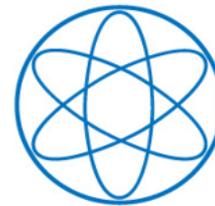


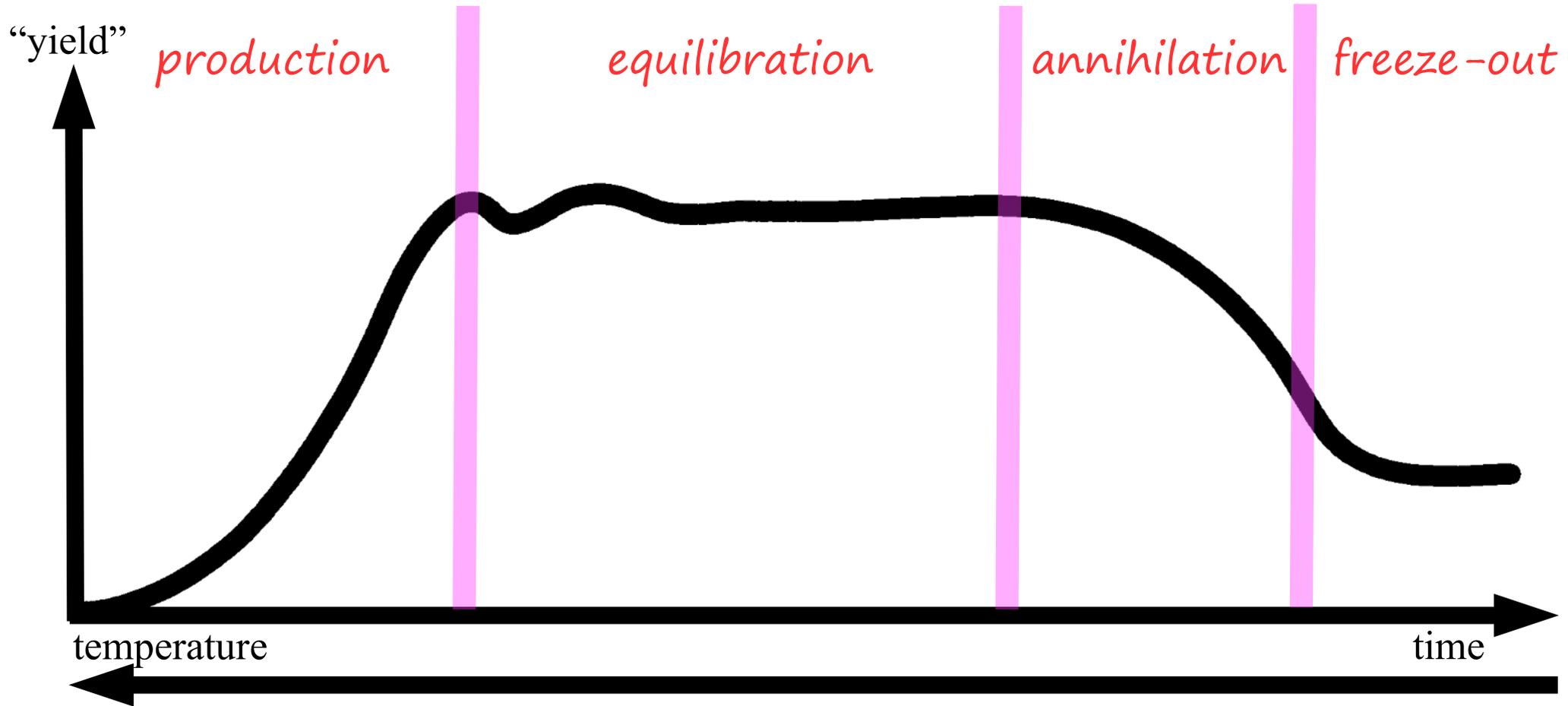
Particle Dark Matter

Alejandro Ibarra



KMI/NITEP School 2026
Nagoya
March 2026

WIMP history (in a nutshell)



The universe at $T \sim 1 \text{ GeV}$

$z = 20.0$

200 million years after the Big Bang

50 Mpc/h



$z = 0.0$

50 Mpc/h



Volker Springel
Max-Planck-Institute
for Astrophysics



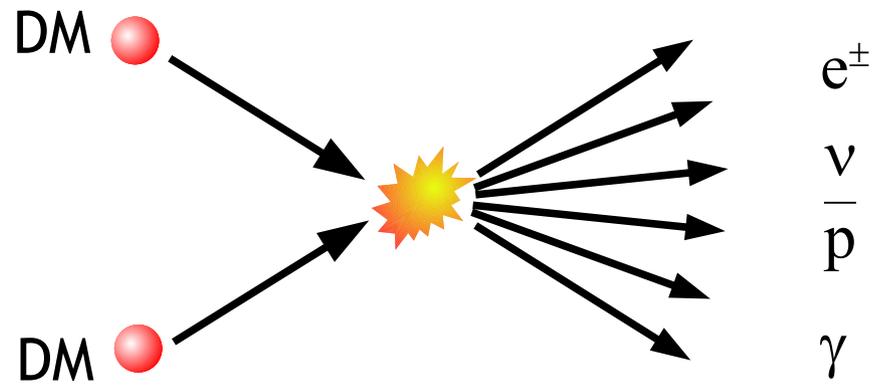
z=0.0

Distance Sun to Milky Way Center ~ 8.5 kpc

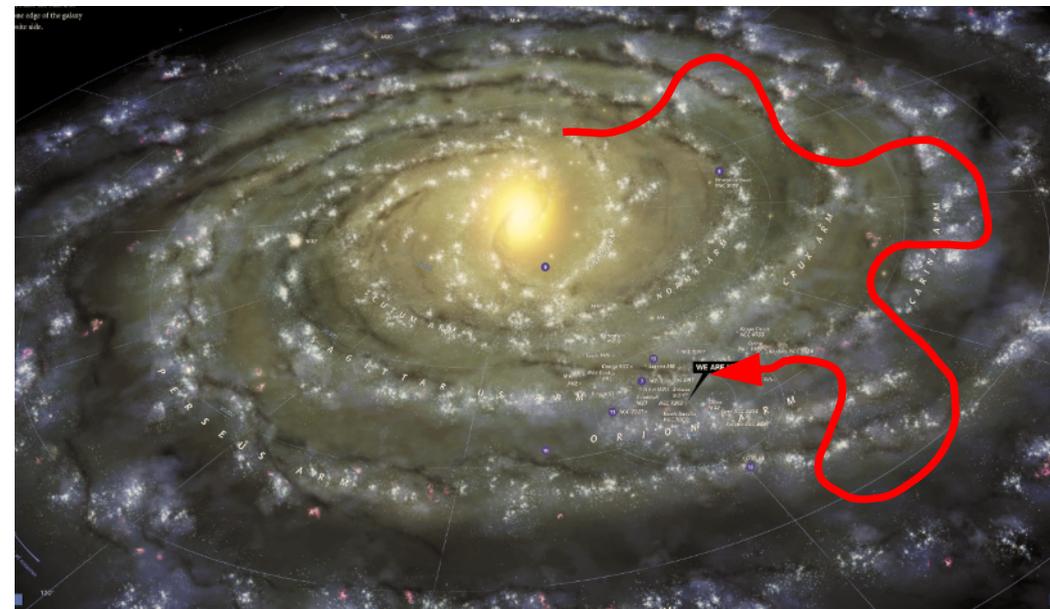
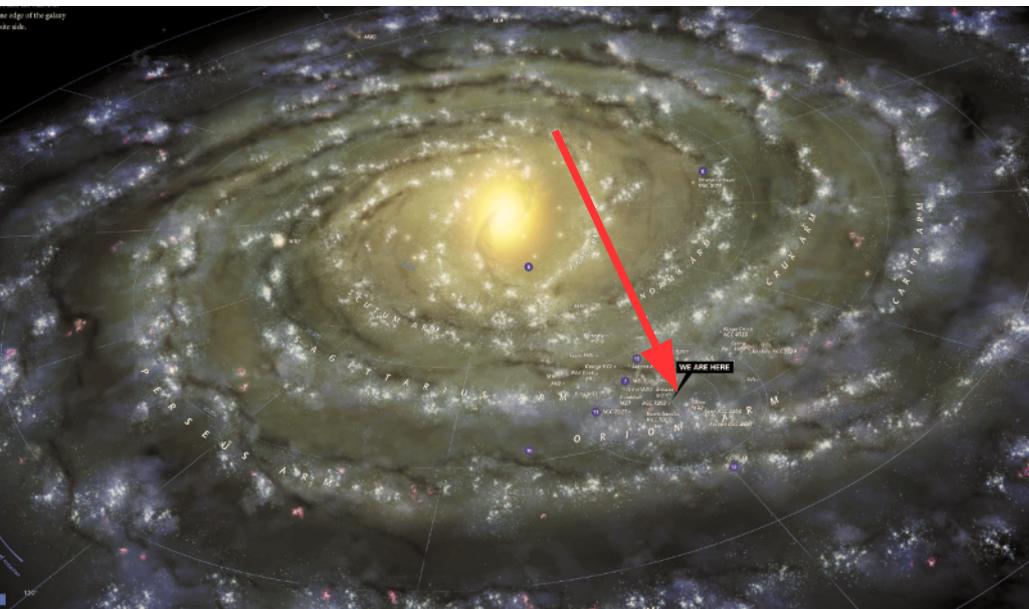
8 kpc



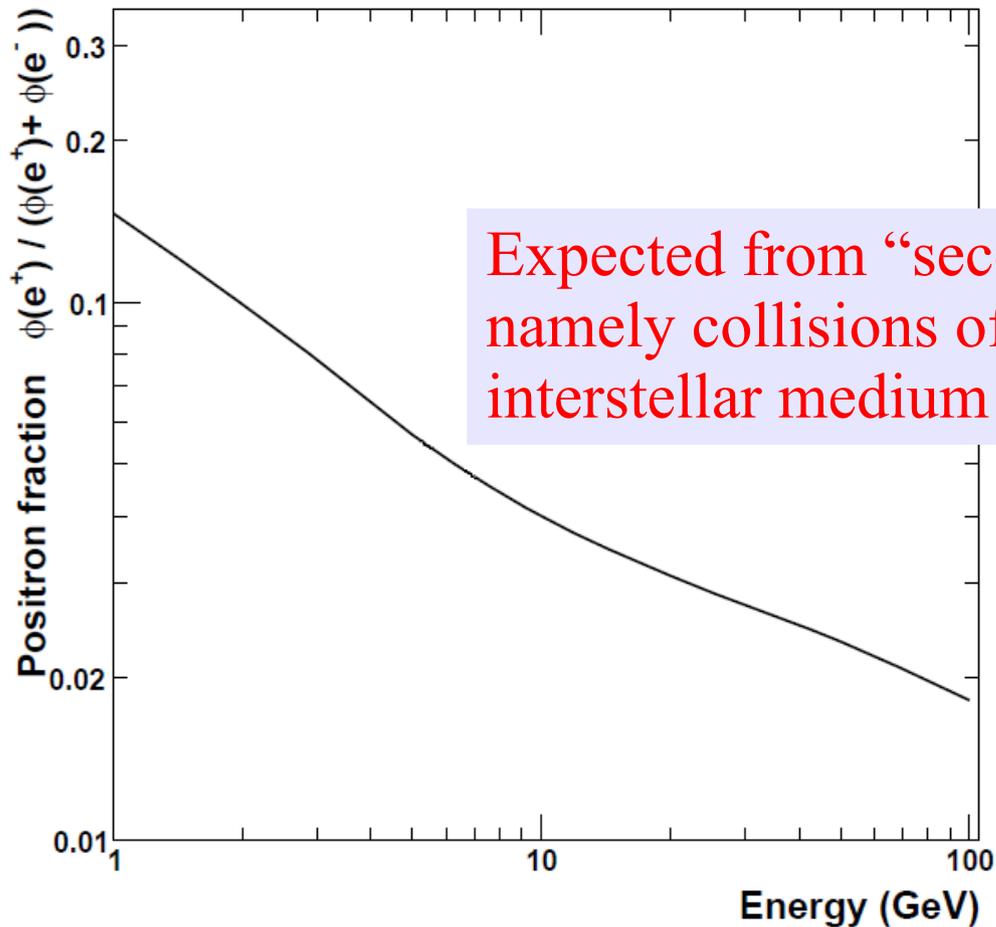
Probing the annihilation cross-section



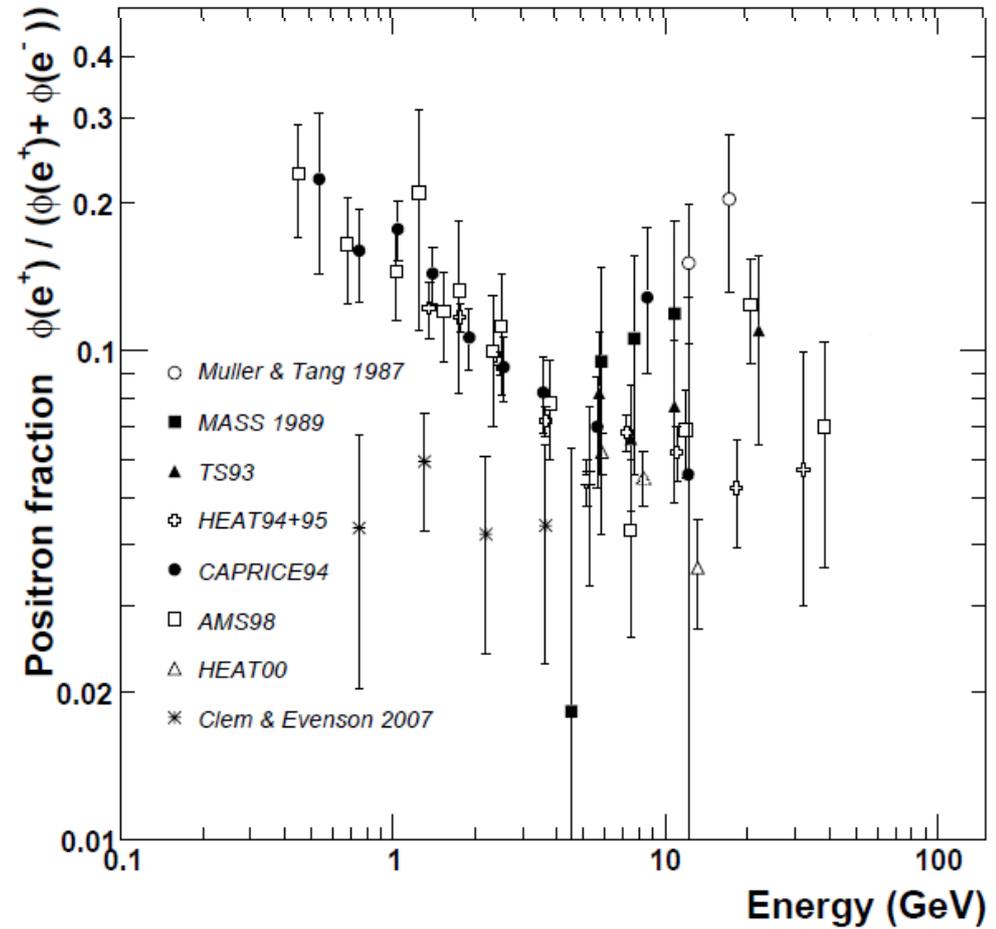
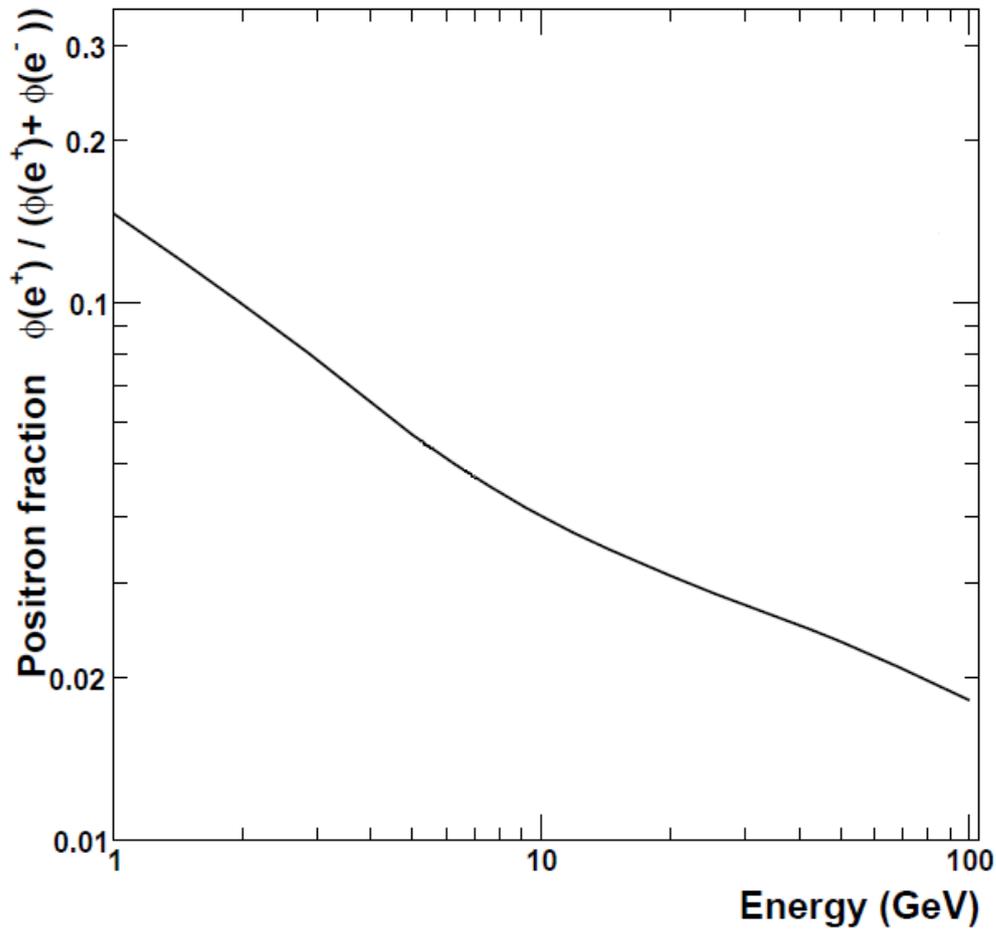
Neutral particles propagate in straight lines practically without losing energy. Charged particles, on the other hand, propagate in a complicated way through the tangled magnetic field of our Galaxy.



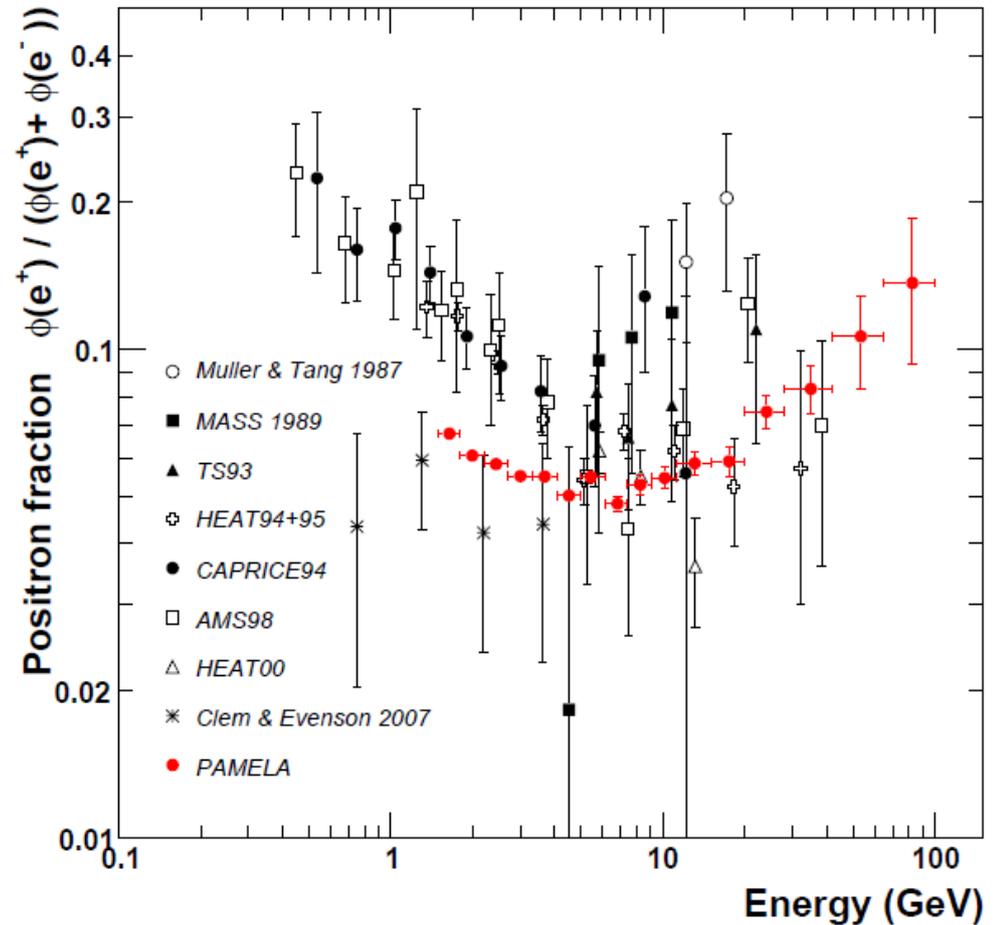
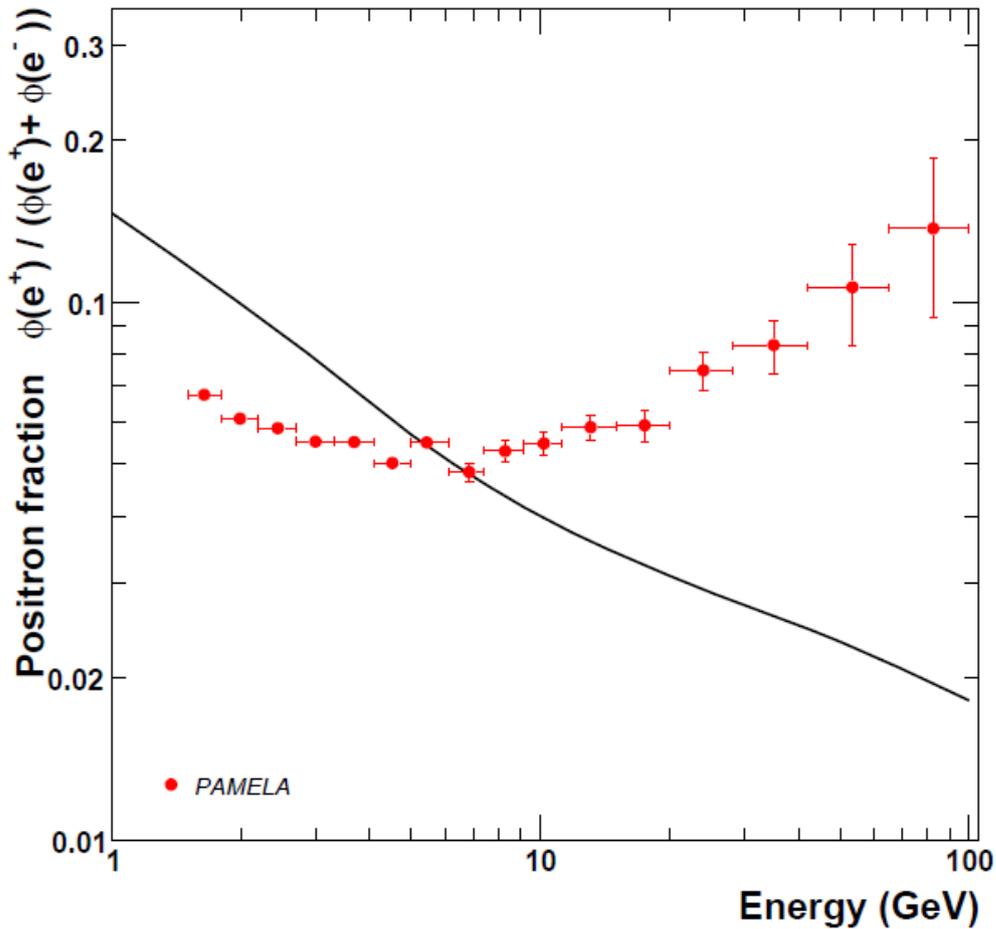
Experimental results: positrons



Experimental results: positrons

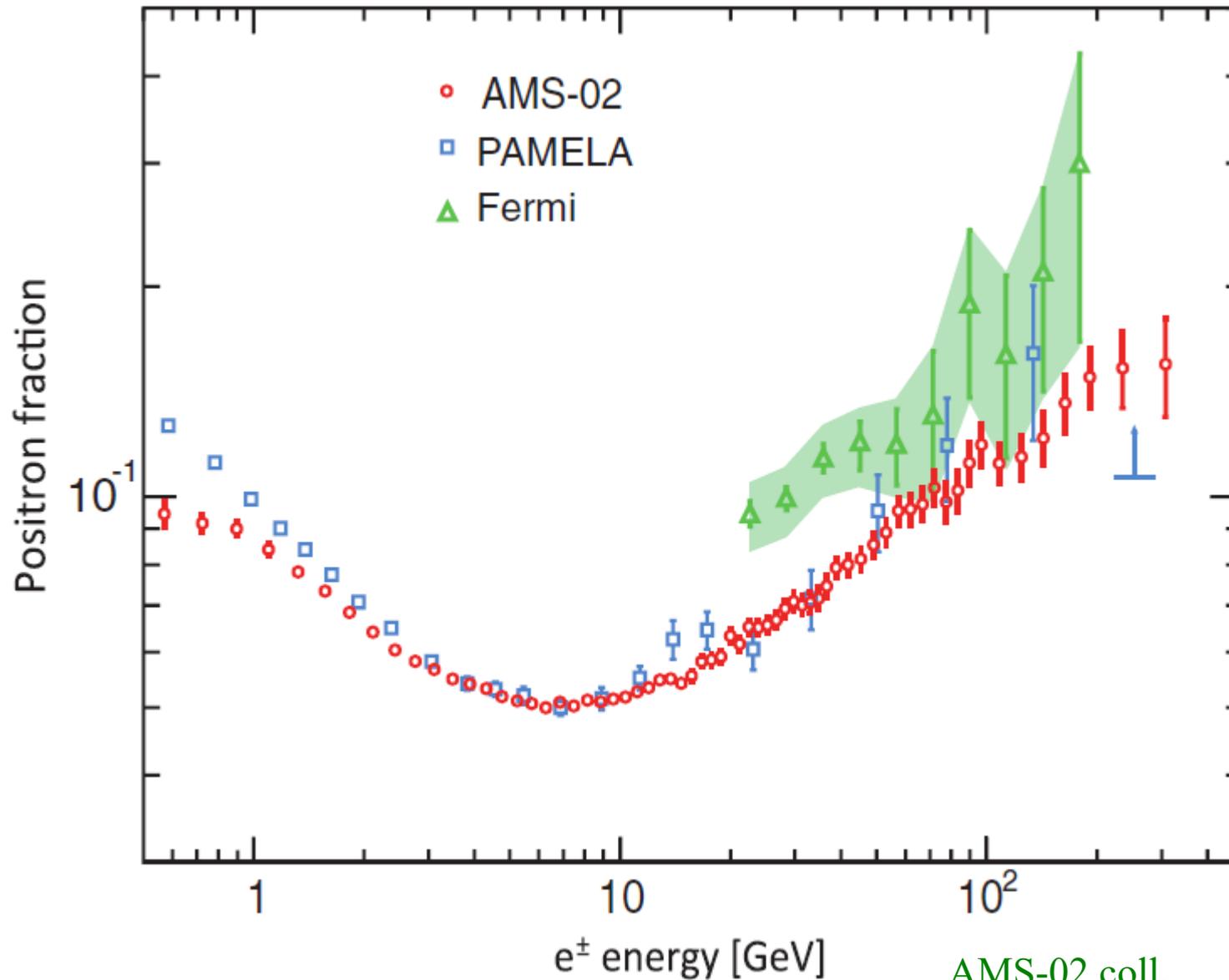


Experimental results: positrons



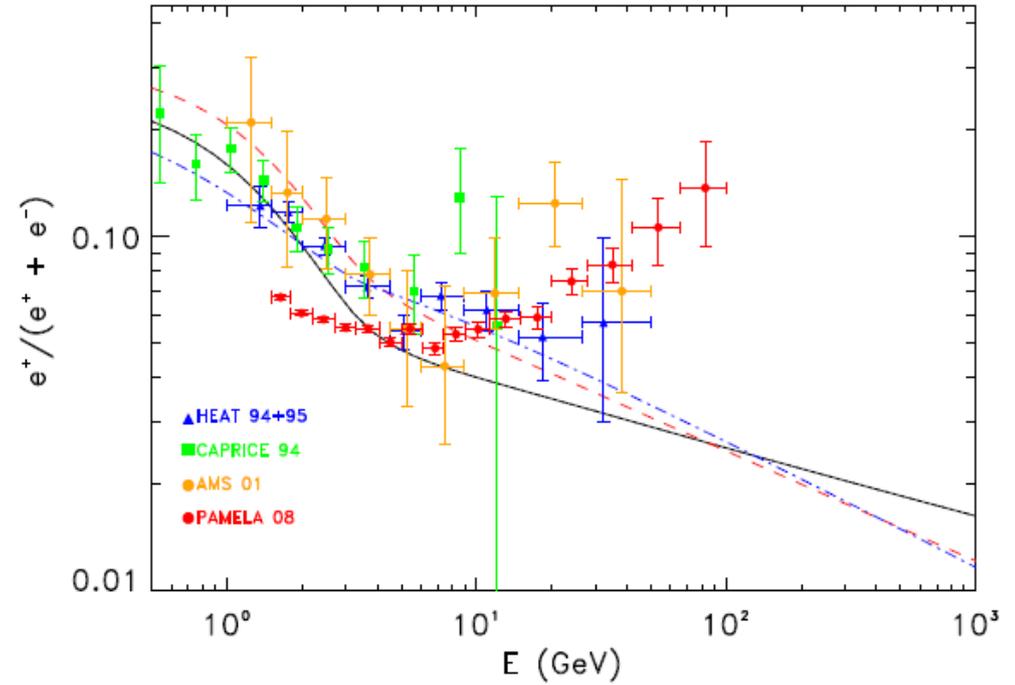
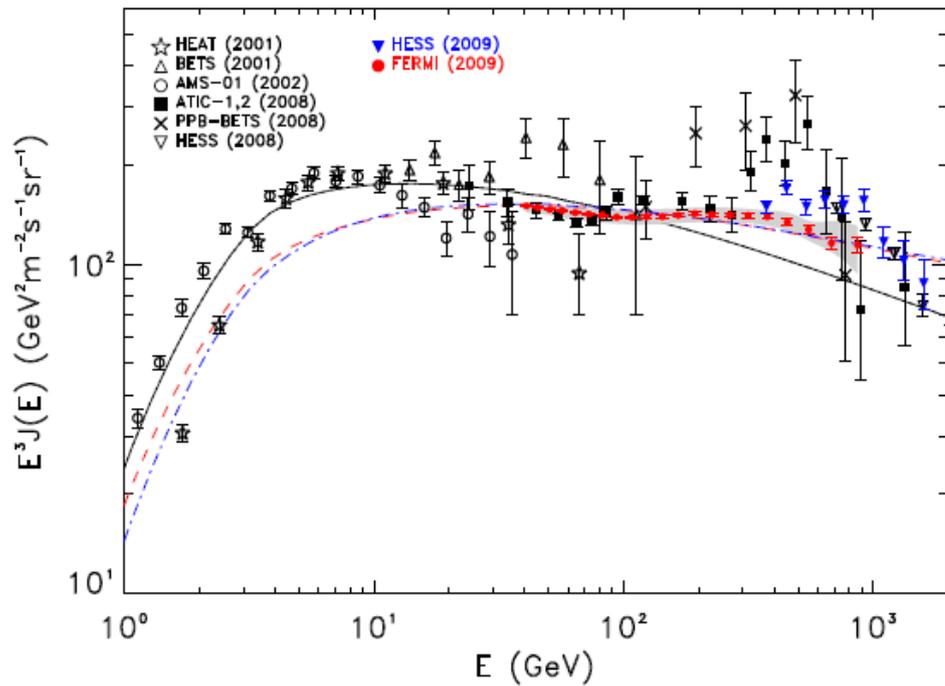
PAMELA coll.
arXiv:0810.4995

Experimental results: positrons



AMS-02 coll.
Phys.Rev.Lett. 110 (2013) 14, 141102

More puzzles: the electron+positron flux

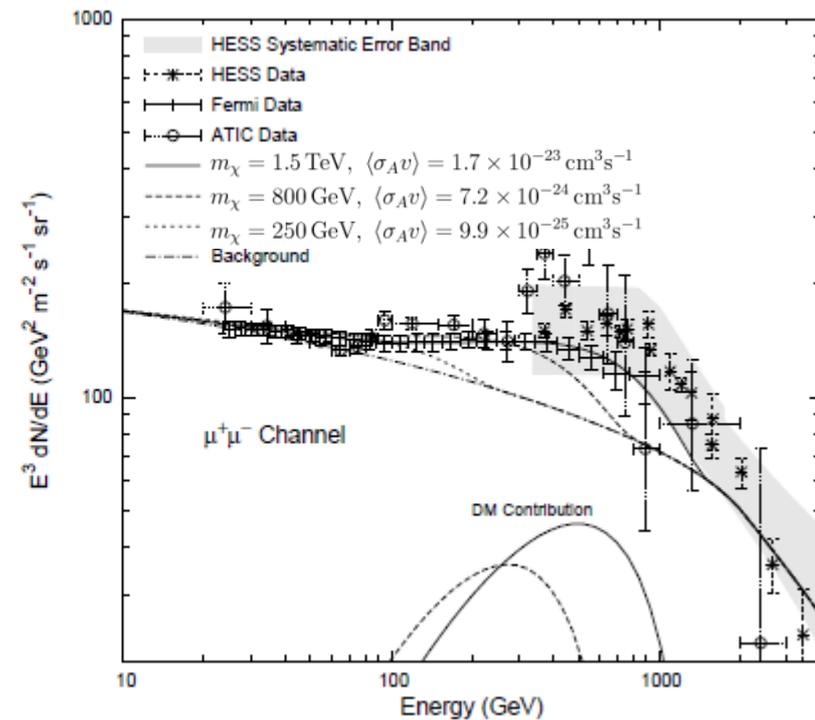
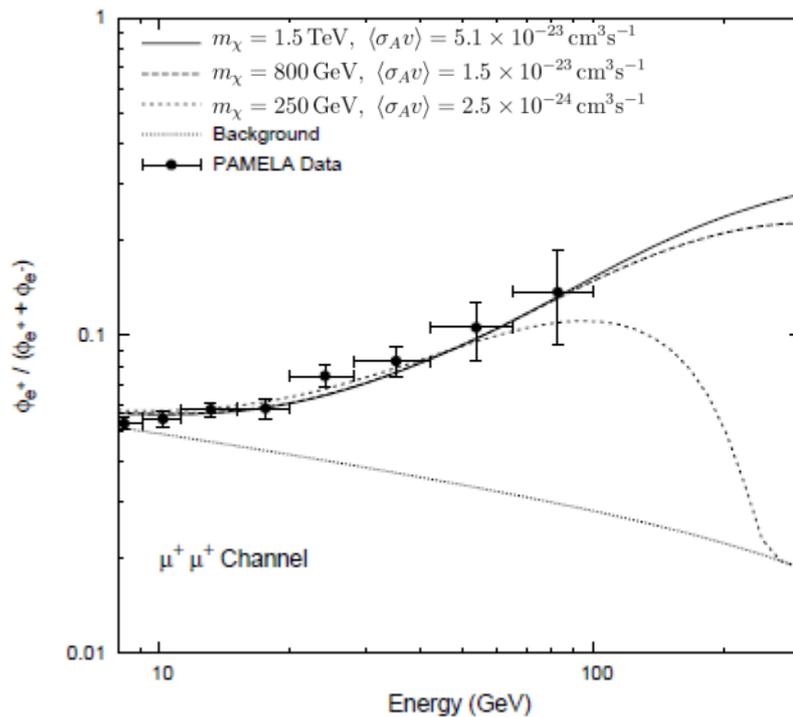


Evidence for a primary component of electrons and positrons

Dark matter interpretation

An electron/positron excess could be explained by dark matter annihilations

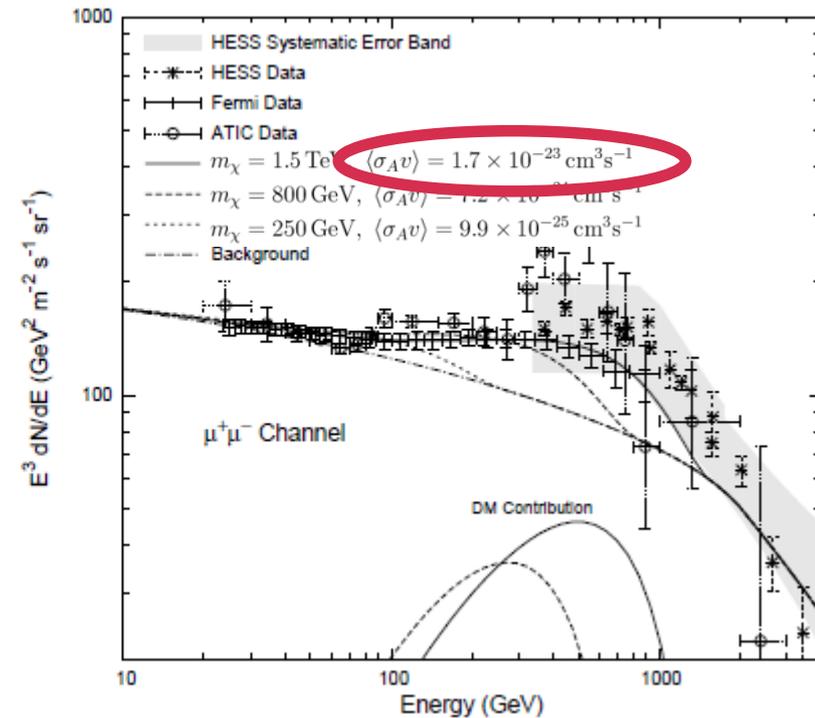
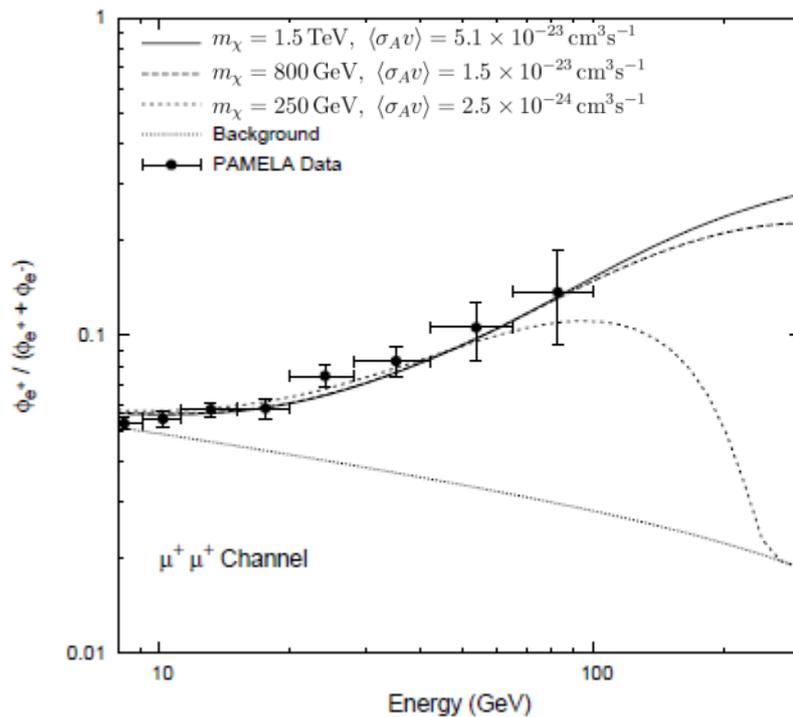
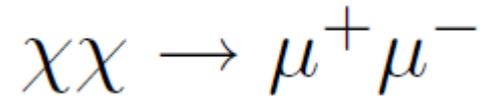
$$\chi\chi \rightarrow \mu^+\mu^-$$



Cholis et al.
arXiv:0811.3641

Dark matter interpretation

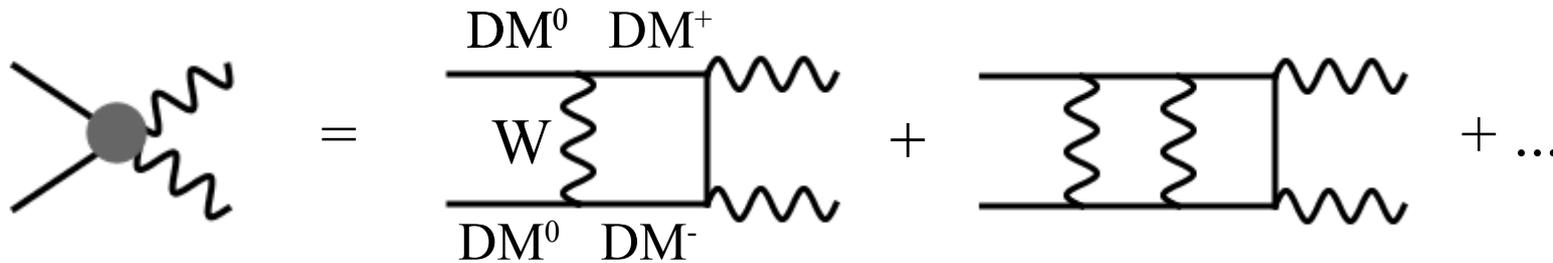
An electron/positron excess could be explained by dark matter annihilations



Cholis et al.
arXiv:0811.3641

Large cross-sections?

Consider a dark matter candidate charged under $SU(2)_L$

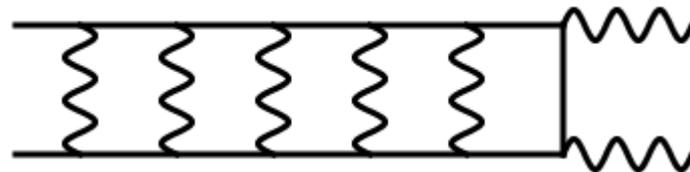


The expansion parameter is not α_2 , but rather $\frac{\alpha_2 m_{\text{DM}}}{M_W}$

The perturbative calculation cannot be trusted if

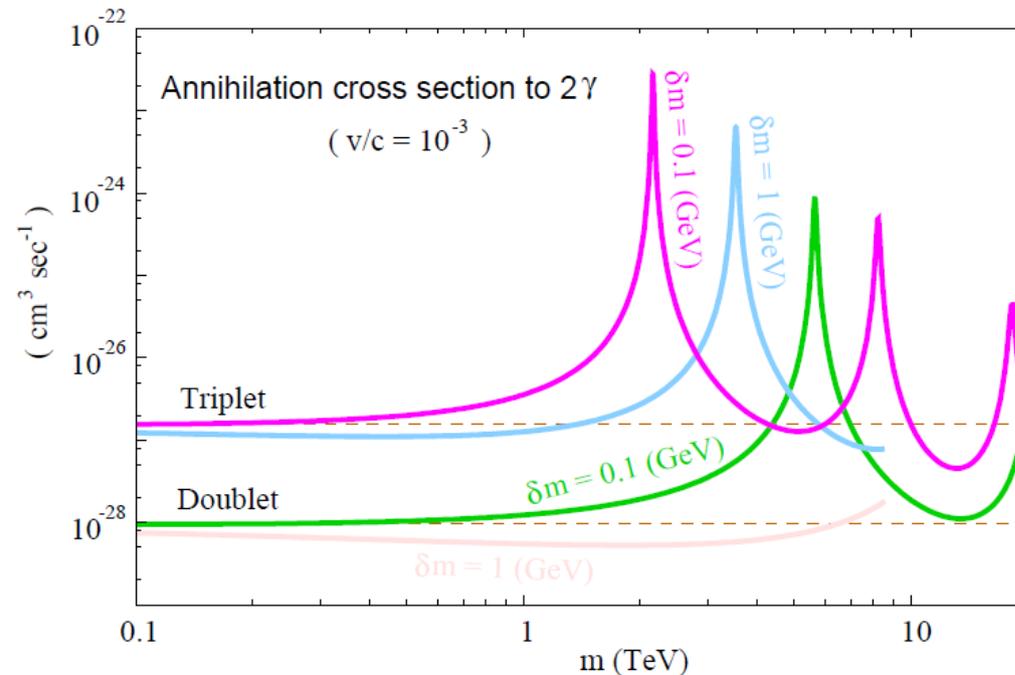
$$m_{\text{DM}} \gtrsim \frac{M_W}{\alpha_2} \sim 2 \text{ TeV}$$

Necessary to resum diagrams at all loops

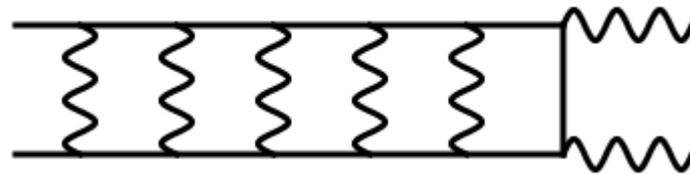


Generically leads to an enhancement of the cross section (Sommerfeld enhancement). Hisano, Matsumoto, Nojiri

Large cross-sections?

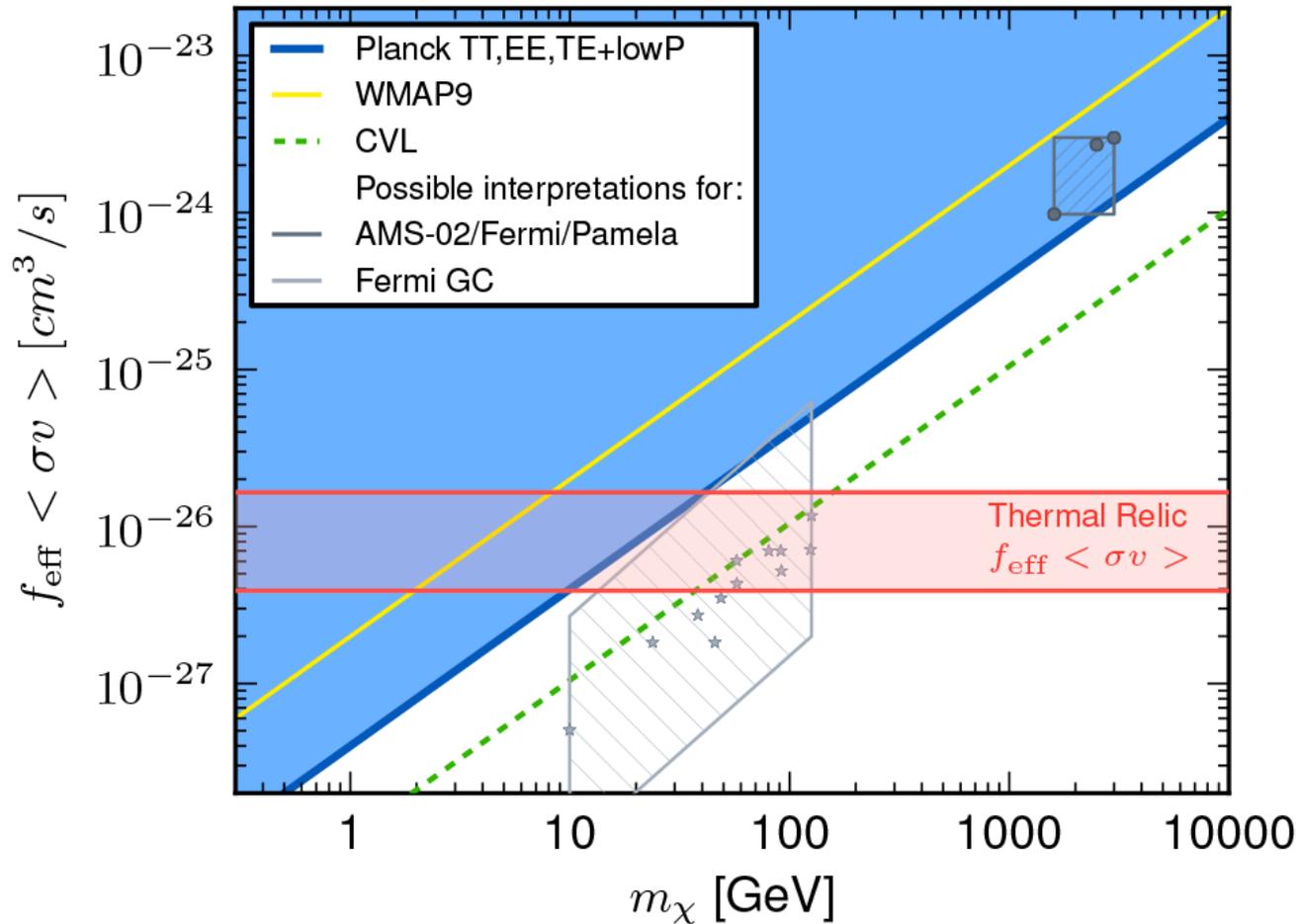


Necessary to resum diagrams at all loops

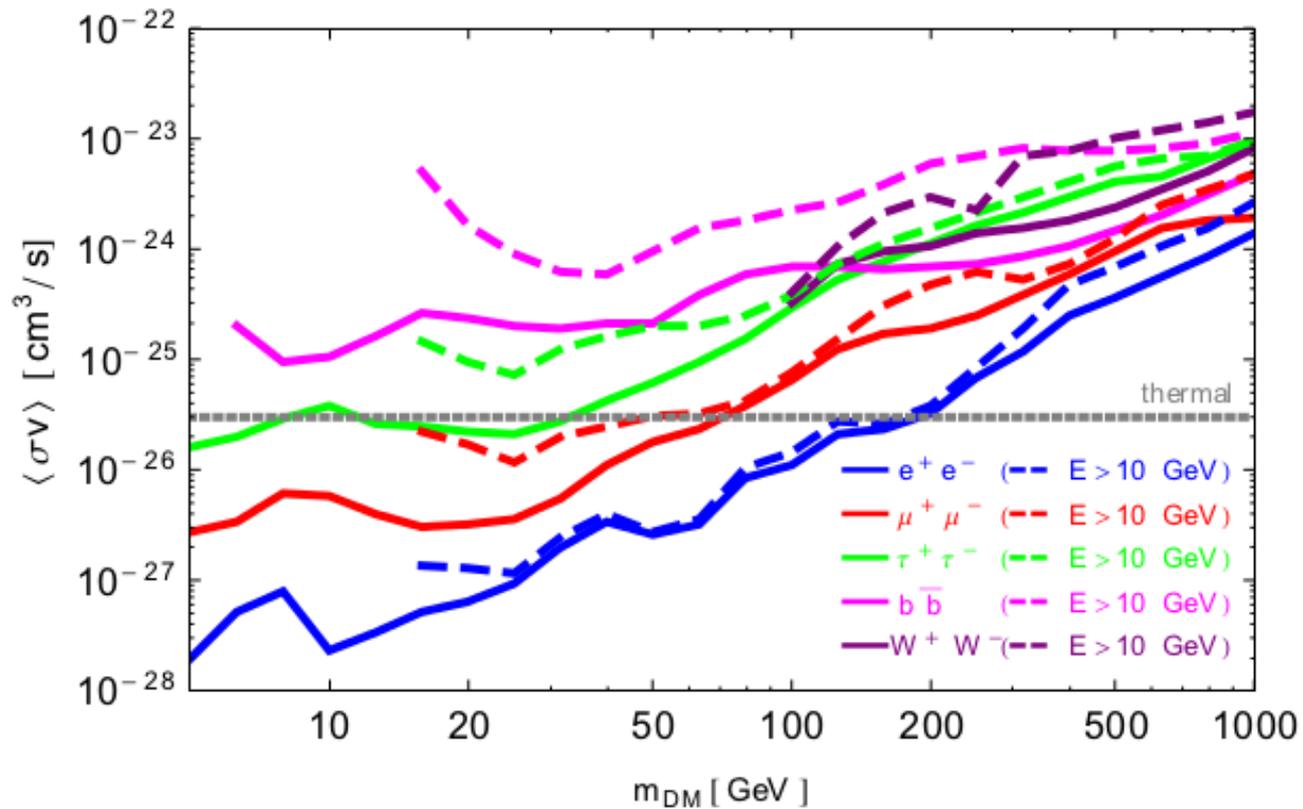


Generically leads to an enhancement of the cross section
(Sommerfeld enhancement). Hisano, Matsumoto, Nojiri

However, in tension with other observations



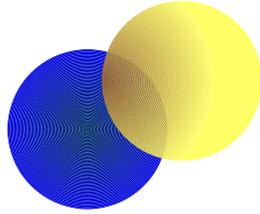
Limits on the DM annihilation cross-section



AI, Lamperstorfer, Silk
Bergström et al.

