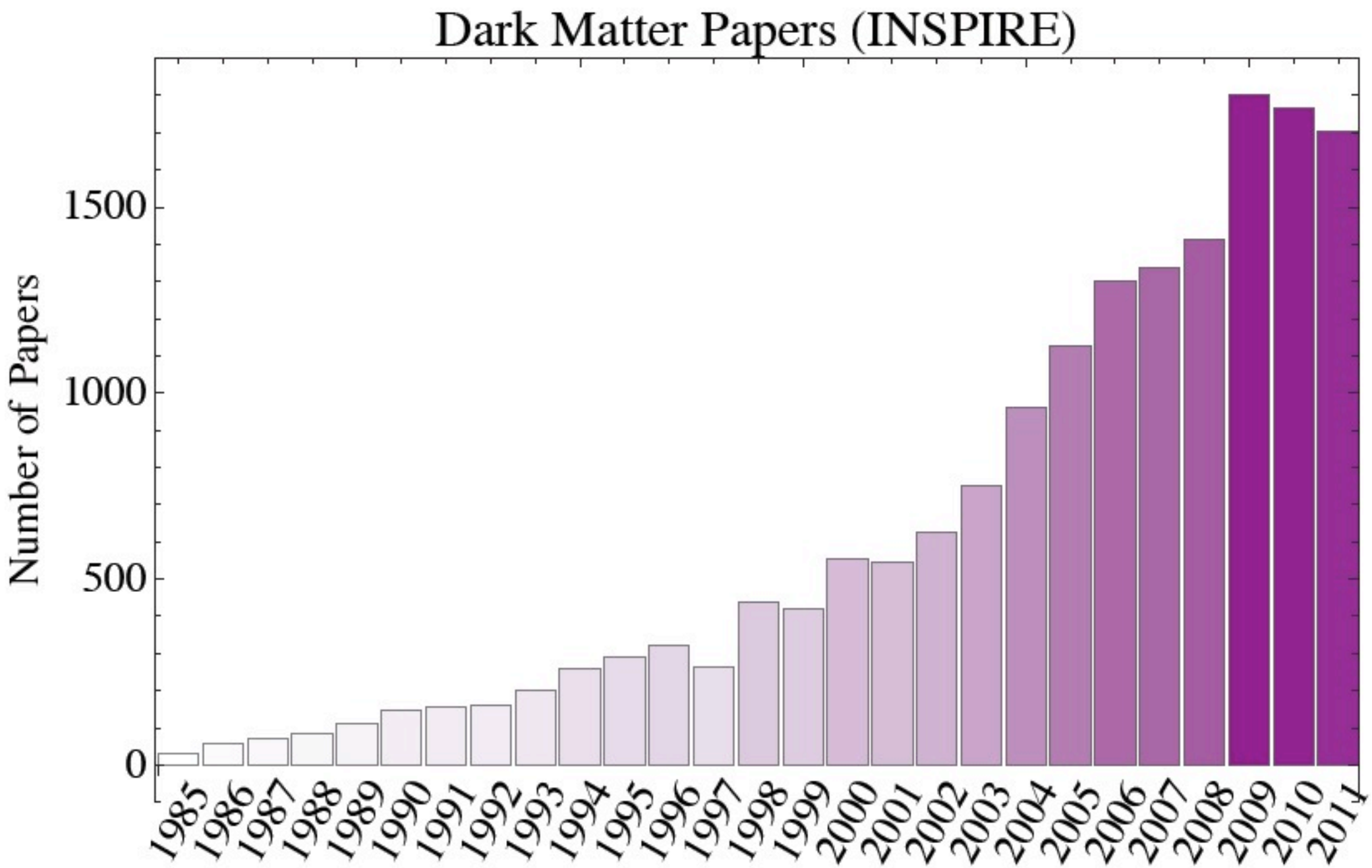
New Results in Dark Matter

Pearl Sandick
University of Utah


Dark Matter Papers (INSPIRE)
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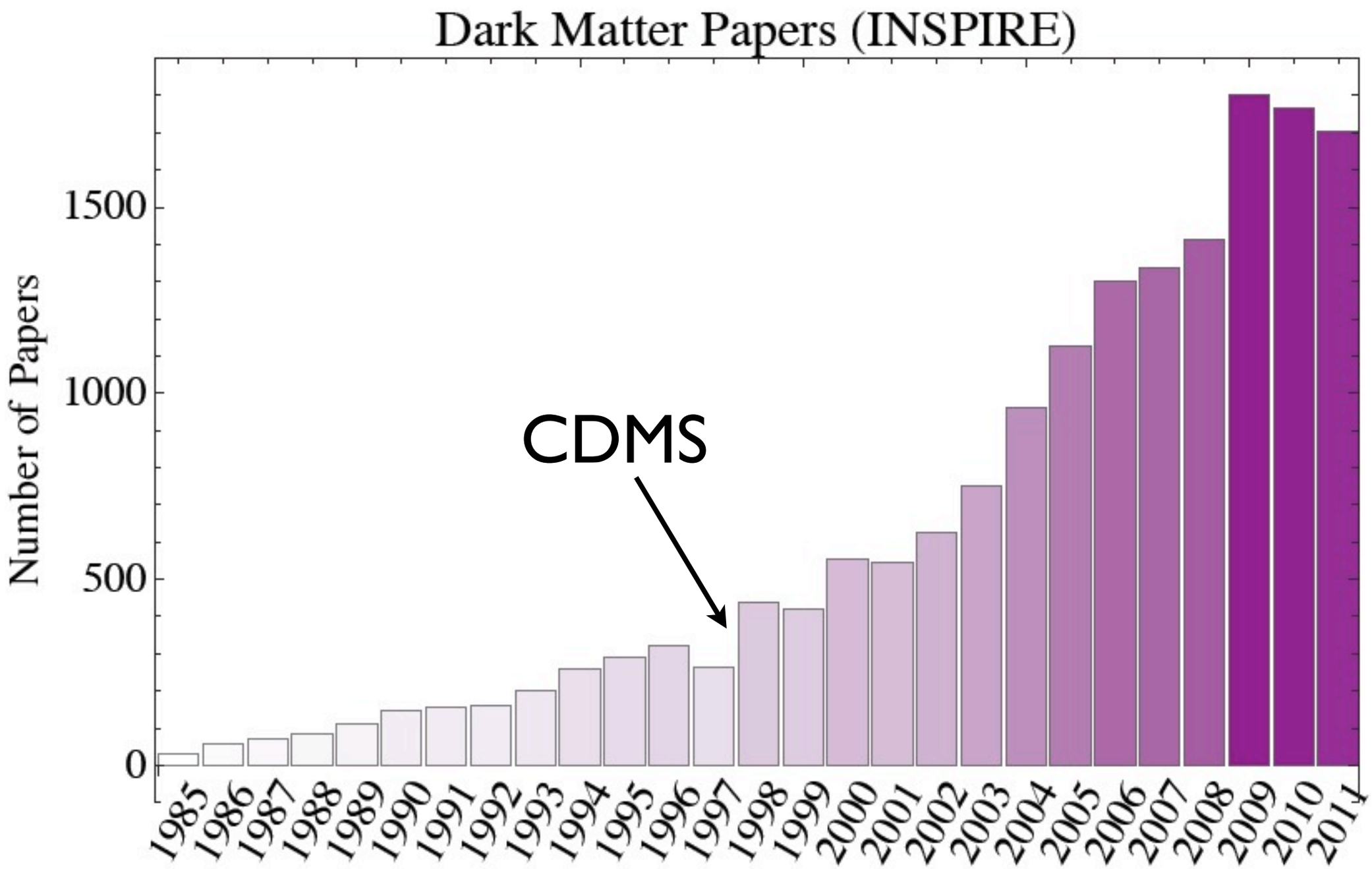
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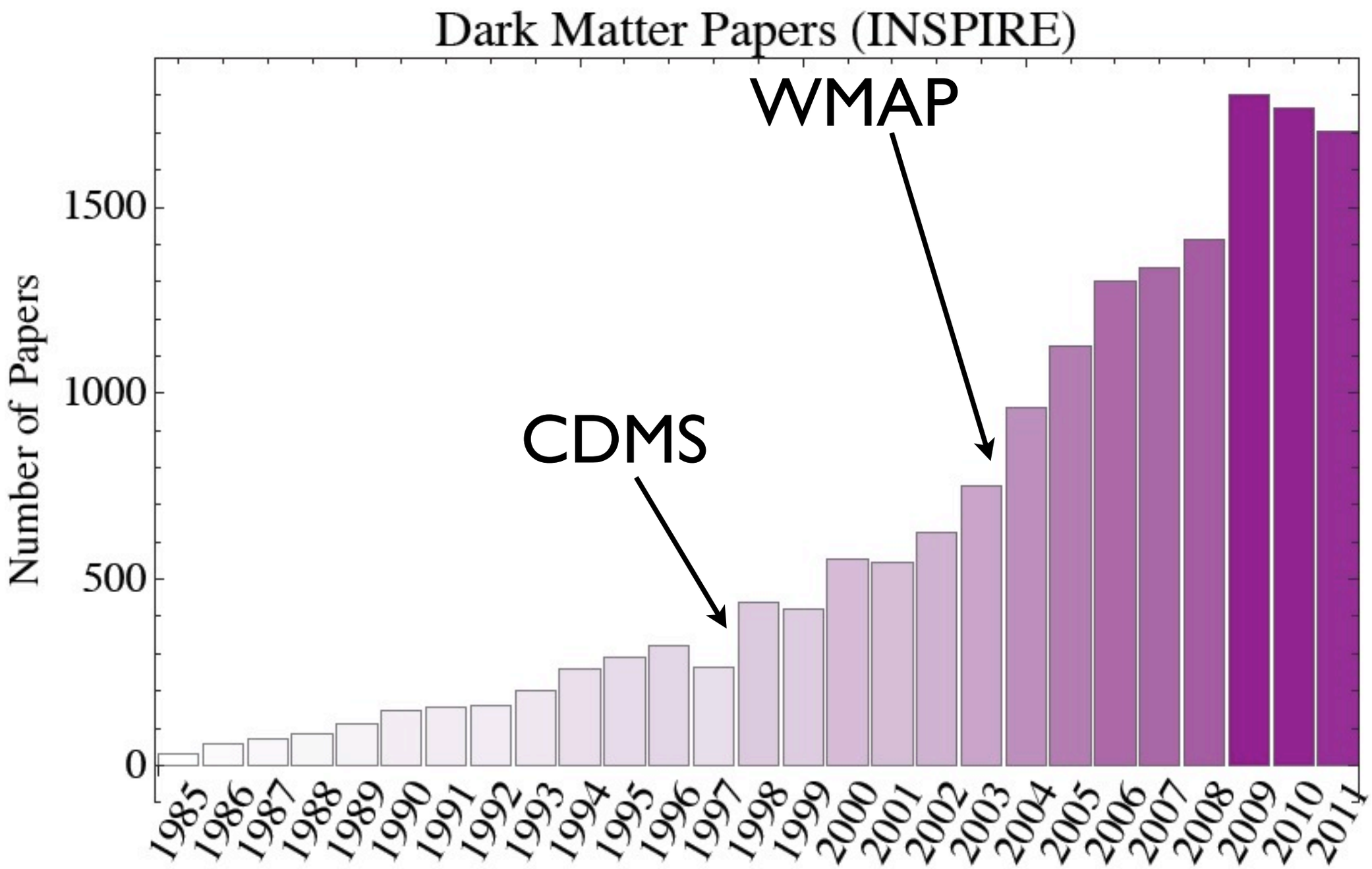
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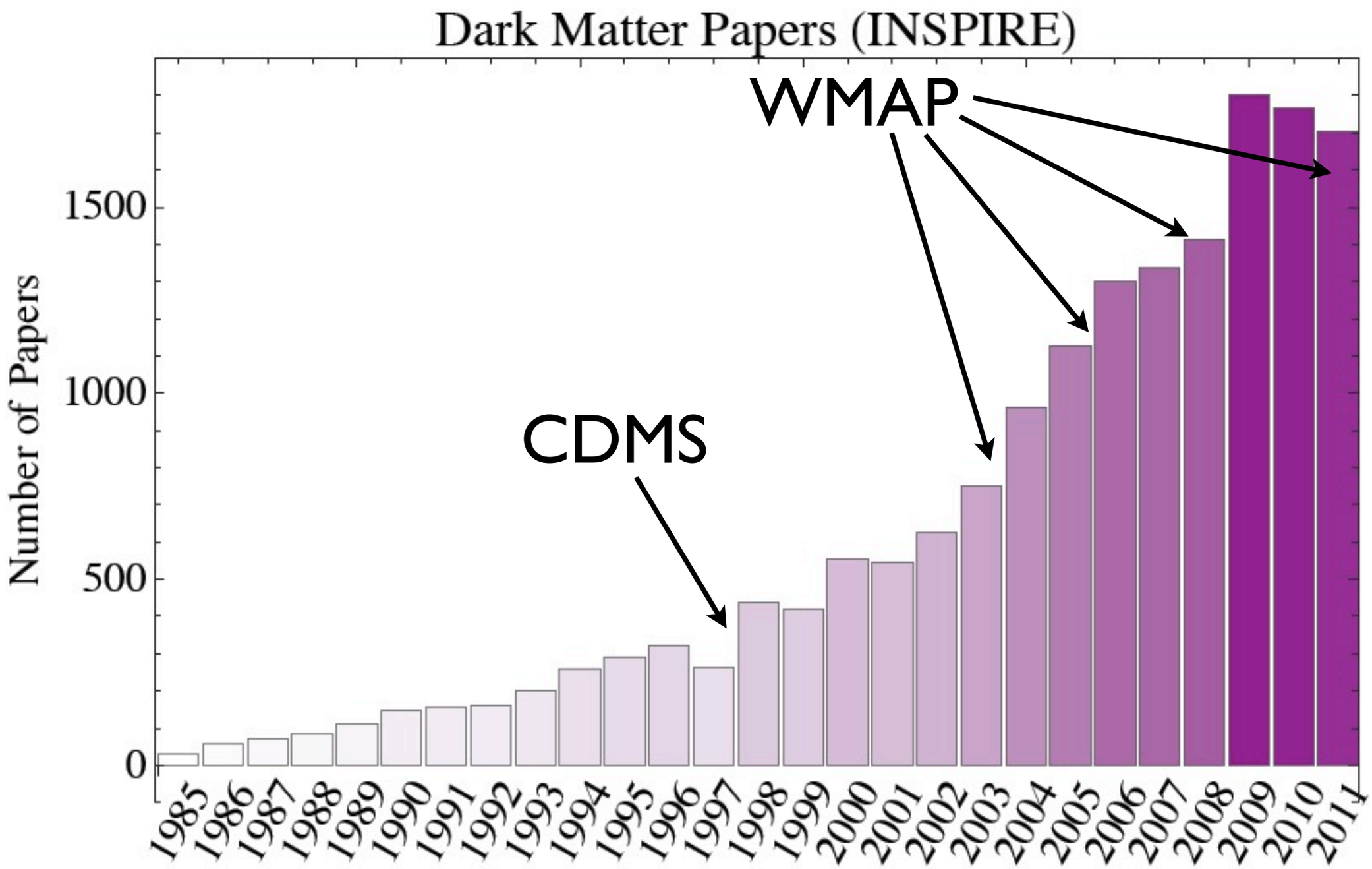
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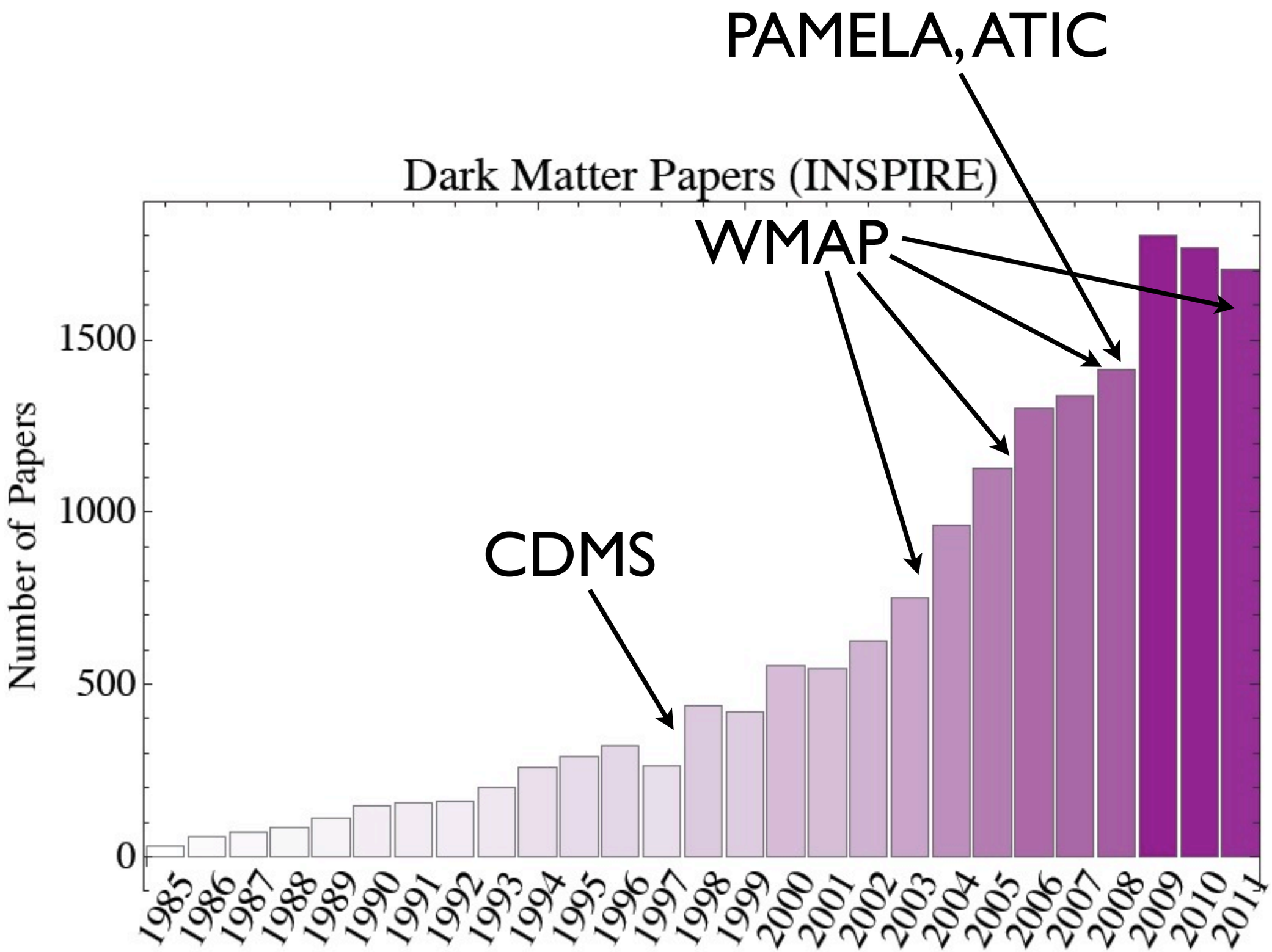
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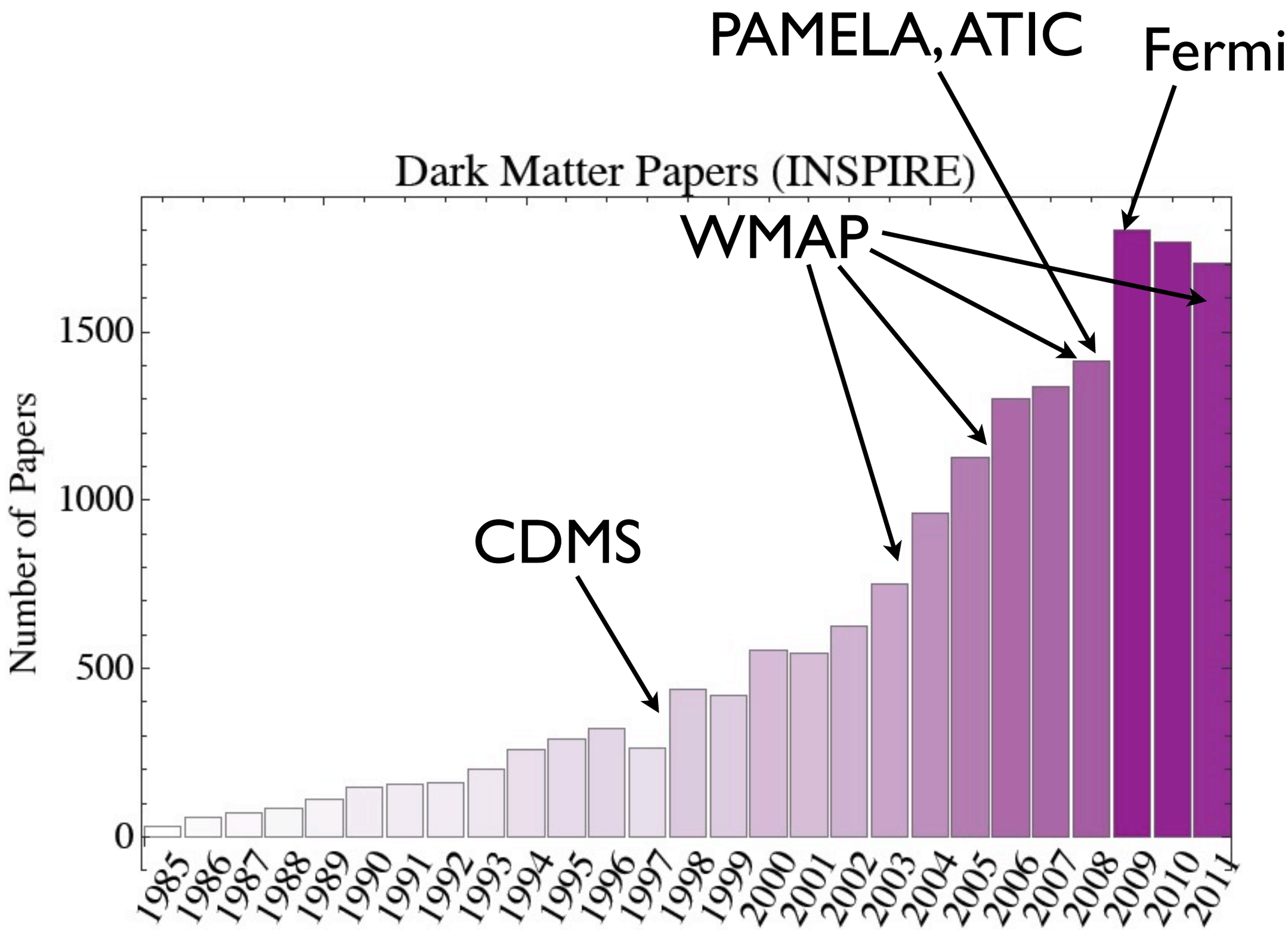
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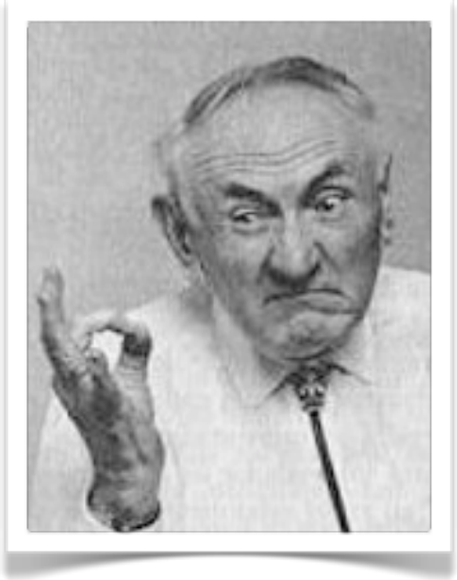
Old Results in Dark Matter



- Fritz Zwicky: used Doppler shift to measure peculiar velocities of galaxies at the edge of the Coma Cluster
  - Virial Theorem $\langle \mathrm{KE} \rangle = -\frac{1}{2}\langle \mathrm{GPE} \rangle \implies M = \frac{2\langle r \rangle \langle v^2 \rangle}{G}$
  - Velocities implied MUCH more mass than that visible

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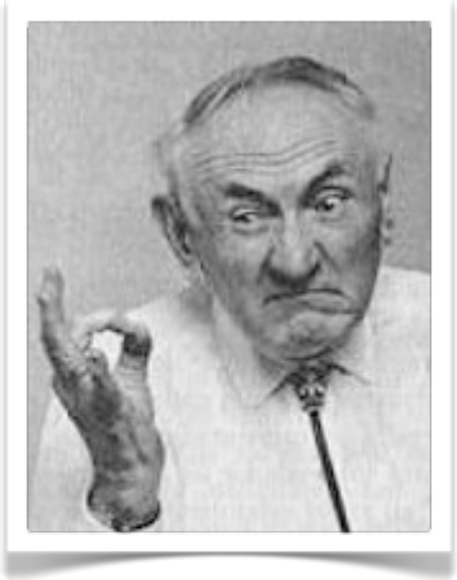

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"If this [overdensity] is confirmed we would arrive at the astonishing conclusion that dark matter is present [in Coma] with a much greater density than luminous matter."

F. Zwicky, Helvetica Physica Acta 6: 110-127 (1933)

Old Results in Dark Matter

- Vera Rubin: Galactic Rotation Curves (1960's-70s)

Steele, Mottram, Newsam & the LT Project

$$v_{rot.}^2 = \frac{GM(r)}{r^2}$$

$$\Rightarrow v_{rot.} = \sqrt{\frac{GM(r)}{r}}$$

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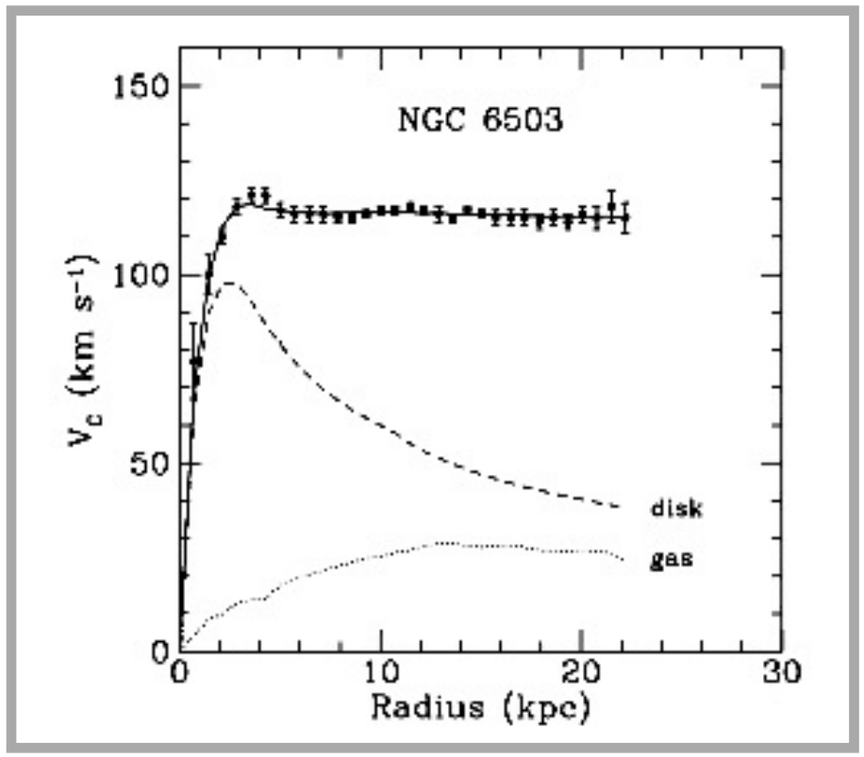

Begeman et al. (1991)

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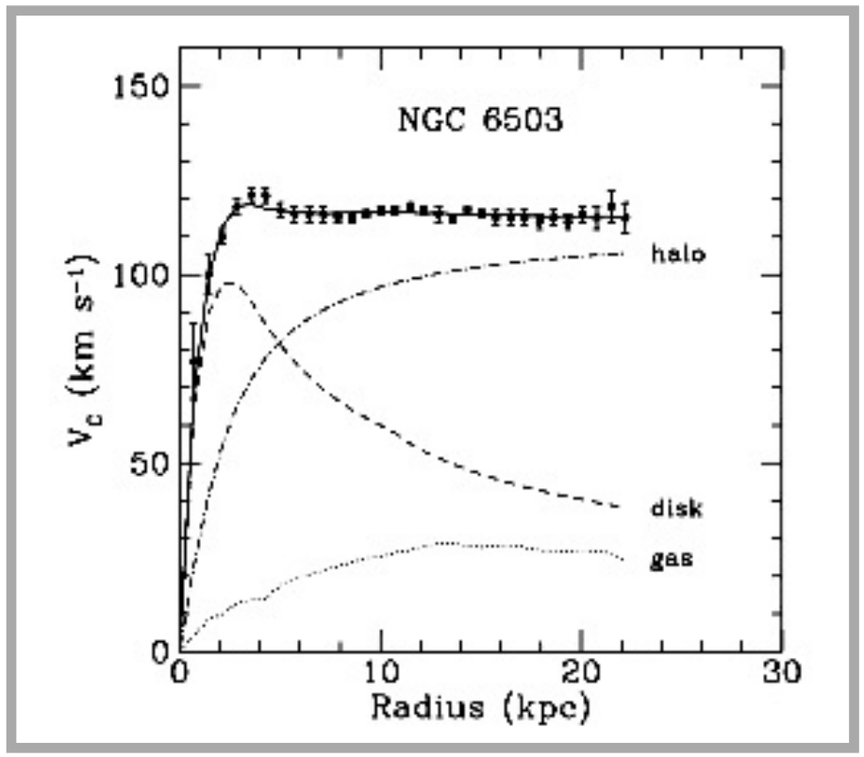

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The Bullet Cluster

Clowe et al. (2006)

✓ Optical (galaxies)

✓ X-ray measurements

✓ Weak gravitational lensing

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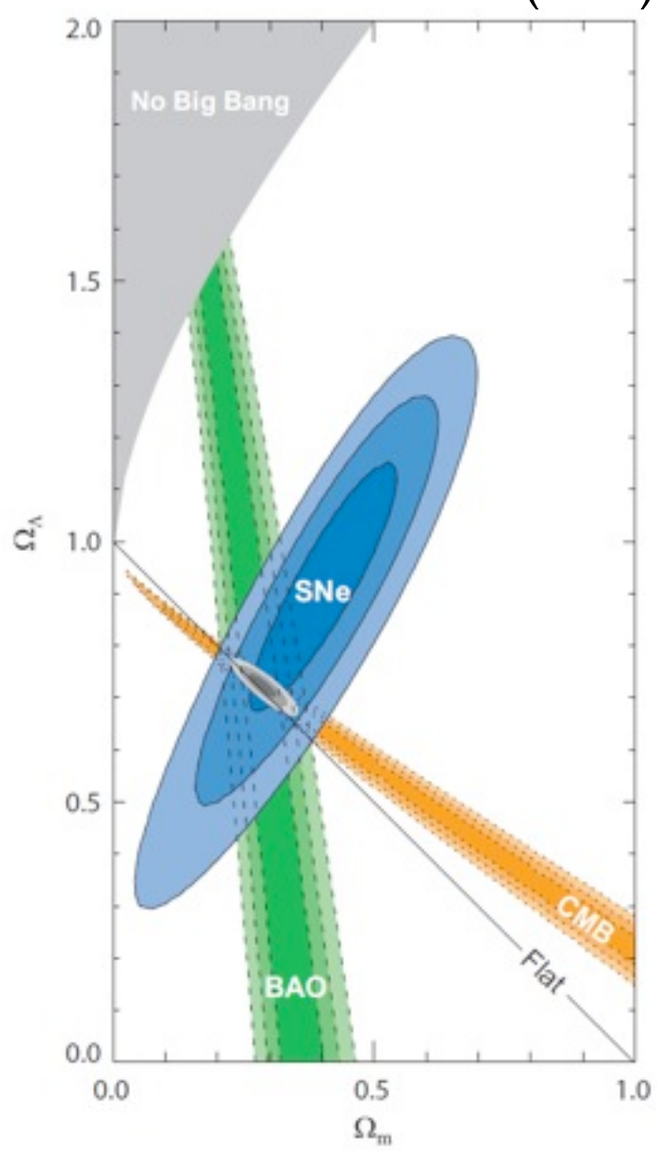
Dark matter is definitely needed to explain this.

Natarajan & Zhao (2008)

Concordance Model

Kowalski et al. (2008)



$\Omega_m = 0.279 \pm 0.015$

=

$\Omega_{DM} = 0.233 \pm 0.0013$

+

$\Omega_b = 0.0462 \pm 0.0015$

Komatsu et al. (2009)

What We Know:

- It's necessary.
- It's non-baryonic (BBN+CMB, structure).
- Its abundance is $\Omega_{DM} = 0.233 \pm 0.0013$.
- It's neutral (heavy isotope abundances).
- It's stable or very long-lived.
- It's largely non-relativistic (cold).

What could it be?

- Standard Model particles?
  - No cold DM in the SM!
  - Neutrinos are HOT DM.
- Beyond the SM:
  - axions, sterile neutrinos, SUSY particles (neutralino, gravitino, axino, or sneutrino), Kaluza Klein states (LKP), Little Higgs heavy photons (LTP) or scalars, mirror matter, WIMPzillas, solitons (Q-balls)...

What could it be?

Weakly
Interacting
Massive
Particles

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Relic Abundance

1. New (heavy) particle χ in thermal equilibrium:

$$\chi\chi \rightleftarrows f\bar{f}$$

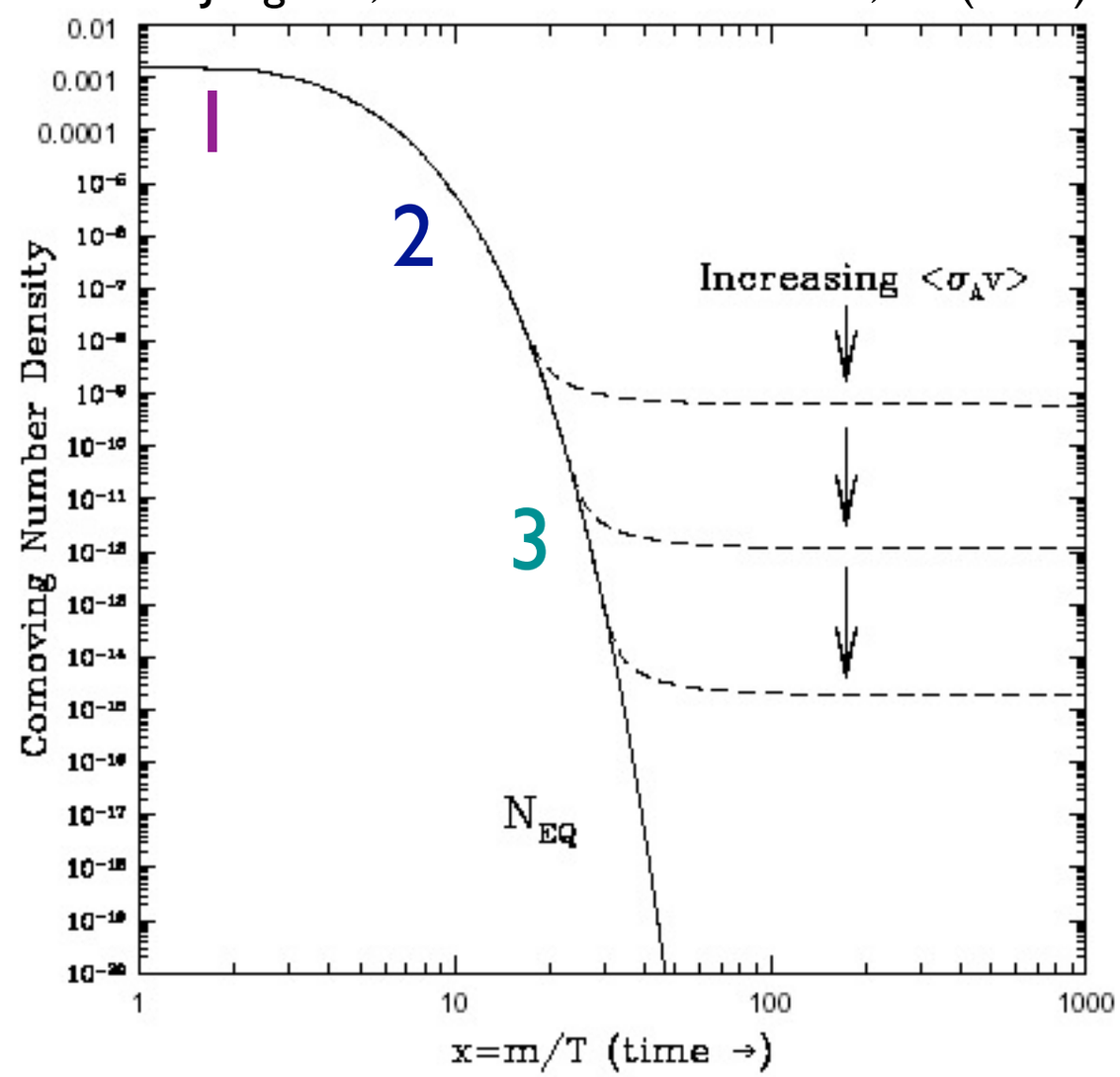
2. Universe expands and cools:

$$\chi\chi \overset{\rightarrow}{\not\leftarrow} f\bar{f}$$

3. χ's "freeze out"

$$\chi\chi \overset{\not\rightarrow}{\not\leftarrow} f\bar{f}$$

Jungman, Kamionkowski & Griest, PR (1996)



Relic Abundance

Expansion and annihilation compete to determine the number density:

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma v_{rel} \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

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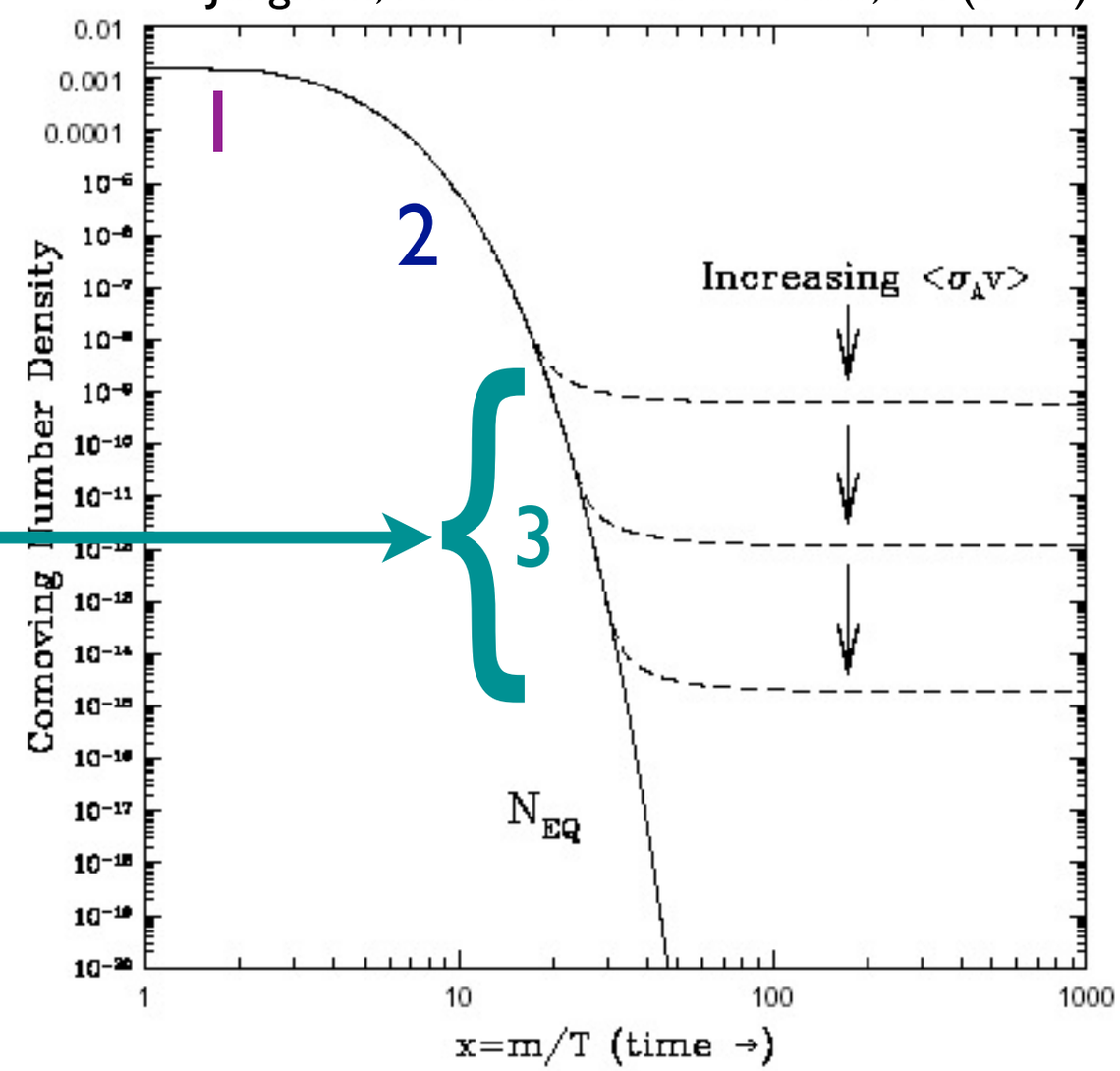

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Stable matter with GeV-TeV mass and weak-scale annihilation cross section yield

$$\Omega_\chi h^2 \approx 0.1$$

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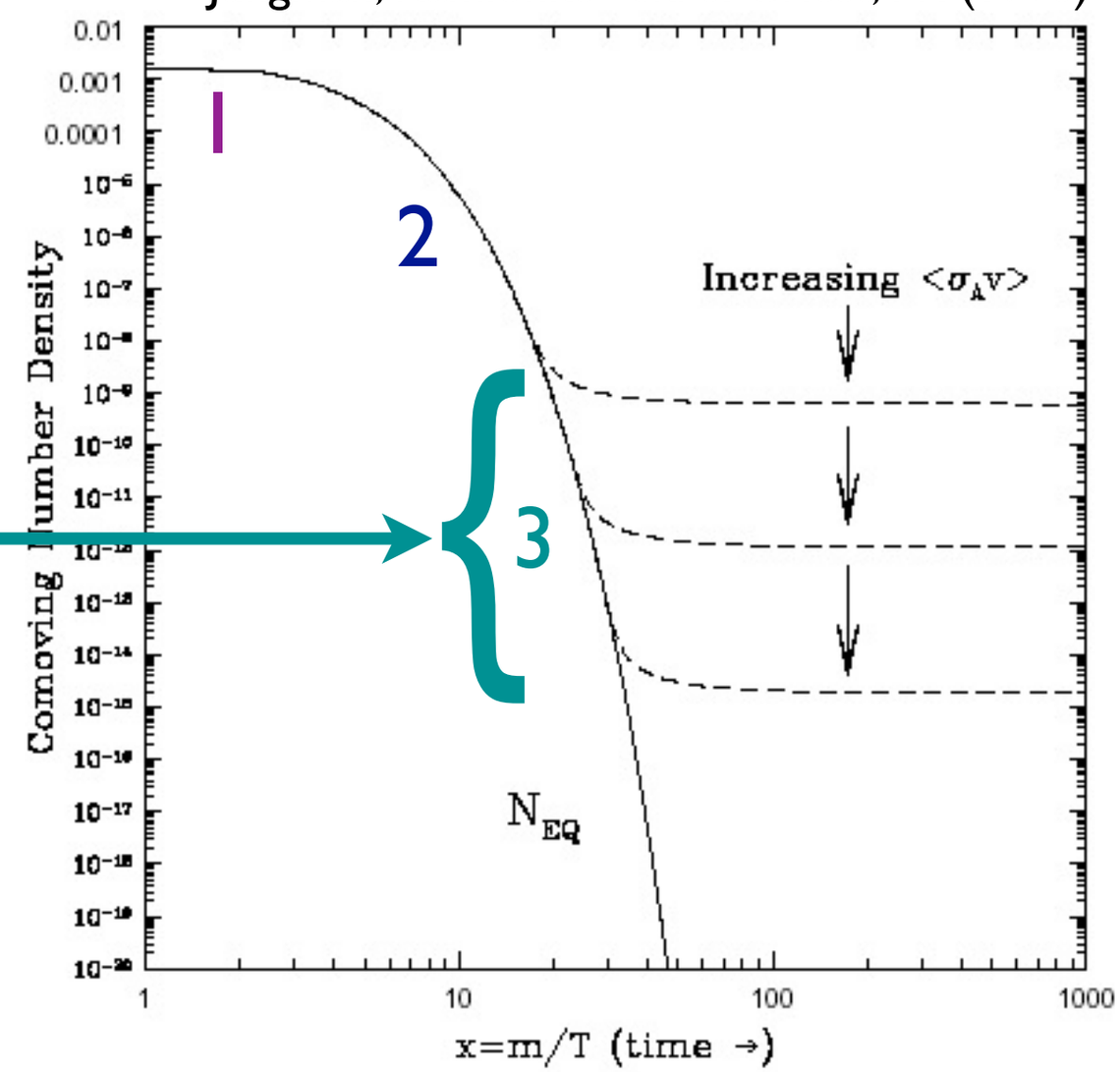

WIMP "Coincidence"

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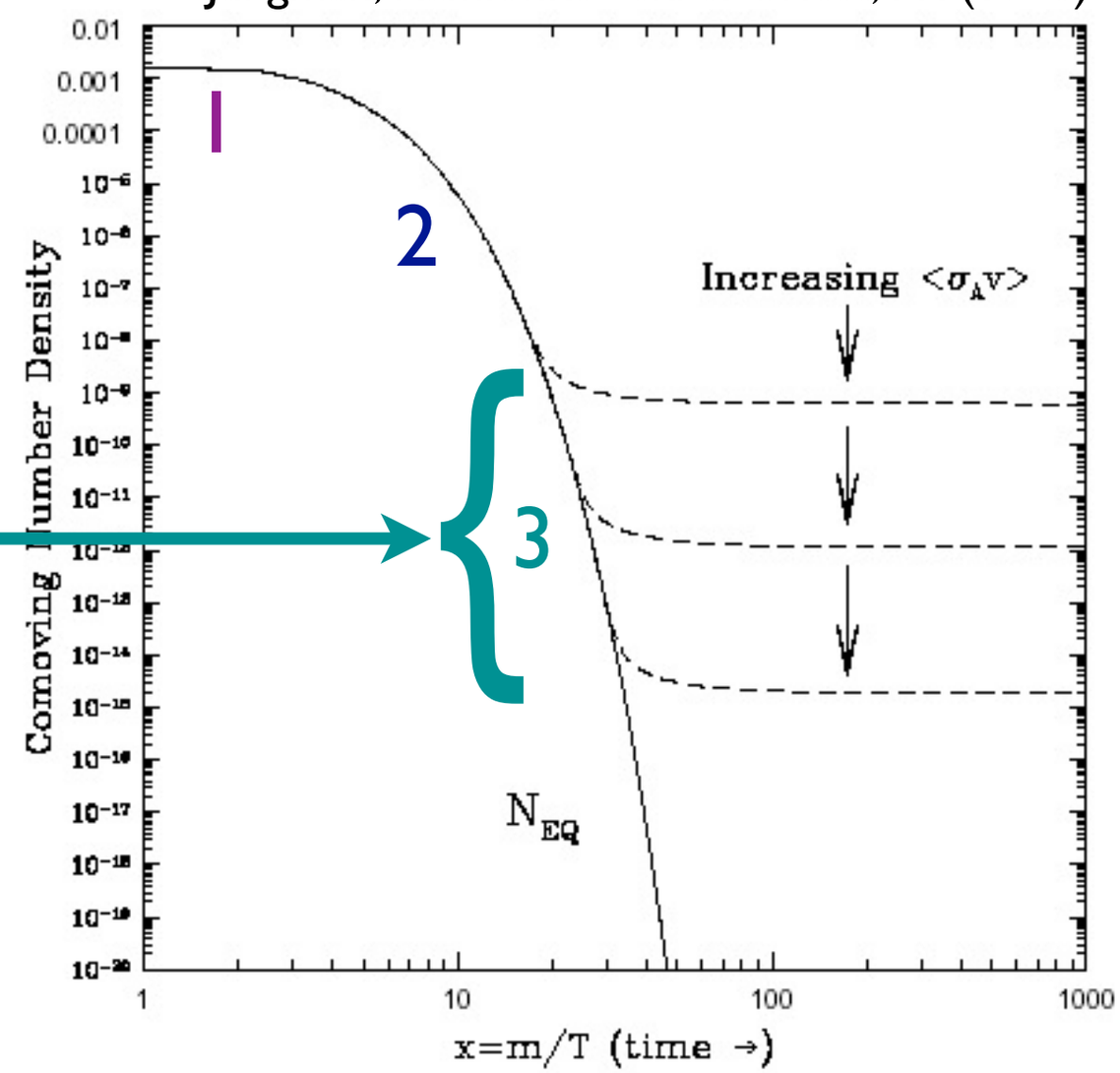

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We DO NOT KNOW that dark matter is made of WIMPs.

