Searching for Dark Matter (WIMPs in particular)

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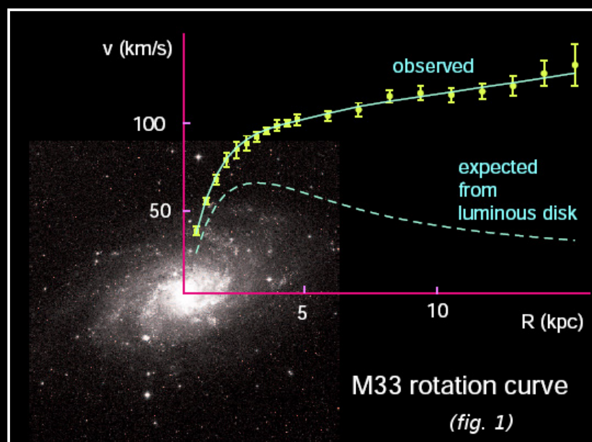
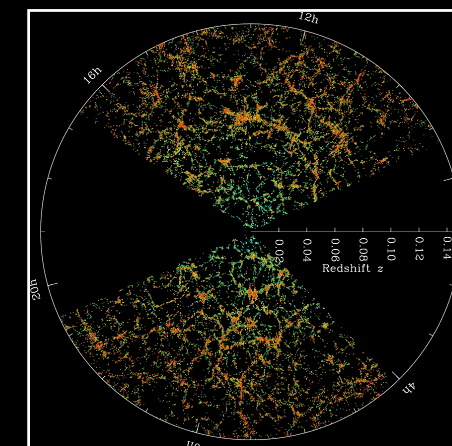
Région de Bruxelles-Capitale Brussels Hoofdstedelijk Gewest
INNOVIRIS Empowering Research
attract Brains for Brussels

Credit: The Marenostrum Numerical Cosmology Project

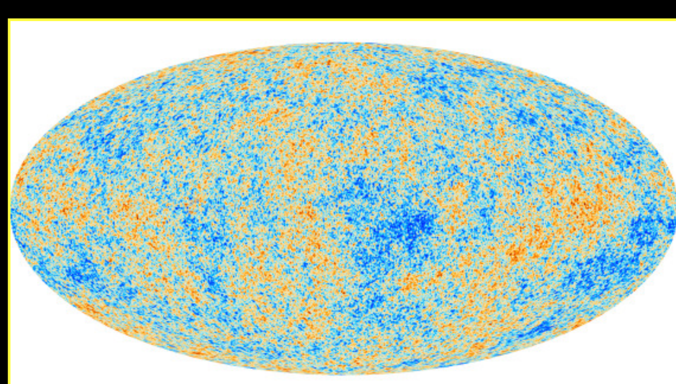
Gravitational evidences of DM at all scales

- First gravitational indirect evidence for DM found in 1933 by the astrophysicist Fritz Zwicky

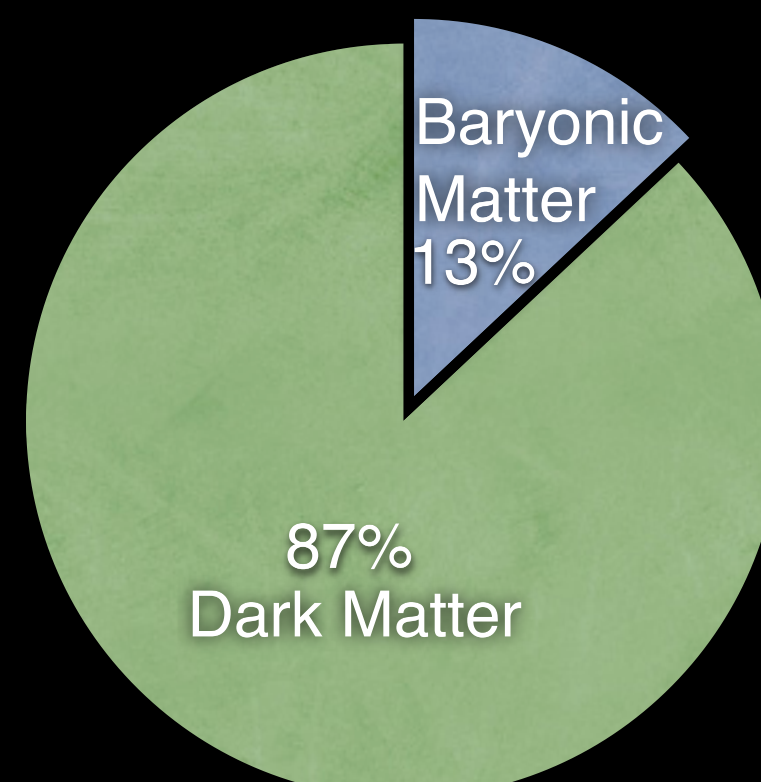




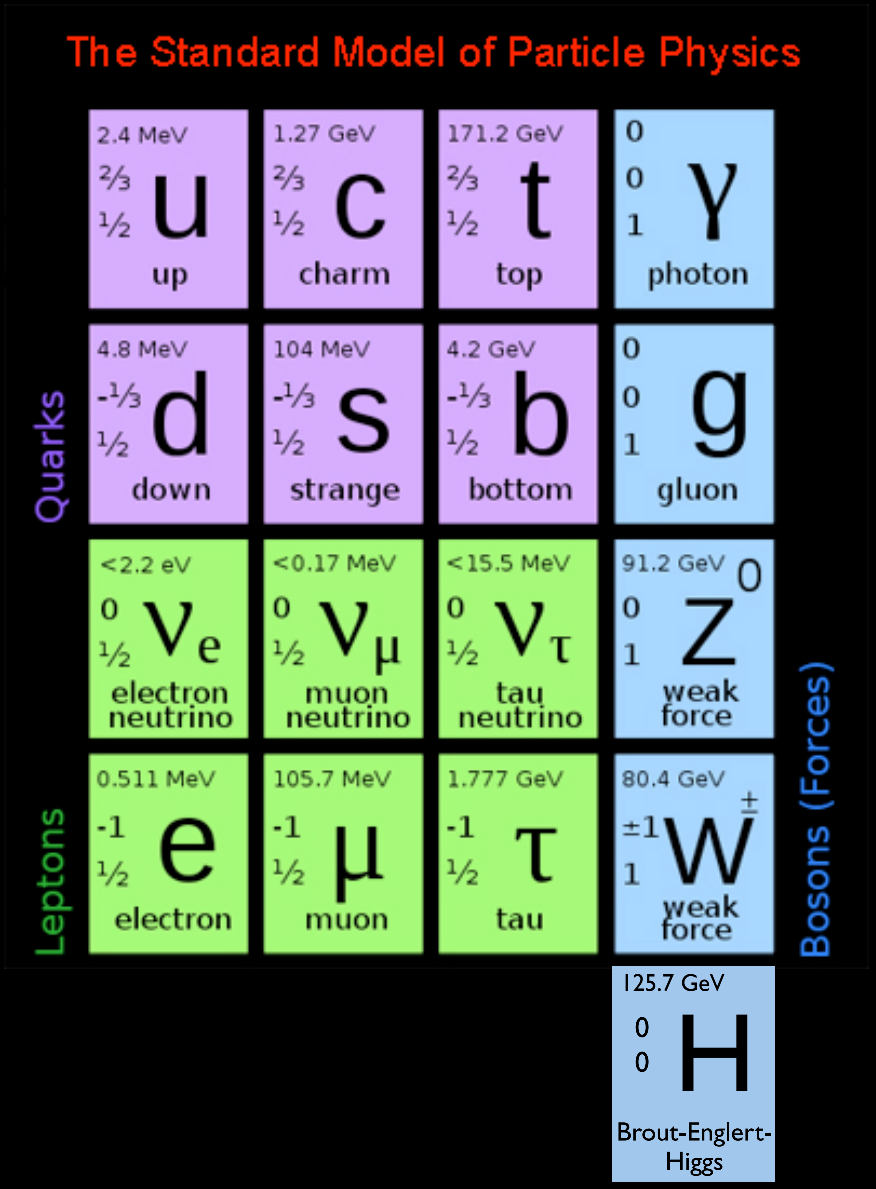
- Cosmology measures the matter and energy content of the universe (Planck 2015):



Parameter	*Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02225 ± 0.00016
$\Omega_c h^2$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04077 ± 0.00032
τ	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.094 ± 0.034
n_s	0.9645 ± 0.0049
H_0	67.27 ± 0.66
Ω_m	0.3156 ± 0.0091
σ_8	0.831 ± 0.013
$10^9 A_s e^{-2\tau}$	1.882 ± 0.012



What constitutes the Dark Matter?



- Neutral
- Massive enough to cluster and account for large scale structures
- Stable at least on cosmological scale
- Thermally (or non-thermally) produced

Leads to models of particle physics beyond the standard model

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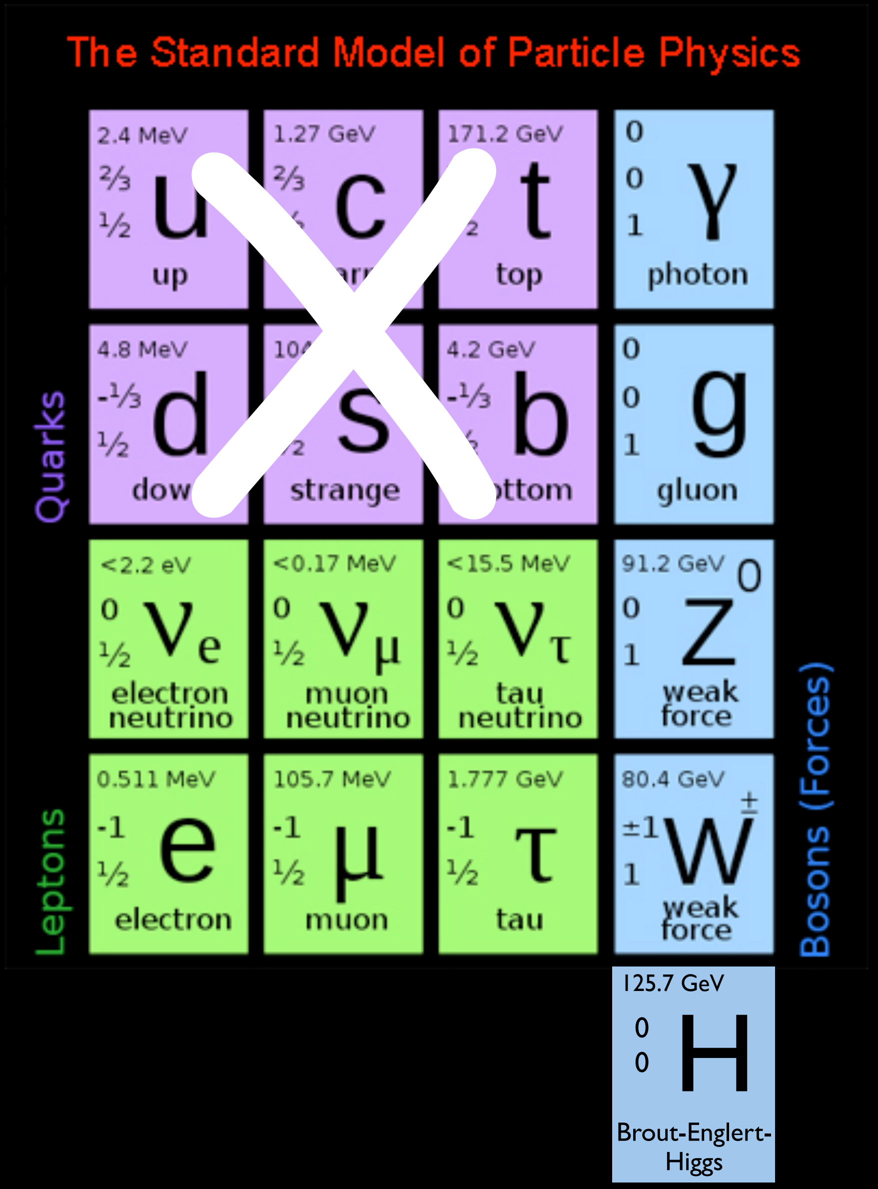

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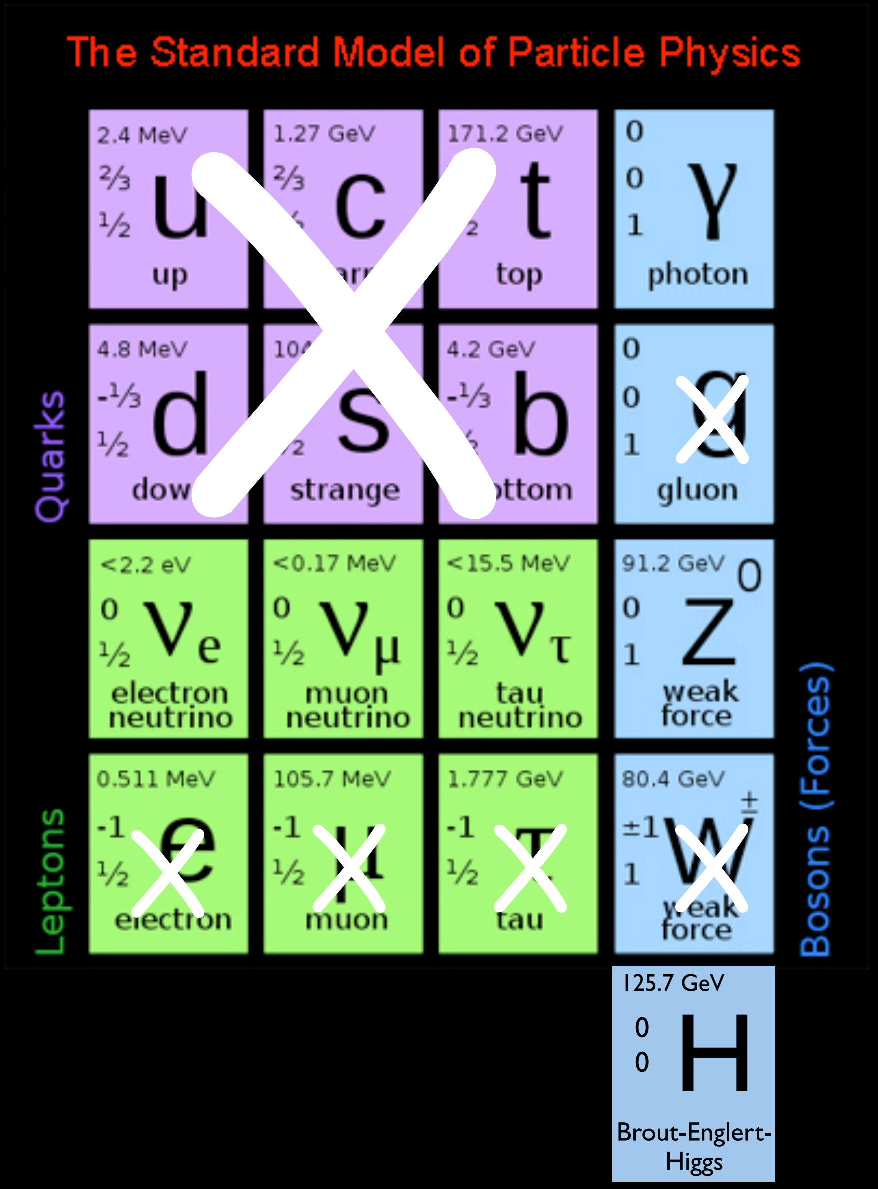

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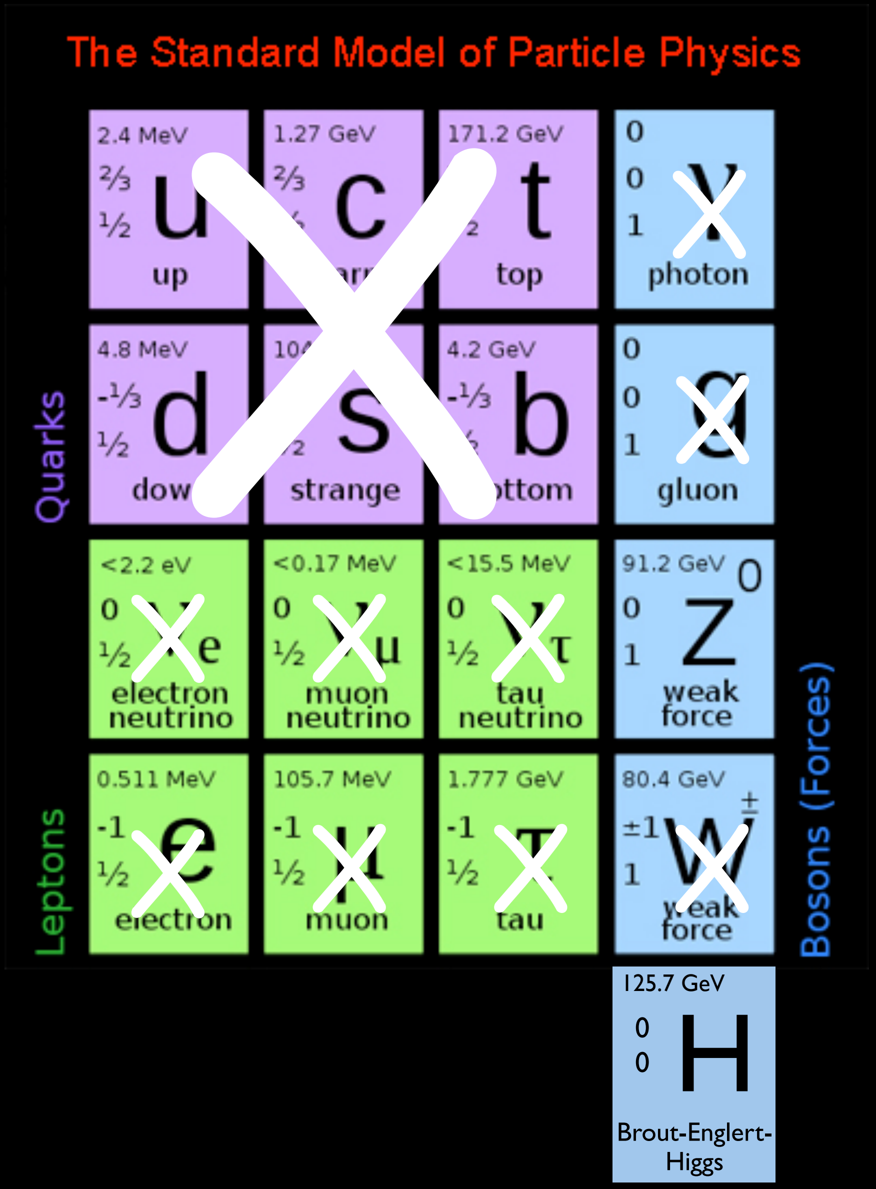