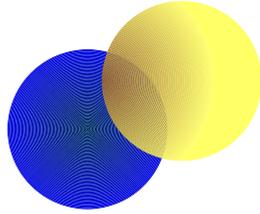
Antideuterons

deuteron

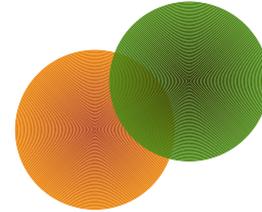


Antideuterons

deuteron

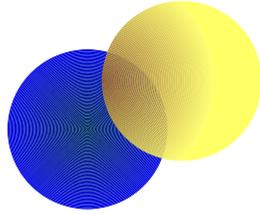


antideuteron

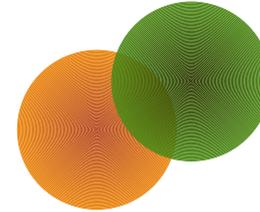


Antideuterons

deuteron



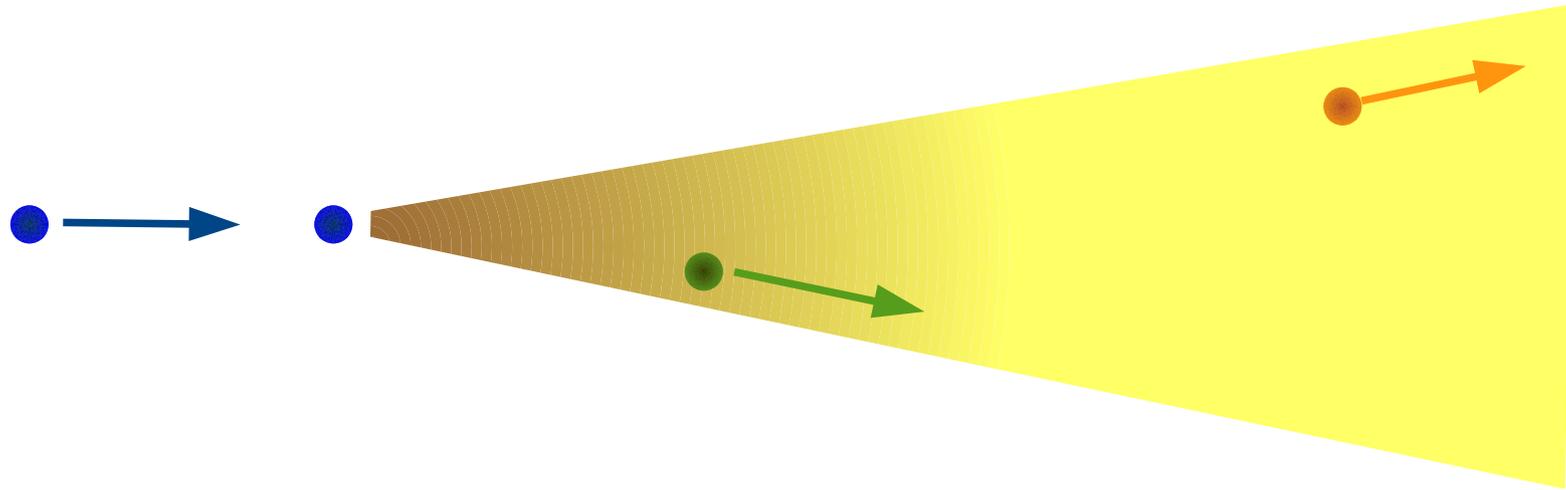
antideuteron



How to produce antideuterons in high energy processes?

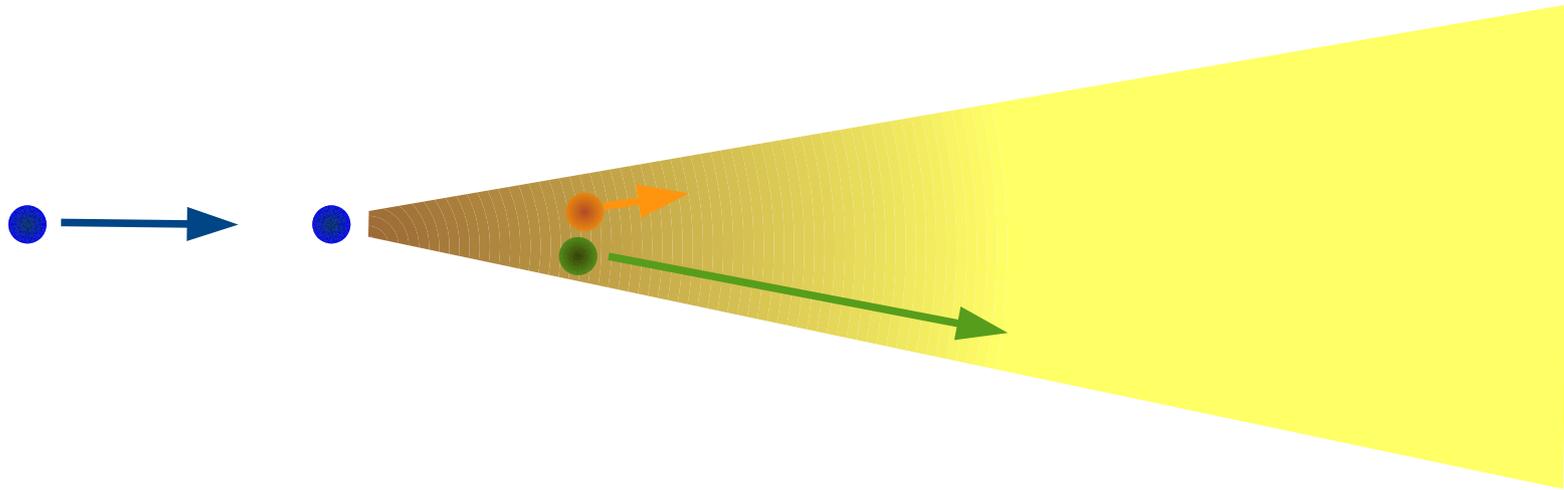


Antideuterons and the coalescence model



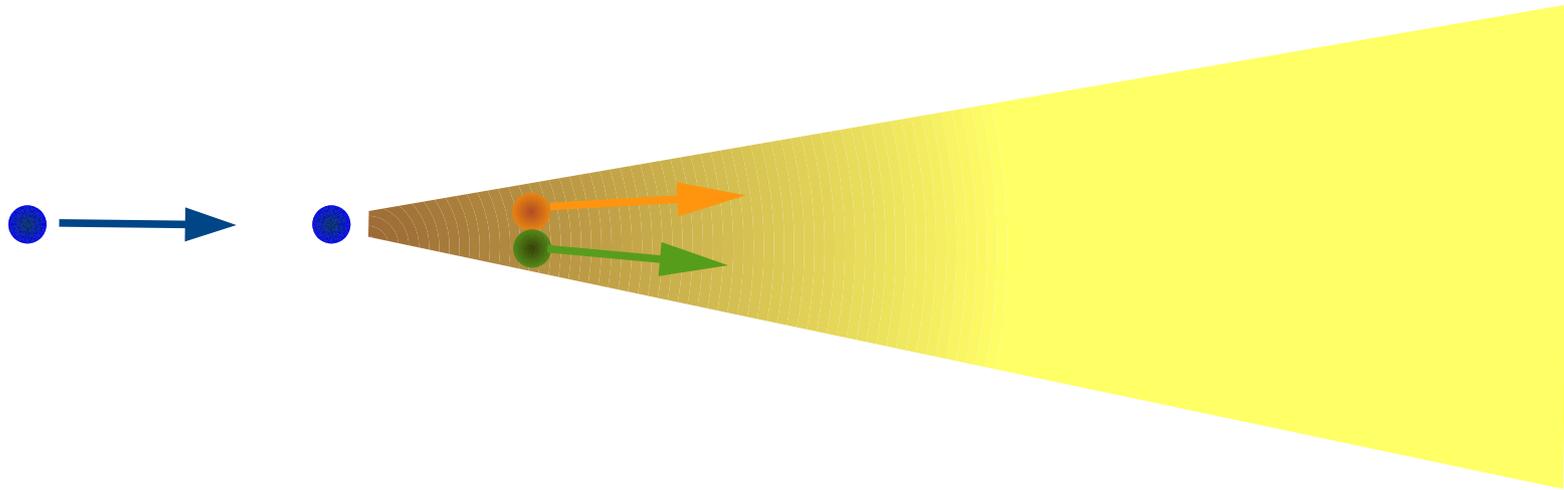
If the antineutron and the antiproton are far away from each other, no coalescence (e.g. if the antiproton is produced in a weak decay)

Antideuterons and the coalescence model



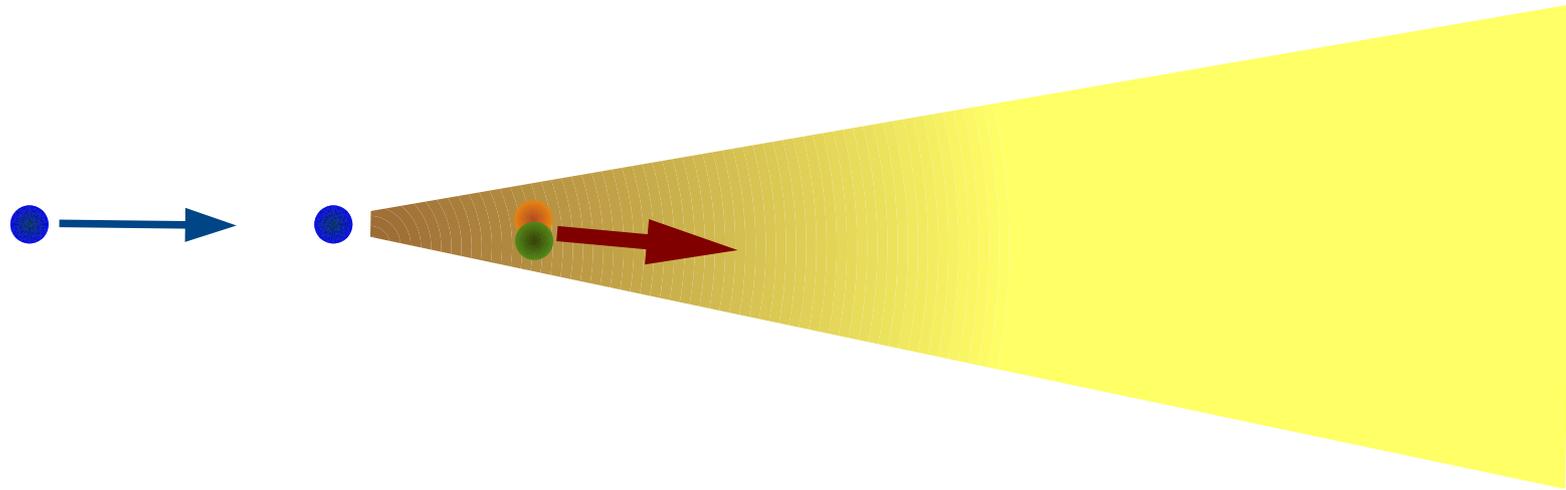
If the antineutron and the antiproton have very different momenta, no coalescence.

Antideuterons and the coalescence model



If the antineutron and the antiproton are close in position space and in momentum space → **coalescence**

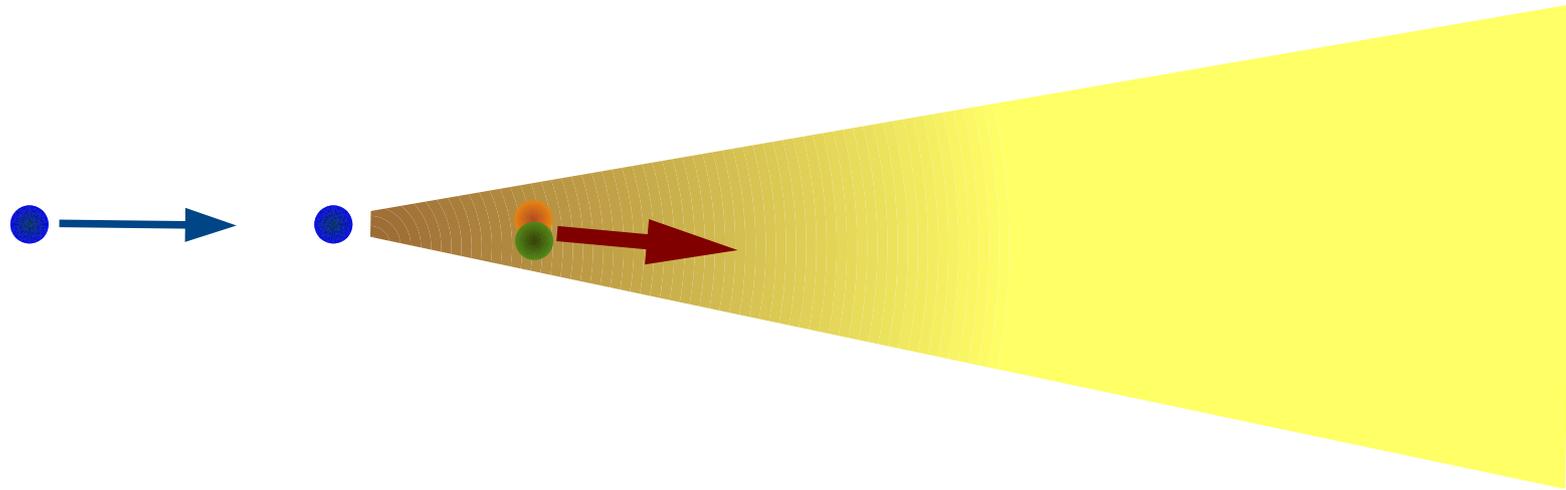
Antideuterons and the coalescence model



If the antineutron and the antiproton are close in position space and in momentum space → **coalescence**

Coalescence model: two antinucleons form an antideuteron if they are close in position space and their distance in momentum space is smaller than a certain value, p_0 , the coalescence momentum.

Antideuterons and the coalescence model



If the antineutron and the antiproton are close in position space and in momentum space → **coalescence**

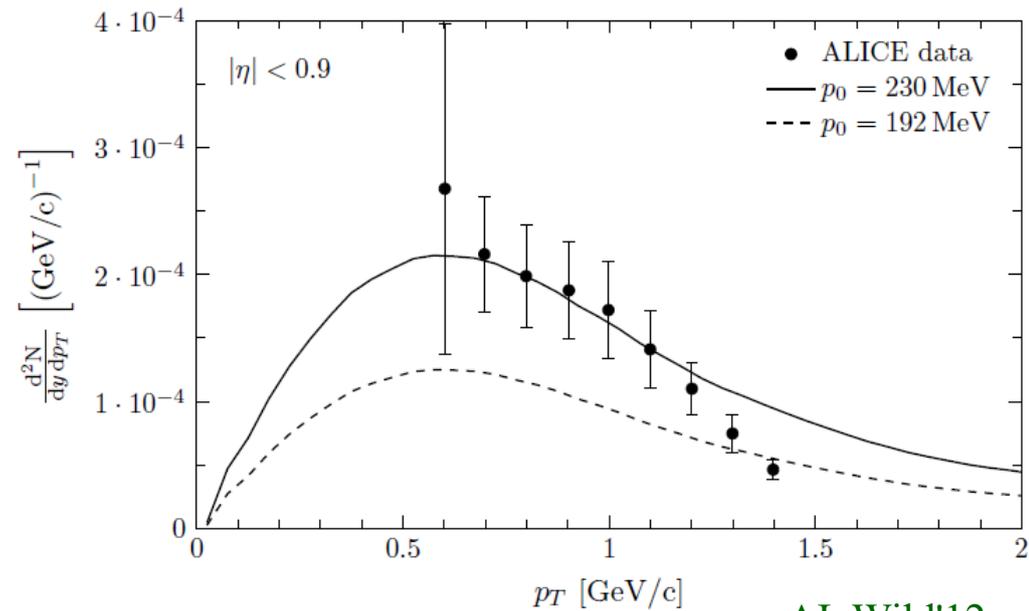
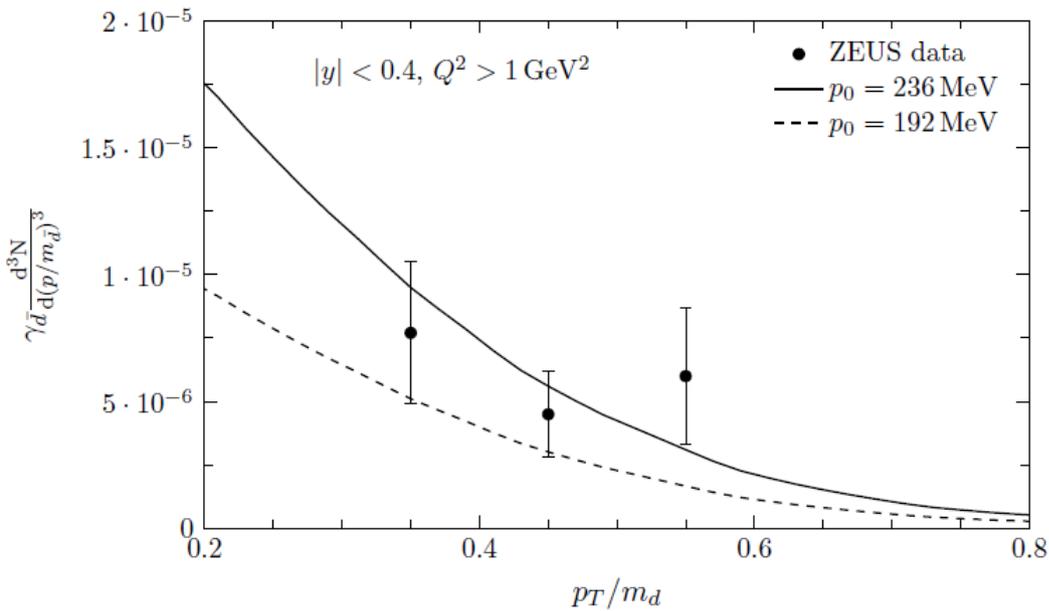
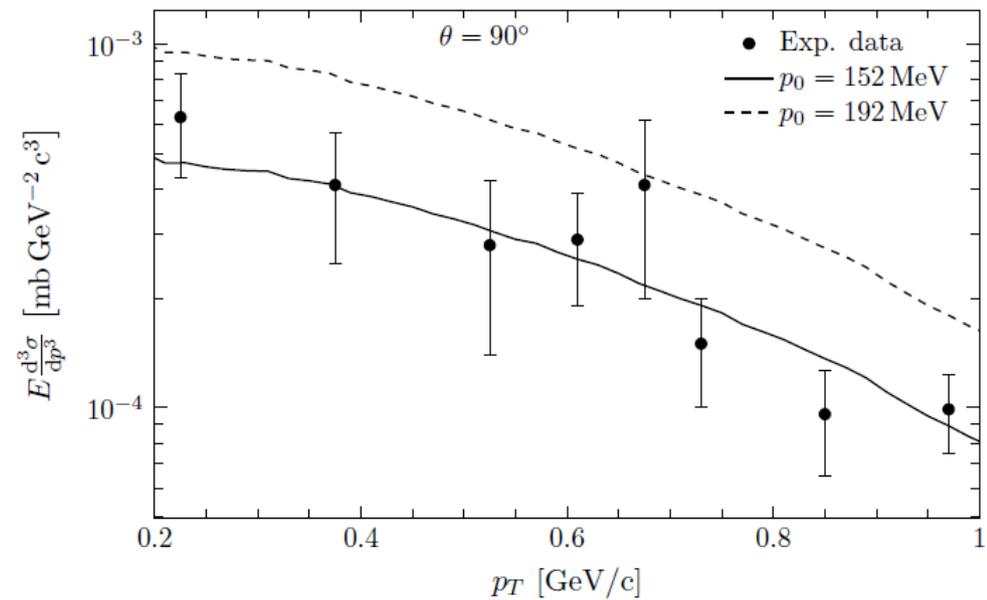
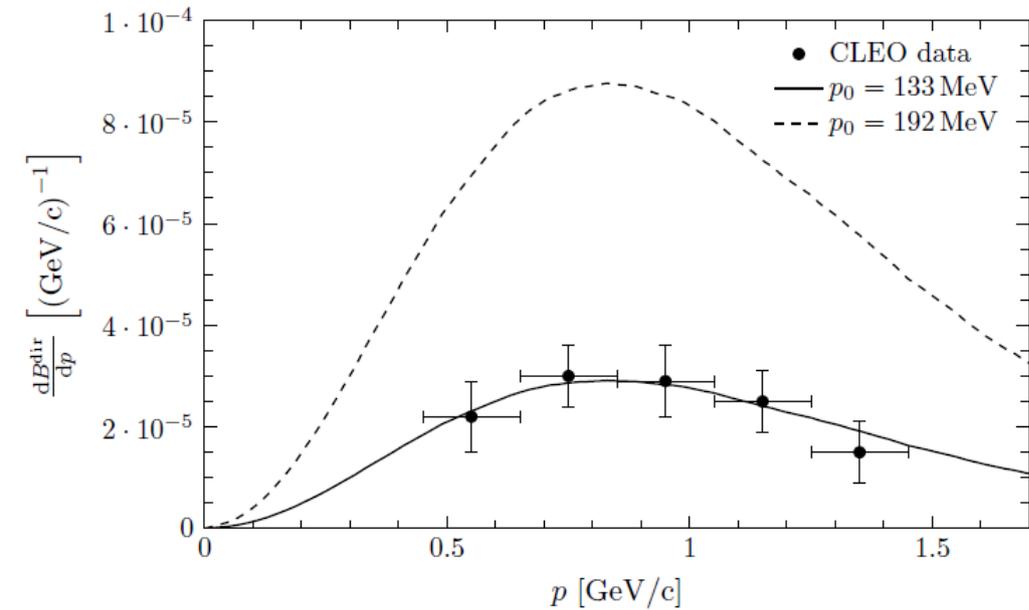
Coalescence model: two antinucleons form an antideuteron if they are close in position space and their distance in momentum space is smaller than a certain value, p_0 , the coalescence momentum.

The coalescence momentum can be determined from some process, e.g. Z boson decay.

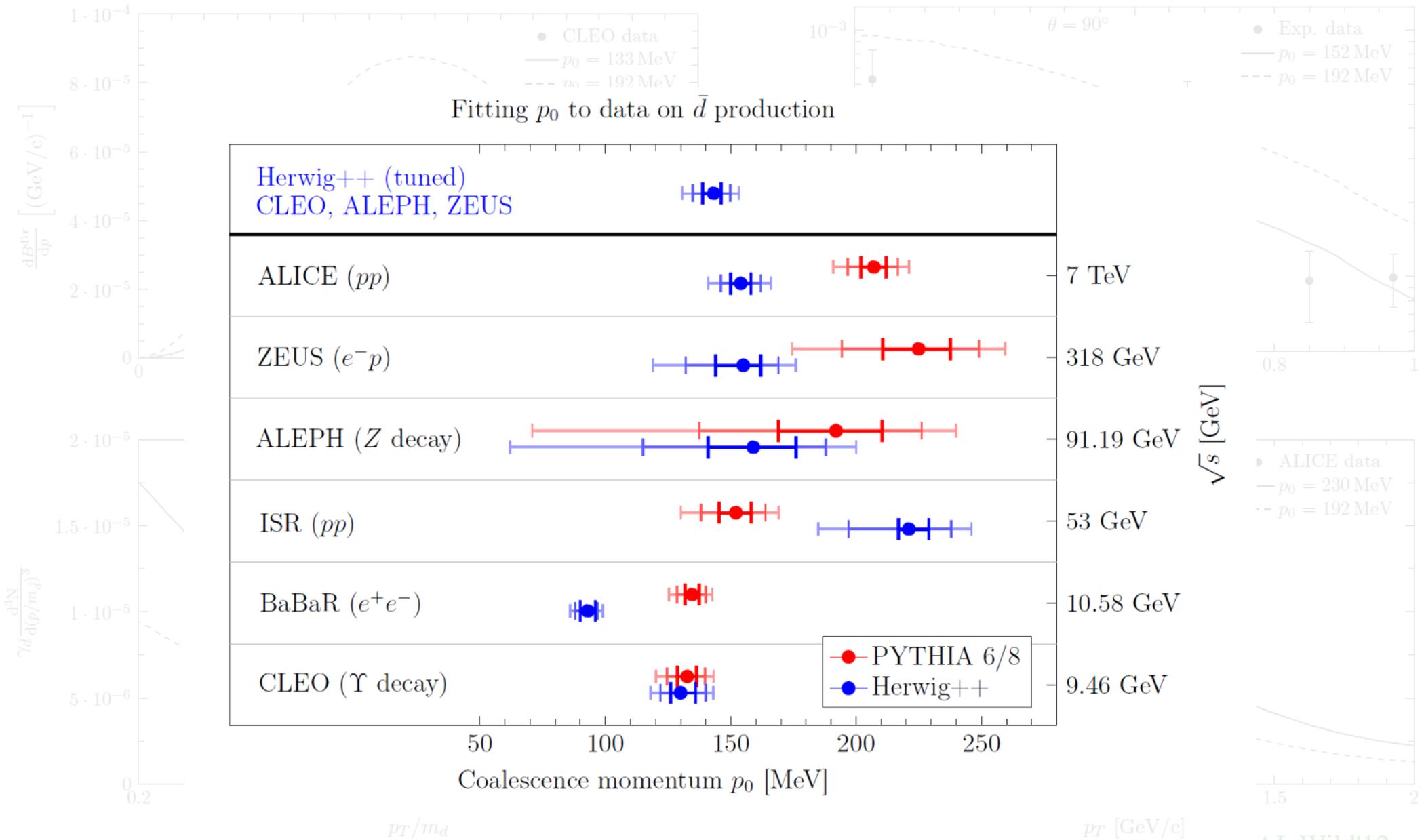
Number of antideuterons per hadronic decay: $(5.9 \pm 1.8 \pm 0.5) \times 10^{-6}$

$$p_0 \sim 192 \text{ MeV}$$

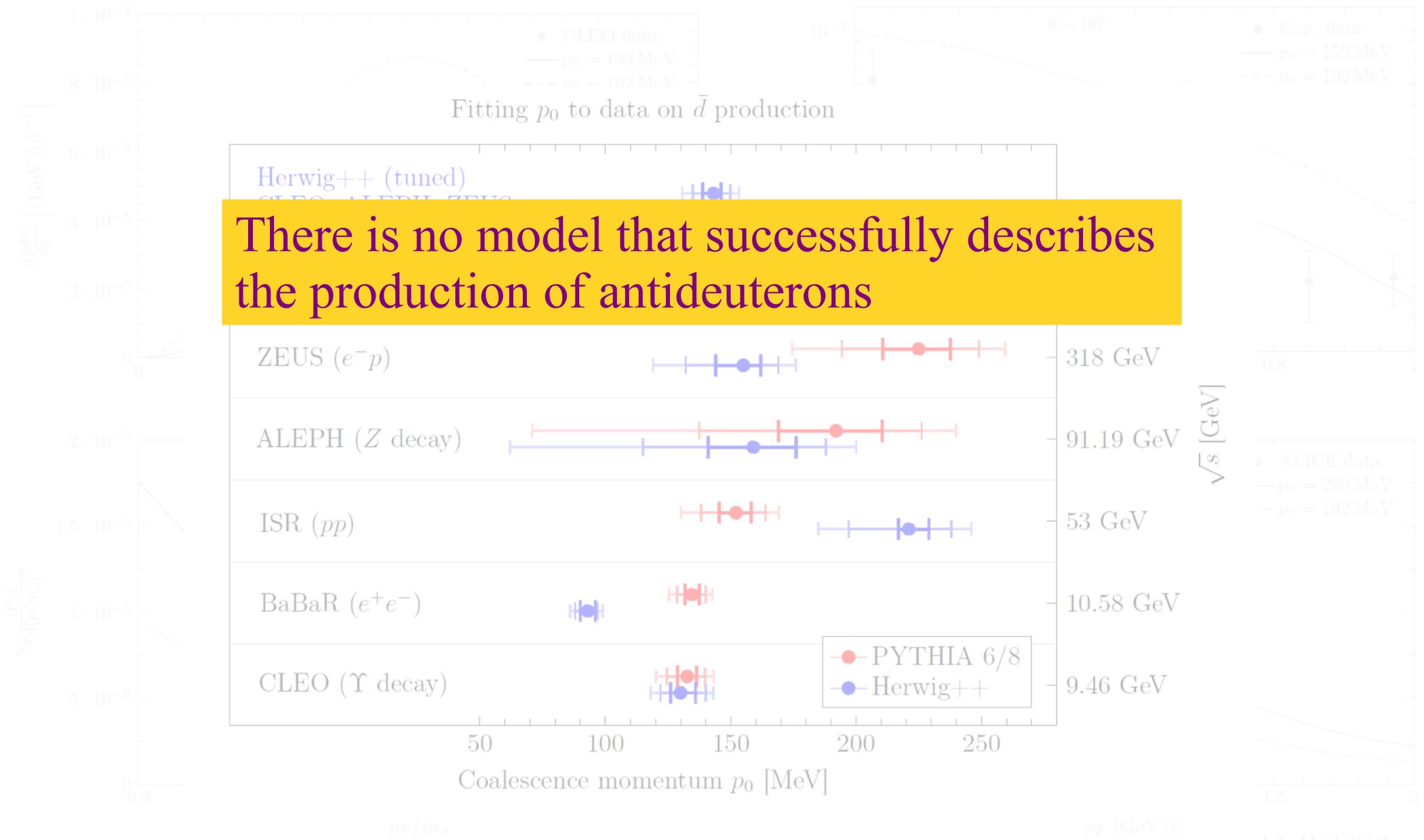
Antideuterons and the coalescence model



Antideuterons and the coalescence model

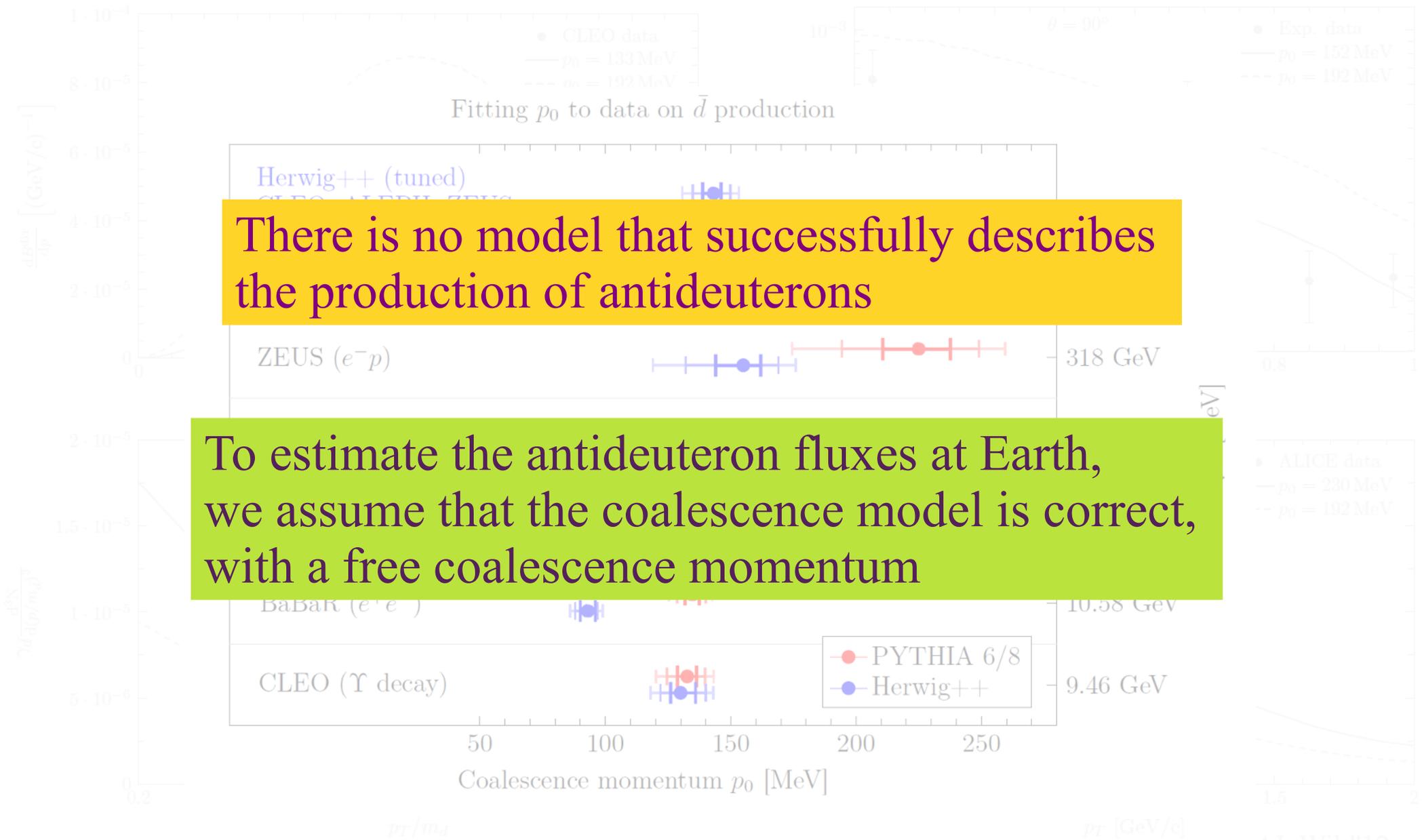


Antideuterons and the coalescence model



There is no model that successfully describes the production of antideuterons

Antideuterons and the coalescence model

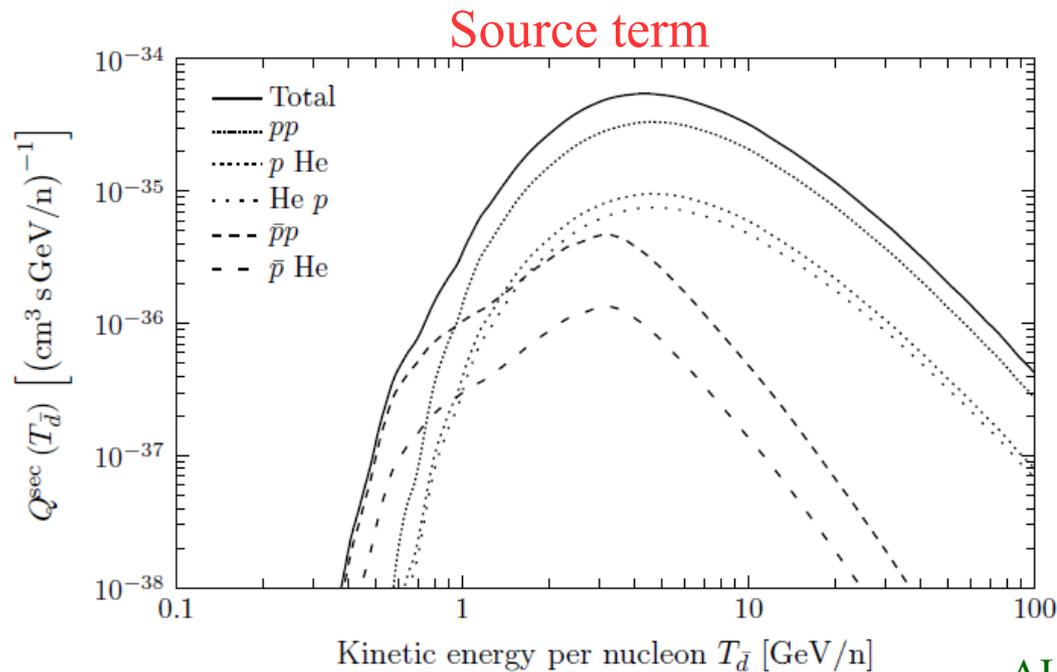


Why do we care
about antinuclei?

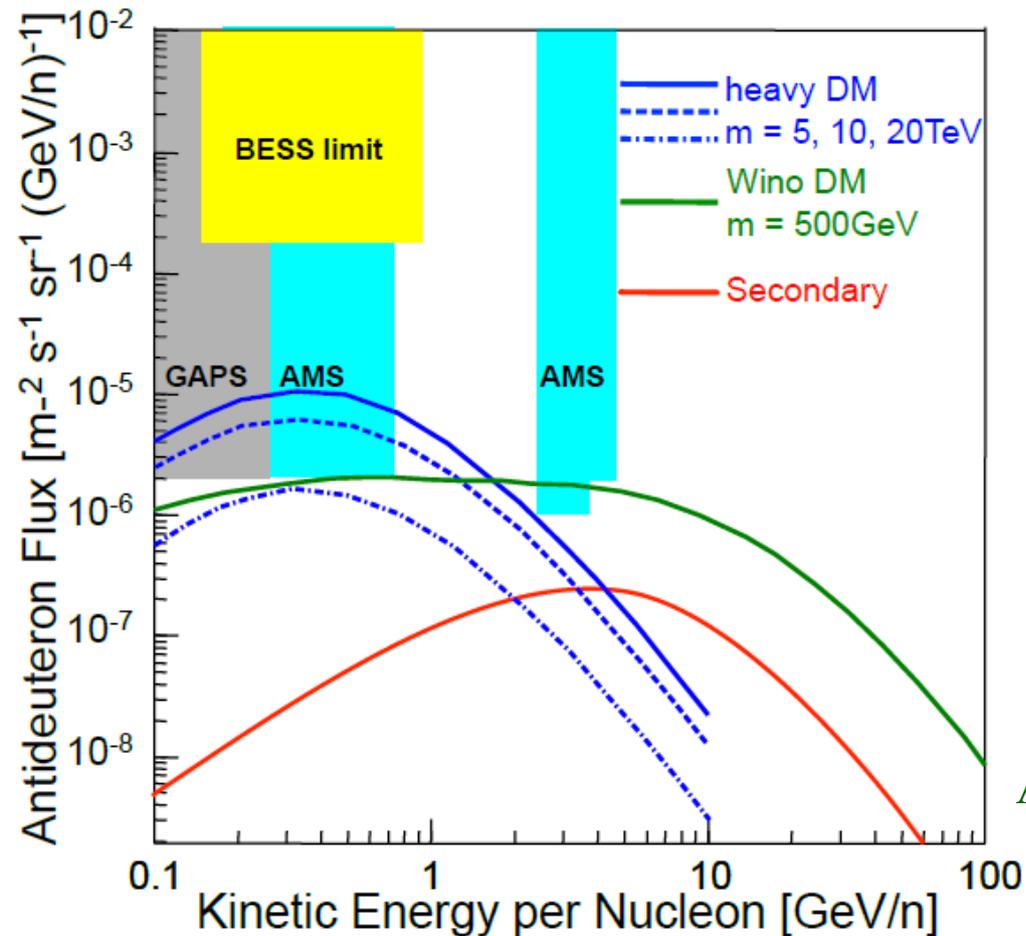
Antideuteron sources in the galaxy

- “Secondary” antideuteron production: $pp \rightarrow \bar{d} n p p p$
- Threshold energy (c.o.m.) $\sqrt{s} = 6m_p$
- Threshold energy of the incoming proton (galactic frame) $T_p^{\text{thr}} = 16m_p$

The center of momentum frame of the collision is very boosted \rightarrow most of the antideuterons inherit a large kinetic energy



Antideuteron flux at Earth

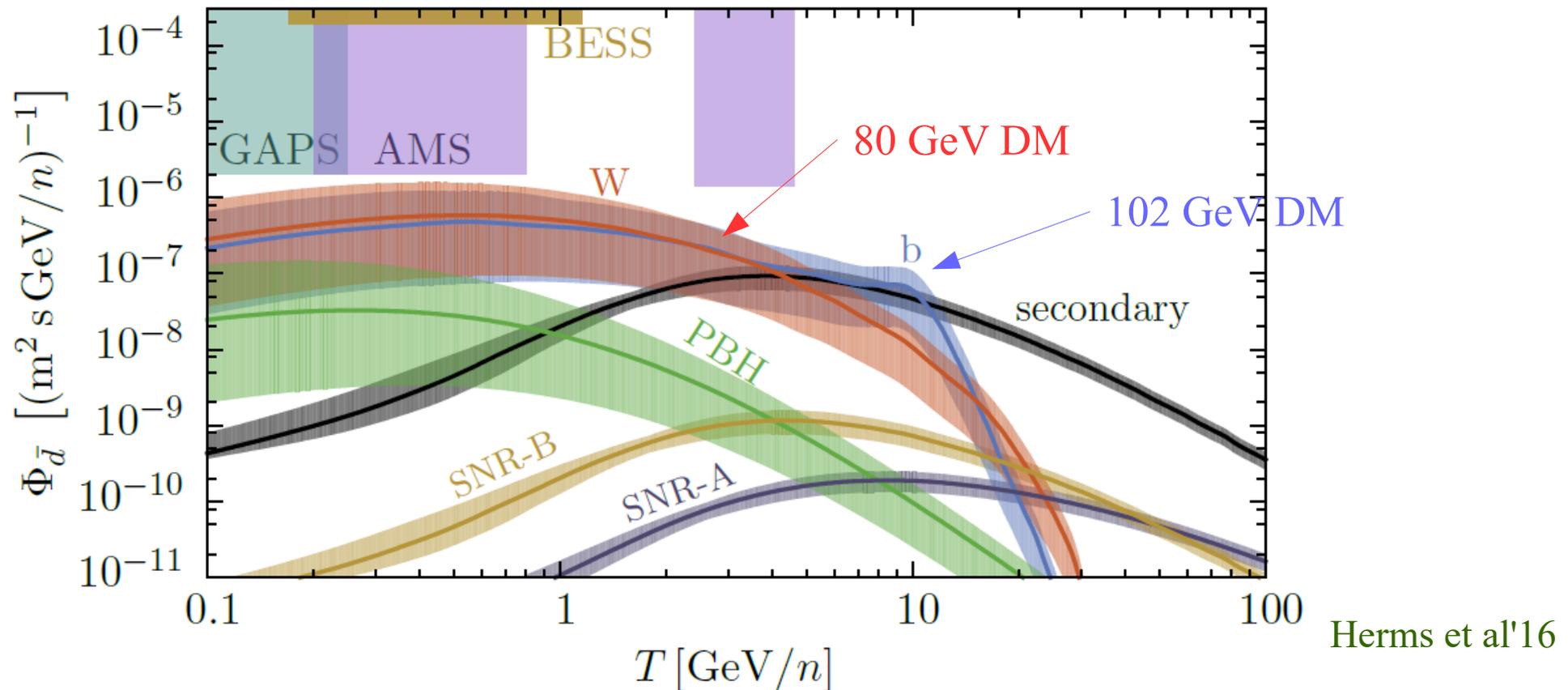


Arakami et al'16

No astrophysical backgrounds expected at GAPS or AMS-02.
The observation of antideuteron events would point to an exotic origin.

Antideuterons from dark matter annihilation

Note that the antideuteron flux highly correlated to the antiproton flux
→ strong limits on the antideuteron flux from the non-observation of an antiproton excess in PAMELA.



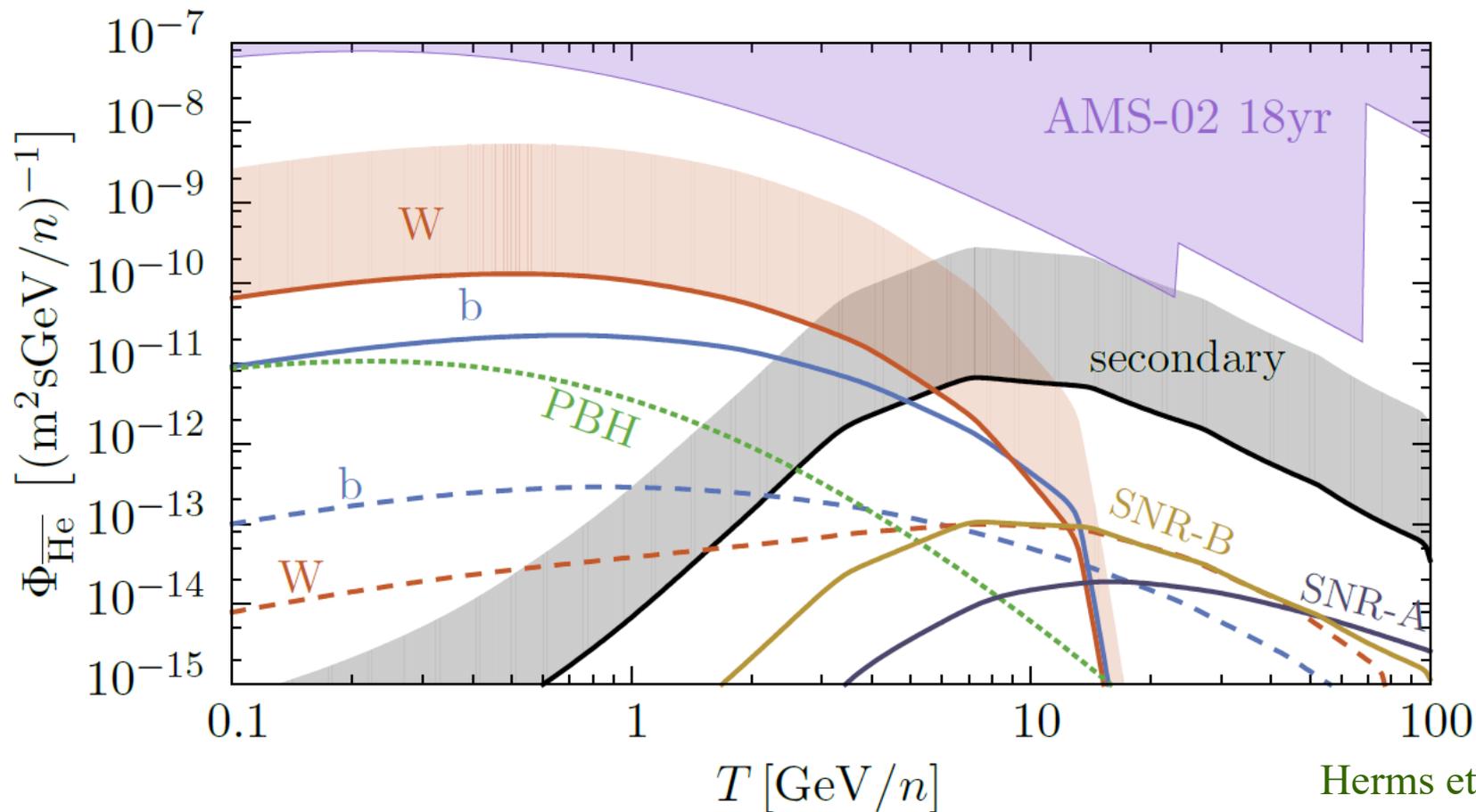
However, big uncertainties from the formation mechanism of antideuterons

Antihelium nuclei from dark matter annihilation

- Formed when **two** antiprotons and one antineutron coalesce.

