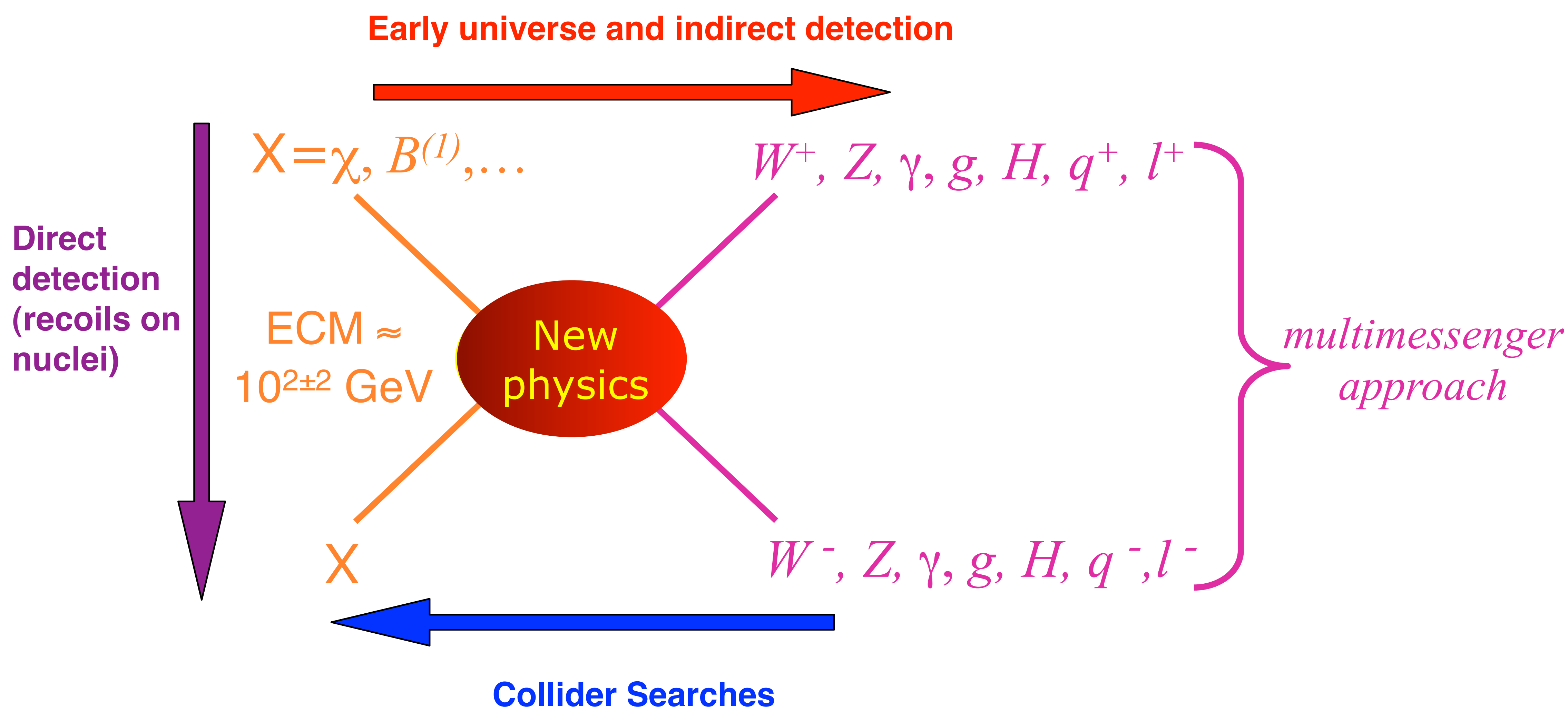
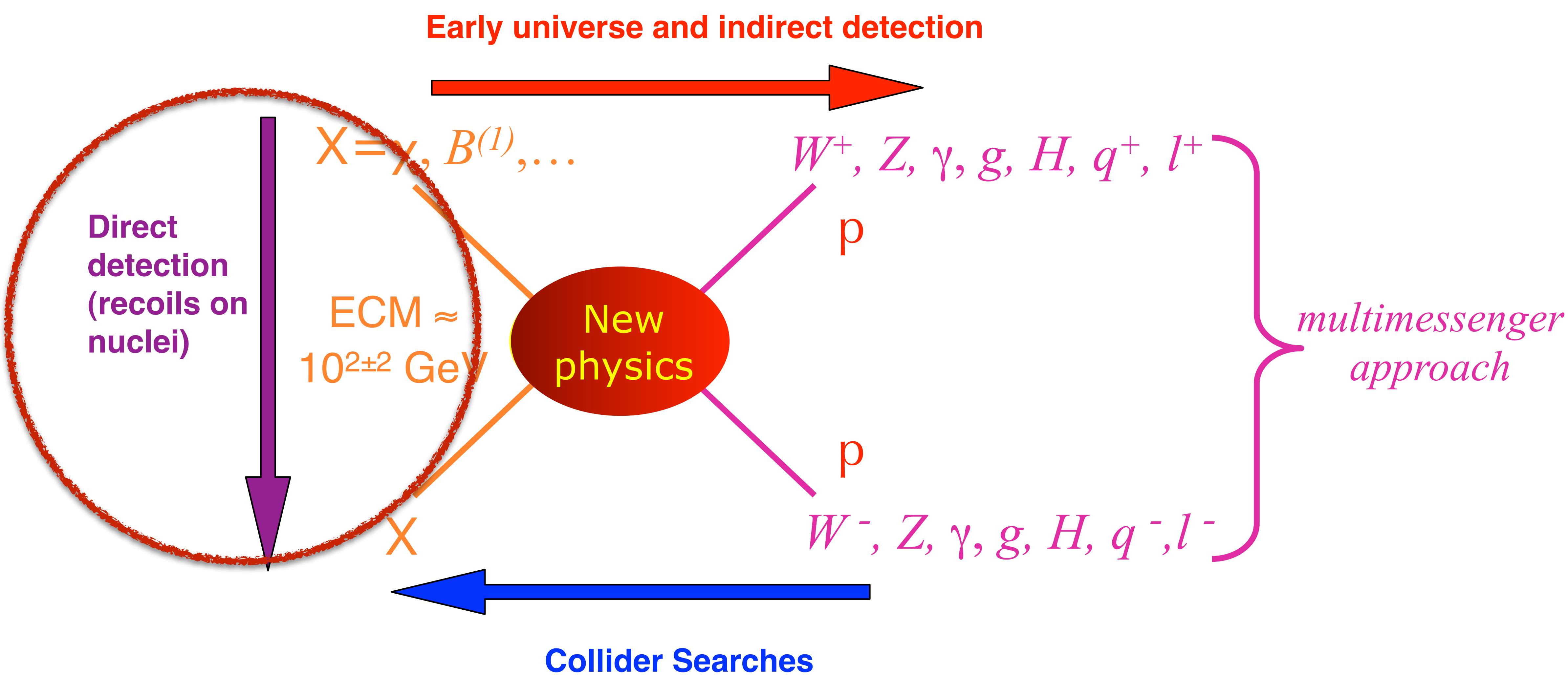
Dark Matter
The (WIMP) hunt

Dark Matter Strategies



Note: I focus here on **WIMPs**:

$10^{2\pm2}$ GeV mass particle interacting with 'weak' like cross sections


Early universe and indirect detection
X=χ, B(1),…
Direct detection (recoils on nuclei)
ECM ≈ 10^2±2 GeV
New physics
W+, Z, γ, g, H, q+, l+
p
p
W-, Z, γ, g, H, q-, l-
multimessenger approach
X
Collider Searches

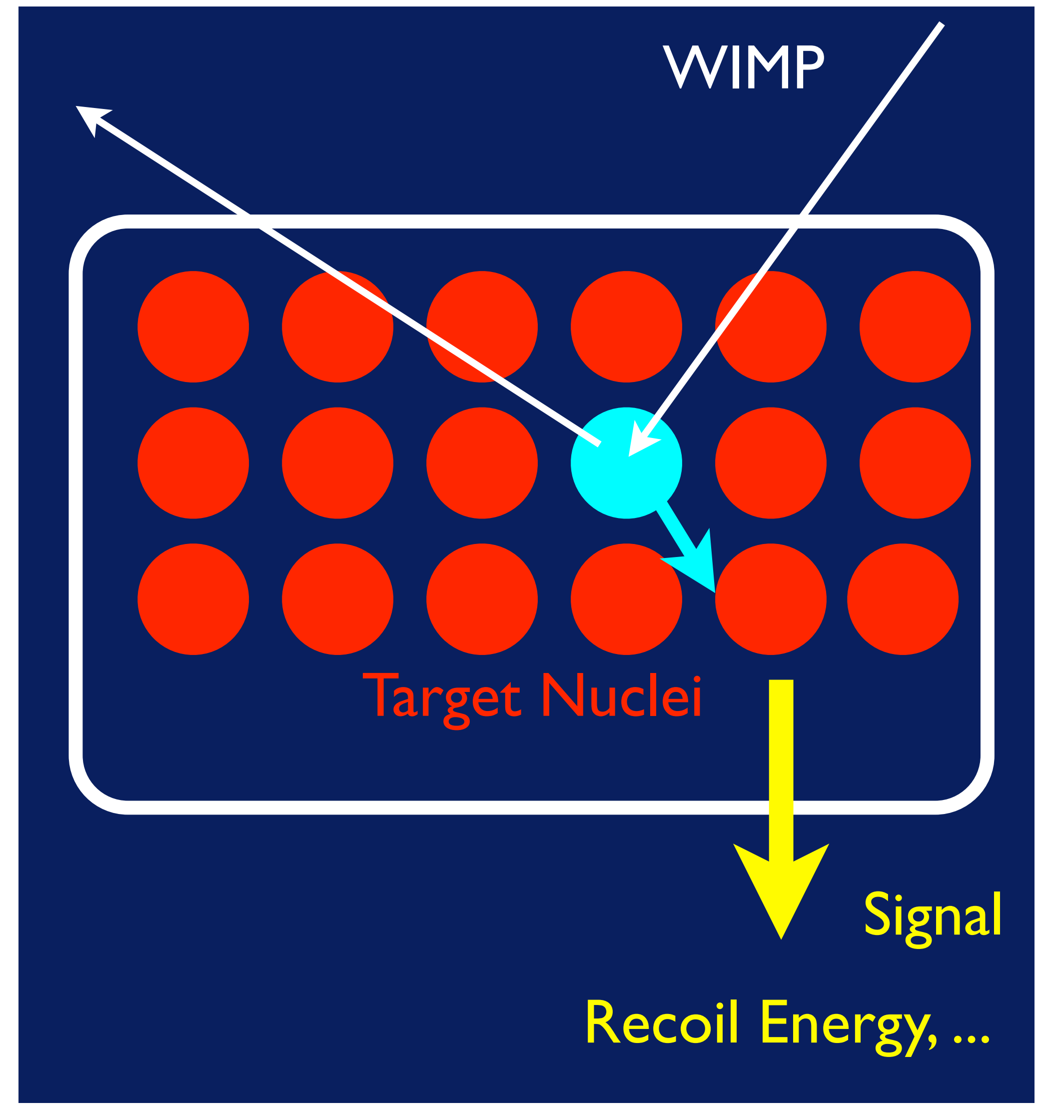
Dark Matter
Direct detection

The basic strategy of direct detection is to look for the low energy recoil of a heavy nucleus when a WIMP hits it.

as simple as that ....

Next few slides:

1. theoretical expectations for a signal
2. challenges -> backgrounds!



Theory:

velocity distribution of DM

$$\frac{dR}{dE_R} = N_T n_X \int_{v_{min}}^{v_{esc}} d\vec{v}\ |\vec{v}| f(\vec{v}) g(\vec{v}) \frac{d\sigma_{XA}}{dE_R},$$

Number of target nuclei
(mass of the detector, A)

scattering cross section with a nucleus of mass A

$n_X = \dfrac{\rho_0}{m_\chi}$ = 0.4 GeV/cm^3/m_x

Number of DM particles

Theory:

$$\frac{dR}{dE_R} = N_T \; n_X \int_{v_{min}}^{v_{esc}} d\vec{v} \; |\vec{v}| \; f(\vec{v}) \; g(\vec{v}) \frac{d\sigma_{XA}}{dE_R},$$

- **f(v): velocity distribution** of DM

Often a truncated Maxwellian distribution is assumed:

$$f_{\rm gal}(\vec{v}) \approx \begin{cases} N \exp\left(-v^2/\bar{v}^2\right) & v < v_{\rm esc} \\ 0 & v > v_{\rm esc} \end{cases}$$

$$\bar{v} \simeq 220\,\mathrm{km/s} \qquad v_{\rm esc} \simeq 550\,\mathrm{km/s}$$

(corresponds to an iso-thermal sphere)

Theory:

$$\frac{dR}{dE_R} = N_T\ n_X \int_{v_{min}}^{v_{esc}} d\vec{v}\ |\vec{v}|\ f(\vec{v})\ g(\vec{v}) \frac{d\sigma_{XA}}{dE_R},$$

cross section with a nuclei A:

- for **spin independent interactions** and the same for protons and neutrons, the low energy scattering amplitude from a nucleus with mass number A is a coherent sum of A single nucleon scattering amplitudes.

$$\frac{\sigma_{XA}^{SI}}{\sigma_{Xp}^{SI}} = \left(\frac{\mu(A)}{\mu(p)}\right)^2\ A^2$$

also depends on the reduced mass, through the phase space.

$$\mu = \frac{M_A M_B}{M_A + M_B}$$

- for **spin dependent** interactions the scattering amplitude changes sign with the spin orientation. Paired nucleons therefore contribute zero to the scattering amplitude

$$\frac{\sigma_{XA}^{SD}}{\sigma_{Xp}^{SD}} = \left(\frac{\mu(A)}{\mu(p)}\right)^2 \frac{[\lambda^2 J(J+1)]_A}{[\lambda^2 J(J+1)]_p} \left(\frac{C_{XA}}{C_{Xp}}\right)^2$$

➡ There is no A^2 enhancement in this case! **Limits typically weaker.**

Theory:

$$\frac{dR}{dE_R} = N_T\ n_X \int_{v_{min}}^{v_{esc}} d\vec{v}\ |\vec{v}|\ f(\vec{v})\ g(\vec{v}) \frac{d\sigma_{XA}}{dE_R},$$

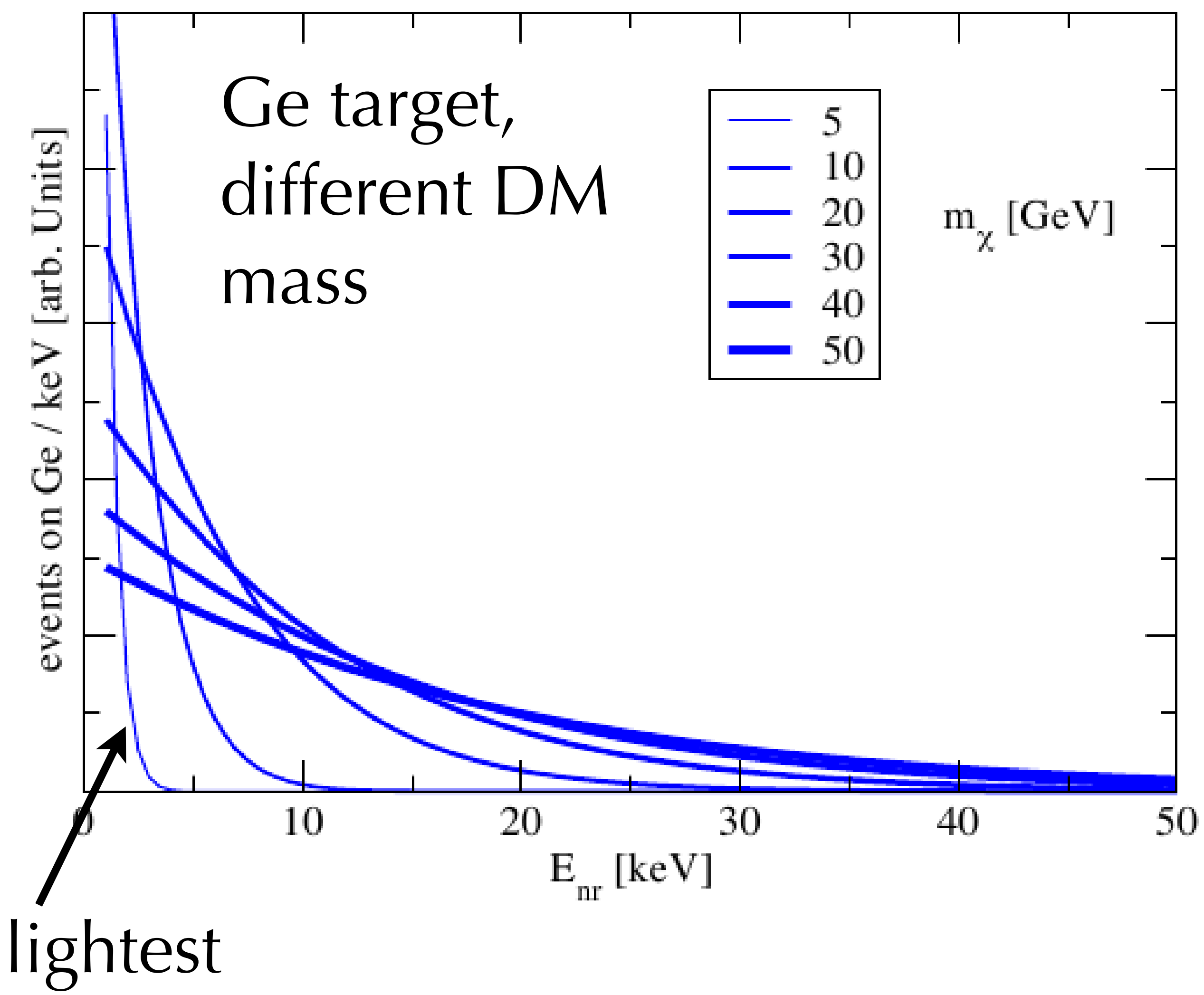
- **recoil energy and vmin**: depends on the mass of DM and target nucleus and DM velocity

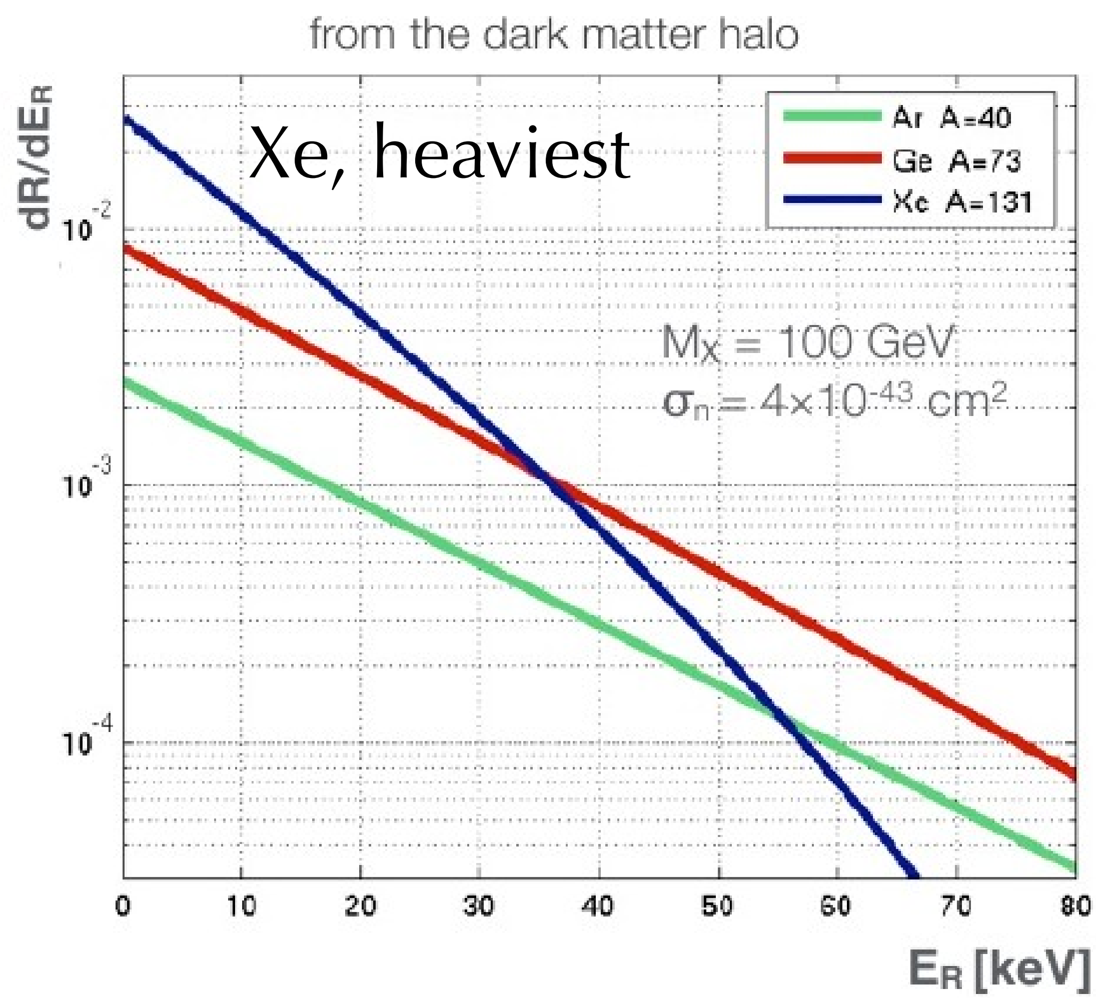
$$E_R = \frac{4m_A\ m_X}{(m_A + m_X)^2}(\frac{1}{2}m_X v_X^2)\left(\frac{1 - \cos\theta_{CM}}{2}\right)$$

Each detector has an energy threshold -> **there exist a min velocity which ca produce an observable recoil!** Example: A = 16, m = 1 GeV and an energy threshold of 600 eV, the minimal DM velocity to produce a detectable recoil is vmin = 680 km/s.

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

WIMP Recoil Spectra





→expect different rates for different targets (cross checks!)

→rate scales with A^2 → heaviert targets favored (for scalar couplings)

→ spectrum rises exponentially → low detector threshold desired

→ low-mass WIMPs → lighter target and/or low threshold necessary

from Schumann, M., 2013.

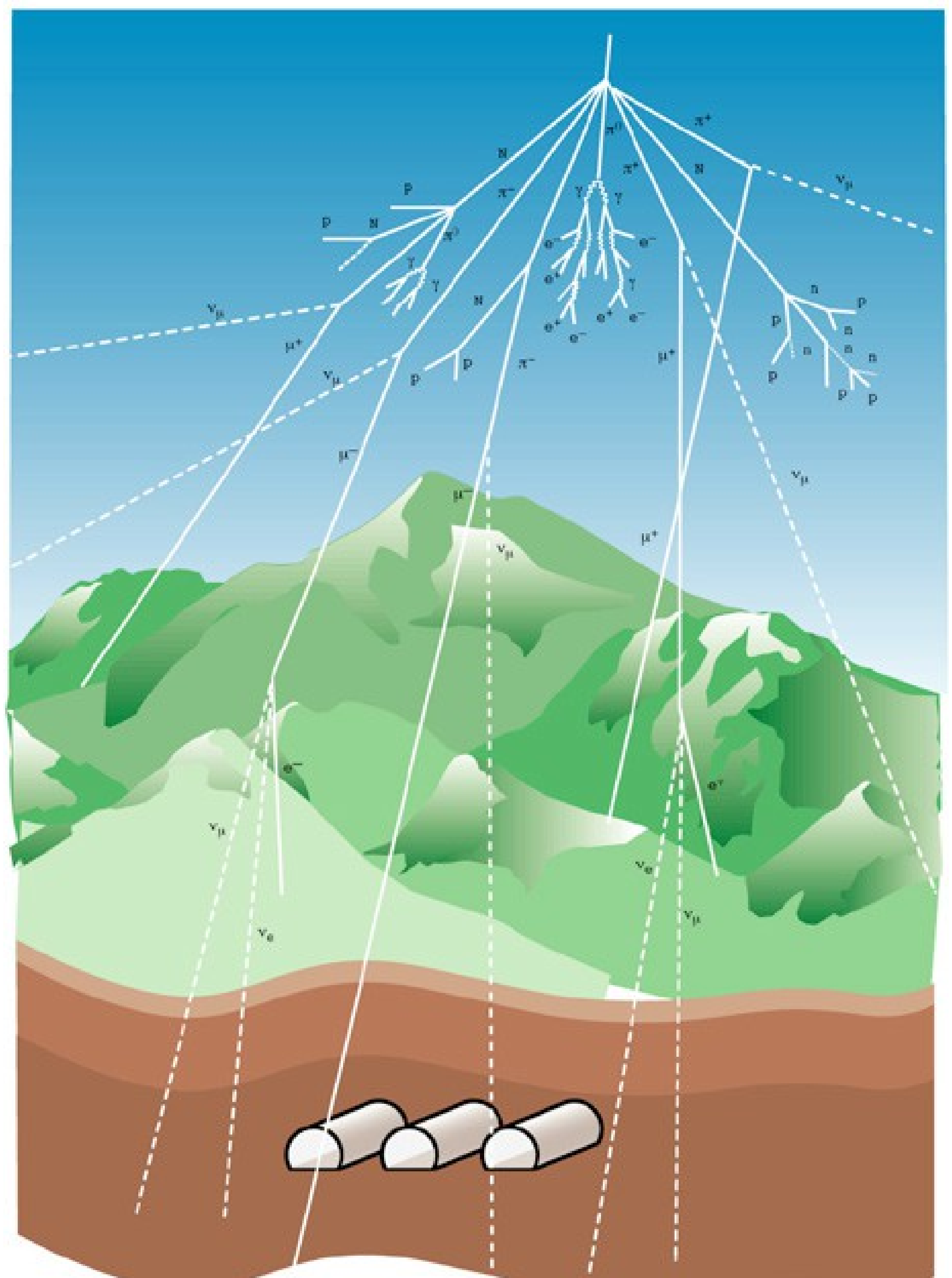
Expected rates: <0.1 events /kg/day!

Natural radioactivity: 1 banana ~1M decays/day

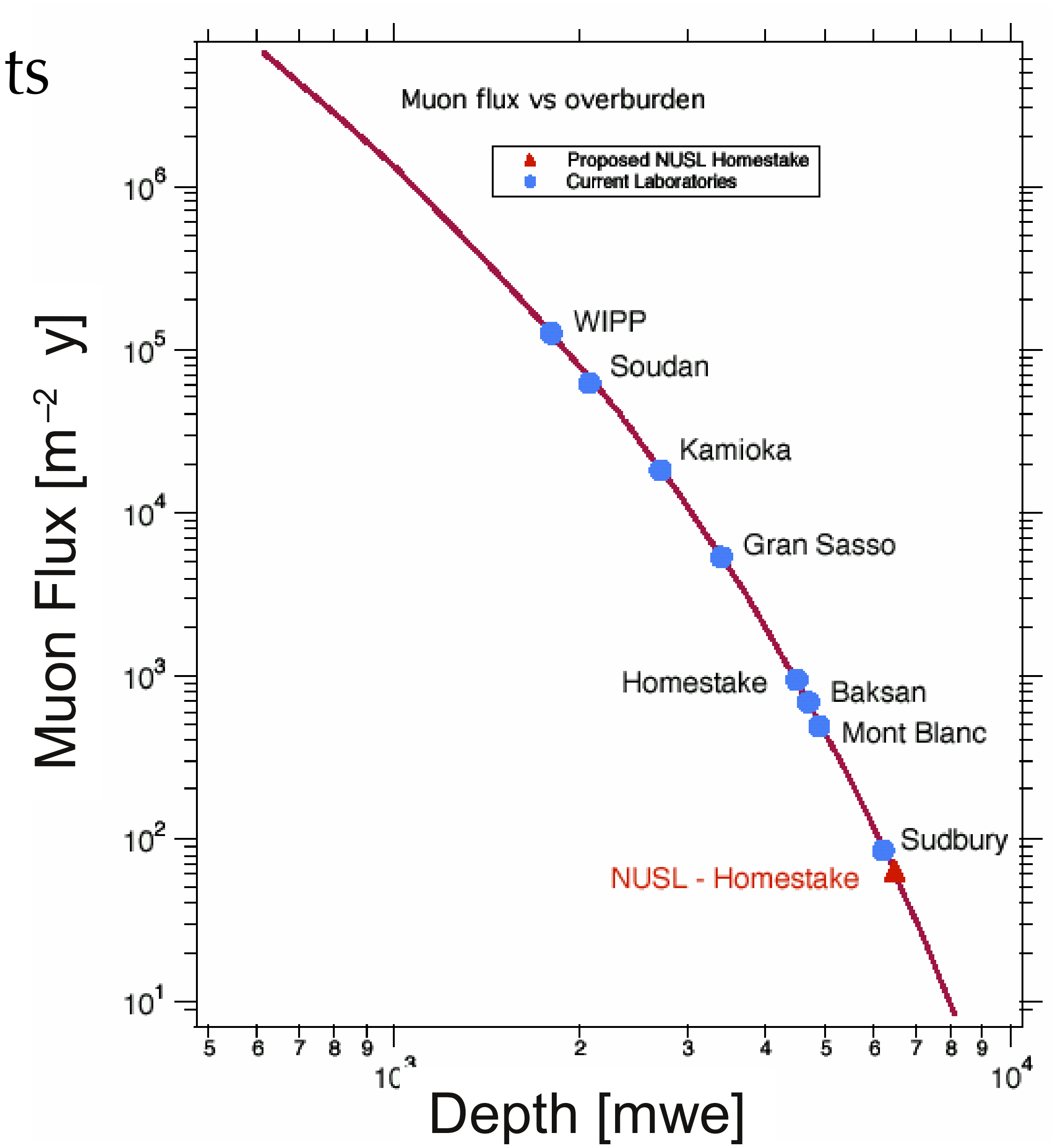
Backgrounds: electrons, neutrons, neutrinos: from cosmic rays and natural radioactivity!

Strategy 01: go deep! (get as much shielding as possible) -

'location, location, location!' J. Collar

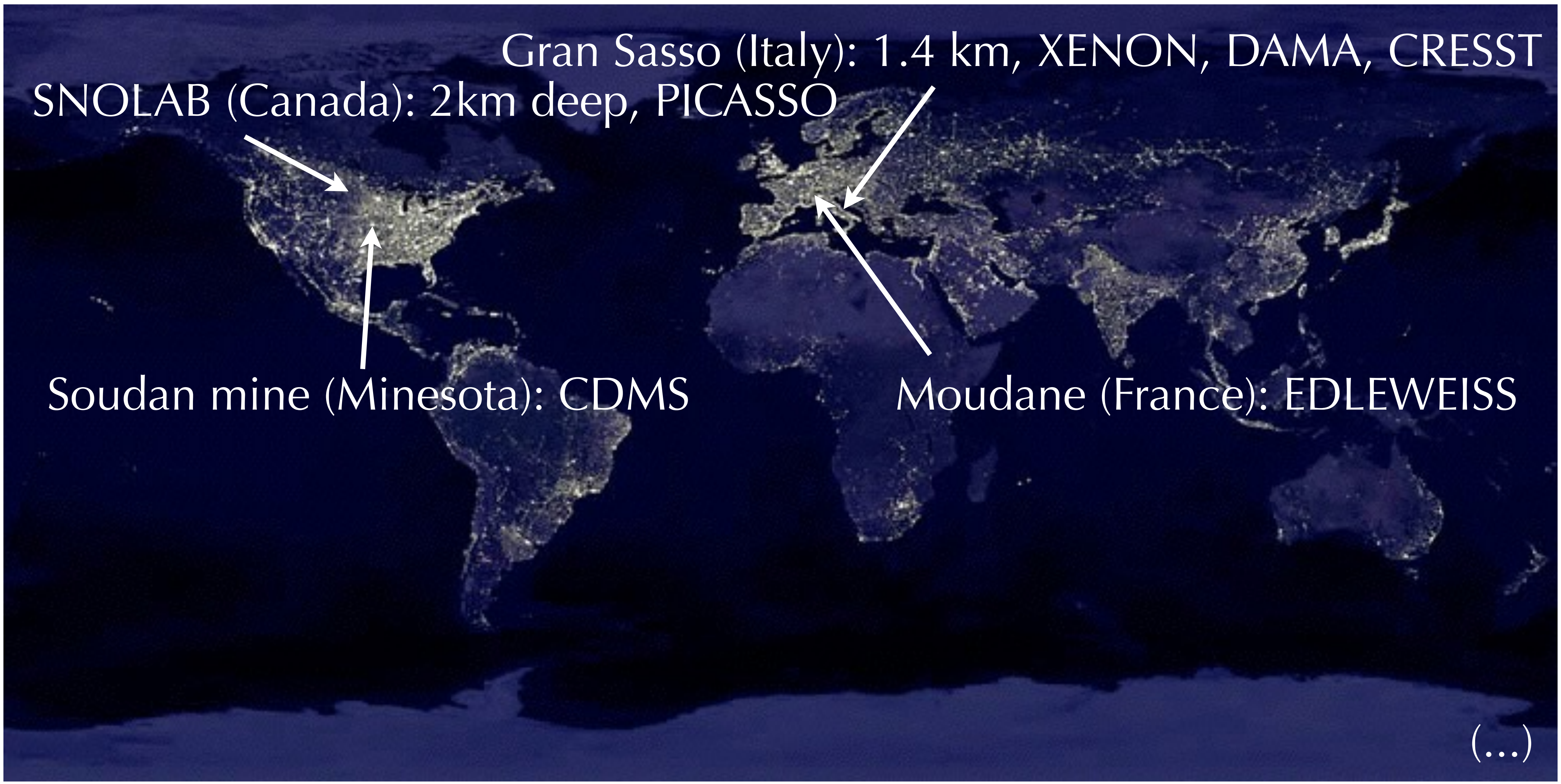


experiments located ~>1km deep



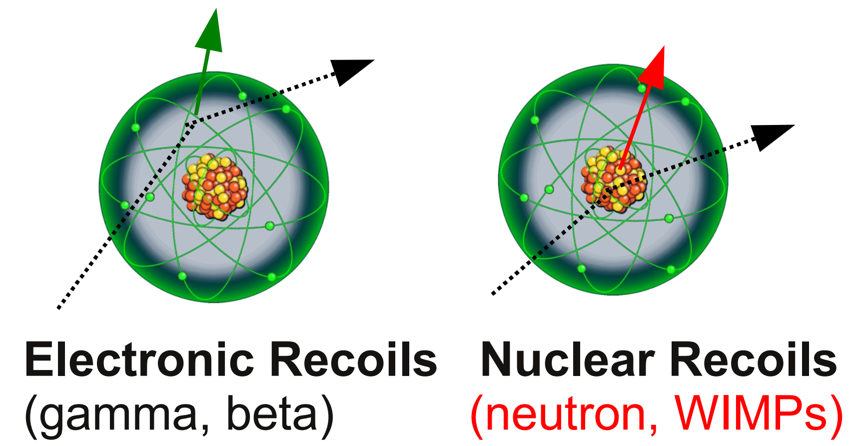
Strategy 01: go deep! (get as much shielding as possible)

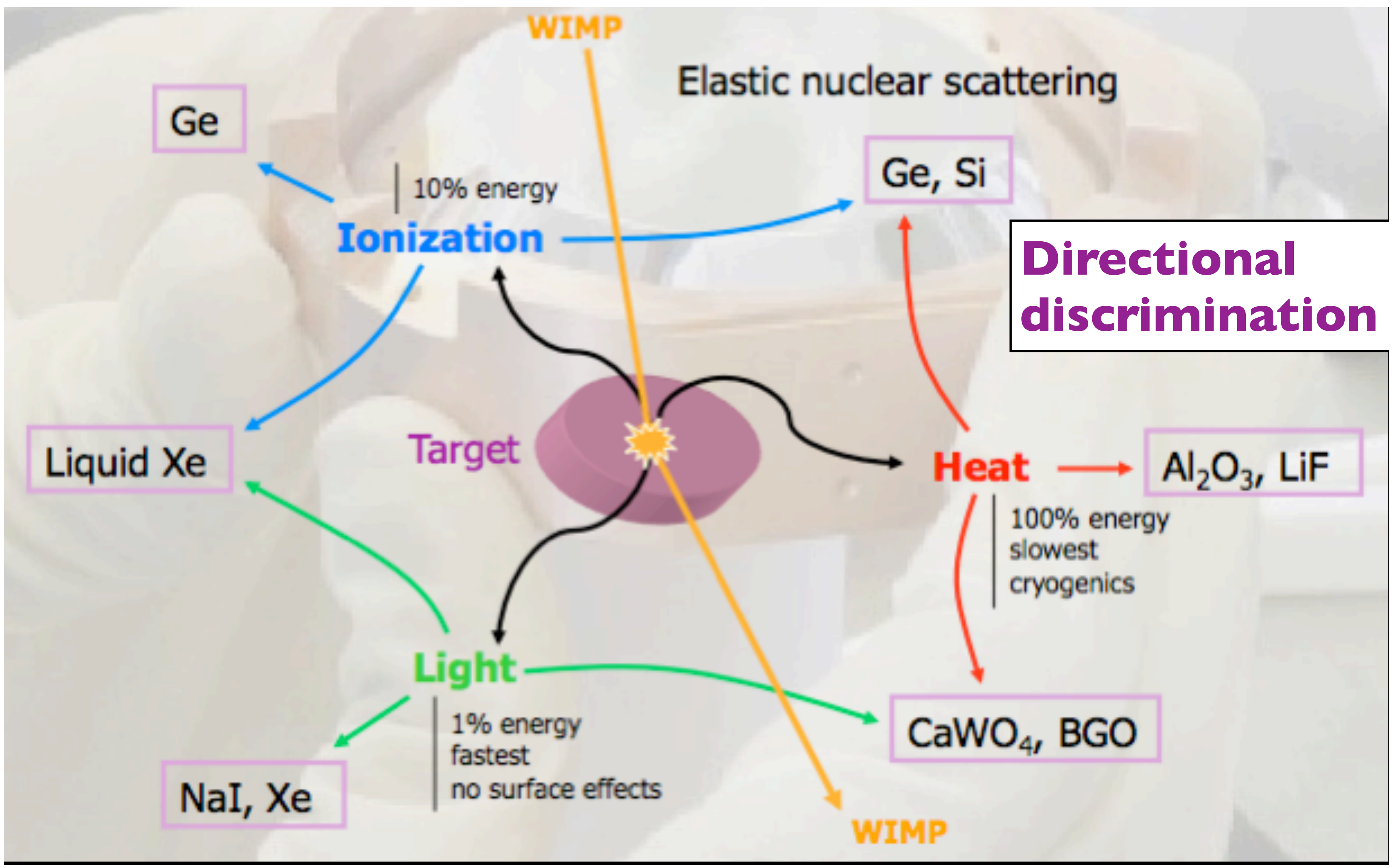
Several current labs:

