Lectures in Astroparticle Phenomenology
II. Dark Matter

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Lecture Plan

Yesterday: (campus) Particle Cosmology

- ΛCDM
- Power spectra of cosmological perturbations
- Reheating, Big Bang nucleosynthesis, cosmic strings

Today: Dark Matter

- Theories
- Production
- Direct + indirect detection

Thursday (campus): Global Fits

- Techniques, status and coming developments

Outline of Lecture 2

1. Background and models
   - Introduction
   - Models and requirements
2. Production of dark matter
3. Detection of dark matter
   - Indirect detection
   - Direct detection
   - Impacts of dark matter on stars **(optional)**

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How we know dark matter exists

(Clowe et al., *ApJL* 2006)

The only way to consistently explain:

1. rotation curves + vel. dispersions
2. gravitational lensing
3. cosmological data
   - Large-scale structure (2dF/Chandra/SDSS-BAO) says $\Omega_{\rm matter} \approx 0.27$
   - BBN says that $\Omega_{\rm baryonic} \approx 0.04$
   - $\implies \Omega_{\rm non-baryonic} \approx 5 \times \Omega_{\rm baryons}$
   - CMB (WMAP) and SN1a agree; also indicate that $\Omega_{\rm total} \approx 1$
   - $\implies$ universe is 23% dark matter, 4% baryonic (visible) matter, 73% something else

What we know about it

Must be:

- massive (gravitationally-interacting)
- unable to interact via the electromagnetic force (dark)
- non-baryonic
- "cold(ish)" (in order to allow structure formation)
- stable on cosmological timescales
- produced with the right relic abundance in the early Universe.

Good options:

- Weakly Interacting Massive Particles (WIMPs)
- sterile neutrinos
- gravitinos
- axions
- axinos
- hidden sector dark matter (e.g. WIMPless dark matter)

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- MAssive Compact Halo Objects (MACHOs)
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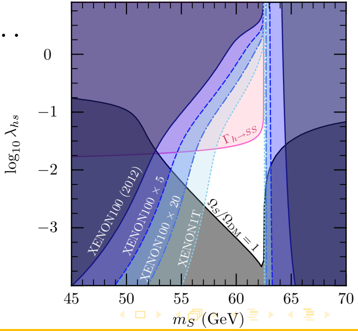
WIMPs at a glance

- Dark because no electromagnetic interactions
- Cold because very massive ($\sim$10 GeV to $\sim$10 TeV)
- Non-baryonic and stable - no problems with BBN or CMB
- Weak-scale annihilation cross-sections *naturally* lead to a relic abundance of the right order of magnitude (more later)
- Simplest example is scalar singlet dark matter:

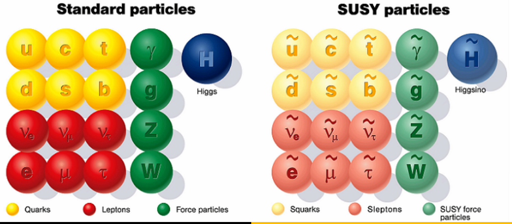
$$\mathcal{L}_S = -\frac{\mu_S^2}{2} S^2 - \frac{\lambda_{hs}}{2} S^2 H^\dagger H + \ldots$$



Cline, Kainulainen, PS & Weniger *Phys Rev D* 2013

WIMPs at a glance

- Many theoretically well-motivated particle candidates
  - Supersymmetric (SUSY) neutralinos χ if *R*-parity is conserved - lightest mixture of neutral higgsinos and gauginos
  - Inert Higgses - extra Higgs in the Standard Model
  - Kaluza-Klein particles - extra dimensions
  - right-handed neutrinos, sneutrinos, other exotic things. . .
- Weak interaction means scattering with nuclei
  $\implies$ detection channel
- Many WIMPs are Majorana particles (own antiparticles)
  $\implies$ self-annihilation cross-section



Ways to detect WIMPs

- Direct detection – nuclear collisions and recoils
- Indirect detection – annihilations producing SM particles
- Impacts on stars – the Sun and “dark stars”
- Direct production – missing E_T or otherwise – LHC, Tevatron

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Thermal and non-thermal production

