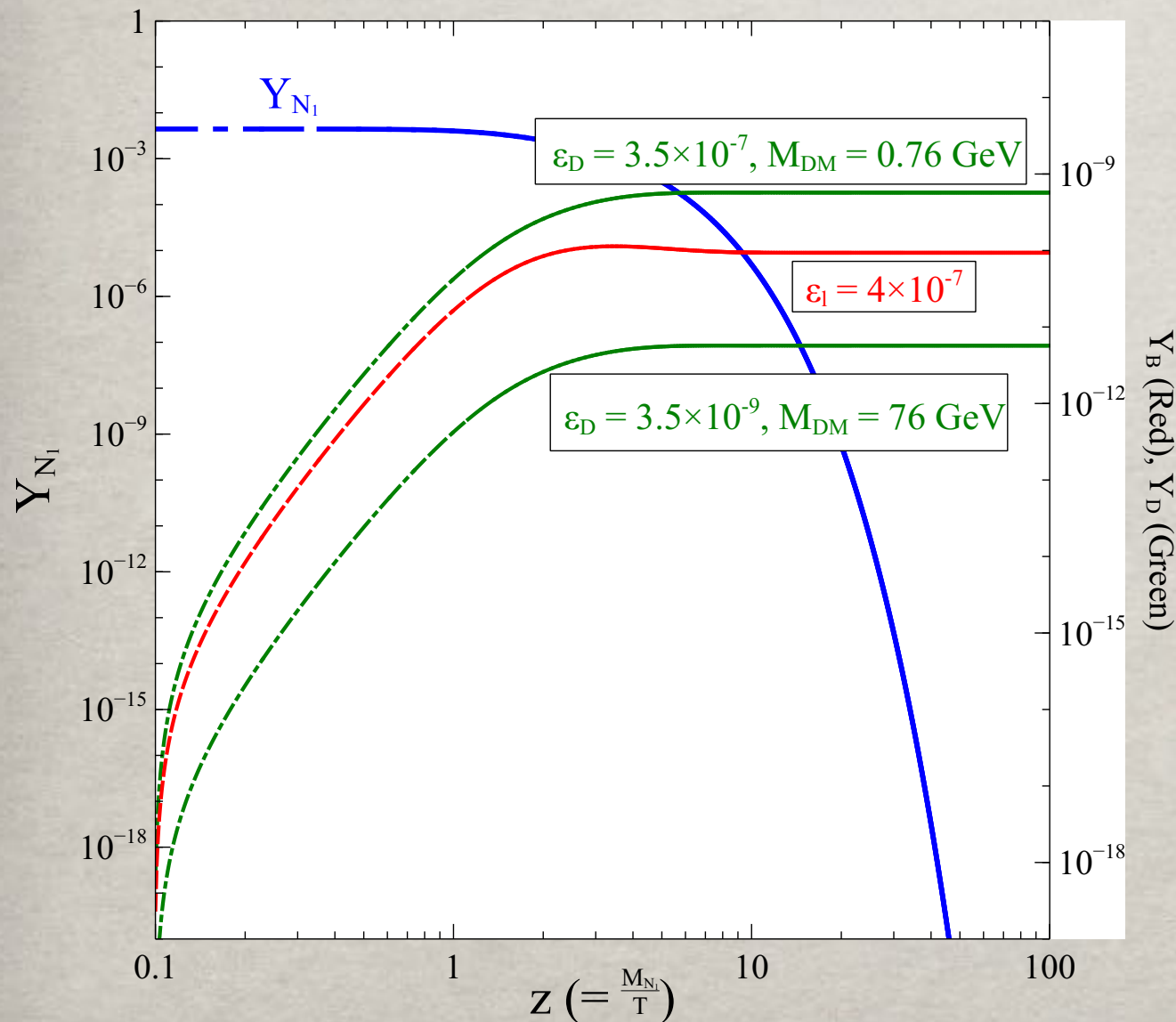
For one real and one imaginary columns of Yukawas, then

we have $\text{Real} ((y^{\dagger}y)_{12}^*)^2$ and exactly $\epsilon_{\ell} = \epsilon_D$.

Similarly in case of $\alpha_1\alpha_2 > |(y^{\dagger}y)_{12}|$ we also obtain practically equal CP violation in the decays.