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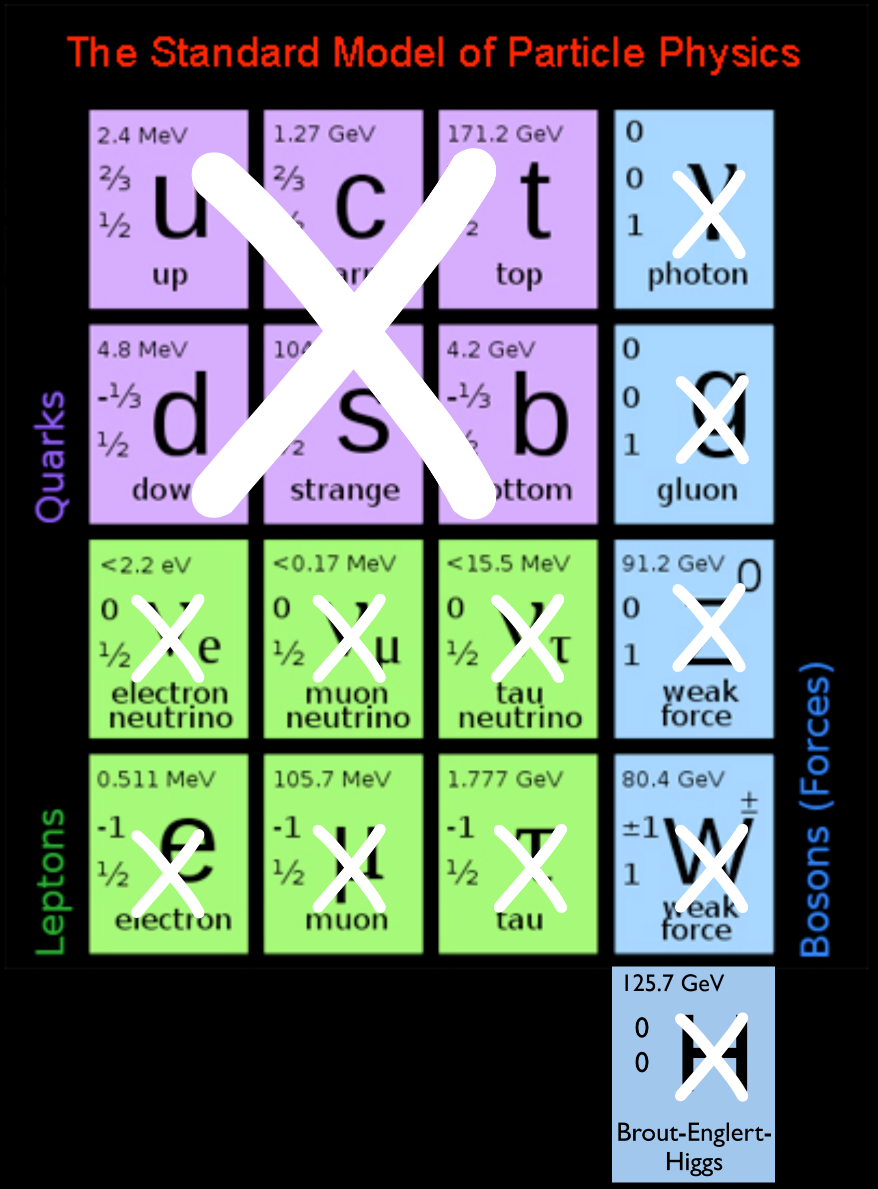
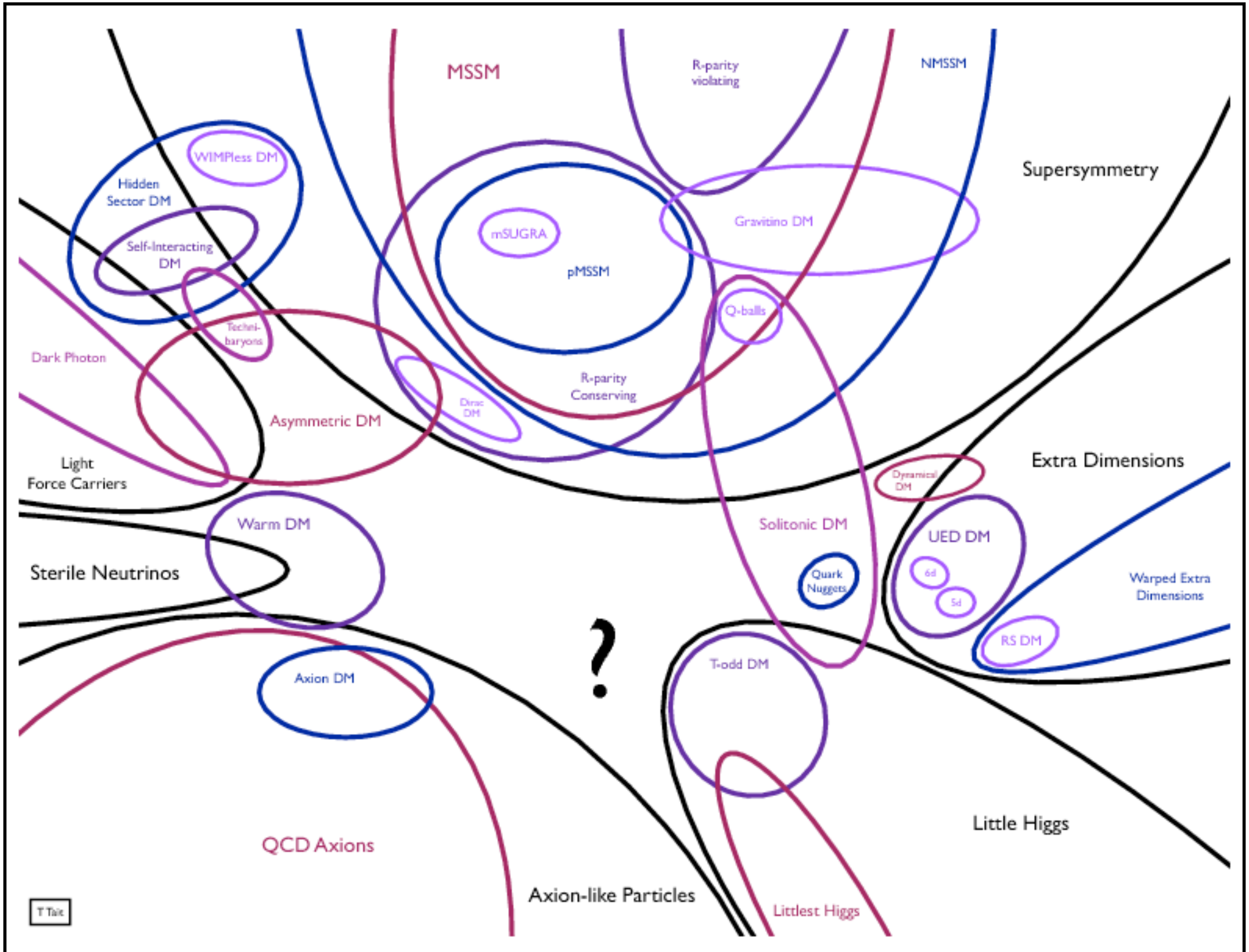
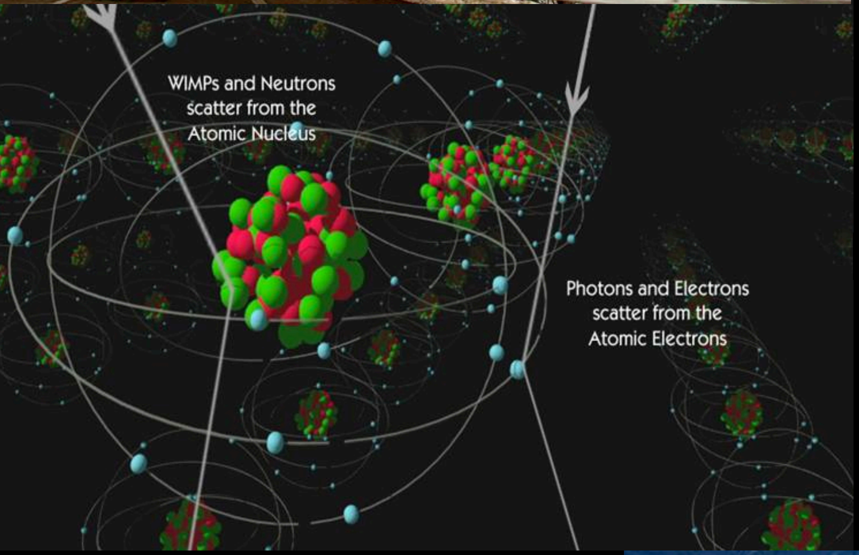


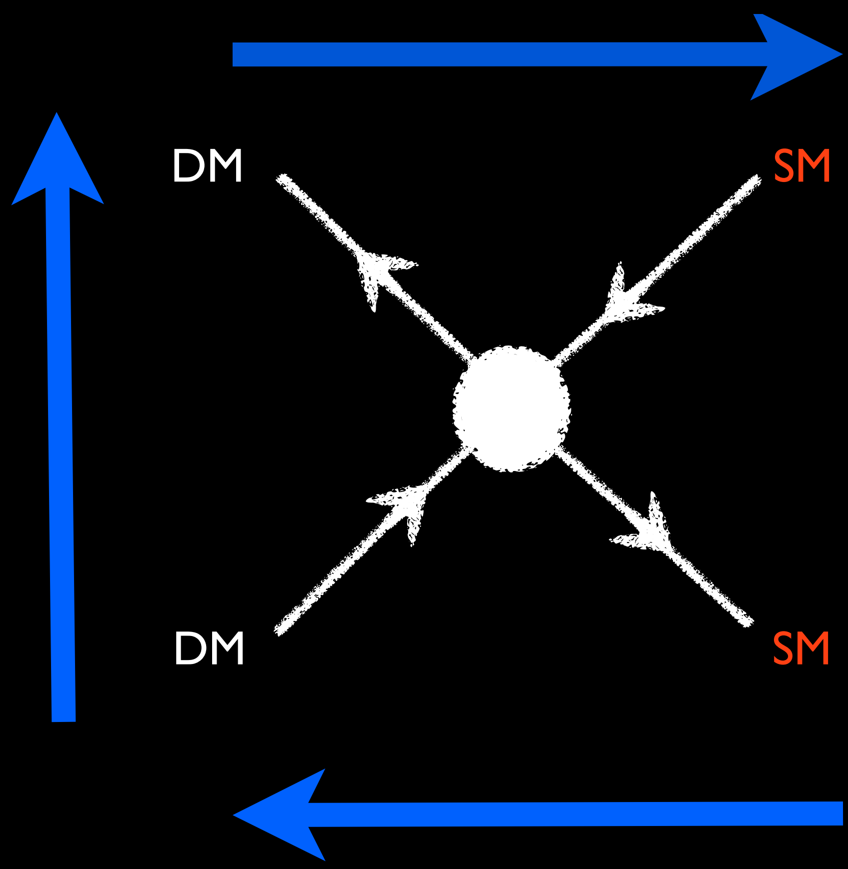
Leads to models of particle physics beyond the standard model

Zoo of dark matter candidates



WIMPs: weakly interacting massive particles





Several searches already ongoing

Several new probes planned for the next future

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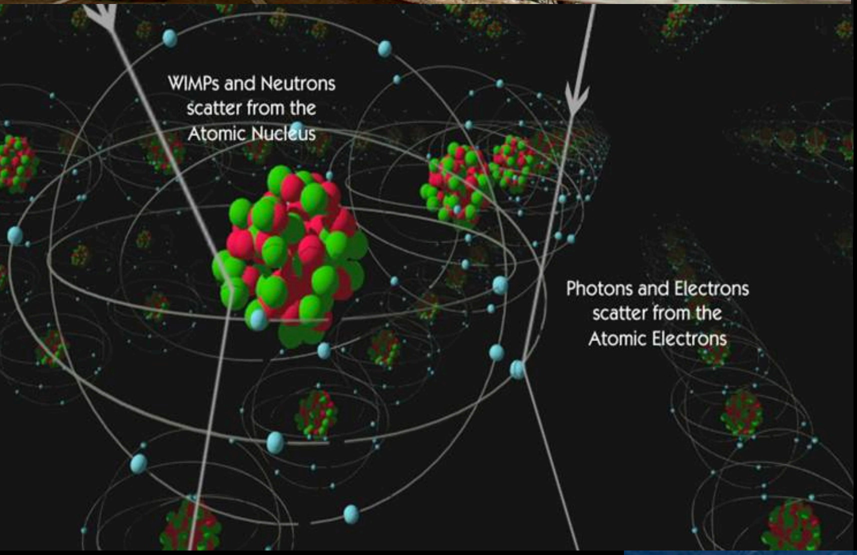
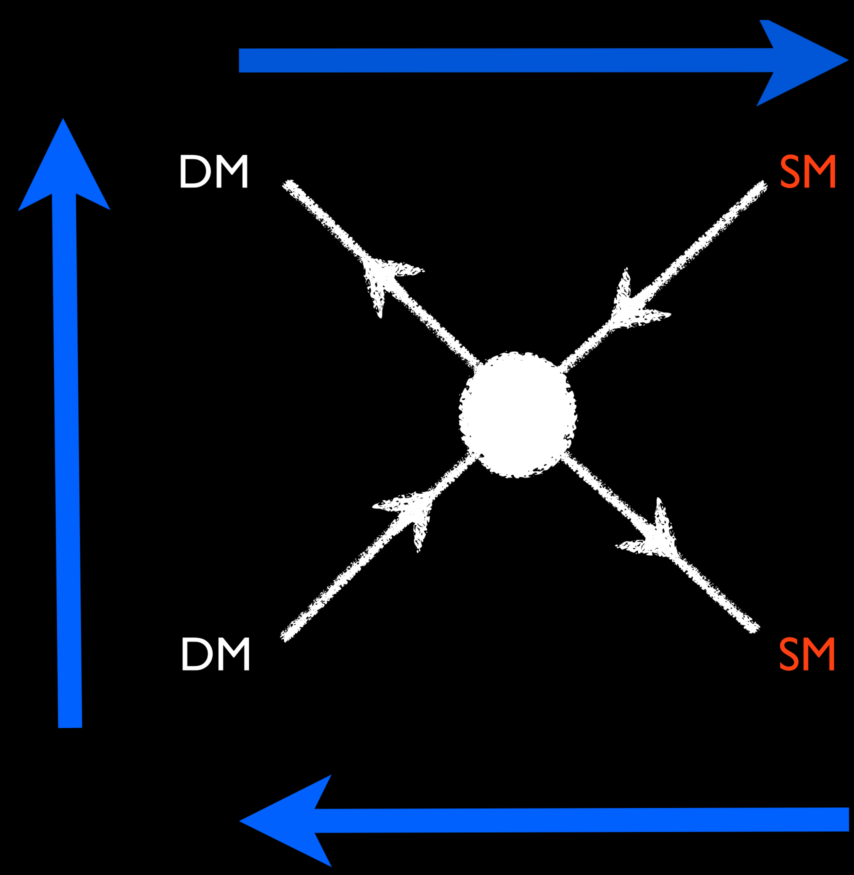


Freeze-out early Universe



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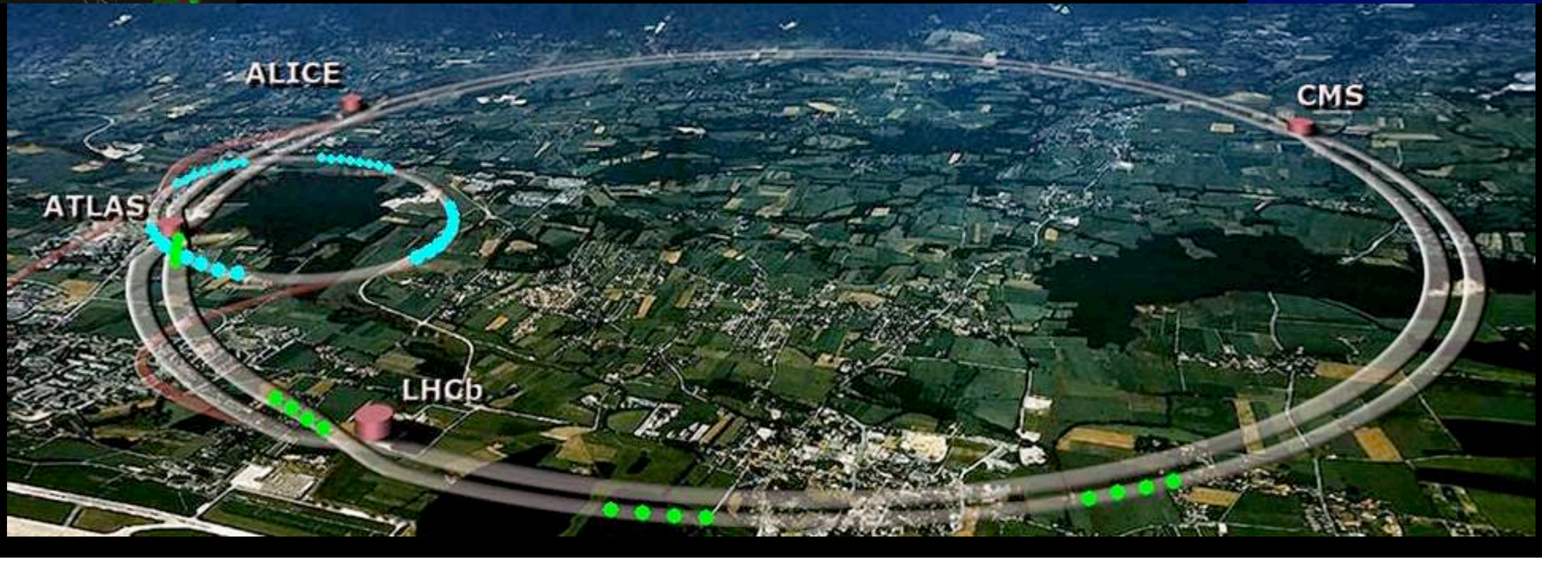

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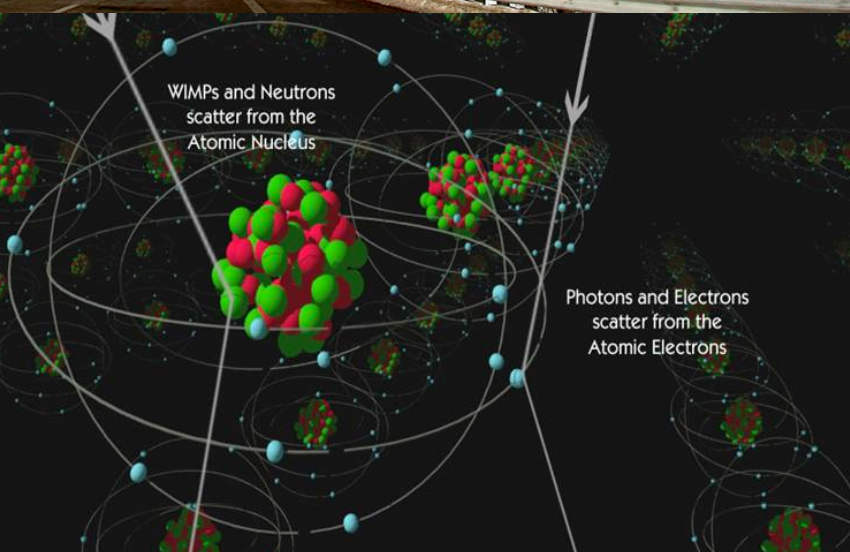