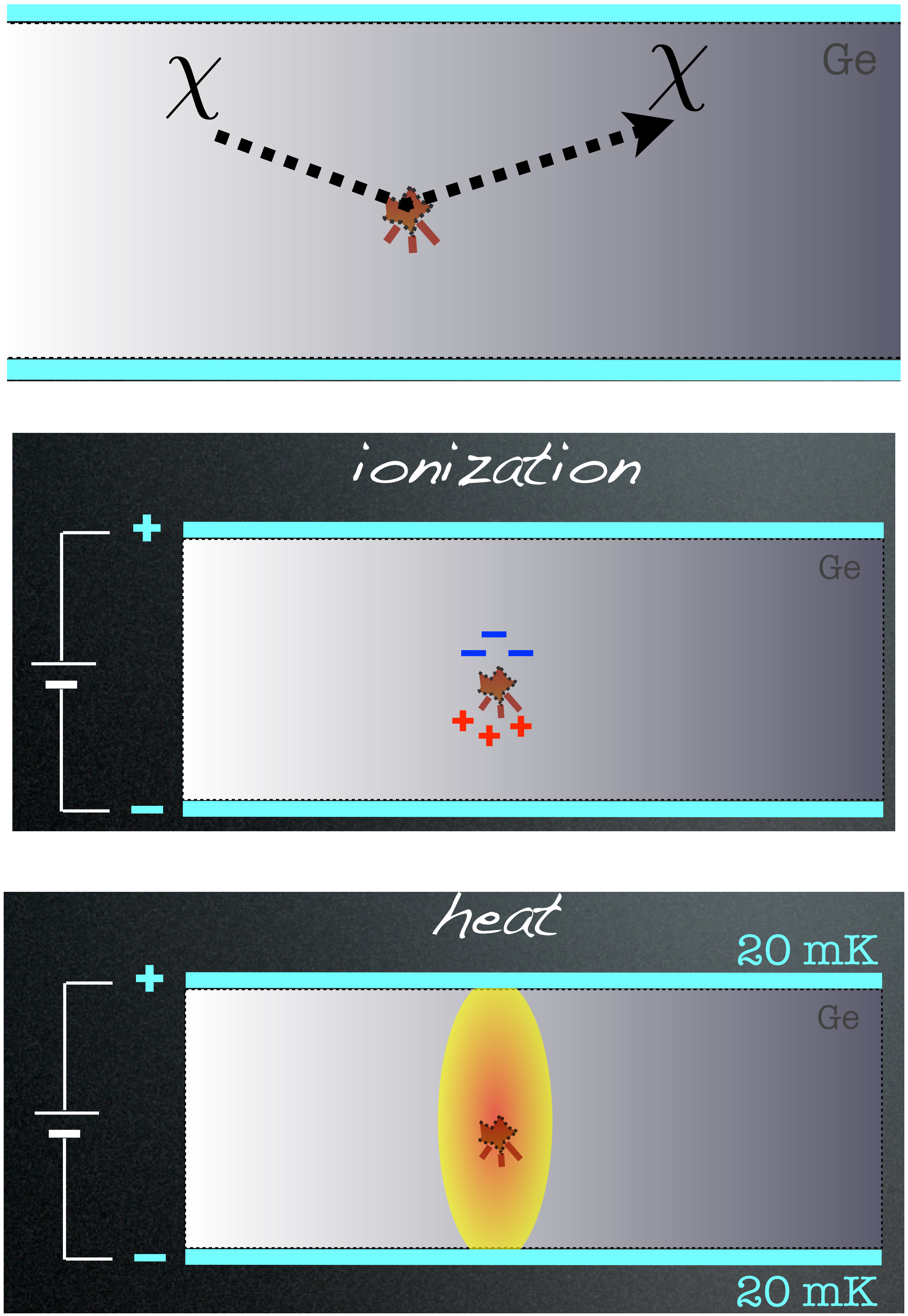


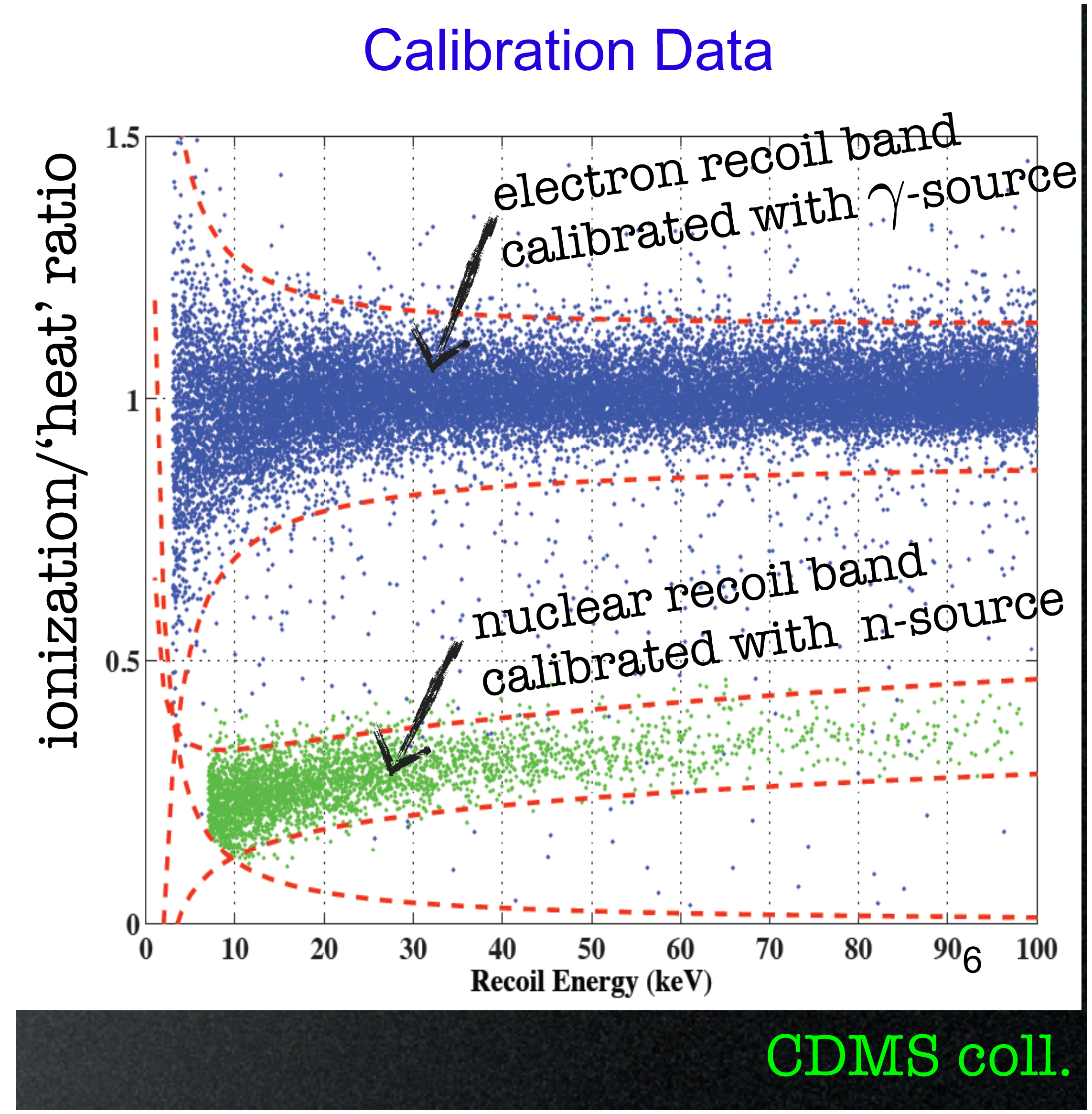
Strategy 02: use double handle! measure two signals to discriminate signal from background, on event-by-event basis.

- WIMPs (and neutrons) scatter off nuclei
- γ and β backgrounds scatter off electrons
- energy loss process different for these two types of recoil



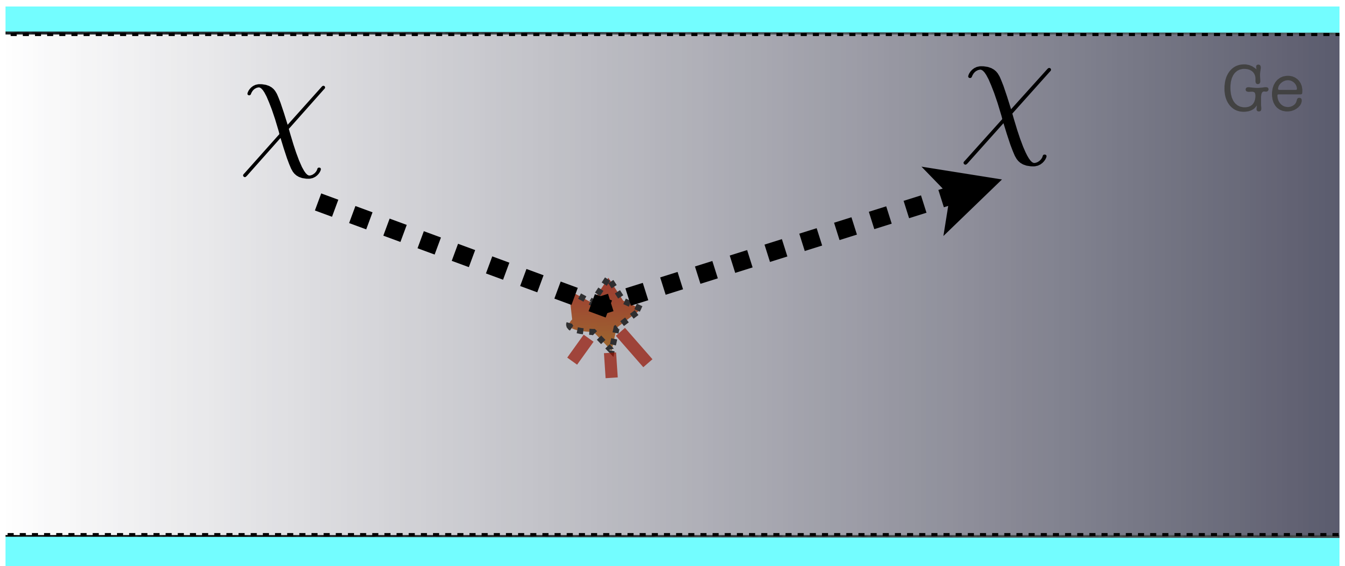


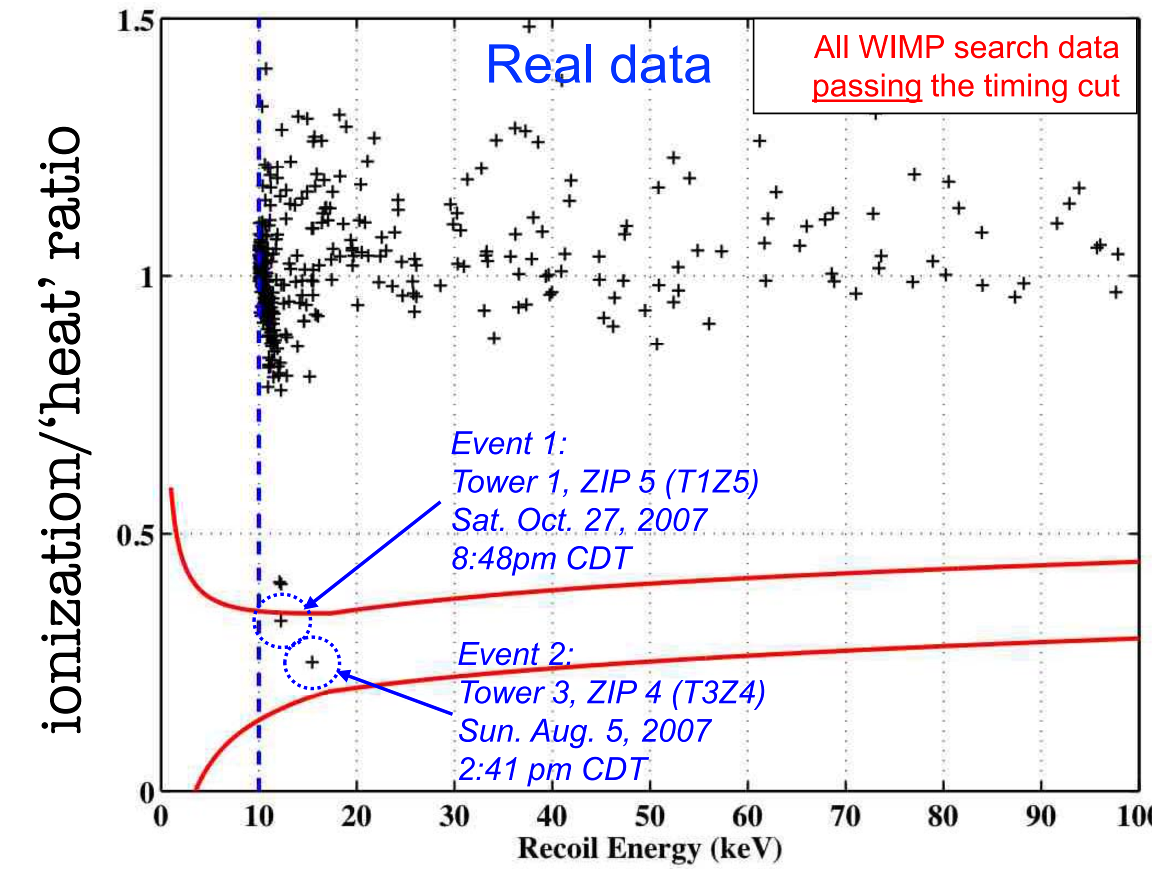


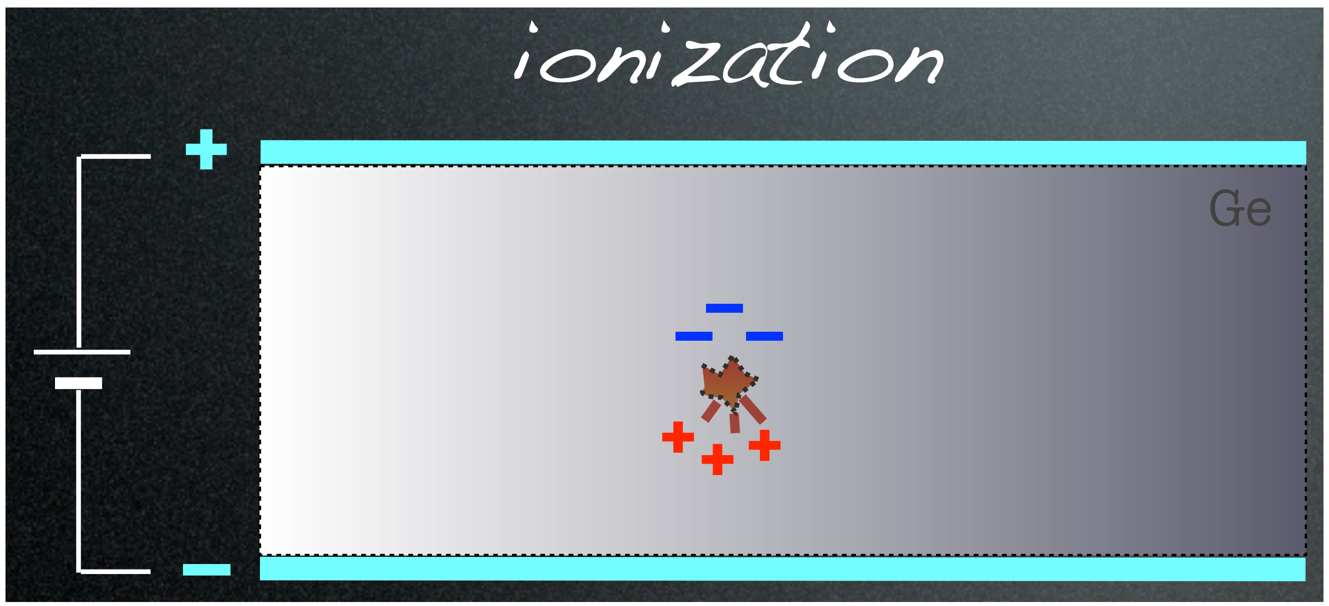


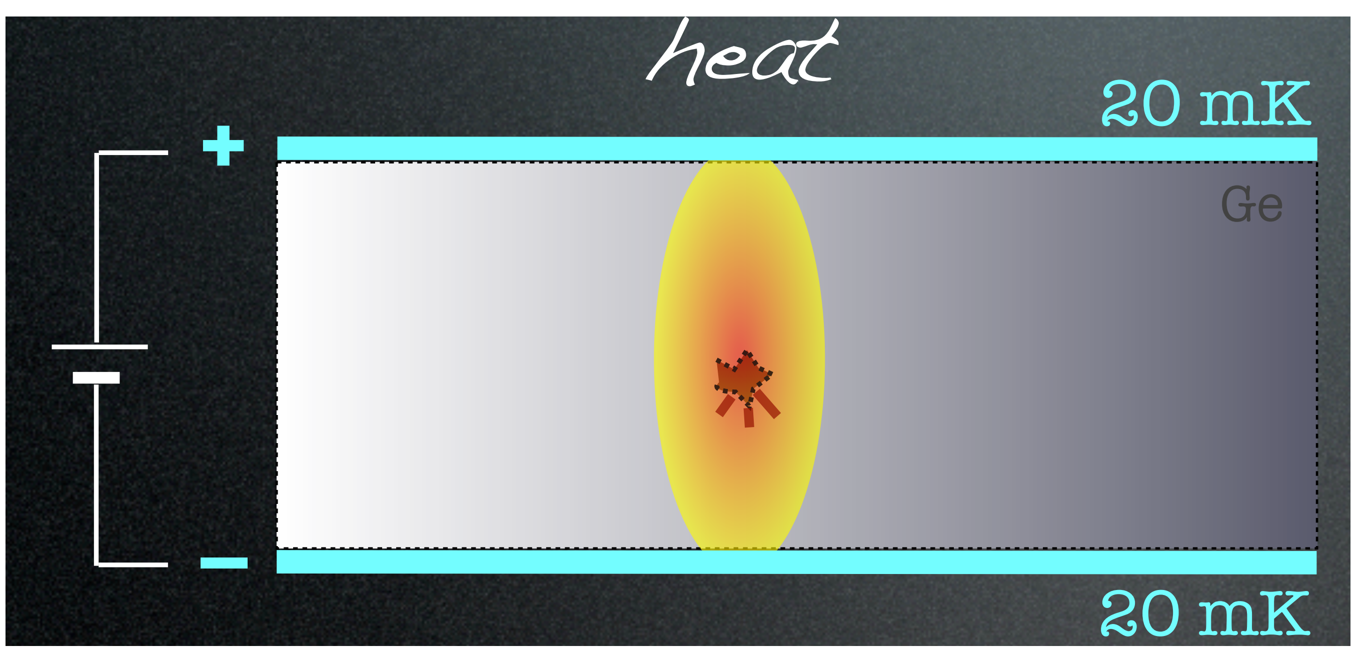
Single scatter interactions from neutrons cannot be distinguished from WIMP signals. Controlling Neutrons:

- go deep
- run simulations
- Use Event Topology (n might double scatter)
- self shielding









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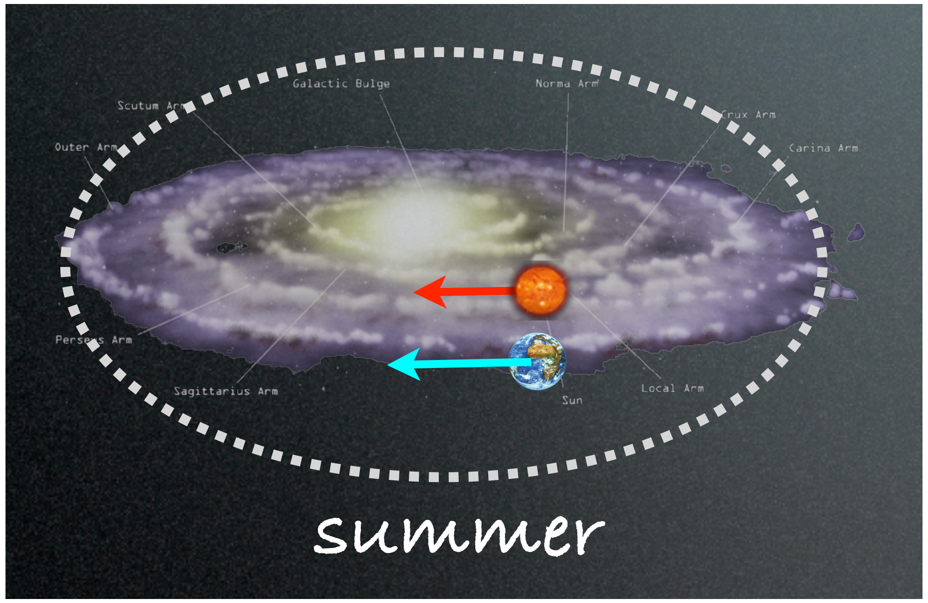
Strategy 03: or look for specific annual variations (characteristic for DM)!



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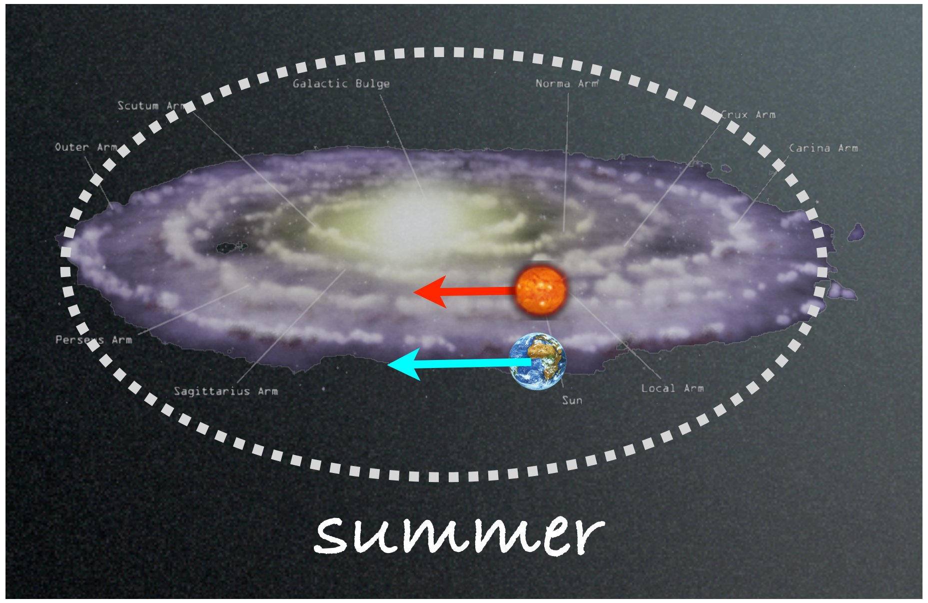

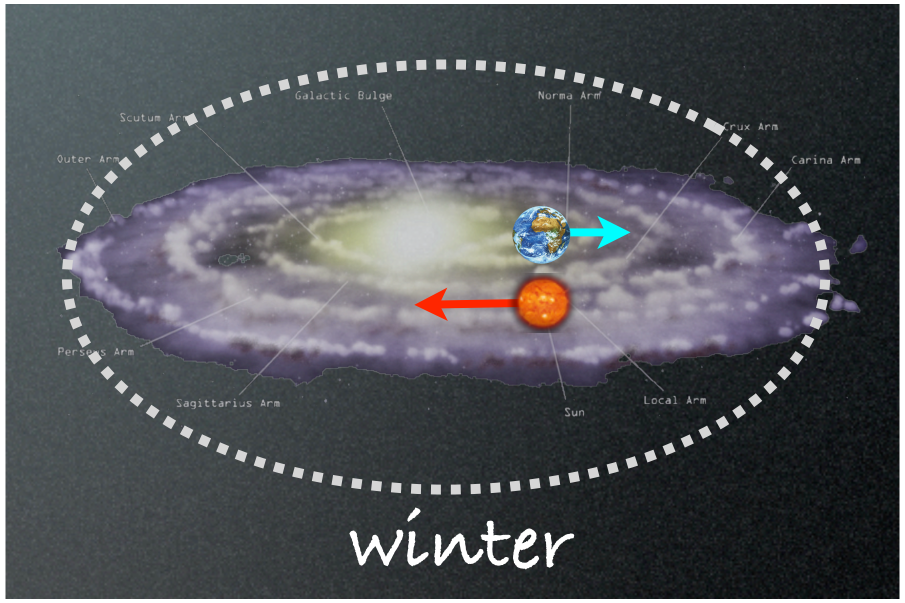

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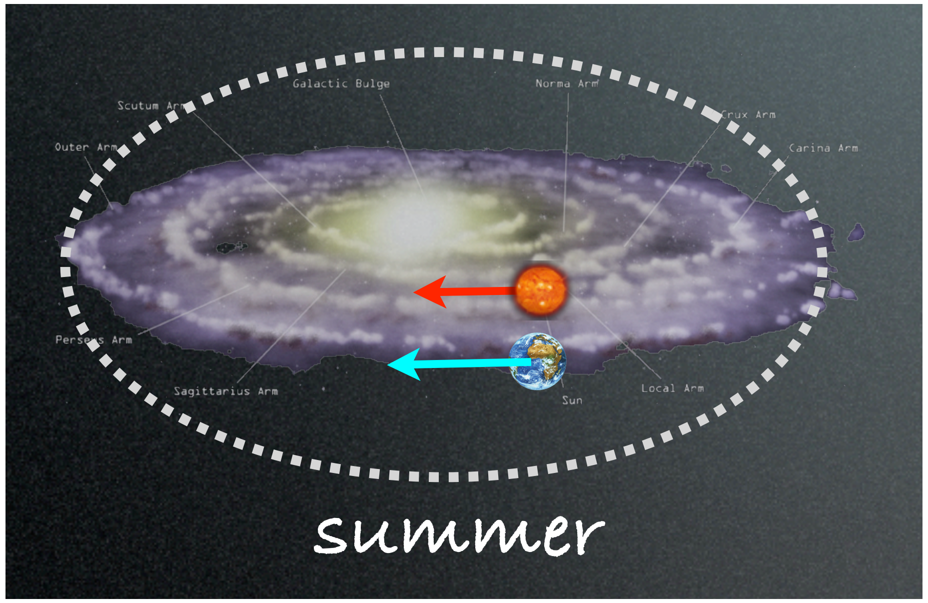
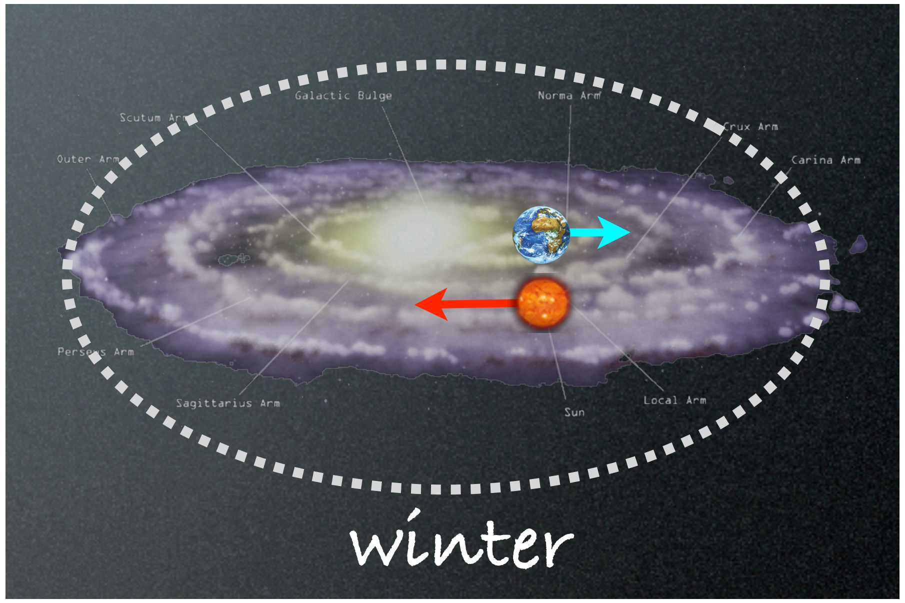
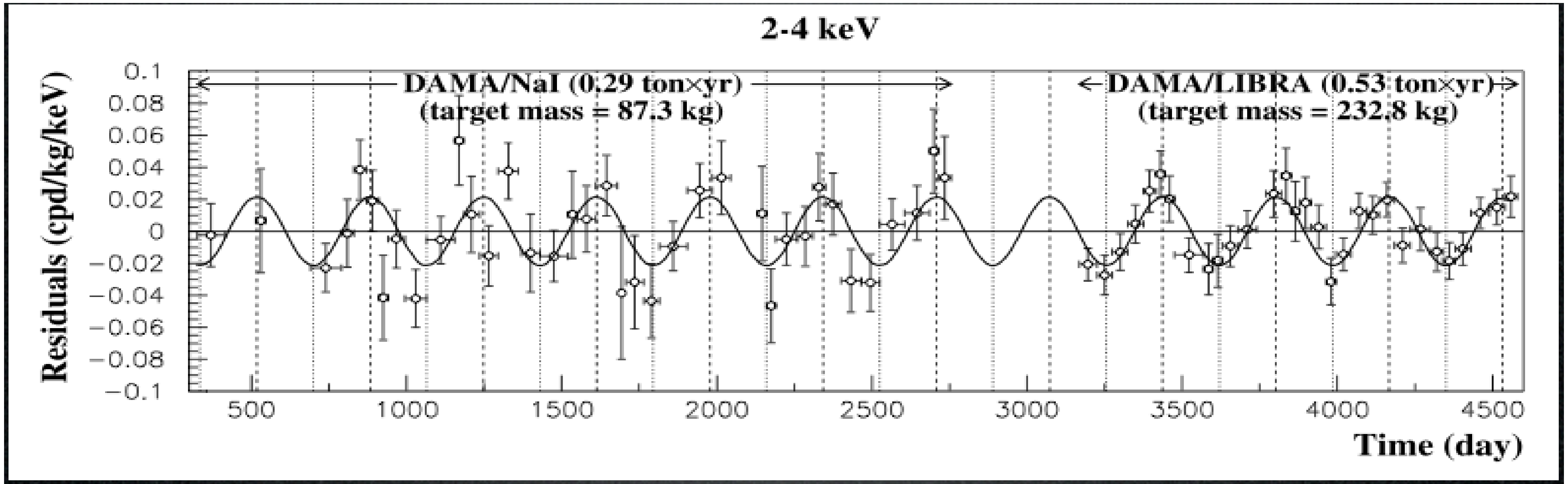






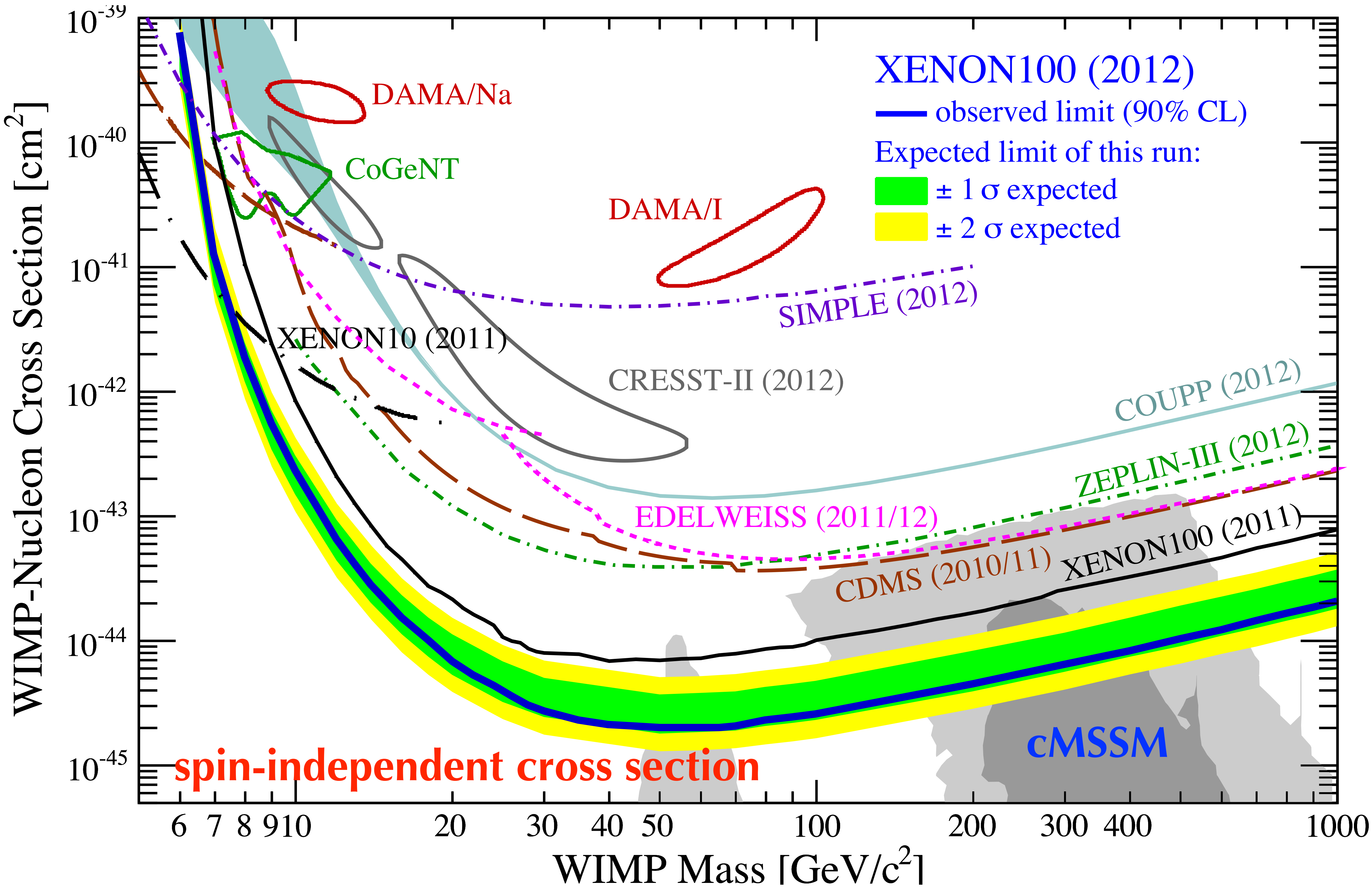
DAMA Coll., 0804.2741, 2008

DAMA collaboration actually observed a signal at >~10 sigma!

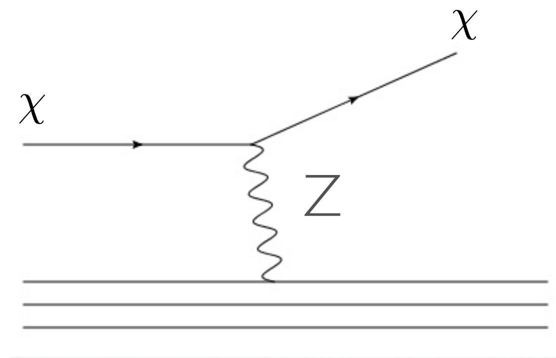
It, however, appears to be ruled out by other experiments.

The Status: many experiments constantly pushing the sensitivity!

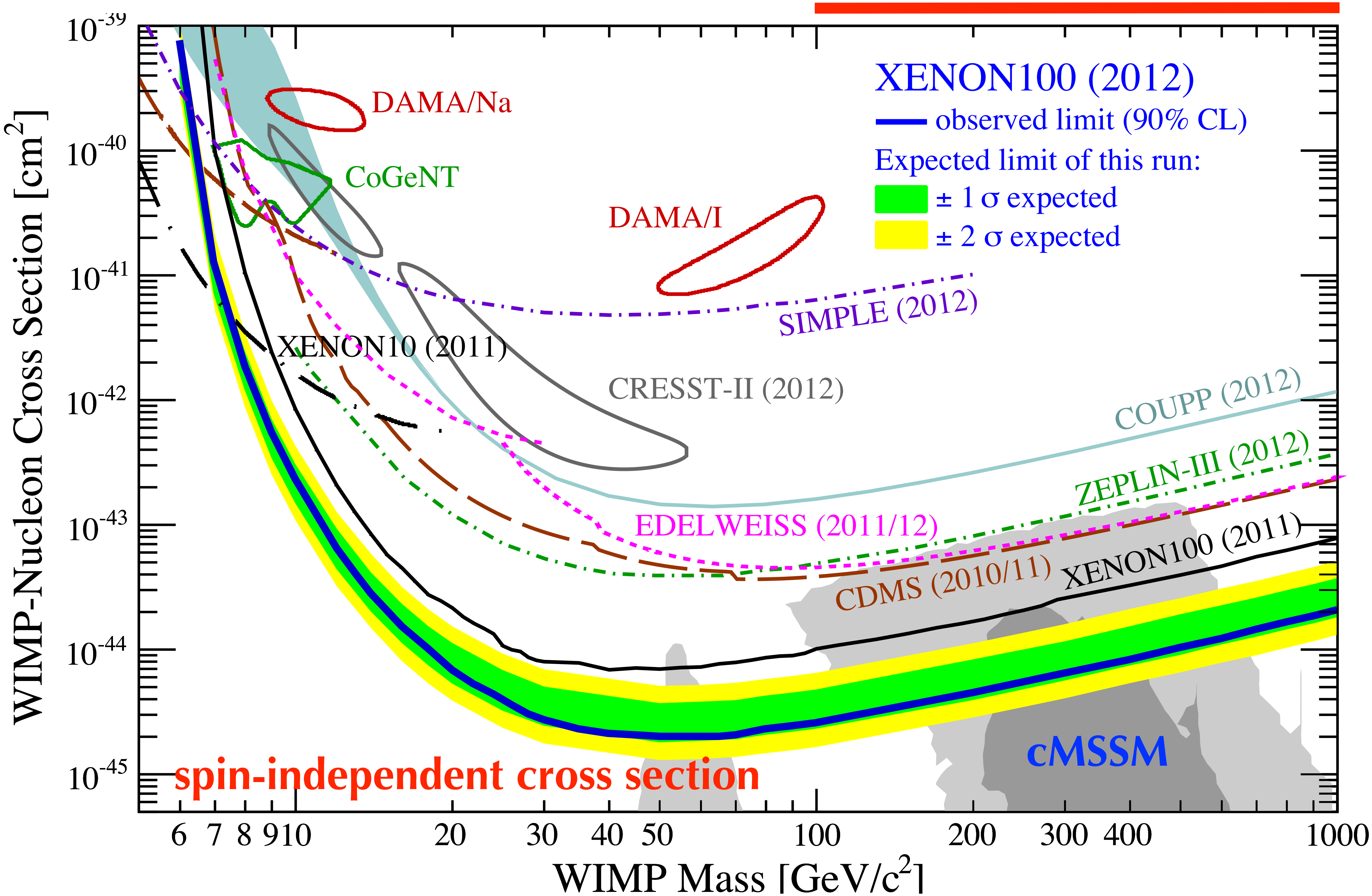
but what are the reference cross section values?



