



Indirect detection of Dark Matter

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EEEEEOOOO
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Who am I?



Imperial College
London

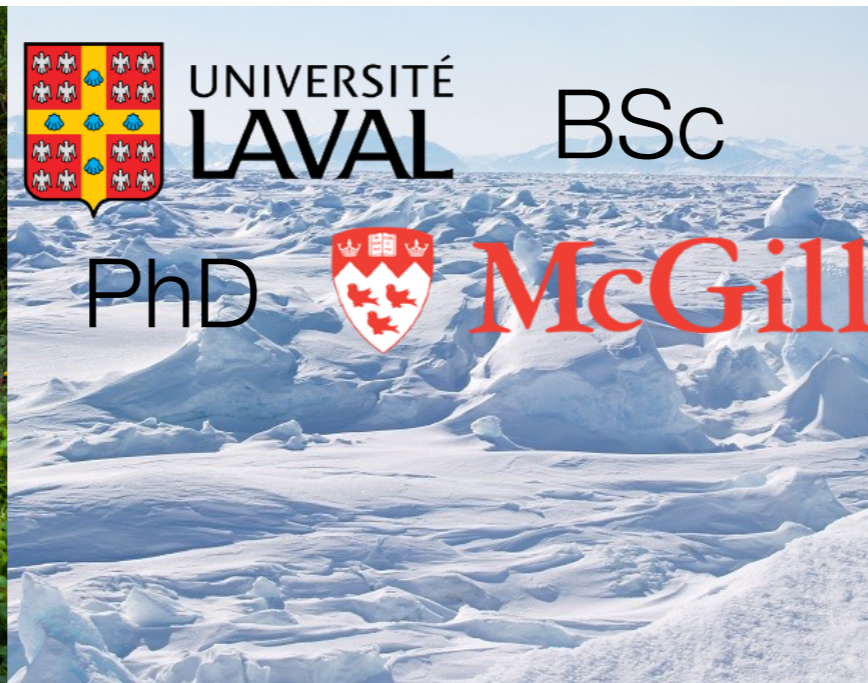
Durham
University

UNIVERSITÉ
LAVAL BSc

PhD  McGill



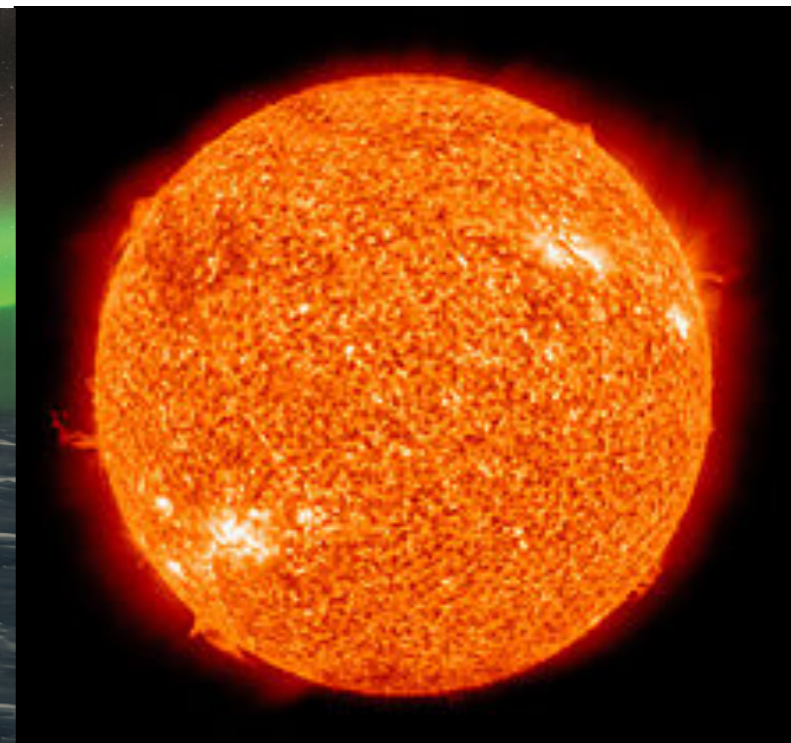
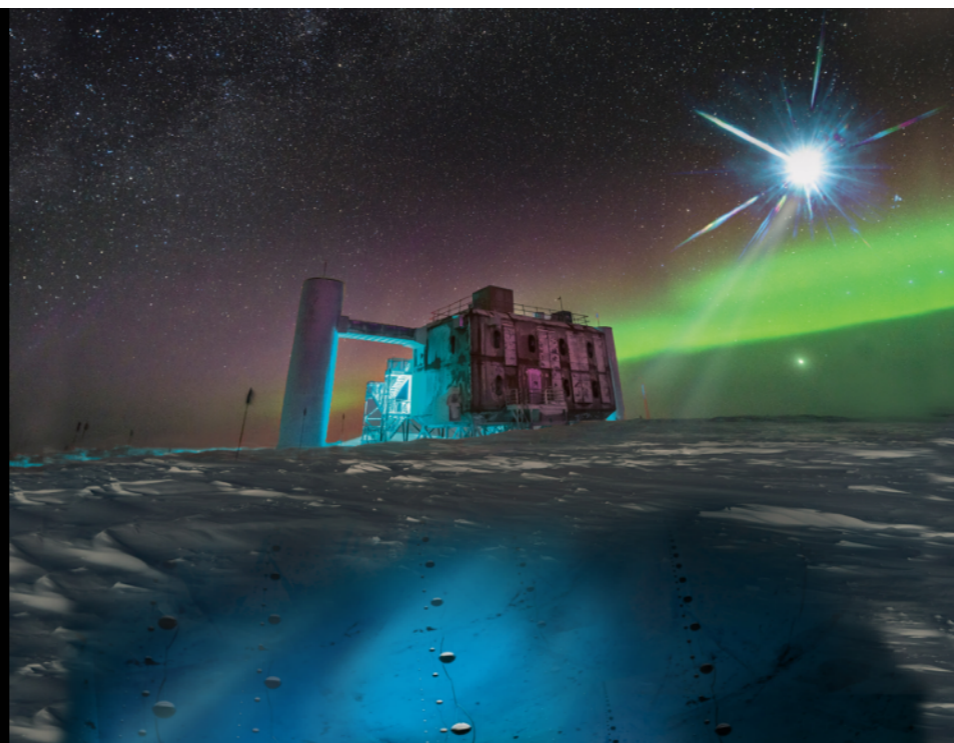
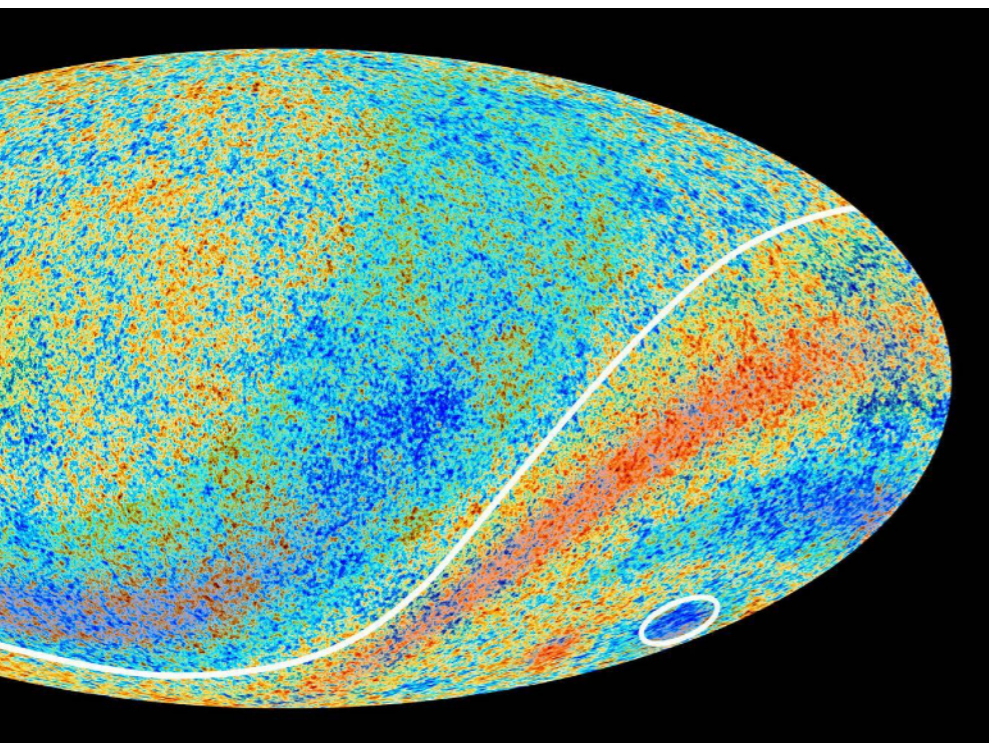
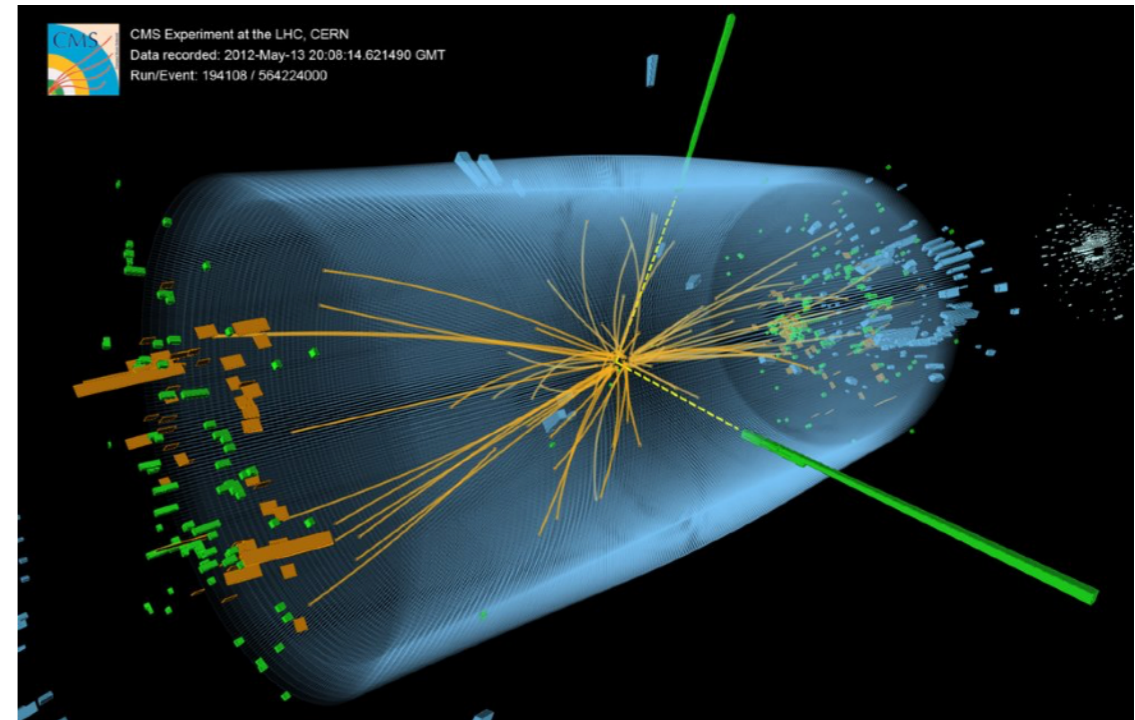
UNIVERSITAT
DE VALÈNCIA



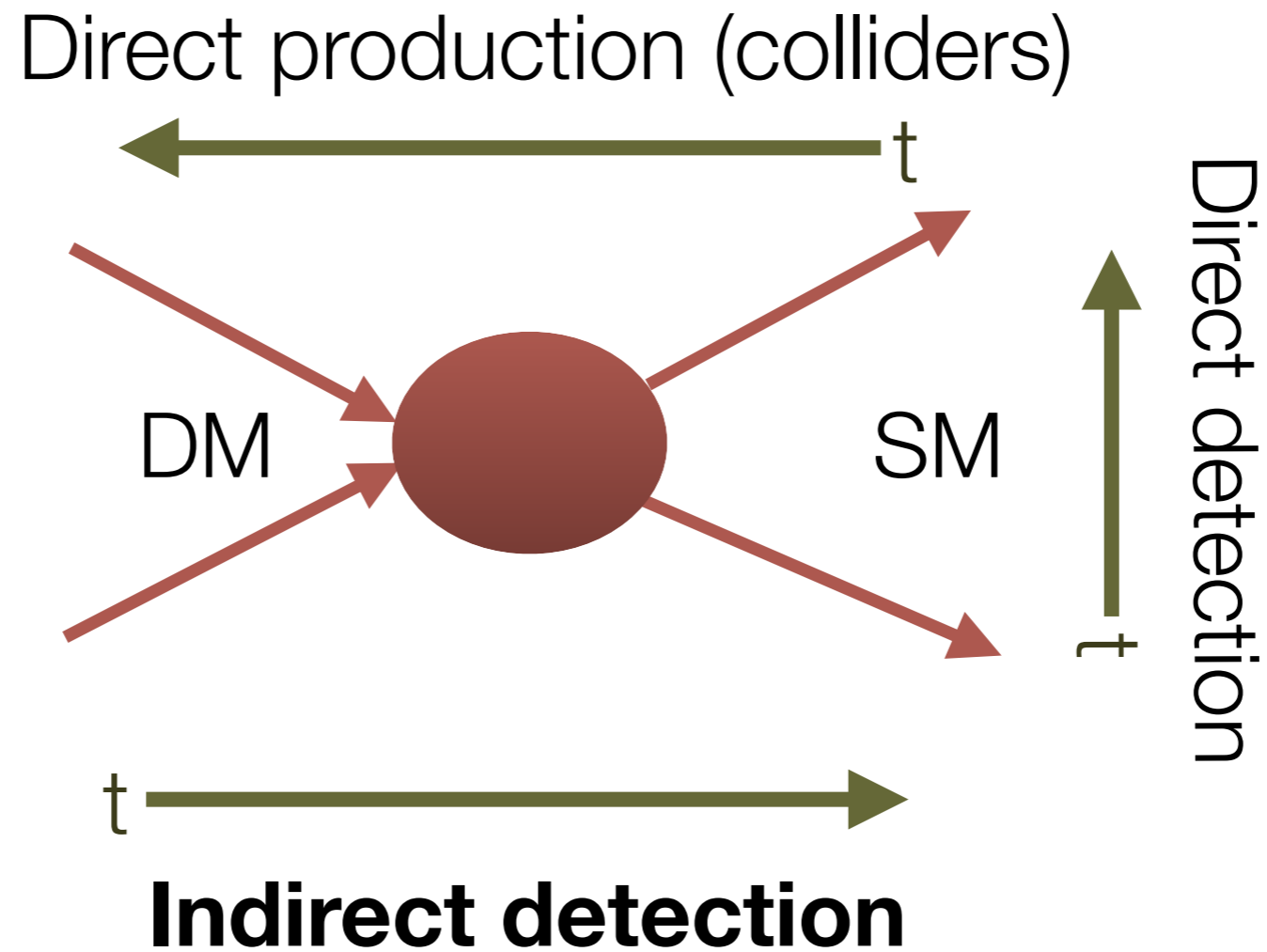
Astroparticle theory

How can we use *all the data* to understand the Universe?