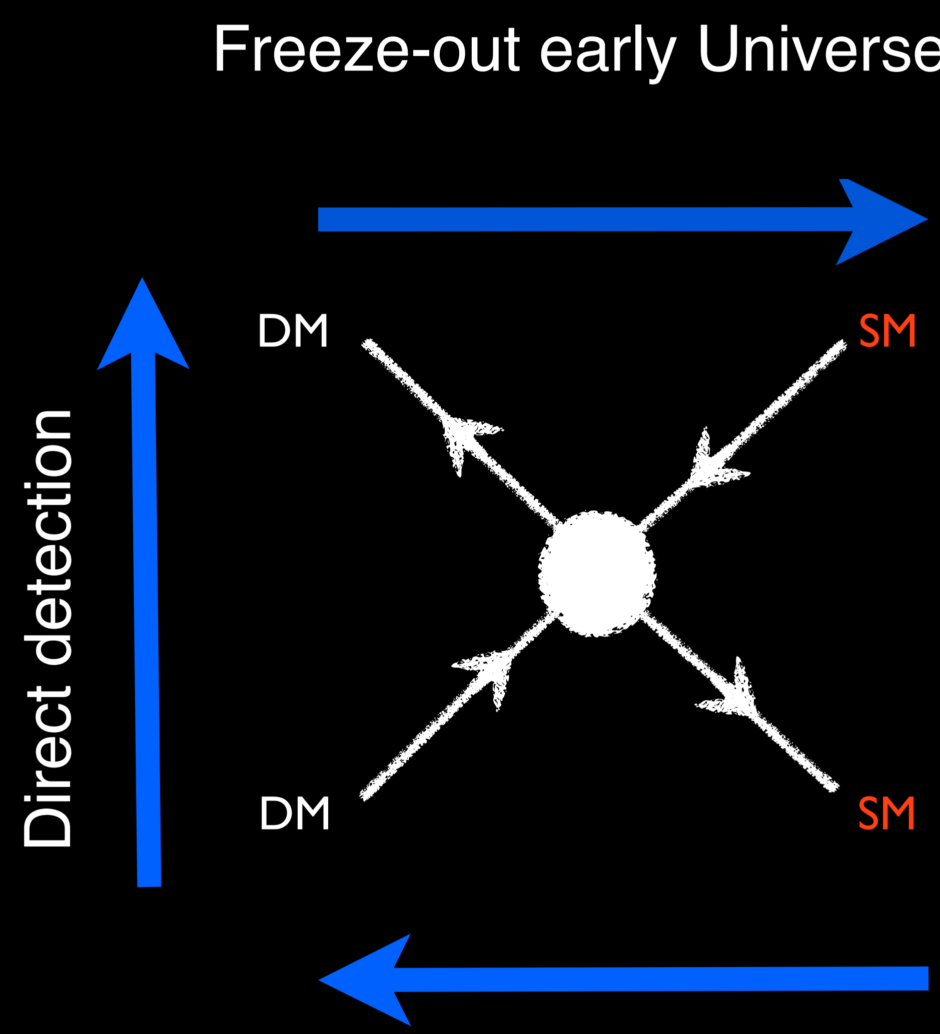

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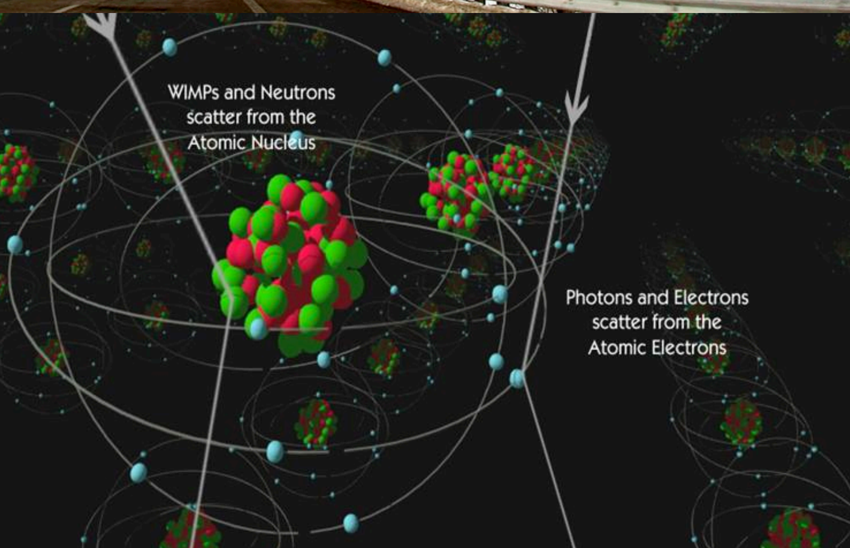

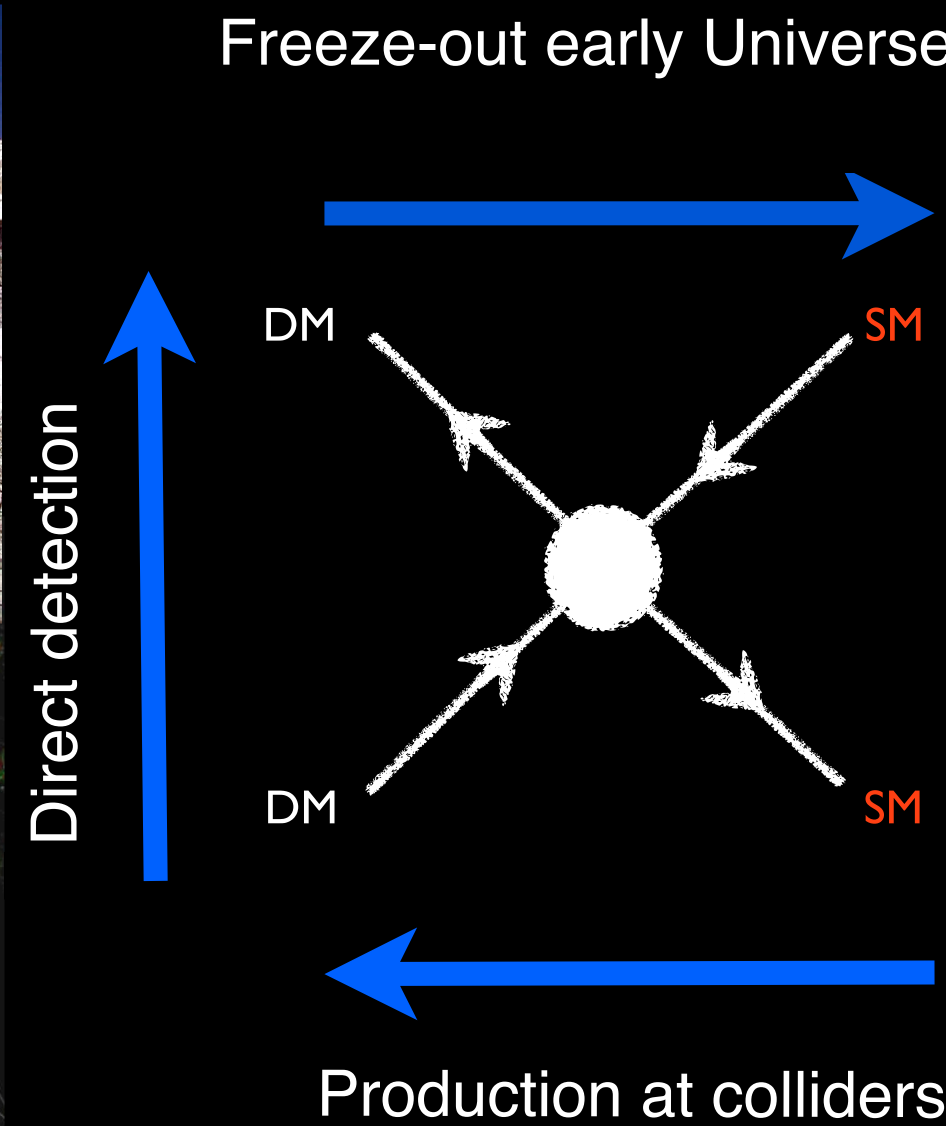

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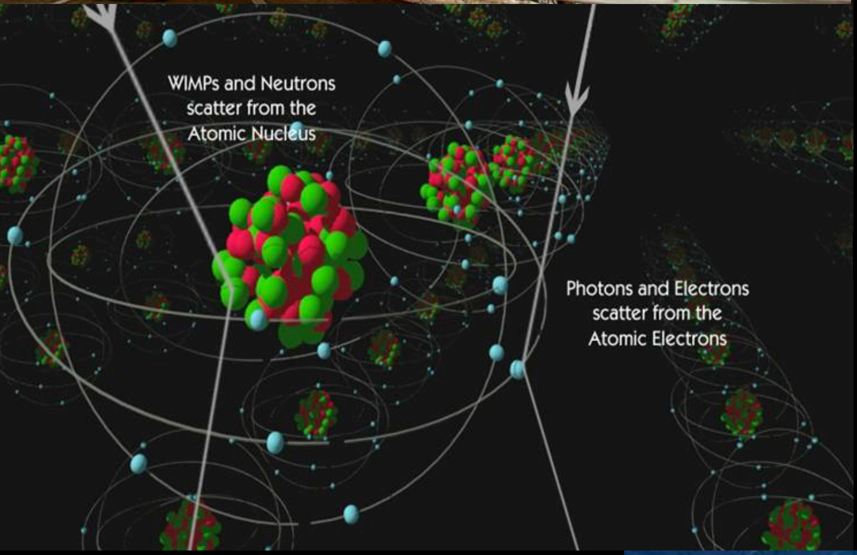
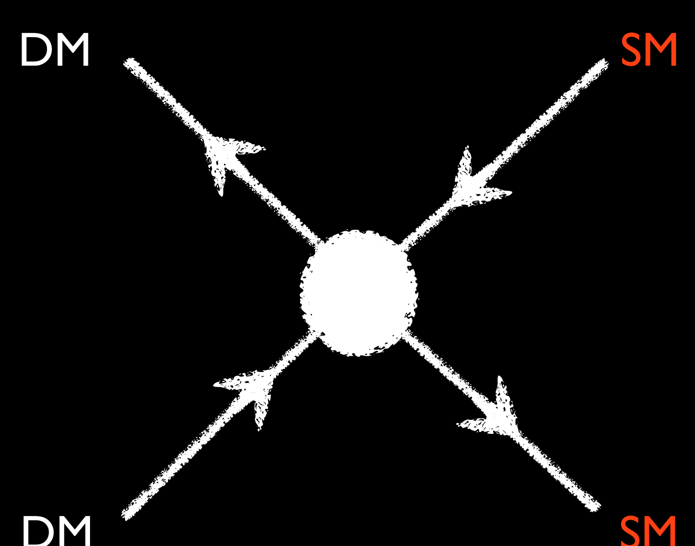


Freeze-out early Universe
Indirect detection

Direct detection



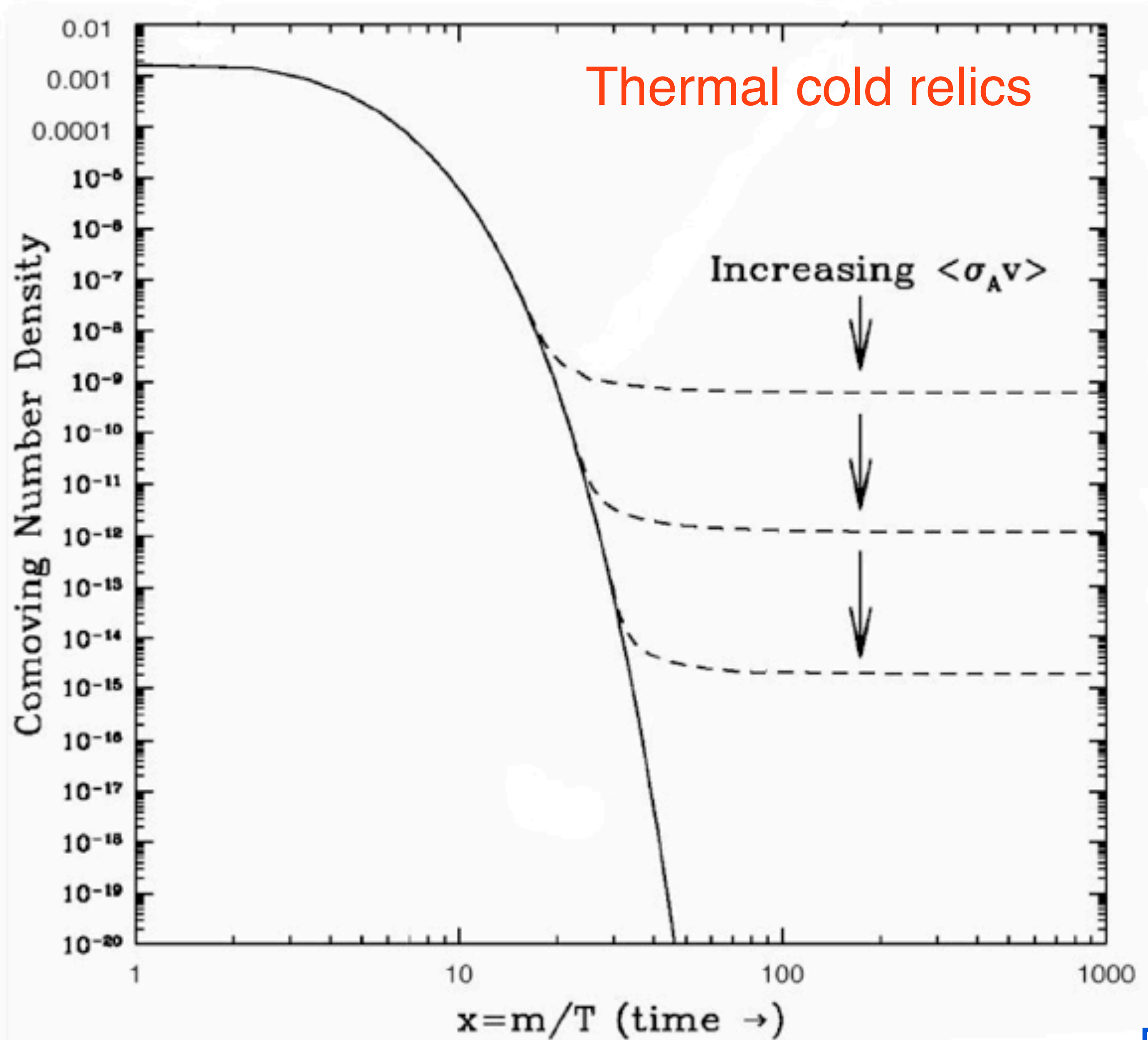
Production at colliders

Several searches already ongoing

Several new probes planned for the next future

WIMPs and relic density (fundamental constraint)

Lee & Weinberg '77, Gunn et al. '78, Steigman et al. '78, Kolb & Turner '81, Ellis et al. '84, Scherrer & Turner '85, Griest & Seckel '91



$$\chi + \overline{\chi} \leftrightarrow \mathrm{SM} + \overline{\mathrm{SM}}$$

$$\Gamma = n < \sigma_A v > \sim \mathrm{H}$$

$$\Omega_{\mathrm{DM}}\mathrm{h}^2 \sim 0.3\left(\frac{10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{< \sigma_A v >}\right)$$

GeV to TeV scale DM candidates with weak scale interactions

$$\Omega_{DM}h^2 = 0.1199 \pm 0.0015$$

Experimental error is so small!

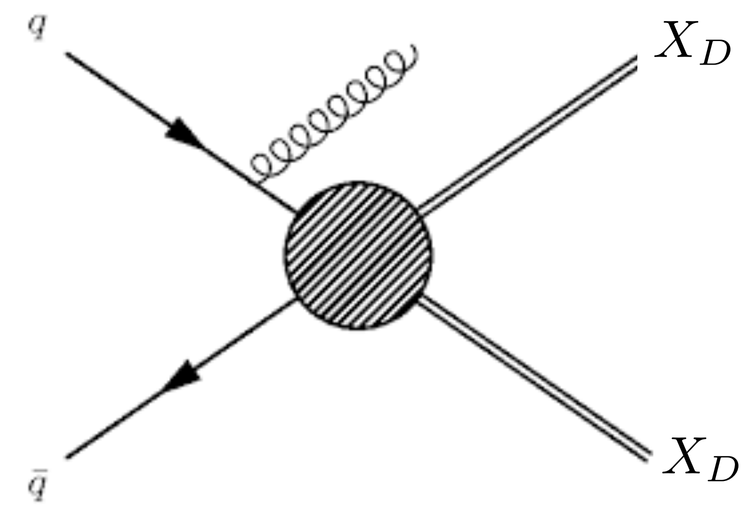
All is dominated by theoretical error!!

(SUSY 1 loop relic density calculations change the tree level value by ~ 20%)

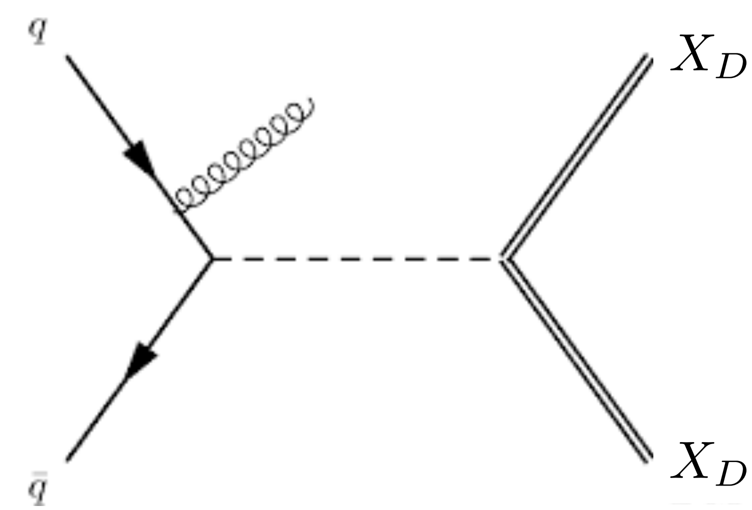
Search for DM at LHC

Found a Brout-Englert-Higgs boson but no sign of new physics

- LHC Run 1: Constraints based on effective operators and mono-X searches ($X=\gamma$,g,Z,H,W,l,...)



