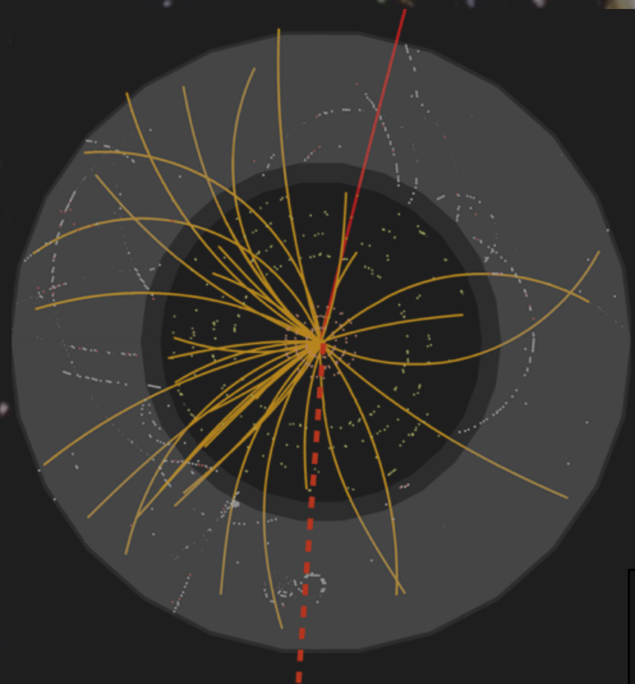
Dark Matter: Overview



Thomas Lohse
Humboldt-Universität zu Berlin

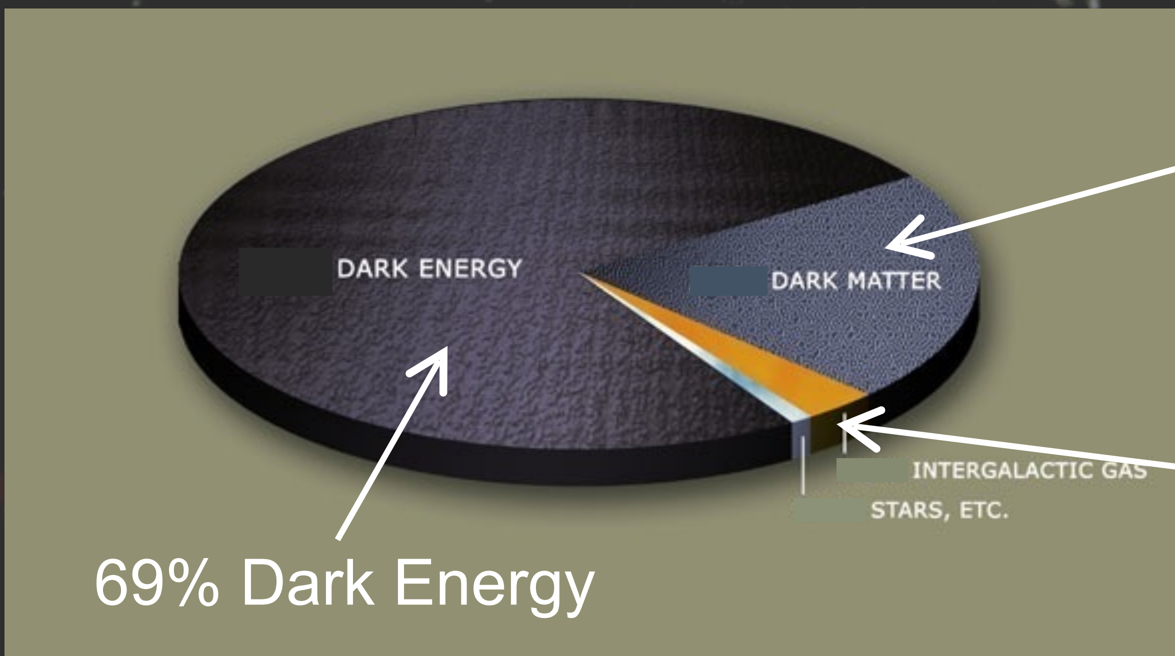
HAP Workshop 2014 on indirect dark matter searches

Dark Matter:

- Why ?
- What ?
- Where and how ?

Space - The Final Frontier

What's out there?



26% Dark Matter

5% Standard Model stuff

What we claim to understand is only 5%!

Some questions for your generation

- >80% of matter is dark → true? what's behind this?
  - ➢ is there a variant of **Super-Symmetry** ?
  - ➢ are there more than 3 spatial dimensions ?
- Is the 125 GeV particle the only **Higgs** boson ?
- Why is there matter but no (primordial) **antimatter** ?
- Why is the matter/antimatter asymmetry so crazily small:

$$\frac{N(\text{baryons})}{N(\text{photons})} \approx 6 \times 10^{-10} \quad ?$$

Understanding dark matter may be the golden key!

Part I

Why

do we think there is dark matter

?

a)

Gravitational Dynamics

Graviational Dynamics (1): Galaxy Clusters

spread in redshift → kinetic energy

virial theorem → gravitational energy

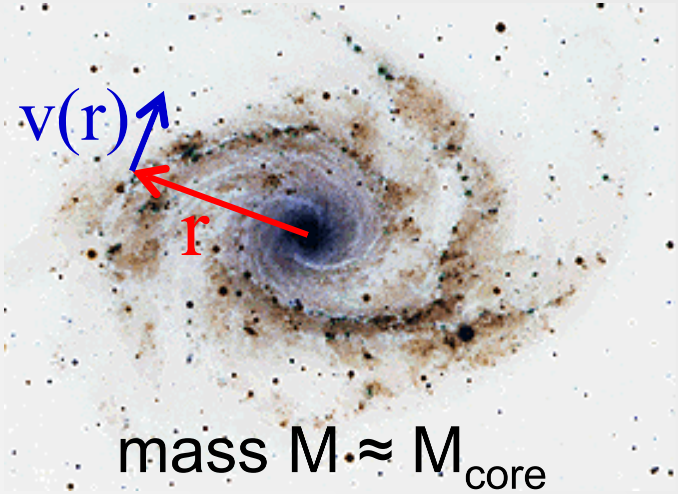
$\Downarrow$

Clusters are several hundred times more massive than what we see

Fritz Zwicky (1898 – 1974)
Coma Cluster, 1933

Coma Cluster
APOD, 2.5.2010, Dean Rowe

Graviational Dynamics (2): Galaxy Rotation



mass M ≈ M_{core}

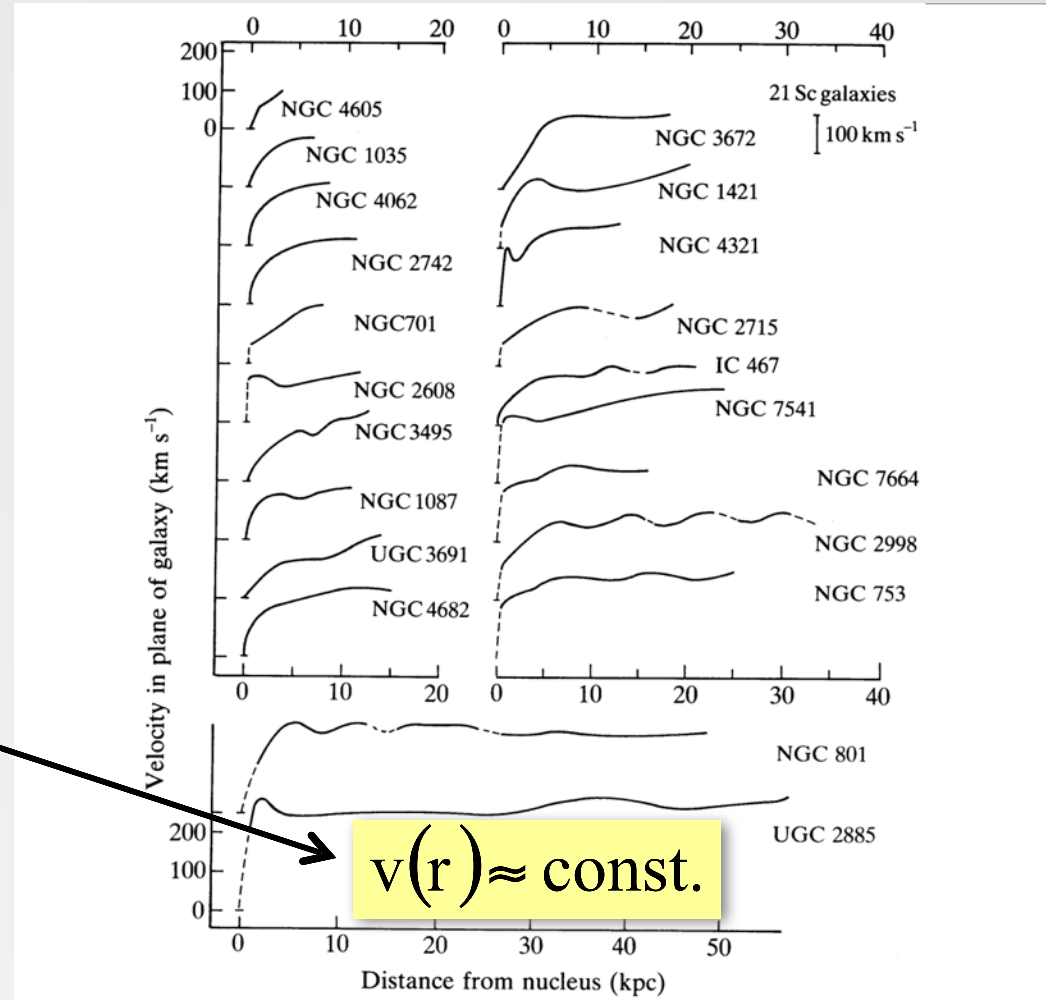
$$\frac{M}{r^2} \propto F_G = F_{centrif.} \propto \frac{v^2}{r}$$

$$\Rightarrow \quad \boxed{v(r) \propto \frac{1}{\sqrt{r}}}$$

Galaxy is a big ball of invisible matter ... with a few stars here and there

Local density:
$$\rho_{DM} \cong 0.3\,\mathrm{GeV/cm^3}$$

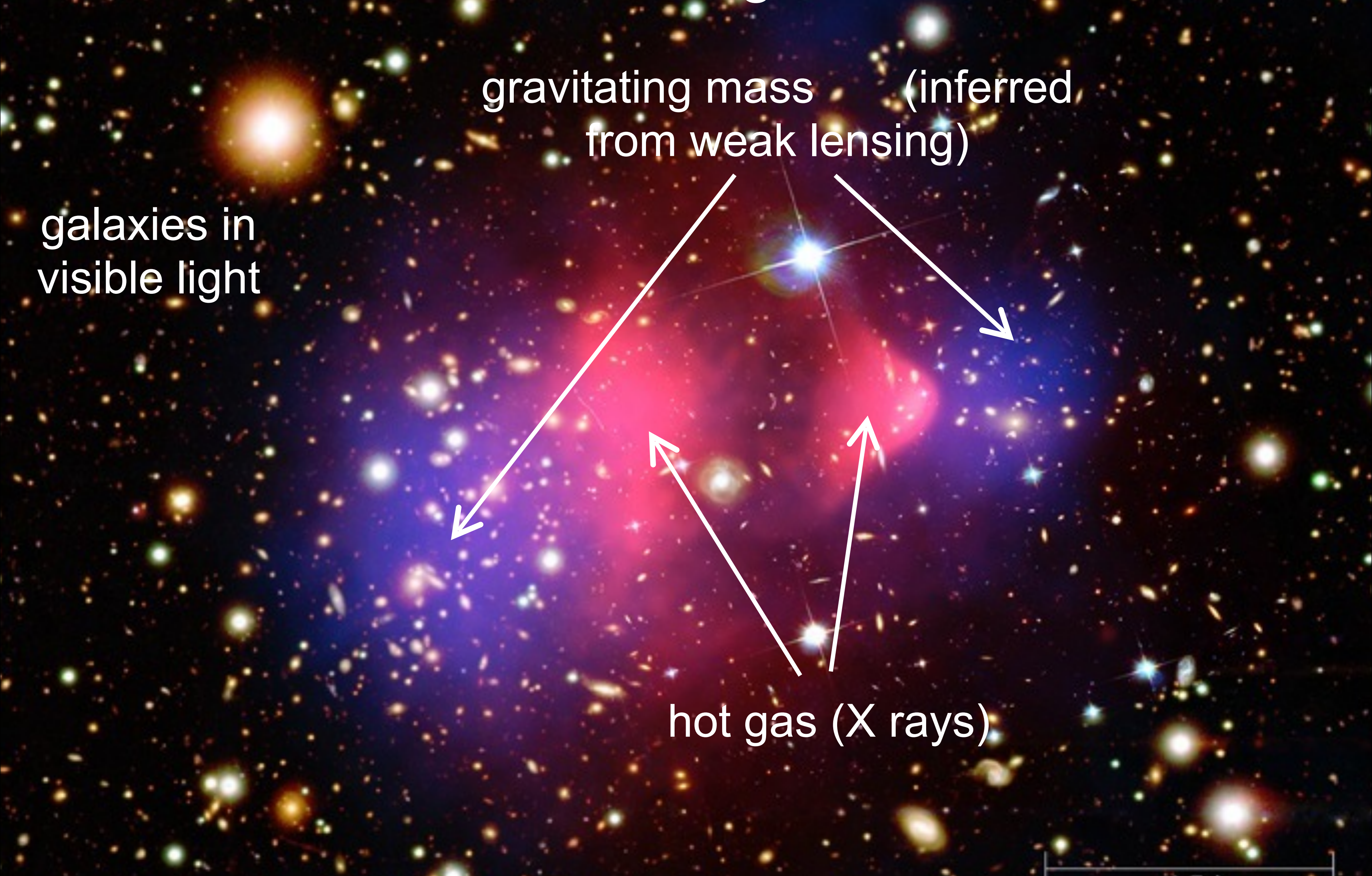
galaxy rotation curves



$$\boxed{v(r) \approx \text{const.}}$$

Fig. 11.4 Rotational velocities as a function of nuclear distance determined from emission line spectra for several galaxies (adapted from Rubin and Ford 1980; courtesy Professor Rubin and the *Astrophysical Journal*, published by the University of Chicago Press).

Weak Gravitational Lensing: Bullet Cluster



NASA/CXC/CfA/STScI

b)

Cosmology

Standard Big Bang Cosmology tells us:

$$\Omega_{\text{photons}} \ll \Omega_{\text{baryons}} \ll \Omega_{\text{cold dark matter}} \ll \Omega_{\text{dark energy}}$$

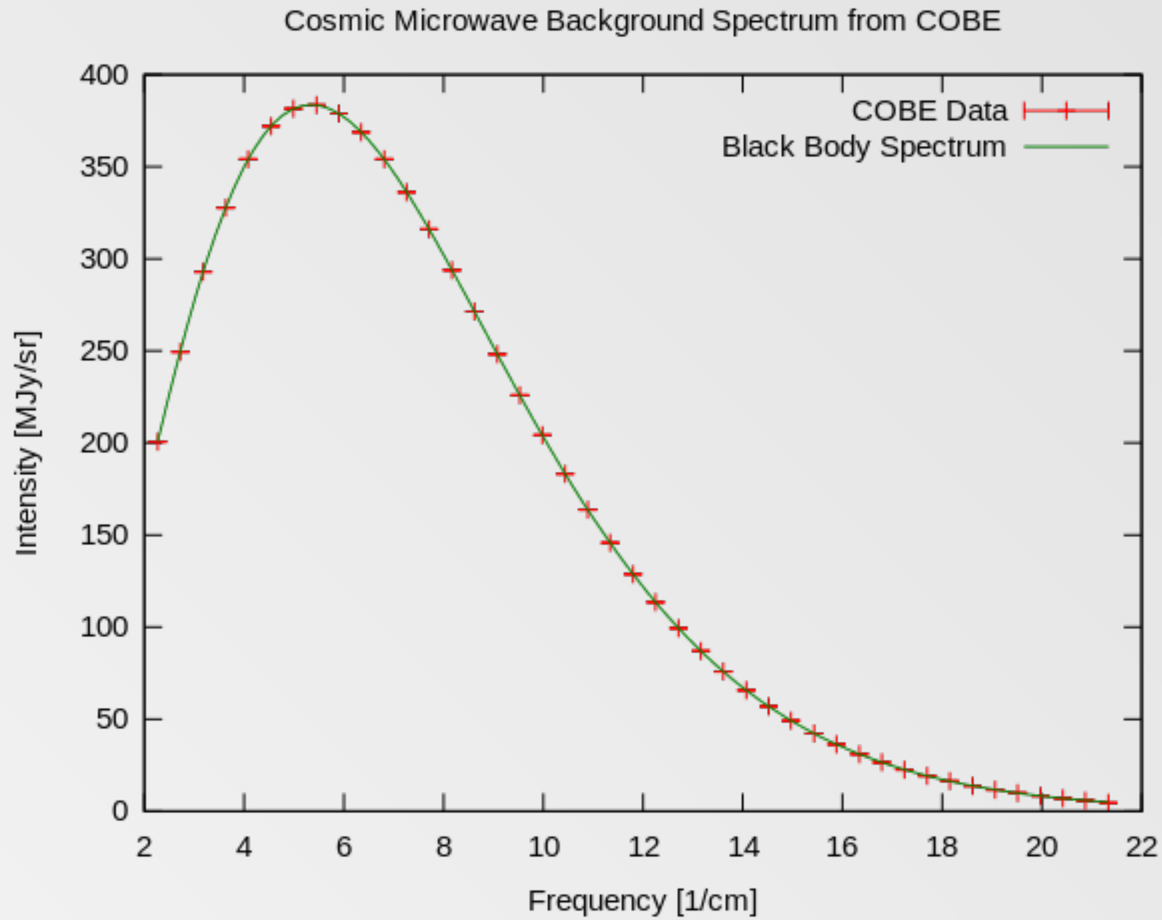
$\Rightarrow$ the Standard Model stuff is not enough!

Derived from a cocktail of cosmological probes:

- Cosmic Microwave Background (CMB)
- Supernovae Ia (and other standard candles)
- Galaxy surveys, large scale structure and Baryon Acoustic Oscillation (BAO)
- weak lensing (cosmic shear) as tracer for mass distribution
- Lyman α forest as tracer for intergalactic hydrogen
- X ray luminosity of galaxy clusters as tracer for total mass

CMB (1):

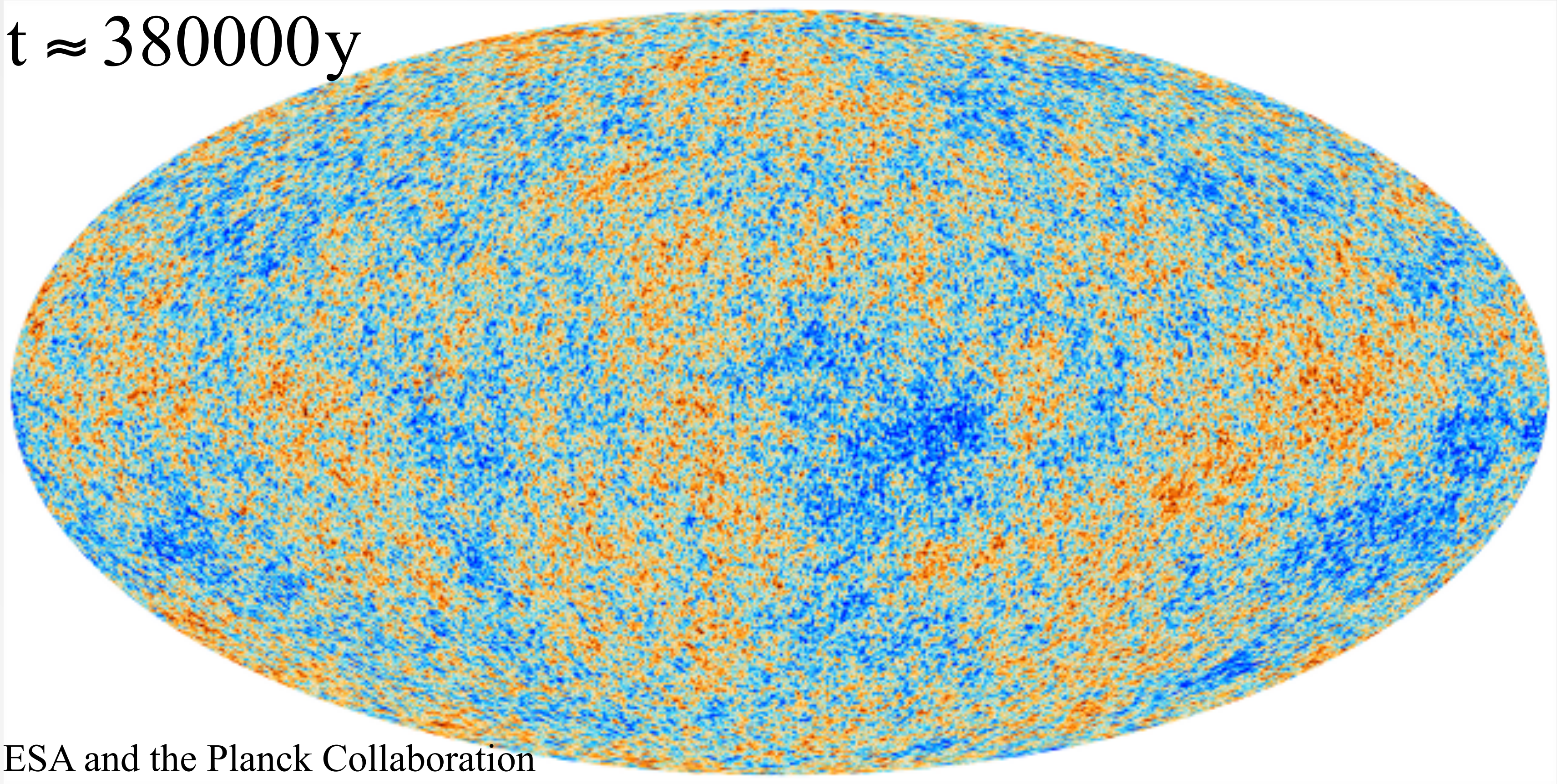
this dominates the energy density of photons



perfect black body spectrum, T = 2.725 K

$$\Rightarrow n_\gamma \approx 411\,\mathrm{cm}^{-3}, \quad \Omega_\gamma < 10^{-4}$$ negligible

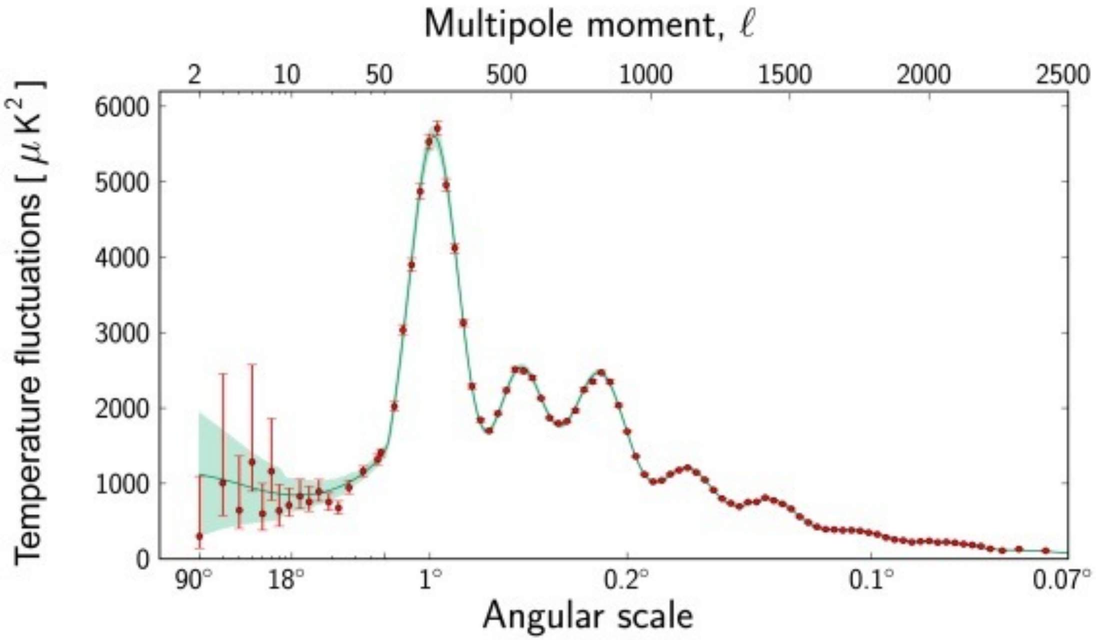
CMB (2): Temperature Anisotropies (10^{-5} level)

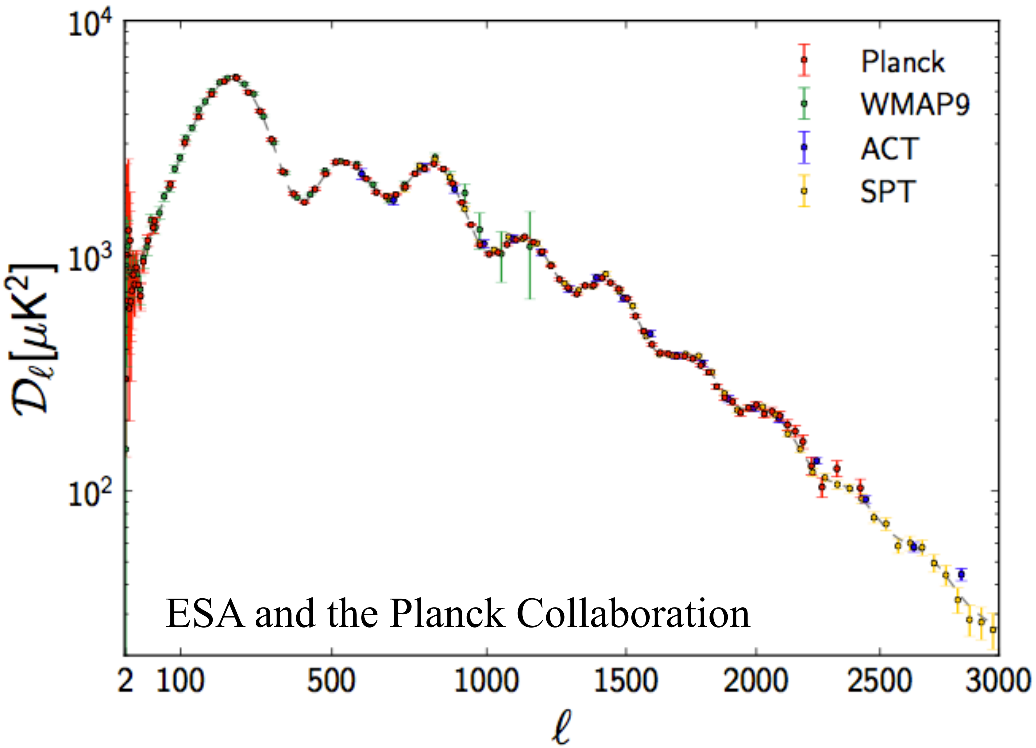


- from primordial quantum-fluctuations, stretched out by inflation
- tracer of initial mass distribution at time of decoupling
- matter dominated by gravity from then on