Main tools: high-energy gamma rays
cosmic rays, neutrinos, but also
astronomy & cosmology



Indirect searches of DM



The search for production of Standard Model particles by Dark Matter

Production of SM particles by DM

Channel

Rate

Annihilation

WIMPs

$$\frac{\rho_\chi^2}{m_\chi^2} \langle \sigma v \rangle$$

Decay

sterile neutrinos, WIMPs, axions

$$\frac{\rho_\chi}{m_\chi} \Gamma_\chi$$

Condensation

axions

Oscillation

sterile neutrinos,

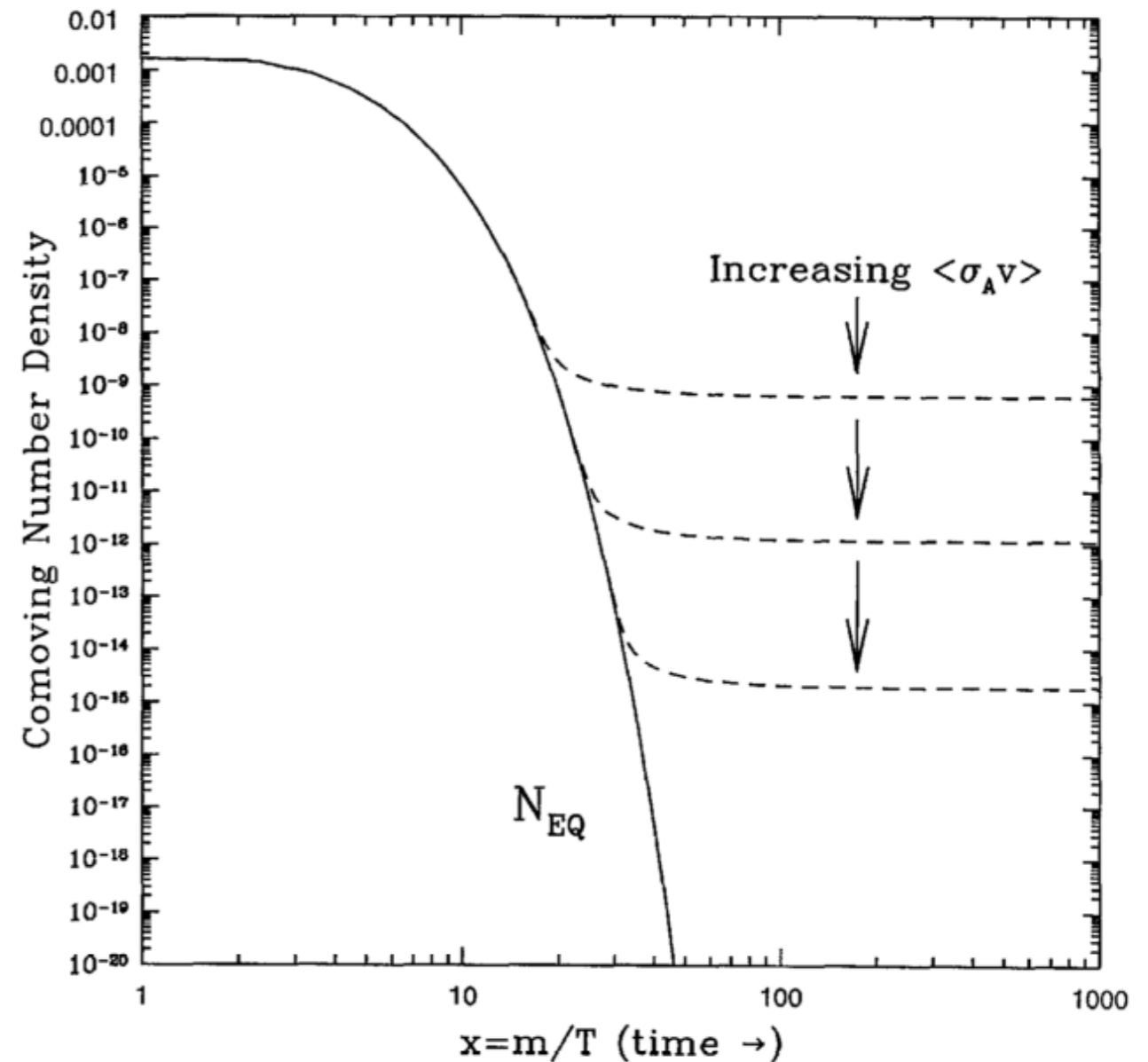
axions

...

Why DM \leftrightarrow SM: the WIMP miracle and all that

$a^3 n_\chi \propto \exp(-m/T)$
 (thermal equilibrium)
 until
 $n_\chi \langle \sigma v \rangle_{\text{ann}} \simeq H$
 \downarrow
 thermal freeze-out
 Ω_χ set by $\langle \sigma v \rangle_{\text{ann}}$

time $\sim 1/T$



$$\Omega_\chi = 0.3 \rightarrow \langle \sigma v \rangle_{\text{ann}} \simeq 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

What is $\langle \sigma v \rangle$?

- Annihilation rate: $N_\chi N_\chi \sigma v$
- N_χ : number of DM particles
- σ : cross section
- v relative velocity — actually follows a distribution $f(v)$, so we need to *average* over all velocities to get the rate:
 $\langle \sigma v \rangle = \int \sigma v f(v) dv$. In most (but not all) particle physics models this (σv) turns out to be constant.
- rate per unit volume = $\rho_\chi^2 \langle \sigma v \rangle / m_\chi^2$

DM annihilation: where do we look?

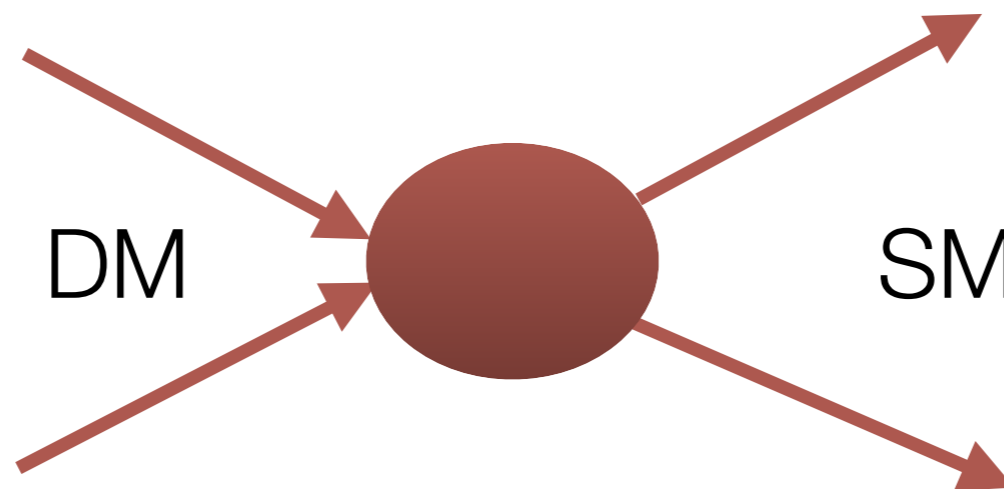
Thermal production
with constant cross-
section



Ongoing self-annihilation
into SM particles as
structure forms

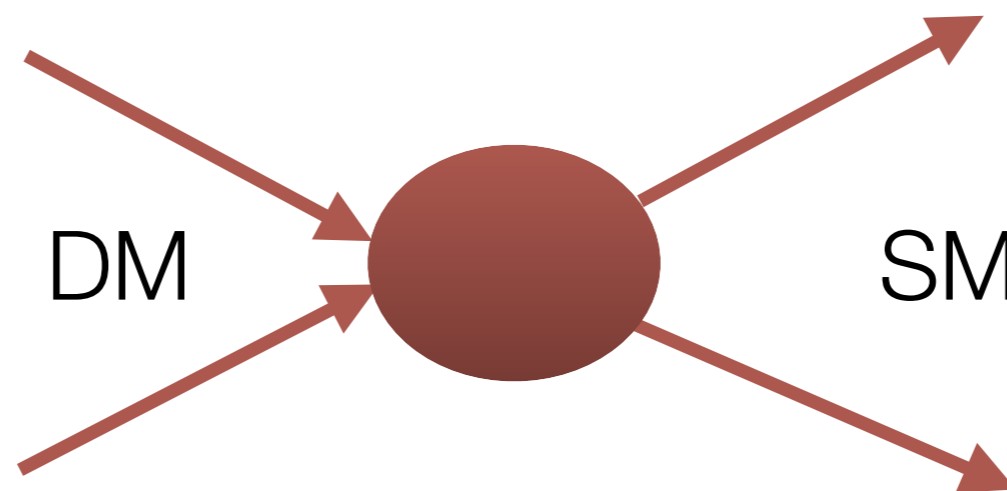
$$\Gamma_{\text{ann}} = n_{\chi}^2 \langle \sigma v \rangle_{\text{ann}}$$

Look where $n_{\chi}^2 \propto \rho_{\chi}^2$ is large



Products to look for in astrophysical signals

- Charged (anti)particles: depend on ISM composition
- Gamma-rays: line of sight; look for large clumps of DM
- Neutrinos: close: Need large flux to detect

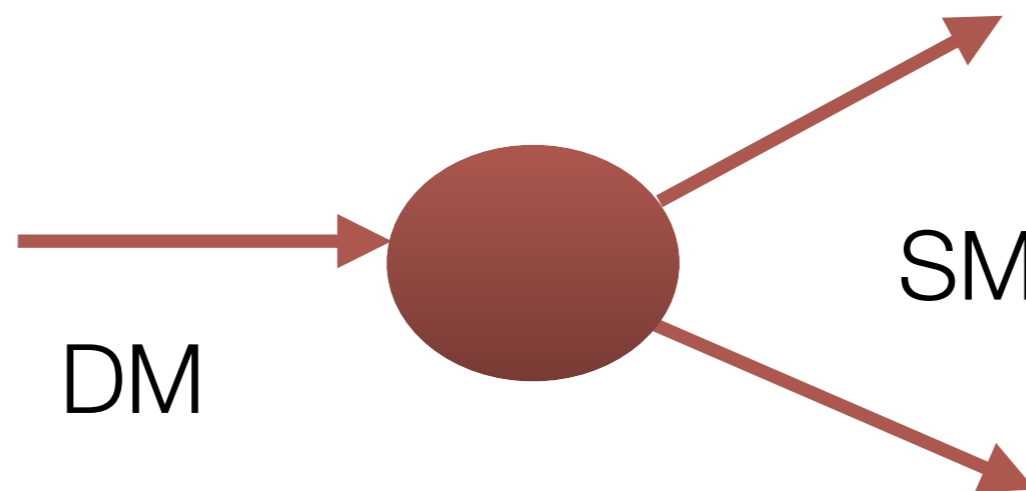


Decays

- Can apply most of these arguments to **decays** and place a constraint on the **lifetime** of DM

- Observable effects for $\tau_\chi \lesssim 10^{25} \text{ s}$

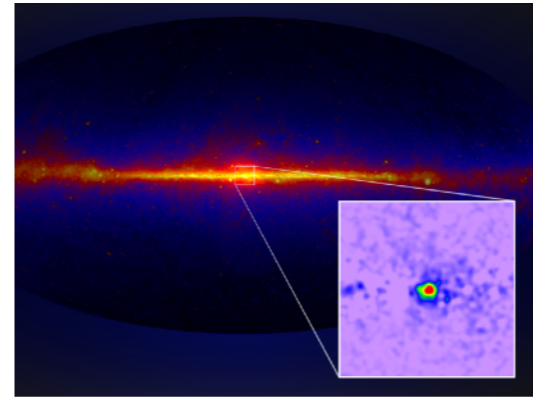
- ~same, but $\phi_{\gamma, e^+, \nu \dots} \sim \frac{n_\chi}{\tau_\chi}$



