Indirect detection of Dark Matter

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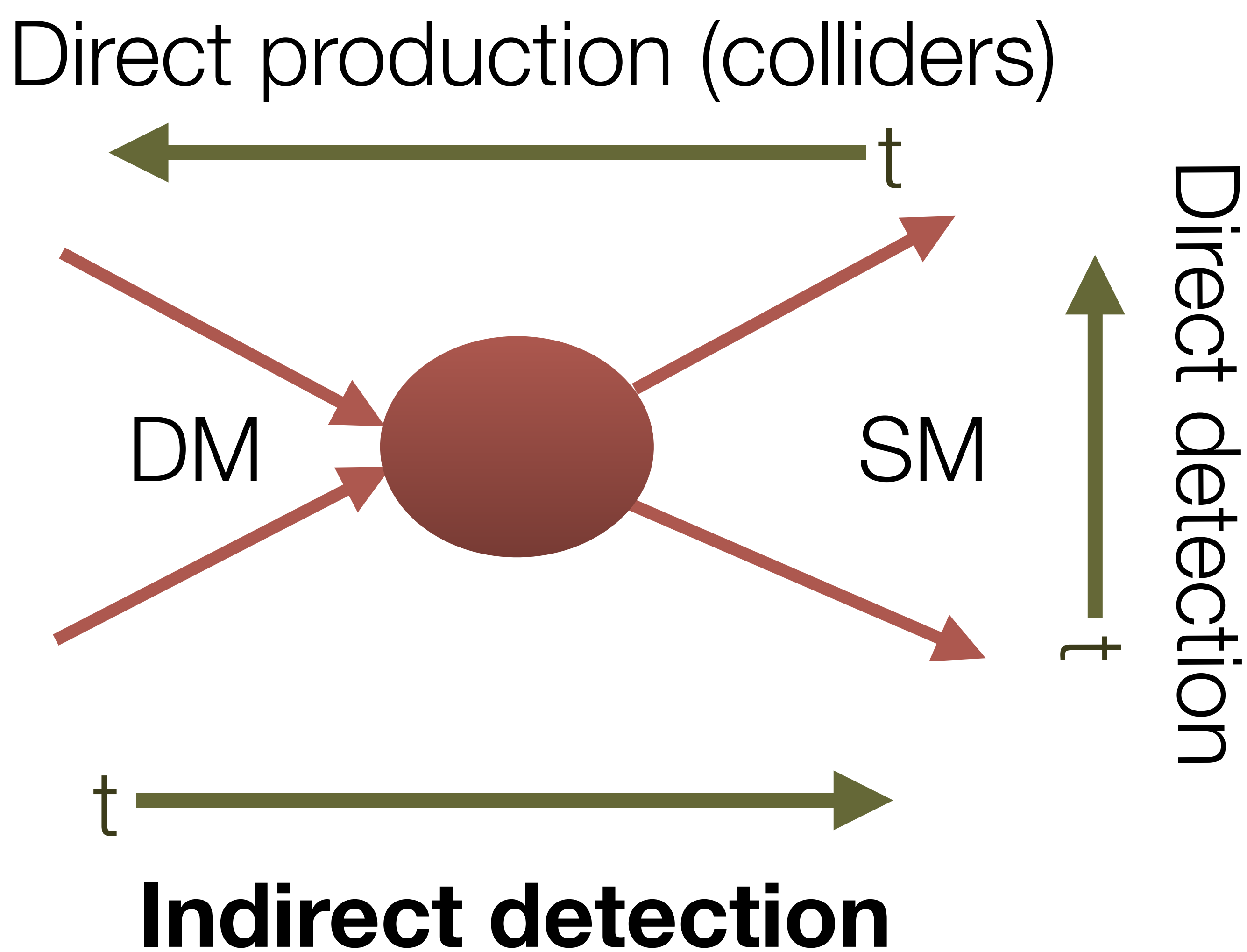
YETI school 2015
IPPP Durham

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 <-> SM: the WIMP miracle and all that

time ~ 1/T

$$a^3 n_\chi \propto exp(-m/T)$$

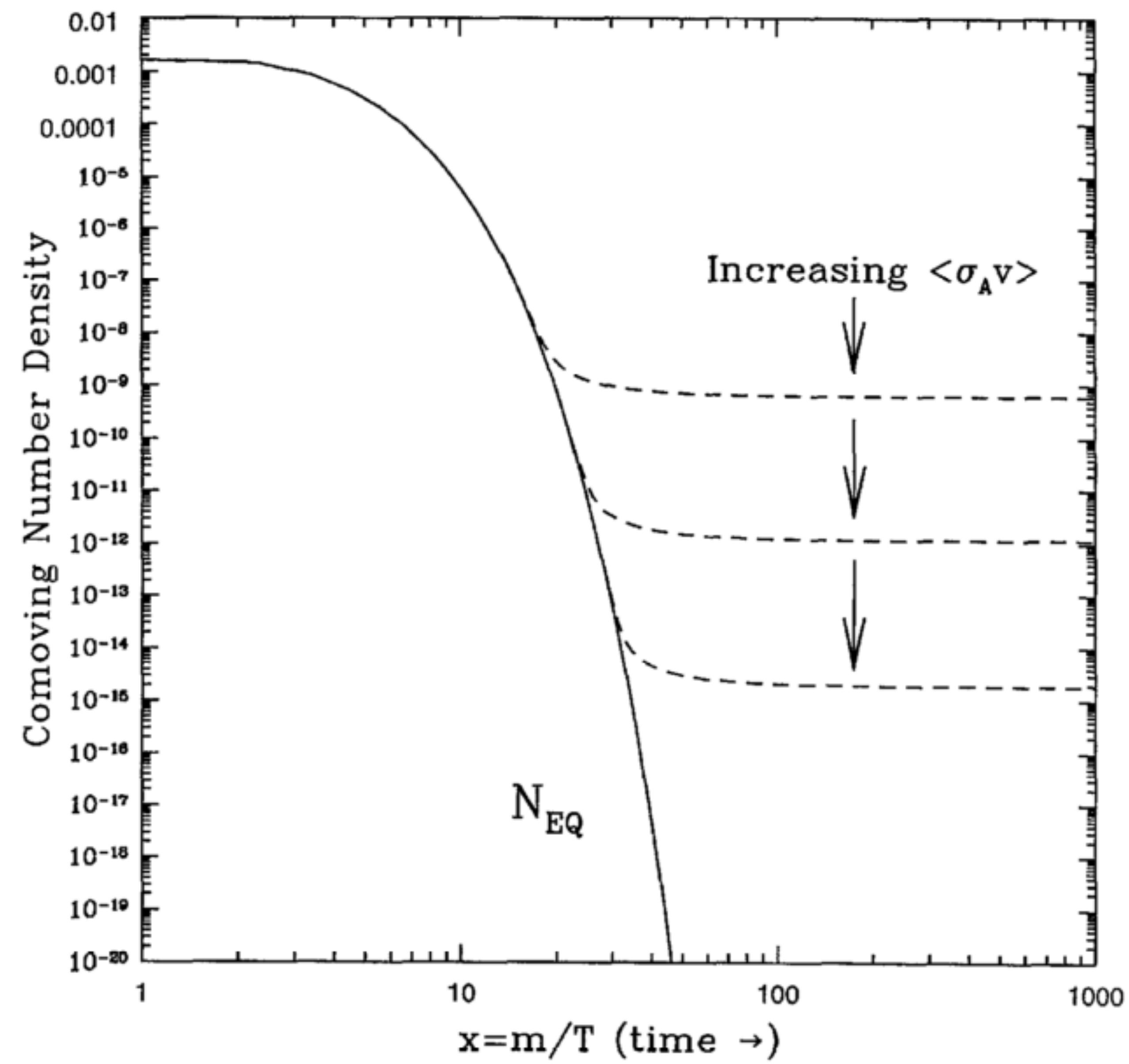
(thermal equilibrium)

until

$$n_\chi \langle \sigma v \rangle_{\rm ann} \simeq H$$

thermal freeze-out

Ω_χ set by $\langle \sigma v \rangle_{\rm ann}$



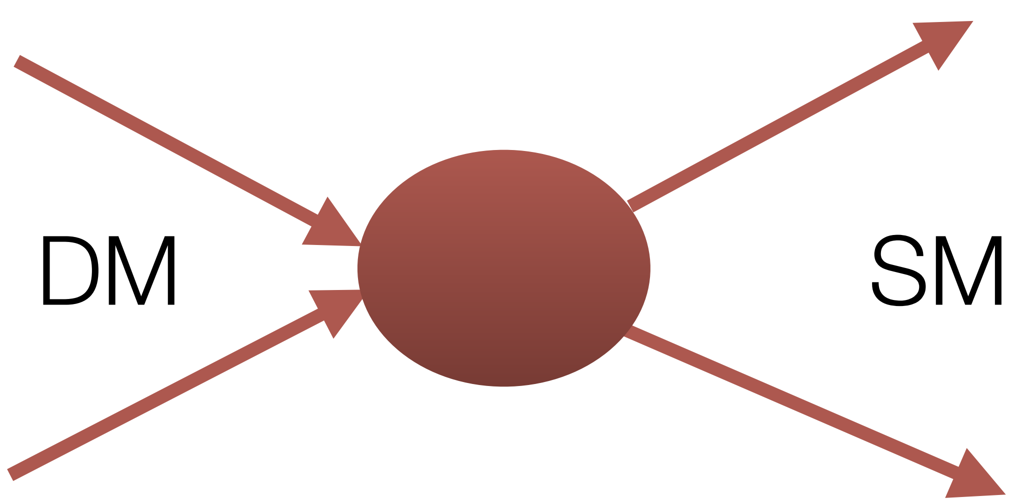
$$\Omega_\chi = 0.3 \rightarrow \boxed{\langle \sigma v \rangle_{\rm ann} \simeq 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}}$$

DM annihilation: where do we look?

Thermal production with constant cross-section → Ongoing self-annihilation into SM particles as structure forms

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

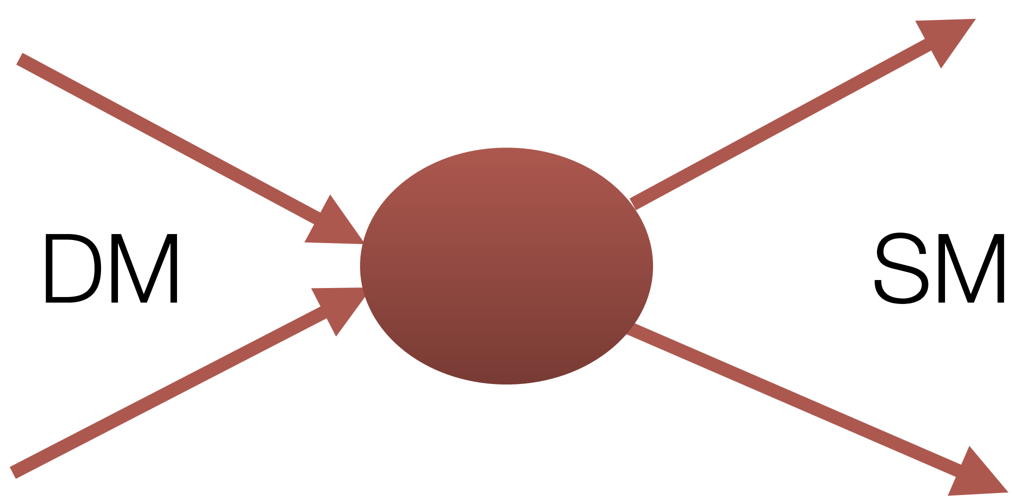
Look where $n_\chi^2 \propto \rho_\chi^2$ is large



*not necessarily thermal <sv>!!