Expansion in $Y_{\ell m}$:

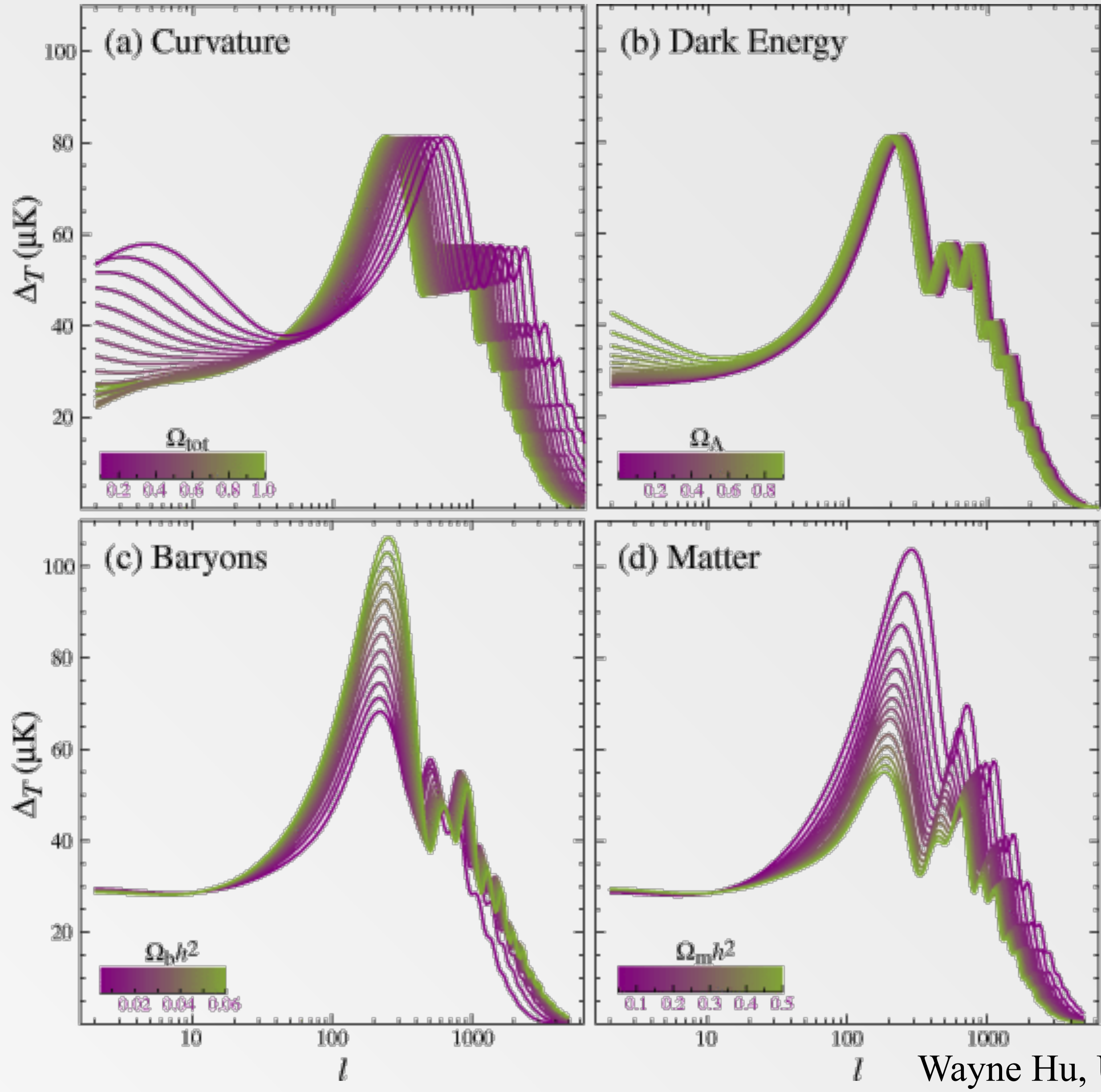
- ➢ power spectrum of T-fluctuation vs. scale ℓ
- ➢ representing intensities of matter-light oscillations
- ➢ very sensitive to (some) cosmological parameters…
- ➢ …in particular to baryon/dark matter ratio





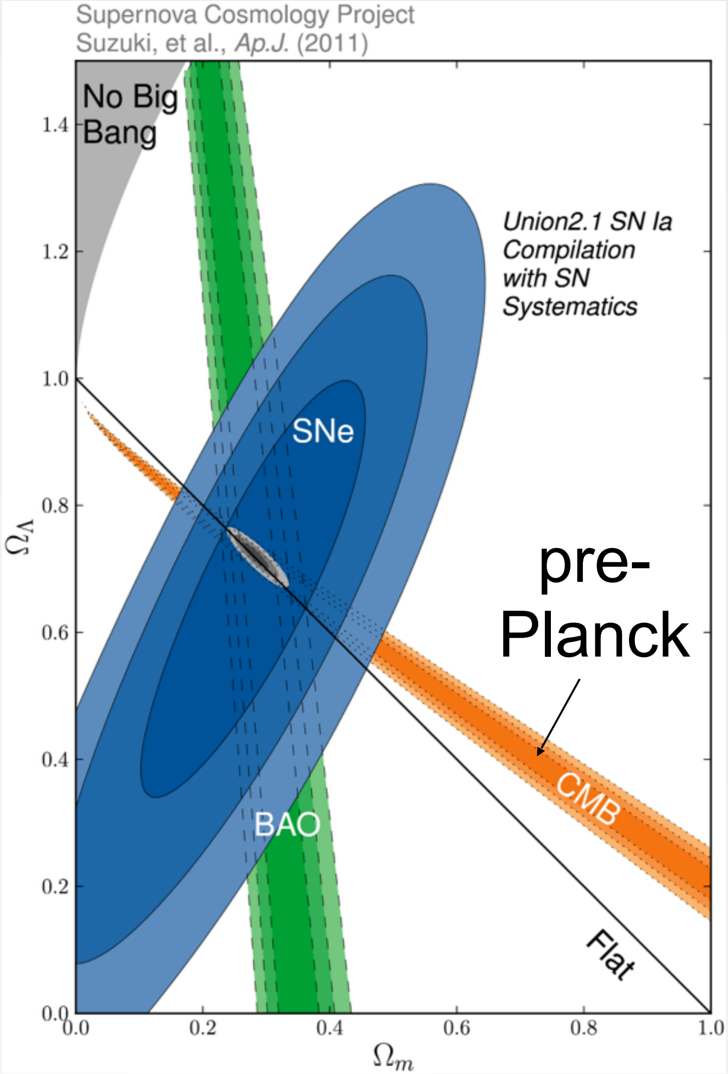
ESA and the Planck Collaboration

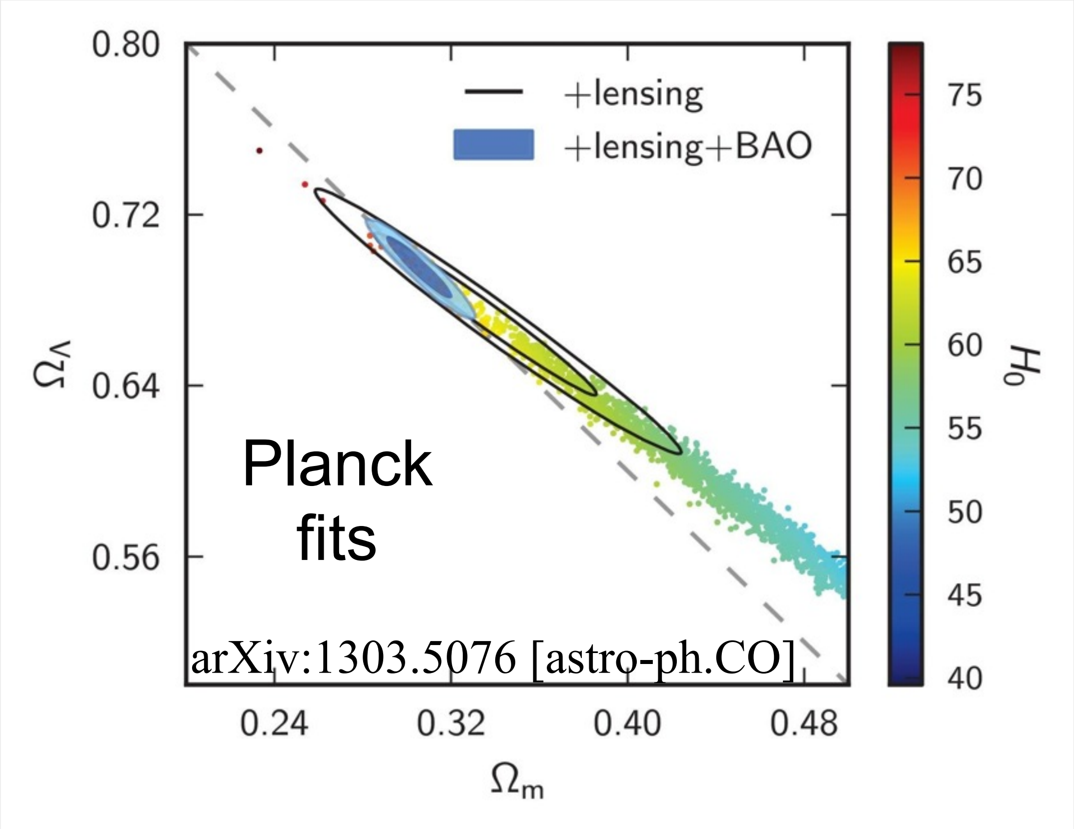
Parameter sensitivity of the CMB power spectrum:



Wayne Hu, U. Chicago

Parameter degeneracies exist $\Rightarrow$ combined fits using complementary probes





$\Rightarrow$ flat Universe with

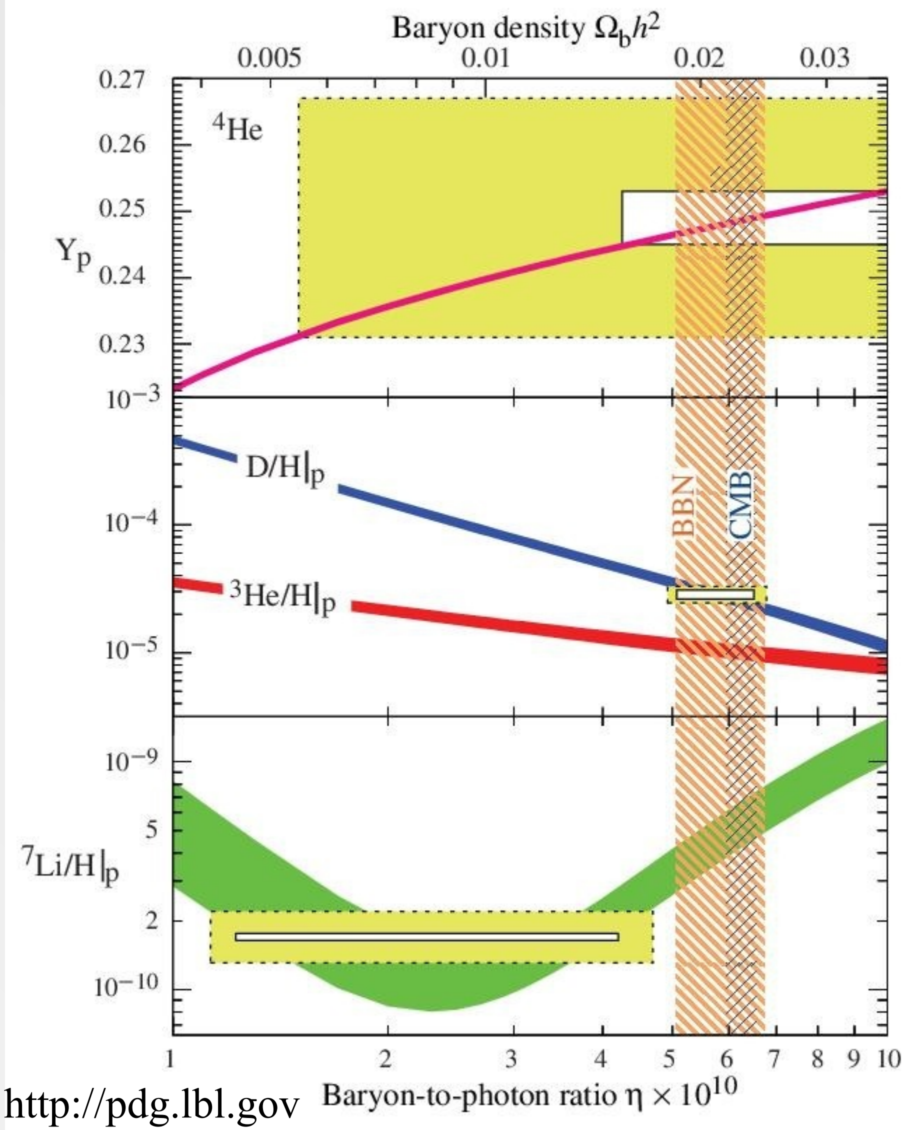
$$\Omega_m \approx 0.3 \quad \Omega_\Lambda \approx 0.7$$

and $\Omega_b \approx 0.05$

An independent path: Big Bang Nucleosynthesis (BBN)

- Light elements formed in the primordial plasma (1s < t < 200s)
- Tricky to measure (from places “free” of contributions from stars)
- the coctail:
  - n / p freeze-out from weak interaction equilibrium at t ≈ 1s
  - fusion of nucleons/nuclei
  - photons → nuclear fission
  - neutrons decay
- hence sensitive to photon and nucleon (→baryon) density
- pretty consistent picture for

$$\eta \equiv \frac{n_b}{n_\gamma} \approx 6\times10^{-10}$$



http://pdg.lbl.gov

Agrees with cosmological parameter fits (CMB & other probes)

Part II

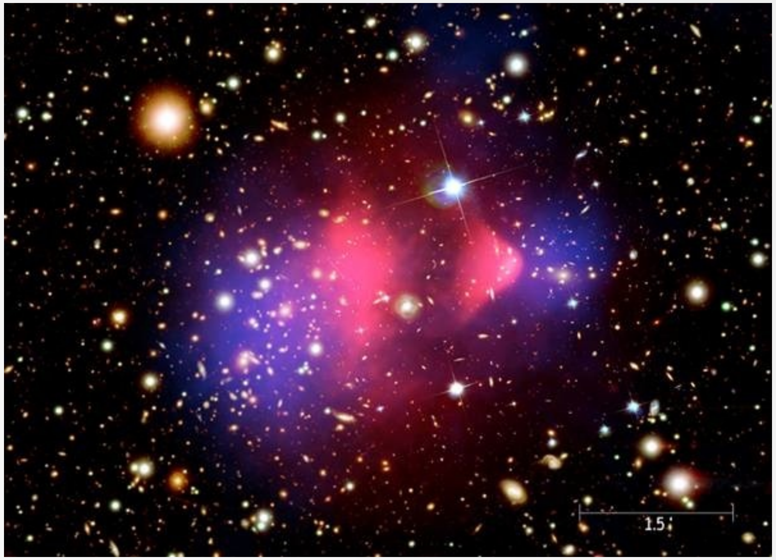
What

(the hell) is dark matter

?

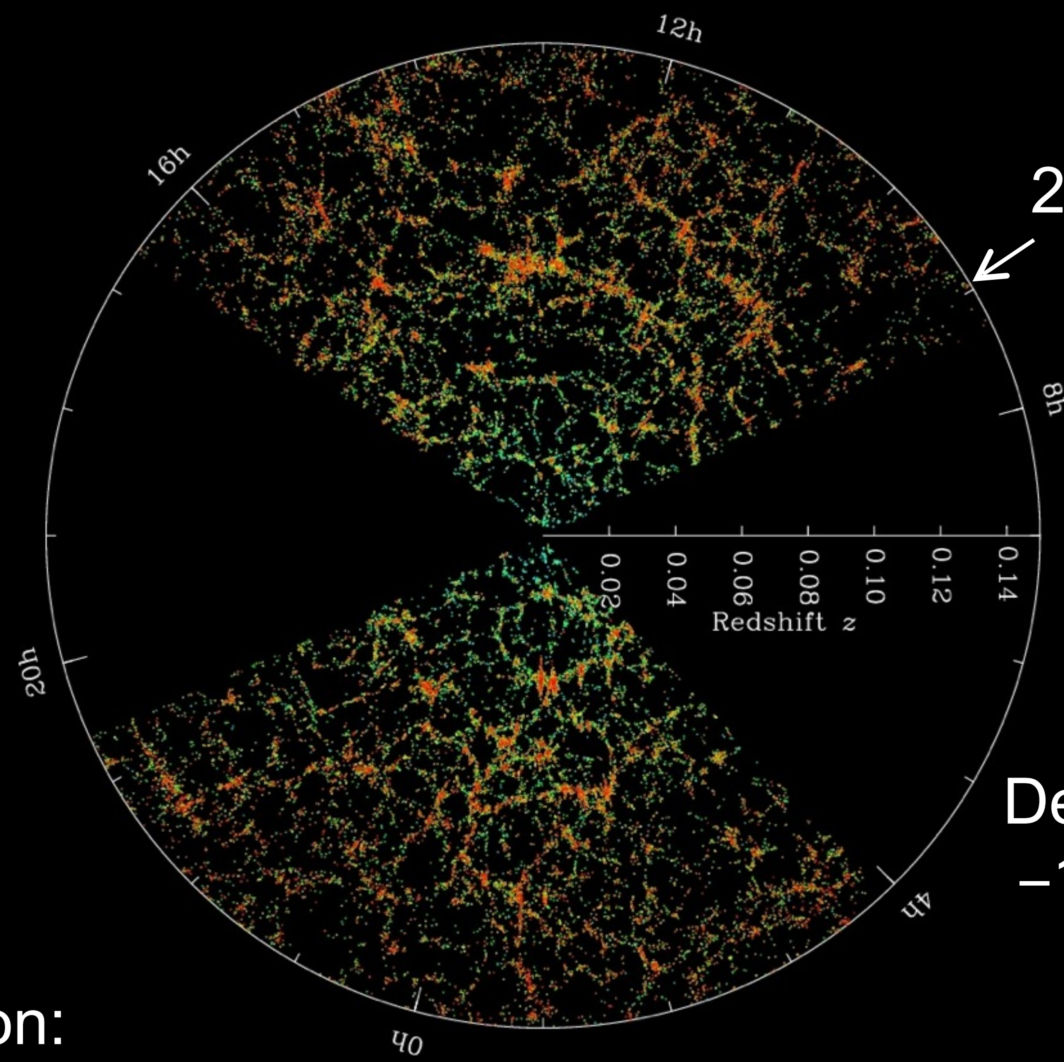
Assume it is some sort of particles:

- stable on cosmological time scales (or they would be gone)
- no electromagnetic radiation
- hence electrically neutral
- no strong interaction either or we would feel them



- they feel gravity
- and probably (hopefully) other weak interactions
- in any case they were driving the large scale structure formation

The Sloan Digital Sky Survey



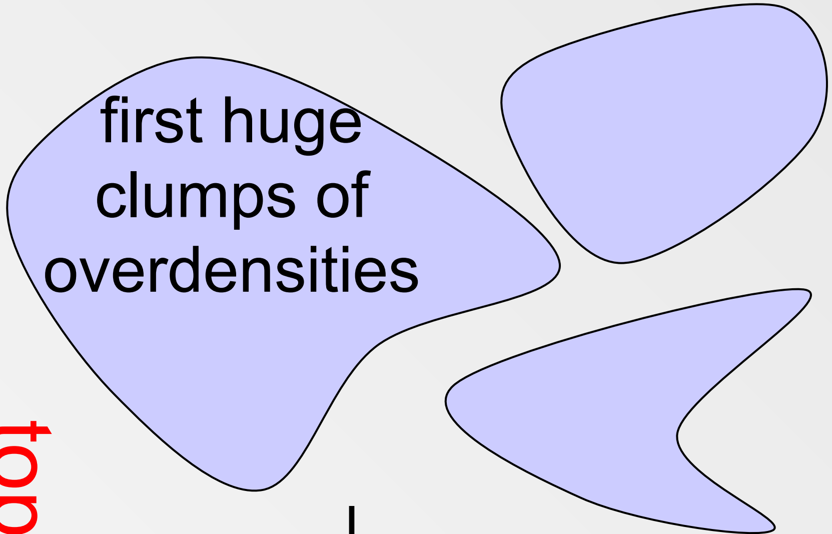
2 Billion light years

Declination slice –1.25°…+1.25°

Conclusion:

The DM particles must have been slow (v c) already at time of decoupling, because…

relativistic dark matter

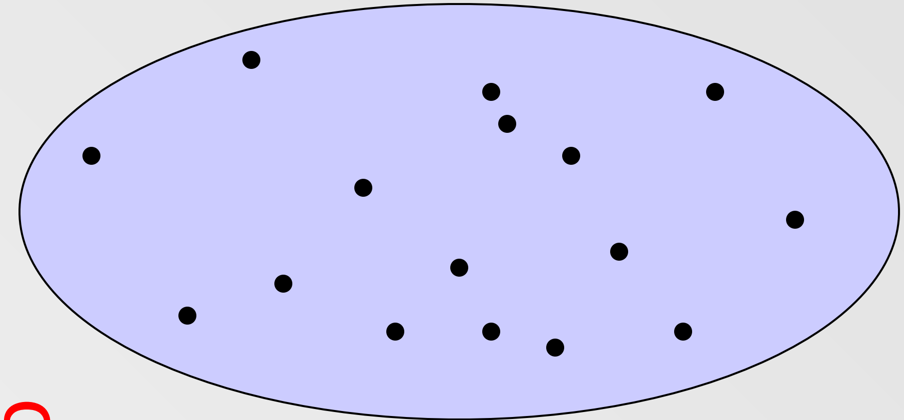


top down

fragmentation to
smaller structures

fragmentation to galaxies
typically at $z<1$

slow dark matter



bottom up

small seeds of overdensities

first galaxies at z1

(super)clusters, filaments,
voids

This is what we see!

Consequence (1):

Dark Matter particles are either

- cold $\leftrightarrow$ massive (i.e. non-relativistic when decoupling from thermal equilibrium)

$\Rightarrow$ **W**eakly **I**nteracting **M**assive **P**articles

- non-thermally produced and slow and possibly light

Consequence (2):

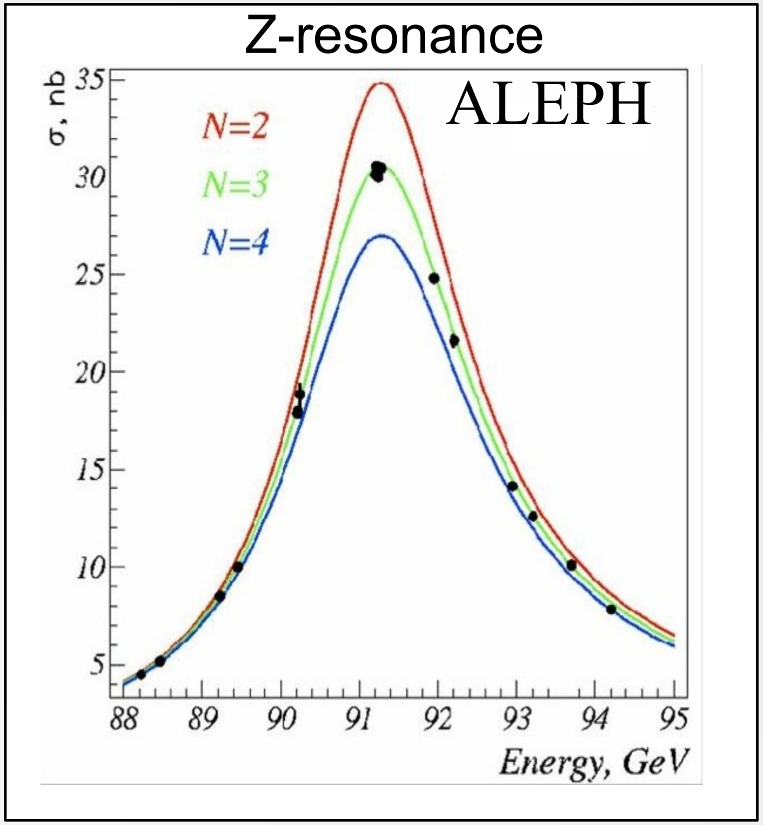
Standard (light!) neutrinos are excluded:

$$\Omega_\nu < 0.0062 / h^2$$ negligible

Consequence (2) in different words:

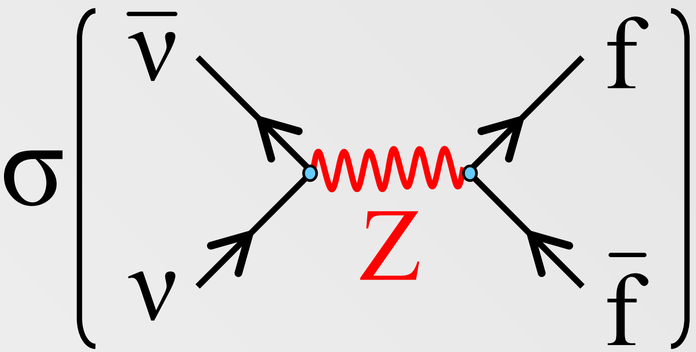
dark matter standard neutrinos have to be heavy!