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- It's stable or very long-lived.
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We DO NOT KNOW that dark matter is made of WIMPs.

(But we suspect it might be.)

What could it be?

Weakly
Interacting
Massive
Particles

- Standard Model particles?
  - No cold DM in the SM!
  - Neutrinos are HOT DM.
- Beyond the SM:
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What could it be?

Many theories that address the shortcomings of the Standard Model involve new physics at the weak scale, and therefore often address the dark matter question, too.

- Beyond the SM:
  - axions, sterile neutrinos, SUSY particles (neutralino, gravitino, axino, or sneutrino), Kaluza Klein states (LKP), Little Higgs heavy photons (LTP) or scalars, mirror matter, WIMPzillas, solitons (Q-balls)...

Additional Ingredient

- It's not enough to have a theory with extra particles at the weak scale; also need a symmetry to make the lightest new particle stable.
- No problem! We need this anyway (proton stability, neutron-antineutron oscillations, large neutrino masses...)

Theory	Z_2 Parity	Dark Matter
SUSY	R-parity	LSP
UED	KK-parity	LKP
Little Higgs	T-parity	LTP

To Catch a WIMP

- Colliders
  - ✓ Produce WIMPs directly; missing energy signature
  - ✓ Observe decays of Next-to-Lightest particles to DM

SM + SM → DM + DM

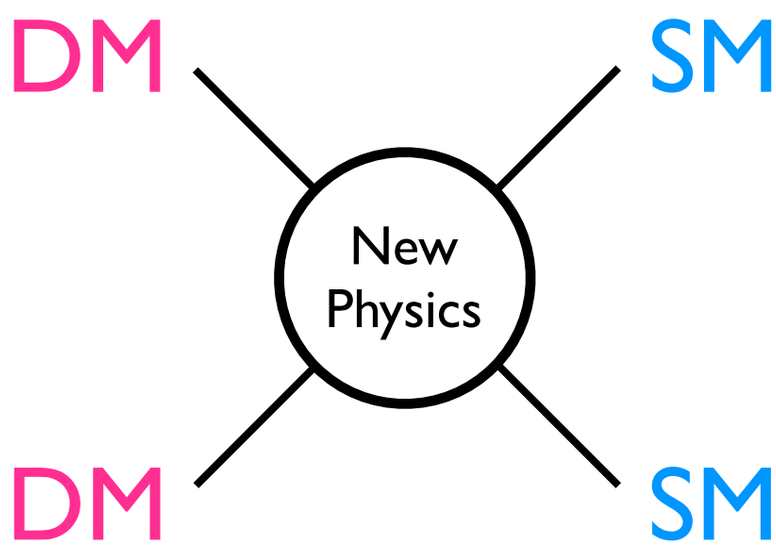
- Direct Detection
  - ✓ Observe WIMPs through interactions with nuclei in terrestrial detectors

DM + SM → DM + SM

- Indirect Detection
  - ✓ Observe the products of WIMP annihilation or decay in terrestrial or space-based detectors

DM + DM → SM + SM

Diary of a WIMPy Particle



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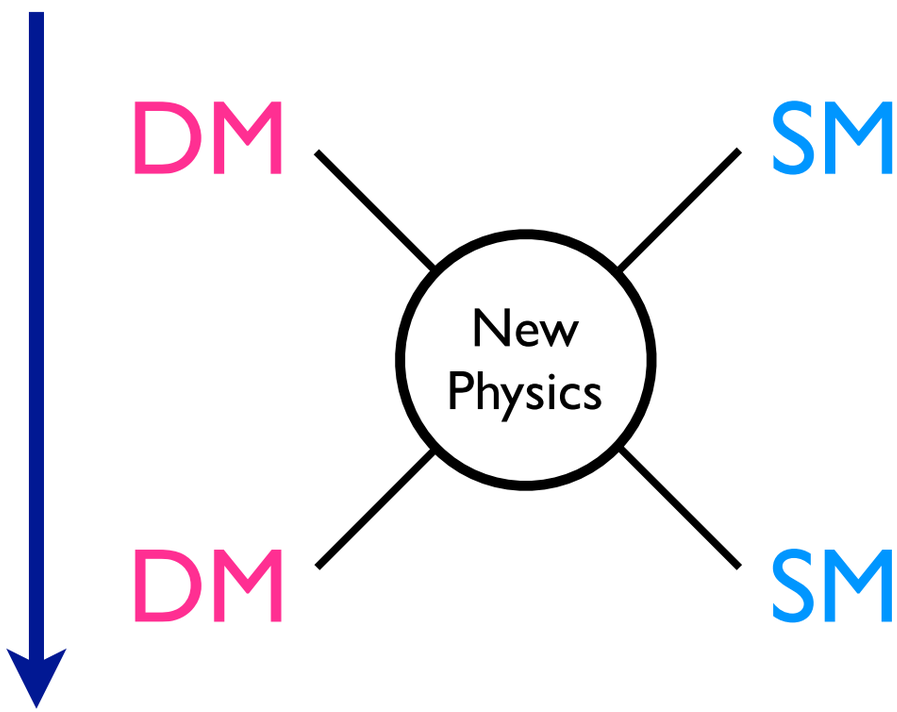

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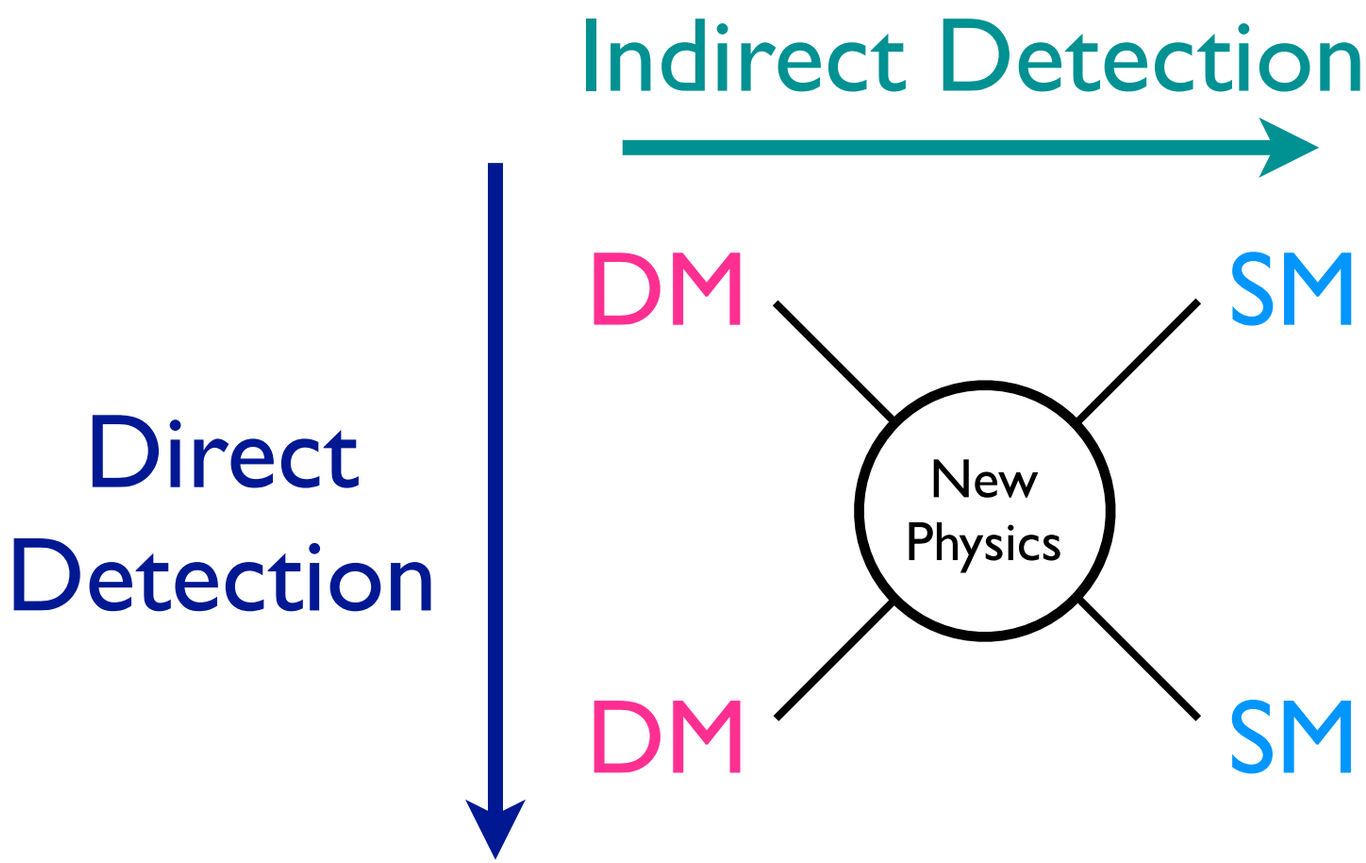

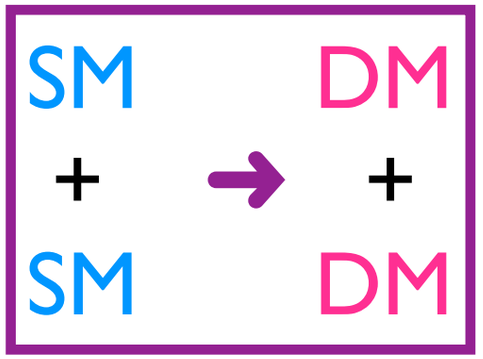

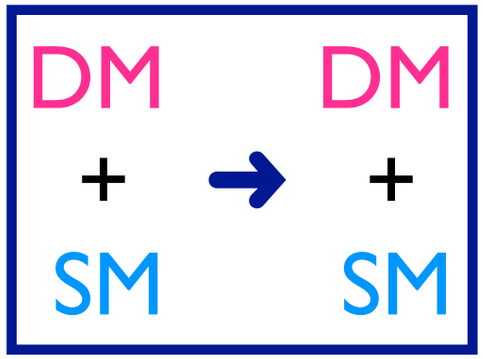

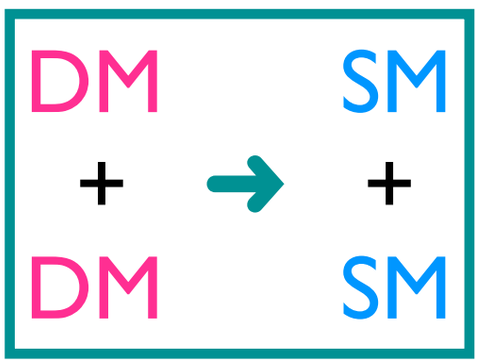

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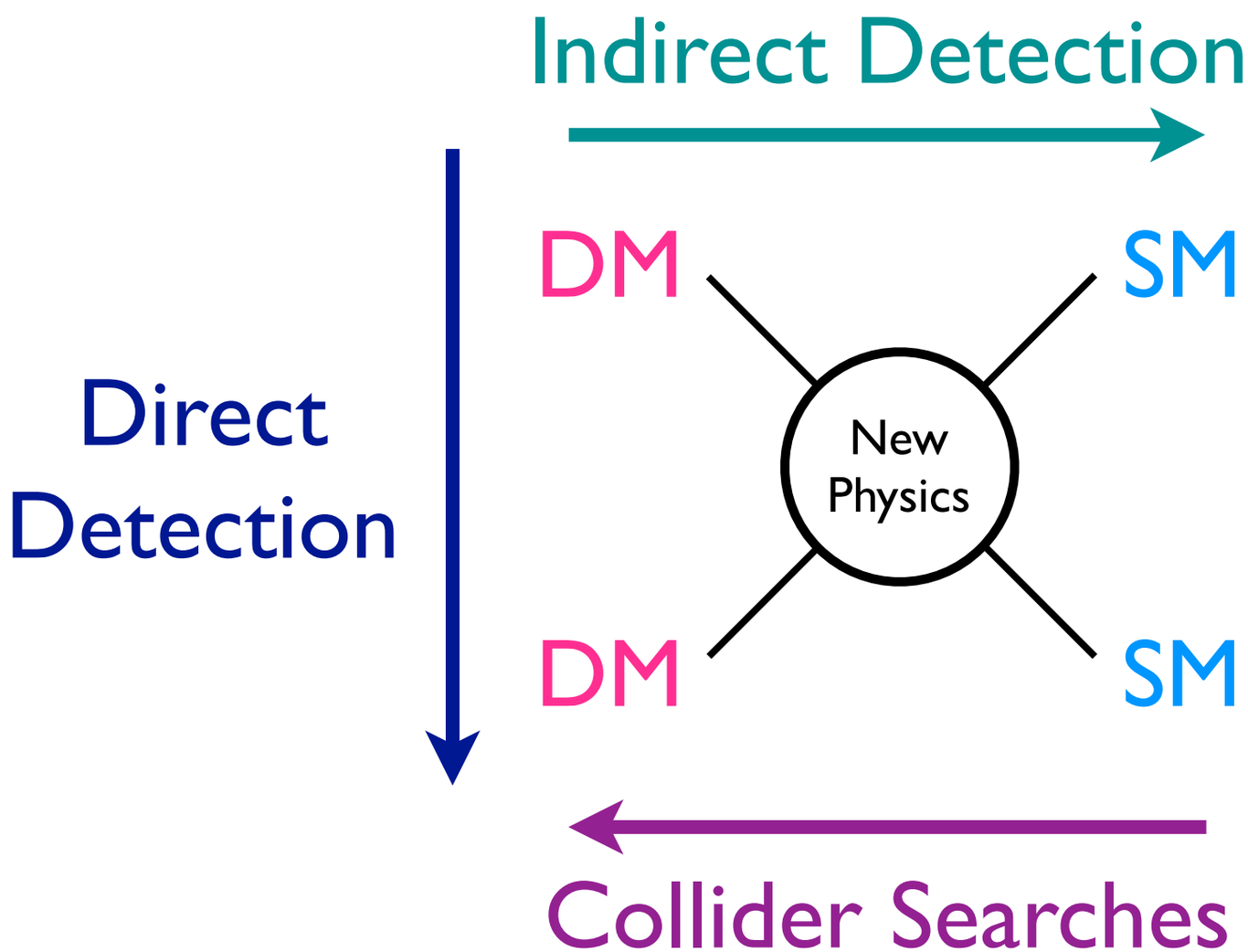
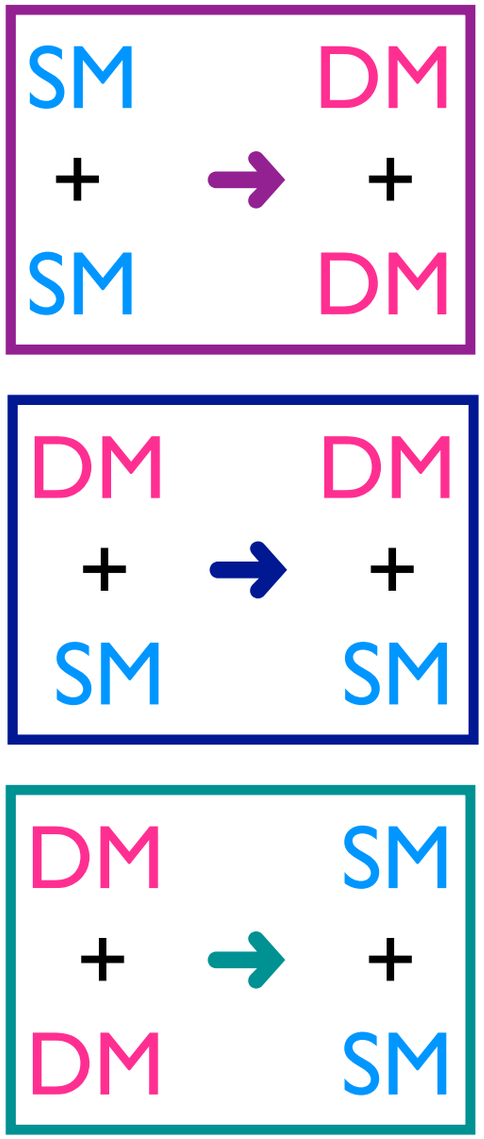
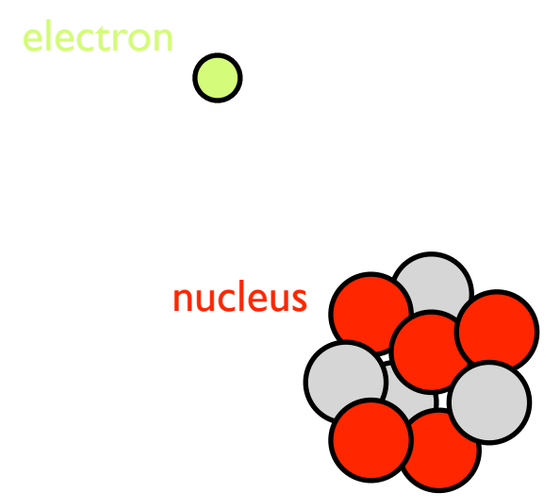




Direct Detection

- If WIMPs are the dark matter, they are all around us, and will *occasionally* bump into nuclei.



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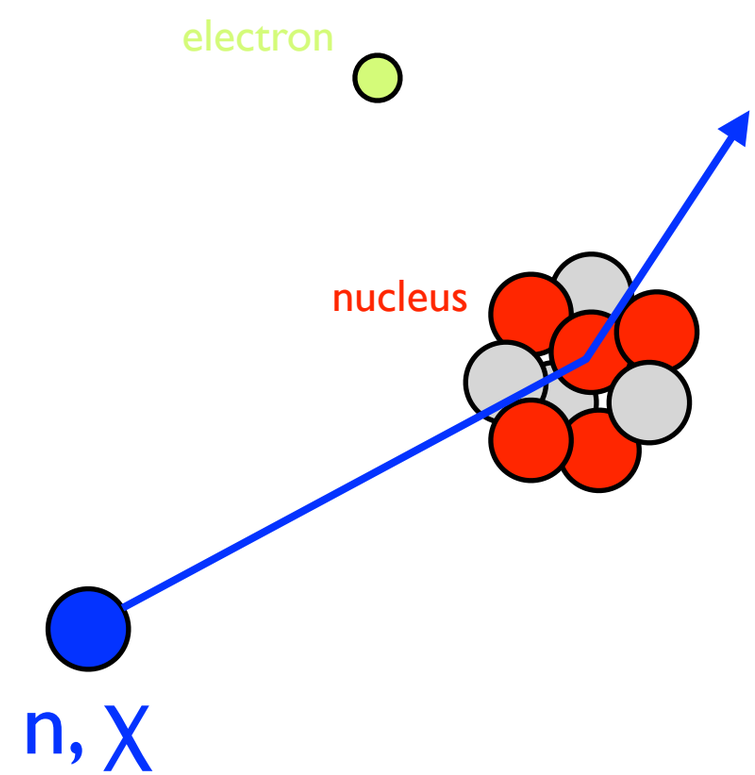

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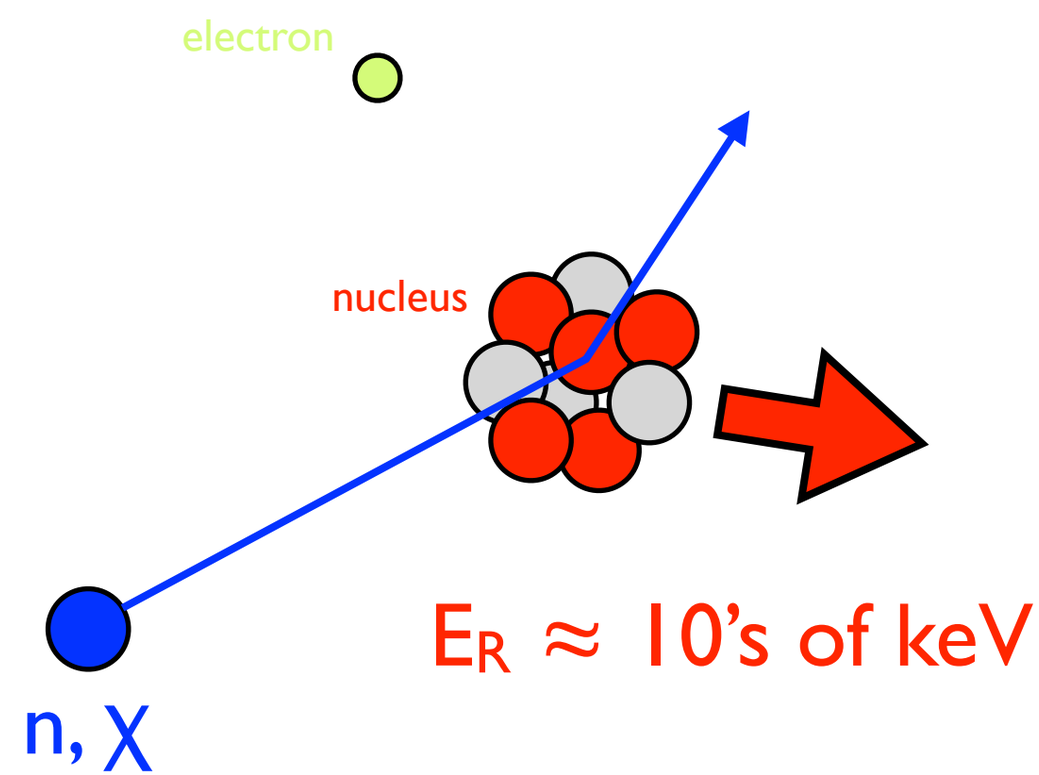
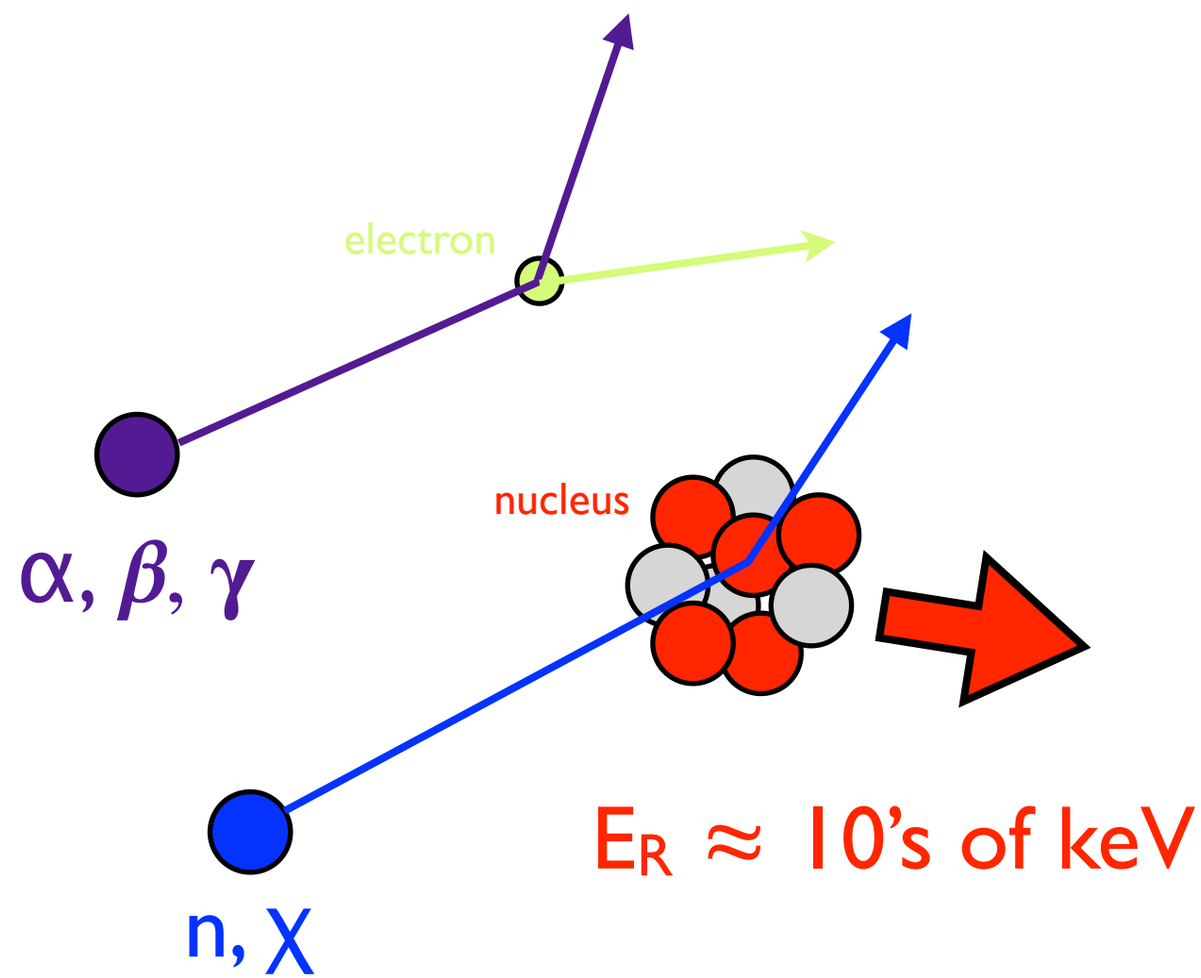


Direct Detection

- If WIMPs are the dark matter, they are all around us, and will *occasionally* bump into nuclei.

- background ≫ signal
- scatterings produce
  - ★ ionization
  - ★ scintillation
  - ★ phonons



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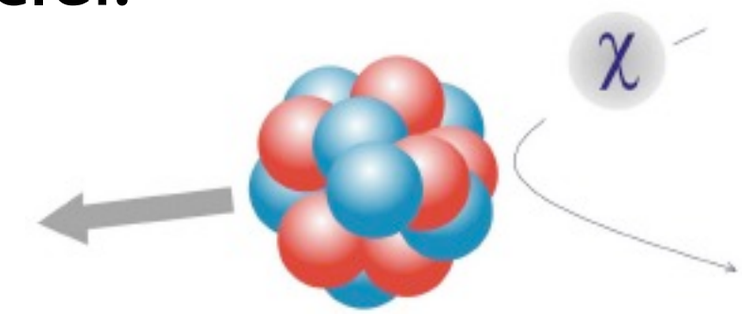
➡ How *occasionally*?



$$\frac{dR}{dE_R}(E_R) = \frac{1}{m_N}\int_{v>v_{min}(E_R)} d^3\vec{v}\,\frac{\rho_0 v}{m_\chi} f(\vec{v}+\vec{v}_e)\,\frac{d\sigma_{\chi N}(v,E_R)}{dE_R}$$

Differential Rate (counts/ton/yr/keV)

Flux of WIMPs

Velocity Distribution

Probability of Interaction w/ Target Nucleus

What do we expect?

- For any dark matter candidate, can calculate the expected elastic scattering cross section:

$$\mathcal{L}_{int} = \alpha_{ijk} \left(\bar{\chi}\Gamma_i\chi\right)\left(\bar{q}_k\Gamma_j q_k\right)$$

$$\Gamma_i = \begin{array}{cc} \gamma_0 & \text{scalar} \\ \gamma_0\gamma_5 & \text{pseudoscalar} \\ \gamma_\mu & \text{vector} \\ \gamma_\mu\gamma_5 & \text{axial vector} \\ \sigma_{\mu\nu} & \text{tensor} \\ \sigma_{\mu\nu}\gamma_5 & \text{axial tensor} \end{array}$$

- scalar-scalar and vector-vector
  - spin-independent scattering
  - nucleus participates coherently
- axial-axial and tensor-tensor
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  - unpaired neutron or proton

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$\sigma \sim A^2$
If target nuclei are heavy,
better sensitivity to SI scattering

γ_μ	vector
$\gamma_\mu\gamma_5$	axial vector
$\sigma_{\mu\nu}$	tensor
$\sigma_{\mu\nu}\gamma_5$	axial tensor

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γ_μ vector
$\gamma_\mu\gamma_5$ axial vector

σ depends on spin
Important for
capture/annihilation in the sun

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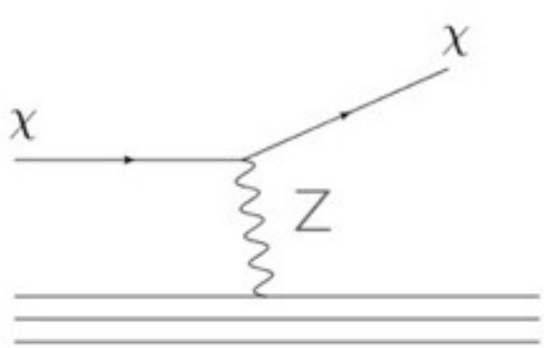
What do we expect?

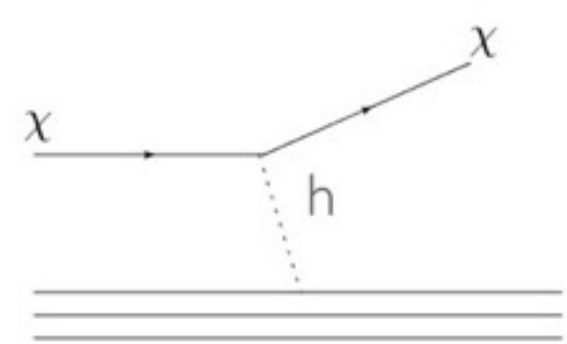
- At the most basic level, if we have a dark matter particle that scatters on quarks, there are two possibilities for the interaction (without adding new particles):

time →

- Z boson exchange



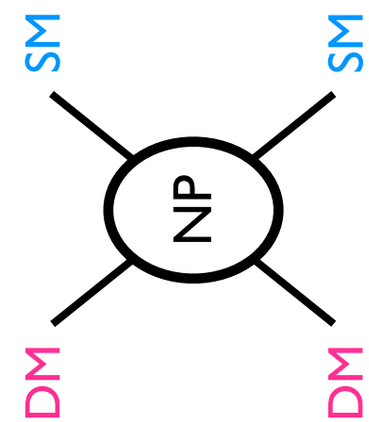
- Higgs boson exchange



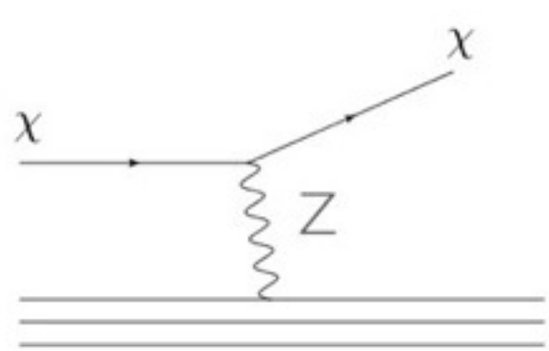
What do we expect?

- At the most basic level, if we have a dark matter particle that scatters on quarks, there are two possibilities for the interaction (without adding new particles):

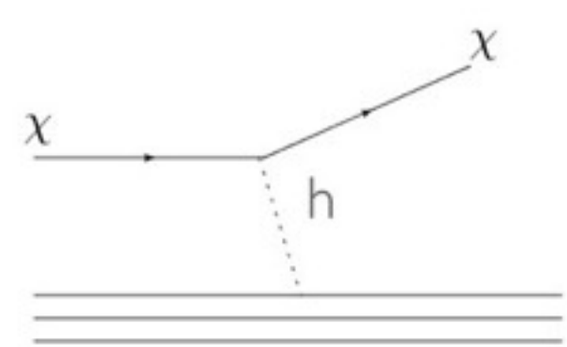
time →



- Z boson exchange

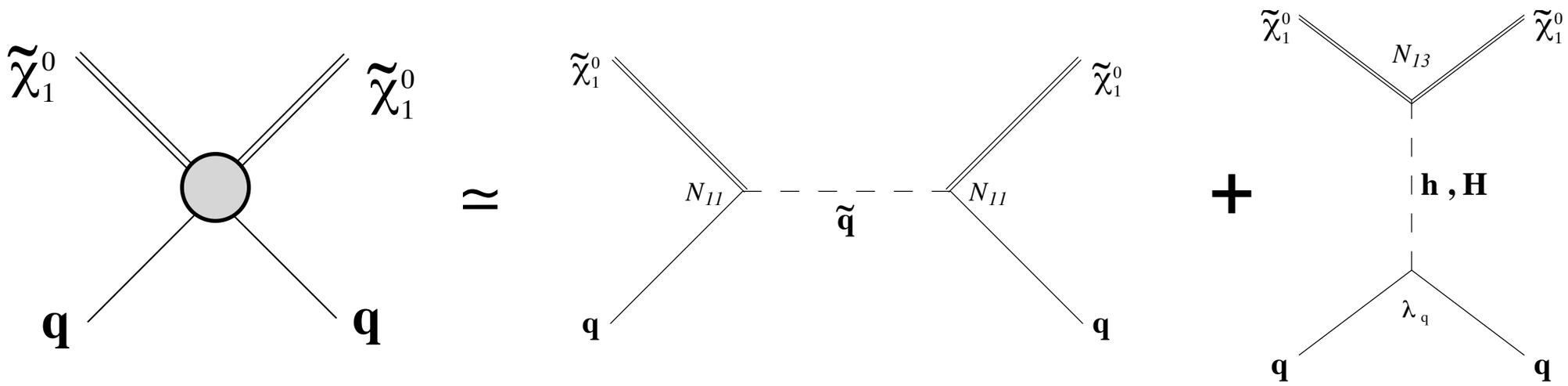


- Higgs boson exchange



What do we expect?

For SUSY neutralino dark matter?



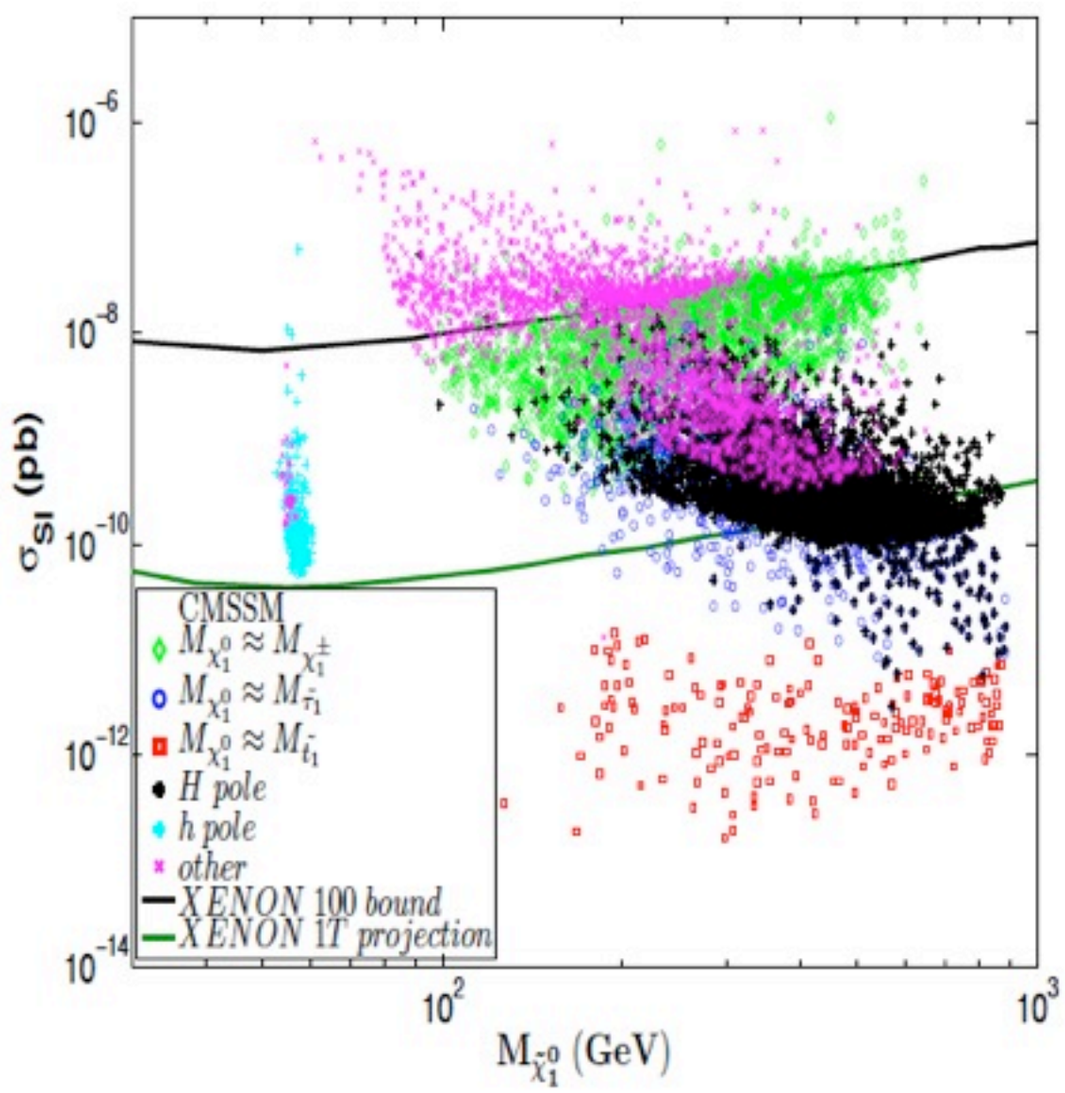
$\mathcal{L}_{SI} = \alpha_q \bar{\chi}\chi\bar{q}q$

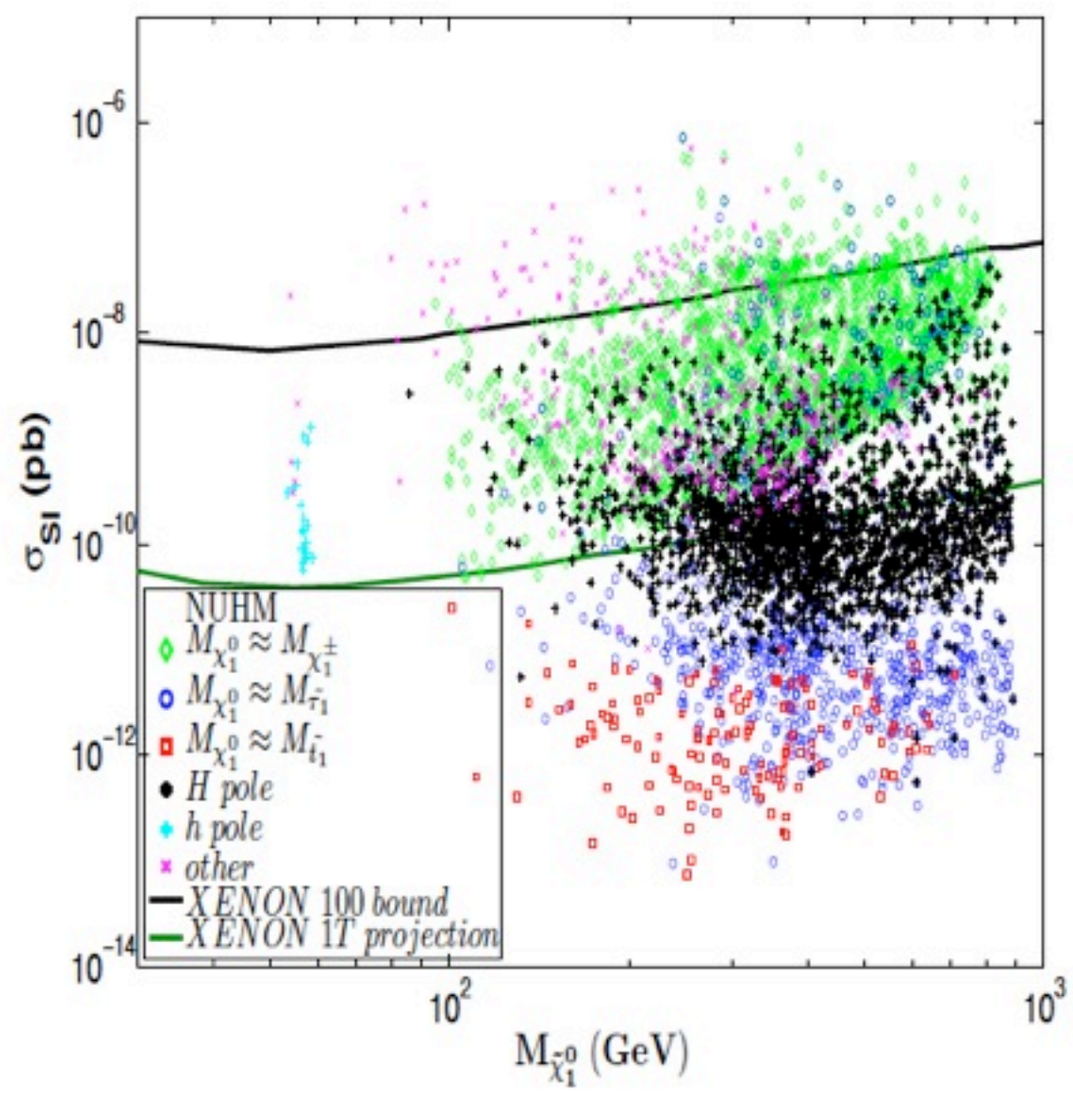
squark exchange

higgs exchange

What do we expect?