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

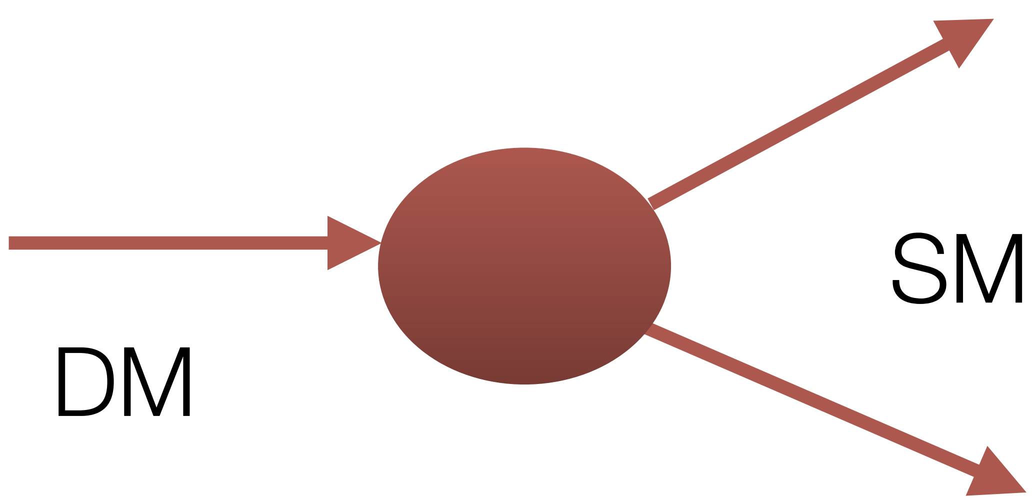


Decays

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

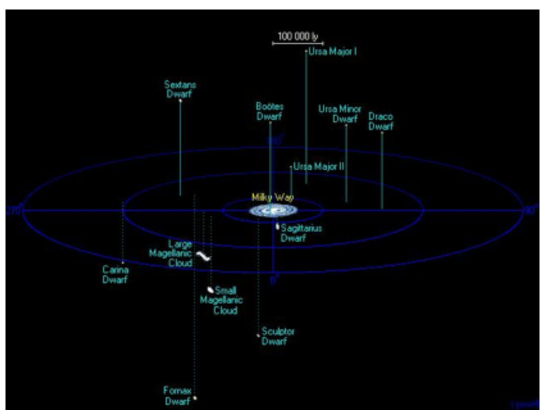
- Observable effects for $\tau_\chi \lesssim 10^{25}\mathrm{s}$

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



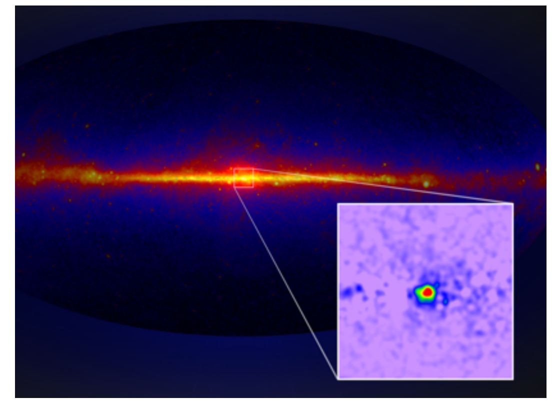
Indirect DM signals: where to look

Local
Cosmic
Ray flux

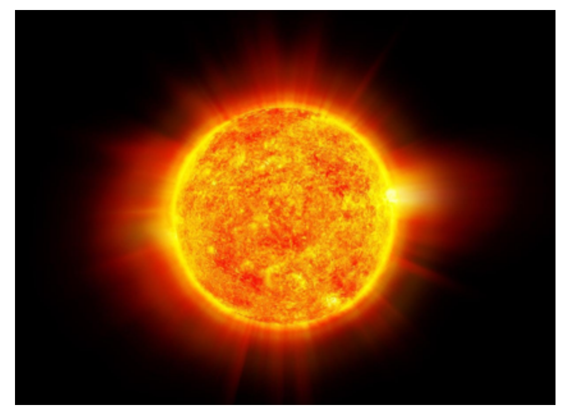


Dwarf
galaxies

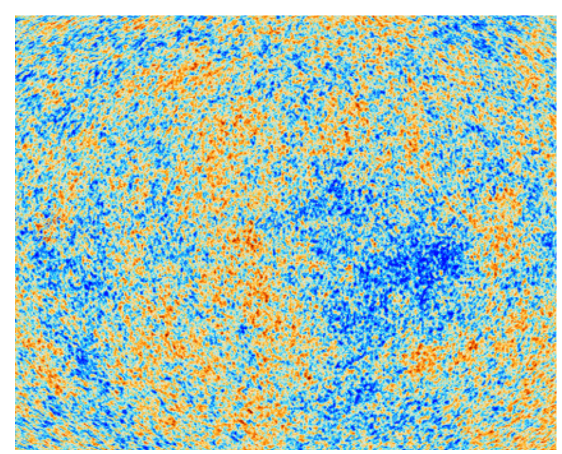
Galaxy
Clusters



Galactic
center

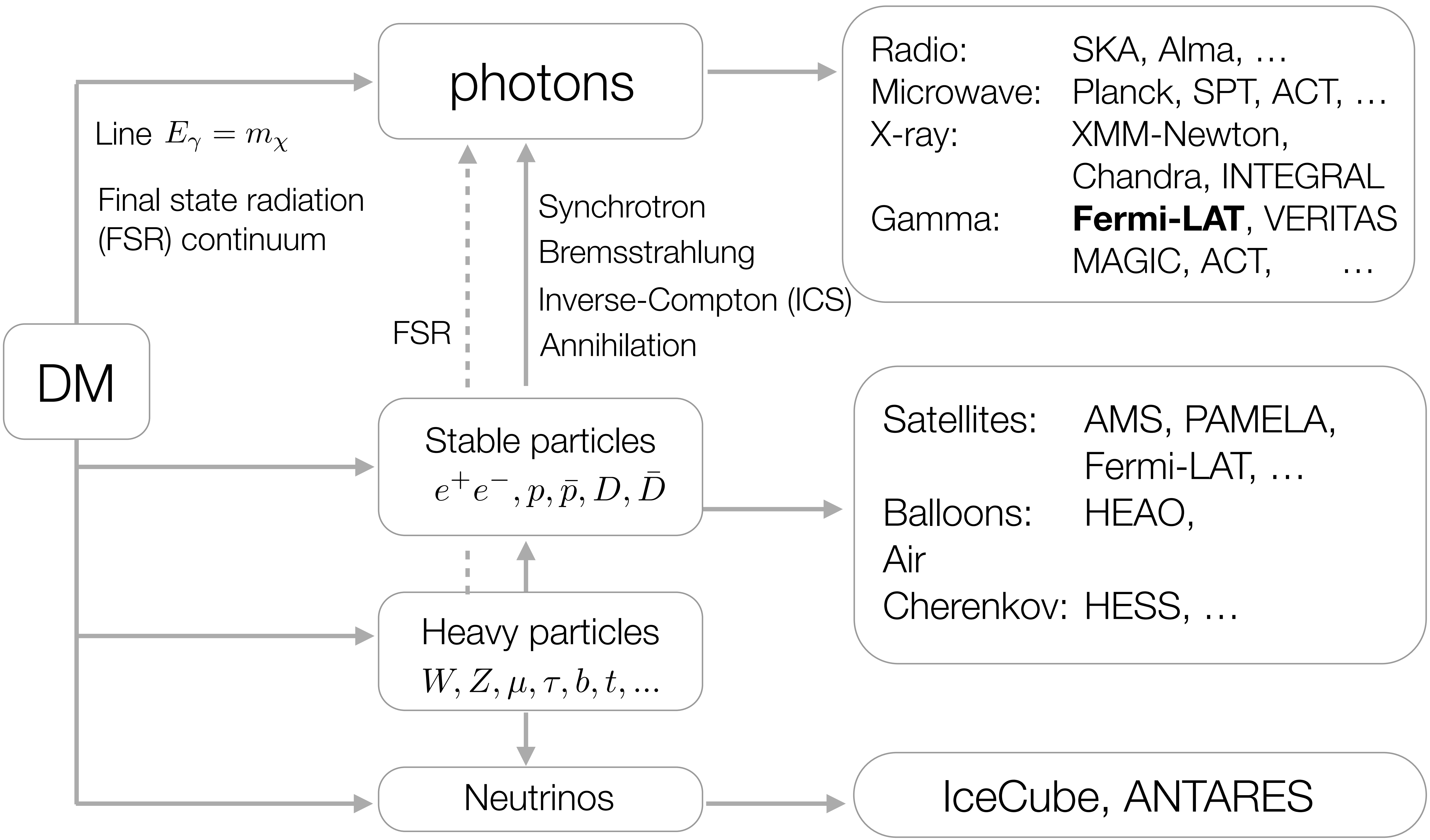


Solar
neutrinos



CMB +
background
light

Indirect signals: what to look for



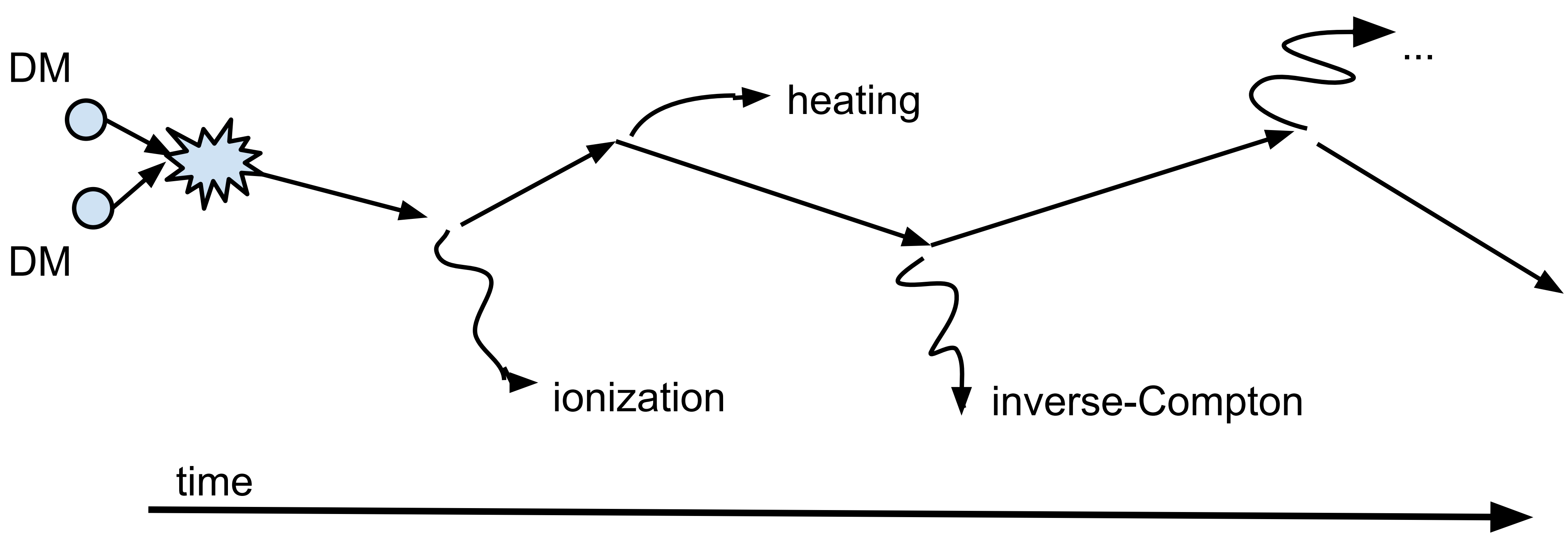
Before Structure: Extragalactic background light