But:



$$\Rightarrow \quad m_\nu > \tfrac{1}{2} m_Z \approx 45\,\mathrm{GeV}$$

$$\Downarrow$$



too large

$\Rightarrow$ DM relic density too small

(see below)

What remains:

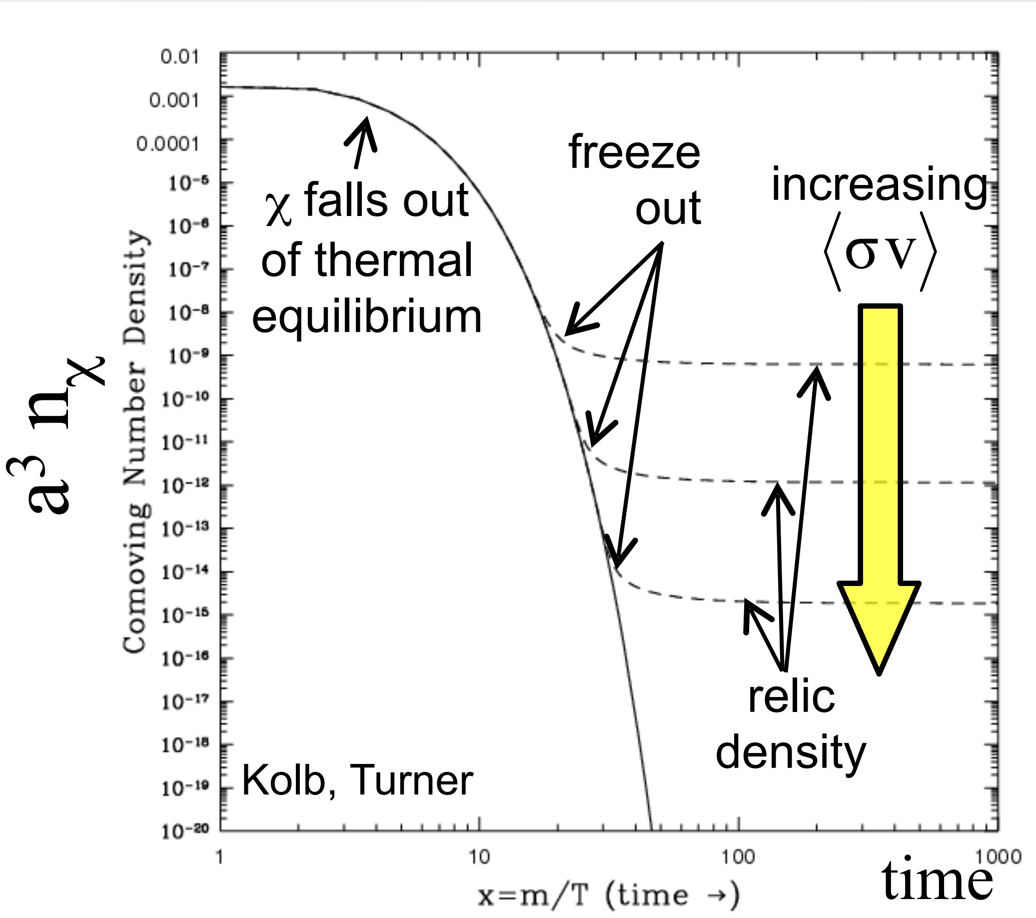
There could be (massive) sterile neutrinos…

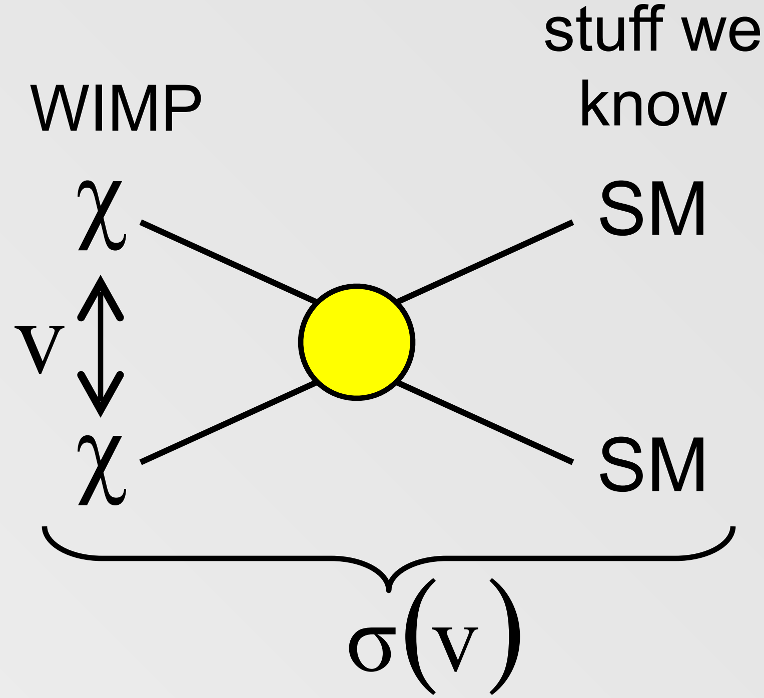
a)

WIMPs

Some Candidates

The WIMP miracle





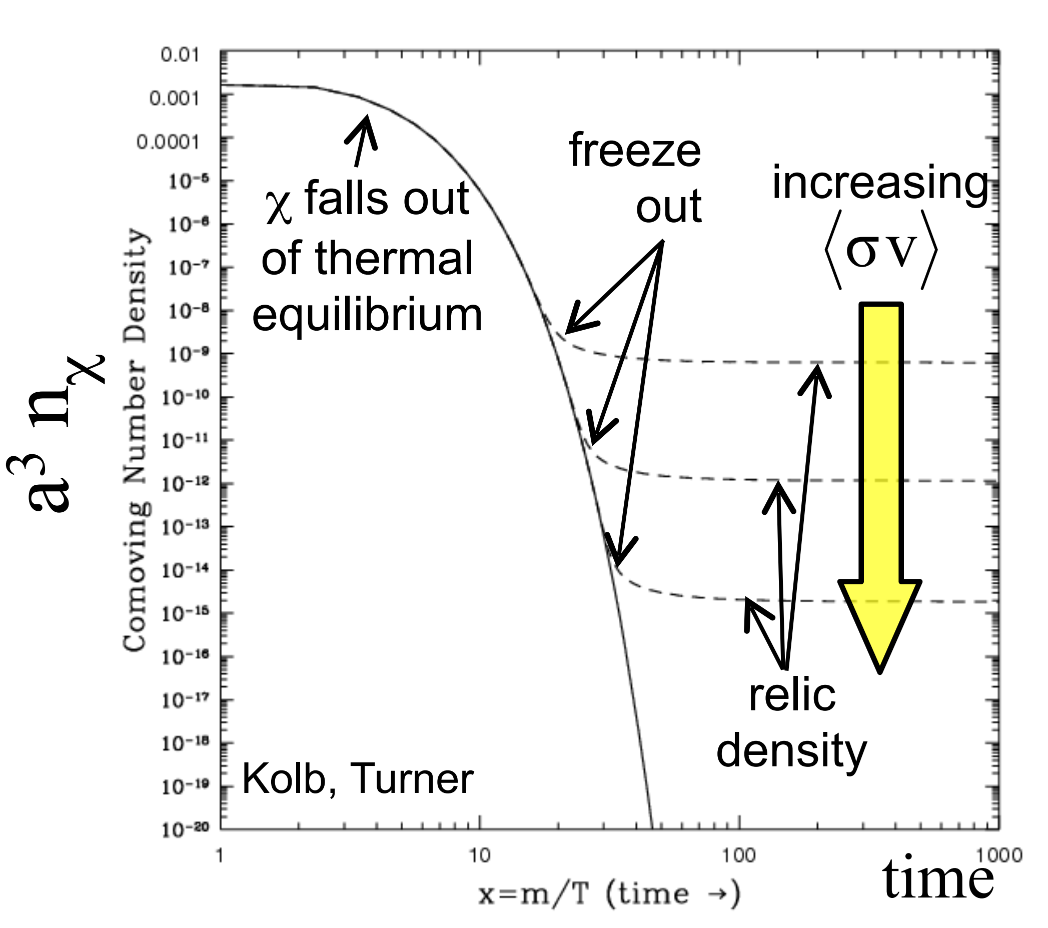
$$T \rightarrow \rho(v) \rightarrow \langle \sigma v \rangle$$

annihilation rate per volume

$$\propto \langle \sigma v \rangle n_\chi^2$$

freeze out point: annihilation rate falls below expansion rate H

The WIMP miracle



predicted relic density today:

$$\Omega_\chi \approx \frac{3\times 10^{-27}\,\mathrm{cm}^3/\mathrm{s}}{h^2\langle\sigma v\rangle}$$

~ 0.2 (observed)

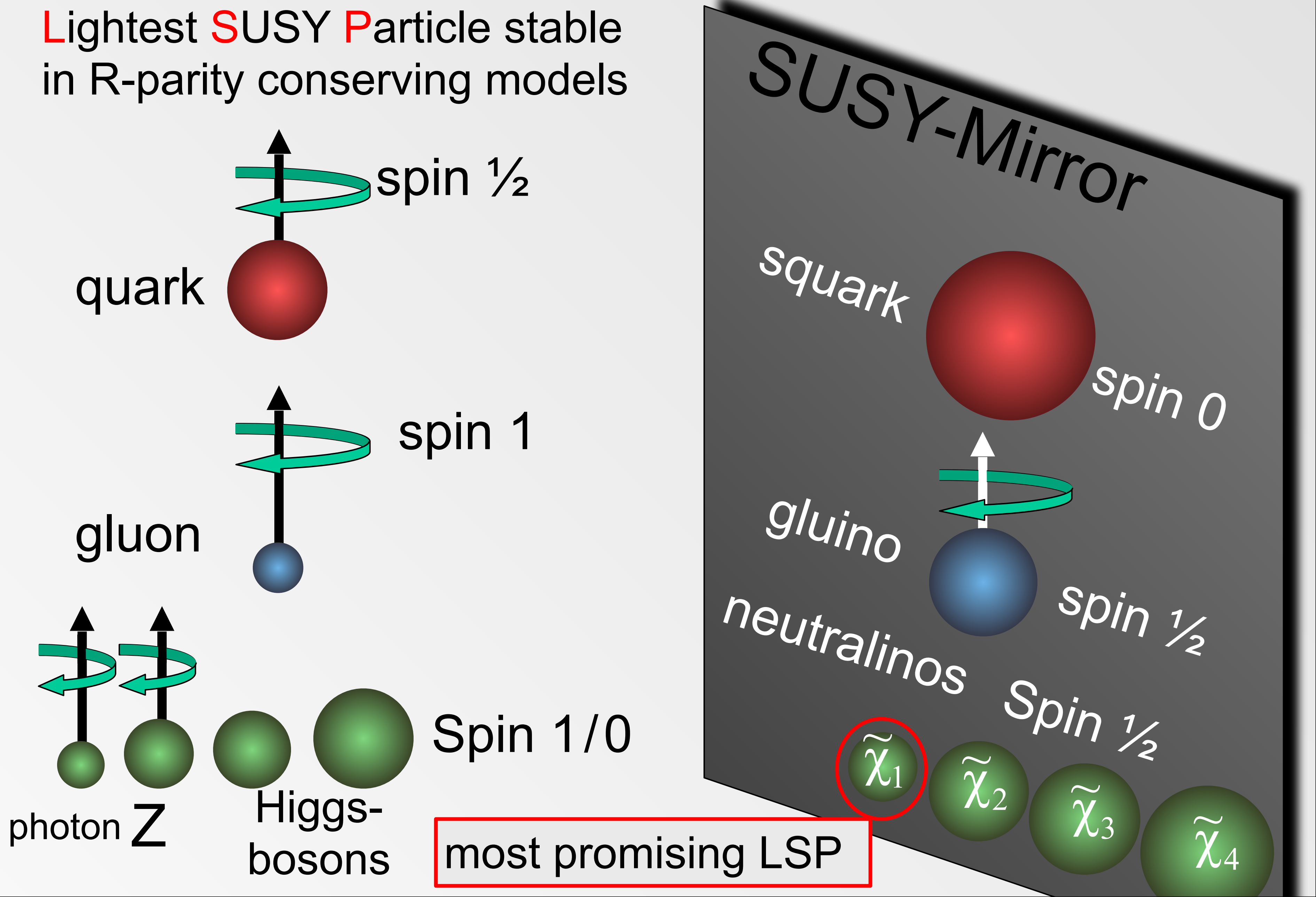
indeed expected for (e.g.) weak interaction scale/strength

Is this really a miracle???

Anyway, keep in mind: $\boxed{\langle\sigma v\rangle \approx 3\times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}}$

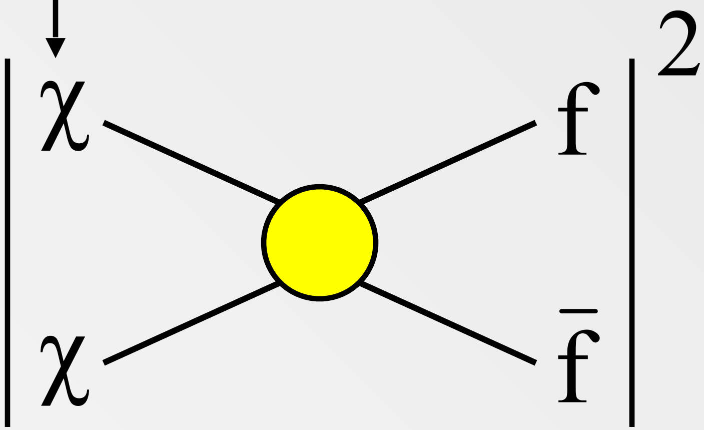
• Candiate 1: Supersymmetry (SUSY)

Lightest SUSY Particle stable
in R-parity conserving models



Neutralino annihilation to fermions:

Majorana fermions



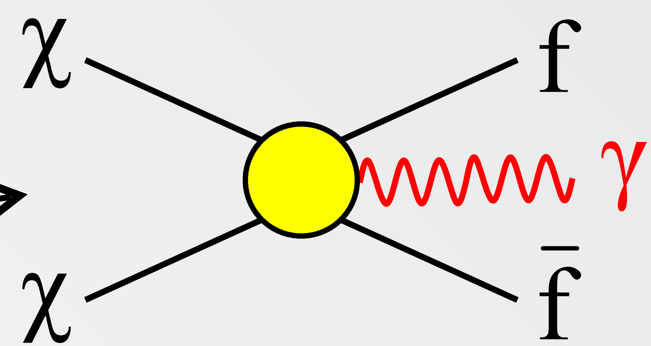
Helicity suppression

$$\propto \frac{m_f^2}{m_\chi^2}$$

→ heaviest energetically allowed quark dominates final state

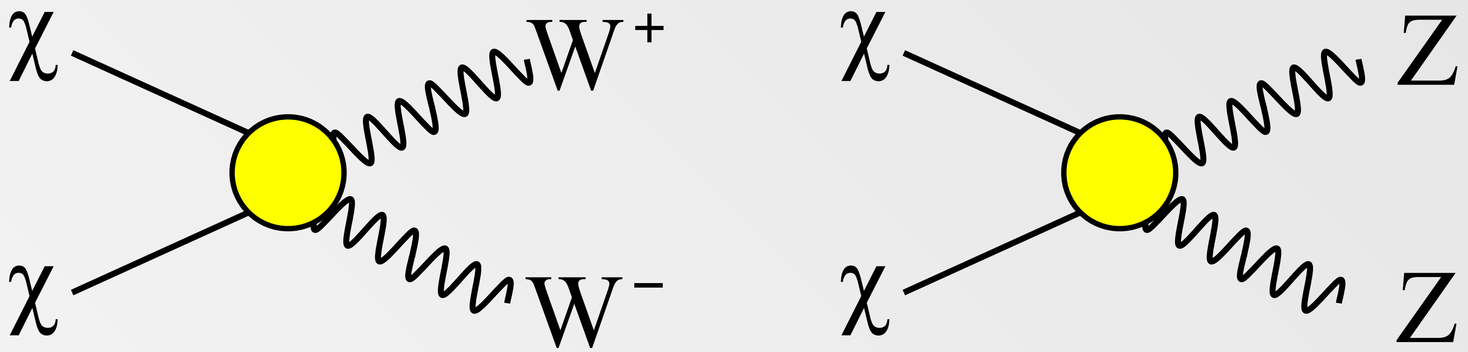
→ internal bremsstrahlung is very important for final state gamma rays with $E_\gamma \to m_\chi$

this can avoid helicity suppression at cost α/π



Neutralino annihilation to bosons:

If χ has large mixing with $SU(2)_L$-partners (Wino, Higgsino)

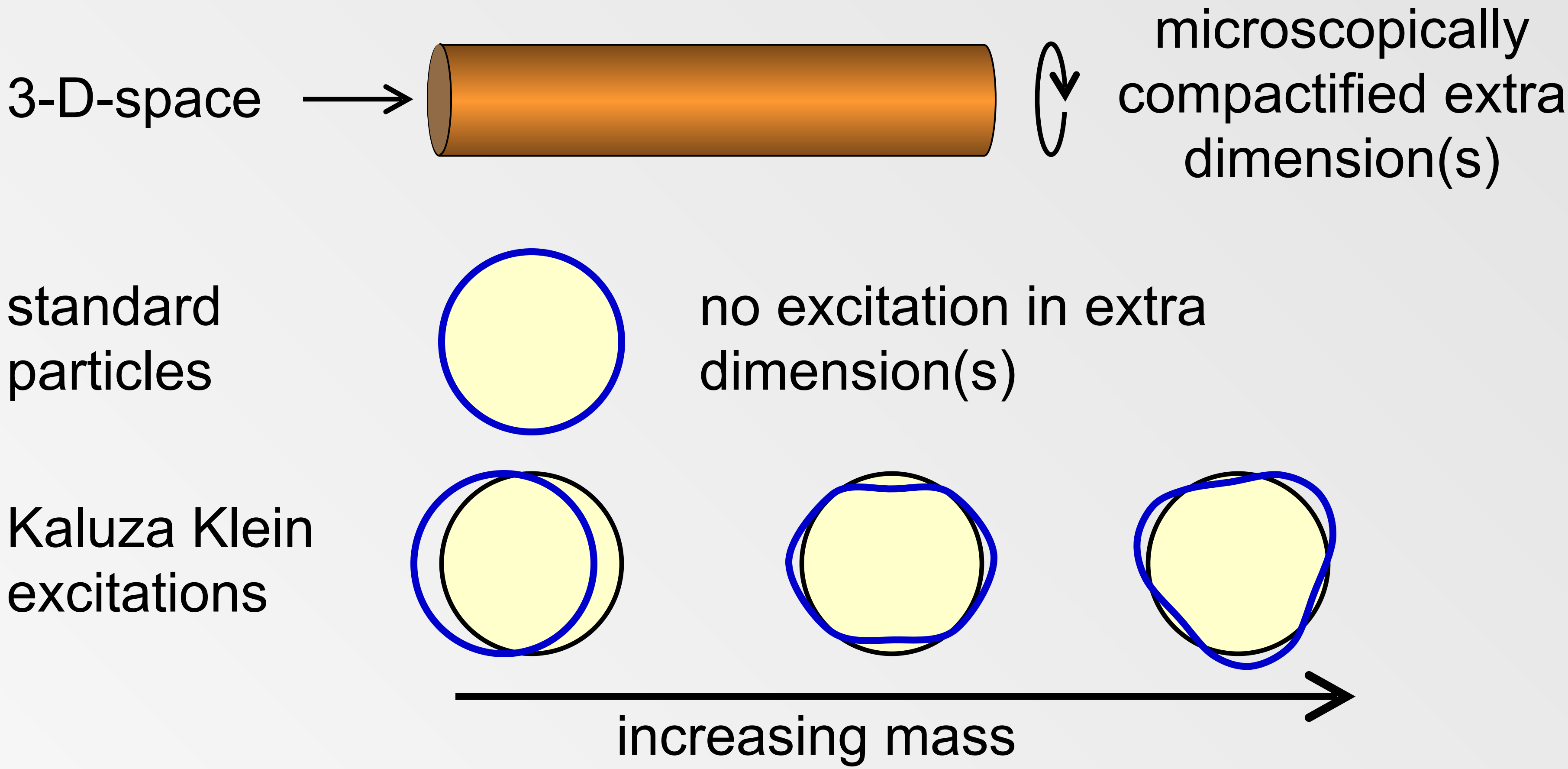


important sources of

→ prompt (⇒ high energy) electrons/positrons

→ prompt (⇒ high energy) neutrinos

• Candidate 2: Extra Dimensions (Kaluza Klein excitations)



WIMP = lightest (neutral, stable) Kaluza Klein excitation
(stable due to a conserved KK parity)

Most popular KK dark matter WIMP:

charge	gauge group	SM gauge boson
weak hyper-charge Y	$U(1)_Y$	B
weak isospin I_3	$SU(2)_L$	W^0 $W^\pm$

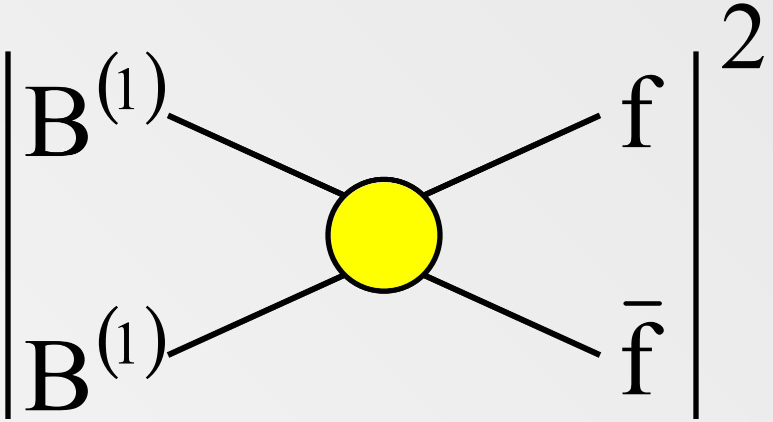
$\rightarrow$ $\boxed{B^{(1)}}$

first KK excitation of the weak hypercharge gauge boson

Remember the physical neutral gauge bosons in the SM:

$$\begin{pmatrix} \textbf{Photon} \\ \textbf{Z-Boson} \end{pmatrix} = \theta_W \begin{pmatrix} B \\ W^0 \end{pmatrix}$$

$B^{(1)}$ annihilation to fermions:



$$\propto \quad Y_f^4$$

f	[illegible]$_R$	u_R	[illegible]$_L$, ν_L	u_L, d_L
$Y = 2(Q - I_3)$	-2	$\frac{4}{3}$	-1	$\frac{1}{3}$

the winners are:
up-type quarks and charged leptons

Many other WIMP candidates…

- other KK states (Z, H, neutrino, graviton,…)
- Little Higgs dark matter
- technicolor states
- mirror dark matter
- ...

and subtleties affecting $\langle \sigma v \rangle_{\text{today}}$

- (near) mass degeneracies and co-annihilation
- resonance effects
- threshold effects
- …

ask our theorists if you want to know more about this! ☺

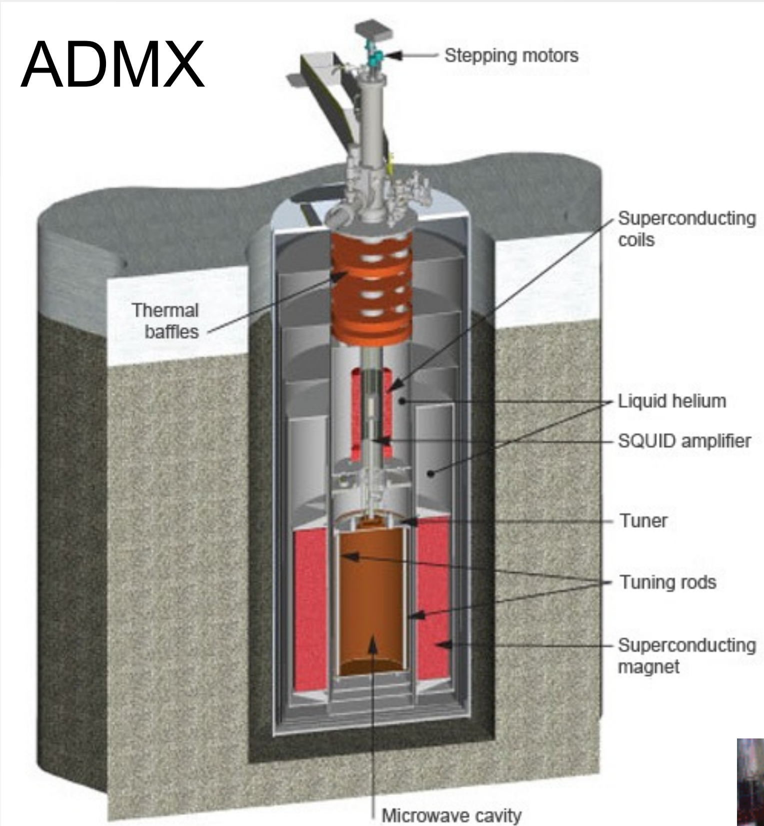
b)

Axions

a non-thermally produced light
DM candidate

$$\boxed{10^{-6}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-3}\,\mathrm{eV}}$$

