Detecting Dark Matter: Overview, Issues, and Perspectives

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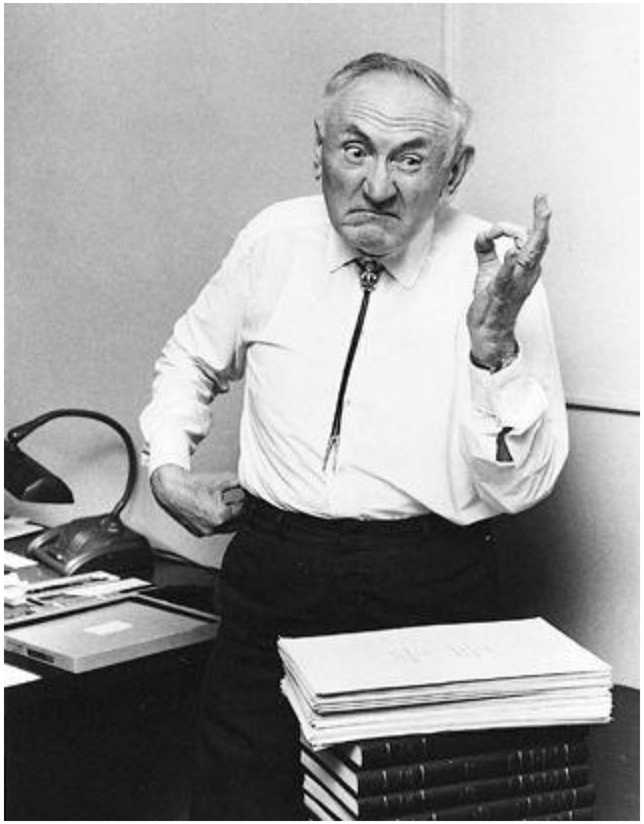
Dunkle Materie

- Overview
  - Why? Where? What?
- How to detect it?

  (when it = WIMPs)
  - Accelerators
  - Indirect searches
  - Direct searches
- Future, thoughts and perspectives

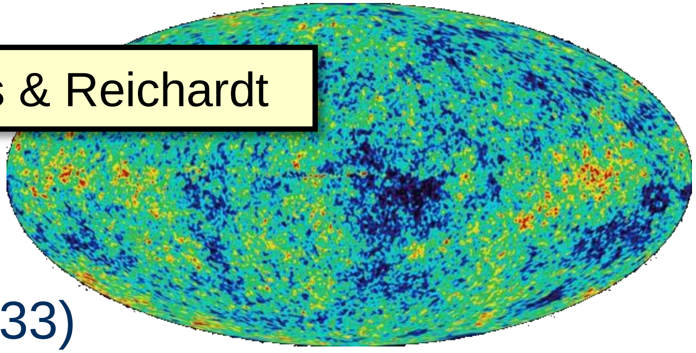


Ask questions at any point !

Dark Matter Overview

Why Dark Matter?

Talks by Davis & Reichardt



NASA/WMAP Science Team

- Indirect evidence
  - Velocities of galaxies in clusters (Zwicky 1933)
  - Galaxy rotation curves (Rubin 1960's)
  - Cosmic microwave background
  - Big bang nucleosynthesis
  - Structure formation
  - Gravitational lensing

Colley et al. (HST)

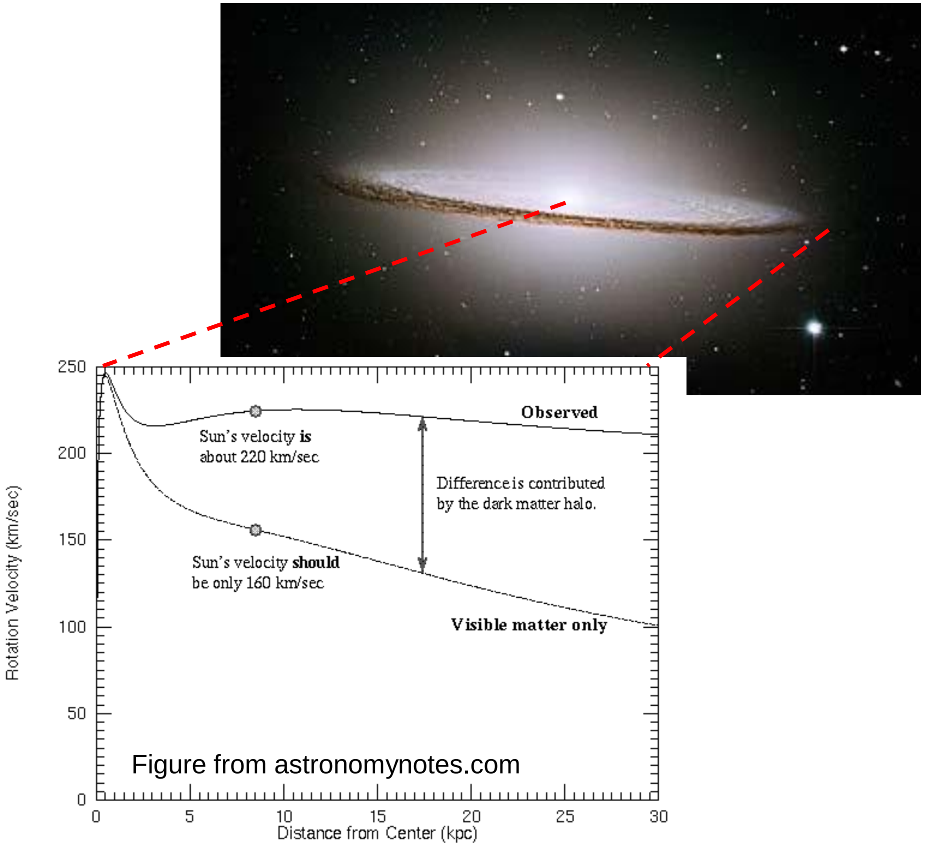
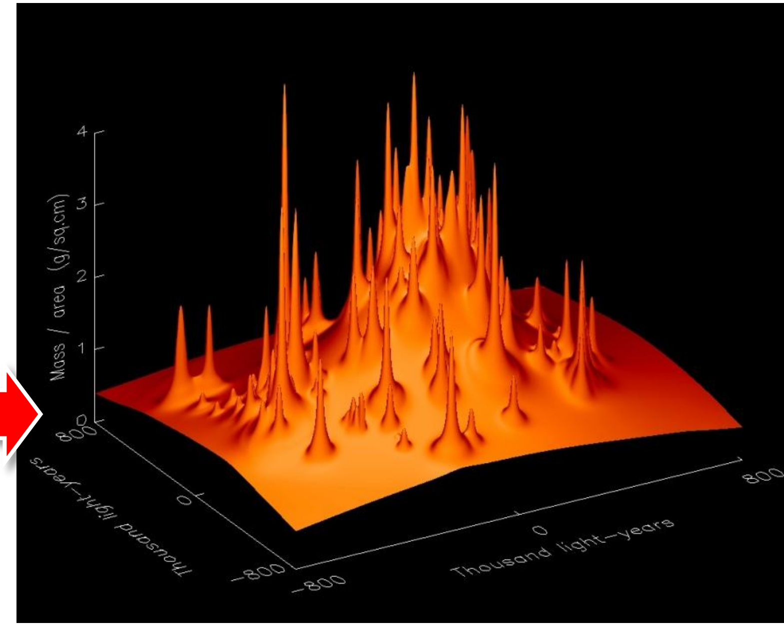


Figure from astronomynotes.com

Where is Dark Matter?

Colley et al. (HST)



Kochanski, Dell'Antonio & Tyson

- Large scales: galaxy clusters, filaments, etc.
  - Gravitational lensing, structure formation [$\Rightarrow$ DM is cold(ish)]
- Small scales
  - Galactic center: cusp vs. core?
  - Dwarf galaxies and smaller structure
  - Smooth vs. clumped? (J-factor)

Talks by:
Kaplinghat, Mack, Lewis

What is Dark Matter?

Is it…

- …astrophysical objects?

  Massive Astrophysical Compact Halo Objects (MACHOs)

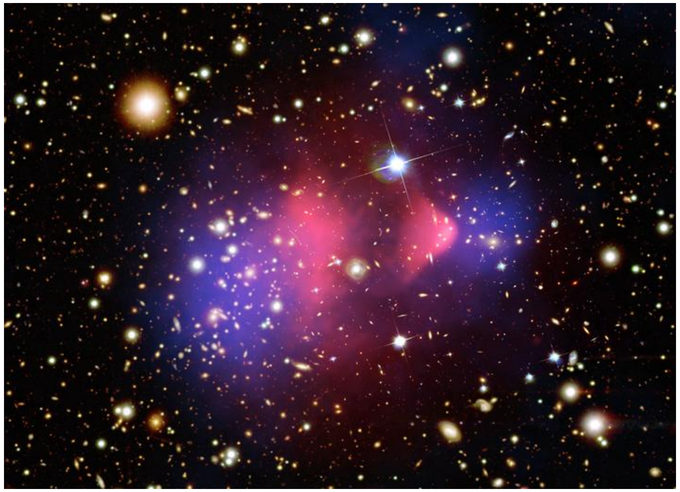
  - Microlensing searches: **not significant contribution to DM**

- …a modification to gravity?

  MOdified Newtonian Dynamics (MOND), Tensor-Vector-Scalar gravity (TeVeS)

  - Bullet cluster: **disfavored**
  - …also: poor fit to CMB & LSS

see Mould poster



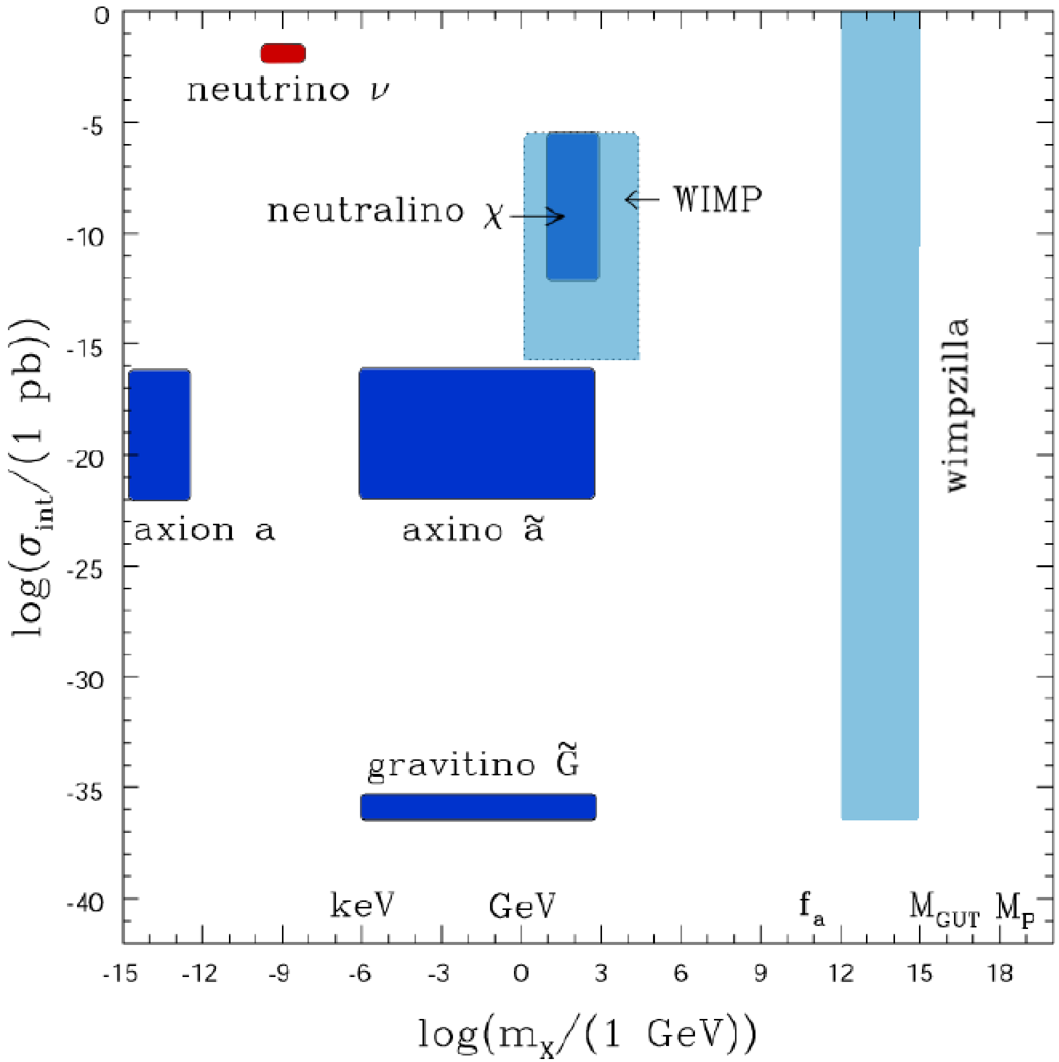
NASA/CXC/CfA/M.Markevitch et al.; NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; ESO WFI

What is Dark Matter?

