ICTP Summer School on Particle Physics
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Dark Matter

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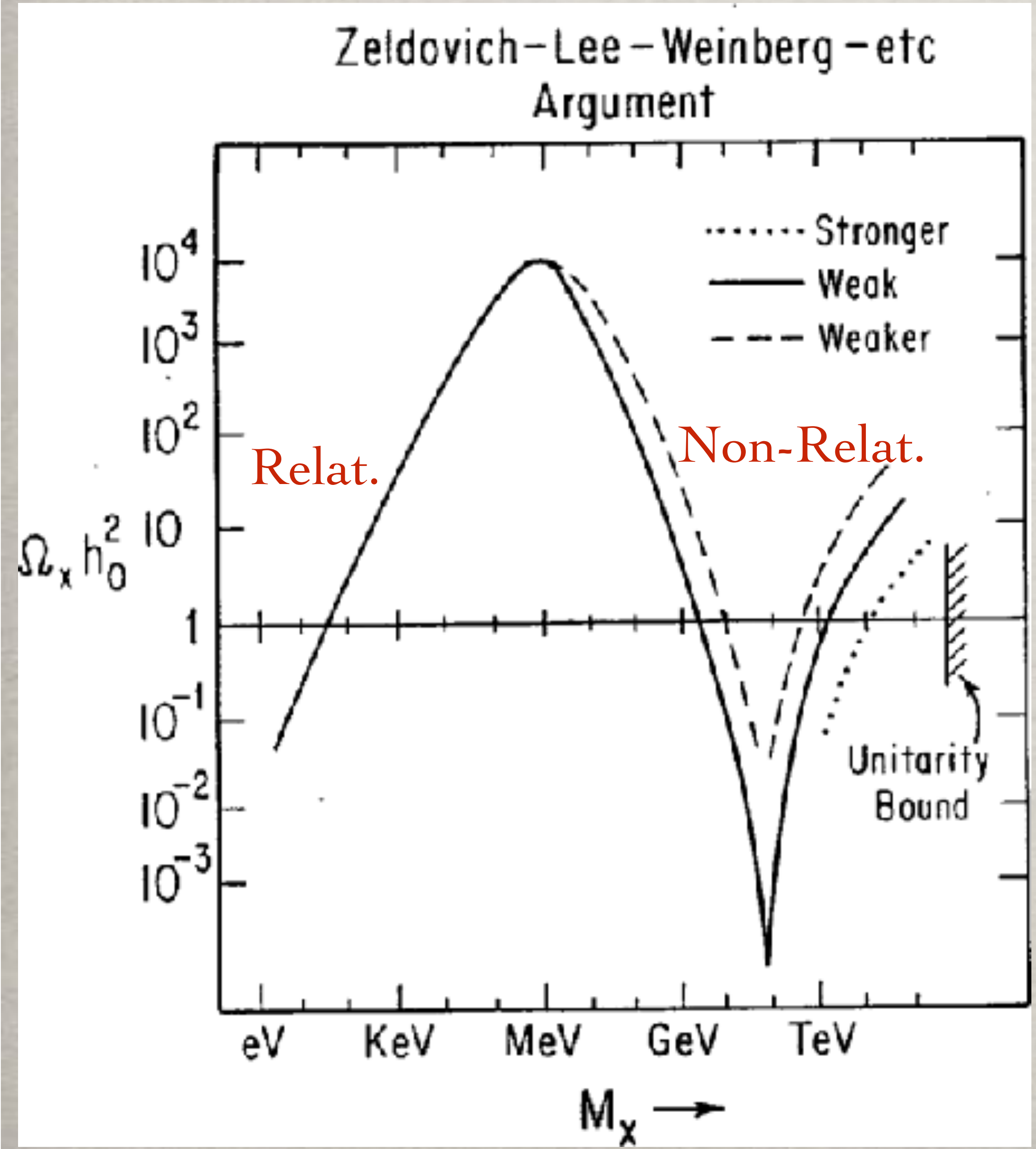
$[q,p]=i\hbar$

Outline

- Lecture 1:
  Introduction to Dark Matter evidence
- Lecture 2 & 3:
  Boltzmann equation and DM as Weakly Interacting Particles
- Lecture 4:
  Asymmetric/FIMP/SuperWIMP DM

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)

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

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

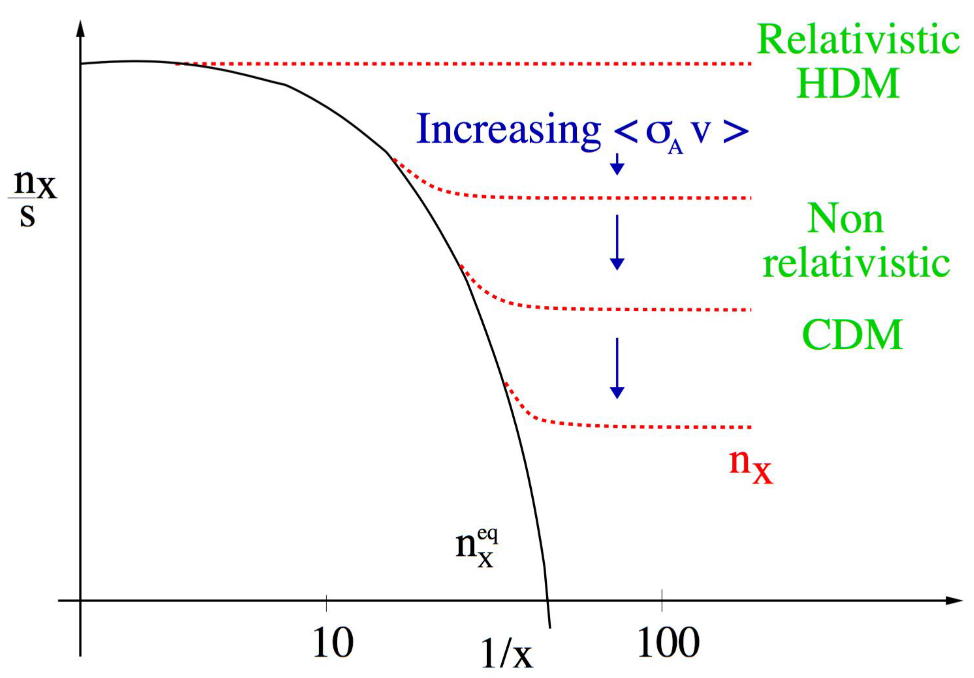
Hubble expansion Collision integral

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

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

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 !

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 σ is sufficiently large after freeze-out

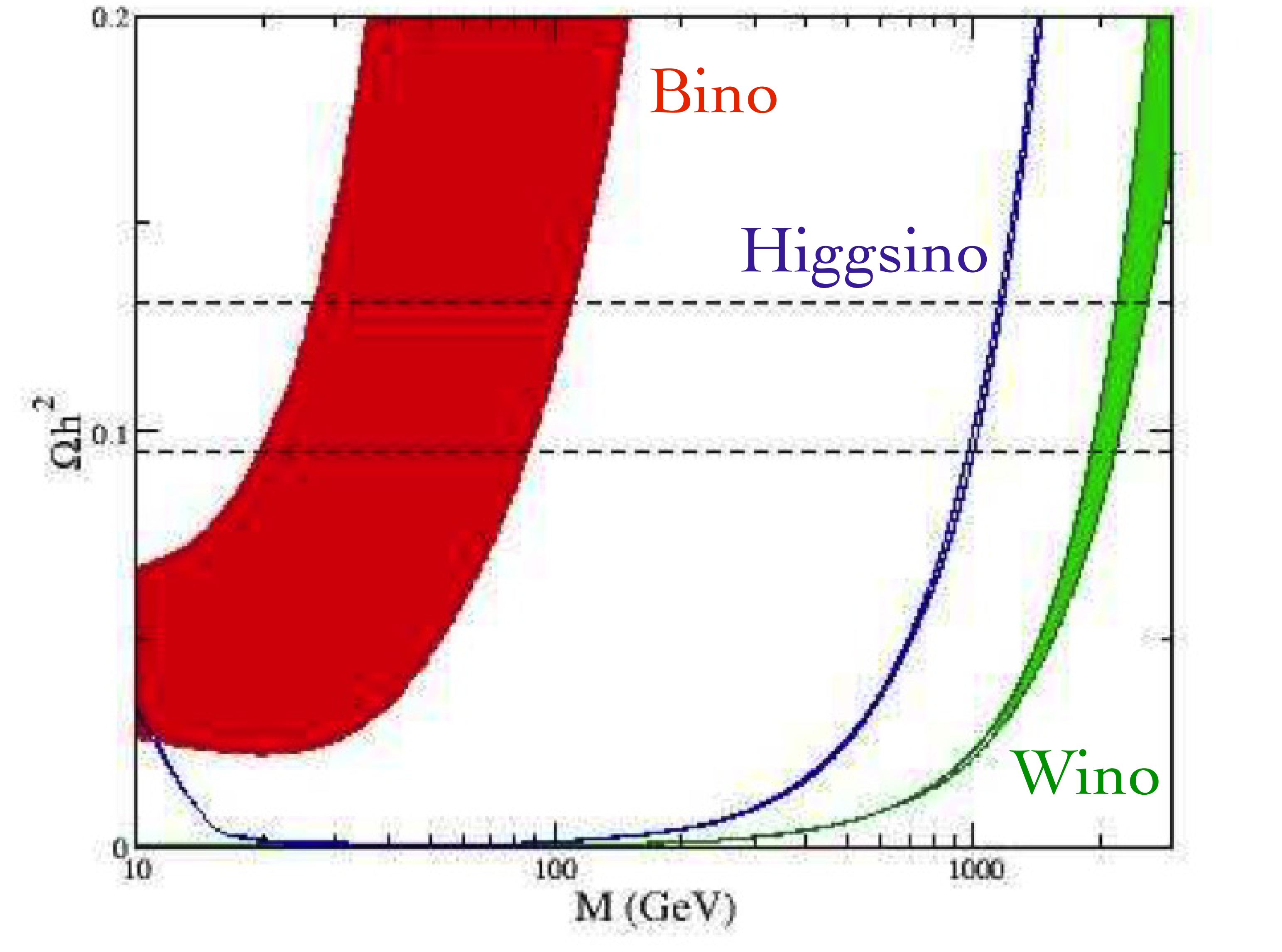
$$Y_X(x) \simeq \frac{1}{\frac{s(m_X)}{H(m_X)}\int_{x_f}^{x}\frac{dx}{x^2}\langle\sigma(X + X \to \text{anything})v\rangle(x)}$$