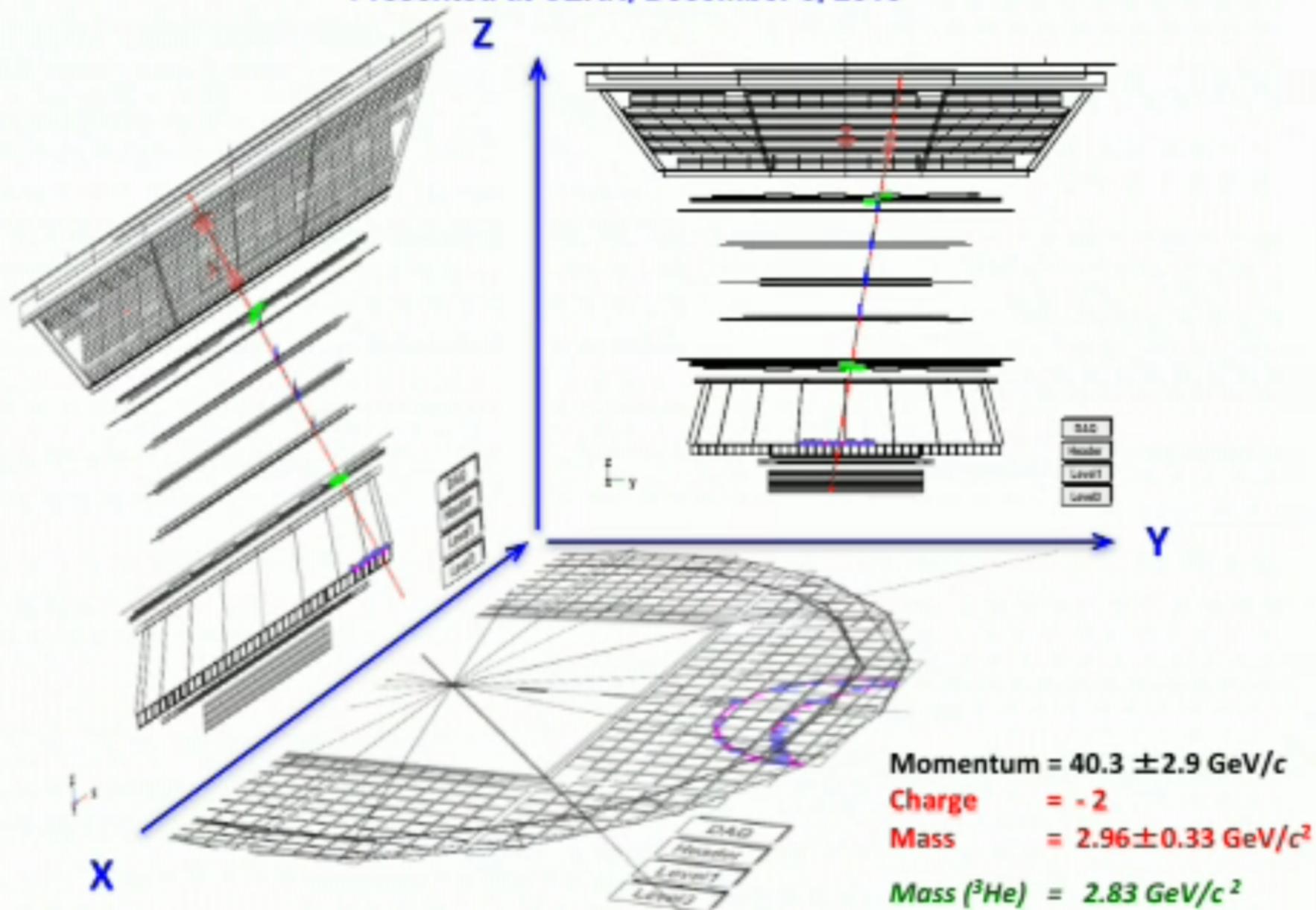
Carlson, Coogan, Linden, Profumo, AI, Wild '14

Cirelli, Fornengo, Taoso, Vittino '14



An anti-Helium candidate:

Presented at CERN, December 8, 2016



To date, we have observed eight events in the mass region from 0 to 10 GeV with $Z = -2$.

All eight events are in the helium mass region.

All eight events are clean single-track events without additional hits.

All eight events are in the momentum range < 100 GeV/c (where the momentum resolution is better than 10%).

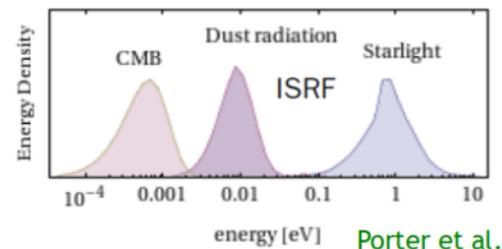
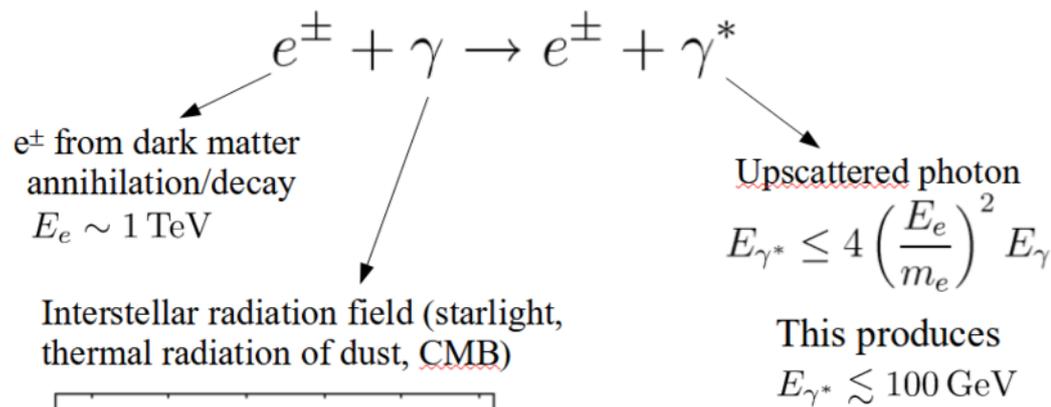
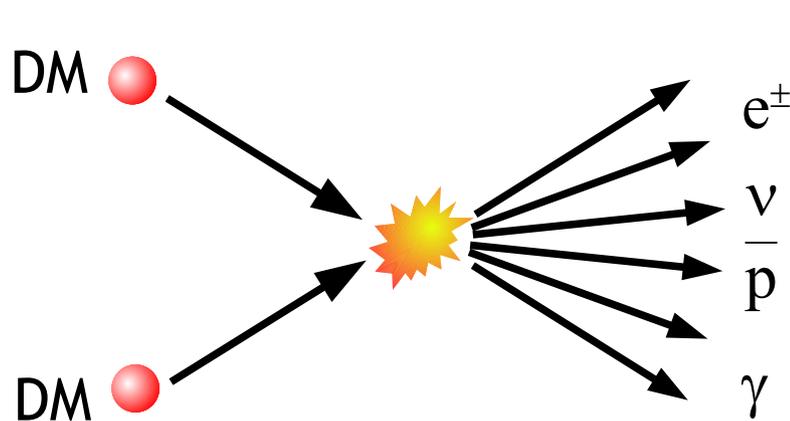
Gamma-rays

Production of gamma-rays

The gamma ray flux from dark matter annihilations/decays has two components:

- Prompt radiation of gamma rays produced in the annihilation/decay (final state radiation, pion decay...)
- May contain spectral features.

- Inverse Compton Scattering radiation of electrons/positrons produced in the annihilation/decay.
- Always smooth spectrum.

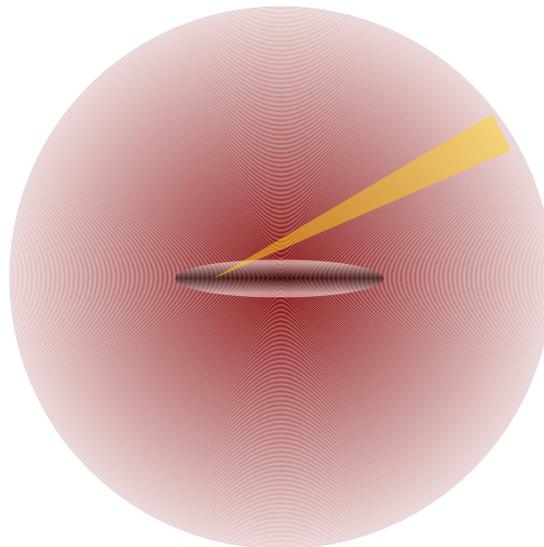


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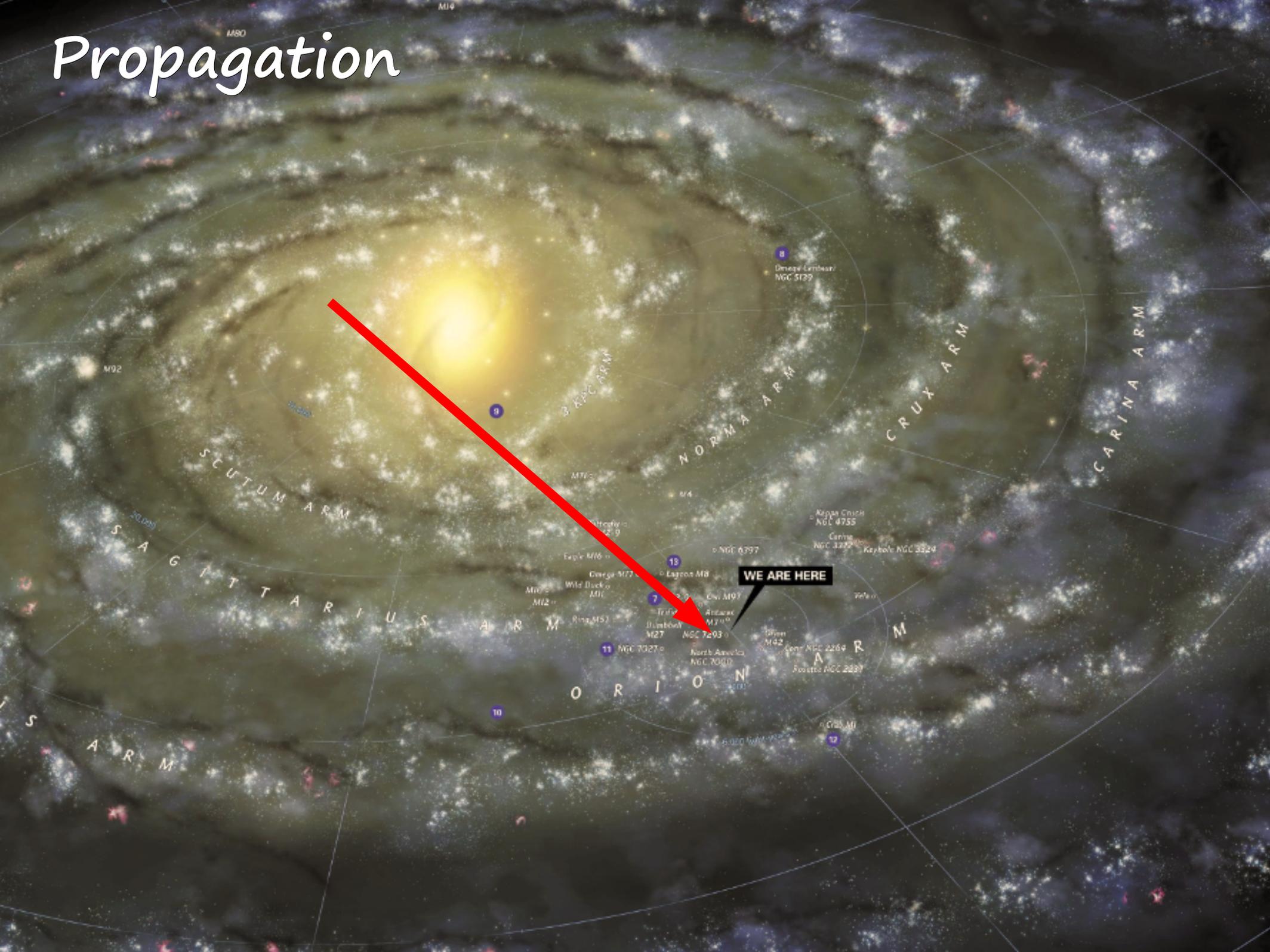
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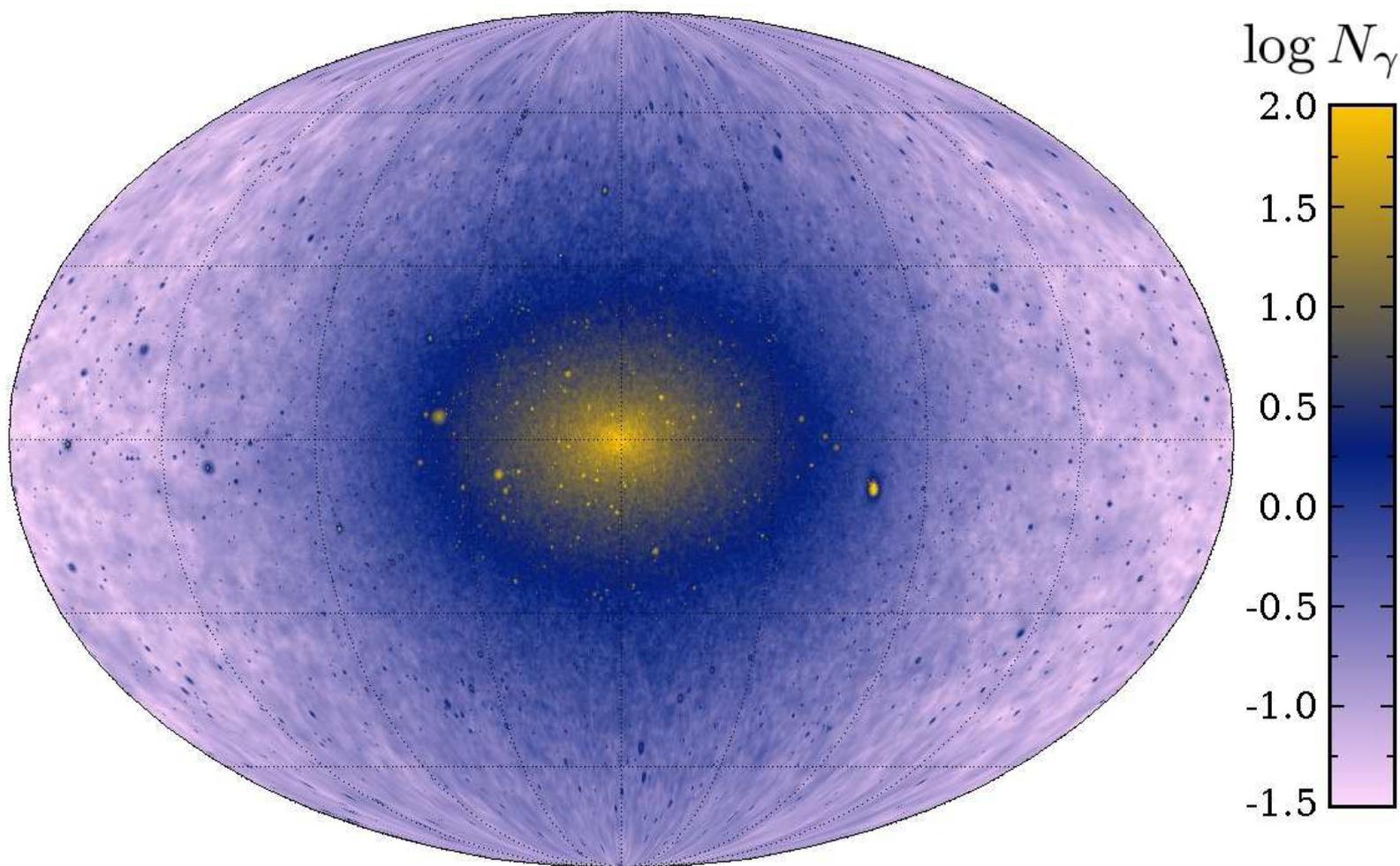
Integrate over the line of sight

Propagation



Where to look for *annihilating* dark matter

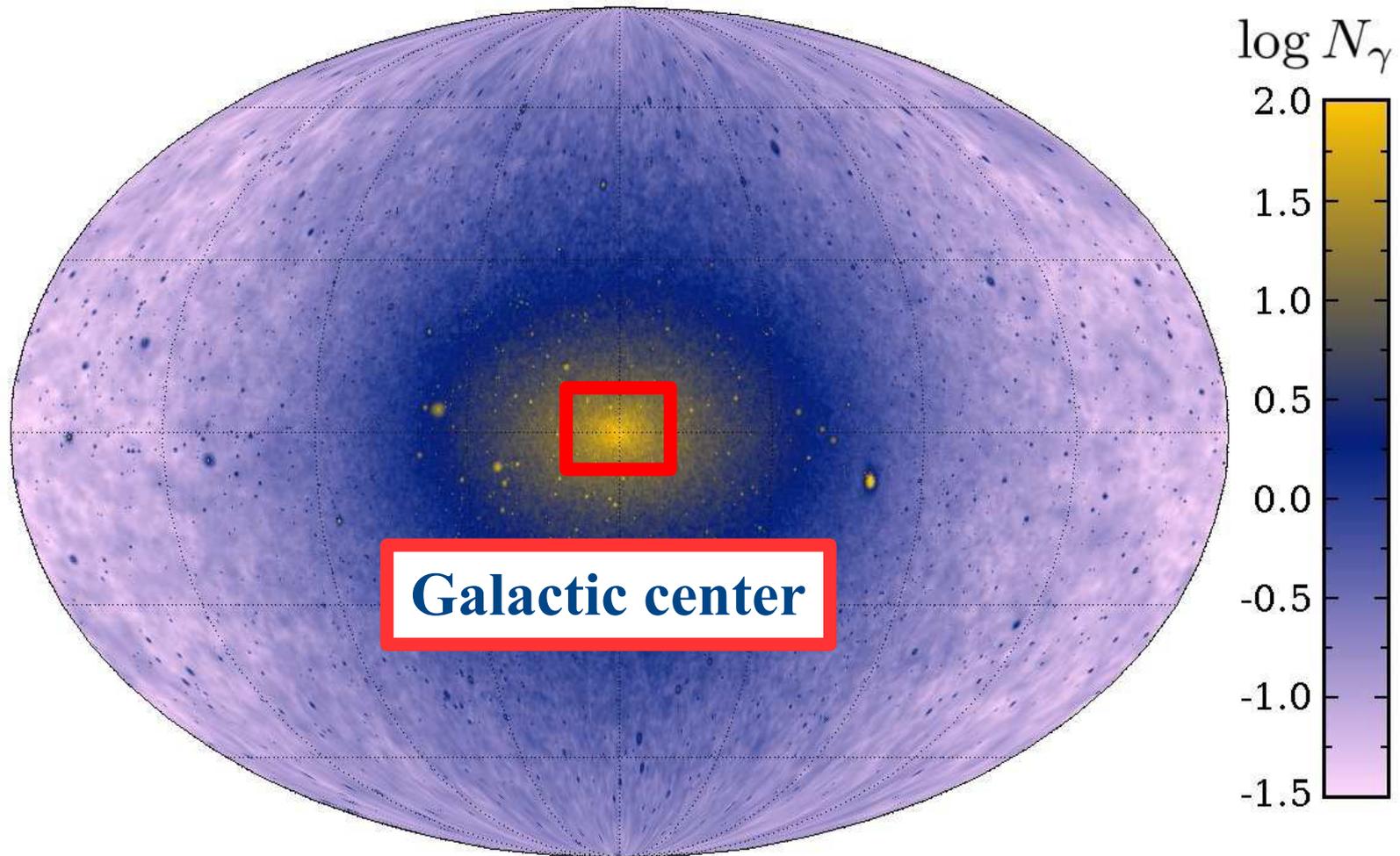
Baltz et al.
arXiv:0806.2911



Kuhlen, Diemand, Madau

Where to look for *annihilating* dark matter

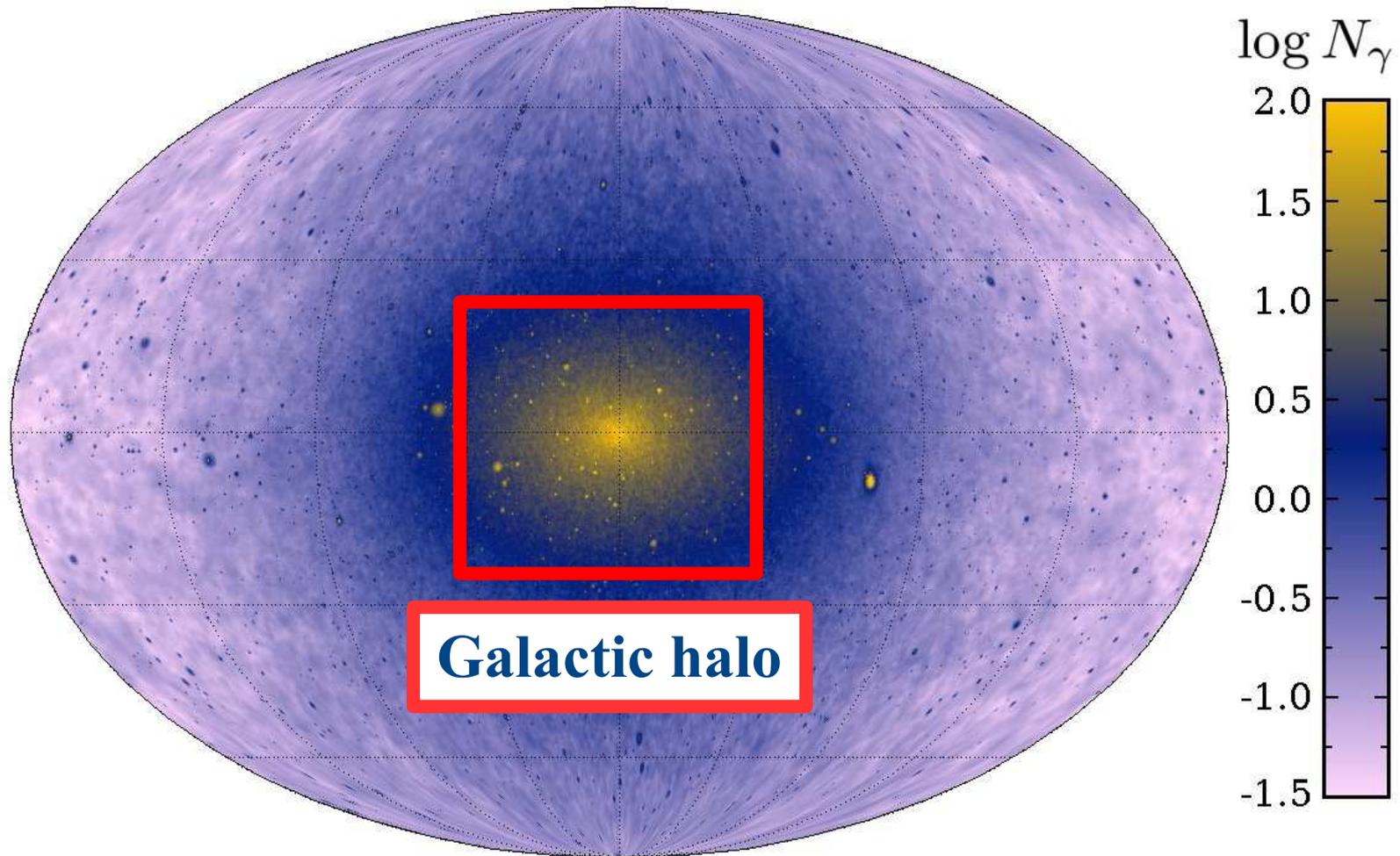
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Kuhlen, Diemand, Madau

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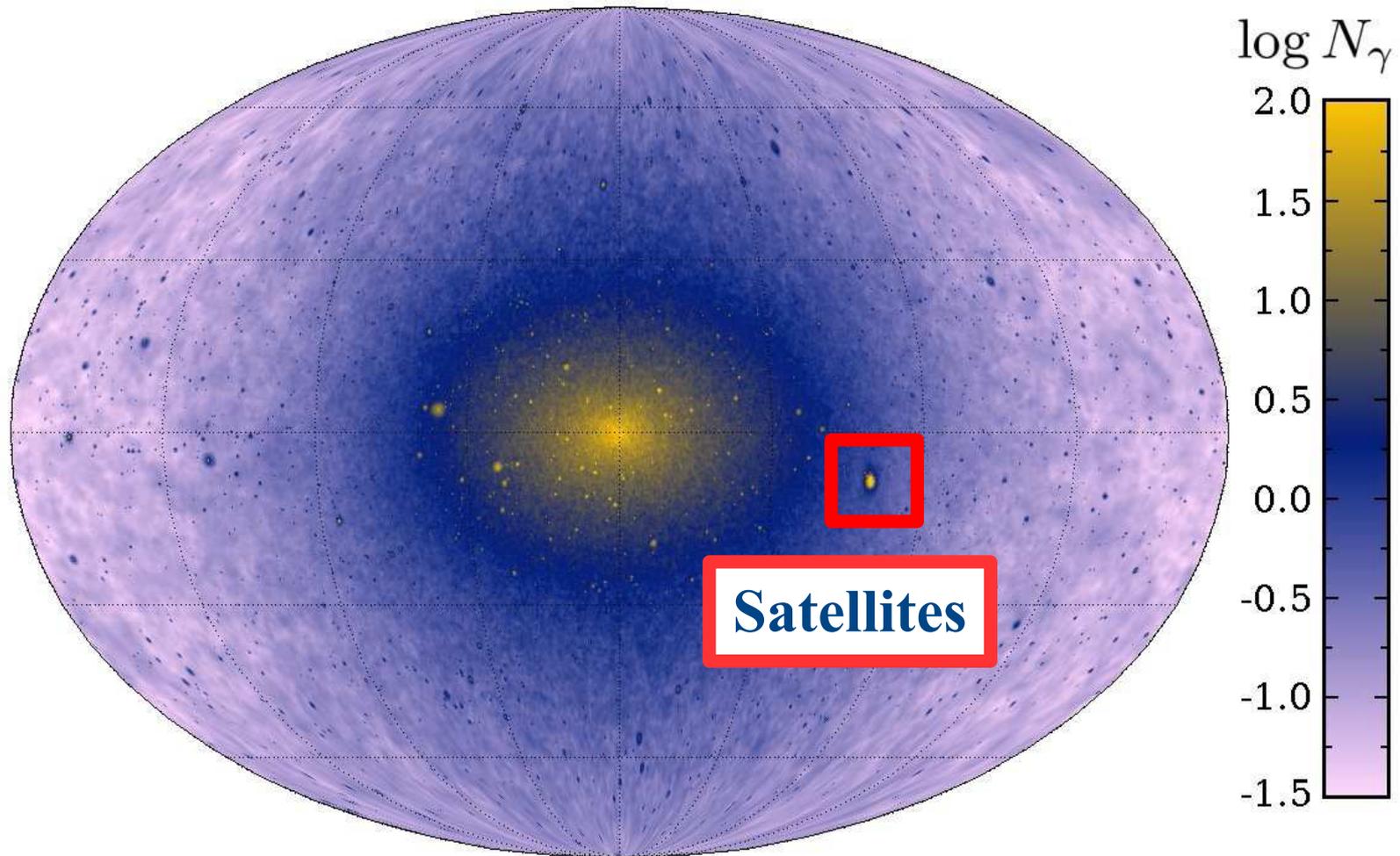
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Kuhlen, Diemand, Madau

Where to look for *annihilating* dark matter

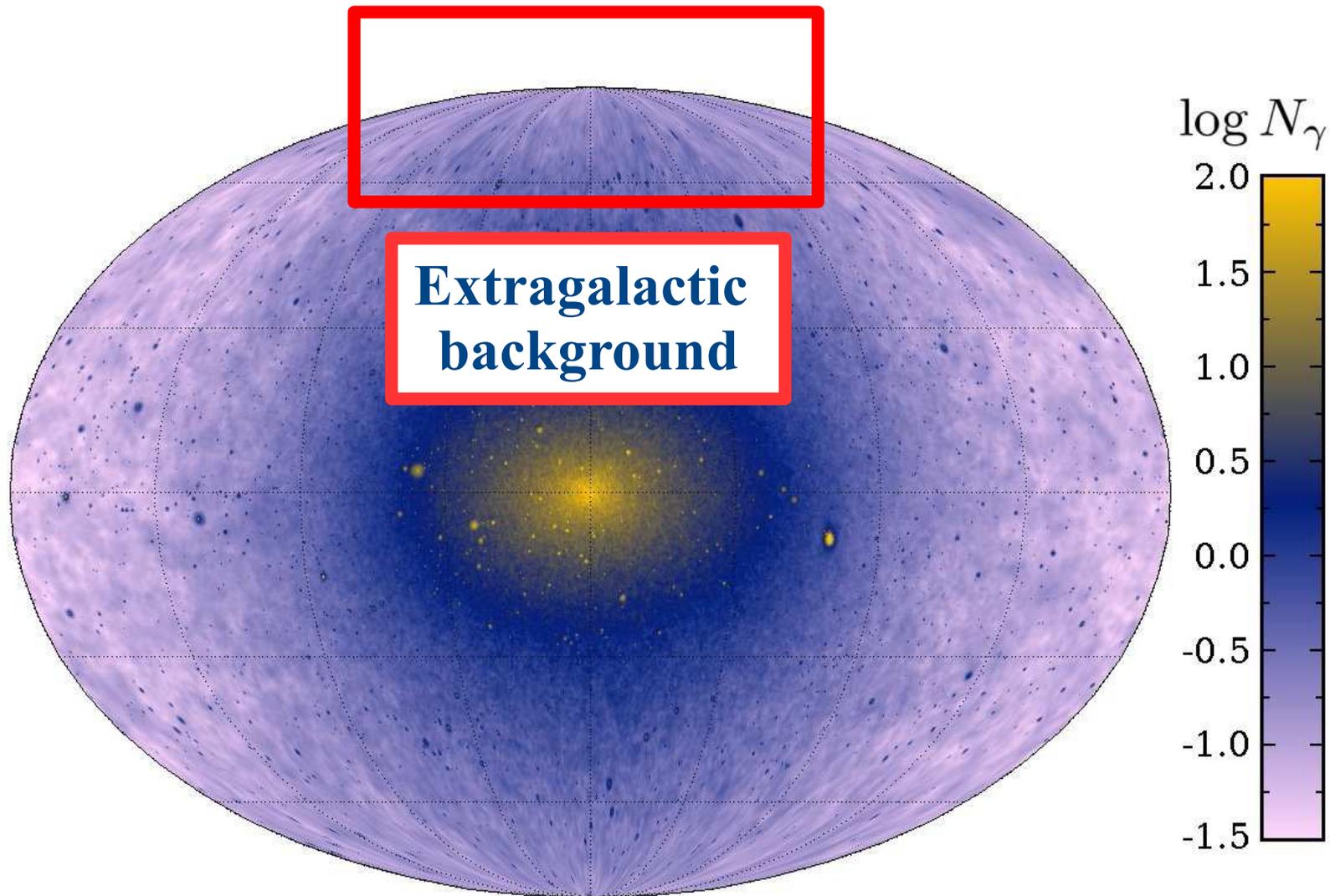
Baltz et al.
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Kuhlen, Diemand, Madau

Where to look for *annihilating* dark matter

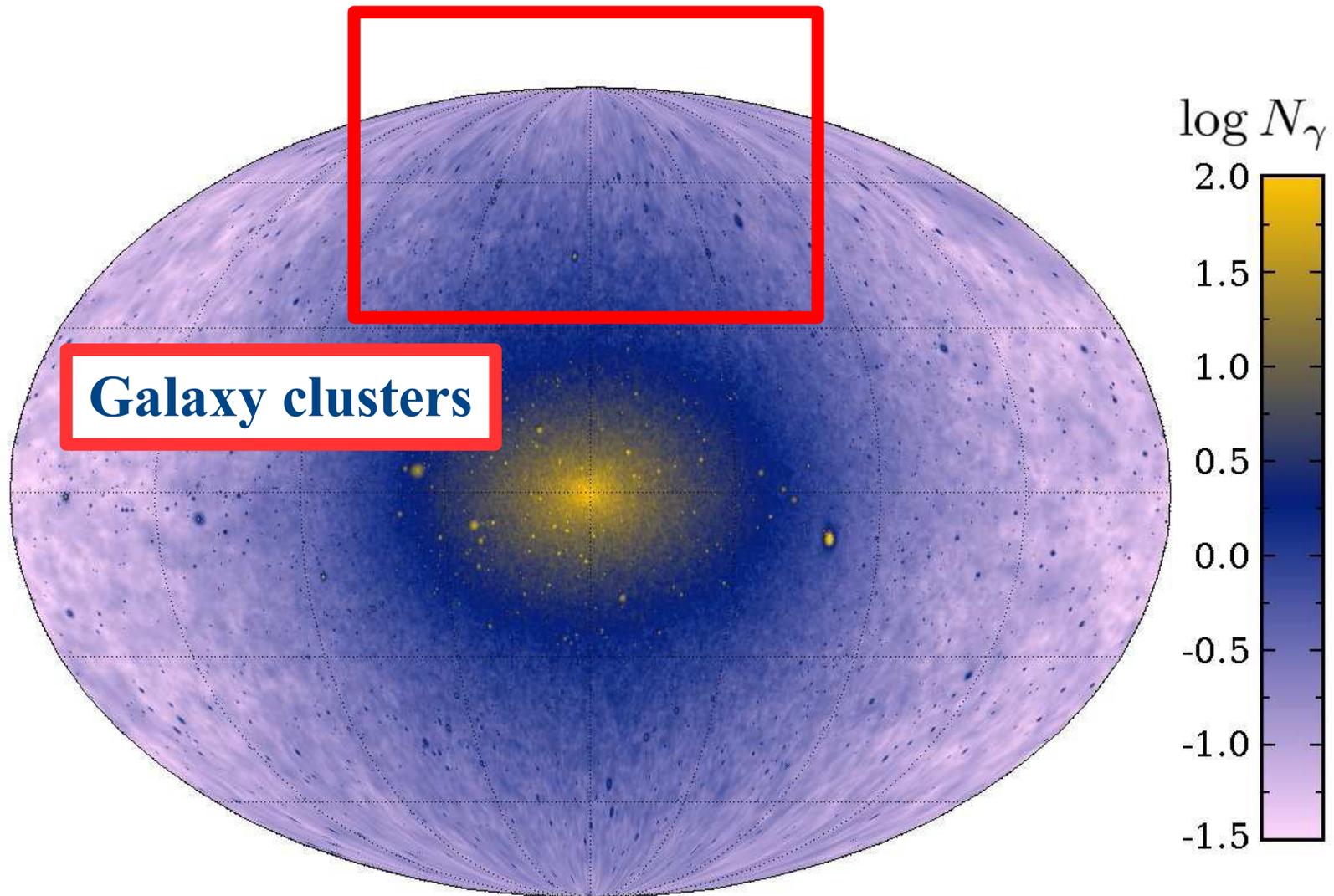
Baltz et al.
arXiv:0806.2911



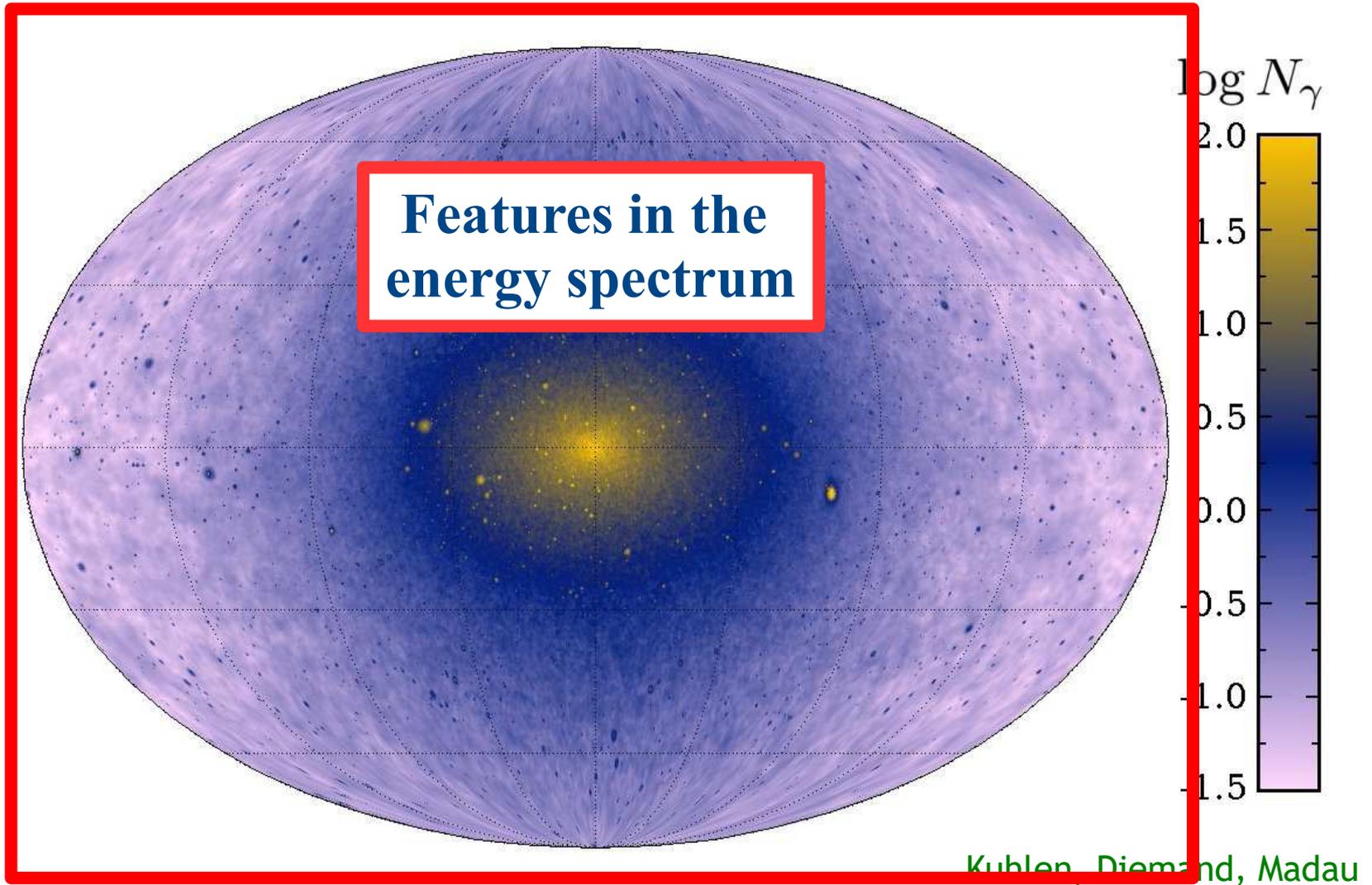
Kuhlen, Diemand, Madau

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Kuhlen, Diemand, Madau

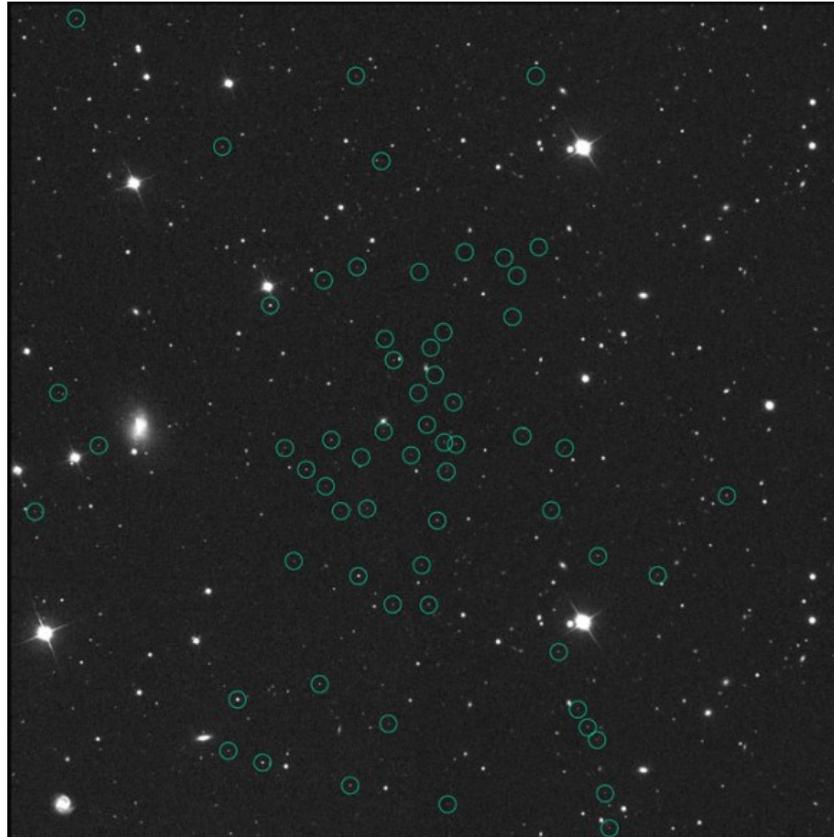


A promising target for detection: dwarf galaxies



Segue 1: Optical image

A promising target for detection: dwarf galaxies



Segue 1: Optical image

A promising target for detection: dwarf galaxies



Segue 1: Optical image

A promising target for detection: dwarf galaxies



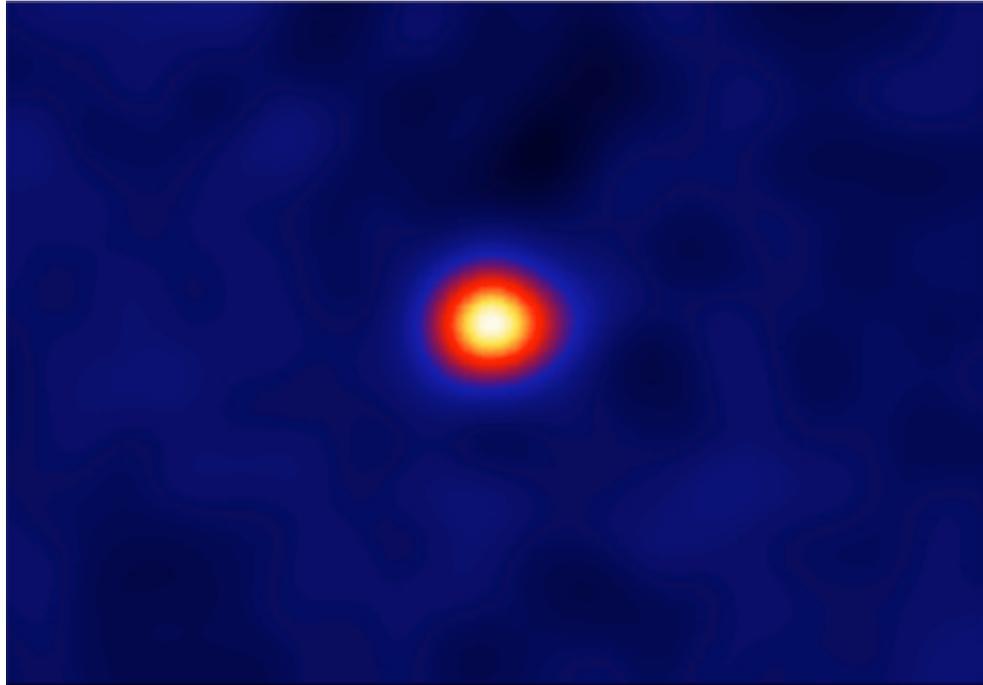
Segue 1: Optical image

Mass-to-light ratio

$\sim 3400 M_{\text{sun}}/L_{\text{sun}}$

Most DM-dominated
object known so far!

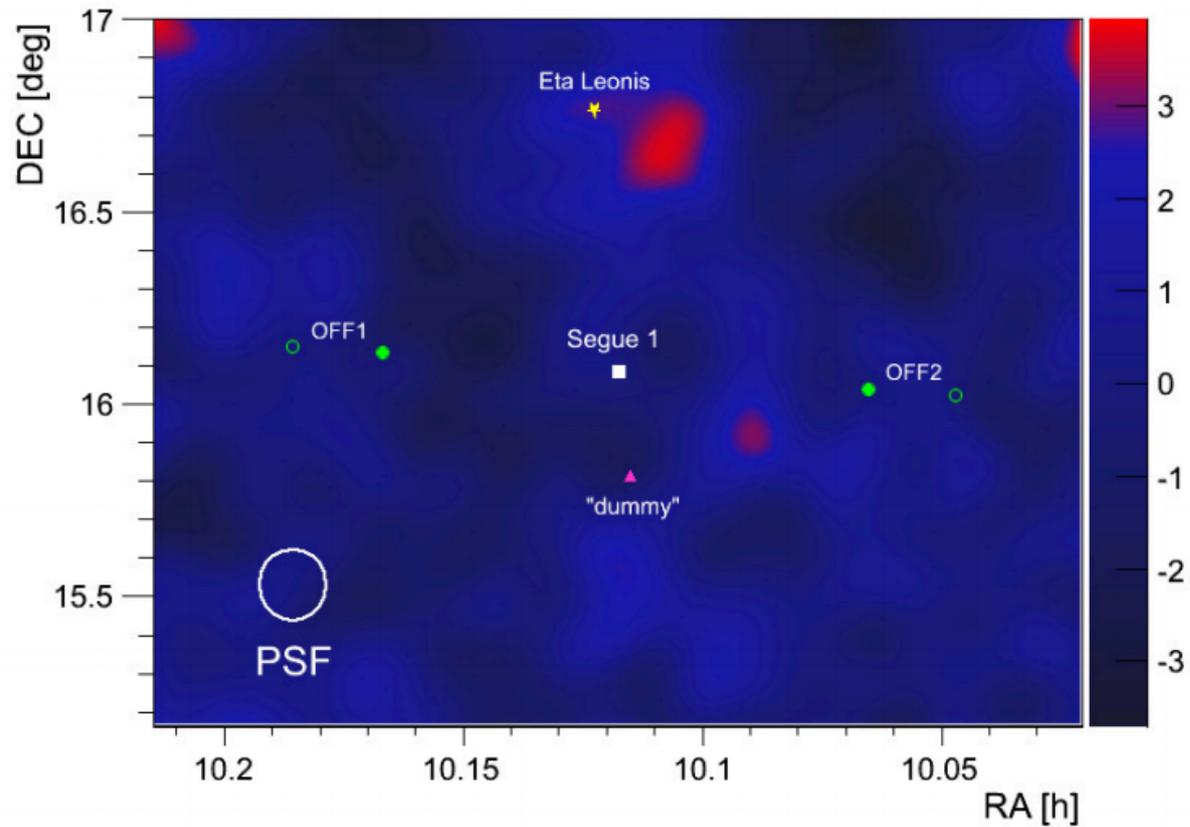
A promising target for detection: dwarf galaxies



Segue 1: Gamma-ray image

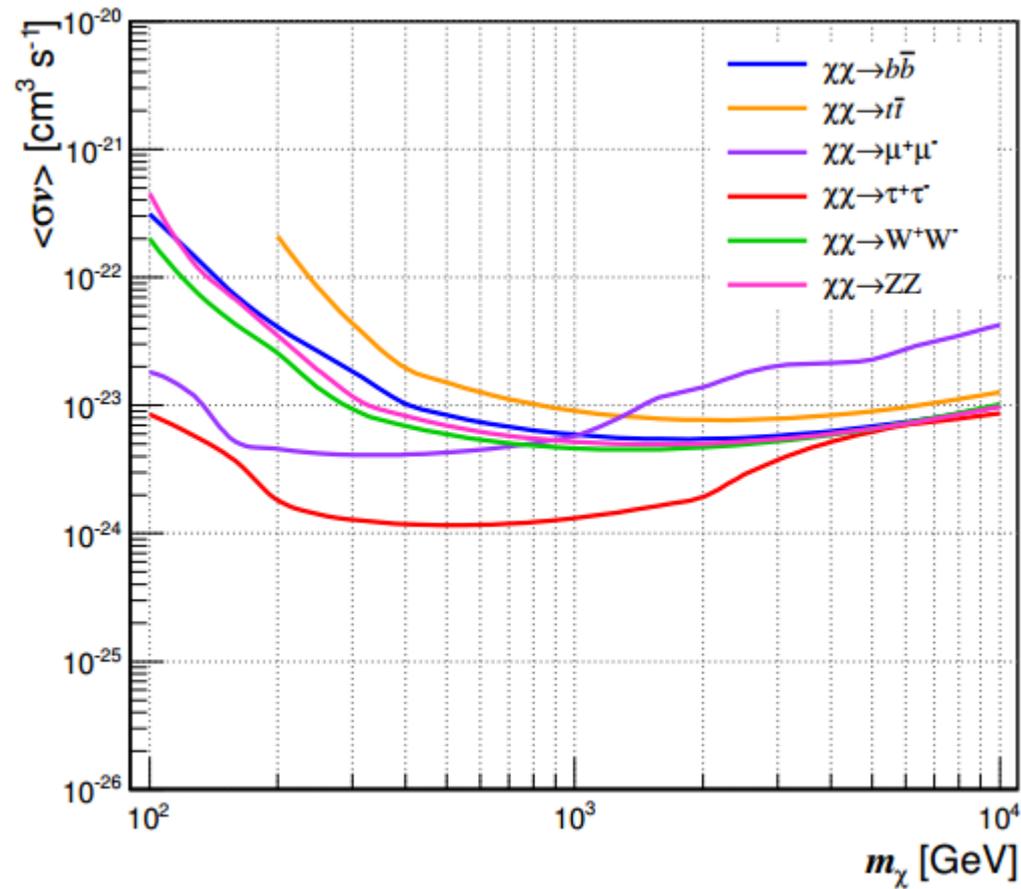
(simulated!)