Annihilating DM should yield an isotropic background flux:

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

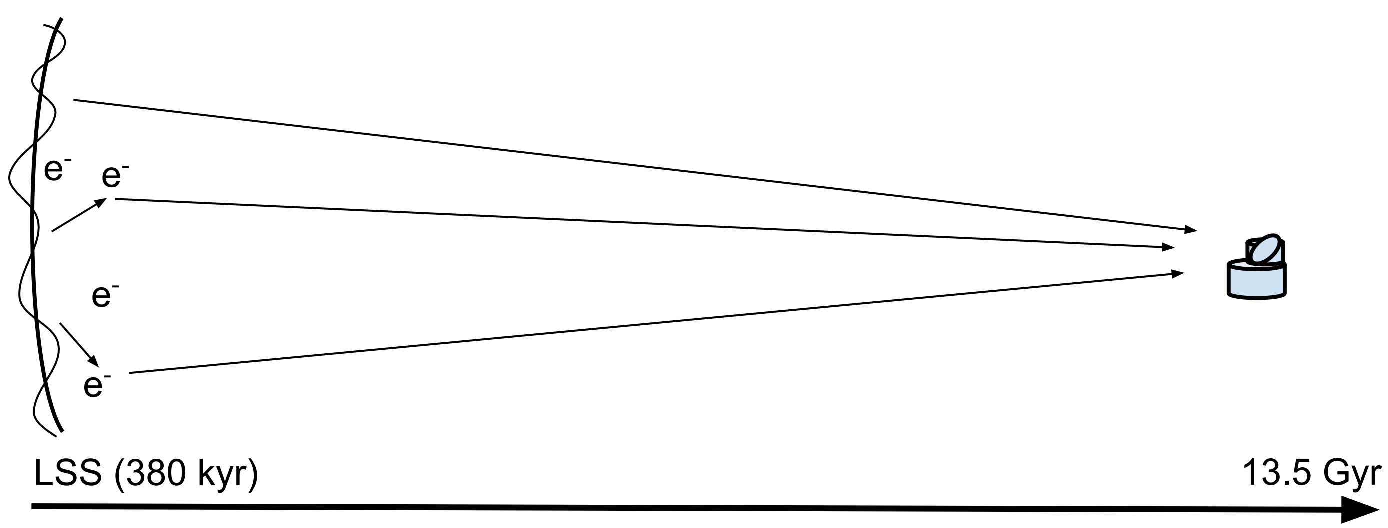
Very faint relative to galactic light -> very difficult to see

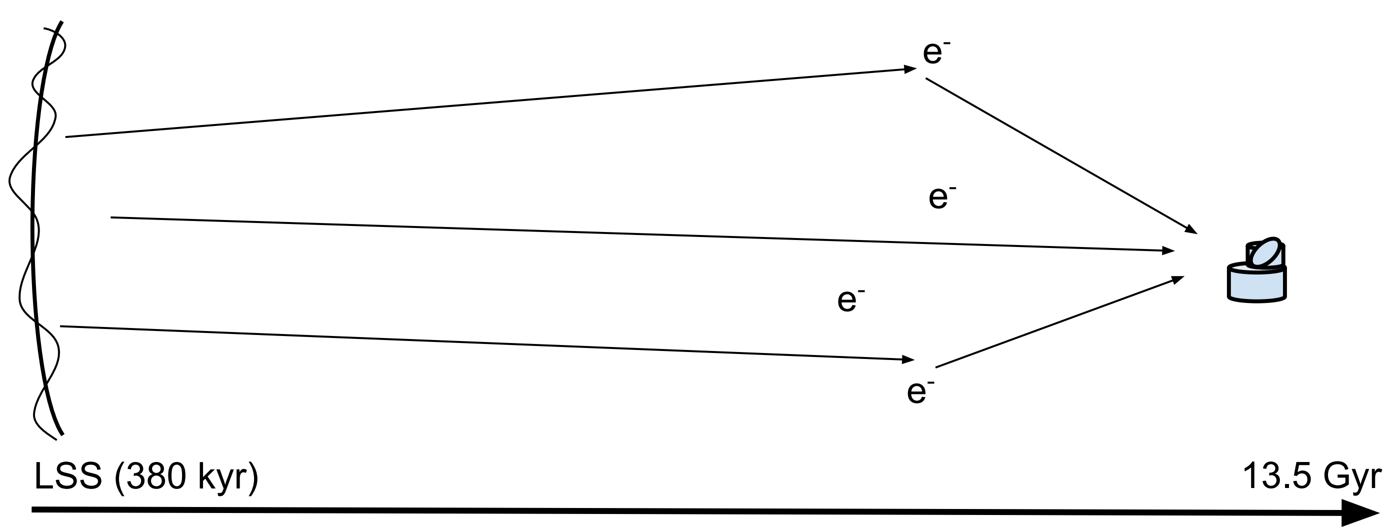
Annihilating DM has a more immediate effect on the IGM:

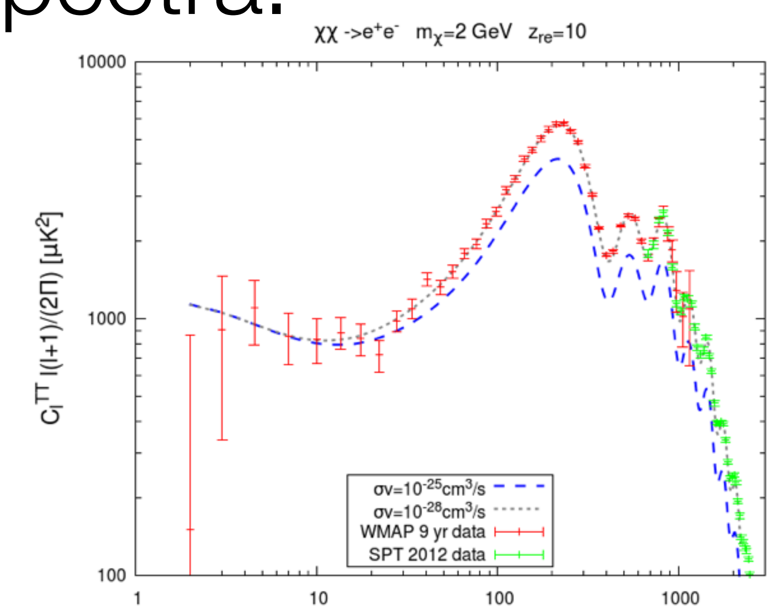


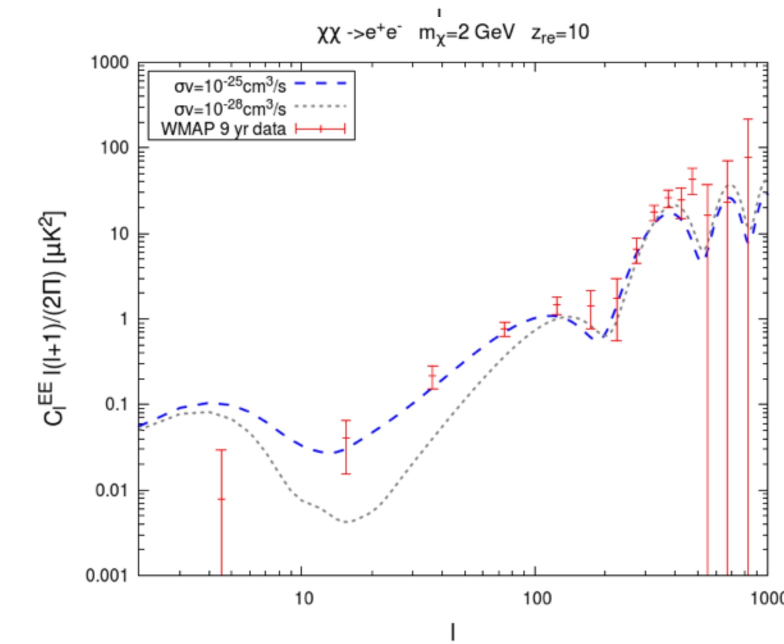
The CMB

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



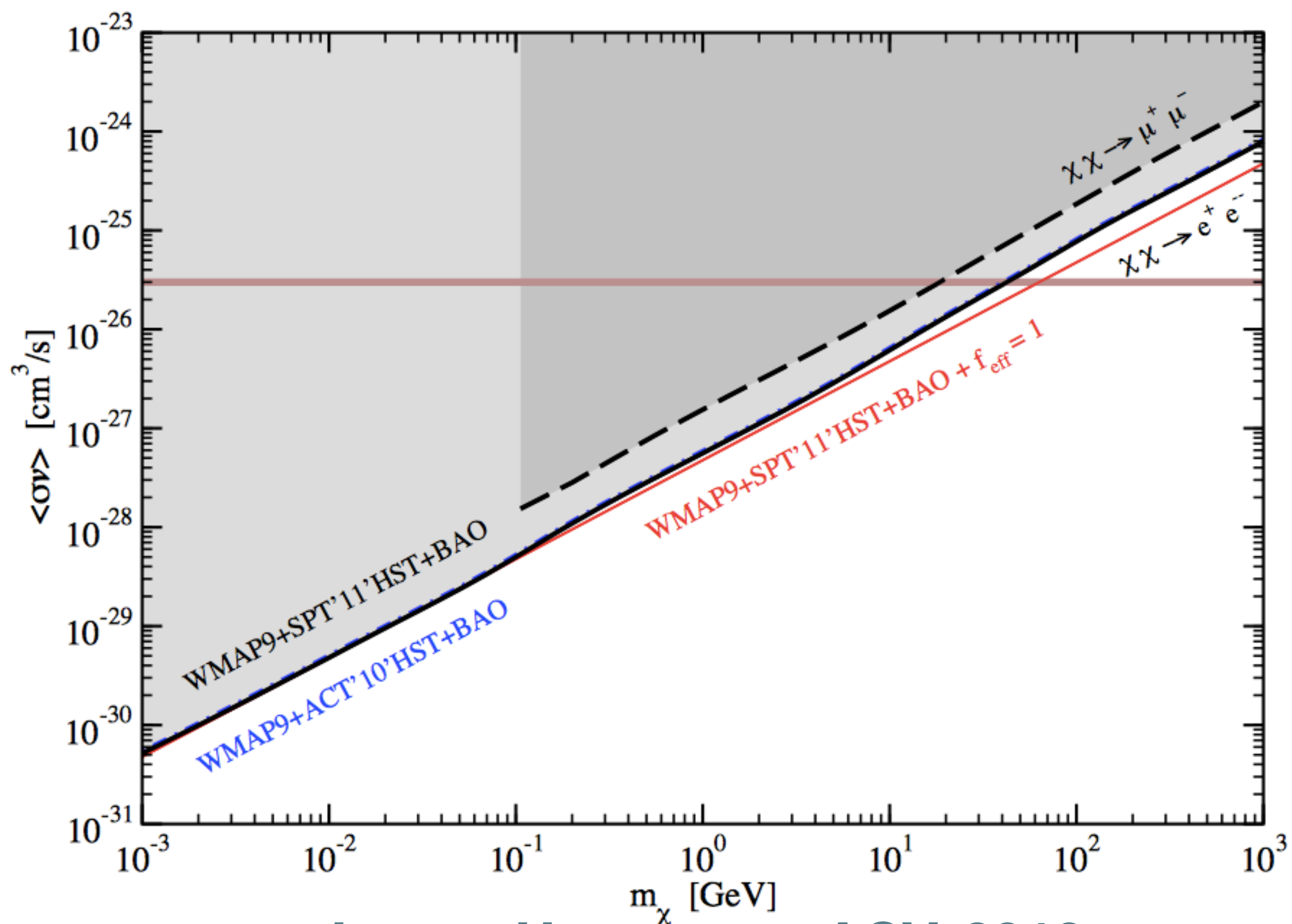






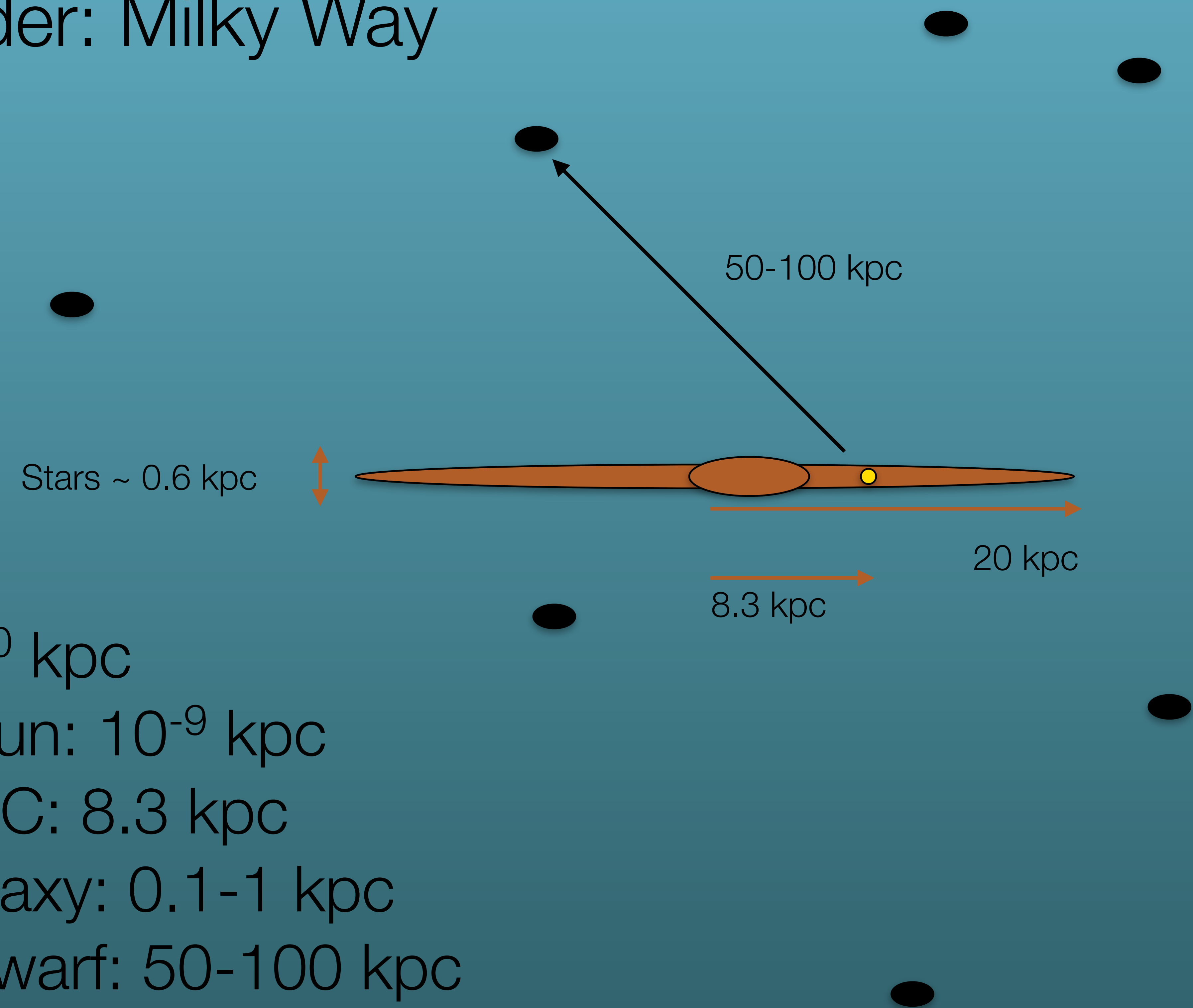
The CMB

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



Lopez-Honorez … ACV, 2013

Quick Reminder: Milky Way

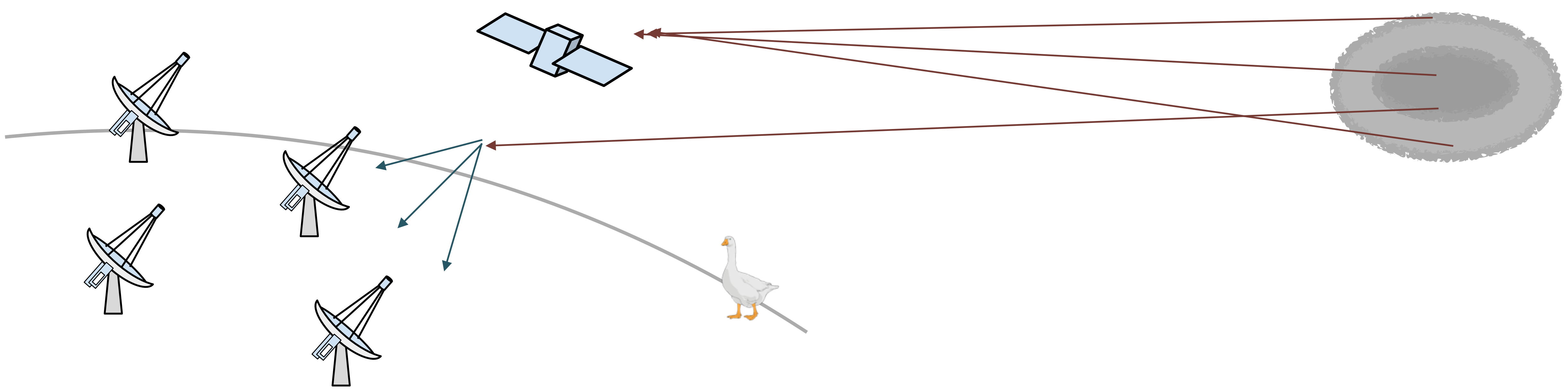


Scales:

- 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 —> large signal.
  - **WIMPs**: GeV-TeV masses: **GeV—TeV gamma rays**



Dwarf Satellites and Galaxy Clusters

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:

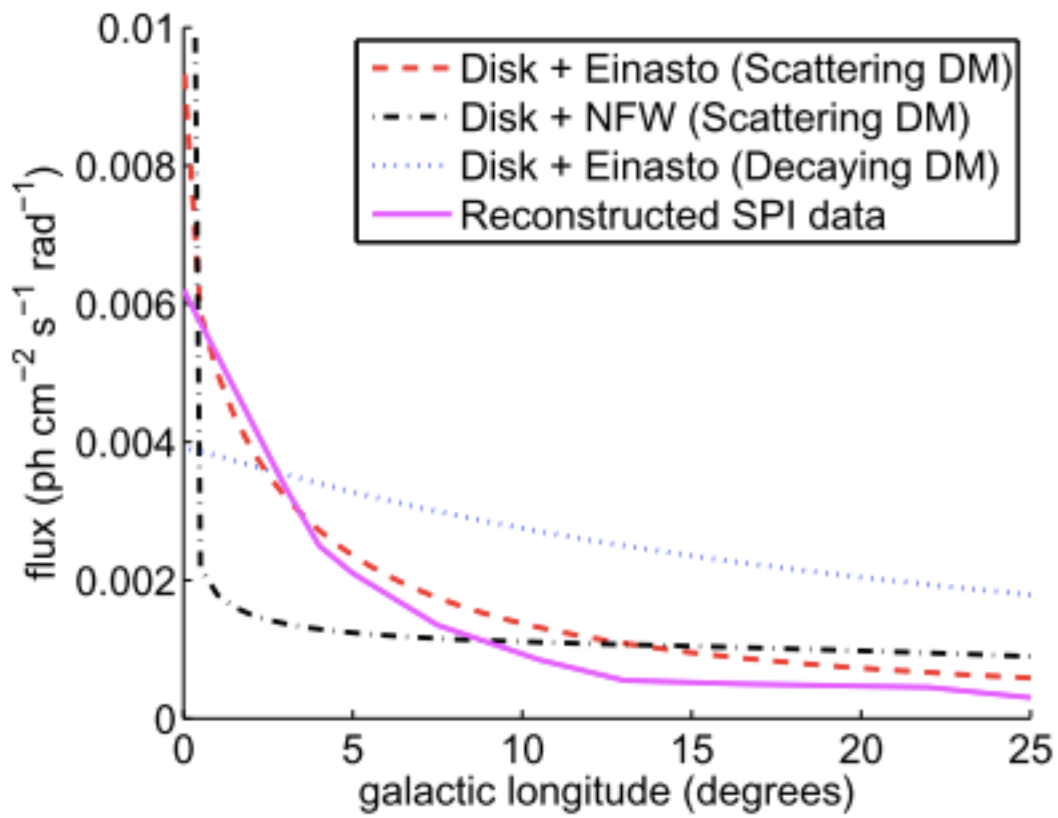
$$J = \int d\Omega \int_{\text{l.o.s.}} d\ell \rho_\chi^2(\ell, \Omega)$$

$\rho_\chi(\vec{r})$	DM density
ℓ	Distance along line of sight
Ω	Solid angle in the sky

Decays

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

$$J \to \int d\Omega \int_{\mathrm{l.o.s.}} d\ell \rho_\chi(\ell, \Omega)$$



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

Astrophysical Content

J-factor only needs to be computed once per satellite*

$$J = \int d\Omega \int_{\mathrm{l.o.s.}} d\ell \rho_\chi^2(\ell, \Omega) \qquad \rho(r) = \frac{\rho_0 r_0^3}{(r + r_0)(r^2 + r_0^2)}$$

Requires DM profile (from sims), dwarf mass, distance & angular size (from observations)

dSph	D (kpc)	δD (kpc)	l	b	$\overline{J} \times 10^{17}$ $(GeV^2 cm^{-5})$	$\delta J_{high} \times 10^{17}$ $(GeV^2 cm^{-5})$	$\delta J_{low} \times 10^{17}$ $(GeV^2 cm^{-5})$	α_c
Carina	103	4	260.1	-22.2	2.69	0.47	0.54	0.27°
Draco	84	8	86.4	34.7	29.2	7.52	5.84	0.27°
Fornax	138	9	237.1	-65.7	5.66	1.38	1.51	0.56°
LeoI	247	19	226.0	49.1	3.07	1.00	1.51	0.11°
LeoII	216	9	220.2	67.2	3.98	8.11	3.52	0.08°
Sculptor	87	5	287.5	-83.2	18.3	4.08	3.85	0.42°
Sextans	88	4	243.5	42.3	23.6	58.3	17.2	0.89°
Ursa Minor	74	12	105.0	44.8	25.0	18.9	17.7	0.49°

arXiv:1203.2954

*unless cross-section depends on kinematics!