A MINIMAL ADM MODEL

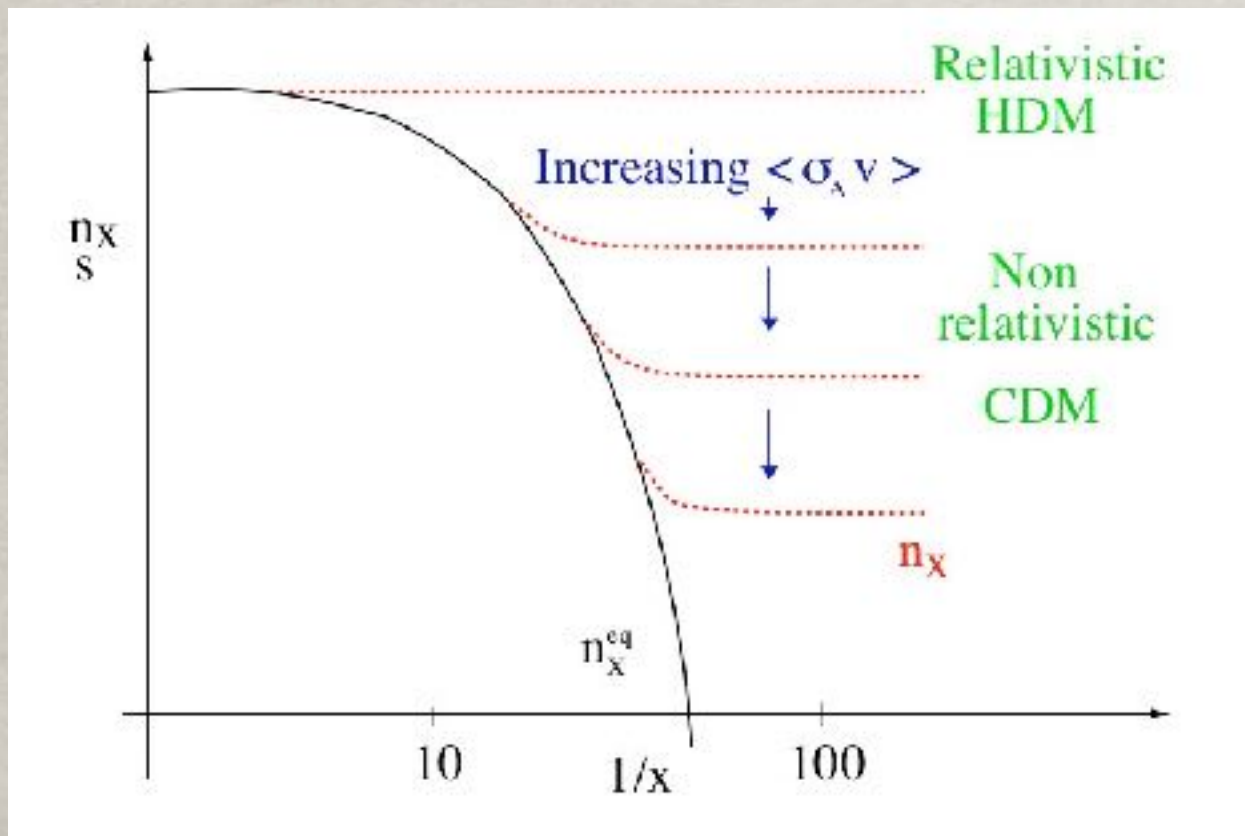
[A. Biswas, S. Choubey, LC & S. Khan 2018]



Even if the CP parameter is the same, also wash-out processes play a role and naturally give a larger asymmetry in the DM sector than in the lepton sector !

ASYMMETRIC DARK MATTER

But DM must annihilate sufficiently strongly to erase the symmetric DM component, so it must interact more strongly than a WIMP (in our case within a hidden sector).