A promising target for detection: dwarf galaxies



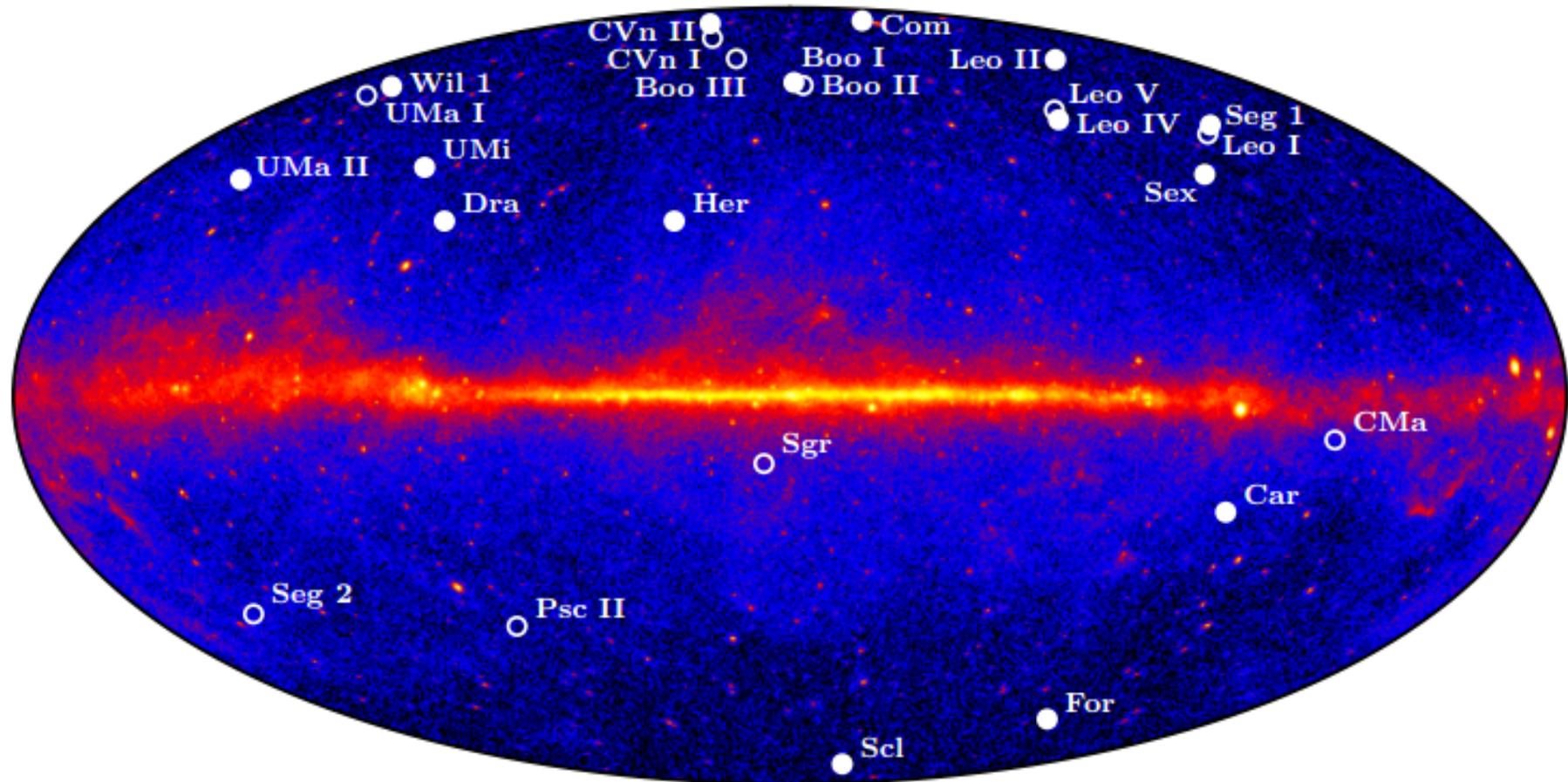
Gamma-ray image taken with the MAGIC telescopes

A promising target for detection: dwarf galaxies

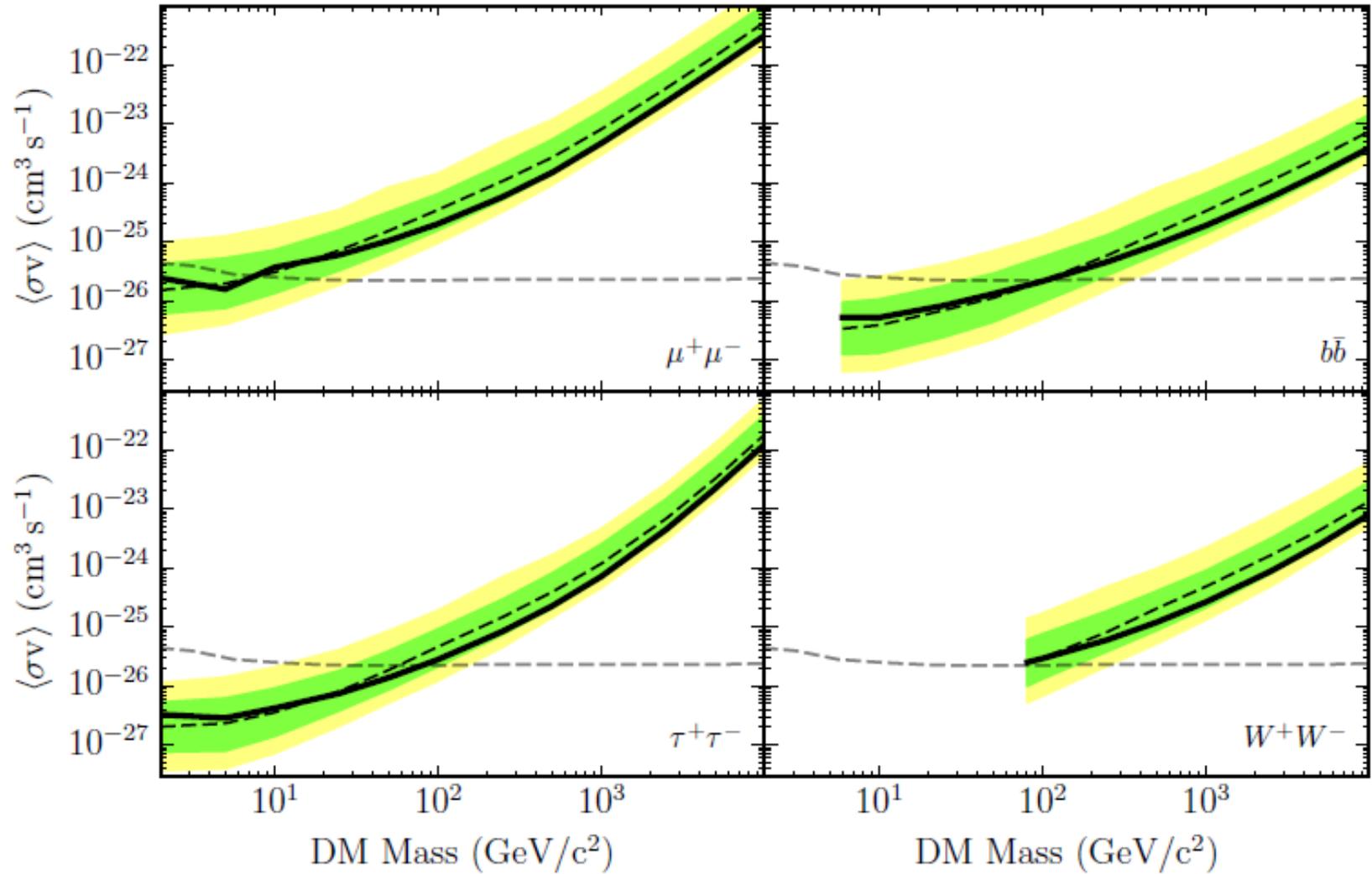


MAGIC coll.
arXiv:1312.1535

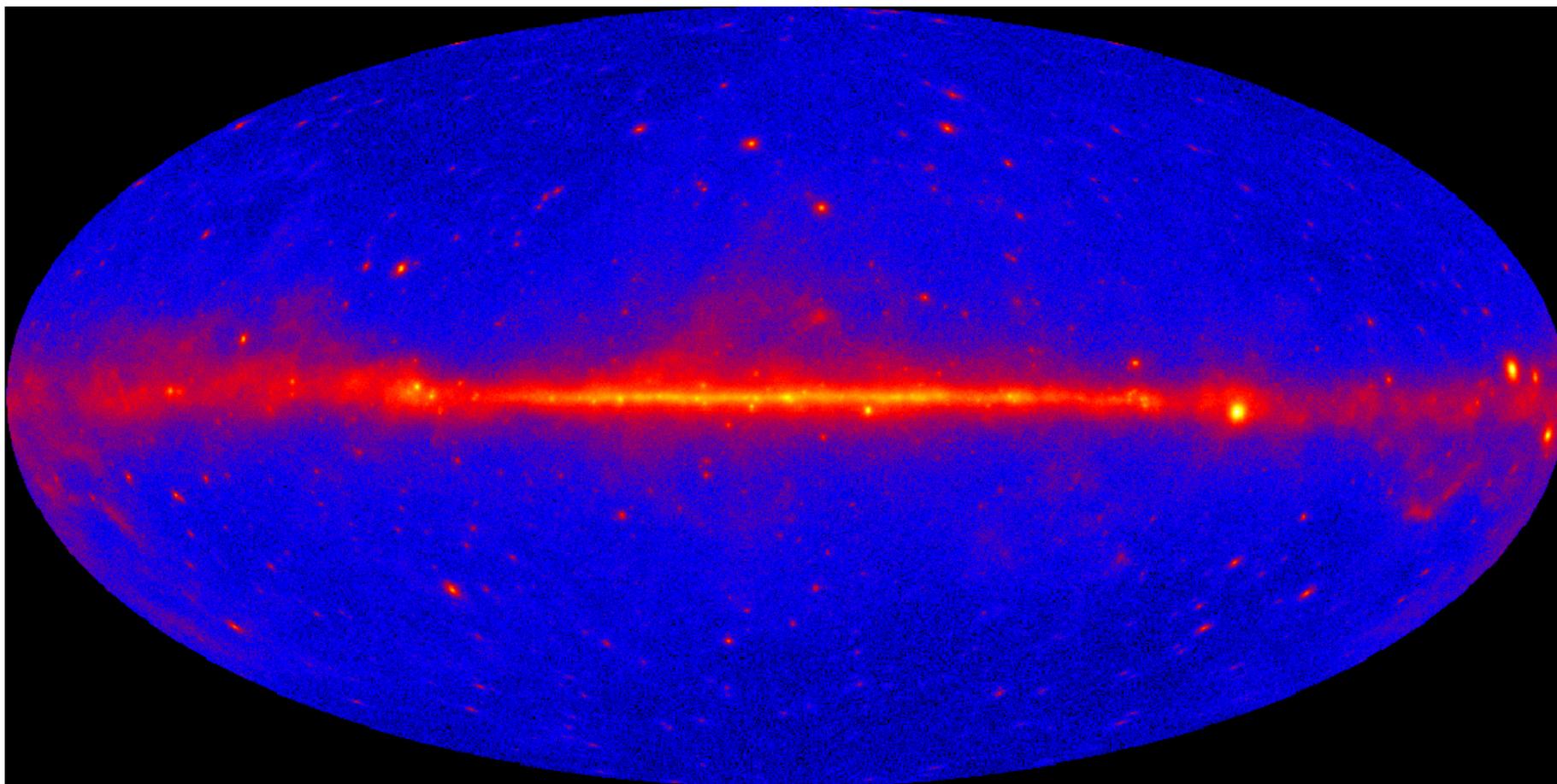
A promising target for detection: dwarf galaxies



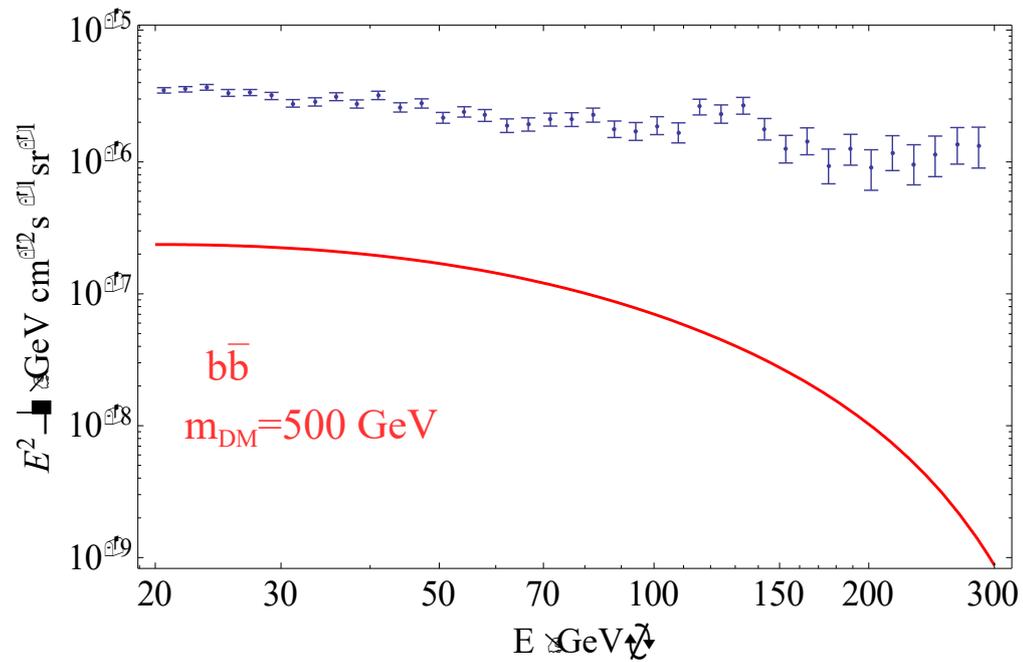
A promising target for detection: dwarf galaxies



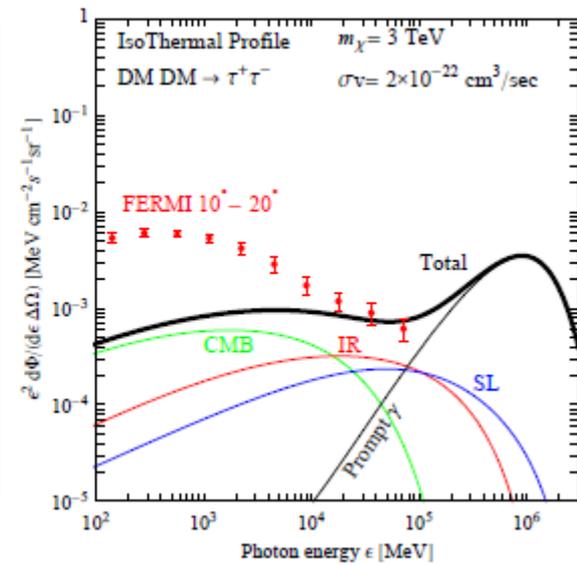
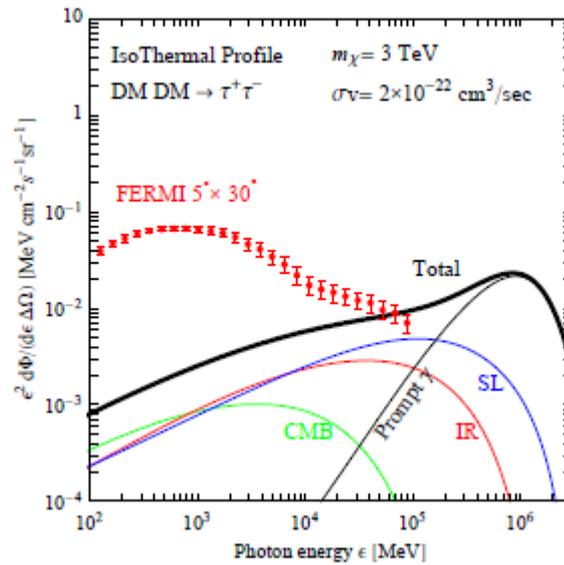
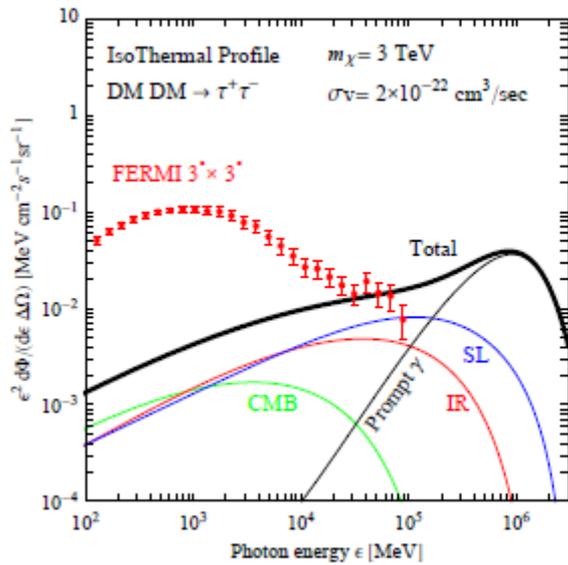
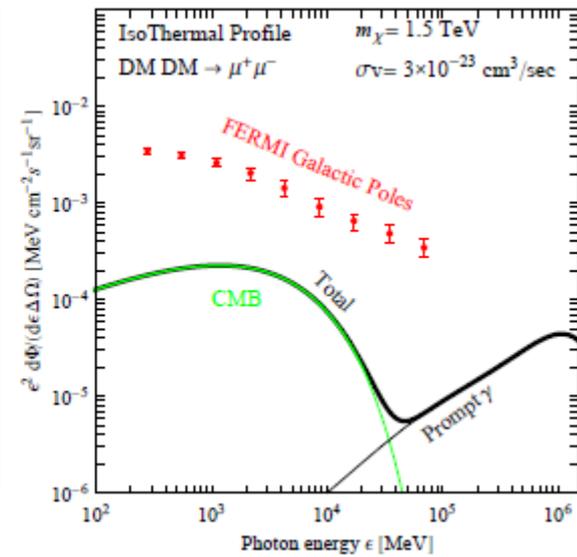
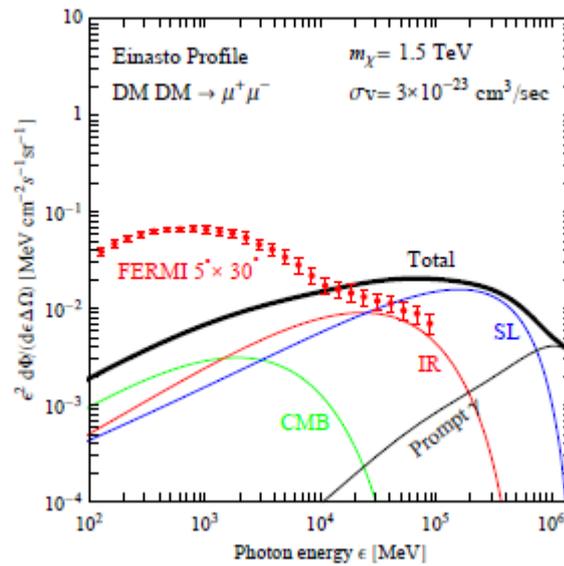
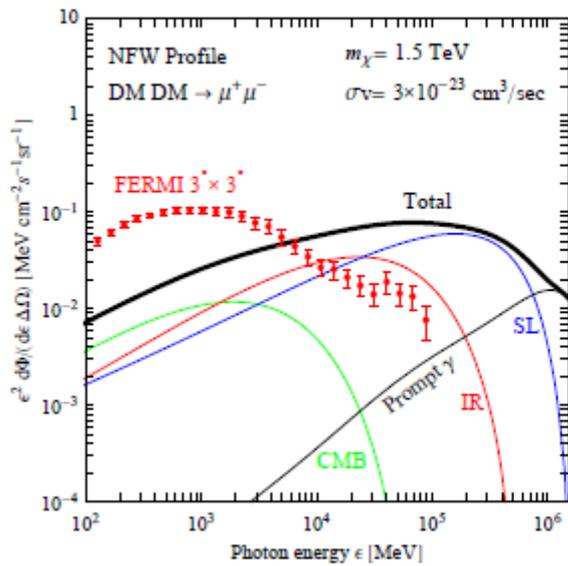
Diffuse Galactic emission



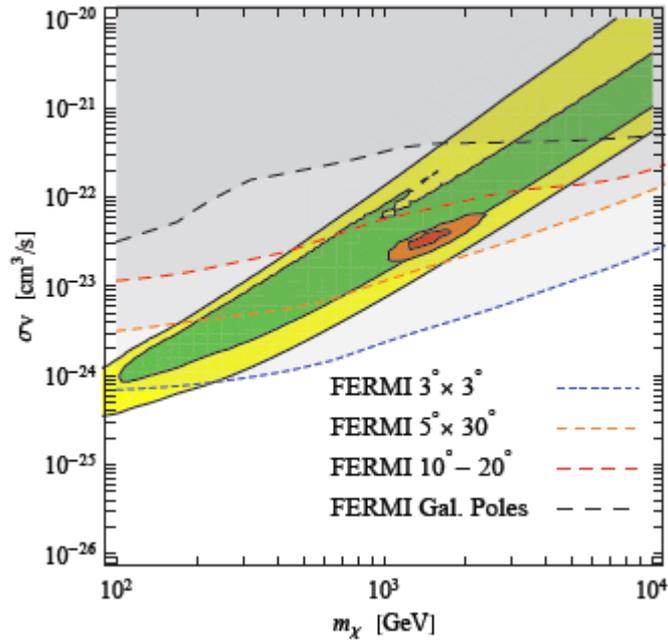
Search for DM in the galactic center region



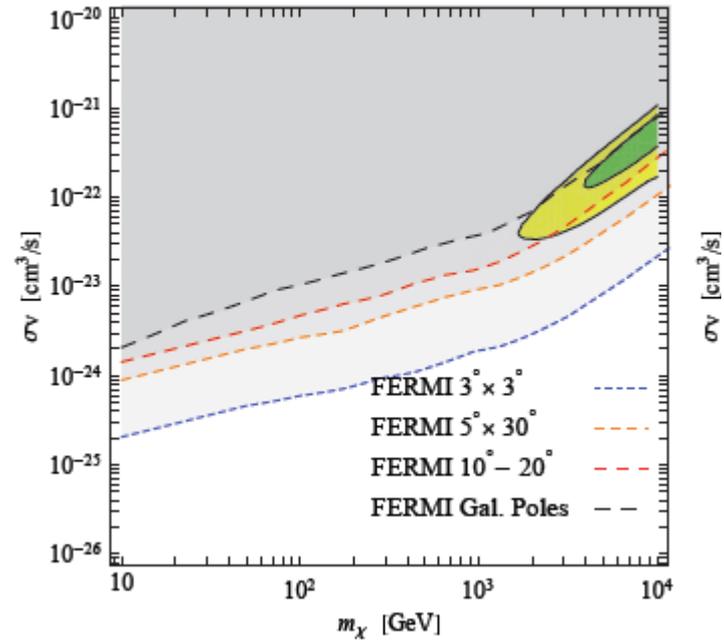
Conservative approach: demand that the flux from dark matter annihilation does not exceed the measured flux



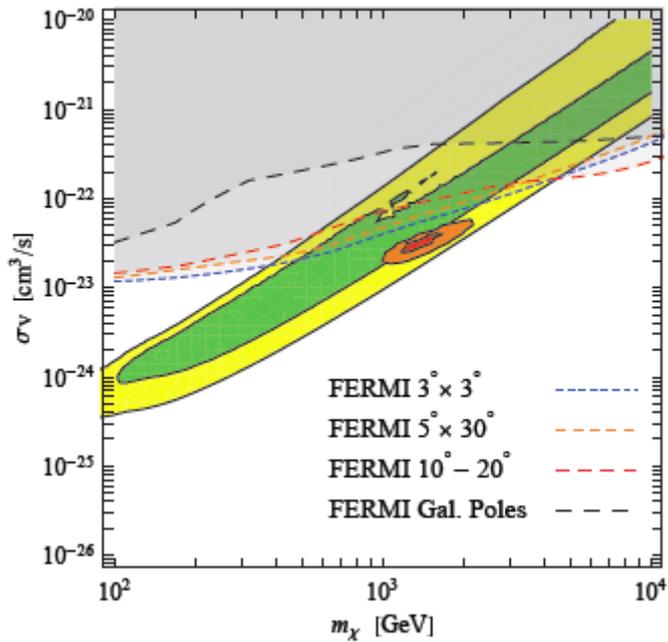
DM DM $\rightarrow \mu\mu$, Einasto profile



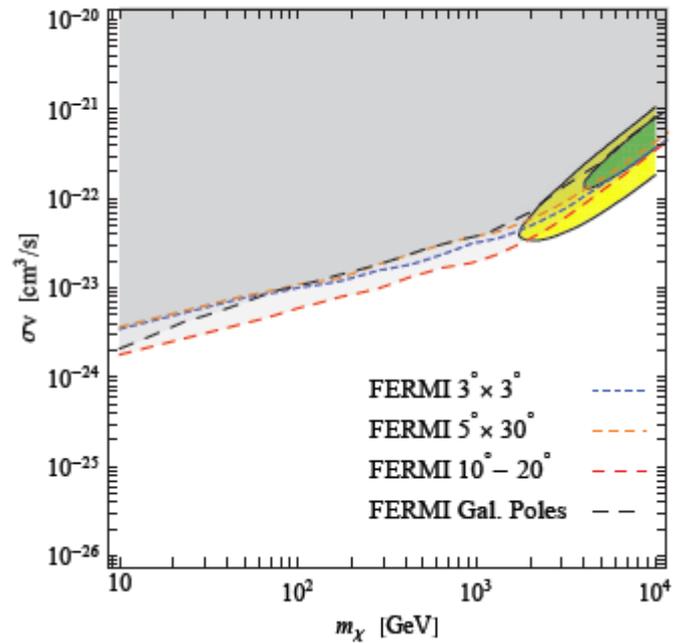
DM DM $\rightarrow bb$, Einasto profile



DM DM $\rightarrow \mu\mu$, Iso profile



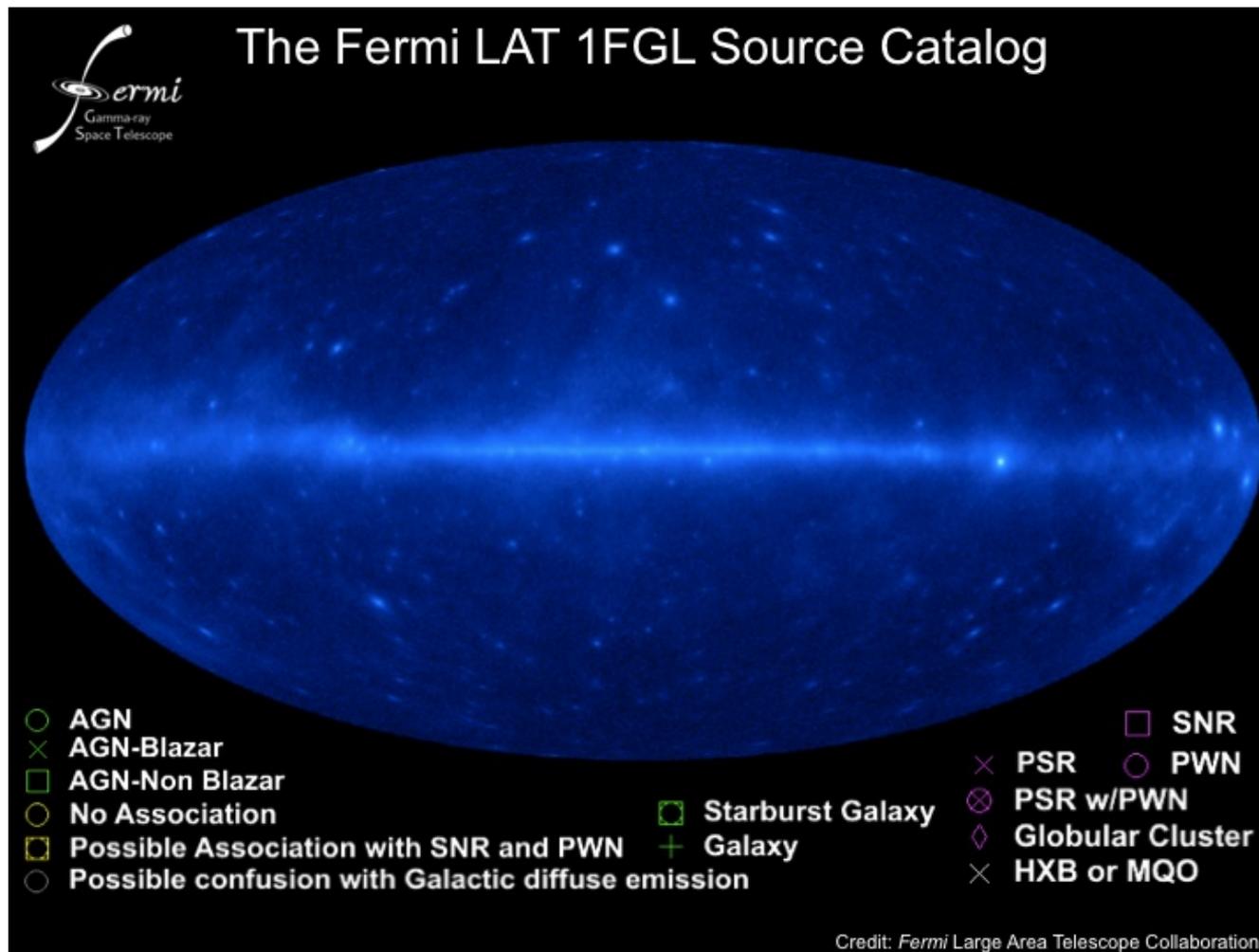
DM DM $\rightarrow bb$, Iso profile



Galactic center

However, one could do better. Some backgrounds are well understood

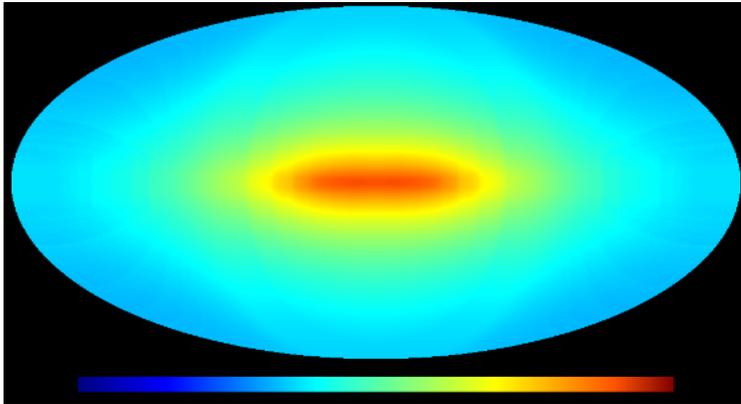
Background I: sources



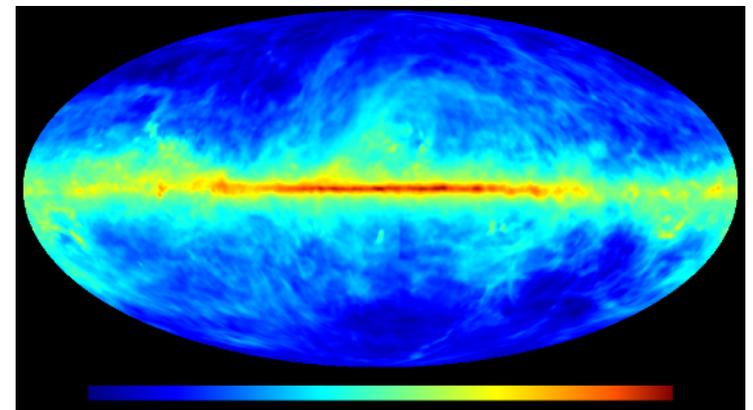
Galactic center

However, one could do better. Some backgrounds are well understood

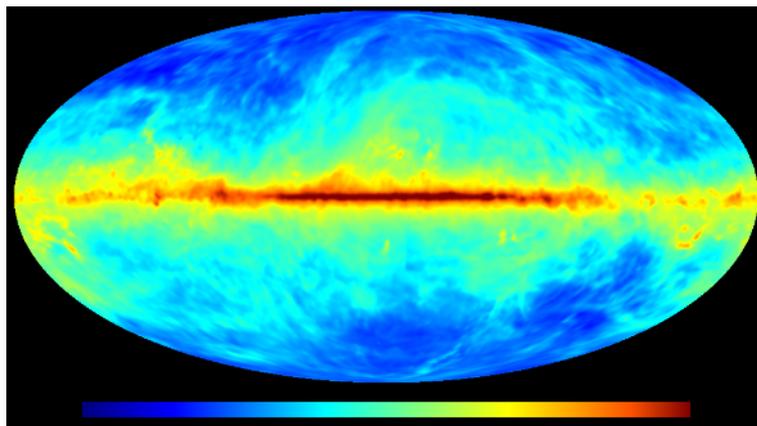
Background II: modelling of the diffuse emission



Inverse compton



Bremmstrahlung

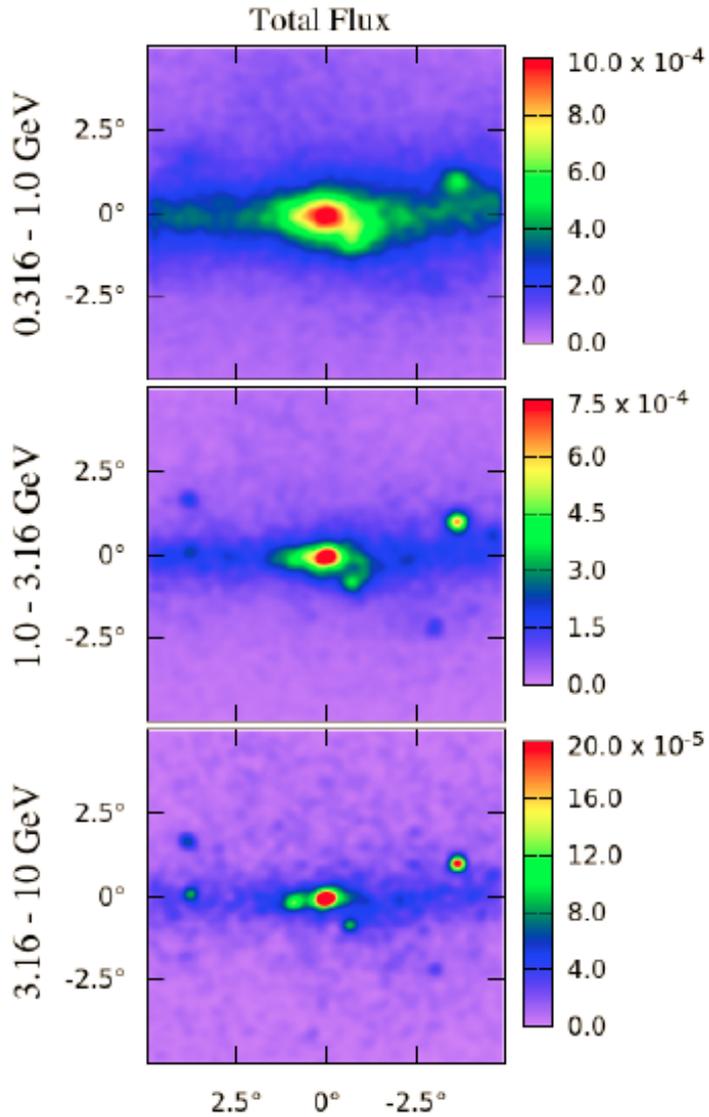


π^0 -decay

Region $|b| < 5^\circ$, $|l| < 5^\circ$

Daylan et al. '14
Goodenough, Hooper '09, '10
Hooper, Linden '11
Huang et al '13
Abazajian et al '14

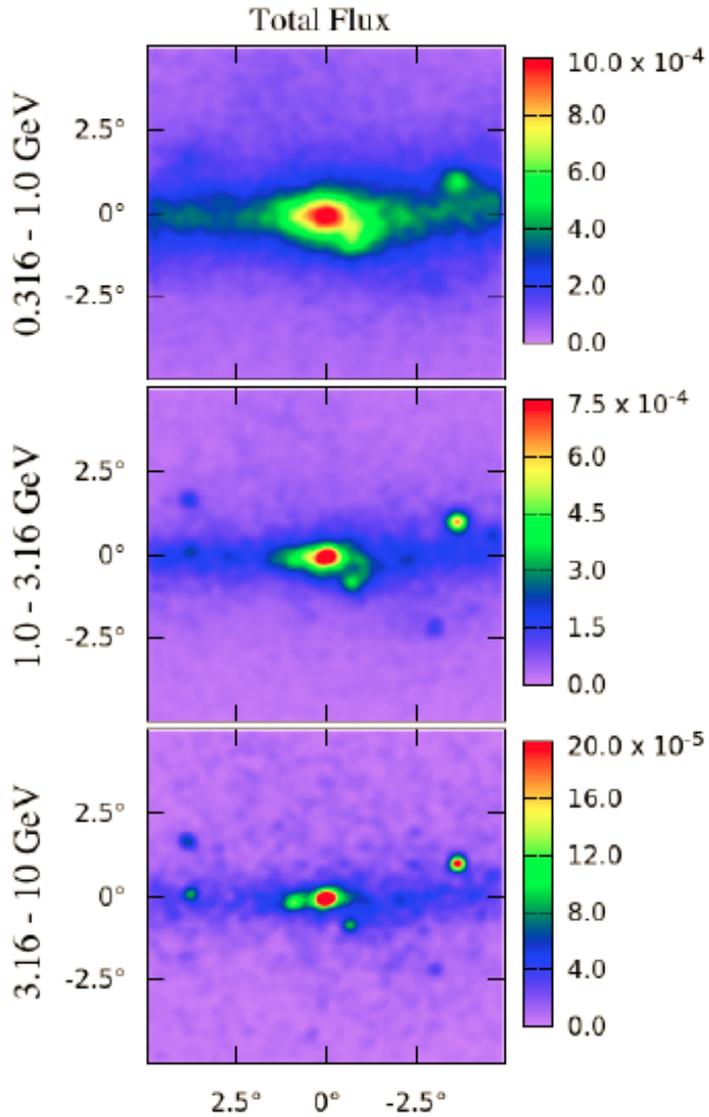
...



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Daylan et al. '14
Goodenough, Hooper '09, '10
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Abazajian et al '14

...



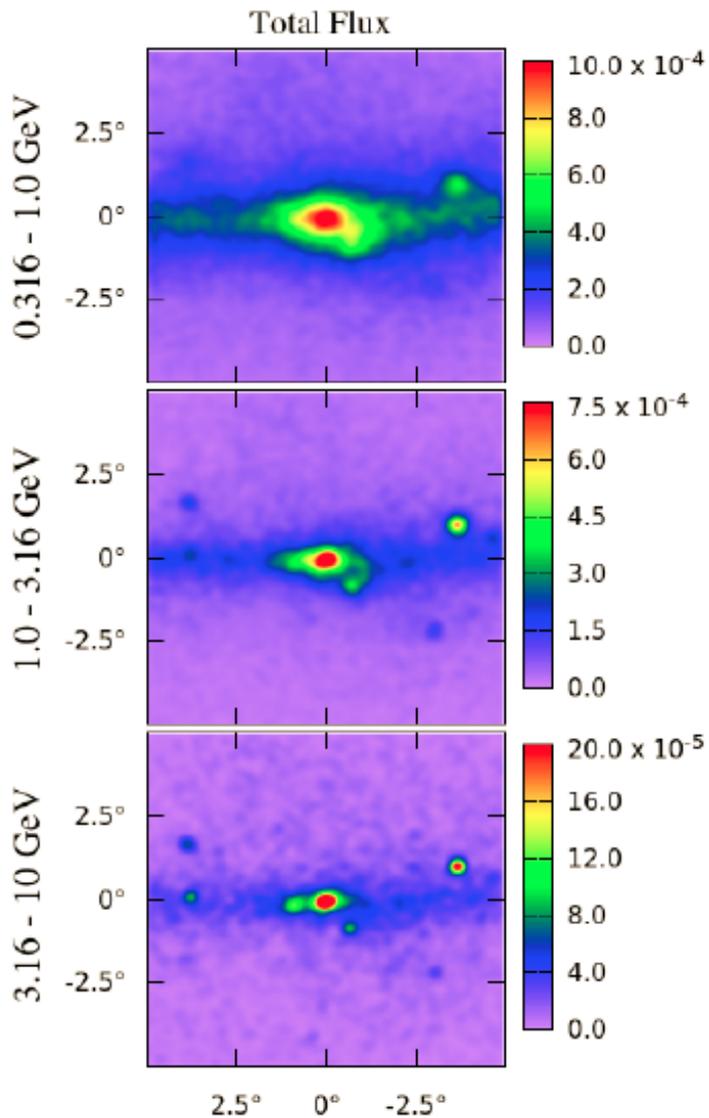
Subtract

- Sources from 2FGL

Region $|b| < 5^\circ, |l| < 5^\circ$

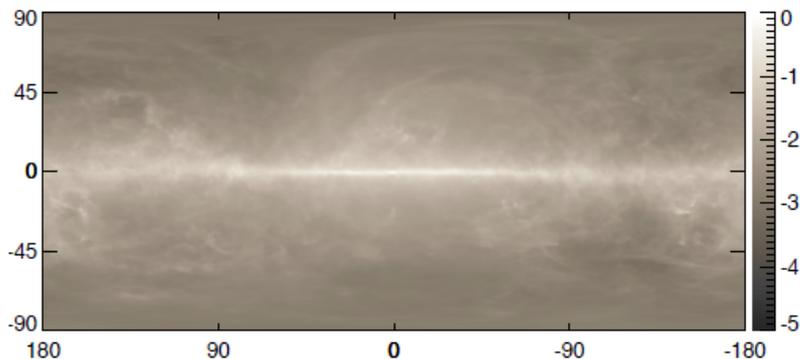
Daylan et al. '14
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...



Subtract

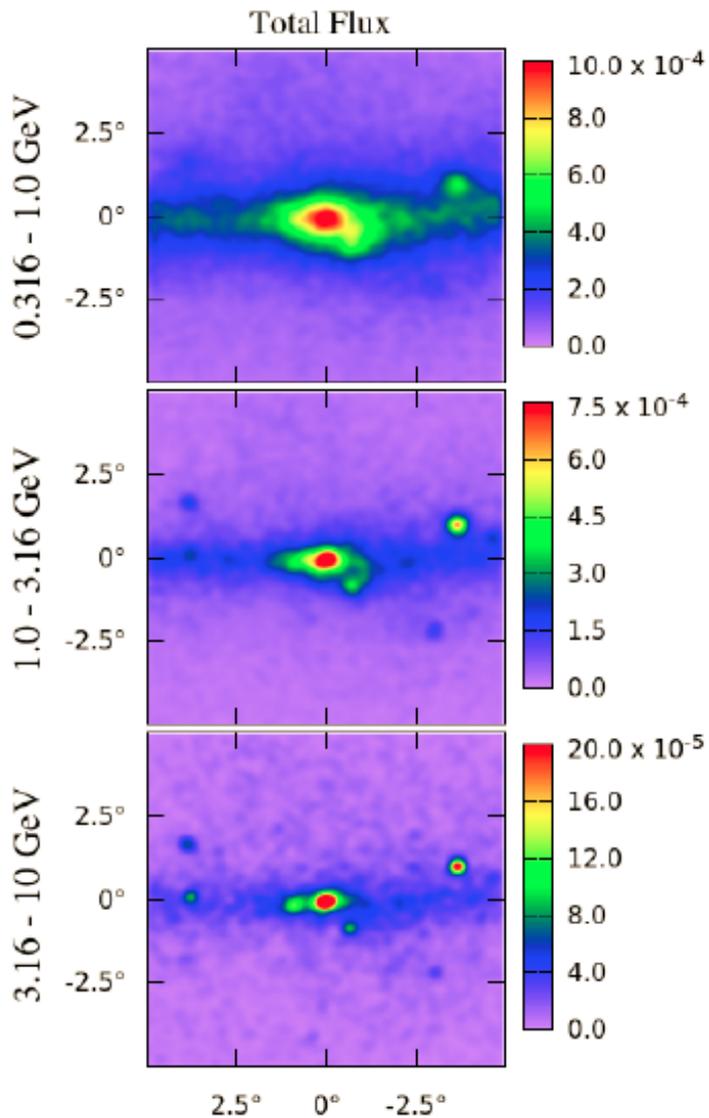
- Sources from 2FGL
- Spatial template for diffuse galactic emission
 - π^0 component
 - Bremsstrahlung component
 - ICS component



Region $|b| < 5^\circ$, $|l| < 5^\circ$

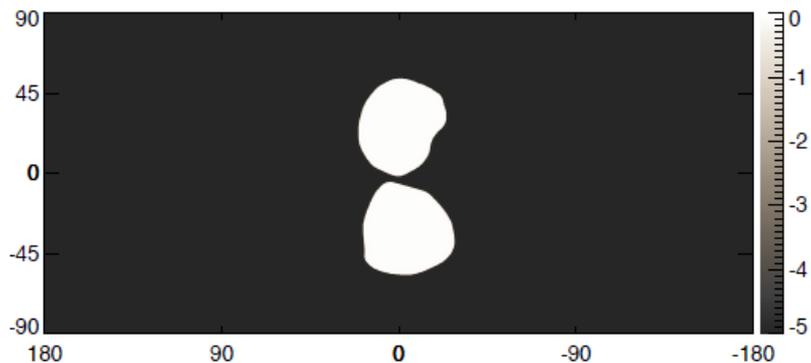
Daylan et al. '14
Goodenough, Hooper '09, '10
Hooper, Linden '11
Huang et al '13
Abazajian et al '14

...



Subtract

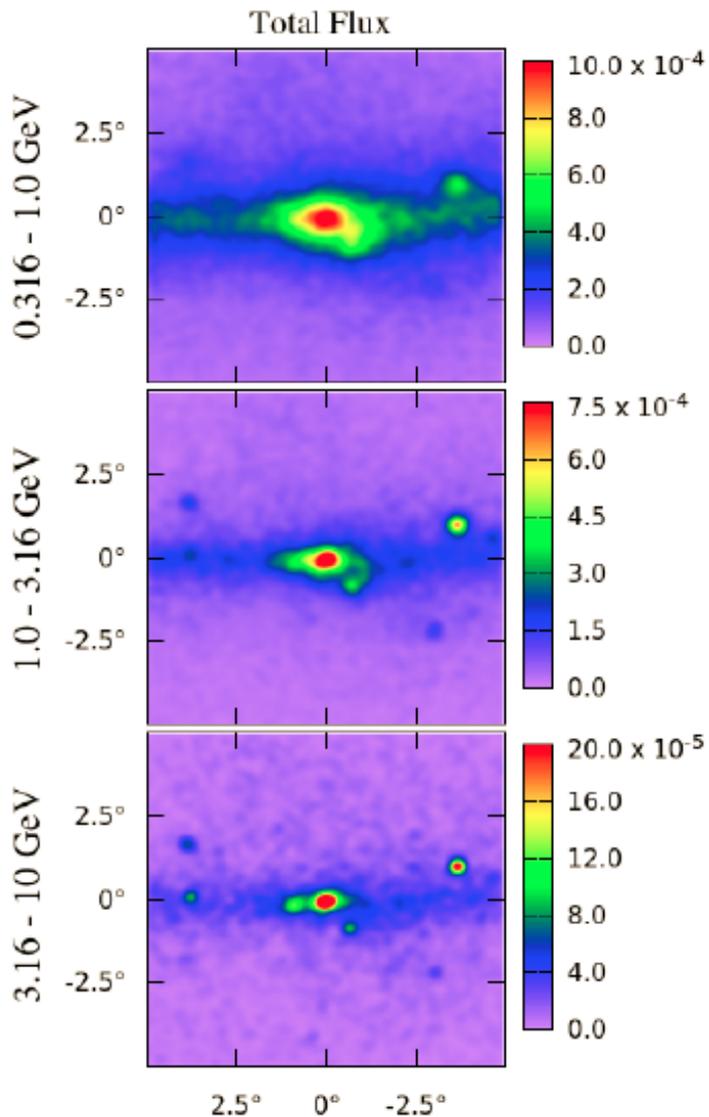
- Sources from 2FGL
- Spatial template for diffuse galactic emission
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 - Bremsstrahlung component
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Daylan et al. '14
Goodenough, Hooper '09, '10
Hooper, Linden '11
Huang et al '13
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...