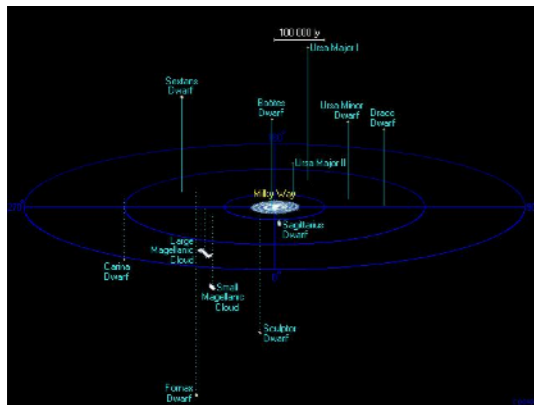
Indirect DM signals: where to look



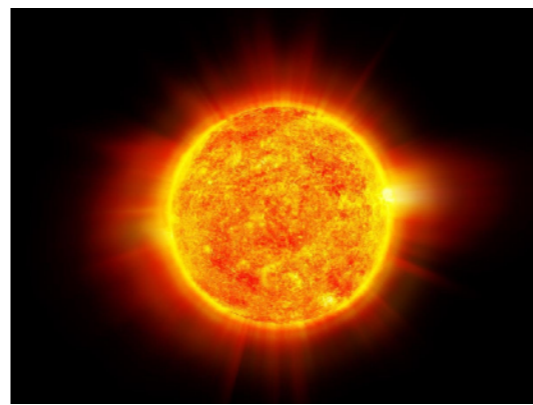
Local
Cosmic
Ray flux



Galactic
center



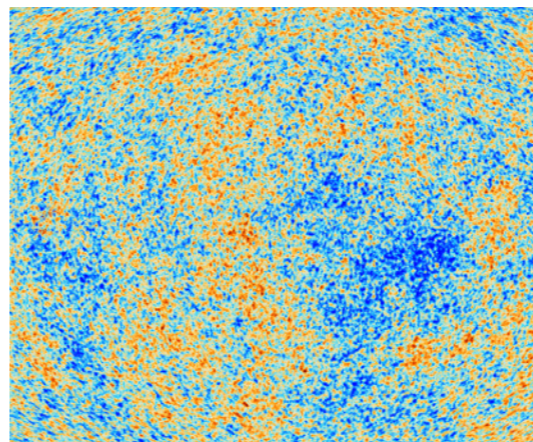
Dwarf
galaxies



Solar
neutrinos

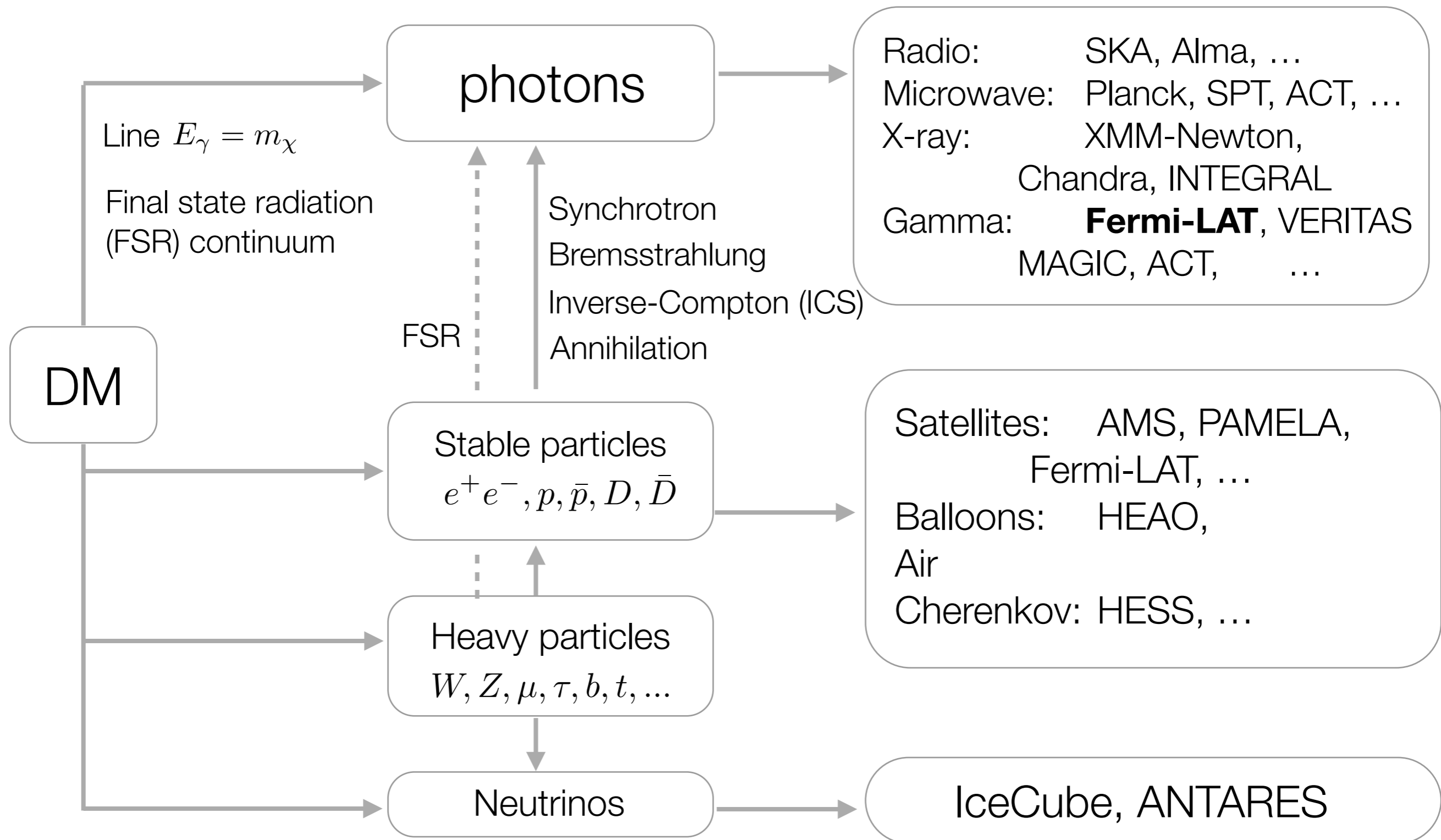


Galaxy
Clusters



CMB +
background
light

Indirect signals: what to look for



Summary



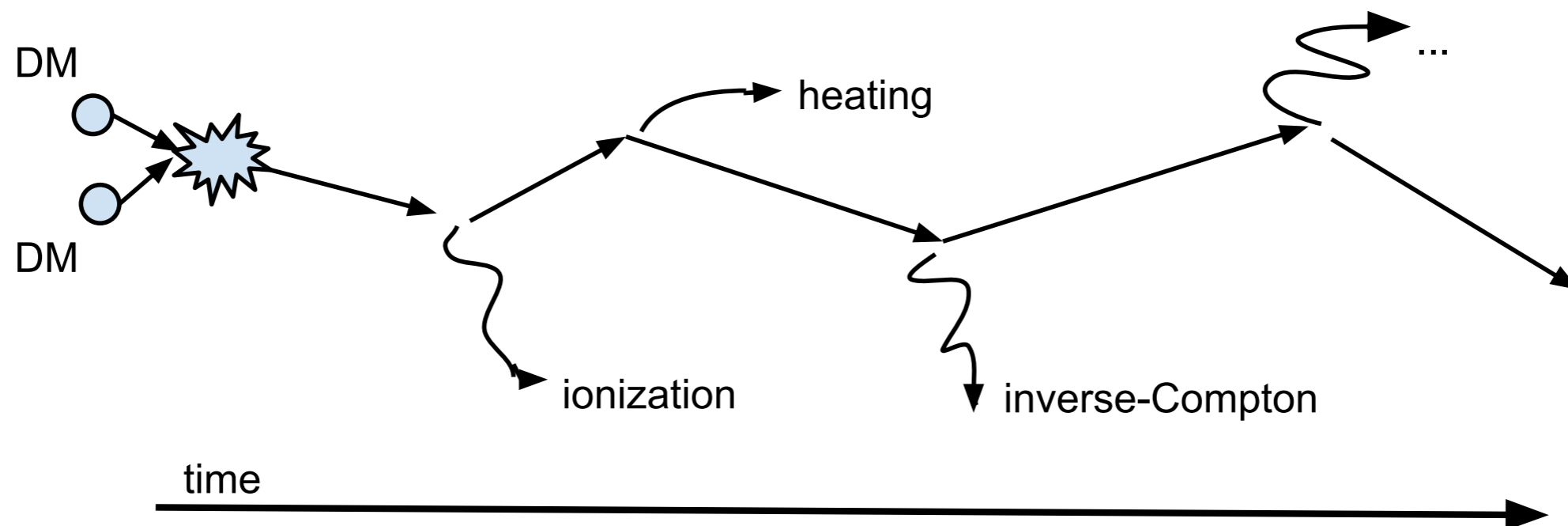
Before Structure: Extragalactic background light

Annihilating DM should yield an isotropic background flux:

$$\frac{dE}{dV dt} \propto n_{\chi}^2(z) m_{\chi} \langle \sigma v \rangle_{ann} = \rho_c^2 \Omega_{0,DM}^2 (1+z)^6 \frac{\langle \sigma v \rangle_{ann}}{m_{\chi}}$$

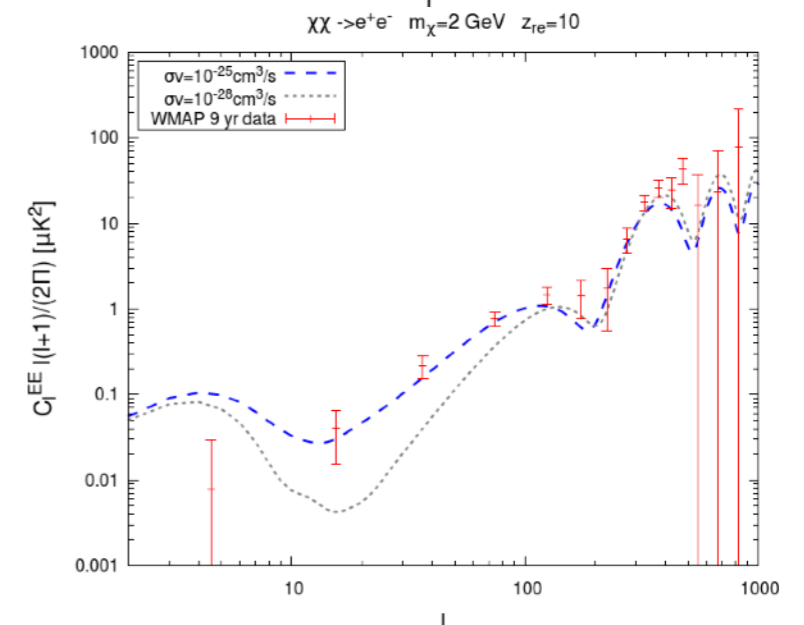
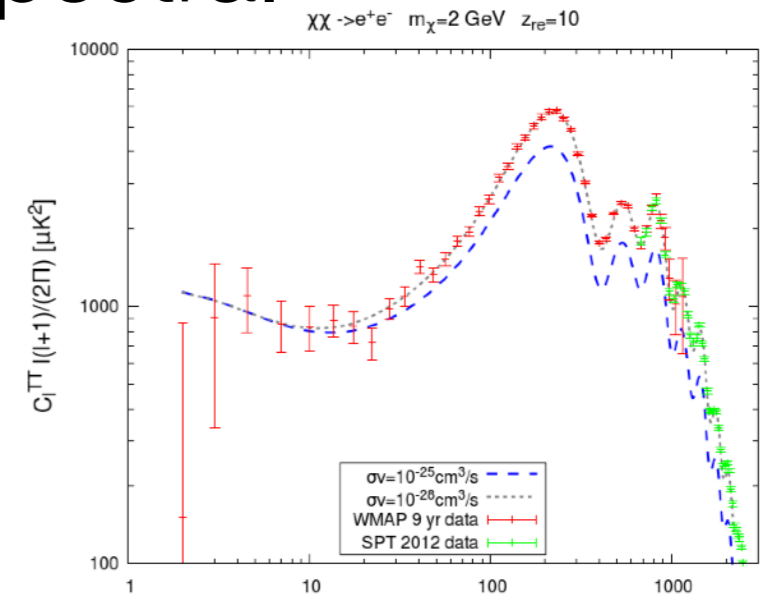
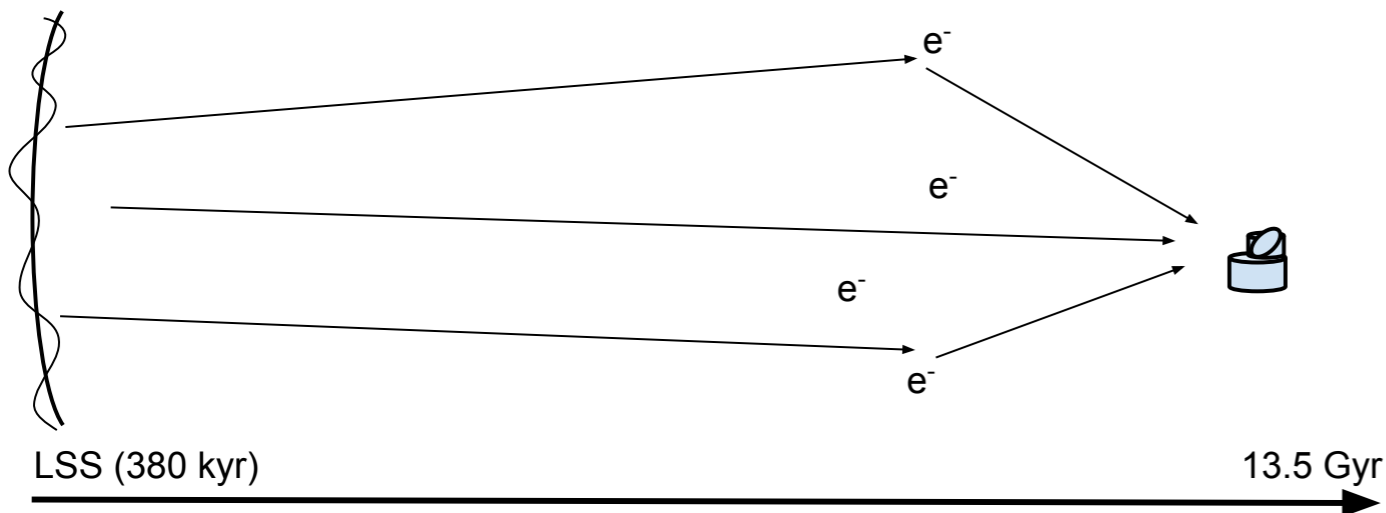
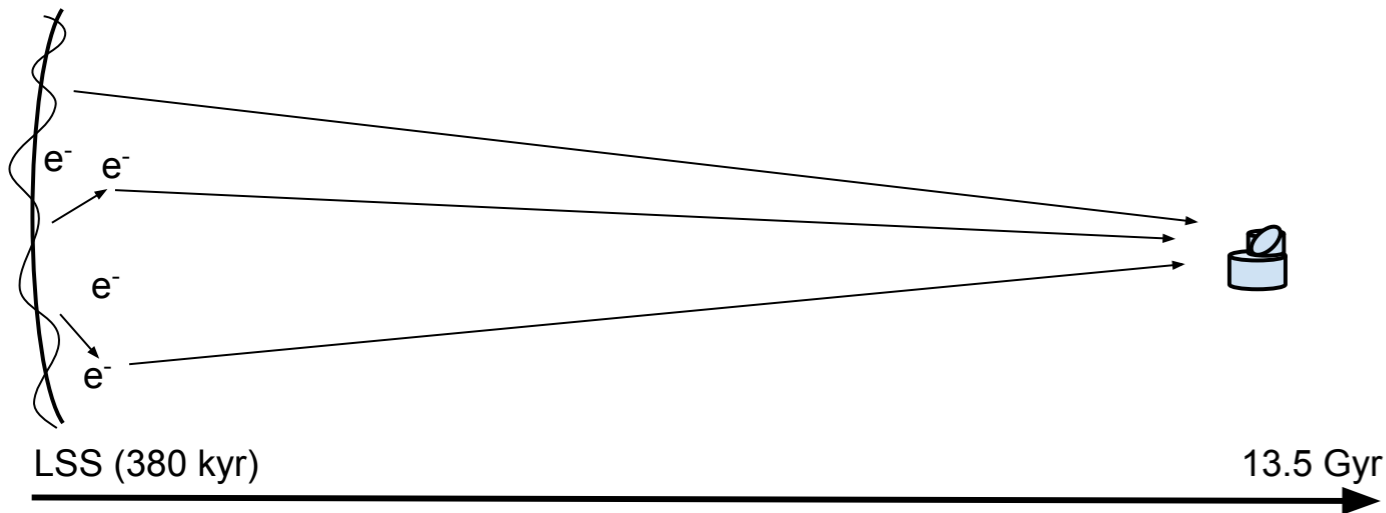
Very faint relative to galactic light -> very difficult to see