The Status:



$$\sigma_0 \approx \frac{G_f^2 \mu^2}{2\pi} \sim 10^{-39}\mathrm{cm}^2$$



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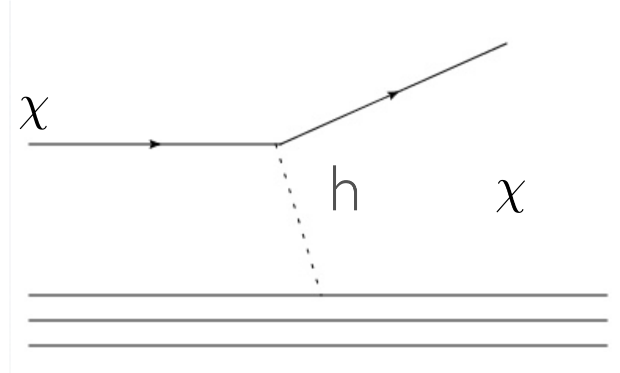
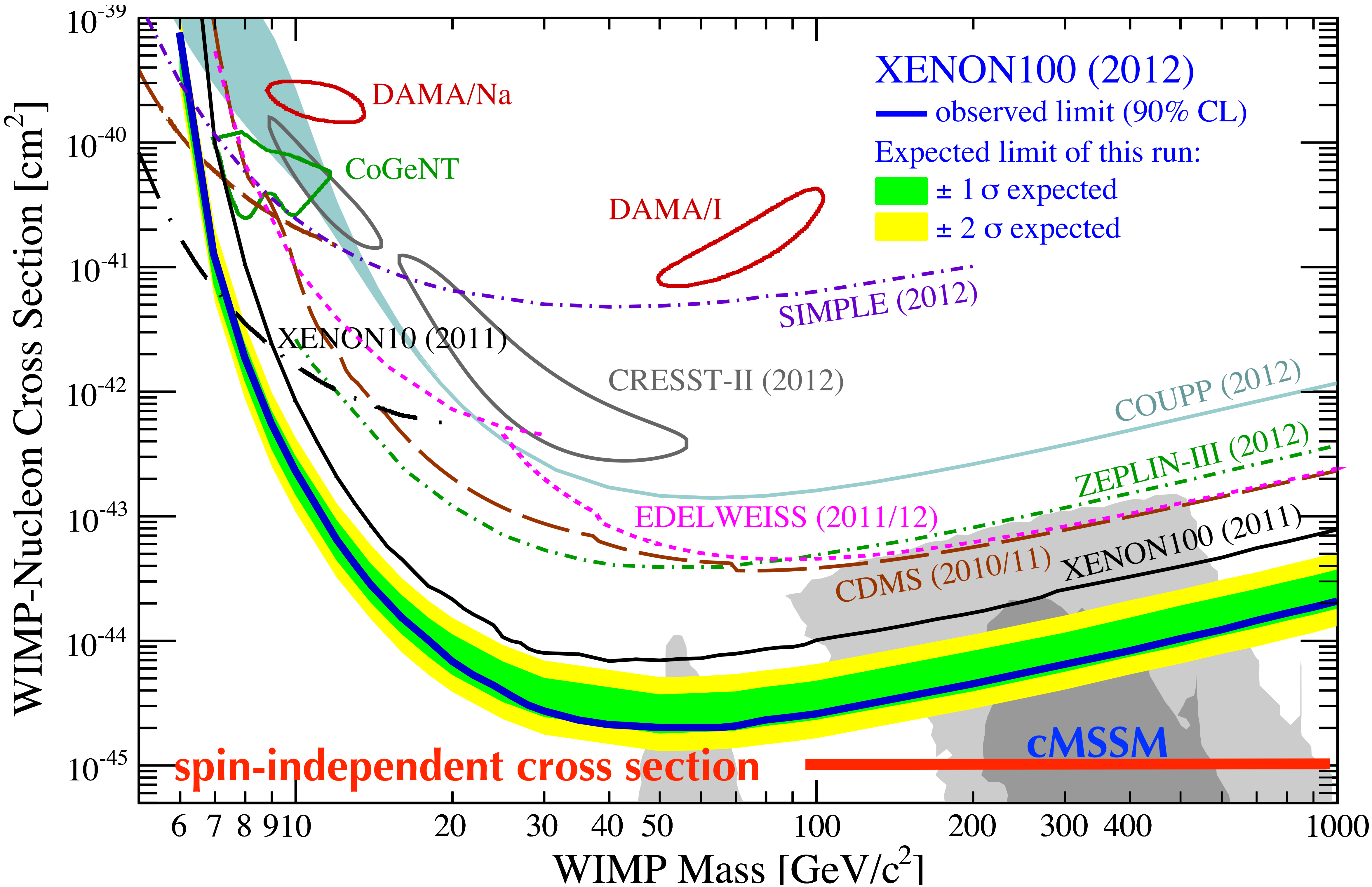


$$\sigma_0 \sim 10^{-39}\mathrm{cm}^2 \times 10^{-6}$$
$$\sim 10^{-45}\mathrm{cm}^2$$



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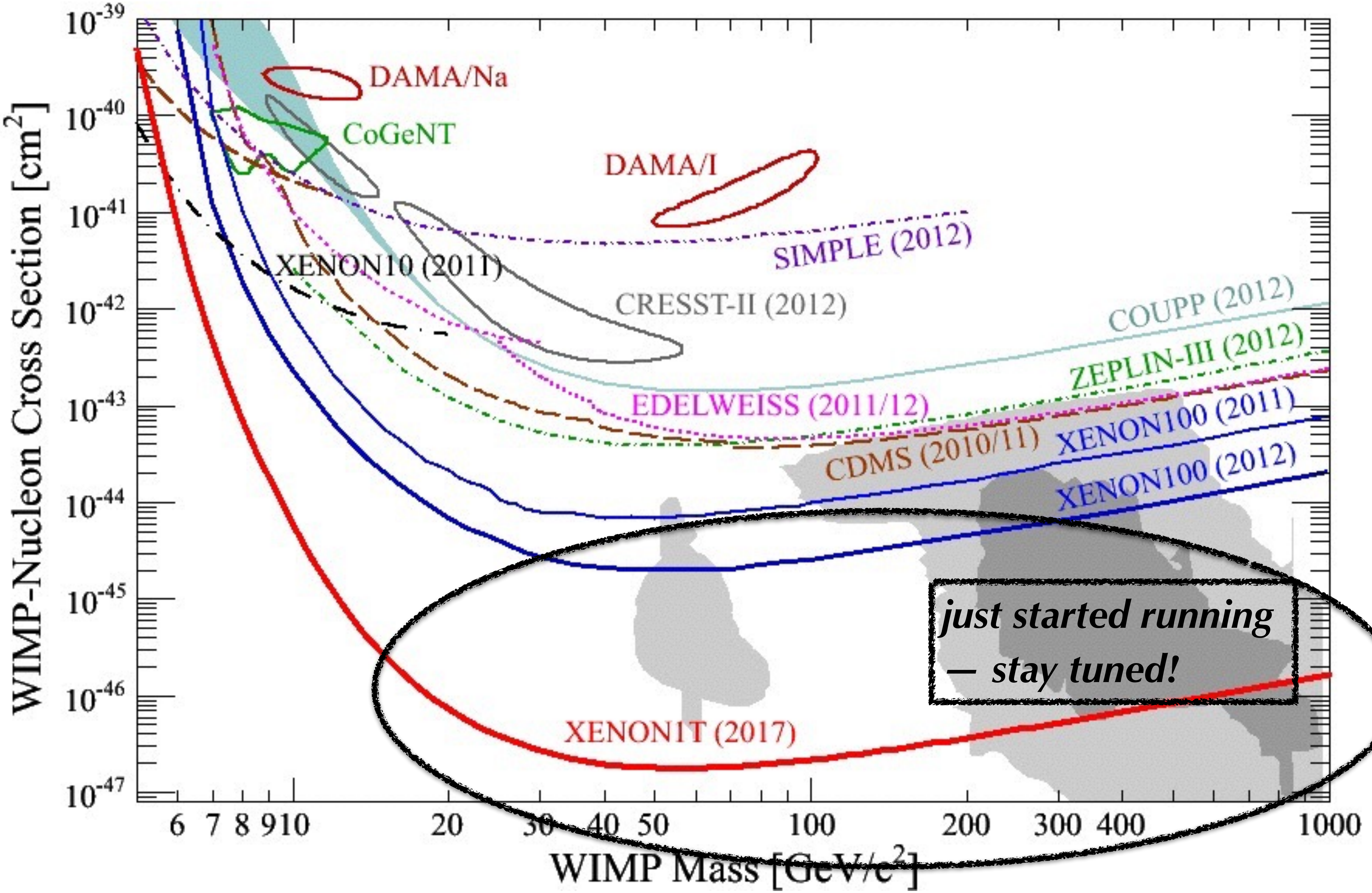
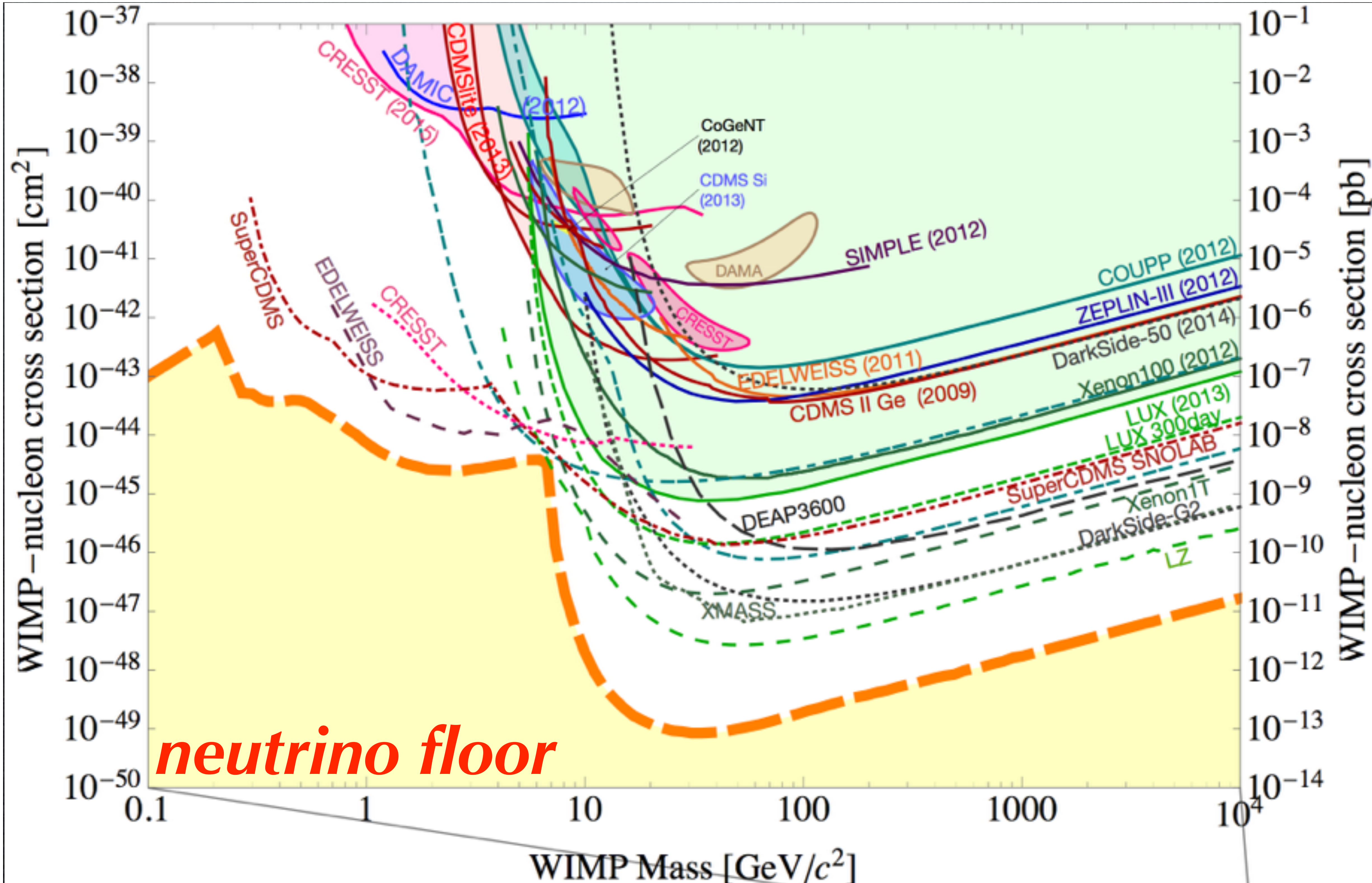


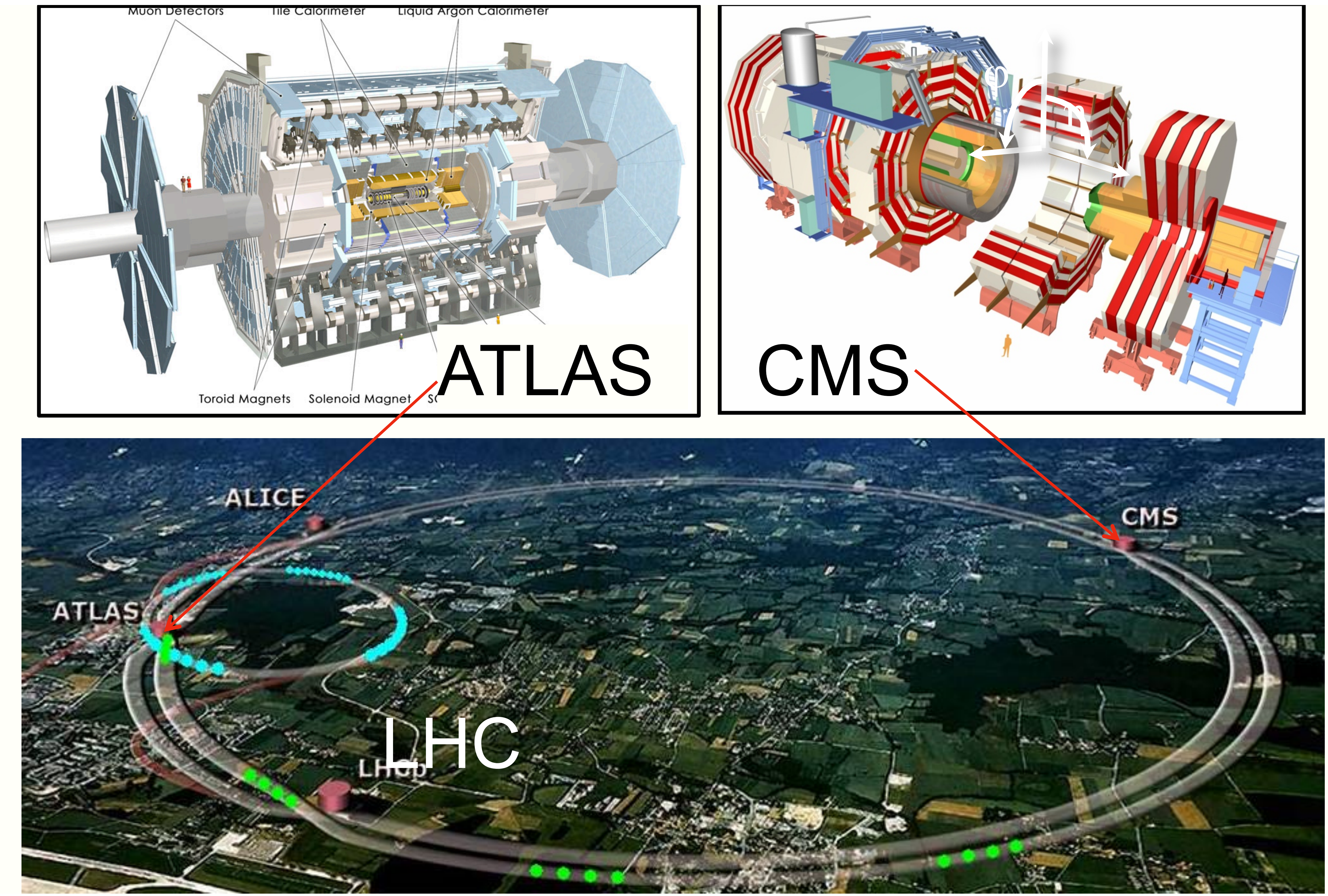
WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]
DAMA/Na
CoGeNT
DAMA/I
SIMPLE (2012)
XENON10 (2011)
CRESST-II (2012)
COUPP (2012)
ZEPLIN-III (2012)
EDELWEISS (2011/12)
XENON100 (2011)
CDMS (2010/11)
XENON100 (2012)
XENON1T (2017)
just started running
— stay tuned!

BUT, limited by the neutrino floor!



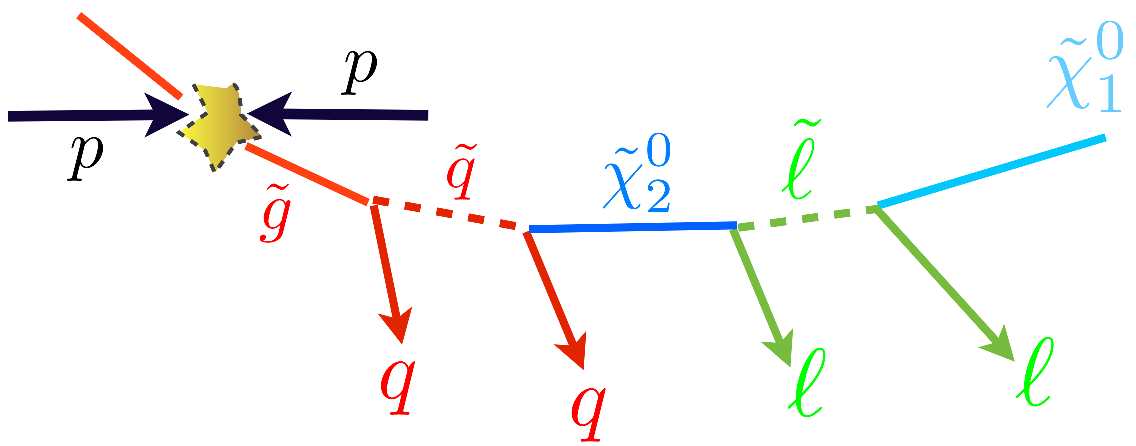
E. Figueroa-Feliciano - ICRC 2015

Dark Matter
Collider searches



What can collider tell us about DM:

Search strategy 1. **look for a specific signatures of a given model** (SUSY, UED...):



e.g. look for a 4jets+4lepton+MET

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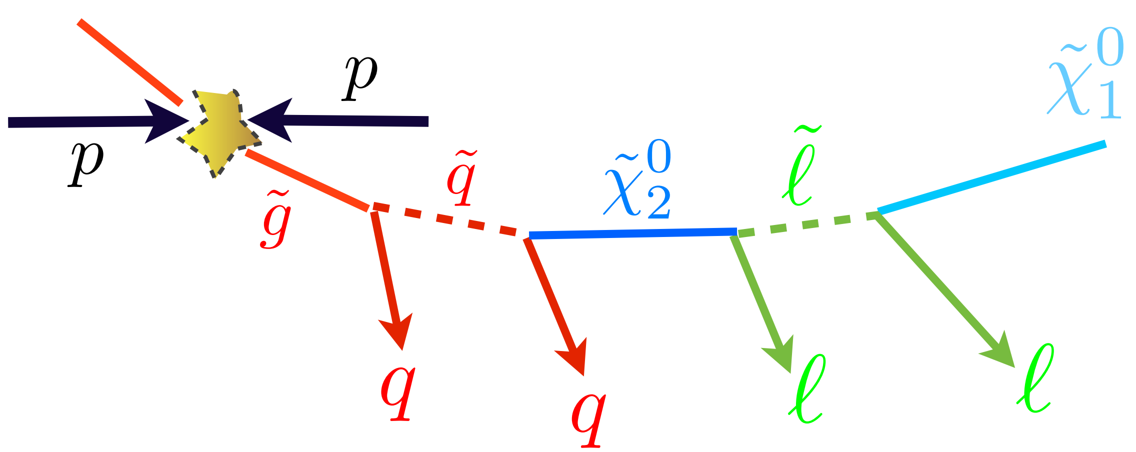

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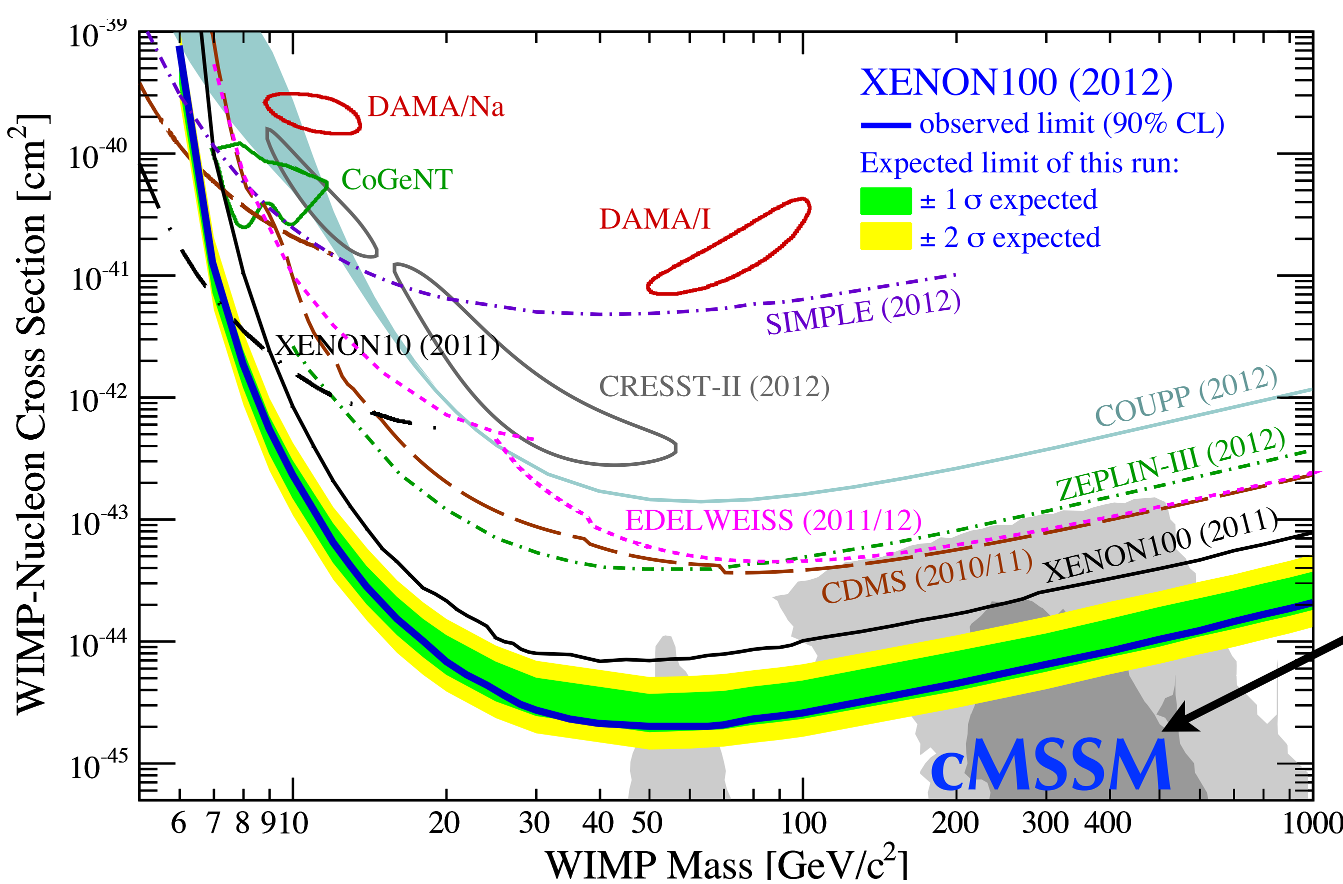


However, one might want to use a more model independent search!

Within fixed theoretical frameworks it is not simple to gain physical insight to many questions.

for example

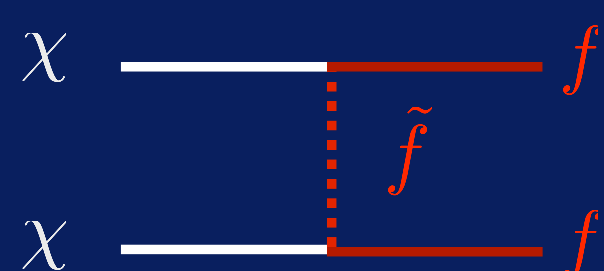
'What happens to this point if we raise stop mass by 5 GeV'? (T. Tait, 2010)

Strategy 02. or use **Effective Field Theory** (EFT) approach!

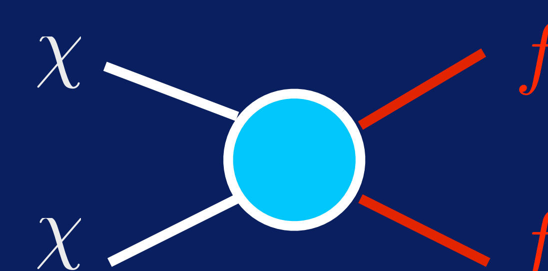
Ignore degrees of freedom at shorter distances (or, equivalently, at higher energies)

Relevant degrees of freedom consist of the Standard Model + the WIMP (and nothing else...). **New physics parametrized by the cut-off energy scale**.

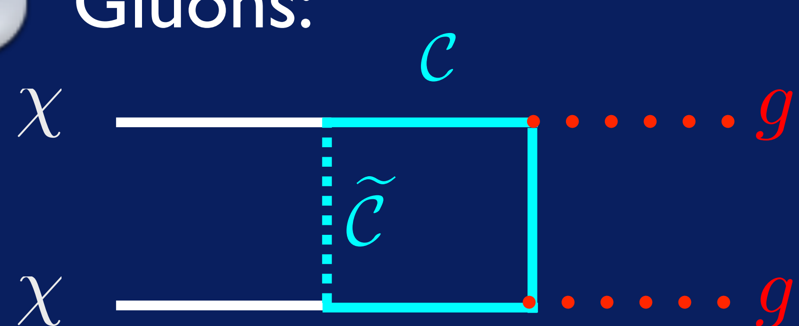
- Quarks:



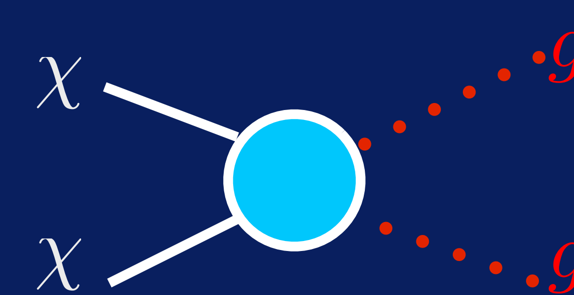
$$\sim \frac{g^2}{M_{\tilde{f}}^2} \leftrightarrow \frac{1}{\Lambda_f^2} =$$



- Gluons:



$$\sim \alpha_S \frac{g^2}{M_{\mathcal{C}} M_{\tilde{\mathcal{C}}}^2} \leftrightarrow \frac{\alpha_S}{\Lambda_g^3} =$$



- Each requires new states with masses heavier than the WIMP.

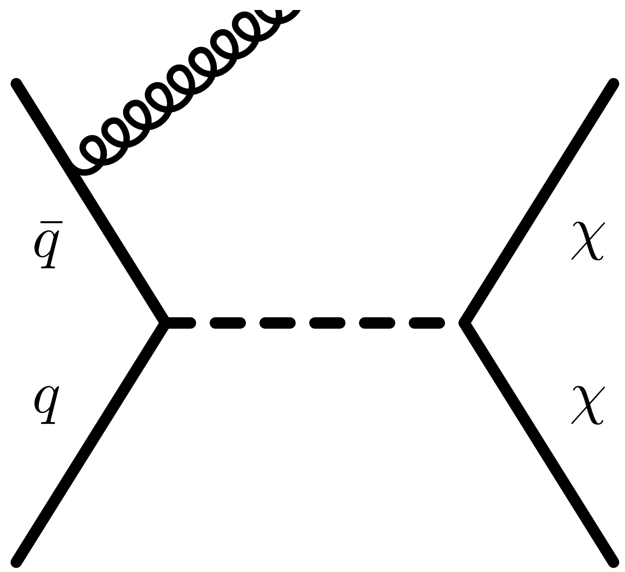
Strategy 02. or use **Effective Field Theory** (EFT) approach!

Not fully model independent, 'type' of interaction needs to be assumed.

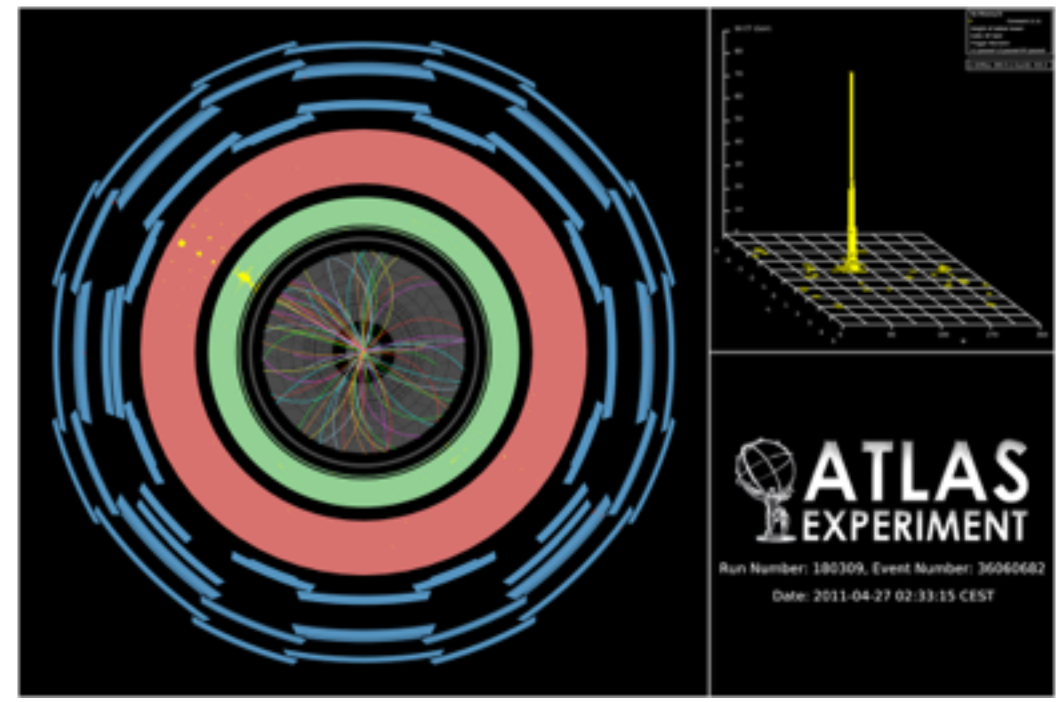
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D

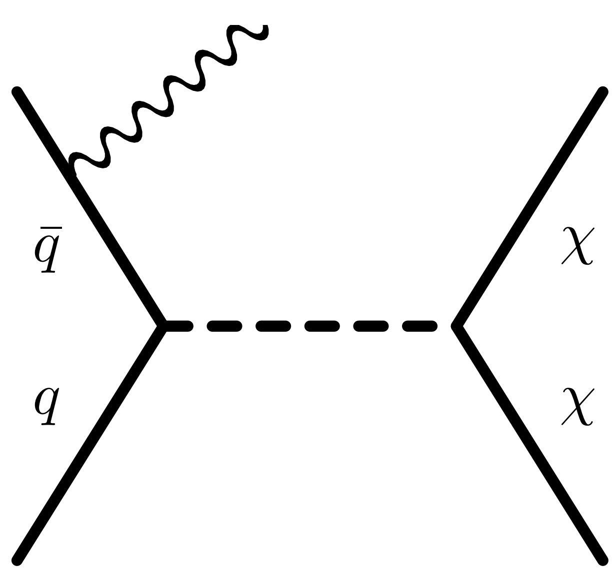
Strategy 02. use **Effective Field Theory** (EFT) approach!

+ **Look for generic collider signatures of DM**: DM is long lived, escapes from a detector carrying missing energy! Only processes followed by mono-jet or mono-photon can be observed (leave trace in a detector).



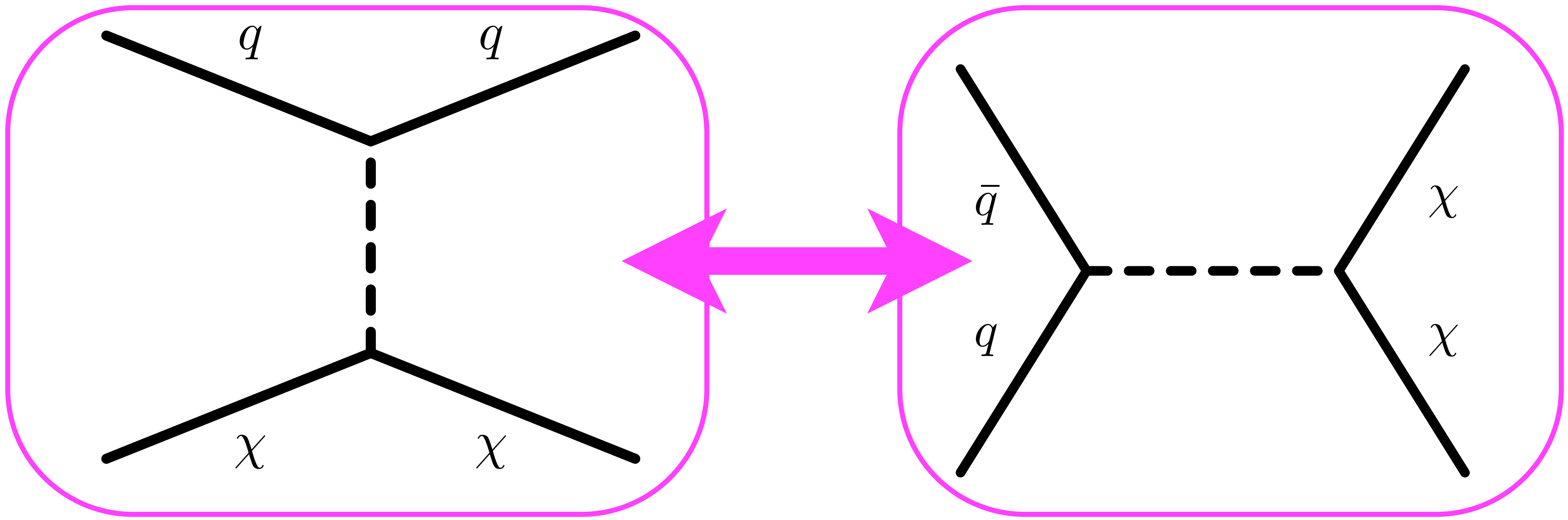
“Monojets”





“Monophotons”

Synergy: moreover one can use EFT to relate production cross sections with elastic scattering ones.