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

Well-tempered neutralino

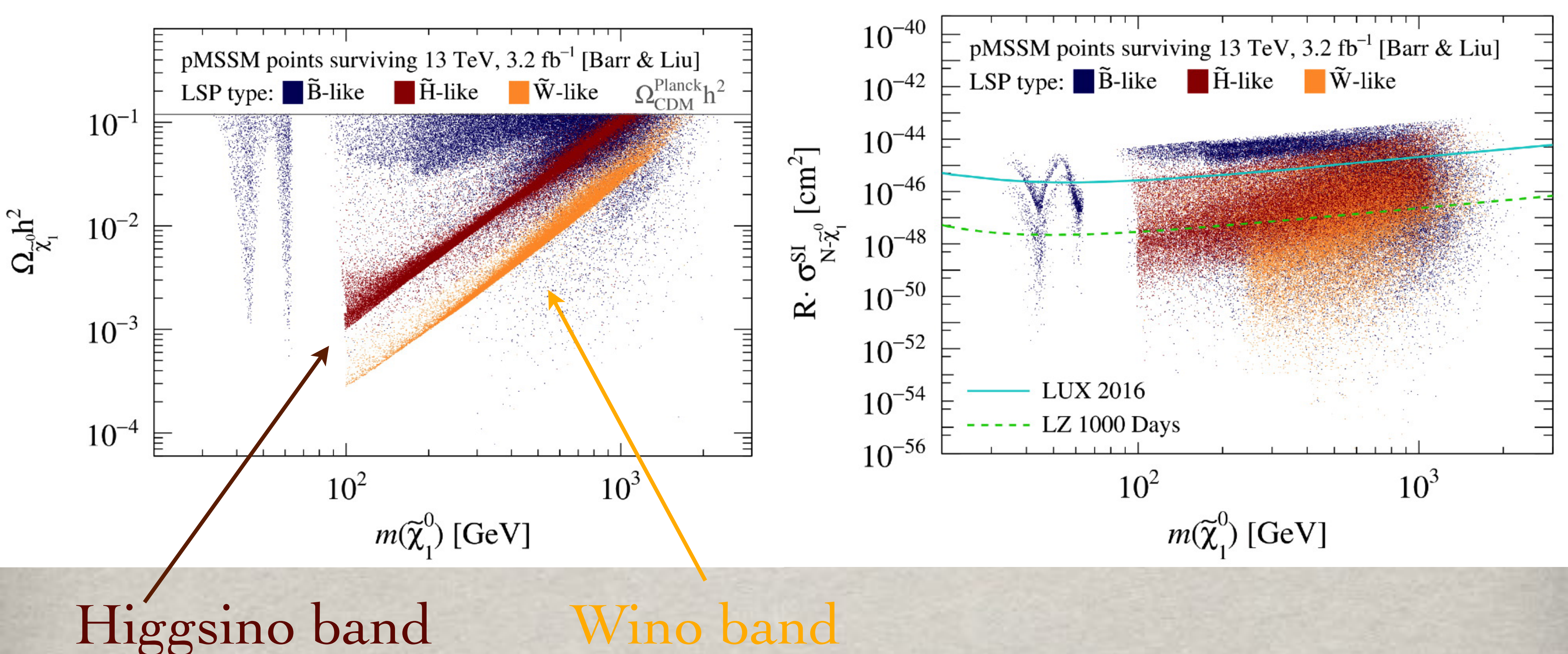
Relic density strongly dependent on neutralino nature !!!

[Arkani-Hamed, Delgado & Giudice 0601041]



SUSY MODELS STILL ALIVE

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

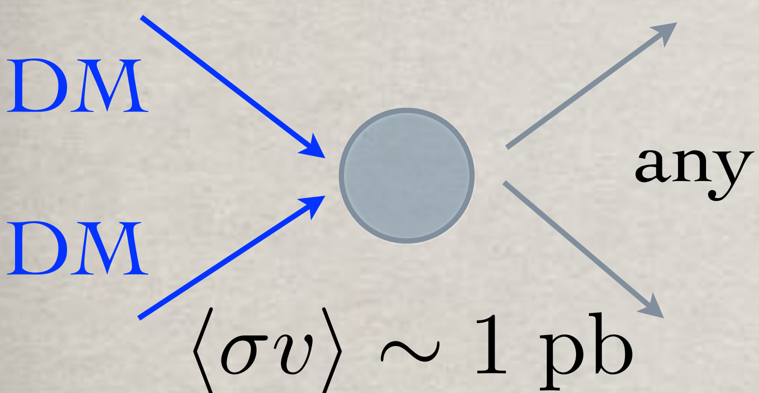


Wino DM challenged by Indirect Detection, but Higgsino parameter space still viable (and also some Bino-like...)

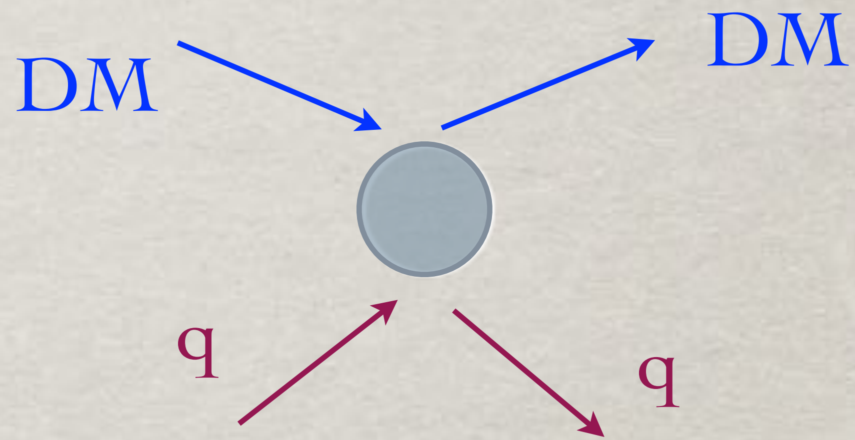
How to detect a WIMP

THE WIMP CONNECTION

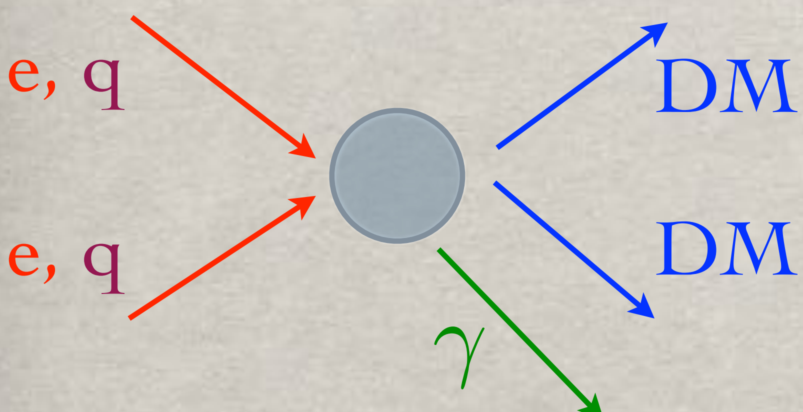
Early Universe: $\Omega_{CDM}h^2$



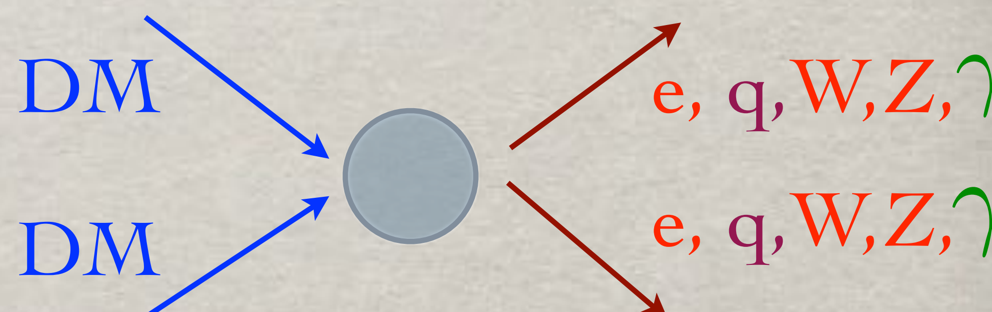
Direct Detection:



Colliders: LHC/ILC

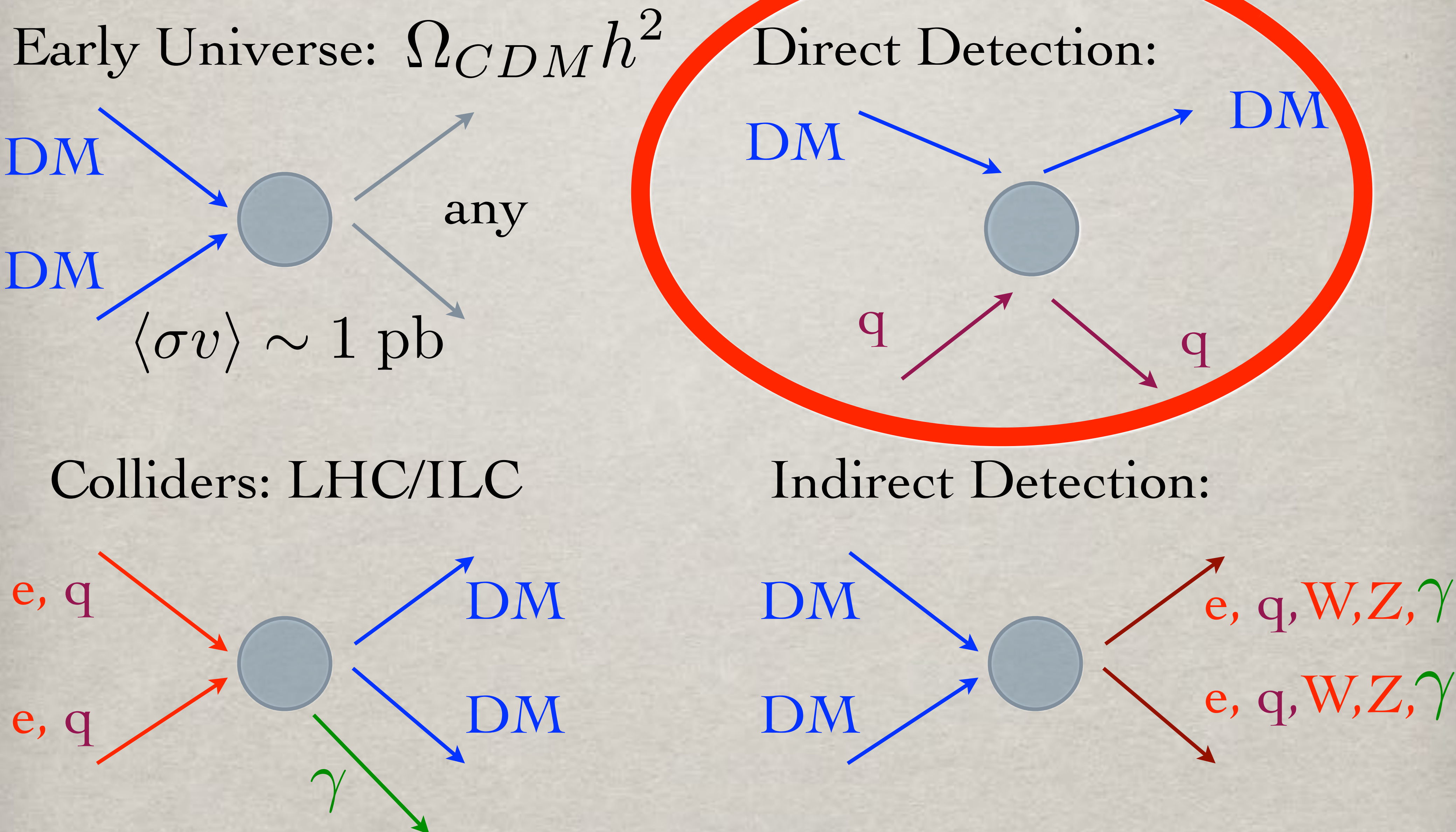


Indirect Detection:



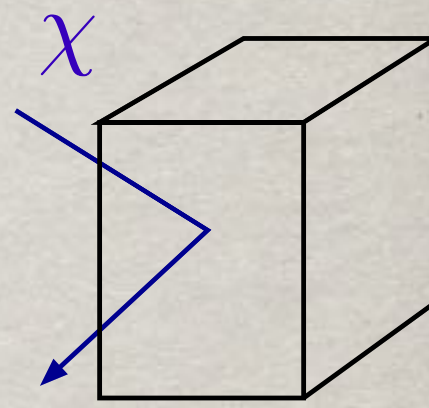
3 different ways to check this hypothesis !!!