- LHC Run 2: New approach based on simplified DM models and mono-X searches ($X= \gamma$,g,Z,H,W,l,...)
- ATLAS/CMS Dark matter forum arXiv:1507.00966



$$\mathcal{L}_{X_D}^{Y_0} = \bar{X}_D (g^S_{X_D} + i g^P_{X_D} \gamma_5) X_D \, Y_0$$

$$\mathcal{L}_{\rm SM}^{Y_0} = \sum_{i,j} \left[\bar{d}_i \frac{y^d_{ij}}{\sqrt{2}} (g^S_{d_{ij}} + i g^P_{d_{ij}} \gamma_5) d_j + \bar{u}_i \frac{y^u_{ij}}{\sqrt{2}} (g^S_{u_{ij}} + i g^P_{u_{ij}} \gamma_5) u_j \right] Y_0$$

Relevant parameters:
DM mass
Mediator mass
Mediator width
Coupling DM-Mediator
Coupling quark(SM)-Mediator

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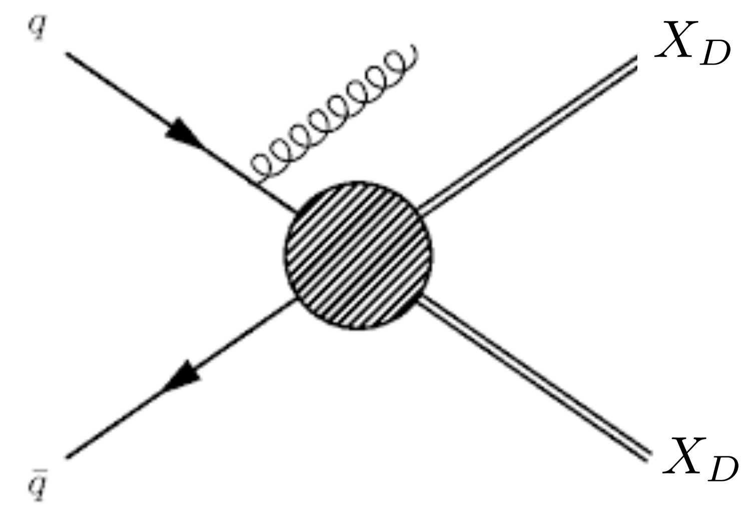


- LHC Run 2: New approach based on simplified DM models and mono-X searches

In the framework of simplified models, accurate computations at NLO (no DM pheno):

- O. Mattelaer and E. Vryonidou, DM production through loop-induced processes at the LHC: the s-channel mediator case, arXiv:1508.00564
- M. Backovic, M. Kraemer, F. Maltoni, A. Martini, K. Mawatari, M. Pellen, Higher-order QCD predictions for DM production at the LHC with in simplified models with s-channel mediator, arXiv:1508.05327

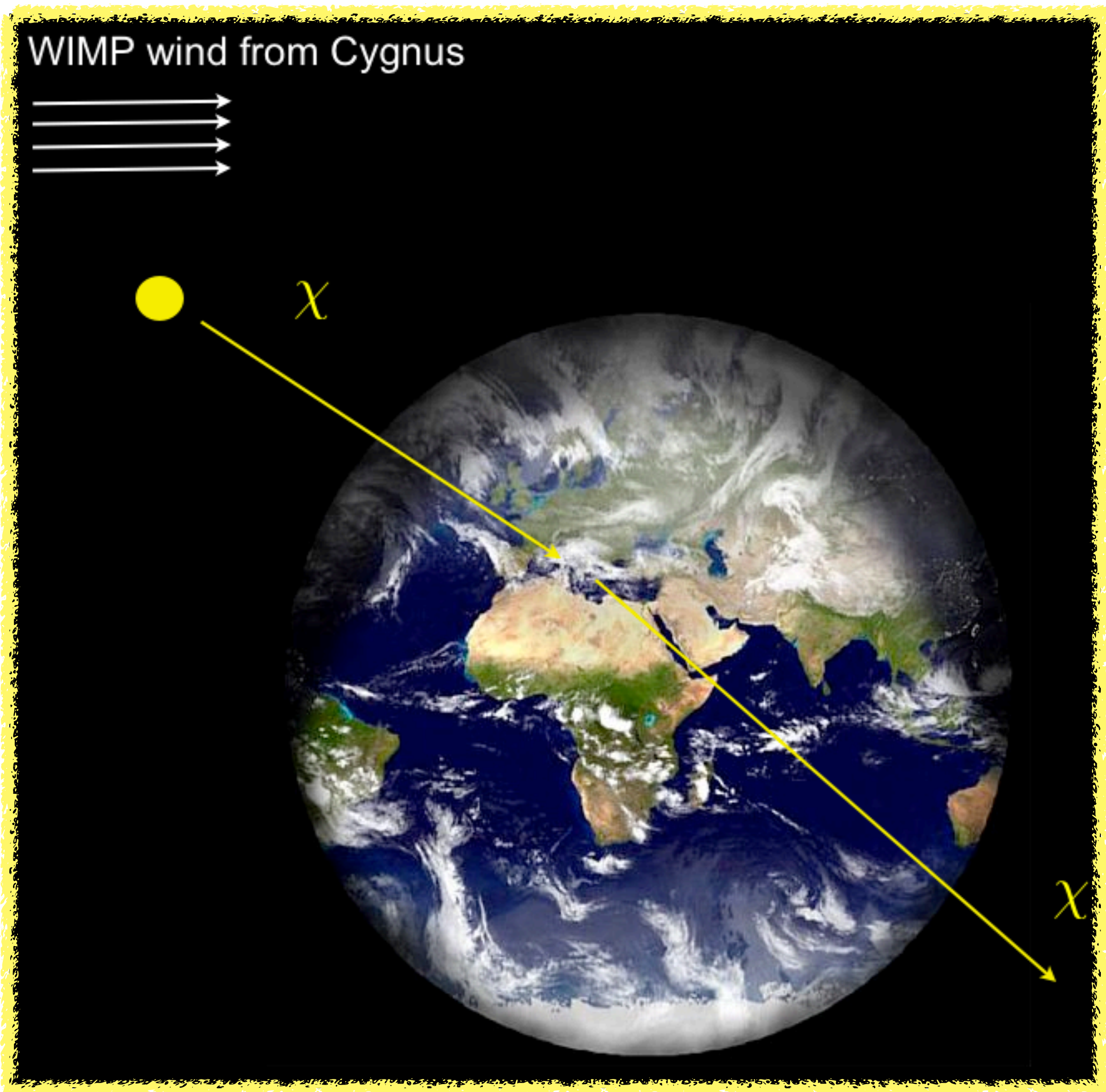
$$\mathcal{L}^{Y_0}_{\rm SM} = \sum_{i,j} \left[\bar{d}_i \frac{y^{ij}_d}{\sqrt{2}} (g^S_{d_{ij}} + i g^P_{d_{ij}} \gamma_5) d_j + \bar{u}_i \frac{y^{ij}_u}{\sqrt{2}} (g^S_{u_{ij}} + i g^P_{u_{ij}} \gamma_5) u_j \right] Y_0$$

Mediator width
Coupling DM-Mediator
Coupling quark(SM)-Mediator

DM direct detection

Goodman & Witten ’85

By definition WIMPs do not have only gravitational interaction



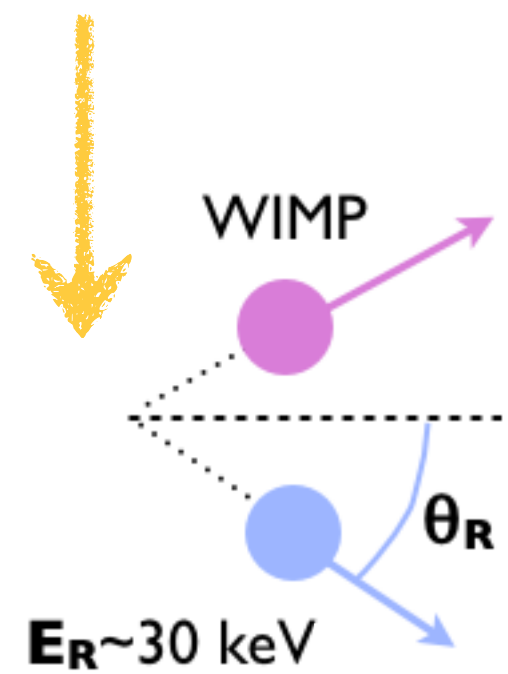
WIMP
from galactic halo

Target Nucleus
in laboratory

v ~ 230 km/s

v_T ~ 0 km/s

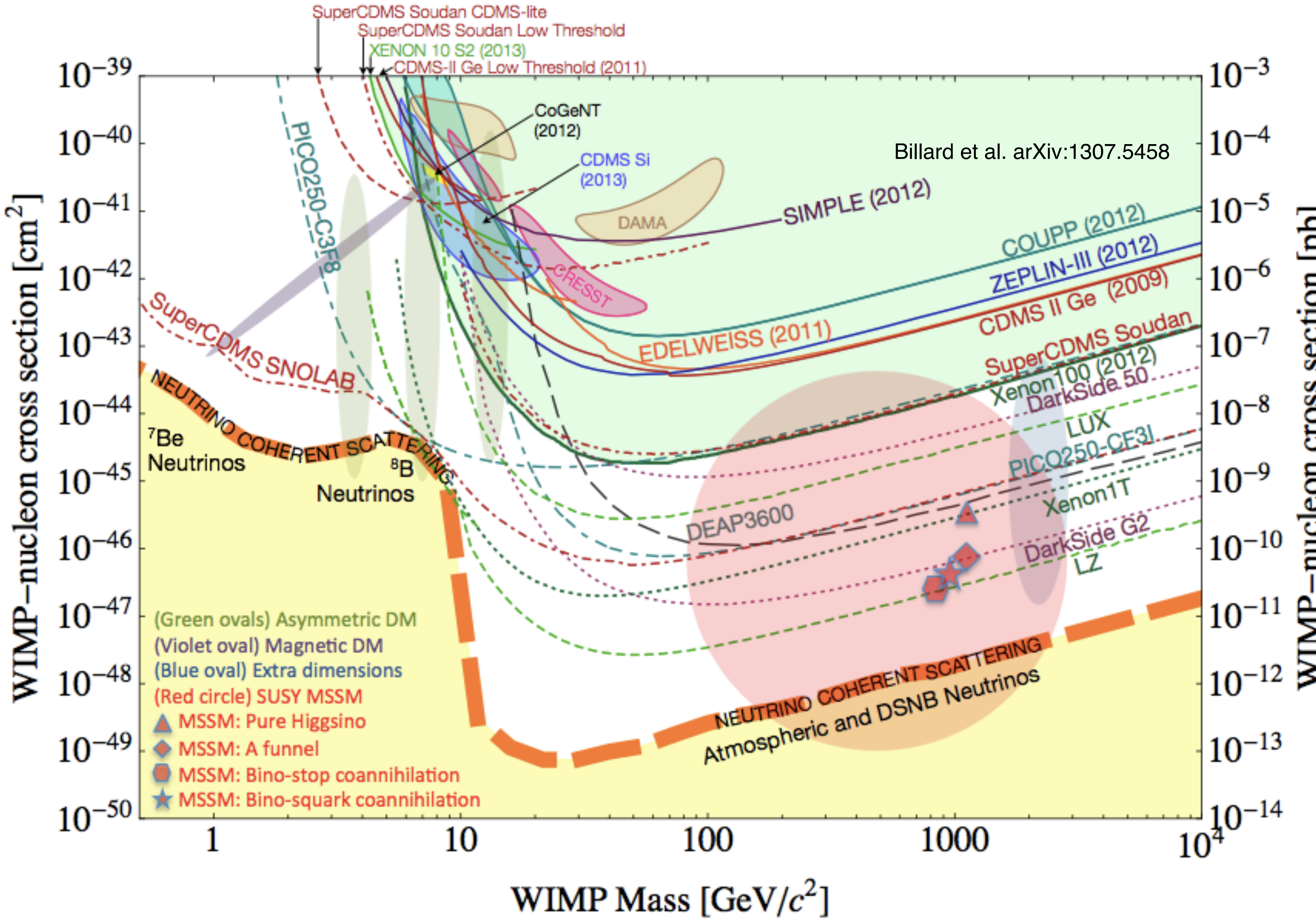
Elastic collision



Momentum transfer ~ MeV =
non relativistic process

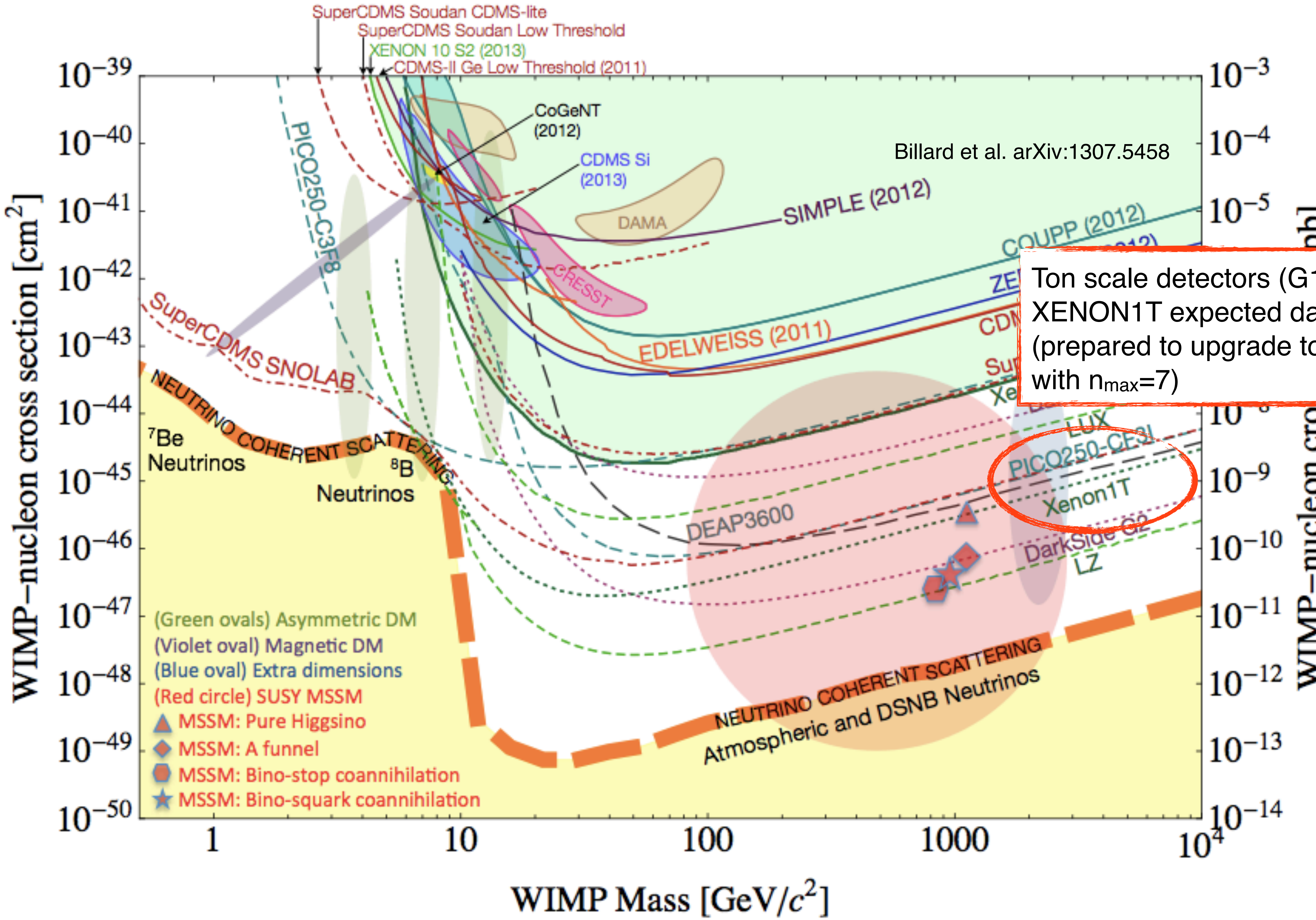
$$E_R = \frac{\mu^2 v^2}{m_T}(1 - \cos\theta)$$

DM direct detection experimental status



Several assumption go into the plot!

DM direct detection experimental status



Ton scale detectors (G1):
XENON1T expected data for 2017
(prepared to upgrade to XENONnT with n_{max}=7)

Several assumption go into the plot!

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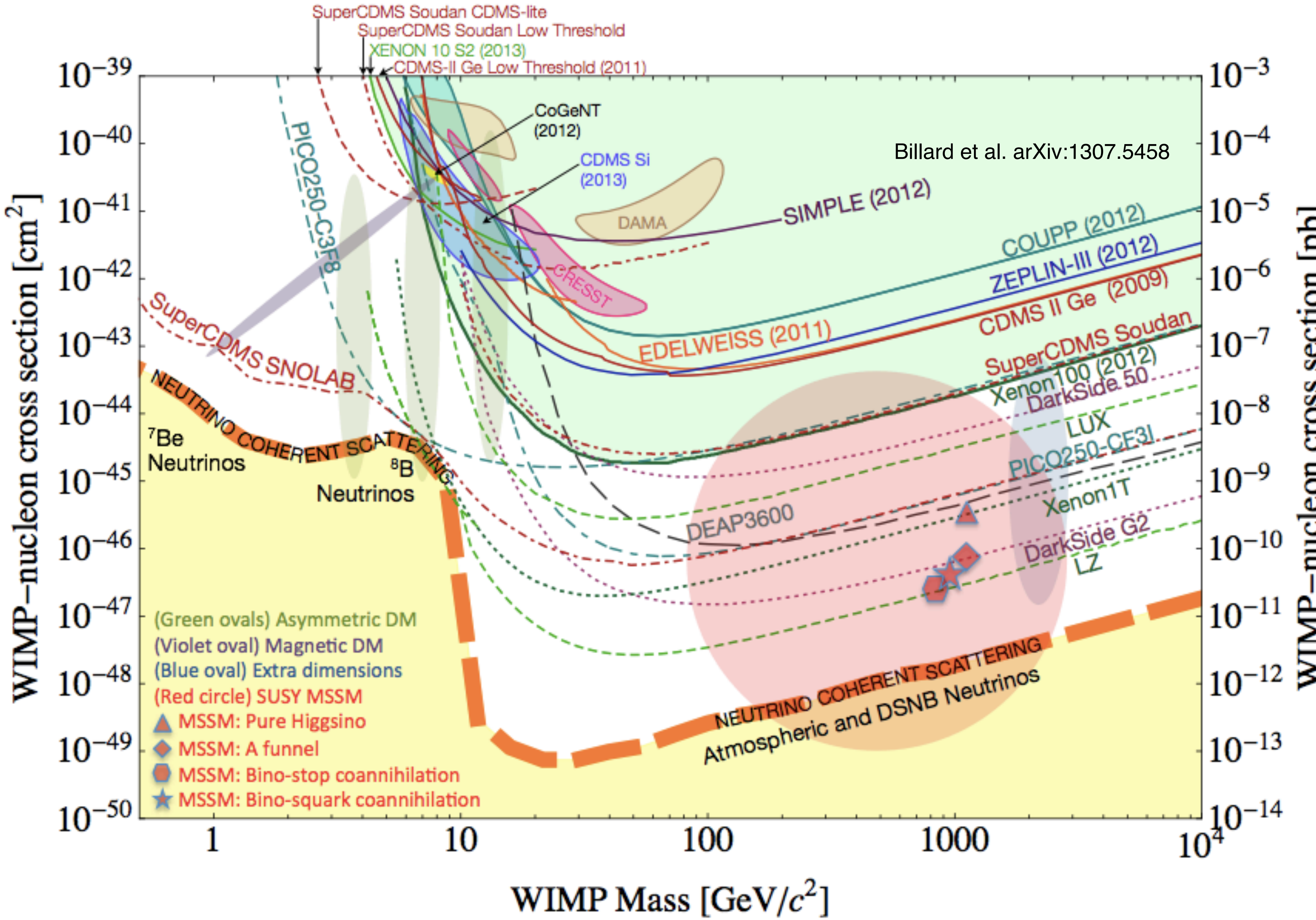