Rich experimental program (for axions & axion-like particles)



tunable high Q microwave cavity

LHC magnet pointing at the sun

laser shining through a wall in a magnet but also…

extragalactic background light

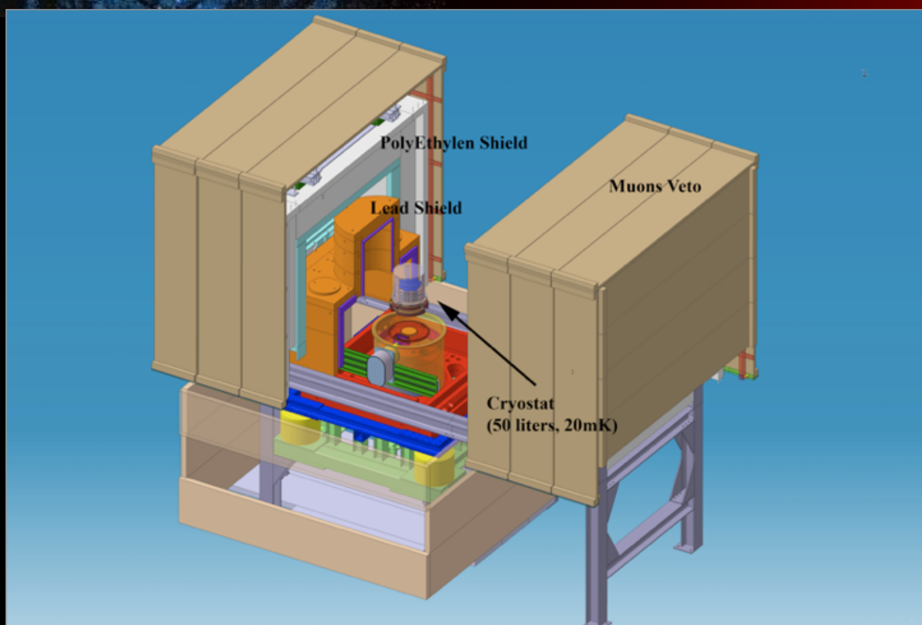
γ γ γ e^+ e^-

axion

γ

features in AGN spectra

e.g. Horns, Meyer, Raue, PR D87, 035027 (2013)



direct searches can look for e-recoils,

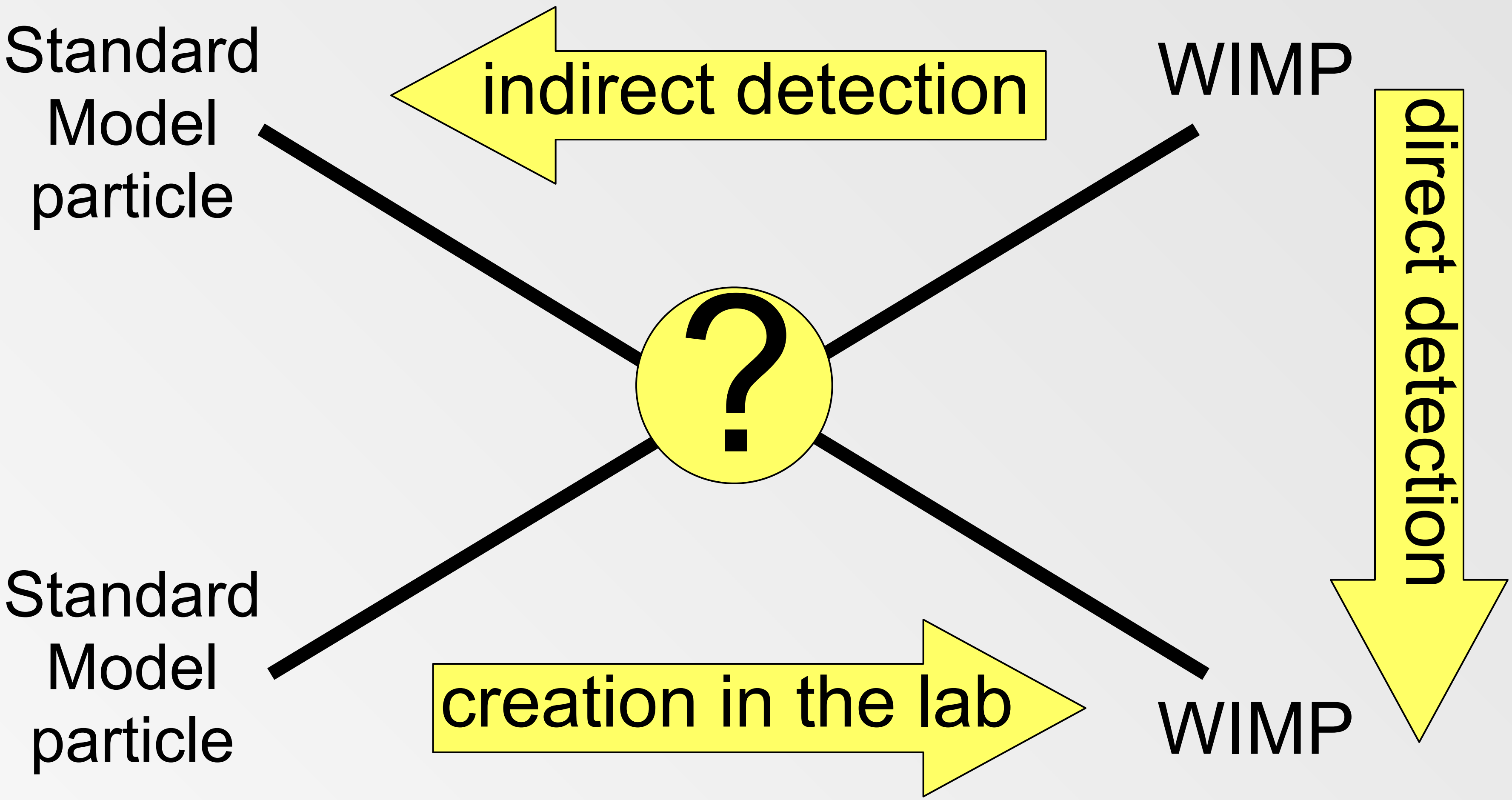
e.g. EDELWEISS-II, arXiv:1307.1488 [astro-ph.CO]

Part III

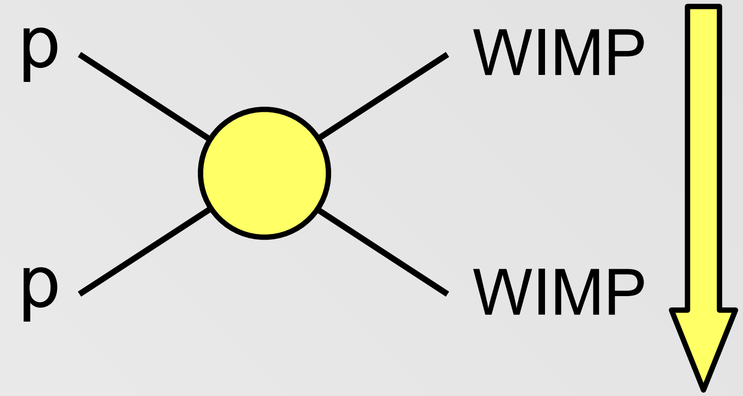
How to look for DM experimentally

Where to search in theUniverse

WIMP detection - the threefold way



a)

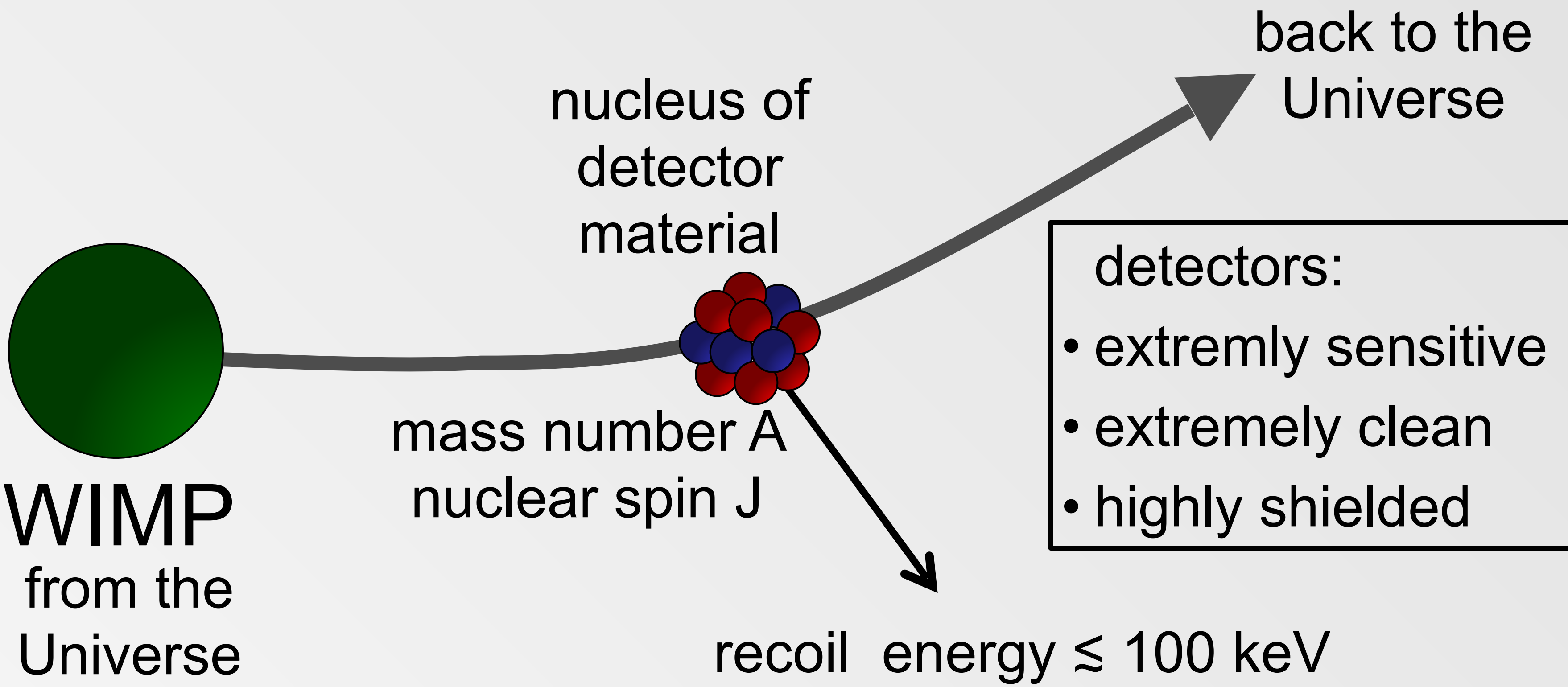


Direct Searches

...

sit down and wait

Highly shielded (deep underground) detectors



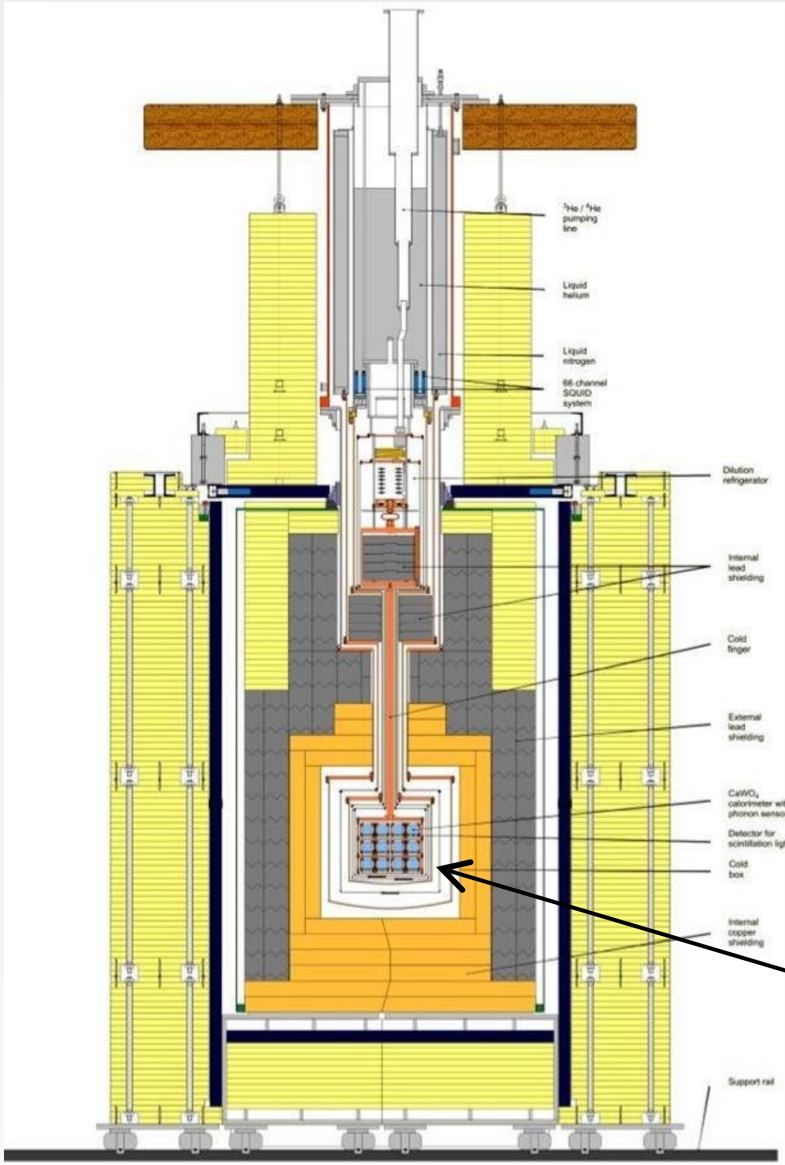
Signature from: ionisation / phonons / photons

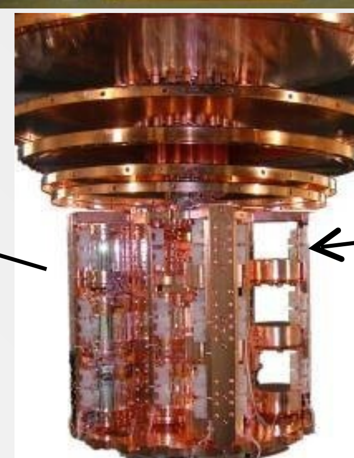
Cross section: spin independent part $\propto A^2$ dominant
spin dependent part $\propto f(J)$

Material: heavy, varying targets with $J \neq 0$ (from p or n)

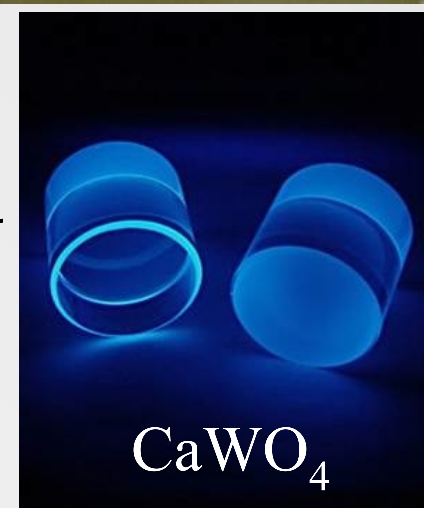
Direct WIMP Searches in the World

Example 1: Cryo detector CRESST (Gran Sasso)

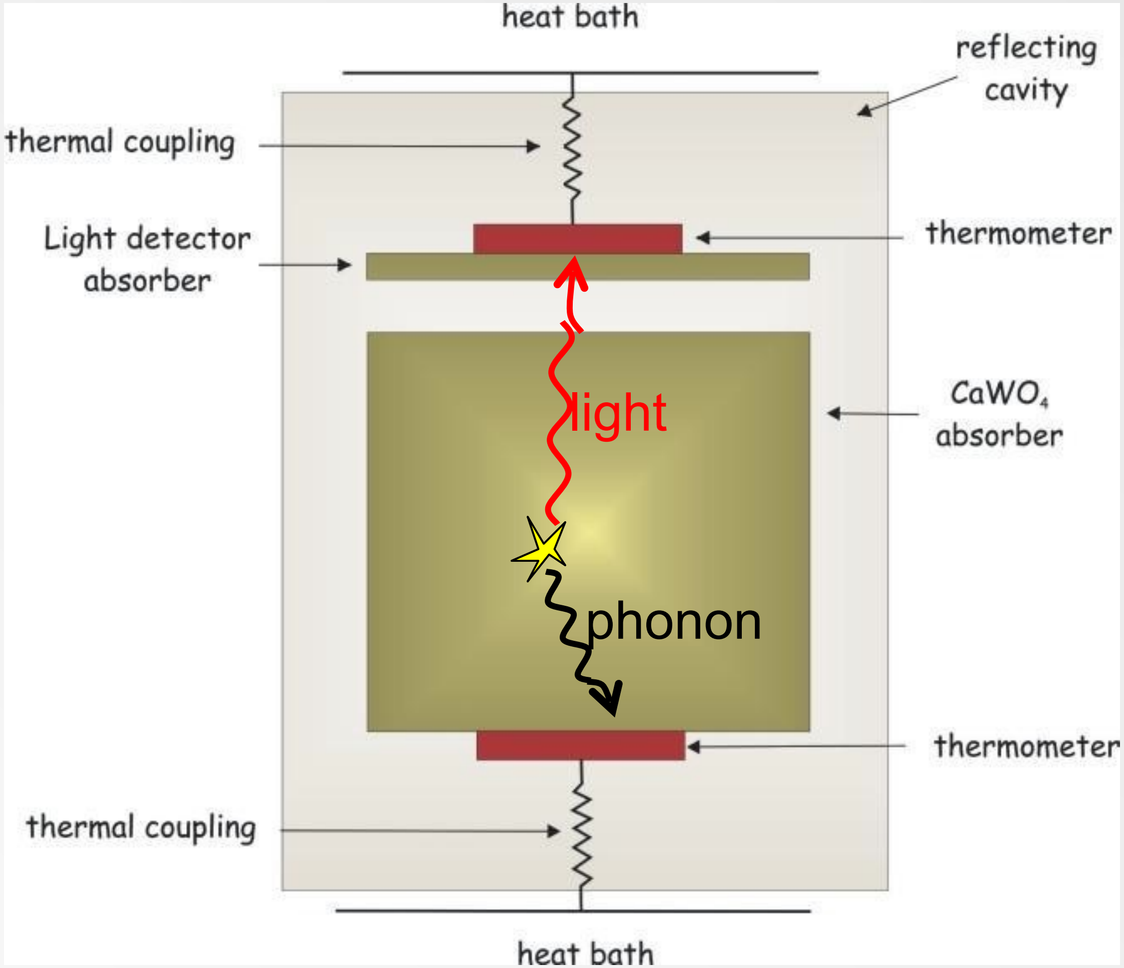




10 kg crystals



Detection: supraconducting thermomenters



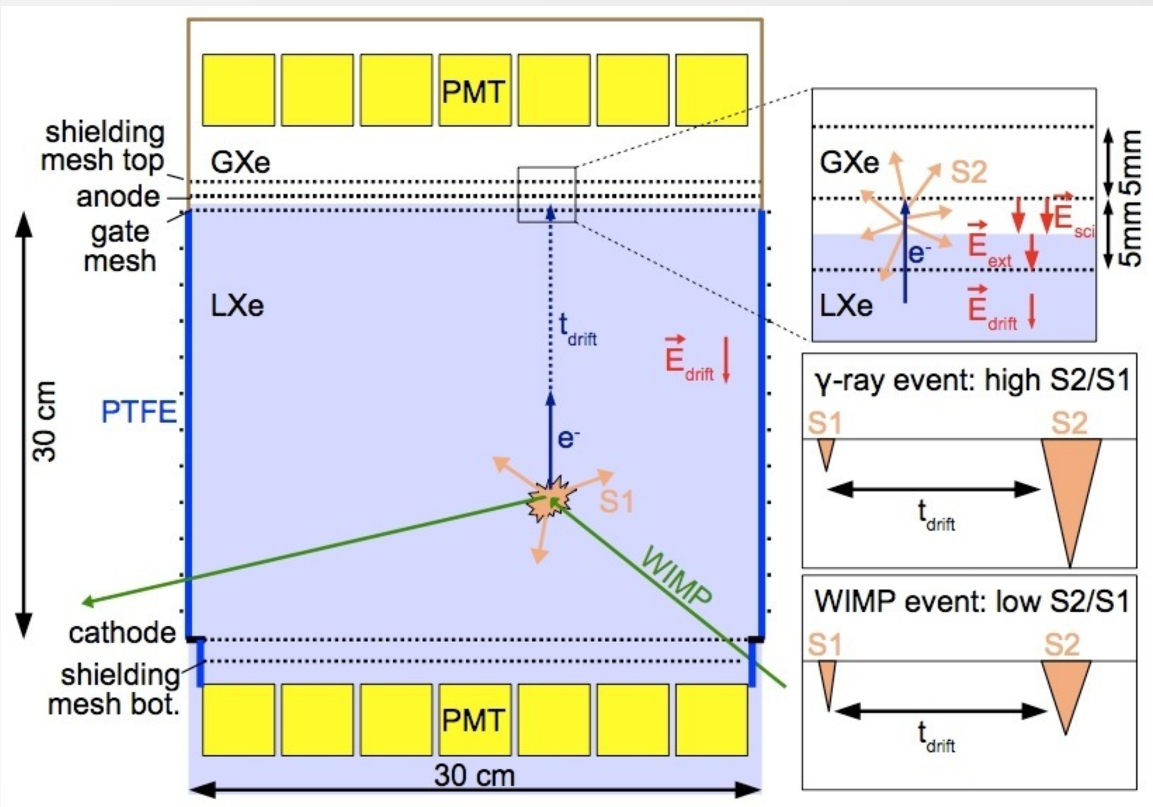
supraconducting phase-transition-
tungsten-thermometer (SPT)

	phonons	light
WIMP	✓	(✓)
backgr ound	✓	✓

detector moduls
at < 10 mK

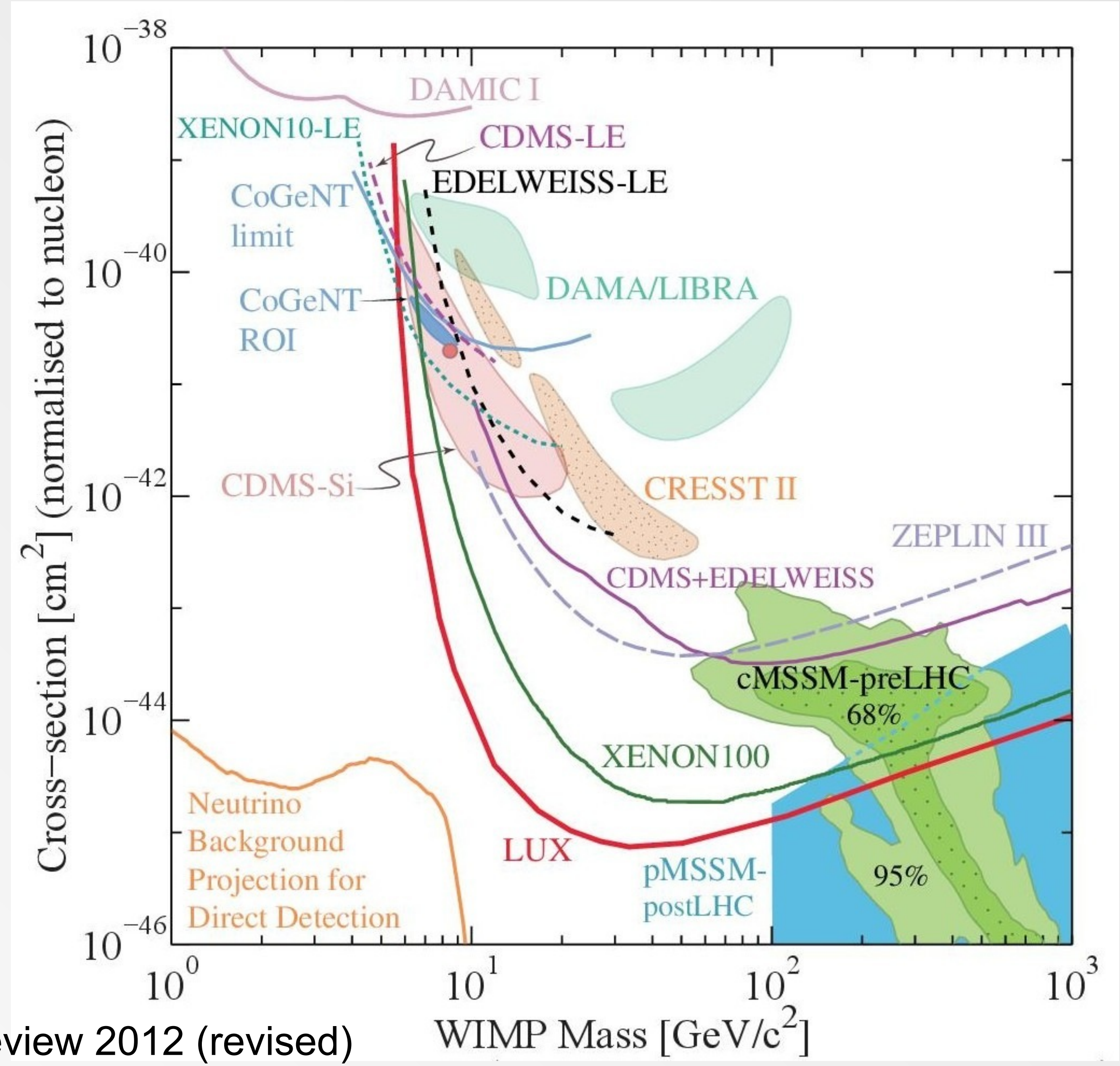
Example 2: Nobel gas detector XENON (Gran Sasso)

2 phase liquid/gas Xenon
Time Projection Chamber



	scintill.	ionization
WIMP	✔	(✔)
backgr ound	✔	✔

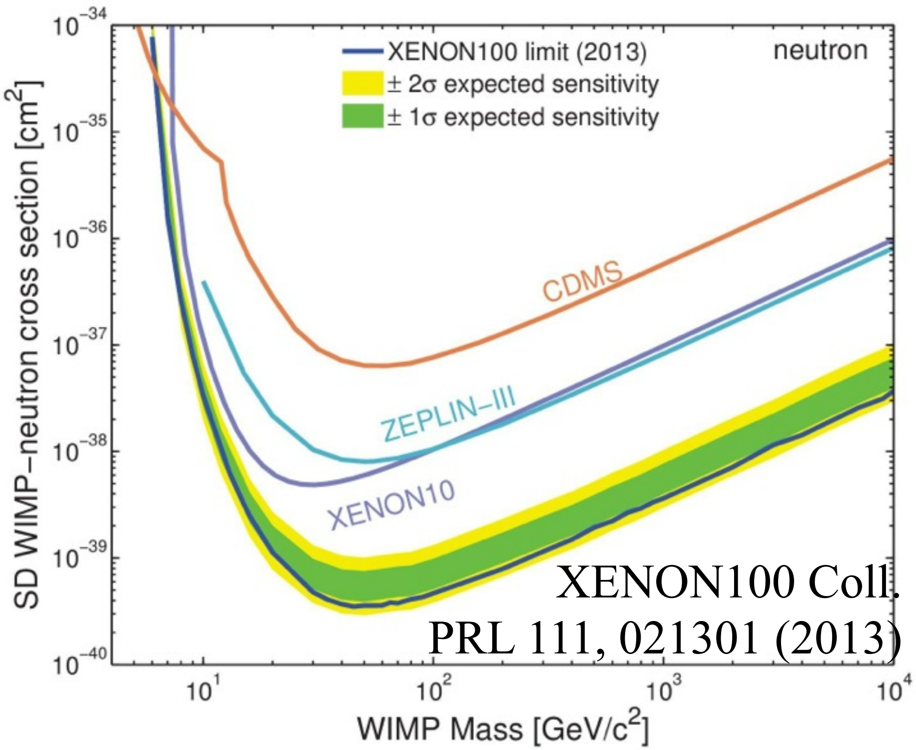
The latest exclusion limits (spin independent x-section)



PDG review 2012 (revised)