THE WIMP CONNECTION



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:

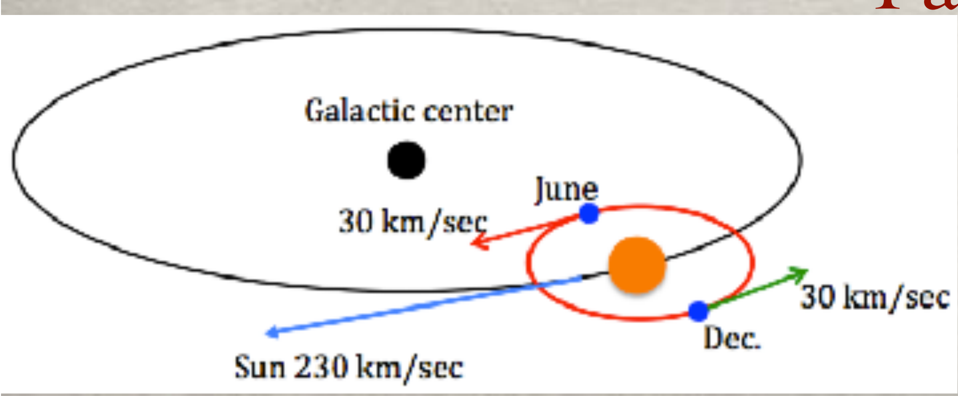
with $$\Delta E = \frac{4 m_{DM} m_N}{(m_{DM} + m_N)^2} \, E_{kin}^{DM}$$

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

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:

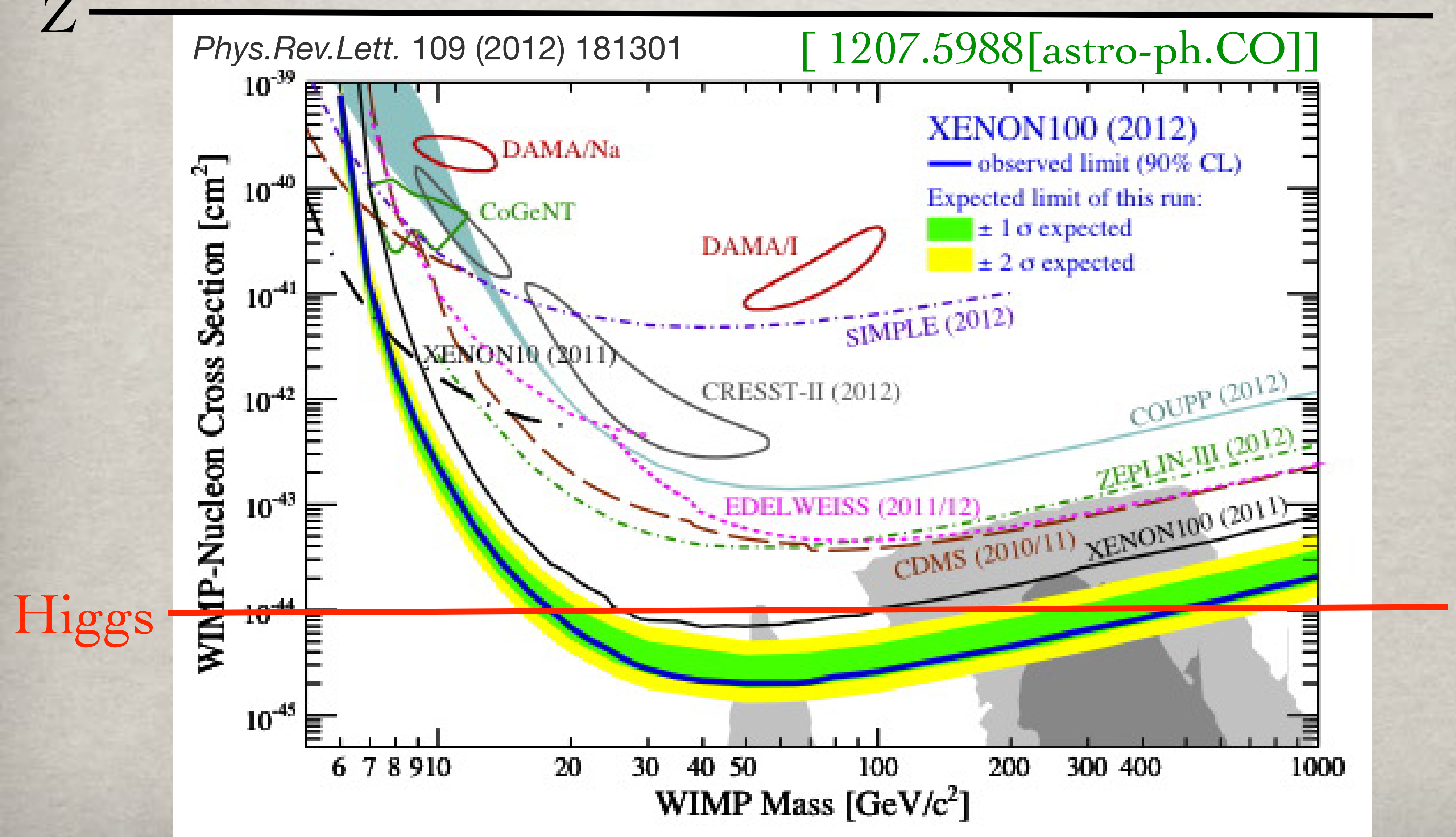
$$\sigma \sim \lambda_{Z\chi}^2 G_F^2 m_p^2 \sim 10^{-38} \lambda_{Z\chi}^2 cm^2 = 10^{-2} \ \lambda_{Z\chi}^2 \text{ pb}$$

- 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

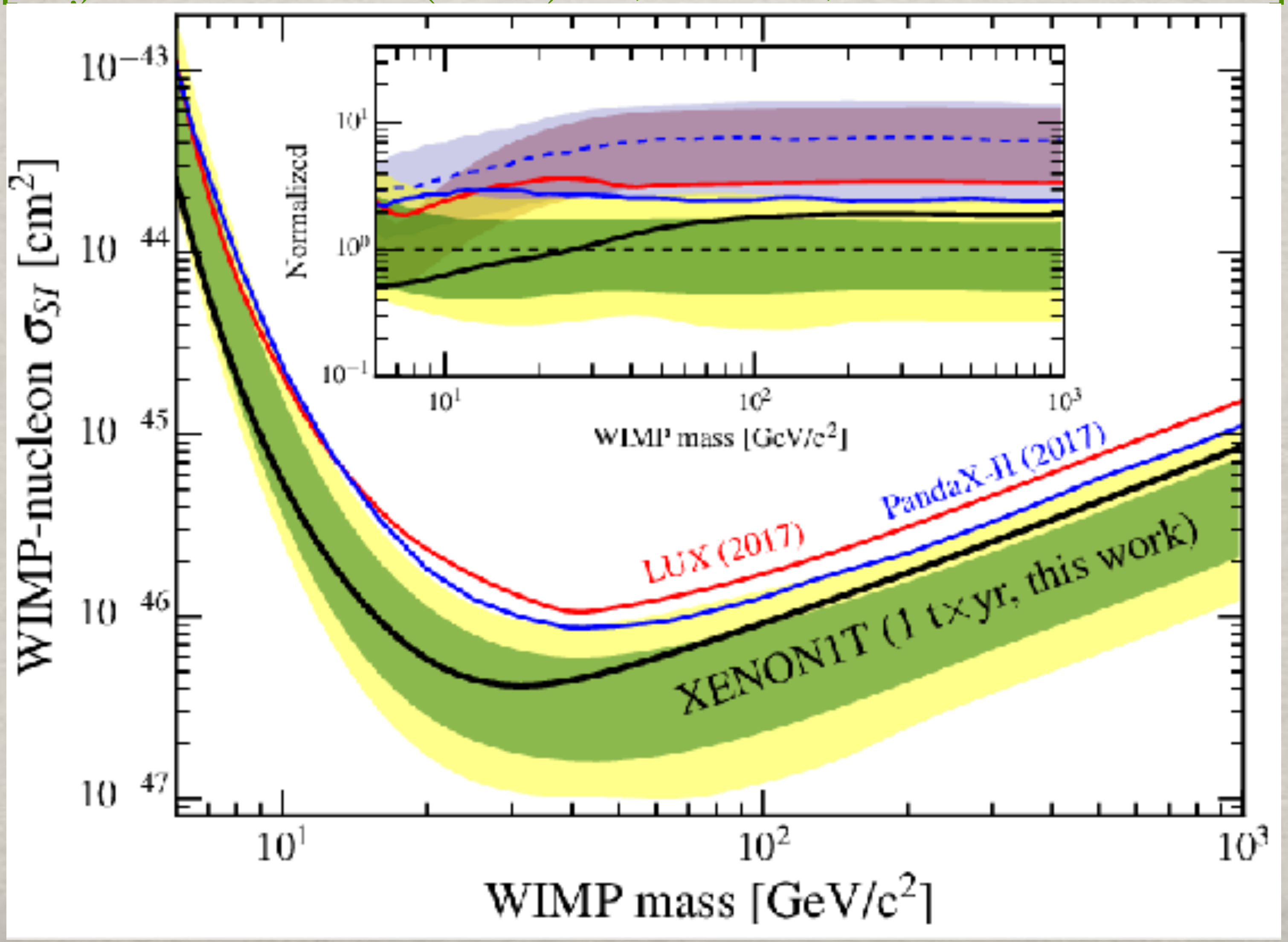
A large part of parameter space already excluded by searches:
Z-type cross-section is out, now we are exploring Higgs-type



NOW STRONGER BOUNDS

The XENON1T experiment results, new XENONnT appeared this year, with small improvement:

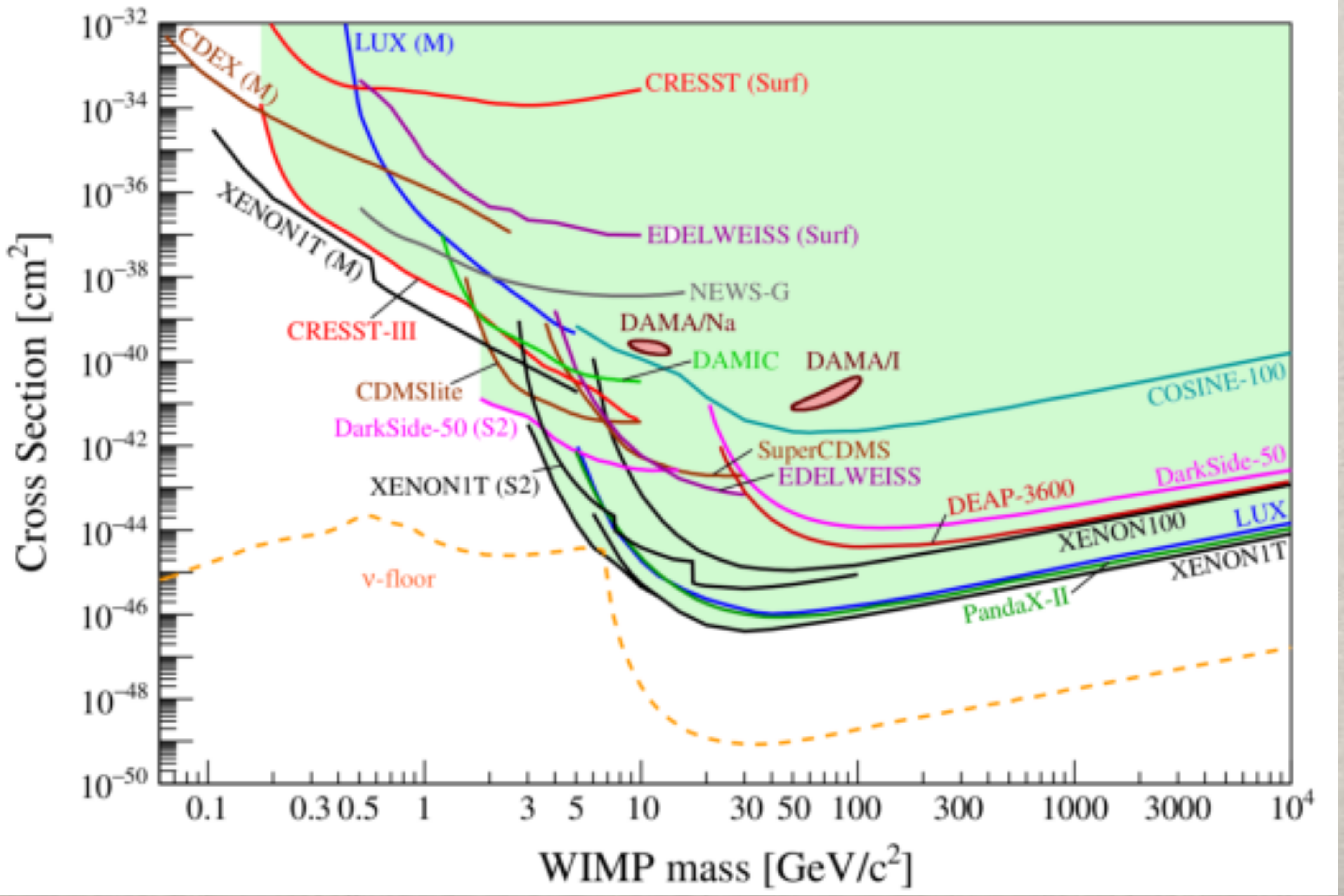
[*Phys.Rev.Lett.* 121 (2018) 11, 111302, arXiv: 1805.12562]