...Particles!

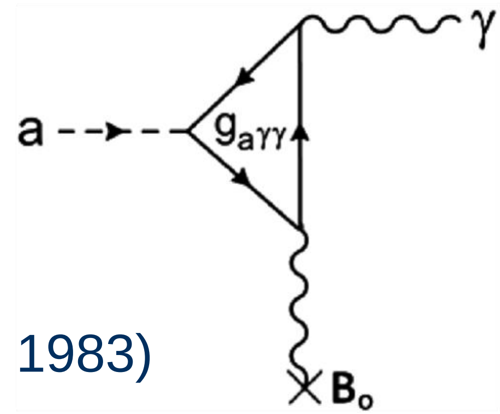
- Axions
- WIMPs
- Gravitino
- Sterile neutrinos
- WIMPzilla
- …

Roszkowski (2004)

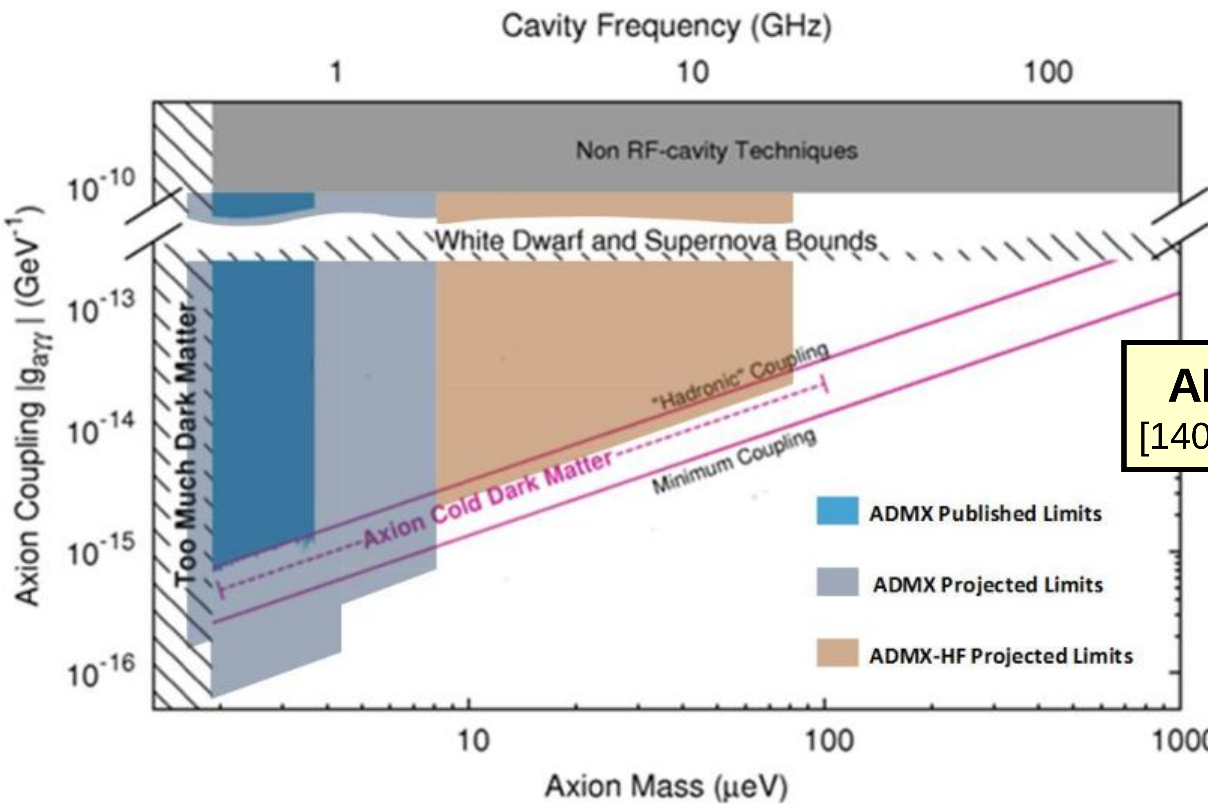


Axions

Talk by Parker

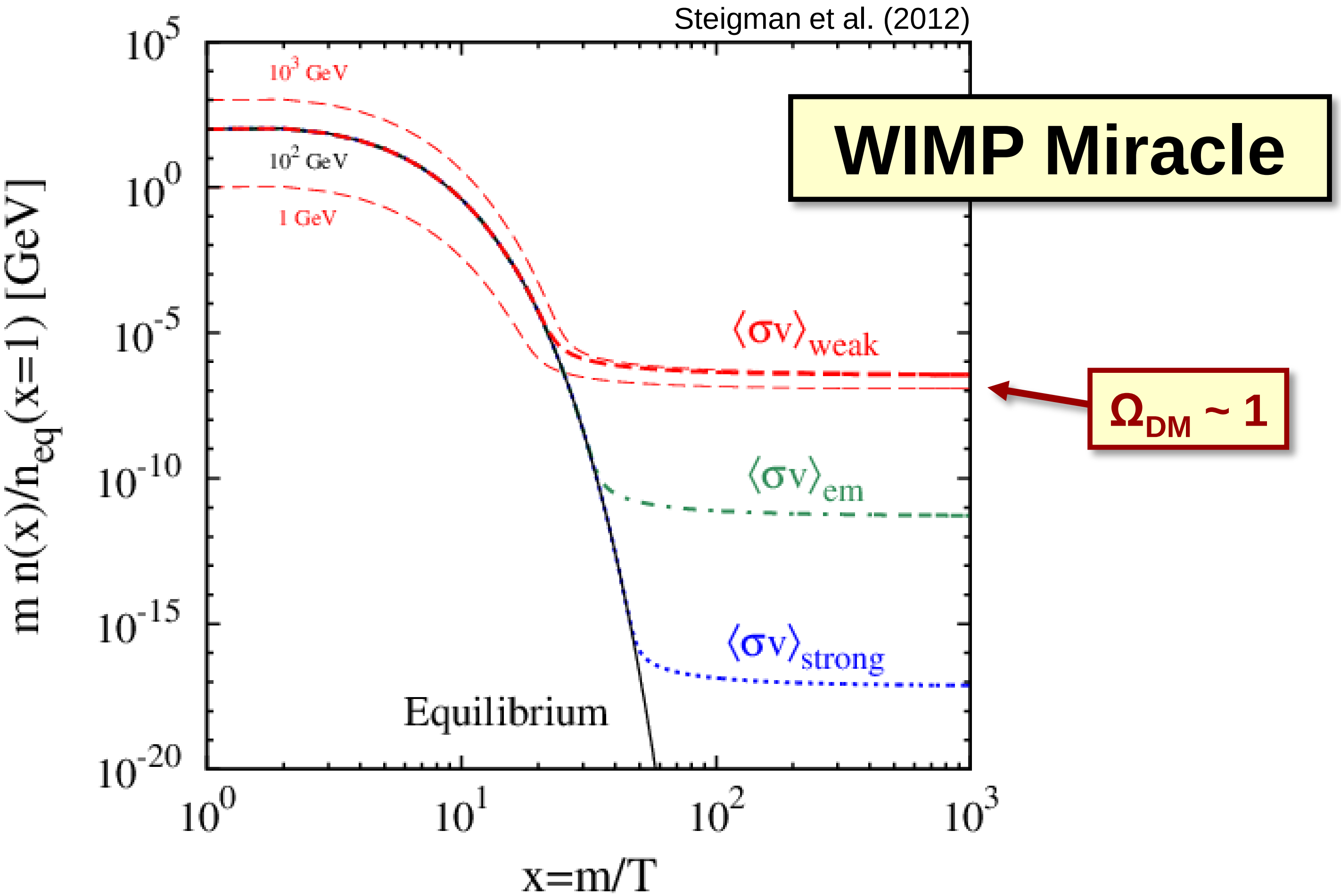


- Strong CP problem
- Axion-photon coupling
  - ⇒ inverse Primakov conversion in RF cavity (Sikivie 1983)



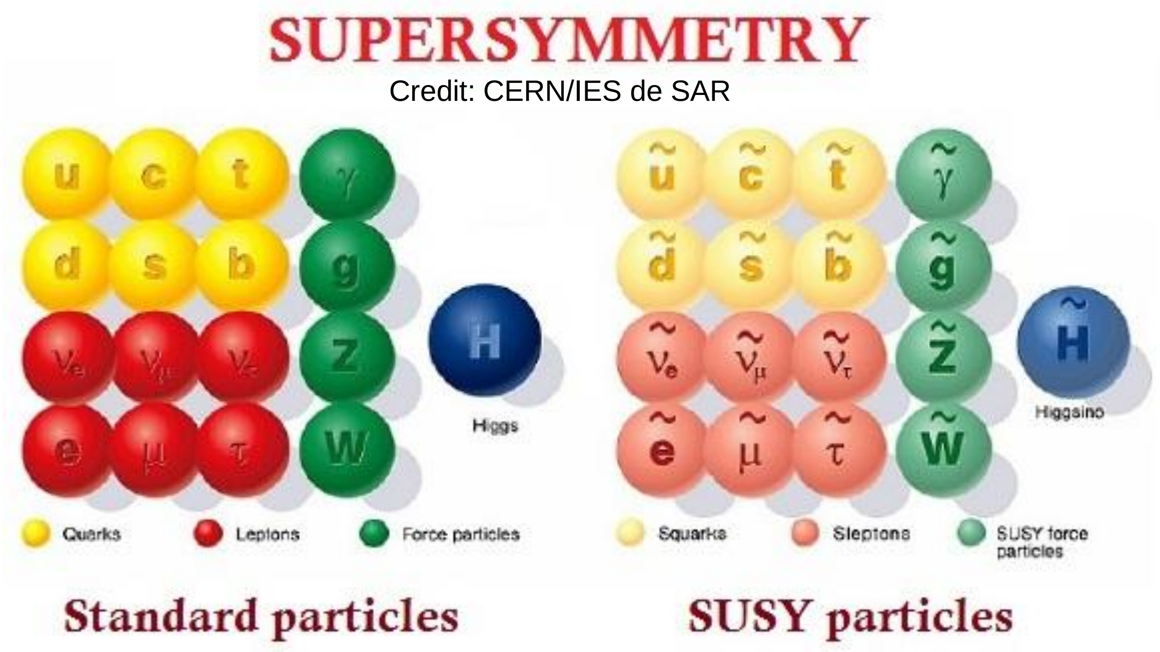
ADMX
[1403.5332]

WIMPs (Weakly Interacting Massive Particles)



WIMPs: neutralino

Often fiducial case



- Supersymmetry (SUSY) solves hierarchy problem
- Natural DM candidate:
  Neutralino as lightest supersymmetric partner (LSP)

WIMPs: non-neutralino

Many possibilities… (not mutually exclusive)

Kaluza-Klein	Kolb & Slansky (1984)
Asymmetric	Petraki & Volkas (2013) [review]
Self-interacting	Spergel & Steinhardt (1999)
Composite	(various)
Mirror/atomic	Berezhiani (2004); Foot (2014) [review] Cyr-Racine & Sigurdson (2012) [review]
Inelastic	Hall et al. (1997); Smith & Weiner (2001)
…	

Talks by Kaplinghat & Foot

Distinguish by cosmology, detection signatures….