*unless cross-section depends on kinematics!

Example: you're investigating DM that annihilates with a cross-section $\langle \sigma v_{\rm rel} \rangle \propto v_{\rm rel}^2$. The kinematics are different depending on the DM location within a distribution: this becomes part of the astro contribution — part of *J.*

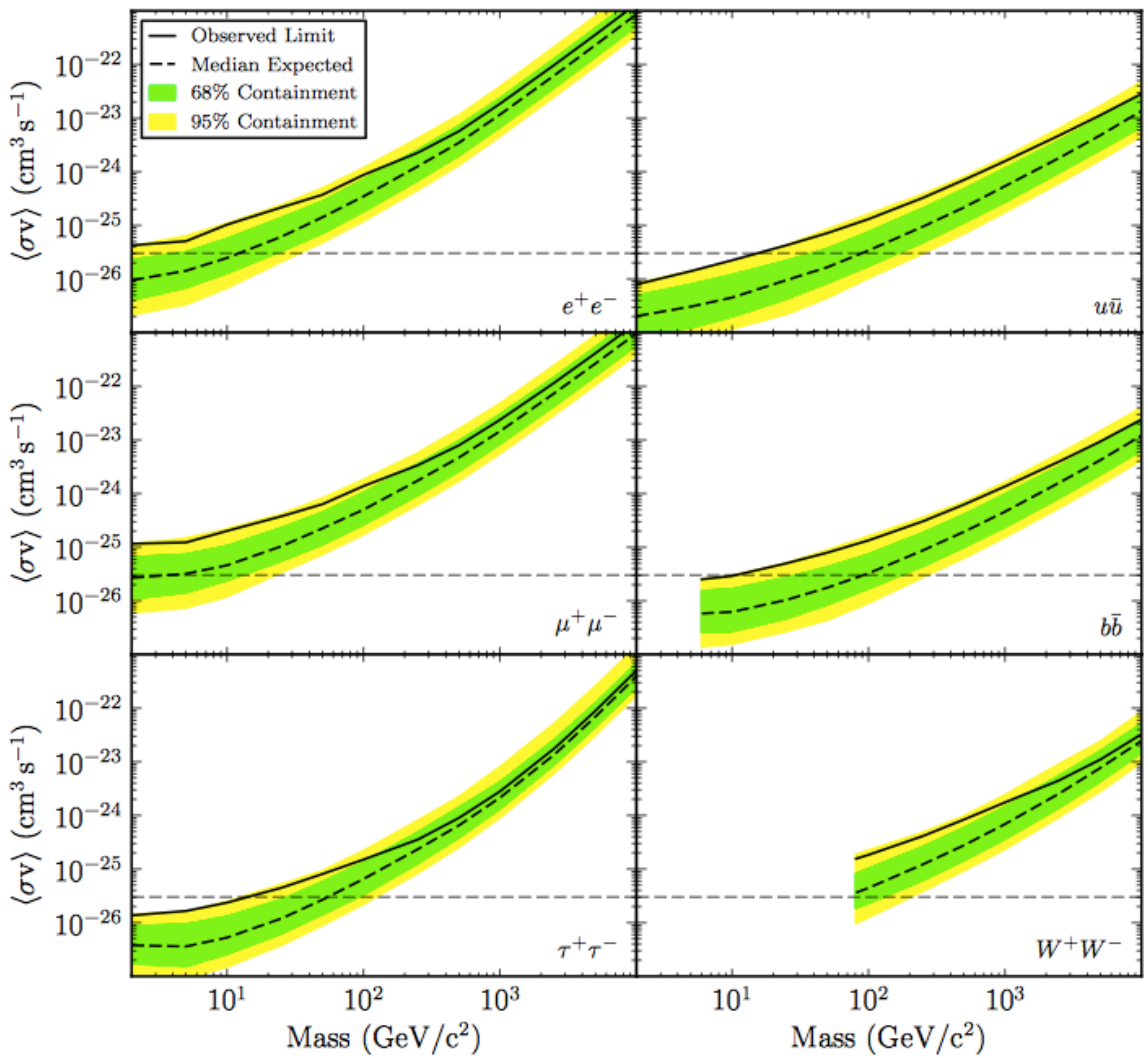
$$J = \int d\Omega \int d\ell \rho_\chi^2(\vec{r}) \to \int d\Omega \int d\ell \sigma_v^2(\vec{r}) \rho_\chi^2(\vec{r})$$

To get v(r): solve the Jeans equation in spherical coordinates based on the DM profile you have chosen.

$$\sigma_v^2(\vec{r}) = \langle v^2(\vec{r}) \rangle \qquad \frac{d\rho\sigma_v^2}{dr} = -\rho \frac{G_N M(< r)}{r^2}$$

This leads to a very different astro signal!

Fermi Constraints from 25 Dwarf Galaxies

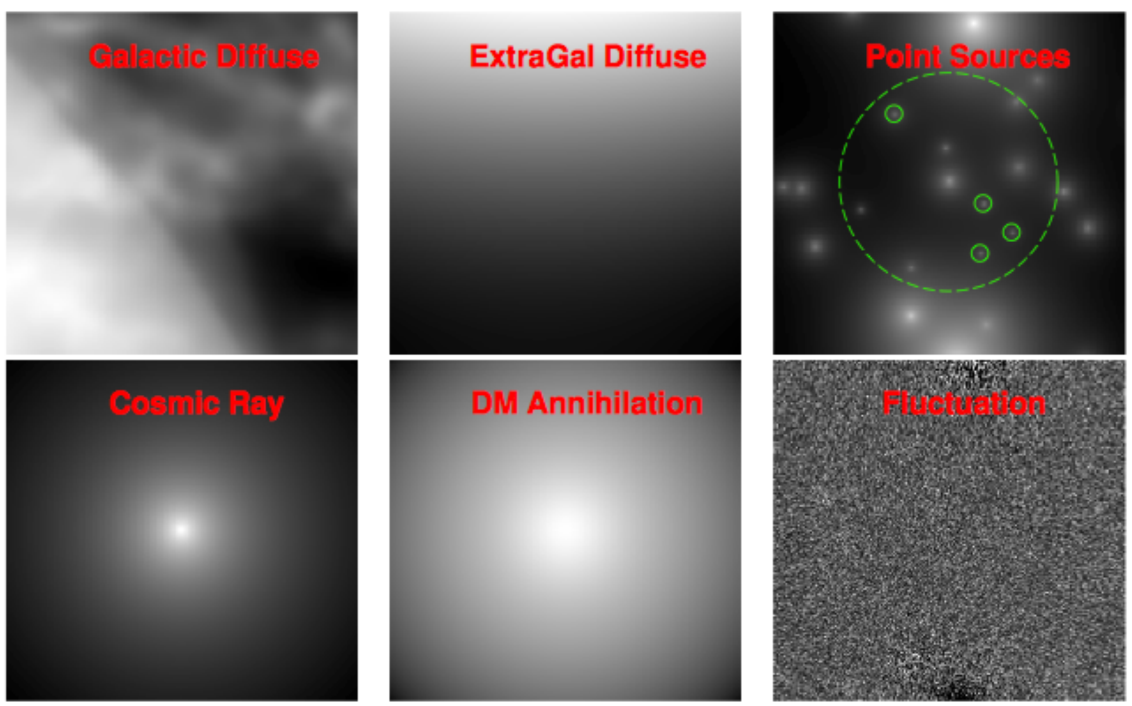


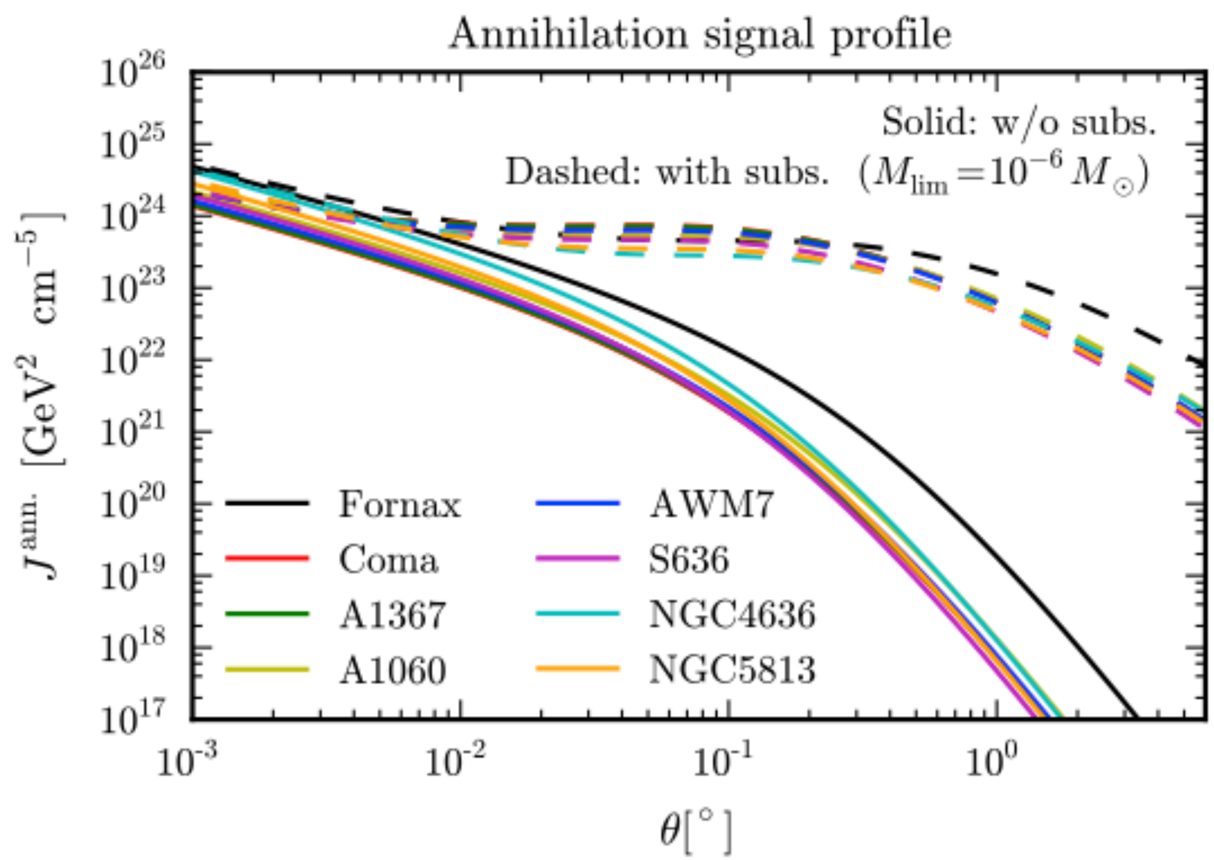
Some resources for spectra & J factors

- Cholis & Salucci: http://arxiv.org/abs/1203.2954v2
- Fermi study of 25 Dwarf Galaxies: http://arxiv.org/abs/1310.0828
- **Poor particle physicist's cookbook for indirect detection**: http://www.marcocirelli.net/PPPC4DMID.html