Future of DM DD

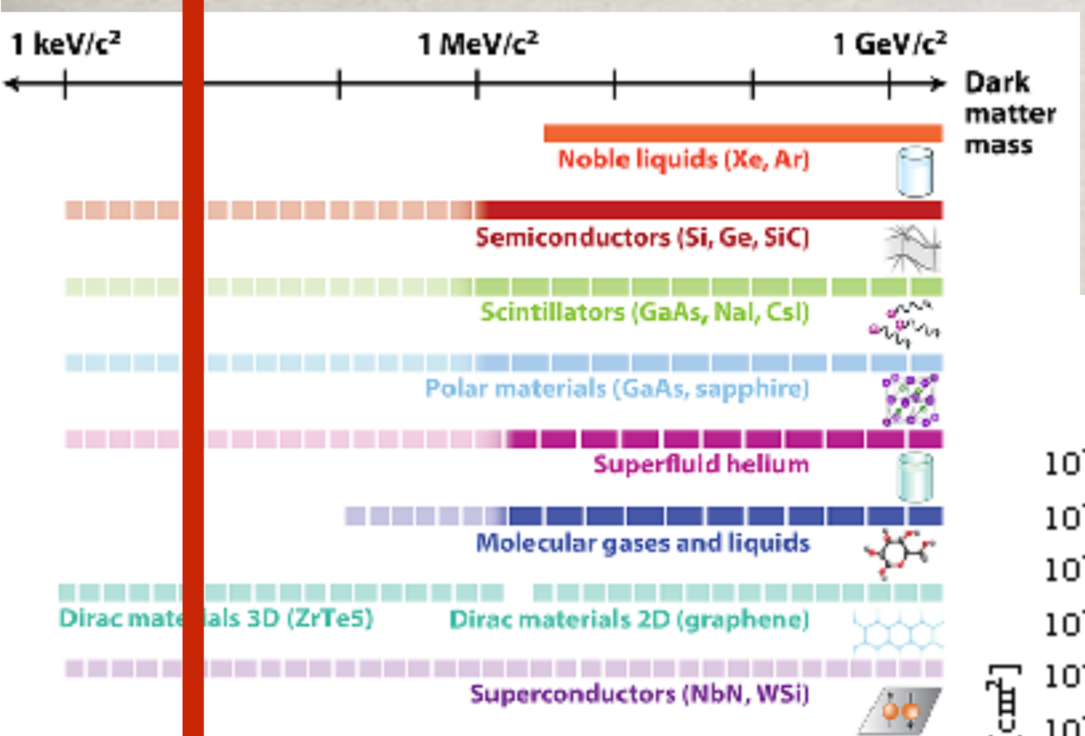
Neutrino background limits how far one can go. But there are already ideas on ways to suppress this background...

Rept.Prog.Phys. 85 (2022) 5, 056201 [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:

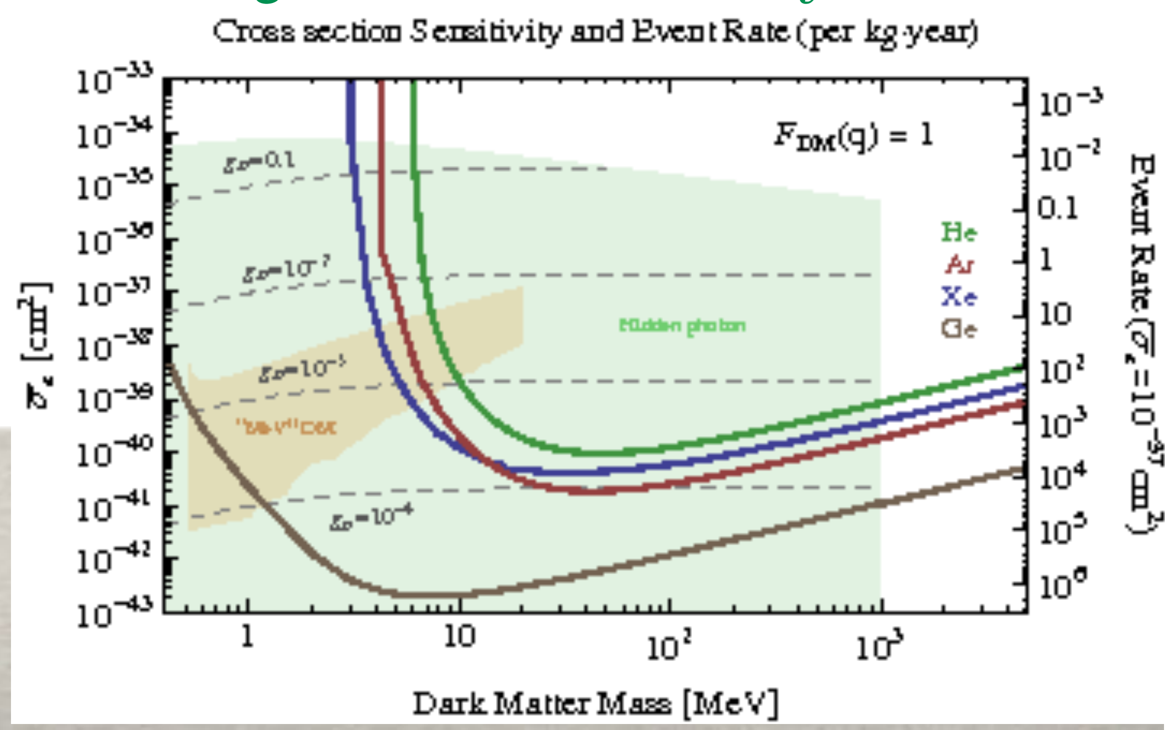


[R. Essig 2104.07634]

Warm DM

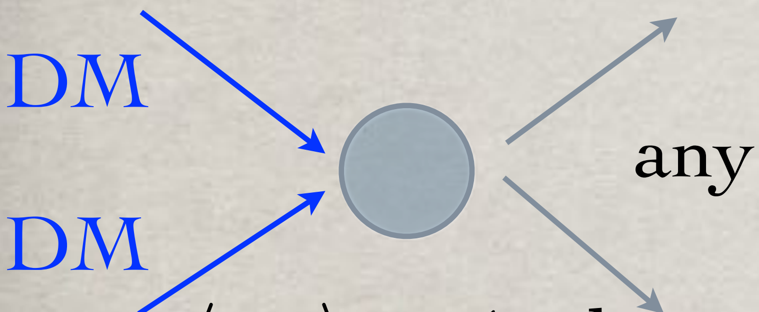
Cold Dark Matter

[Essig, Mardon & Volansky 1108.5383]



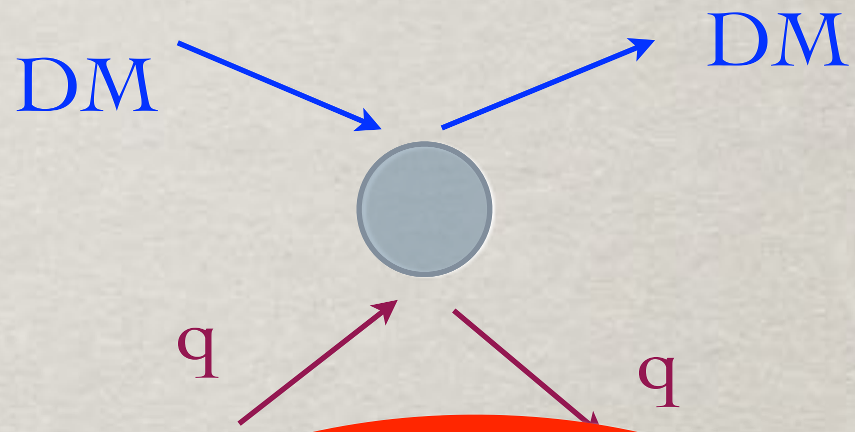
THE WIMP CONNECTION

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

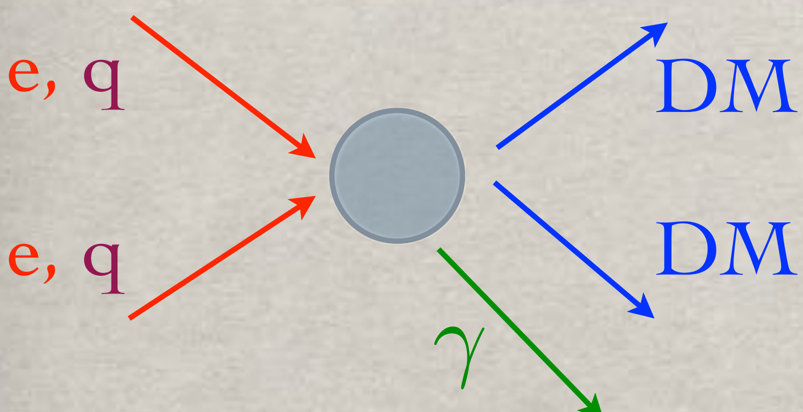


$\langle \sigma v \rangle \sim 1 \text{ pb}$

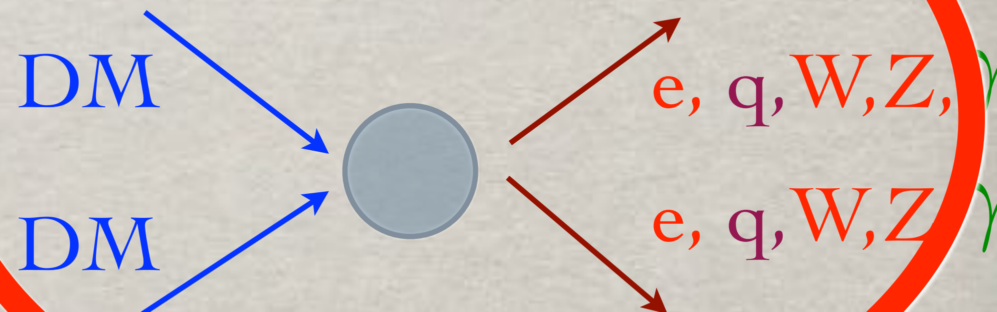
Direct Detection:



Colliders: LHC/ILC



Indirect Detection:



3 different ways to check this hypothesis !!!