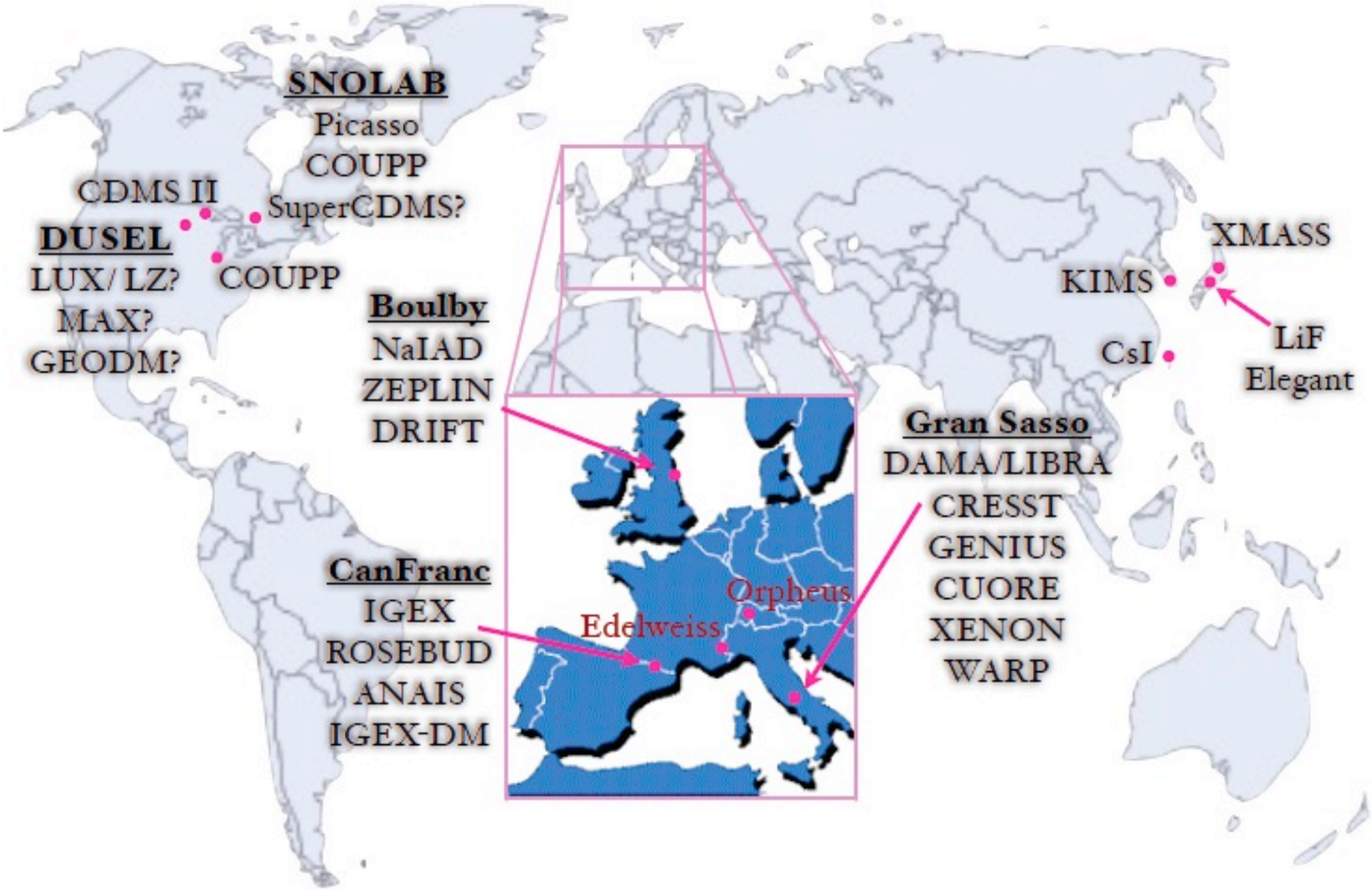
For SUSY neutralino dark matter?





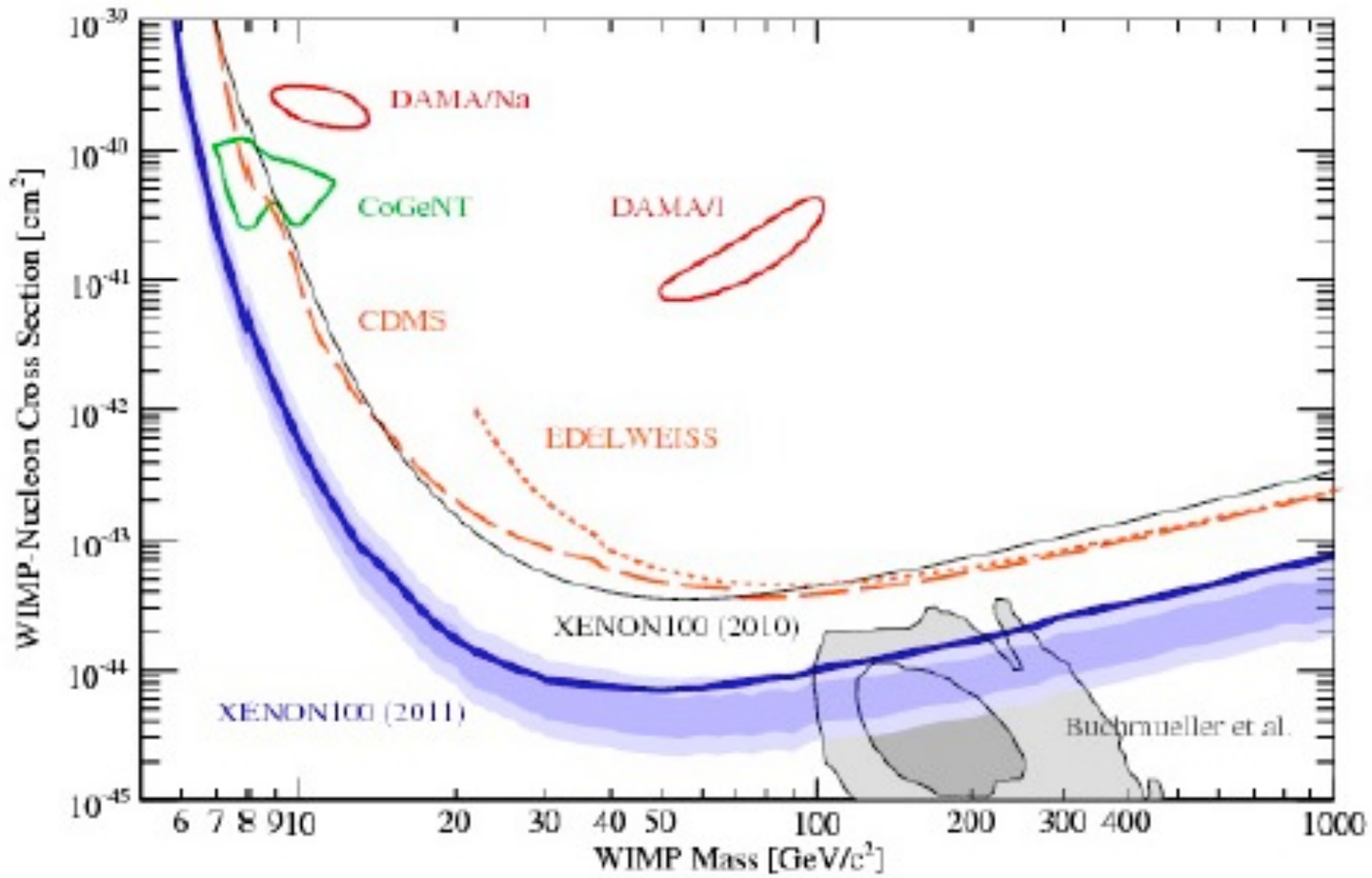
Amsel, Freese & Sandick (2011)

Worldwide Effort



Current Limits

XENON-100 (2011)



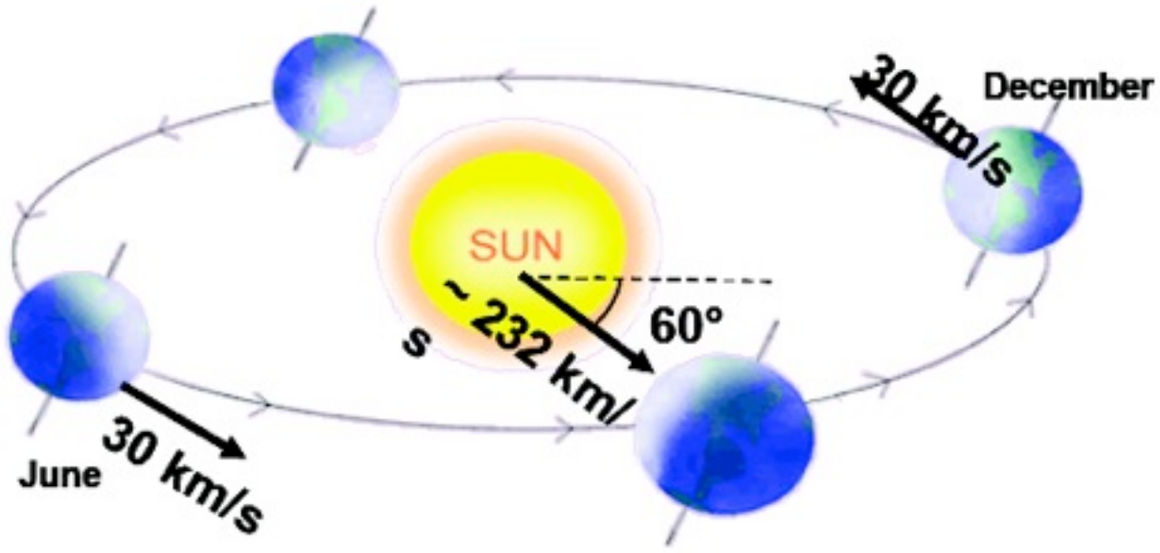
- Comparison to theoretical predictions becoming interesting
  - Null results ➔ limits on parameters

DAMA/LIBRA

- The DAMA collaboration found an annual modulation signal compatible with signal expected from dark matter particles.
- **8.9σ signal** in DAMA/LIBRA as of February 2010.

!! Only experiment to search for annual modulation. (All others reject BG.)

!! Only experiment to use NaI. (**DM-ICE** online now!)



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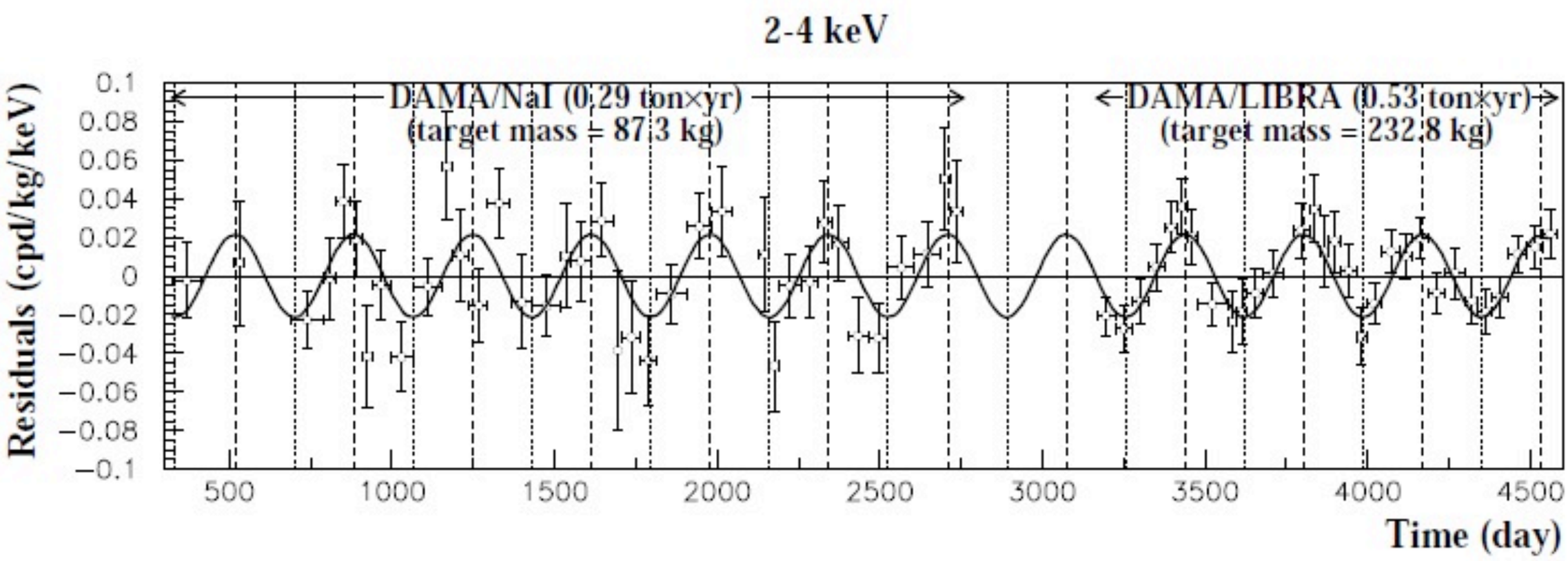
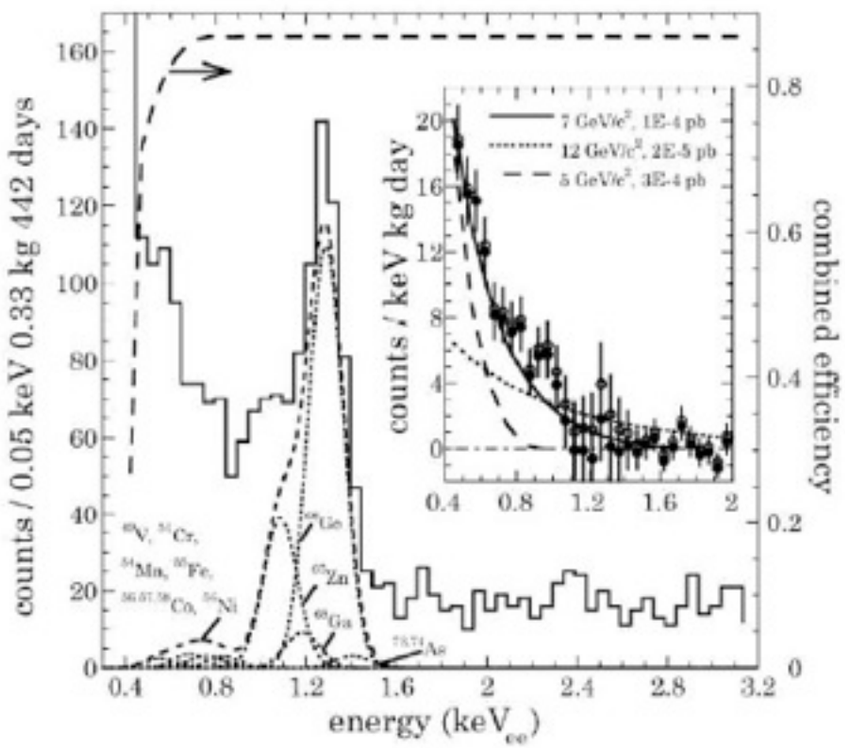
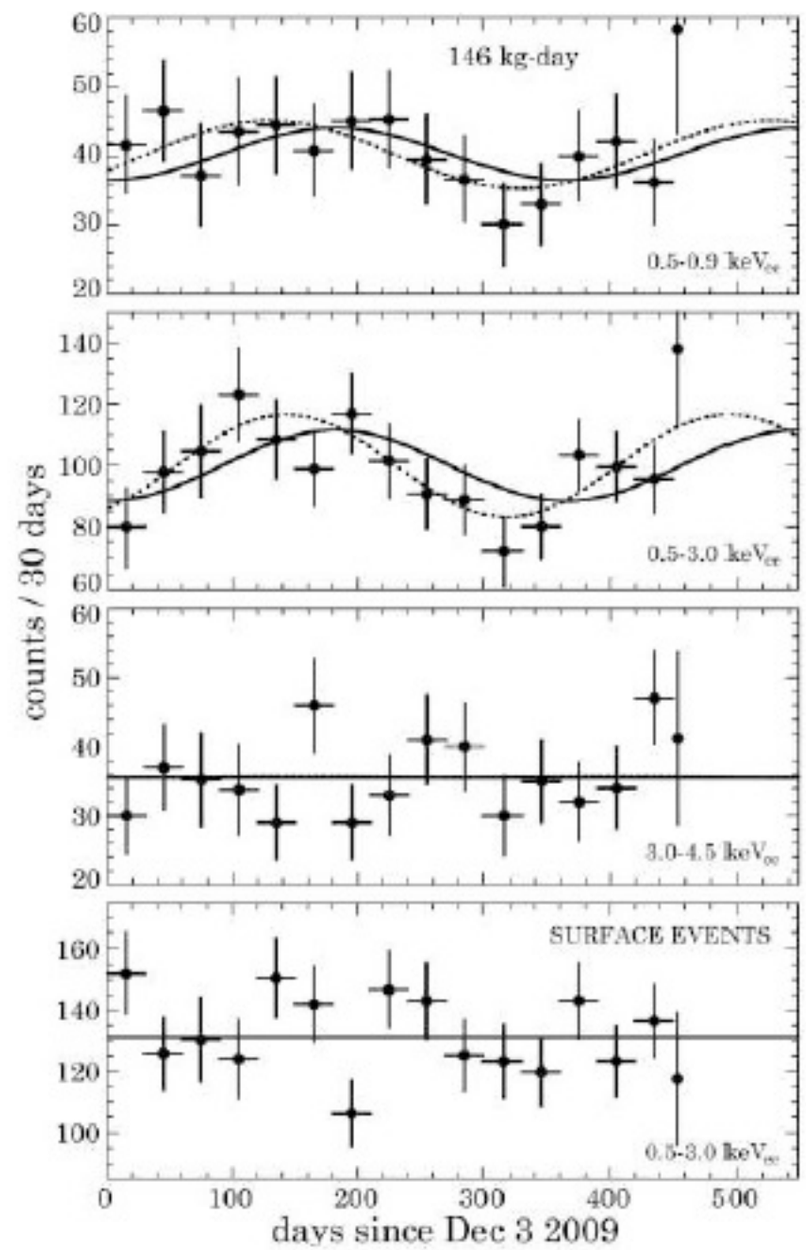


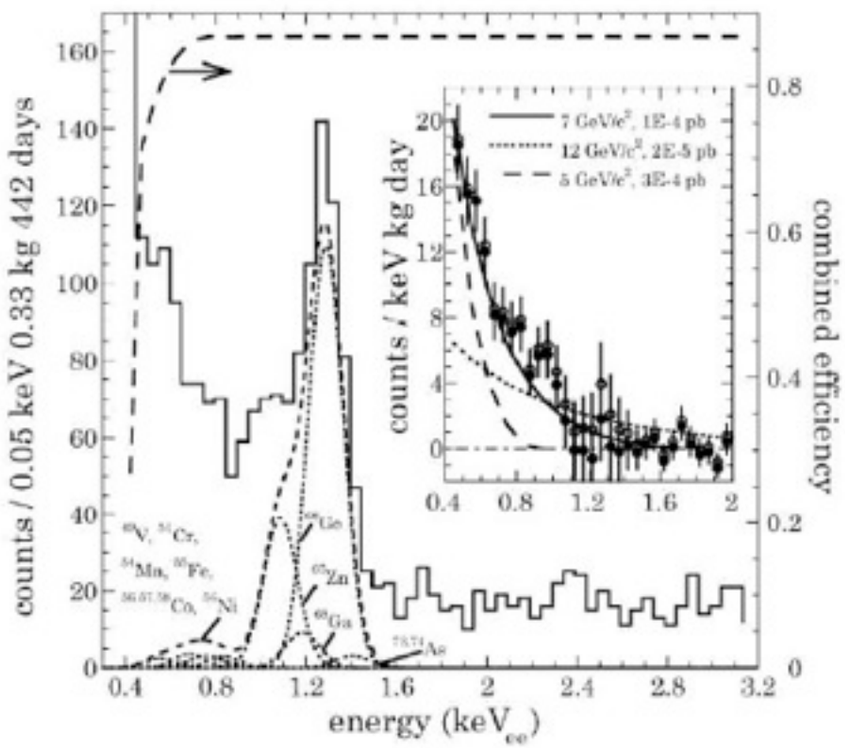
CoGeNT



Aalseth et al. (2011)



CoGeNT



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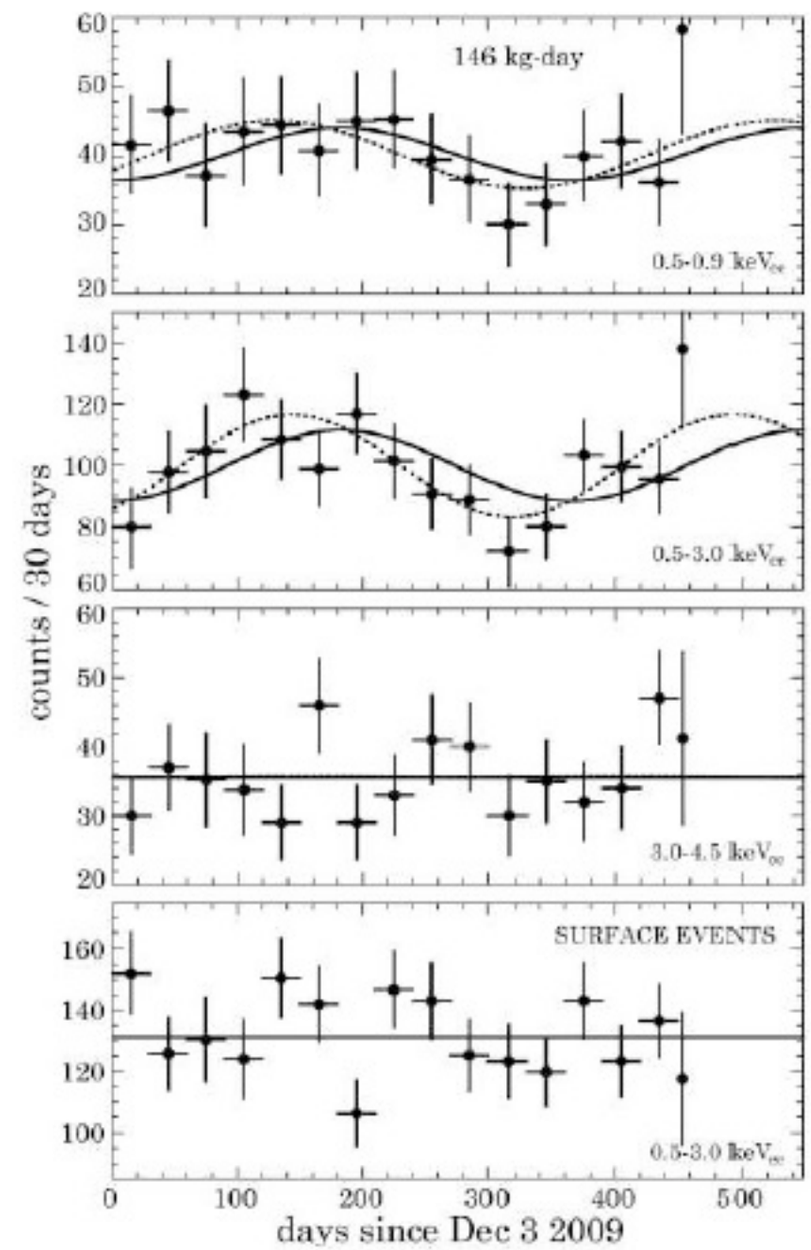
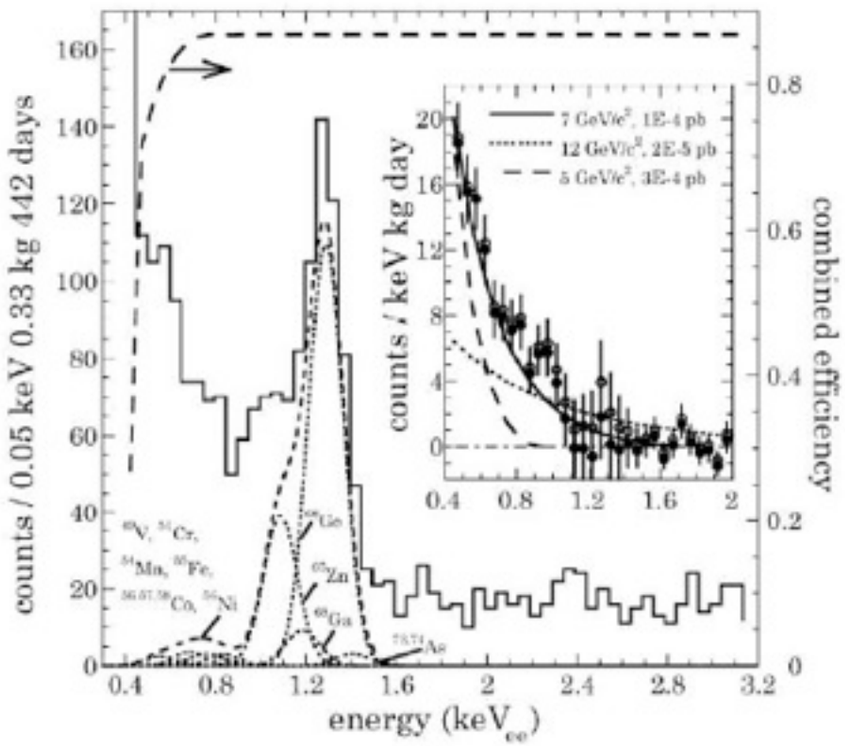


- Very low E_R threshold

CoGeNT



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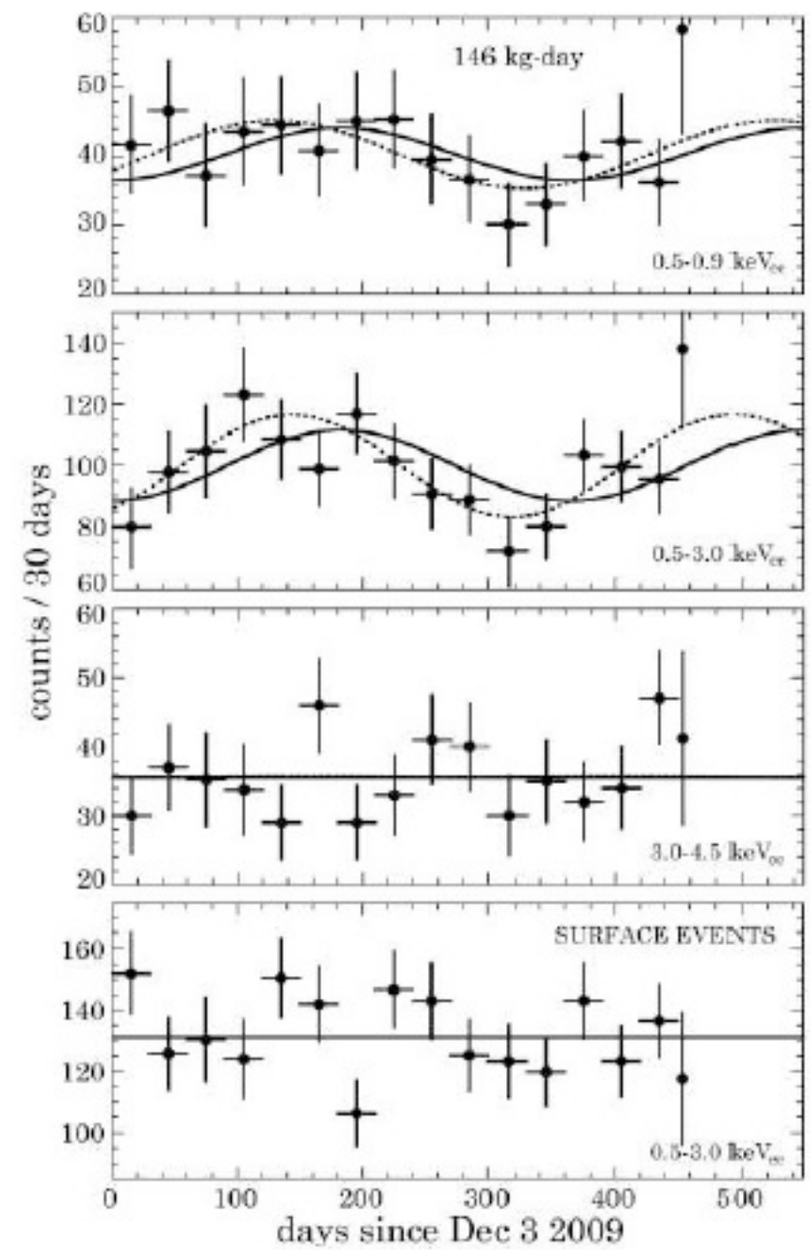
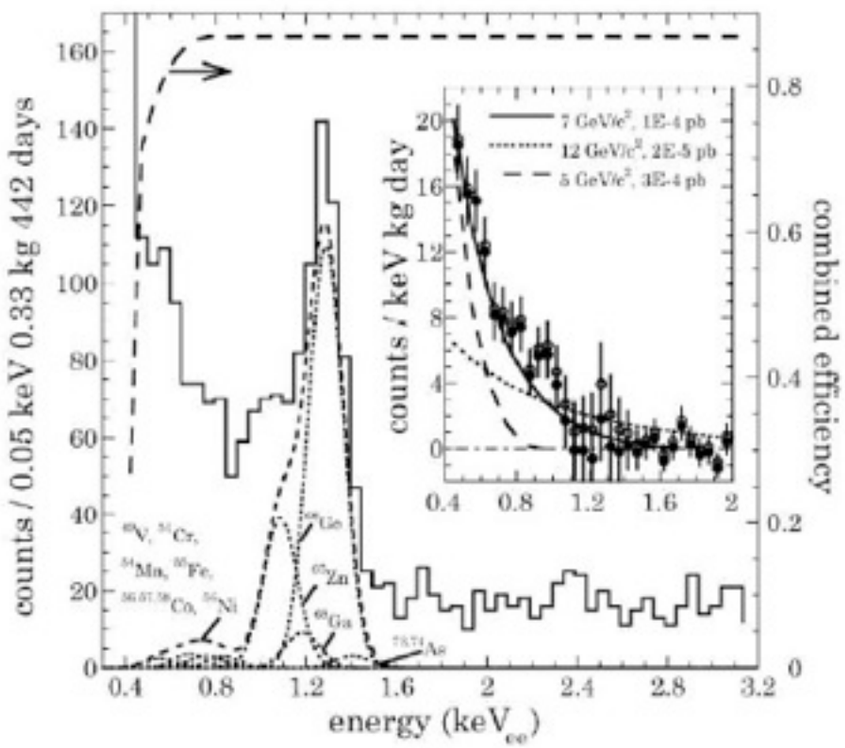


- Very low E_R threshold
- Excess reported in Feb.'10

CoGeNT



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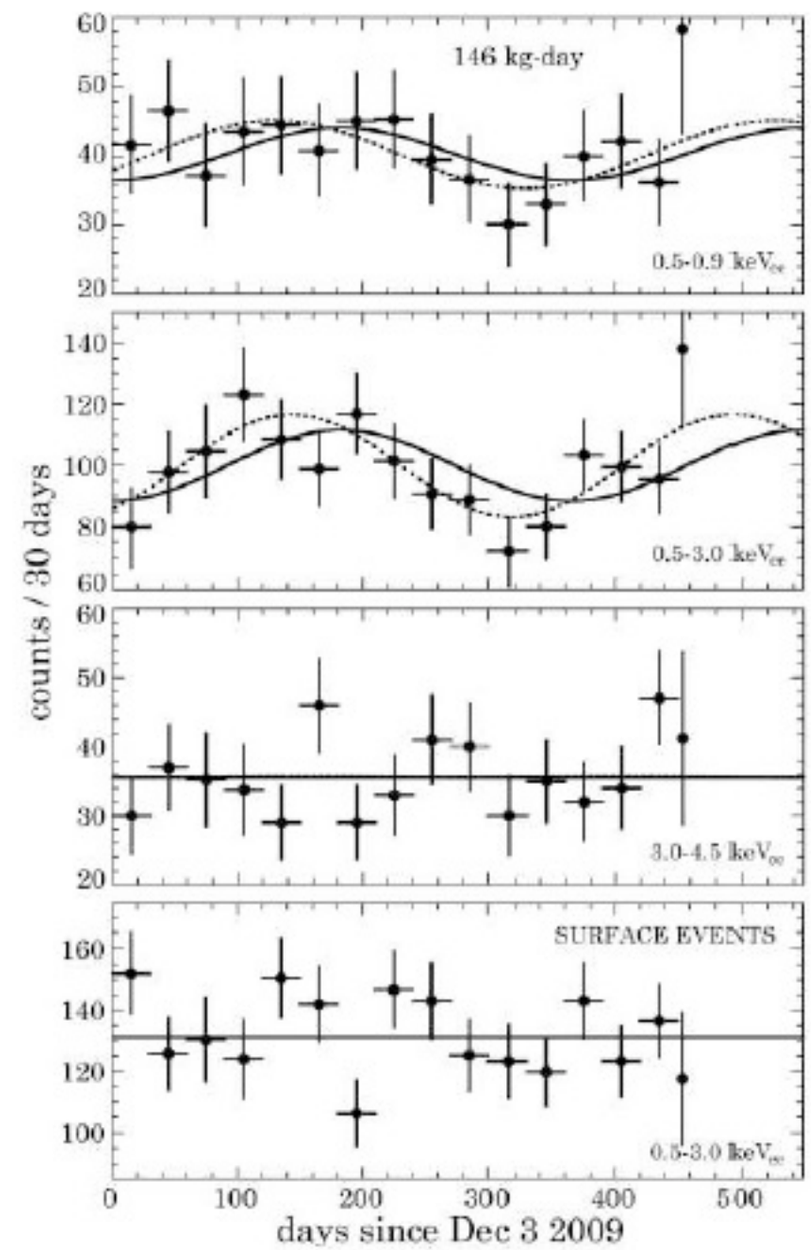
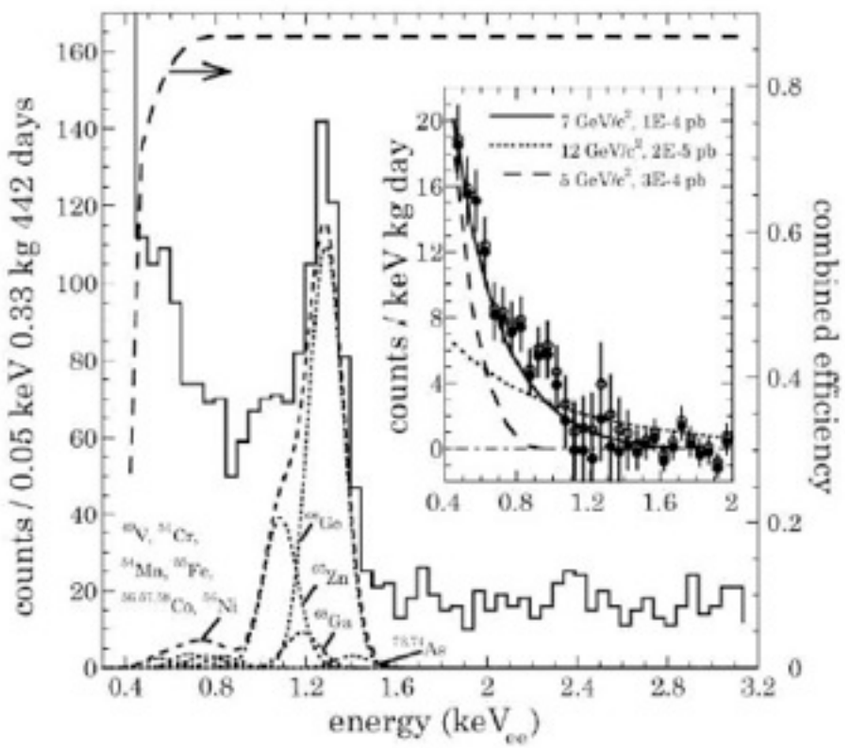