Annihilating DM has a more immediate effect on the IGM:



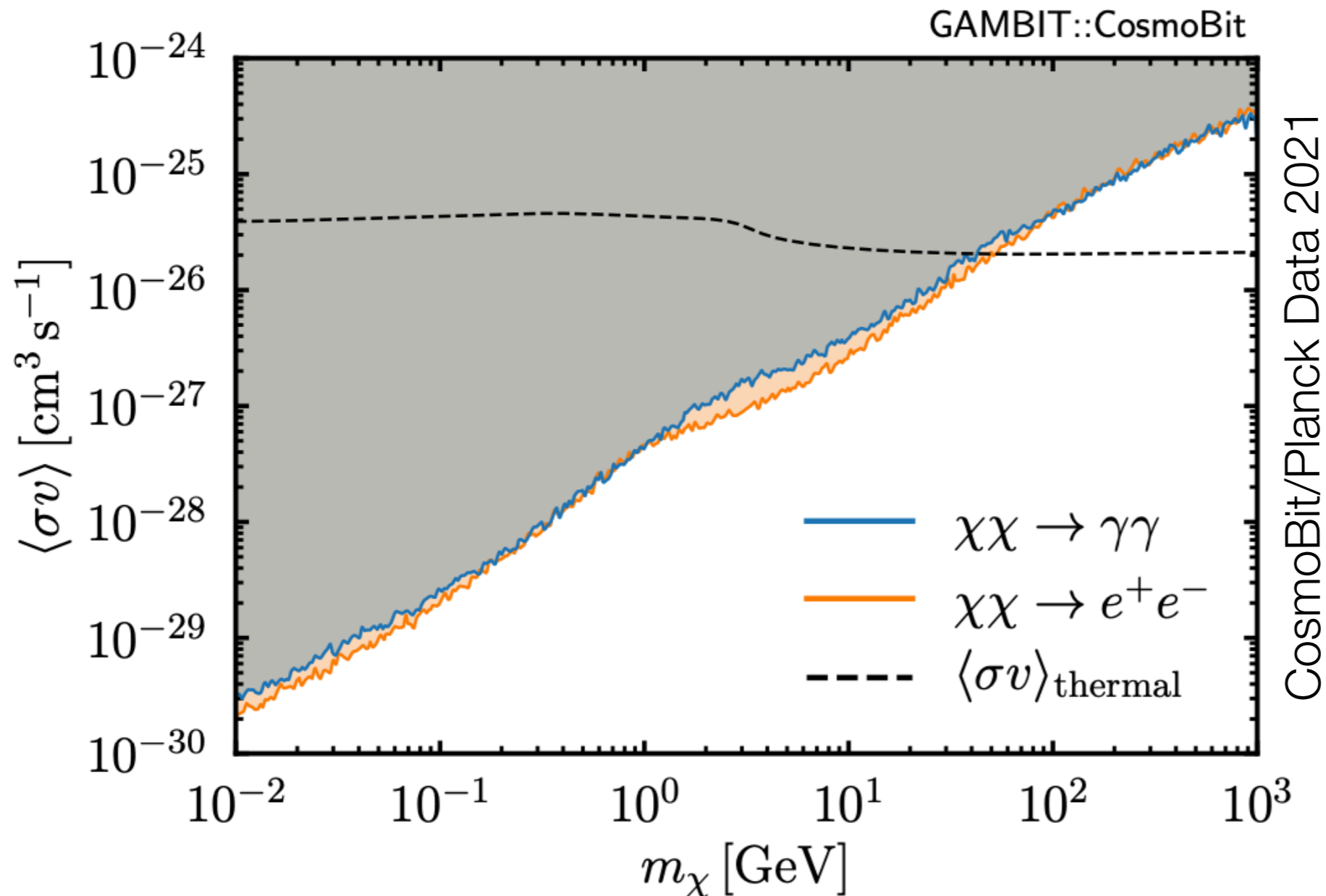
The CMB

Injection of electromagnetic energy causes ionization: the extra free electrons can rescatter CMB photons, yielding a distinctive imprint on the CMB power spectra.

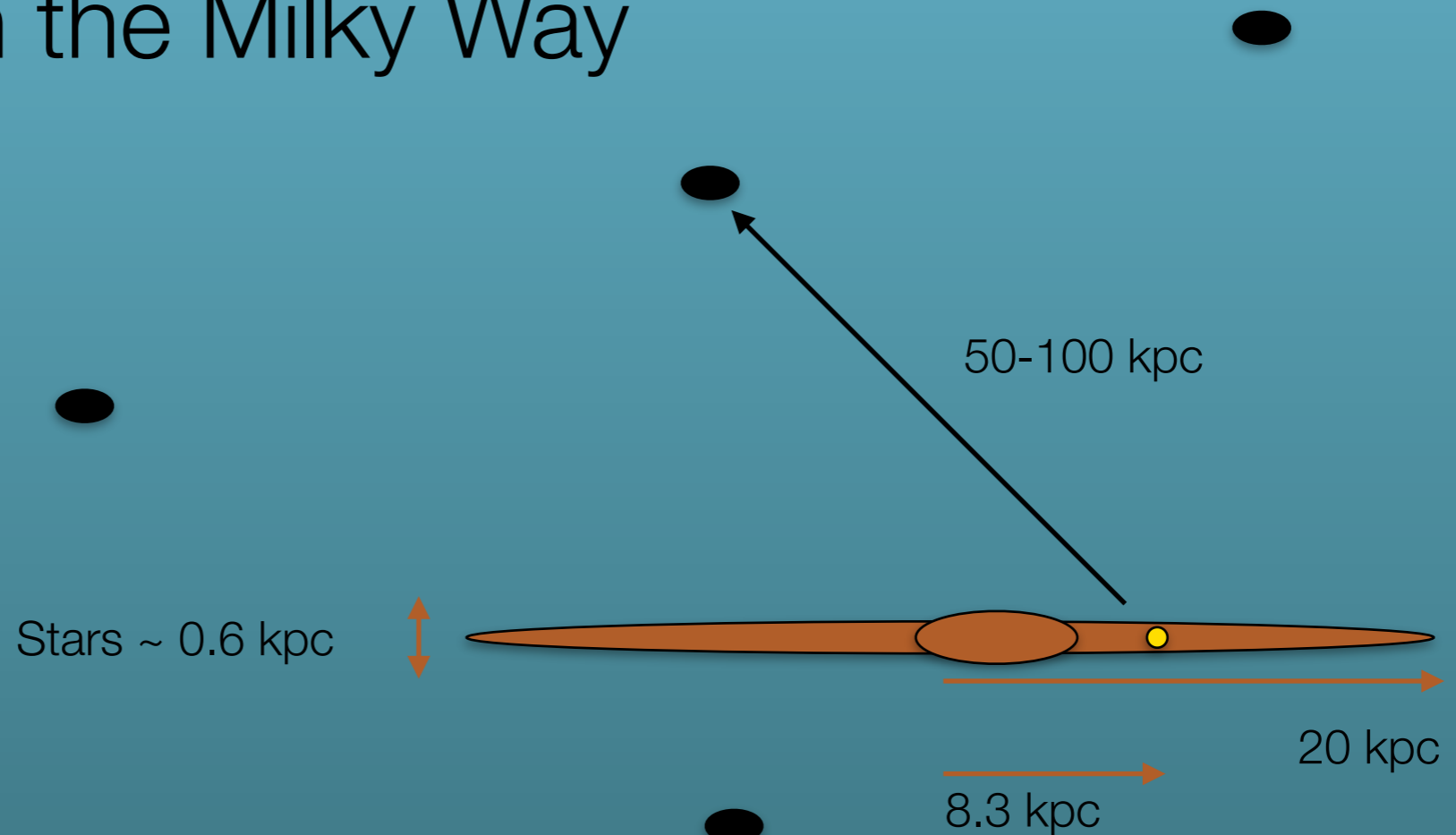


The CMB

$$\frac{dE}{dV dt} \propto n_{\chi}^2(z) m_{\chi} \langle \sigma v \rangle_{ann} = \rho_c^2 \Omega_{0,DM}^2 (1+z)^6 \frac{\langle \sigma v \rangle_{ann}}{m_{\chi}}$$



Dark matter in the Milky Way

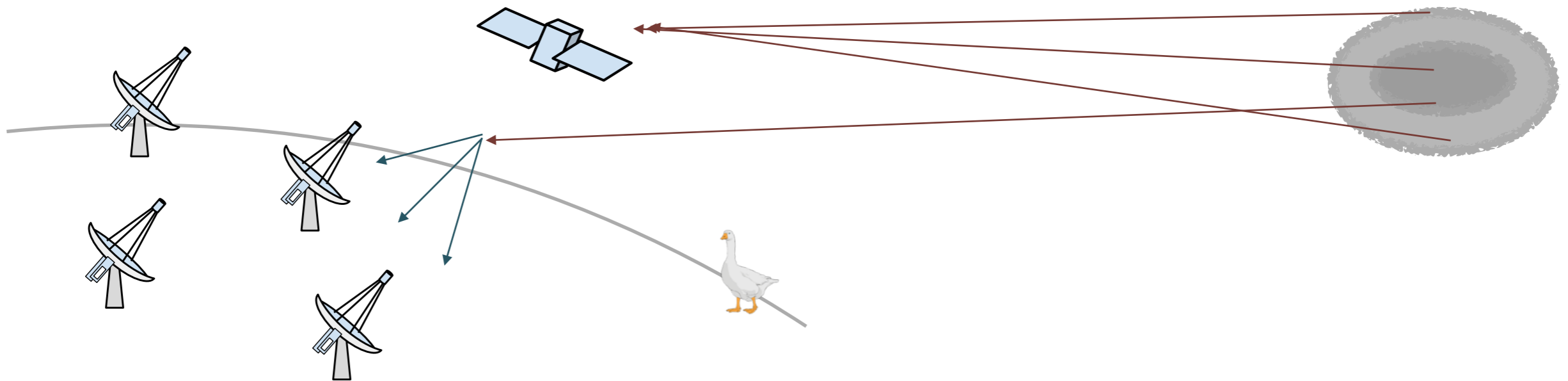


Scales:

- You: 10^{-20} kpc
- Dist. to Sun: 10^{-9} kpc
- Dist. to GC: 8.3 kpc
- Dwarf galaxy: 0.1-1 kpc
- Dist. to dwarf: 50-100 kpc
- Milky Way: ~ 40 kpc
- Cluster: ~ Mpc

Dwarf Satellites and Galaxy Clusters

- Prototypical candidate for DM indirect detection:
 - Few baryons: low background
 - Large DM content \rightarrow large signal.
 - **WIMPs**: GeV-TeV masses: **GeV–TeV gamma rays**



Dwarf Satellites and Galaxy Clusters

$$\text{DM annihilation: } \frac{d\Phi_\gamma}{dE} = \int \int \frac{\langle \sigma v \rangle}{4\pi} \frac{\rho_\chi^2(\ell, \Omega)}{2m_\chi^2} \frac{dN_\gamma}{dE} d\ell d\Omega \equiv \Phi^{PP} J$$

Particle physics content:

$$\Phi^{PP} = \frac{\langle \sigma v \rangle}{4\pi} \frac{1}{2m_\chi^2} \frac{dN_\gamma}{dE}$$