Thermal Production

Everything is in perfect thermal equilibrium in early Universe

$\Longrightarrow$
- Particle populations are all in equilibrium (cf Saha, Boltzmann Eqs) $\rightarrow$ set by T
- Velocities are all in kinetic equilibrium (cf Maxwell dist) $\rightarrow$ set by T

$\Longrightarrow$ As stuff falls out of equilibrium, populations and velocities must be evolved explicitly

$\Longrightarrow$ Always present at some level, not always dominant in $\Omega_{\rm DM}$

Non-thermal Production

Any other process that dominates the DM relic density

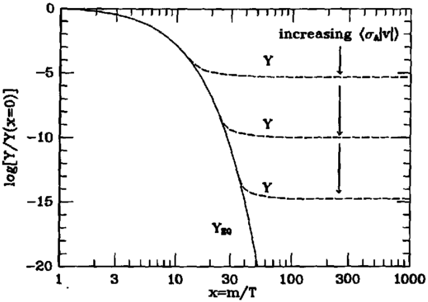
- Some other heavy BSM particle X decays $\rightarrow$ DM
- Decays/evaporations of topological defects like cosmic strings
- Evaporation of PBHs
- Not always present

Thermal production

(Kolb & Turner 1990) → DarkSUSY, MicrOmegas, MadDM, SuperIsoRelic, BYO homebrew, etc

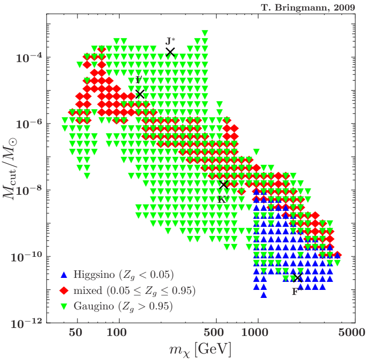
Thermal relic particle populations (=relic density) are obtained by solving the Boltzmann Equation:

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = \langle\sigma v\rangle({n_{\chi,\,\mathrm{eq}}}^2 - {n_\chi}^2) \tag{1}$$



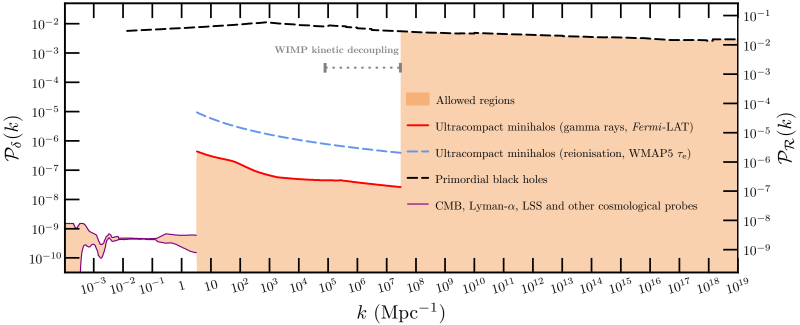
Kinetic decoupling and small-scale structure

- Particle production and abundance is chemical freeze-out
- Particle velocities and final DM temperature are determined by kinetic freeze-out
- Typically happen kind of around the same time, but very model-dependent
- Kinetic decoupling temperature → kinetic decoupling scale → minimum DM halo mass
- Impacts boost factors for indirect detection ($\Phi \propto \rho^2$), minihalo searches



Kinetic decoupling and small-scale structure

Reminder from last lecture: Validity of UCMH limits depend a bit on kinetic decoupling scale



Outline of Lecture 2

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What is indirect detection?

Looking for Standard Model particles produced by dark matter annihilation or decay:

- gamma-rays – *Fermi*, HESS, CTA
- anti-protons – PAMELA, AMS-02
- anti-deuterons – GAPS
- neutrinos – IceCube, ANTARES
- e^+e^- – PAMELA, *Fermi*, ATIC, AMS-02
  $\rightarrow$ secondary radiation: inverse Compton, synchrotron, bremsstrahlung
- secondary impacts on the CMB, reionisation

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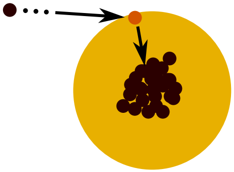
Finding dark matter with neutrino telescopes

The cartoon version:

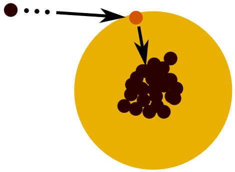
Finding dark matter with neutrino telescopes