- Very low E_R threshold
- Excess reported in Feb.'10
- Excess confirmed in June

CoGeNT



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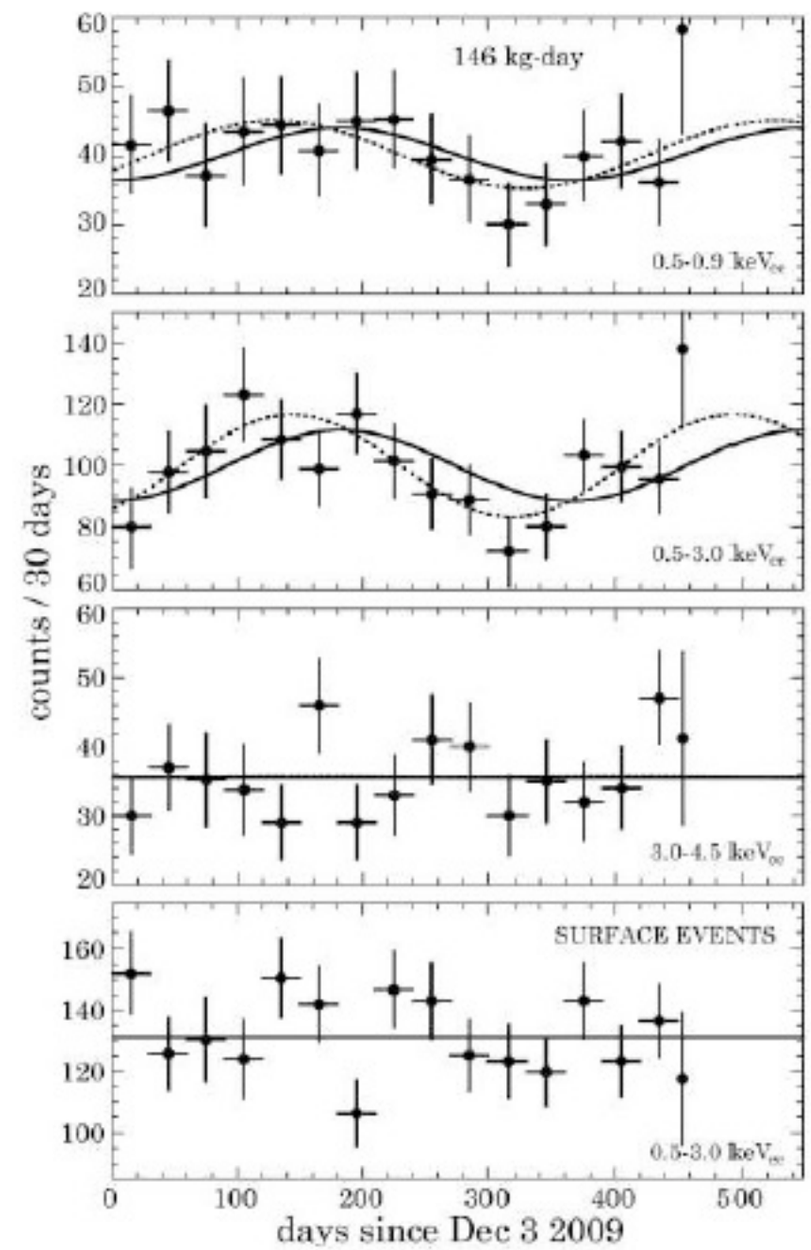
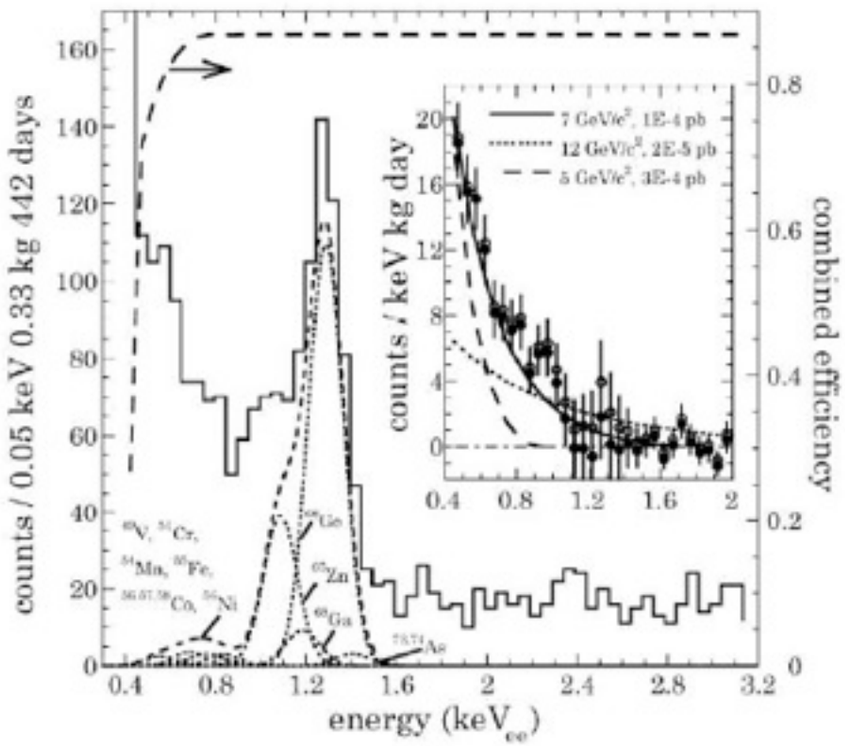
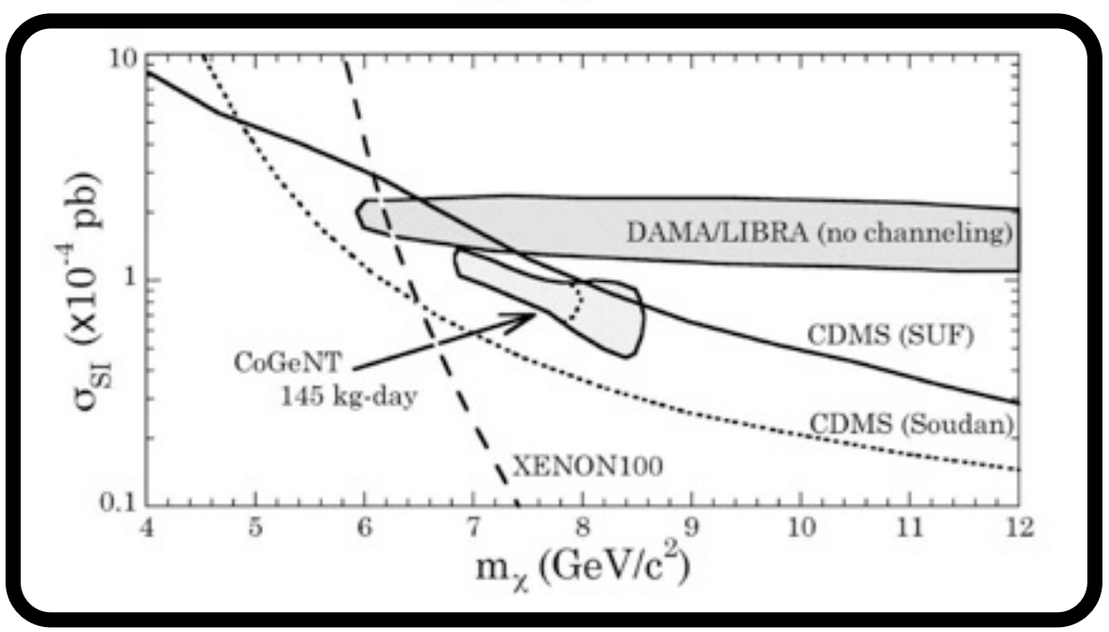


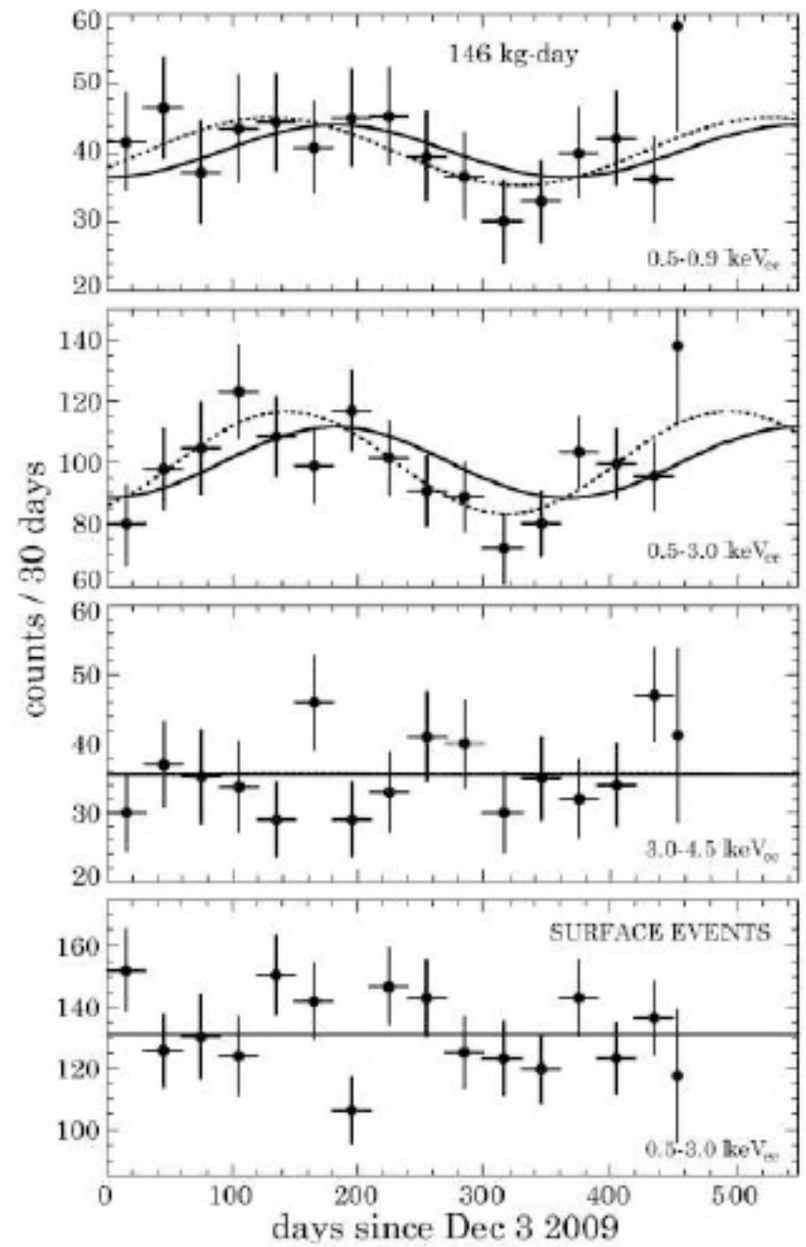
- Very low E_R threshold
- Excess reported in Feb.'10
- Excess confirmed in June
- + annual modulation!!

CoGeNT

Aalseth et al. (2011)







CRESST-II

Angloher et al. (2011)

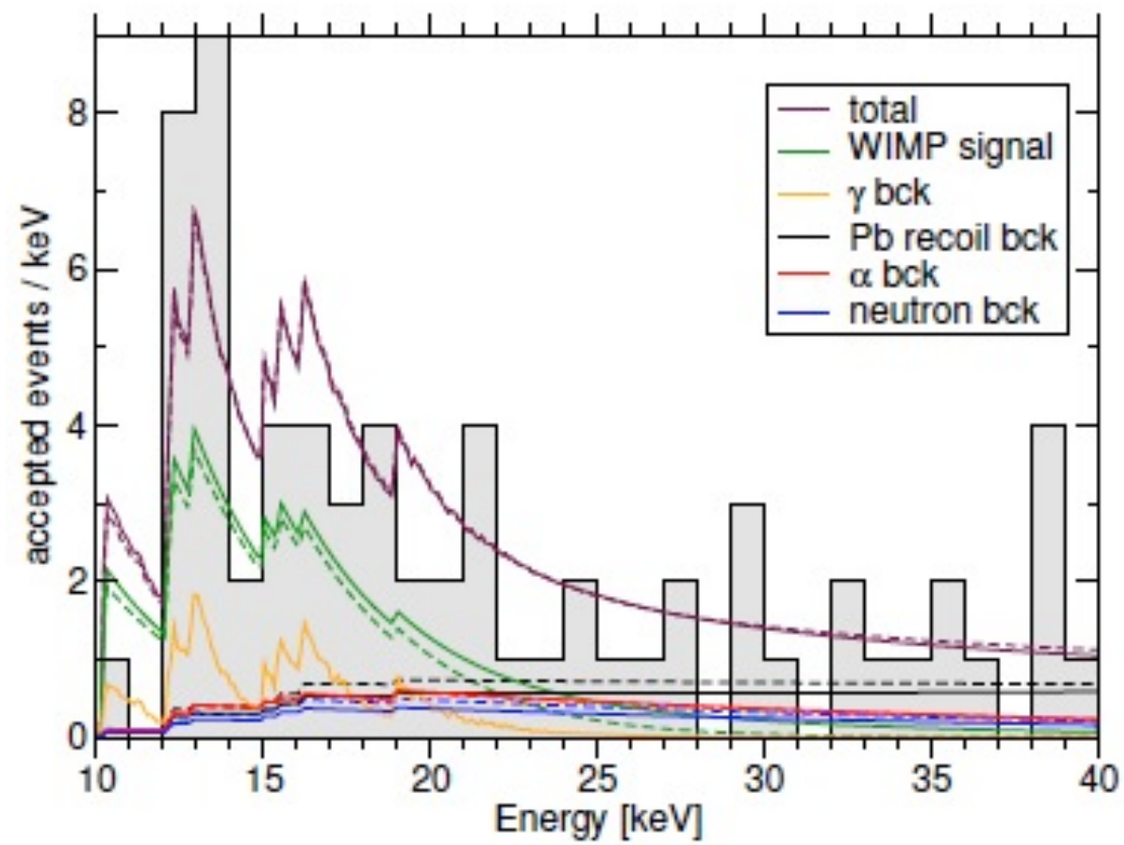
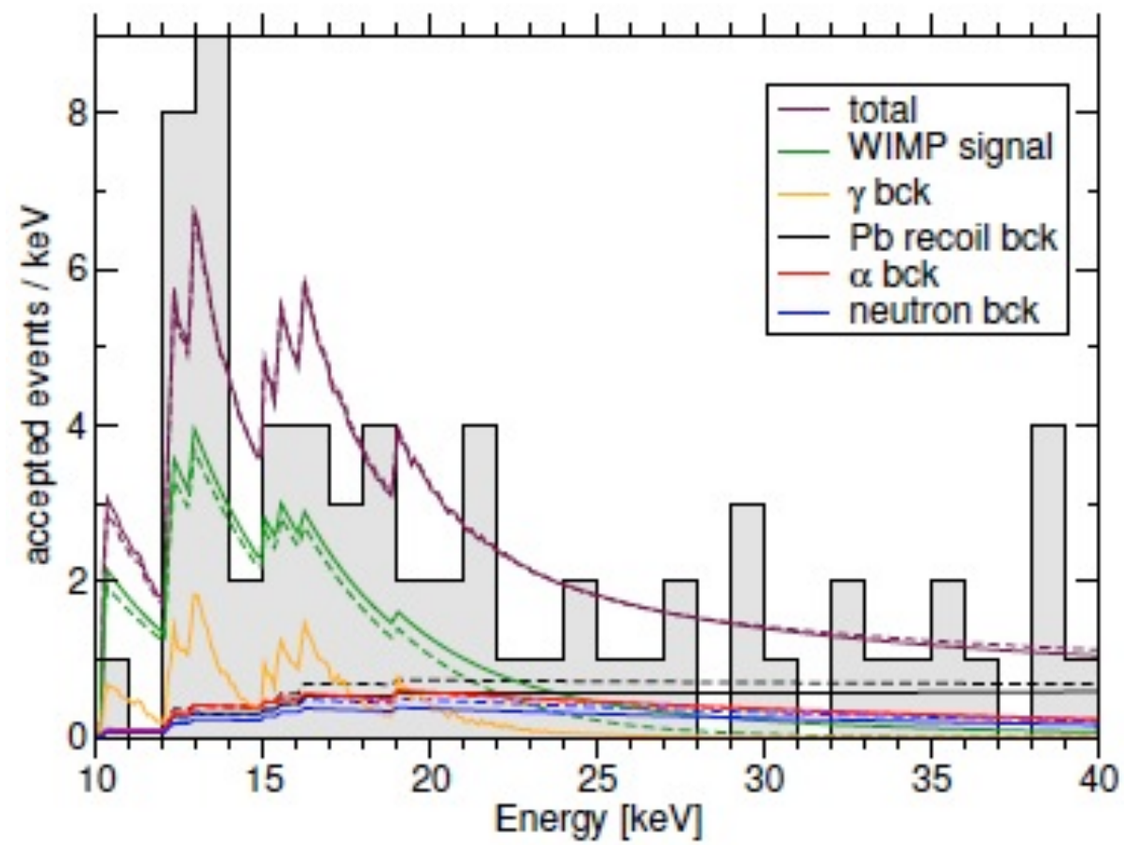


Fig. 11. (Color online) Energy spectrum of the accepted events from all detector modules, together with the expected contributions from the considered backgrounds and a WIMP signal, as inferred from the likelihood fit. The solid and dashed lines correspond to the fit results M1 and M2, respectively.

CRESST-II

- $CaWO_4$ in Gran Sasso

Angloher et al. (2011)



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CRESST-II

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- Excess presented mid-2010

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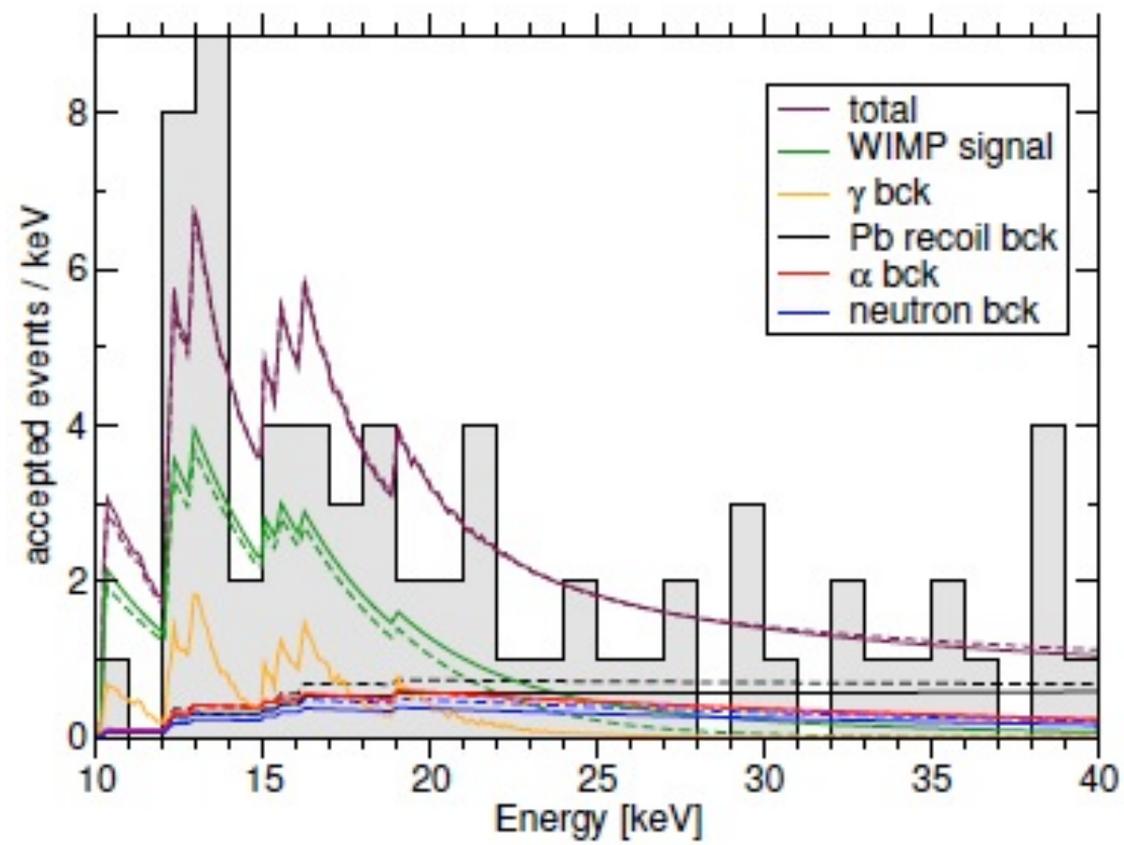

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CRESST-II

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- Paper in Sept. 2011

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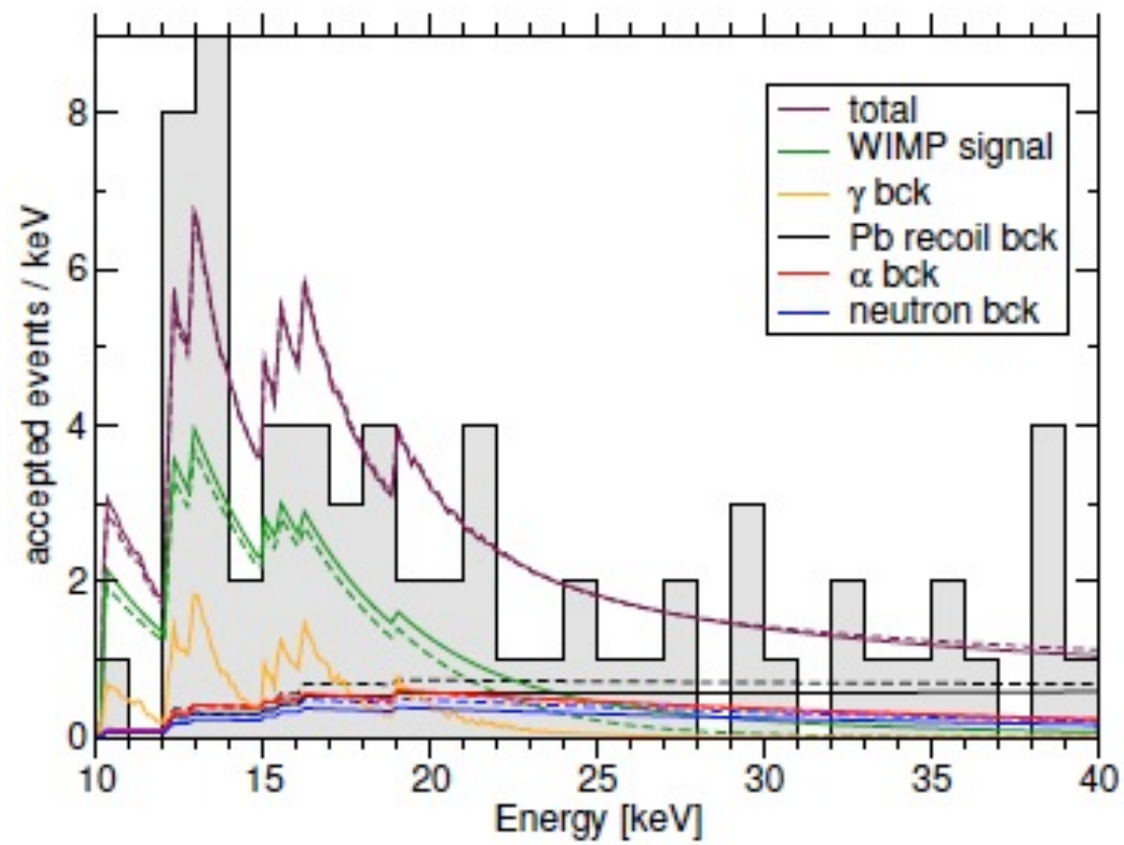

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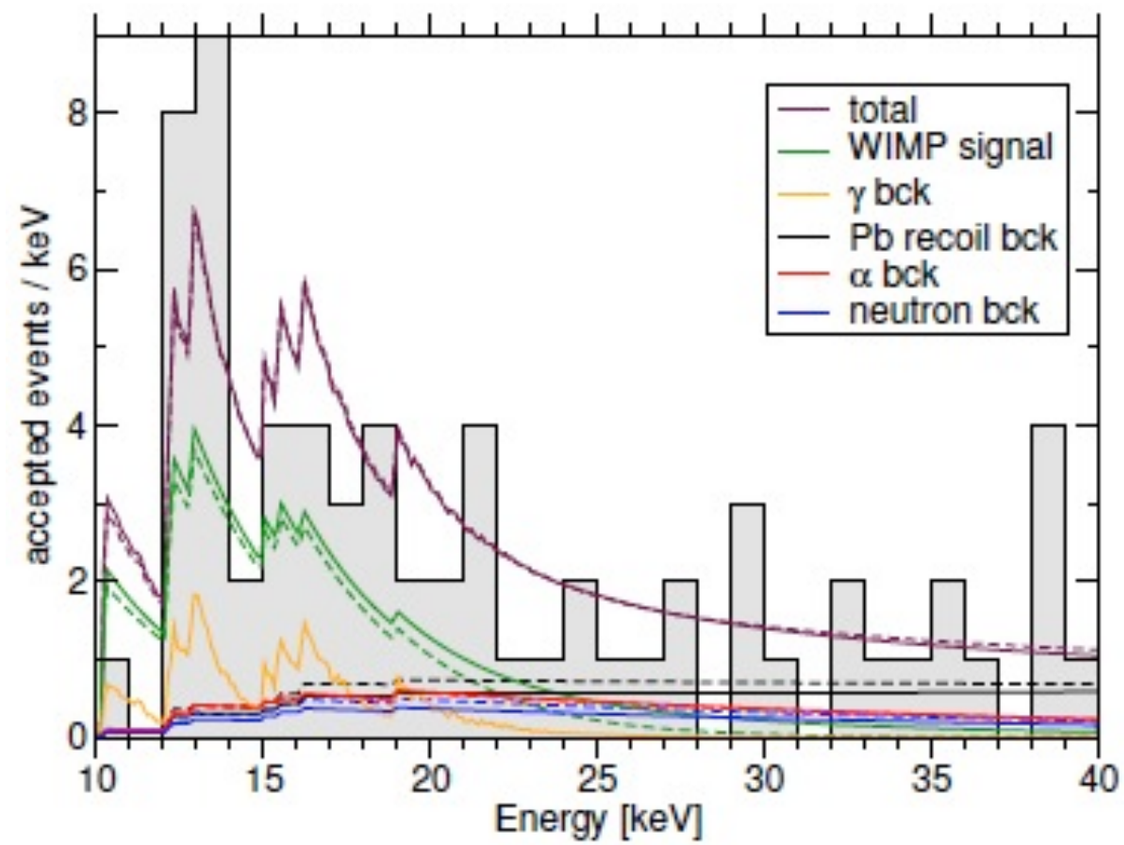
CRESST-II

- $CaWO_4$ in Gran Sasso
- Excess presented mid-2010
- Paper in Sept. 2011
  - Observed 67 events

Angloher et al. (2011)



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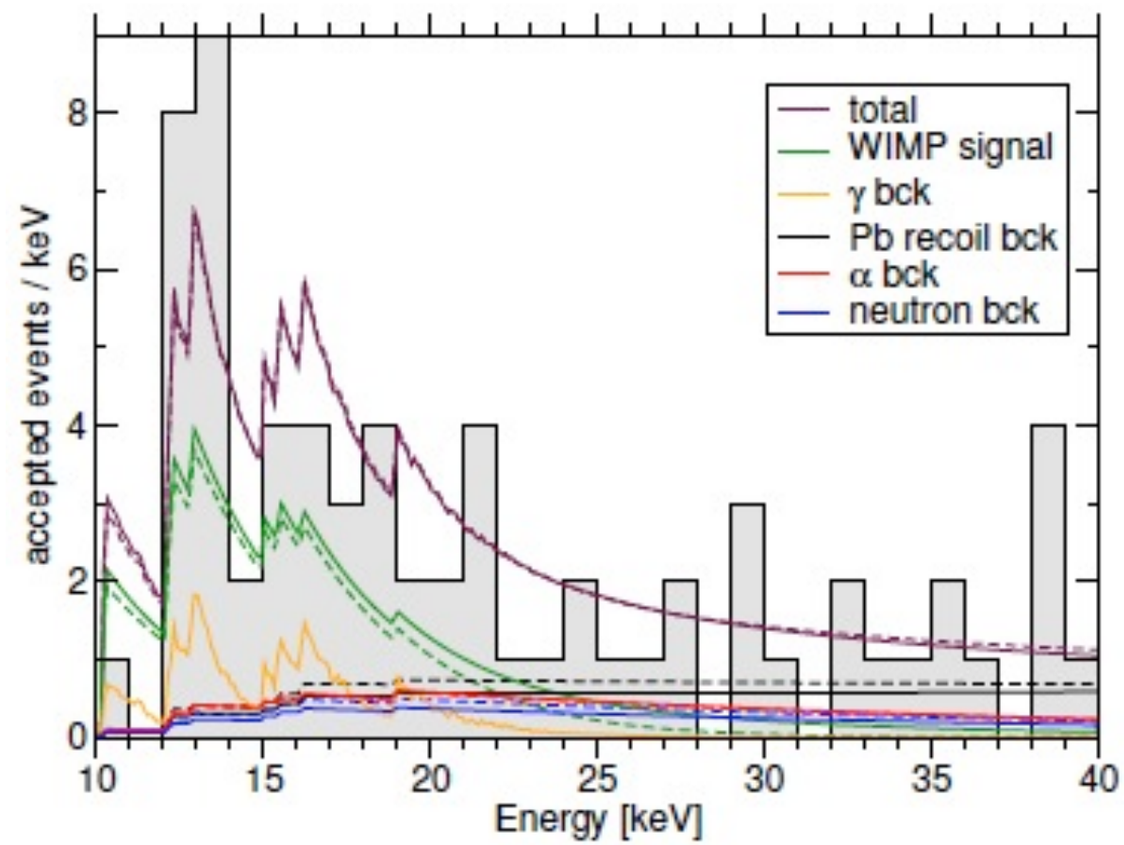
CRESST-II

- $CaWO_4$ in Gran Sasso
- Excess presented mid-2010
- Paper in Sept. 2011
  - Observed 67 events
  - Not a zero-bg expt.

Angloher et al. (2011)



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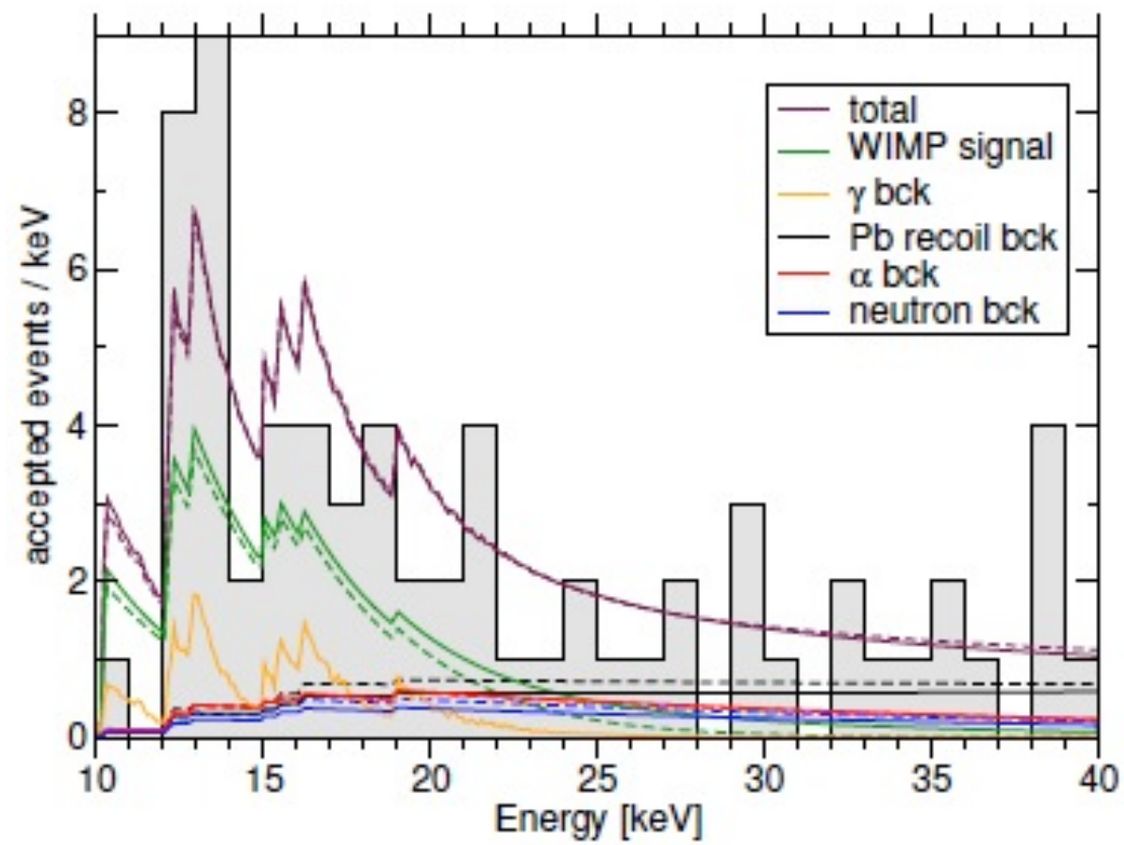
CRESST-II

- $CaWO_4$ in Gran Sasso
- Excess presented mid-2010
- Paper in Sept. 2011
  - Observed 67 events
  - Not a zero-bg expt.
- Dark matter analysis

Angloher et al. (2011)



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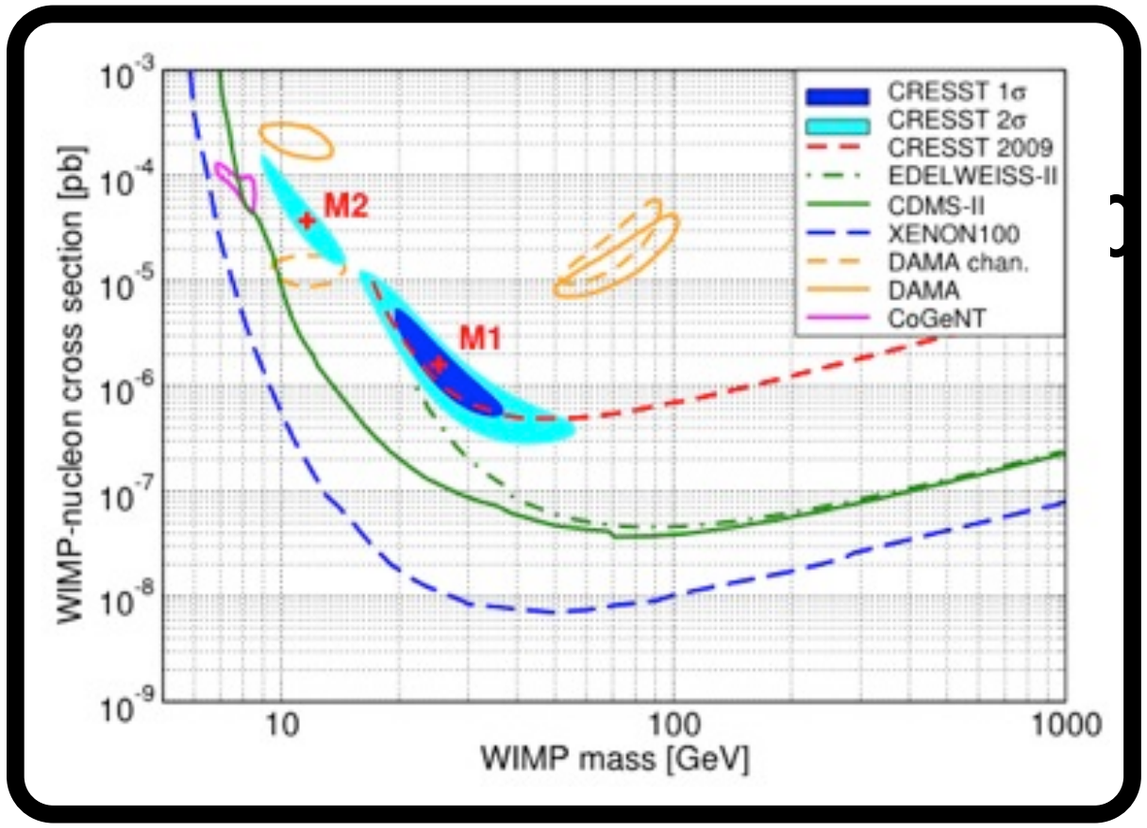

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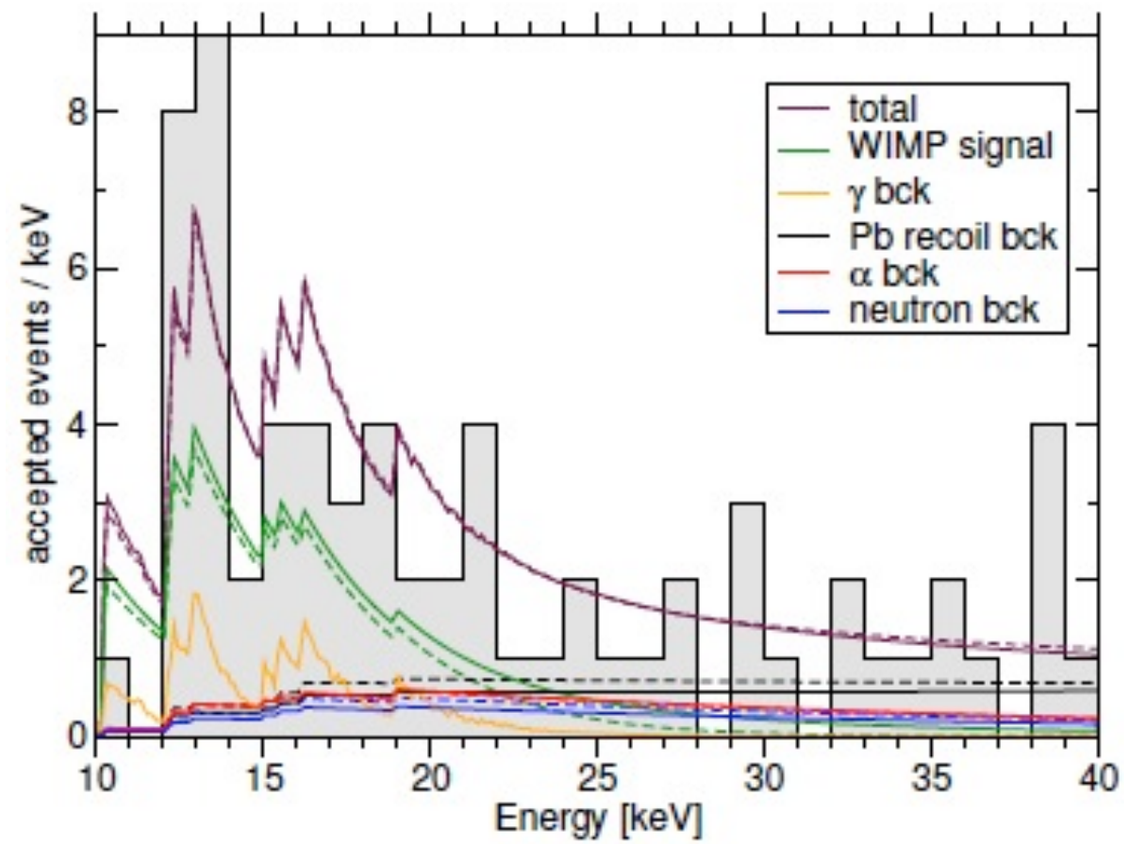

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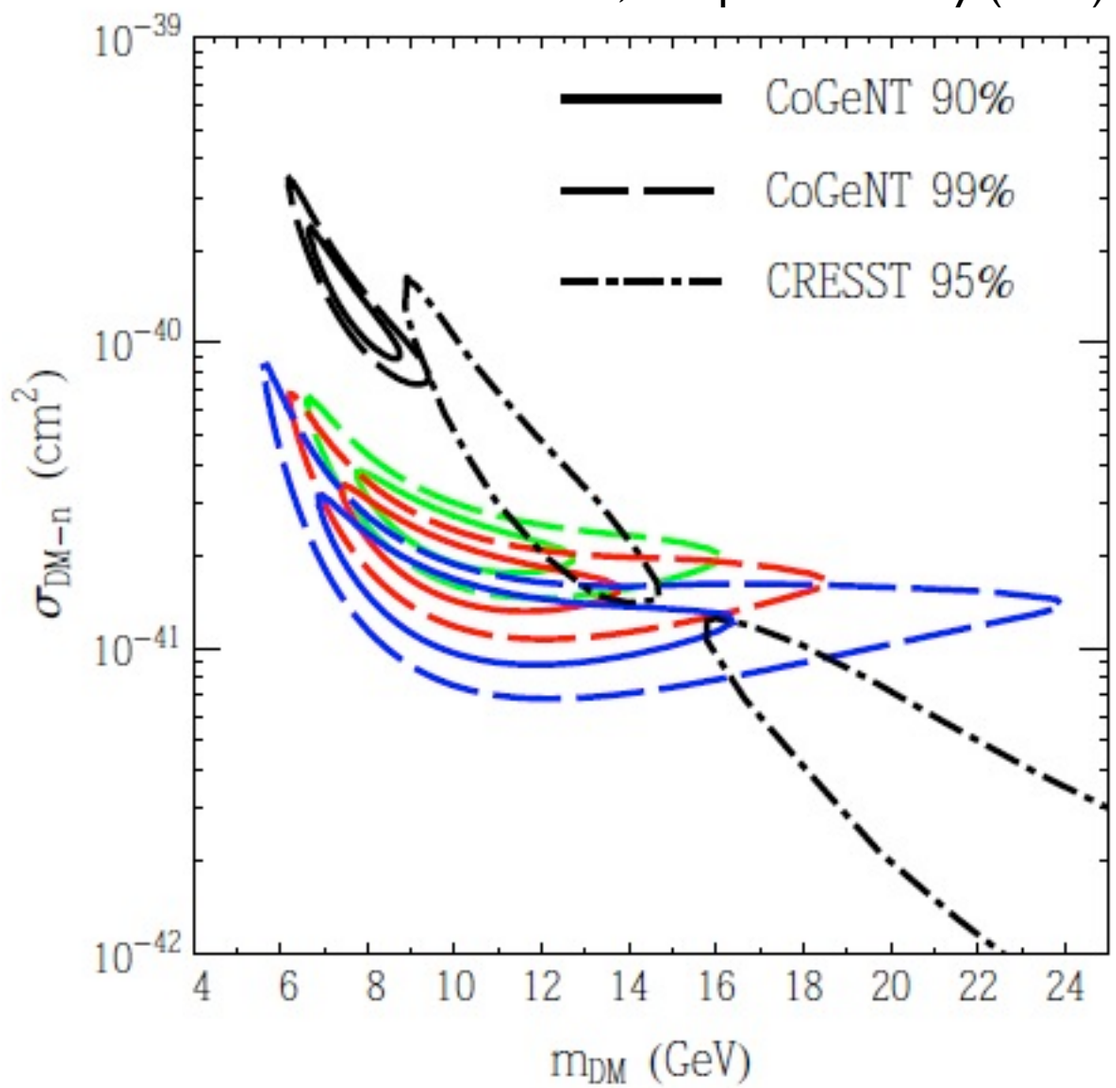
Compatible?

We conclude that the landscape of dark matter direct detection is evolving rapidly, and **there is currently no known way of explaining all the positive signals (DAMA, CoGeNT and CRESST) simultaneously with all the null results.** It is therefore crucial that these signals, but also the null results, are scrutinized carefully, and experimental cross-checks are carried out to test them as model-independently as possible.
Kopp, Schwetz & Zupan (2011)

Kelso, Hooper & Buckley (2011)



Direct Detection Summary

- Many experiments are looking for WIMP-nucleon collisions.
- If dark matter is not WIMPs, we're barking up the wrong tree...
- In light of recent events at several experiments, there has been much enthusiasm for light ~10 GeV dark matter (not standard SUSY).
- Rapid progress towards a resolution of tensions - stay tuned!

Next generation of direct detection experiments will probe VERY low SI cross sections.

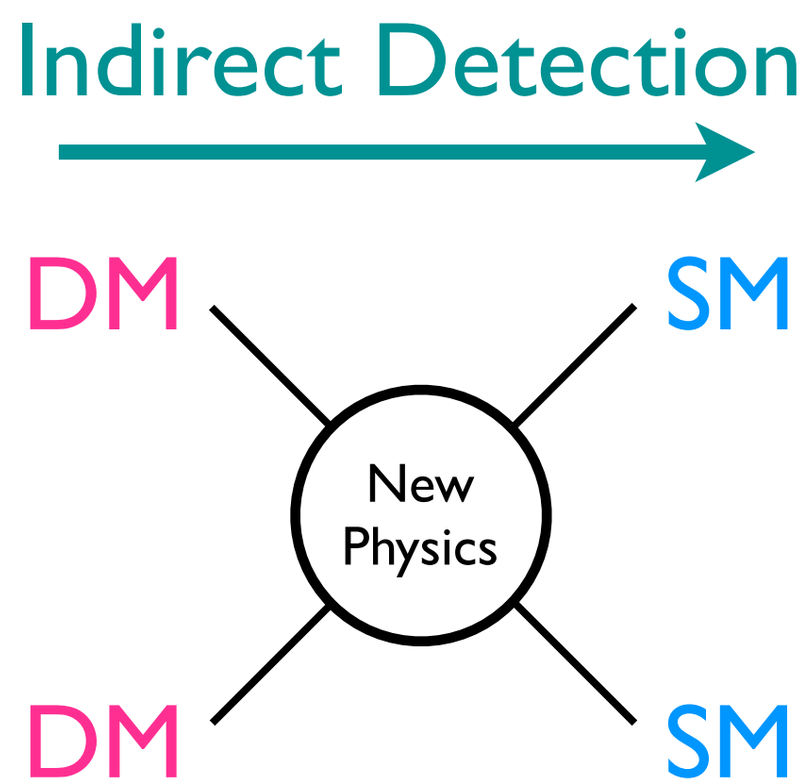
Most of parameter space in simple SUSY extensions of the Standard Model.

Indirect Detection

- "Dark matter has already been indirectly detected: gravitational interactions"
- But: gravity is universal - tells us nothing about the particle nature of dark matter.