$\langle \sigma v \rangle$ Annihilation cross-section

m_χ DM mass

$\frac{dN_\gamma}{dE}$ Photon spectrum per annihilation

Astrophysical content:

$$J = \int d\Omega \int_{\text{l.o.s.}} d\ell \rho_\chi^2(\ell, \Omega)$$

$\rho_\chi(\vec{r})$ DM density

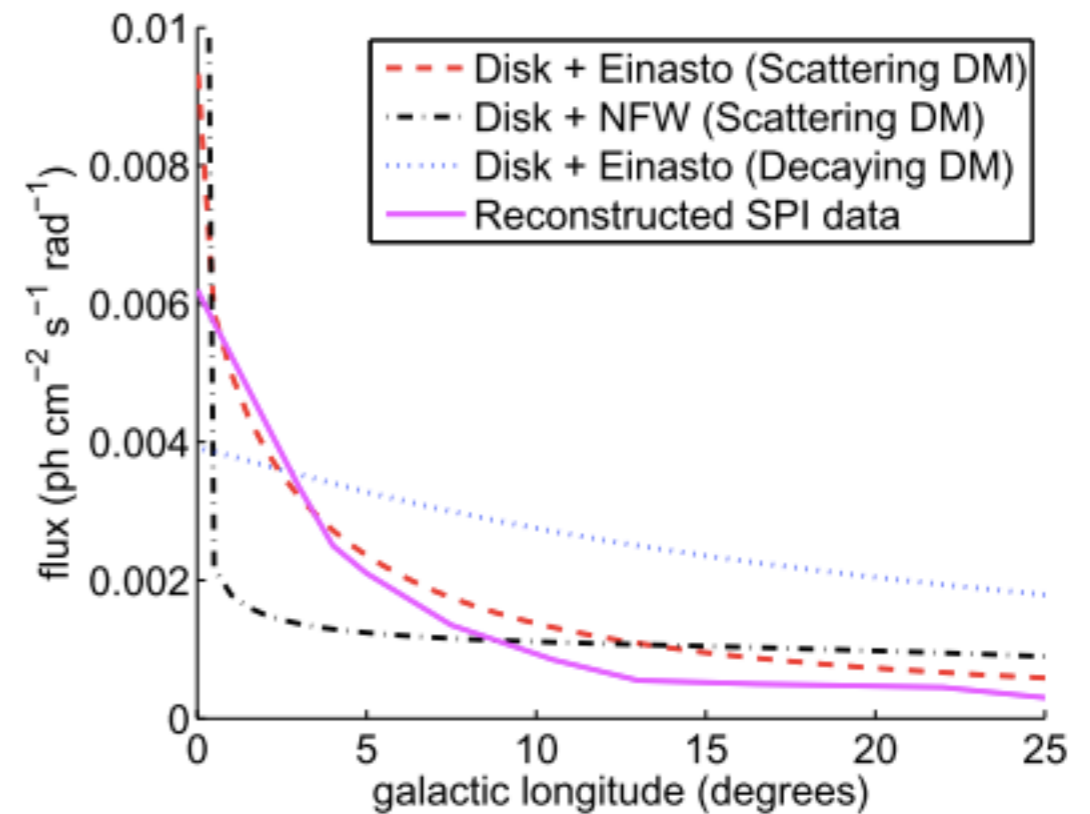
ℓ Distance along line of sight

Ω Solid angle in the sky

Decays

$$\Phi^{PP} \rightarrow \frac{\Gamma_\chi}{4\pi} \frac{1}{m_\chi} \frac{dN_\gamma}{dE}$$

$$J \rightarrow \int d\Omega \int_{\text{l.o.s.}} dl \rho_\chi(l, \Omega)$$



Significant change in the angular profile

Particle physics content

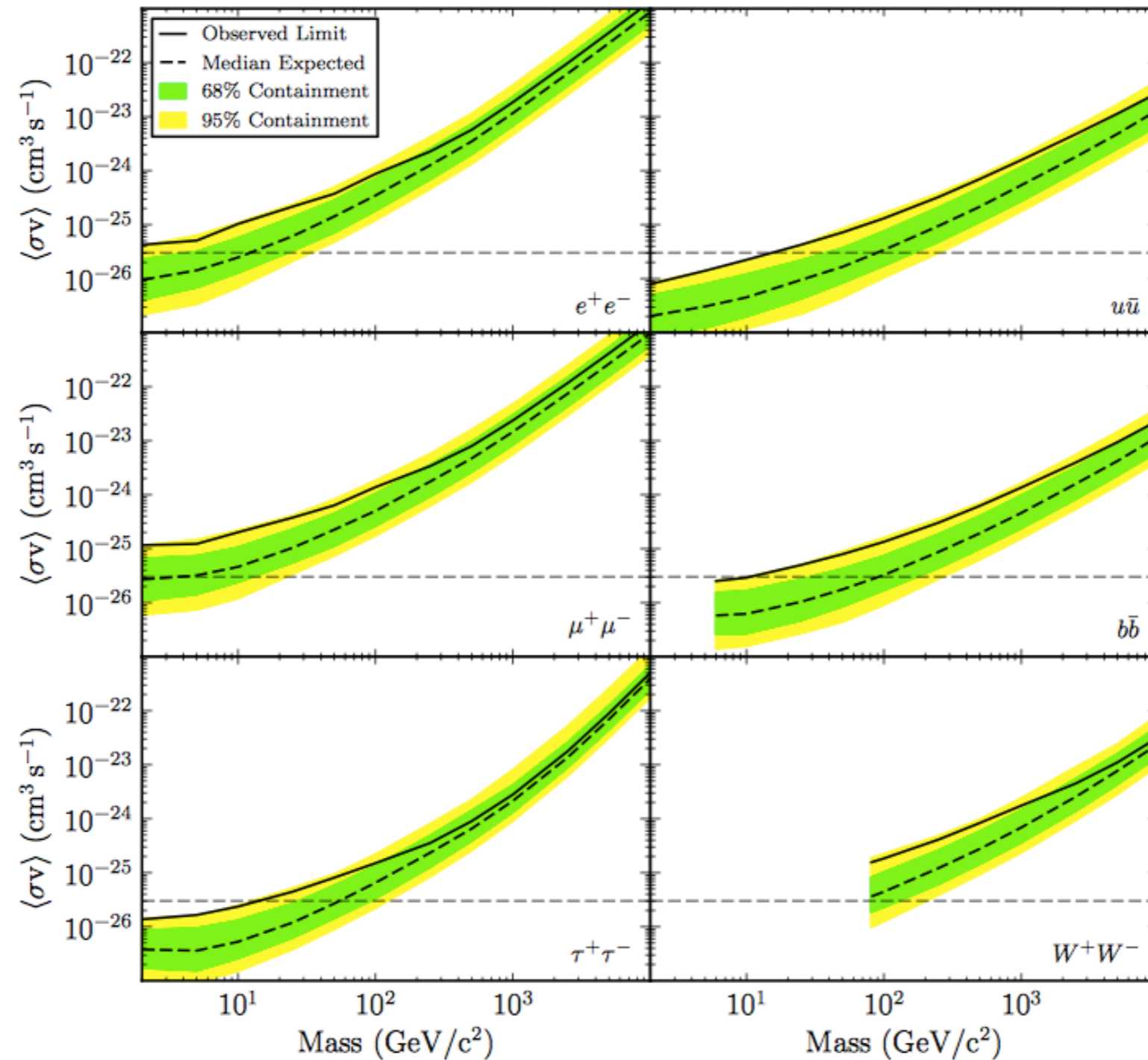
$\langle\sigma v\rangle$ Constrained by cosmological abundance in the case of a WIMP

Γ Lifetime must be larger than age of Universe

$\frac{dN_\gamma}{dE}$ Spectrum from each channel you are considering (e.g. W^+W^- , bb , etc)
Compute with event generator like Pythia or use tabulated spectra (see for example <http://www.marcocirelli.net/PPPC4DMID.html>)

Constrain annihilation rate into specific channel or full model prediction

Fermi Constraints from 25 Dwarf Galaxies

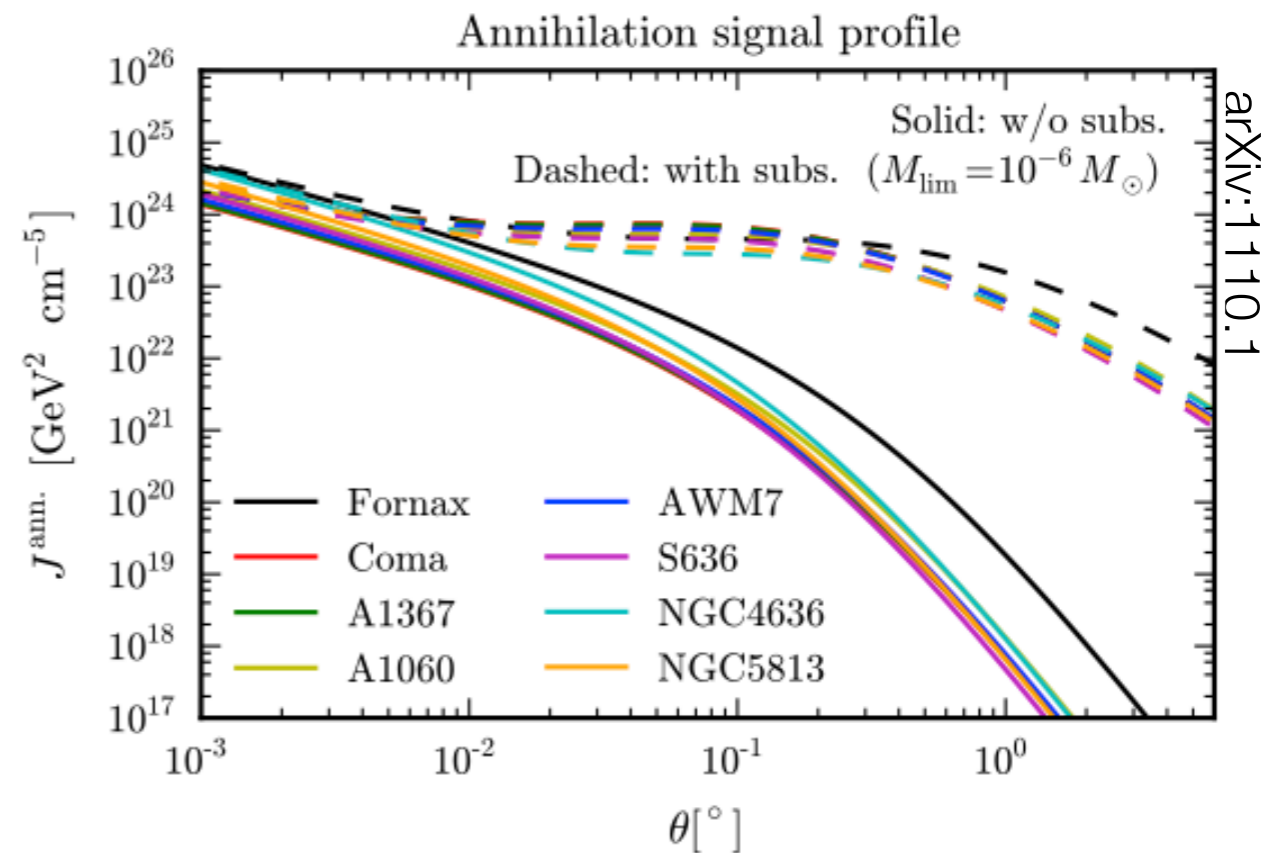
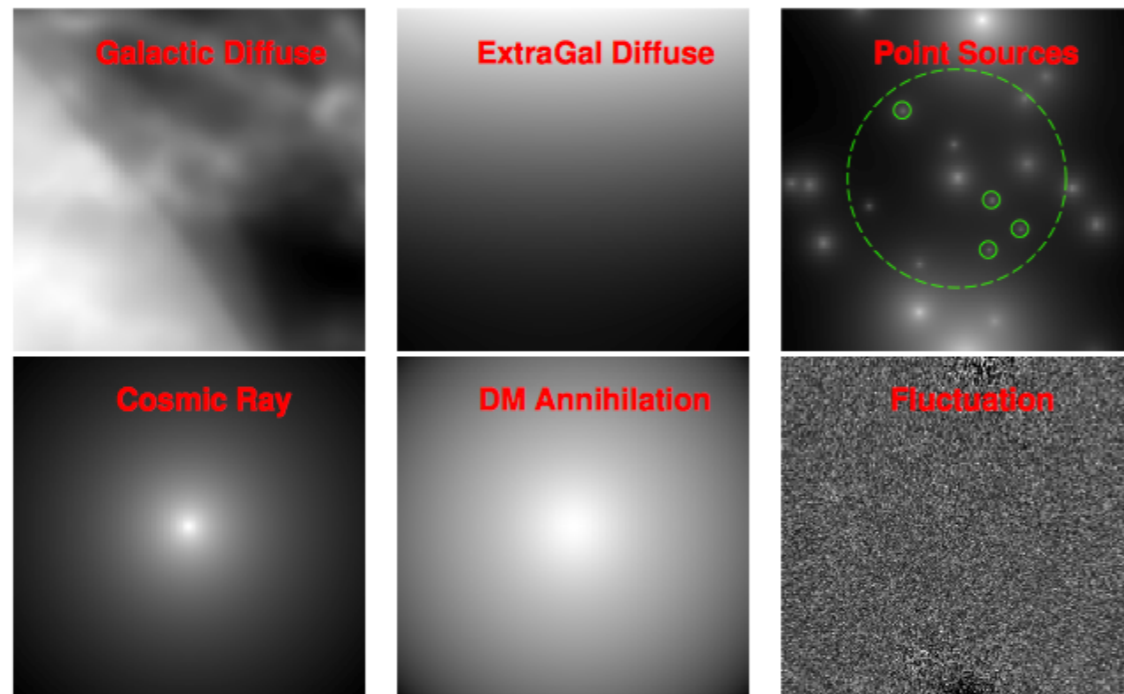


Galaxy clusters

Procedure (and formulae) essentially unchanged, except

-**Backgrounds** can be trickier;

-**Substructure** greatly modifies the profiles:

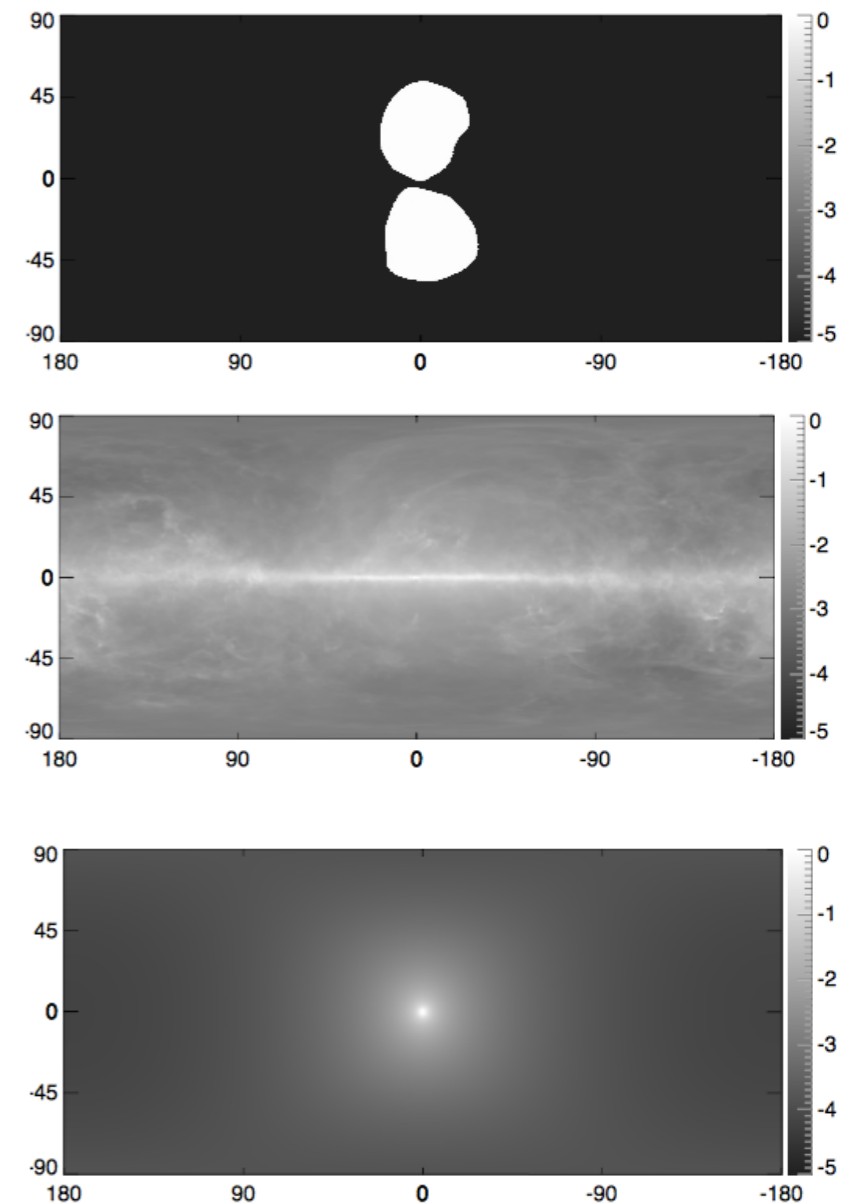


[arXiv:1110.1529](https://arxiv.org/abs/1110.1529)

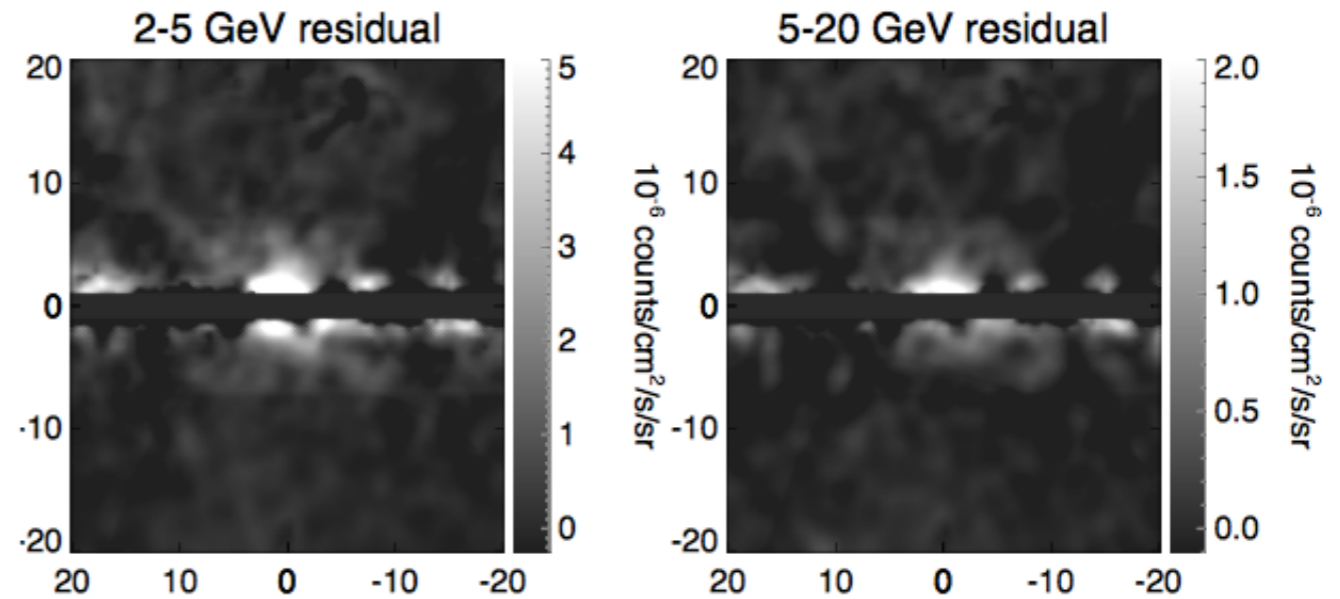
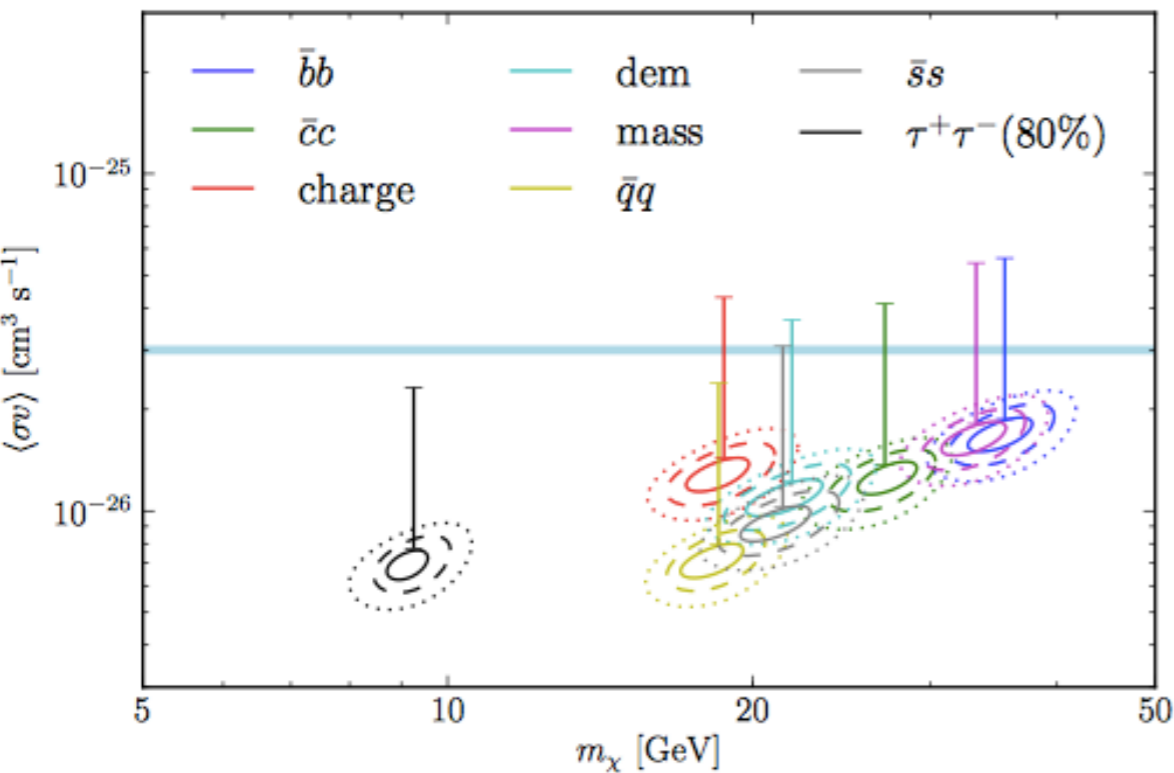
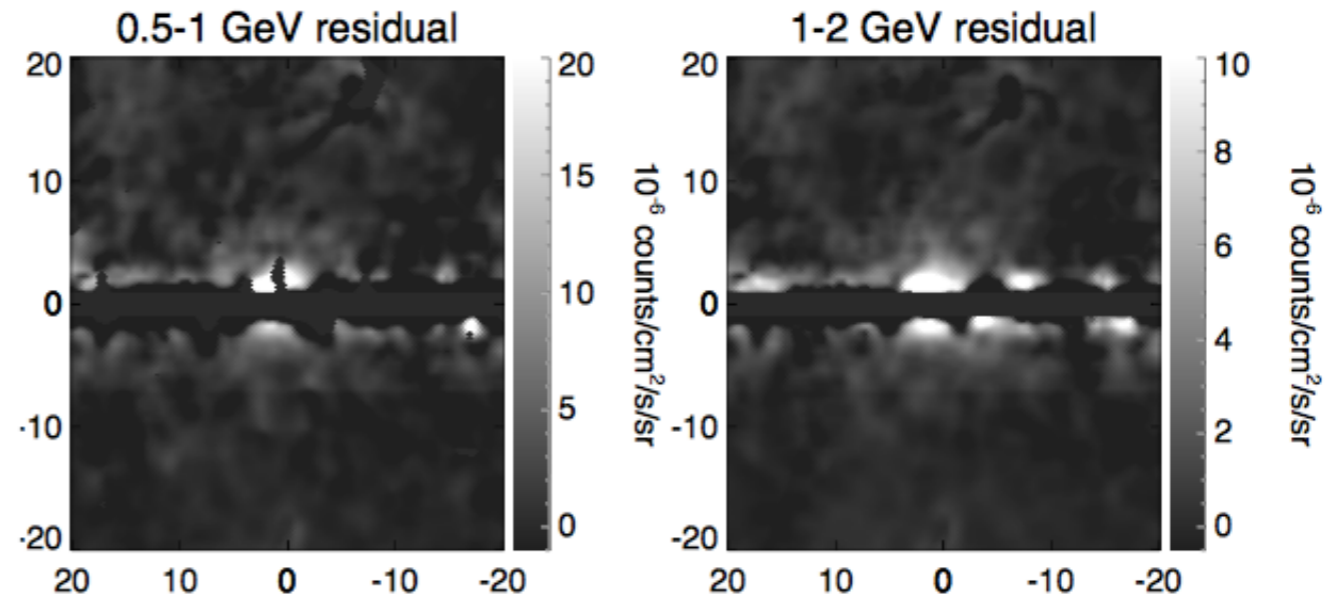
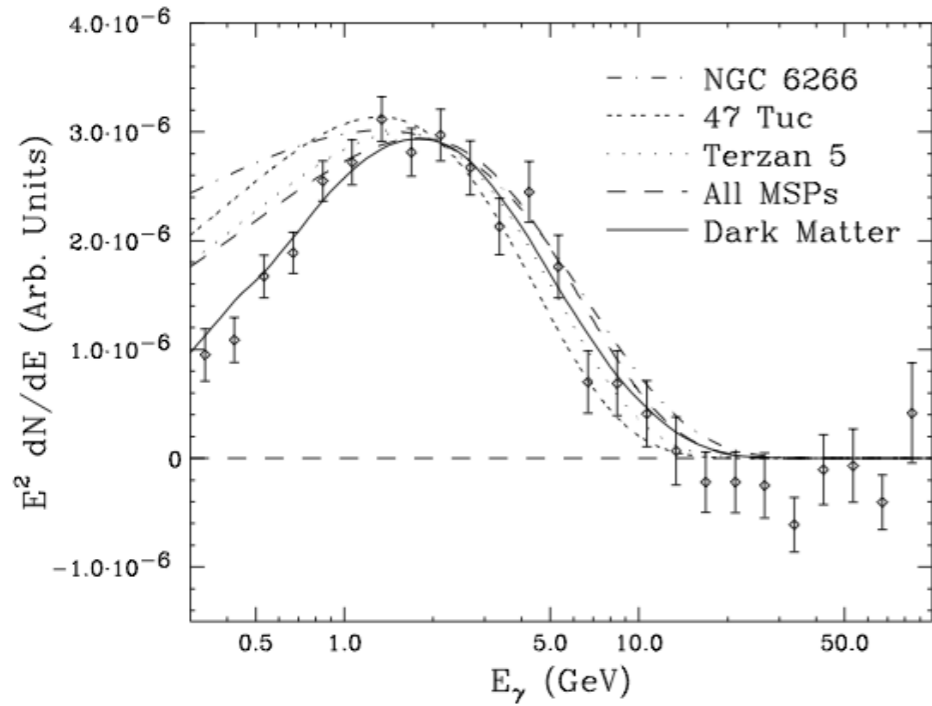
[arXiv:1207.6749](https://arxiv.org/abs/1207.6749)

The Galactic Centre

- Very large concentration of DM, and thus of DM annihilation products, but
- A **lot** of background
 - 1) Remove point sources e.g. with fermi-lat point source catalogue
 - 2) Create (or download) template for diffuse background (shape and spectra), structures, Fermi bubbles
 - 3) Create template for DM model (shape and spectra)
 - 4) Vary simultaneously to obtain fit