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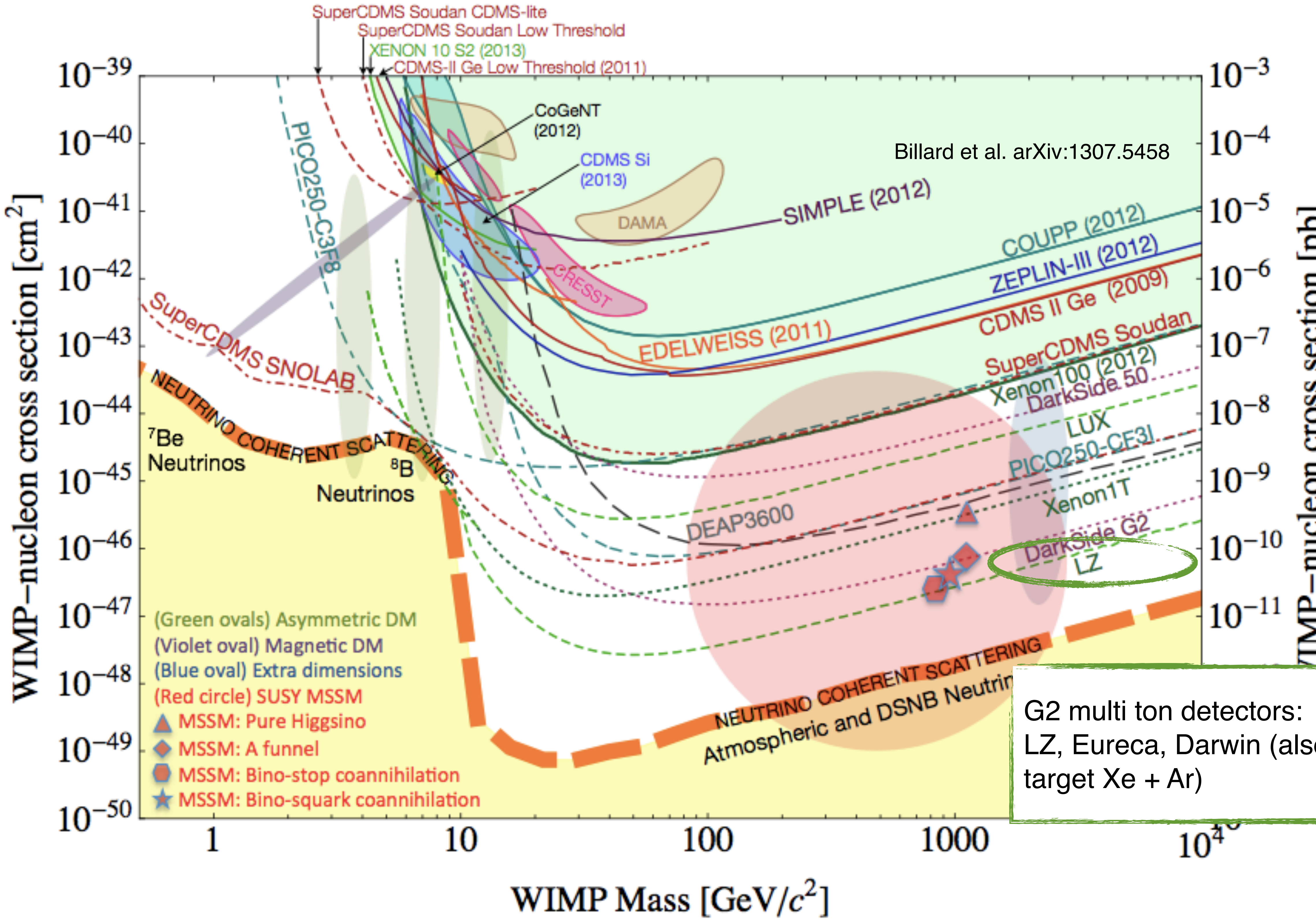
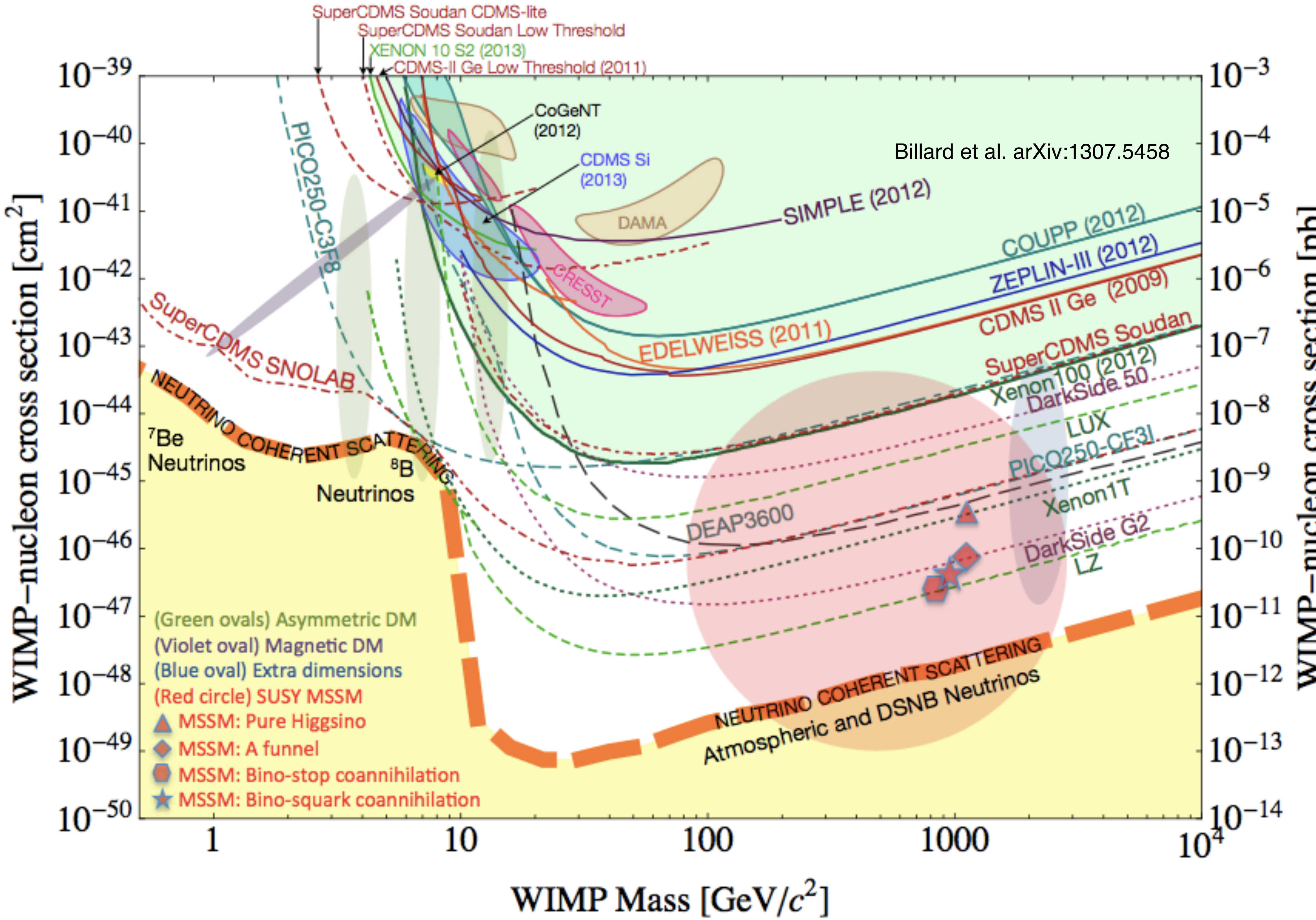


G2 multi ton detectors:
LZ, Eureca, Darwin (also multi-target Xe + Ar)

Several assumption go into the plot!

DM direct detection experimental status



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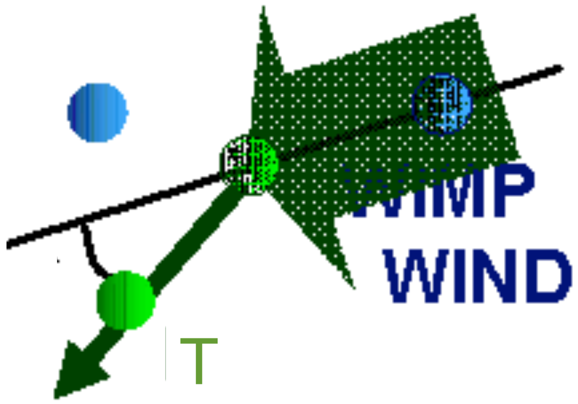
Dark Matter differential event rate



$$\frac{dR_T}{dE_R} = \frac{\xi_T}{m_T}\frac{\rho_\odot}{m_{DM}}\int_{v\geqslant v_{min}} d^3v \, \frac{f(\vec{v})}{v}\frac{d\sigma_T}{dE_R}$$

$$v_{min} = \sqrt{\frac{m_T E_R}{2\mu^2}}$$

$$\frac{d\sigma_T}{dE_R} = \frac{m_T \sigma_n^{SI}}{2\mu_n^2}\frac{\left(f_p^2 Z + (A-Z) f_n^2\right)^2}{f_n^2}\mathcal{F}^2(E_R)$$

- Spin Independent (SI) is NOT the only interaction!
- f_n and f_p can be different!

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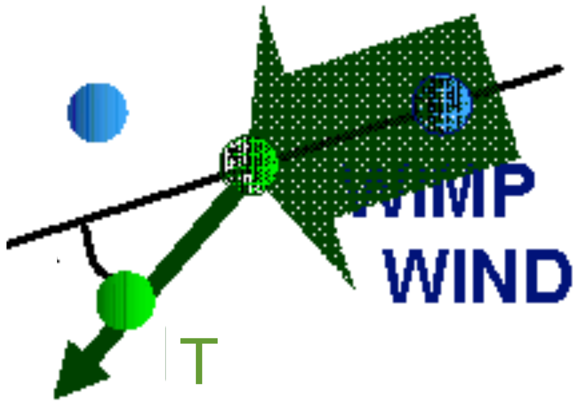

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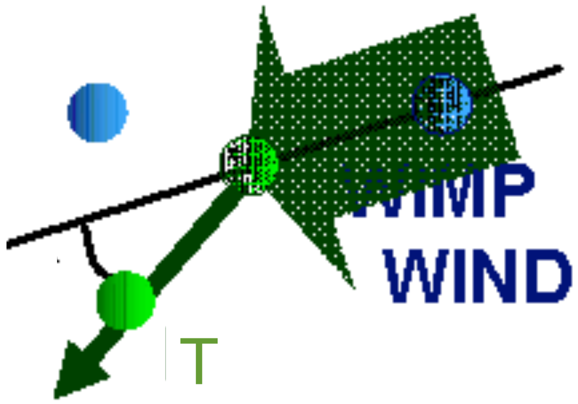

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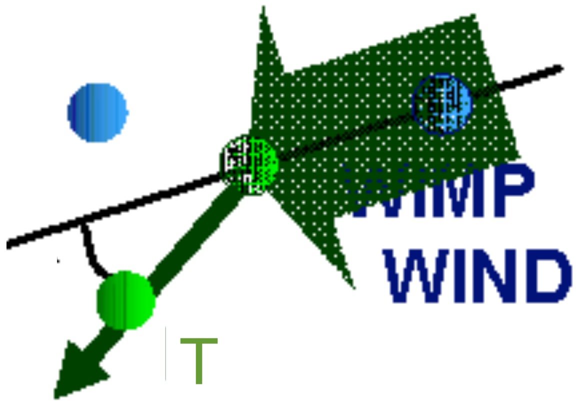

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Depend on DM velocity distribution and astrophysical parameters

• f(v) is not a Maxwell-Boltzmann distribution!

• Astrophysical parameters not well measured

$$v_0^{obs} = 230 \pm 24.4 \text{ km s}^{-1}$$
$$v_{esc}^{obs} = 544 \pm 39 \text{ km s}^{-1}$$
$$\rho_\odot^{obs} = 0.4 \pm 0.2 \text{ GeV cm}^{-3}$$

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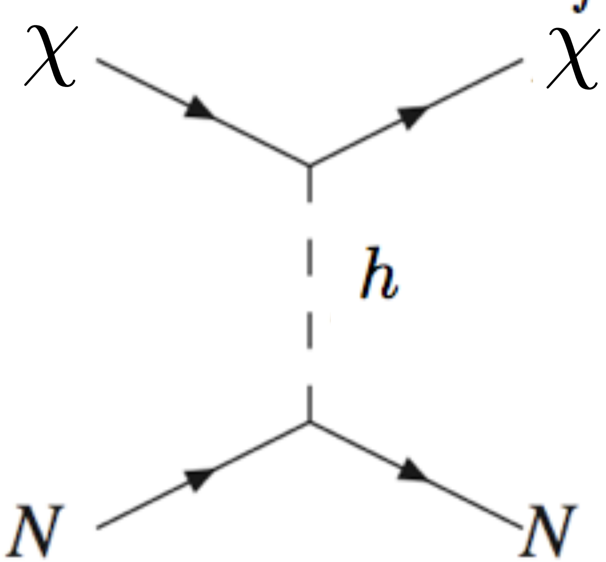
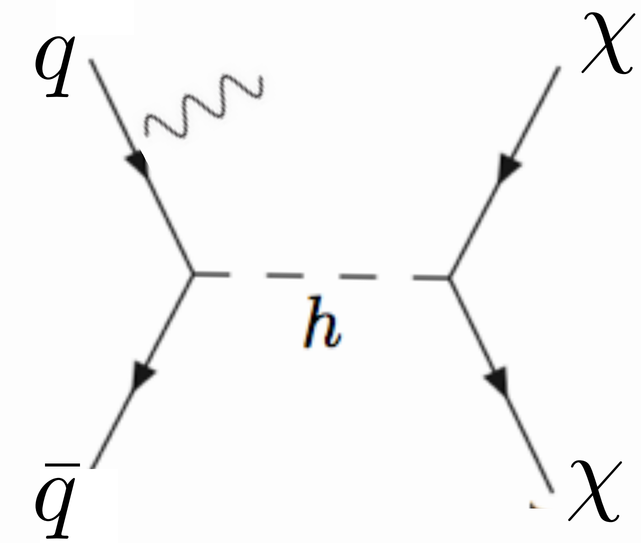
Dark Matter direct detection (DD)

SI: $\mathscr{L}_{\rm int} = -\frac{y_{\rm DM}}{\sqrt{2}} h\bar{\chi}\chi - \sum_f \frac{y_f}{\sqrt{2}} h\bar{f}f$



tight connection
with simplified models

LHC



There several other interaction possible for DD (as well as for LHC)
Coy dark matter has nice phenomenology

$$\mathscr{L}_{\rm int} = -i\frac{g_{\rm DM}}{\sqrt{2}} a\bar{\chi}\gamma_5\chi - ig\sum_q \frac{g_q}{\sqrt{2}} a\bar{q}\gamma_5 q$$

effective contact operator allowed for DD
($v_{DM} \sim 10^{-3}$ c)

$$\mathscr{L}_{\rm eff} = \frac{1}{2\Lambda_a^2} \sum_{N=p,n} g_N\, \bar{\chi}\gamma^5\chi\, \bar{N}\gamma^5 N$$

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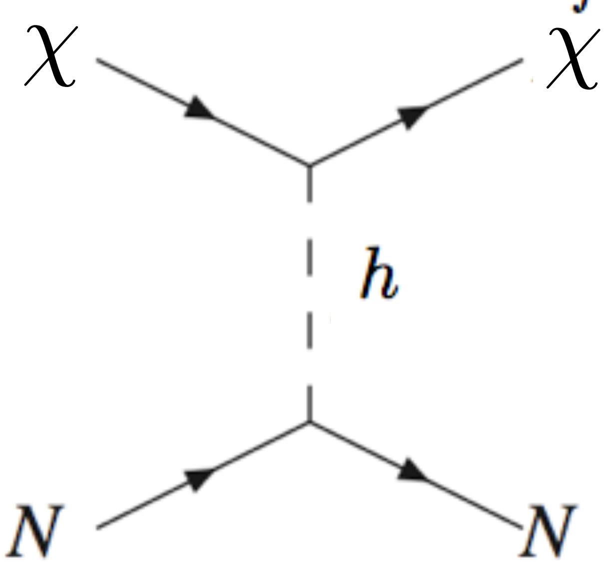
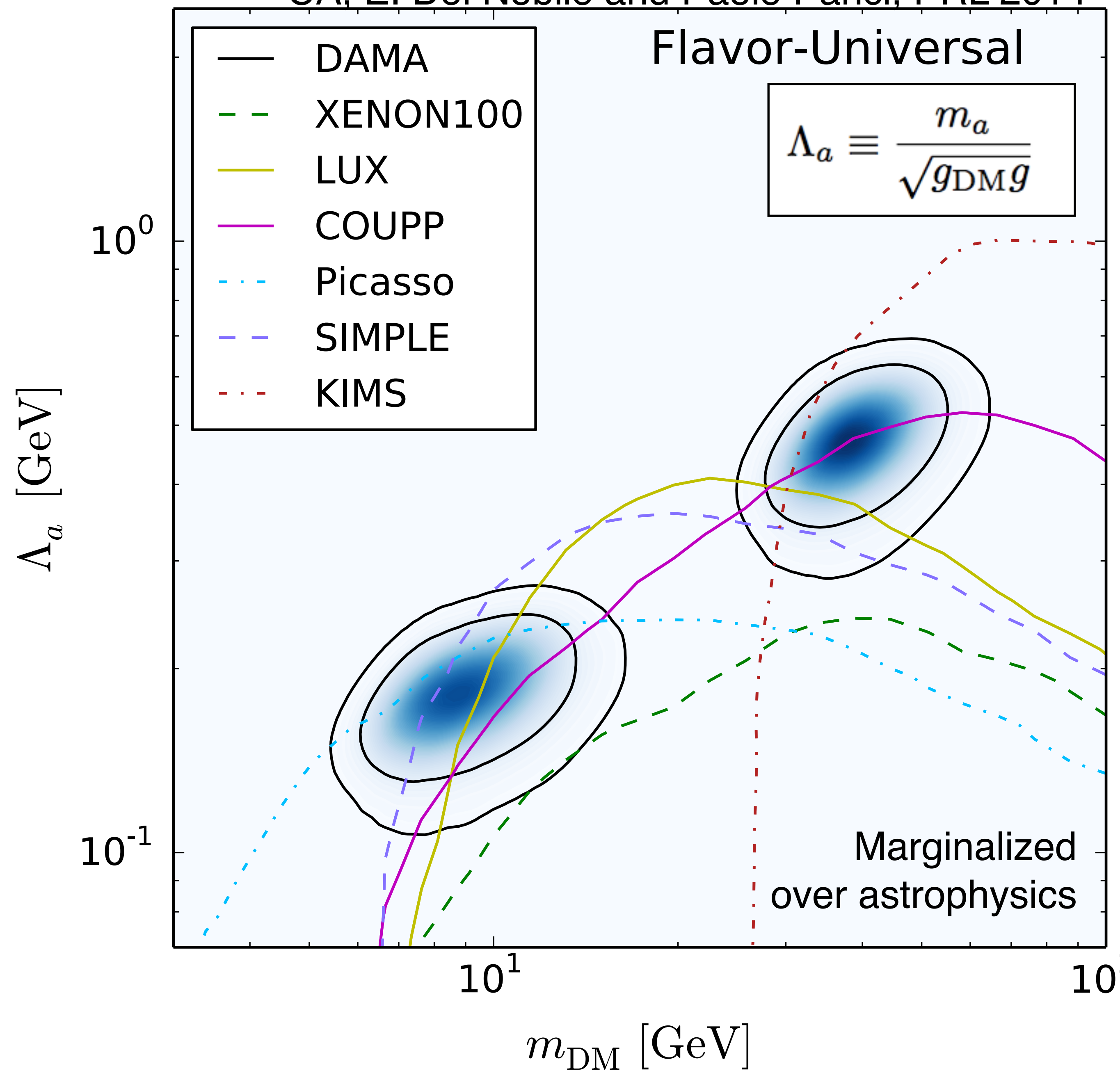


wi

CA, E. Del Nobile and Paolo Panci, PRL 2014



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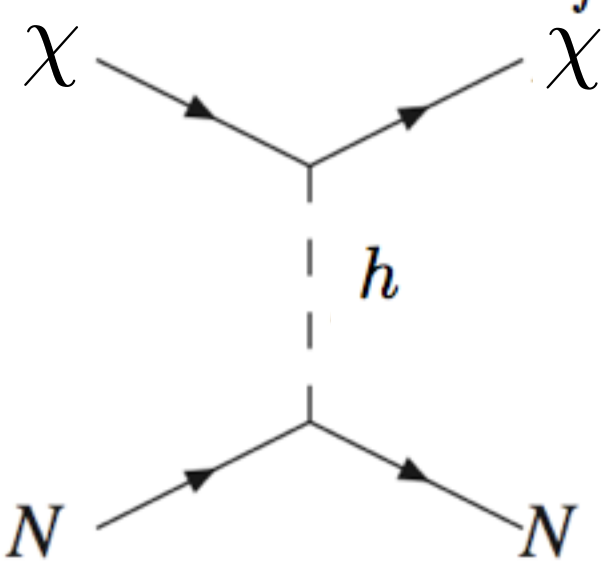