WIMPs: generic

Effective operator approach

- See e.g. Barger et al. (2008); Beltran et al. (2008)

- Effective field theory (EFT) in heavy mediator limit
  - See e.g. Cao et al. (2009)

- Non-relativistic limit
  - Fan et al. (2010); Fitzpatrick et al. (2012)

$$\bar{\chi}\chi\bar{N}N$$
$$i\bar{\chi}\chi\bar{N}\gamma^5 N$$
$$i\bar{\chi}\gamma^5\chi\bar{N}N$$
$$\bar{\chi}\gamma^5\chi\bar{N}\gamma^5 N$$
$$P^\mu\bar{\chi}\chi K_\mu\bar{N}N$$
$$P^\mu\bar{\chi}\chi\bar{N}i\sigma_{\mu\alpha}q^\alpha N$$
$$P^\mu\bar{\chi}\chi\bar{N}\gamma_\mu\gamma^5 N$$
$$iP^\mu\bar{\chi}\chi K_\mu\bar{N}\gamma^5 N$$
$$\bar{\chi}i\sigma^{\mu\nu}q_\nu\chi K_\mu\bar{N}N$$
$$\bar{\chi}i\sigma^{\mu\nu}q_\nu\chi\bar{N}i\sigma_{\mu\alpha}q^\alpha N$$
$$\bar{\chi}i\sigma^{\mu\nu}q_\nu\chi\bar{N}\gamma^\mu\gamma^5 N$$
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$$\bar{\chi}\gamma^\mu\gamma^5\chi K_\mu\bar{N}N$$
$$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}q^\alpha N$$
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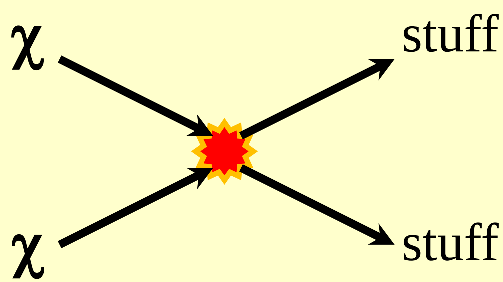
$$iP^\mu\bar{\chi}\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}q^\alpha N$$
$$iP^\mu\bar{\chi}\gamma^5\chi\bar{N}\gamma_\mu\gamma^5 N$$
$$P^\mu\bar{\chi}\gamma^5\chi K_\mu\bar{N}\gamma^5 N$$

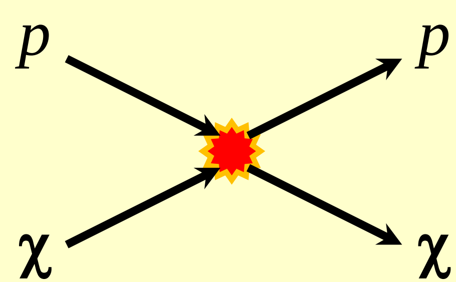
Fitzpatrick et al. (2012)

WIMPs: detection

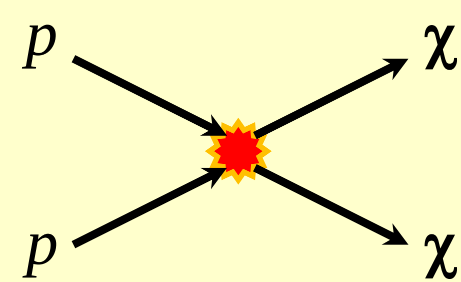
Interactions with Standard Model particles



Annihilation



Scattering



Production

Indirect Detection:
Halo (cosmic-rays),
capture in Sun (ν's)

Direct Detection:
Look for scattering
events in detector

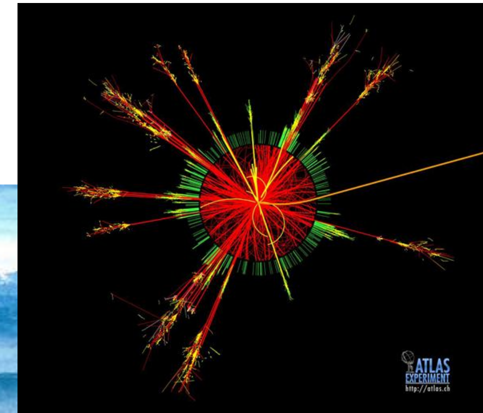
Accelerators:
LHC

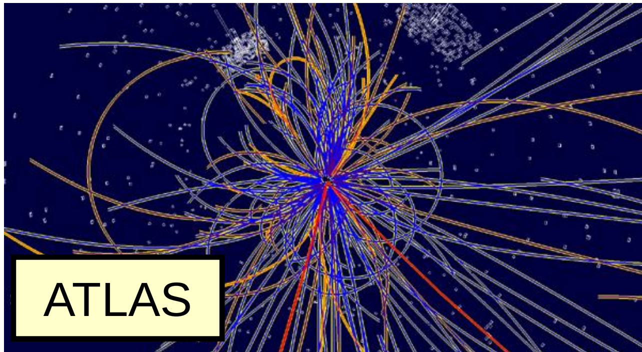
Detecting WIMP Dark Matter

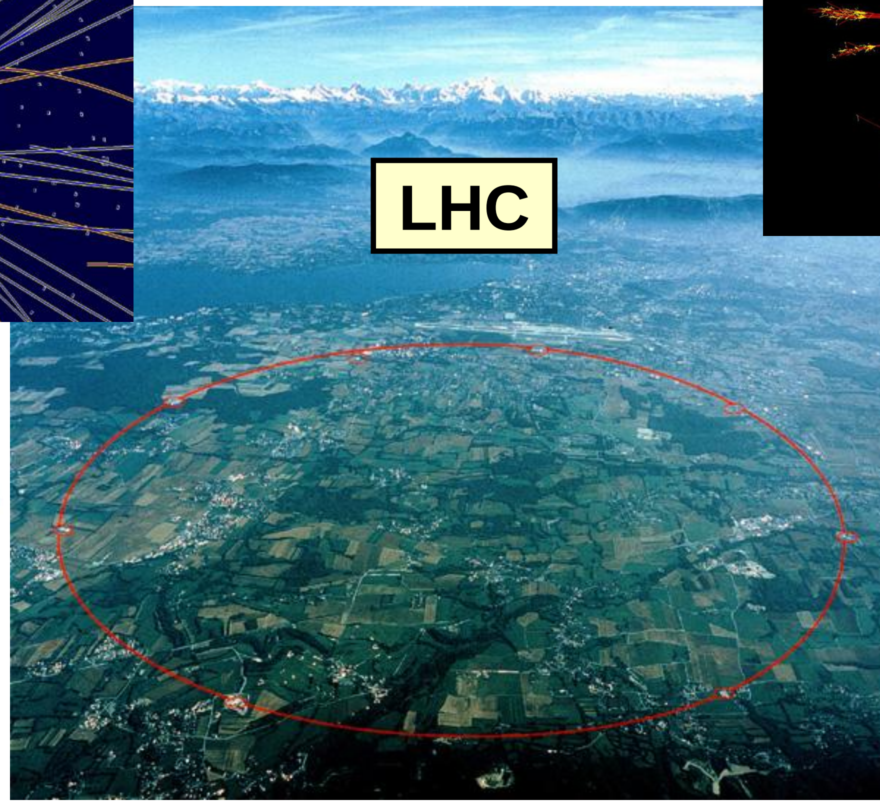
Colliders

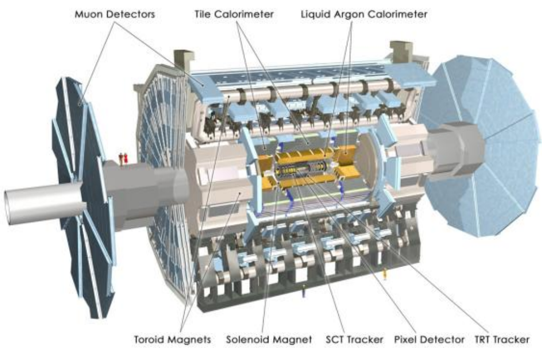
Collider DM searches

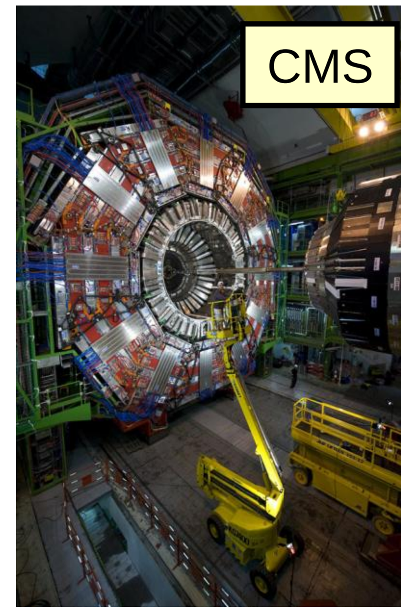
Talk by Bell







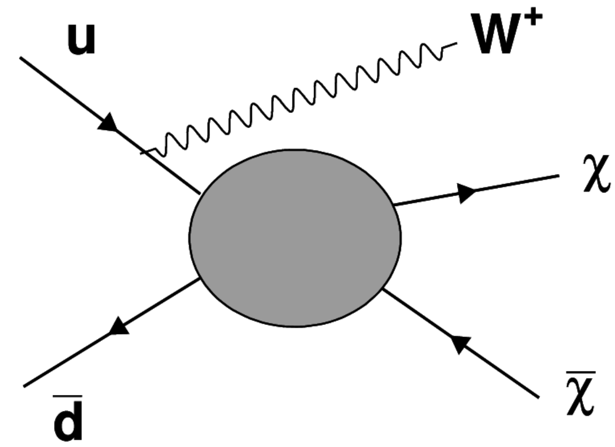




Signature: missing energy

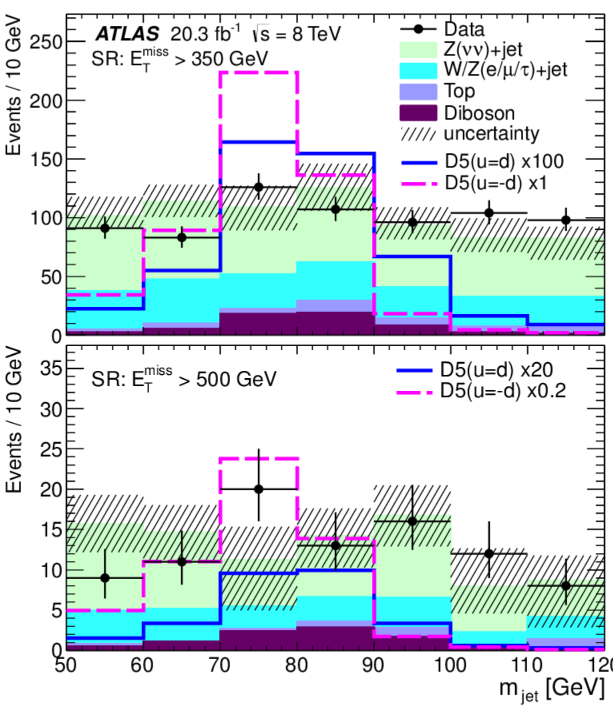
Many possible channels, mostly very model dependent
…but: mono-jets, mono-photons, mono-Z [Bell et al. (2012)],…

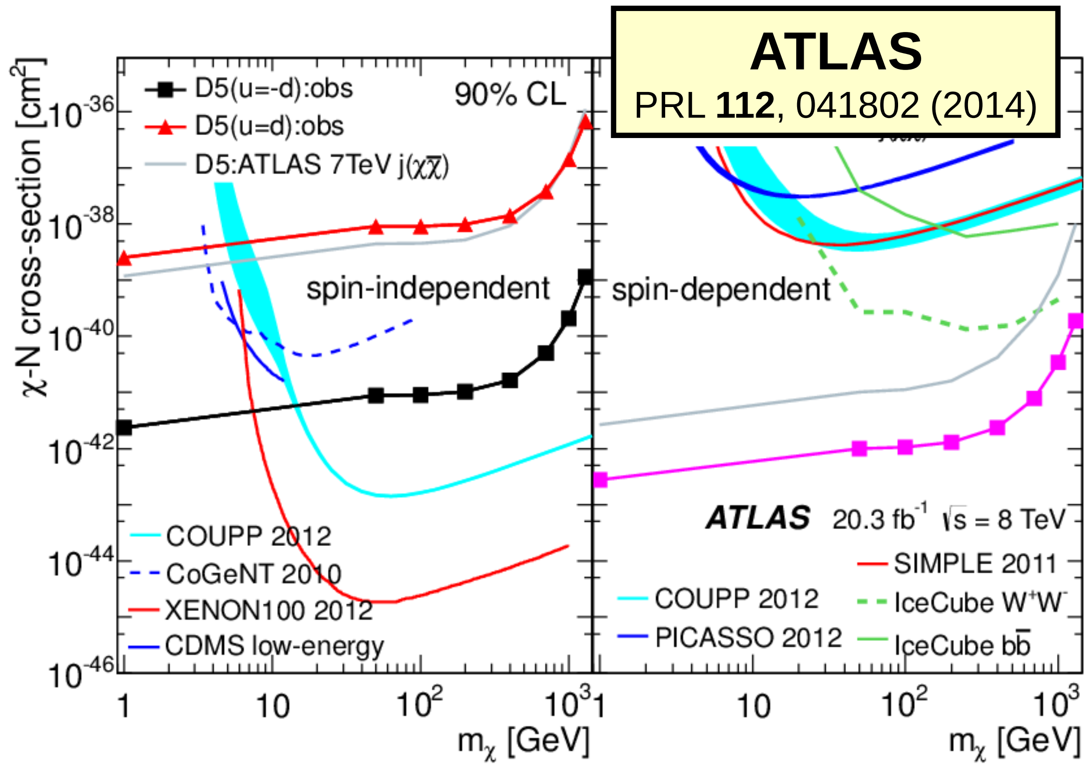
LHC: monojets



Signature: single jet
+ missing energy

See also Han, Kobakhidze, Liu, Saavedra, Wu & Yang (2014)