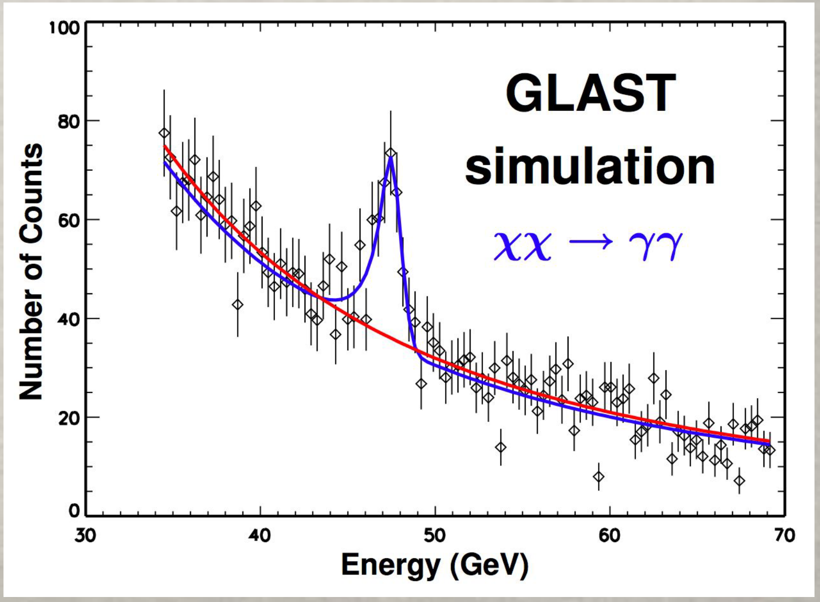
THE HOPE: DETECT DM !

- 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(θ)

- 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.



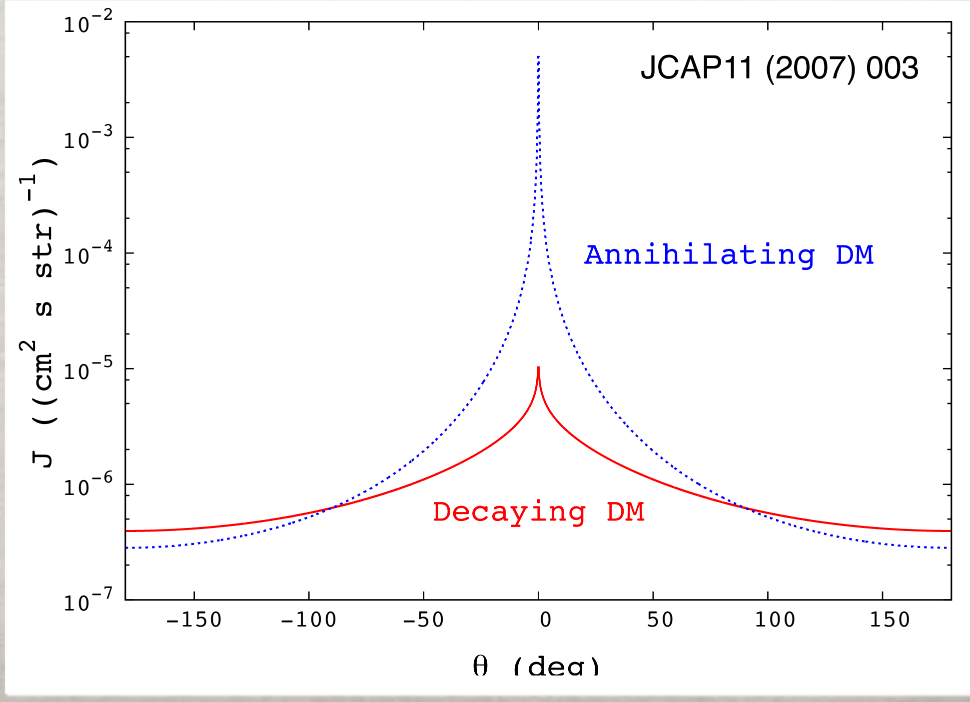
DECAYING DM

- 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(θ)

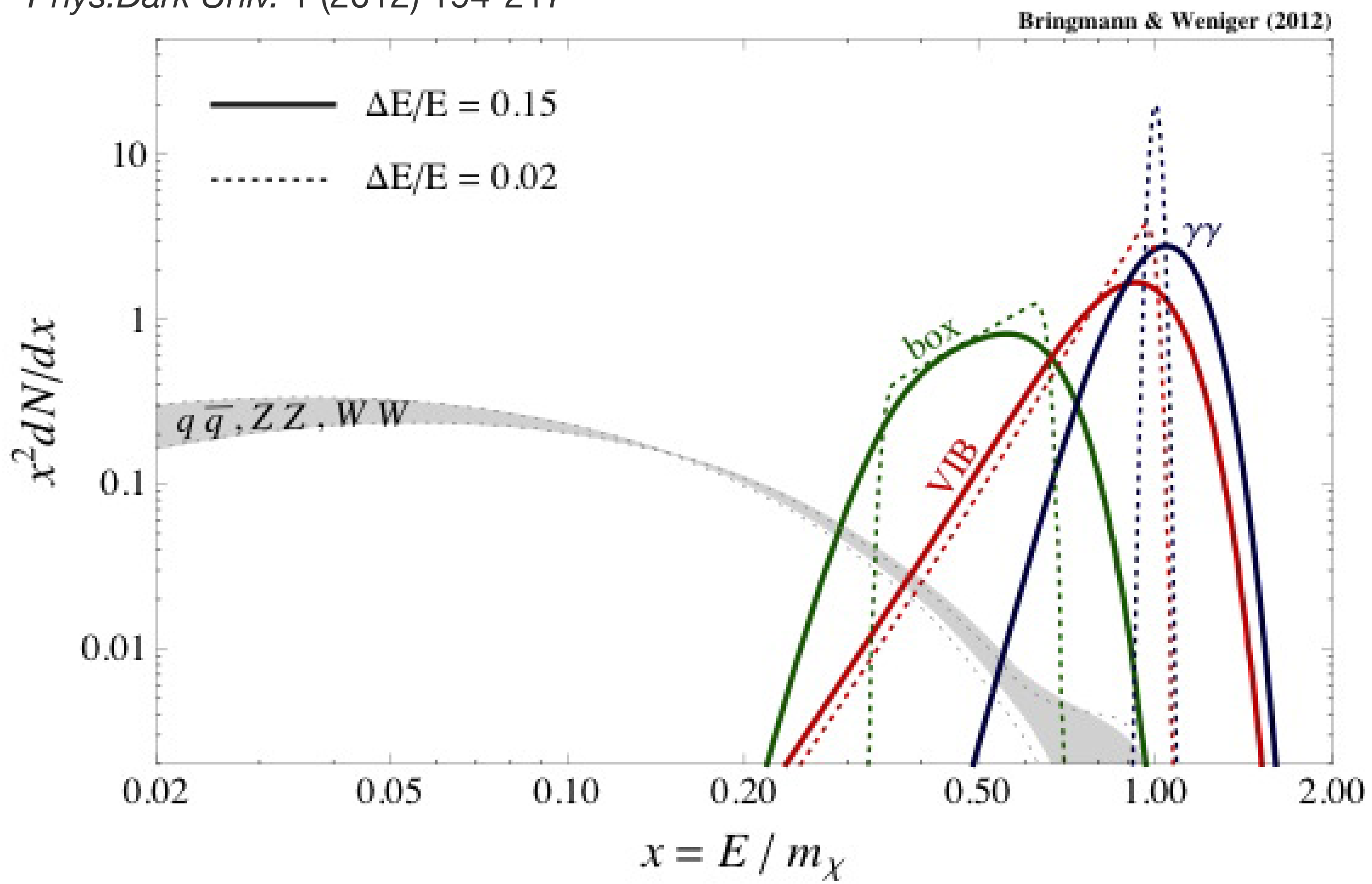
- Very weak dependence on the Halo profile; what matters is the DM lifetime...
- Galactic & extragalactic signals are comparable...
- Spectrum in gamma-rays given by the decay channel! Smoking gun: gamma line...



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 !

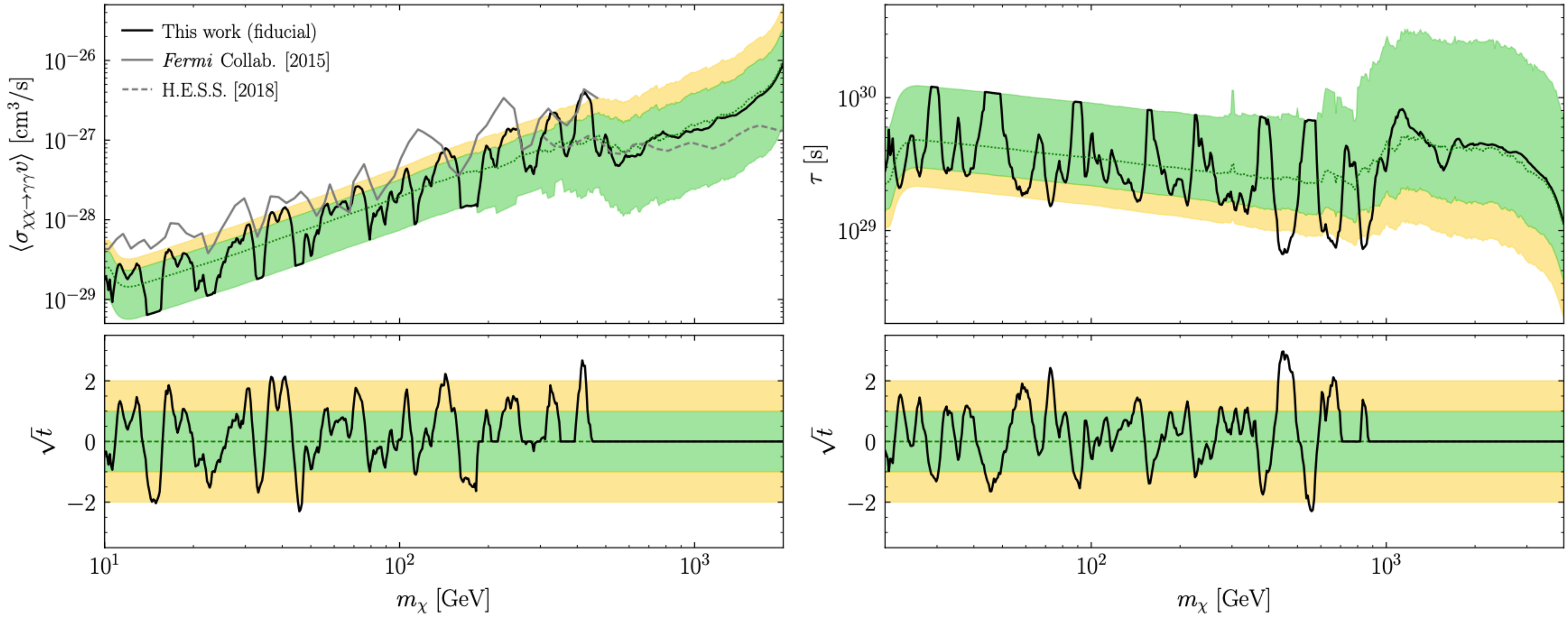
Phys.Dark Univ. 1 (2012) 194-217



Bounds on line from DM

New limits on the possible observation of a photon line from the FERMI data, reaching down to 3 orders of magnitude below the thermal cross-section:

[Joshua W. Foster et al, arXiv:2212.07435 **[hep-ph]**]