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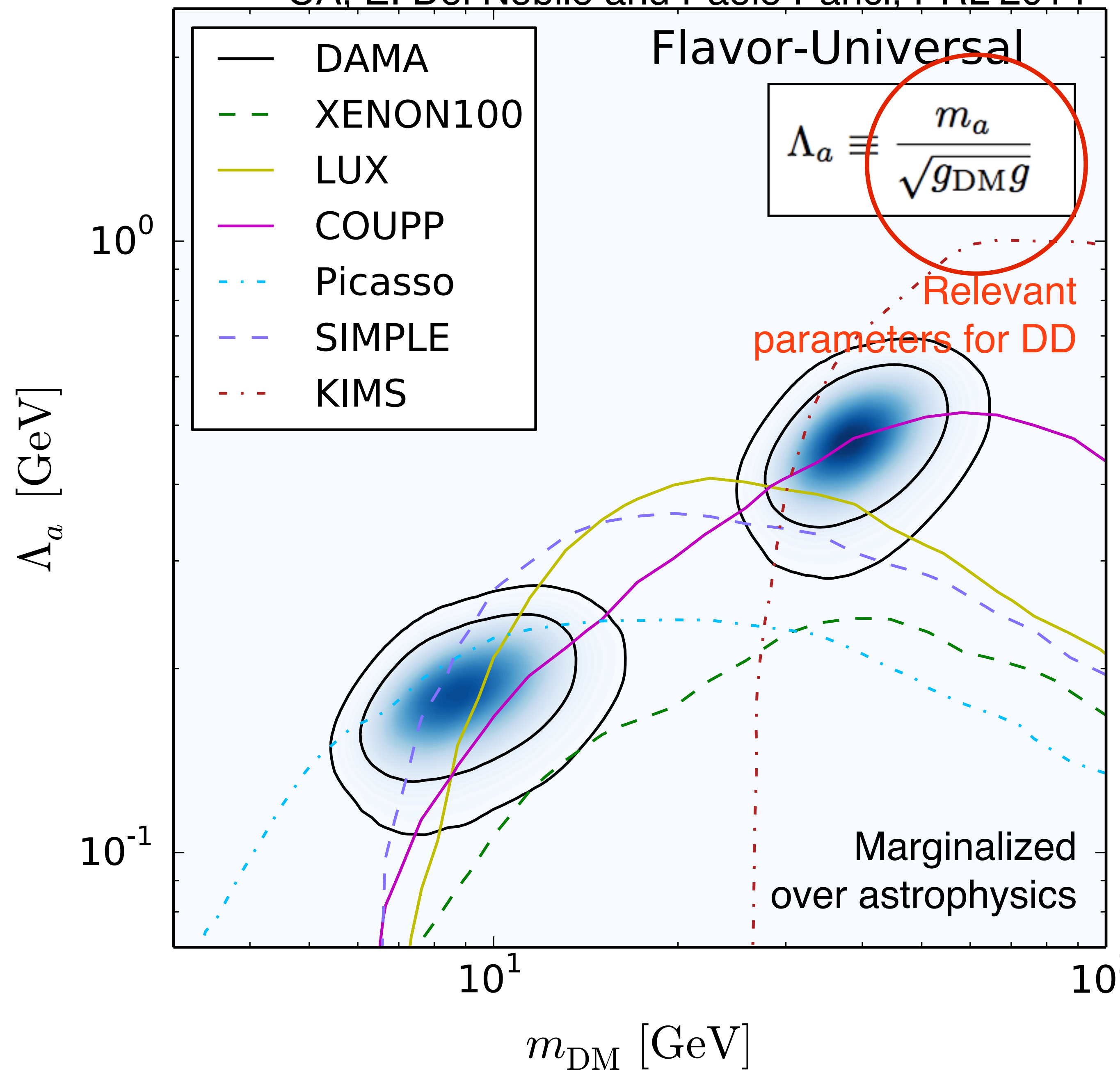

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Possible future directions LHC-DD

- NLO calculations for all possible simplified dark matter models (t-channel, all type of mediators)

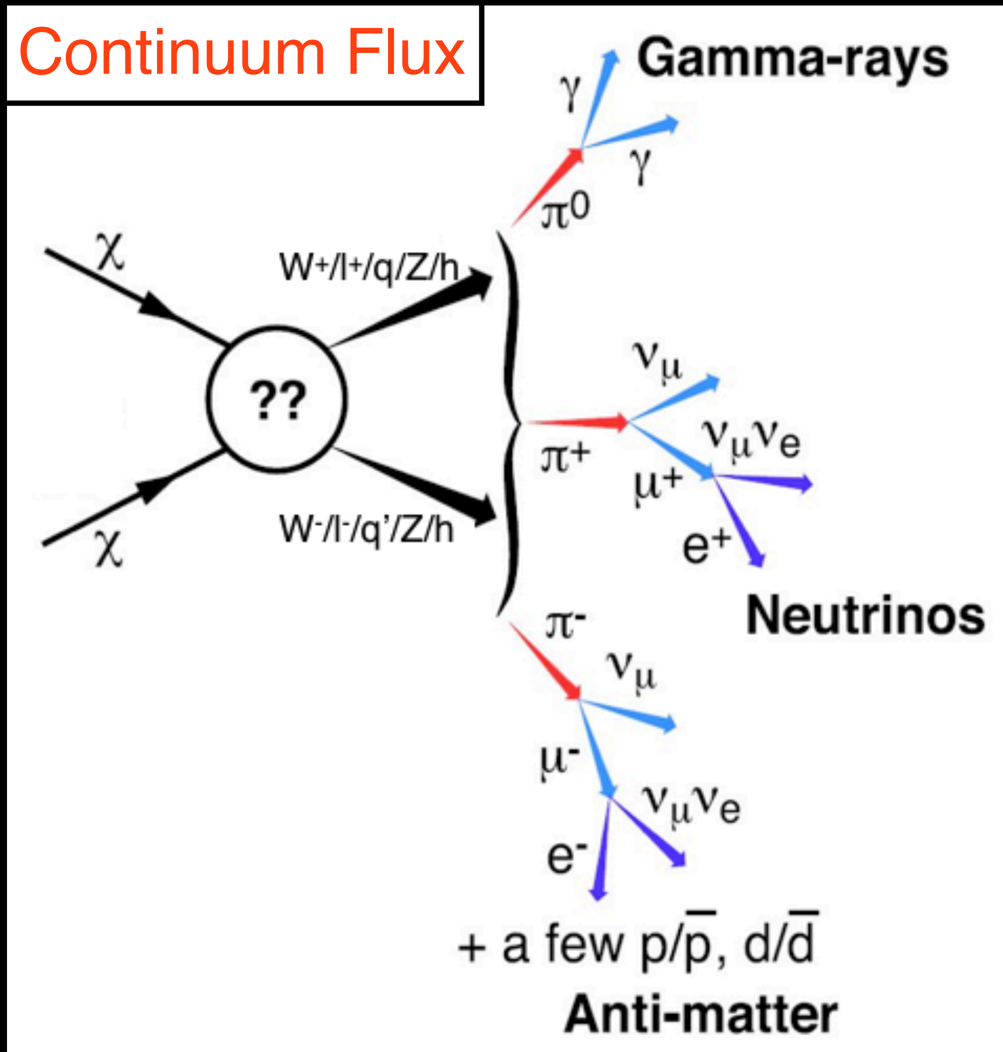
- USE DM search complementarity to constrain the free parameters of the simplified models for all type of interactions:
  - relic density
  - direct detection constraints
  - no astrophysics at LHC but astro uncertainties for direct detection

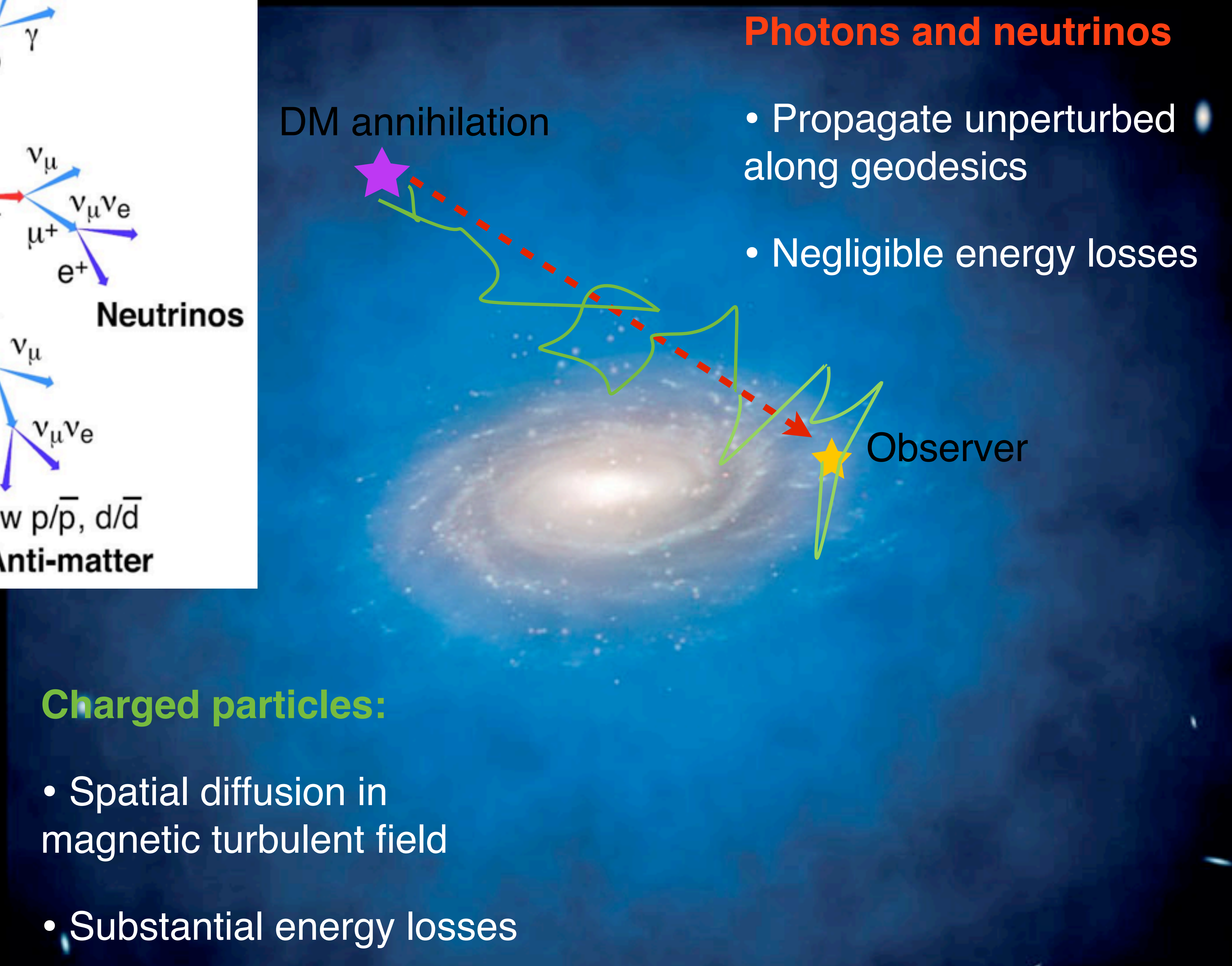
- MadDM direct detection can be improuved with:
  - Velocity distribution functions for the DM to impact astrophysical uncertainties (CA, J. Hamann and Y. Wong, arXiv:1105.5121)
  - New nuclear form factors to provide accurate and correct computations of direct detection bound (CA, E. Del Nobile and Paolo Panci, PRL 2014)
  - micromegas (competitor code) doesn't have these features!!

- Impact of nuisance parameters on the theoretical parameters easily assessed with MCMC or nested sampling methods (CA, J. Hamann, R. Trotta and Y. Wong, arXiv: 1111.3238)

- Experimental likelihoods (similarly to MadAnalysis)

DM indirect detection





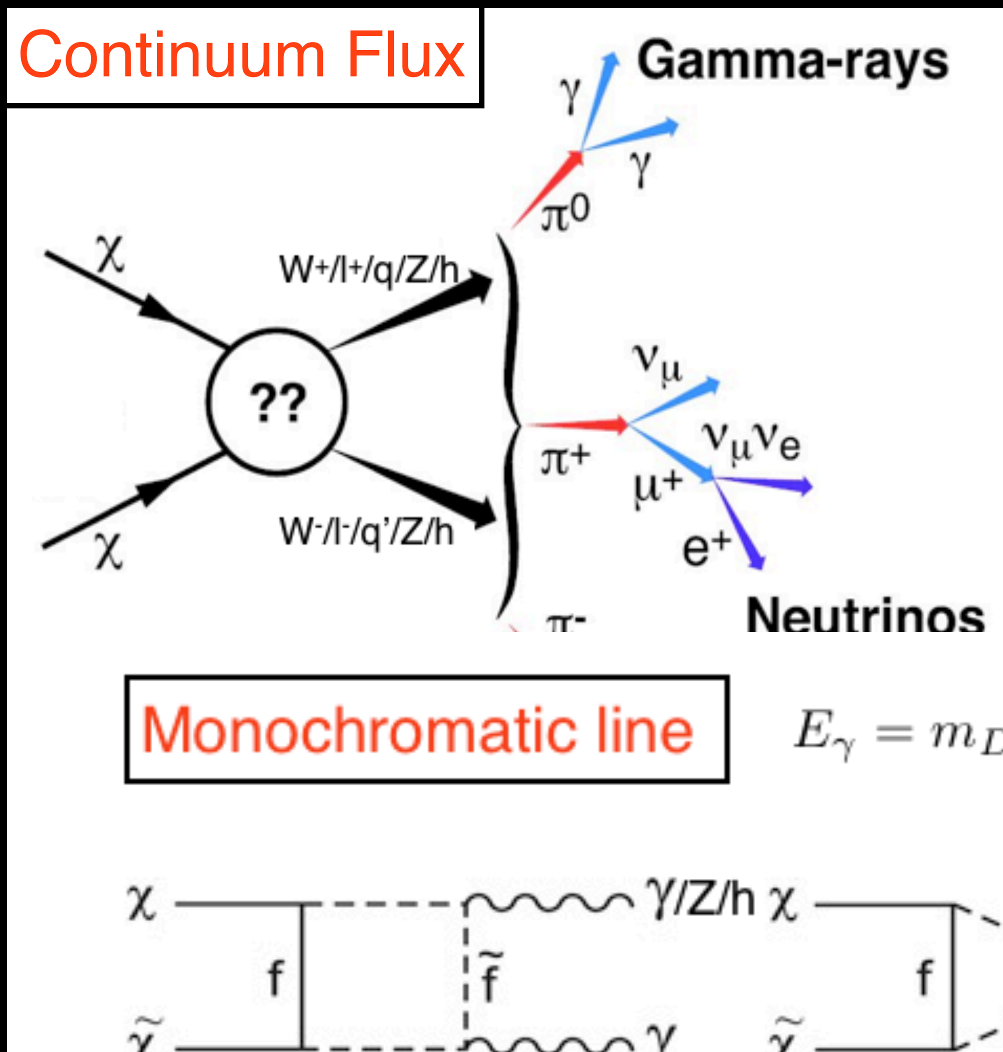
Photons and neutrinos

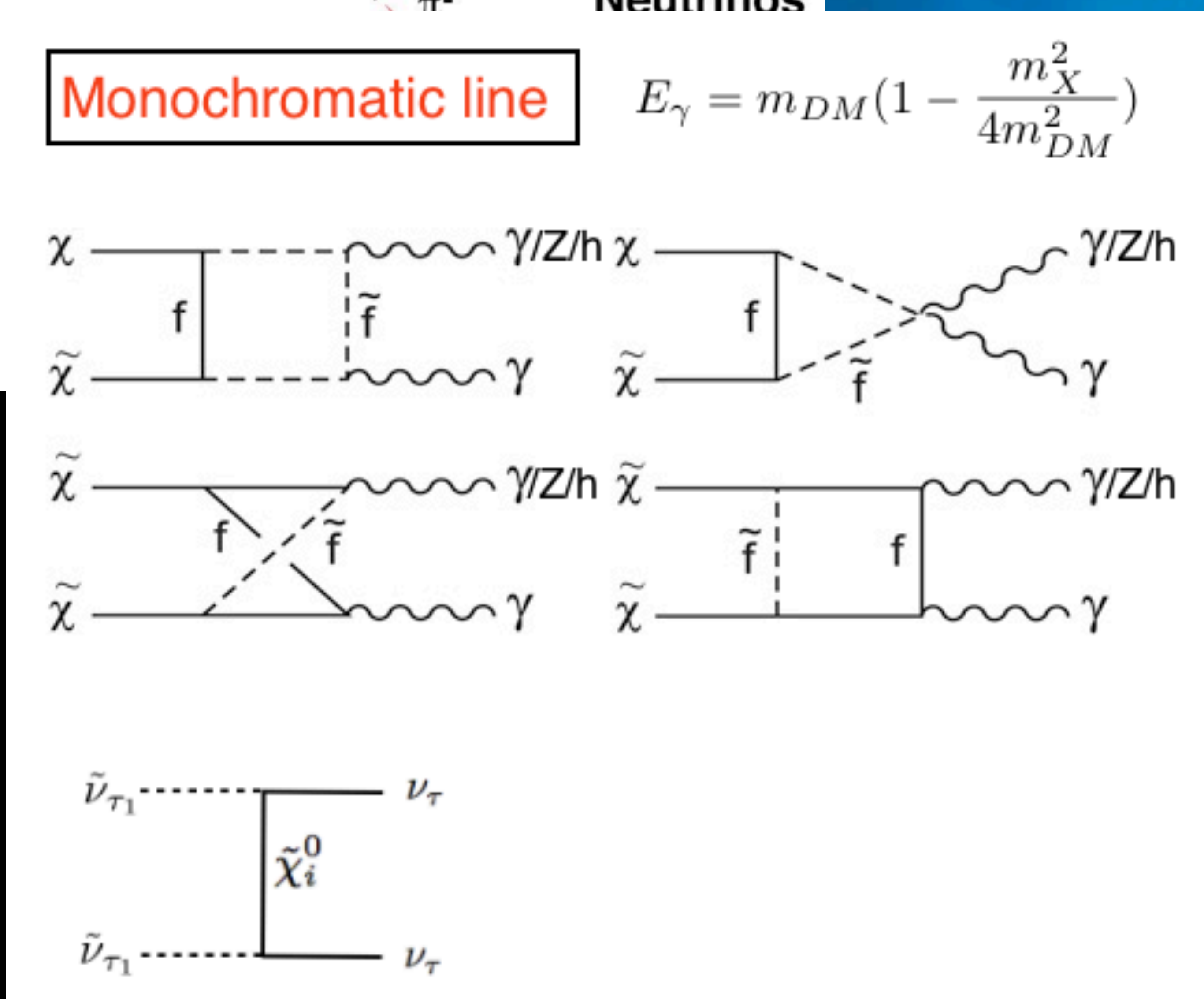
- Propagate unperturbed along geodesics
- Negligible energy losses