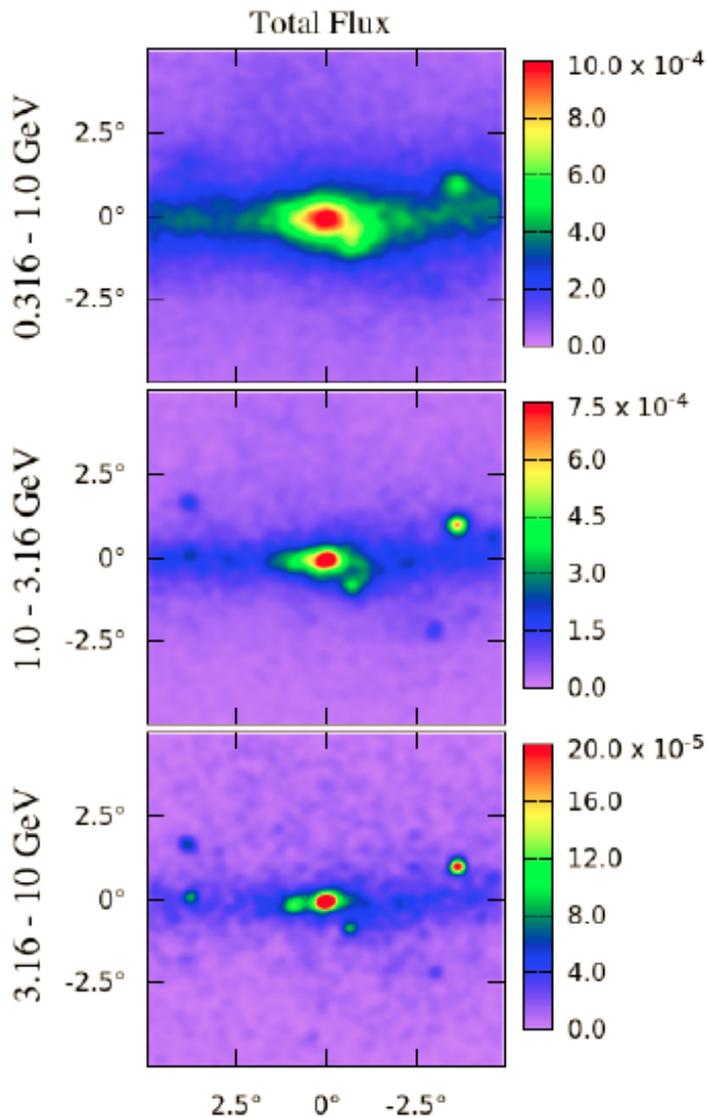
Subtract

- Sources from 2FGL
- Spatial template for diffuse galactic emission
 - π^0 component
 - Bremsstrahlung component
 - ICS component
- Fermi bubbles
- Isotropic (extragalactic) component

Region $|b| < 5^\circ, |l| < 5^\circ$

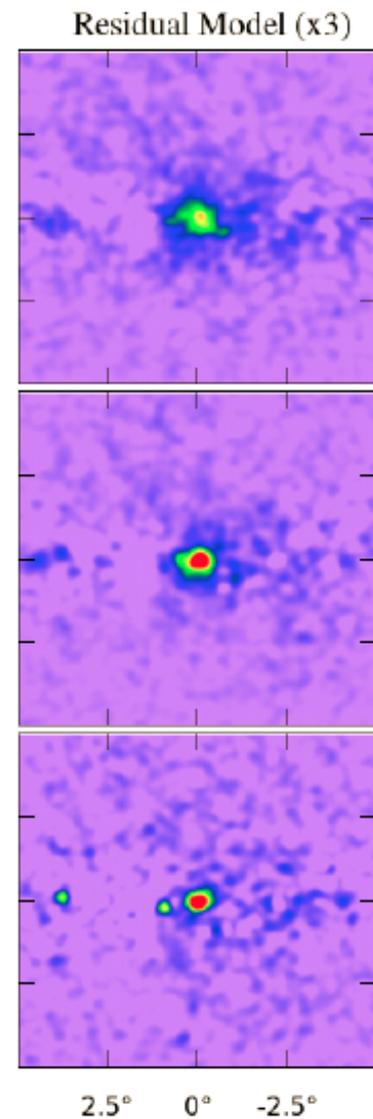
Daylan et al. '14
Goodenough, Hooper '09, '10
Hooper, Linden '11
Huang et al '13
Abazajian et al '14

...



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- Sources from 2FGL
- Spatial template for diffuse galactic emission
 - π^0 component
 - Bremsstrahlung component
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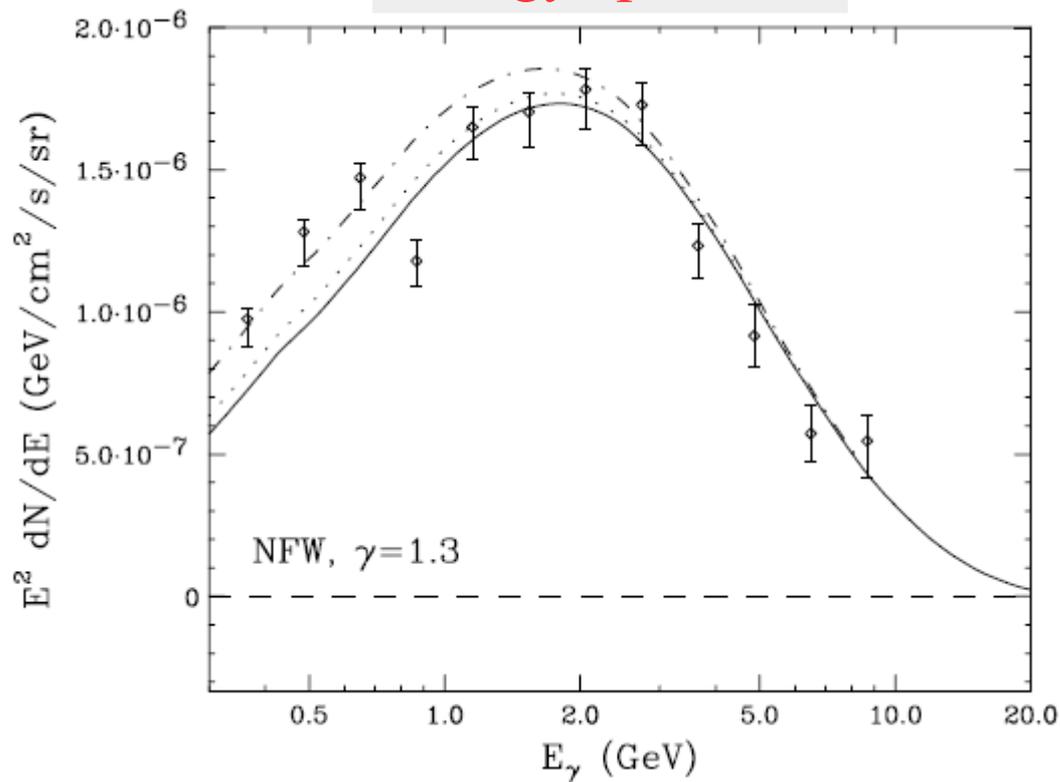


Region $|b| < 5^\circ, |l| < 5^\circ$

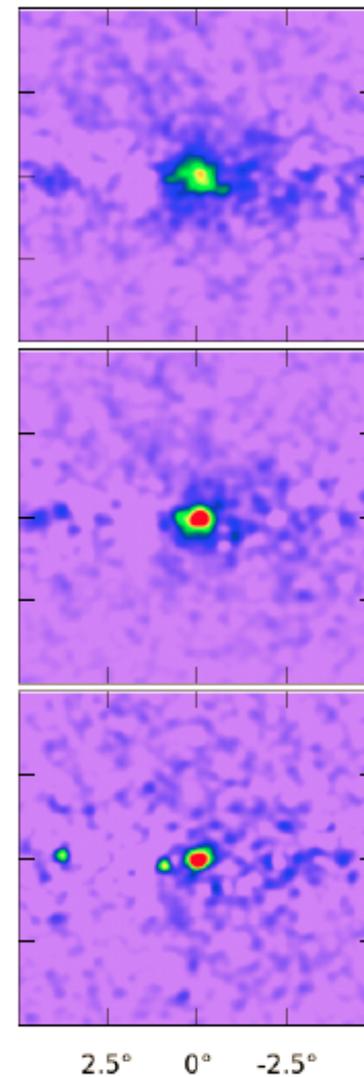
Daylan et al. '14
Goodenough, Hooper '09, '10
Hooper, Linden '11
Huang et al '13
Abazajian et al '14

...

Energy spectrum



Residual Model (x3)

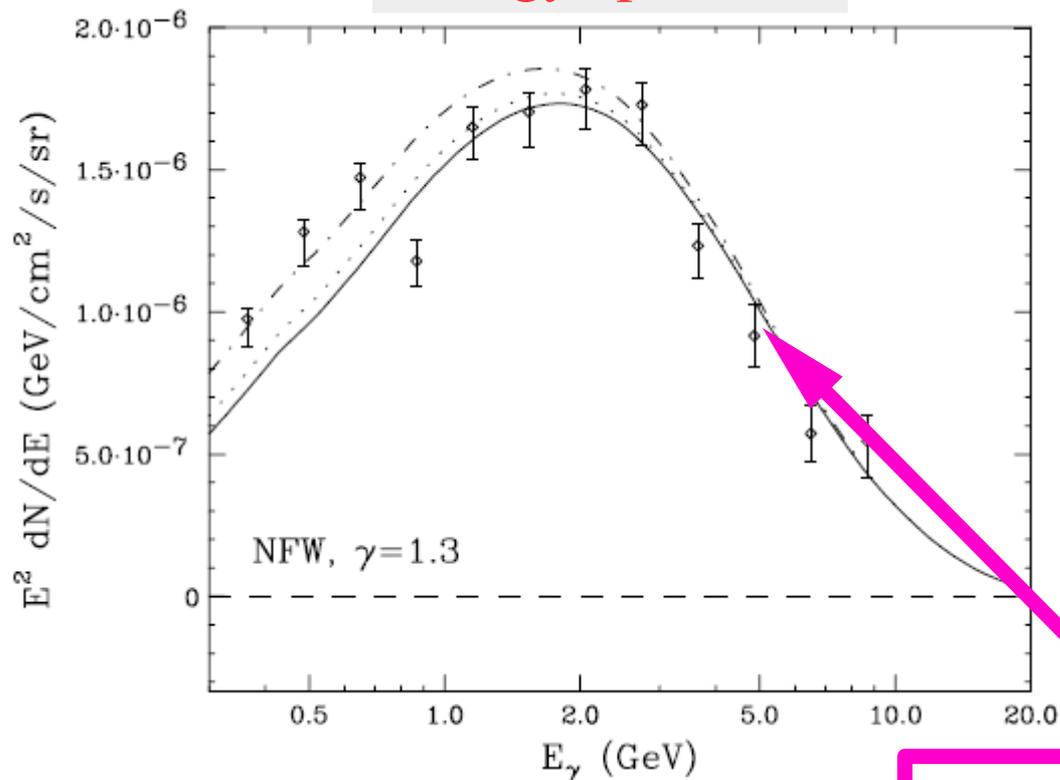


Region $|b| < 5^\circ, |l| < 5^\circ$

Daylan et al. '14
Goodenough, Hooper '09, '10
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Abazajian et al '14

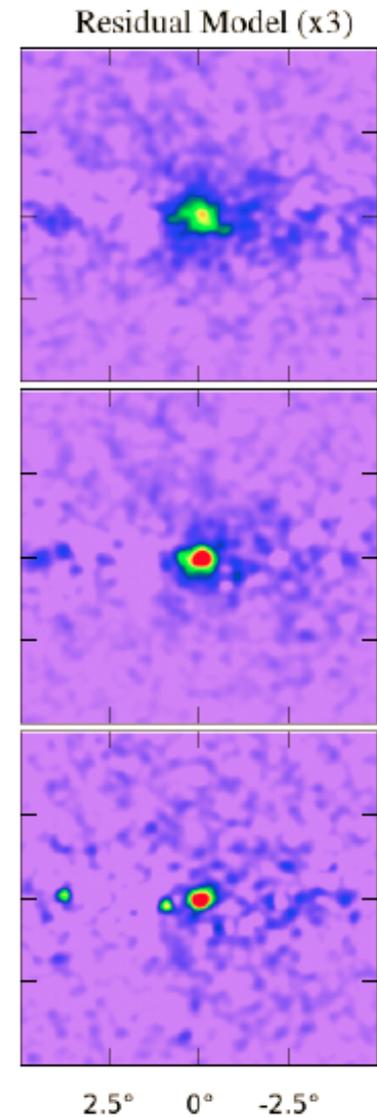
...

Energy spectrum



$DM DM \rightarrow b \bar{b}$
 $m_{DM} = 35.25 \text{ GeV}$
 $\sigma v = 1.0 \times 10^{-26} \text{ cm}^3/\text{s}$

Typical WIMP parameters!

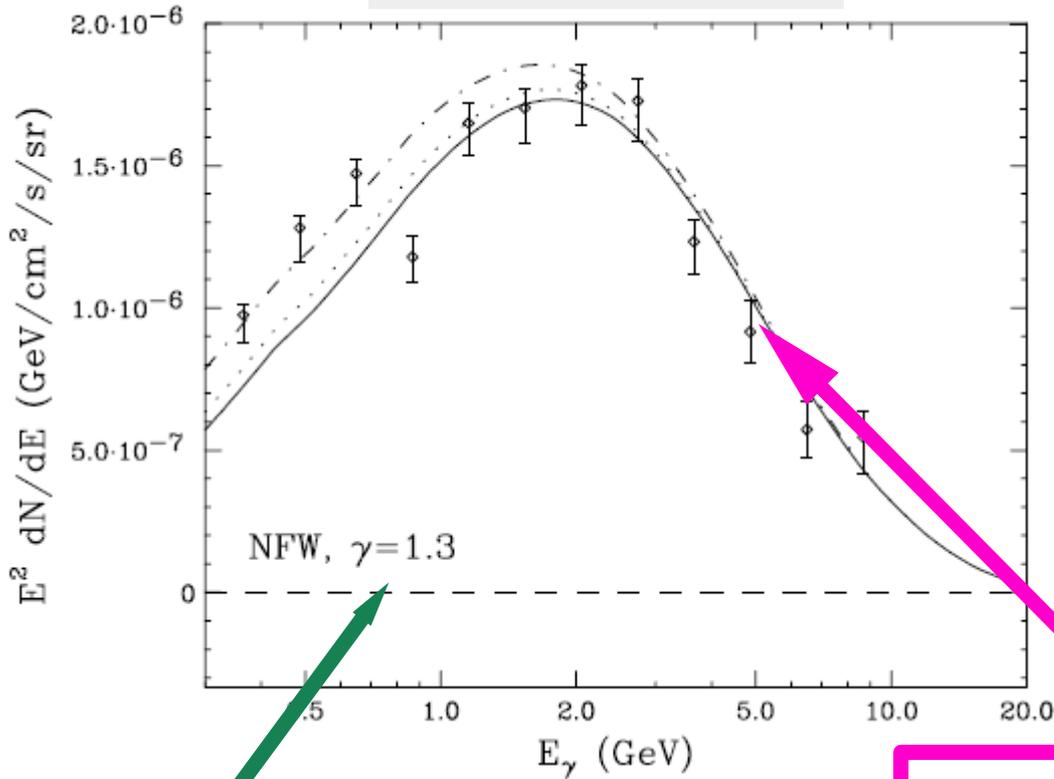


Region $|b| < 5^\circ, |l| < 5^\circ$

Daylan et al. '14
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...

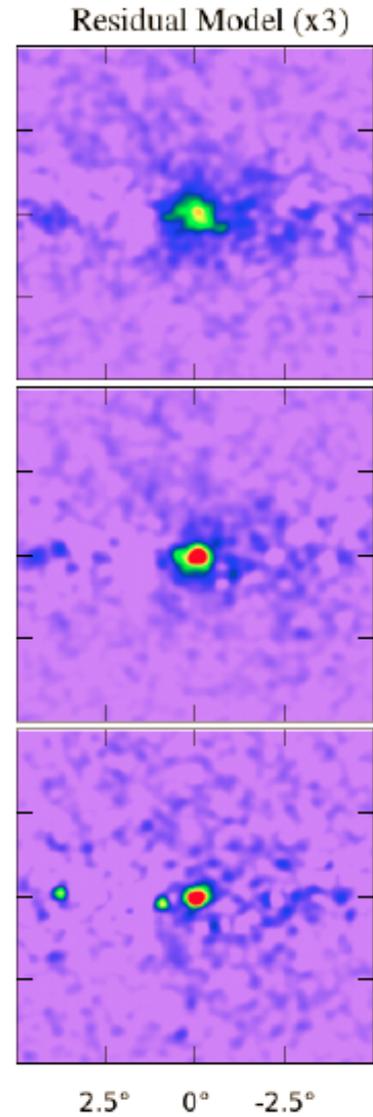
Energy spectrum



The signal is spherically symmetric and goes as $r^{-2.6}$. Requires a slightly more cuspy profile than standard NFW.

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Typical WIMP parameters!



The excess does look like a WIMP signal

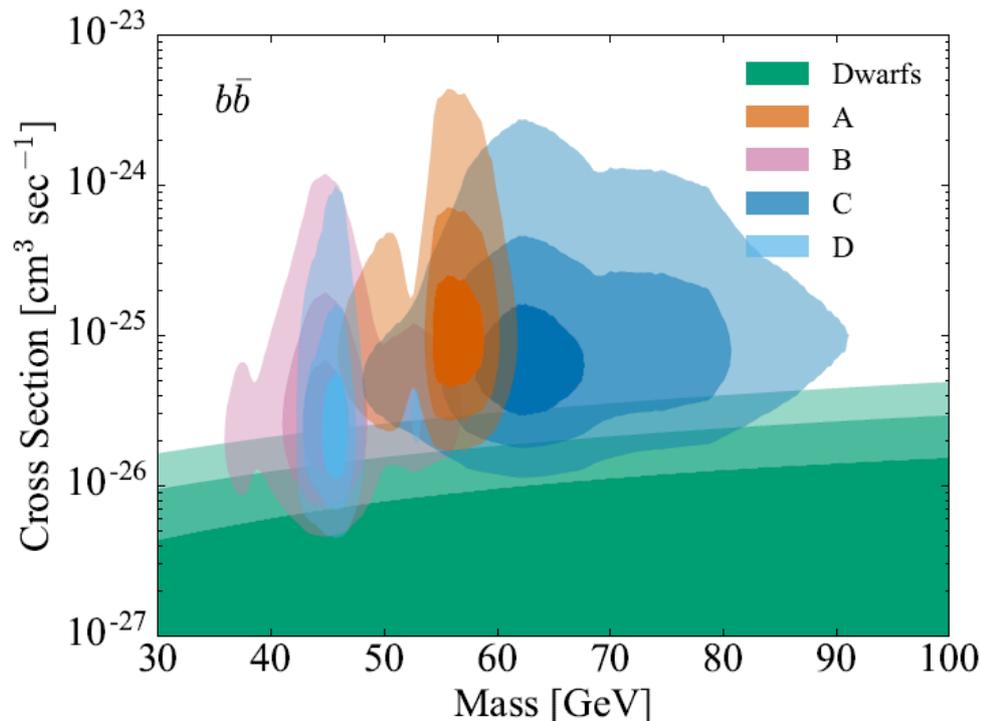
- The excess is extended: it is also observed in the region $1^\circ < |b| < 20^\circ$, $|l| < 20^\circ$, with roughly the same spectrum.
- The excess looks spherically symmetric.
- The excess is present for any diffuse background model.
- The excess is “theoretically sound”: simple models can reproduce the observations.

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However...

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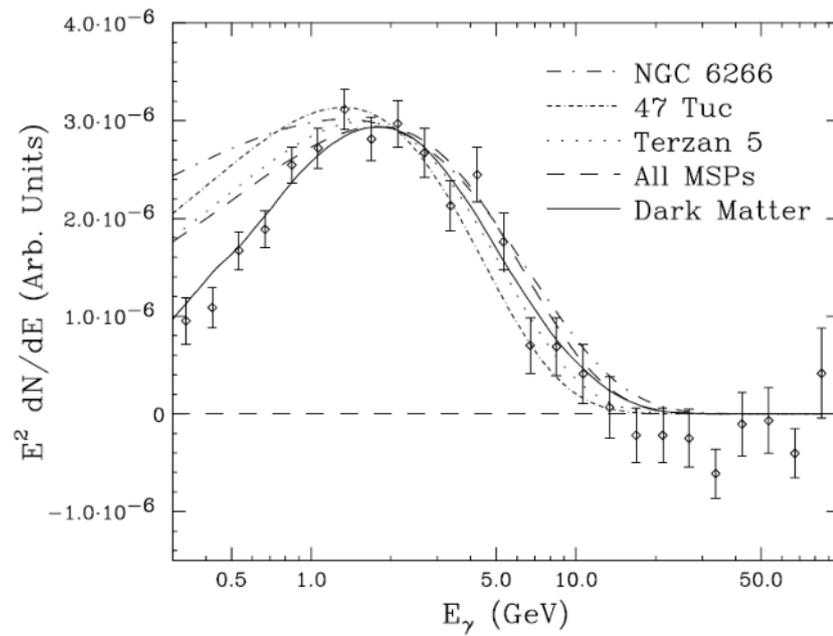
Keeley et al. '17

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Similar energy spectrum
as MSPs.

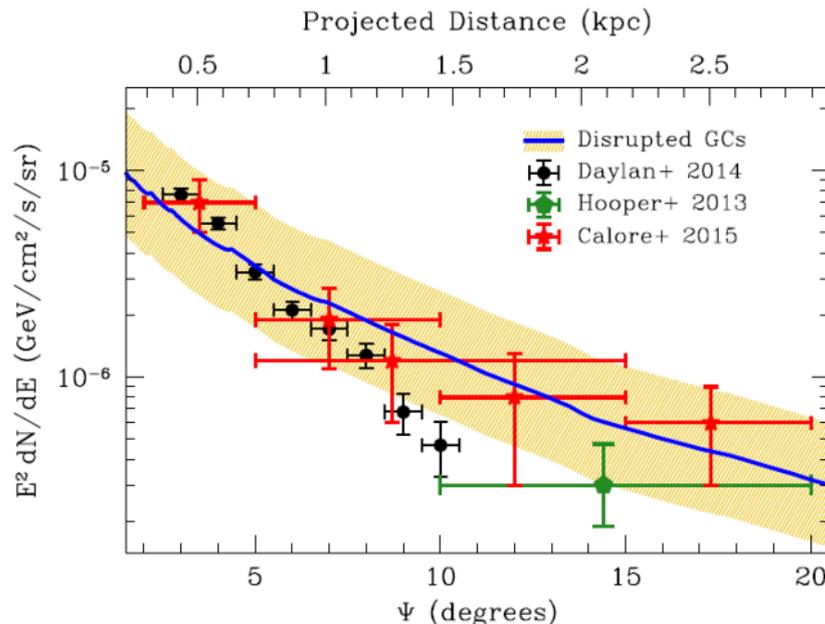
Daylan et al. '14

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Similar morphology and intensity as the one predicted from tidally disrupted globular clusters

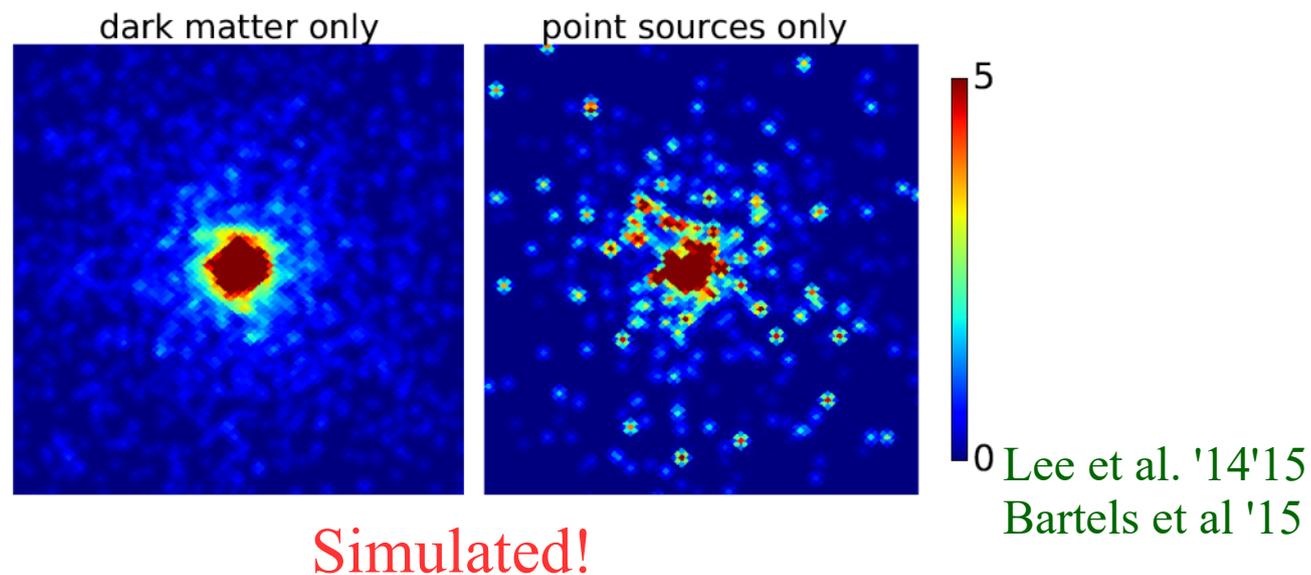
Brandt, Kocsis '15

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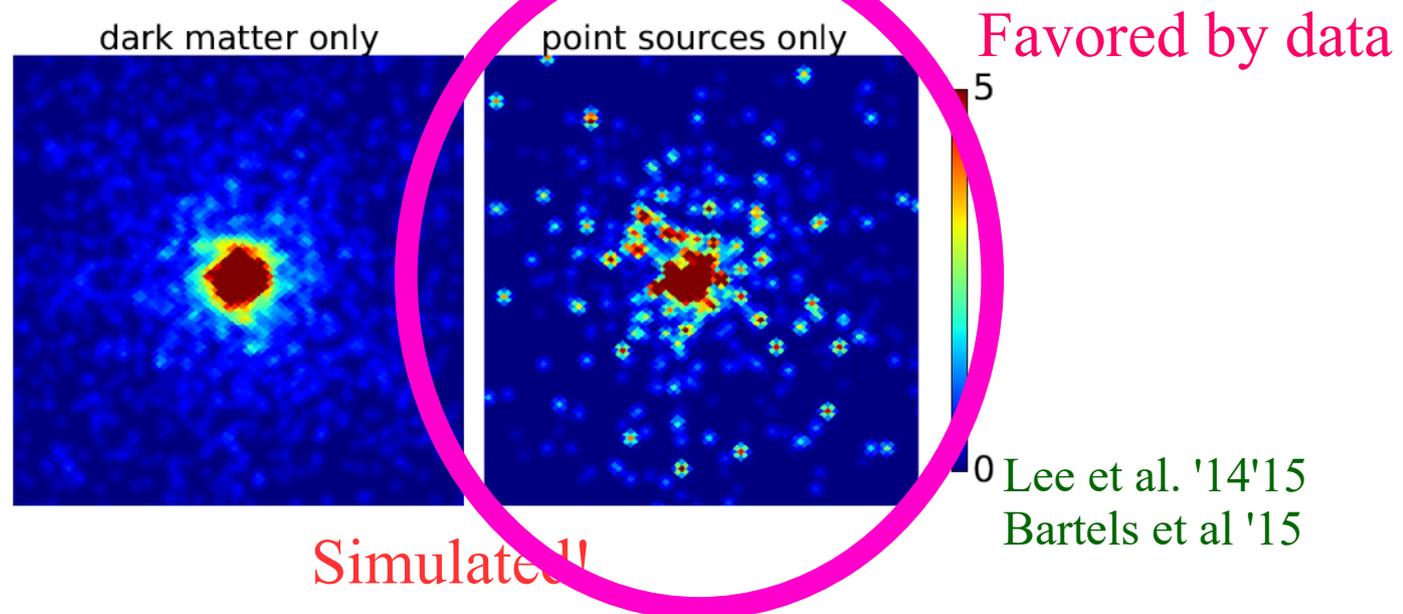


The excess does look like a WIMP signal

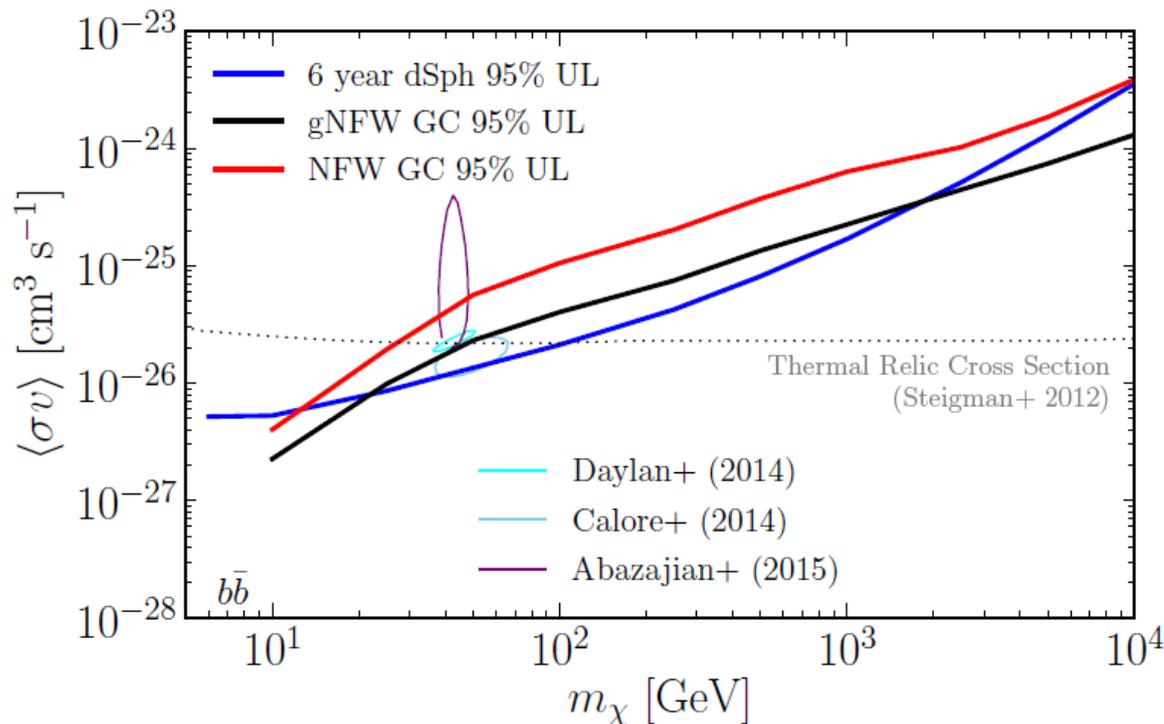
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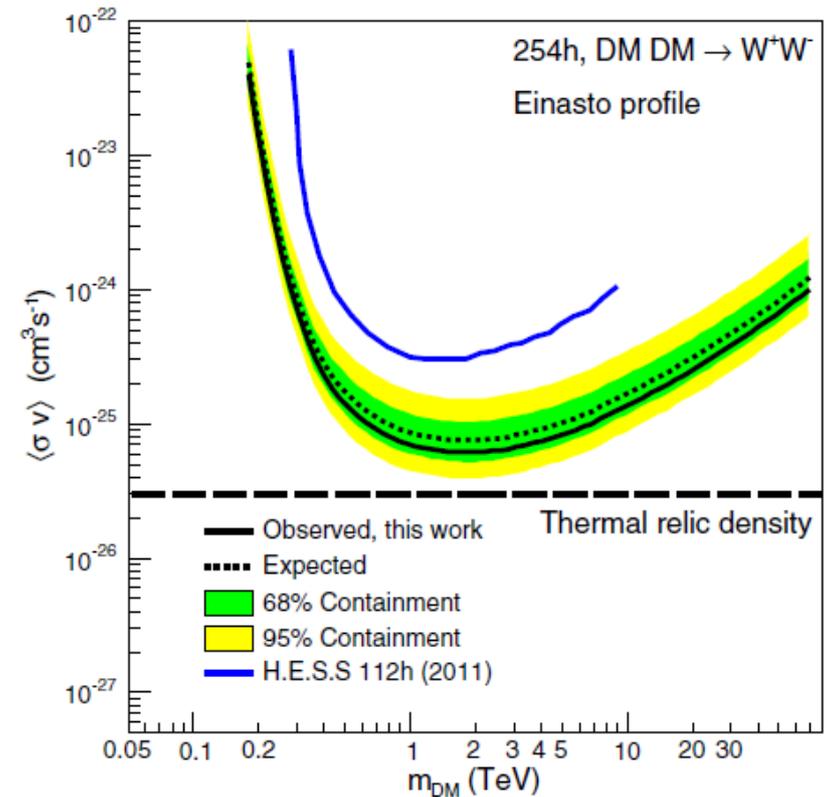
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Constraints on WIMP parameters

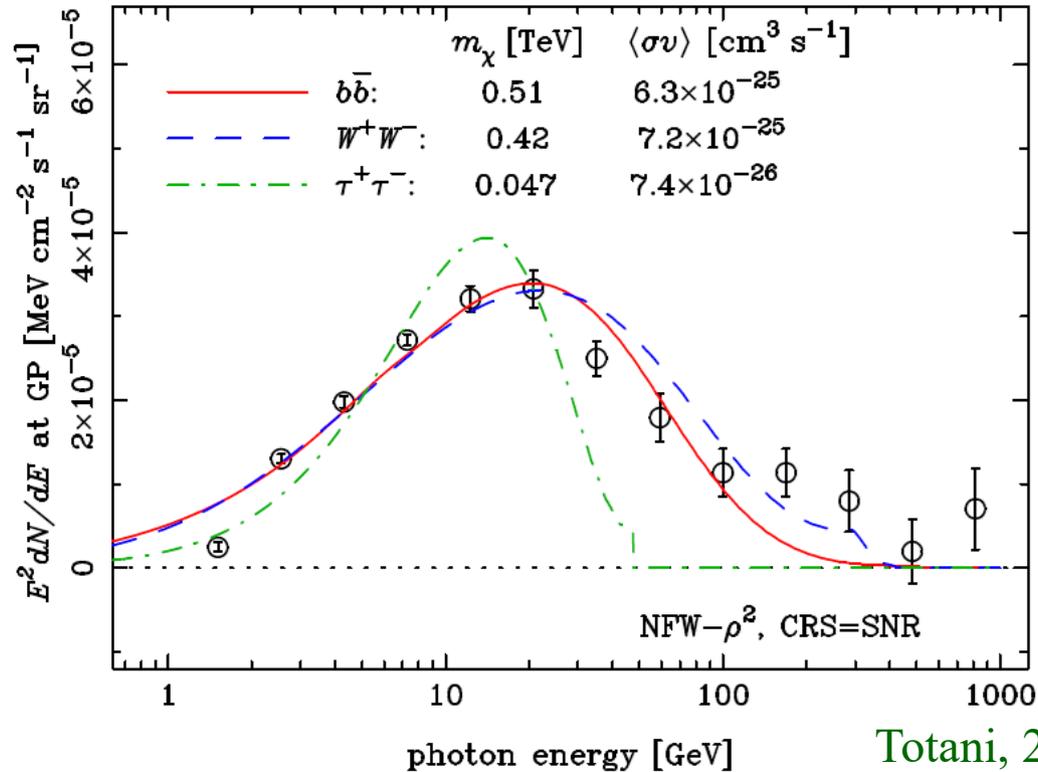


Fermi-LAT collaboration
 arXiv:1704.03910



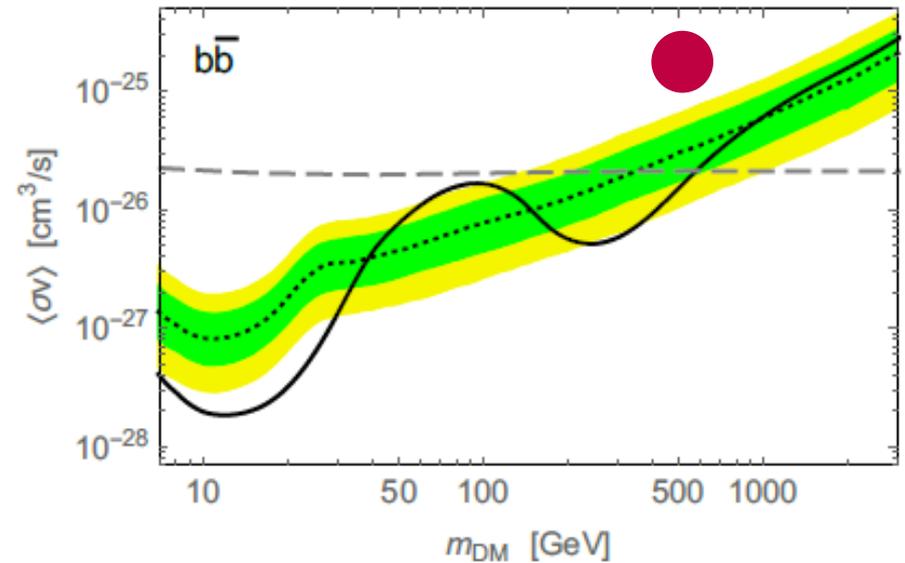
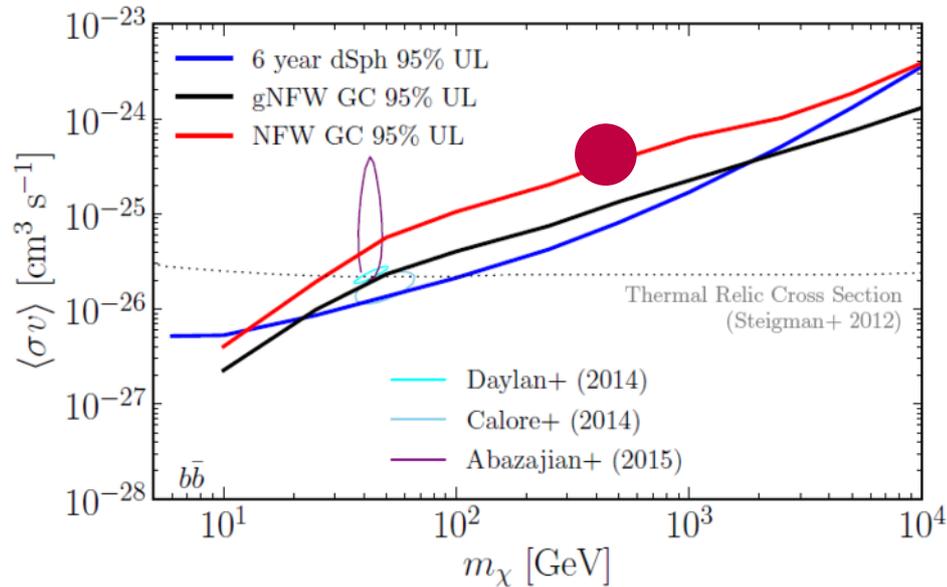
H.E.S.S. Collaboration
 arXiv:1607.08142

A new gamma-ray excess?



- Spatially very extended: $|\ell| < 60^\circ, 10^\circ < |b| < 60^\circ$
- Peaks at ~ 20 GeV
- Points to a DM mass of 400-500 GeV
- Requires a fairly large cross-section

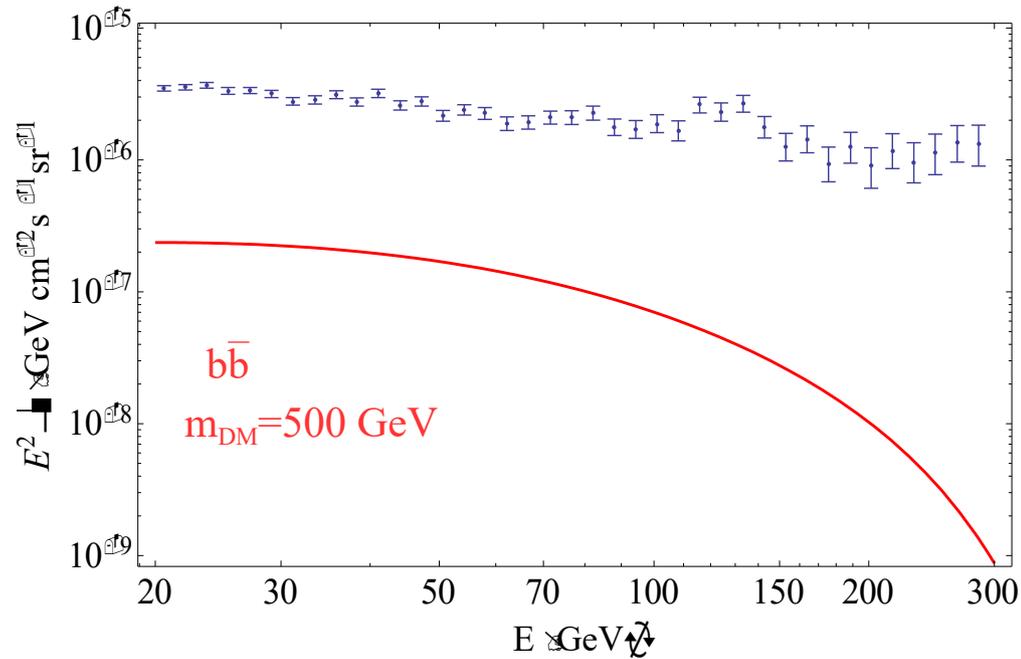
A new gamma-ray excess?



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- Peaks at ~ 20 GeV
- Points to a DM mass of 400-500 GeV
- Requires a fairly large cross-section
- In tension with dwarf galaxy constraints and antiproton constraints
- Modelling of backgrounds extremely difficult

Gamma-ray features

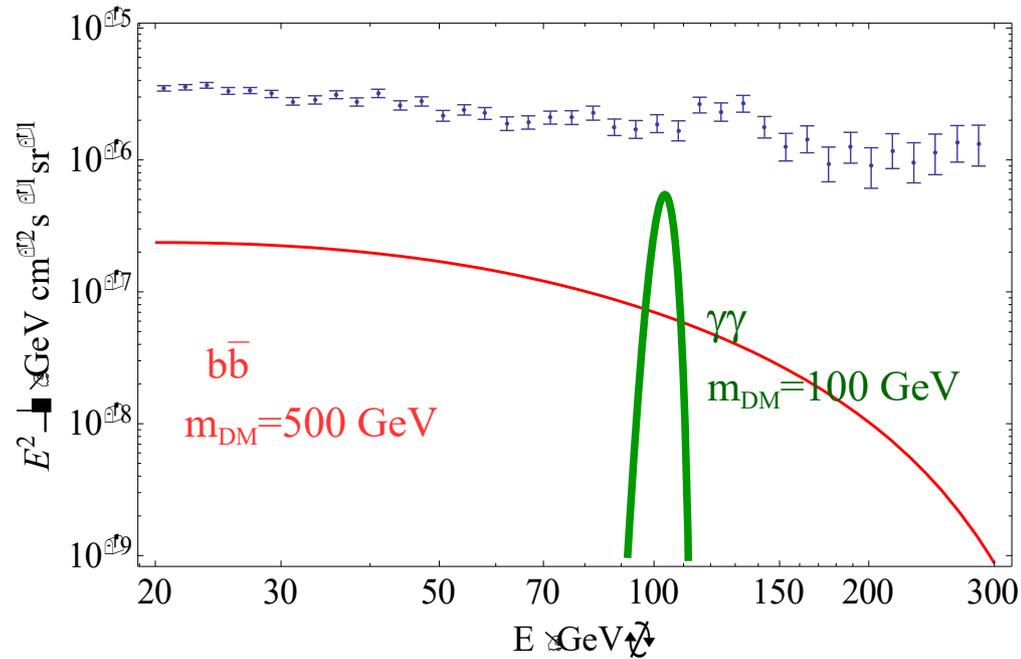
Idea: Search for a gamma-ray excess with an energy spectrum qualitatively different from the background.