Spin dependent x-section limits much weaker

χ-neutron-scattering

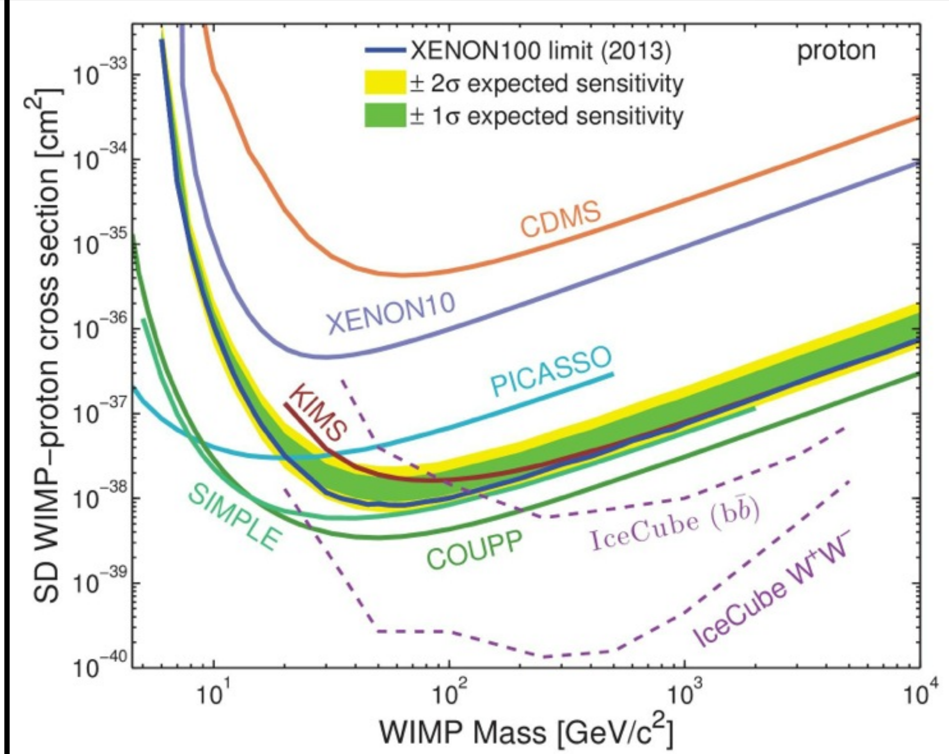


XENON100 Coll.
PRL 111, 021301 (2013)

$$\left.\begin{array}{l} {}^{129}\mathrm{Xe}\left(J = \frac{1}{2}\right) \\ {}^{131}\mathrm{Xe}\left(J = \frac{3}{2}\right) \end{array}\right\}$$ unpaired neutron

48% abundance in XENON100

χ-proton-scattering

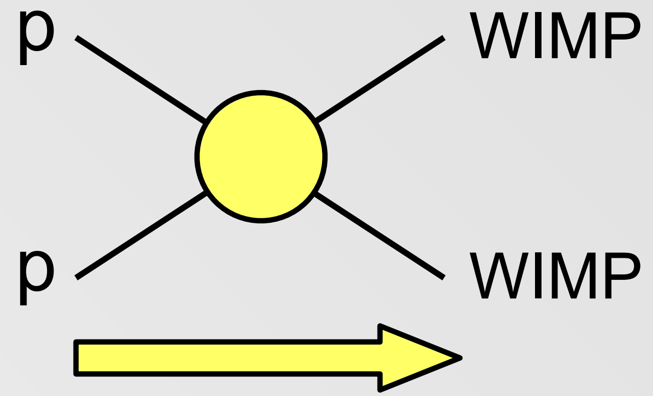


no unpaired protons

Better target: ${}^1_1\mathrm{H}$ (e.g. our Sun)

→ indirect detection via ν's

b)

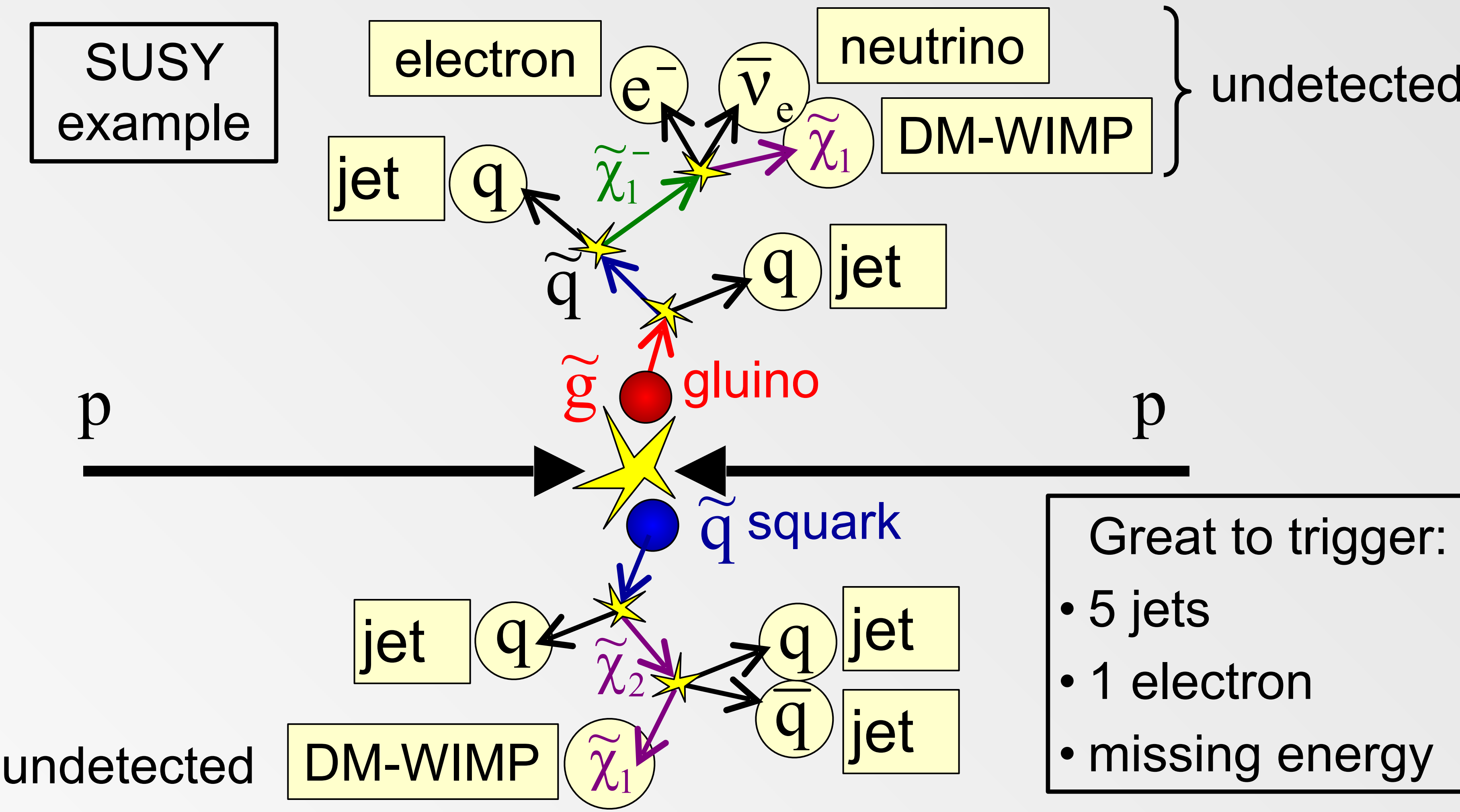


LHC

make your own
dark matter

LHC collides gluons/quarks

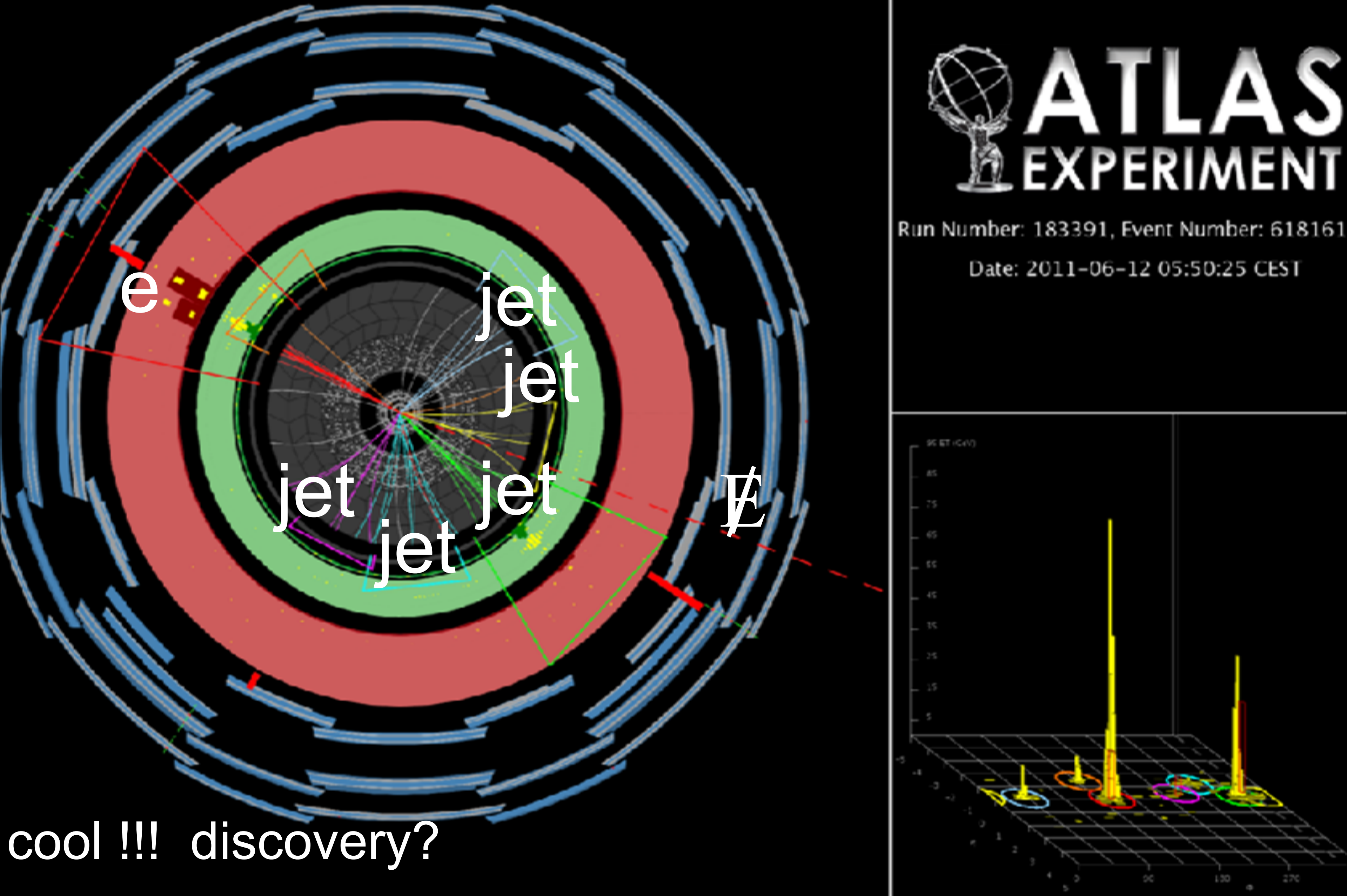
p + p → new strongly interacting states → decay chain → WIMPs



Great to trigger:

- 5 jets
- 1 electron
- missing energy

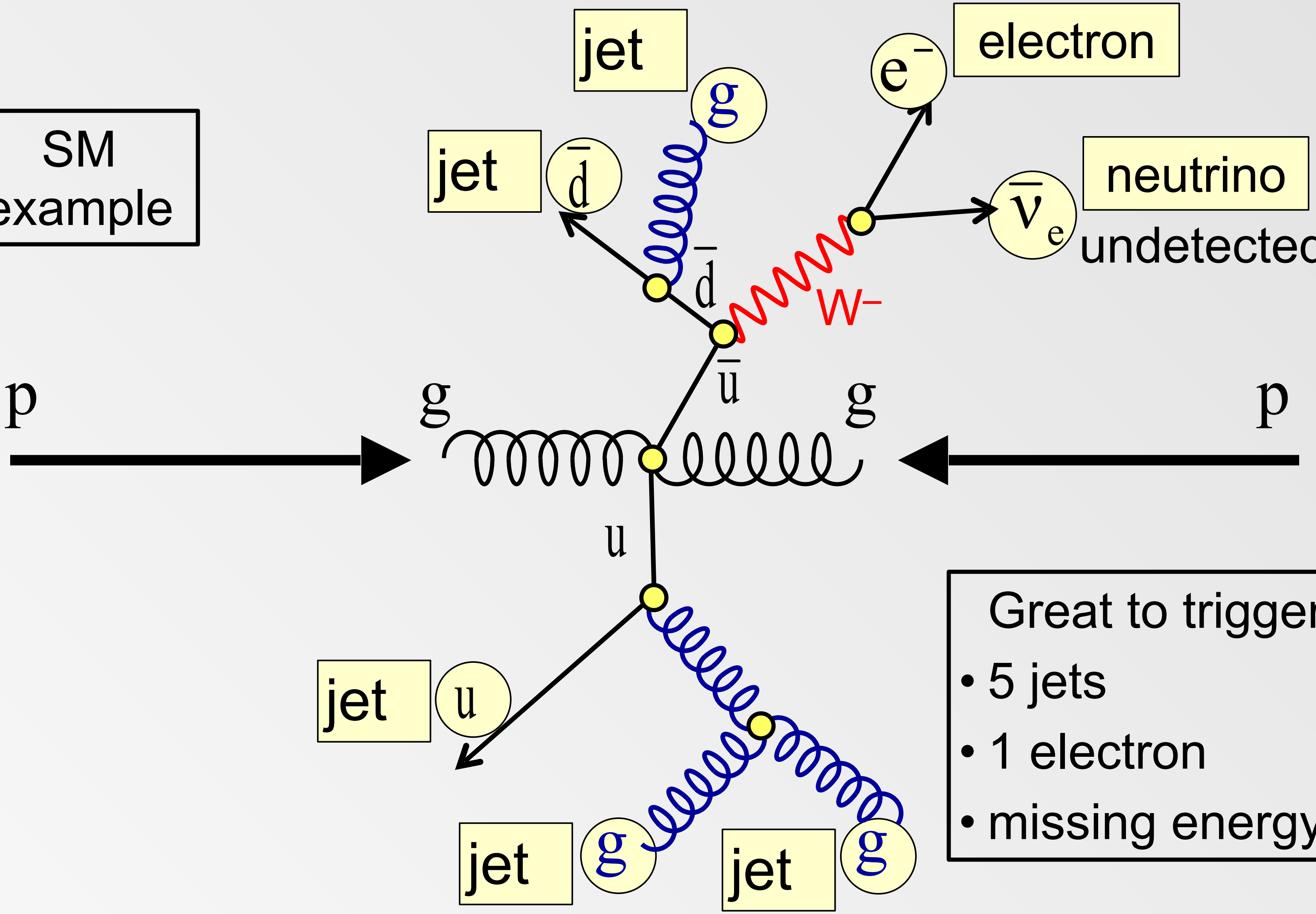
isolated electron, 5 jets, $\not{E}$



cool !!! discovery?

well…not quite: the SM can do this too

SM example



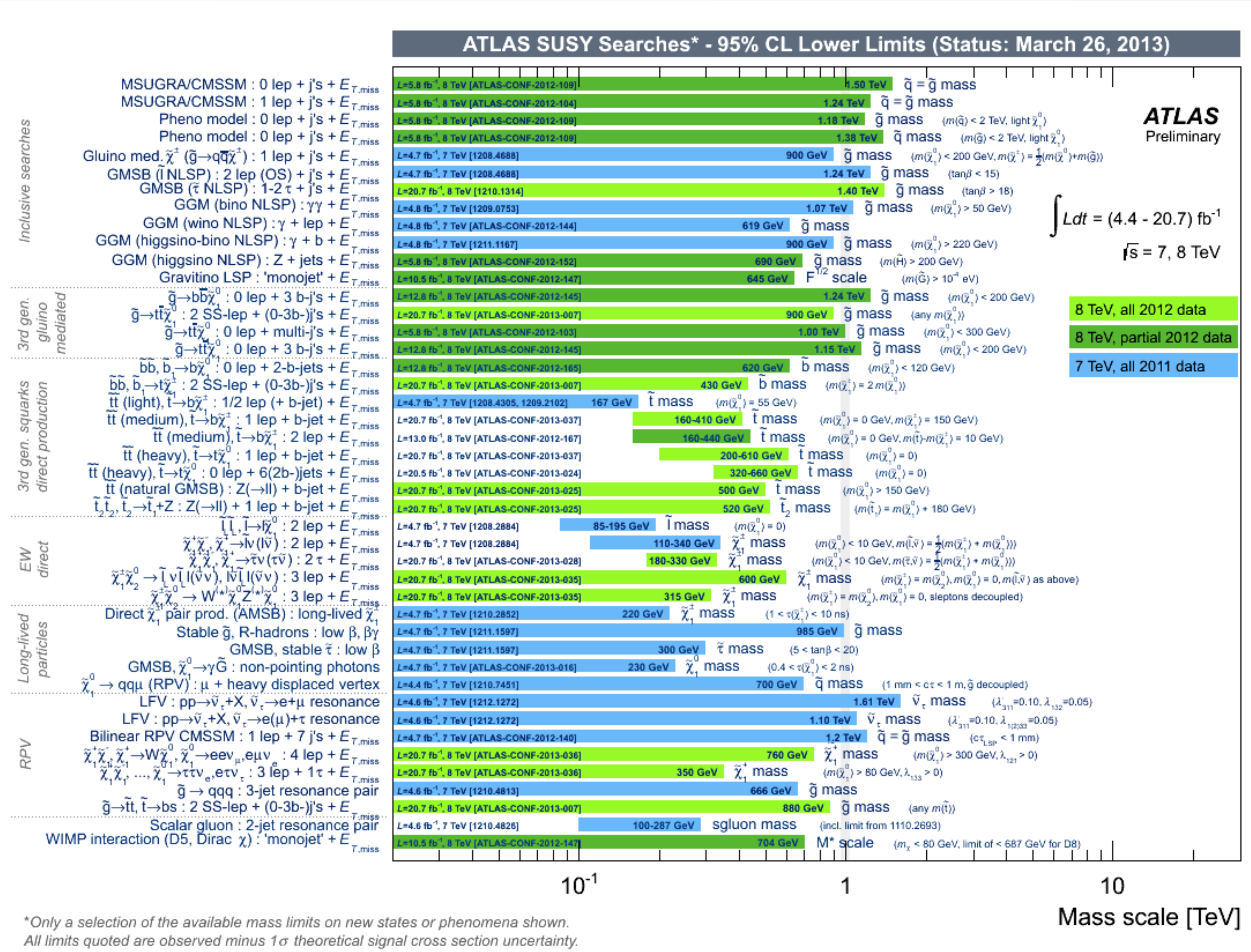
Great to trigger:

- 5 jets
- 1 electron
- missing energy

The name of the game: Understand the backgrounds very well!

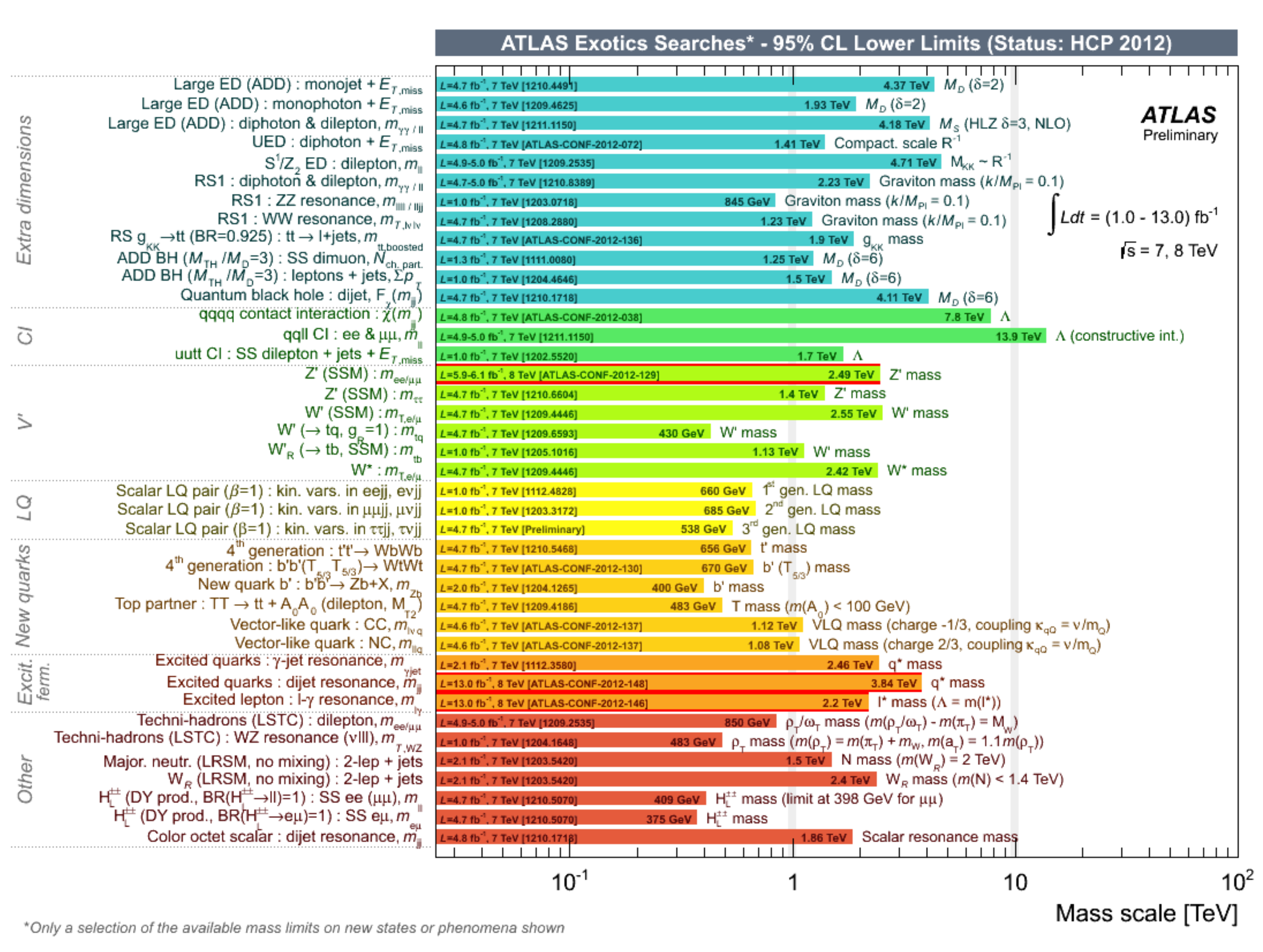
…so SUSY, where are you?

squarks & gluinos
3rd gen squarks
EW
LLP
RPV
Other

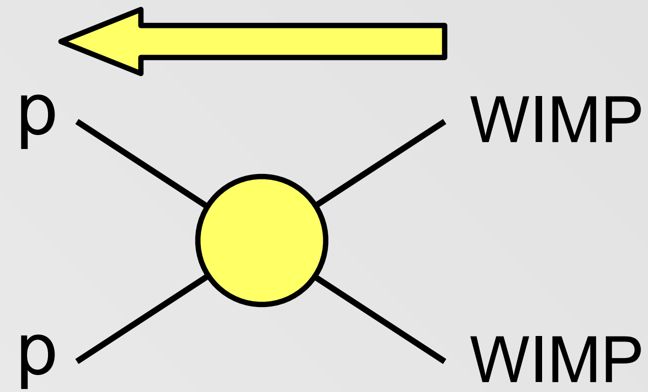


nothing yet; mostly sensitive to strongly interacting gluinos/squarks; mass sensitivity beyond 1 TeV

…if not SUSY, is anybody else around?