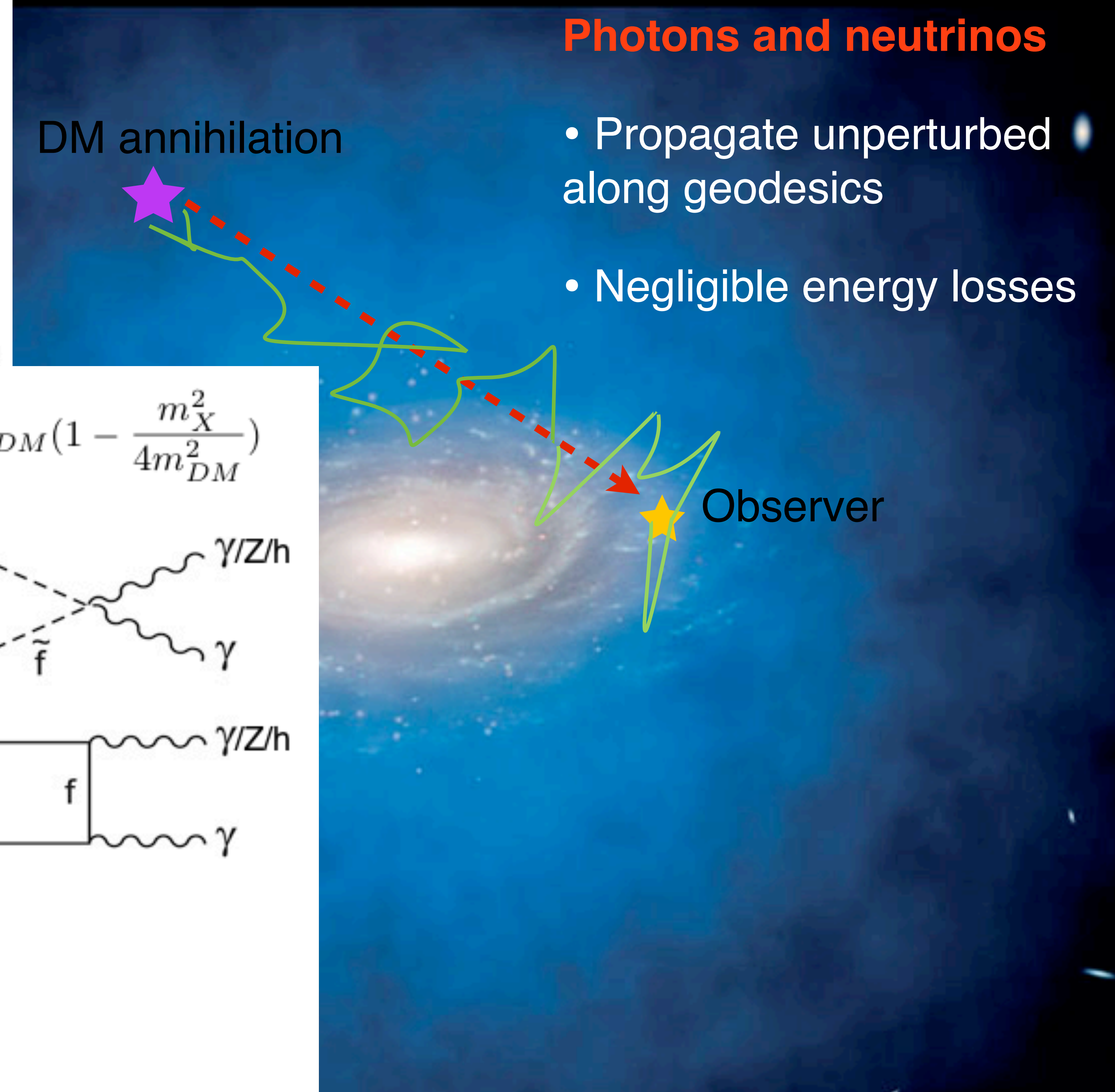
Charged particles:

- Spatial diffusion in magnetic turbulent field
- Substantial energy losses

DM indirect detection



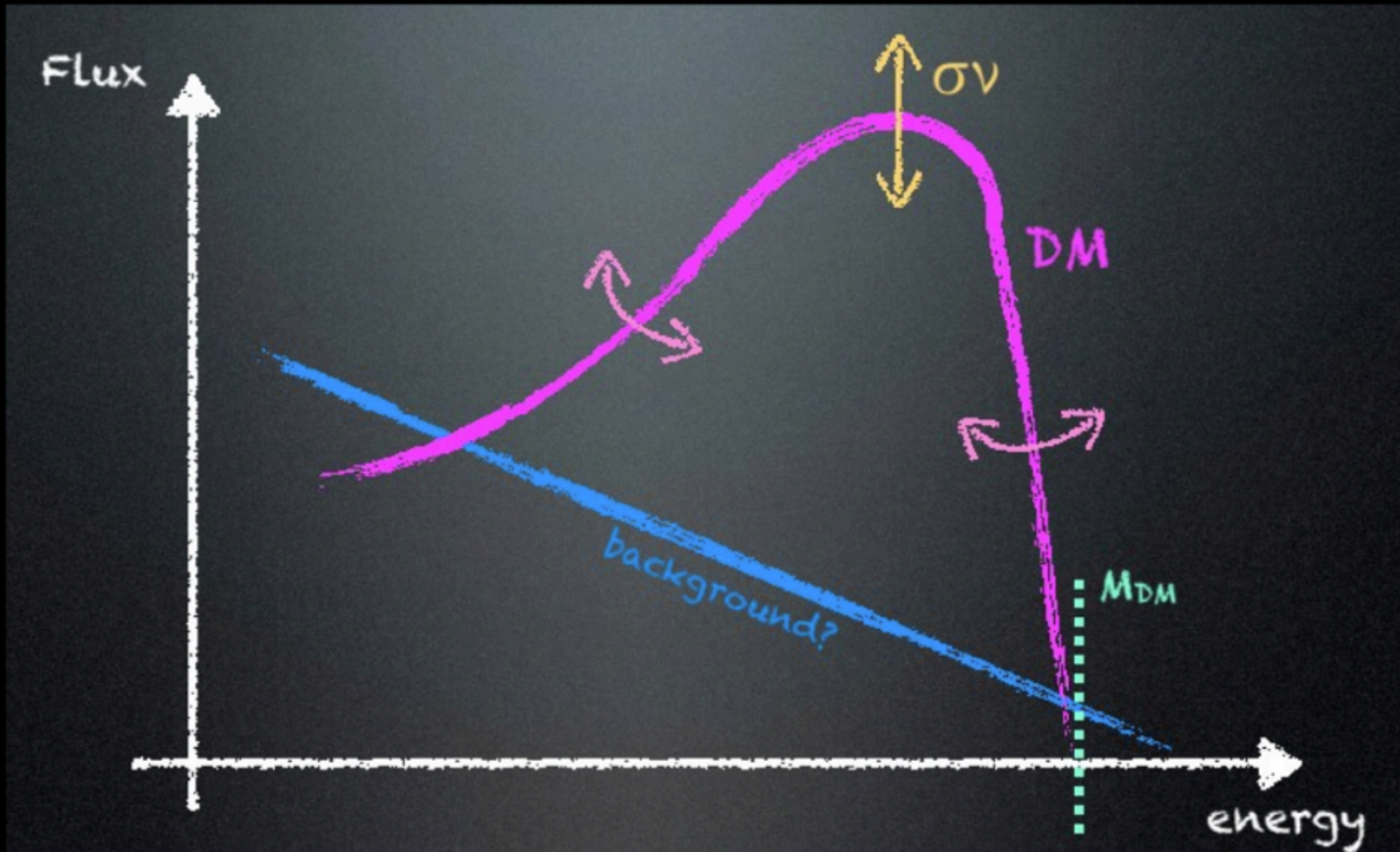




Photons and neutrinos

- Propagate unperturbed along geodesics
- Negligible energy losses

DM indirect detection: how the signal looks like



Credit: M. Cirelli

Relevant parameters

- Background parameters
- Annihilation cross-section
- DM mass
- Annihilation channels (i.e. Energy spectrum)

$$\frac{d^2\Phi_X}{dE\,d\Omega} \propto \frac{1}{8\pi}\,\frac{\langle\sigma v\rangle \rho^2_{DM}(r(\Omega))}{m^2_{DM}}\,\frac{dN_X}{dE}$$

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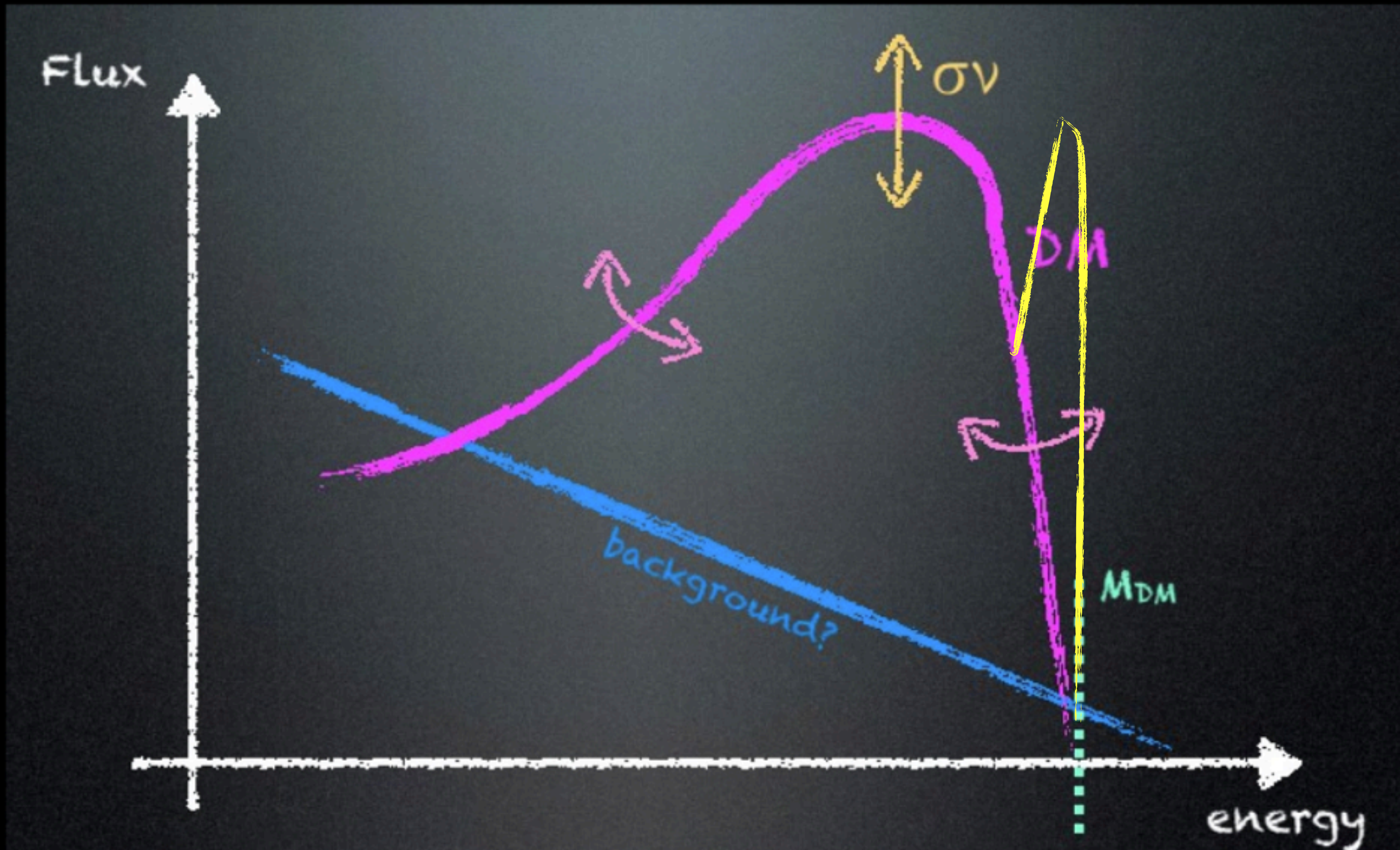

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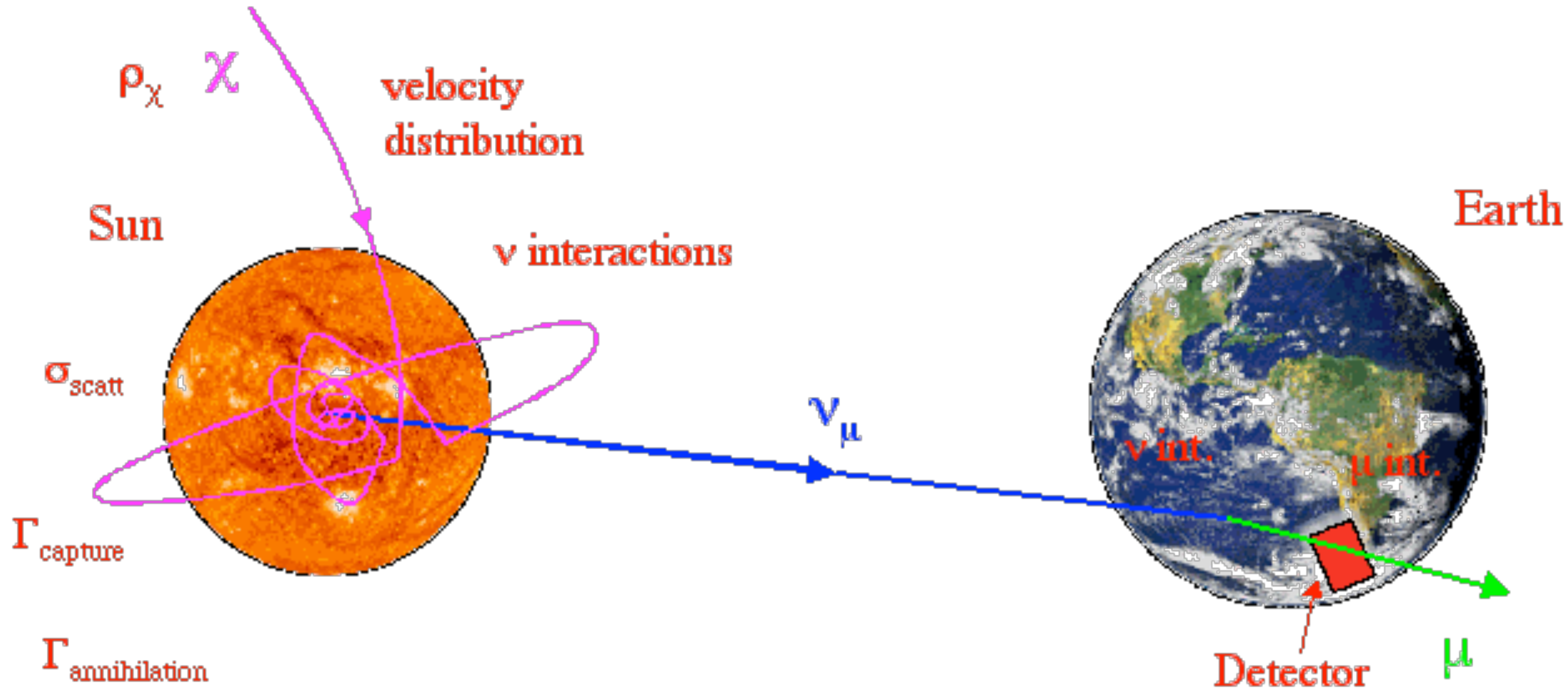
Neutrinos from the Sun



DM annihilating into the Sun (or Earth)

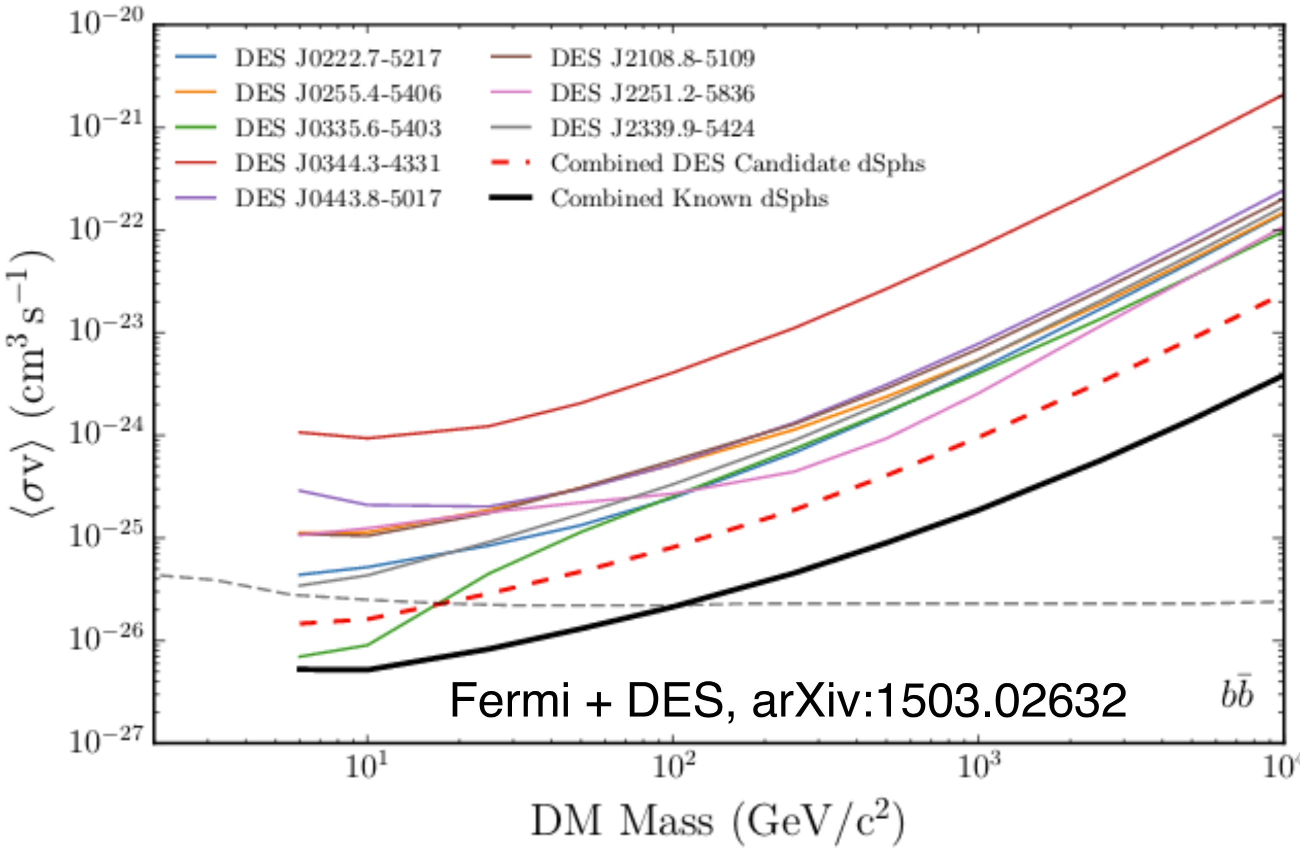
- Only neutrino can escape from the Sun center/surface

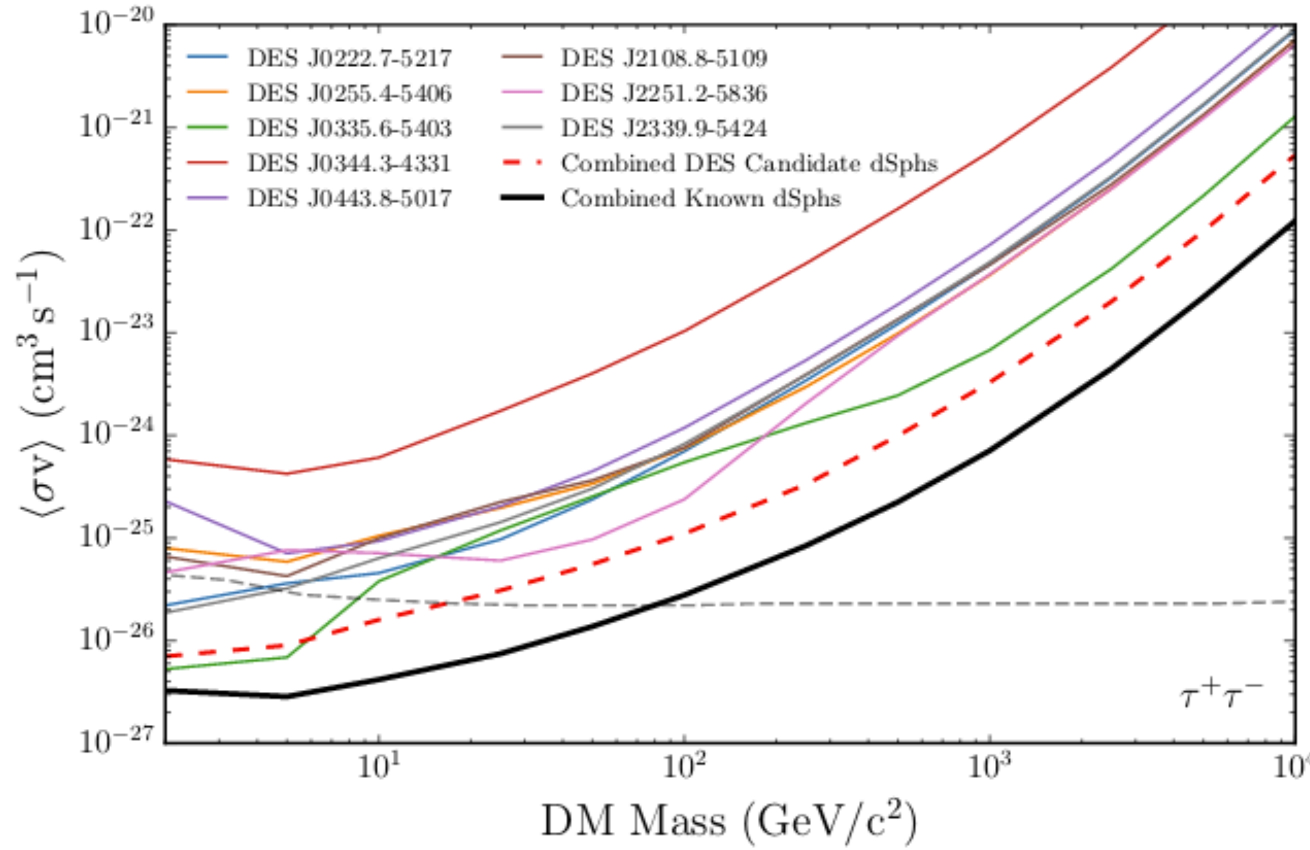
- The detection of GeV-TeV neutrinos from the Sun by IceCube/KM3Net/Pingu/... would be a clear indication in favor of DM origin of the signal