“Smoking gun” for dark matter: no (known) astrophysical process can produce a sharp feature in the gamma-ray energy spectrum

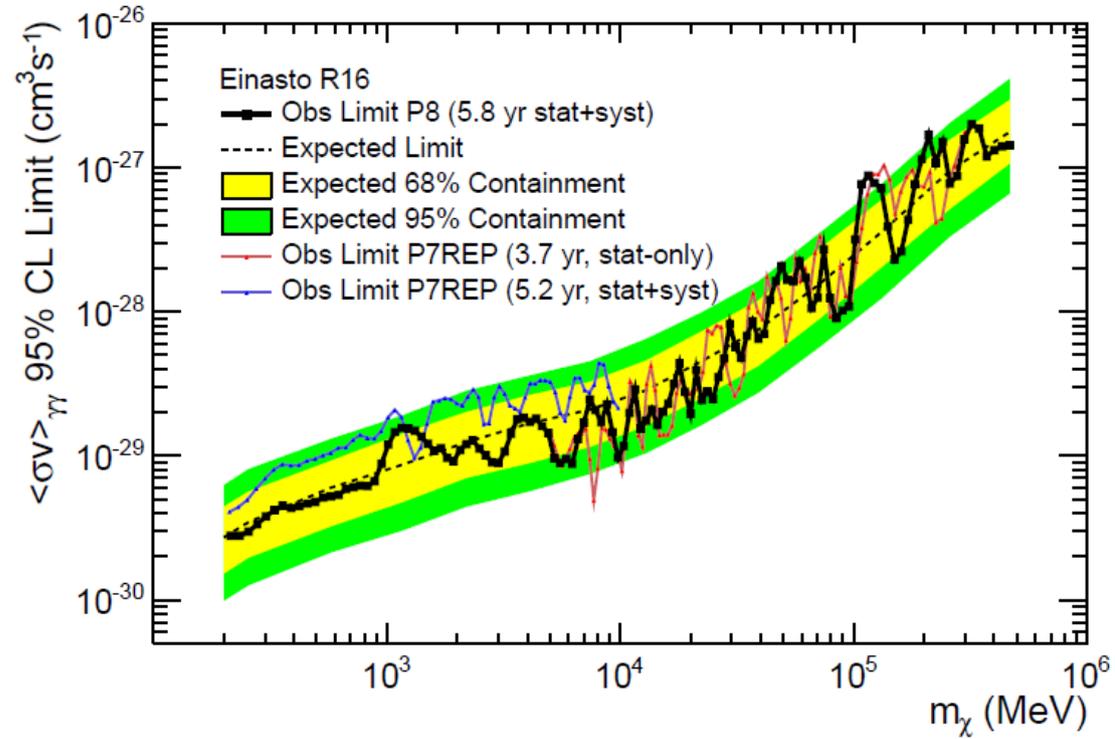
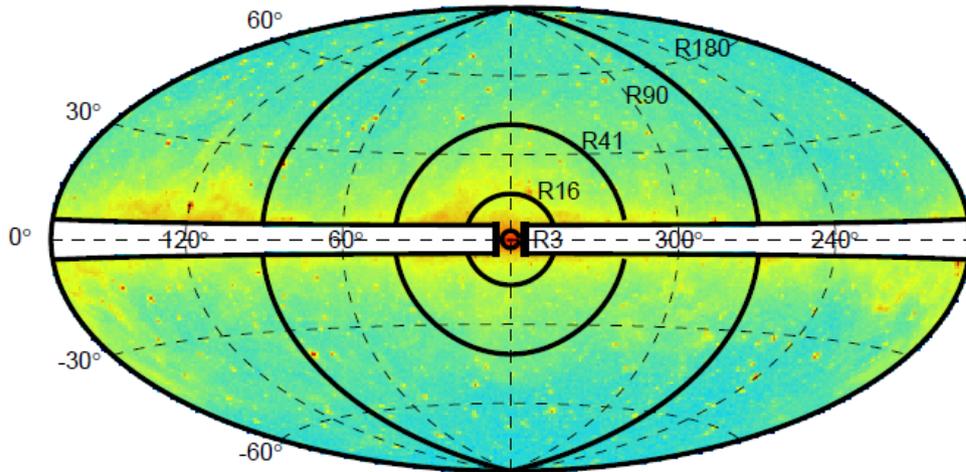
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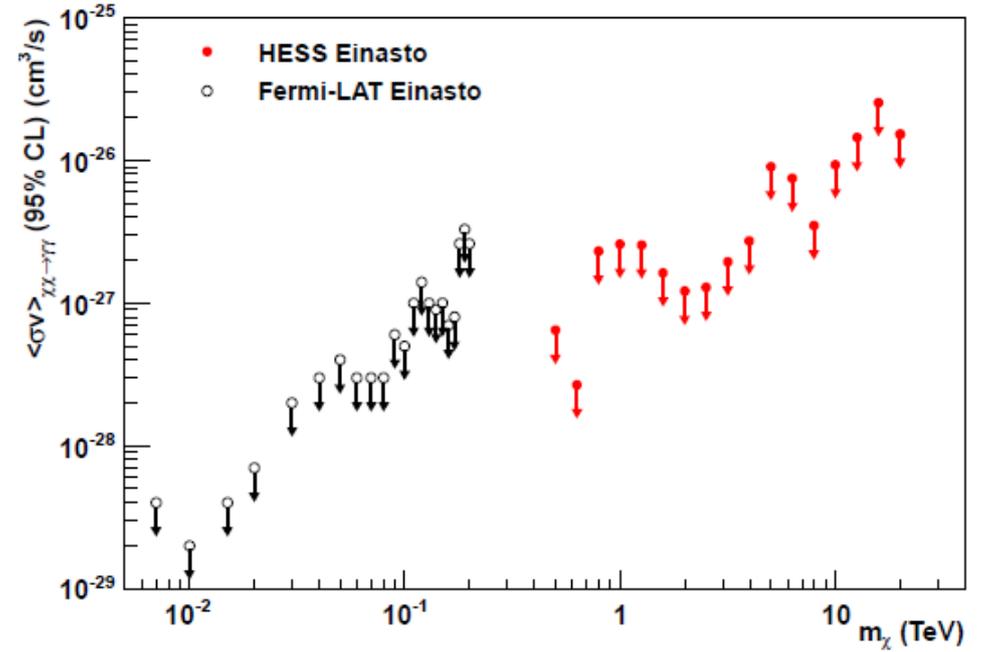
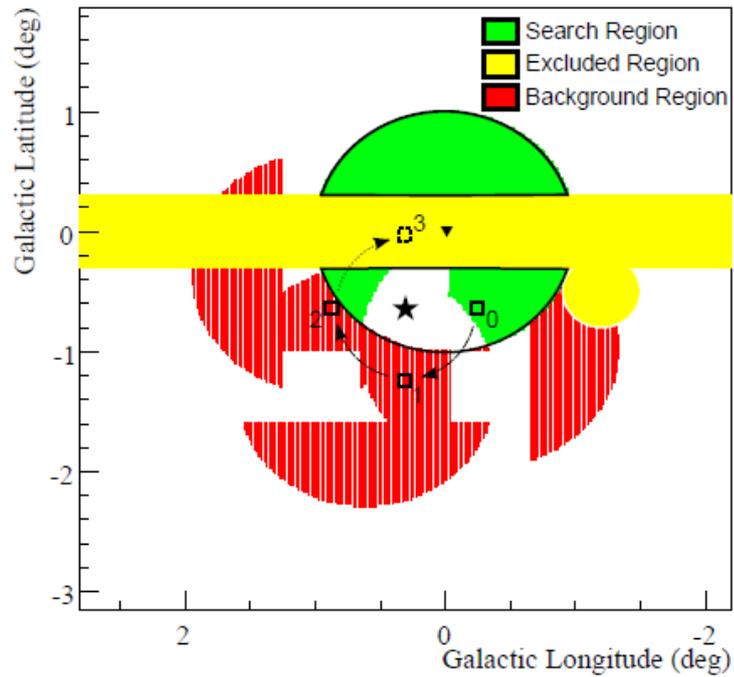
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Gamma-ray features



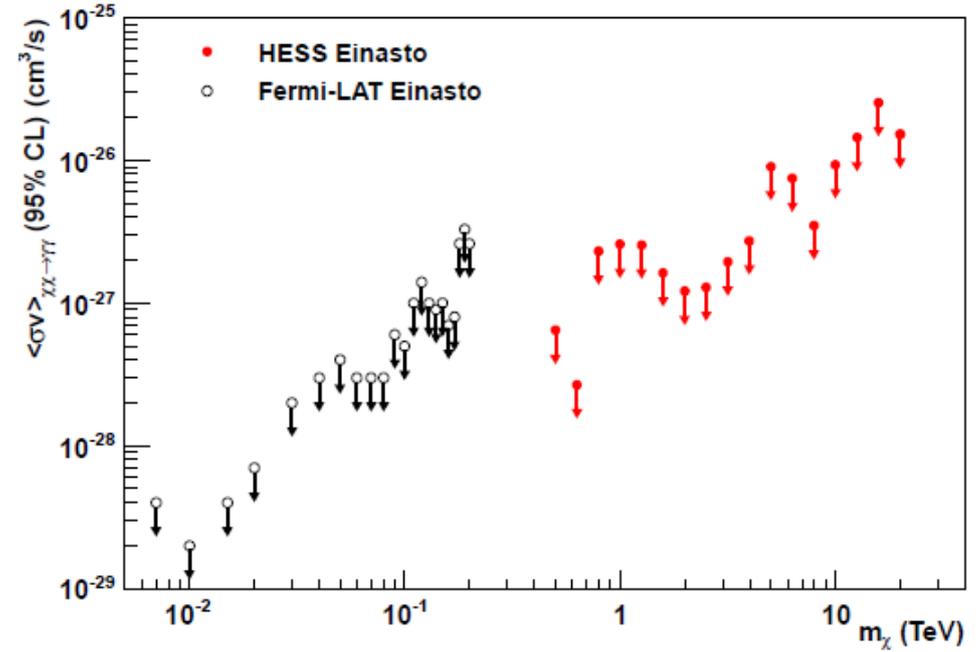
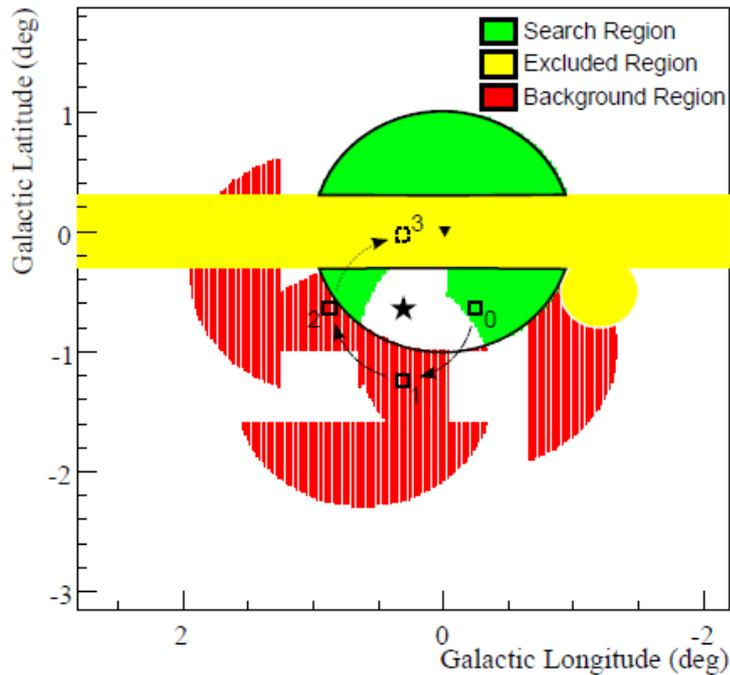
Fermi collaboration
arXiv:1503.02641

Gamma-ray features

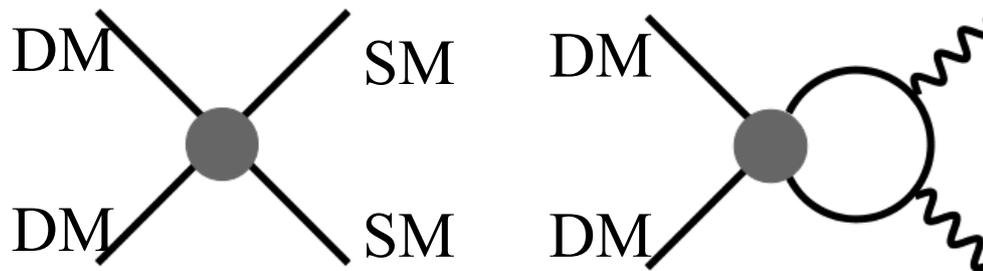


H.E.S.S. collaboration
arXiv:1301.1173

Gamma-ray features

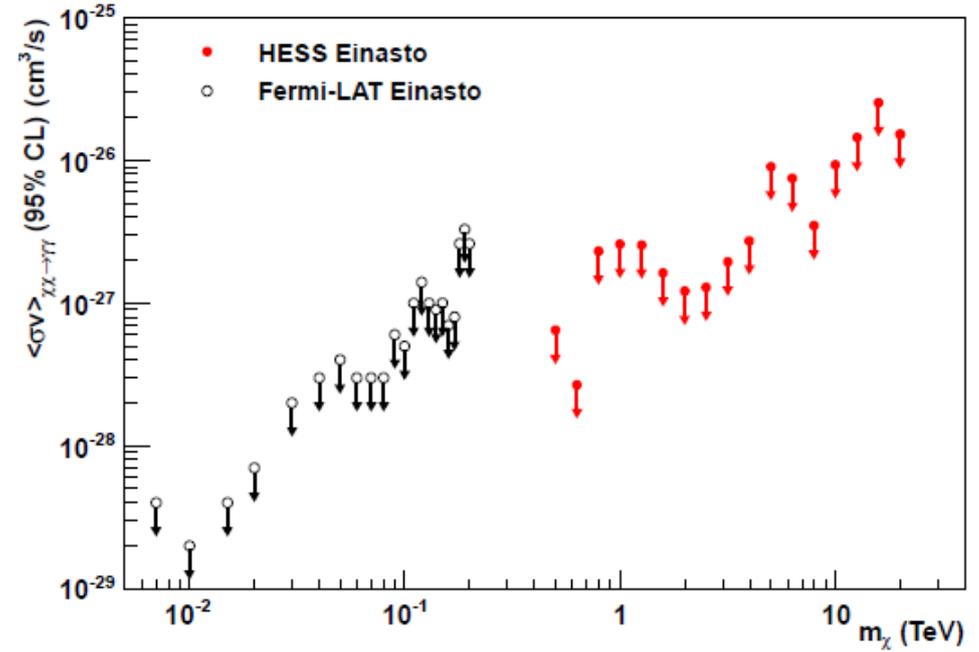
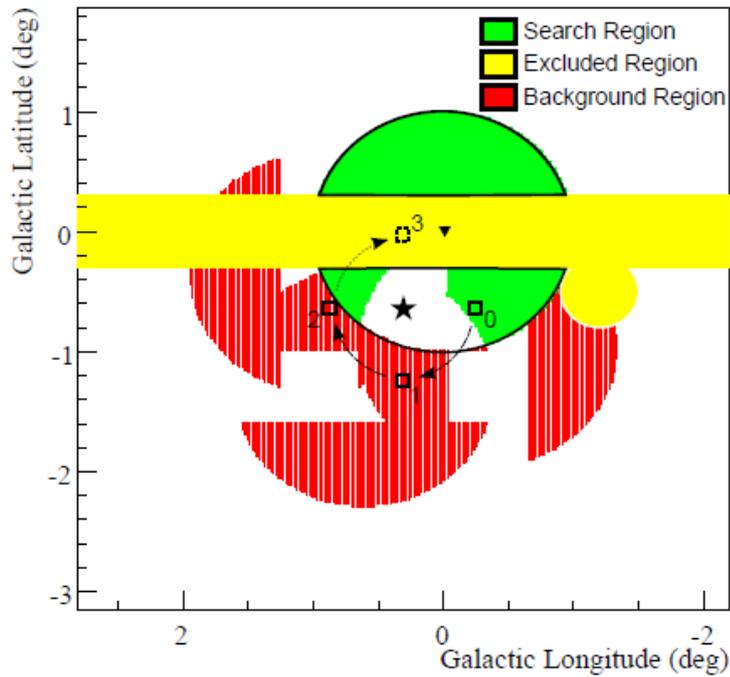


The annihilation $\text{DM DM} \rightarrow \gamma \gamma$ typically arises at the one loop level

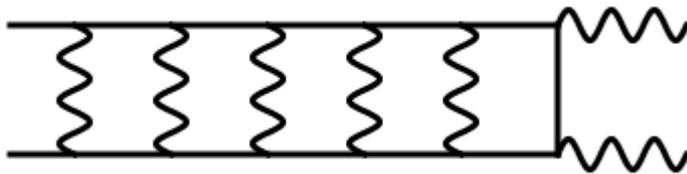


$$(\sigma v)_{\gamma\gamma} \sim \mathcal{O}(\alpha^2)(\sigma v)_{\text{thermal}} \sim 10^{-30} \text{cm}^3 \text{s}^{-1}$$

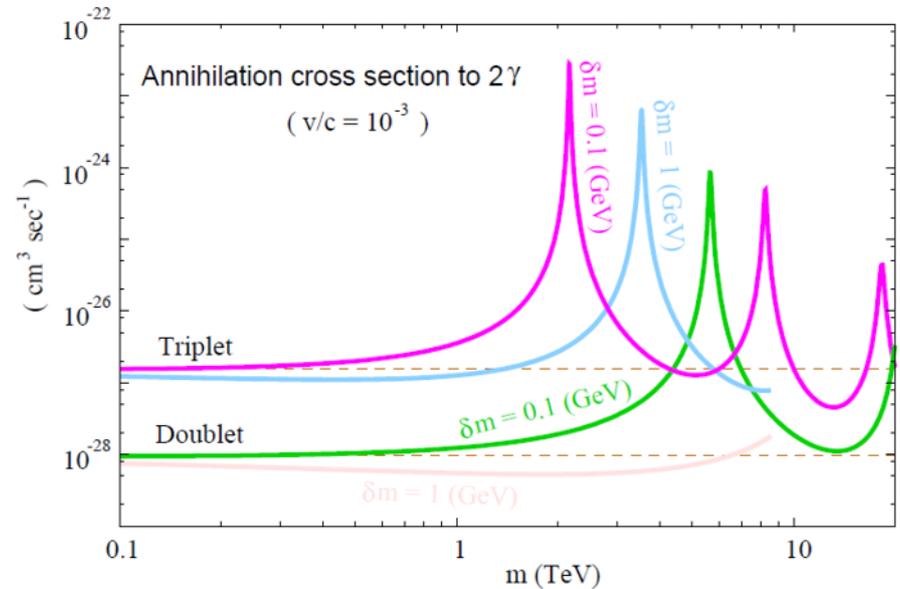
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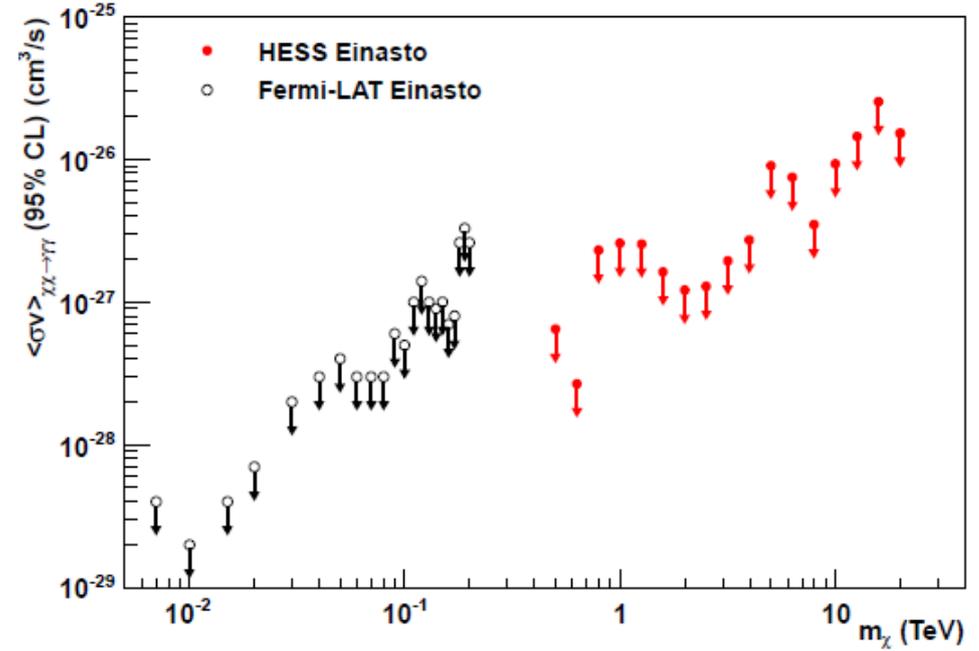
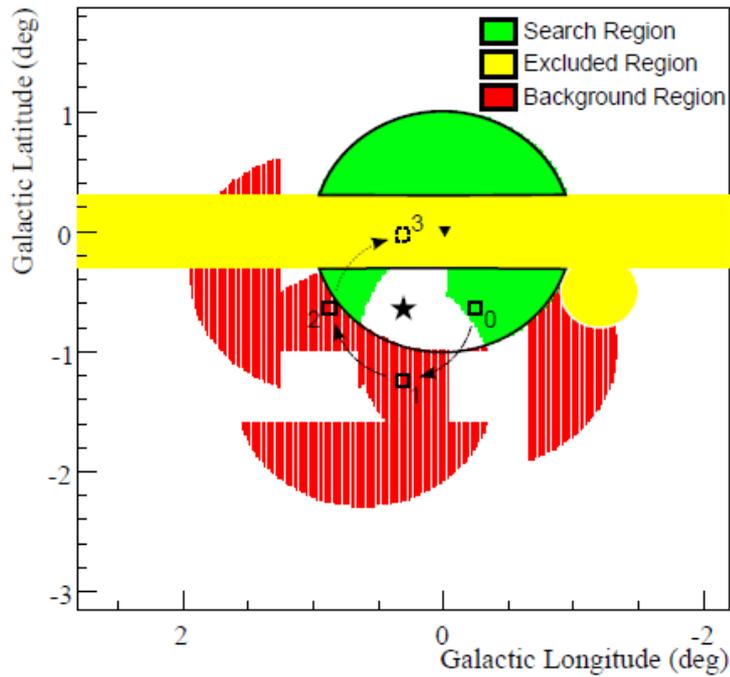
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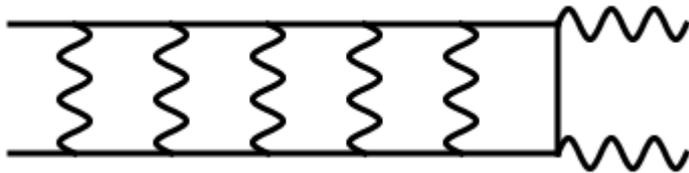
Hisano, Matsumoto, Nojiri



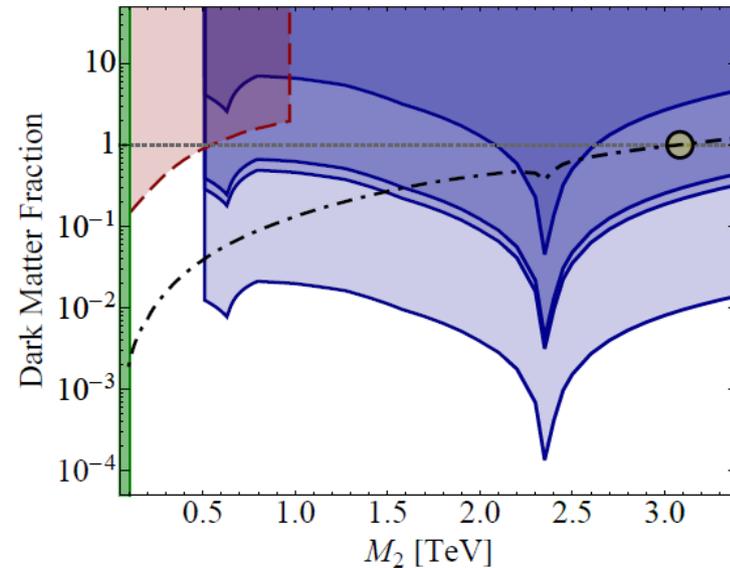
Gamma-ray features



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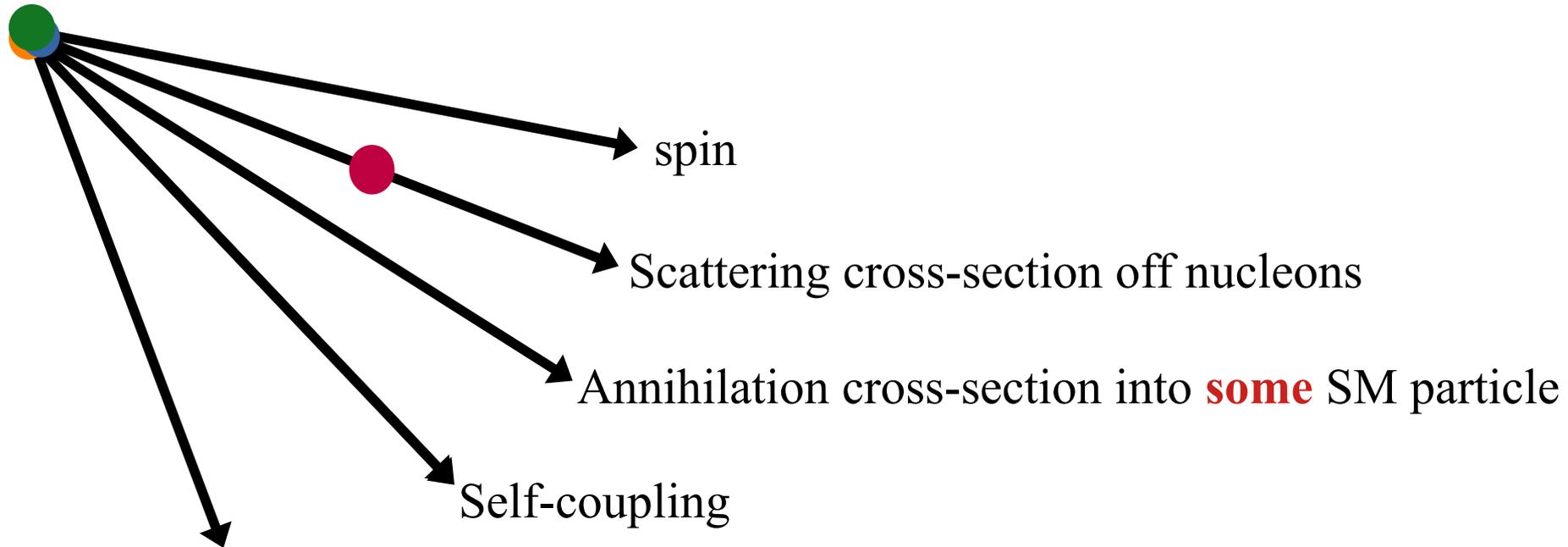


Hisano, Matsumoto, Nojiri



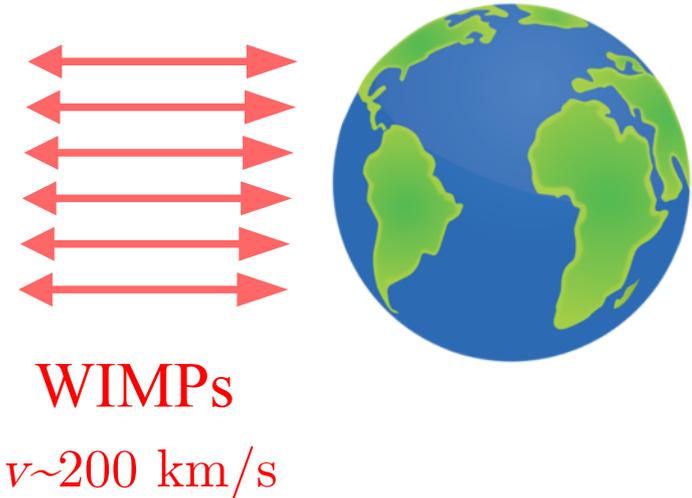
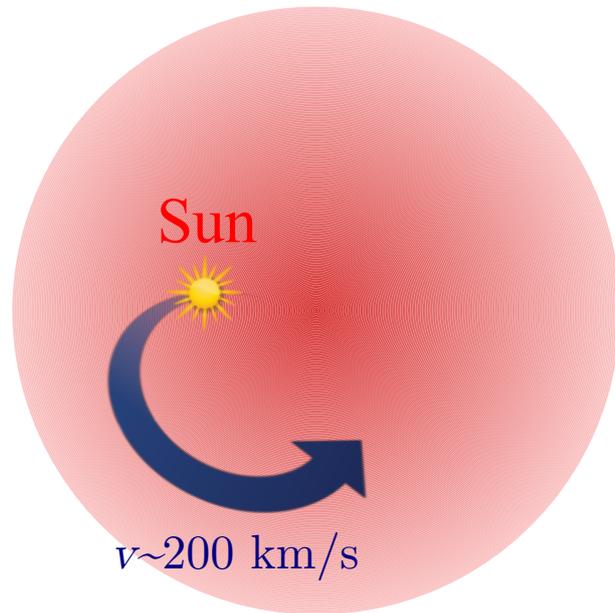
Cohen et al

Probing the scattering with nucleons

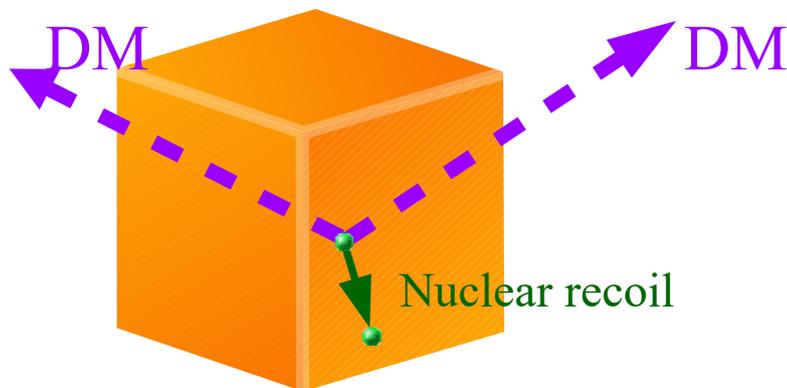


Probing the scattering with nucleons

The Sun (and the Earth) might be moving through a “gas” of dark matter particles.



Once in a while a dark matter particle will interact with a nucleus. The nucleus then recoils, producing vibrations, ionizations or scintillation light in the detector.



No significant excess detected so far

Implications for Particle Physics

How to translate an upper limit on the scattering rate (or a measurement) into information on the dark matter properties?

Important: the momentum transferred in the scattering to the target is small:

Typical kinetic energy of a DM particle at the location of the Earth:

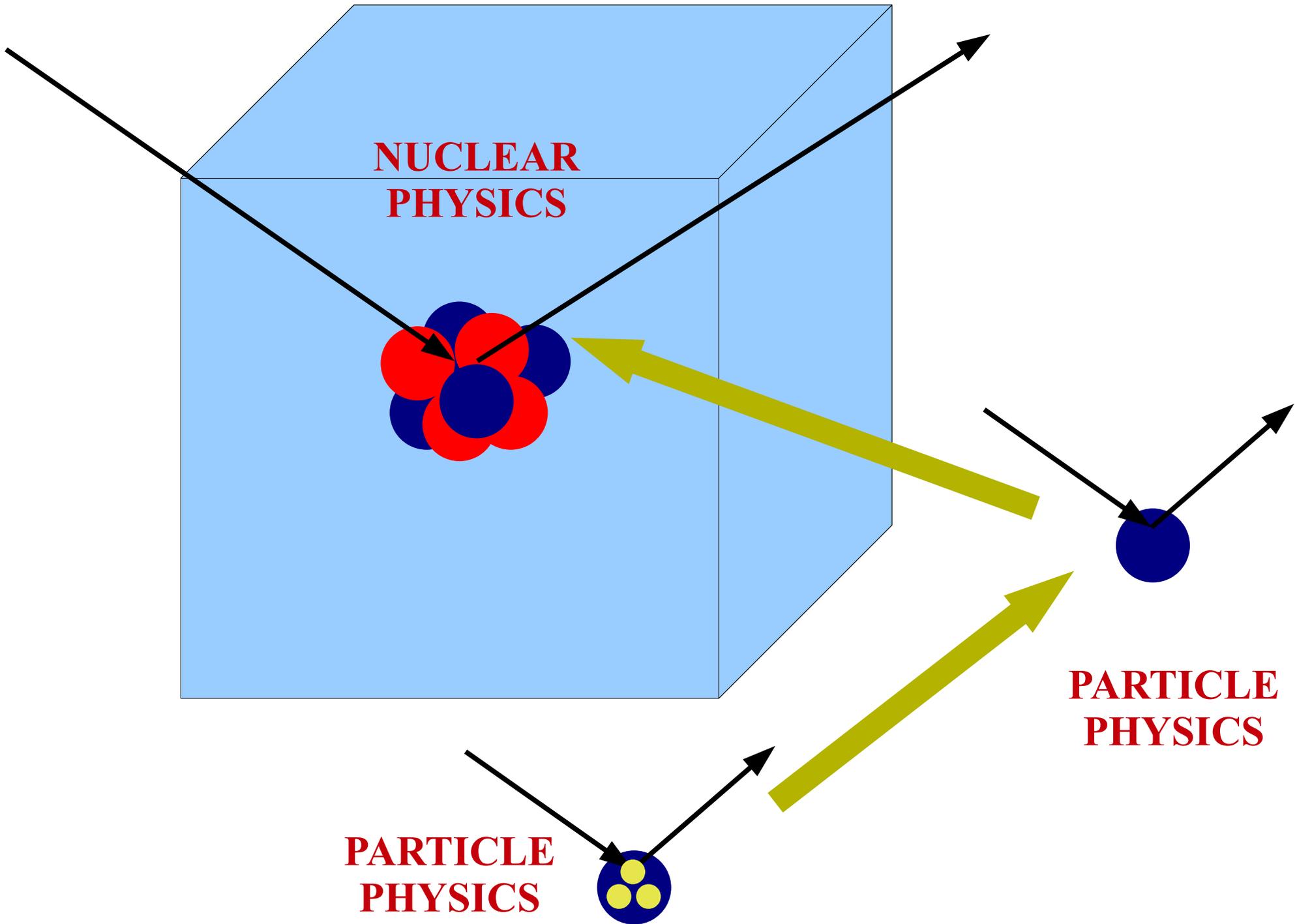
$$E_{\text{kin}} = \frac{1}{2} m_{\text{DM}} v^2 \sim 30 \text{ keV}$$

$m_{\text{DM}} = 100 \text{ GeV}$

⇒ Momentum transferred < $E_{\text{kin}} \sim 30 \text{ keV}$

⇒ The DM cannot “see” the constituents of the nucleus, nor the constituents of the proton

⇒ Coherent scattering with the whole nucleus.



Implications for Particle Physics

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Assume for the moment that all DM particles have the same velocity v

Interaction rate with one nucleus in the detector = flux \times cross section

$$R = \frac{\rho_{\text{DM}}}{m_{\text{DM}}} v \sigma_{\text{DM,N}}(v, E_R)$$

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Differential event rate normalized by the mass of the target nucleus

$$\frac{dR}{dE_R} = \frac{\rho_{\text{DM}}}{m_{\text{DM}} m_N} v \frac{d\sigma_{\text{DM,N}}}{dE_R}(v, E_R)$$

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Dark matter particles in the Solar System have a velocity distribution $f(v)$

Differential event rate normalized by the mass of the target nucleus

$$\frac{dR}{dE_R} = \frac{\rho_{\text{DM}}}{m_{\text{DM}}m_N} \int_{v_{\text{min}}}^{\infty} d^3v v f(\vec{v}) \frac{d\sigma_{\text{DM},N}}{dE_R}(v, E_R)$$

(units: counts/kg/day/keV)

Implications for Particle Physics

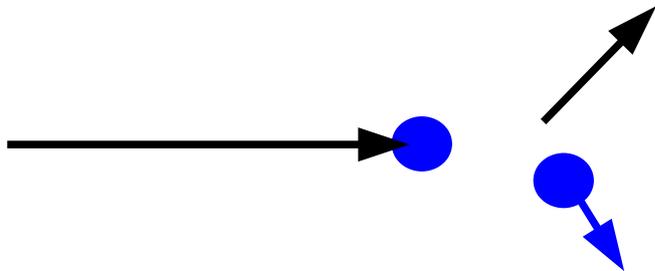
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Minimum DM velocity to produce a recoil with energy E_R .



$$v_{\text{min}} = \sqrt{\frac{m_N E_R}{2\mu_N^2}}$$

$$\mu_N = m_{\text{DM}}m_N / (m_{\text{DM}} + m_N)$$

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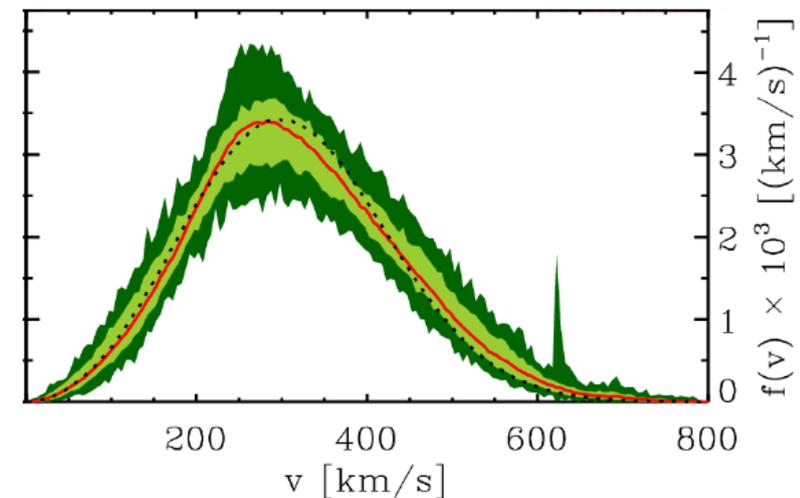
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Local DM density

ASTROPHYSICS

dark matter
Velocity distribution
(Maxwellian?)

$$f(\vec{v}) \sim \exp(-|\vec{v}|^2/v_0^2)$$



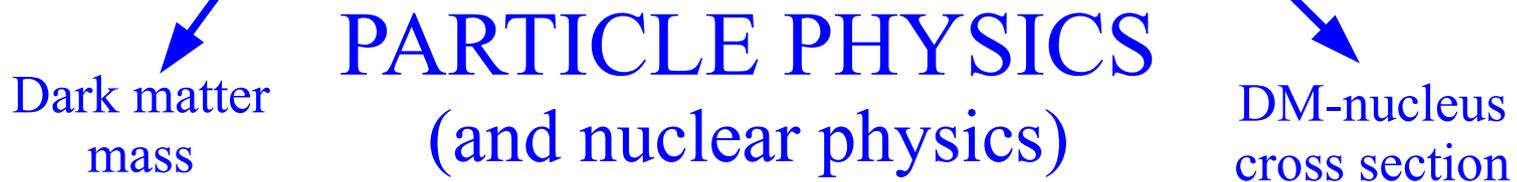
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DETECTOR
CHARACTERISTICS

Target nucleus
mass

Implications for Particle Physics

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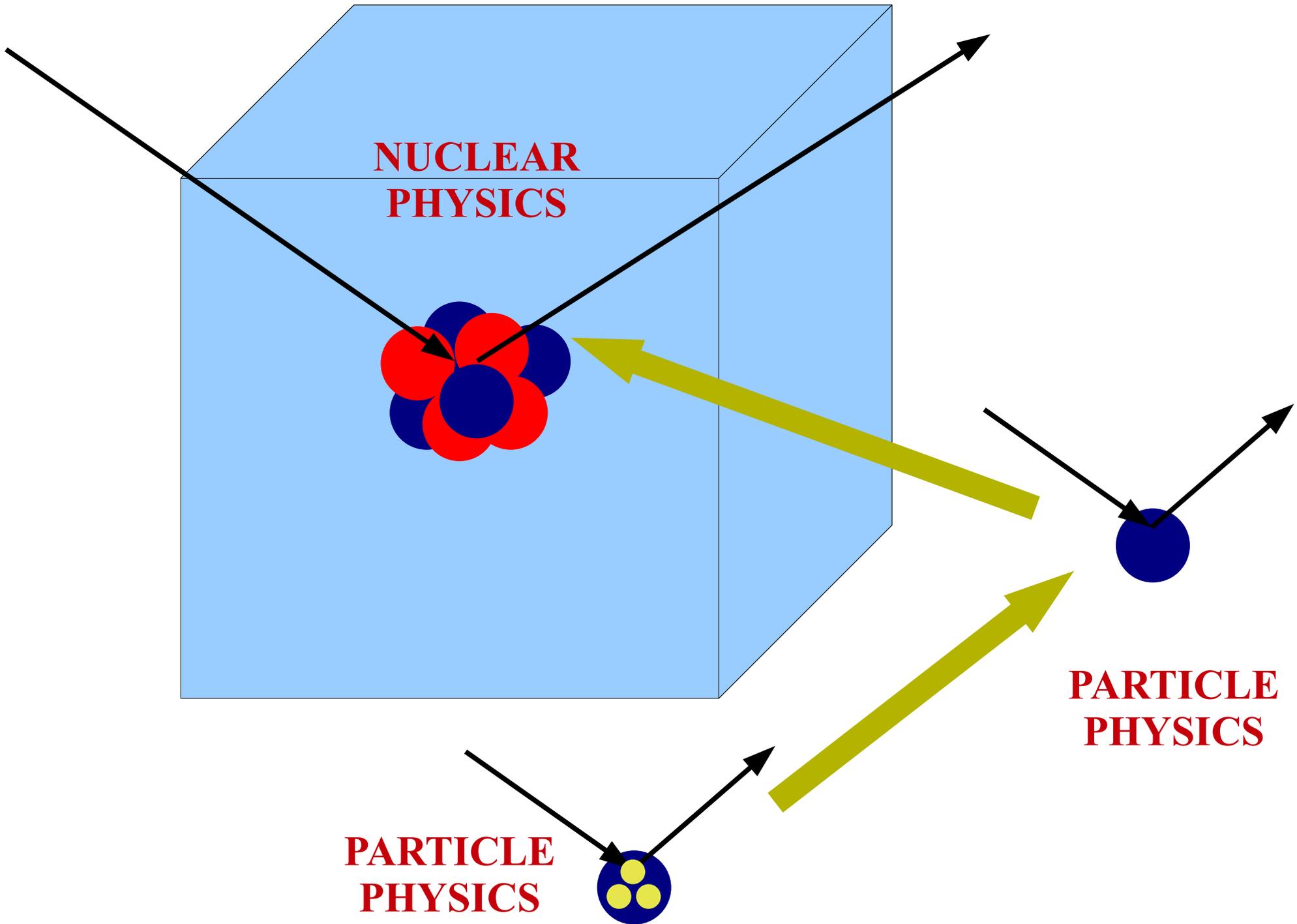
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Event rate is calculated by integrating over all possible recoil energies

$$R = \int_{E_T}^{\infty} \frac{\rho_0}{m_{\text{DM}} m_N} \int_{v_{\min}(E_R)}^{\infty} d^3v v f(\vec{v}) \frac{d\sigma_{\text{DM},N}}{dE_R}(v, E_R)$$

threshold energy of the detector.
Typically a few keV.

DETECTOR
CHARACTERISTICS

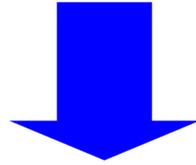


From DM-quark interactions to scatterings off nuclei

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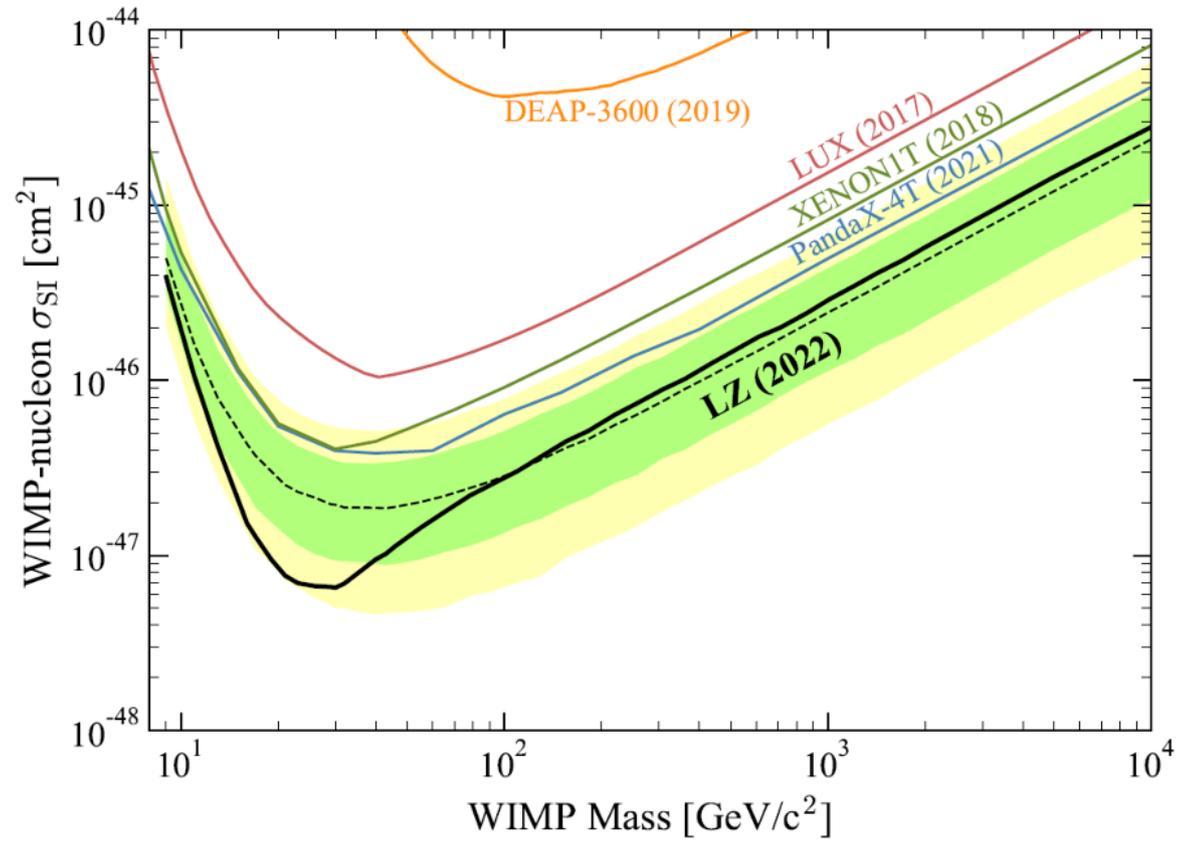
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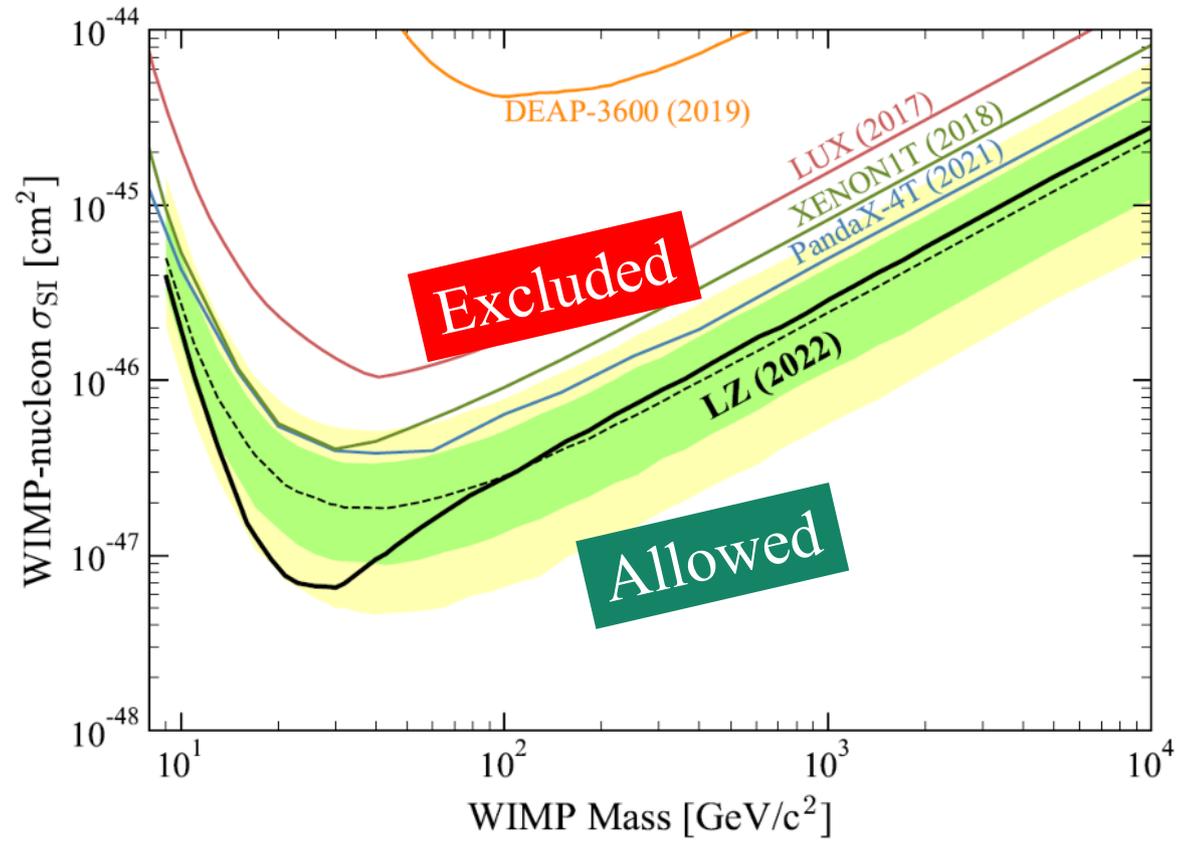
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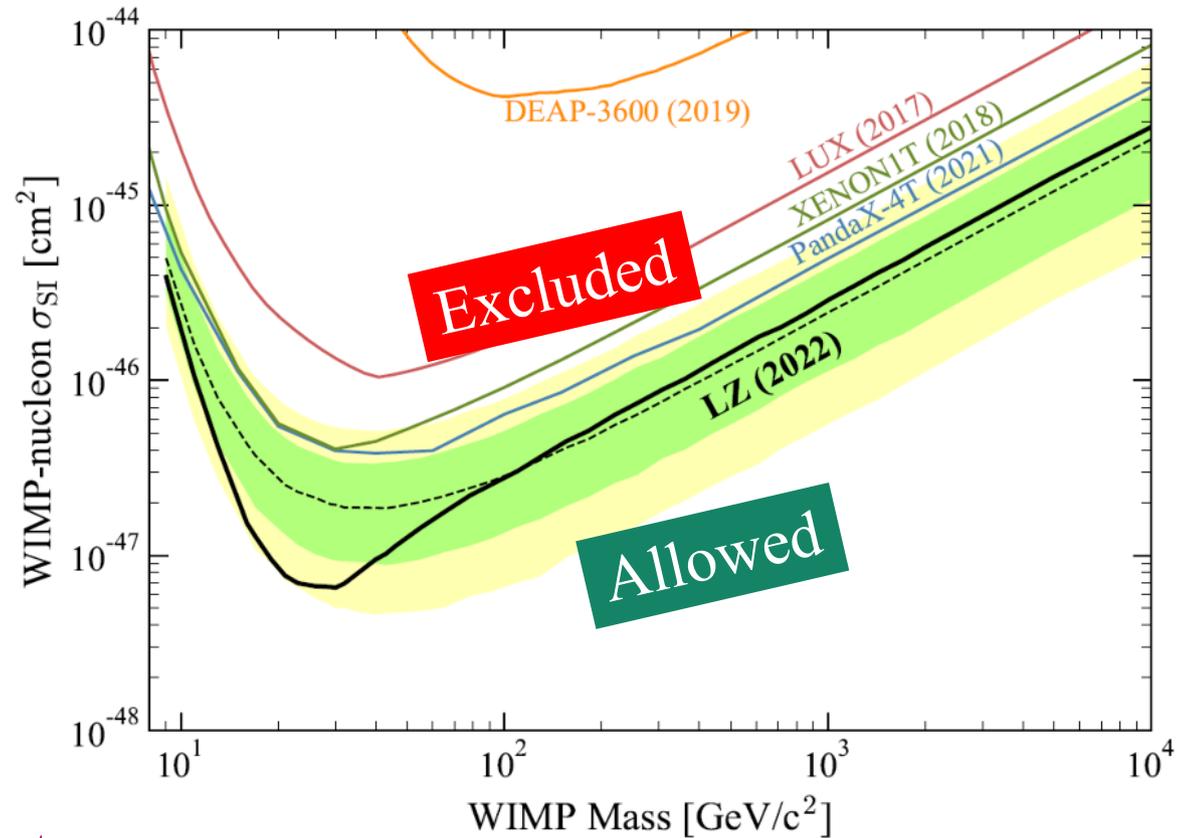
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Smallprint:

- DM interacts only through the spin-independent interaction
- DM couples with equal strength to protons and neutrons (isoscalar)
- Local DM density $\rho=0.3 \text{ GeV/cm}^3$.
- DM velocity distribution given by a Maxwell-Boltzmann, truncated at the escape velocity.