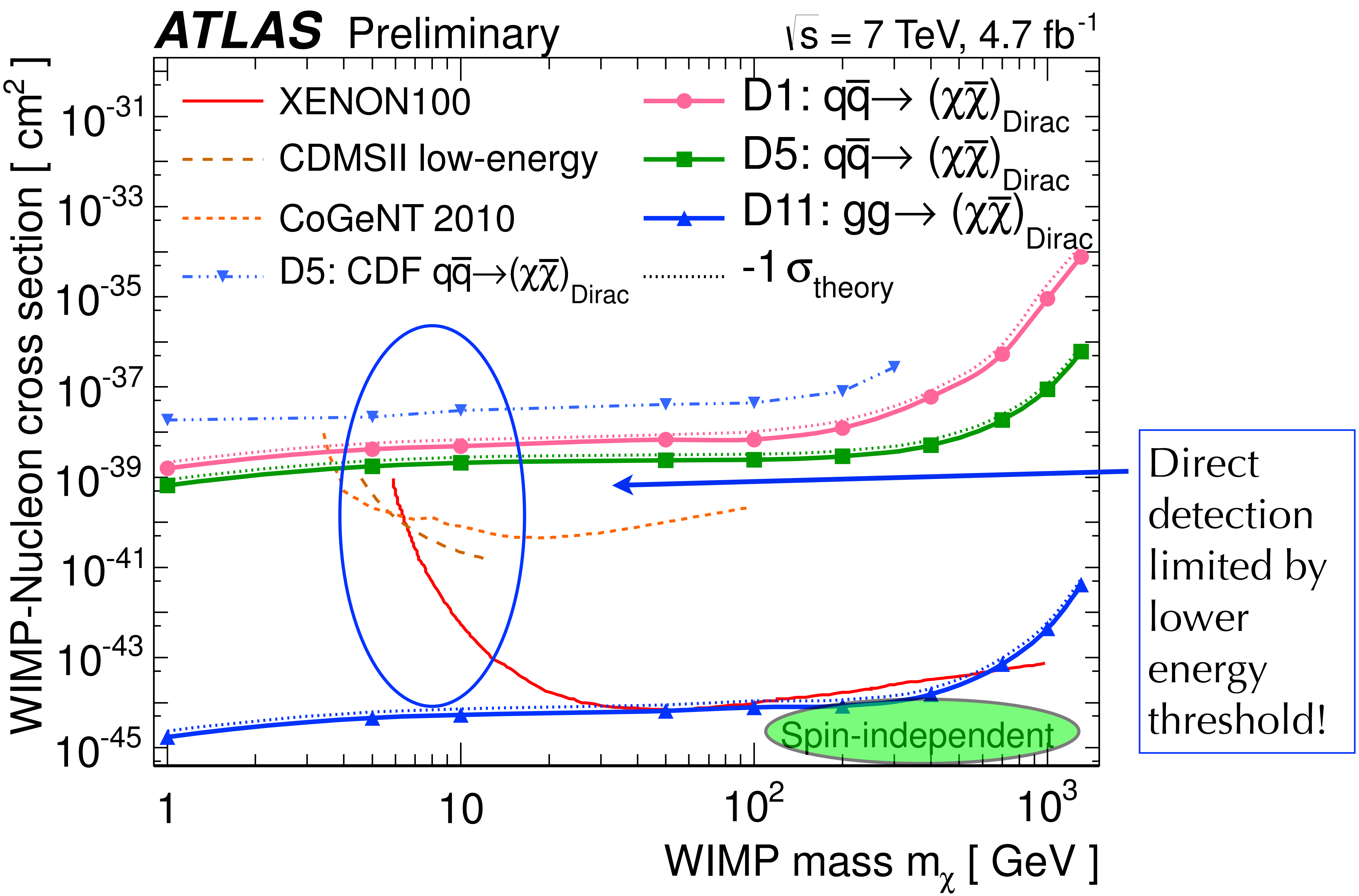


Direct detection **Collider searches**

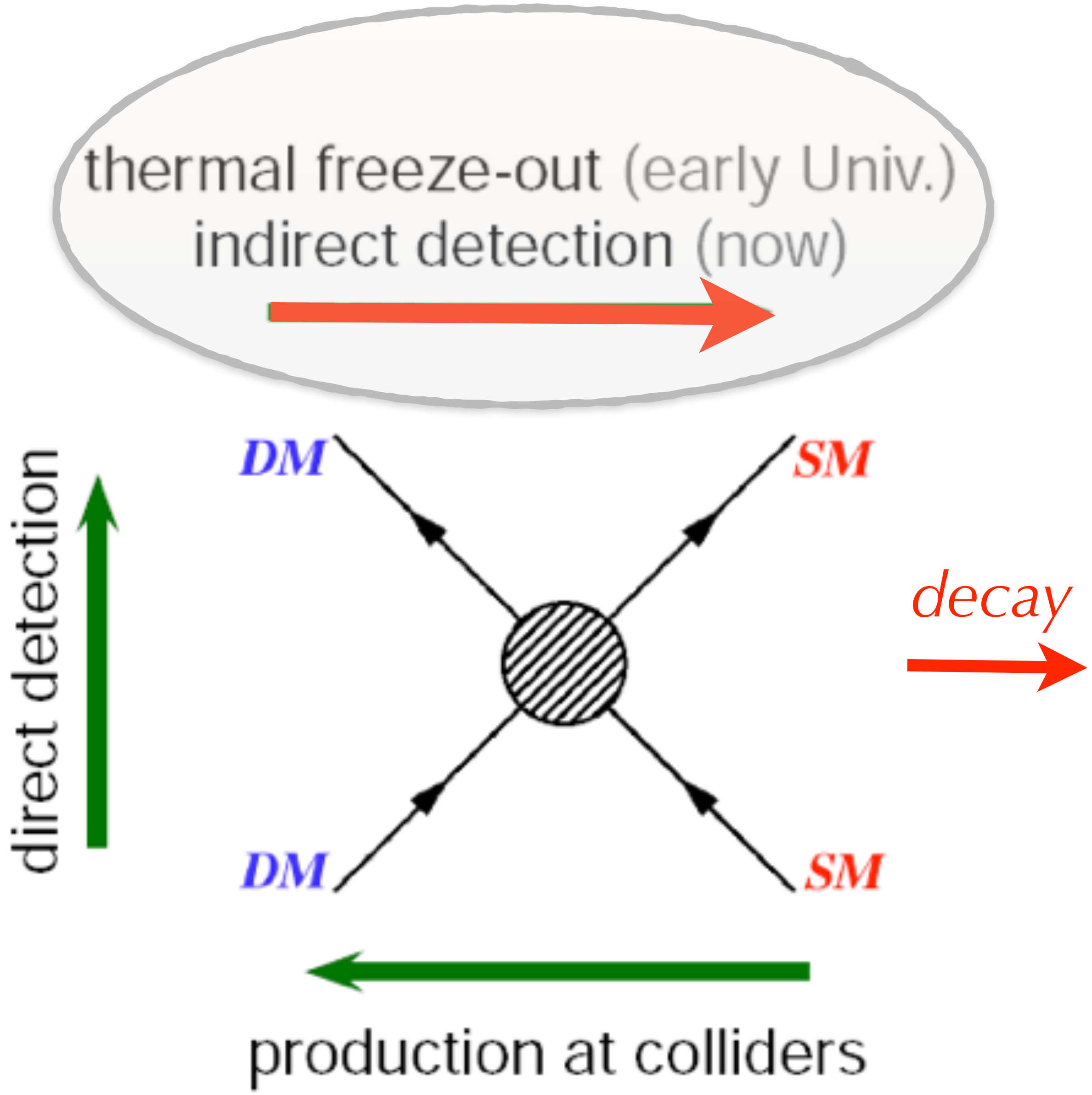
$$\sigma(\chi N \to \chi N) \sim \frac{g_q^2 g_\chi^2}{M^4}\mu_{\chi N}^2 \qquad \sigma(pp \to \bar{\chi}\chi + X) \sim \frac{g_q^2 g_\chi^2}{(q^2 - M^2)^2 + \Gamma^2/4}E^2$$

both signals depend on the 'cut-off' scale M (above which the details of new physics become important and the effective theory breaks), and therefore can be directly compared!

monojets: collider constraints are very strong for lighter dark matter and fall off when the dark matter mass exceeds the typical energy reach of the collider.



Dark Matter
Indirect searches

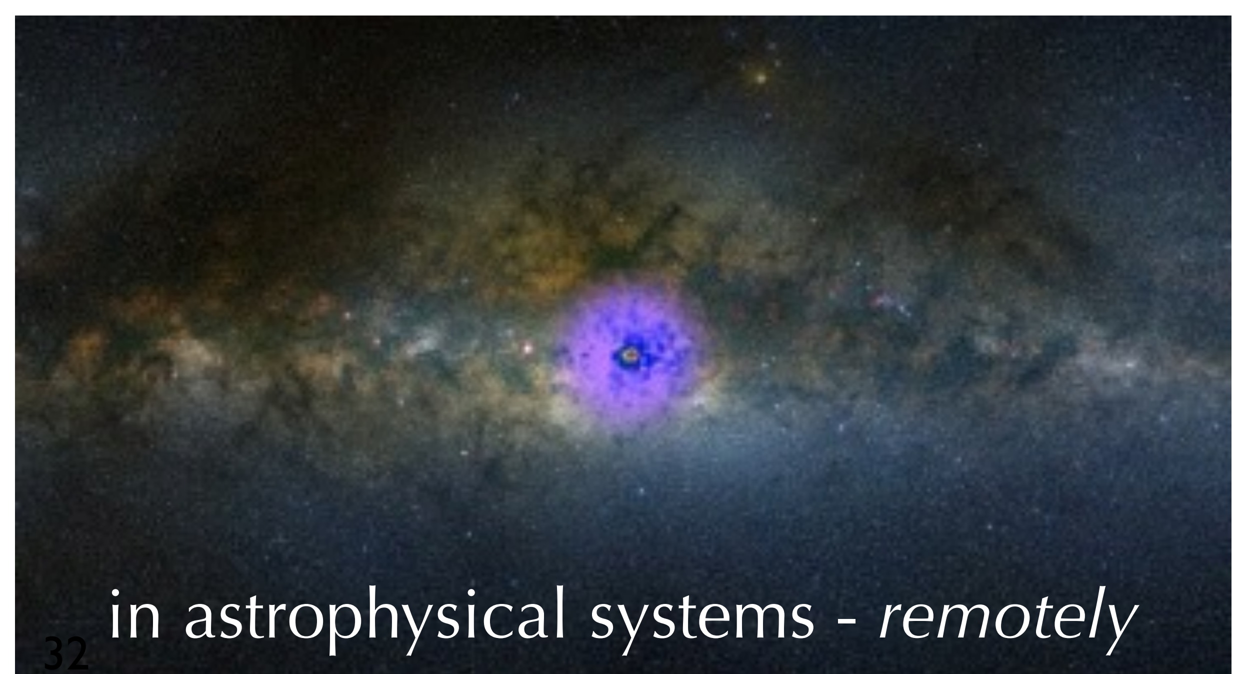


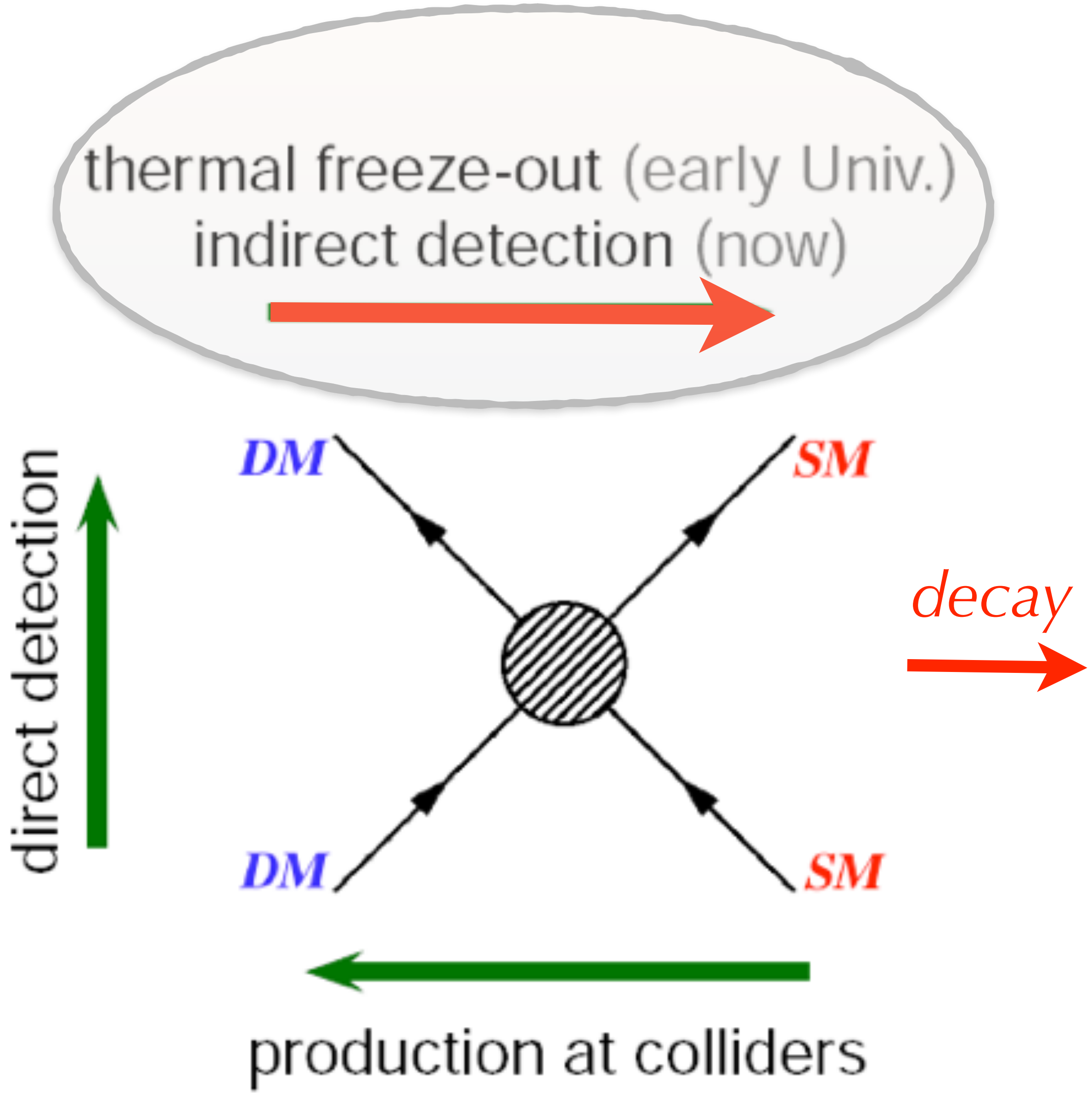
γ, ν, $e^{\pm}$, $p^{\pm}$, D^{-}

@ $\mathcal{O}(M_Z)$

In the Early Universe: DM kept in equilibrium w SM by self-annihilations $\langle \sigma v \rangle_{thermal}$.

Today, *DM expected to annihilate with the same* $\langle \sigma v \rangle_{thermal}$, *in places where its* **density is enhanced**!





γ,
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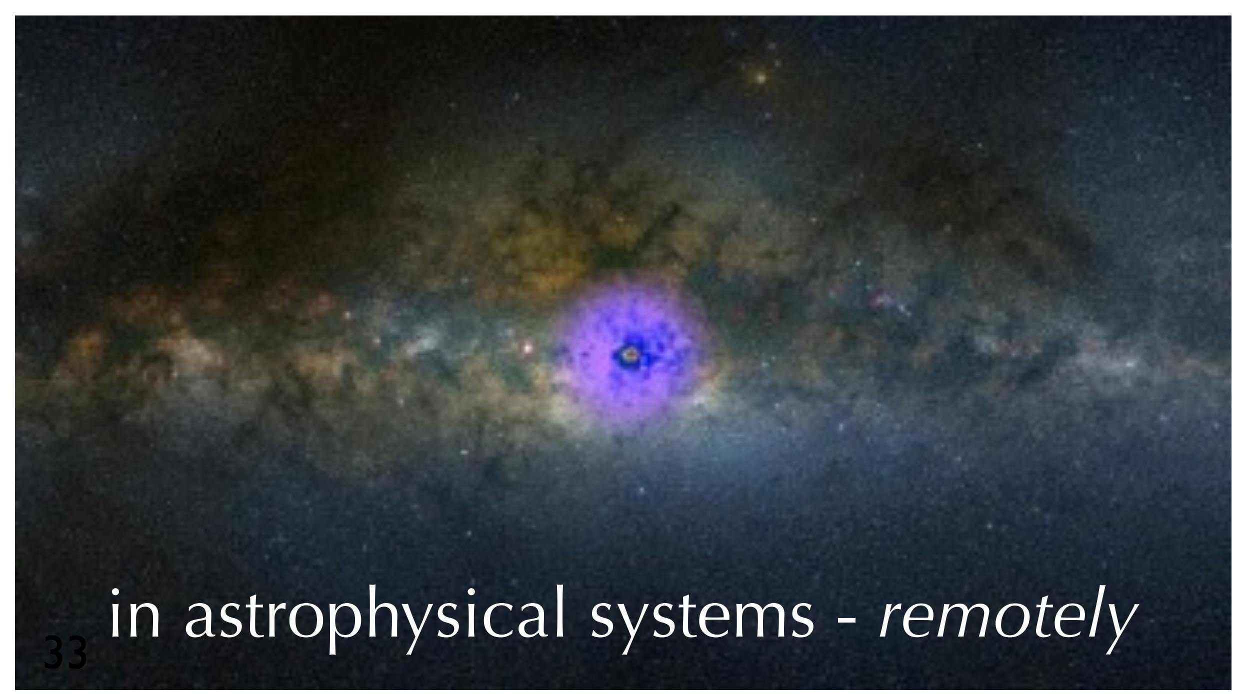
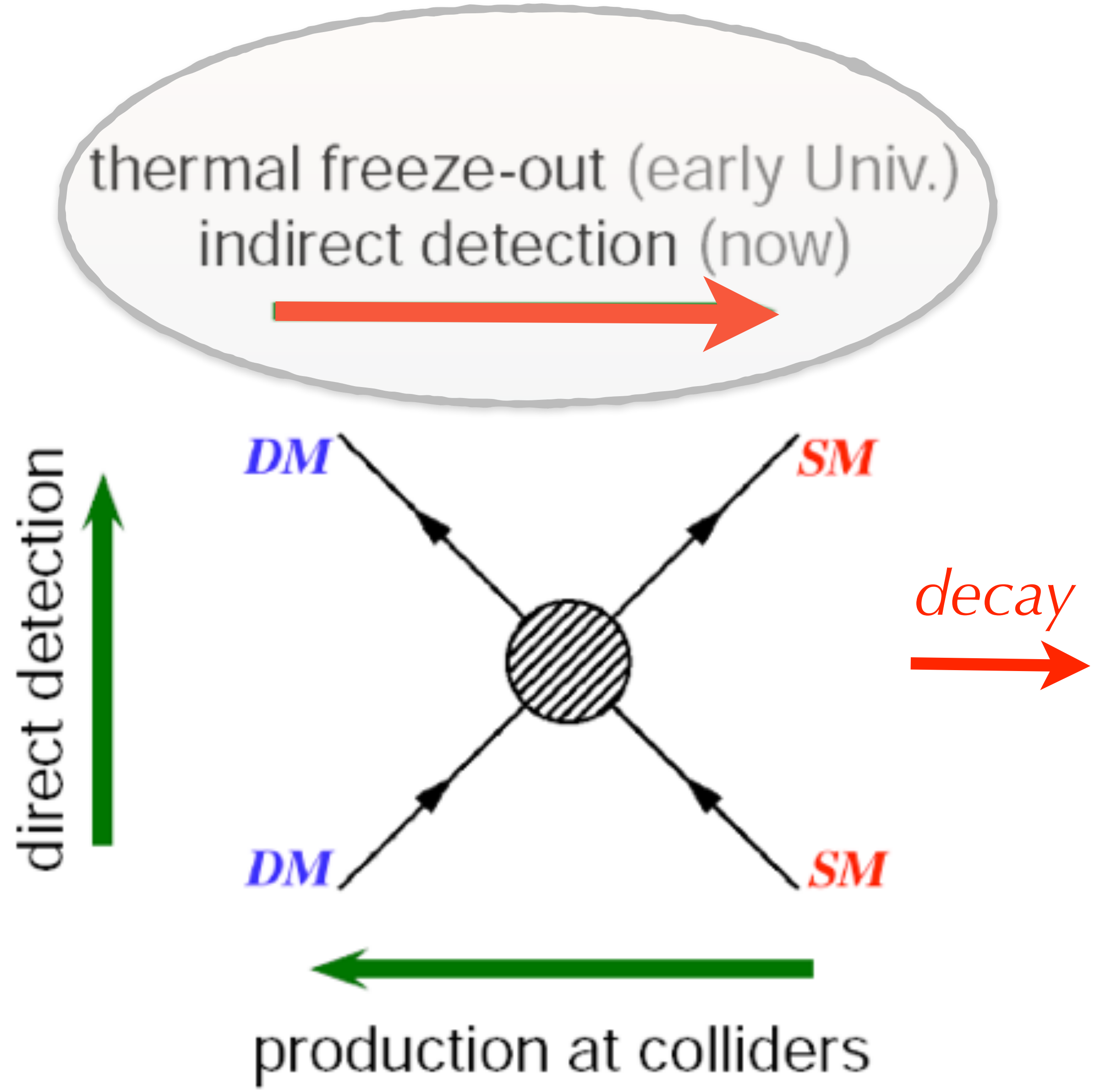
Important:
— indirect searches provide insight into the **early Universe** decoupling

$$\Omega_{\rm DM} \approx \frac{2 \times 10^{-37}{\rm cm}^2}{\langle \sigma_{\rm annih} v \rangle} \approx 0.23$$





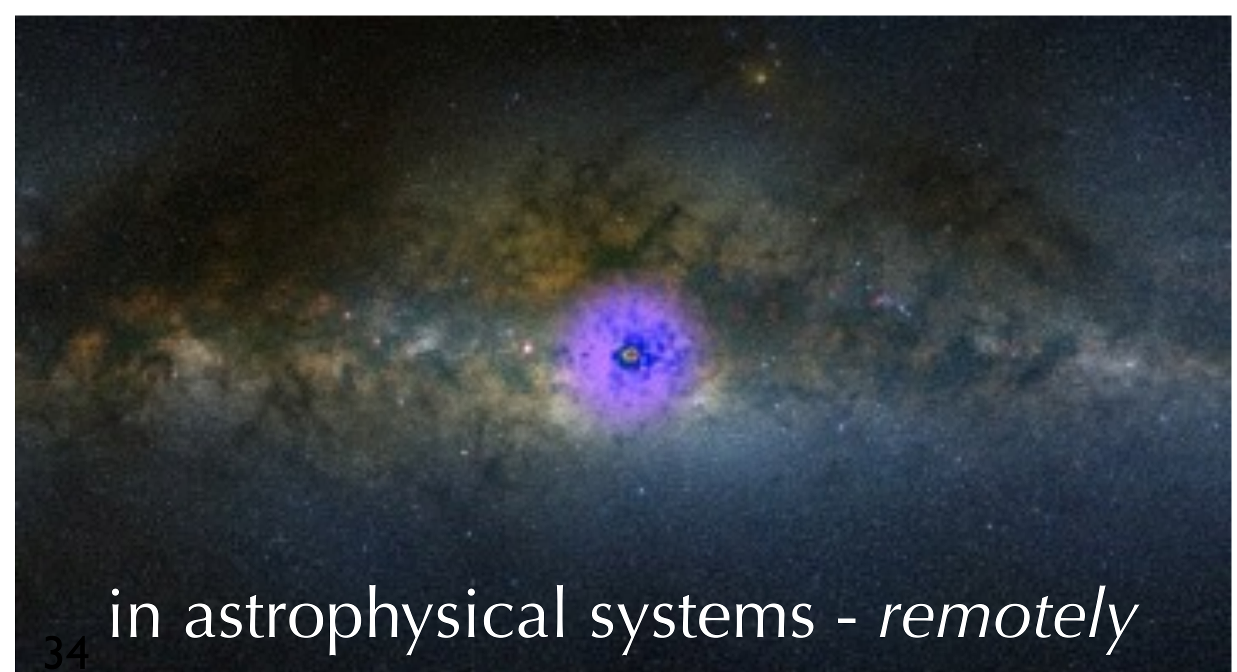
γ,
ν,
$e^{\pm}$,
$p^{\pm}$
D^{-}

@ $\mathcal{O}(M_Z)$

In the Early Universe: DM kept in equilibrium w SM by self-annihilations $\langle \sigma v \rangle_{thermal}$.

Today, *DM expected to annihilate with the same* $\langle \sigma v \rangle_{thermal}$, *in places where its* **density is enhanced***!*

Important:
— indirect detection experiments are **multi-purpose** — learning HE astrophysics in the process



Indirect detection — basics: the DM signal

$$\boxed{\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma}} = \boxed{\frac{1}{4\pi}\,\frac{(\sigma_{\rm ann} v)}{2\,m_\chi^2}} \;\mathrm{X}\; \boxed{\sum_i \mathrm{BR}_i \frac{dN_\gamma^i}{dE_\gamma}} \;\mathrm{X}\; \boxed{\int_{\Delta\Omega} d\Omega \int_{\rm los} ds\, \rho^2(s,\Omega)}$$

this is what we are after!

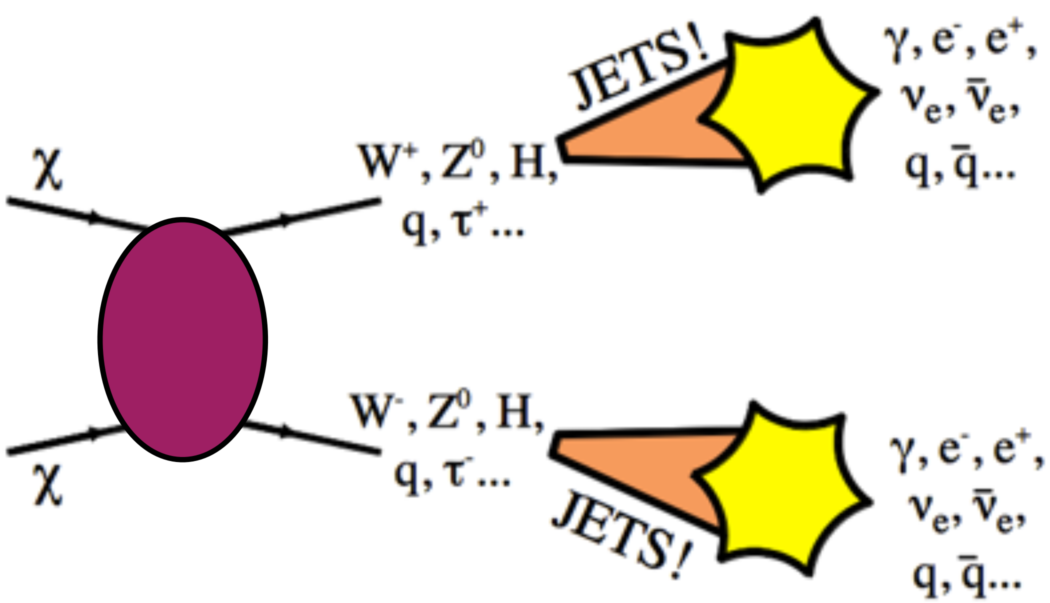
annihilation

Indirect detection — basics: the DM signal

$$\boxed{\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma}} = \boxed{\frac{1}{4\pi}\,\frac{(\sigma_{\mathrm{ann}} v)}{2\,m_\chi^2}} \;\mathrm{X}\; \boxed{\sum_i \mathrm{BR}_i \frac{dN_\gamma^i}{dE_\gamma}} \;\mathrm{X}\; \boxed{\int_{\Delta\Omega} d\Omega \int_{\mathrm{los}} ds\,\rho^2(s,\Omega)}$$

this is what we are after!

flux of SM particles per DM annihilation



simulation of hadronic showers (e.g. PYTHIA)

Indirect detection — basics: the DM signal

for neutral messengers (travel unaffected from production sites)

$$\boxed{\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma}} = \boxed{\frac{1}{4\pi}\frac{(\sigma_{\rm ann} v)}{2\, m_\chi^2}} \times \boxed{\sum_i \mathrm{BR}_i \frac{dN_\gamma^i}{dE_\gamma}} \times \boxed{\int_{\Delta\Omega} d\Omega \int_{\rm los} ds\, \rho^2(s,\Omega)}$$

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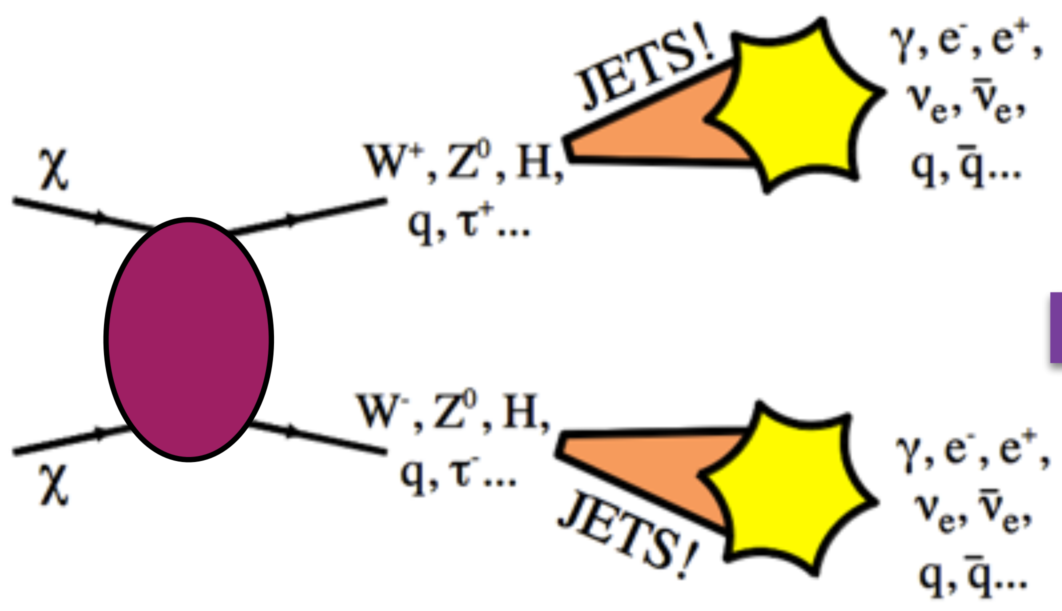
flux of SM particles per DM annihilation



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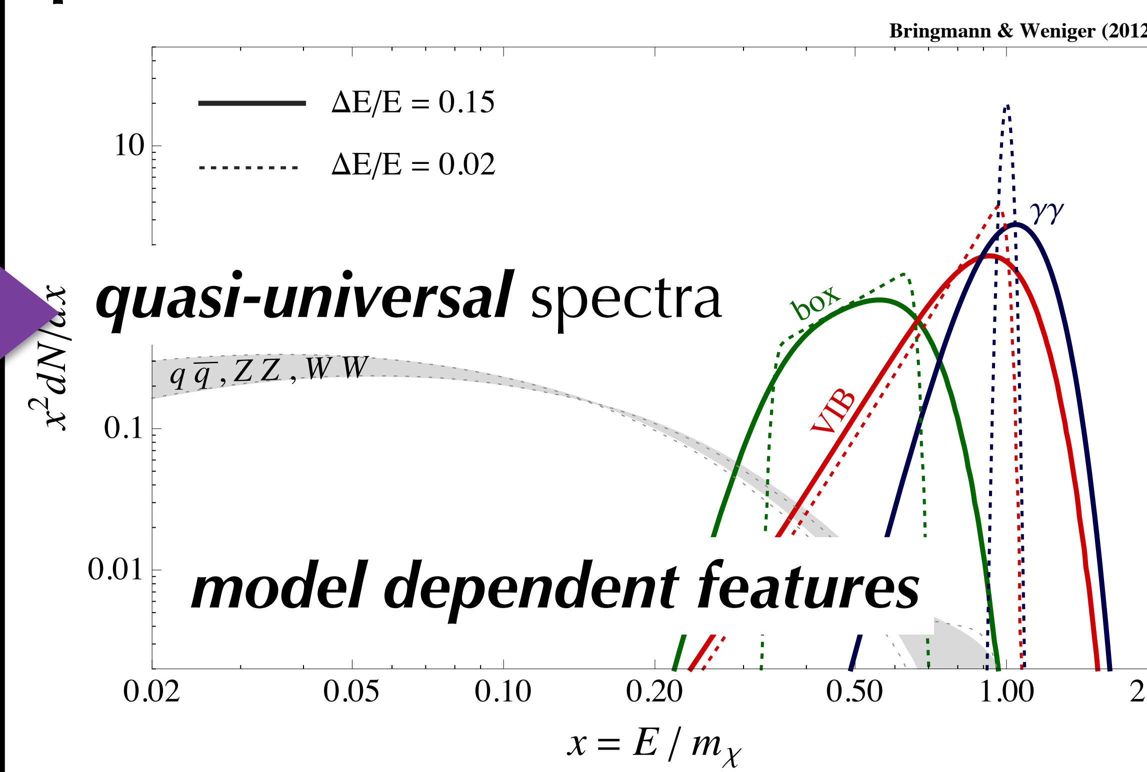

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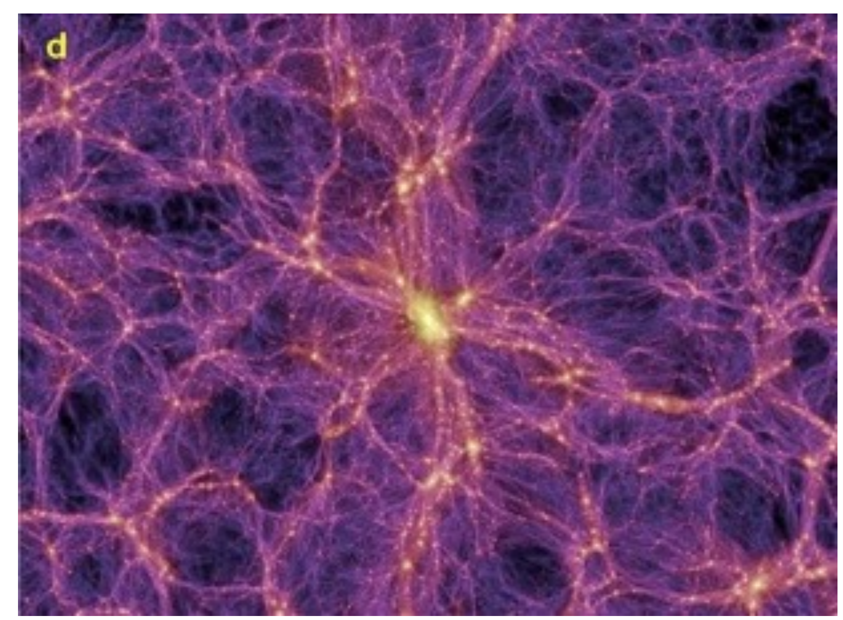
this is what we are after!

integrated DM density squared along the line of site



from N-body simulations of matter clustering (e.g. Millenium simulation)

Indirect detection — basics: the DM signal

for neutral messengers (travel unaffected from production sites)

$$\boxed{\frac{\mathrm{d}\Phi(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma}} = \boxed{\frac{1}{4\pi}\,\frac{(\sigma_{\mathrm{ann}} v)}{2\, m_\chi^2}} \;\mathrm{X}\; \boxed{\sum_i \mathrm{BR}_i \frac{\mathrm{d}N_\gamma^i}{\mathrm{d}E_\gamma}} \;\mathrm{X}\; \boxed{\int_{\Delta\Omega} d\Omega \int_{\mathrm{los}} \mathrm{d}s\, \rho^2(s,\Omega)}$$

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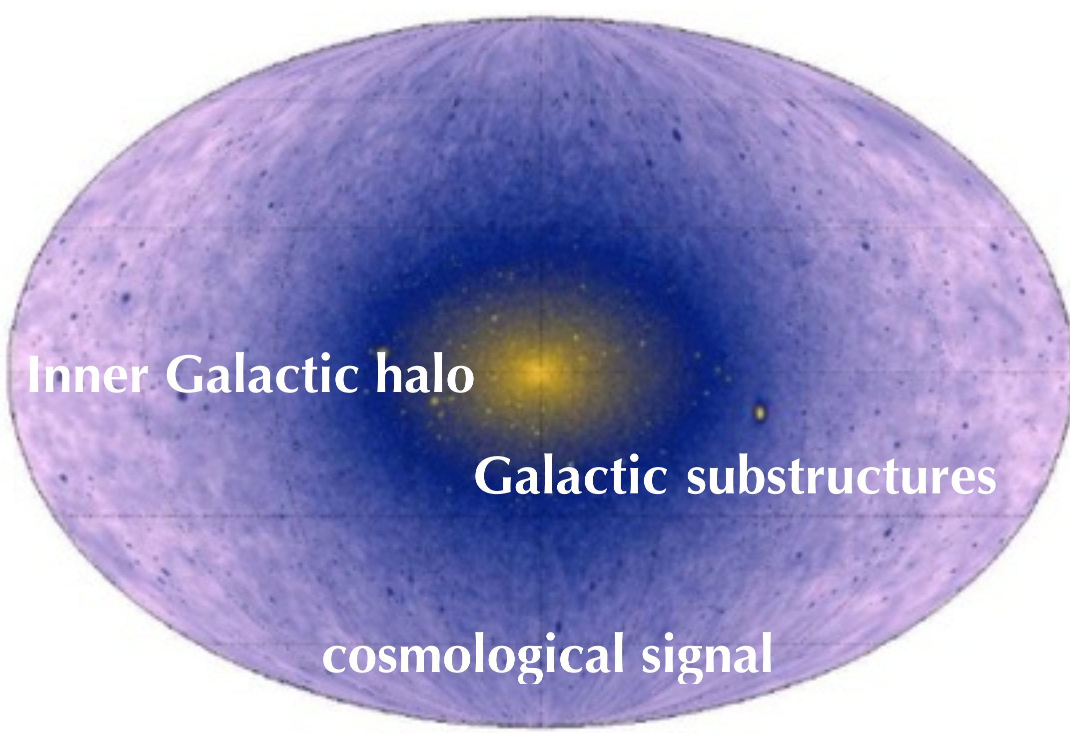
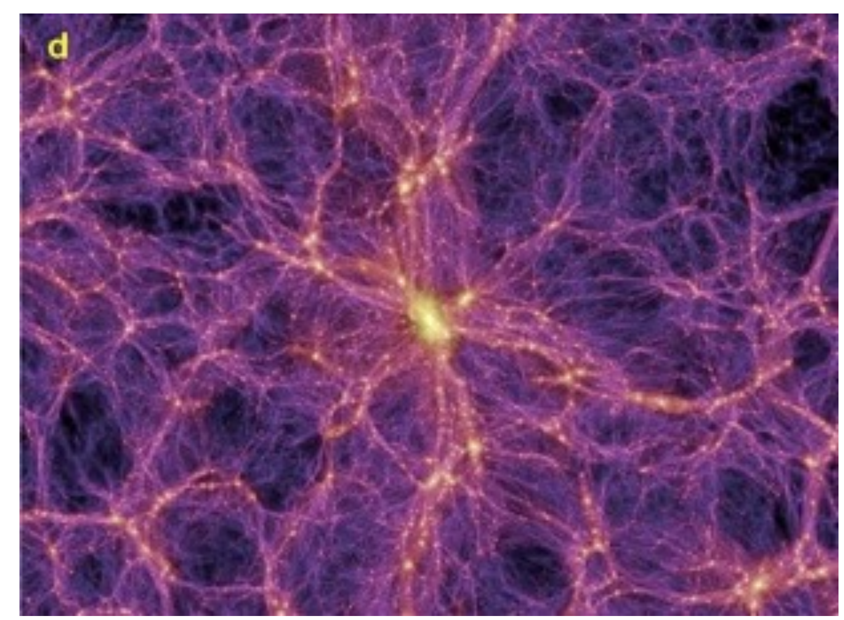


integrated DM density squared along the line of site



from N-body simulations of matter clustering (e.g. Millenium simulation)