Issues

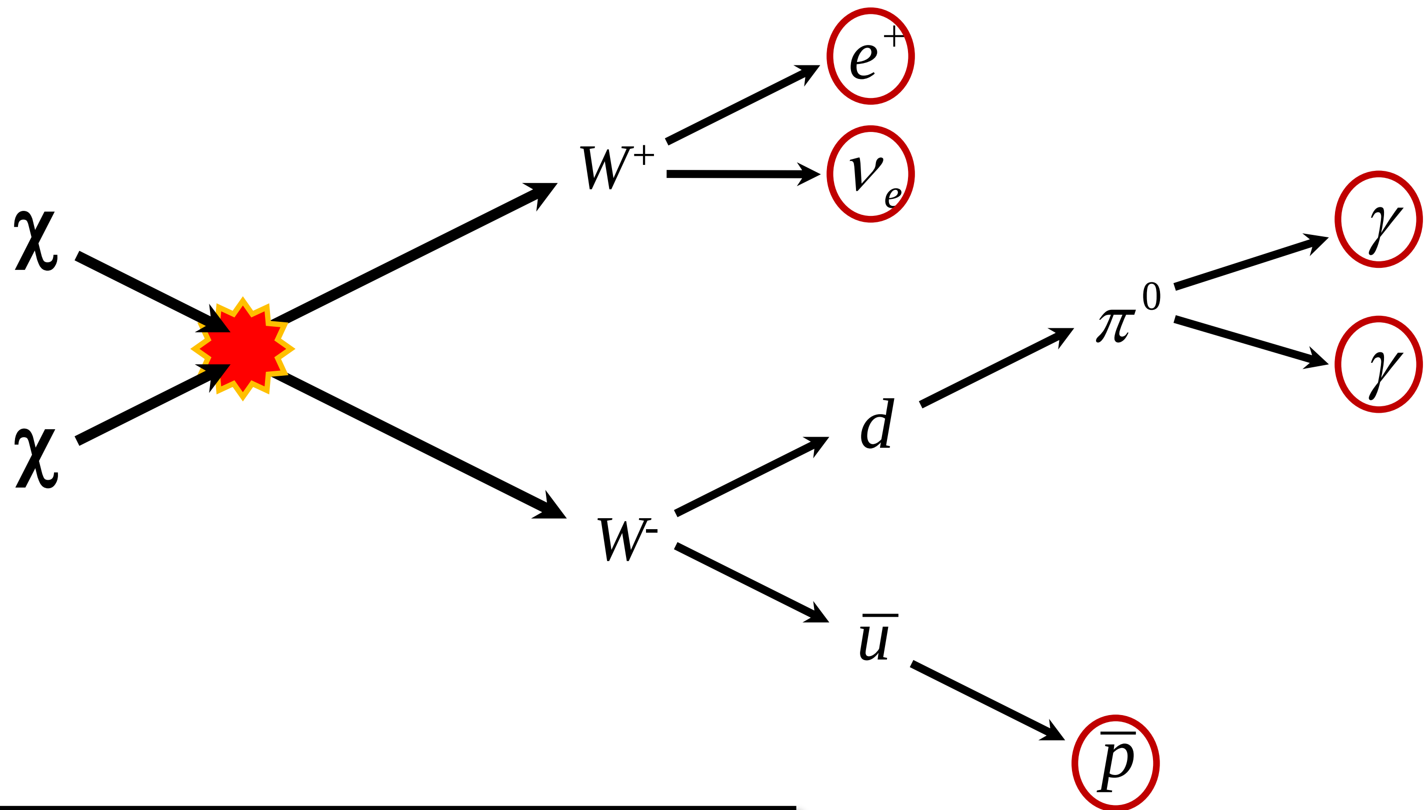
- Backgrounds

- Identifying dark matter particle
  - Distinguishing stable from semi-stable ($\tau > \mu s$)
  - Hadron collider $\Rightarrow$ strong interactions dominate
    …dark matter particle color & EM neutral

- Connecting to other DM searches
  - Relativistic vs. non-relativistic interactions
    $\Rightarrow$ model-dependent comparisons

Indirect Detection

WIMP annihilation

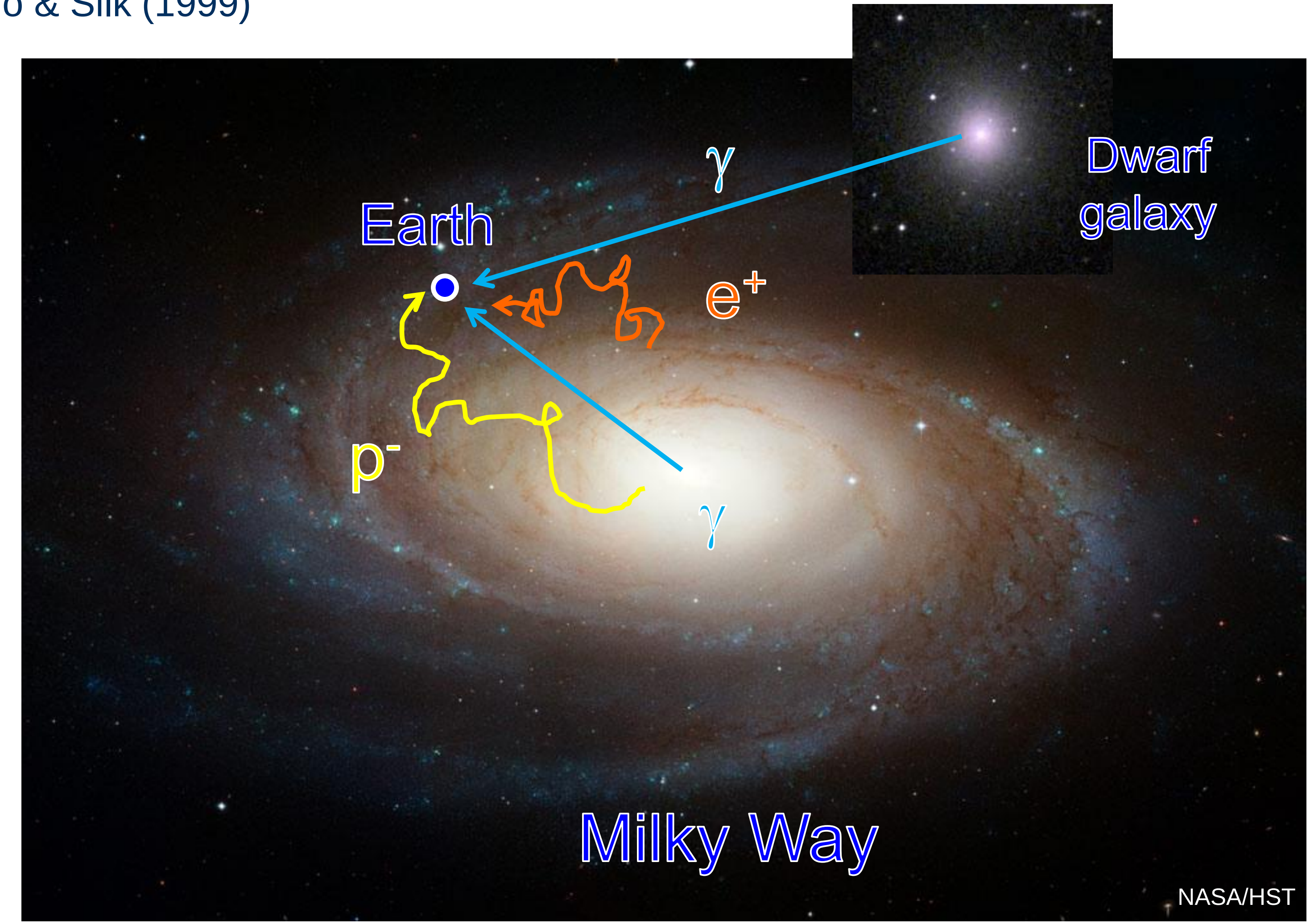


O(GeV) Standard Model particles

Galactic halo: cosmic rays

Talk by Rowell (HESS)

Silk & Srednicki (1984); Ellis et al. (1988)
Gondolo & Silk (1999)



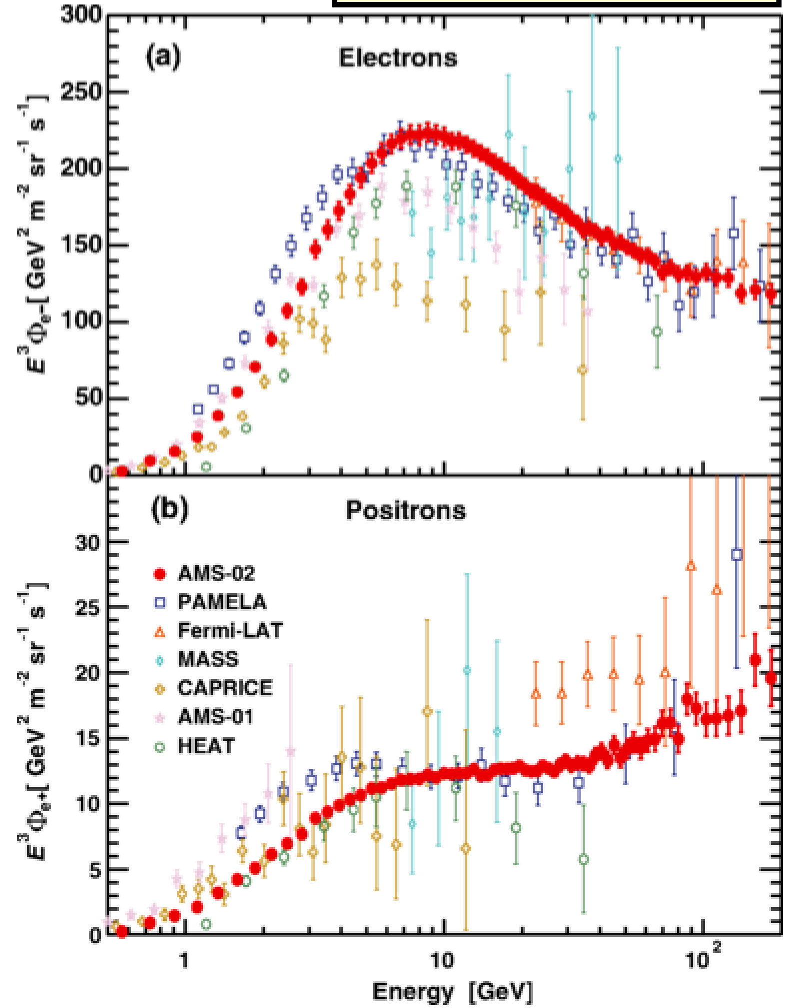
AMS, CTA, Fermi/LAT, HESS, …

Positron excess

HEAT, PAMELA, Fermi/LAT, AMS-02: excess positrons?

- Supernova: accelerate ISM electrons
- DM: e+ & e-
- Can pulsars account for excess? (e+ & e-)
  - See e.g. Delahaye et al. (2014)

AMS-02
PRL **113**, 121102 (2014)



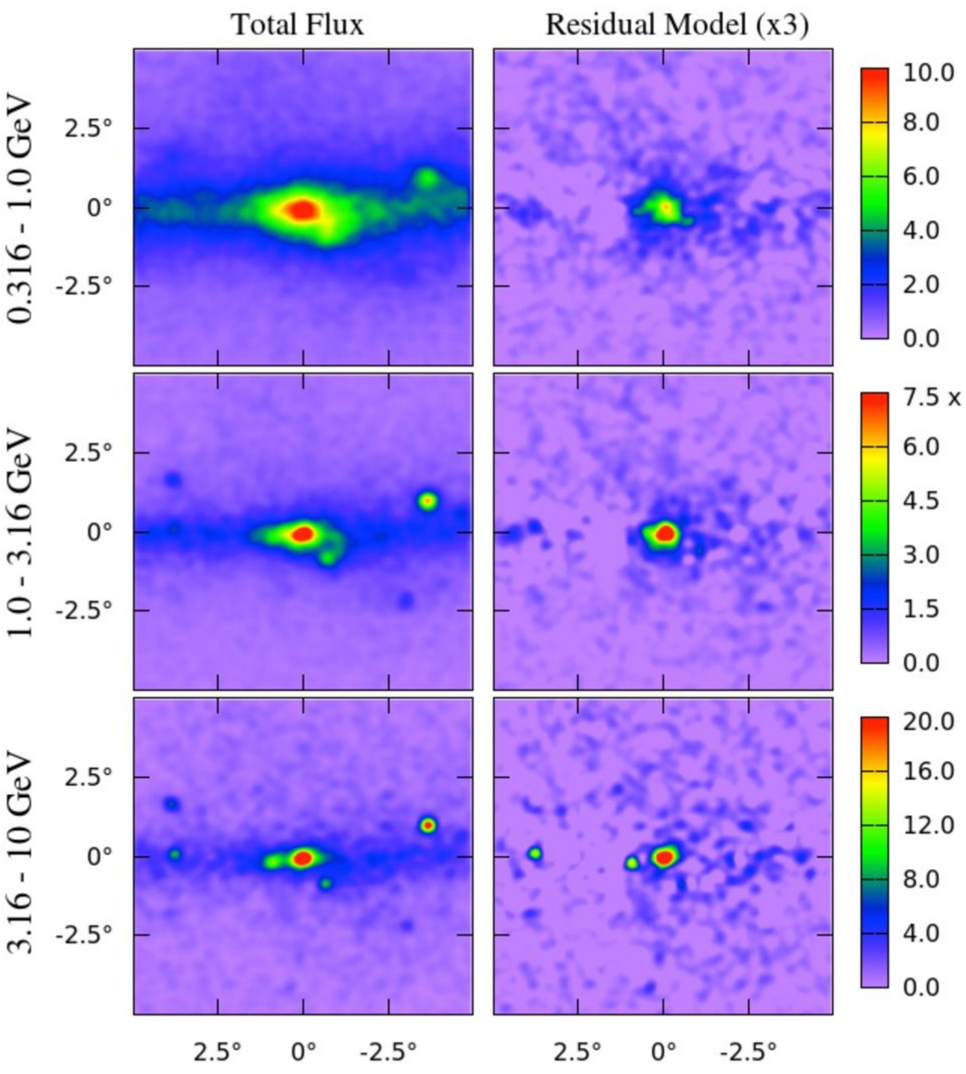
Fermi/LAT gamma-ray excess

Goodenough & Hooper (2009)

Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer (2014)

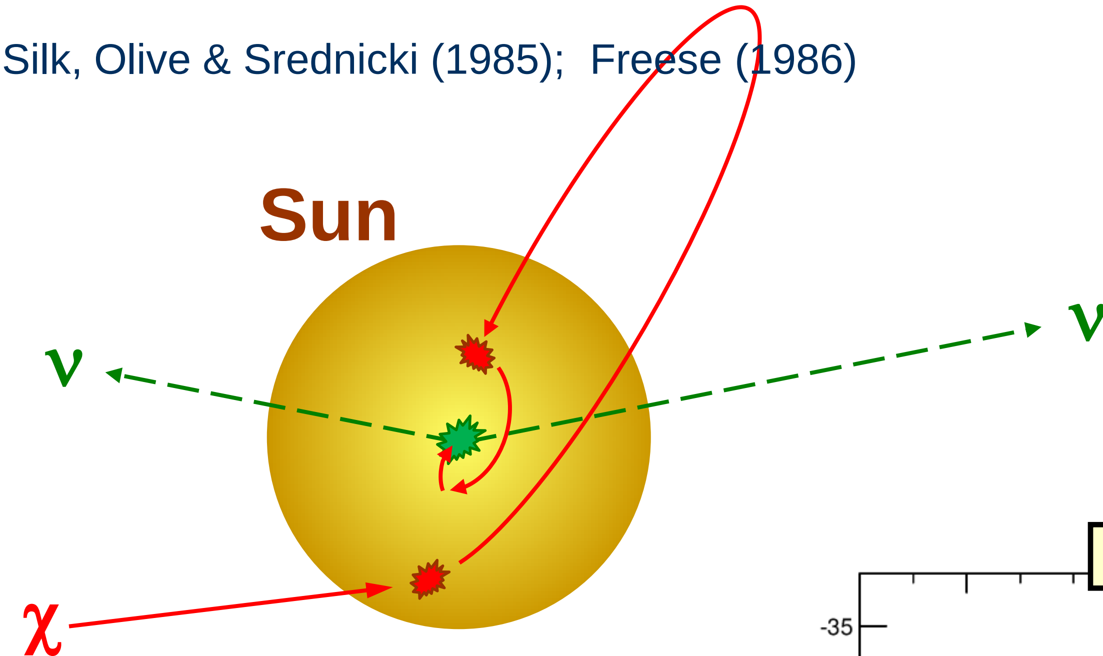
Towards galactic center:

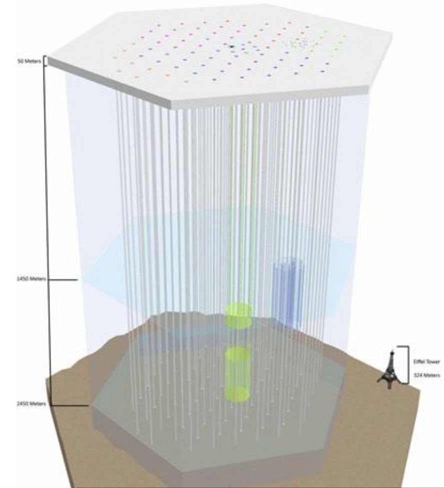
- Model and subtract astrophysical sources
- Excess remains
- Spectrum consistent with DM (30 GeV, $\chi\chi \rightarrow$ b-bbar)



Neutrinos

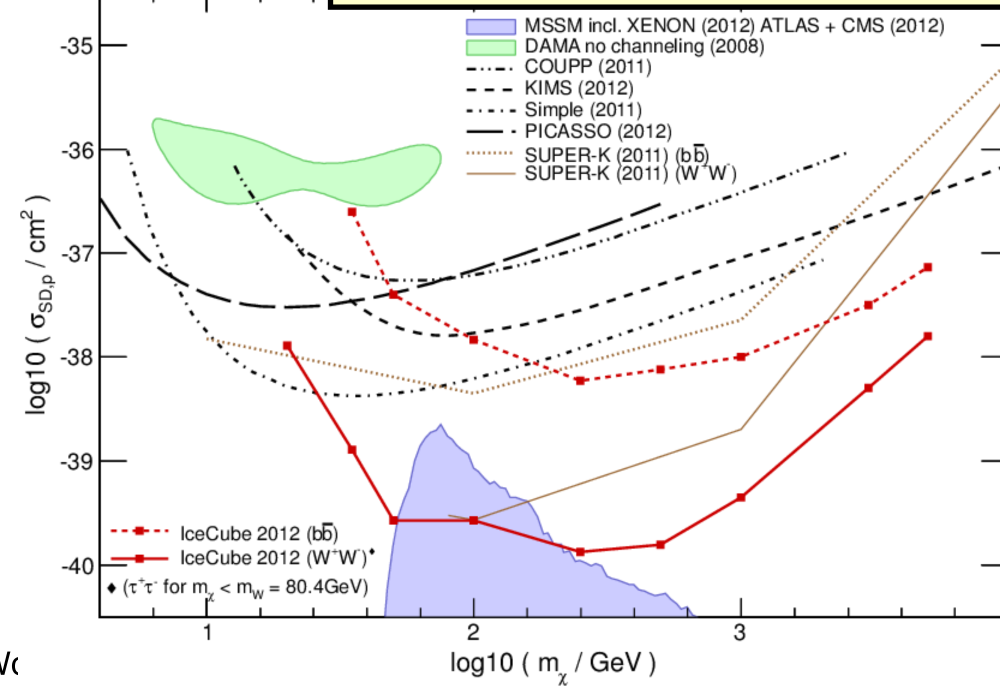
Silk, Olive & Srednicki (1985); Freese (1986)





IceCube/DeepCore
PRL **110**, 131302 (2013)

See also Scott, CS, Edsjö et al. [IceCube] (2012)



AMANDA, ANTARES, IceCube/DeepCore, …

Talk by Hill (IceCube)

Indirect detection

- Other cosmic-ray searches
  - Anti-protons, anti-deuterons,…
  - Spatial: diffuse, point sources, dwarf galaxies, galactic center,…
    e.g. Fermi/LAT dwarf galaxy analysis [Ackerman et al. (2013)]
  - Features in spectrum
    e.g. Fermi/LAT γ-ray line at 130 GeV [Weniger (2012)]

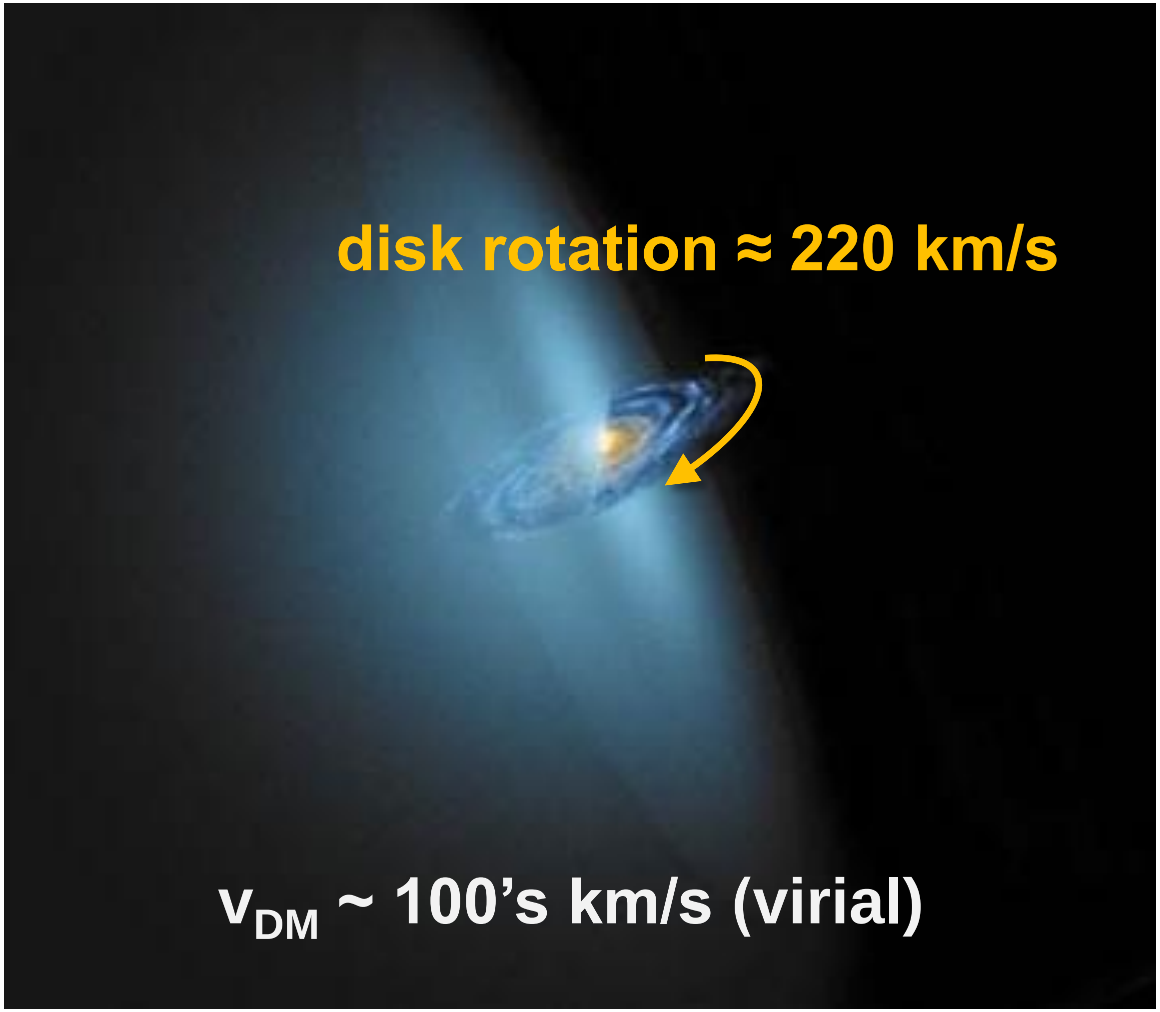
- Modified stellar evolution
  - Anomalous chemical abundances — Monreal et al. (2007)
  - WIMP burners — Salati & Silk (1989)
  - Dark stars — Spolyar, Freese & Gondolo (2008)

- Issues
  - Astrophysical backgrounds
  - Halo modeling and dark matter distribution