Galaxy clusters

Procedure (and formulae) essentially unchanged, except
-**Backgrounds** can be trickier;
-**Substructure** greatly modifies the profiles:





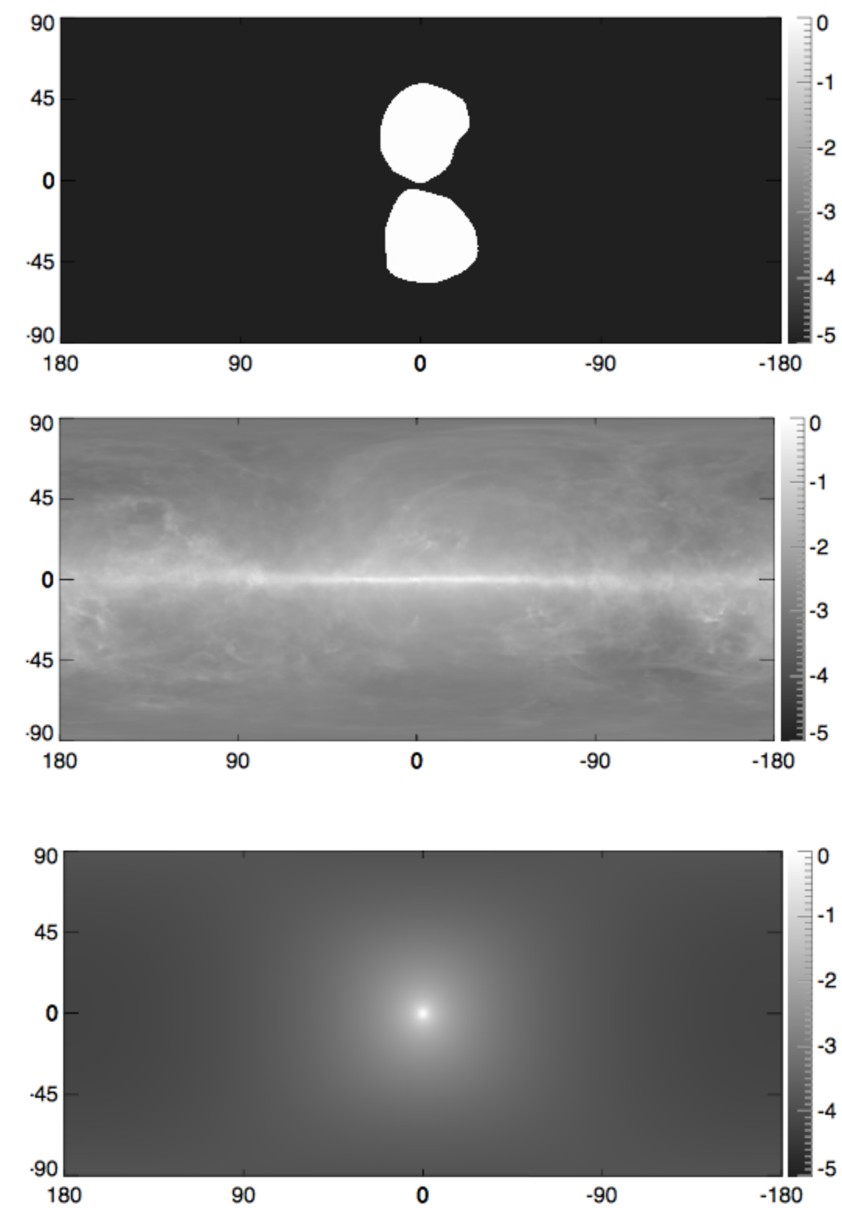
arXiv:

[arXiv:1110.1529]()
[arXiv:1207.6749]()

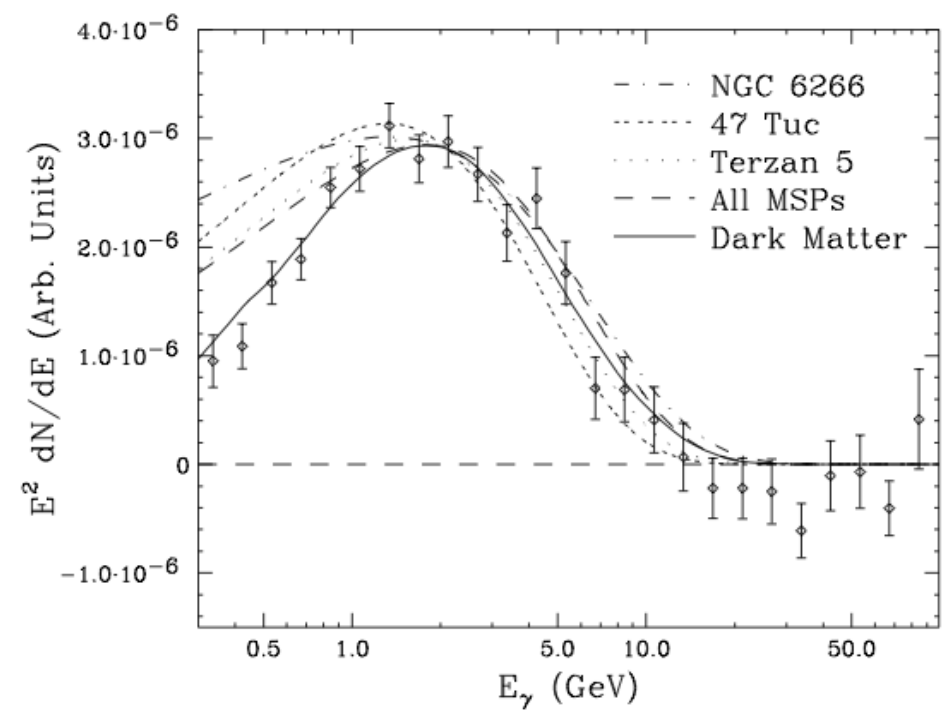
The Galactic Centre

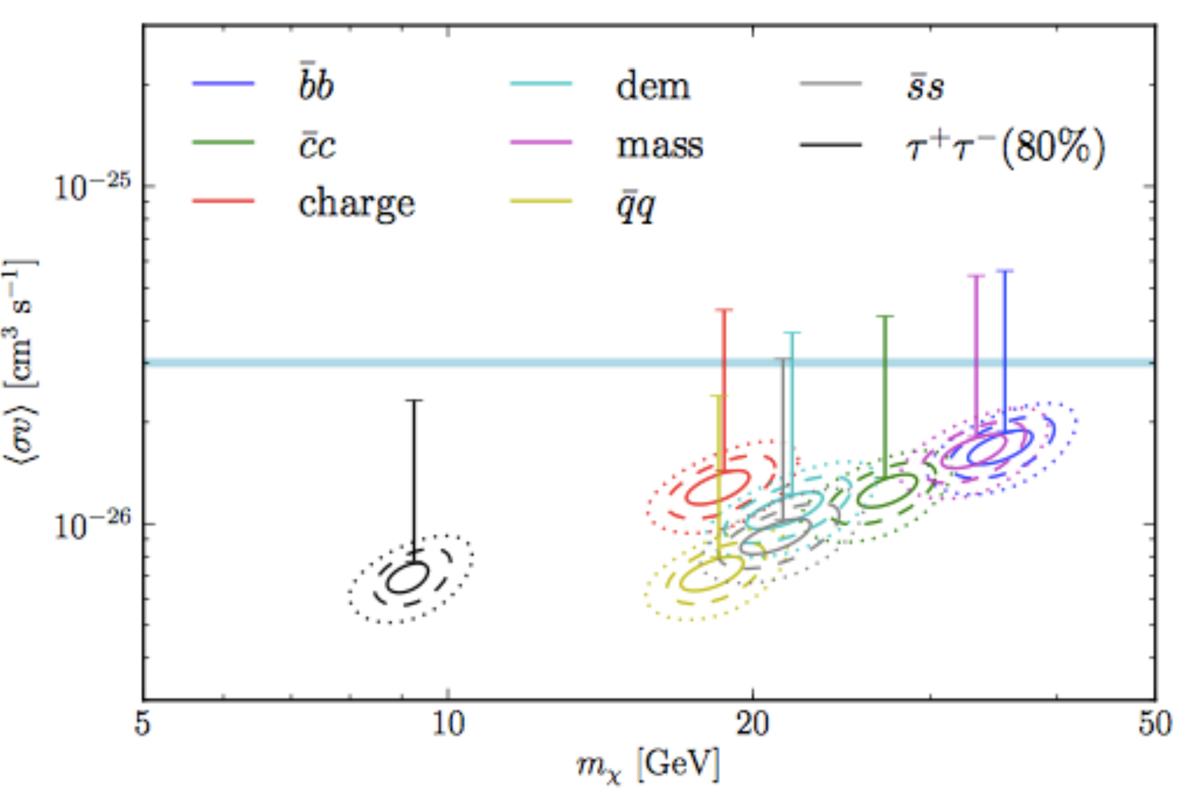
- Very large concentration of DM, and thus of DM annihilation products, but
- A **lot** of background