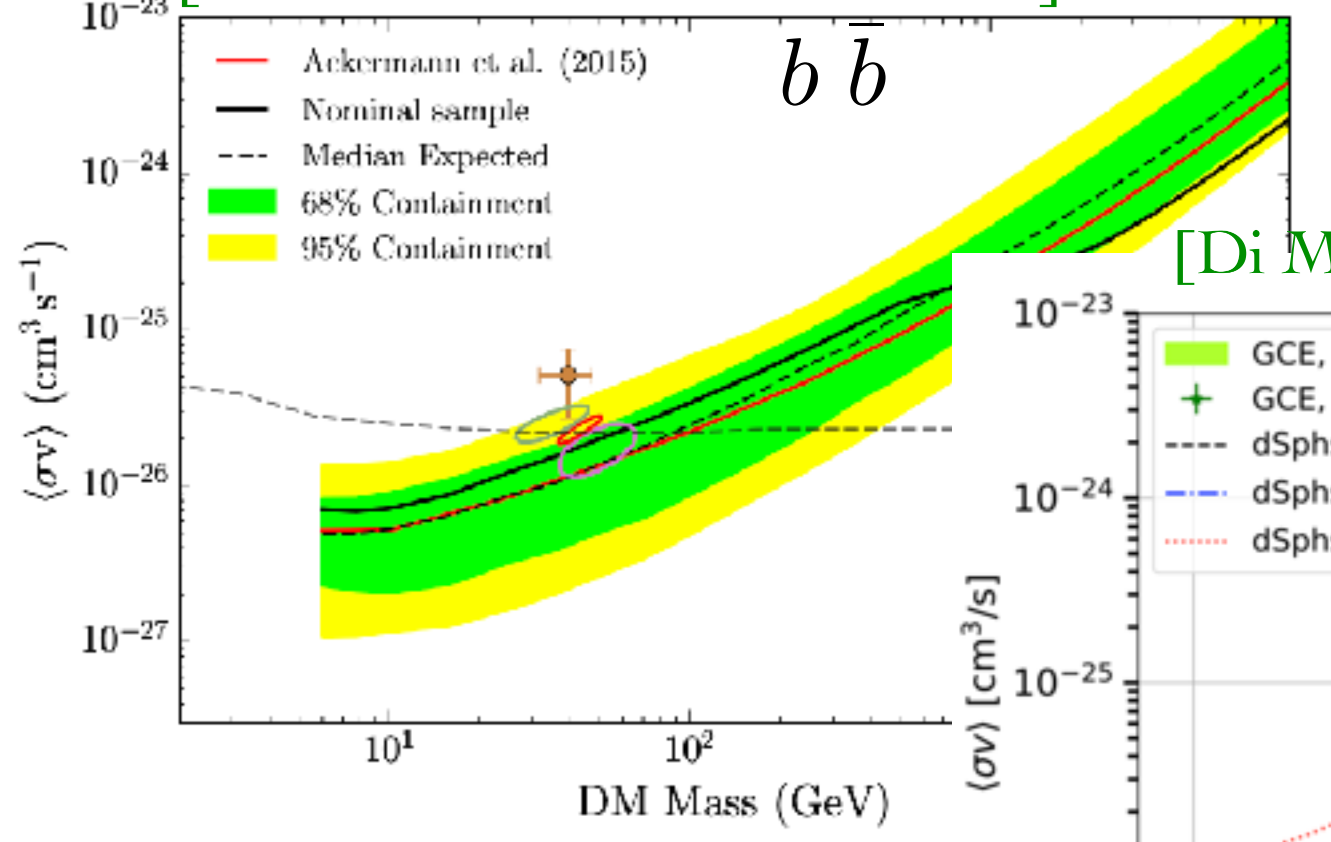


Note lifetime much longer than the age of the Universe !!!

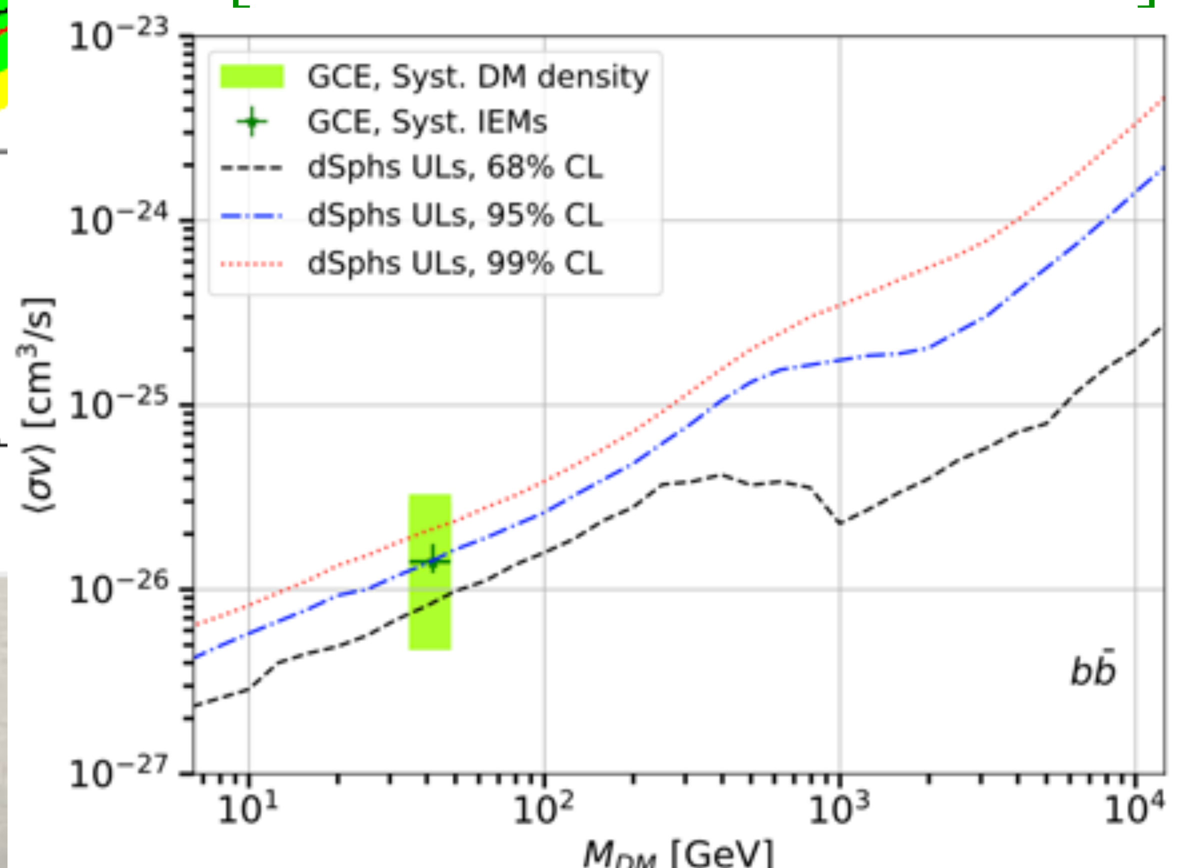
Bounds on WIMP DM

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

[Fermi-LAT & DES 1611.03184]



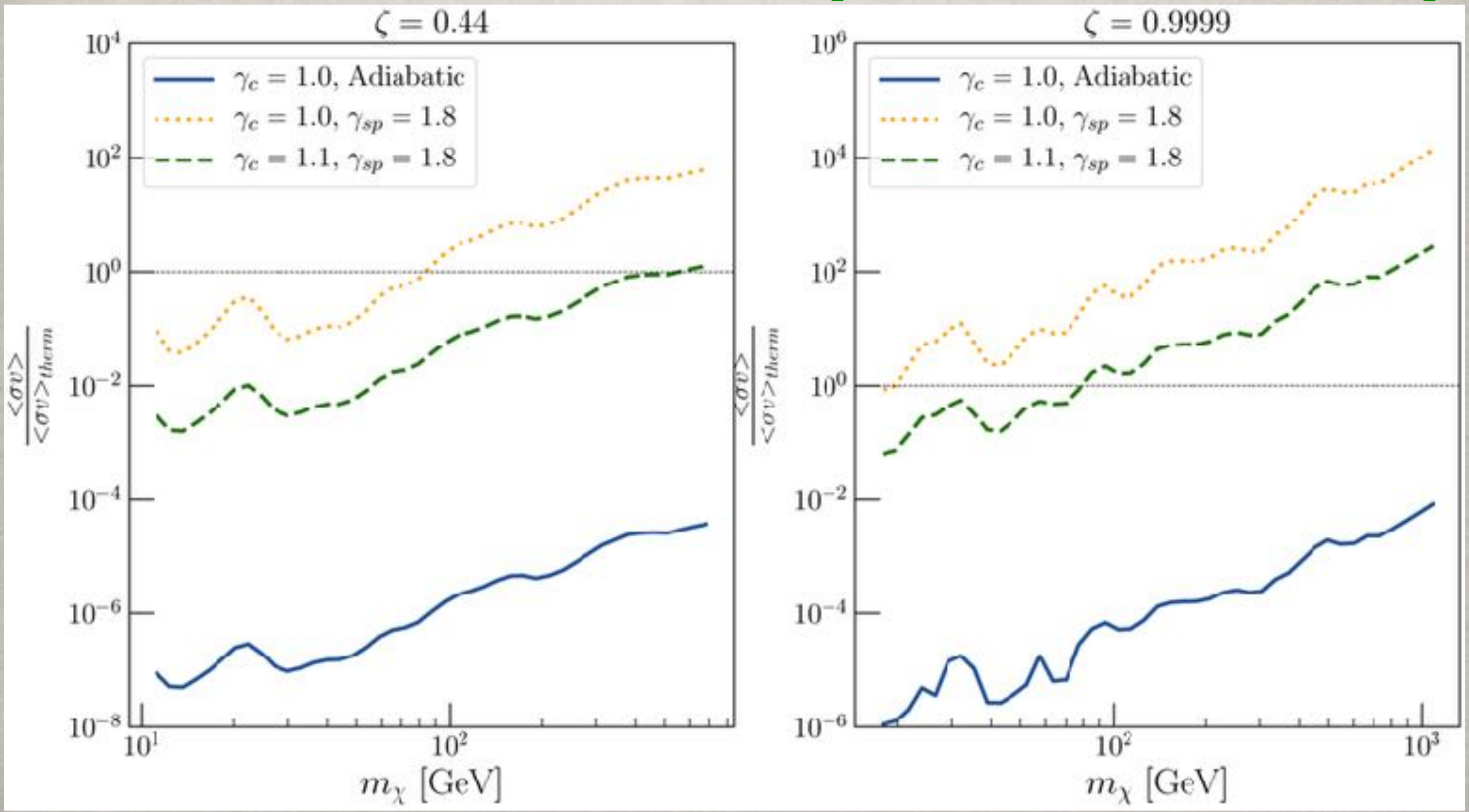
[Di Mauro & Winkler 2101.11027]