Direct Detection

Dark Matter Halo

D. Dixon, cosmographica.com



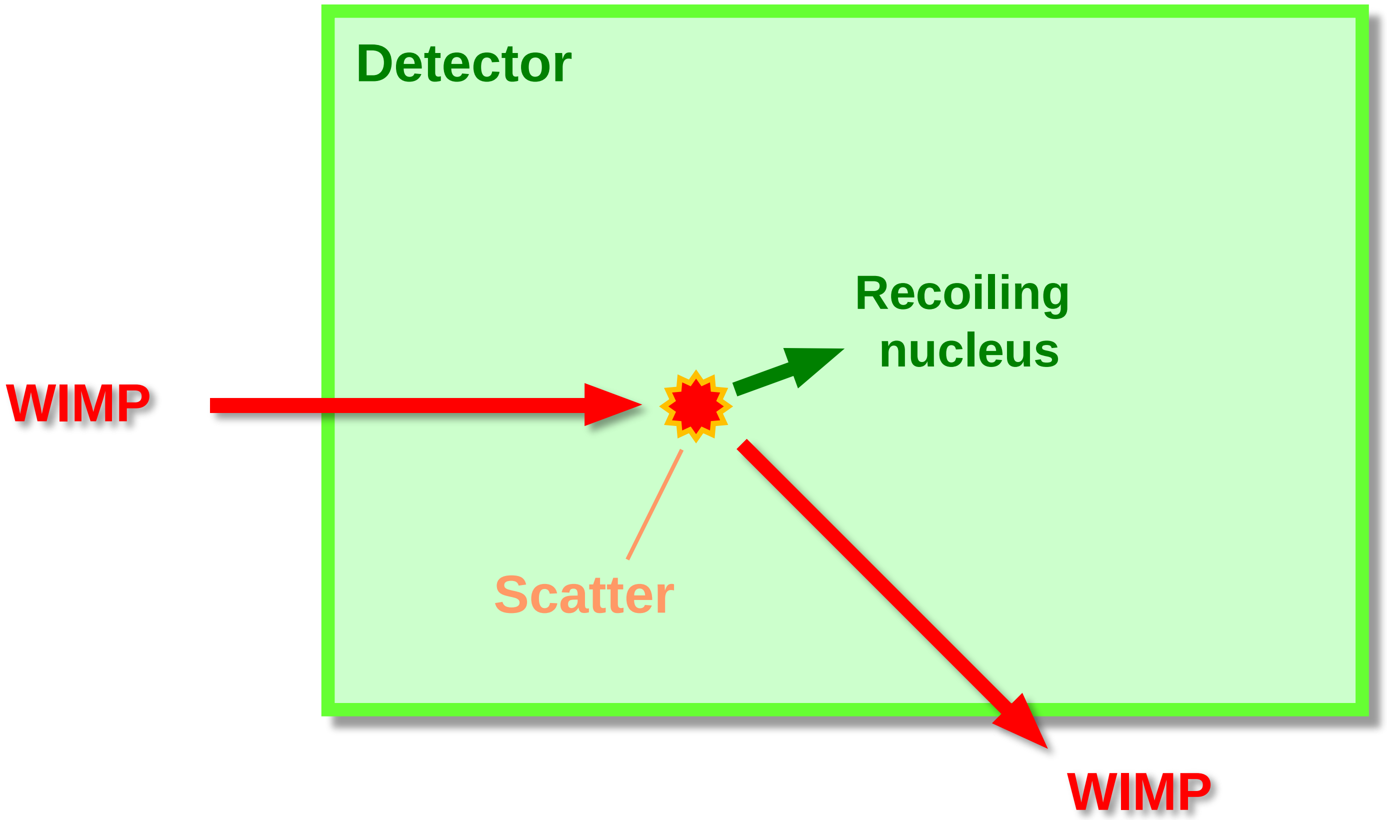
Direct Detection

Goodman & Witten (1985)

See Freese, Lisanti & CS (2012) for a review

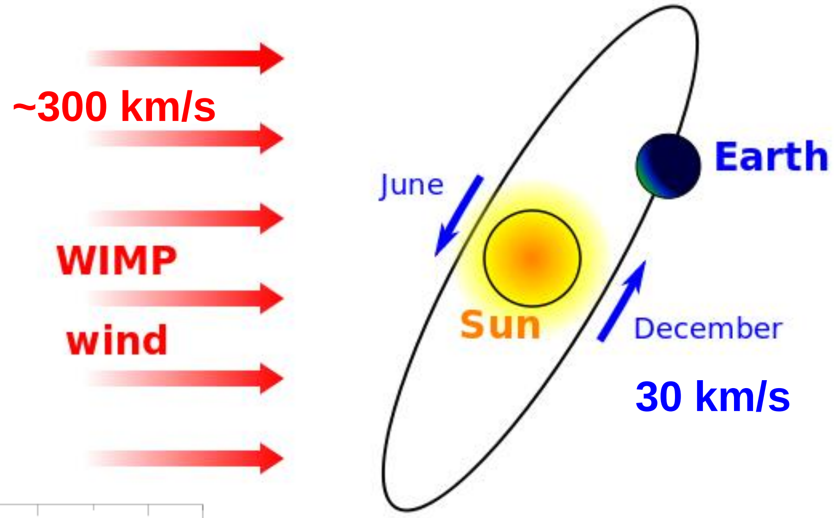
Review talk by Masiero

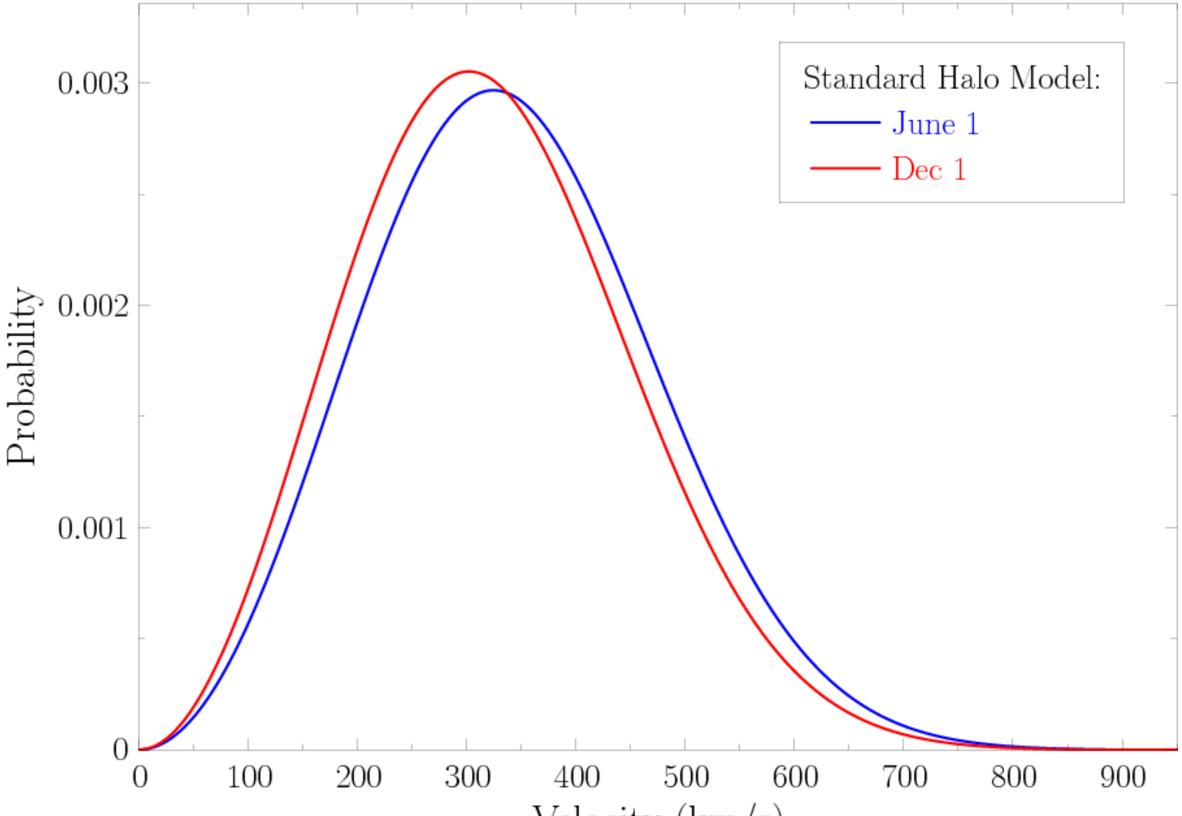
- Non-relativistic: elastic scattering of WIMP off detector nuclei → O(10 keV) recoil



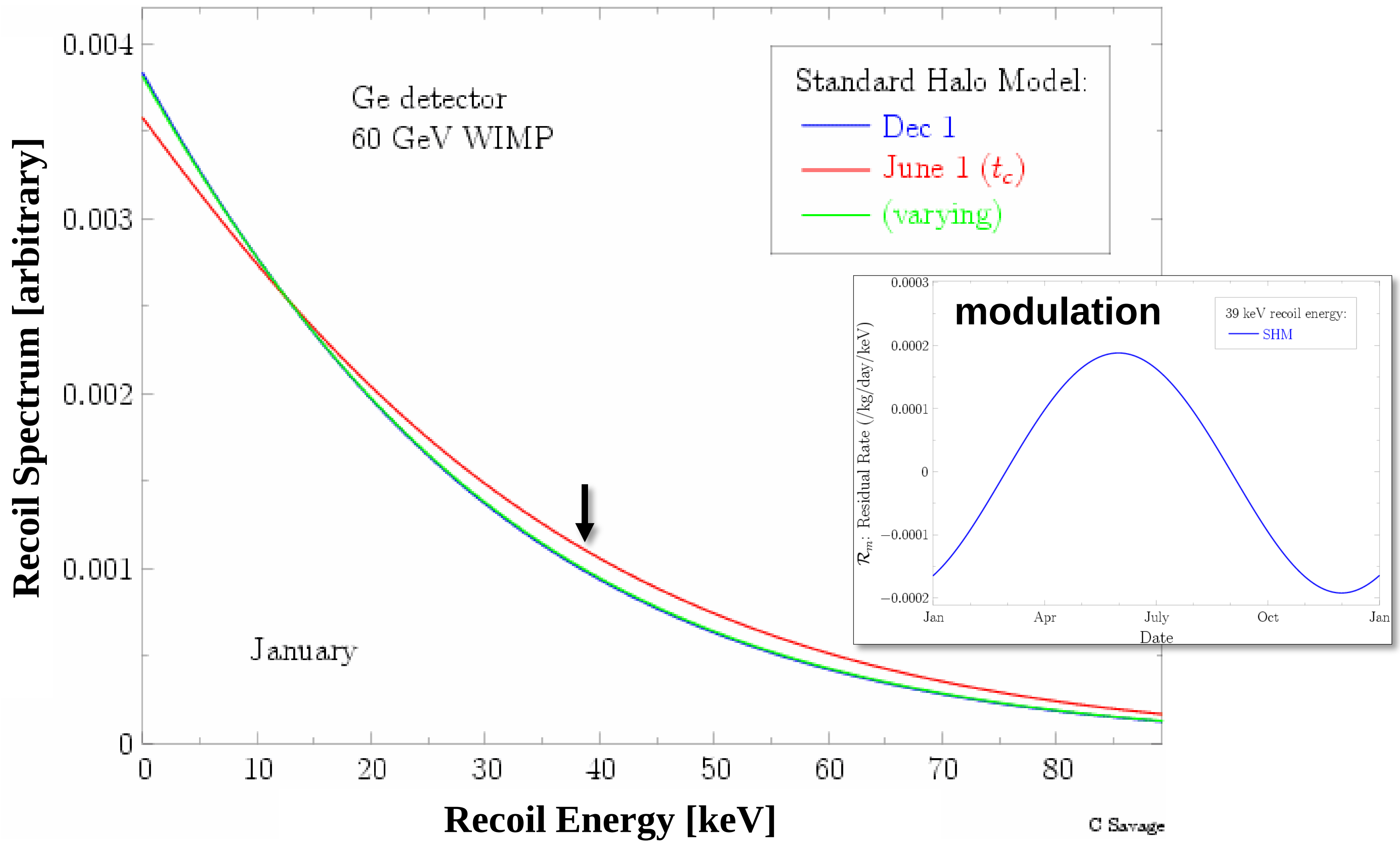
Annual Modulation

Drukier, Freese & Spergel (1986)





Recoil Spectrum



Experiments

Difficulties

- Low energies $\Rightarrow$ very sensitive detectors
- Backgrounds $\Rightarrow$ material selection/screening (radioactive contaminants), deep underground (cosmic rays)

Tomei & Barberio/Volpi

- Counting: CDMS, CoGeNT, COUPP, CRESST, DM-Ice, LUX, SABRE, XENON,…

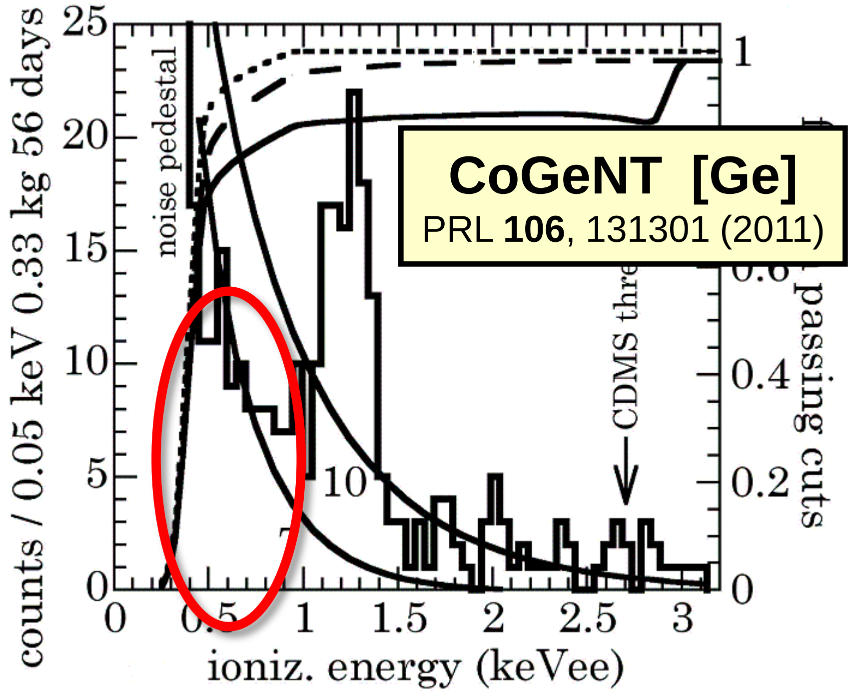
Ragazzi (Gran Sasso), D'Angelo (SABRE)