Nope! Multi-TeV sensitivities reached for many models c)



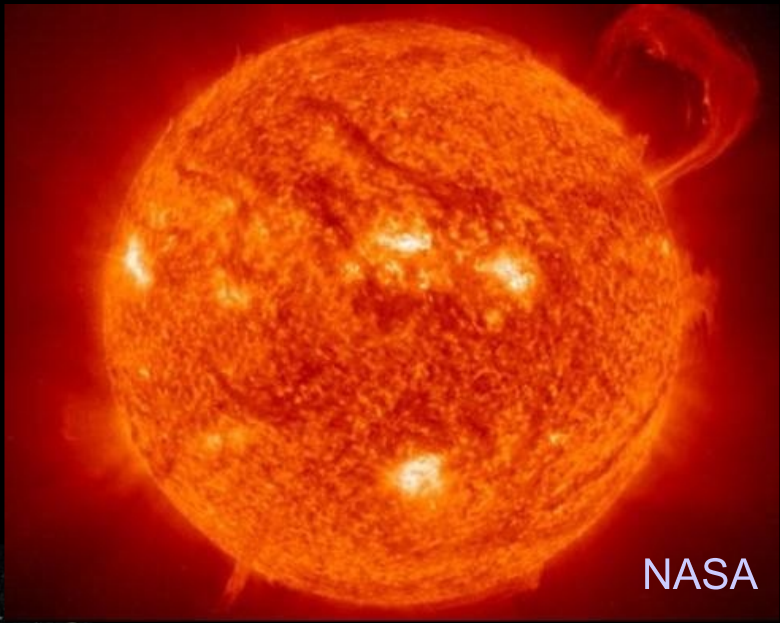
Indirect Searches

watching the Universe

Some of the best places to look

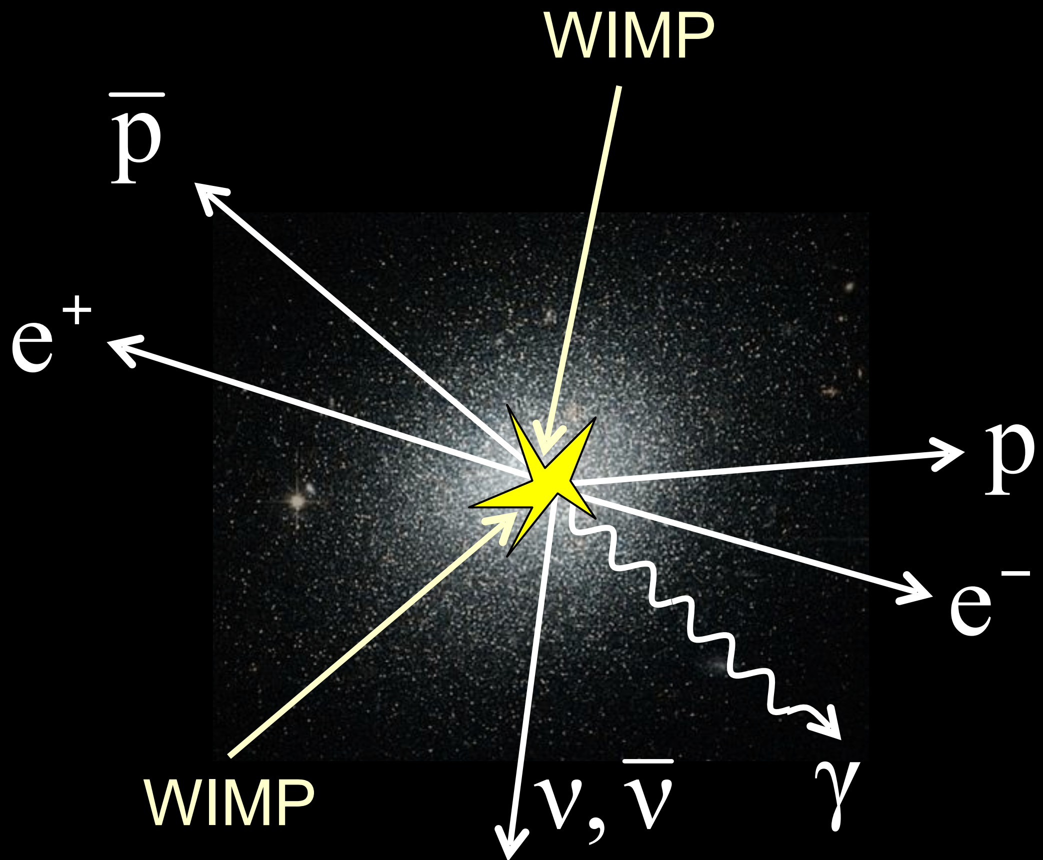
gravitational centres with small astrophysical backgrounds

Galactic Centre



Sun Core

Dwarf Spheroidal Galaxies



characteristic emission of high energy particles

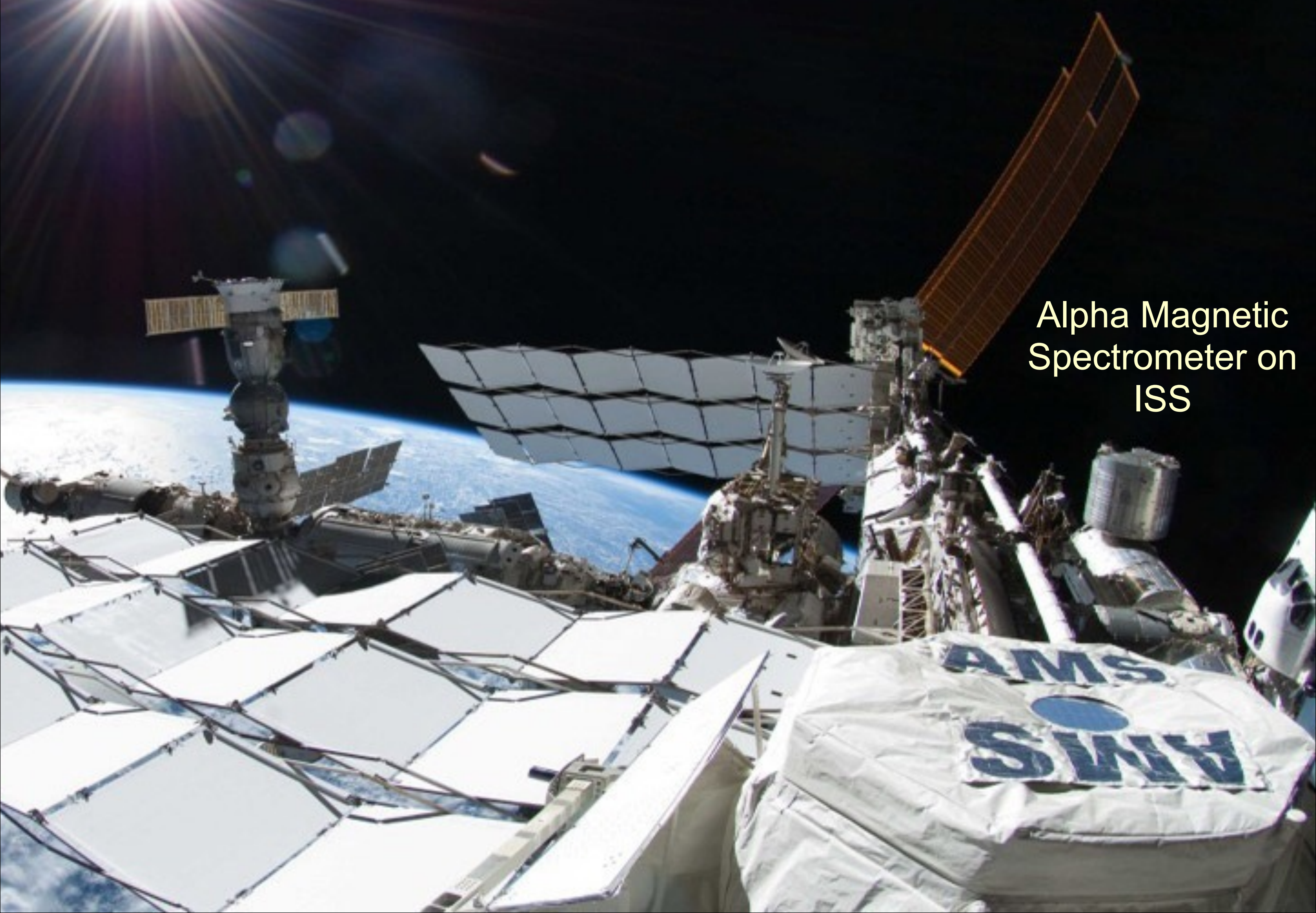
γ gamma rays

$\nu, \bar{\nu}$ neutrinos

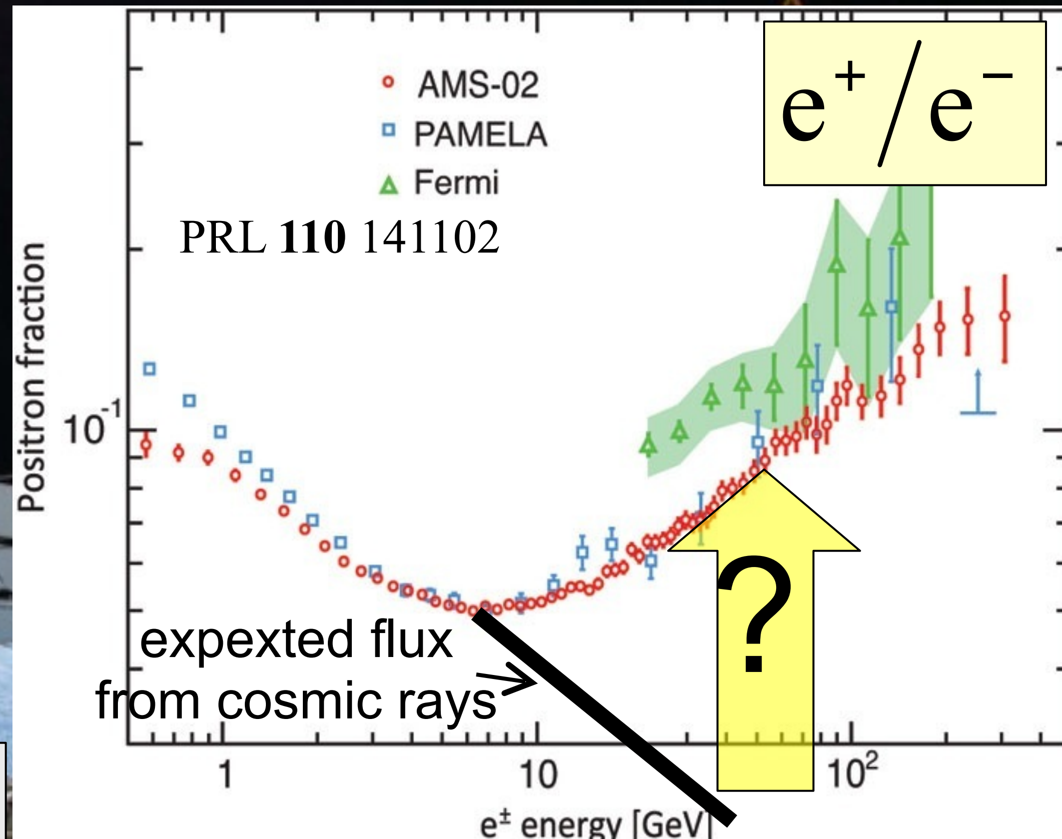
$\bar{p}, e^+$ anti-matter

detectable on earth?

Anti-matter from the Universe



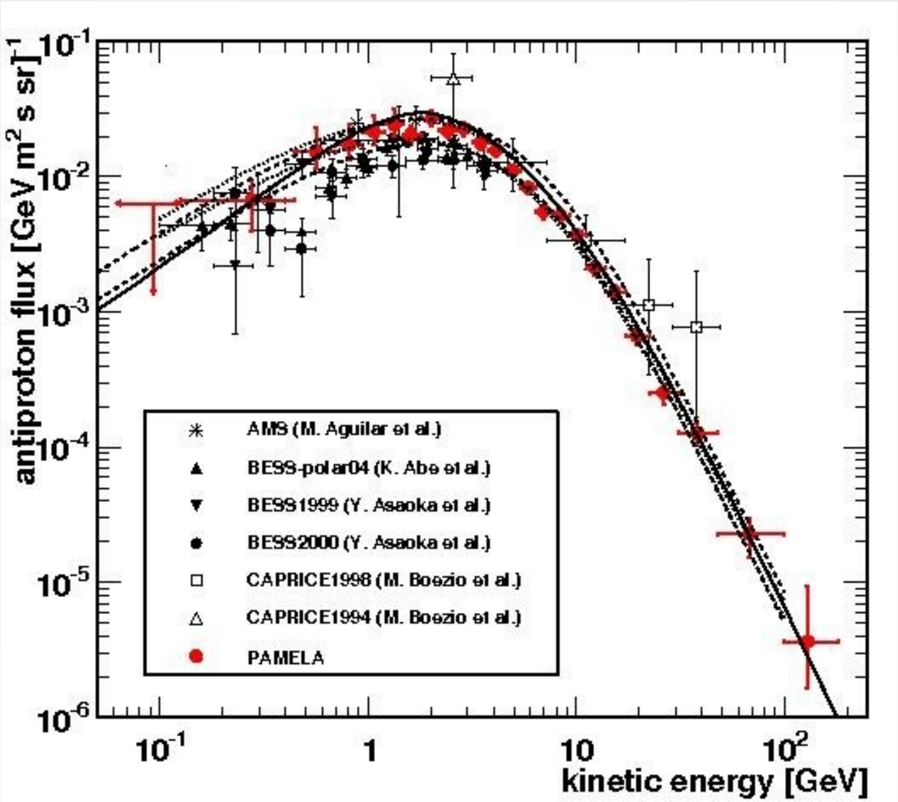
Positron-Anomaly



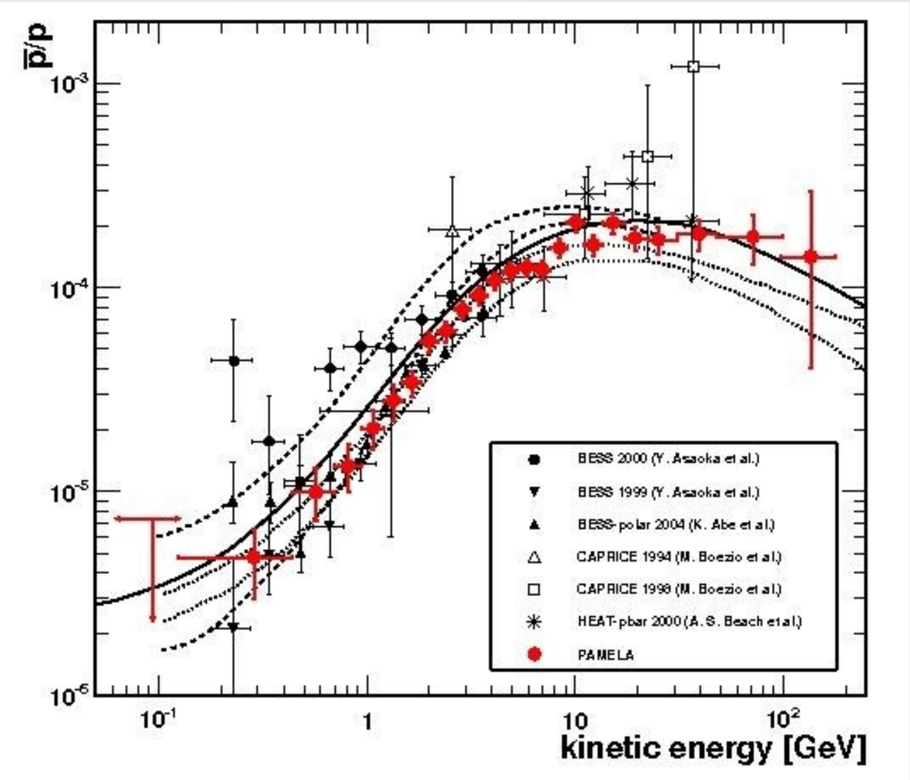
- WIMP annihilation?
- Astrophysical source (close-by pulsar)?

Antiprotons

$\overline{p}$ flux



$\overline{p}/p$



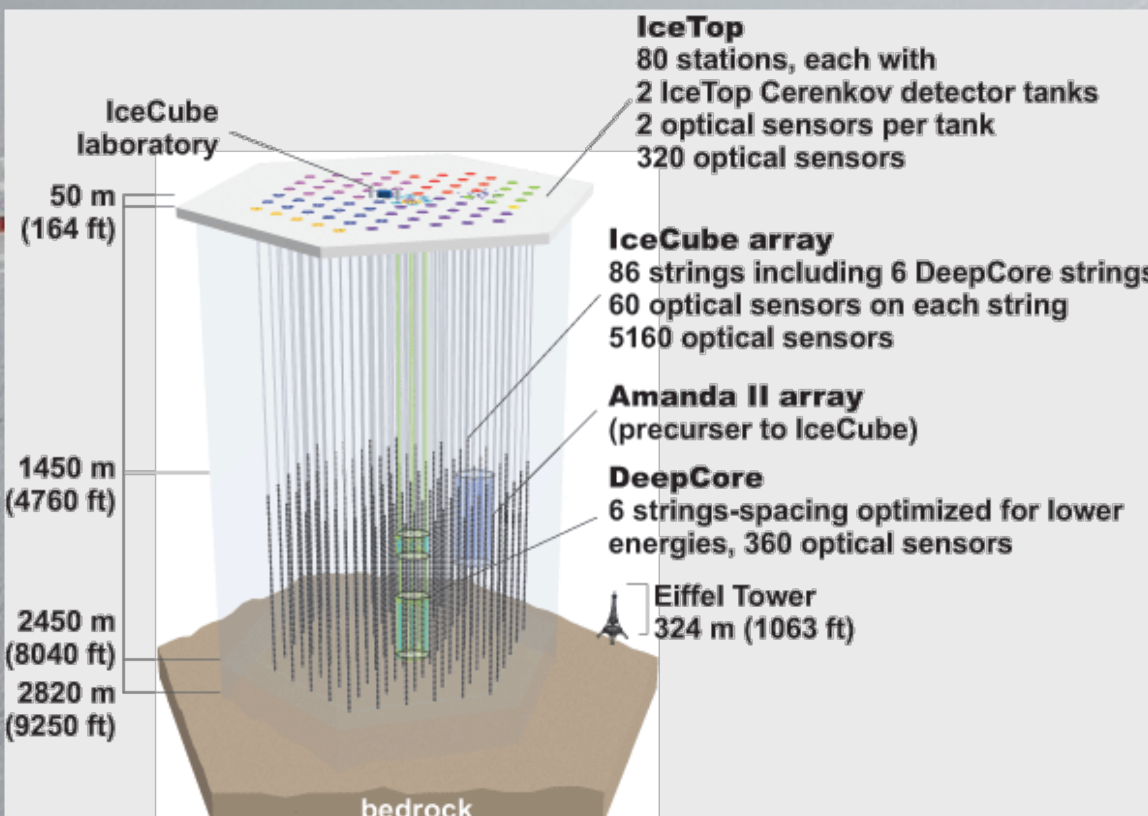
PAMELA Coll., PRL 105, 121101 (2010)

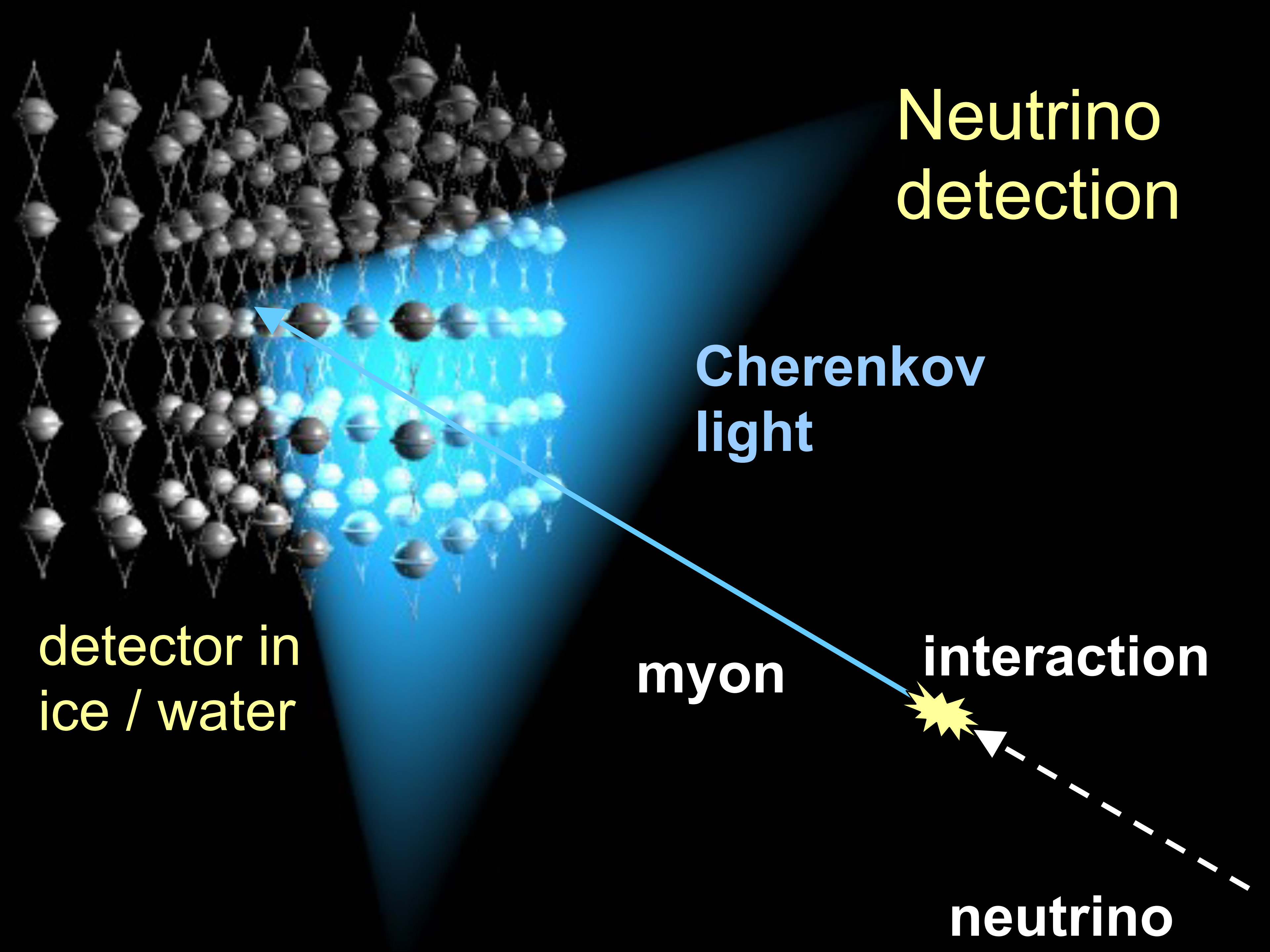
Compatible with cosmic ray propagation models

Neutrinos from dark matter annihilation

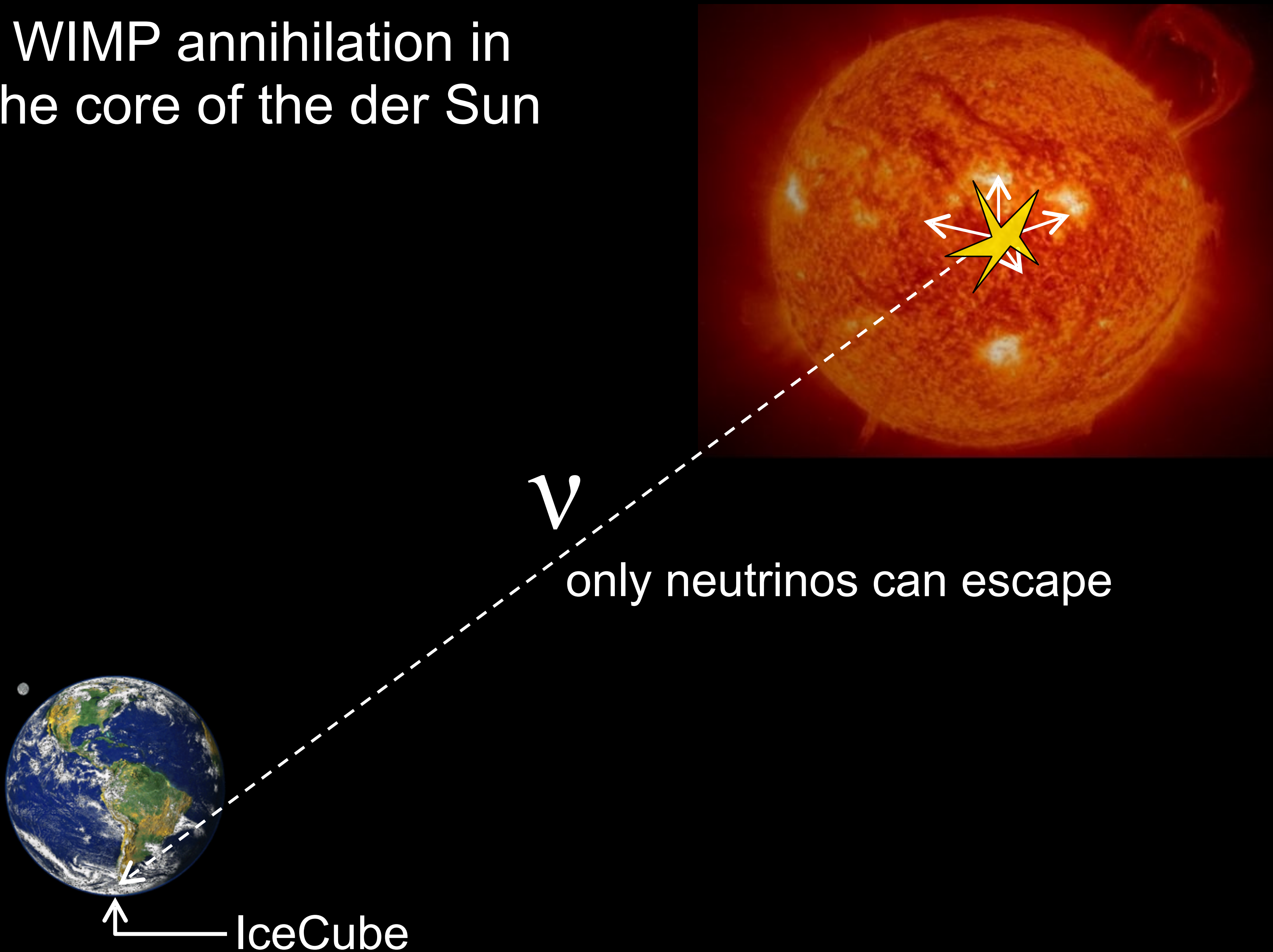
Most sensitive for $m_\chi \gtrsim 100\,\mathrm{GeV}$: IceCube / Deep Core (/ PINGU)

H. Kolanoski
Humboldt
University

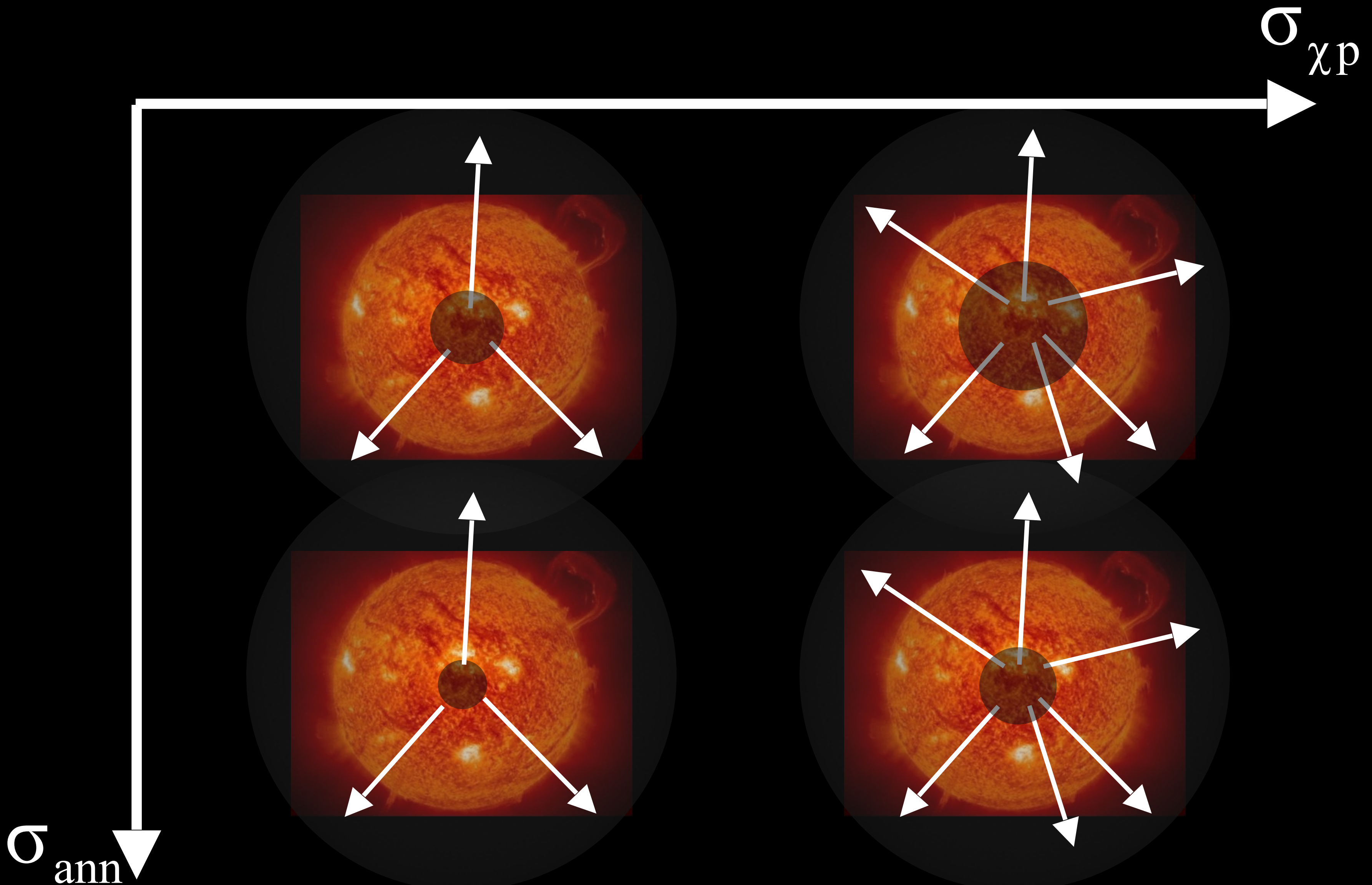



Neutrino
detection
Cherenkov
light
detector in
ice / water
myon
interaction
neutrino