Indirect detection — basics: the DM signal

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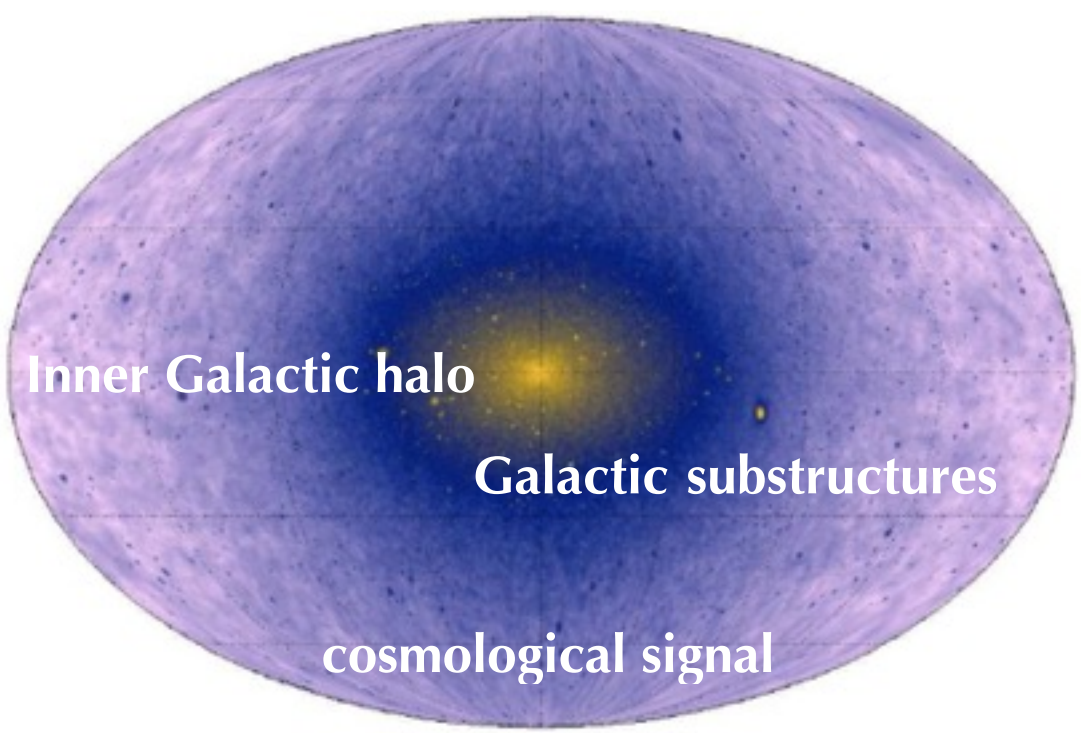
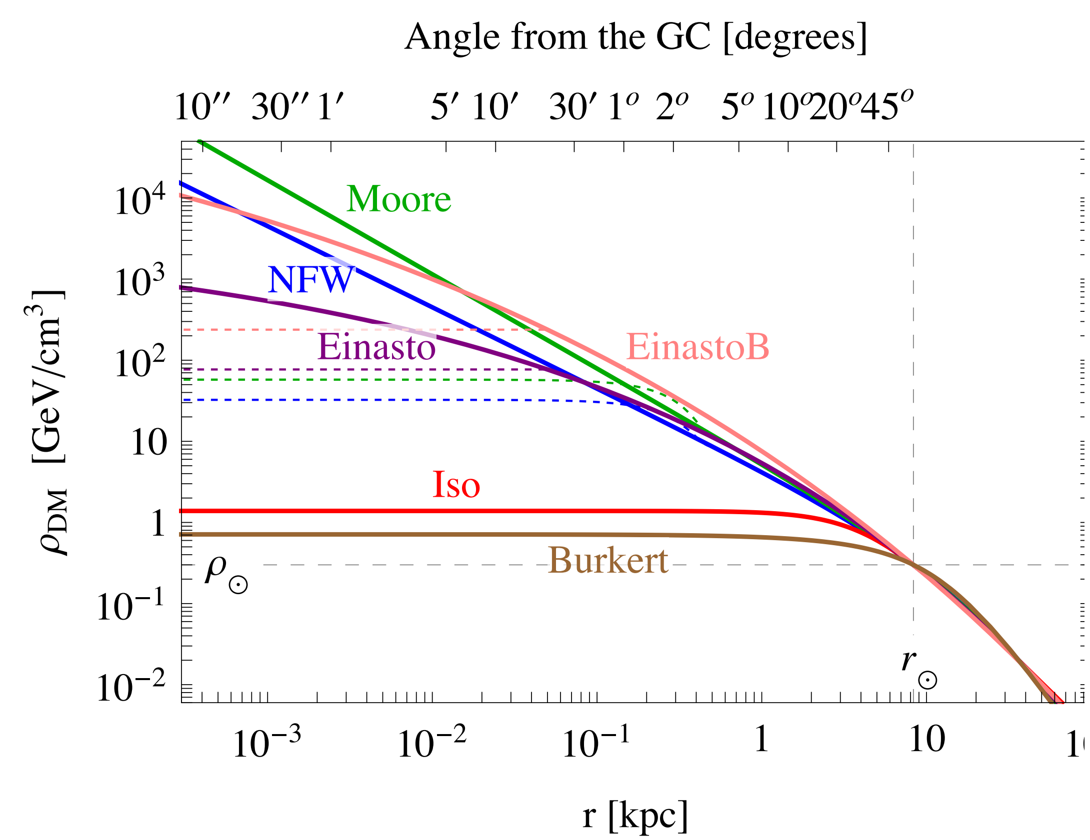
$$\frac{\mathrm{d}\Phi(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\,\frac{(\sigma_{\mathrm{ann}} v)}{2\,m_\chi^2} \times \sum_i \mathrm{BR}_i \frac{\mathrm{d}N_\gamma^i}{\mathrm{d}E_\gamma} \times \int_{\Delta\Omega} d\Omega \int_{\mathrm{los}} \mathrm{d}s\, \rho^2(s,\Omega)$$

this is what we are after!

integrated DM density squared along the line of site



Note: significant uncertainties on small scales



Indirect detection — basics: the DM signal

for neutral messengers (travel unaffected from production sites)

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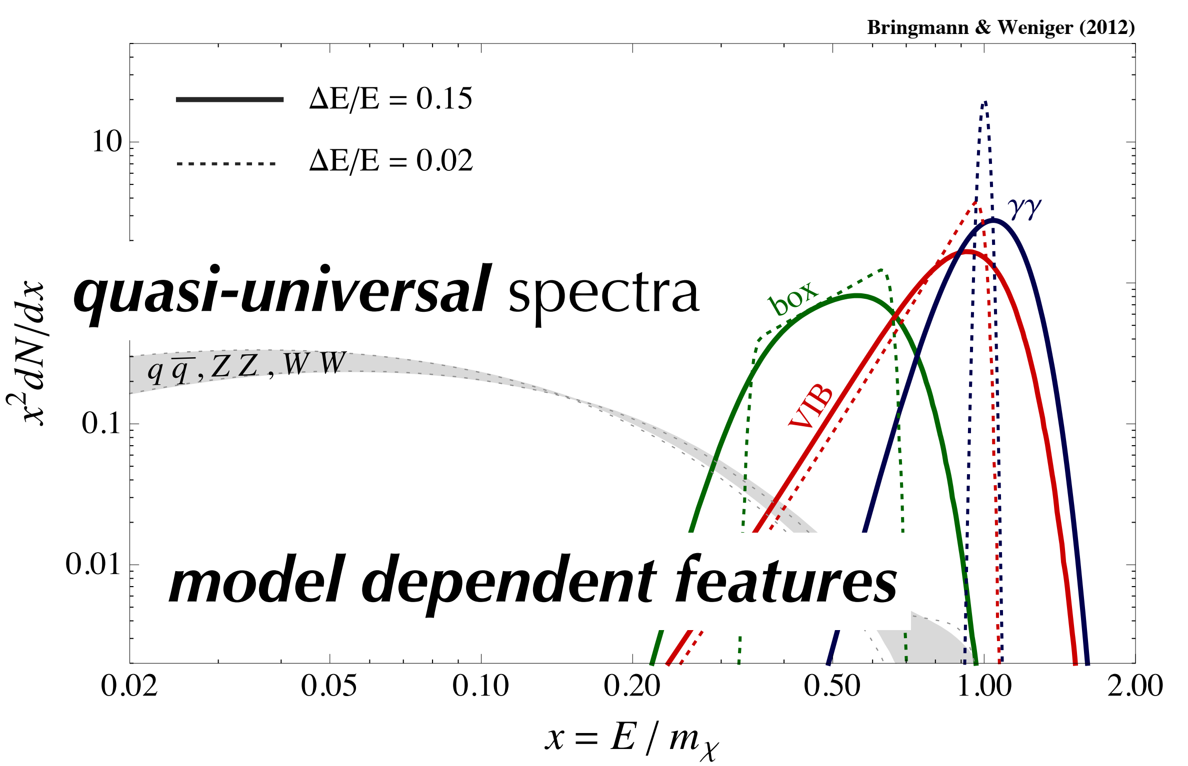
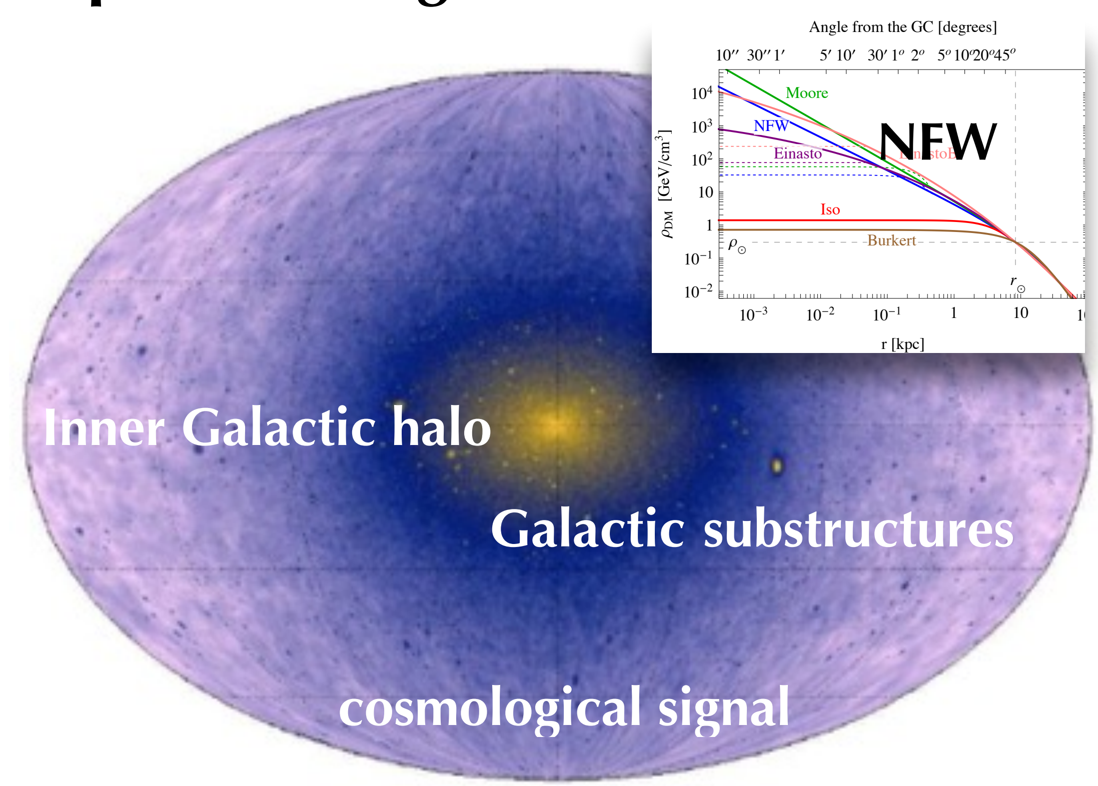
flux of SM particles per DM annihilation



integrated DM density squared along the line of site



Indirect detection — basics: the DM signal

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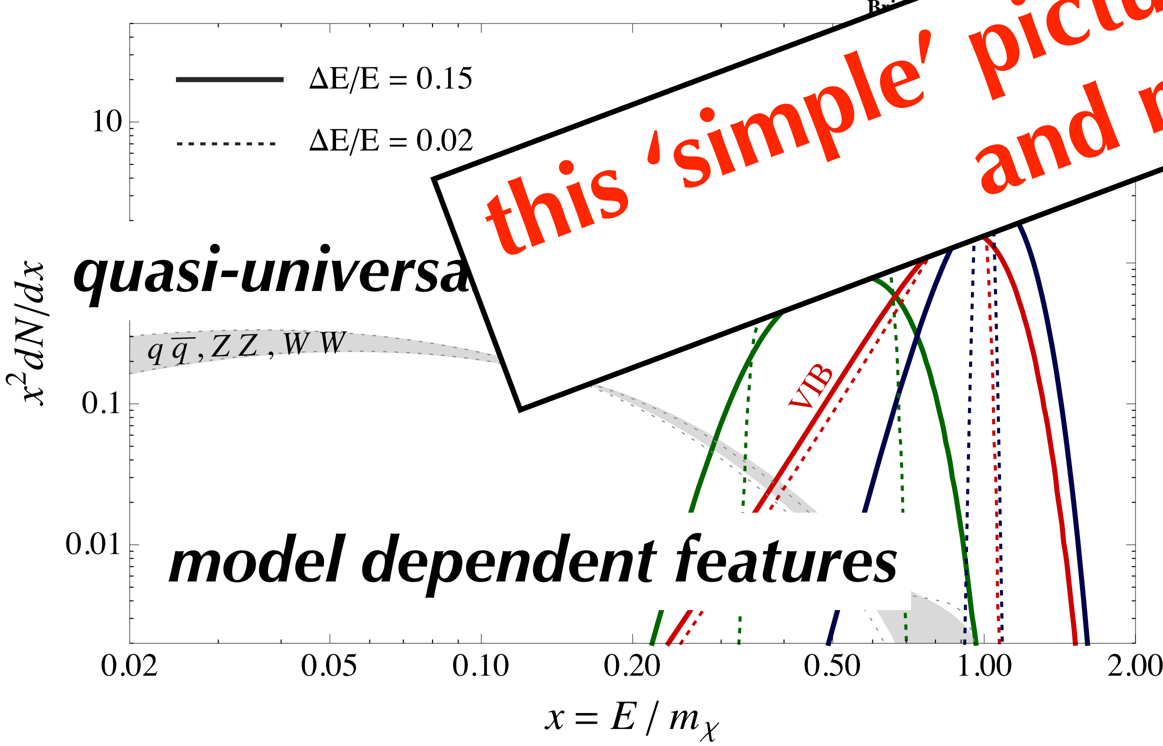
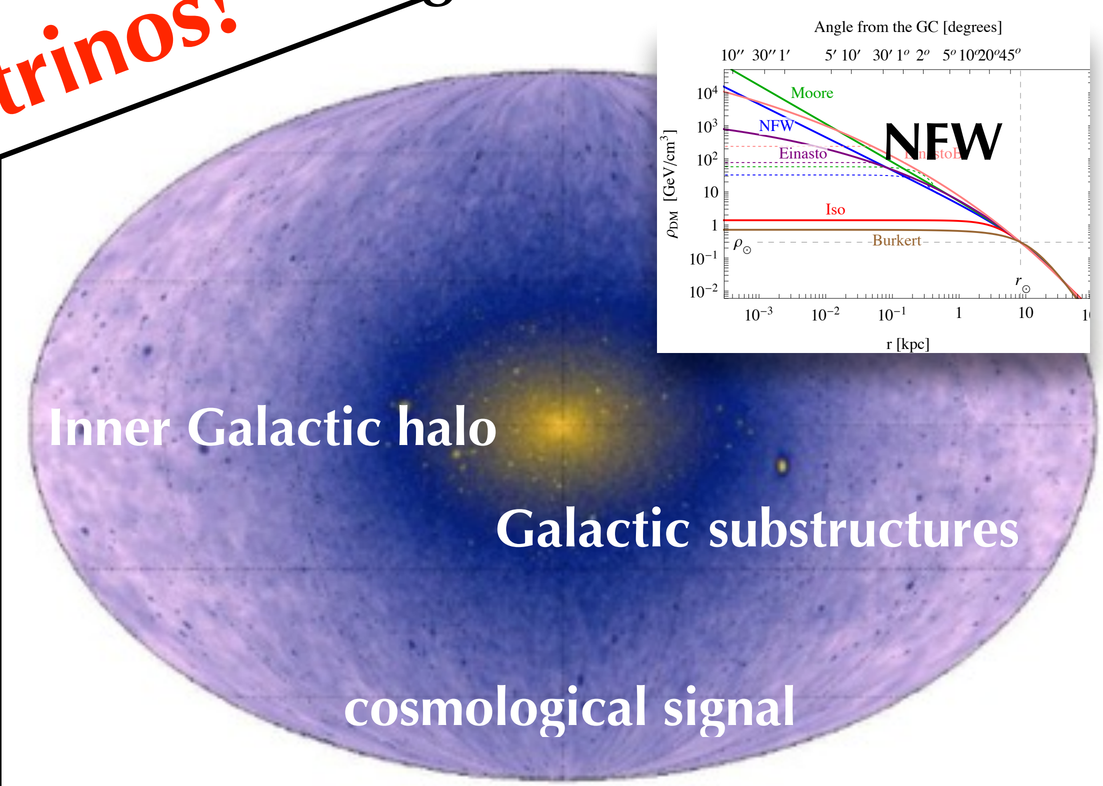
flux of SM particles per DM annihilation



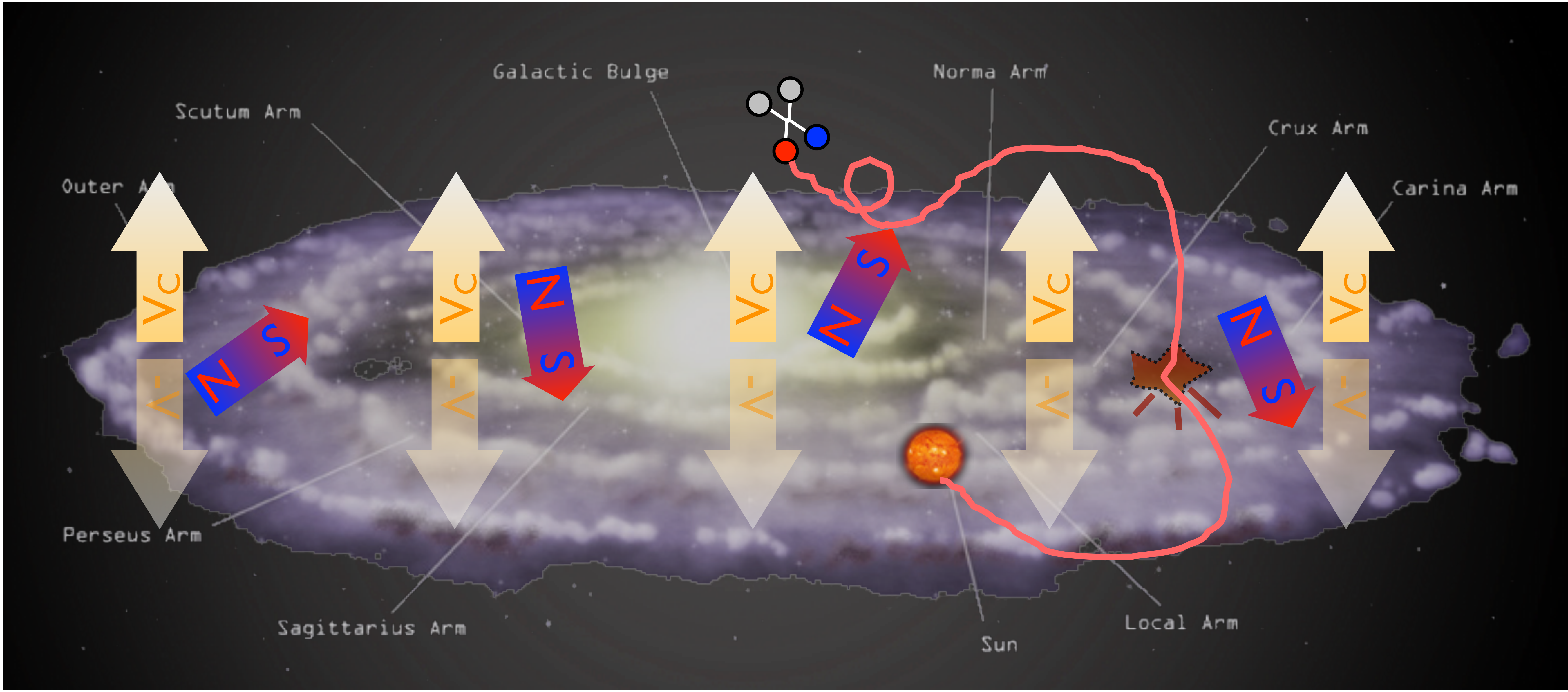
line of site



this ‘simple’ picture holds for photons and neutrinos!

Indirect detection — basics: the DM signal

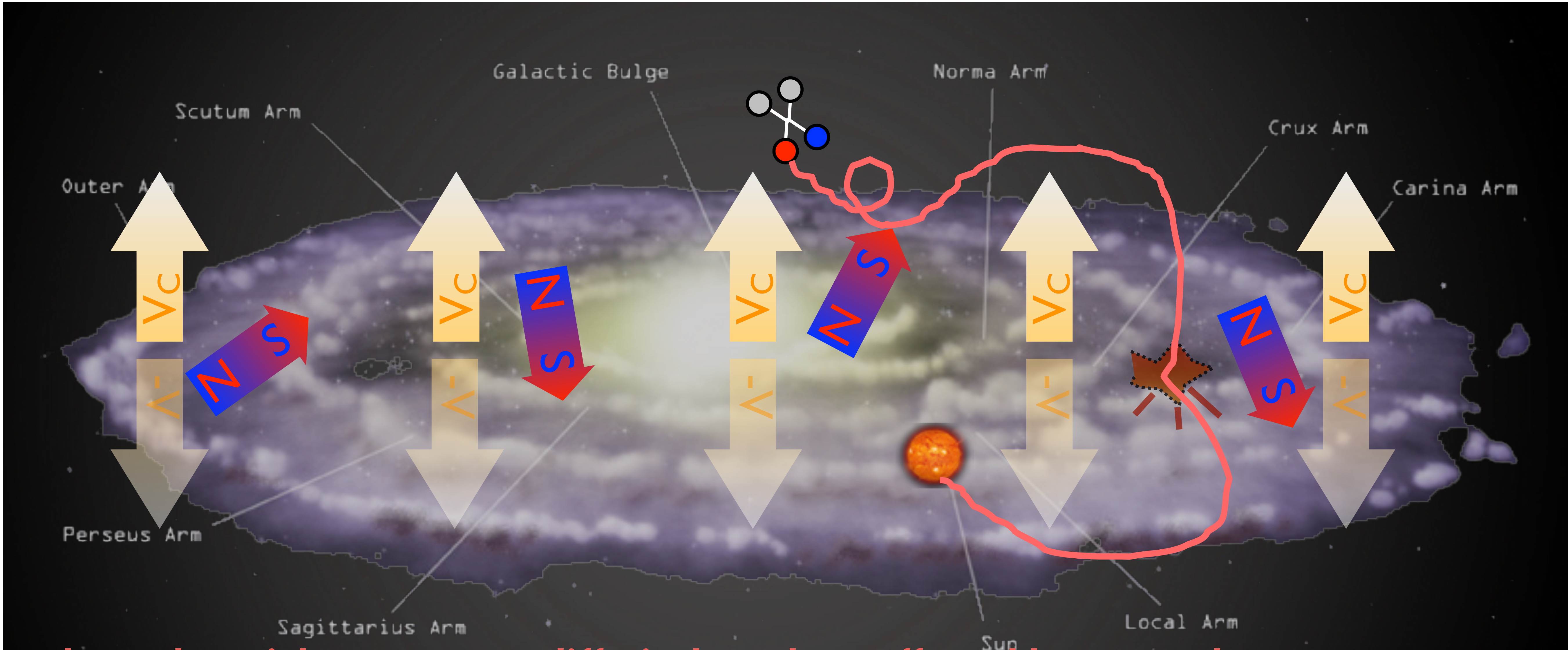
charged messengers: interact with the Galactic medium and fields!



[adapted from: M. Cirelli]

Indirect detection — basics: the DM signal

charged messengers: interact with the Galactic medium and fields!



charged particles propagate diffusively and are affected by energy losses!

Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maur
Brun... '90s, '00s

spectrum

$$\frac{\partial f}{\partial t} - K(E) \cdot \nabla^2 f - \frac{\partial}{\partial E}\left(b(E) f\right) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

diffusion energy loss convective wind source spallations

[uncert]

Indirect detection — basics: the DM signal

photons/neutrinos:

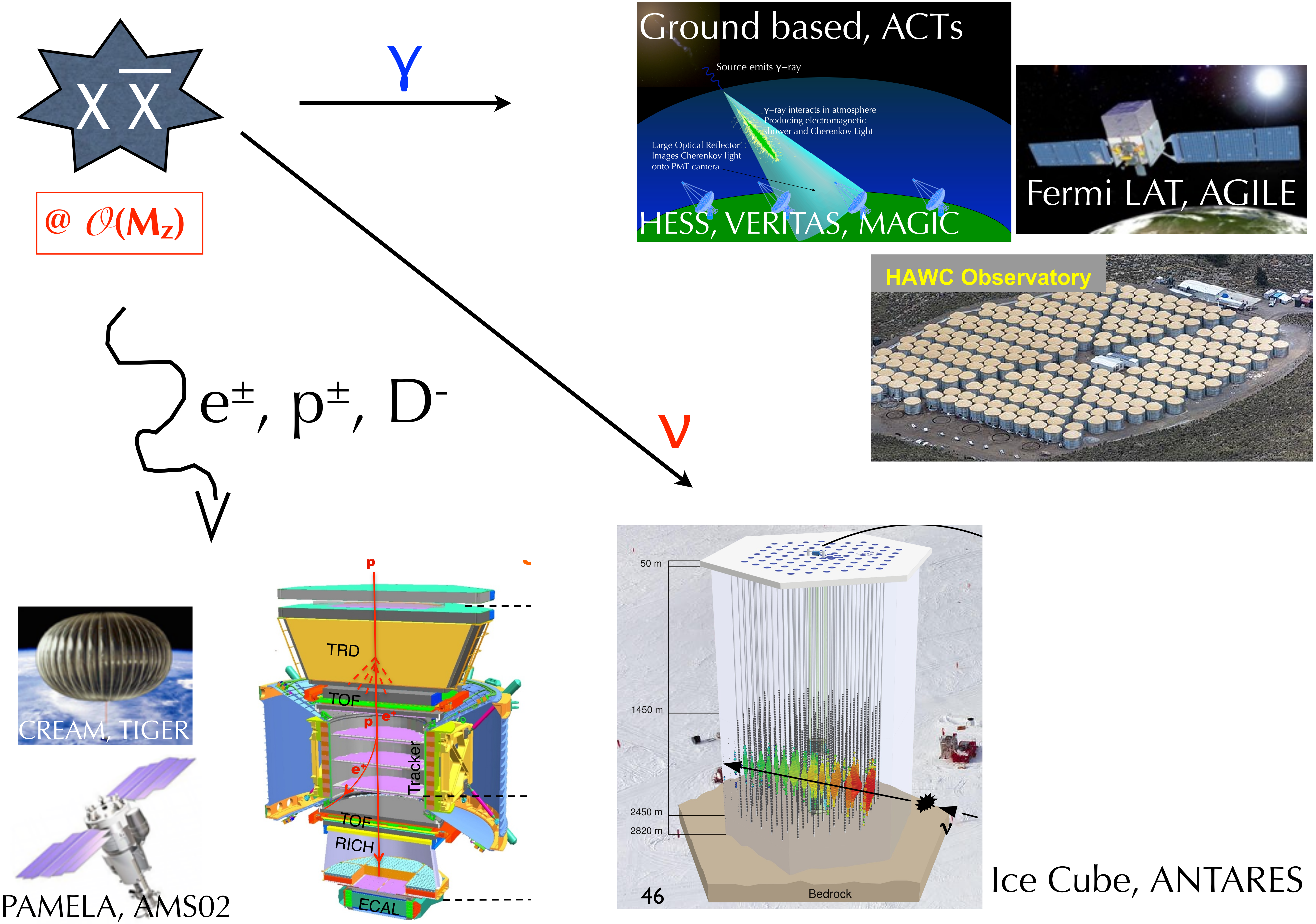
$$\boxed{\frac{\mathrm{d}\Phi(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma}} = \boxed{\frac{1}{4\pi}\;\frac{(\sigma_{\mathrm{ann}} v)}{2\, m_\chi^2}} \;\mathrm{X}\; \boxed{\sum_i \mathrm{BR}_i \frac{\mathrm{d}N_\gamma^i}{\mathrm{d}E_\gamma}} \;\mathrm{X}\; \boxed{\int_{\Delta\Omega} d\Omega \int_{\mathrm{los}} \mathrm{d}s\, \rho^2(s,\Omega)}$$

charged messengers

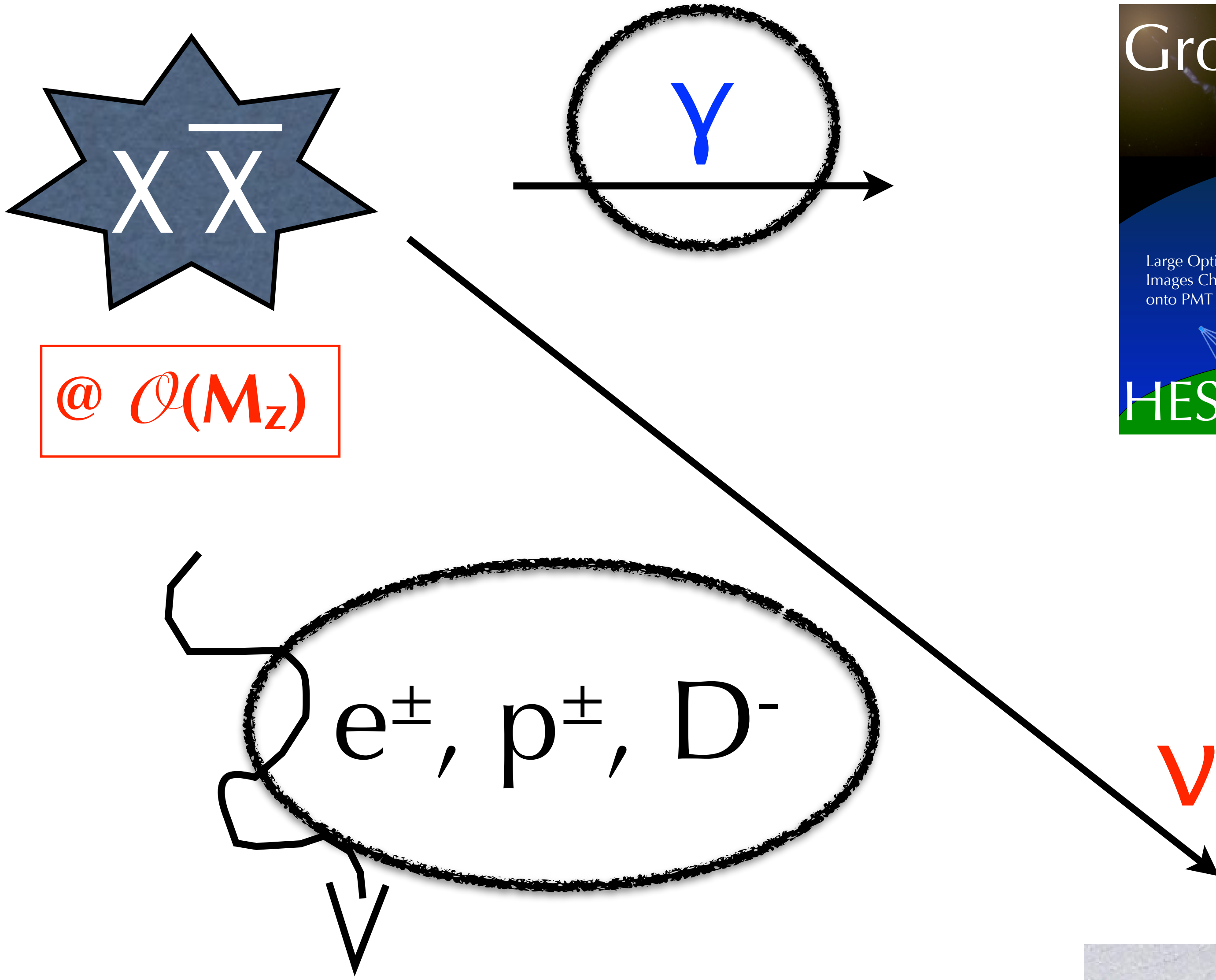
$$\boxed{\frac{\mathrm{d}\Phi(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma}} = \boxed{\frac{1}{4\pi}\;\frac{(\sigma_{\mathrm{ann}} v)}{2\, m_\chi^2}} \;\mathrm{X}\left(\boxed{\text{particle physics}} \;\mathrm{X}\; \boxed{\text{DM clustering}}\right)$$

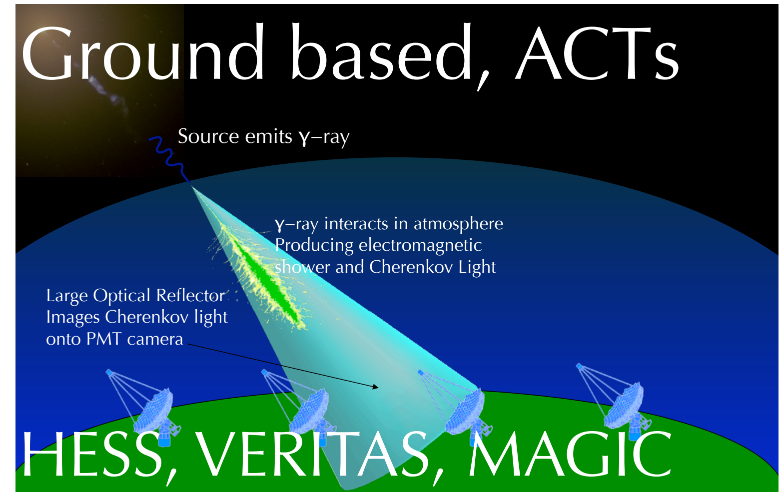
astrophysics

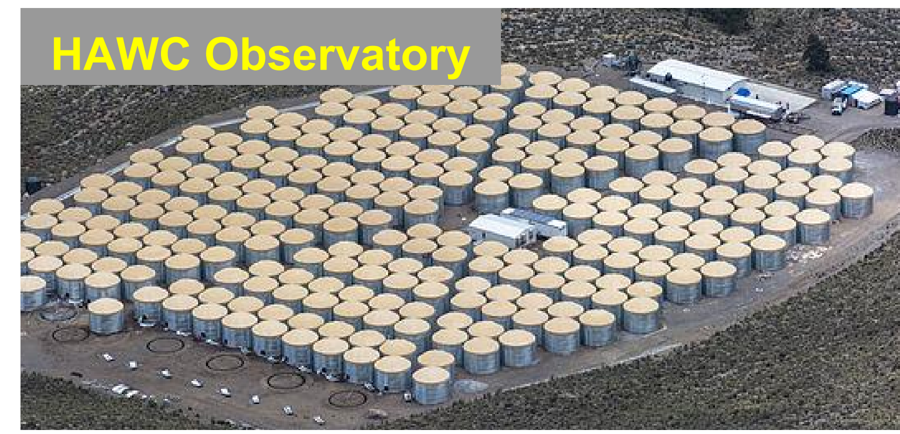
‘The Golden Age’



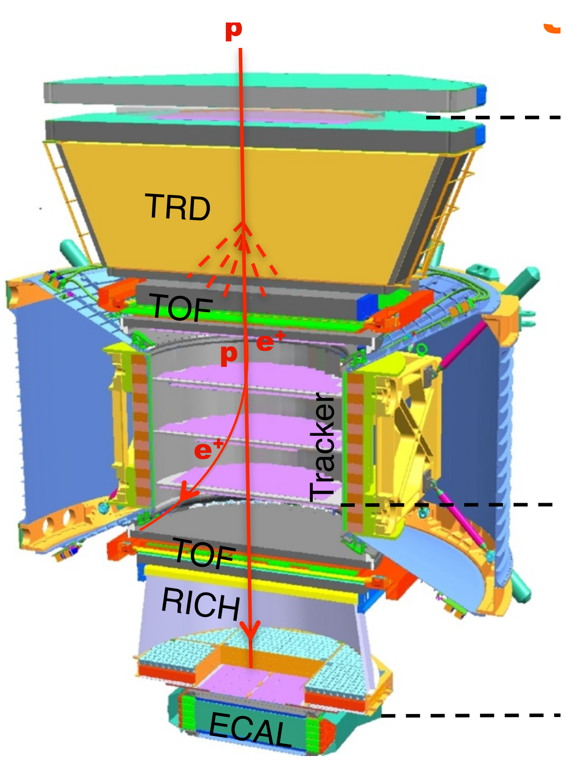
‘The Golden Age’