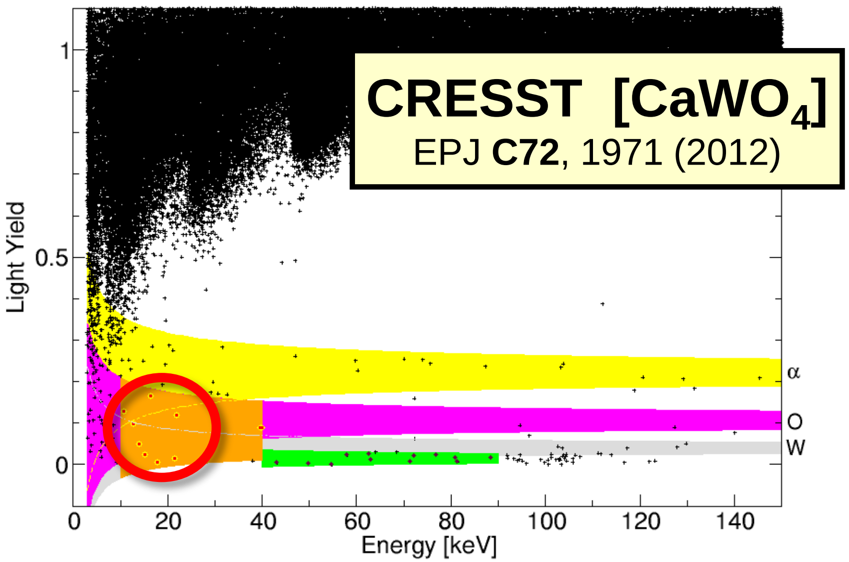
- Modulation: DAMA [+CoGeNT and above]

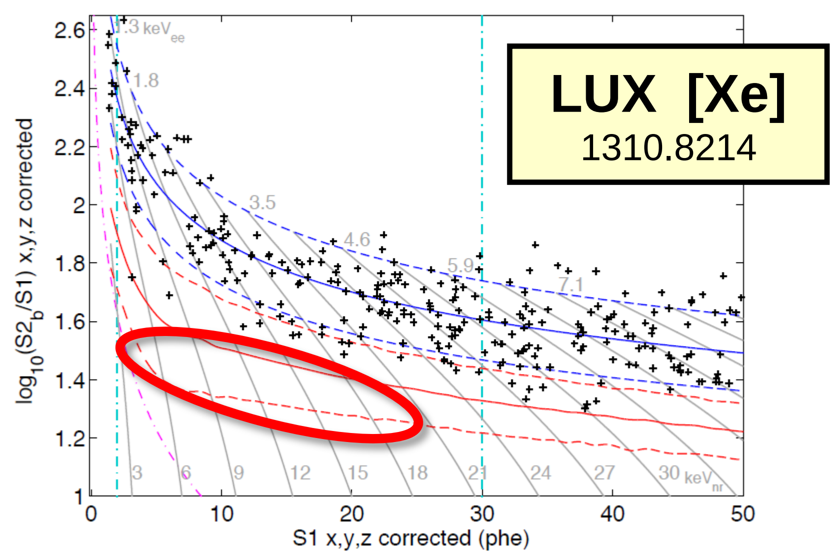
Foot

Experimental Results

- Potential signal:
  CDMS (Si), CoGeNT, CRESST, DAMA
- No signal:
  CDMS (Ge), LUX,...

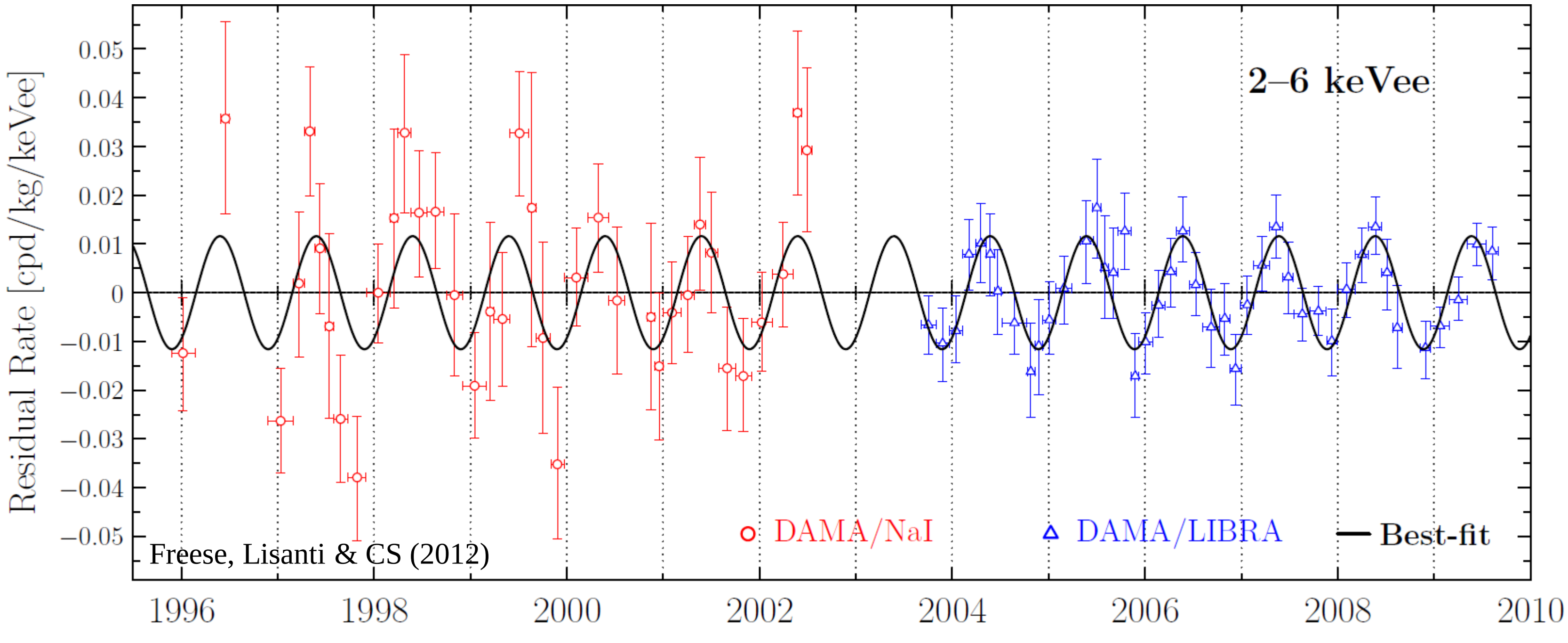






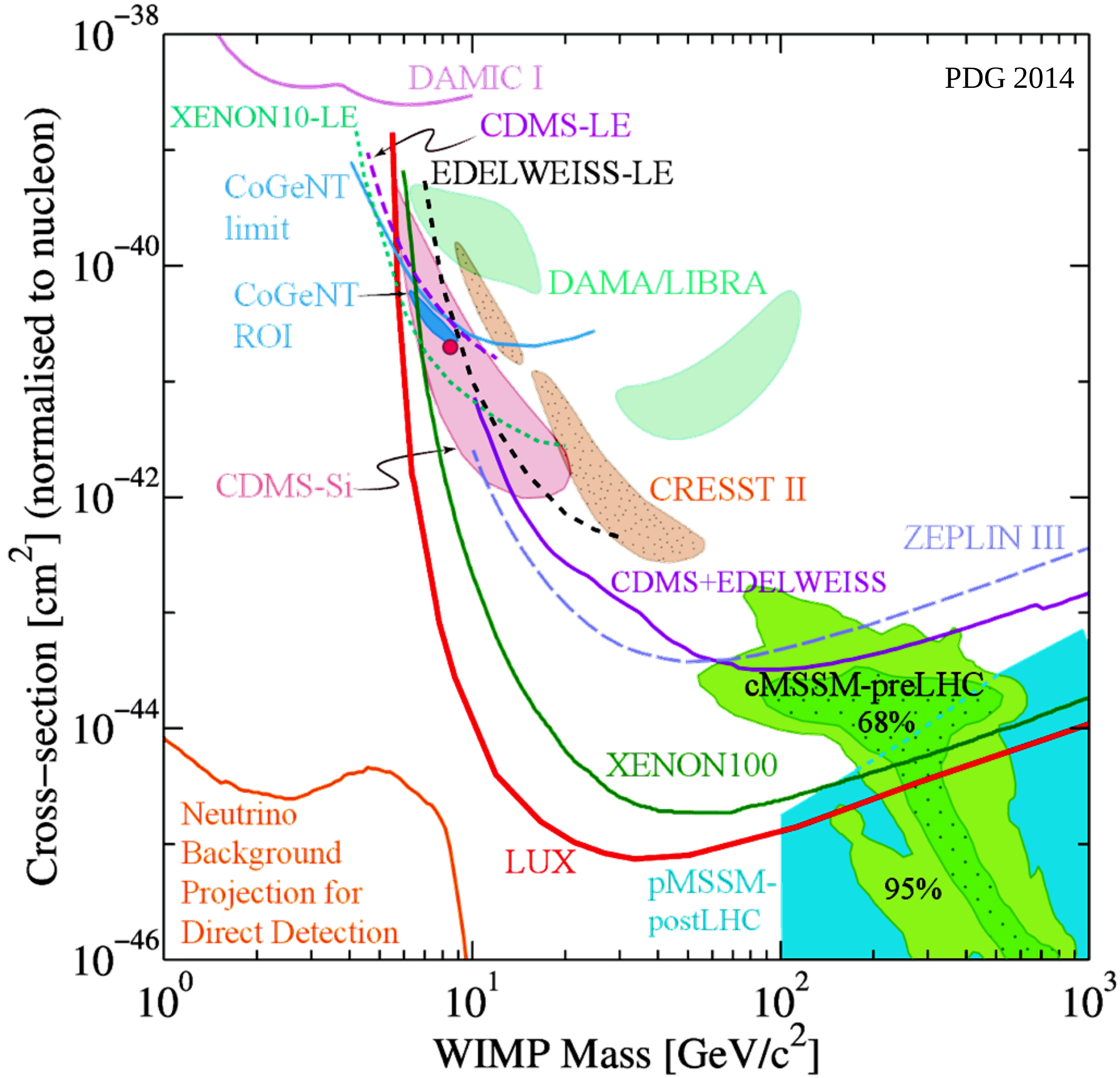
DAMA Results

- Modulation search using NaI crystals (scintillation only)
  - DAMA/NaI: 1996-2002 — R. Bernabei *et al.*, Riv. Nuovo Cim. **26N1**, 1 (2003)
  - DAMA/LIBRA: 2003-2009 — R. Bernabei *et al.*, Eur. Phys. J. **C67**, 039 (2010)



8.9σ annual modulation

Experimental Results



Direct Detection: Issues

Assumptions: neutralino-like w/ scalar interaction,
Standard Halo Model,…

Issues affecting interpretation of results:

- Particle physics (interactions)
- Astrophysical uncertainties (halo)
- Poorly understood/unknown backgrounds
- Statistical analysis
- Detector energy calibrations
- Theoretical issues

  e.g. nuclear physics [Underwood, Giedt, Thomas & Young (2012)]

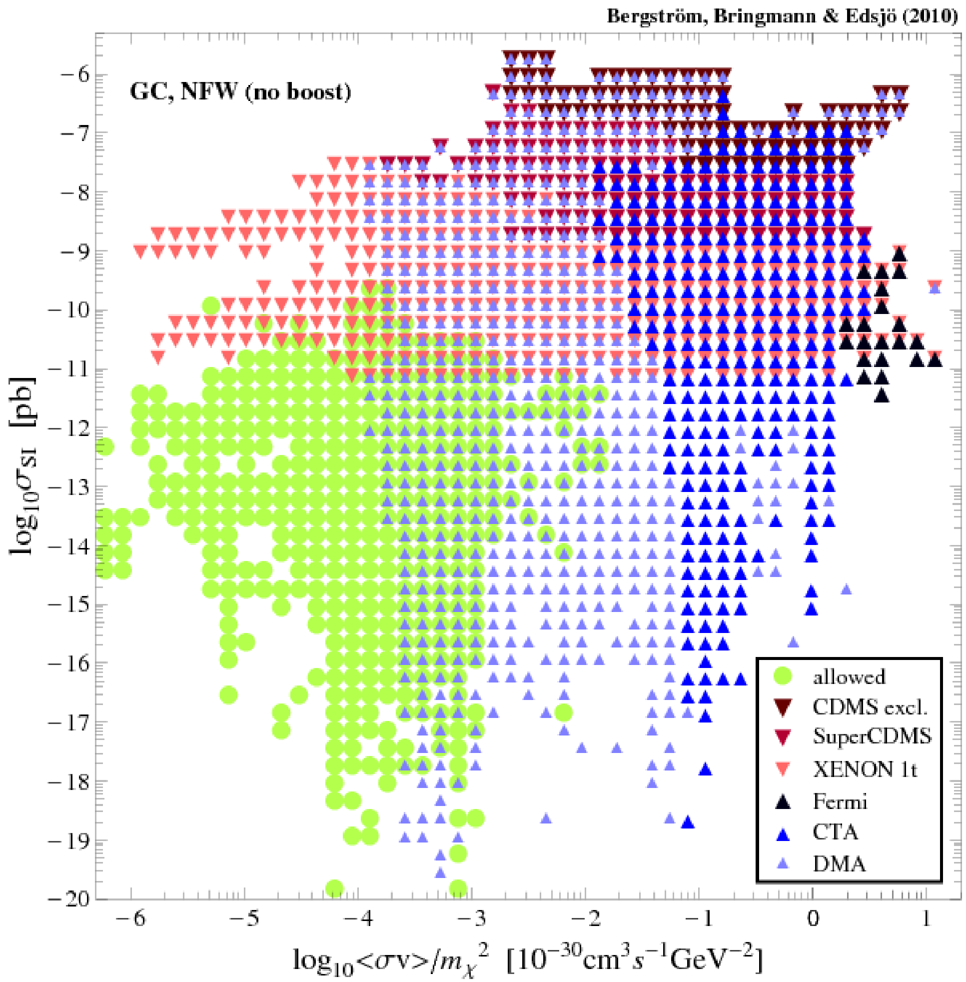
Putting it all together…

Complementarity

Combine direct, indirect, accelerator searches

Direct Detection vs. γ-rays
MSSM, mSUGRA
Bergström, Bringmann & Edsjö (2010)