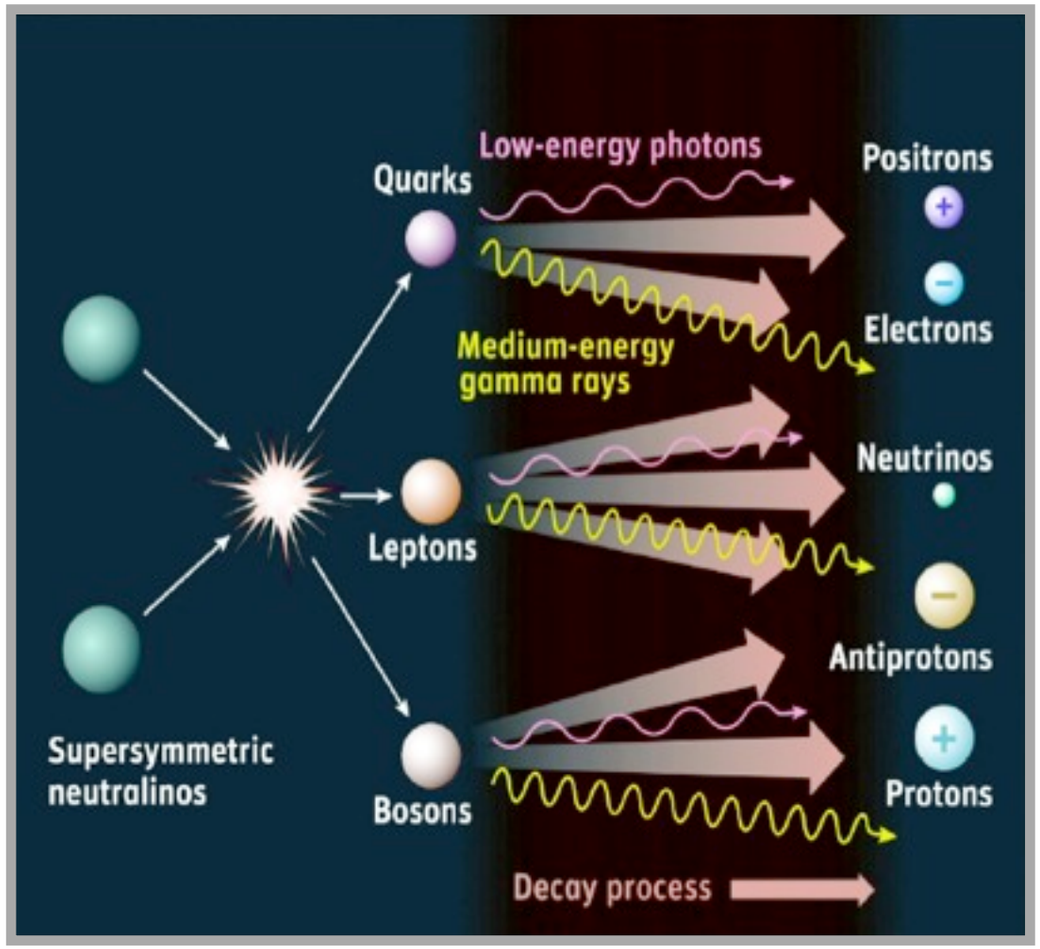
Indirect Detection

- Look for end-products of WIMP annihilation (decay?)
- If WIMPs annihilated in the early universe, this process should still be occurring today.
- Up-side: Many places to look, many experiments looking(ed)
- Downside: Astrophysics is complicated.



Indirect Detection

- WIMP annihilation (or decay)
- Need a LOT of dark matter:
  - In the Milky Way halo
    Ellis, Freese et al. 1987
  - Near the Milky Way GC
    Gondolo and Silk, 2000
  - In the Sun or the Earth
    Silk et al. 1985, Kraus et al. 1986, Freese 1986
  - In nearby dwarf galaxies
    Evans, Ferrer & Sarkar 2004, Sandick et al. 2009
  - In Milky Way substructure
    Evans, Ferrer & Sarkar 2004,
    Sandick et al. 2010, 2011a,b



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  - In Milky Way substructure
    Evans, Ferrer & Sarkar 2004,
    Sandick et al. 2010, 2011a,b

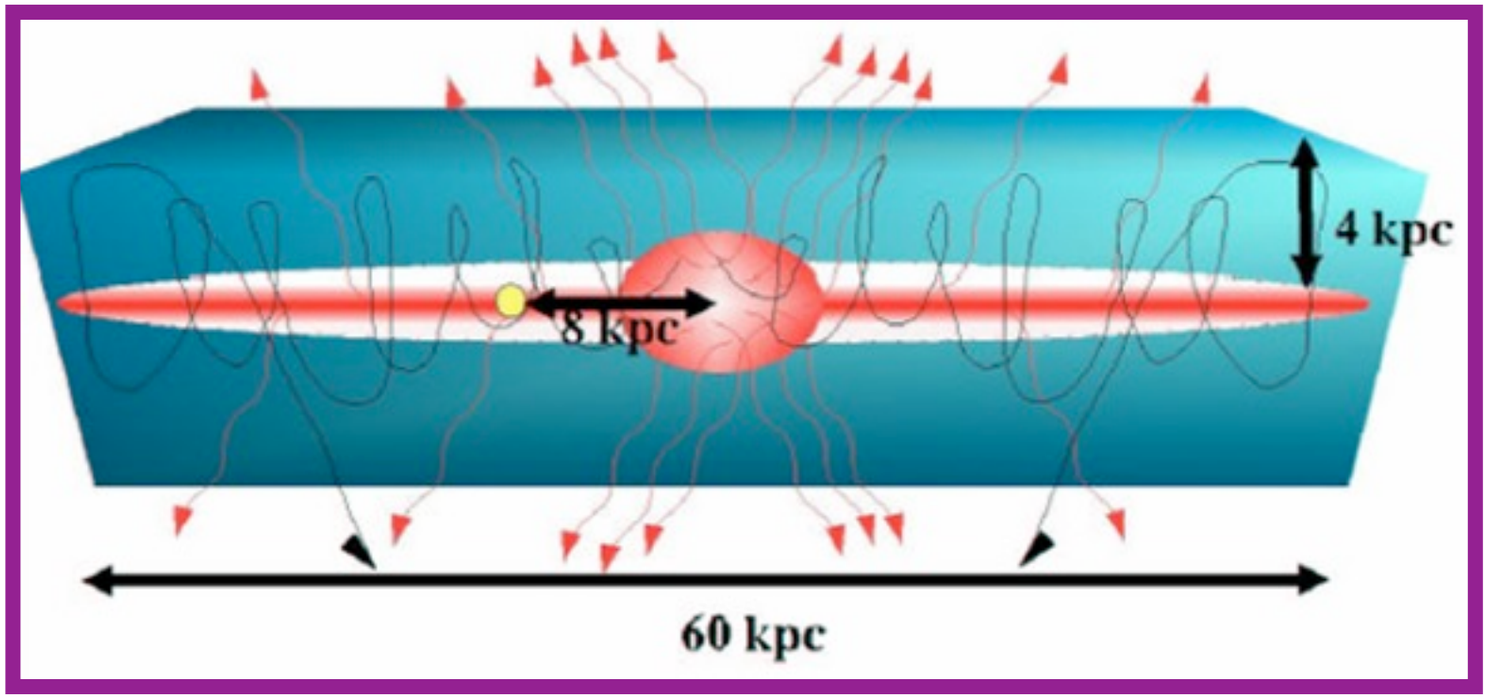
- neutrinos
  - SuperK, IceCube
- high energy photons
  - EGRET, Fermi, VERITAS
- synchrotron radiation
  - WMAP, Planck
- positrons/antiprotons
  - HEAT, ATIC, PAMELA, Fermi, AMS
- antideuterons
  - GAPS, AMS

Neutral vs. Charged Products

- Neutral: Propagate directly from source

$$\frac{d\Phi_f}{dE} = \frac{B_f \langle \sigma v \rangle}{2m_\chi^2} \frac{dN_f}{dE} \int_0^{\theta_{max}} d\theta \, 2\pi \sin\theta \int_0^{s_{max}} ds \, \rho_{DM}^2(r)$$

- Charged: Path and energy altered along the way



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- Charged: Path and energy altered along the way

source

spatial diffusion

convection velocity

radioactive decay

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

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

diffusive reacceleration

momentum change rate

fragmentation losses

See eg. Strong, Moskalenko & Ptuskin (2007)

Neutral vs. Charged Products

- Neutral: Propagate directly from source

$$\frac{d\Phi_f}{dE} = \frac{B_f \langle \sigma v \rangle}{2m_\chi^2} \frac{dN_f}{dE} \int_0^{\theta_{max}} d\theta \, 2\pi \sin\theta \int_0^{s_{max}} ds \, \rho_{DM}^2(r)$$

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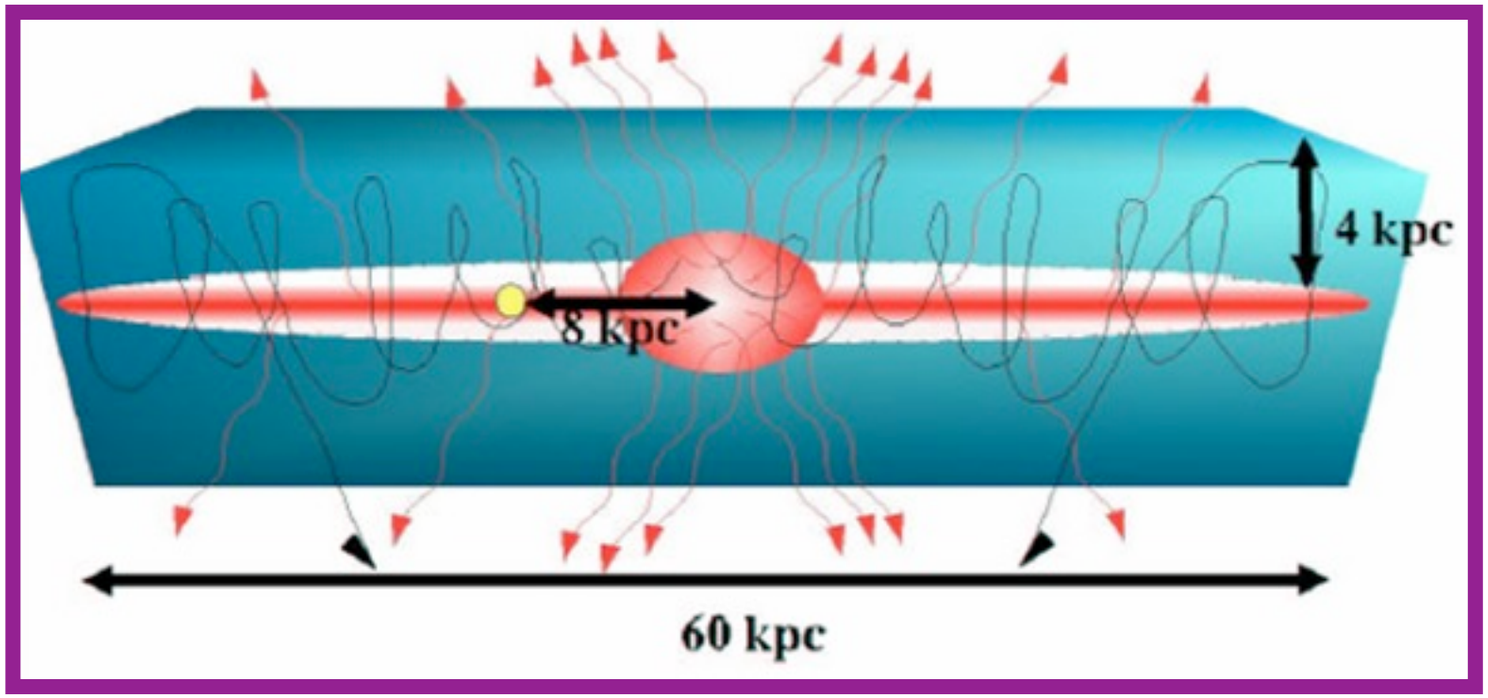


Dark Matter Parameters

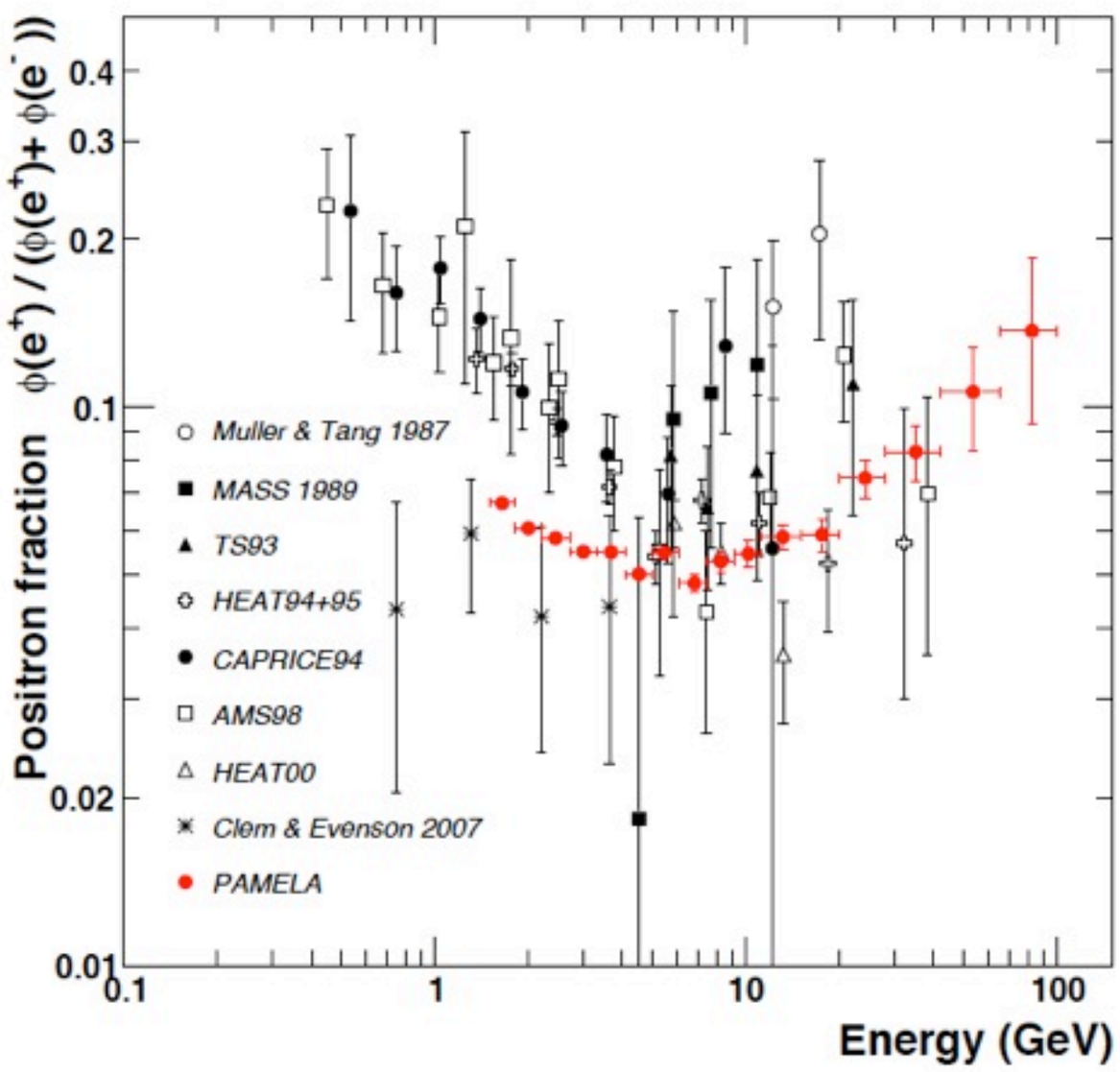
- Parameters directly affecting indirect detection
  - mass, annihilation cross section or decay rate, branching fractions to final states
  - density profile, substructure
- Signal: What are the dark matter properties necessary to accommodate it?
- No Signal: What are the inferred limits on the dark matter properties?

Antimatter

- **WIMP annihilation ⇒ equal numbers of e^+/e^- and p/p.**
- Astrophysical sources produce more matter than antimatter.
- CR spectrum [antimatter content] could be evidence of DMA.

Positron Fraction

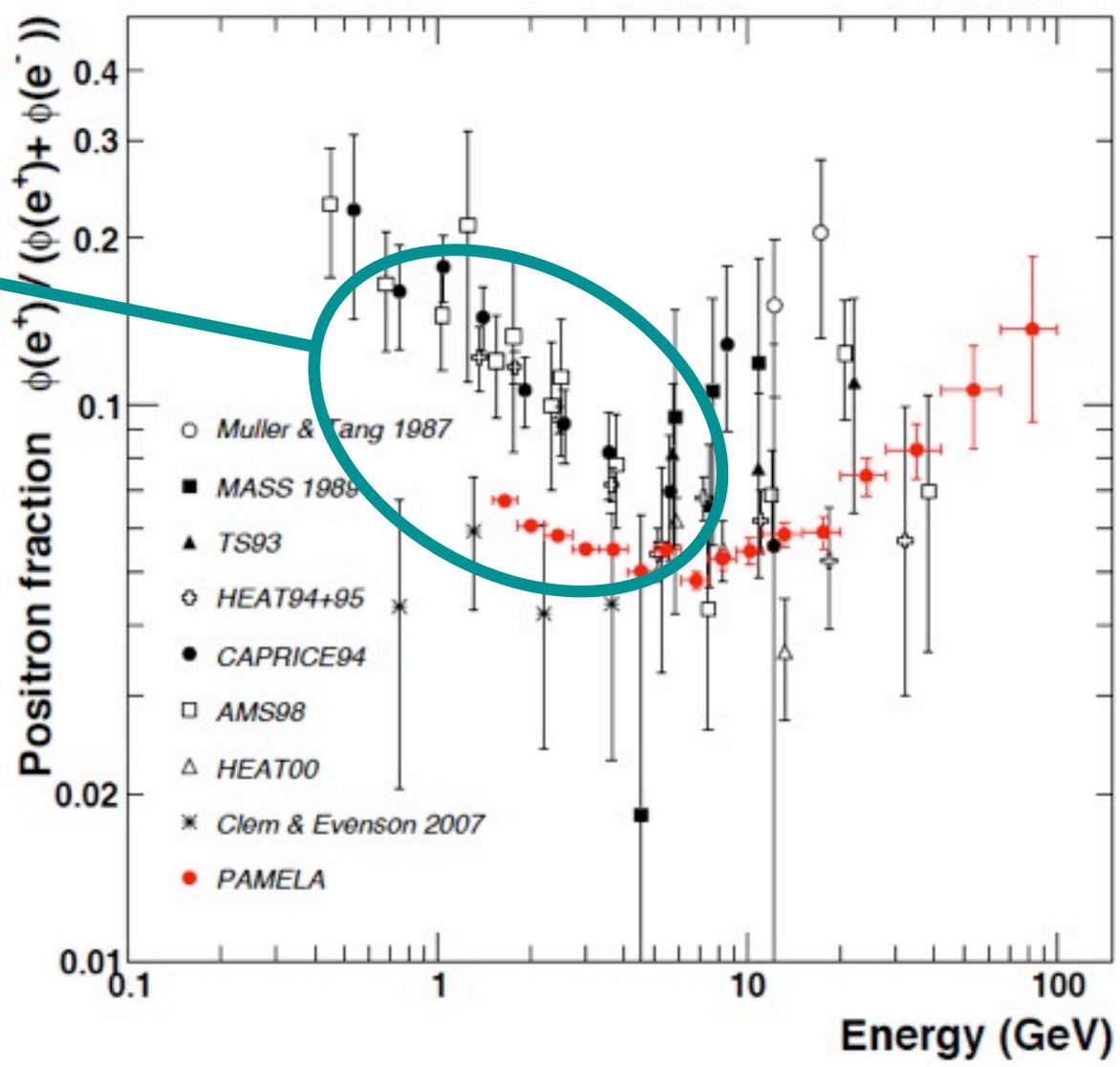
Adriani et al. (2008)



Positron Fraction

What's going on here?

Adriani et al. (2008)



Positron Fraction

Adriani et al. (2008)

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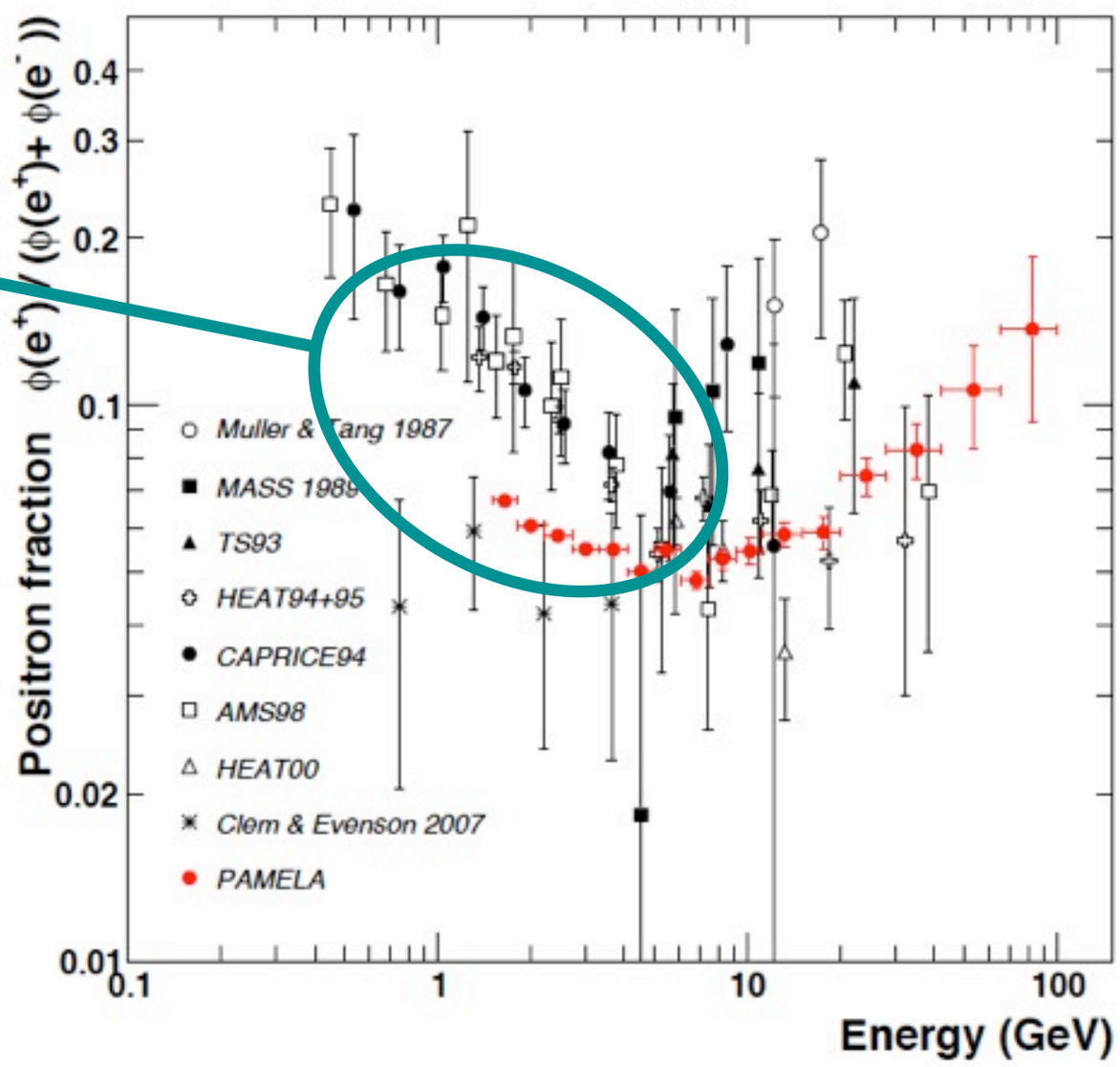
Charge-dependent solar modulation.

No problema.



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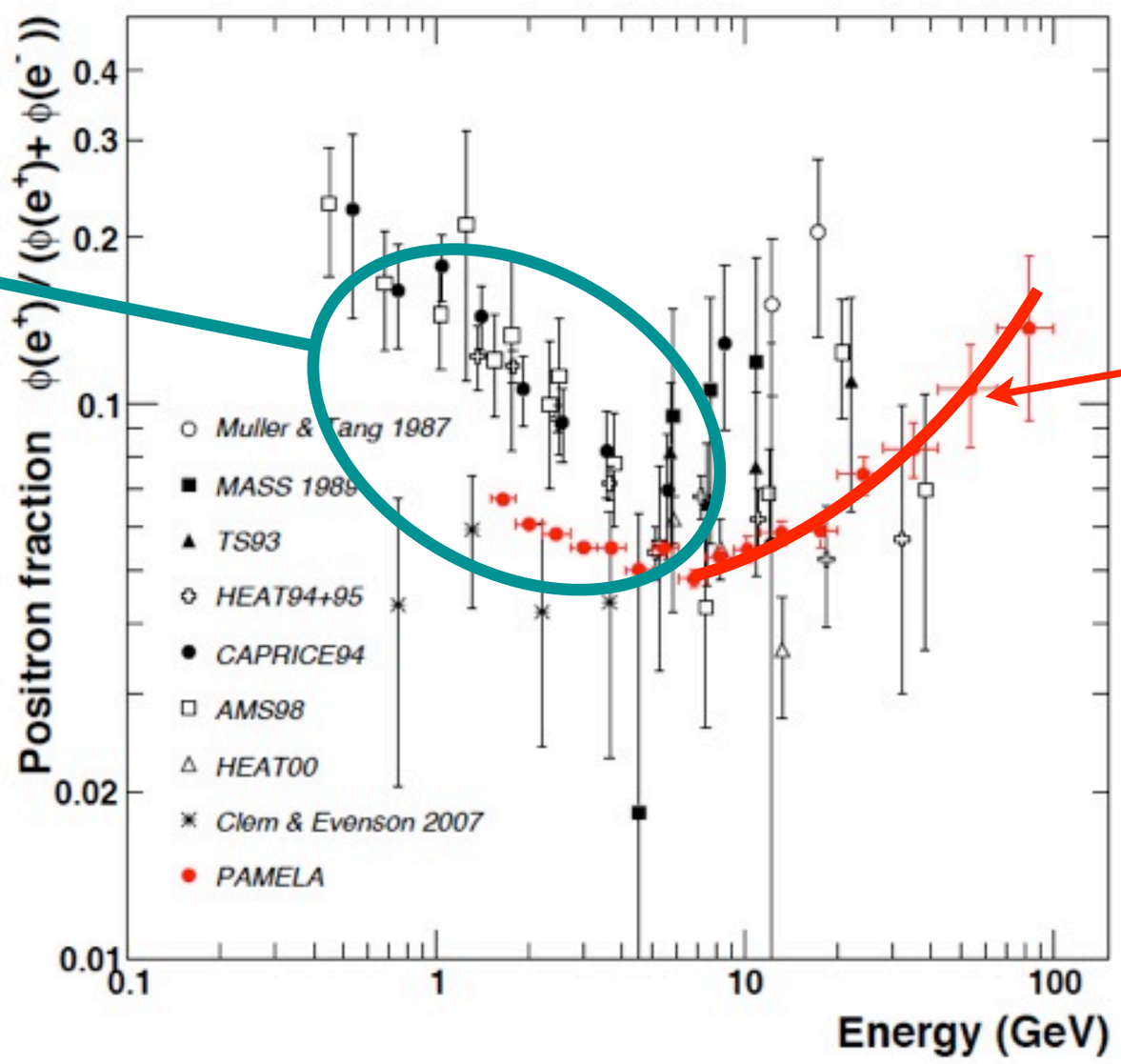

Steep rise above ~10 GeV

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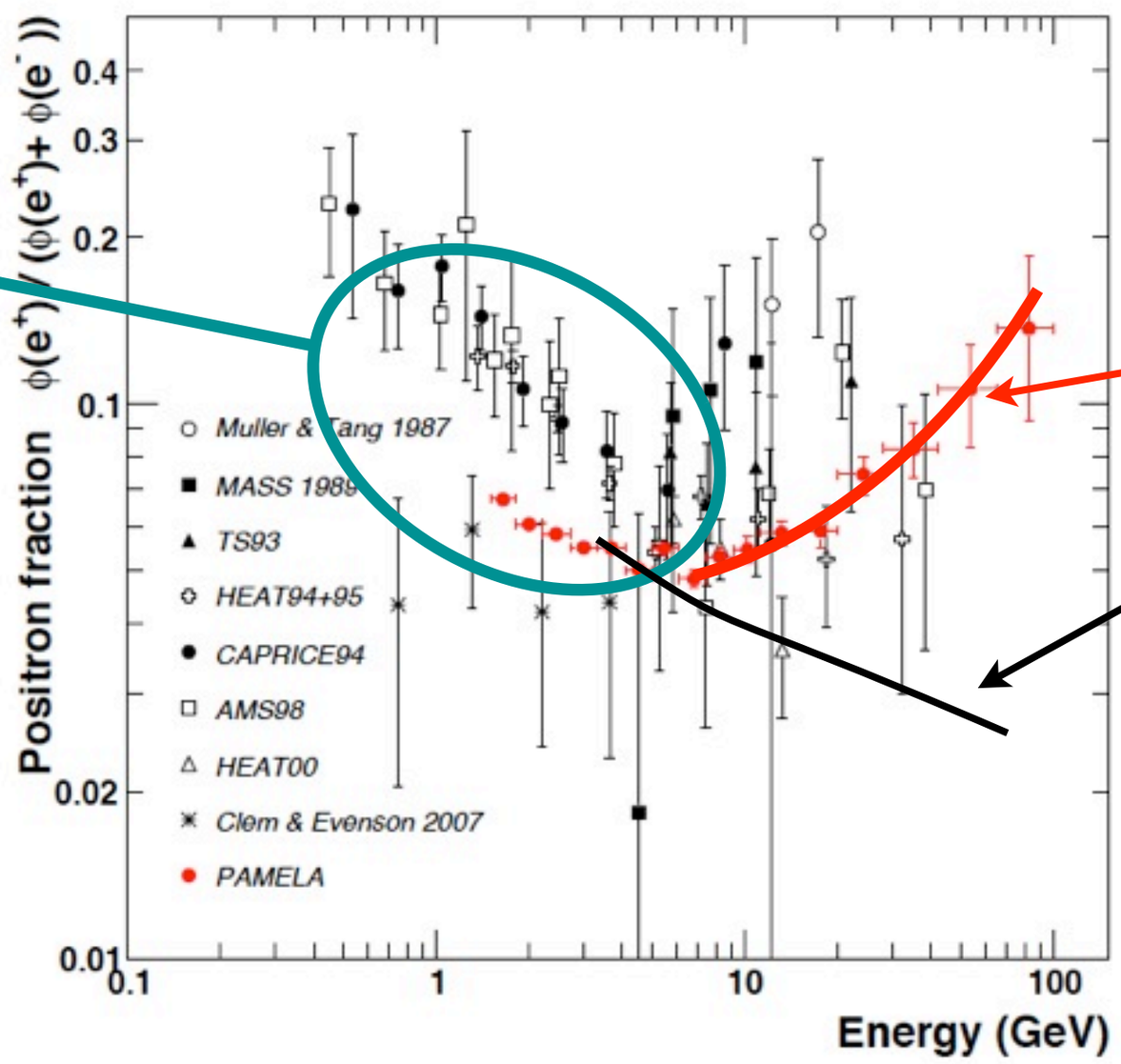


Steep rise above ~10 GeV

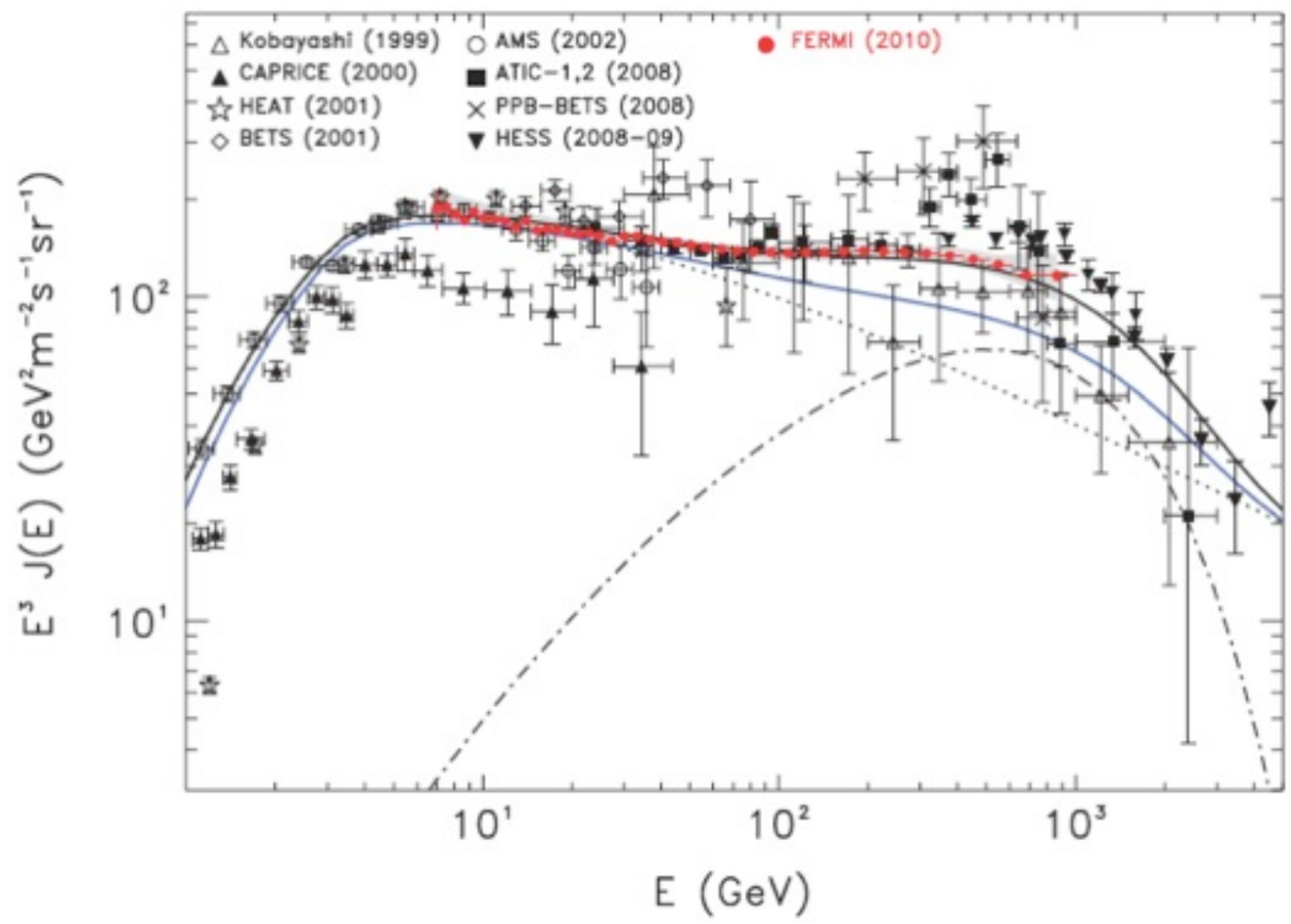
astrophysical expectation

(secondary production)

Fermi

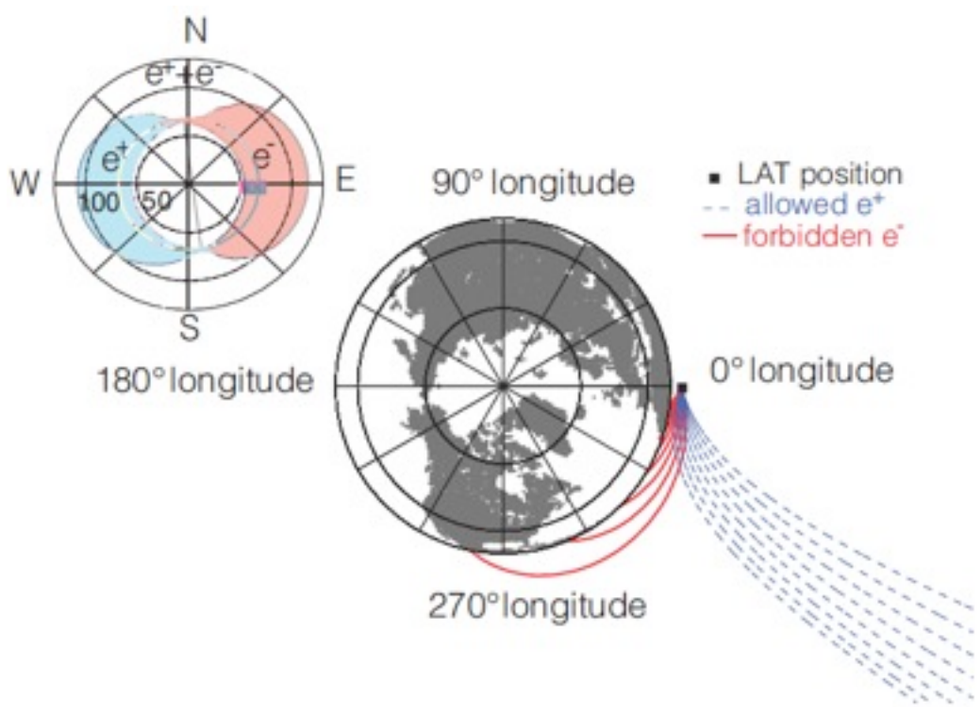
Ackermann et al. (2010)

- ATIC and Fermi (and others) measure electron + positron spectrum.
- Possible excess for E > 100 GeV (higher energy than positron fraction anomaly)



Fermi

- Fermi can measure positron fraction, too!
- Magnet:



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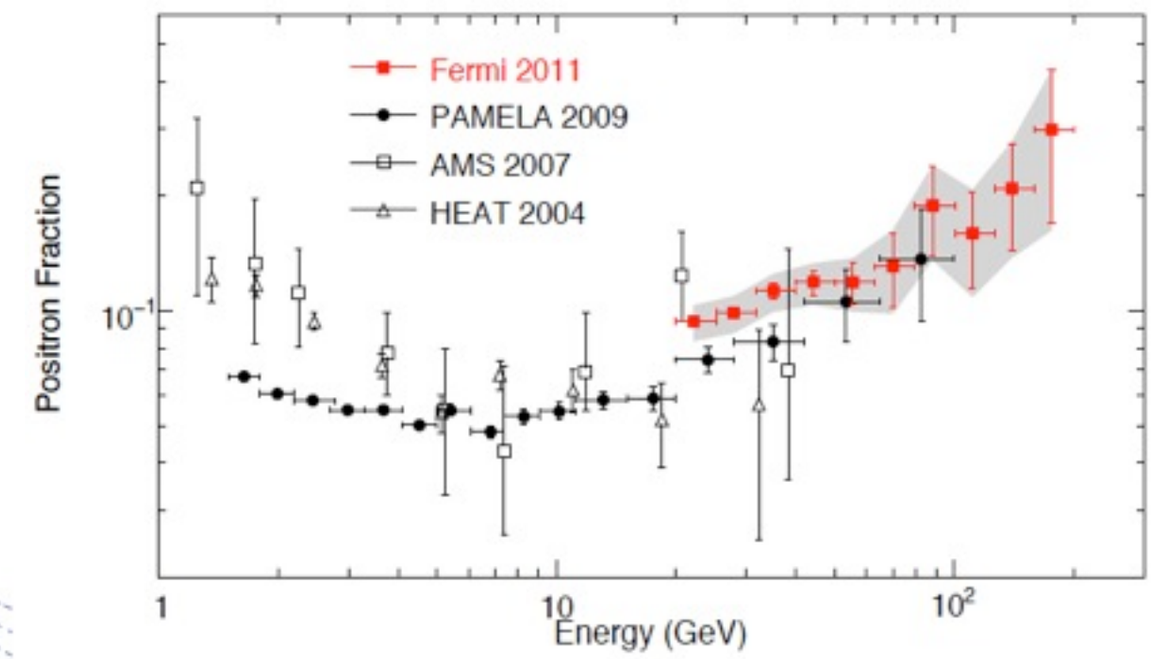

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- CR anomalies could be evidence of dark matter annihilations...
- Challenges:
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  - No substantial excess in antiprotons or gamma rays
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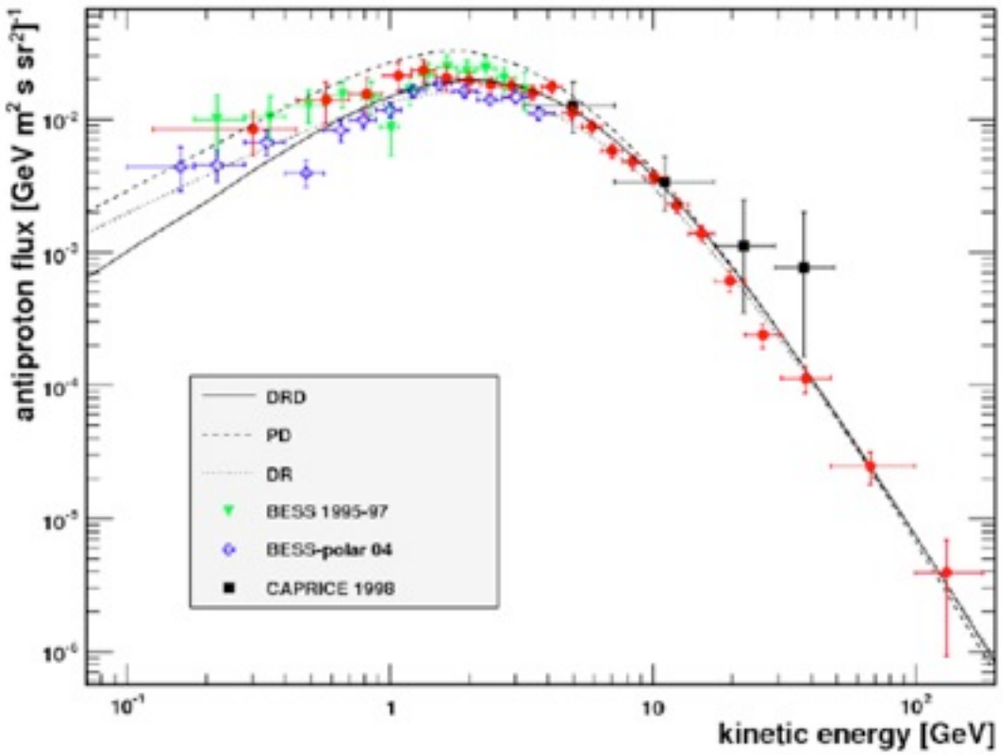

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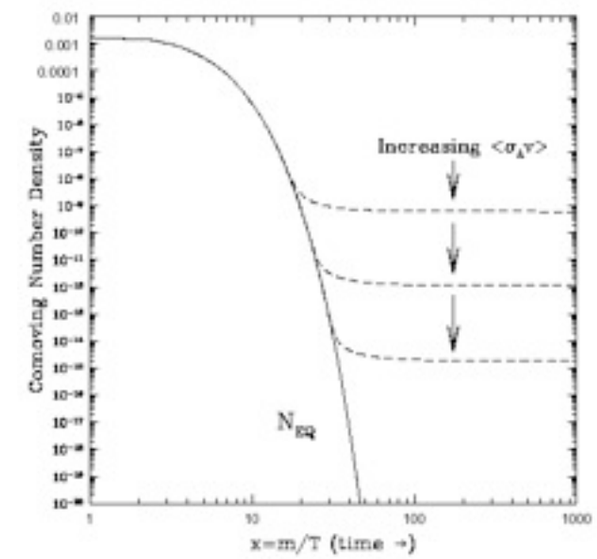
  - High annihilation rate → boosted annihilation rate

Boosted Annihilation Rate



- Thermal WIMP: $\langle \sigma v \rangle_{th} = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$

$$\Gamma = \frac{\langle \sigma v \rangle}{2m_\chi^2} \int_{r_{min}}^{r_{max}} dr 4\pi r^2 \rho_{DM}^2(r)$$

- Boosted Rate from Particle Physics
  - Sommerfeld or Breit-Wigner enhancement or non-thermal production mechanism

$$\langle \sigma v \rangle \gg \langle \sigma v \rangle_{th}$$

  - Significant annihilation at high redshift -> reionization (constrained by CMB) Galli et al. (2009)

- Boosted Rate from Astrophysics
  - Dark Matter Substructure $\int \rho_{DM}^2 r^2 dr > \int (\rho_{DM}^{smooth})^2 r^2 dr$
  - For most dark matter models, this is not enough to explain the rising positron fraction.