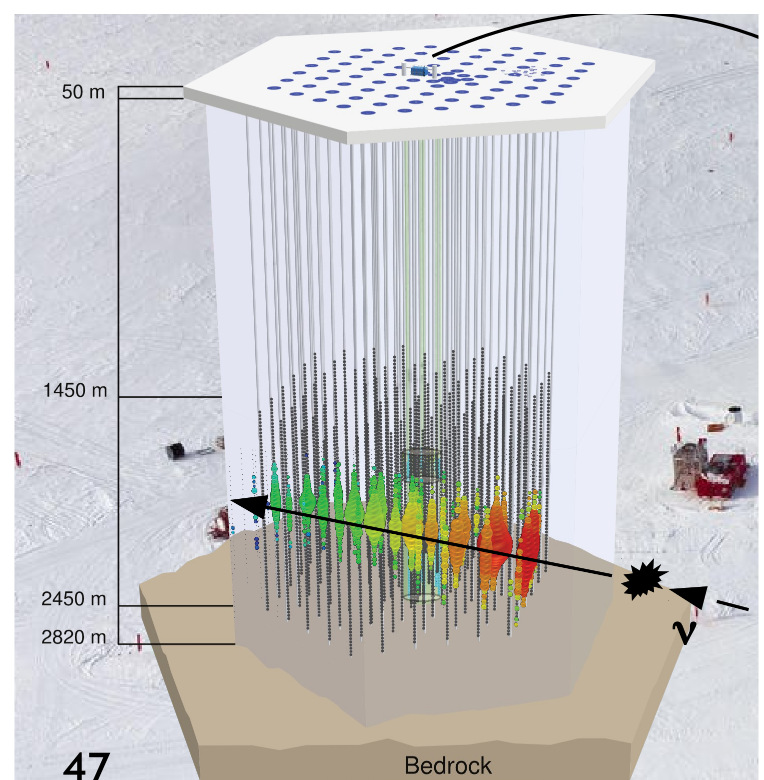






PAMELA, AMS02





Ice Cube, ANTARES

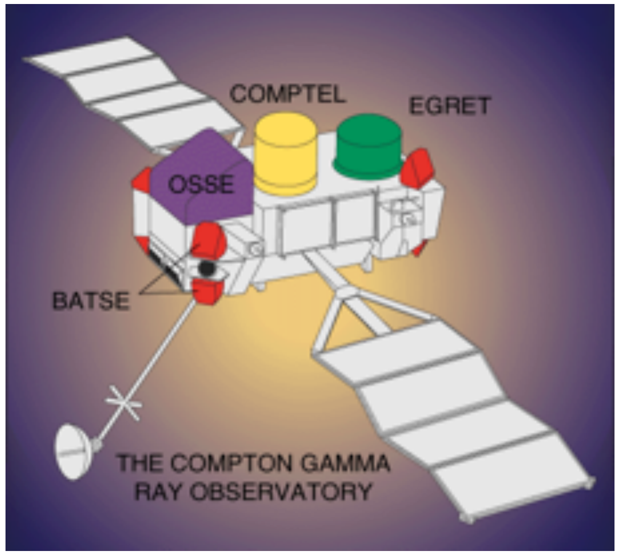
Gamma rays

EGRET *1991-2001*

Fermi LAT *2008-*

AGILE *2007-*

atmosphere is not transparent to gamma rays → ***satellites***



→ ***or ground based:***

i) Imaging Atmospheric Cherenkov Telescopes

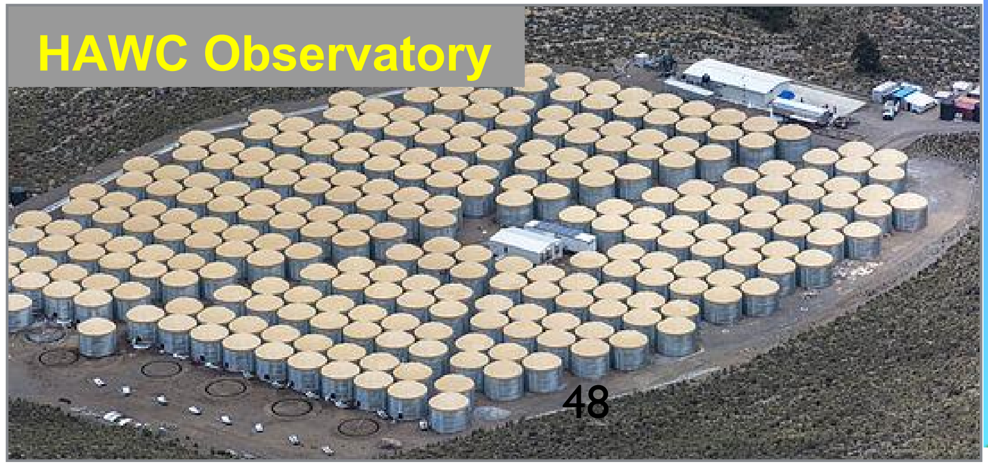
WHIPPLE 10m (1968-2013) - the beginning of gamma ray astronomy

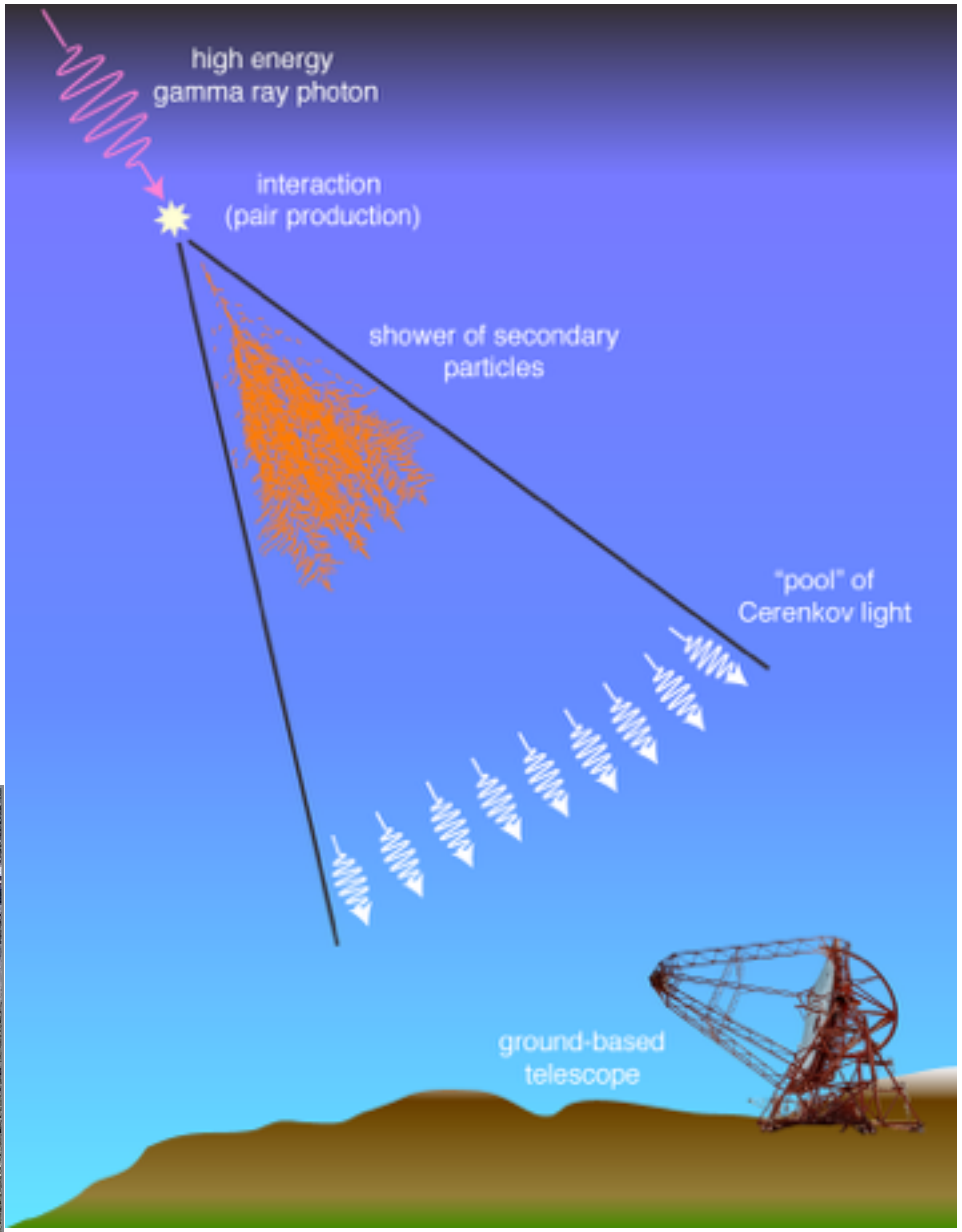
H.E.S.S. (2002 -), ***MAGIC*** (2004 -), ***VERITAS*** (2007 -)

ii) Air shower arrays ('buckets of water')

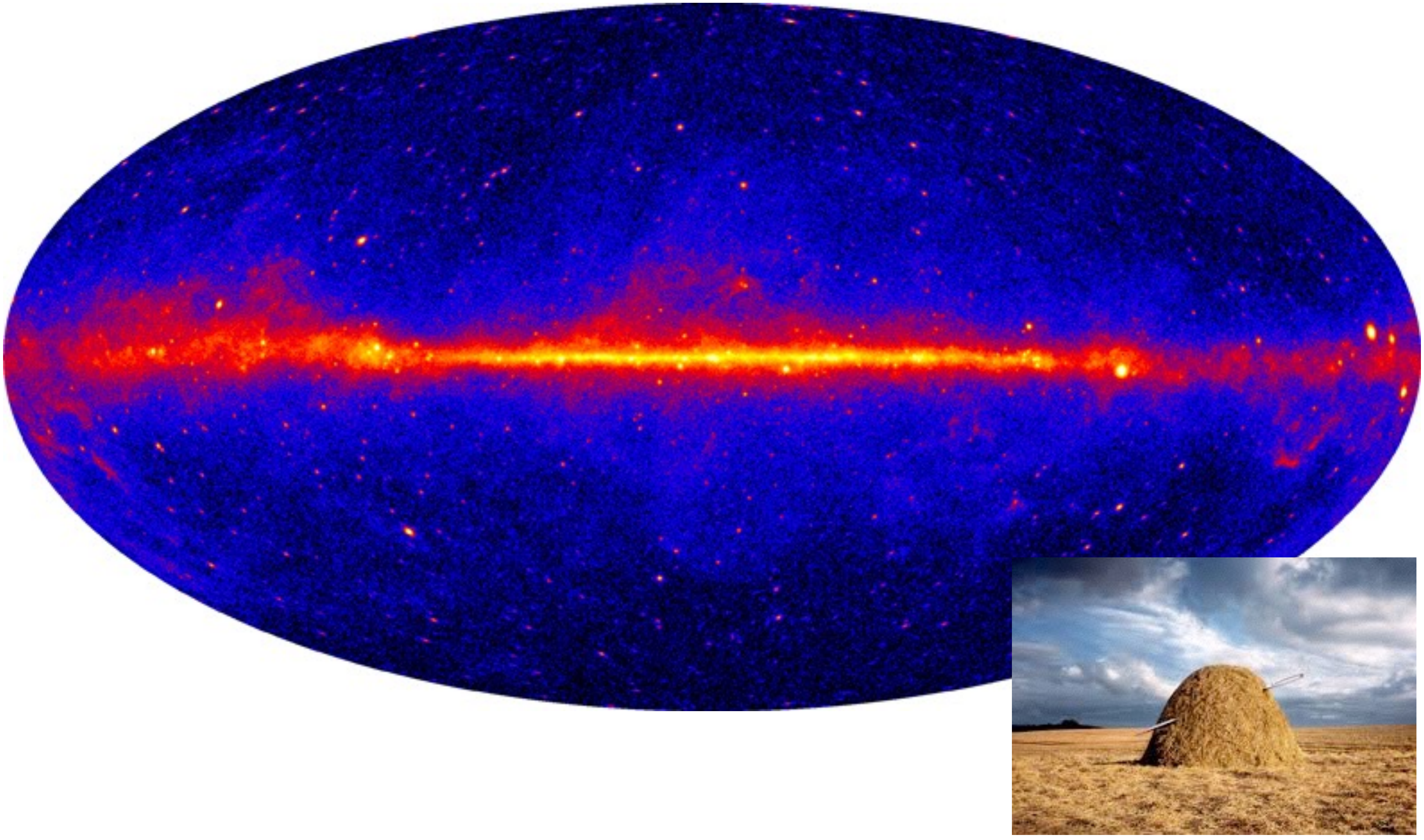
MILAGRO (2001-2008)

HAWC (2010 -)





The Fermi LAT sky

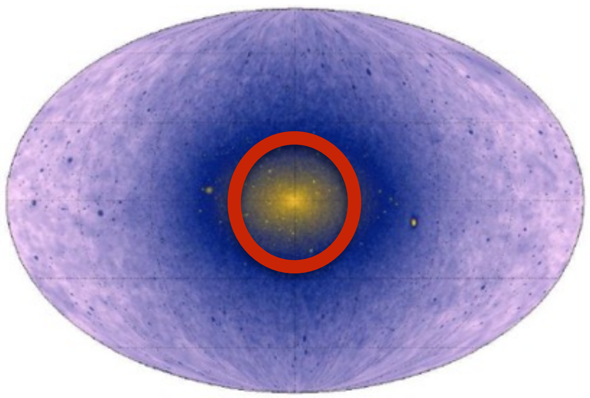


Strategies

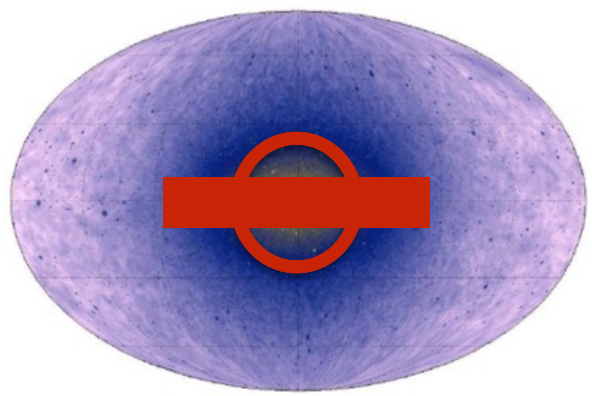
DM spectra should be universal across the targets
- multi-target and multi-messenger strategy!

signal strength

GC

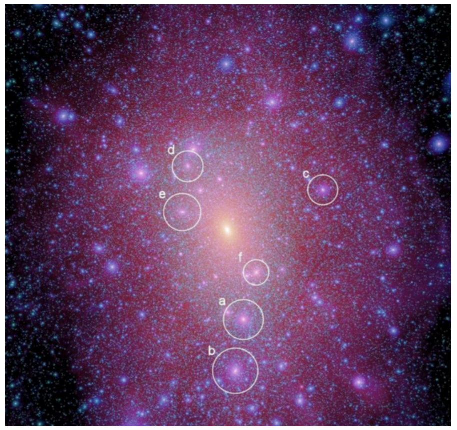


GC halo

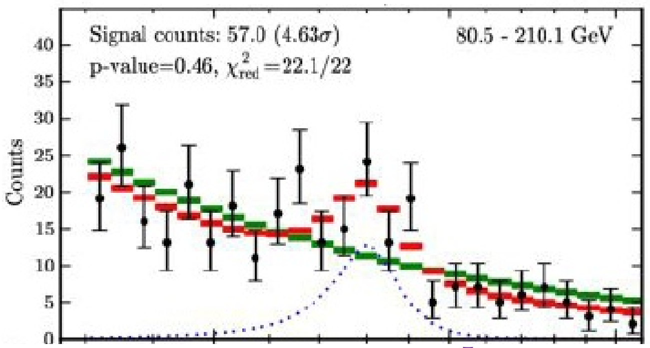


. . .

dwarf satellites



spectral line



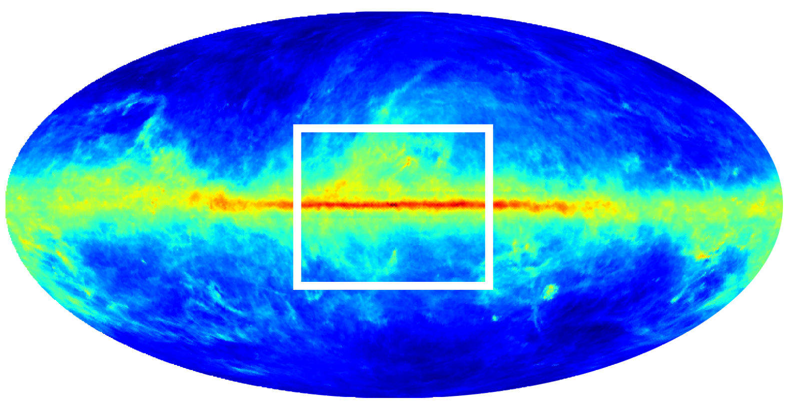
robustness

[adapted from: H.-S. Zechlin]

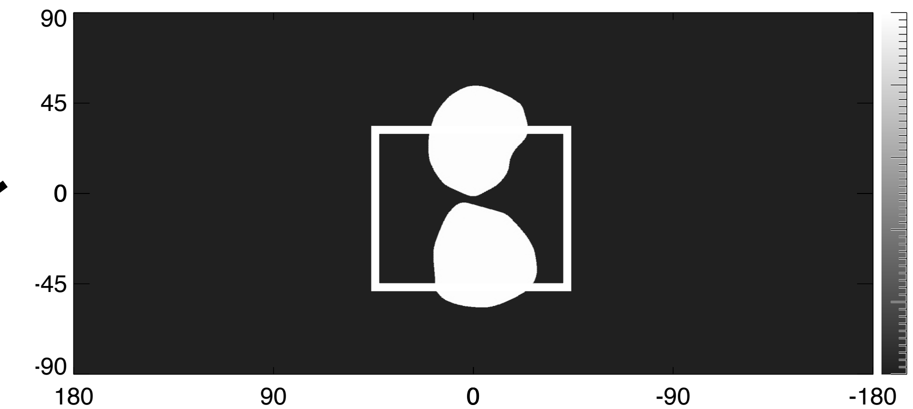
Example: DM search in the inner Galaxy

general approach

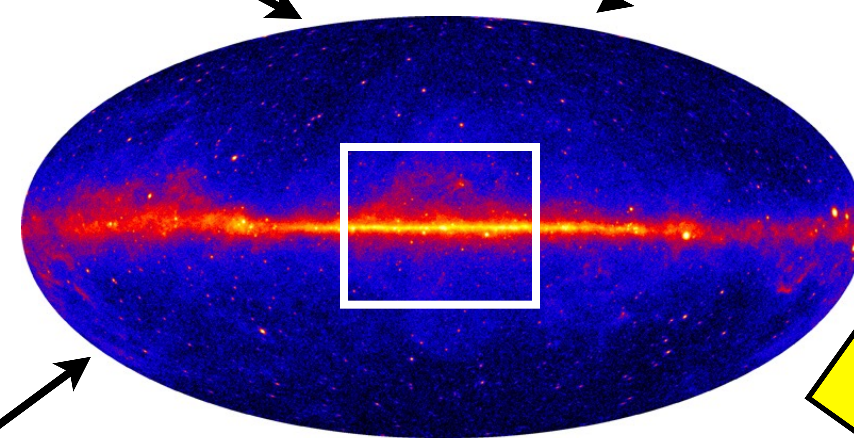
apply ***template fitting*** procedure to the inner ~<20 deg with addition of the FBs



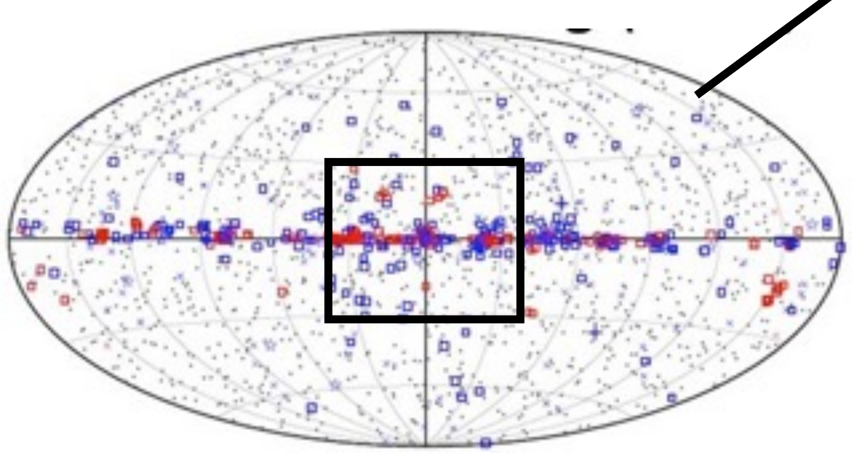
model(s) of the diffuse emission



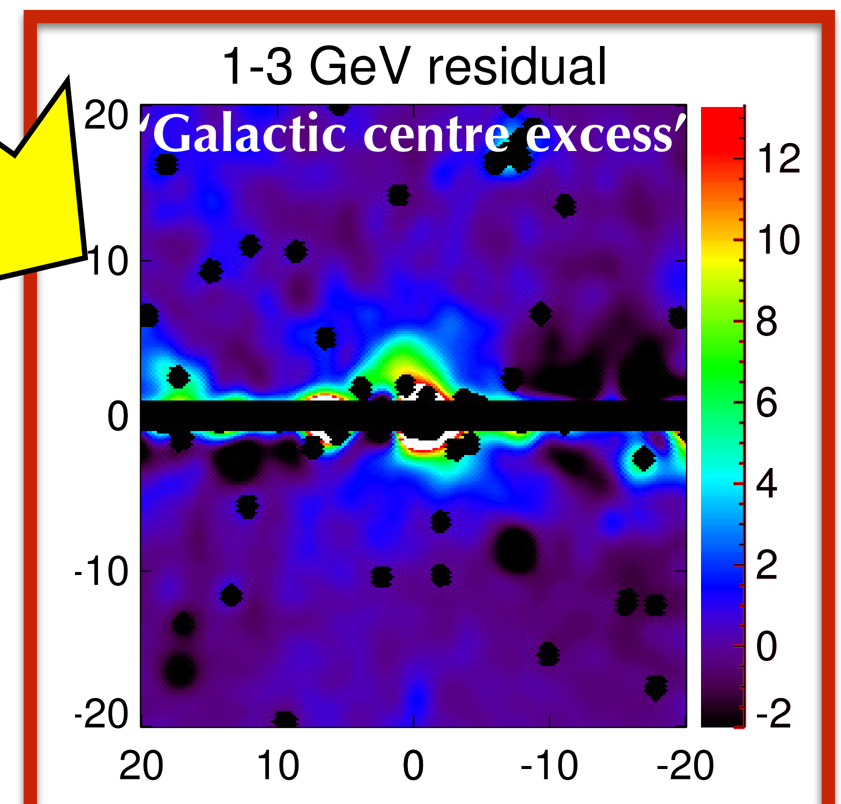
uniform-brightness template for the Fermi Bubbles



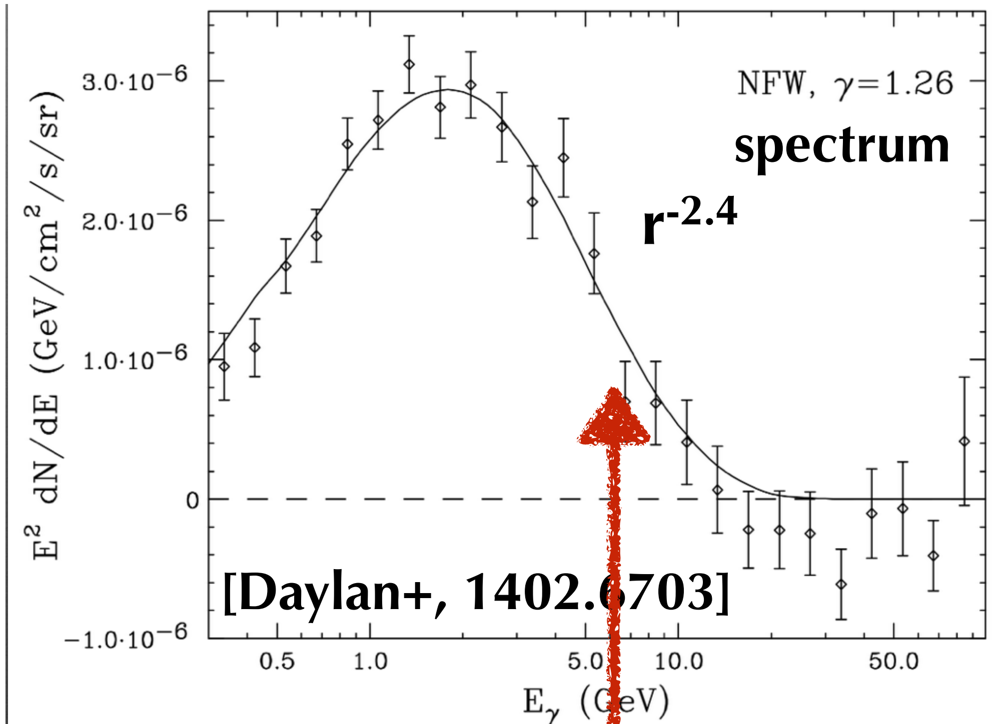
LAT data

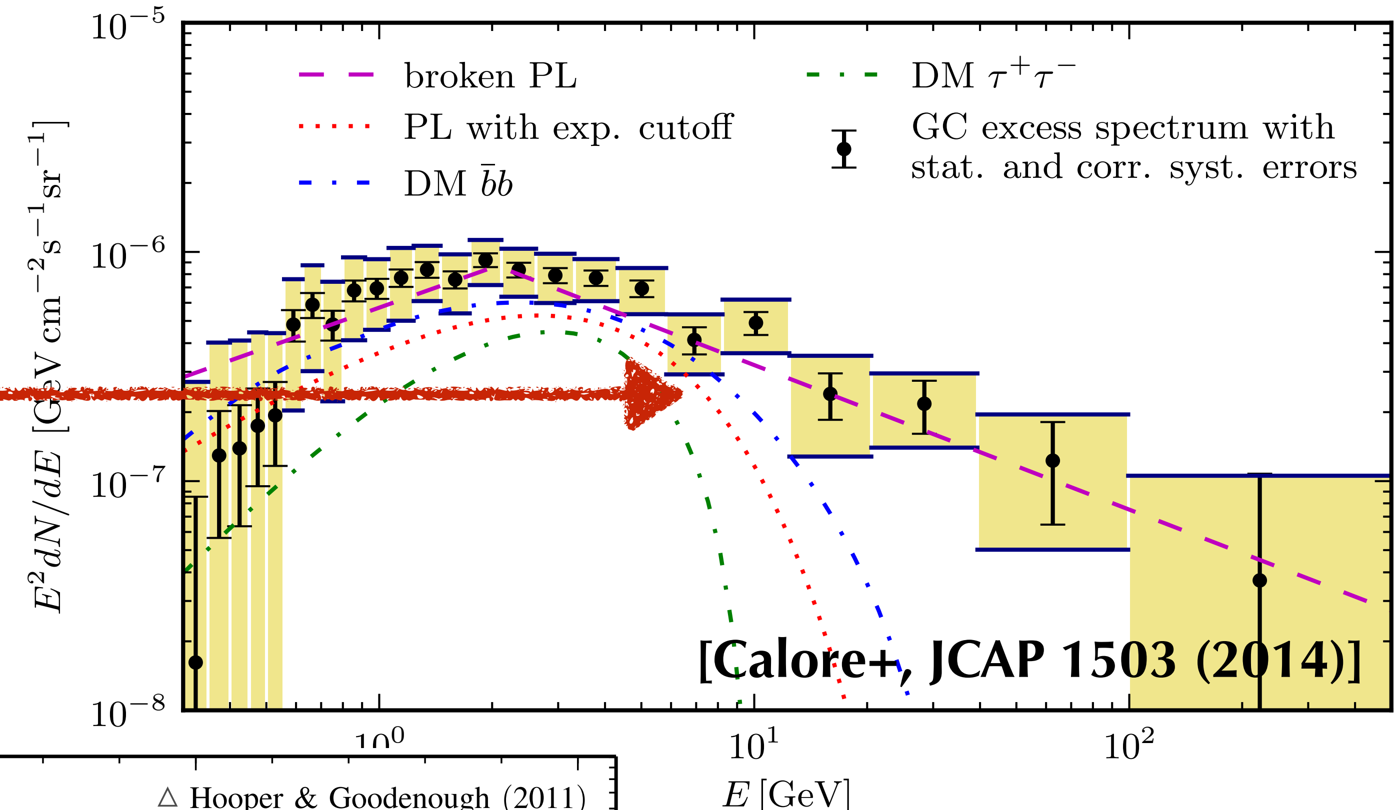


point sources from the catalog



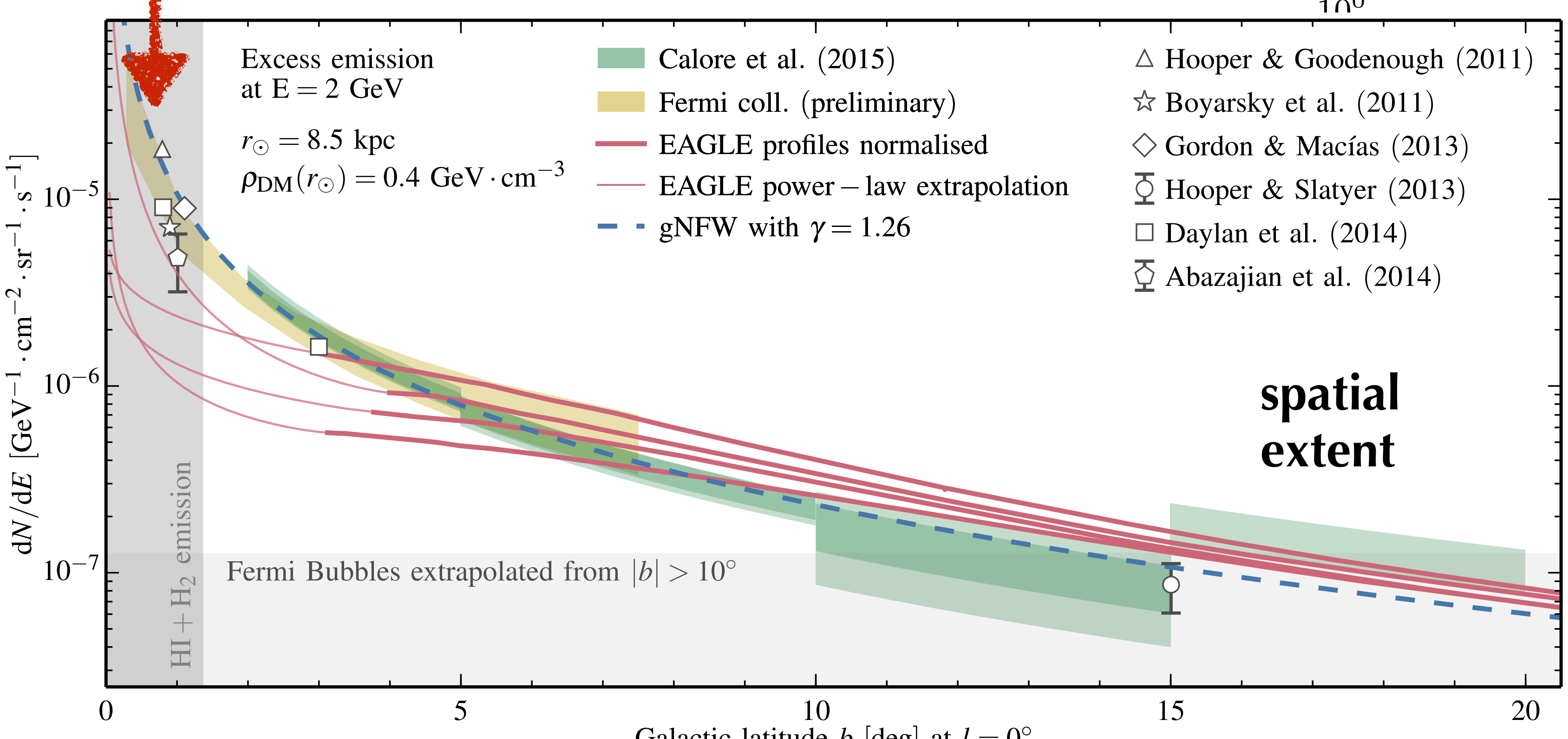
Many works reaching similar results: Vitale & Morseli (2009), Goodenough & Hooper (2009), Hooper & Goodenough (2011, PLB 697 412), Hooper & Linden (2011, PRD 84 12), Abazajian & Kaplinghat (2012, PRD 86 8), 1207.6047, Hooper & Slatyer (2013, PDU 2 118), 1302.6589 Gordon & Macias (2013, PRD 88 8) 1306.5725 Macias & Gordon (2014, PRD 89 6) 1312.6671, Abazajian et al. (2014, PRD 90 2) 1402.4090, Daylan et al. (2014) 1402.6703, 1407.5583 1407.5625 1410.1527

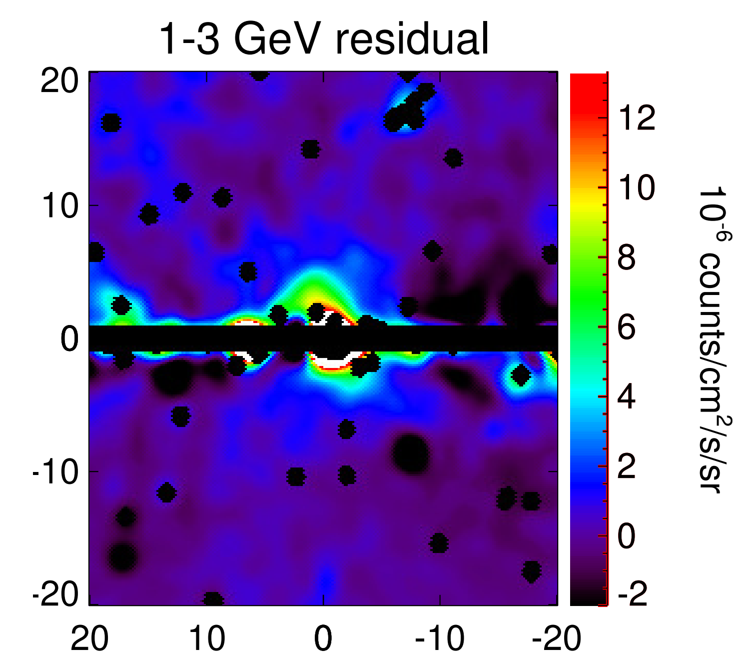




DM spectral fits

DM morphology



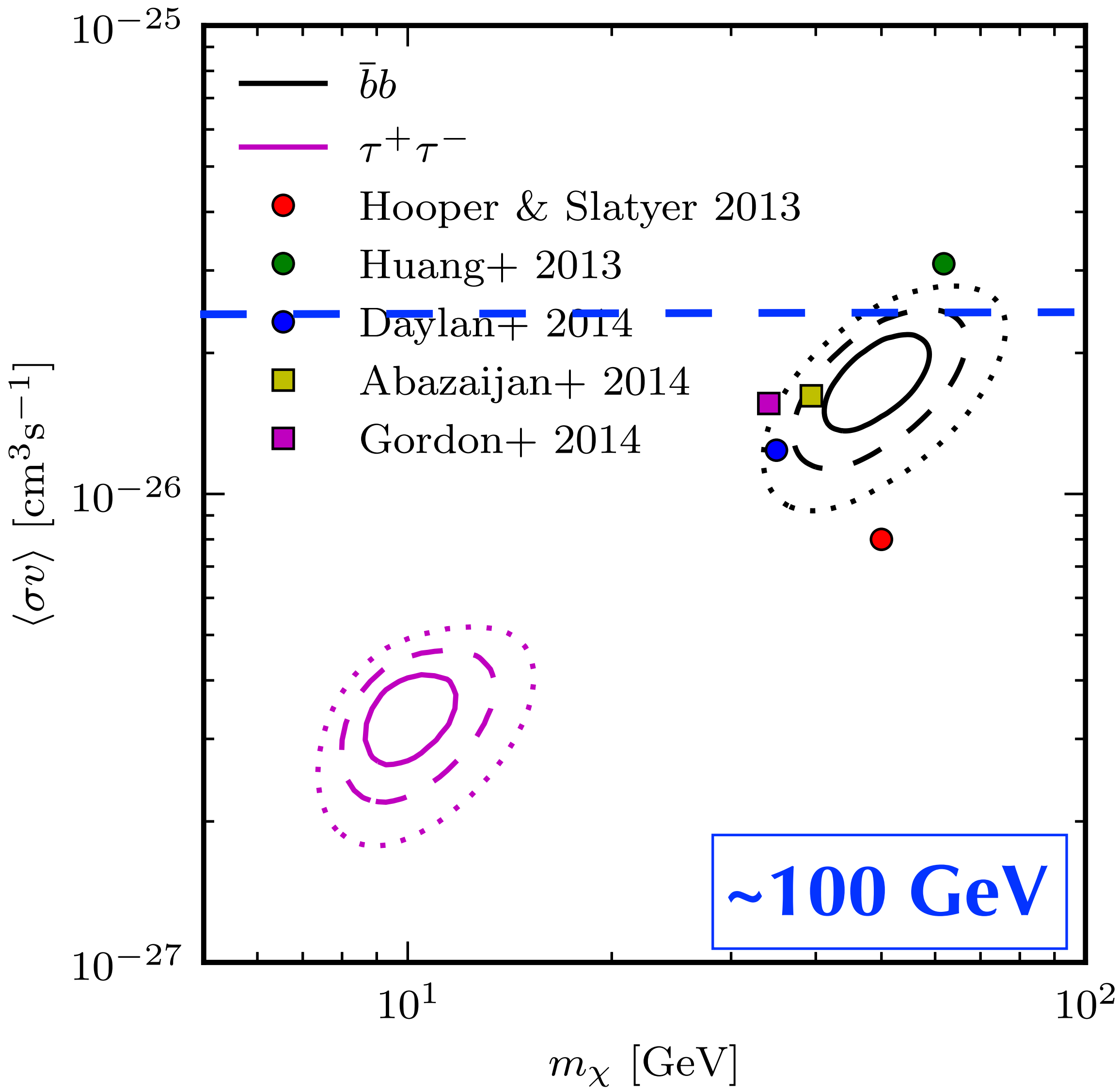


Could it be dark matter?

Right on the spot where WIMP DM is supposed to be!

~thermal cross section

$\langle \sigma v \rangle_{thermal}$.