WIMP annihilation in the core of the der Sun

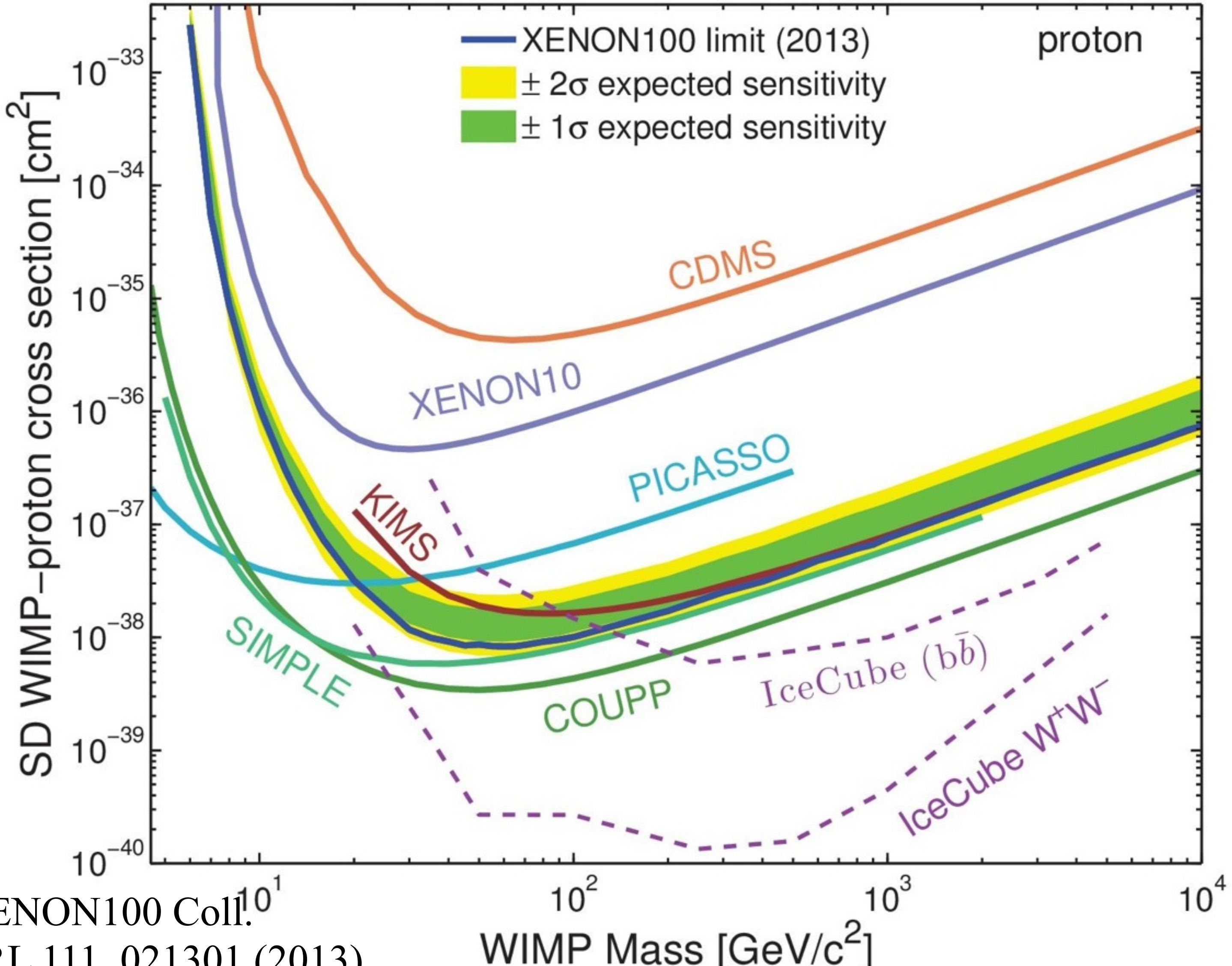


Age 4.5×10^9 y $\Rightarrow$ equilibrium capture vs annihilation rate



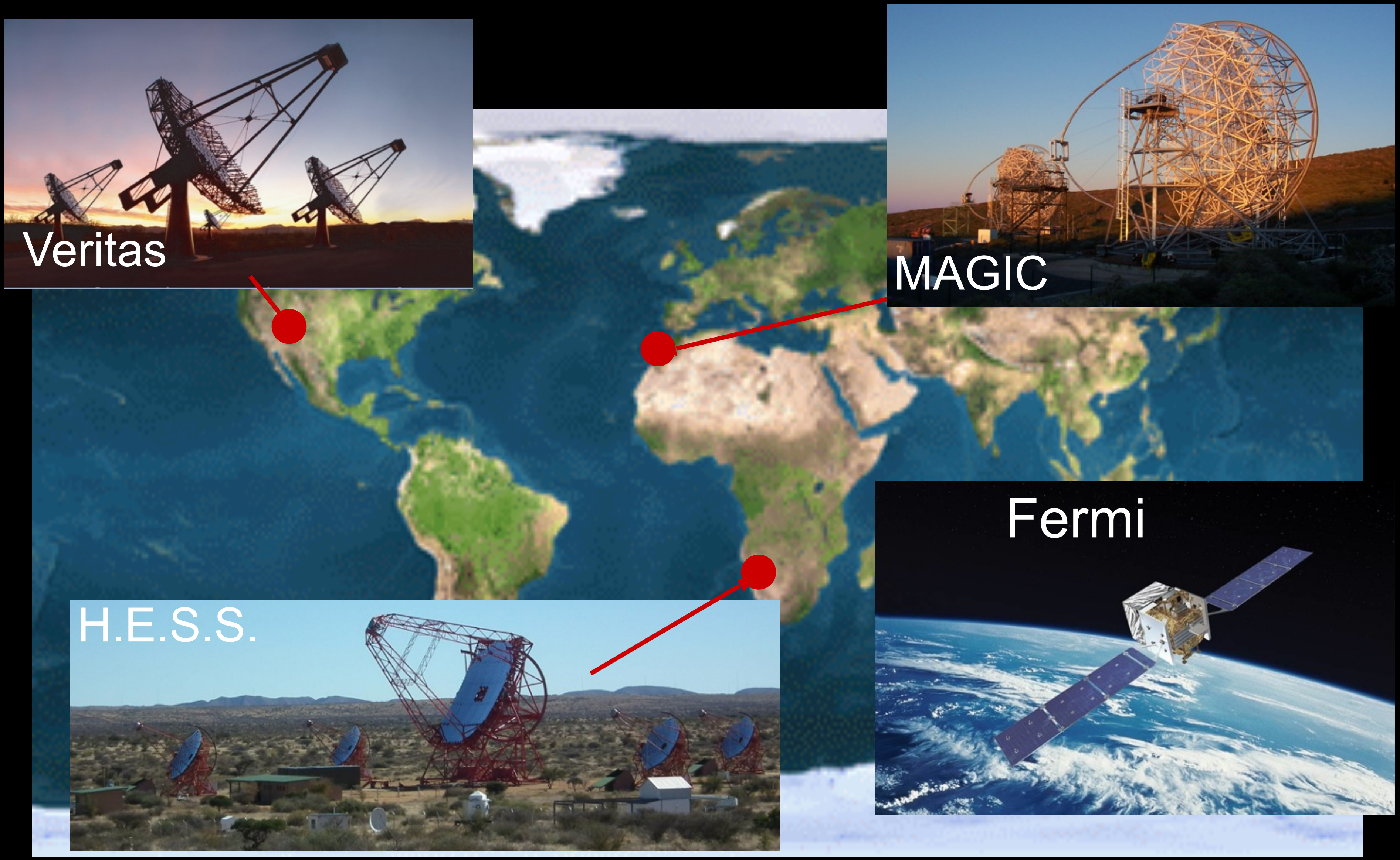
Neutrino flux depends on $\sigma_{\chi p}$, not on σ_{ann}!

IceCube beats direct searches in high mass region for spin dependent proton WIMP scattering

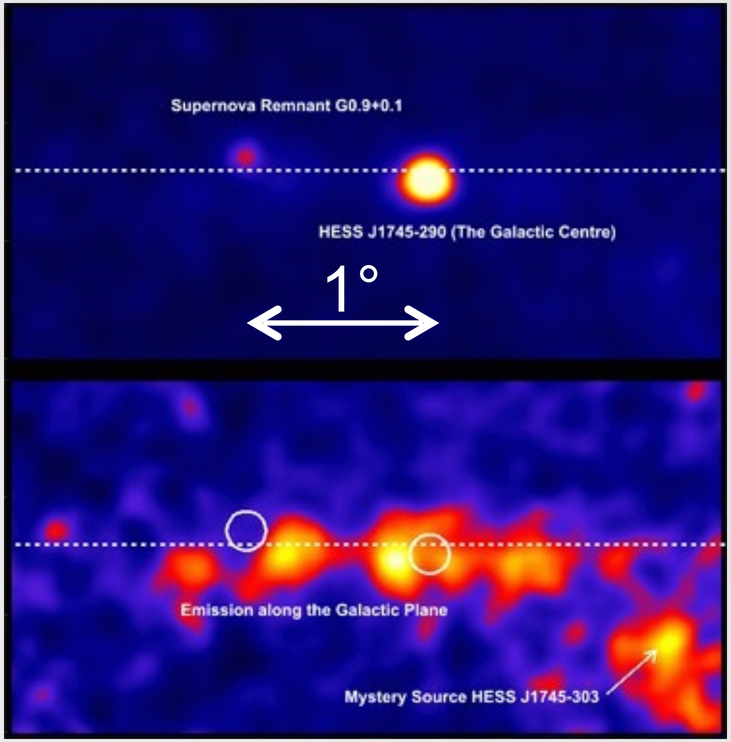


XENON100 Coll.
PRL 111, 021301 (2013)

Gamma Rays from dark matter annihilation



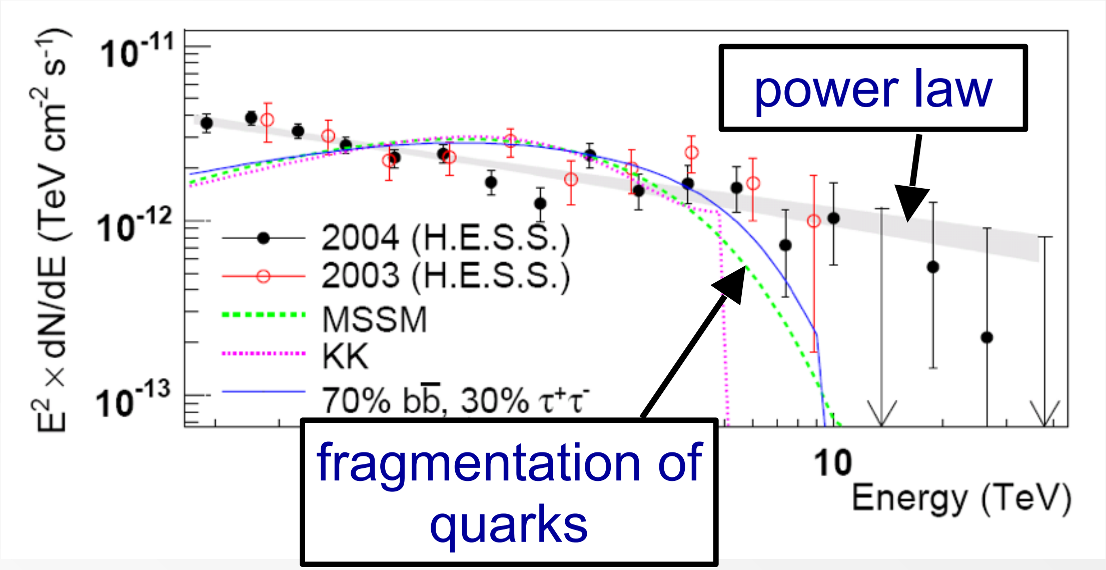
We are (un)lucky: the gamma ray sky is crowded; great astrophysics!



Galactic centre, H.E.S.S.

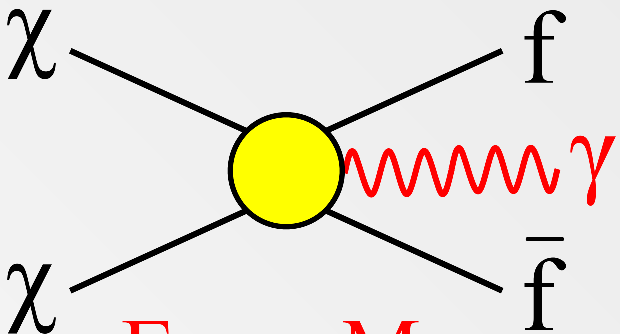
Look for regions with high DM density but low astrophysical gamma ray activity

Galactic centre emission, H.E.S.S.

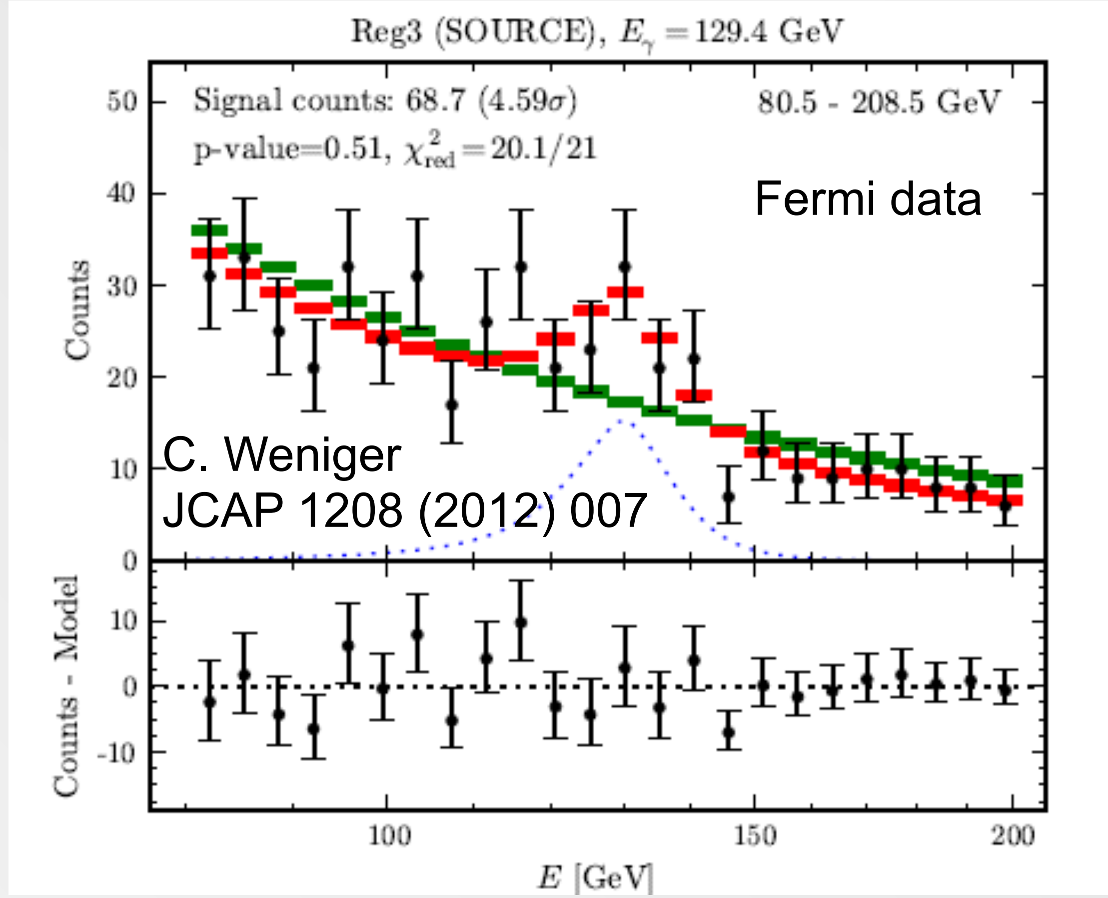


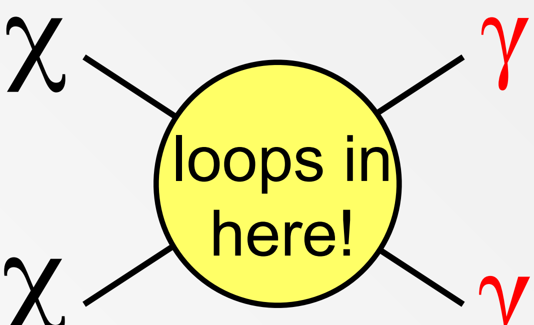
Look for weird spectral shapes, cut-offs …

…or look for the smoking gun:
a line / a bump

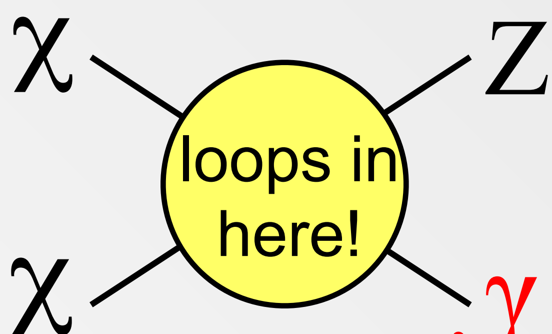


$$E_\gamma \to M_\chi$$

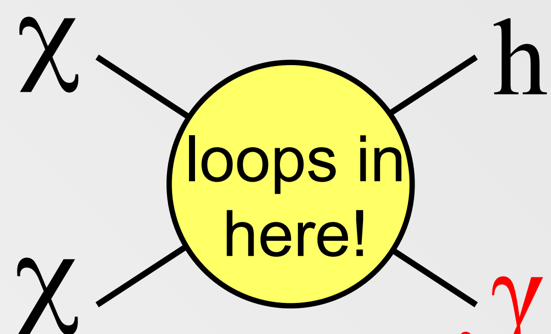




$$E_\gamma \cong M_\chi$$



$$E_\gamma \cong M_\chi - \frac{M_Z^2}{4M_\chi}$$



$$E_\gamma \cong M_\chi - \frac{M_h^2}{4M_\chi}$$

How to compute expected signal fluxes?

- Interaction volume “tested” in dt

$$dV = \sigma(v)v\,dt$$

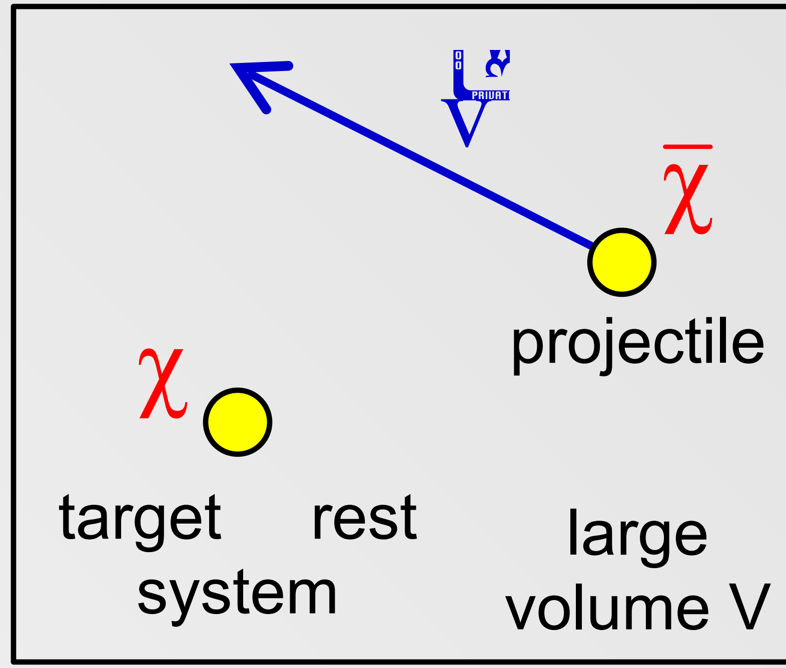
- Annihilation probability in dt in V

$$dp = \frac{dV}{V} = \sigma(v)v\,dt / V$$

- Annihilation rate in V

$$\Gamma = \frac{dp}{dt} = \sigma(v)v / V$$

- Total annihilation rate in V



$$\Gamma_{tot} = \frac{1}{V} \times \sum_{\text{targets, projectiles}} \sigma(v)v = \frac{1}{V} C \langle \sigma v \rangle$$

target-projectile pairs

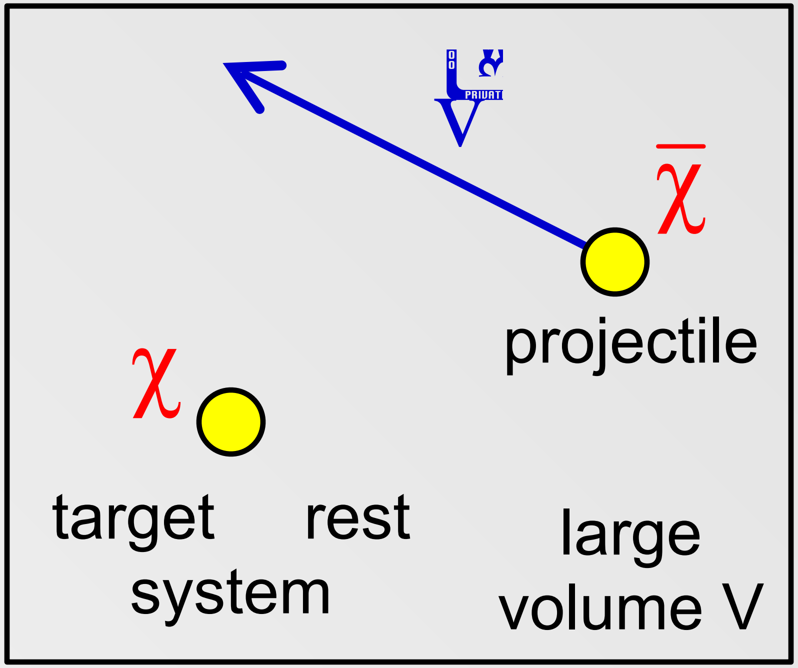
How to compute expected signal fluxes?

- Total annihilation rate in V

$$\Gamma_{\text{tot}} = \tfrac{1}{V} C \langle \sigma v \rangle$$

- Number of pairs

$$C = \begin{cases} N_t N_p = \frac{N^2}{4}, & \chi \neq \bar{\chi} \\ \frac{N(N-1)}{2} \approx \frac{N^2}{2}, & \chi = \bar{\chi} \end{cases}$$



- Use mass density $\rho = N m_\chi / V$

$$\frac{d\Gamma}{dV} = \frac{\Gamma_{\text{tot}}}{V} = \frac{\rho^2}{\nu m_\chi^2} \langle \sigma v \rangle \quad \text{with} \quad \nu = \begin{cases} 4, & \chi \neq \bar{\chi} \\ 2, & \chi = \bar{\chi} \end{cases}$$

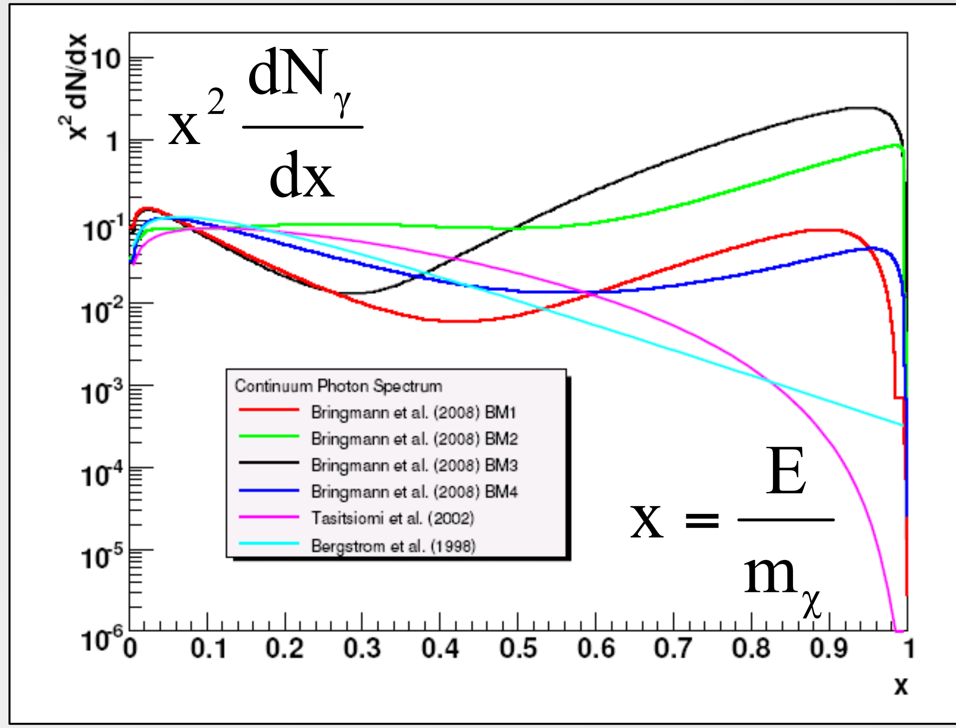
How to compute expected signal fluxes?

$$\frac{d\Gamma}{dV} = \frac{\rho^2}{v m_\chi^2}\langle \sigma v \rangle$$

$$\Downarrow$$

$$\frac{d\Gamma_\gamma}{dV\,dE} = \frac{\rho^2}{v m_\chi^2}\frac{dN_\gamma}{dE}\langle \sigma v \rangle$$

but how much do we see in the detector ?