Can both results be explained?

- With (boosted leptophilic TeV-scale) Dark Matter (PS)
- With nearby dark matter subhalos
- With non-thermal Wino dark matter
- With substructure from the formation of the first stars (PS)

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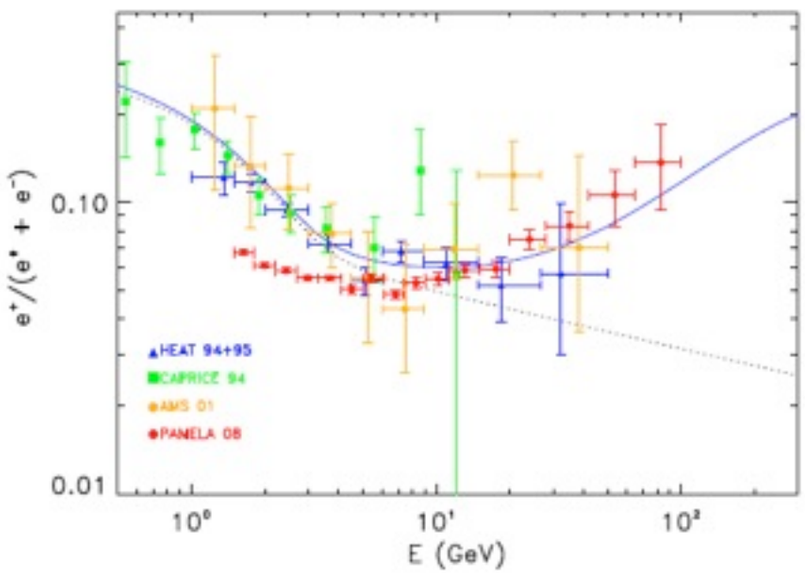
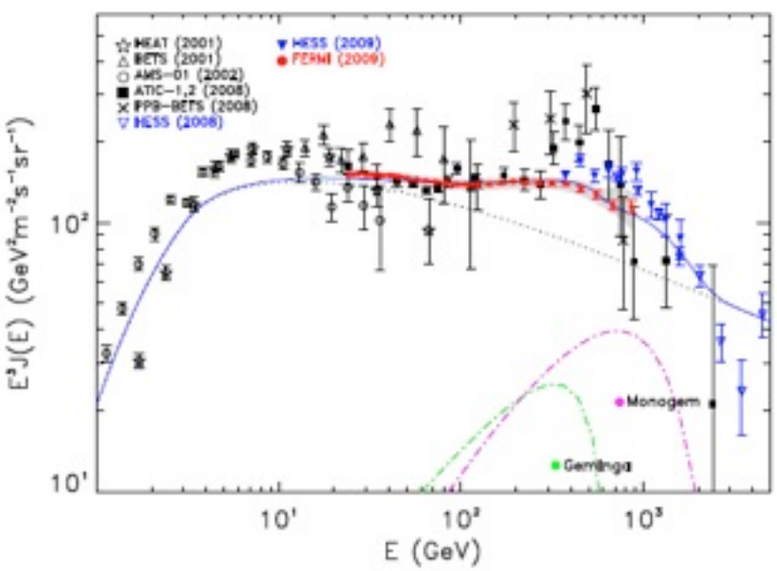
- With pulsars
  Grasso et al. (2009)





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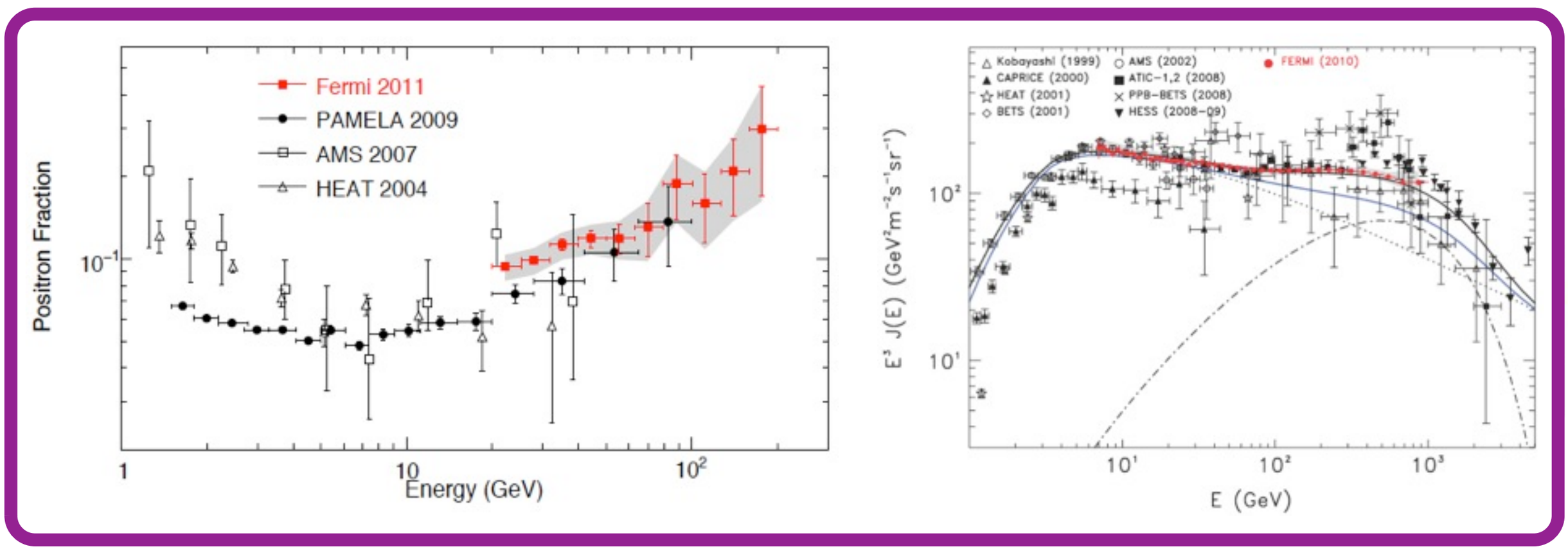
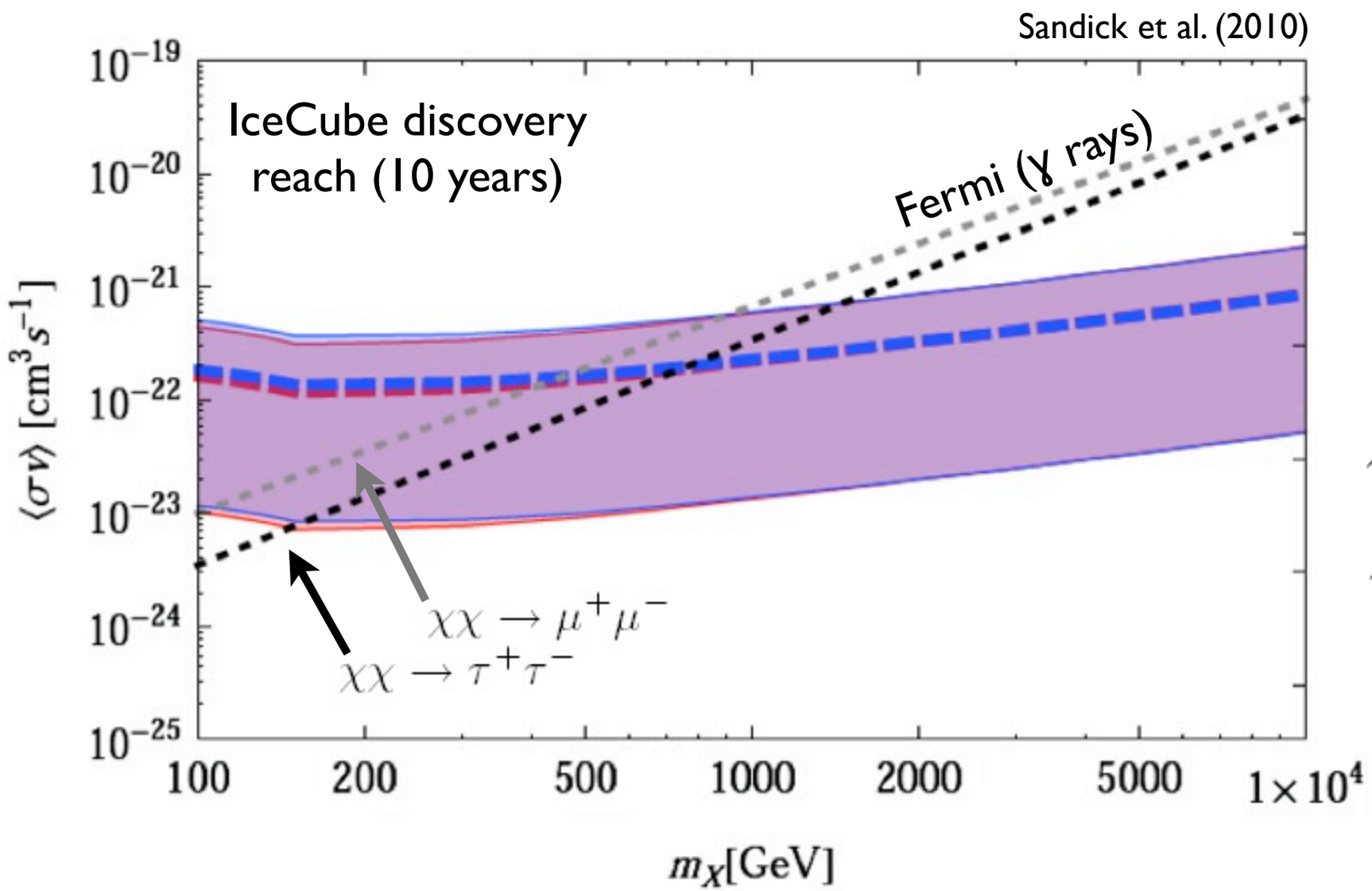


If you believe that one...



$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

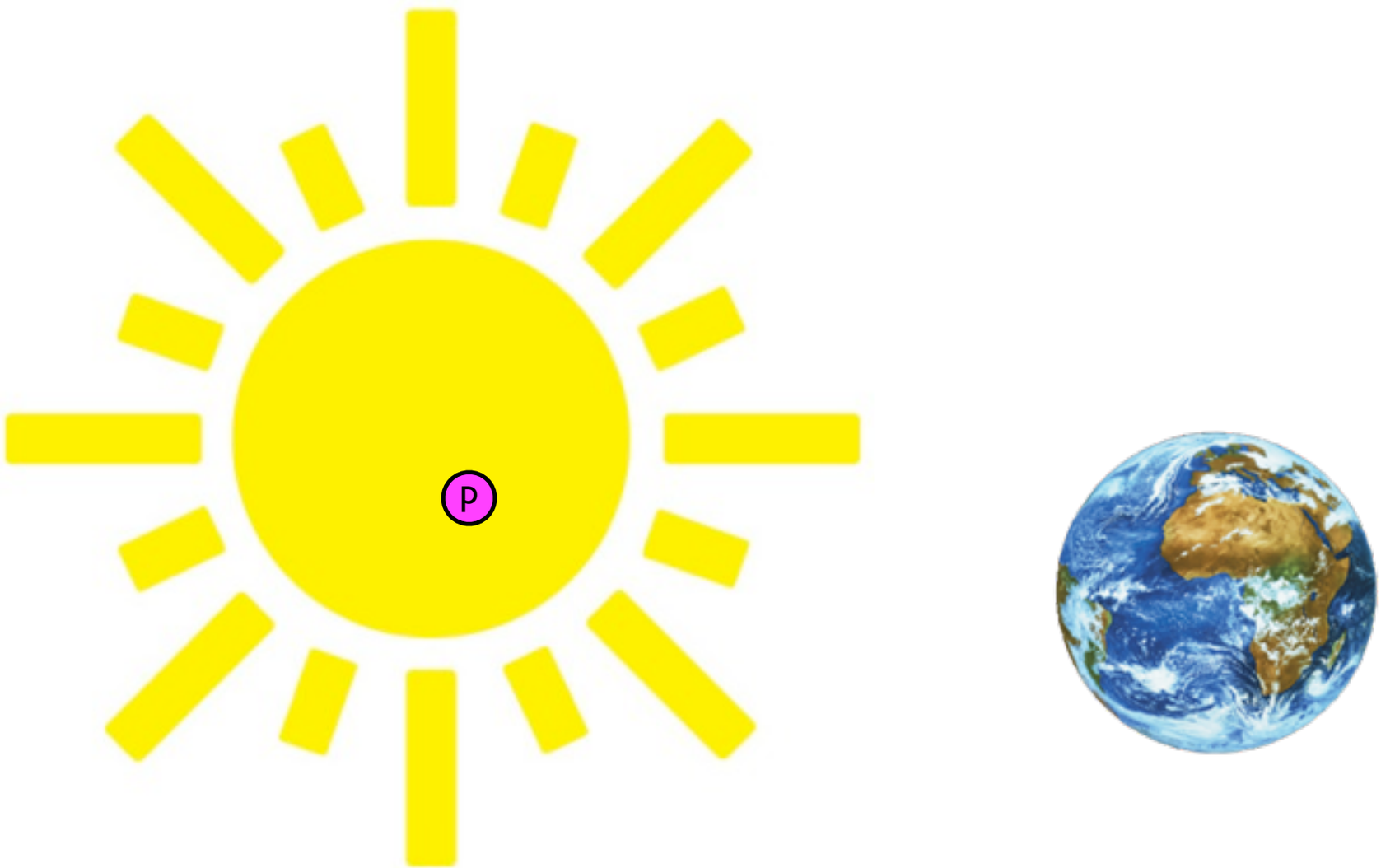
$$\tau^- \to e^- \bar{\nu}_e \nu_\tau (18\%)$$

$$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau (17\%)$$

$$\tau^- \to \pi^- \pi^0 \nu_\tau (26\%)$$

Neutrinos from the Sun

Neutrinos from the Sun



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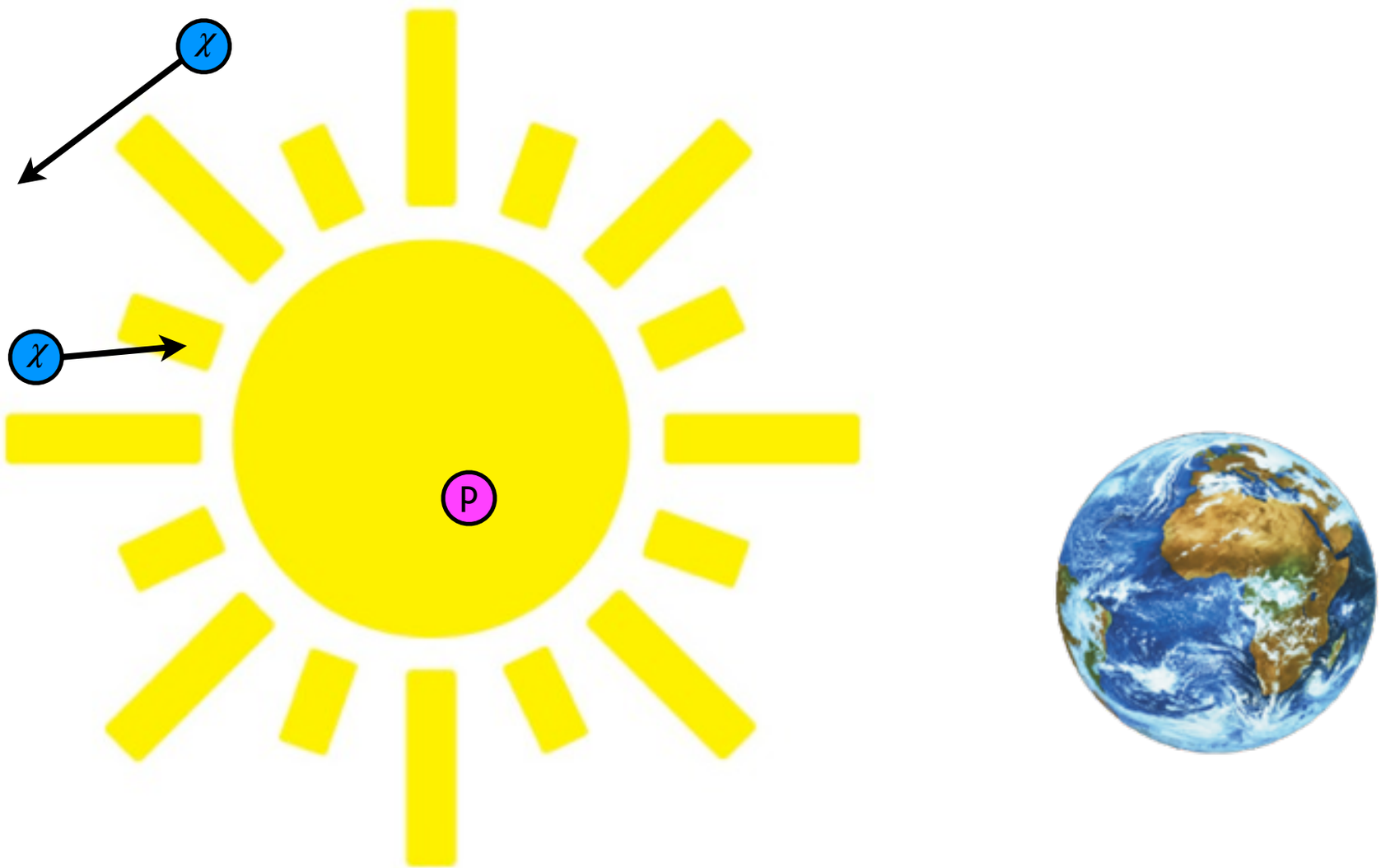

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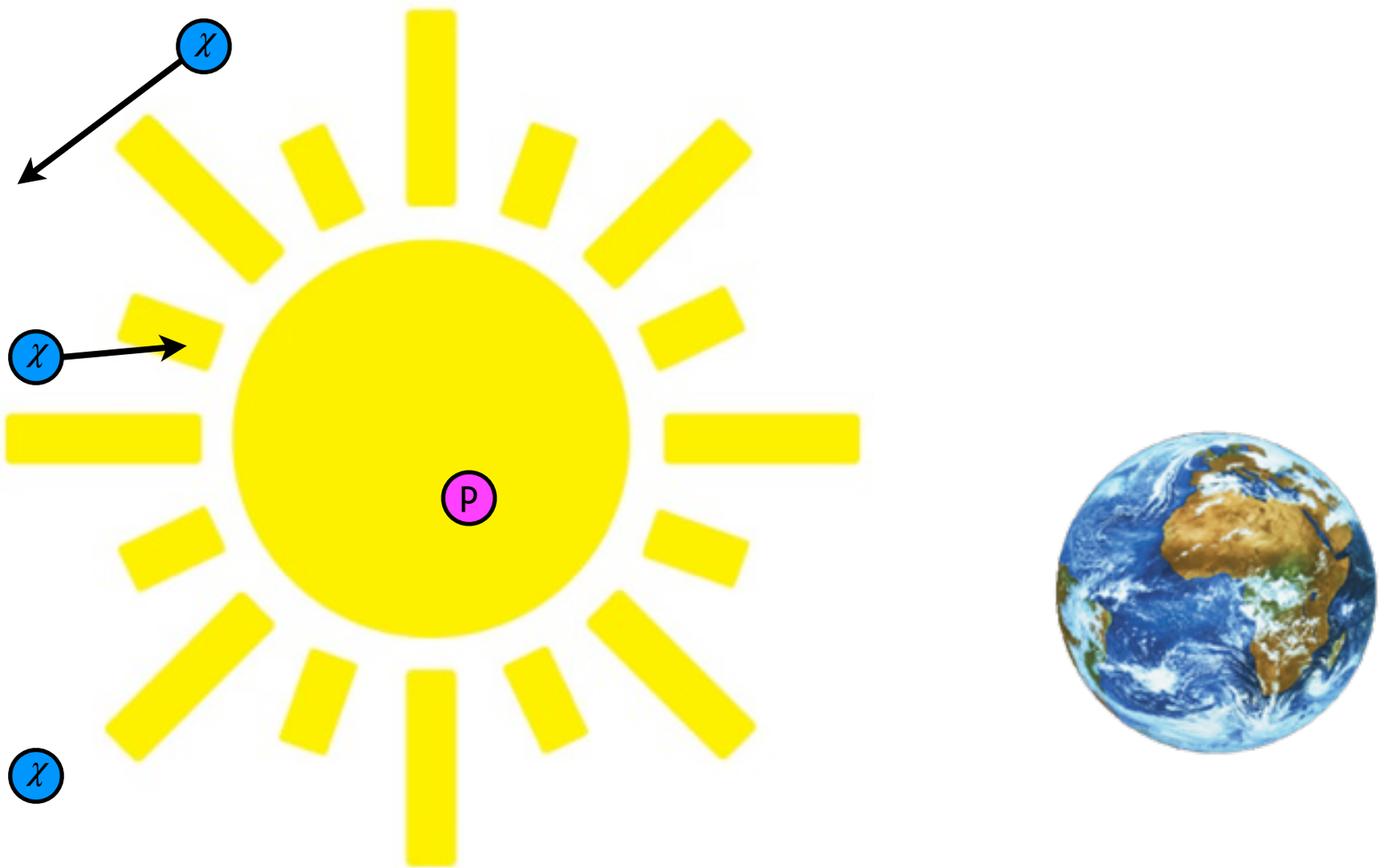

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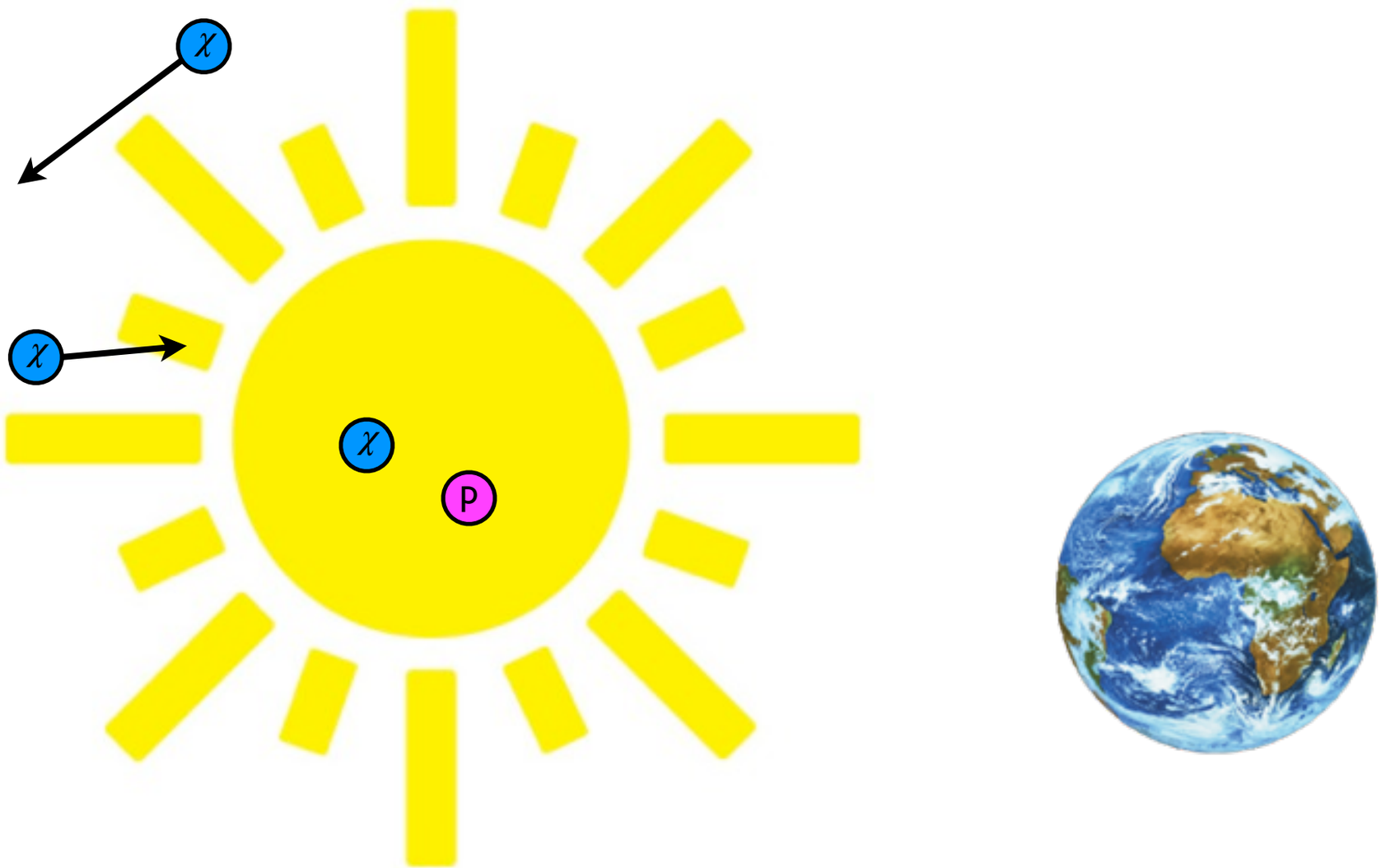

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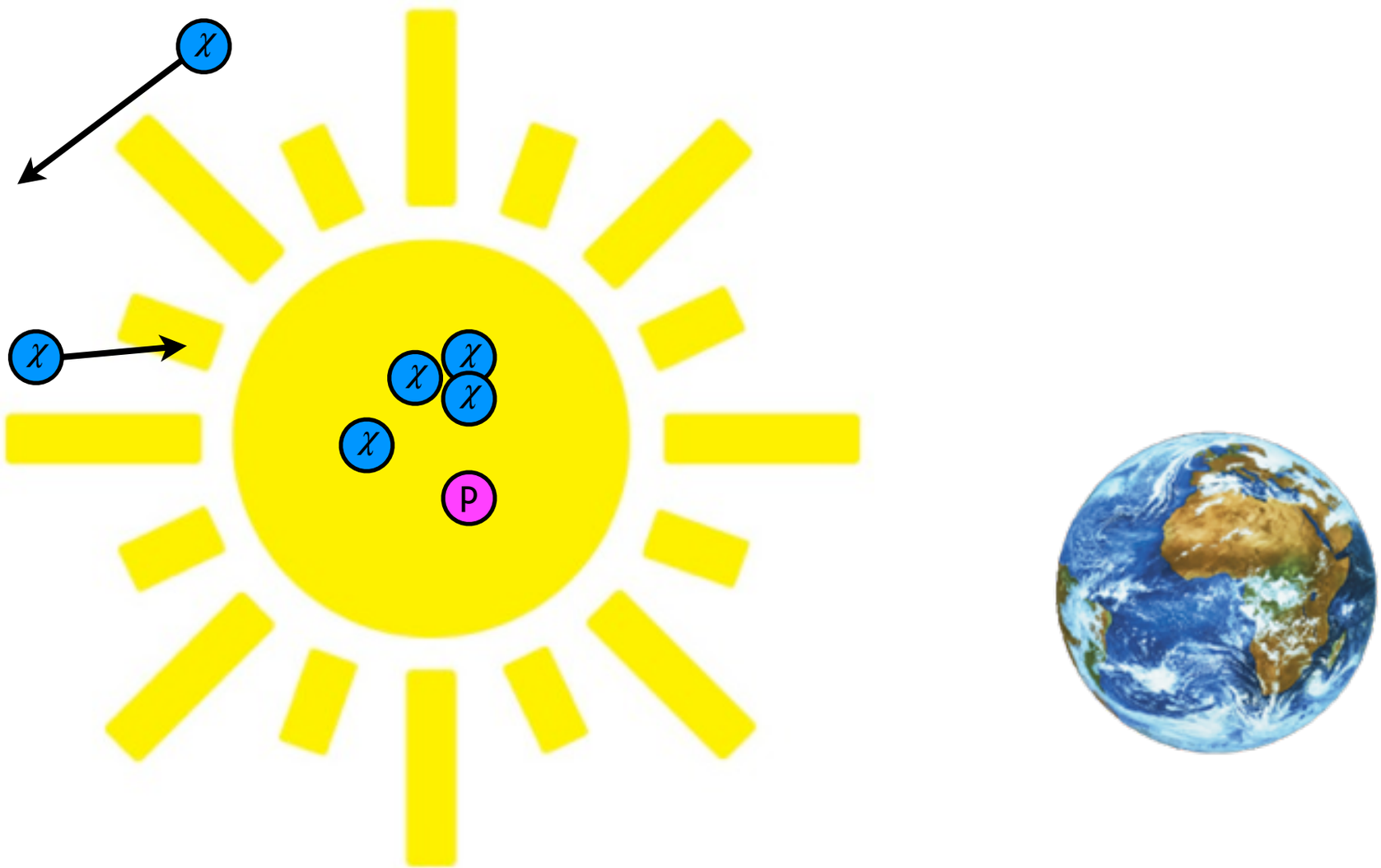

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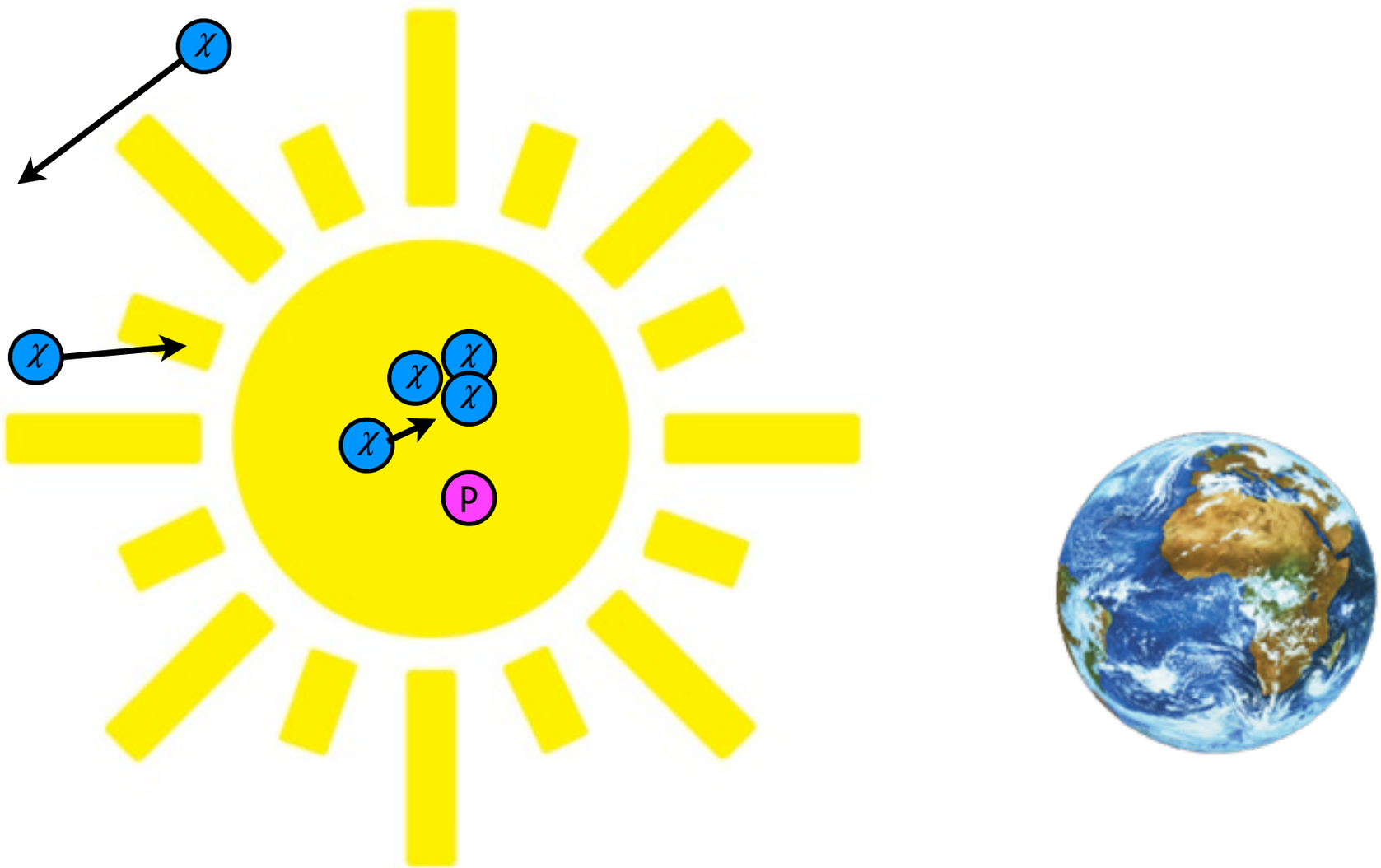

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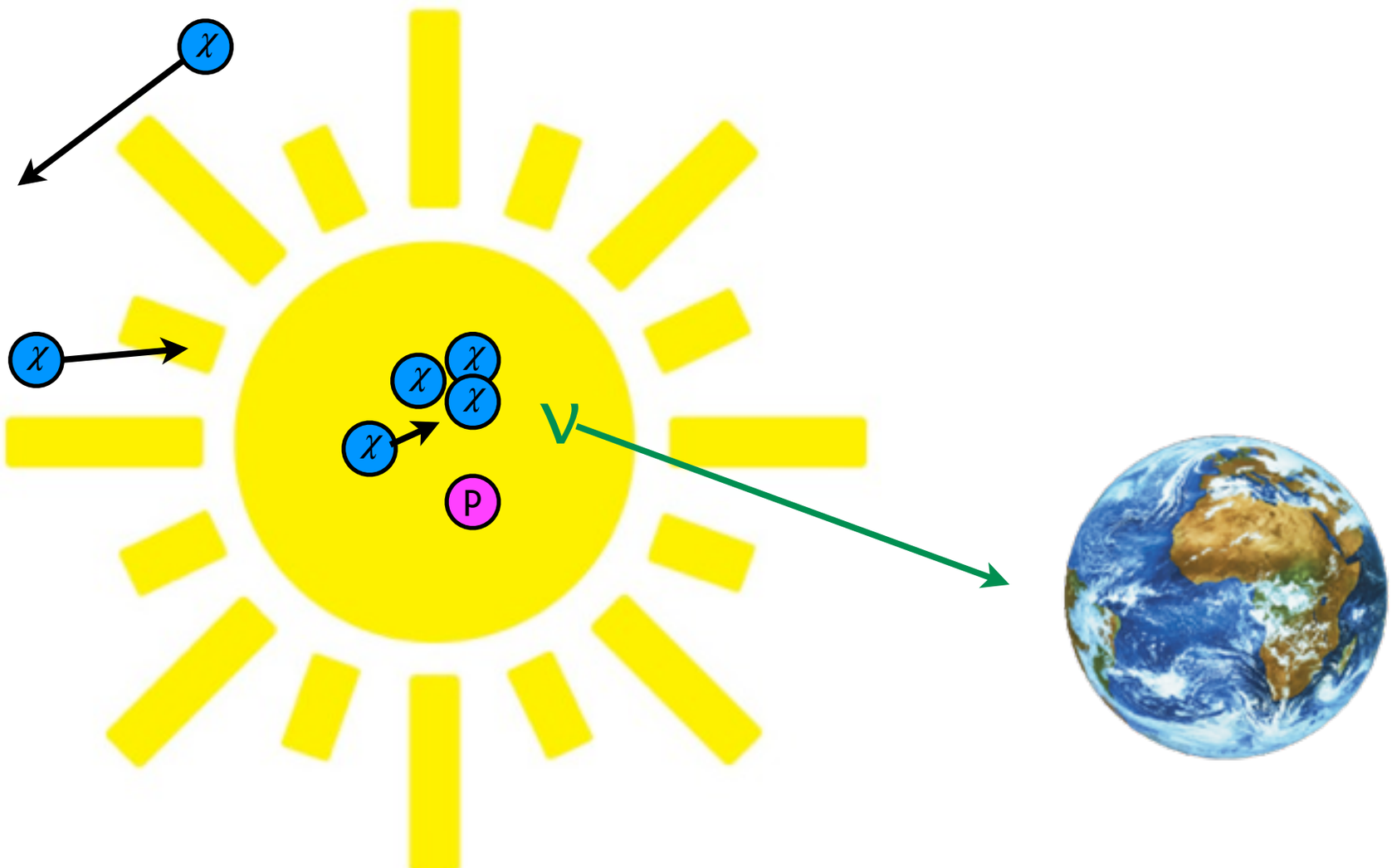

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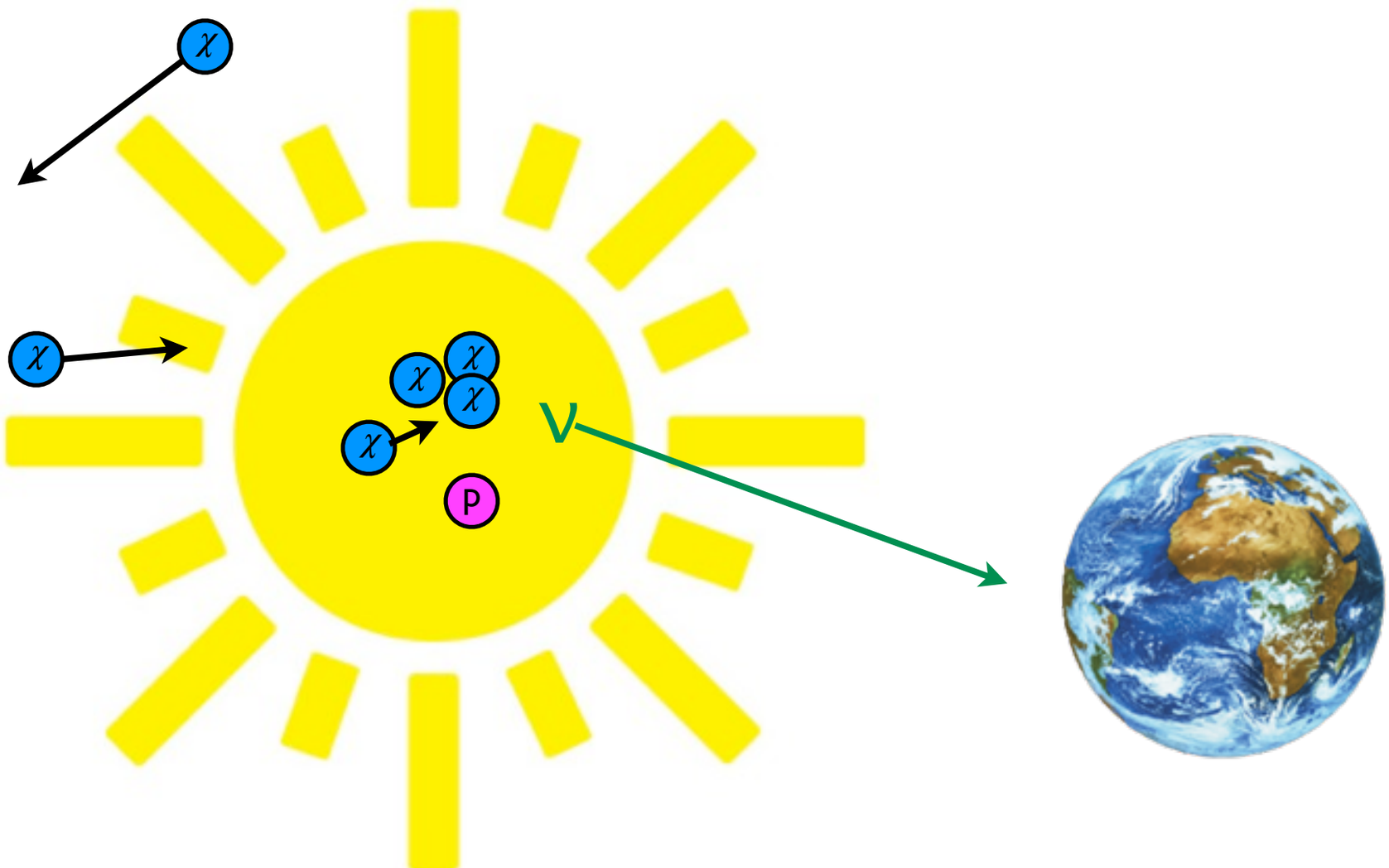