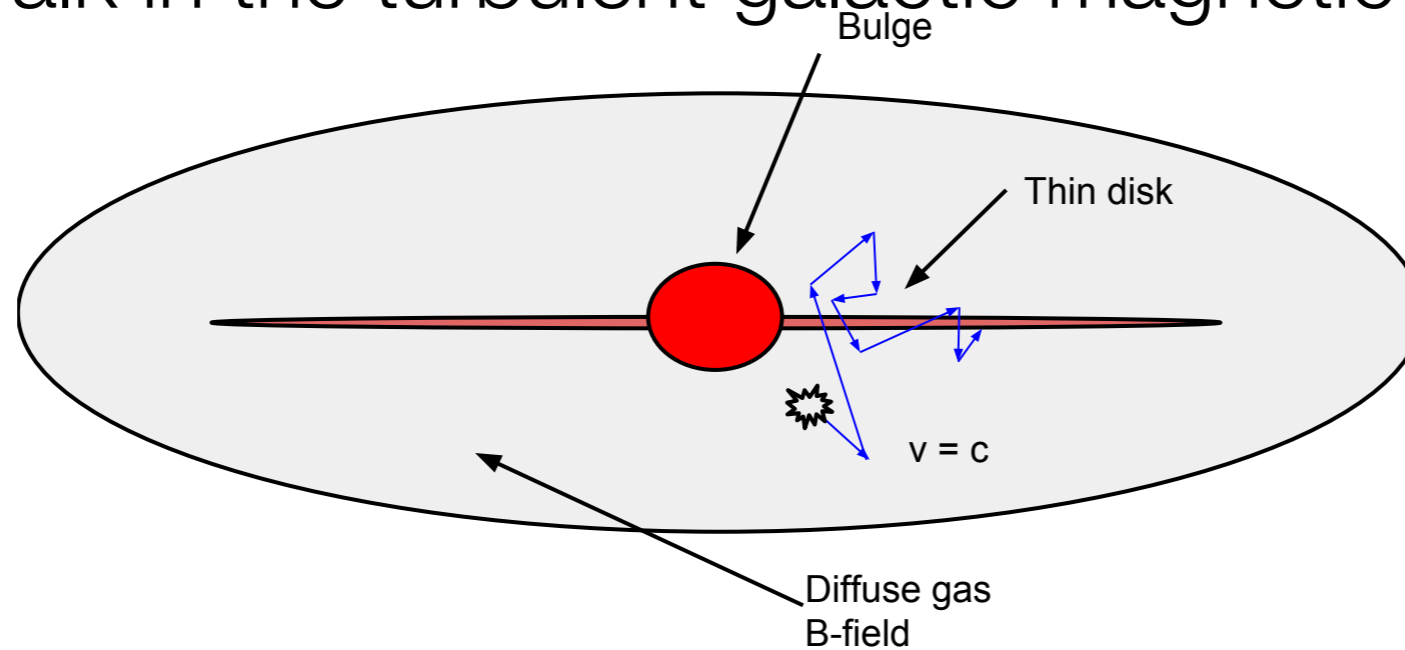


The Galactic Centre excess



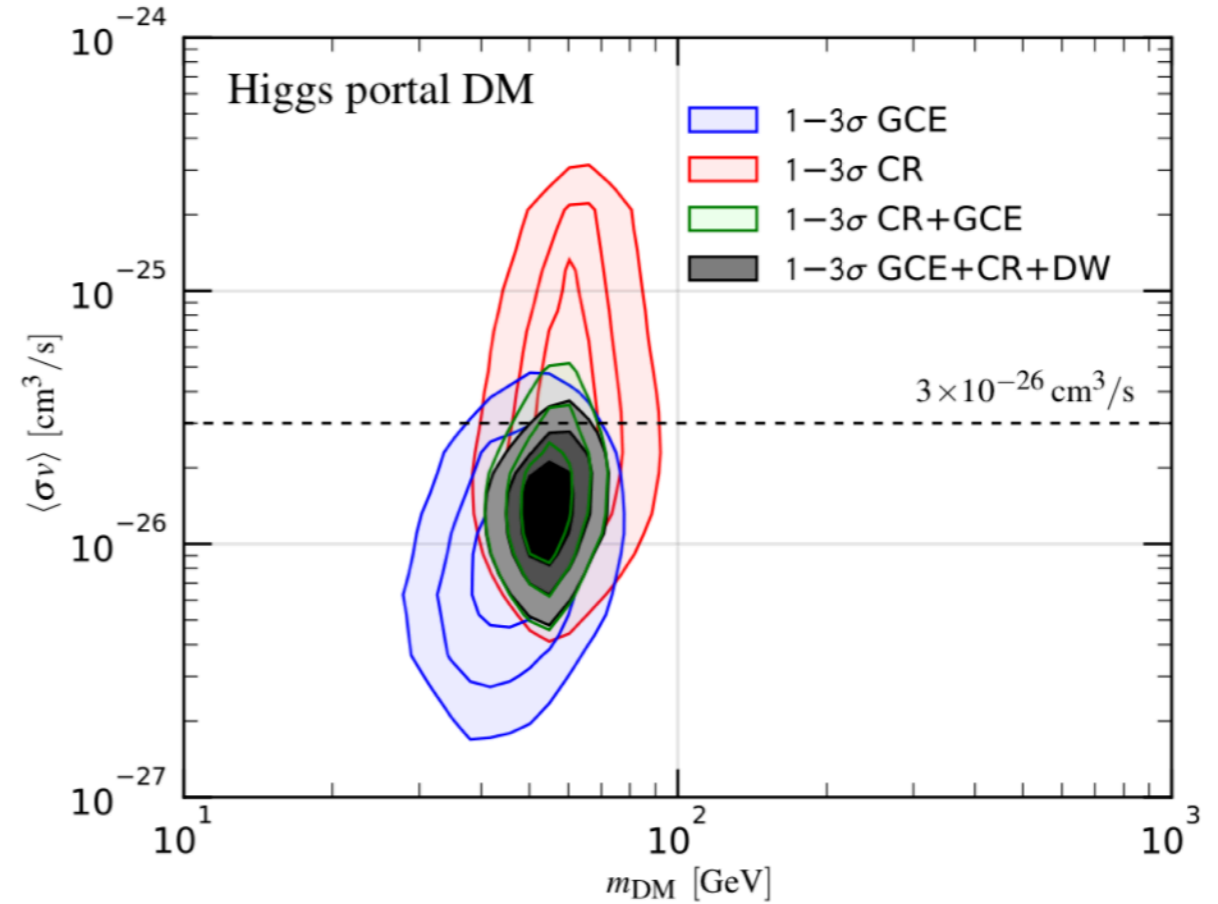
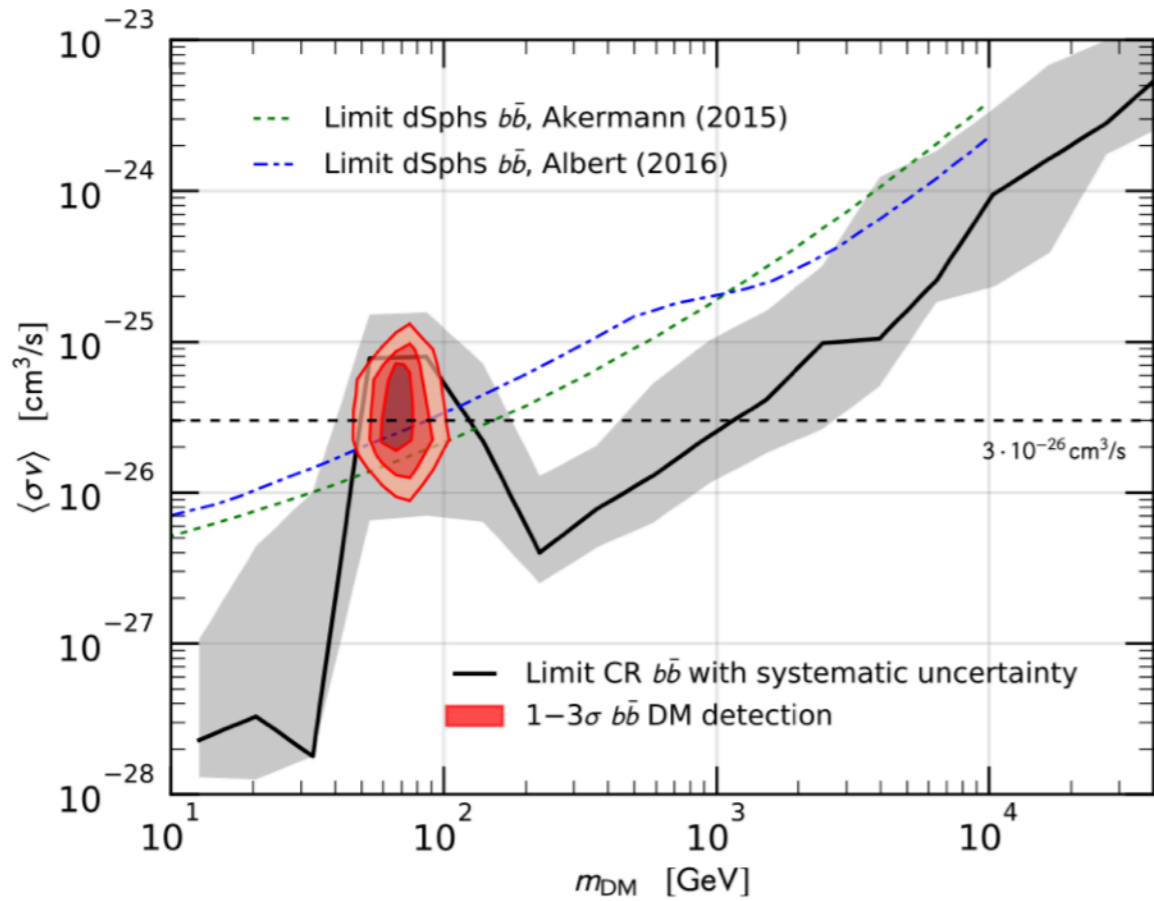
Cosmic Rays

Charged cosmic rays don't travel in a straight line: they diffuse in a random walk in the turbulent galactic magnetic fields.



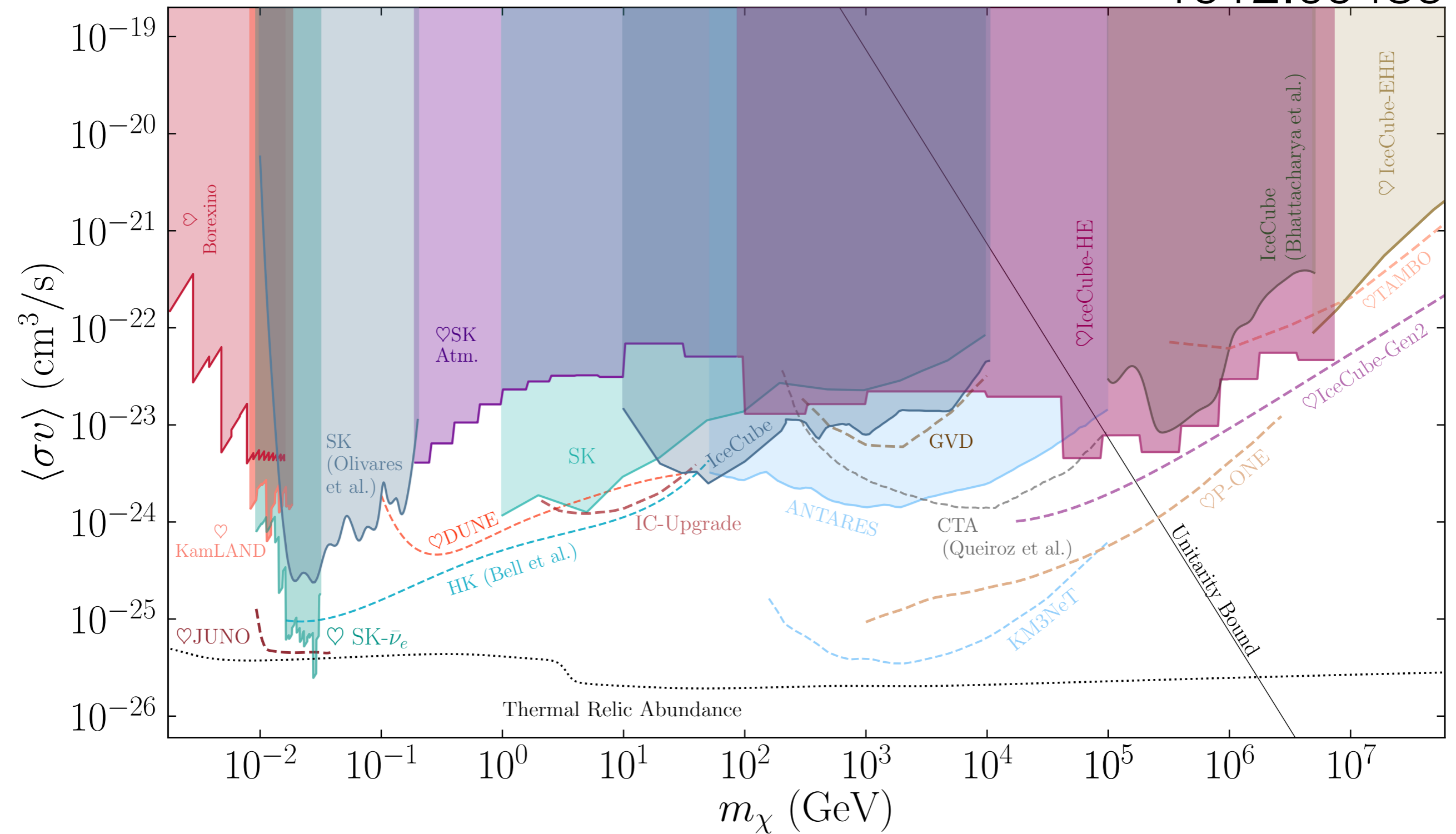
$$\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi$$
$$- \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi ,$$

Cosmic Rays: excess in antiprotons?