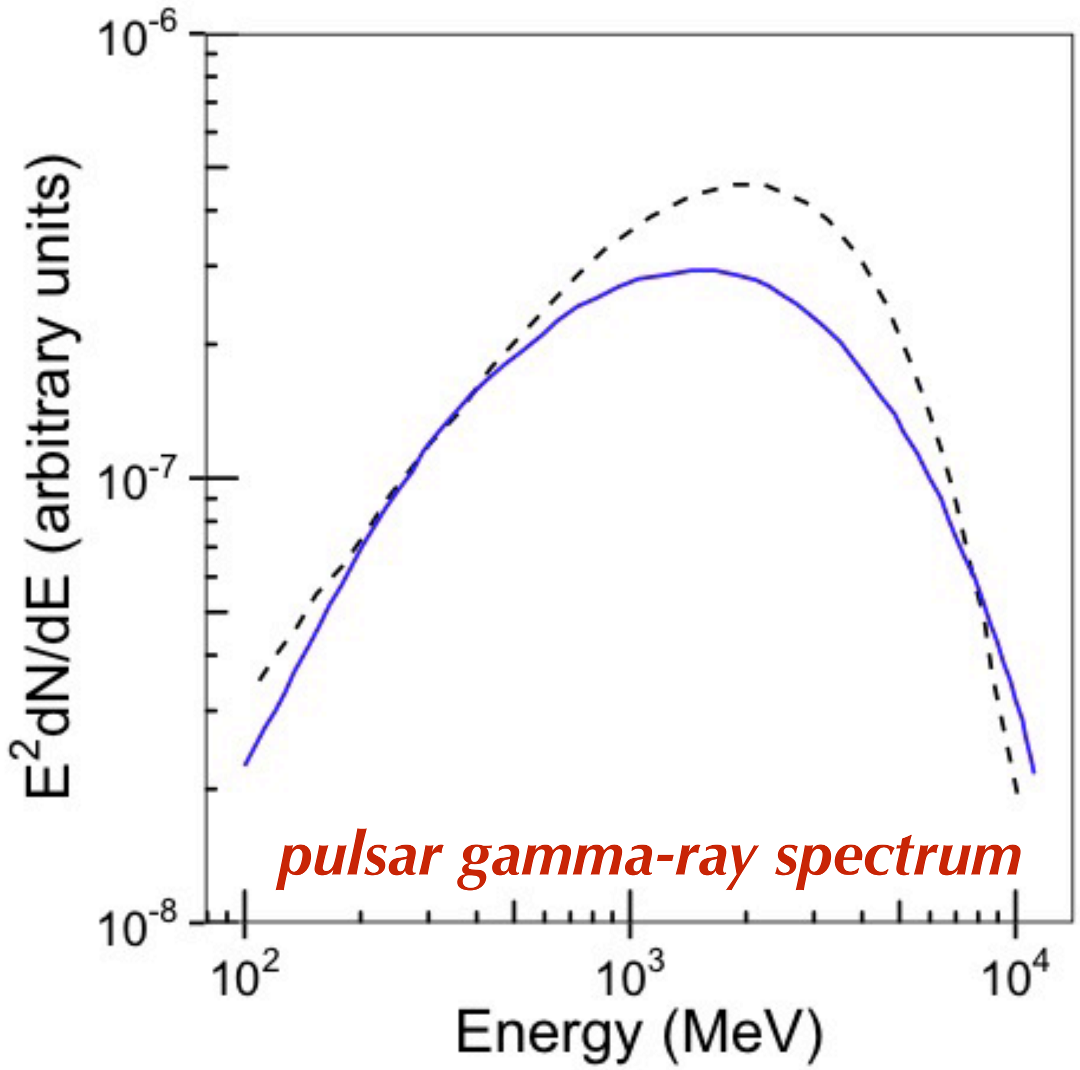


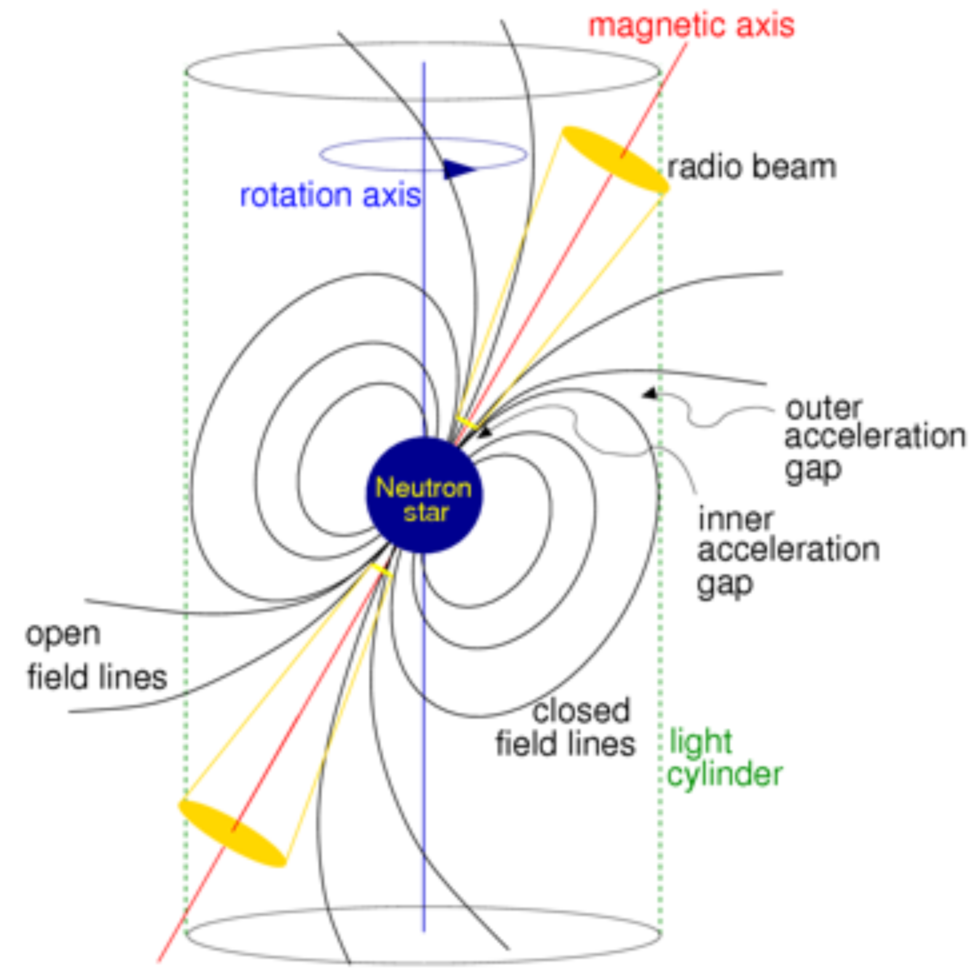
γ

Thermal cross section & <~100 GeV & at the Galactic center
Spatial distribution close to the predicted NFW profiles.

Or…

Spectral twins: Pulsar/DM Annihilation (30 GeV bb channel)



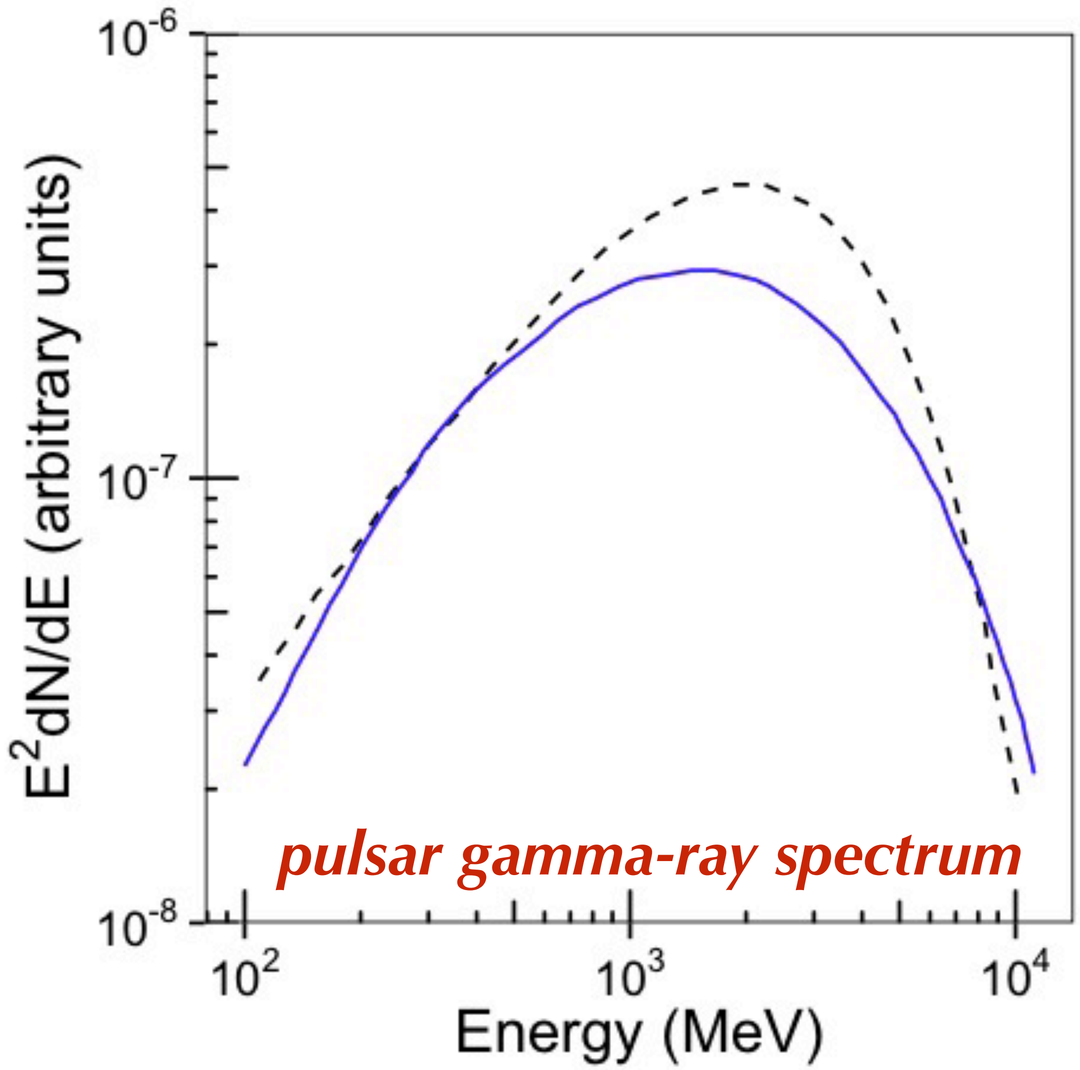


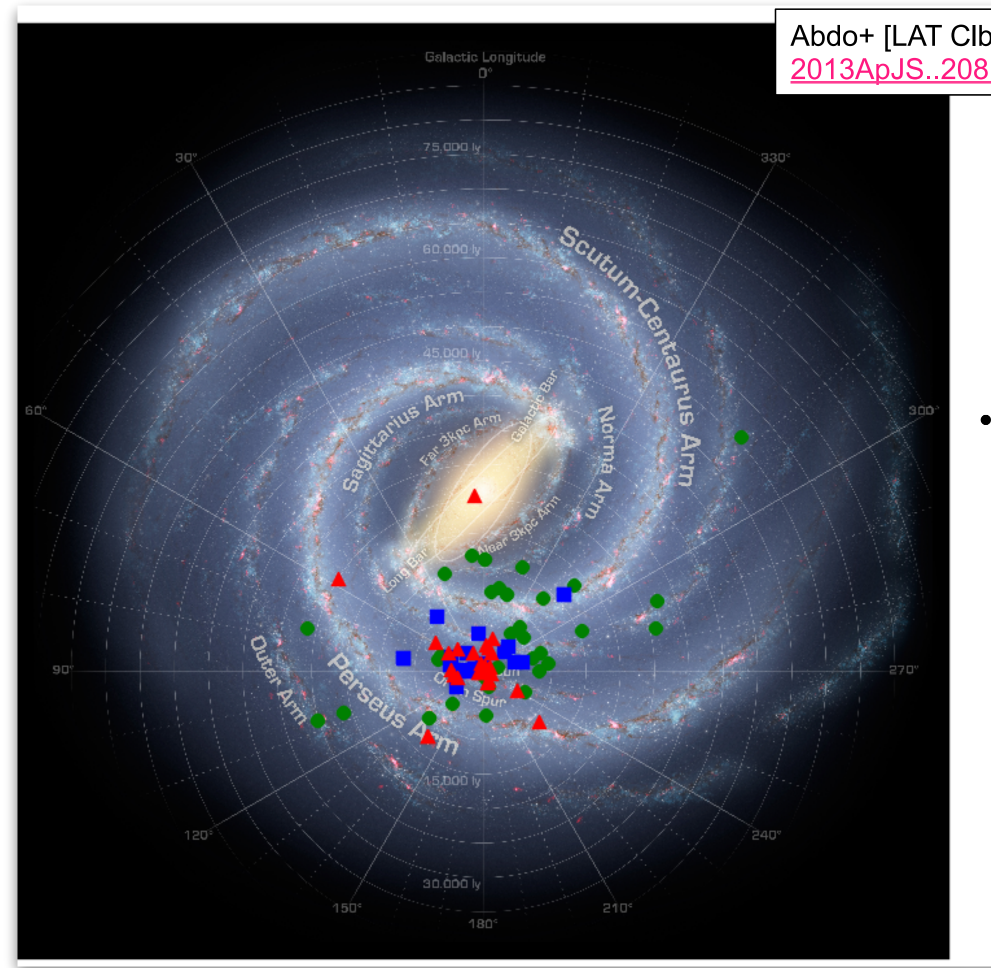
Baltz et al (2007)

But, only a handful gamma-ray pulsars known pre-Fermi LAT.

Or…

Spectral twins: Pulsar/DM Annihilation
(30 GeV bb channel)





Baltz et al (2007)

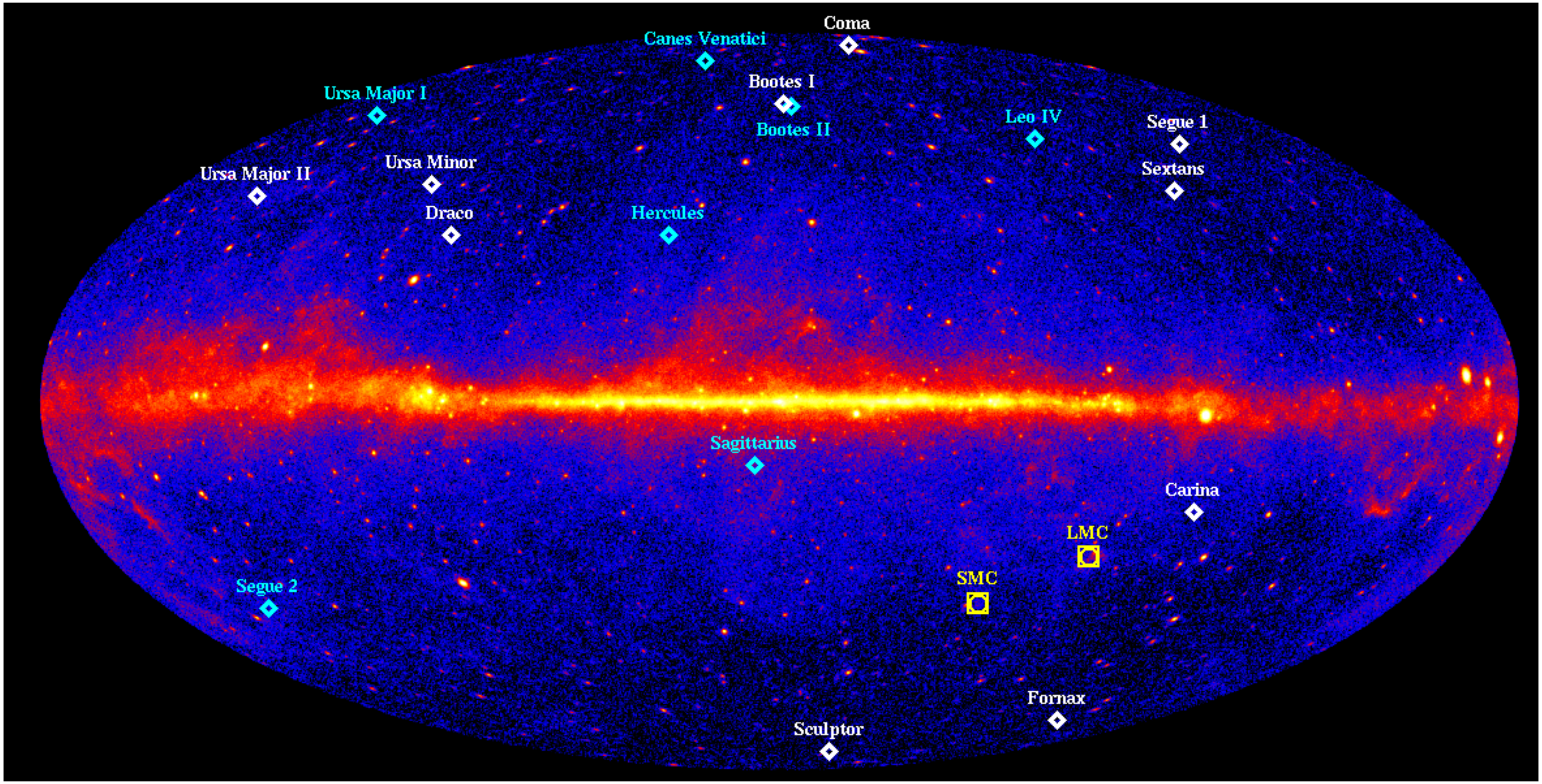
Fermi LAT discovered >100 pulsars in the galaxy
— the Galactic center signal could be coming from them.

How can we test?

multi-target and multi-messenger strategy

Look elsewhere! — Dwarf spheroidal galaxies

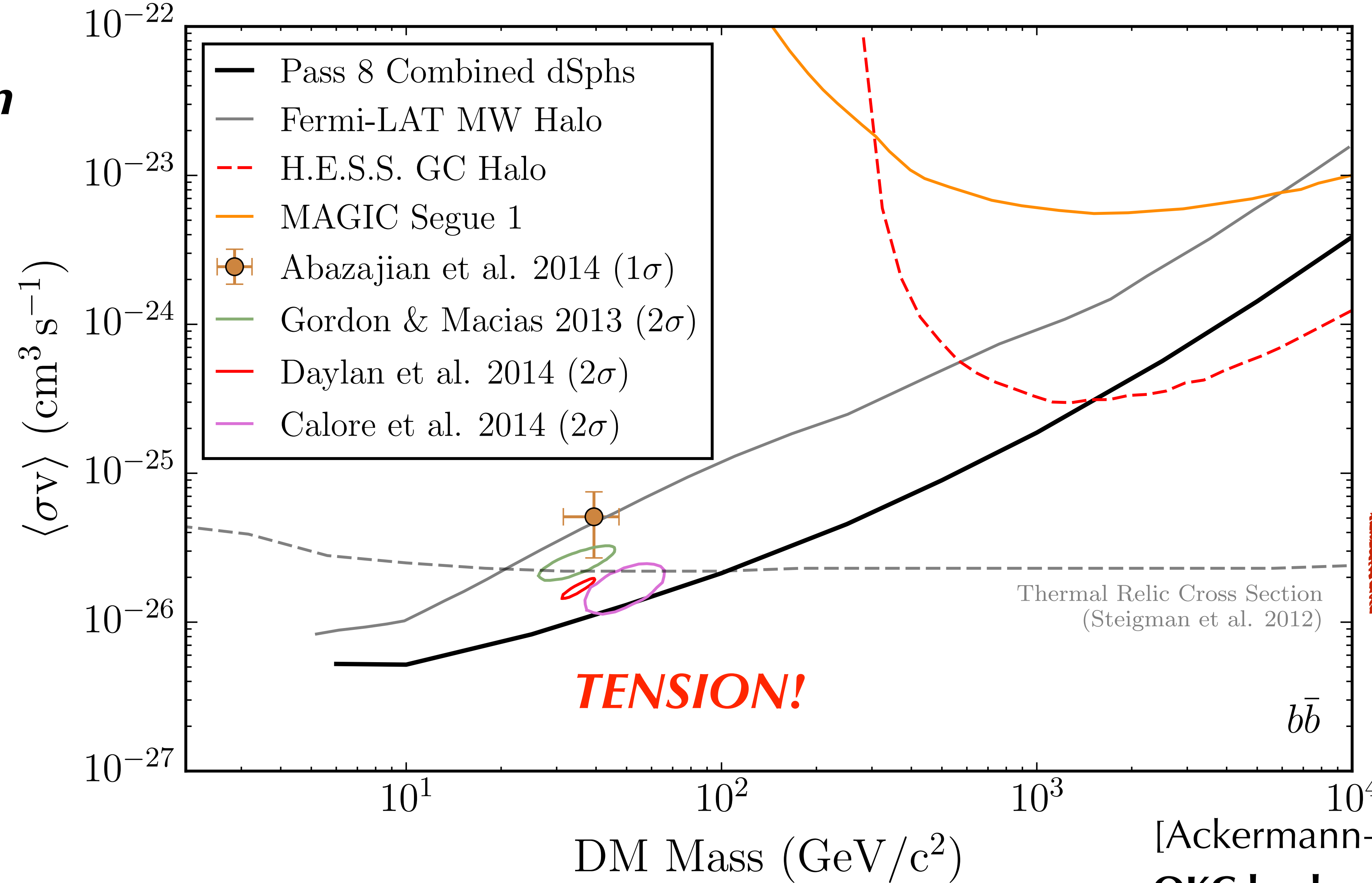
— Small 'satellite' galaxies of the Milky Way.
— Not observed in gamma rays (old, no current high-energy astro processes)



DM search in dwarf galaxies

IDEA: Combine info from **15 dSphs, taking into account the uncertainties in their DM content —> one of the strongest DM limits to date**

annihilation cross section



$\langle \sigma v \rangle$ *thermal*.

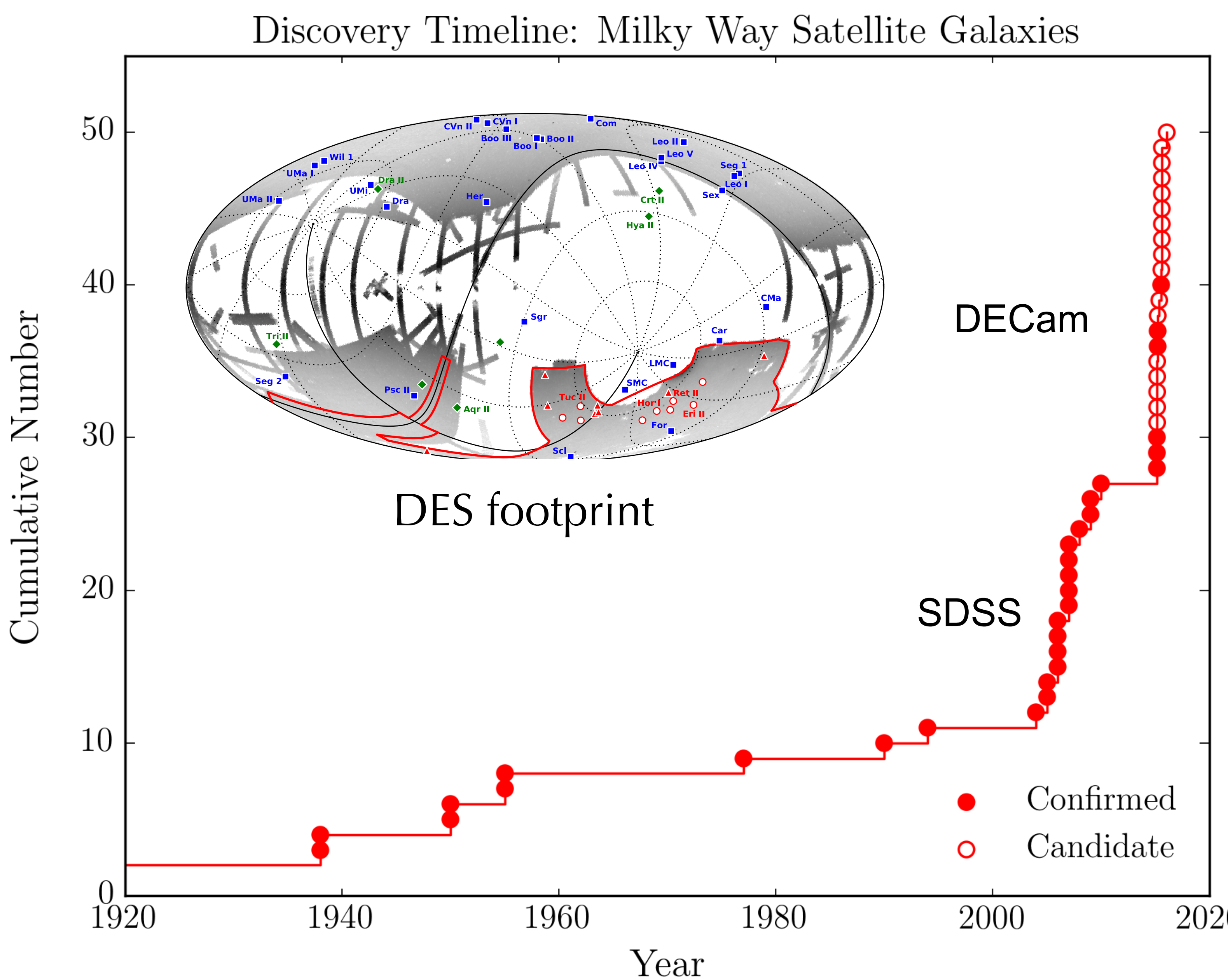
[Ackermann+, 1503.02641 **OKC lead analysis**]

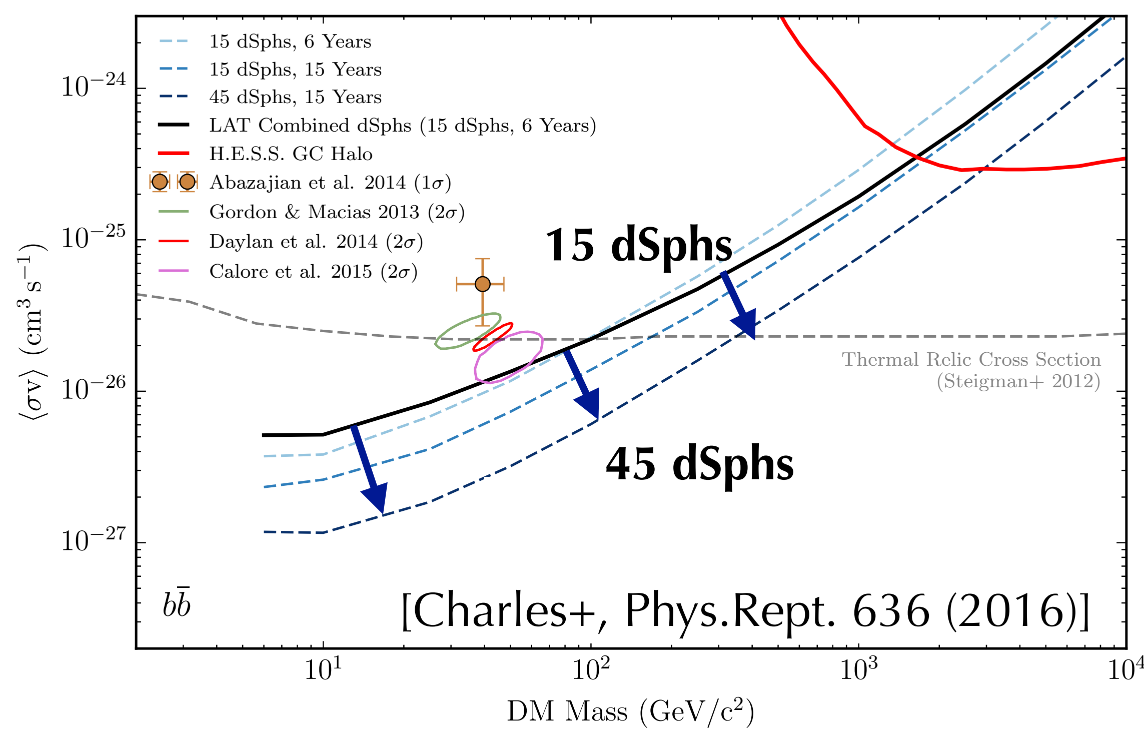
GCE dark matter origin in tension with complementary gamma ray observations

DM search in dwarf galaxies

More targets coming up!

>20+ new dSph candidates reported since 2015 (DES, PANSTARSS)



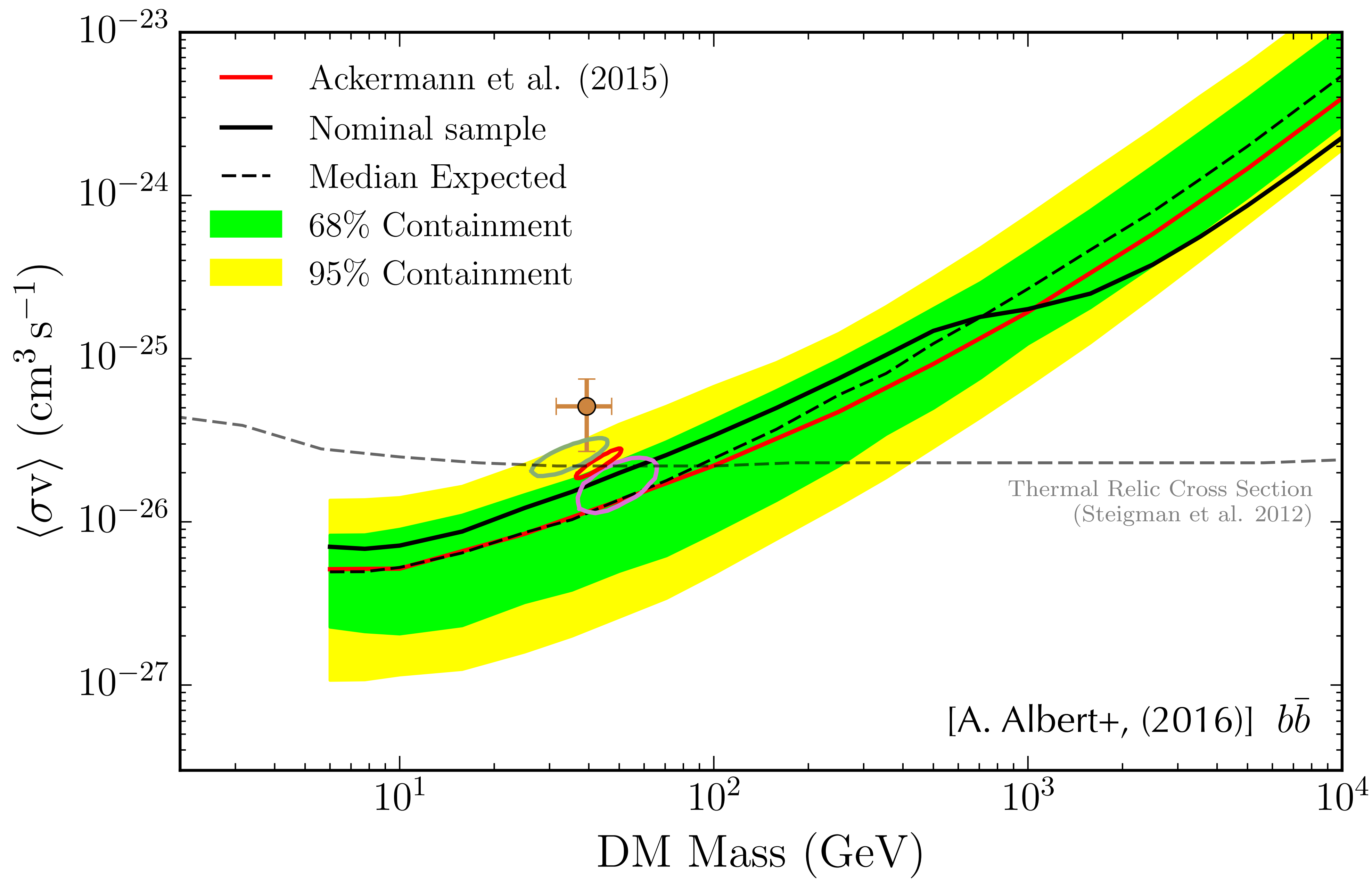


[Bechtol+ 1503.02584, Belokurov+, 1403.3406, Laevens+, 1503.05554]

[Gerringer-Sameth et al. 2015, Hooper & Linden 2015, Li et al. 2016]

DM search in dwarf galaxies

Recent analysis:



Increased sample of **45 dSphs, 28 kinematically confirmed** + 17 candidates.

LAT data coincident with **four** of the newly discovered targets show a ~**2σ (local) γ-ray emission in excess of the background**, weakening the limits by 1.5x at low masses.

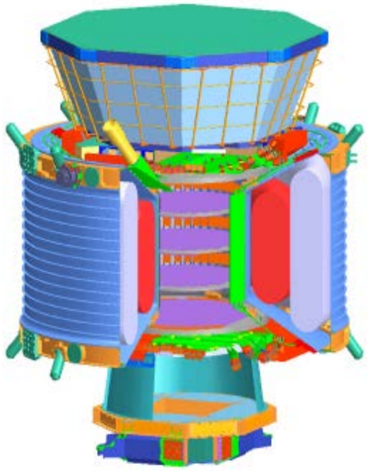
Charged Cosmic rays

at ~100 GeV energies measured by satellites and long duration balloon flights

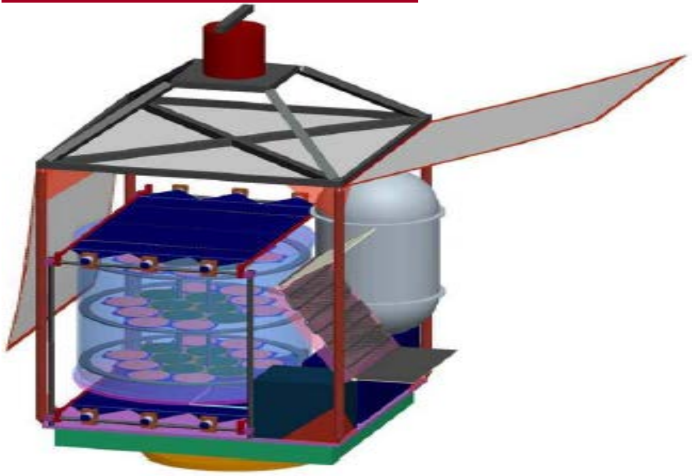
BESS LDBF
2004, 2007

PAMELA
2006-

AMS-02
2011-

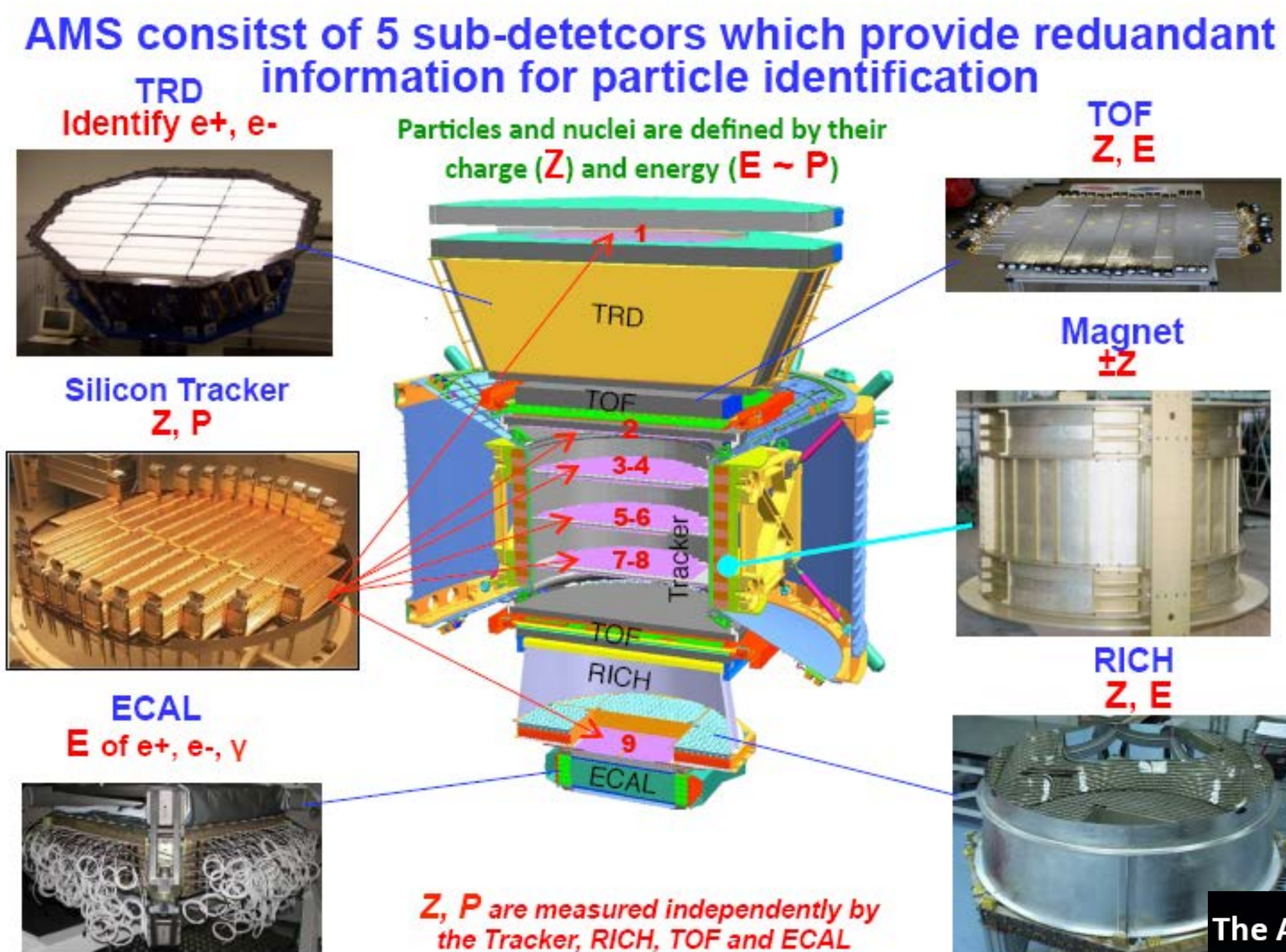


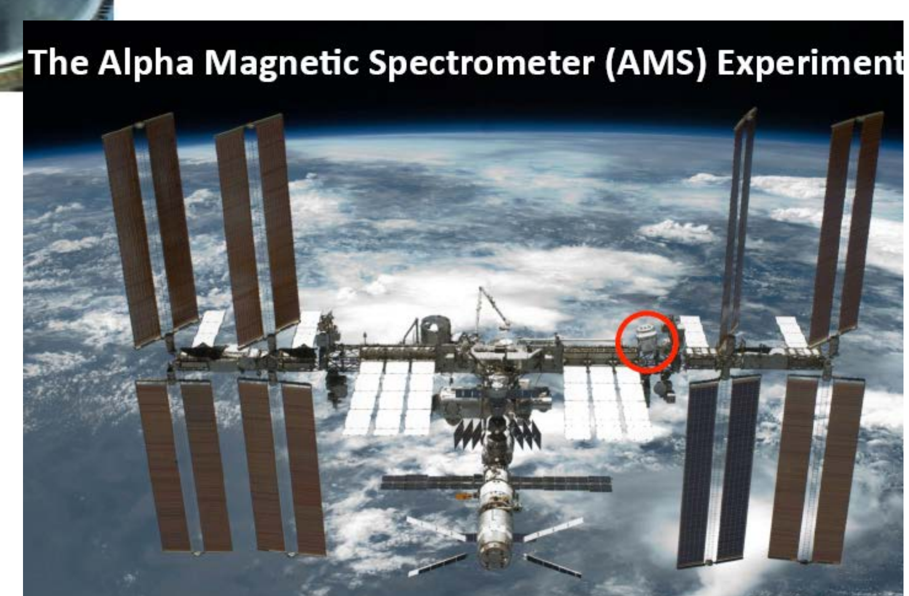
GAPS
2020?