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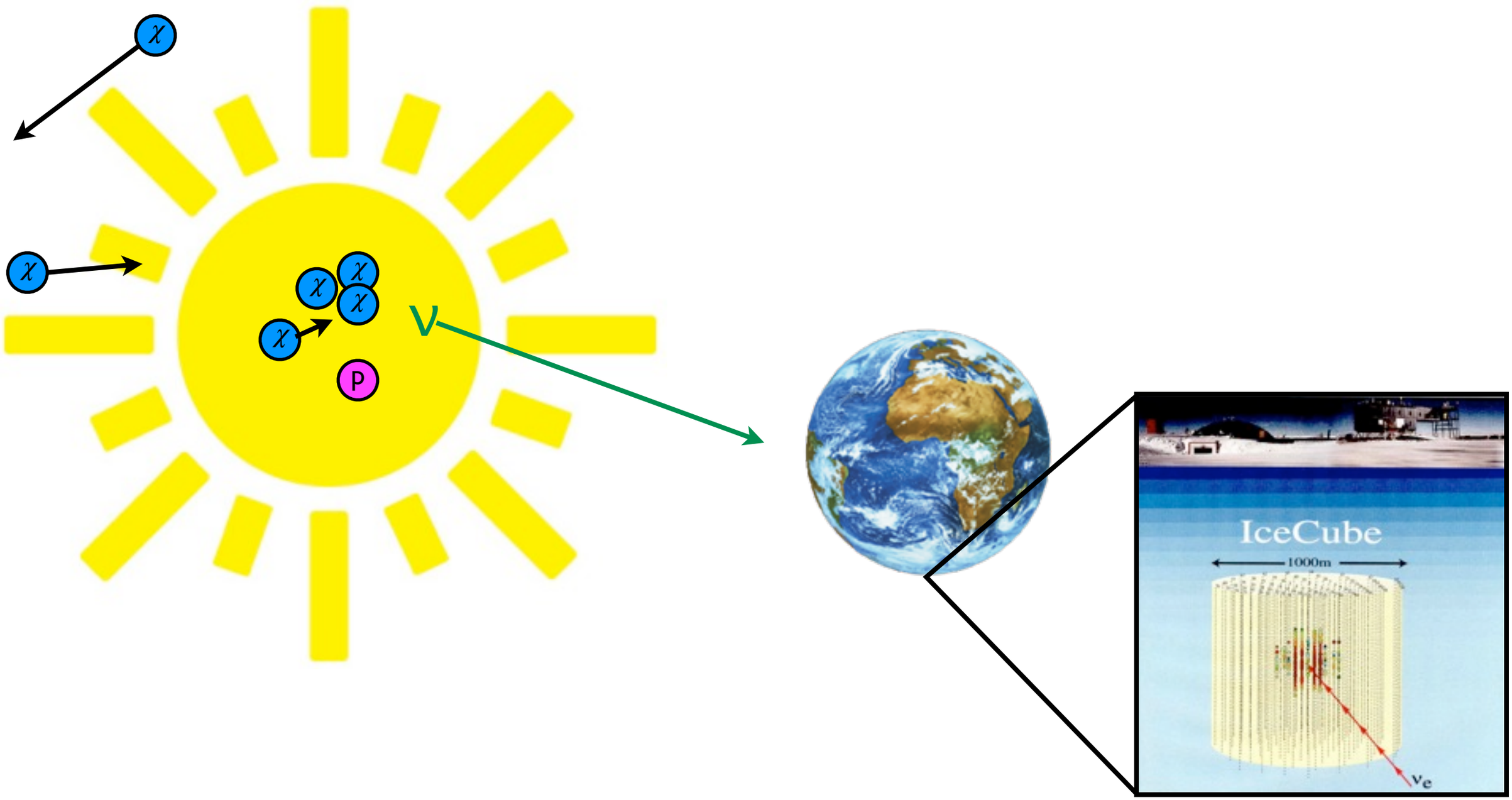
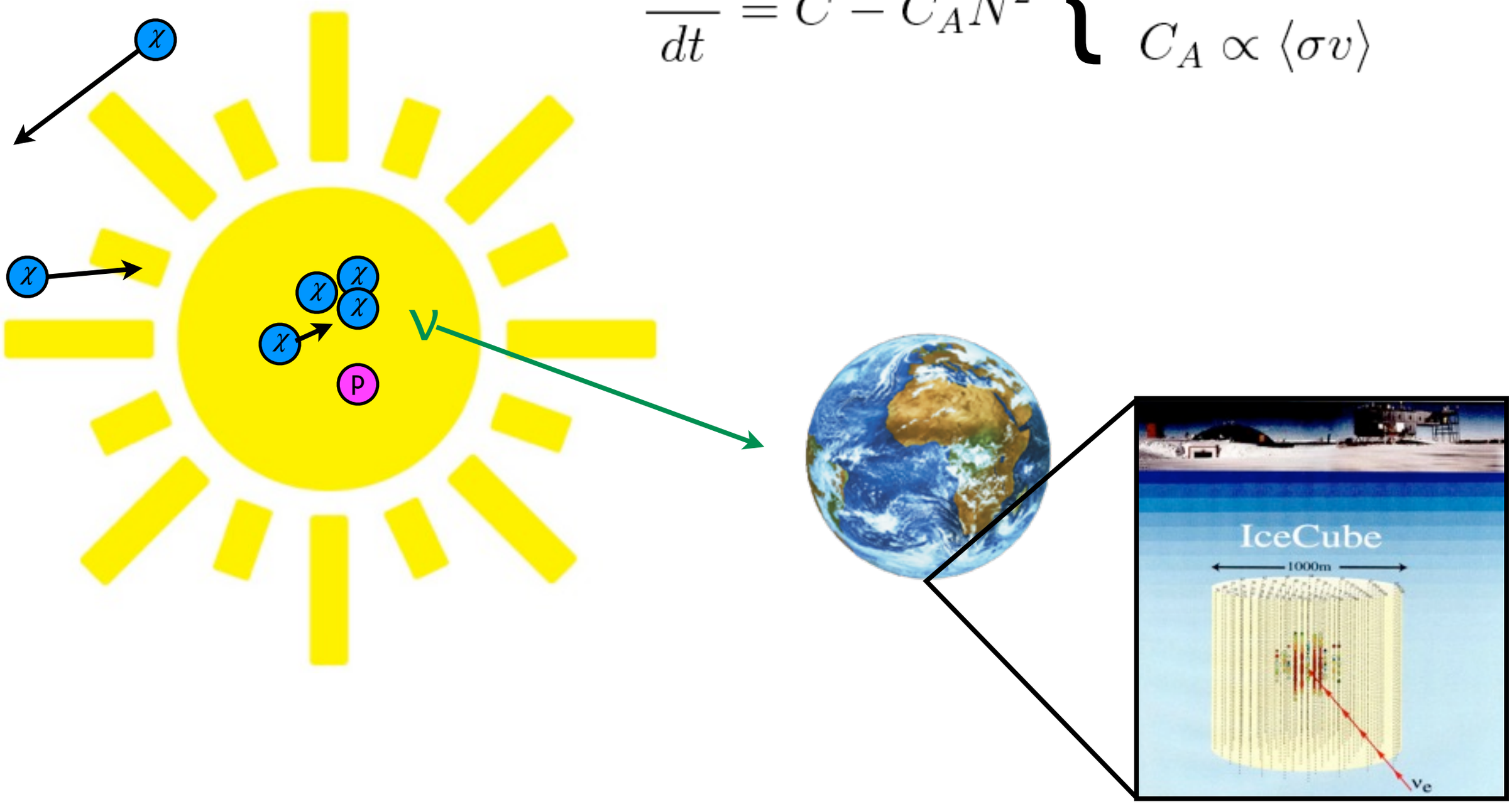


Neutrinos from the Sun

$$\frac{dN}{dt} = C - C_A N^2 \begin{cases} C \propto \sigma_{SD}\, \rho_{DM} \\ C_A \propto \langle \sigma v \rangle \end{cases}$$



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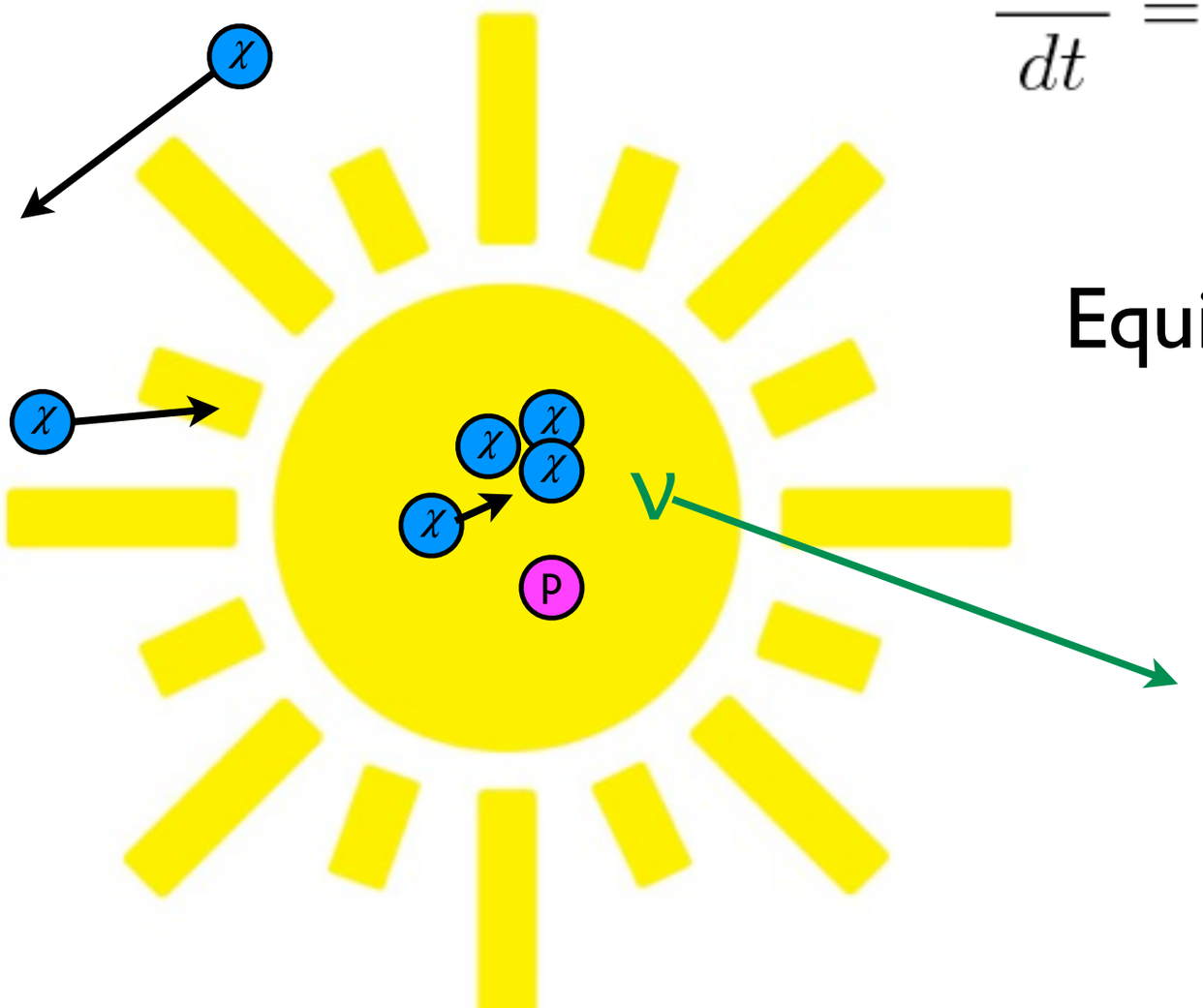
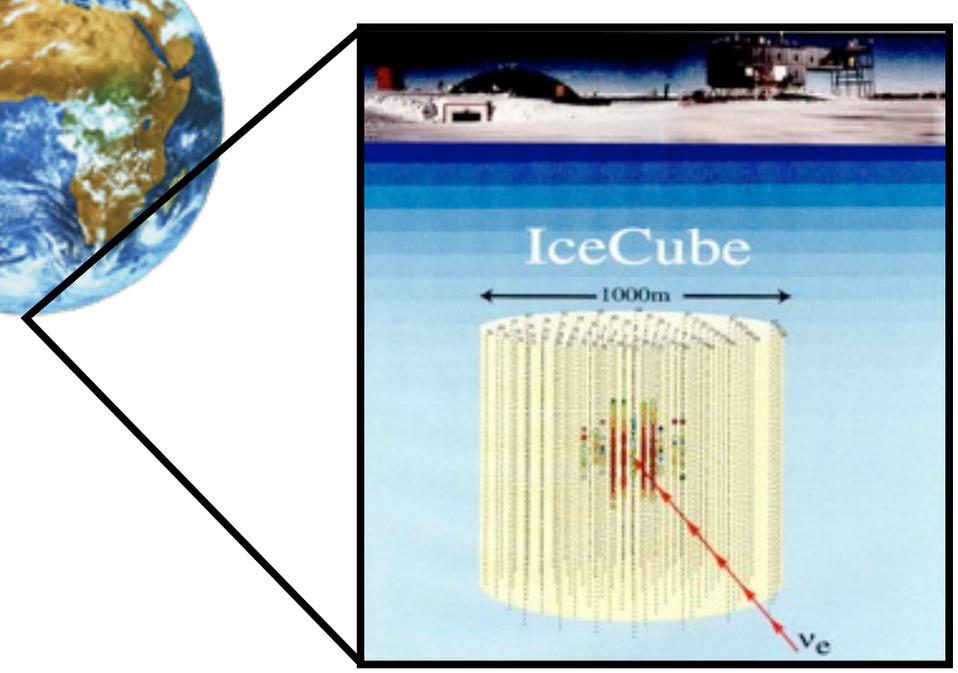
$$\frac{dN}{dt} = C - C_A N^2 \quad \begin{cases} C \propto \sigma_{SD}\, \rho_{DM} \\ C_A \propto \langle \sigma v \rangle \end{cases}$$

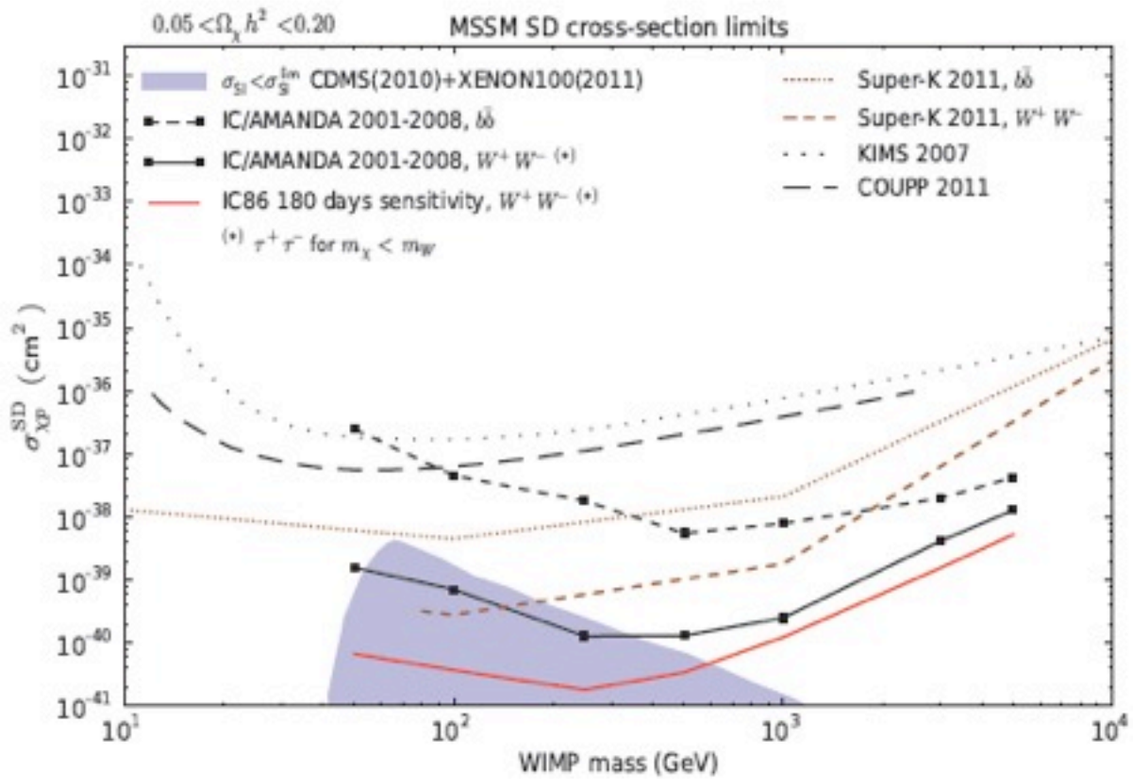
Equilibrium: $\Gamma_A = \frac{C_A}{2} N_{eq}^2 = \frac{C}{2}$

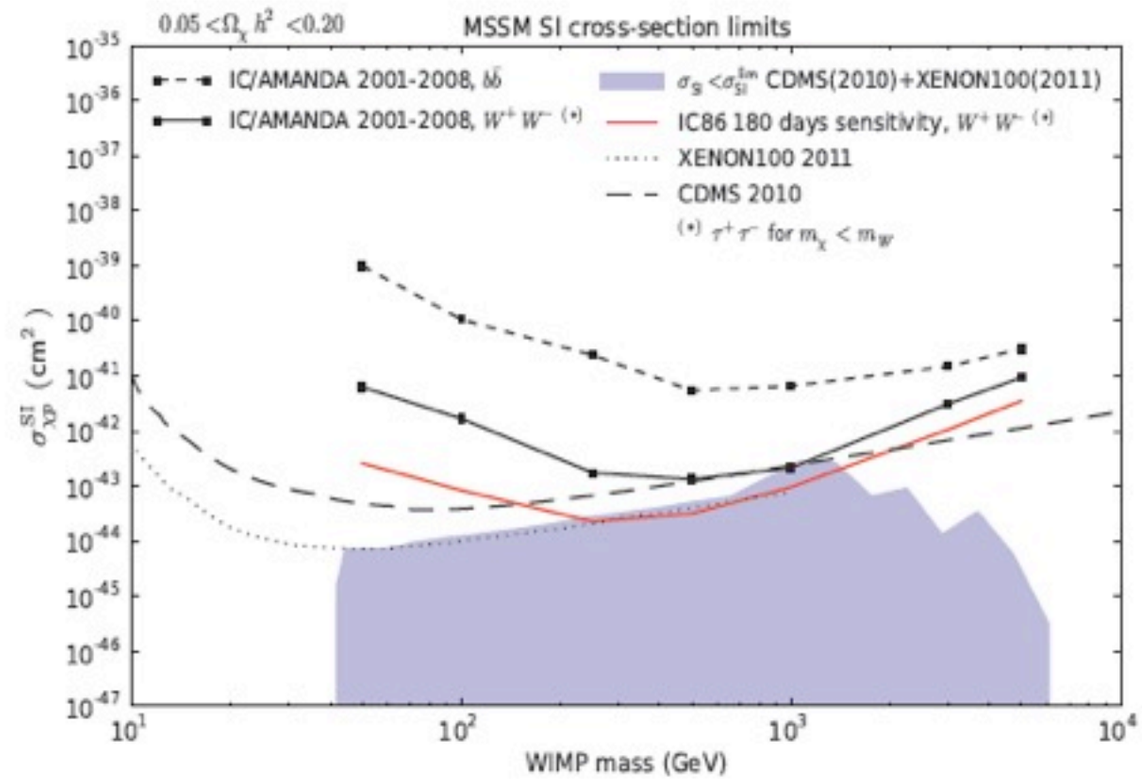




Current Limits

IceCube Collaboration (2011)





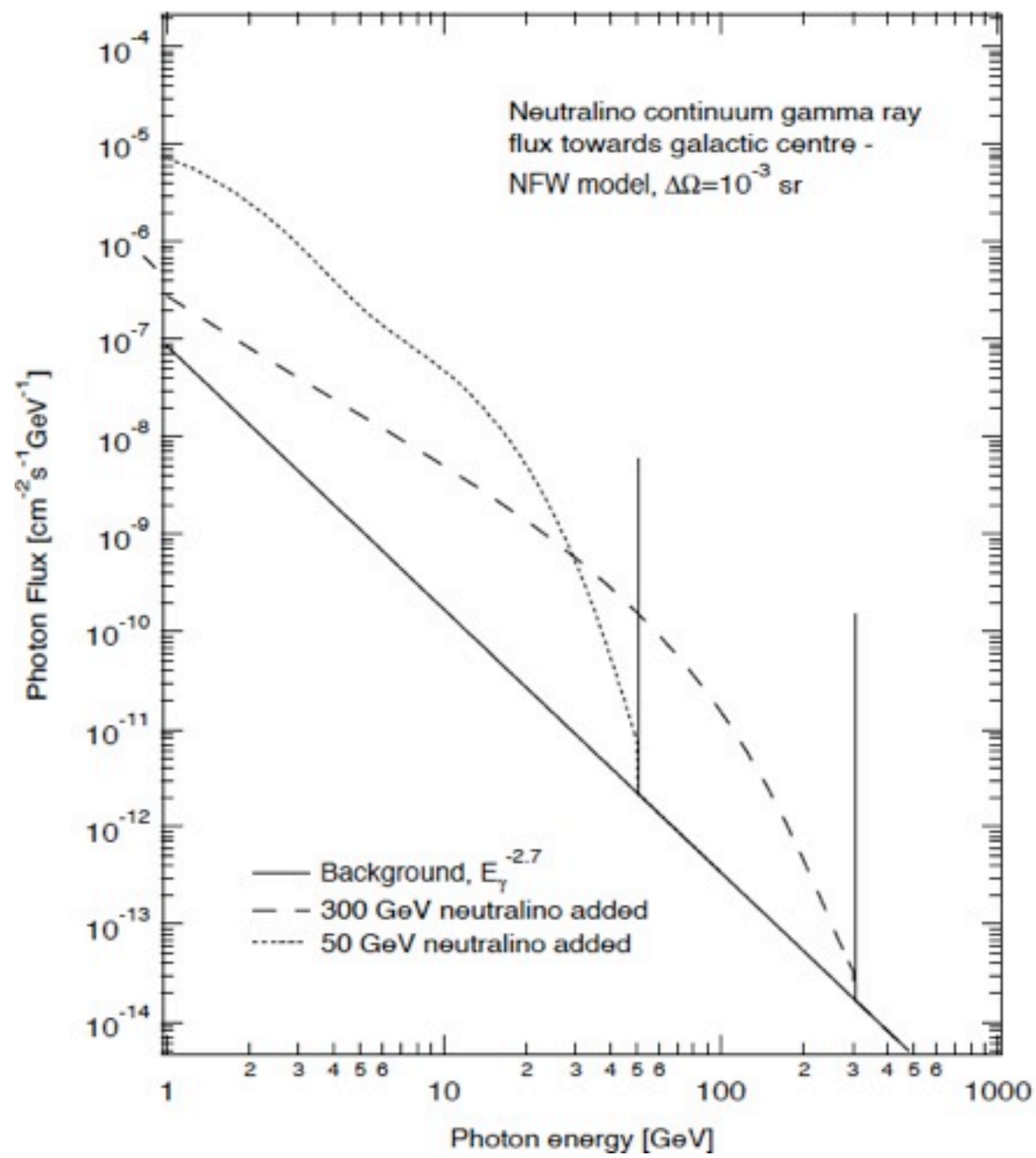
Limits are competitive with current direct detection experiments!

Assumptions: equilibrium, hard/soft channels 100%

Photons

- Continuum Spectrum
  - Galactic Center
  - Galactic Diffuse
  - Extragalactic
  - Dark Matter Subhalos
  - Dwarf Galaxies
  - Galaxy Clusters
- Monochromatic Line

Bergstrom, Ullio & Buckley (1998)



Monochromatic Line

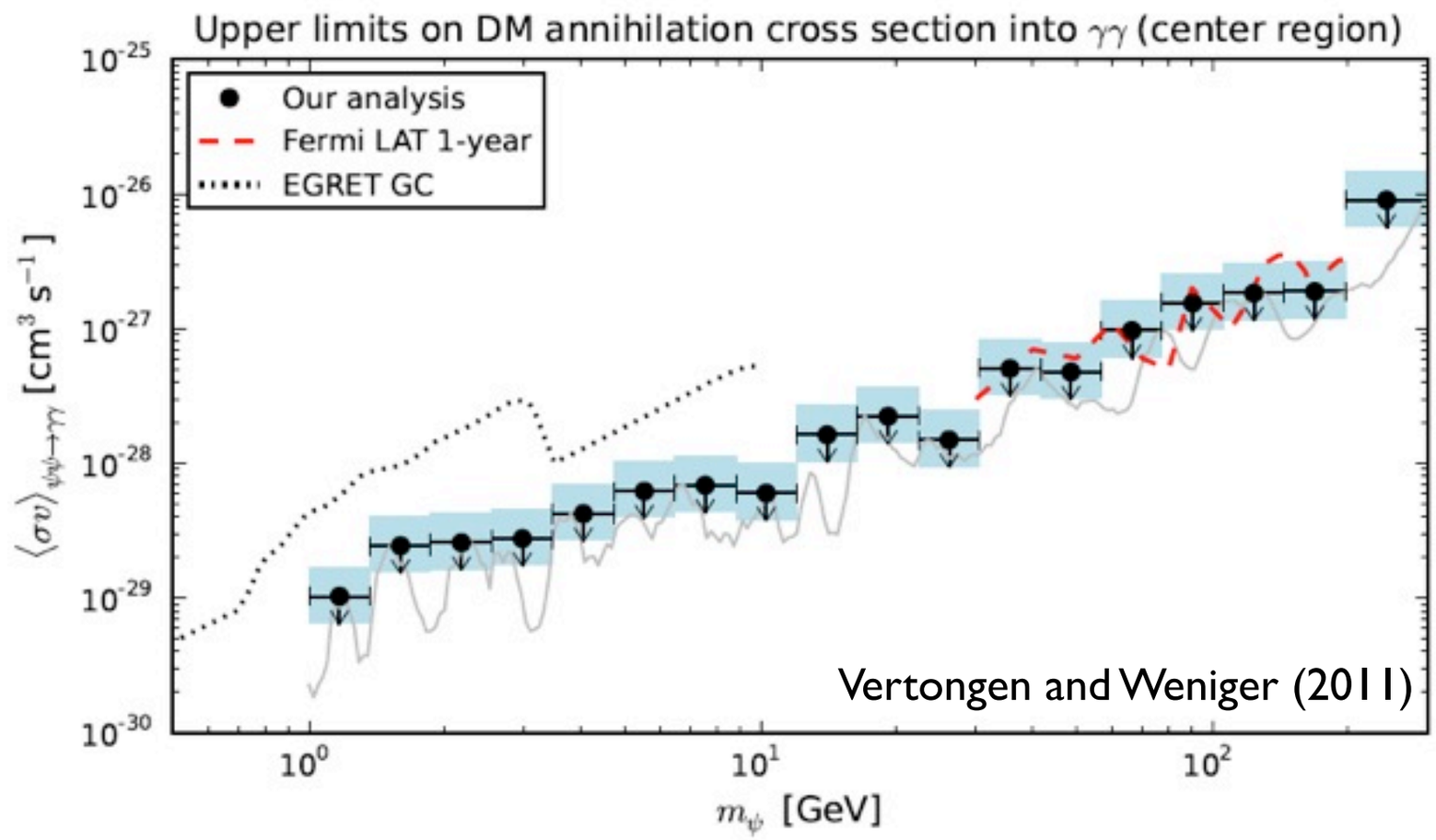
$$\chi\chi \to \gamma\gamma$$

$$E_\gamma = m_\chi$$

$$\chi\chi \to \gamma Y$$

$$Y = Z,\ h^0,\ \text{etc.}$$

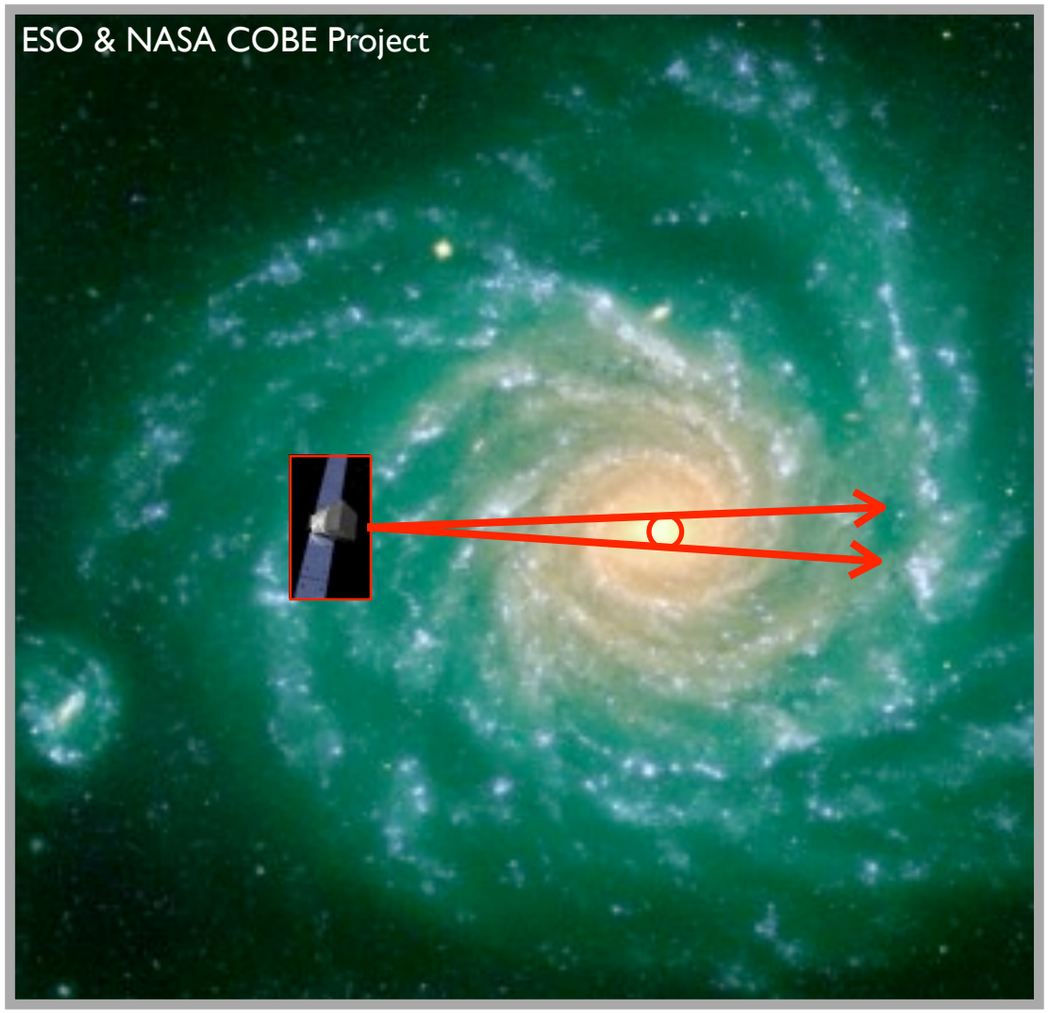
$$E_\gamma = m_\chi - \frac{m_Y}{4m_\chi}$$



Predicted $\gamma\gamma$ branching fractions typically small: 10^{-4} to 10^{-1}

Galactic Center

- Dark matter density expected to be quite large, but...
- Many sources near/along our line of sight to the GC
  → Source Confusion!
- Diffuse emission??? Good handle on astrophysical background emission is crucial to extracting a DM signal.



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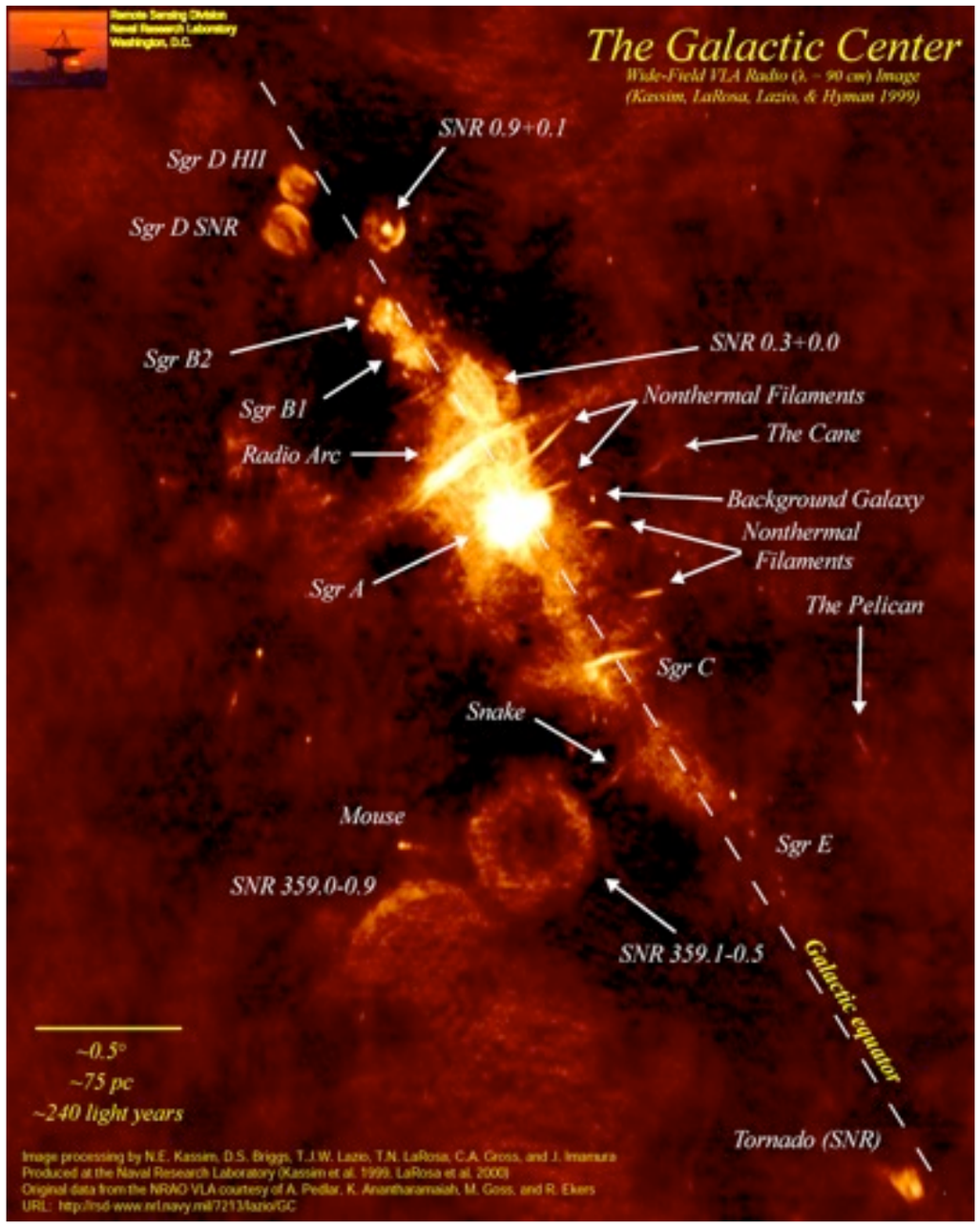
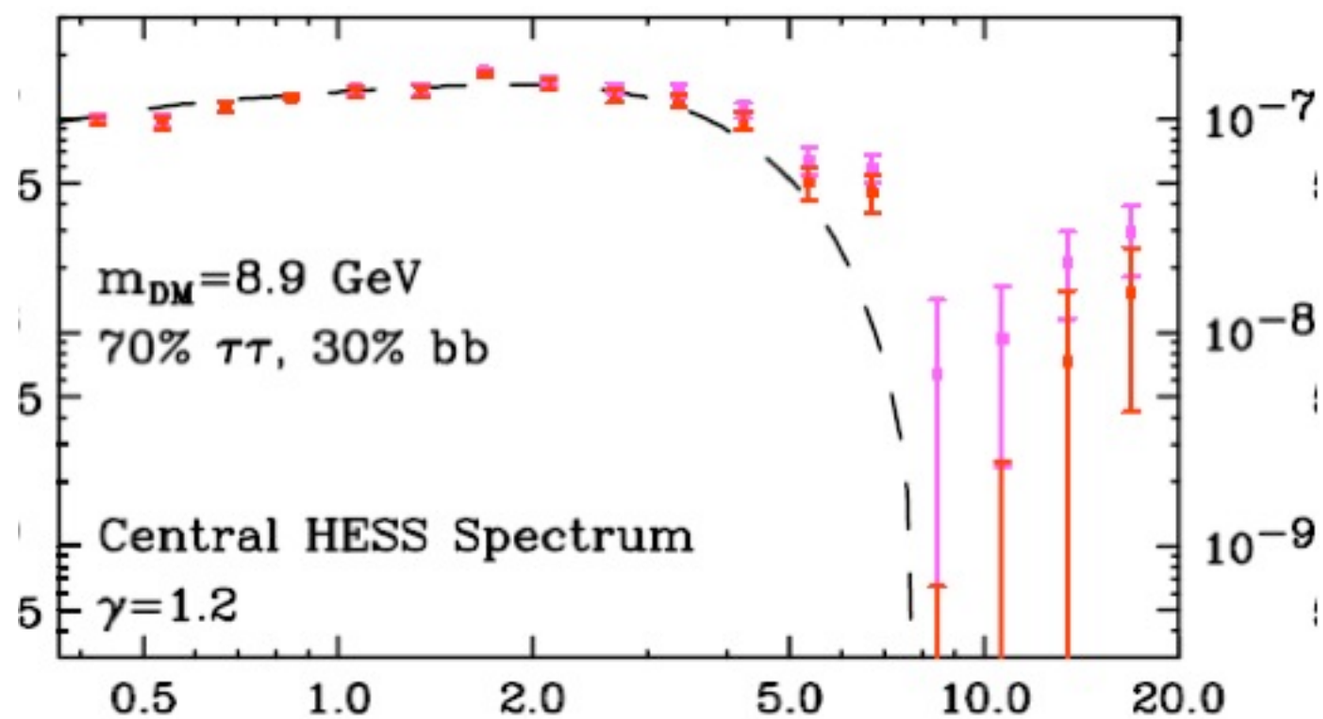


1° of the dynamical center!

Goodenough & Hooper (2011)

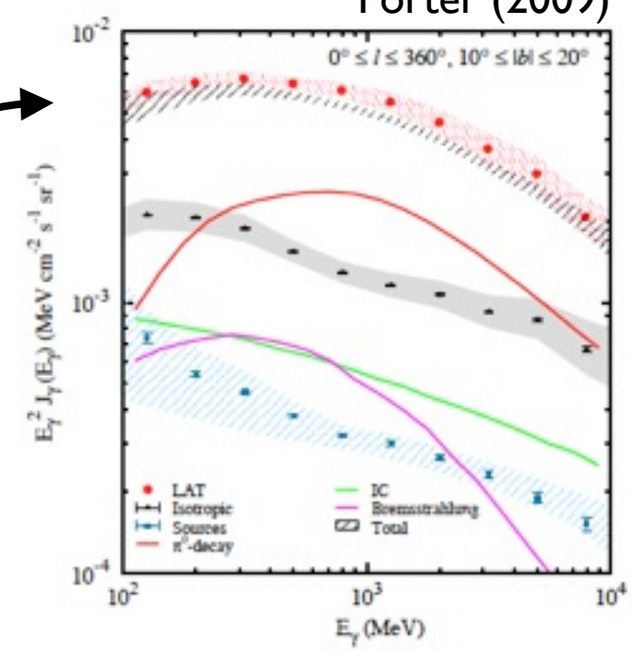


Galactic Diffuse Flux

- There's a lot of dark matter out there, but...
- Diffuse background is complicated (diffuse emission modeling problem)
  - Major components: π^0 decay, e^+/e^- IC with ISRF, e^+/e^- bremsstrahlung with IS gas, point sources
- Understanding backgrounds reduces wiggle room for dark matter model-building.
- Substructure changes the expected gamma-ray flux from annihilations or decays

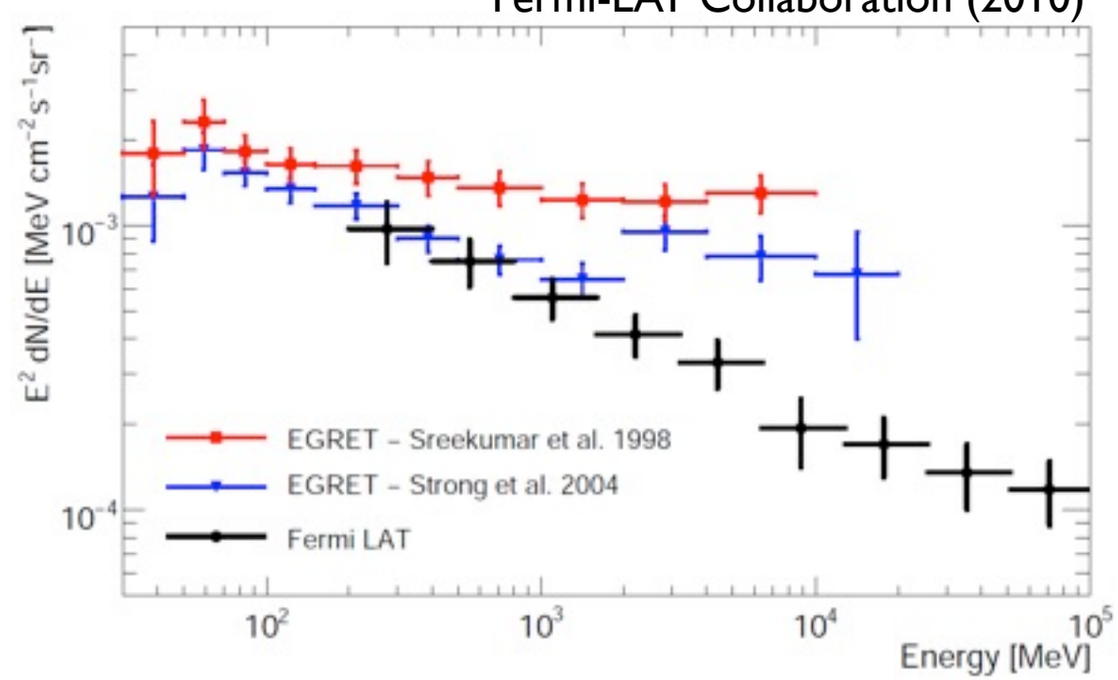
moderate galactic latitudes

Porter (2009)



all-sky diffuse flux

Fermi-LAT Collaboration (2010)



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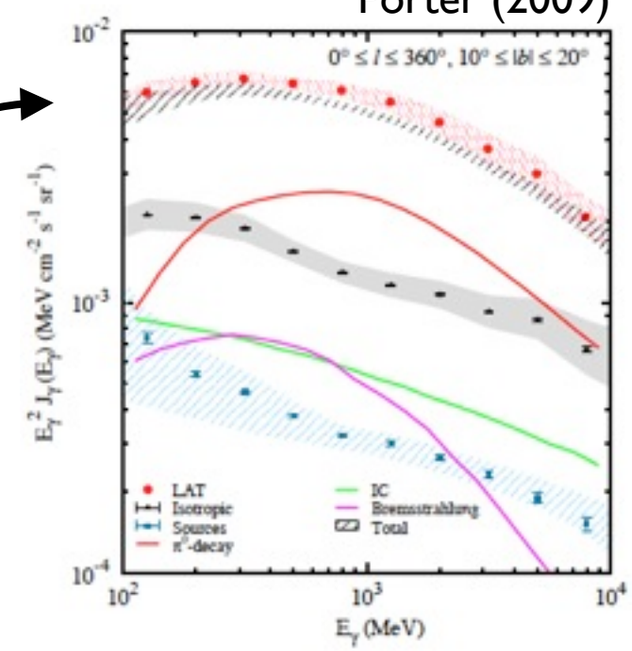
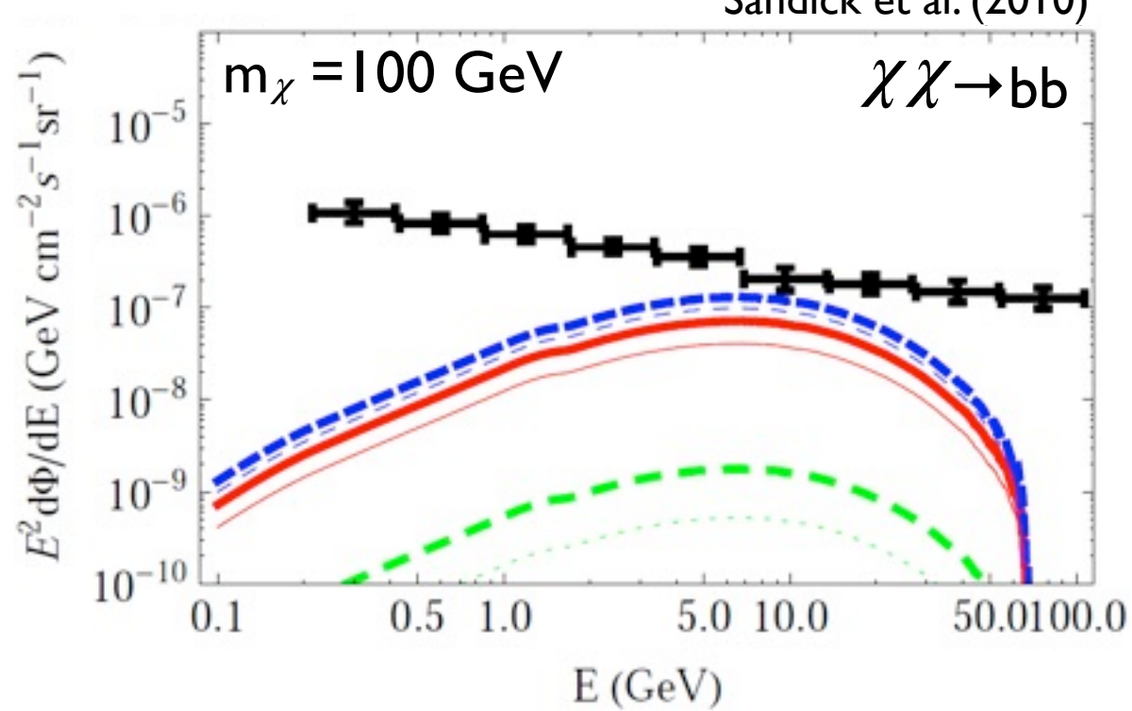


all-sky diffuse flux

Sandick et al. (2010)



Extragalactic (Cosmological) Dark Matter

- Structures: much larger signal than naïve expectation from average DM abundance in the Universe

$$\frac{d\phi_\gamma}{dE_{\gamma,0}} = \frac{\langle\sigma v\rangle}{8\pi}\frac{c}{H_0}\frac{\bar{\rho}_X^2}{m_X^2}\int dz(1+z)^3\frac{\Delta^2(z)}{h(z)}\times\frac{dN_\gamma}{dE_\gamma}(E_\gamma(1+z))e^{-\tau(z,E_\gamma)}$$

- Average overdensity can be very large!
- Extragalactic BG from unresolved gamma-ray sources (eg. Blazars)
- Residual contamination from Galaxy (including Galactic DM signal)

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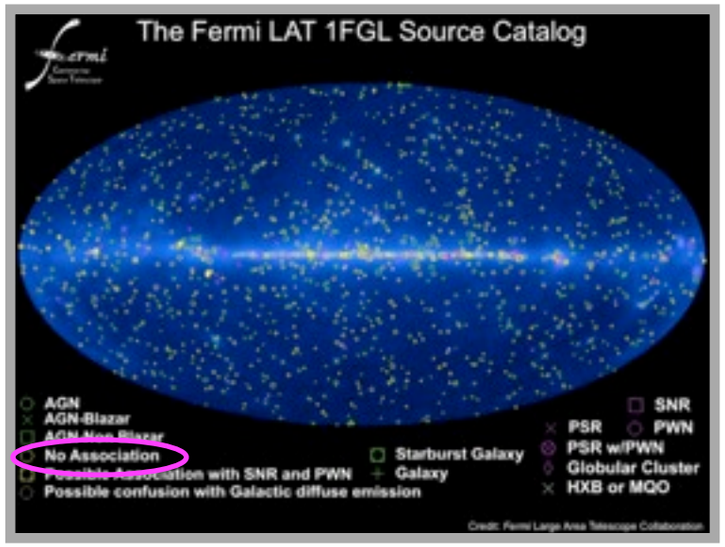
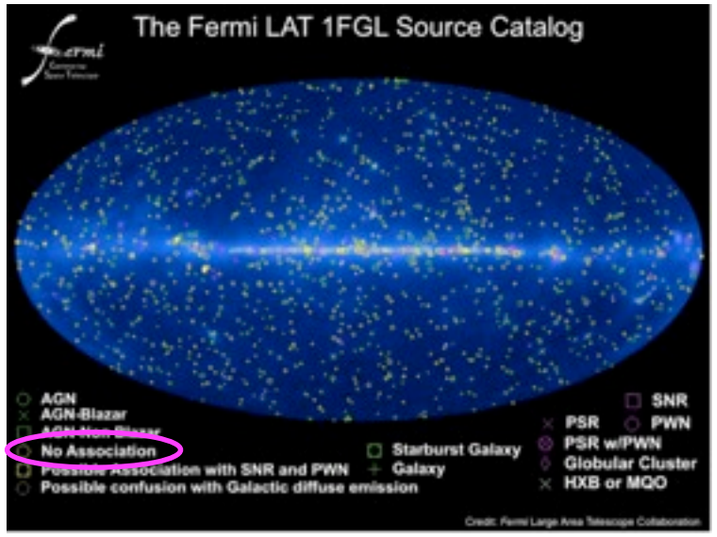
Subhalos, Dwarfs & Clusters, oh MY!