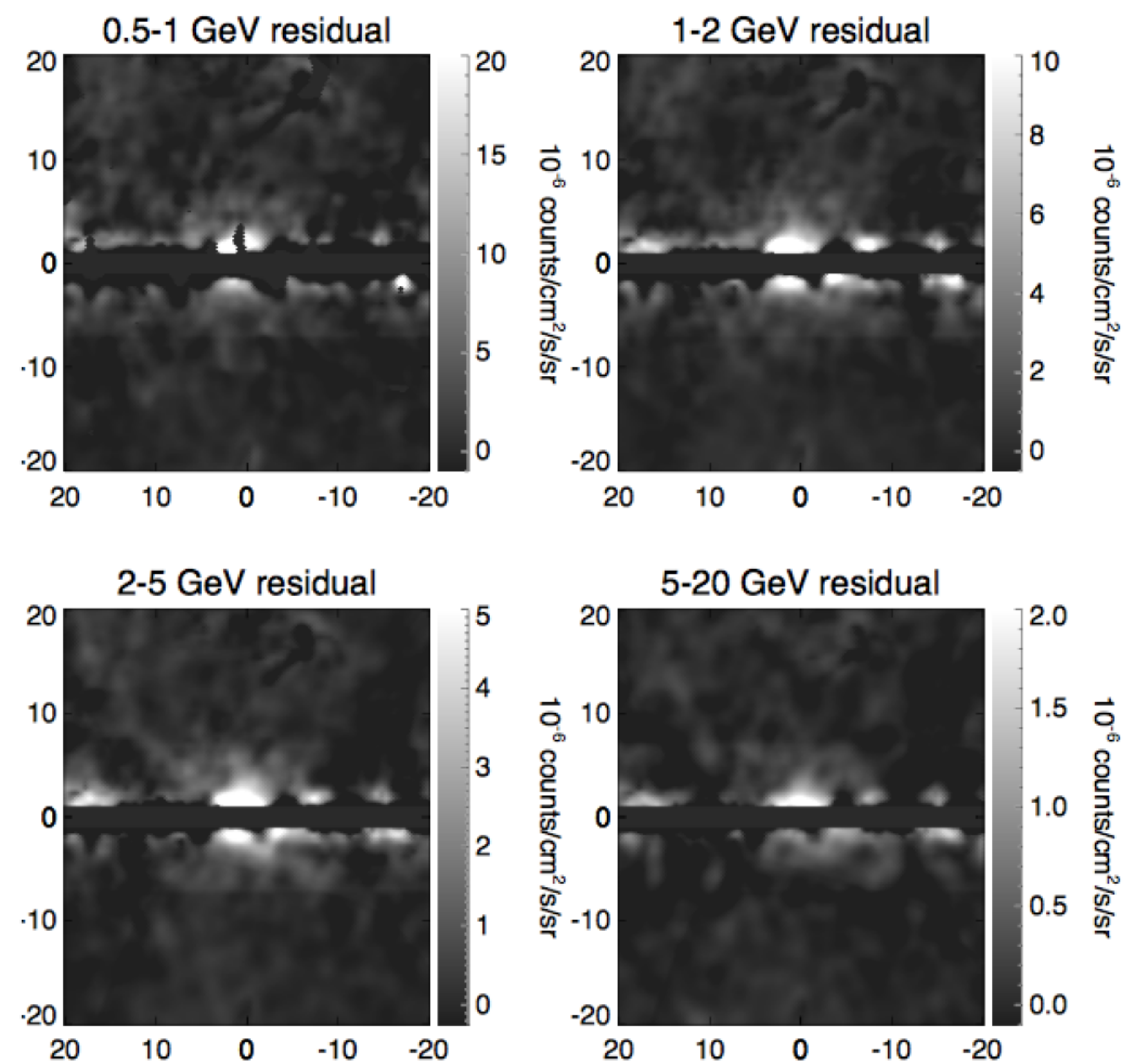
  1) Remove point sources e.g. with fermi-lat point source catalogue
  2) Create (or download) template for diffuse background (shape and spectra), structures, Fermi bubbles
  3) Create template for DM model (shape and spectra)
  4) Vary simultaneously to obtain fit