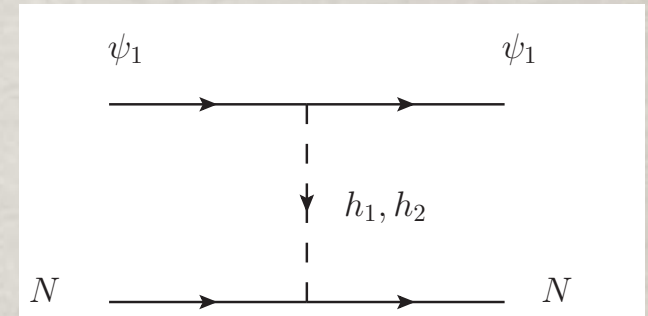
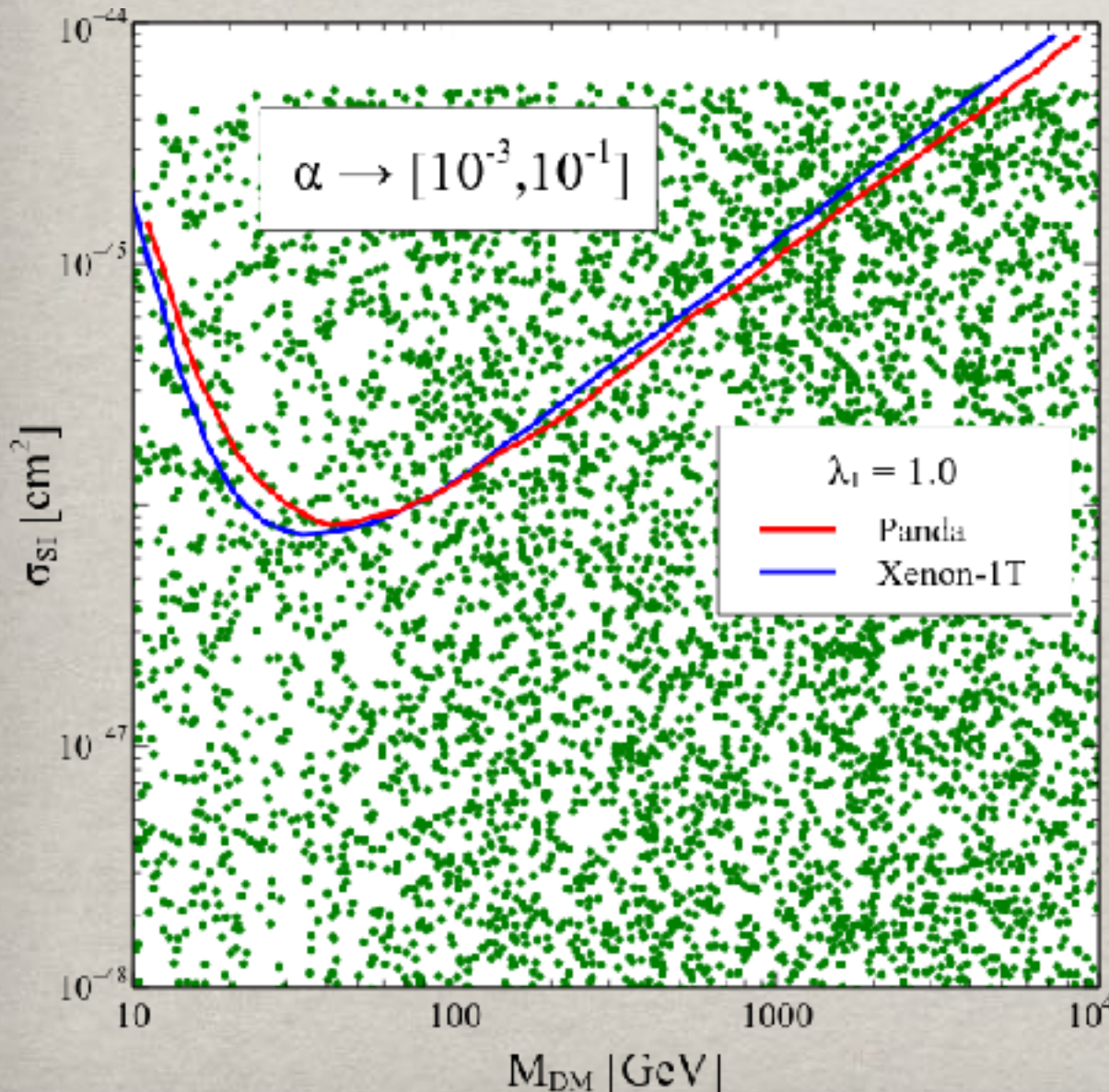


Strong coupling...
...like baryons !

It may accumulate
in stars and change
the star evolution...

DD IN THE ADM MODEL

[A. Biswas, S. Choubey, LC & S. Khan 2018]



Due to the mixing of the scalars after EW symmetry breaking, the DM scatters with normal matter via intermediate Higgs and could be detected in DD (but beware of the cancellation!)

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 or ADM, thermal relics from the primordial thermal bath !
- The WIMP/ADM mechanism are being probed by astrophysical observations and particle physics experiments. No convincing hints were found, but still space to explore...
- Keep looking at interesting models !