- DM objects with unknown locations?
  - Point Sources: Buckley & Hooper (2010), Sandick et al. (2010)
  - Extended Sources: Fermi paper on arXiv yesterday!
- DM-dominated objects with known locations:

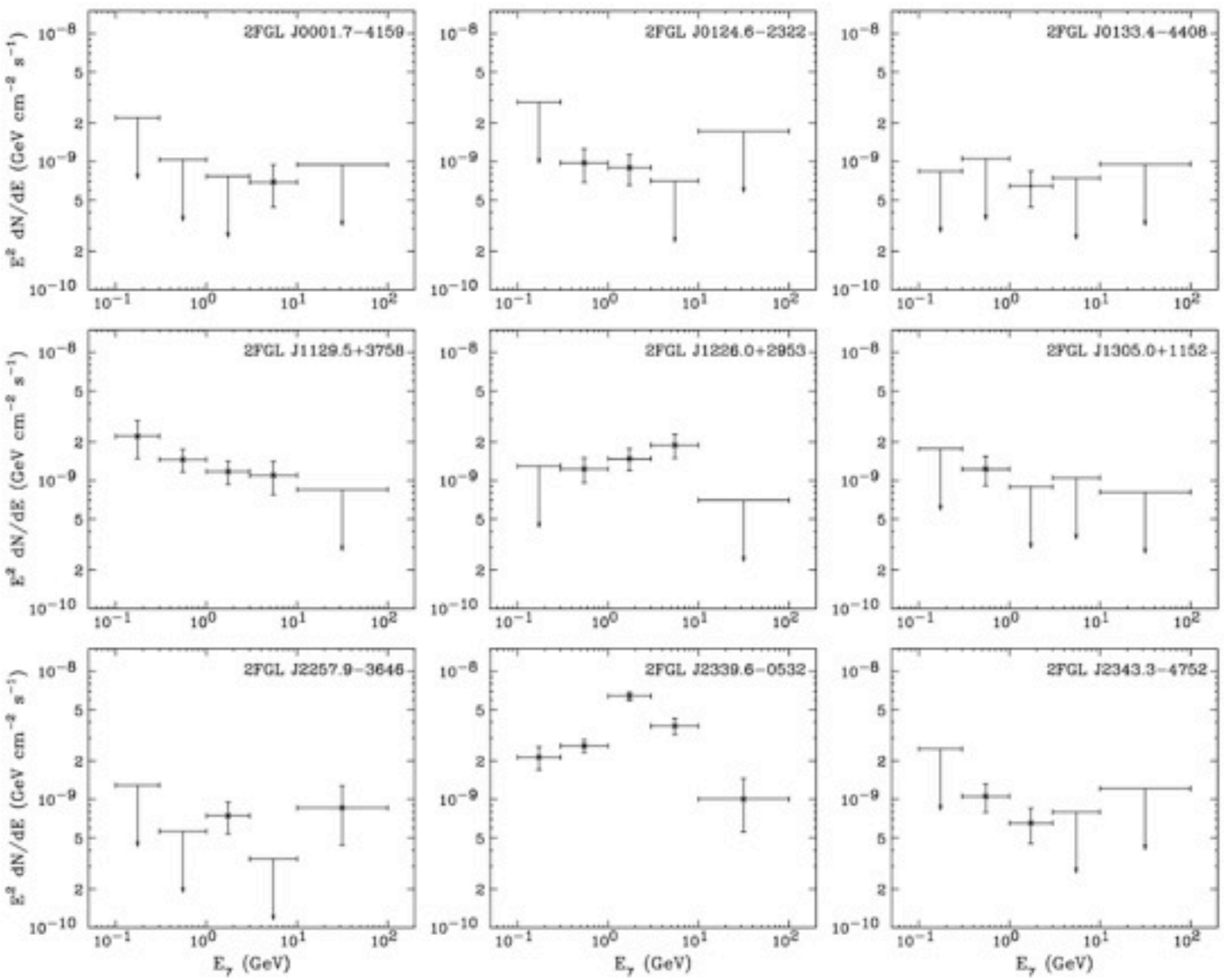
Dwarf Spheroidal Galaxies	Galaxy Clusters
Near (10s to 100s kpc) and localized	Farther (>Mpc) but more massive
No star-forming regions Little-to-no gas or dust →Few sources of gamma rays	May contain AGN
Stellar measurements of DM distribution, but central region (cusp) and substructure uncertain	X-ray studies show gas in hydrostatic equilibrium (lots of dark matter), but distribution uncertain

Subhalos



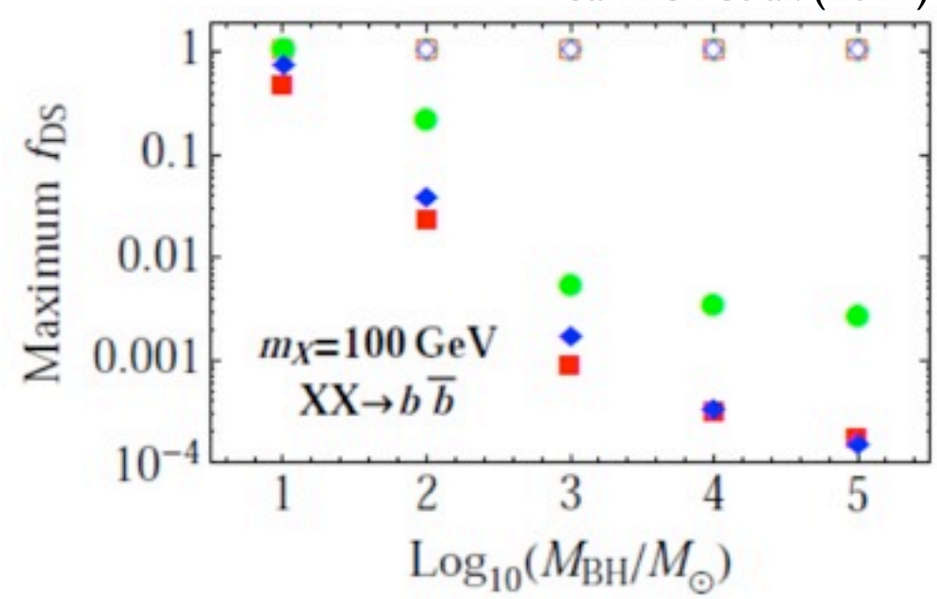
Are spectra compatible with DM signal?

Belikov et al. (2011)



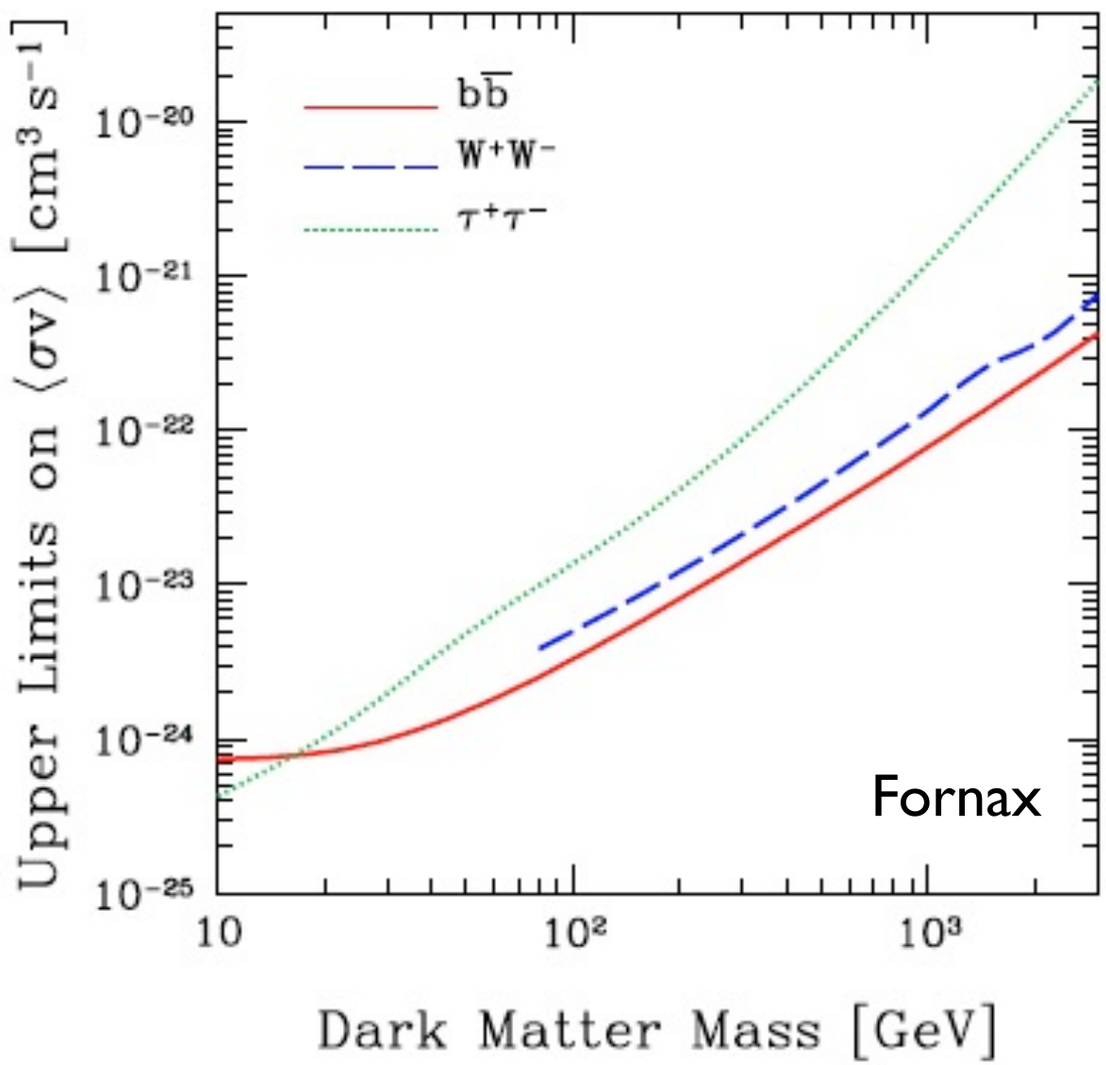
Constrain substructure models:

Sandick et al. (2011)

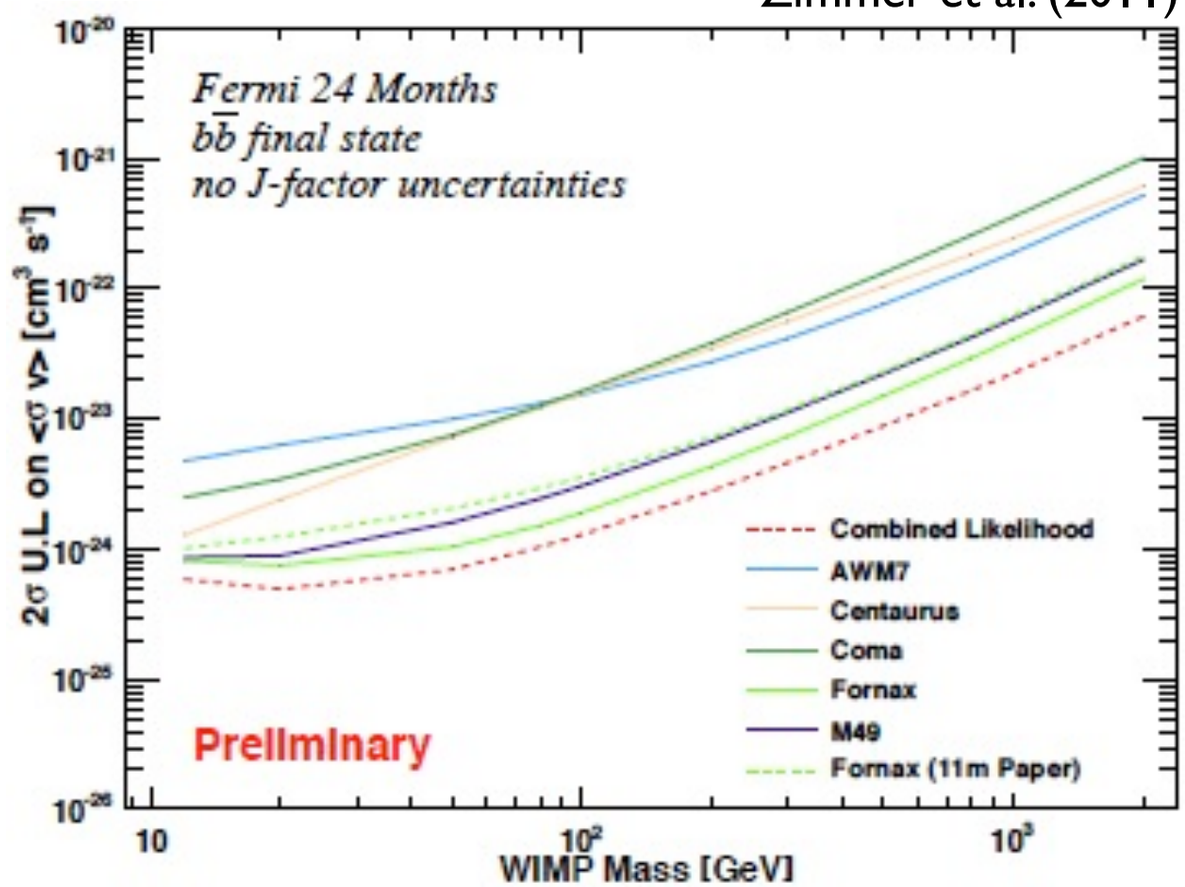


Clusters

Ando & Nagai (2011)

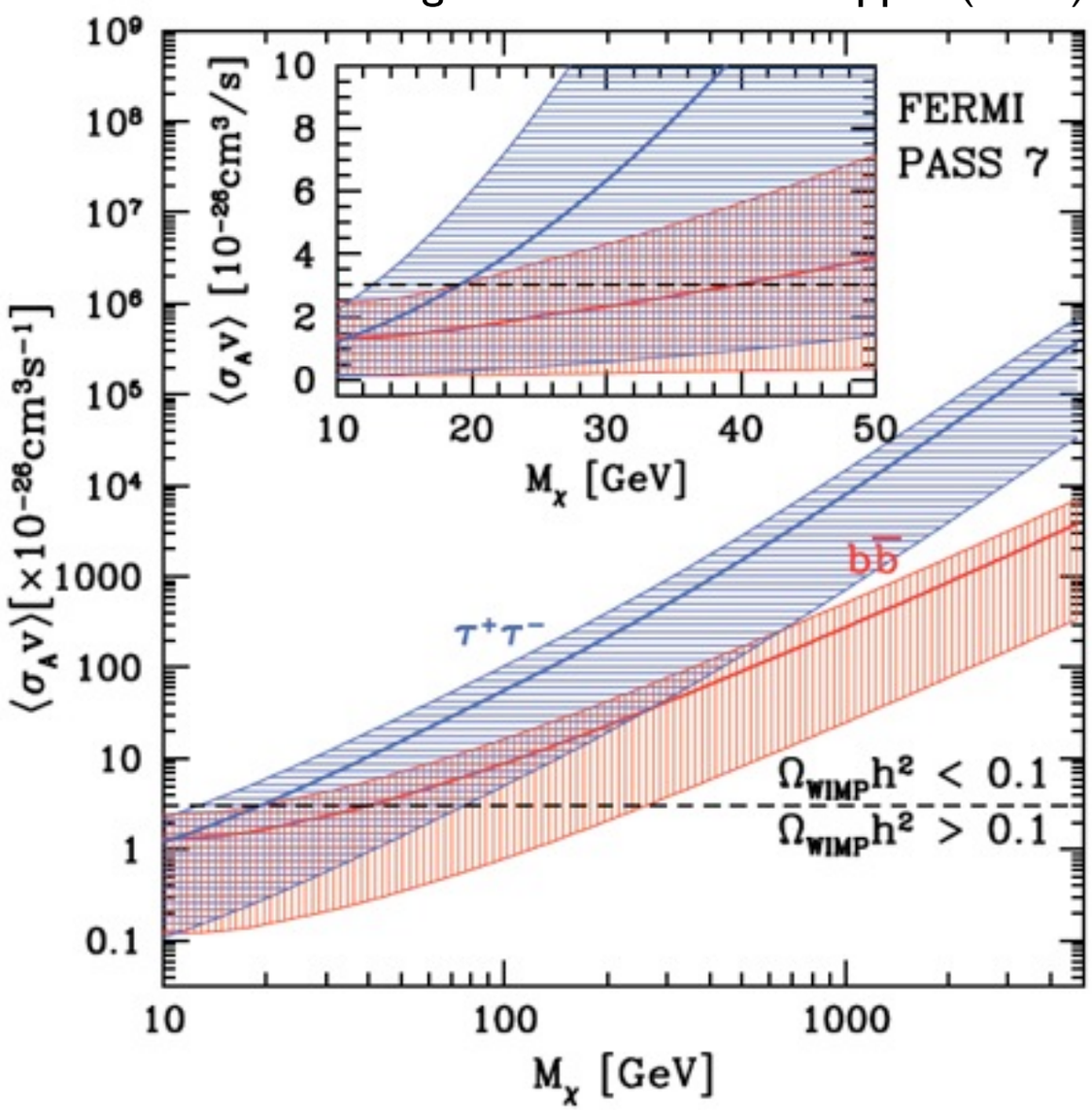


Zimmer et al. (2011)

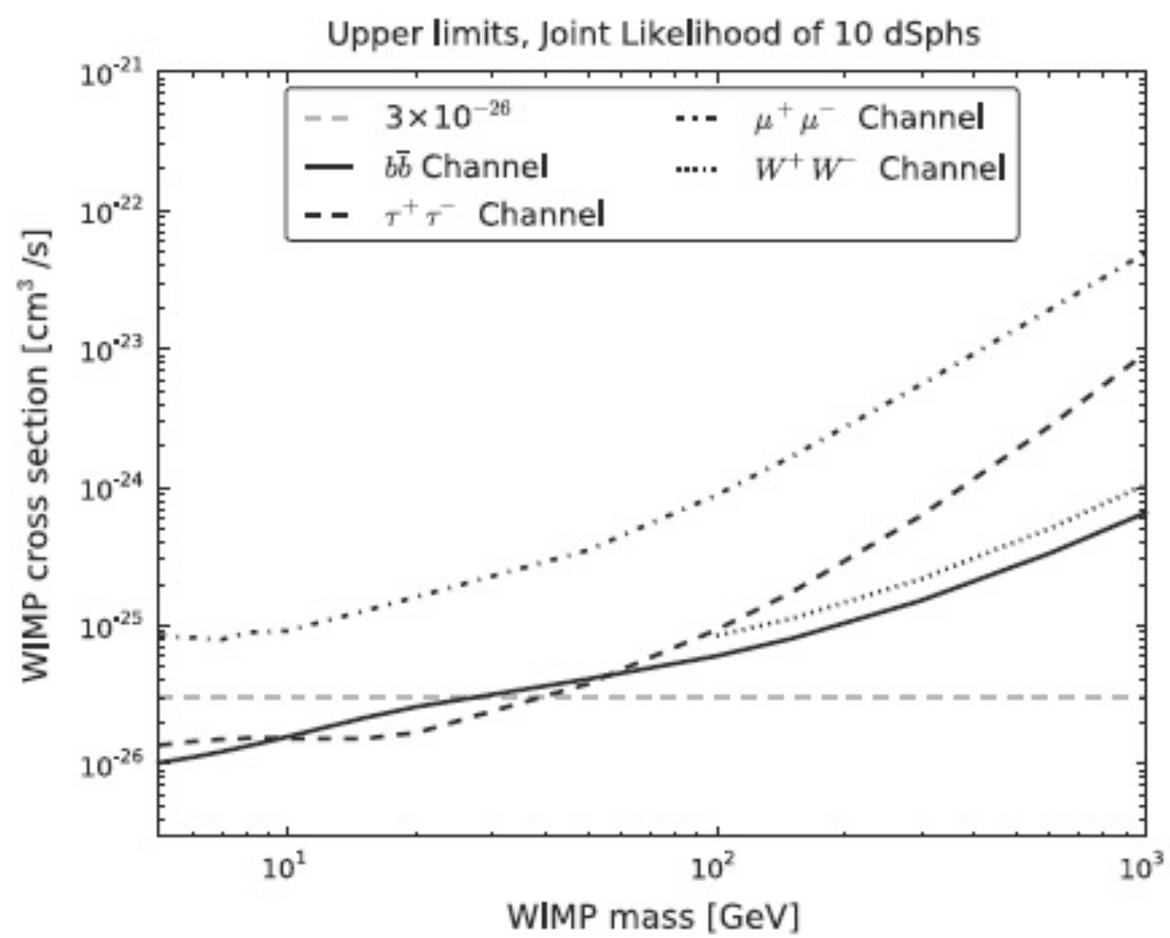


Dwarf Spheroidal Galaxies

Geringer-Sameth & Koushiappas (2011)

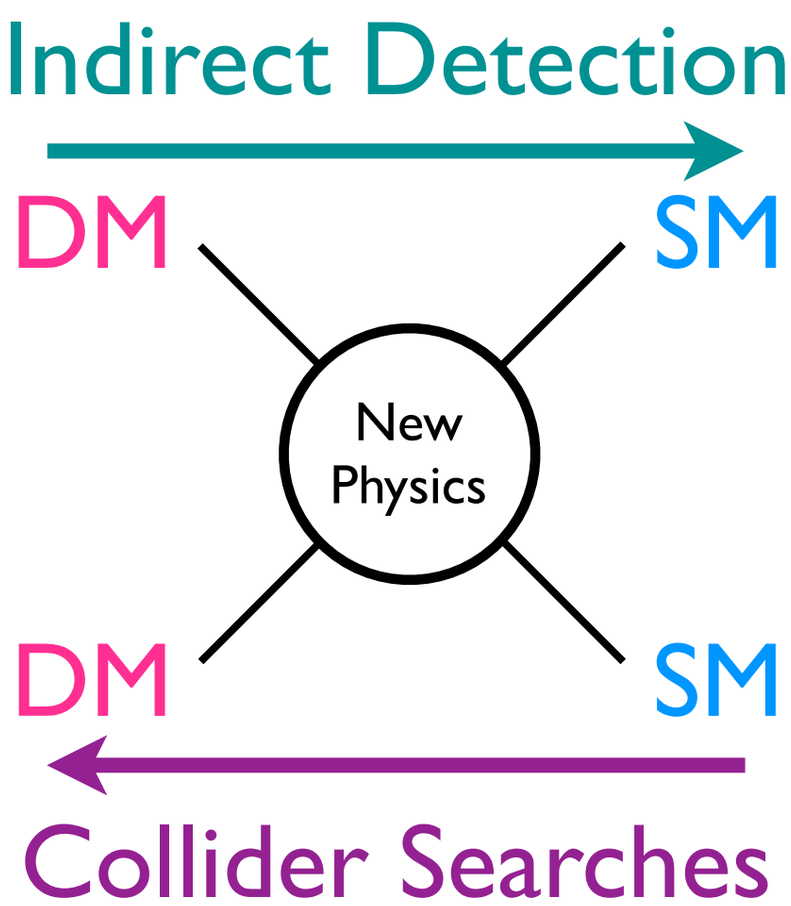


Ackermann et al. (2011)



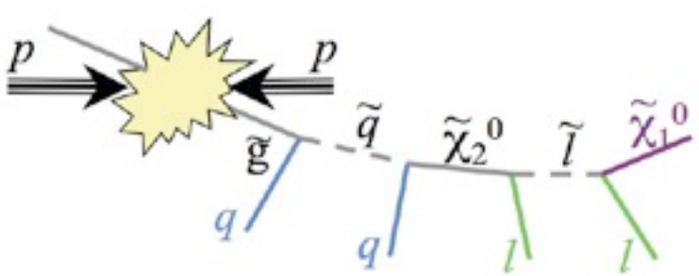
Collider Searches

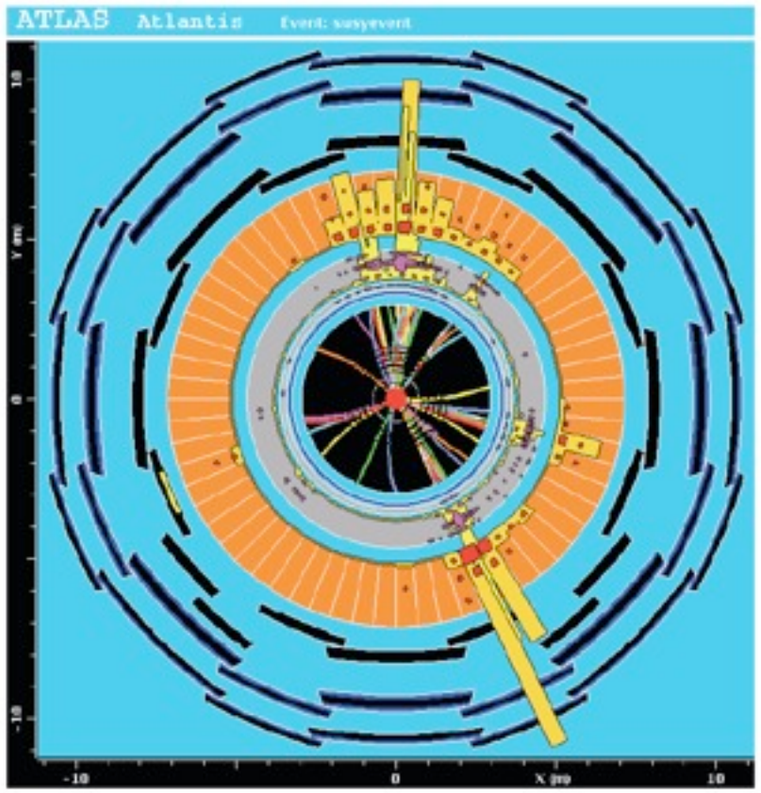
- If dark matter annihilates in the early universe to SM particles, should be able to smash SM particles together to create dark matter.



Collider Searches

- If dark matter annihilates in the early universe to SM particles, should be able to smash SM particles together to create dark matter.
- But DM won't interact in the detector
  - missing energy
  - produce heavier new particles, watch for their decays to dark matter





Figures from Mitsou (2011)

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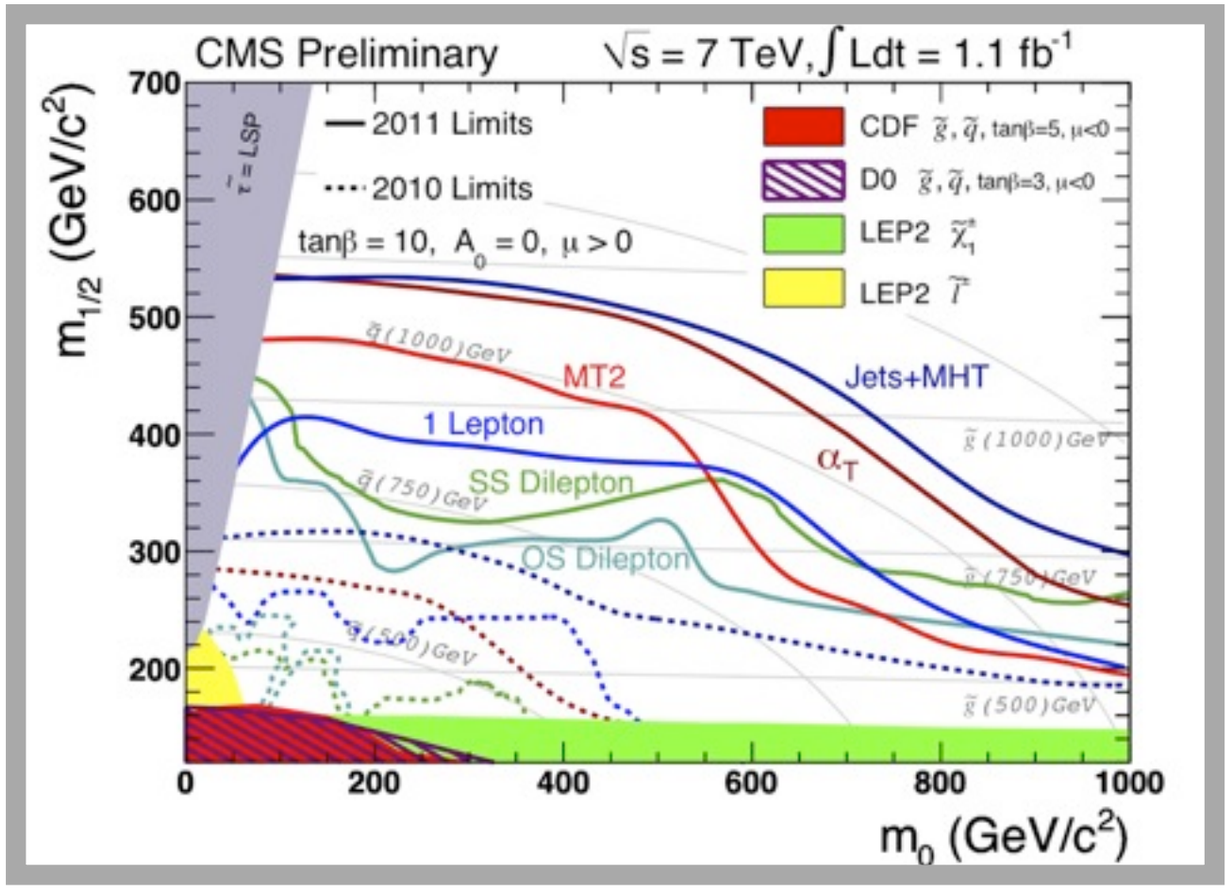

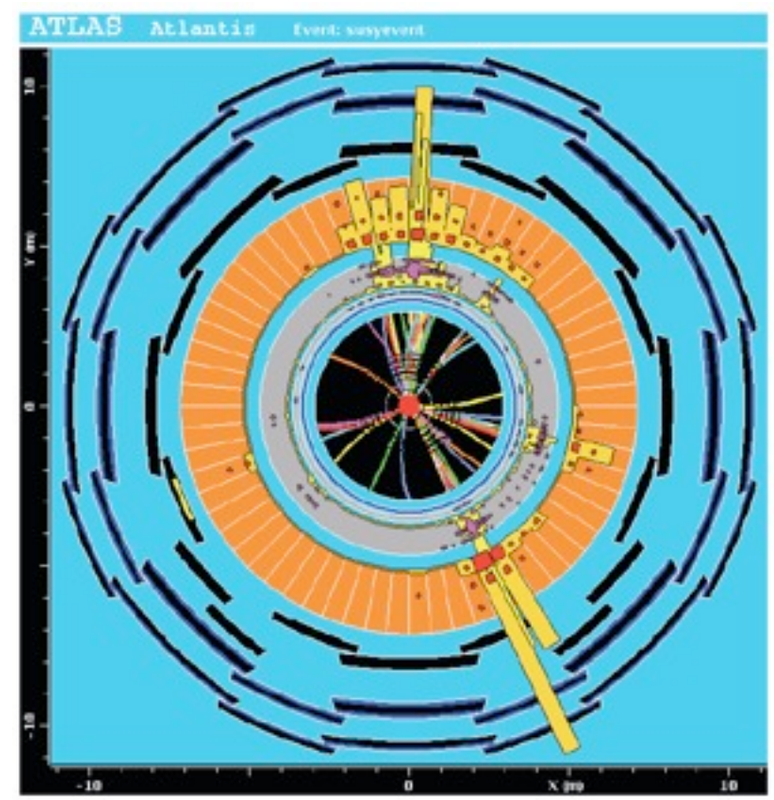

Figures from Mitsou (2011)

Collider Searches

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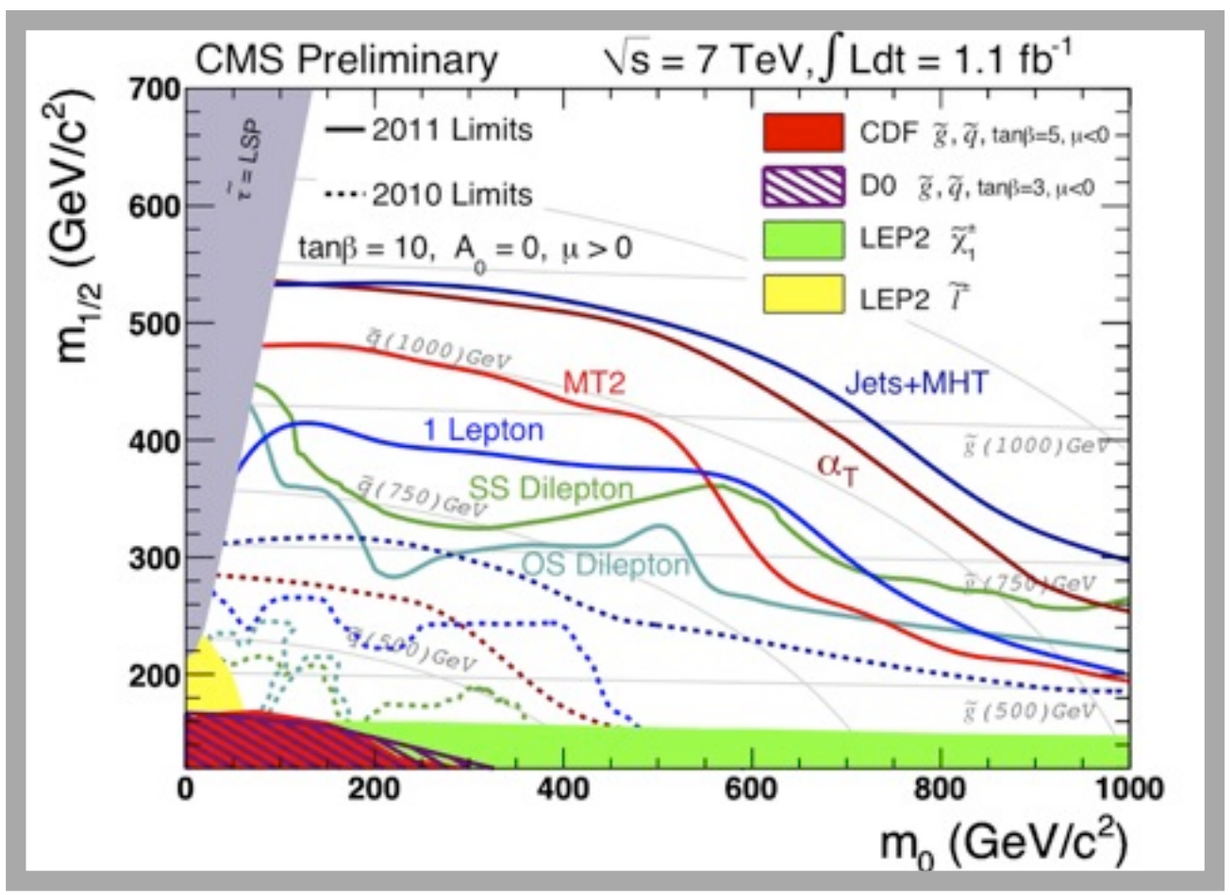
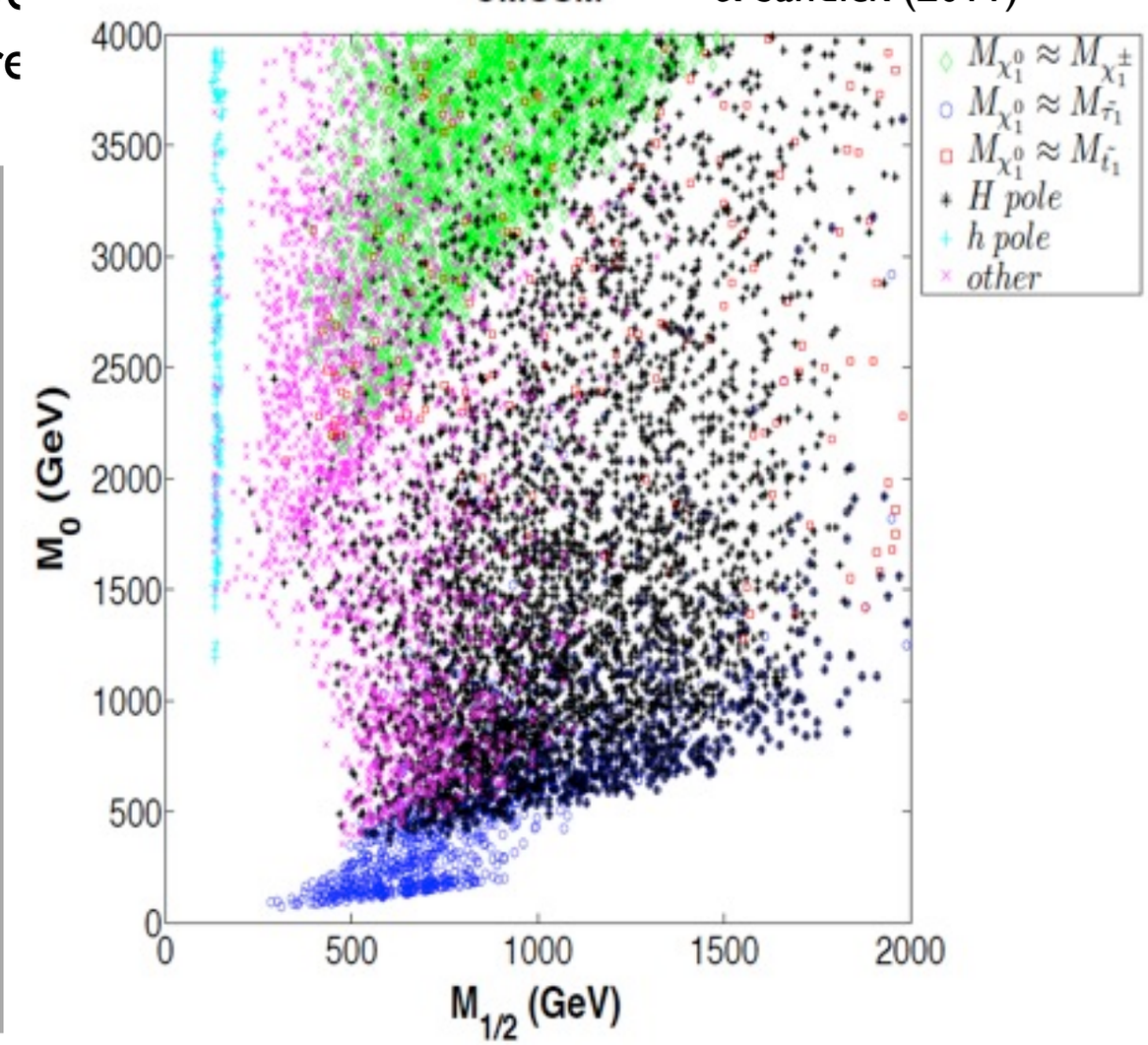


Amsel, Freese
& Sandick (2011)



Summary

- **Advances on all fronts!**
- Direct Detection
  - unambiguous evidence of the particle nature of dark matter
  - resolution of direct detection tensions
- Indirect Detection
  - verification that the dark matter particles we observe terrestrially are actually the ones that are astrophysically and cosmologically relevant
  - annihilation cross section and final states
- Colliders
  - confirm BSM theory, measure dark matter properties