The Galactic Centre excess







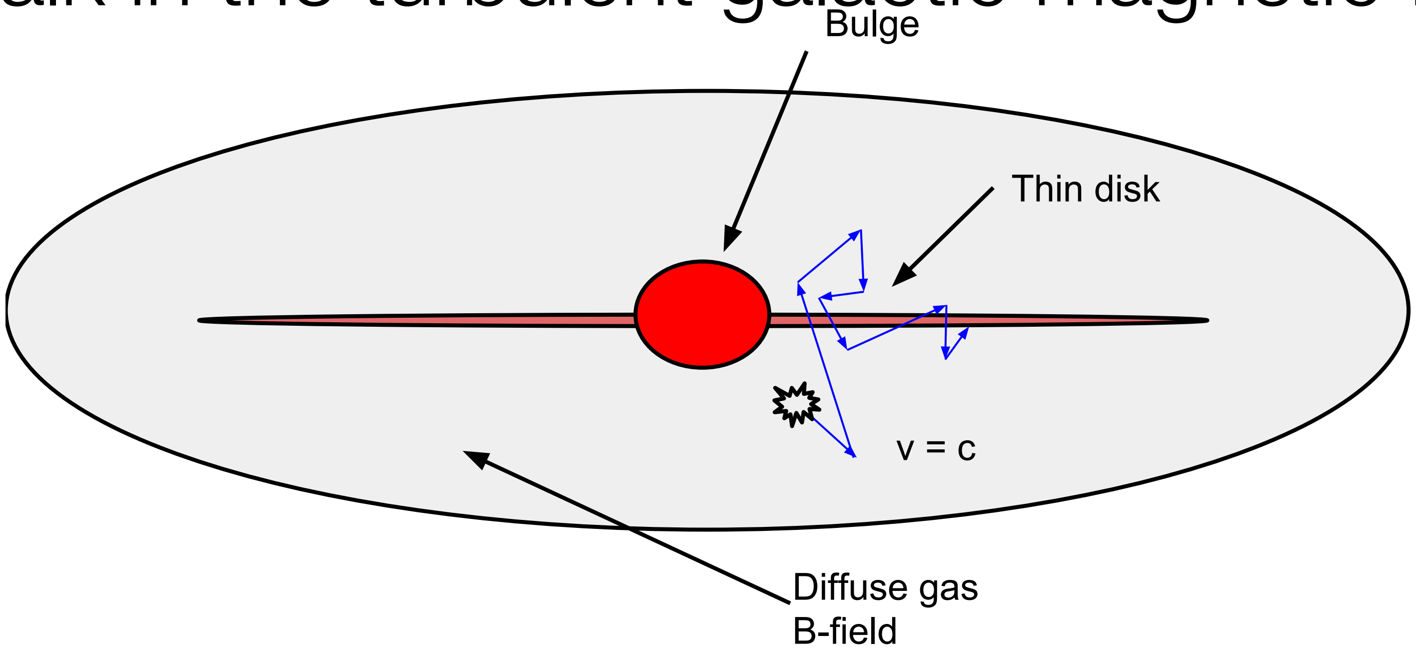
arXiv:1402.6703

The Fermi-LAT data and tools

http://fermi.gsfc.nasa.gov/ssc/data/analysis/

Cosmic Rays

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



$$\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi$$

$$- \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi \, ,$$

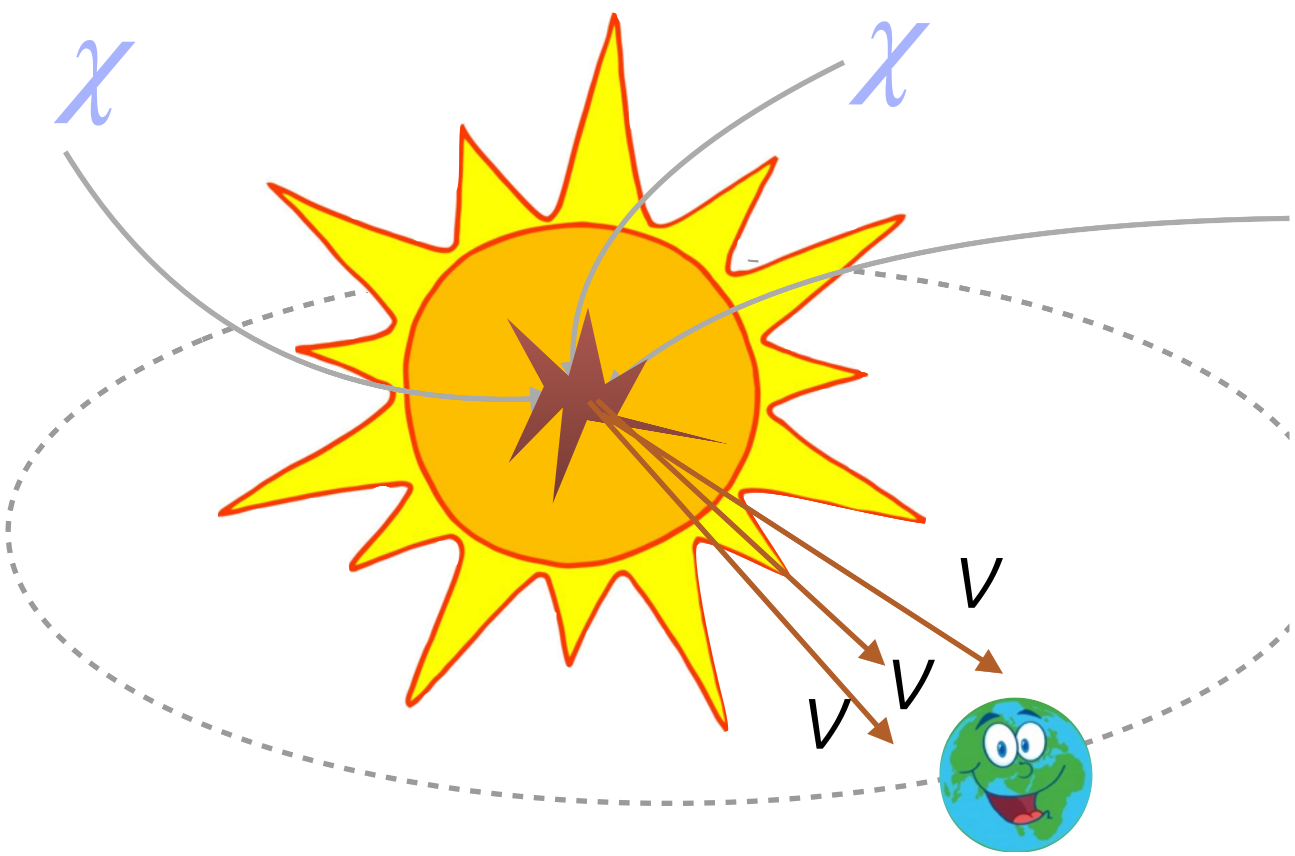
Cosmic Rays

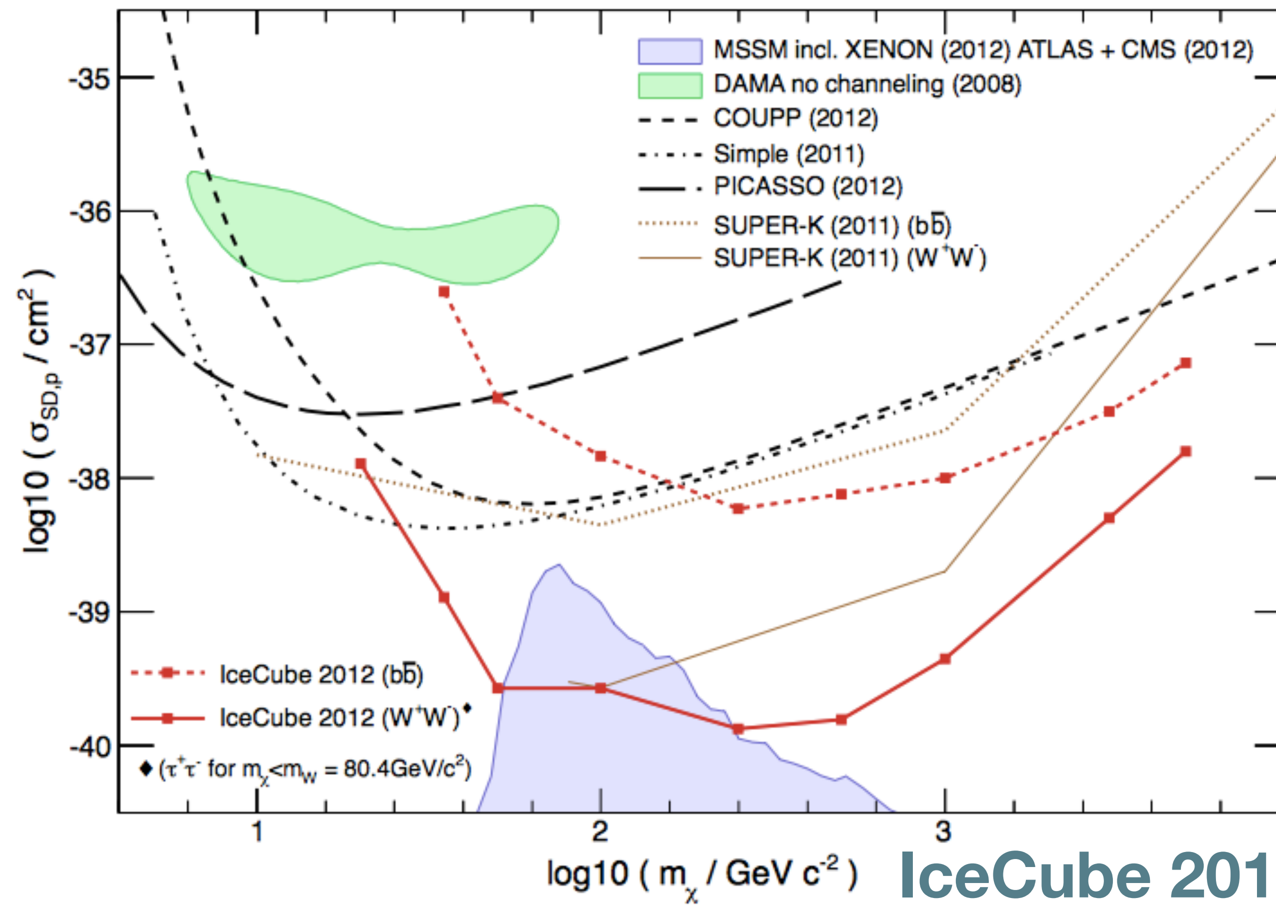
- Due to diffusion and energy loss, CRs do not point back at their source.
- To find flux at earth:

1. Solve diffusion equation
    - Fully numerically (e.g. GALPROP (http://galprop.stanford.edu), DRAGON)
        - Slow, black-boxy, but more precise 3d gas maps, ISR, interaction with other CR species
    - semi-analytically
        - Faster, less precise as you move farther away from Earth. More transparent.
2. Account for solar modulation at low energies (< 20 GeV or so)
3. Compare with data: http://lpsc.in2p3.fr/cosmic-rays-db/

A model that predicts a local CR flux also predicts gamma rays from the GC: these can be *very* constraining.

Neutrinos from the Sun





IceCube 2013

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

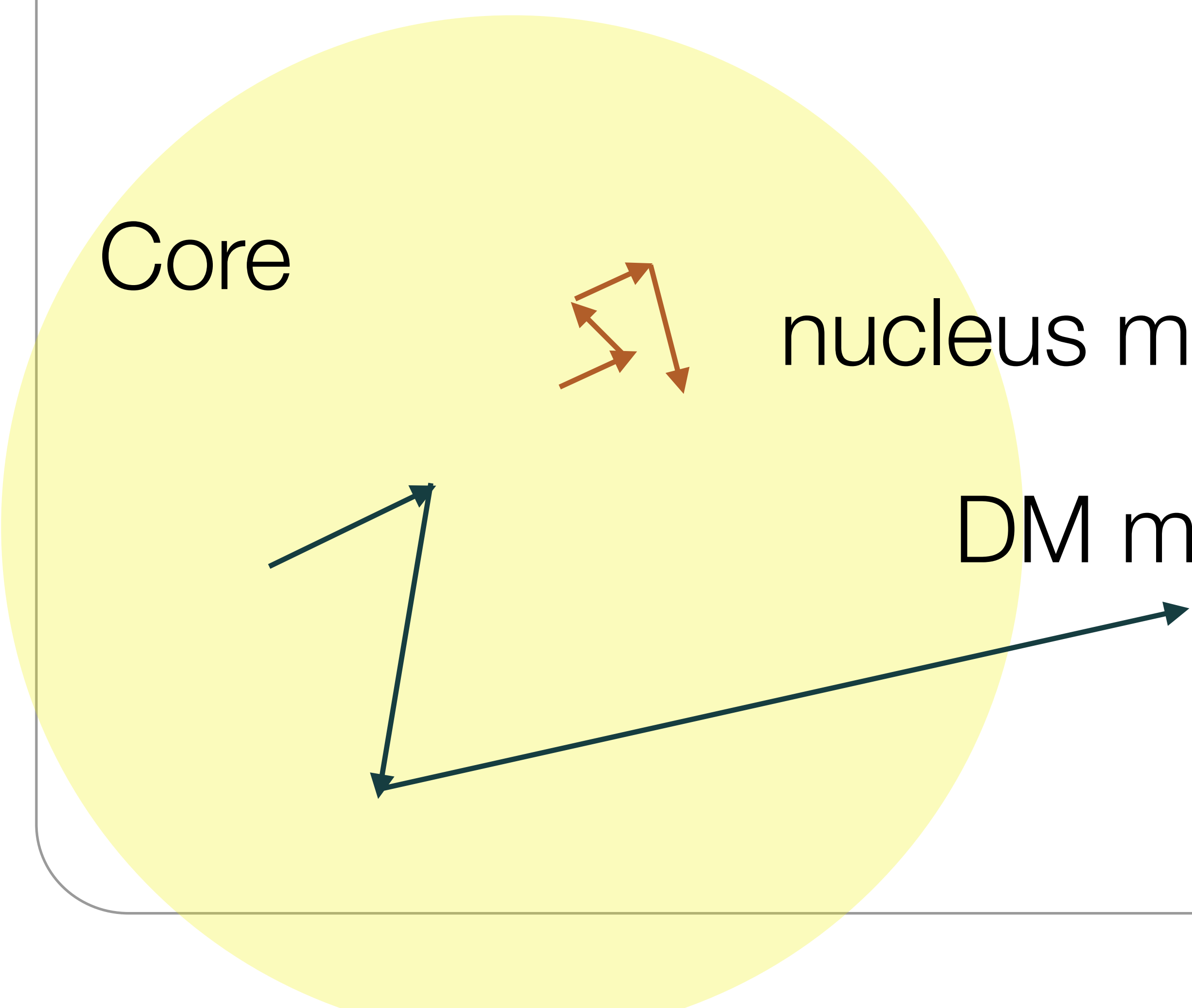
Must include **propagation** properly

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:



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

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

Wimps in the sun: observable effects

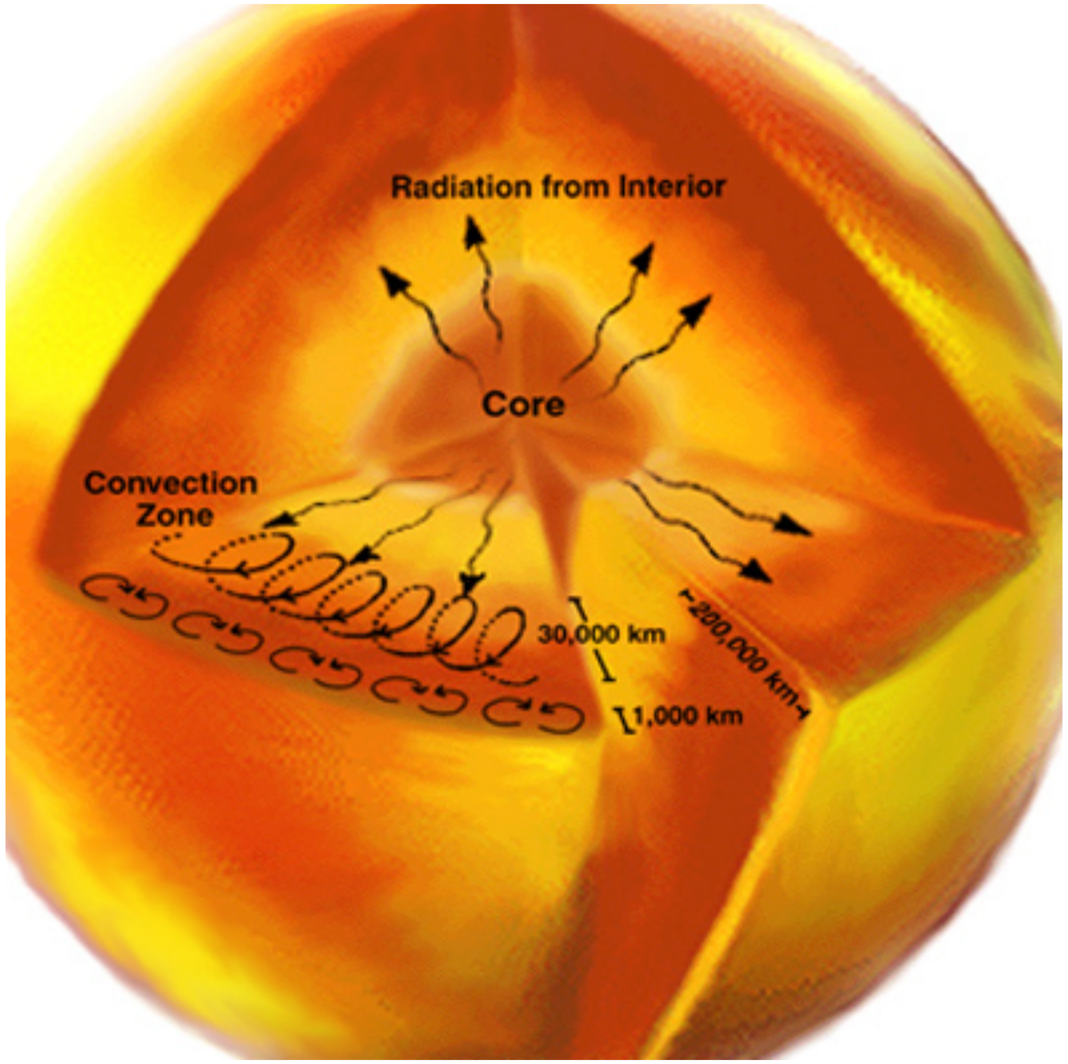
Energy transport

Heat transport away from the core — effects:

<u>Change in temperature</u>
visible with ^{8}B **neutrinos**

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

<u>Change in structure</u>
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	Annihilating heavy (> TeV) "leptophillic" 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

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
- Many constraints, many hints
- Interplay with direct searches, collider data
- Future: incorporating everything: global searches?