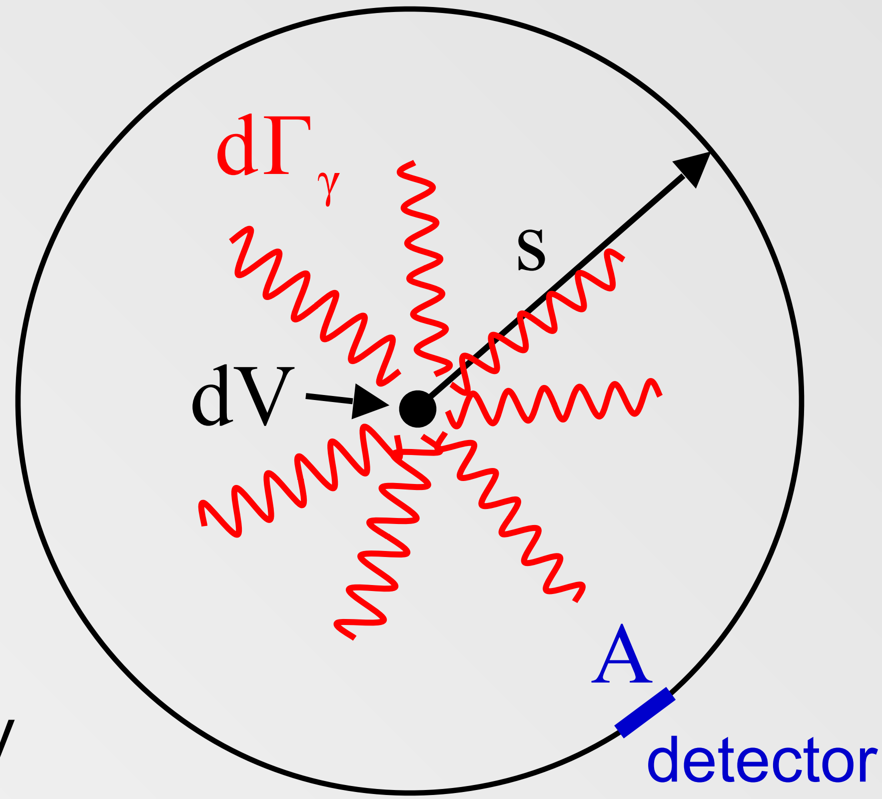


photon spectrum per annihilation

- known well from particle physics
- but depends on branching ratios

How to compute expected signal fluxes?

$$\frac{d\Gamma_\gamma}{dV\,dE} = \frac{\rho^2}{v m_\chi^2} \frac{dN_\gamma}{dE} \langle \sigma v \rangle$$



- rate seen by detector

$$d\Gamma_{det} = \frac{A}{4\pi s^2} d\Gamma_\gamma$$

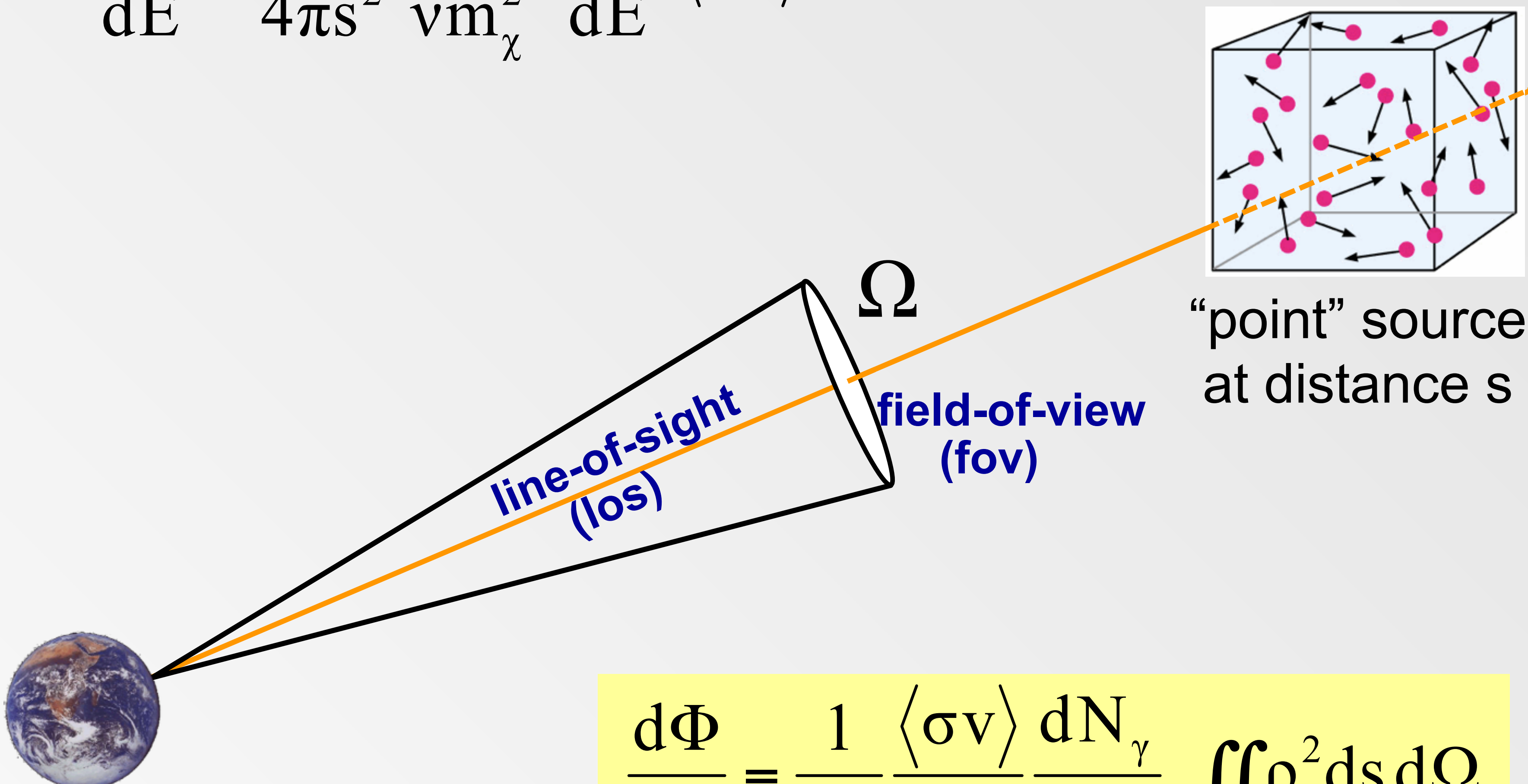
- detected gamma ray flux from dV

$$\frac{d\phi}{dE} = \frac{1}{A} \frac{d\Gamma_{det}}{dE} = \frac{1}{4\pi s^2} \frac{\rho^2}{v m_\chi^2} \frac{dN_\gamma}{dE} \langle \sigma v \rangle dV$$

How to compute expected signal fluxes?

$$\frac{d\phi}{dE} = \frac{1}{4\pi s^2} \frac{\rho^2}{v m_\chi^2} \frac{dN_\gamma}{dE} \langle \sigma v \rangle dV$$

$$dV = s^2 ds\, d\Omega$$



$$\frac{d\Phi}{dE} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{v m_\chi^2} \frac{dN_\gamma}{dE} \iint_{\text{fov, los}} \rho^2 ds\, d\Omega$$

Astrophysical Factor

$$\frac{d\Phi}{dE} = \boxed{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{v m_\chi^2}\frac{dN_\gamma}{dE}} \boxed{\iint \rho^2 \, ds \, d\Omega}$$

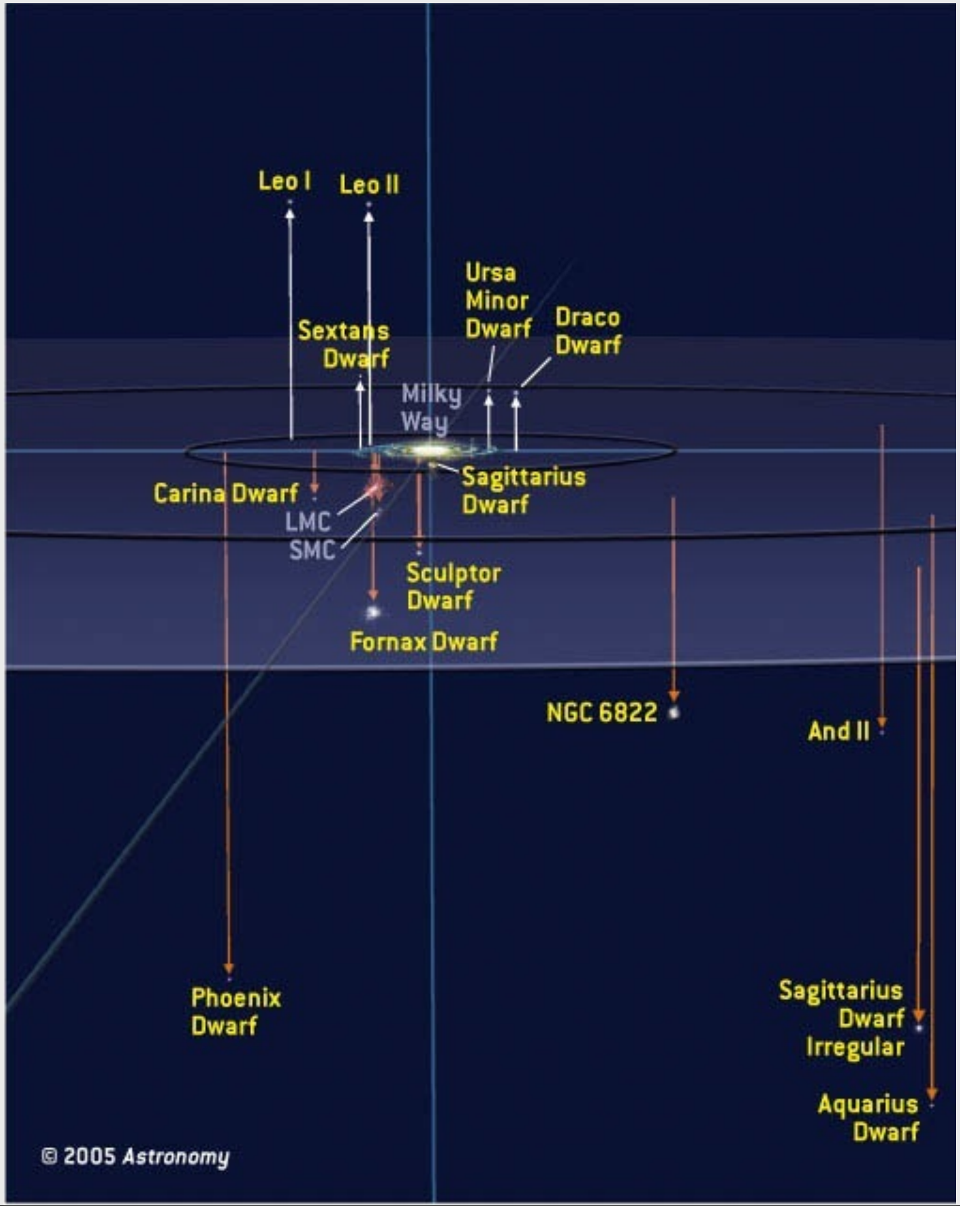
Particle physics factor

Astrophysical factor

J

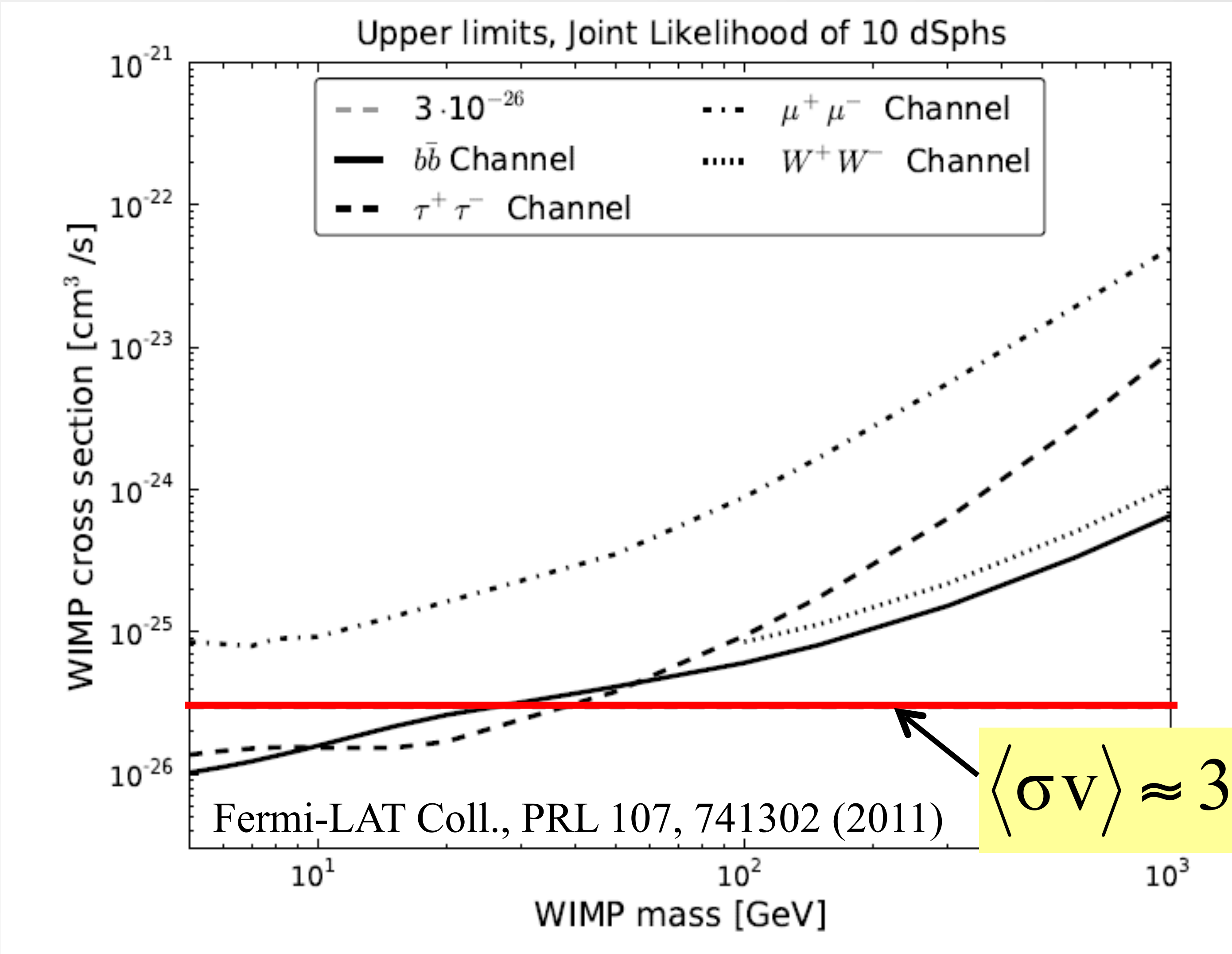
- Units: $[J] = M_\odot^2 \mathrm{kpc}^{-5} = 4.45 \, \mathrm{TeV}^2 \mathrm{cm}^{-5}$
- $\int d\Omega$: to be folded with angular resolution of detector (psf)
- Good targets have large J and small astrophysical backgr.

Candidate 1: Dwarf Galaxies (DG)



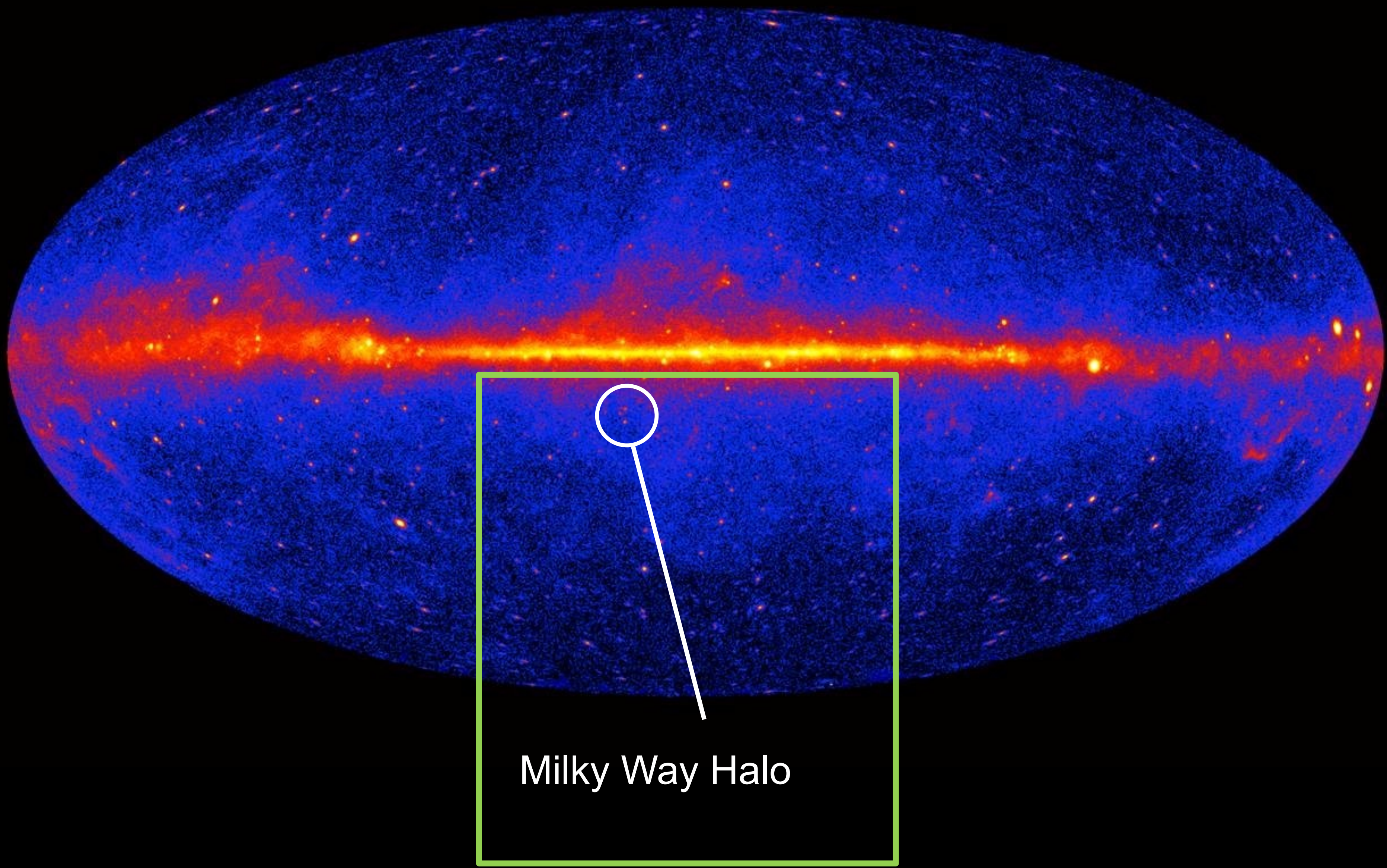
- ~25 DGs are known
- very old objects
- large mass/luminosity ratio
- dark matter dominated (little gas/dust, no star forming activity) $M_{DM} \sim 10^5 - 10^8\ M_\odot$
- close-by (~ 10 kpc)
- compact (~ 1 kpc)
- DM density ($\Rightarrow$ J factors) from stellar kinematics (velocity spread)

Fermi result from stacking analysis

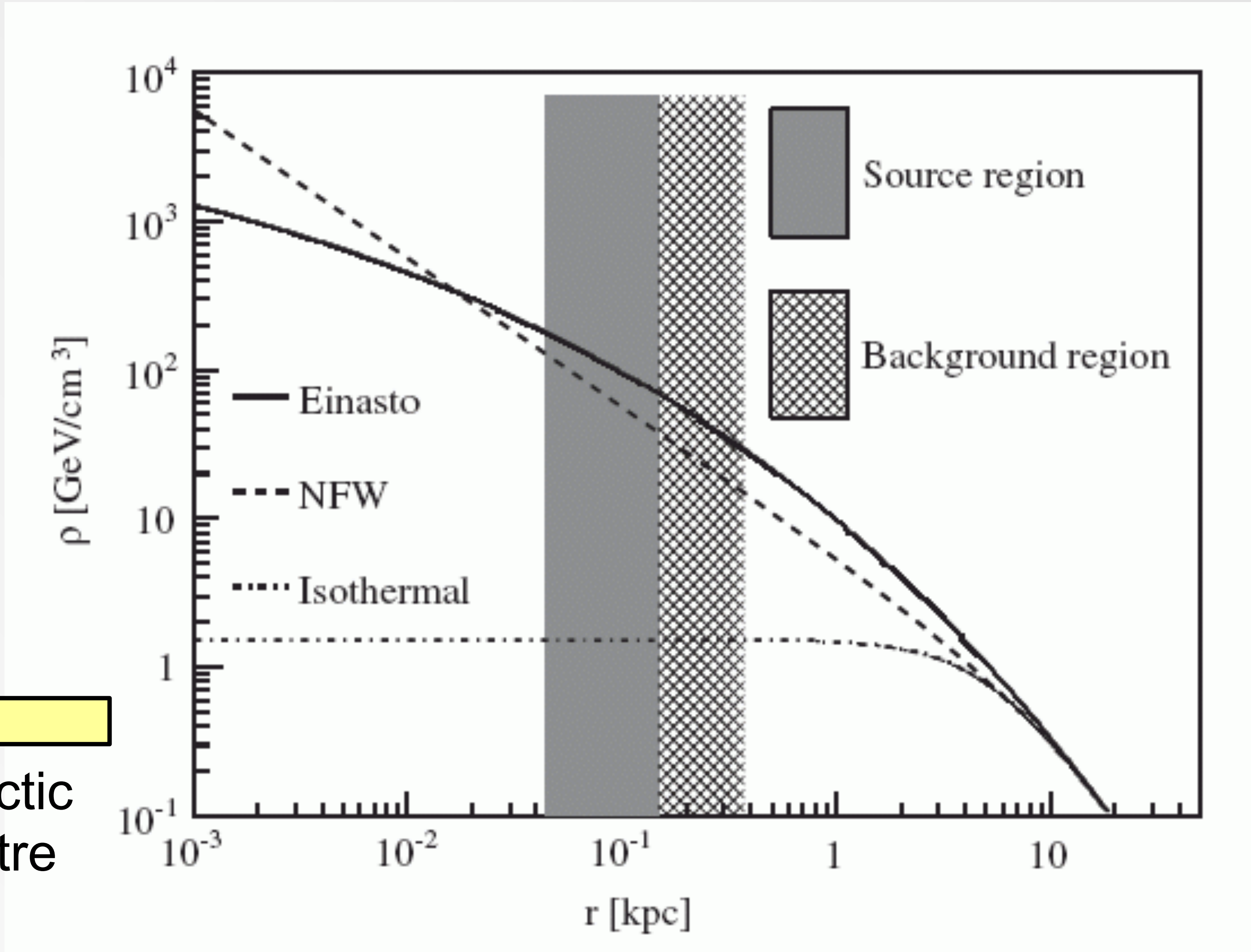


$$\langle \sigma v \rangle \approx 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$$

Candidate 2: Milky Way Halo

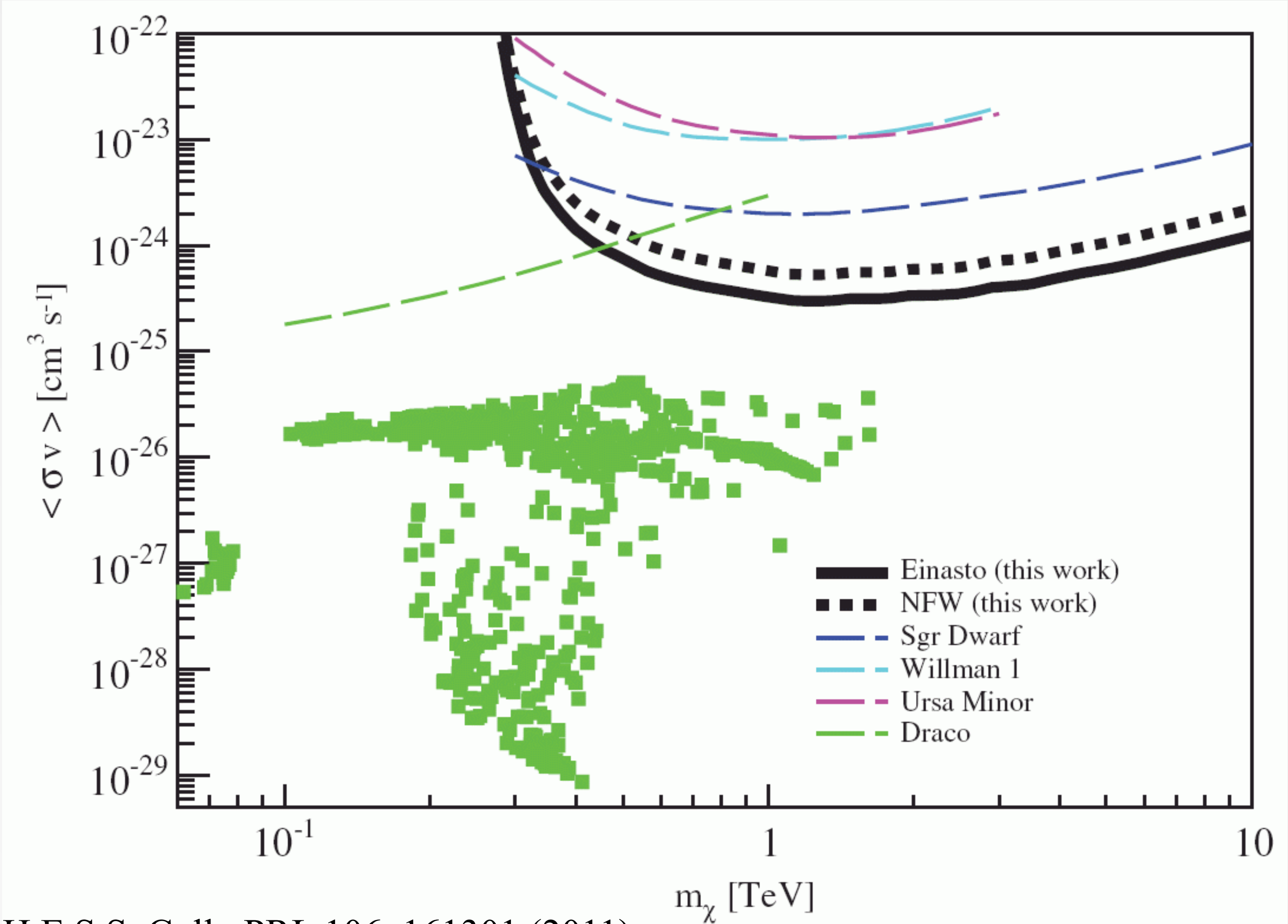


Depends on assumed slope of DM density profile



Galactic
Centre

Very competitive with DGs in high mass range:



H.E.S.S. Coll., PRL 106, 161301 (2011)

Dark Matter:

- Why ? Overwhelming evidence
- What ? A WIMP – the optimistic view
- Where and how ? The threefold way

Good Luck!