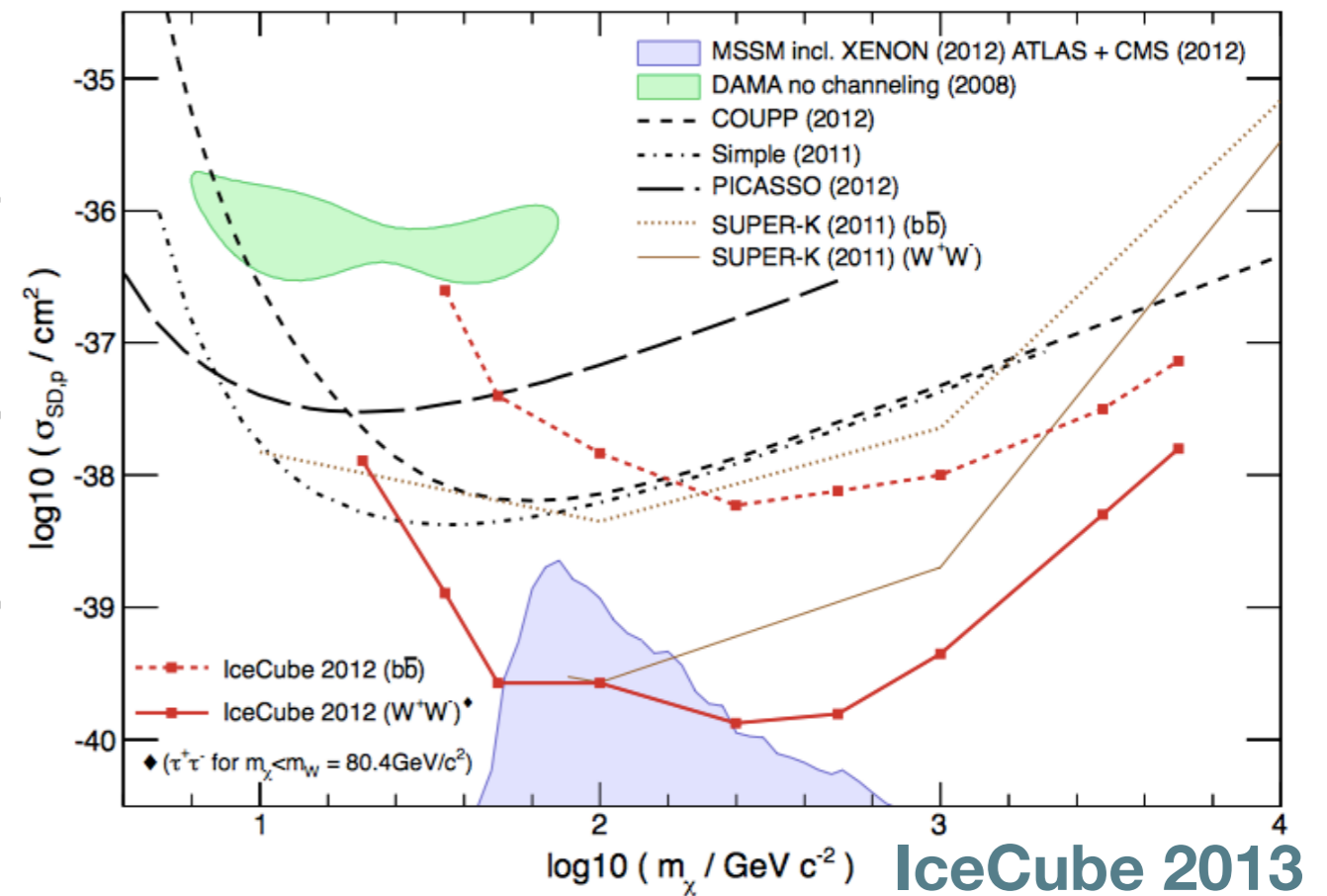
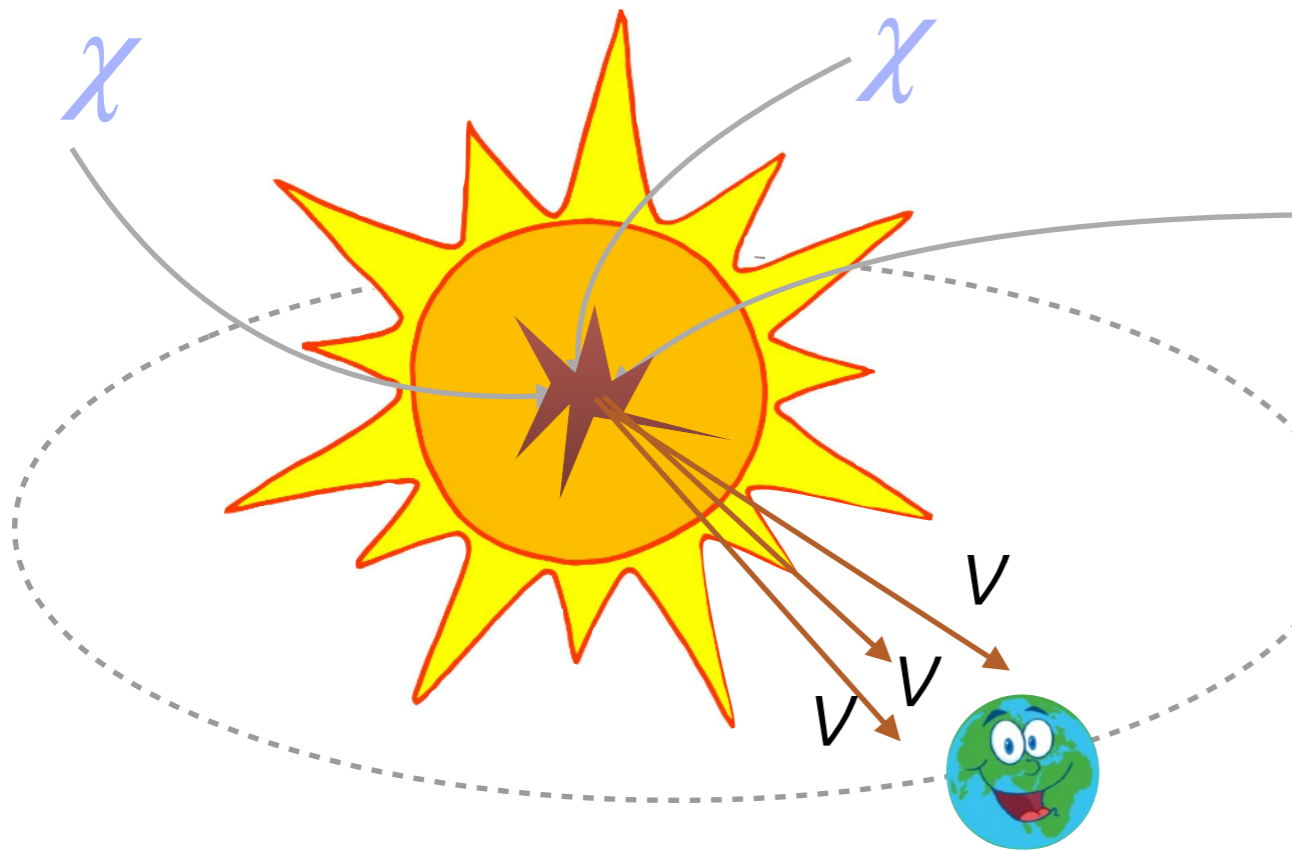


Neutrinos from the galactic centre and other galaxies

1912.09486



Neutrinos from the Sun



Channel- and **model-dependent:** elastic scattering cross-section and branching to neutrinos enter

Must include **propagation** properly

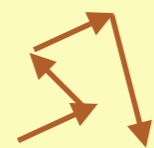
Competitive with other DM detection experiments

DM in the Sun: Other cool effects

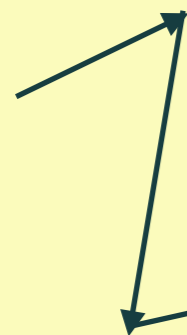
Energy transport

If the self-annihilation is suppressed enough (e.g. in as in **asymmetric DM**), the “cloud” of DM accumulated in the solar core can transport kinetic energy outwards:

Core



nucleus mean free path $\lambda_{\text{nuc}} \ll r_{\text{core}}$



DM mean free path $\lambda_{\chi} \gg \lambda_{\text{nuc}}$

DM in the sun: observable effects

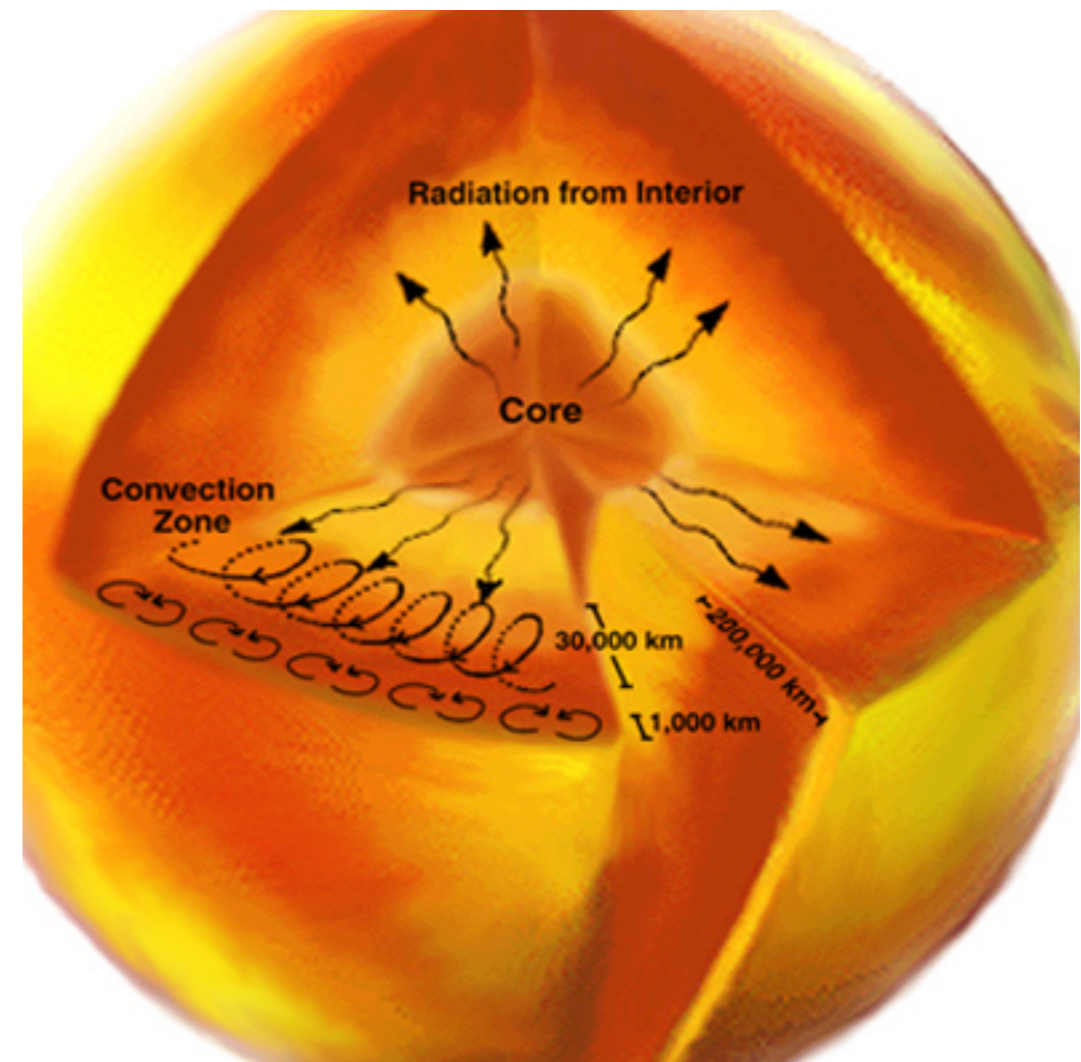
Energy transport

Heat transport away from the core — effects:

Change in temperature
visible with ^8B **neutrinos**

$$\phi_{\nu, ^8\text{B}} \propto T_c^\beta; \beta \sim 20 - 25 !!$$

Change in structure
sound speed and
height of the convective
zone can be inferred
from **helioseismology**



Some Current Indirect Hints of Dark Matter

Usually Called	What is it	DM explanation	Most cited alternative	Is it DM?
511 keV line	Spherically symmetric e+e- annihilation signal from the galactic centre. First seen 40 years ago , most recently by INTEGRAL/SPI	Annihilating light DM ($m < 3$ MeV) or XDM	Pulsars, quasars, low-mass x-ray binaries, black hole, ...	Maybe The shape is right, and nothing else really works
PAMELA/ AMS excess	Excess in local positron fraction ($e^+/e^+ + e^-$) above 100 GeV.	Annihilating heavy ($> \text{TeV}$) “leptophilic” WIMP	Nearby pulsar?	No (ruled out by gamma rays + Planck)
135 GeV line	Gamma ray line at 135 GeV seen in Fermi-LAT data near the galactic centre.	Annihilating WIMP	Systematic error in LAT (also seen when pointing at sun & Earth)	No
3.5 keV line	X-ray line seen in galaxy clusters Perseus and in Andromeda.	Decaying 7 keV sterile neutrino or XDM	Potassium XII, or some highly ionized atom	Maybe Requires nonstandard production

Some Current Indirect Hints of Dark Matter

Usually Called	What is it	DM explanation	Most cited alternative	Is it DM?
Solar Composition problem	10 sigma discrepancy between models of the solar interior and observations	Asymmetric DM transporting energy from the core	Complicated plasma physics, abundances, ...	Maybe
ARCADE excess	Strangely isotropic radio signal below 10 GHz, consistent with extragalactic synchrotron	DM decay to e+e- at $z > 5$??	Maybe
Galactic Centre GeV excess	Continuum excess between 1 and 10 GeV	Annihilating 10-50 GeV WIMP	MS pulsars, problem with CR/ISRF templates?	Maybe
Antiproton excess	Slight bump around 10 GeV	Annihilating 10-50 GeV WIMP	Uncertainties in propagation/cross sections	Maybe

Conclusions

- Many different places to look. Some I didn't mention:
 - Imprints on the matter power spectrum, pre-recombination effects on CMB
 - Self-interaction, e.g. bullet cluster
 - “boosted” DM from interaction with cosmic rays, the Sun
- Many constraints, many hints
- Interplay with direct searches, collider data
- Future: incorporating everything: global searches?