Probing the scattering with nucleons

Consider the Hamiltonian of the SI interaction:

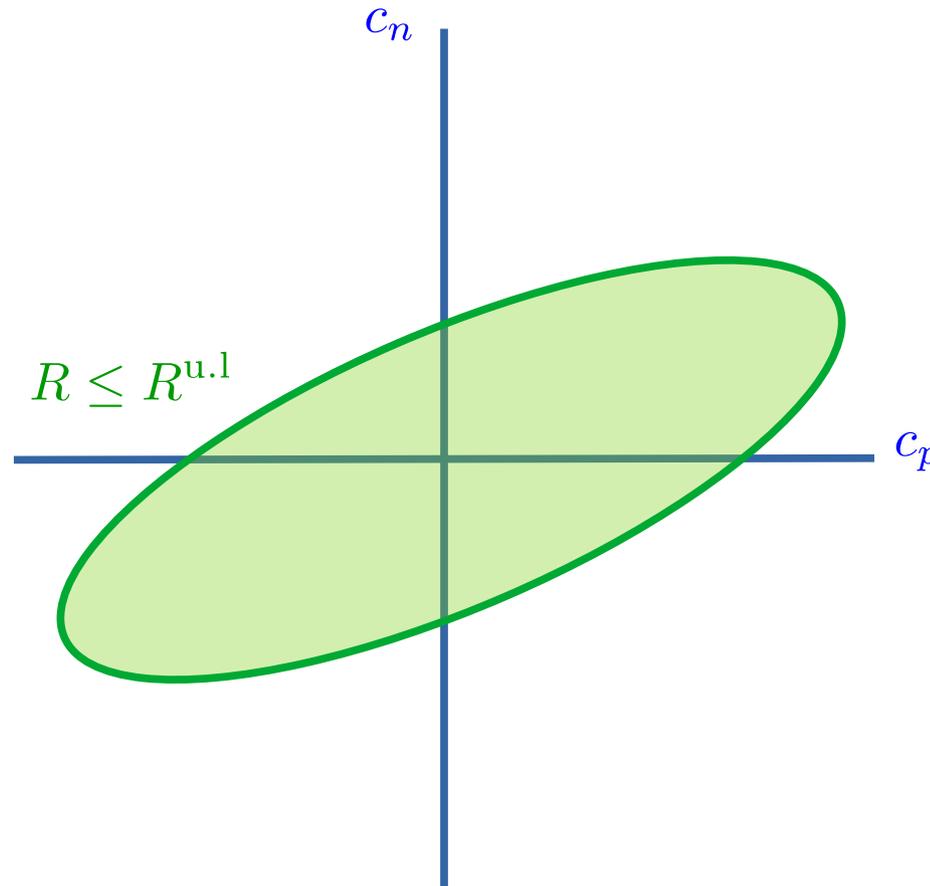
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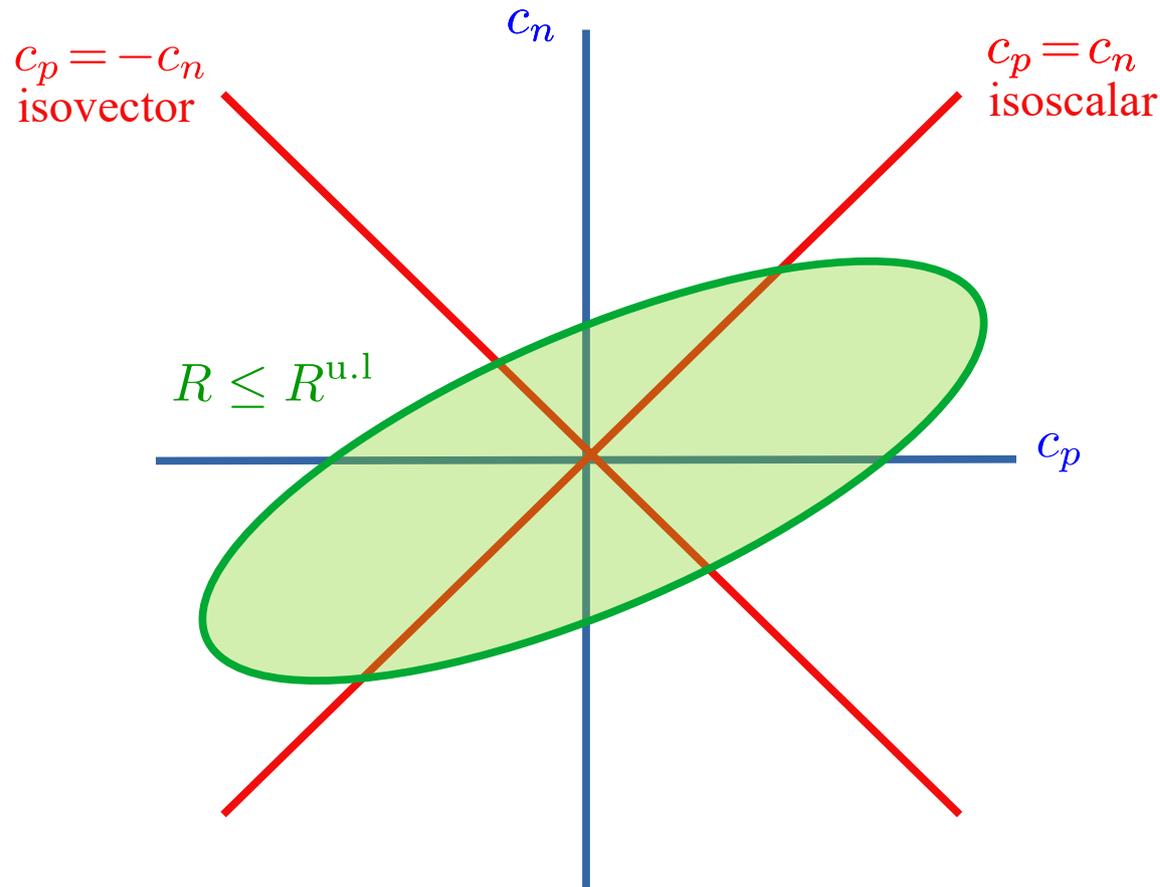


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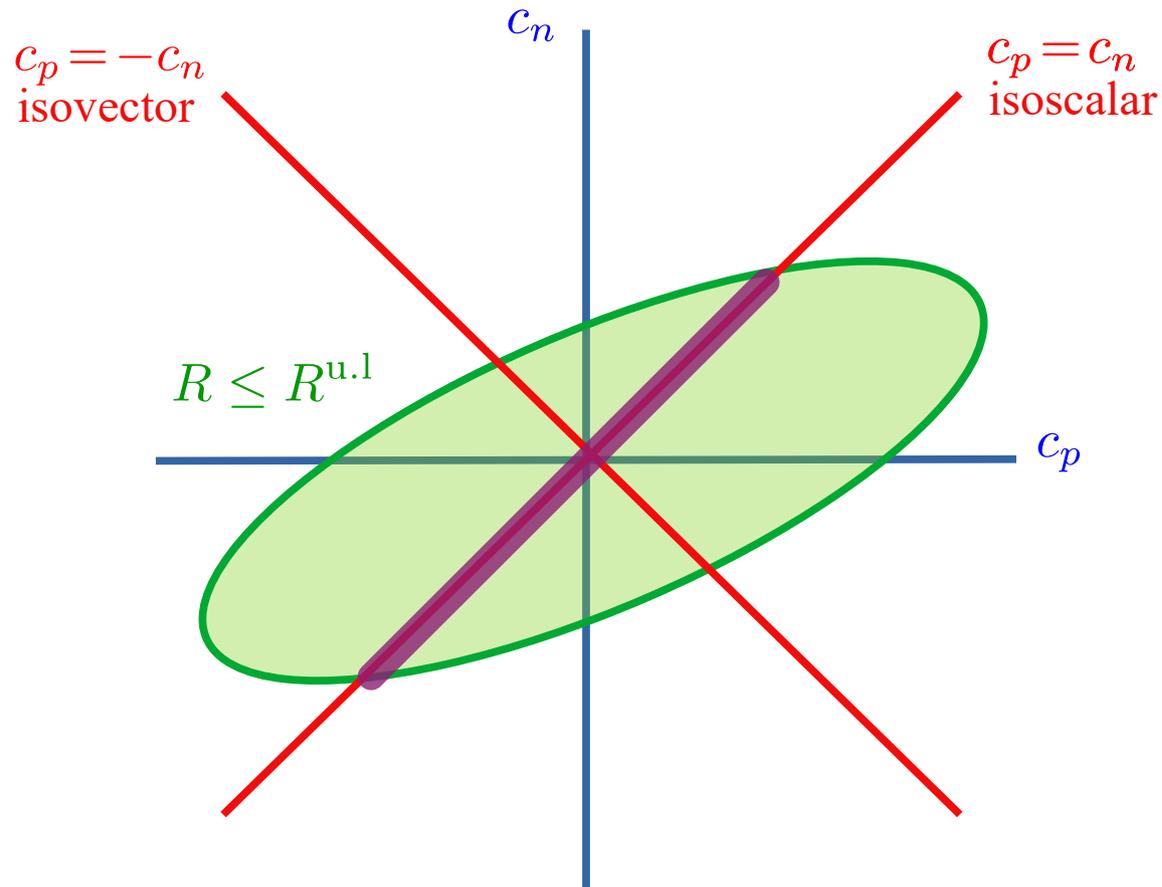


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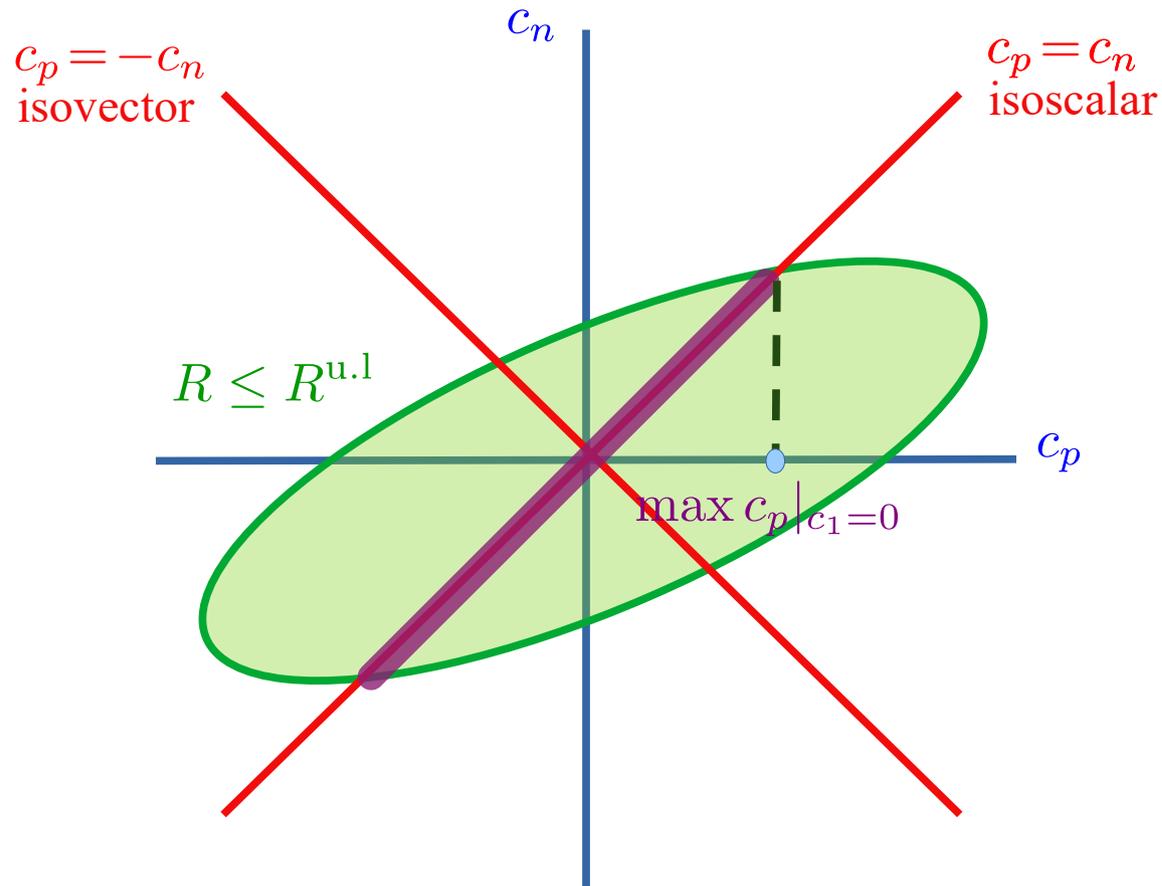


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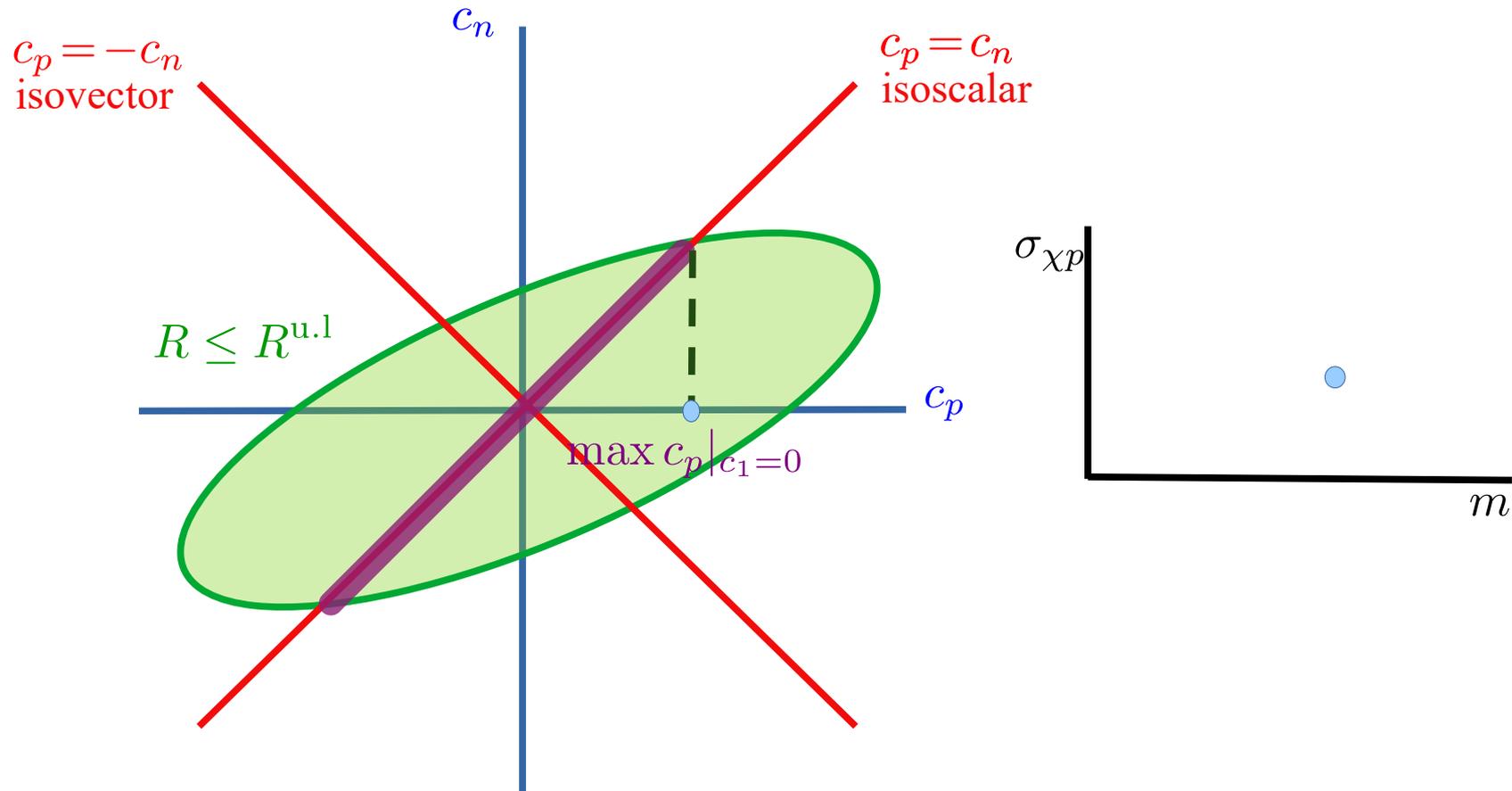


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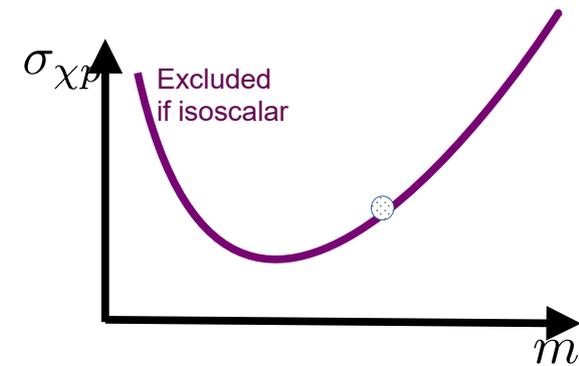
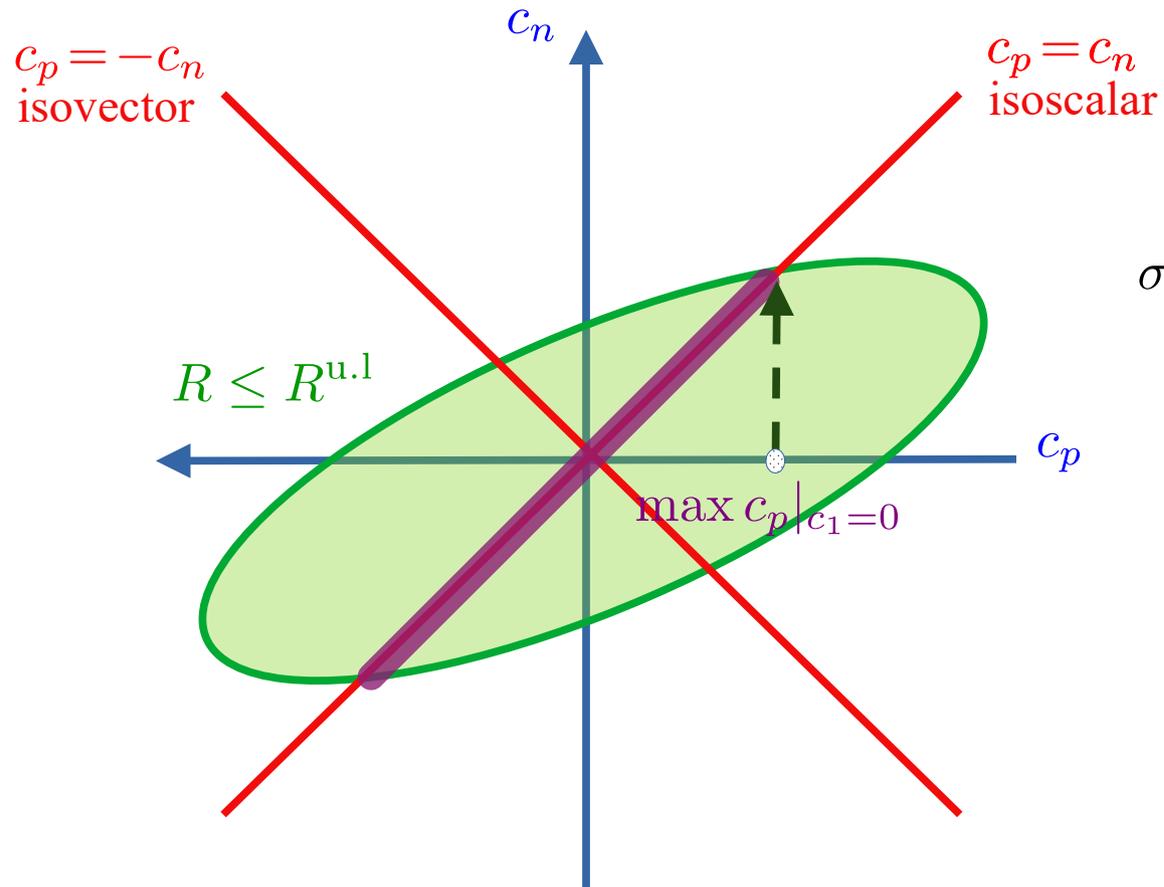


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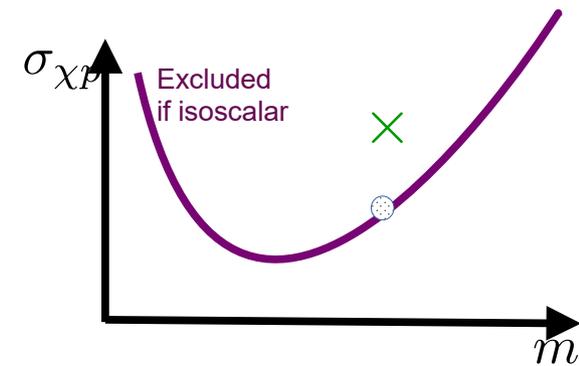
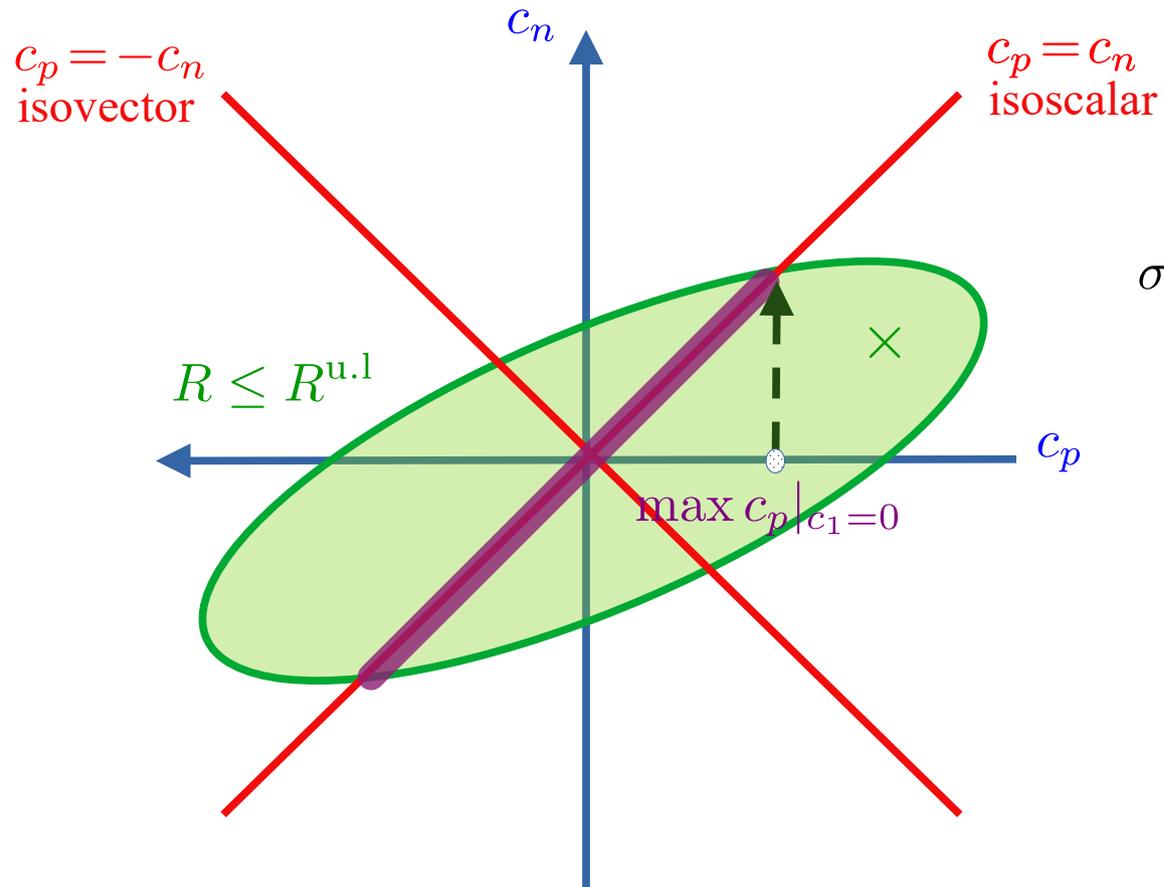


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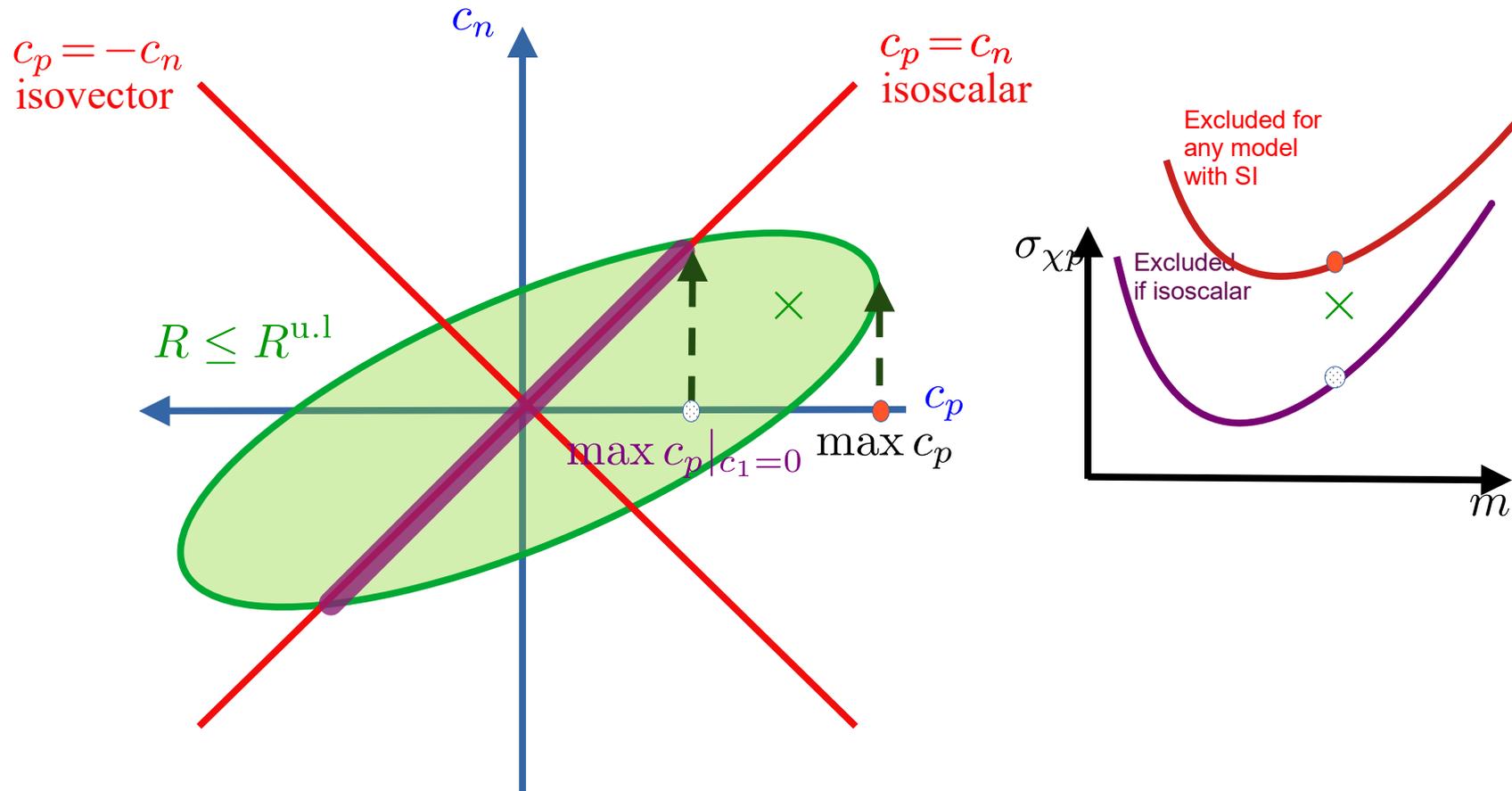


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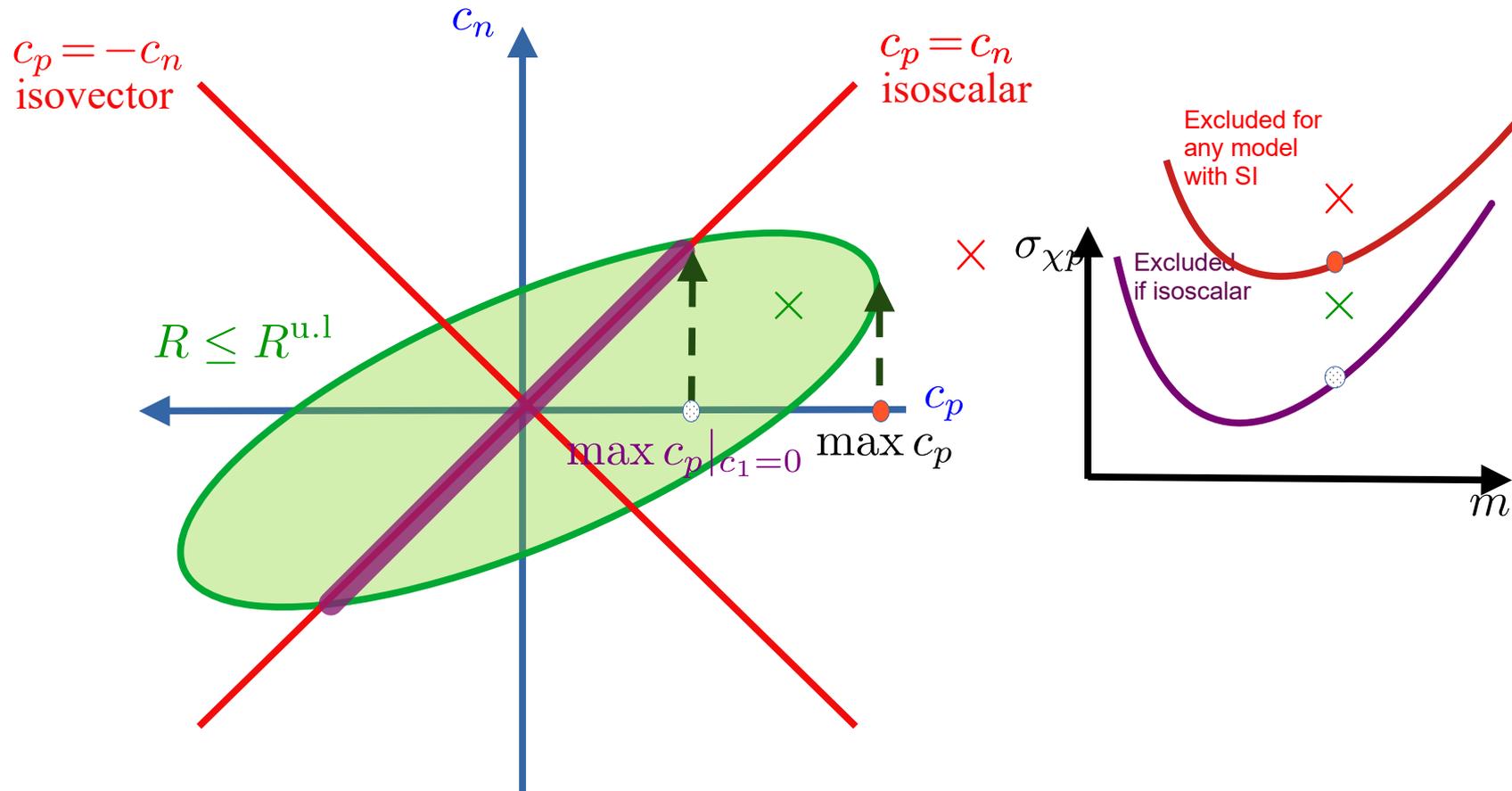


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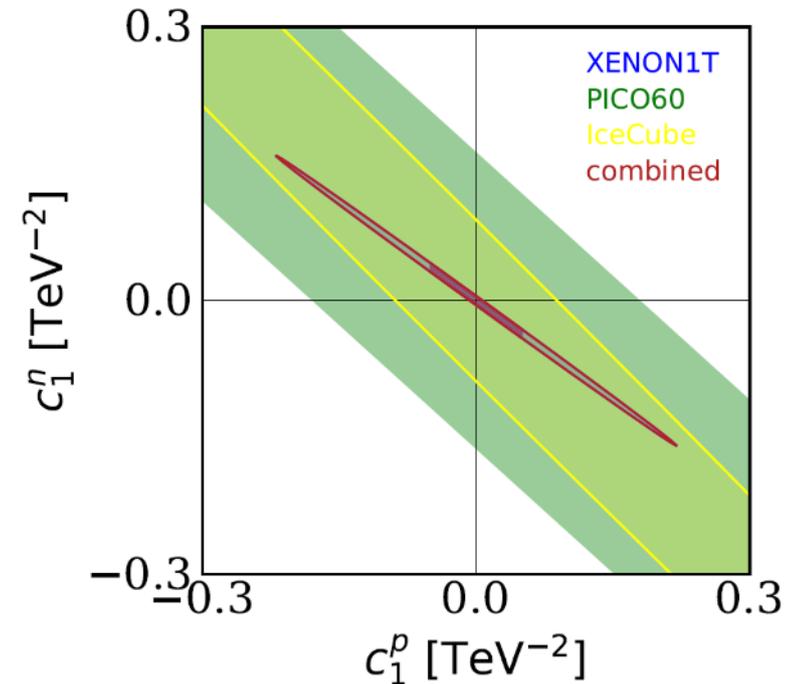
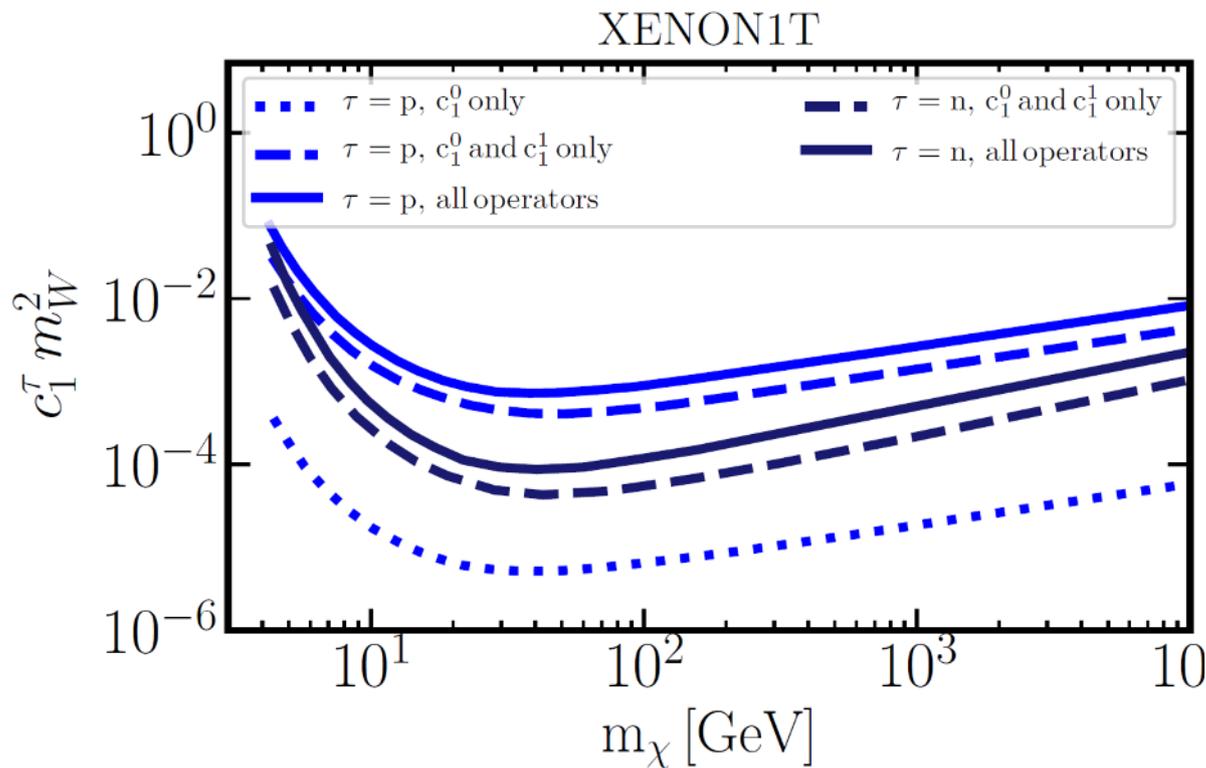


Probing the scattering with nucleons

Consider the Hamiltonian of the SI interaction:

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The two interactions can interfere.



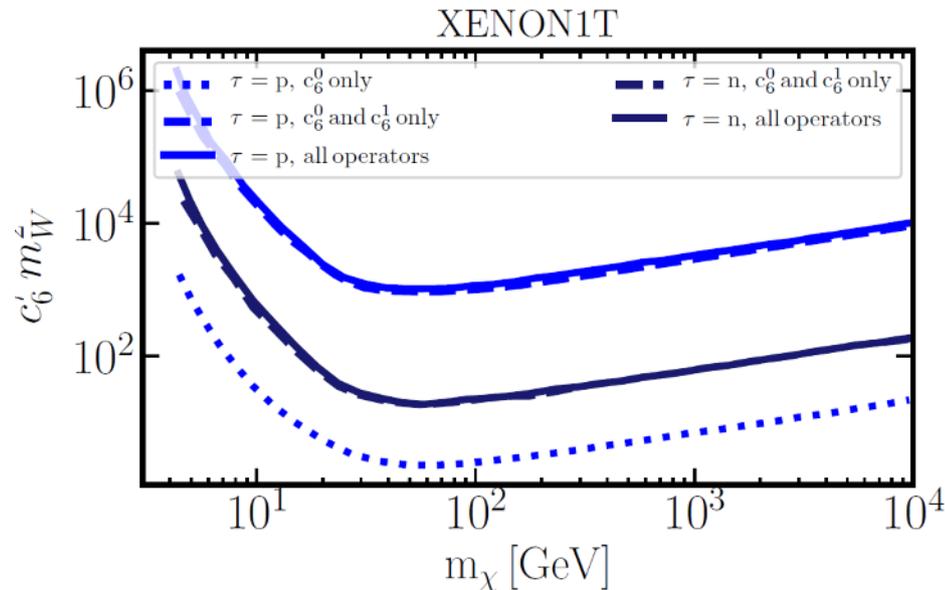
Brenner et al '22

Probing the scattering with nucleons

$\mathcal{O}_1 = 1_X 1_N$	$\mathcal{O}_9 = i\vec{S}_X \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\mathcal{O}_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$
$\mathcal{O}_4 = \vec{S}_X \cdot \vec{S}_N$	$\mathcal{O}_{11} = i\vec{S}_X \cdot \frac{\vec{q}}{m_N}$
$\mathcal{O}_5 = i\vec{S}_X \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{12} = \vec{S}_X \cdot (\vec{S}_N \times \vec{v}^\perp)$
$\mathcal{O}_6 = (\vec{S}_X \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$	$\mathcal{O}_{13} = i(\vec{S}_X \cdot \vec{v}^\perp)(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$
$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$	$\mathcal{O}_{14} = i(\vec{S}_X \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}^\perp)$
$\mathcal{O}_8 = \vec{S}_X \cdot \vec{v}^\perp$	$\mathcal{O}_{15} = -(\vec{S}_X \cdot \frac{\vec{q}}{m_N})((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N})$

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$$\mathcal{L}_{\text{int}} = ig_\chi \phi \bar{\chi} \gamma^5 \chi + ig_N \phi \bar{N} \gamma^5 N$$

Pseudo-scalar mediator

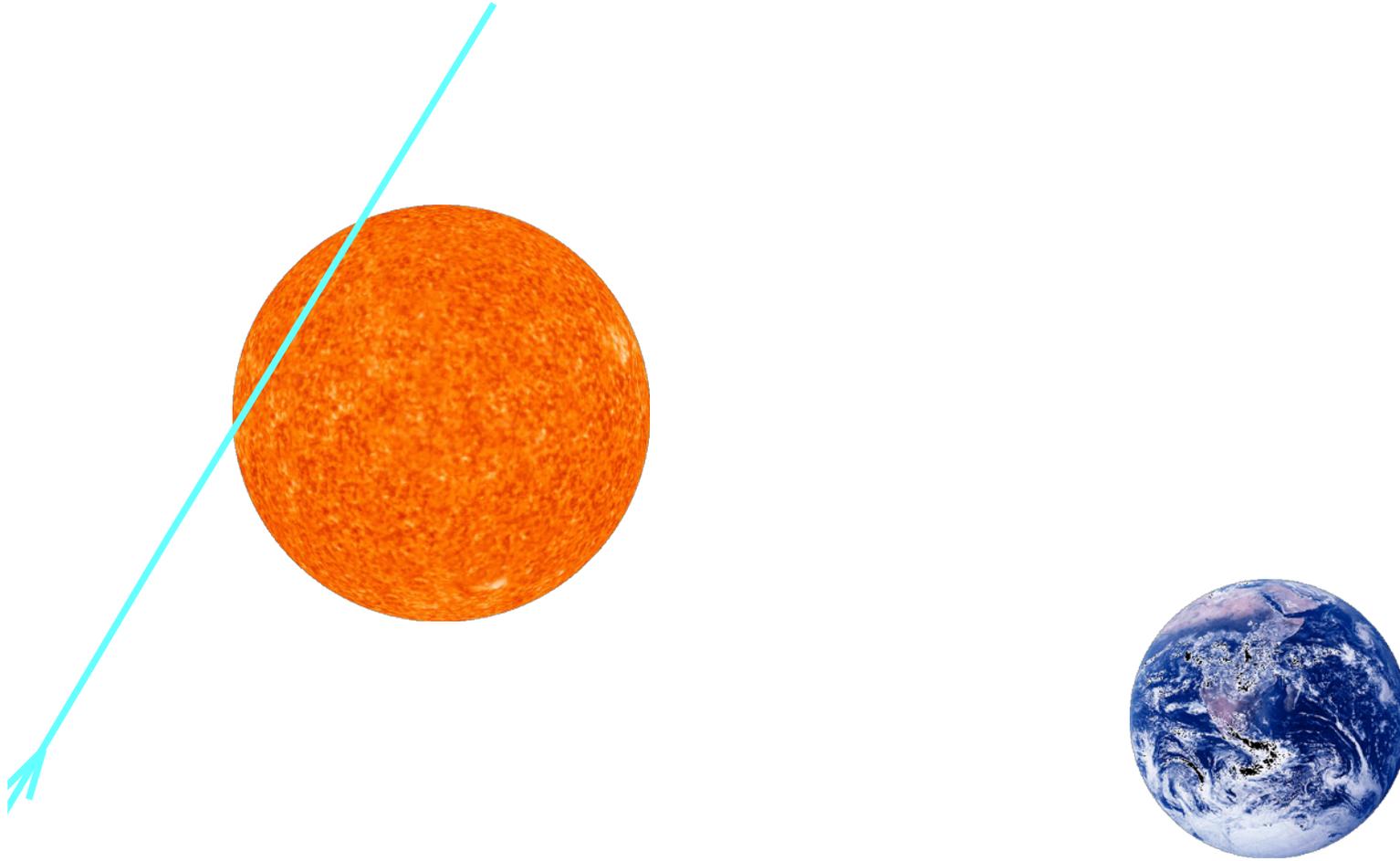
Direct detection: take-home message

Very stringent constraints on DM-nucleon interactions. These constraints put pressure on models where the DM interacts at tree level with the valence quarks (e.g. some SUSY scenarios)

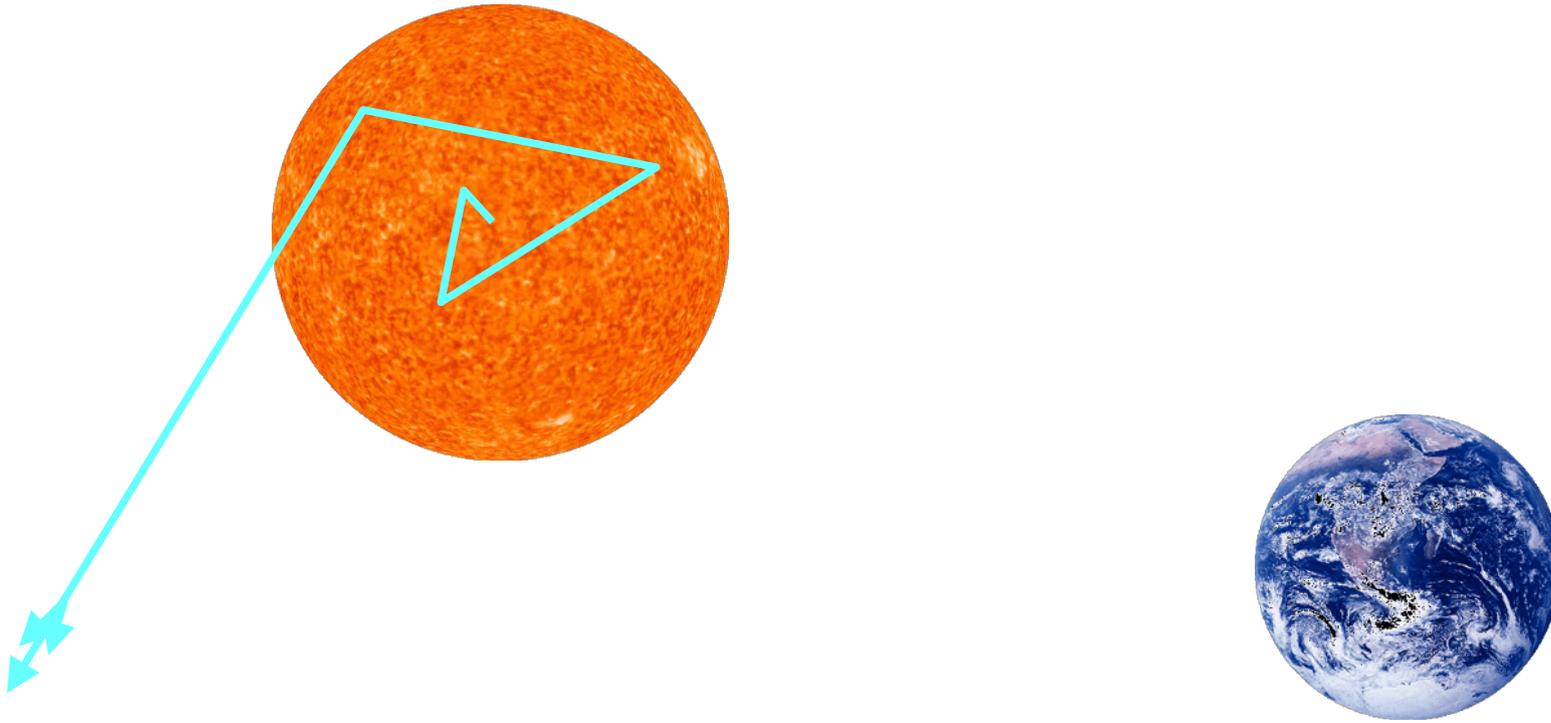
Many possibilities still weakly constrained by direct detection experiments:

- DM coupling only to leptons (especially to the tau)
- DM coupling to heavy quarks
- DM interacting with the nucleon via generalized operators
- Light dark matter
- “unexpected” astrophysics?
- ...