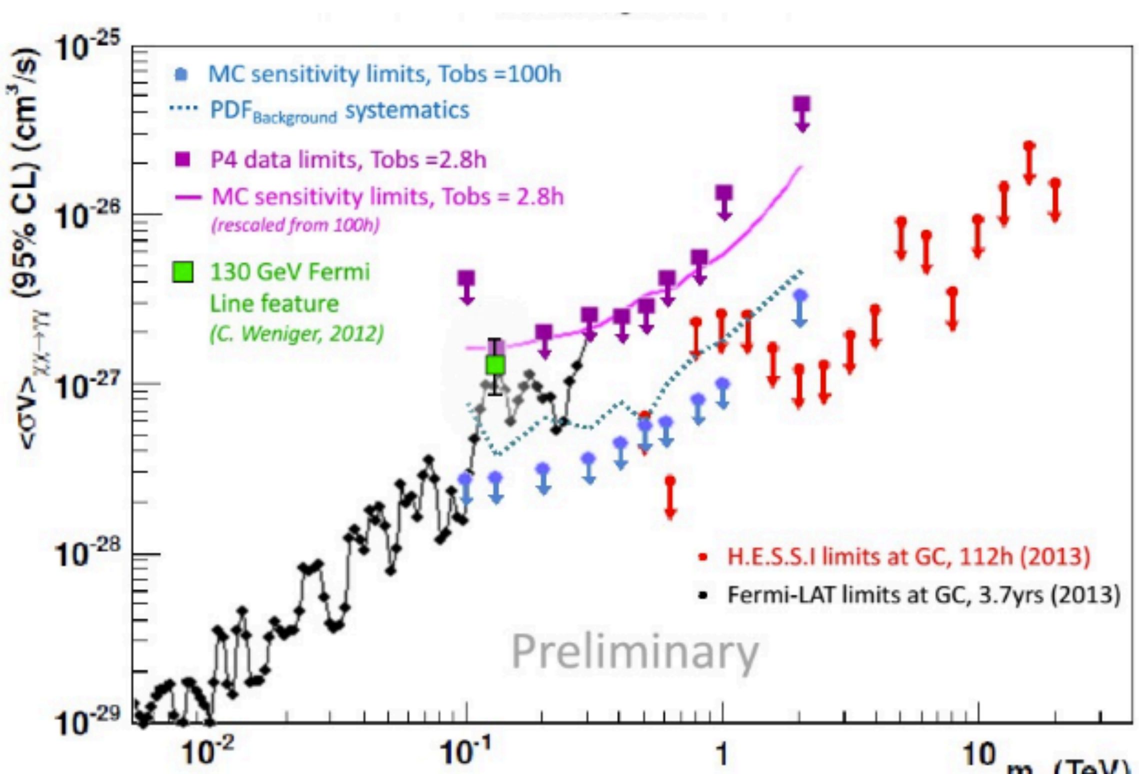
- Complementary with DD (CA, G.Bertone and H. Silverwood, arXiv:1304.5119)

Indirect Detection status

strongest bound from non observation of gamma rays from dwarf galaxies







Kieffer+, HESS coll. ICRC 2015

Future generation ID probes:

- Cherenkov Telescope Array
- Pingu/KM3Net
- GAPS for anti-deuteron
- ...

MadDM & indirect detection

Led by Mihailo

- NLO calculations for a generic dark matter models to produce (gamma/Z/h/neutrino) lines: fully automated

- Compute the energy spectrum of final DM annihilation products as a function of energy (Pythia)

- Compute expected flux: need to implement DM density distribution, line of sight integrals, ...

- For charged particles need of propagation models

- Solar physics for neutrinos from the Sun, one of the WIMP smoking gun signatures

- ....

Indirect detection: hands on astrophysics!
a lot of work to be done...

- Might be worth exploring complementarity with DM simplified models to reduce further available parameter space

DM activities at CP3

1. Seminars and meetings on DM

- CP3 seminar on wednesday: 1 per month seminar on DM (e.g. first scheduled October 14th, Marco Cirelli)
- Informal meeting every week (monday) to discuss projects and progress/results
- DM seminars at ULB and VUB

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2. Series of lectures on DM

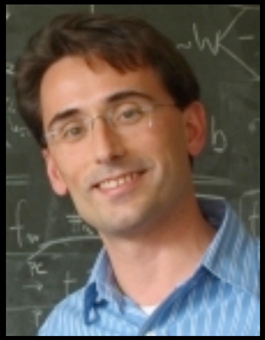
- Dark Matter I by Michel Tytgat (ULB) --- January 2016 (decouplings, freeze-out, WIMPs and beyond)
- Dark Matter II by Chiara Arina --- March 2016 (direct and indirect detection of dark matter)

Projects with ULB and VUB

VUB group	ULB group
▸ Project is supported by Steven Lowette	▸ Project is supported by Michel Tytgat
▸ Collaboration on the simplified models at LHC and complementarity with direct detection	▸ Collaboration on indirect detection of dark matter
▸ MadDM	▸ Collaboration on DM model building

Ideas for acronym focused on Dark Matter to identify the grant (and a logo)

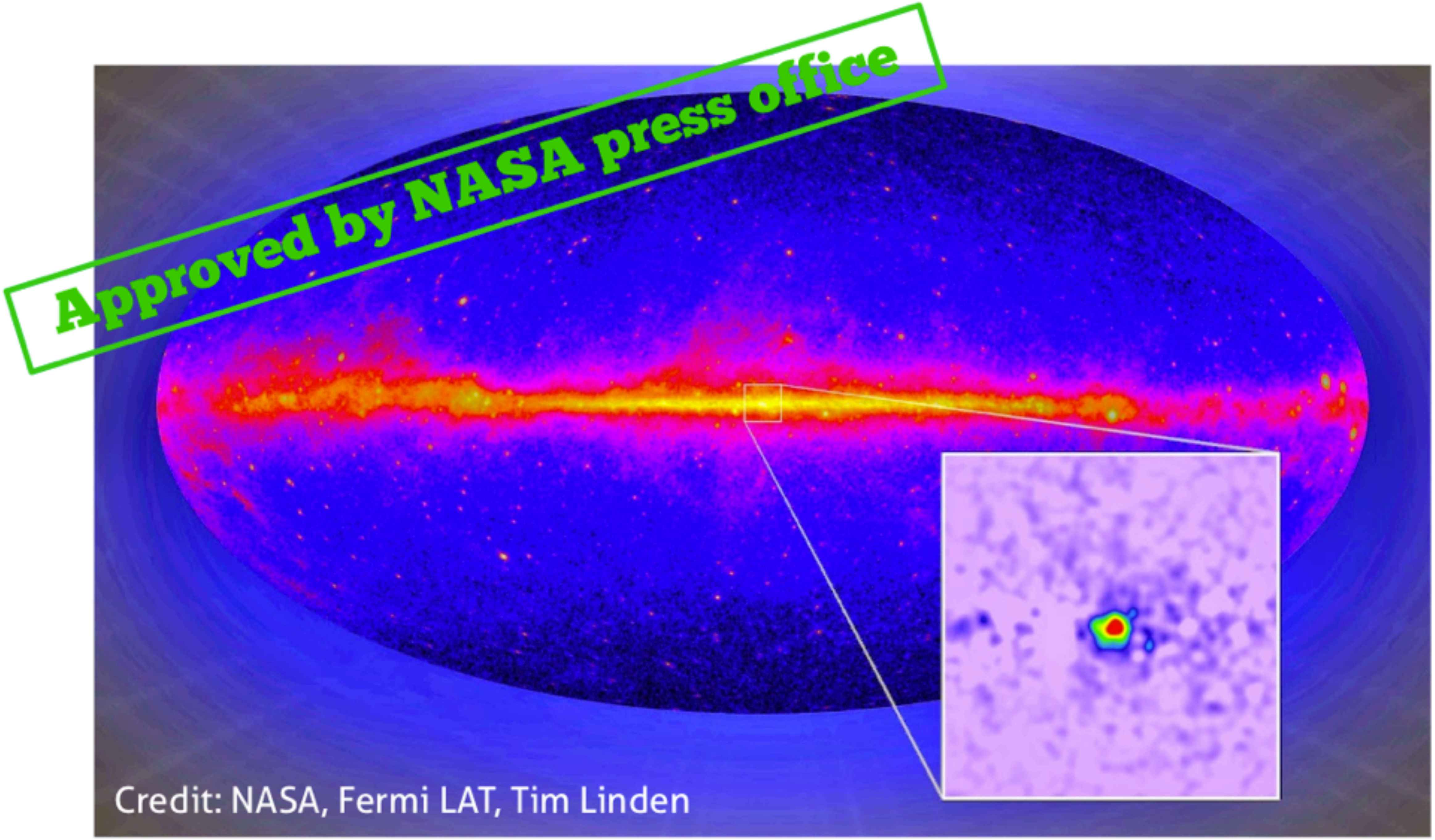
DM group at CP3



- Everyone who is interested in the DM topic and in the projects is welcome to JOIN!!
- More ideas and projects are WELCOME!

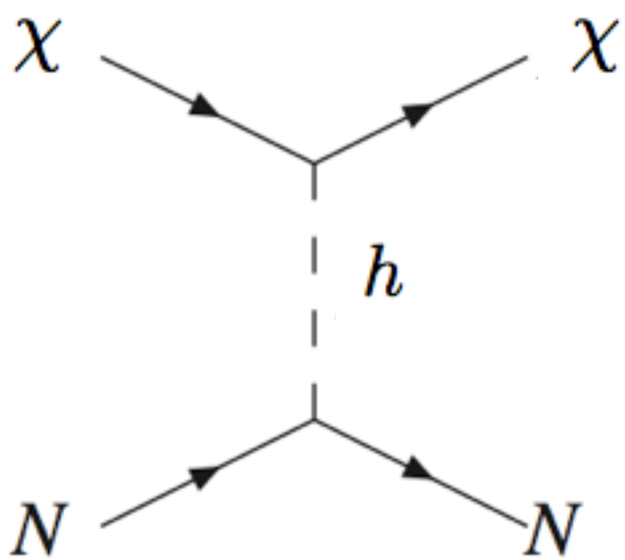
Back up slides

ID status: The Fermi Galactic center excess



Goodenough & Hooper 2009, Vitale+ (Fermi coll.) 2009, Hooper & Goodenough 2011, Hooper & Linden 2011, Boyarsky+ 2011 (no signal), Abazajian & Kaplinghat 2012, Hooper & Slatyer 2013, Huang+ 2013, Gordon & Macias 2013, Macias & Gordon 2014, Zhou+ 2014, Abazajian+ 2014, Daylan+2014, Calore+ 2014, Gaggero+ 2015

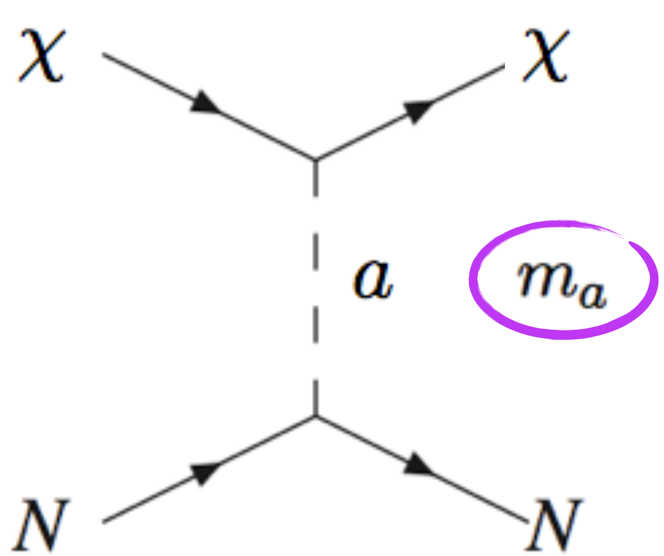
Changing the DM-nucleus interaction



Scalar SI comes from e.g. interaction with Higgs:

$$\mathscr{L}_{\rm int} = -\frac{y_{\rm DM}}{\sqrt{2}} h\bar{\chi}\chi - \sum_f \frac{y_f}{\sqrt{2}} h\bar{f}f$$

$f_n \sim f_p$



Pseudo-scalar interaction (Coy DM):

$$\mathscr{L}_{\rm int} = -i\frac{g_{\rm DM}}{\sqrt{2}} a\bar{\chi}\gamma_5\chi - ig\sum_q \frac{g_q}{\sqrt{2}} a\bar{q}\gamma_5 q$$

1. Flavor-Universal couplings: $g_q = 1$
2. Higgs-like: $g_q = \frac{m_q}{174\,\mathrm{GeV}}$

3 free parameters

Coy DM effective operator I

$$\mathscr{L}_{\rm int} = -i\frac{g_{\rm DM}}{\sqrt{2}} a\bar{\chi}\gamma_5\chi - ig\sum_q \frac{g_q}{\sqrt{2}} a\bar{q}\gamma_5 q$$

effective contact operator
($v_{DM} \sim 10^{-3}$ c)

$$\mathscr{L}_{\rm eff} = \frac{1}{2\Lambda_a^2}\sum_{N=p,n} g_N\, \bar{\chi}\gamma^5\chi\, \bar{N}\gamma^5 N \qquad \Lambda_a \equiv \frac{m_a}{\sqrt{g_{\rm DM}\, g}}$$

- The energy scale is the unknown variable instead of the cross-section
- The coefficients g_N are defined to be

$$g_N = \sum_{q=u,d,s} \frac{m_N}{m_q}\left[g_q - \sum_{q'=u,\dots,t} g_{q'}\frac{\bar{m}}{m_{q'}}\right]\Delta_q^{(N)}$$

Flavor-Universal couplings: $g_p/g_n = -16.4$

Higgs-like: $g_p/g_n = -4.1$

NATURAL violation of isospin

Coy DM effective operator II

$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_\mathrm{R}} = \frac{1}{128\pi}\frac{q^4}{\Lambda_a^4}\frac{m_T}{m_\mathrm{DM}^2 m_N^2}\frac{1}{v^2}\sum_{N,N'=p,n} g_N g_{N'} F_{\Sigma''}^{(N,N')}(q^2)$$

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- This interaction is SPIN-DEPENDENT (SD) as it comes from this non-relativistic operator:

$$\mathcal{O}_6^{\rm NR} = (\vec{s}_\chi \cdot \vec{q})(\vec{s}_N \cdot \vec{q})$$

- DAMA: Iodine (Sodium) has an unpaired proton
- LUX: Xenon has an unpaired neutron
- Natural isospin violation implies an strong suppression/enhancement to DM scattering

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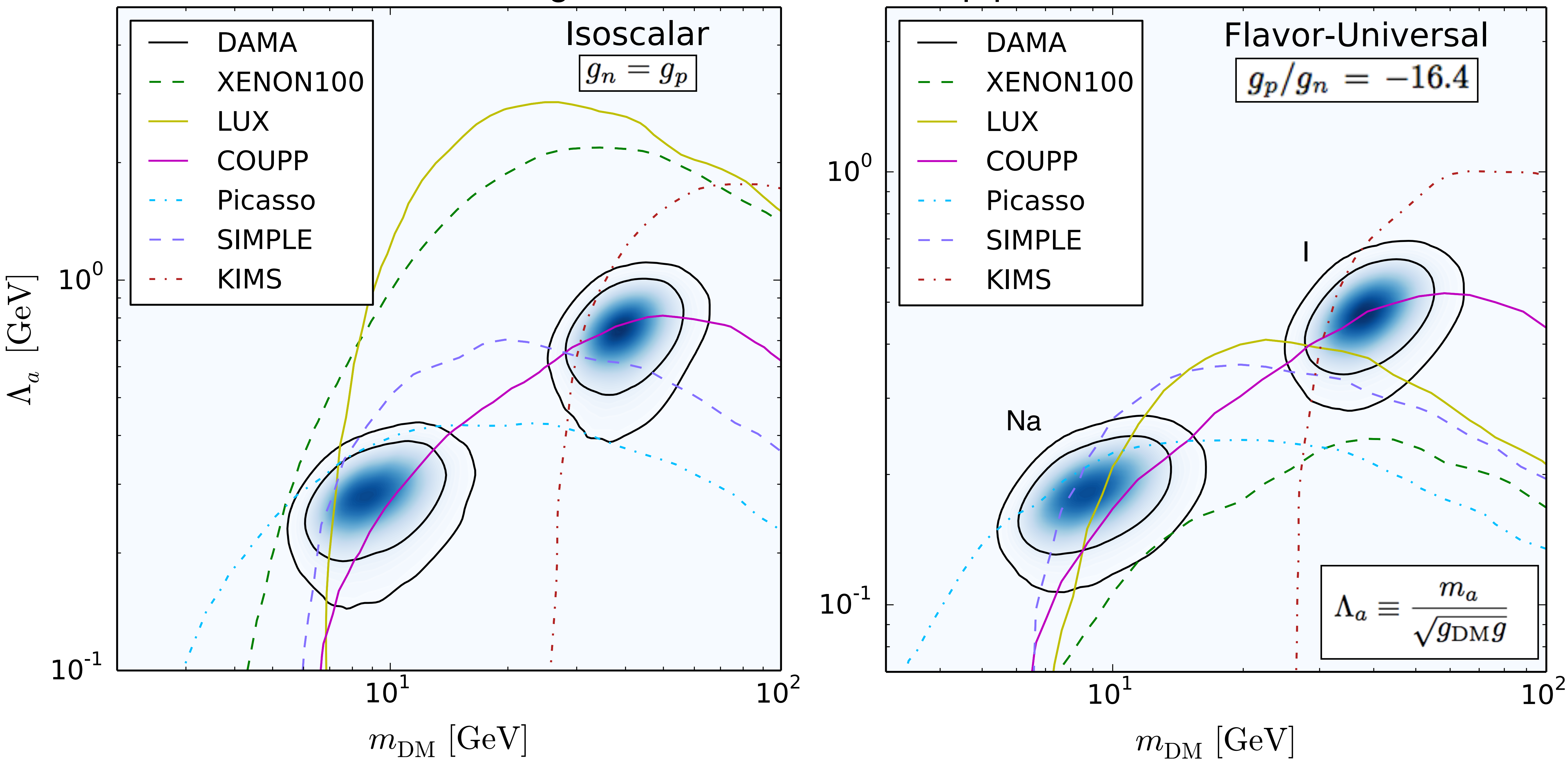
Nuclear form factor:

- Source of uncertainties (number of event can change by a factor ~ 3 for standard SD)
- use of the correct form factor (computed in Fitzpatrick et al. arXiv:1203.3542)

Direct detection of Coy DM

marginalized on astro and exp parameters



$g\, g_q \sim 10^{-3}$-10^{-2}	$m_a \sim$ 35-60 MeV
$g_{DM} \sim$ 0.5-0.8	$m_{DM} \sim$ 20 - 35 GeV