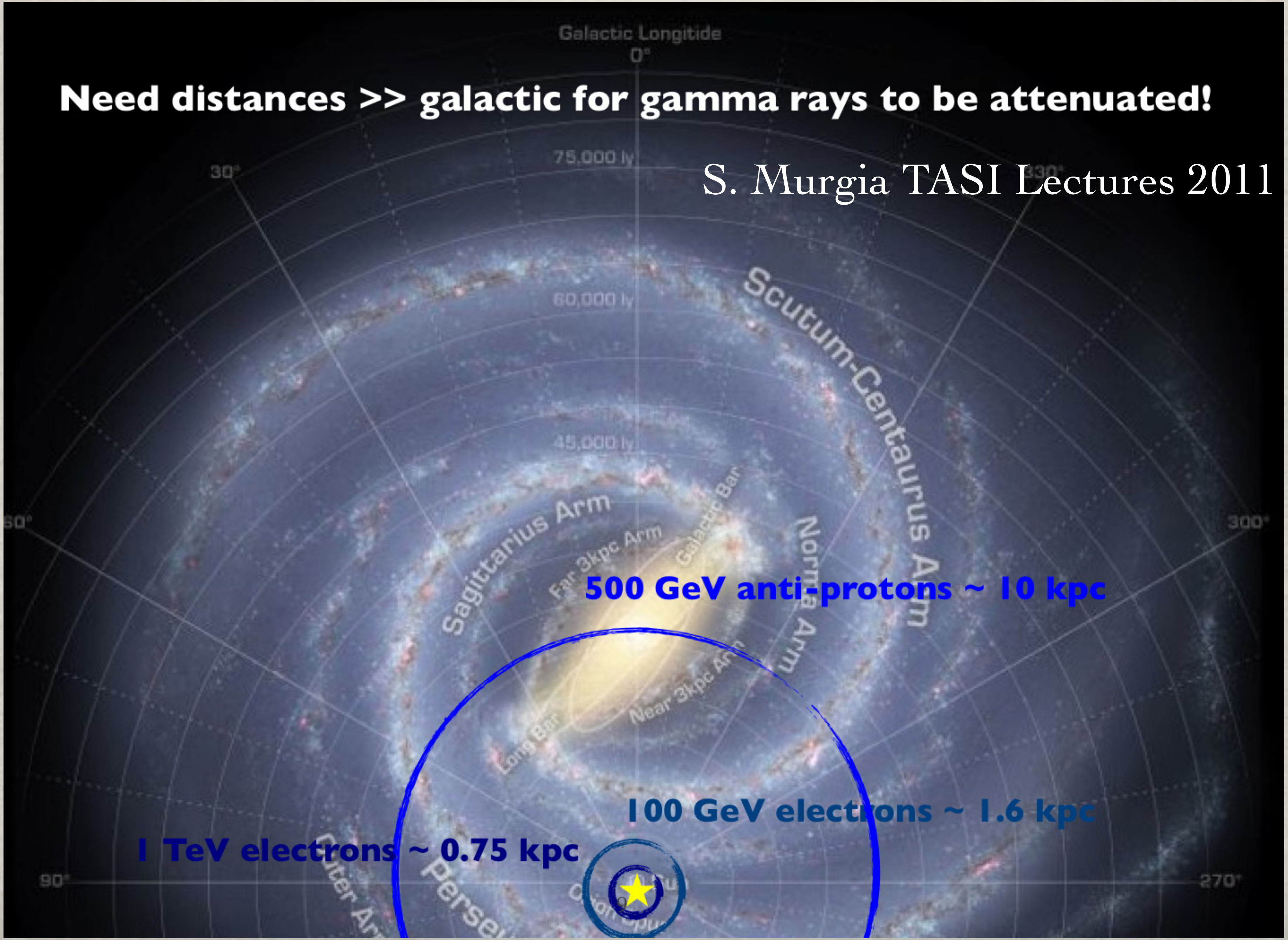
WIMP DM ID: p-wave

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

[FERMI-lat arXive:1904.06261]



GALACTIC PARTICLE'S RANGES



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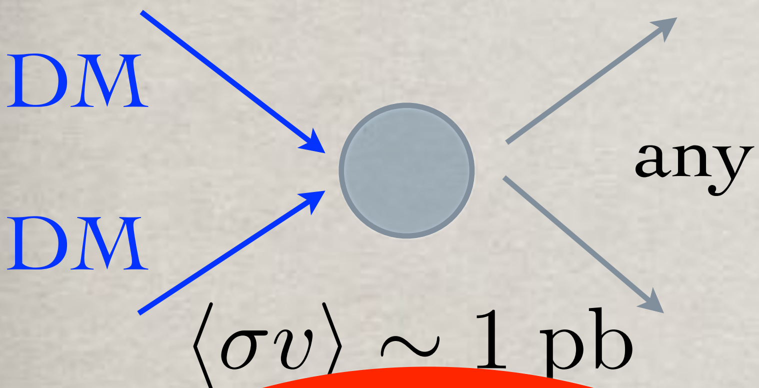
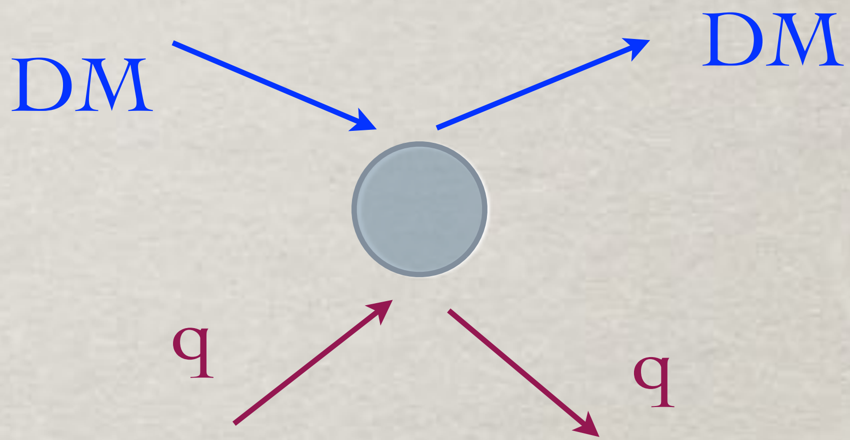
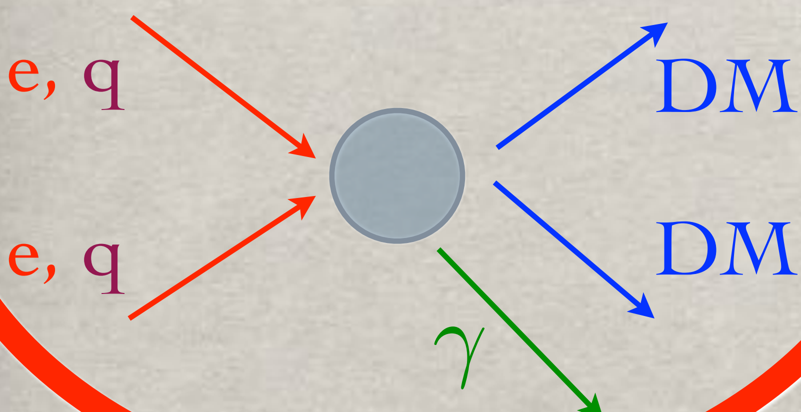


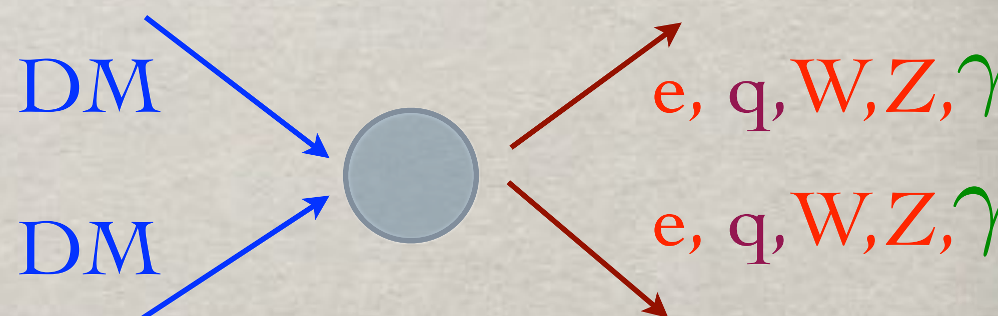
Direct Detection:



Colliders: LHC/ILC



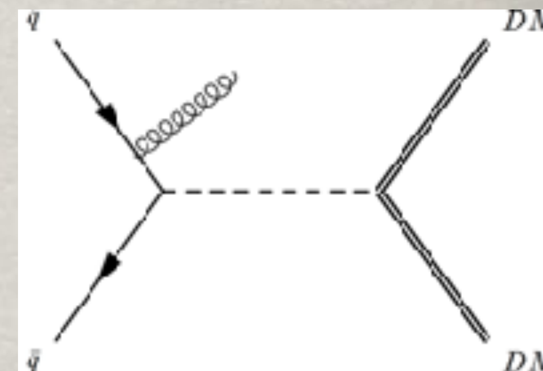
Indirect Detection:

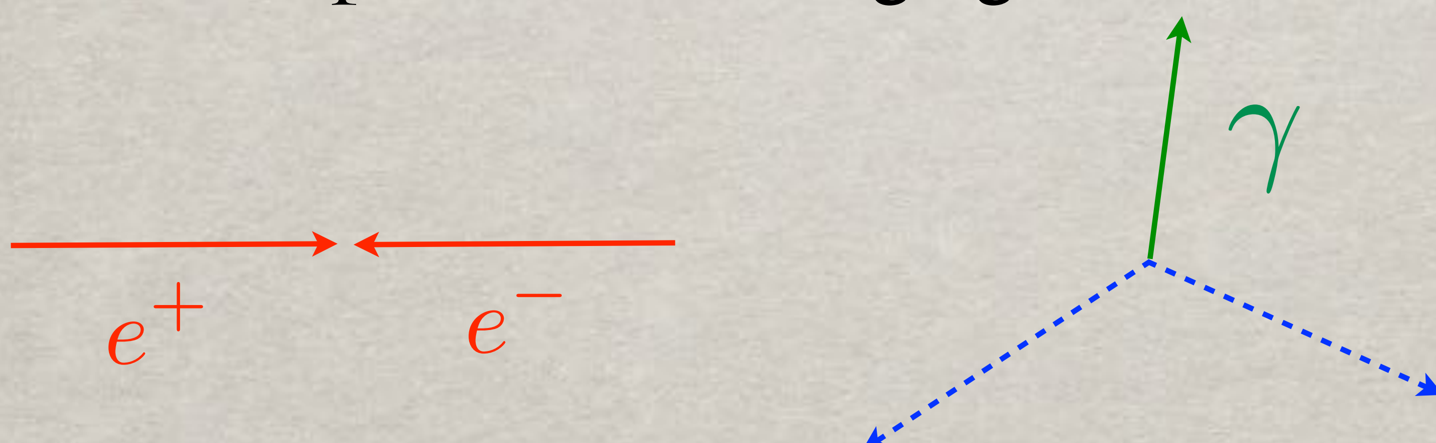


3 different ways to check this hypothesis !!!

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)





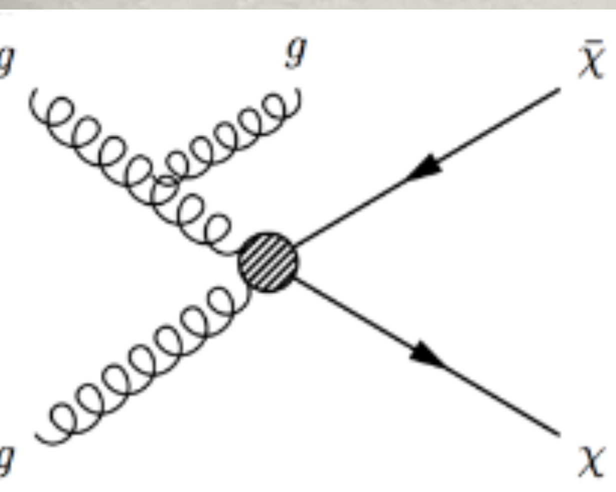
Dark Matter: Missing energy signature

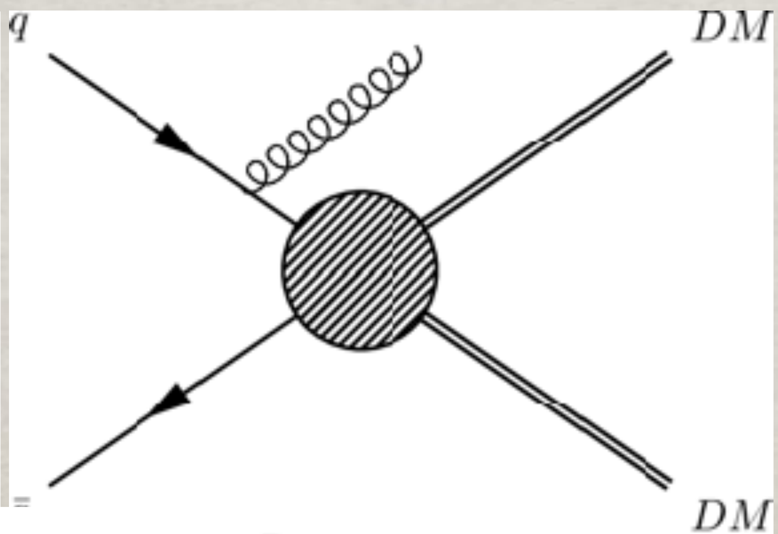
Trouble: need sufficient rate of DM production...