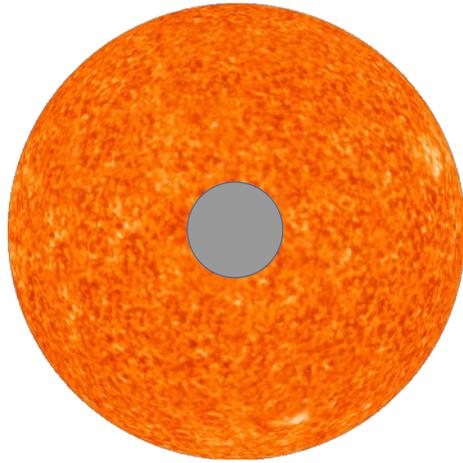
Using the Sun to probe scattering with nucleons

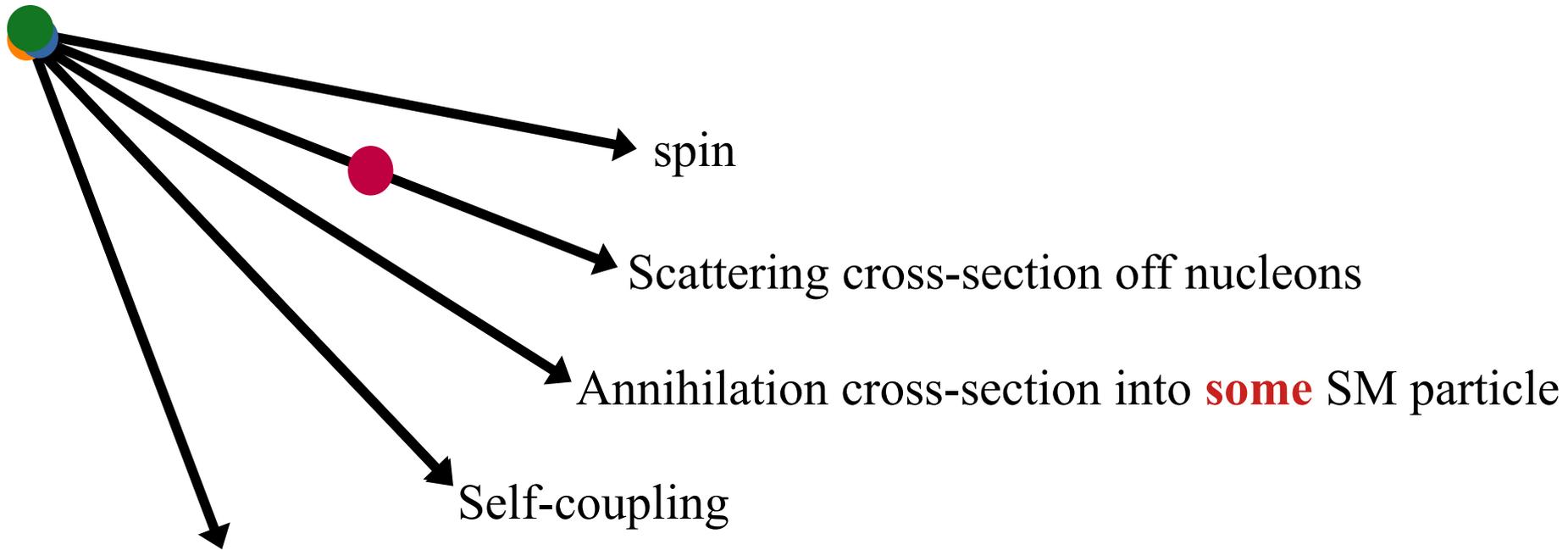


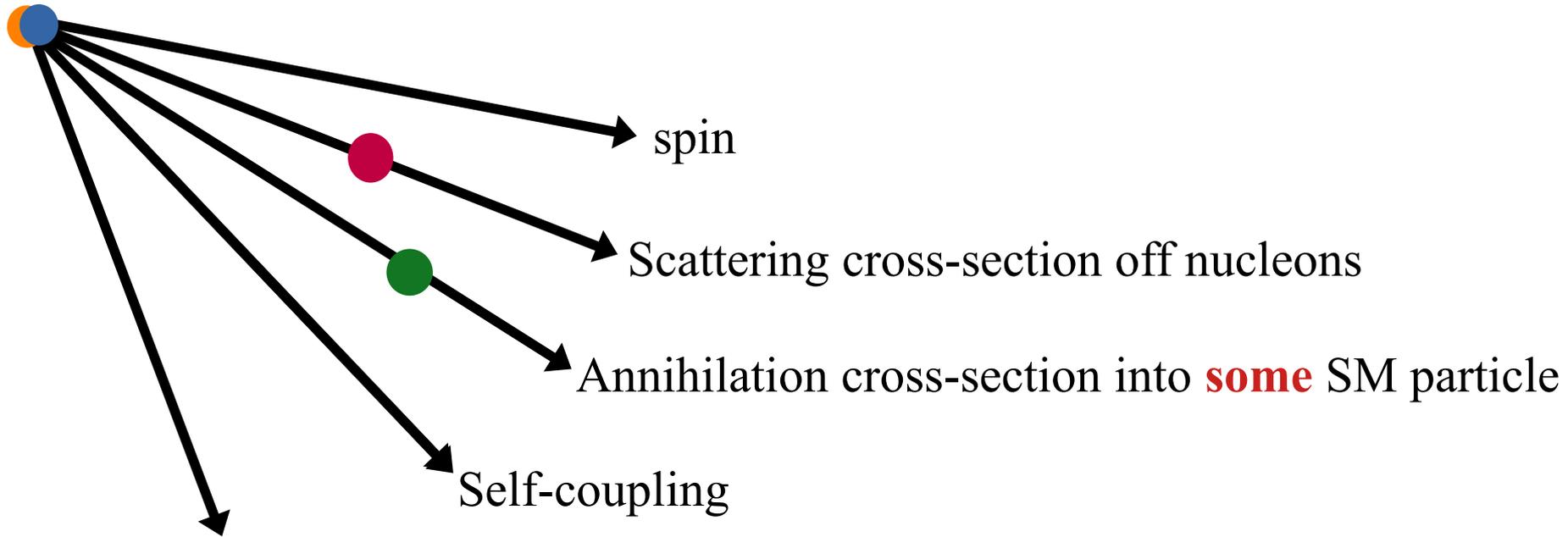
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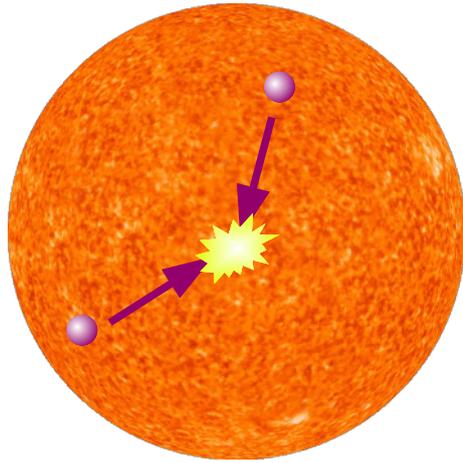
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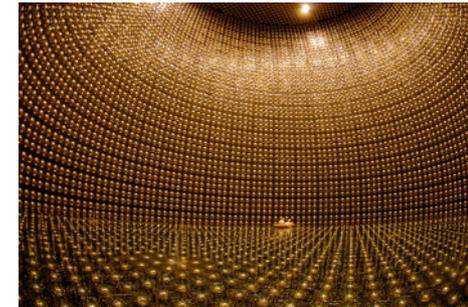
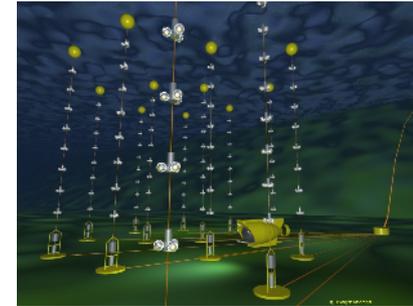
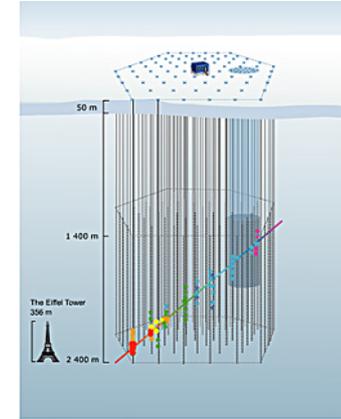
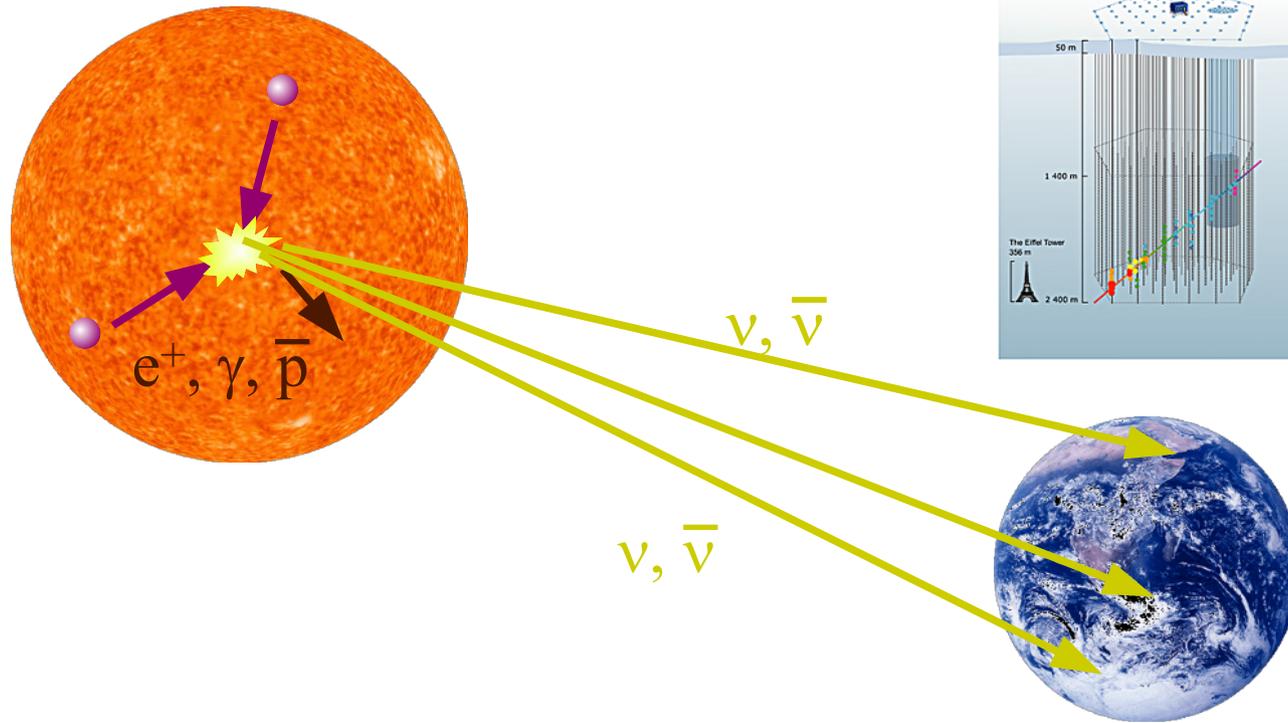




Using the Sun to probe scattering with nucleons

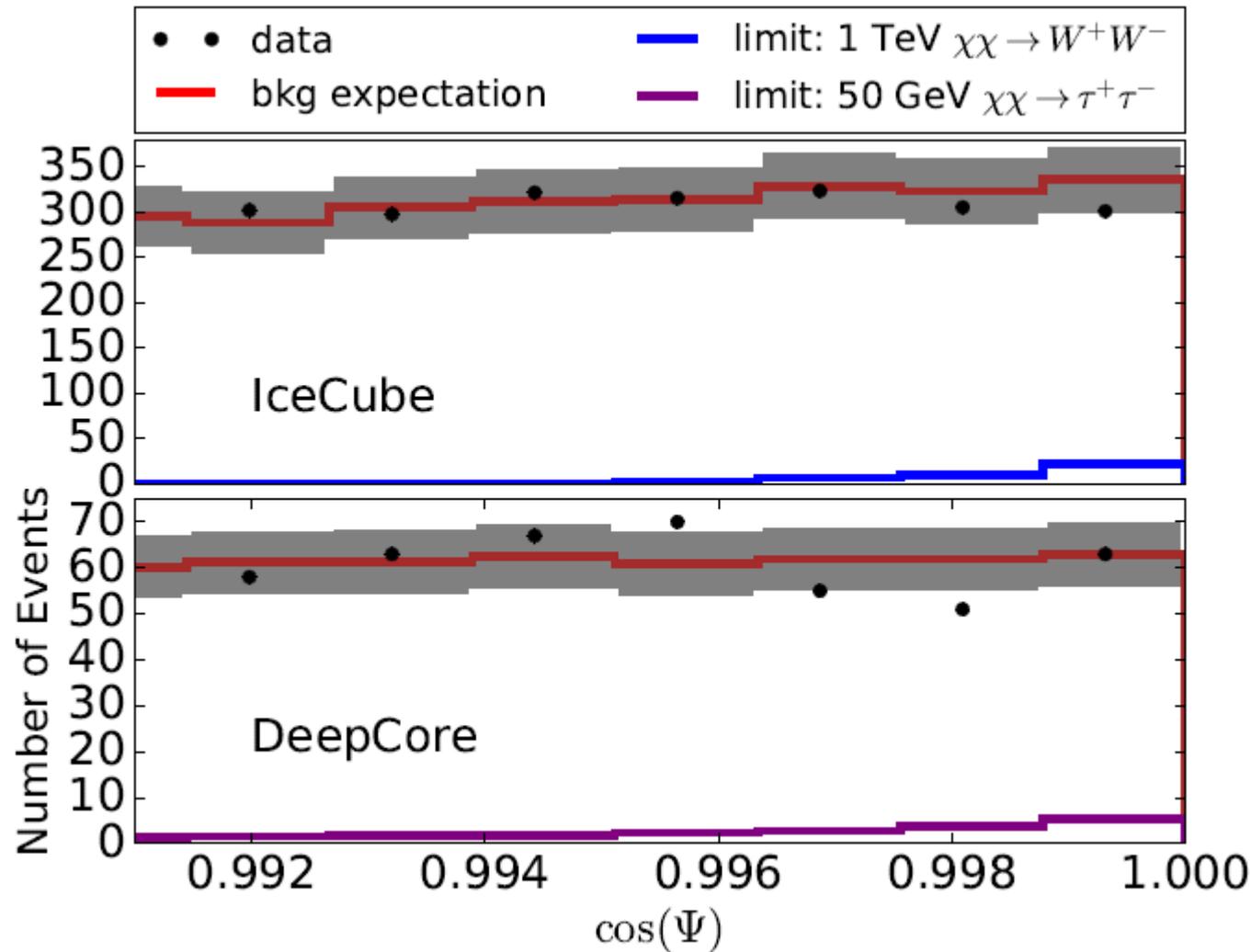


Using the Sun to probe scattering with nucleons

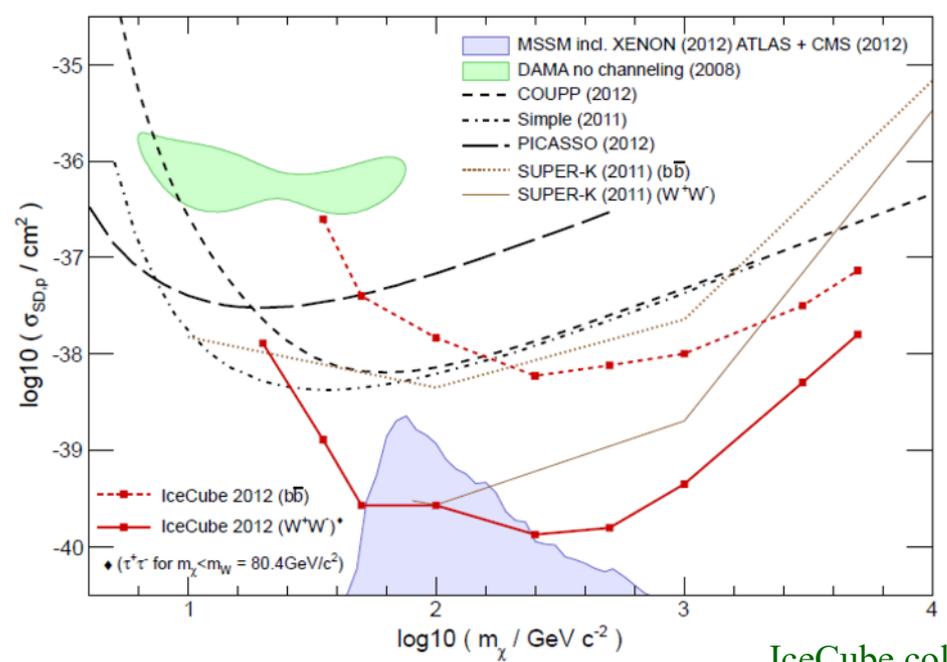
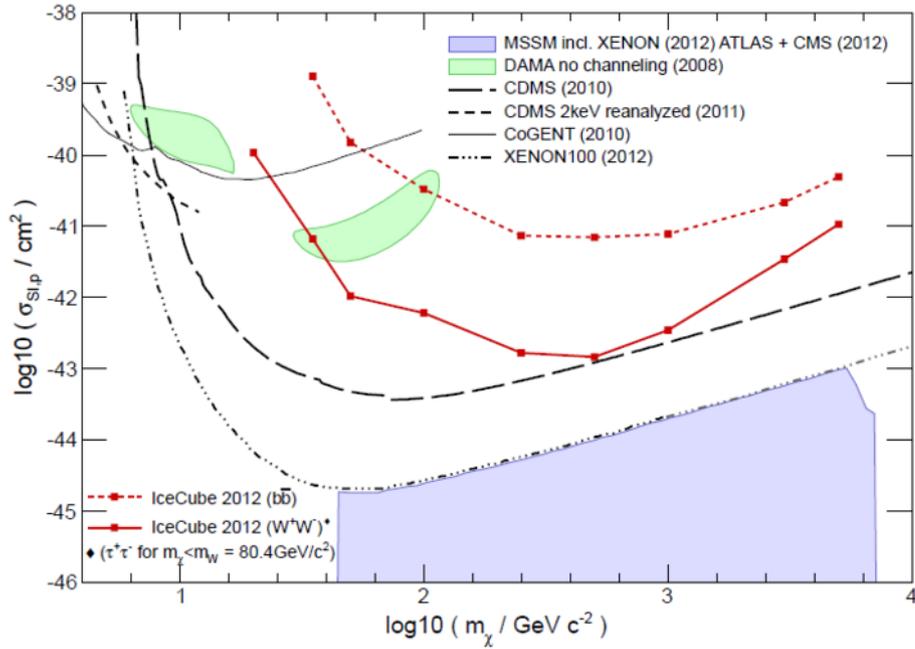


Using the Sun to probe scattering with nucleons

Observations consistent with the background-only hypothesis

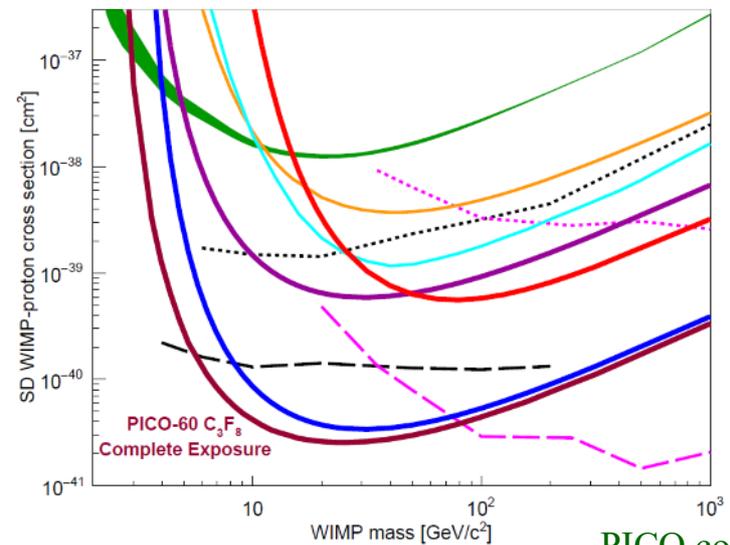
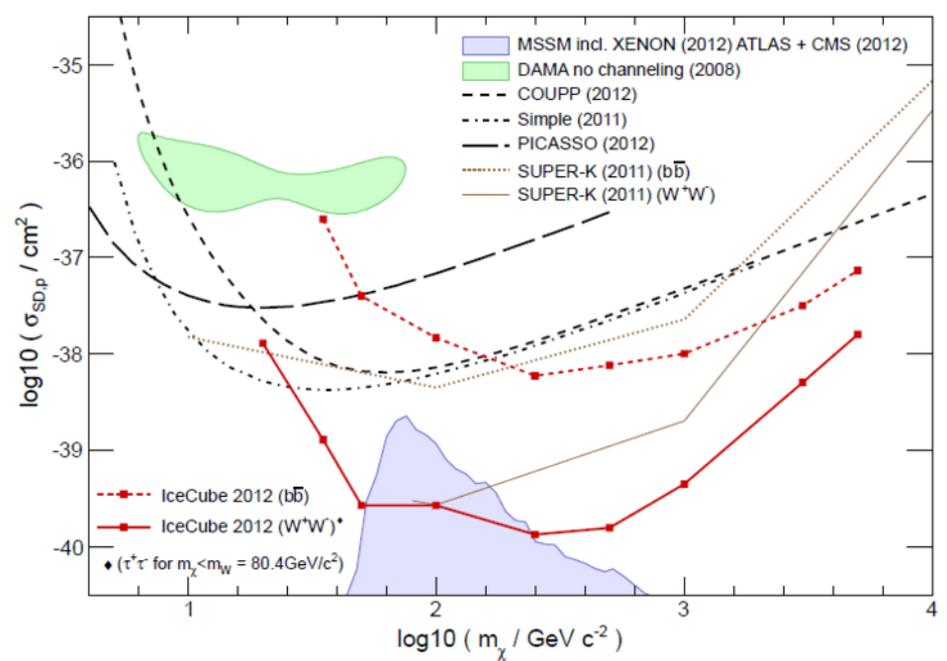
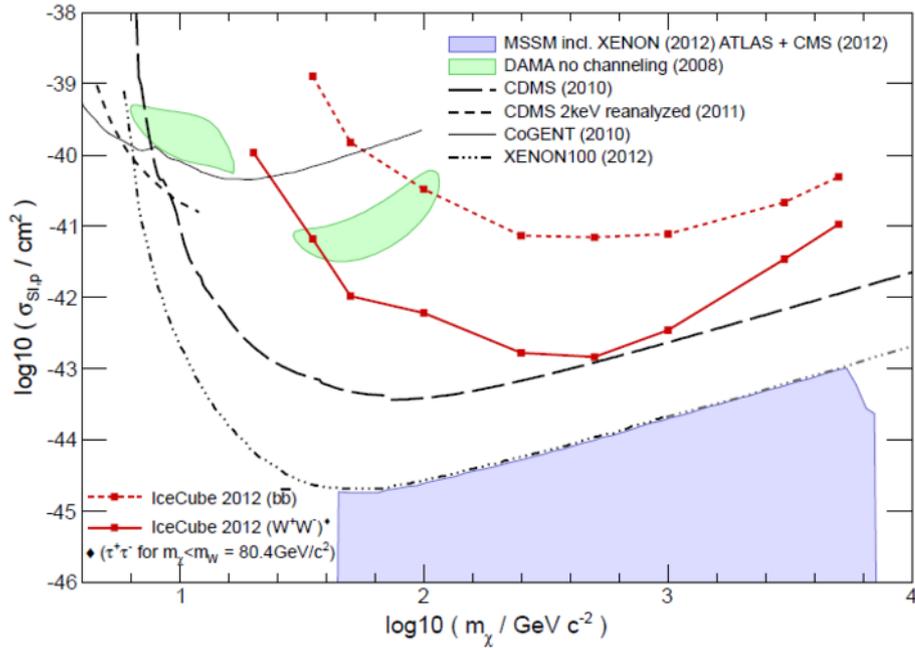


Using the Sun to probe scattering with nucleons



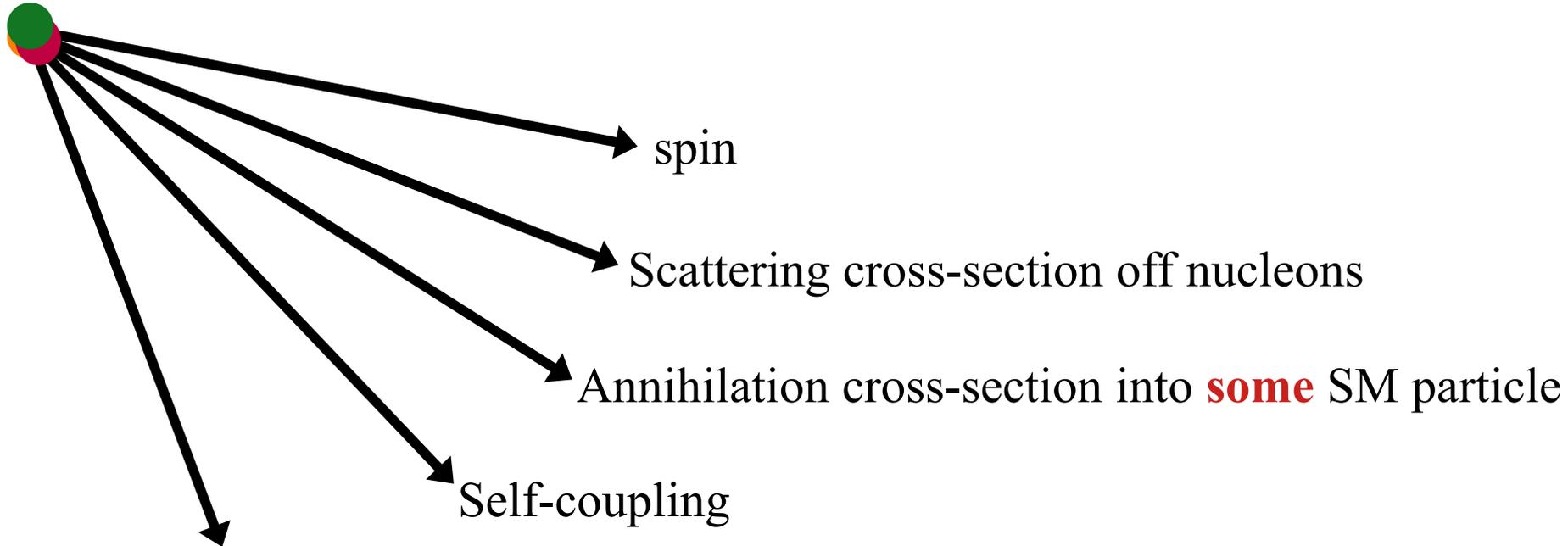
IceCube coll'12

Using the Sun to probe scattering with nucleons



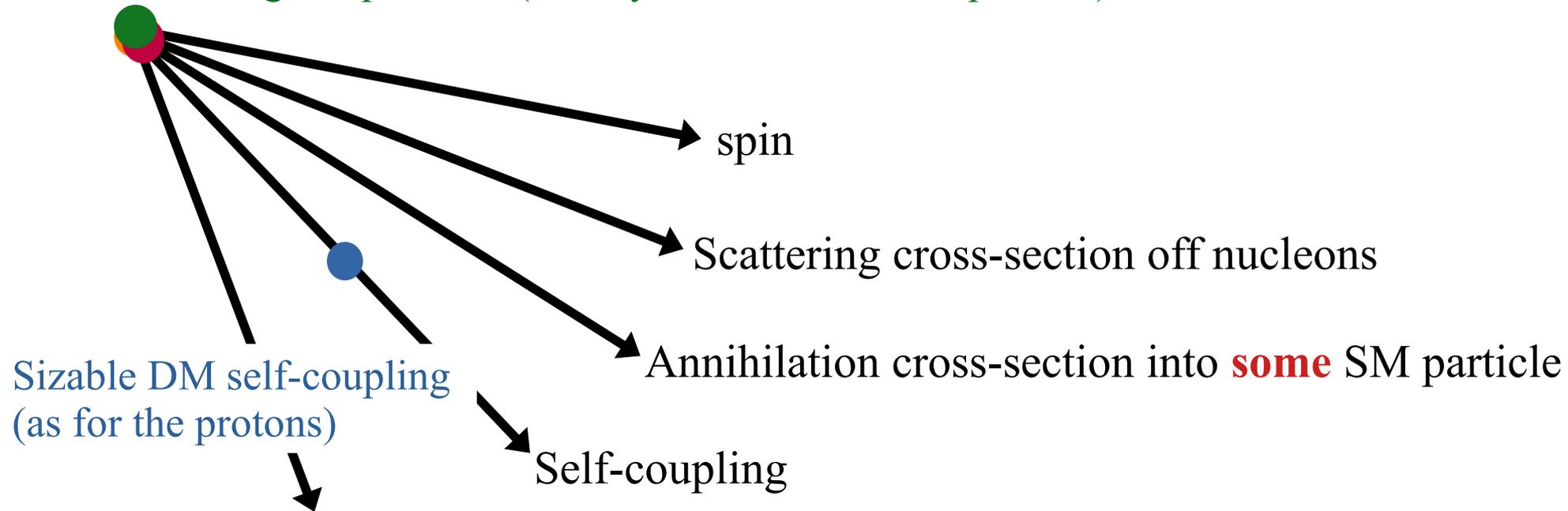
Probing alternative scenarios: ADM

“Asymmetric dark matter”: a symmetry protects DM against annihilations into lighter particles (as baryon number for the protons)



Probing alternative scenarios: ADM

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Probing alternative scenarios: ADM

Protons do not annihilate.

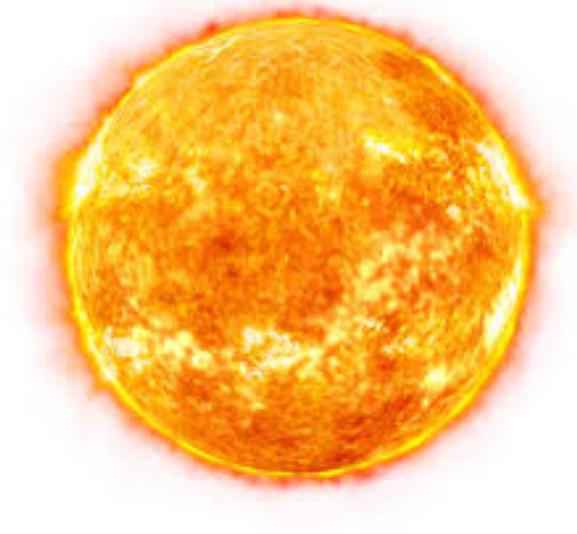
Protons have strong self-interactions

Protons form stars

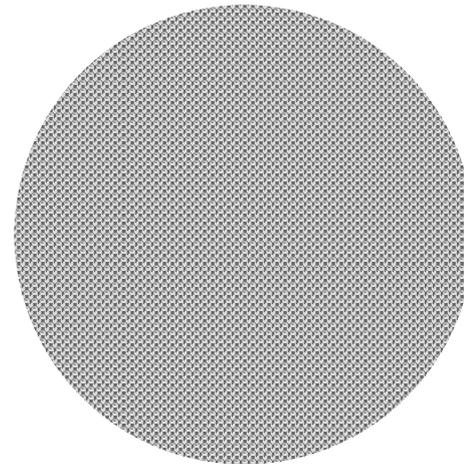


Probing alternative scenarios: ADM

Protons do not annihilate.
Protons have strong self-interactions
Protons form stars



DM does not annihilate.
DM has strong self-interactions
DM form dark stars



Probing alternative scenarios: ADM

Density profile of dark stars calculable from the Klein-Gordon equation in curved spacetime (for bosonic DM) and the Einstein equations:

Colpi et al'86

$$g^{\mu\nu} \nabla_{\mu} \nabla_{\nu} \phi - m^2 \phi - \lambda |\phi|^2 \phi = 0$$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

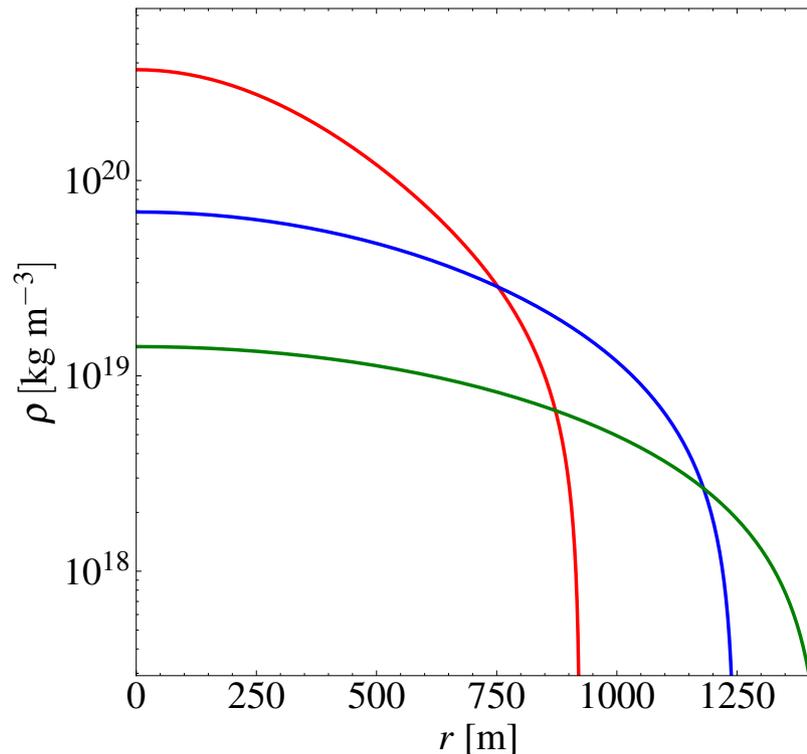
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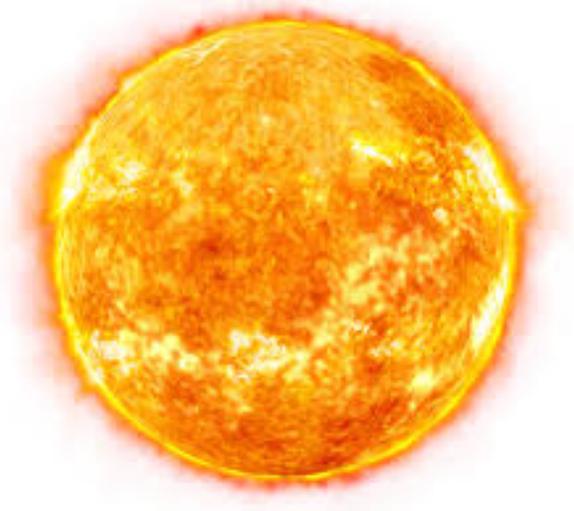


(For $m=1$ GeV, $\lambda=1$)

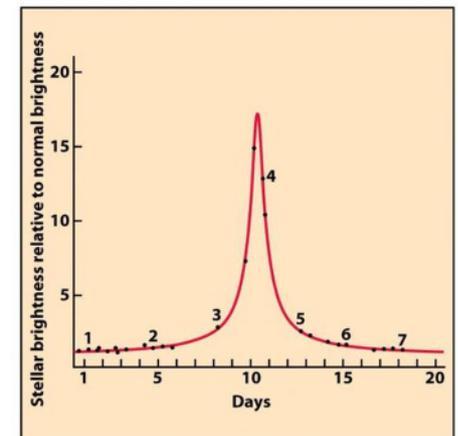
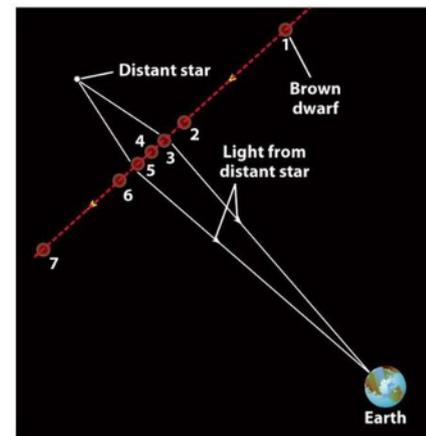
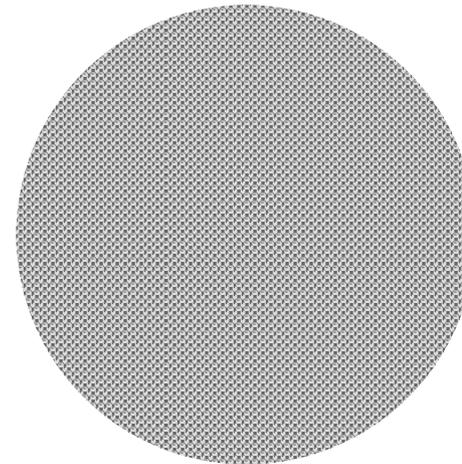
Dark stars are very compact objects

Probing alternative scenarios: ADM

Protons do not annihilate.
Protons have strong self-interactions
Protons form stars

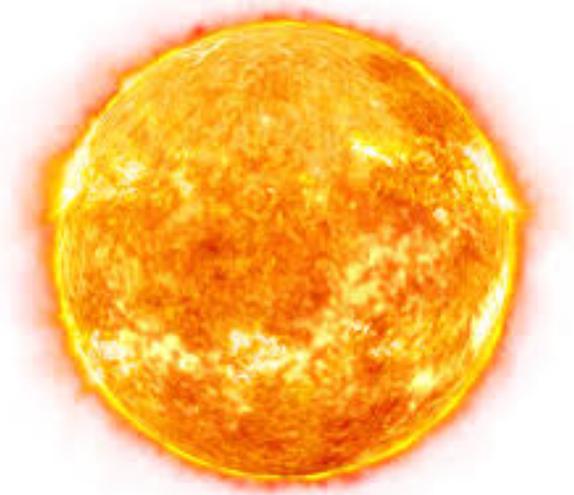


DM does not annihilate.
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DM form dark stars

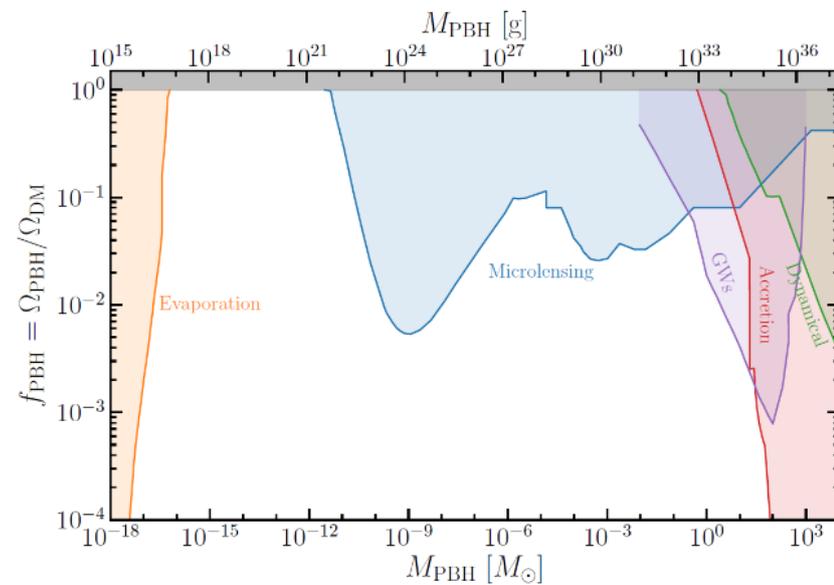
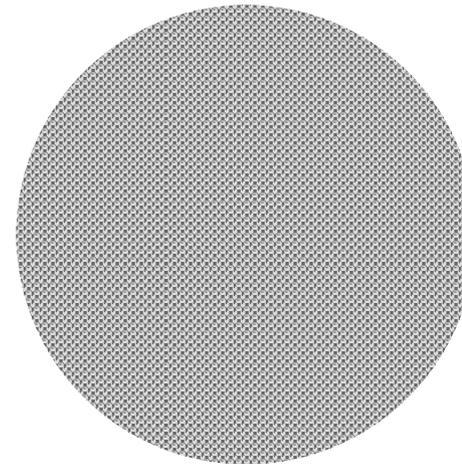


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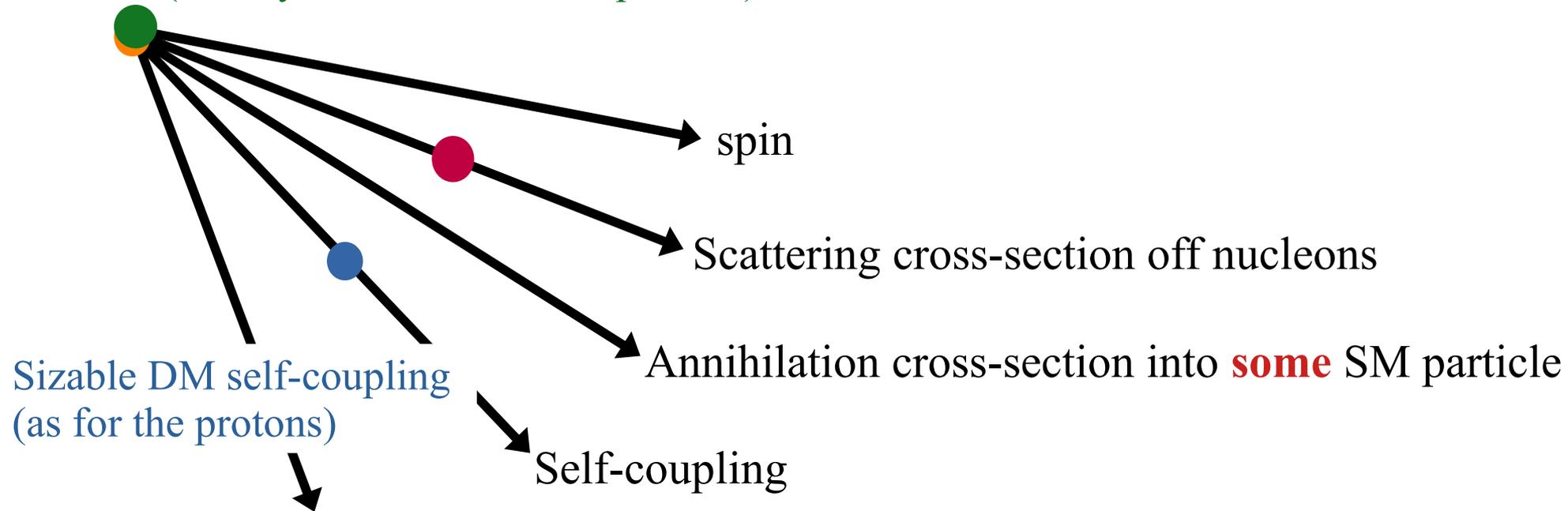


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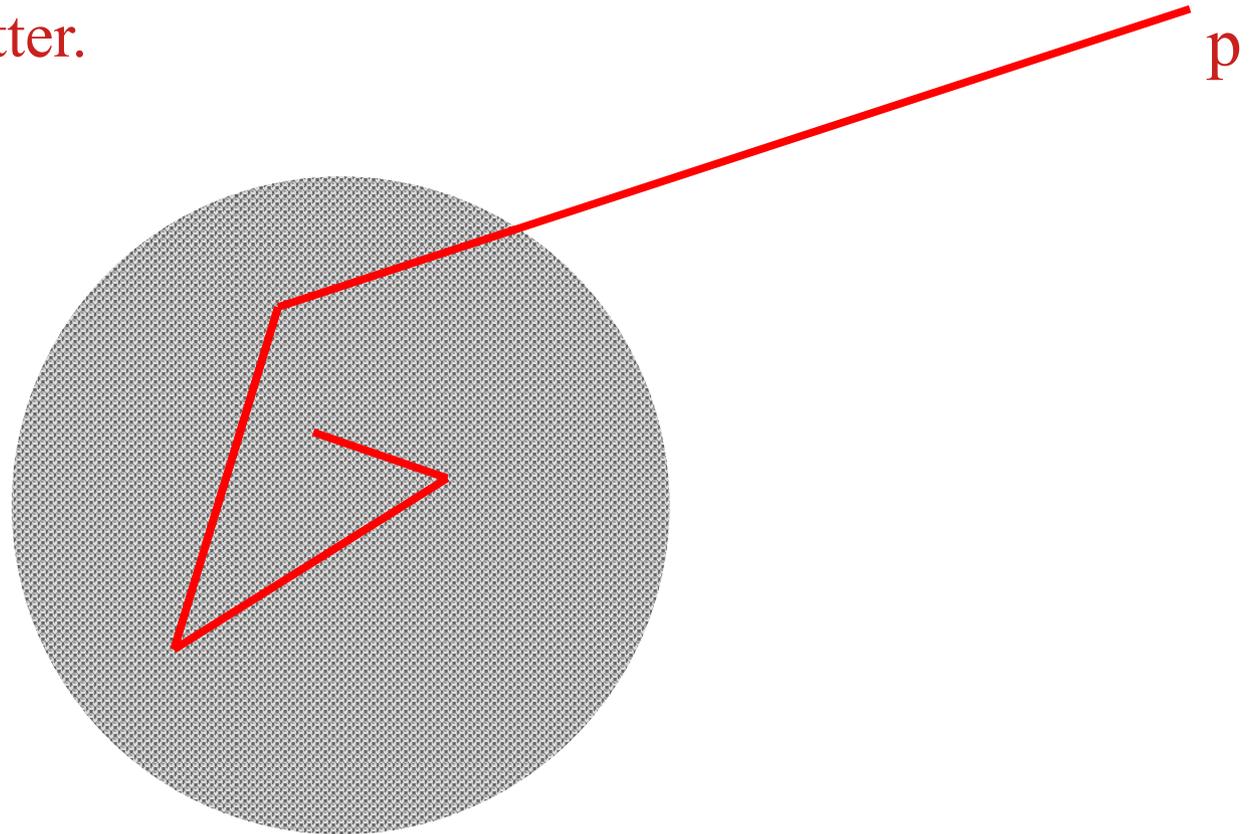
Using DSs to probe scattering with nucleons

“Asymmetric dark matter”: a symmetry protects DM against annihilations
(as baryon number for the protons)



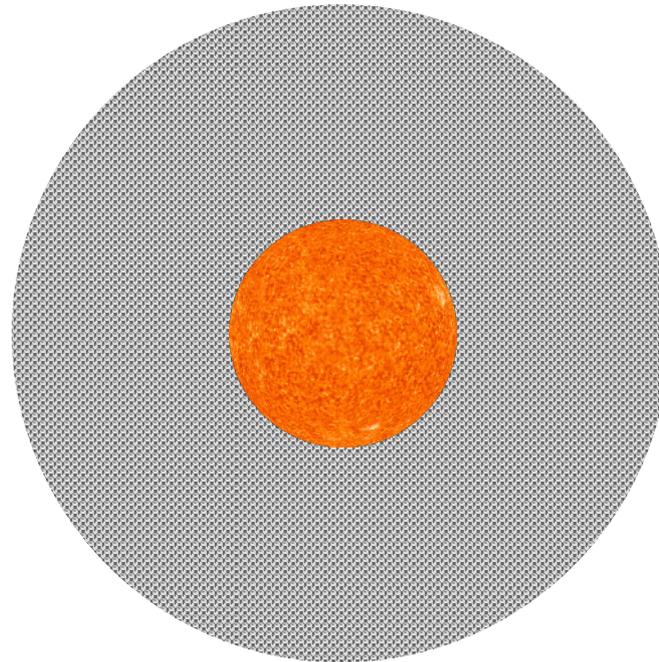
Using DSs to probe scattering with nucleons

Compact dark stars could capture protons, in the same way that stars capture dark matter.

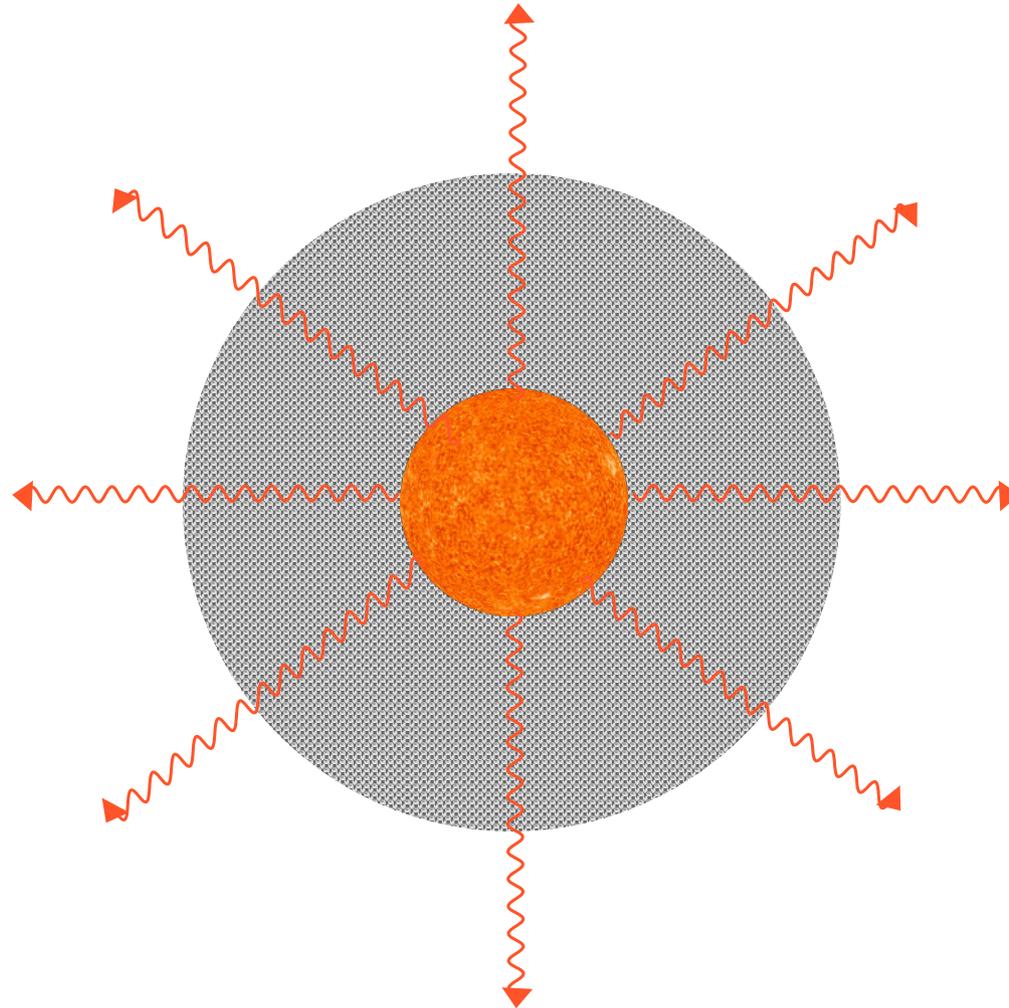


$$C \sim (10^{18} \text{ s}^{-1}) \left[\left(\frac{\sigma}{10^{-45} \text{ cm}^2} \right) \left(\frac{n_p}{10^{-5} \text{ cm}^{-3}} \right) \right] \left(\frac{R_{\text{DS}}}{1 \text{ km}} \right)^3 \left(\frac{M}{M_{\odot}} \right)^{-\frac{3}{2}}$$

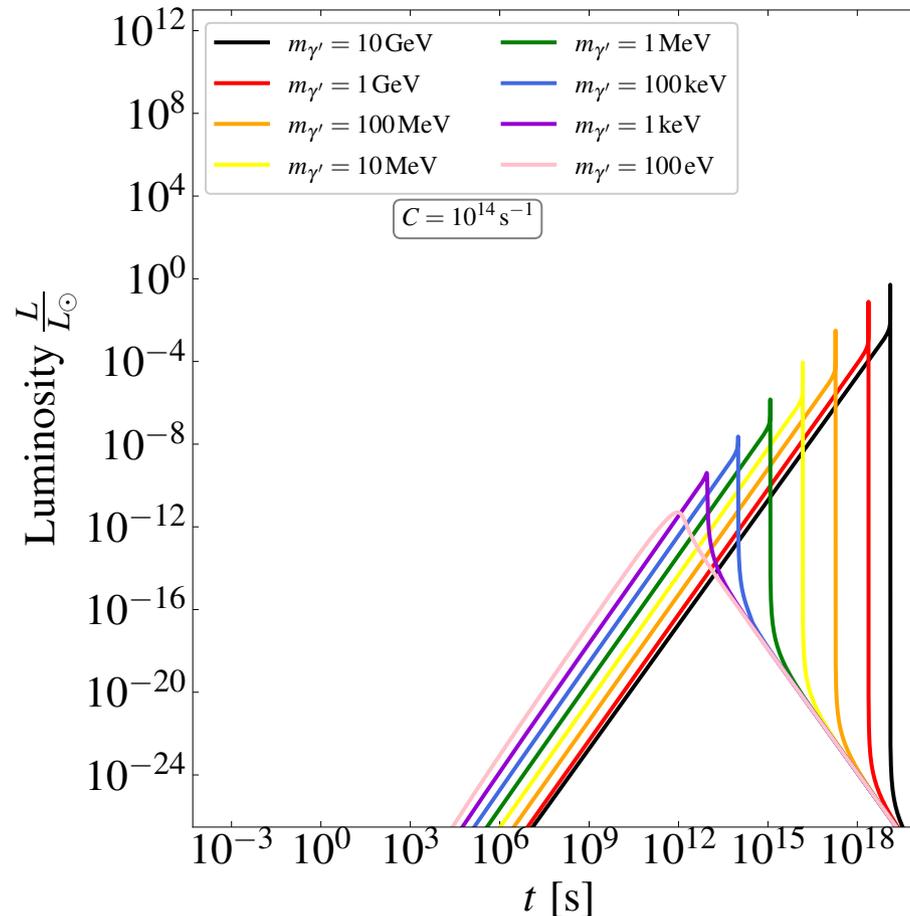
Using DSs to probe scattering with nucleons



Using DSs to probe scattering with nucleons



Using DSs to probe scattering with nucleons



Brenner et al'23

The “dark star” could be very luminous in gamma-rays

If $L=10^{-4} L_{\text{sol}}$, current instruments could detect up to 100 sources, if 1% of the dark matter is in the form of dark stars.

Conclusions

- After 40+ years of search, there is still no concluding evidence that dark matter is made of elementary particles.
- “Traditional” searches put some tension on some WIMP scenarios. Many other scenarios still poorly constrained by data.
- Better experiments are needed, and also new ideas for dark matter detection.

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