SI cross-section
vs.
annihilation cross-section



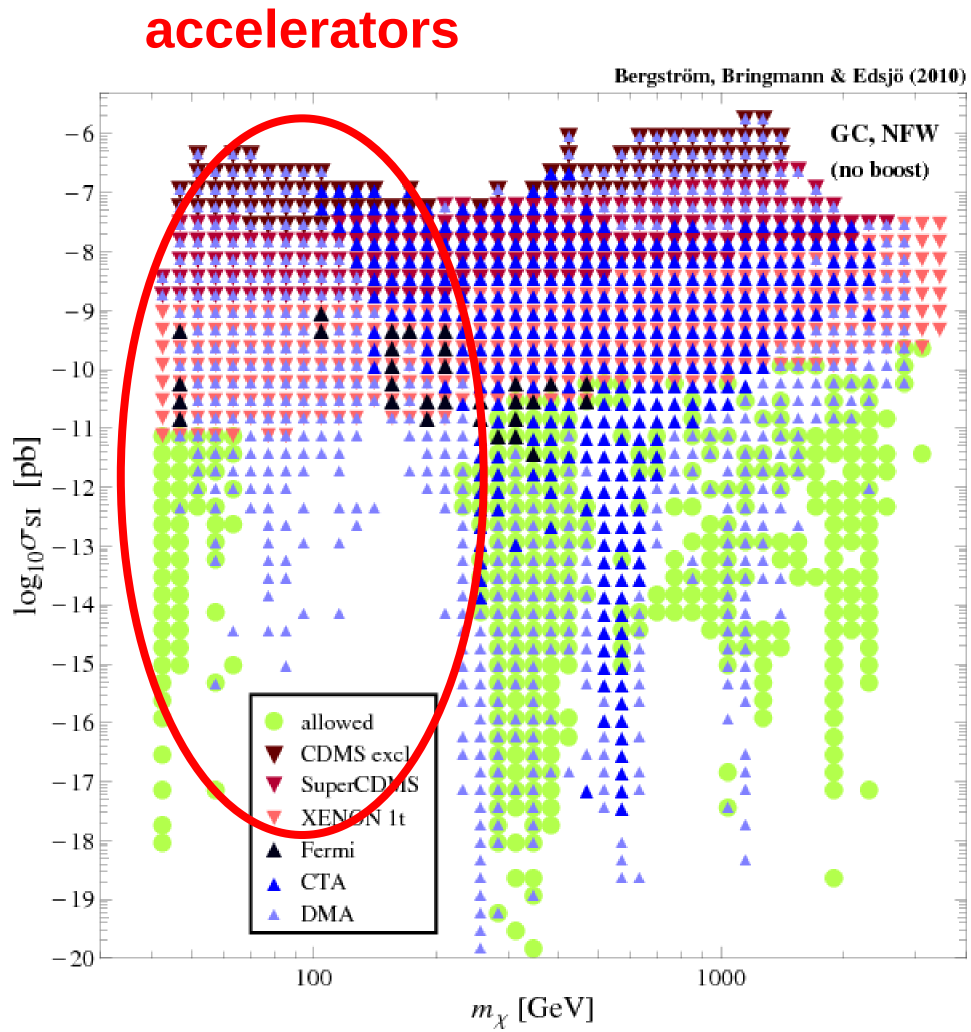
See Trotta *et al.*, JHEP **0812**:024 (2008)

Complementarity

Combine direct, indirect,
accelerator searches

Direct Detection vs. γ-rays
MSSM, mSUGRA
Bergström, Bringmann & Edsjö (2010)

SI cross-section
vs.
neutralino mass



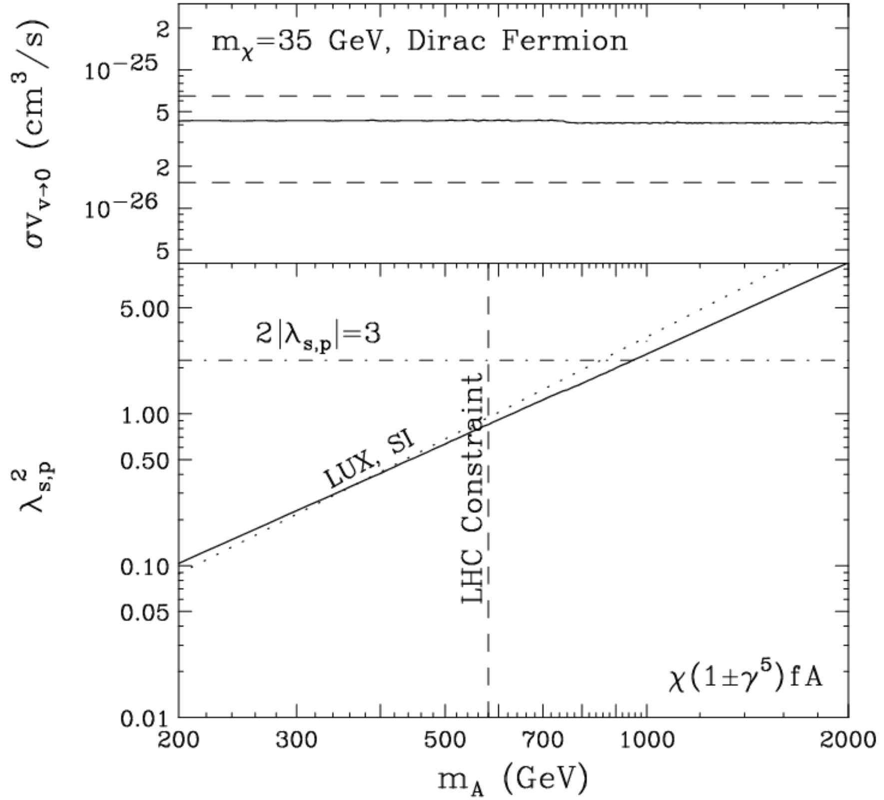
See Trotta *et al.*, JHEP **0812**:024 (2008)

Example:
Simplified DM models for Fermi excess

Berlin, Hooper & McDermott (2014)

- Identify effective interactions that can produce Fermi/LAT γ-ray excess

- Use direct detection & colliders to identify best interactions



Repeated by Balázs & Li (2014):
relaxed assumptions, Bayesian analysis
$\Rightarrow$ Majorana fermion preferred

Future, Thoughts, and Perspectives

Future Experiments

Colliders

- LHC: 14 TeV (2015), high-luminosity upgrade (2025?)
- Linear collider?

- Indirect
  - CALET (e^+e^-, 2014), CTA (2020), …
  - IceCube PINGU: infill of existing volume

- Direct
  - Running: DAMA upgrades (lower threshold)
  - Construction: SuperCDMS, XENON1T,… (+ many others)
  - Future: LUX-ZEPLIN [LZ], XENONnT, DARWIN,…
    [Australian NaI experiment?]

Future of U.S. funding (2014)

Particle Physics Project Prioritization Panel (P5) report: recommended strategy for funding over next 10+ years

- LHC high-luminosity upgrade
- Involvement in Japan-hosted linear collider
- LSST, DESI, neutrino beams, …
- *Increased funding for direct detection experiments*

- NSF/DOE direct detection 2nd generation selection: ADMX-gen2[*axions], LZ (LUX-Zeplin), SuperCDMS
  - Current experiments to continue (e.g. XENON1T)
  - Main implication: no U.S. involvement for XENONnT
  - Additional funding could open up in future (e.g. COUPP-500)

Supersymmetry

- No signal in LHC: is it dead?
  - Mass scales pushed higher
  - Strong constraints on CMSSM
  - Less-constrained MSSM frameworks, beyond MSSM: still fine

    e.g. Non-Universal Higgs Model

    e.g. Baer et al. (2005); Ellis, Olive & Sandick (2008)
  - …but even CMSSM still survives?

    Allanach et al. (2013); Buchmueller et al. (2013)

- LHC 14 TeV run: will it kill SUSY?

- What are alternatives and when will we start focusing on them?

Evaluating potential signals

- Positron excess & Fermi/LAT γ-ray excess
  …just astrophysical backgrounds (e.g. pulsars)?
  - Need improved understanding of backgrounds
  - Need more and higher precision measurements

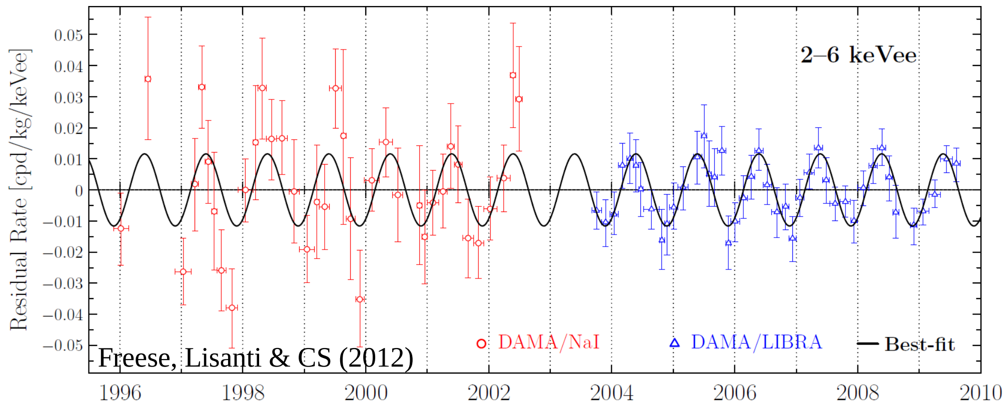
- Direct detection
  - CoGeNT — surface events? [Davis, McCabe & Boehm (2014)]
  - CRESST — lead recoils? [Kuzniak et al. (2012)]
  - CDMS-Si — zero charge events?

Plausible (even probable?) background explanations

Evaluating potential signals… DAMA?

- Many potential modulating backgrounds (e.g. environmental)

- Side checks:
  - No modulation > 90 keVee
  - No modulation in multiple scatter events



- Proposed backgrounds convincingly rejected

- …but hardest signal to reconcile other results. Unconventional WIMP? Novel background? Some other new physics?

Needed: southern hemisphere modulation experiment → **Australia!**

Room for improvement…

Limited data and simplified analyses: "good enough"?
(answer: **NO**)

Where improvement can be made:

- Background characterization
  - Something better than nothing (let Bayes do the work)
- Detector modeling
  - Neglecting efficiencies, energy resolution, etc. give inaccurate results (and lead to faulty conclusions)

  LUX analysis: CS, Scaffidi, White & Williams (in progress)
- Statistical analyses
  - Weak, invalid, misleading, or unavailable

Room for improvement…

Tasks

- Experimentalists: give theorists what they need
- Theorists: tell them what you need
  (and use it properly)

What is needed

- Able to apply results to arbitrary DM models
- Able to calculate likelihood

Room for improvement…

Joint statistical analysis of multiple data sets

- Colliders
- Direct DM searches
- Indirect DM searches
- g-2
- CMB
- Large scale structure formation
- …

Robust means for probing Beyond the Standard Model (BSM) frameworks

GAMBIT Collaboration: heavy Australian involvement
(Athron, Balázs, Farmer, Jackson, Saavedra, White)

Concluding Remarks

Concluding Remarks

- Exciting times:
  if supersymmetry and/or WIMPs exist,
  expect some signal within ~ 5 years

- Australia dark matter:
  Broad experimental/theoretical programs;
  SUSY *and* non-SUSY; CoEPP/CAASTRO
  interaction and collaboration (all positives)

  …will a direct search experiment join the program?