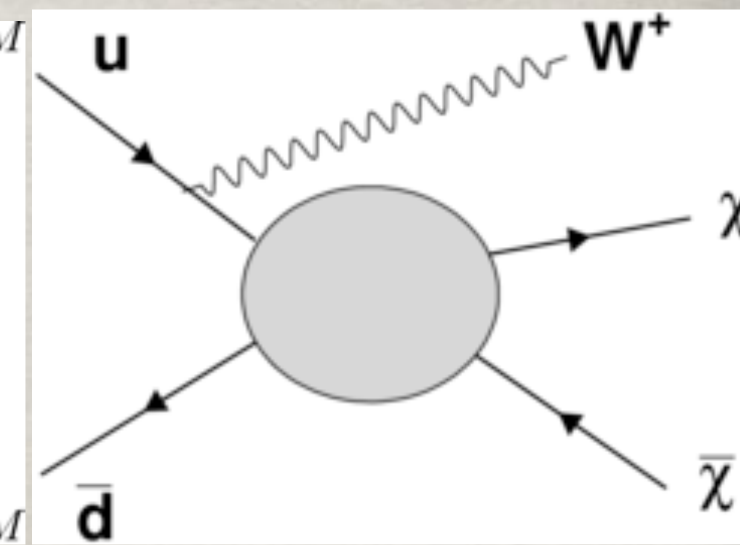
EFT for Dark Matter

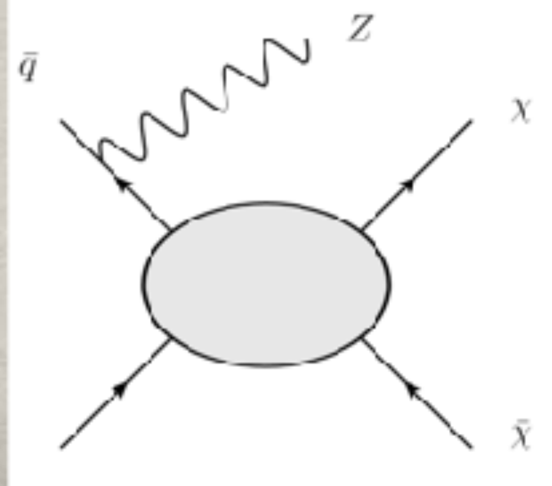
[Beltram et al 2000, Goodman et al 2000 & 2001, Bai et al 2001,....]

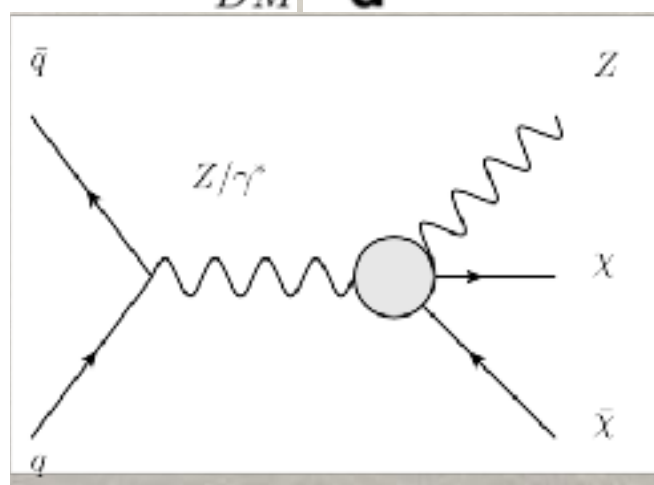
Consider the production of a pair of DM particles together with ISR of a SM particle: gluon, photon, W/Z, top, etc...
EFT: Many different effective operators are possible !





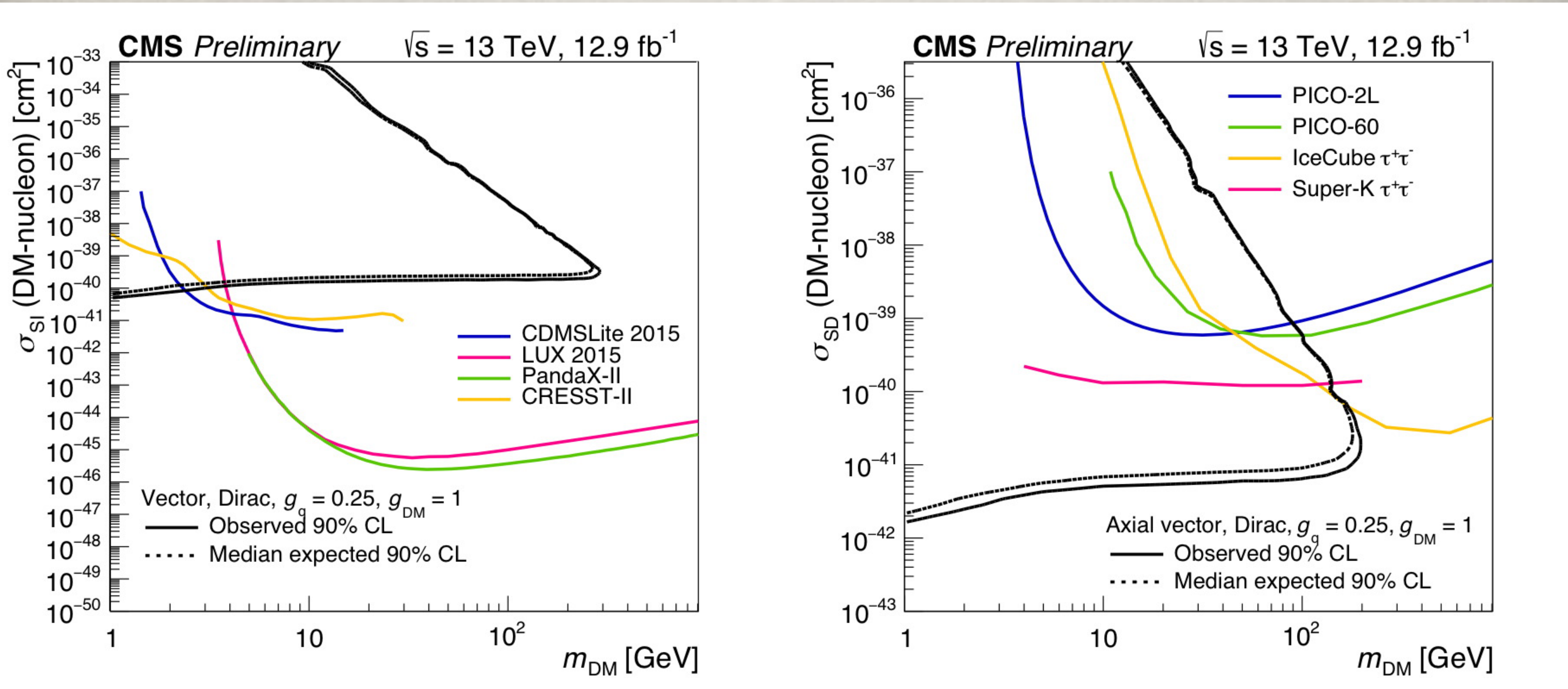






LHC: simplified models I

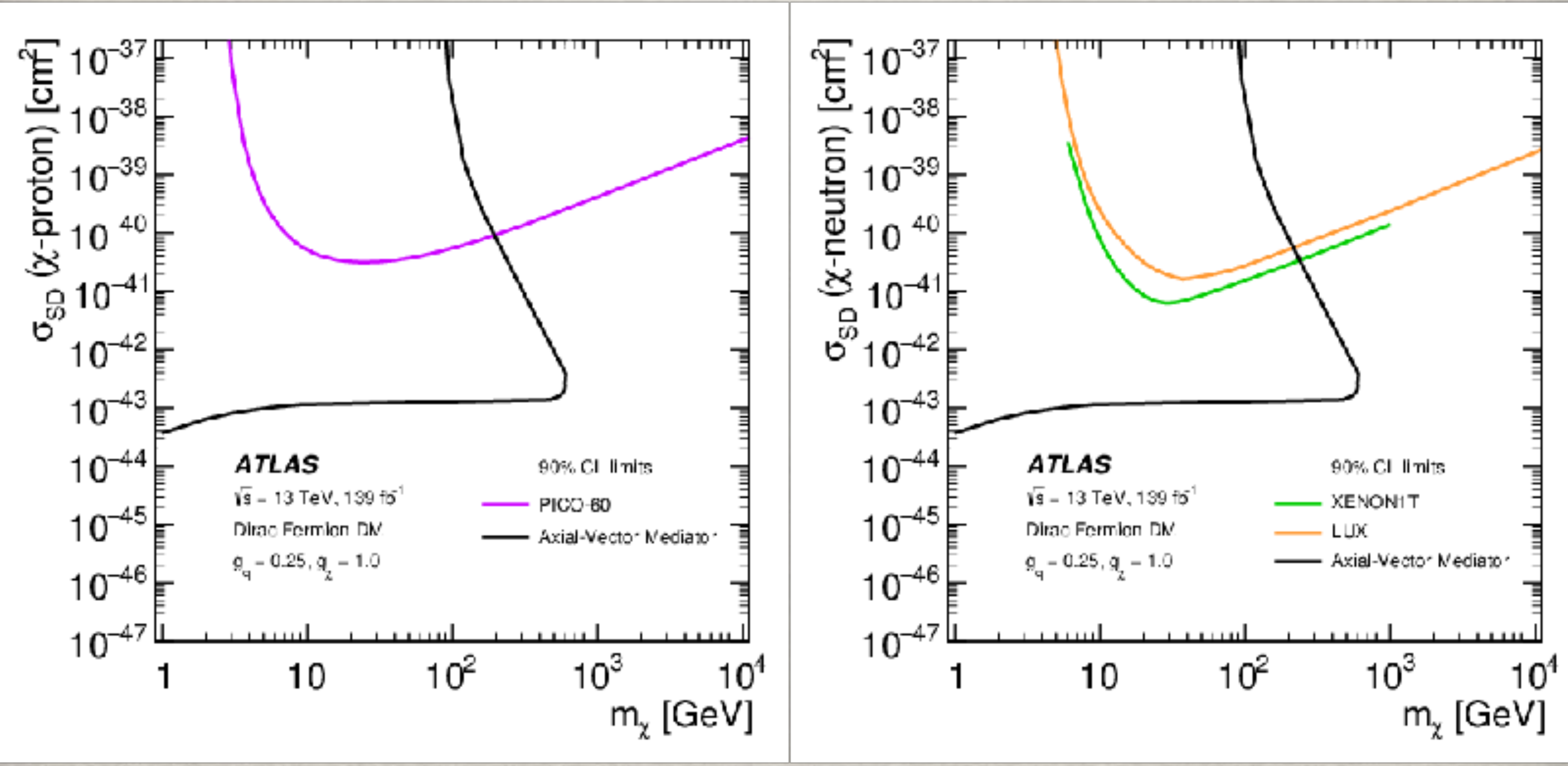
[CMS, EXO-16-039-pas]



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

LHC: simplified models II

[ATLAS 2102.10874 hep-ex]



Very strong bounds for the axial vector case !