Charged Cosmic rays

AMS Experiment on ISS

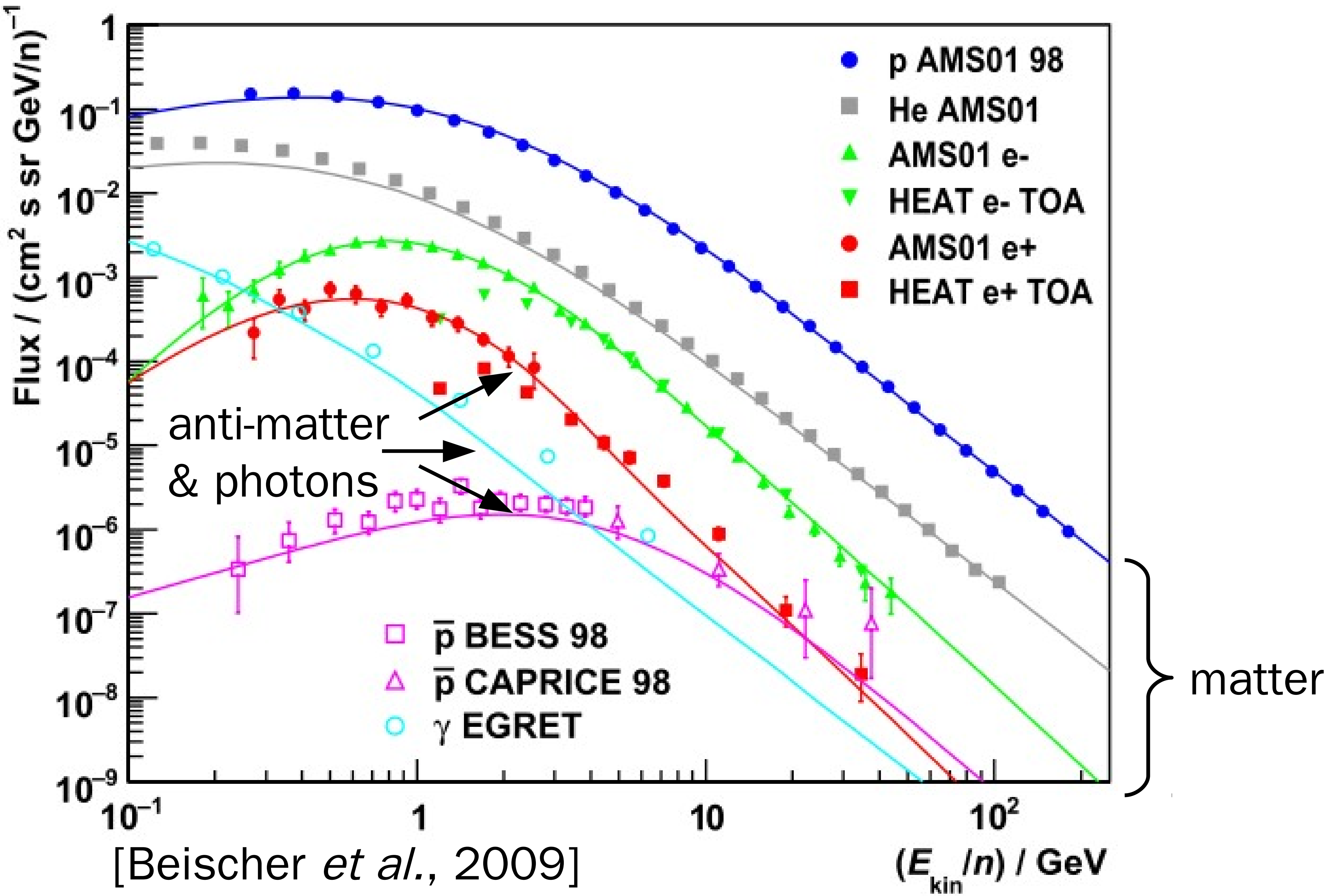




Charged Cosmic rays

Remember: no directional information, only local fluxes

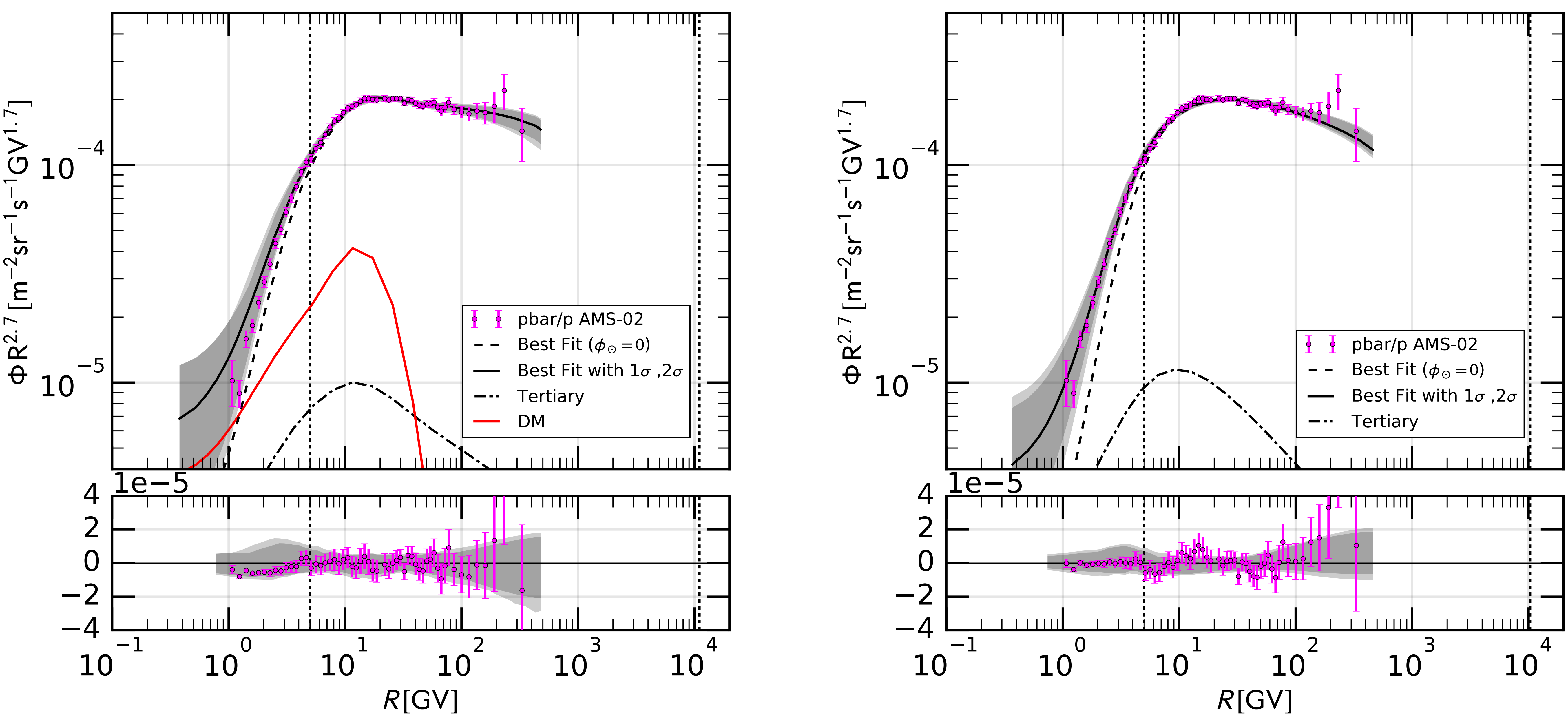
Main DM search strategy: look at **anti-particles**!



[Beischer *et al.*, 2009]

Charged Cosmic rays

example: anti-proton flux



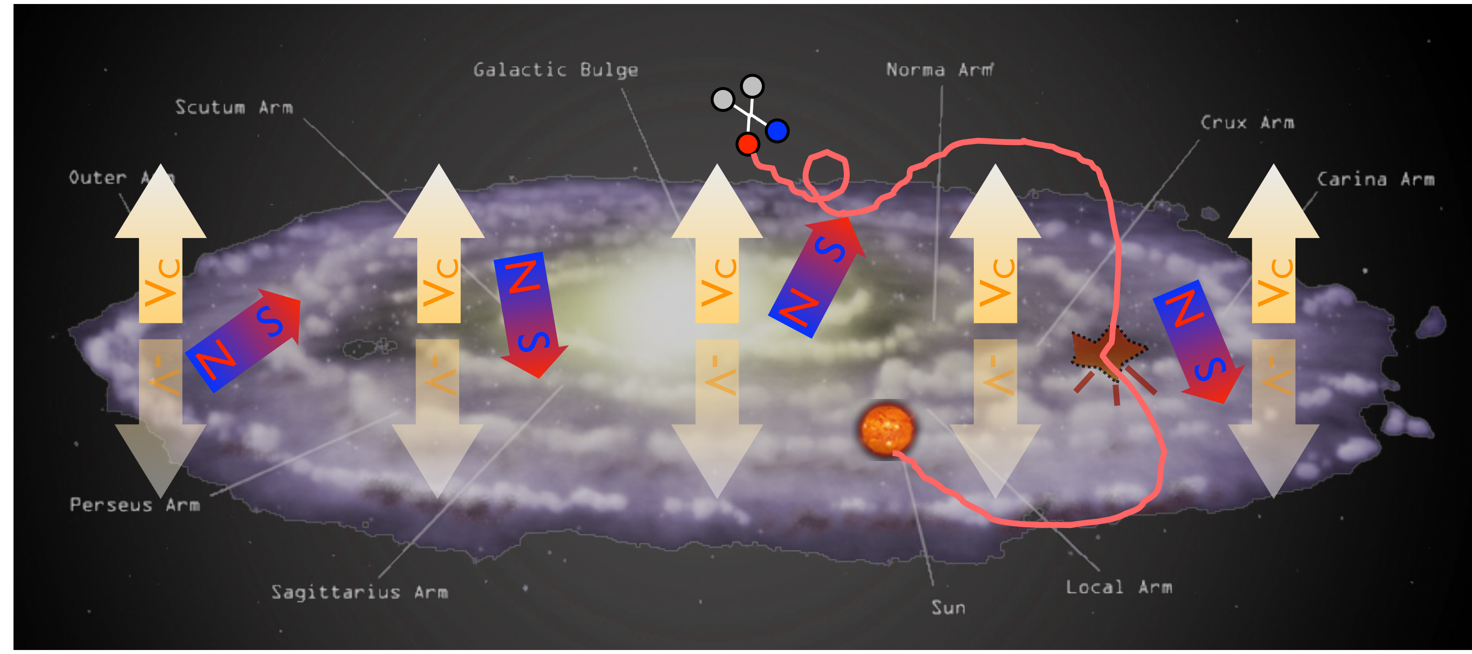
[Cuoco+, PRL 2017]

Charged Cosmic rays

Remember:

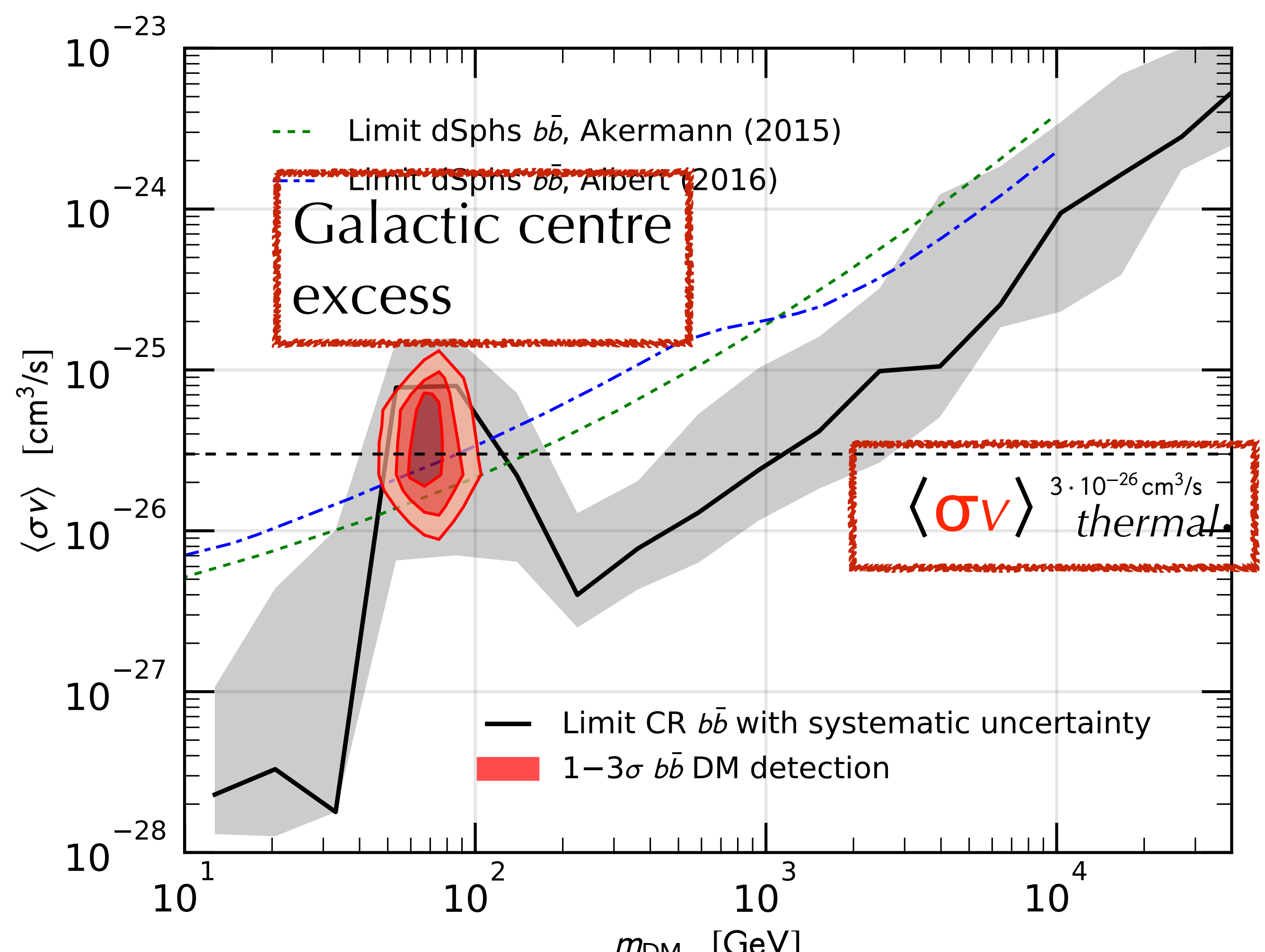
propagation of charged cosmic rays determined by many free parameters

—> significant uncertainties!



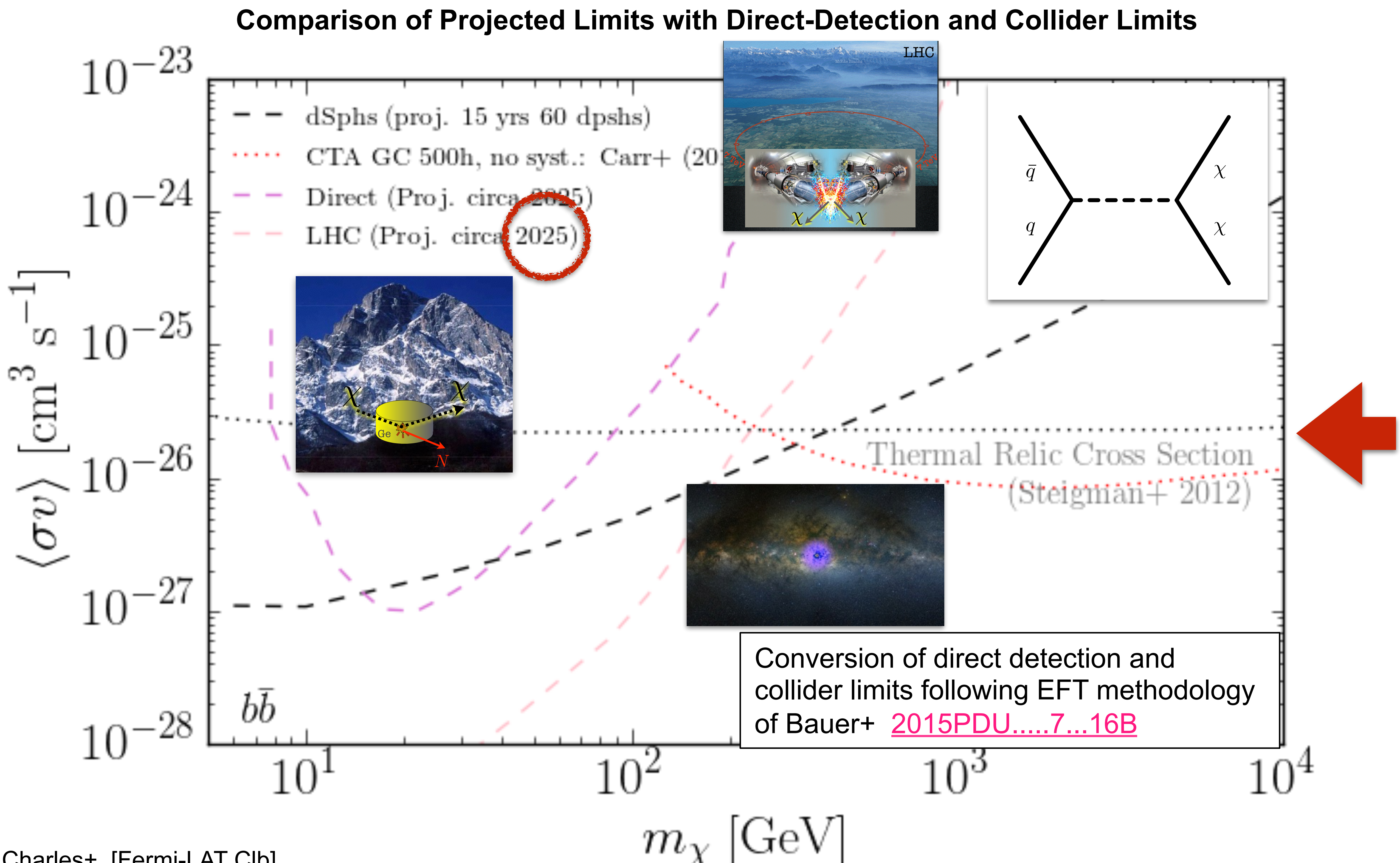
Propagation parameters		Fit without DM	Standard fit with DM	Fit range
$\gamma_{1,p}$		$1.54^{+0.04}_{-0.18}$	$1.41^{+0.19}_{-0.01}$	1.2 - 1.8
$\gamma_{2,p}$		$2.425^{+0.023}_{-0.002}$	$2.531^{+0.008}_{-0.010}$	2.3 - 2.6
γ_1		$1.56^{+0.03}_{-0.18}$	$1.21^{+0.22}_{-0.02}$	1.2 - 1.8
γ_2		$2.388^{+0.021}_{-0.003}$	$2.480^{+0.005}_{-0.005}$	2.3 - 2.6
R_0	$[GV]$	$8.43^{+0.27}_{-1.93}$	$5.01^{+1.30}_{-0.12}$	1.0 - 10
s		$0.38^{+0.11}_{-0.01}$	$0.46^{+0.01}_{-0.06}$	0.05 - 0.9
δ		$0.361^{+0.005}_{-0.043}$	$0.245^{+0.015}_{-0.007}$	0.2 - 0.5
D_0	$[10^{28}\ \mathrm{cm}^2/\mathrm{s}]$	$7.48^{+1.52}_{-1.88}$	$9.84^{+0.26}_{-2.85}$	0.5 - 10.0
v_A	[km/s]	$23.8^{+3.09}_{-0.91}$	$28.5^{+1.5}_{-0.64}$	0 - 30
$v_{0,\mathrm{c}}$	[km/s]	$26.9^{+34.7}_{-3.33}$	$45.3^{+5.69}_{-19.2}$	0 - 100
z_h	[kpc]	$6.78^{+0.22}_{-2.70}$	$5.35^{+1.65}_{-1.27}$	2 - 7
ϕ_AMS	[GV]	580^{+65}_{-50}	520^{+35}_{-35}	0 - 1.8

[Cuoco+, PRL 2017]



multi-target and multi-messenger strategy

Outlook— cornering the WIMPs

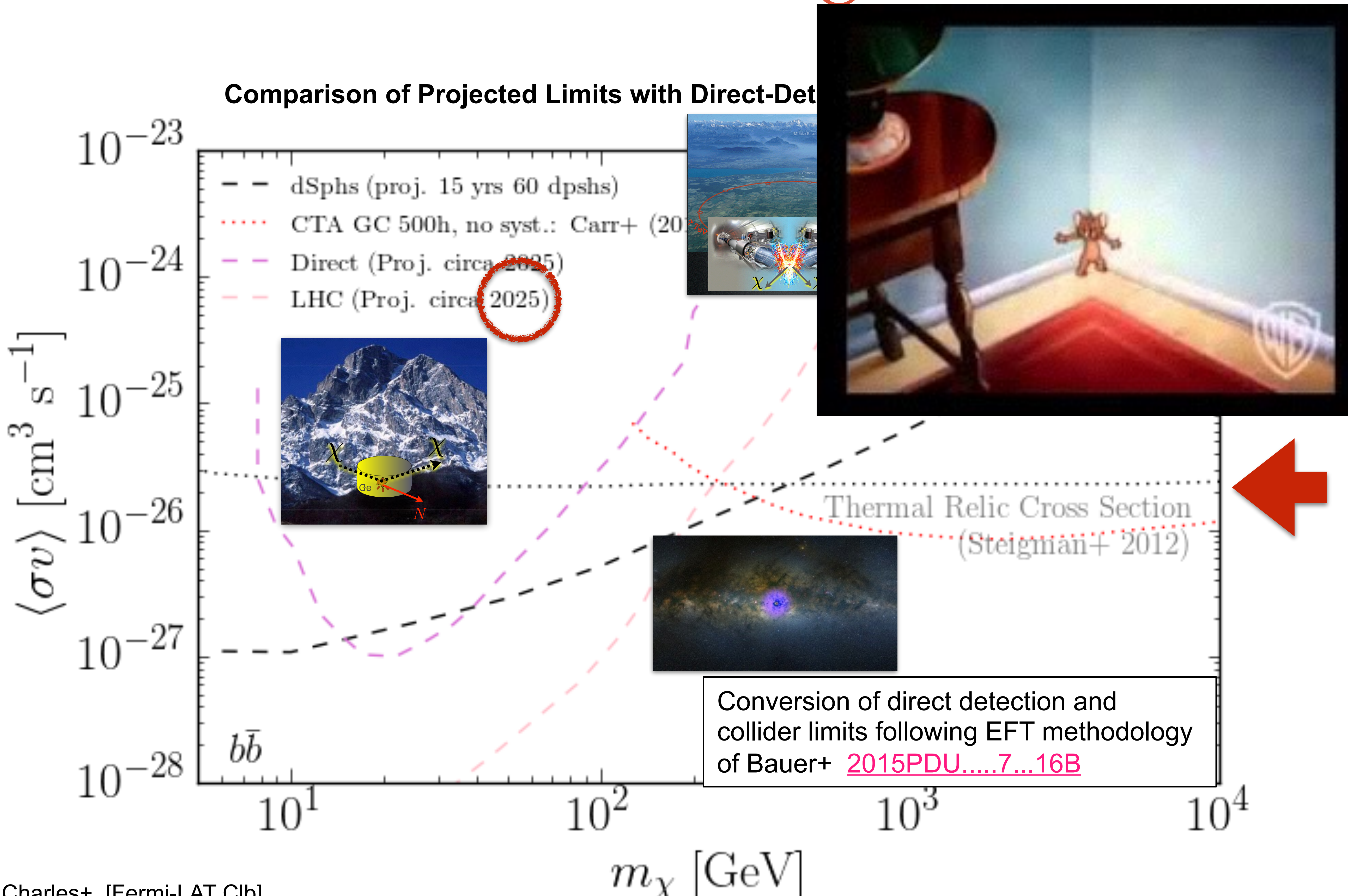


Conversion of direct detection and collider limits following EFT methodology of Bauer+ 2015PDU.....7...16B

Charles+ [Fermi-LAT Clb]
2016PhR...636....1C

Caution: model dependent! EFT assumed here.

Outlook— cornering the WIMPs



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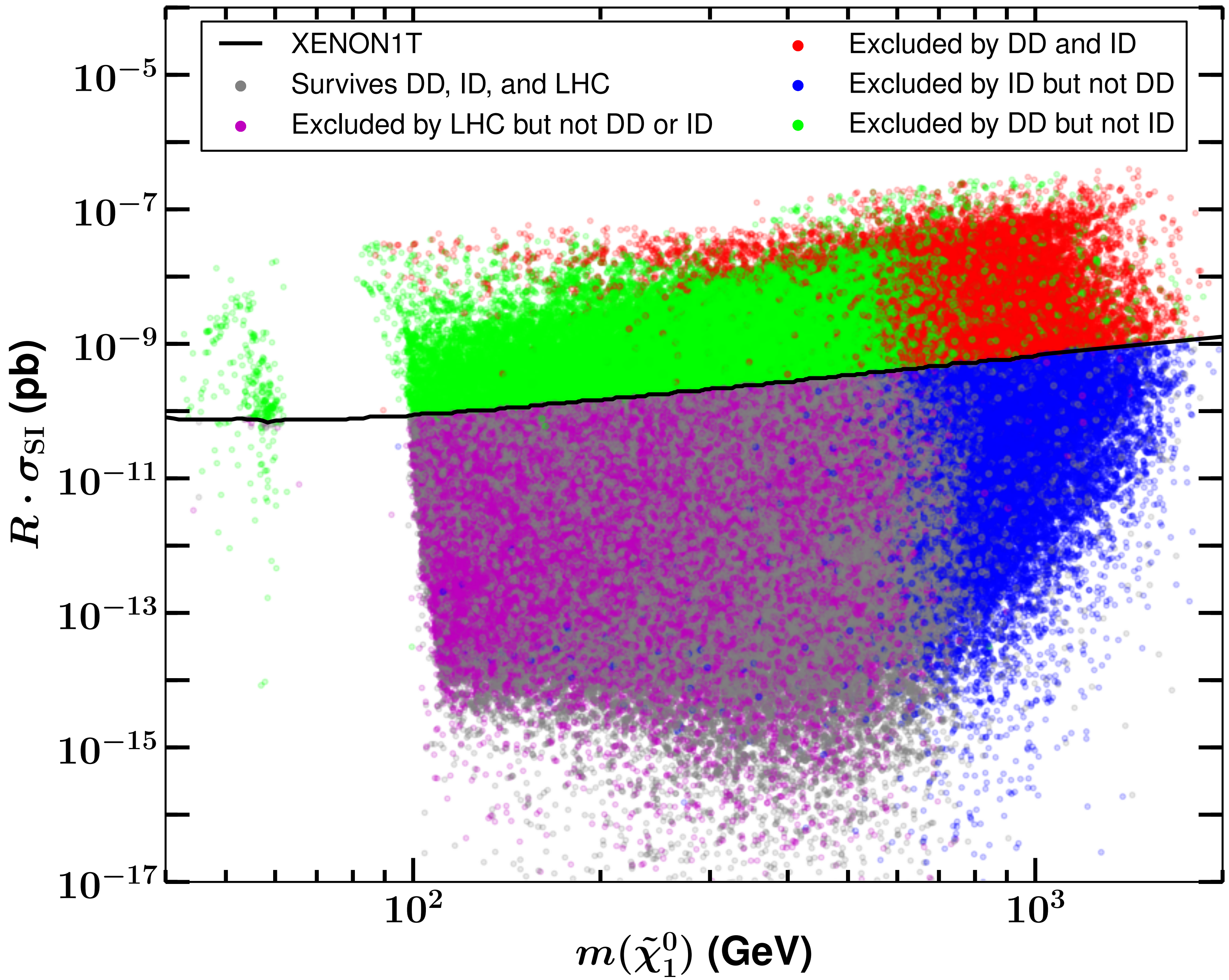


or for MSSM

[Hooper+, DM in the coming decade (2013)]

The community (theorists & experimentalists from many fields) came together over the past ~40 years and **executed a complex strategy** to test the WIMP models.

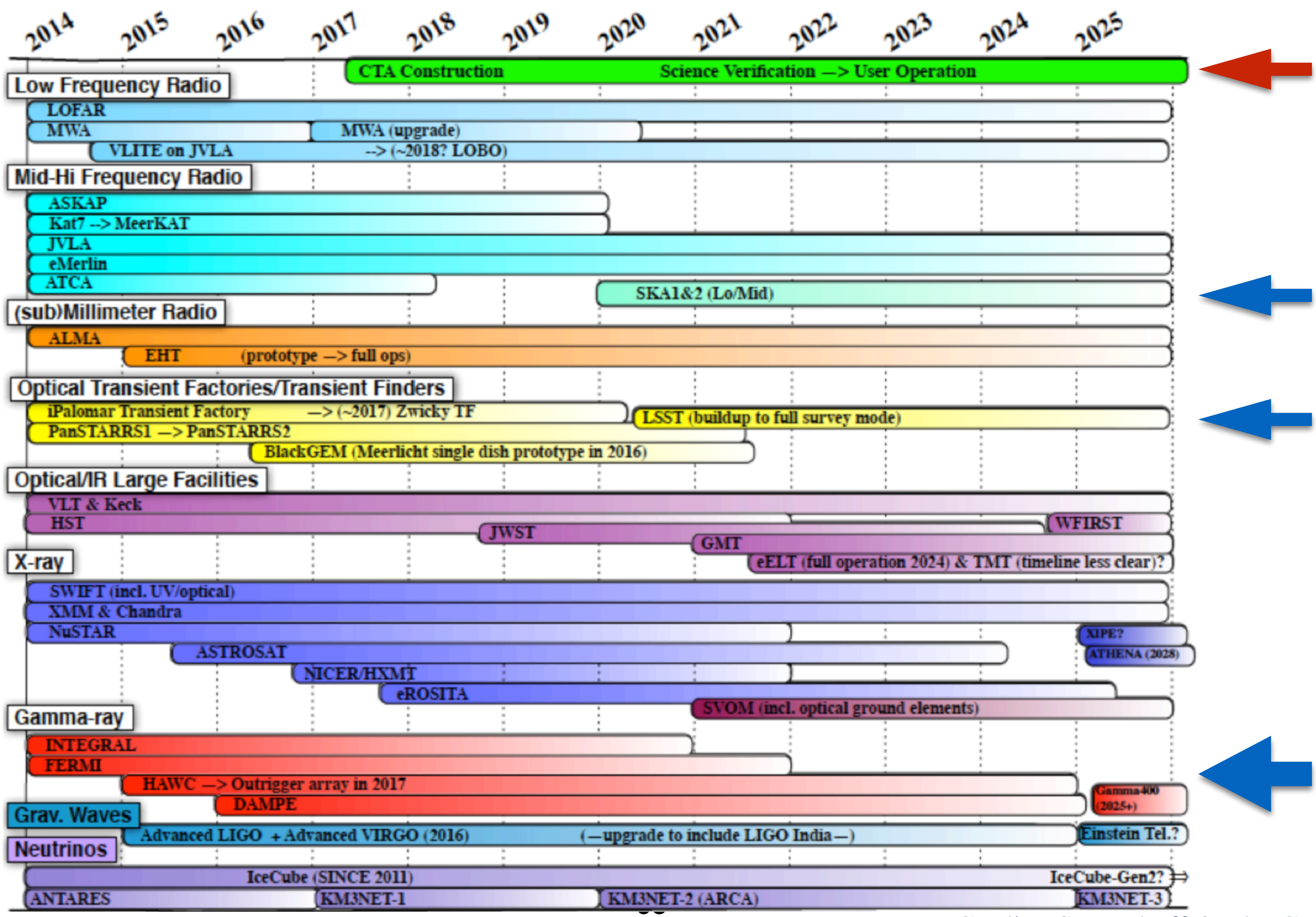
By **~2025**+ n-ton scale direct detection + upgraded LHC + indirect detection should have delivered (bulk of) the message.

Future?

Indirect detection experiments are **multi-purpose** + **many high energy astrophysical experiments planned** in the next decade.

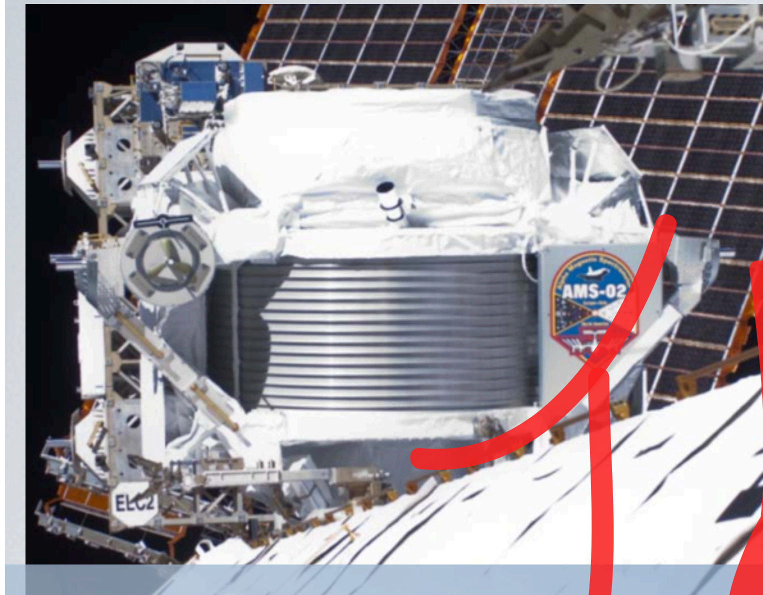
-> we are rapidly increasing our knowledge of astrophysical processes.

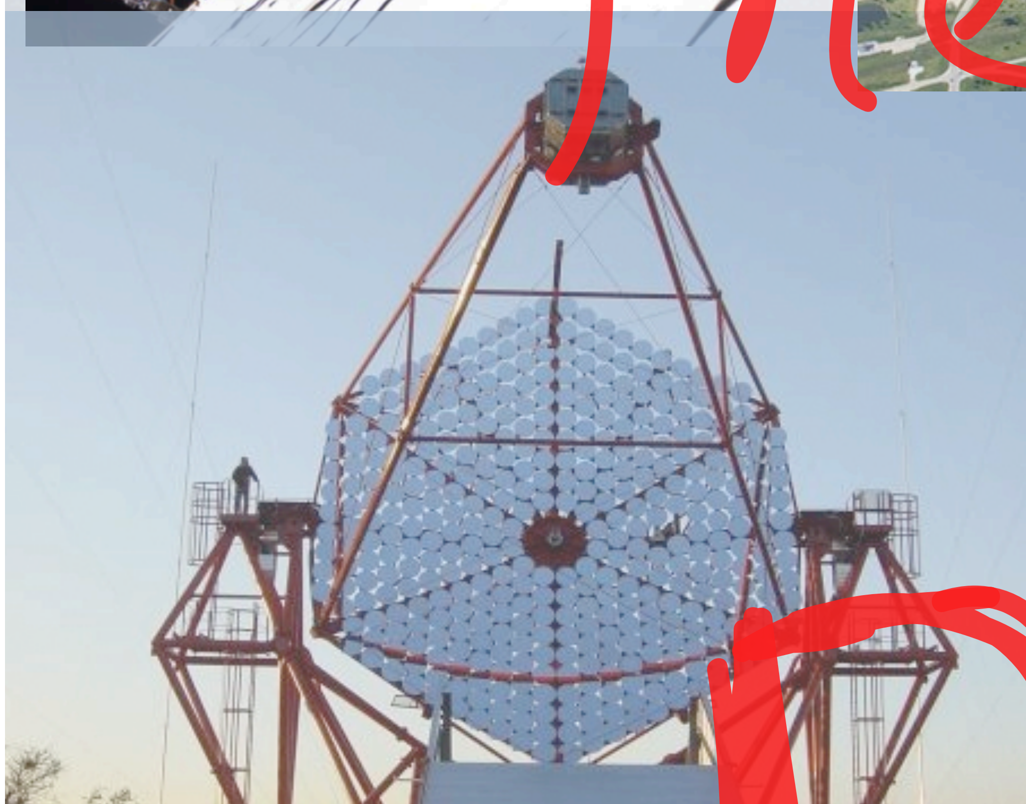
-> we will continue to have better **data** allowing to test for DM (WIMP or not) signatures in **astrophysical objects**, the very places were first evidence for the existence of DM was first discovered.

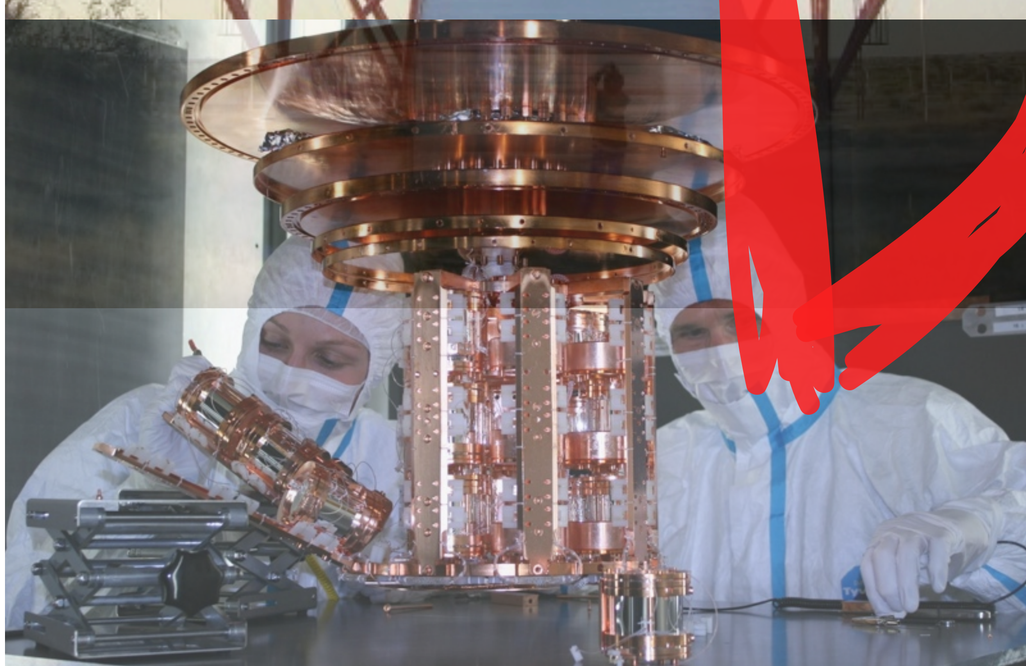


Credits: S. Markoff & The CTA Consortium

The Era of DATA







[from N. Weiner]