The cartoon version:

1. Halo WIMPs crash into the Sun

Finding dark matter with neutrino telescopes



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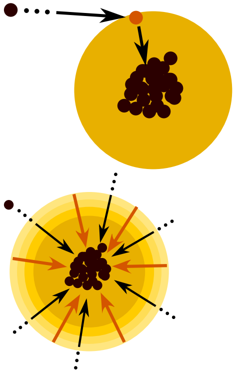
2. Some lose enough energy in the scatter to be gravitationally bound

Finding dark matter with neutrino telescopes



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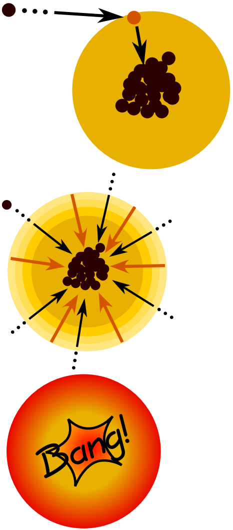
4. Annihilate with each other, producing neutrinos



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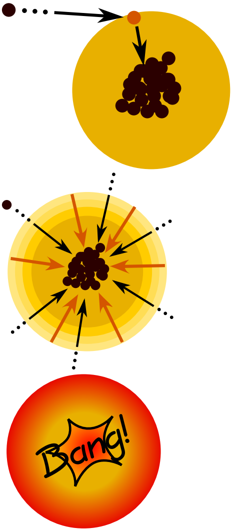

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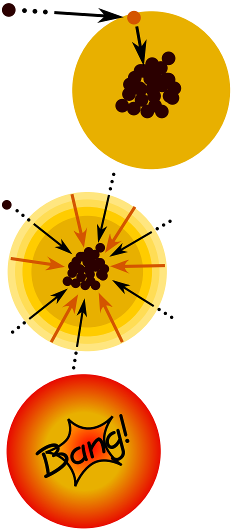
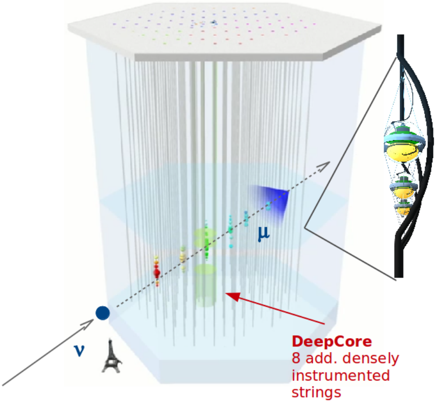
6. Look for Čerenkov radiation from the muons in **IceCube**, ANTARES, etc

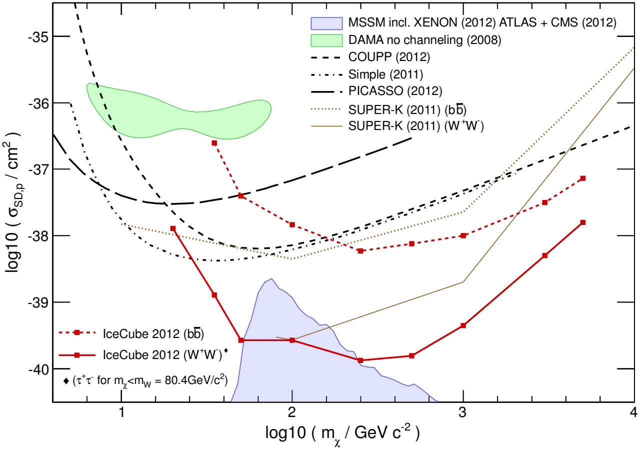


The IceCube Neutrino Observatory

- 86 strings
- 1.5–2.5 km deep in Antarctic ice sheet
- $\sim$125 m spacing between strings
- $\sim$70 m in DeepCore (10$\times$ higher optical detector density)
- 1 km^3 instrumented volume (1 Gton)



Neutrino limits from IceCube

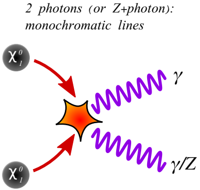


IceCube Collaboration, *Phys. Rev. Lett.* 2013
Theory region: MSSM-25 from Silverwood, PS, Danninger, et al *JCAP* 2012

Gamma-rays from dark matter

- 3 main gamma-ray channels:

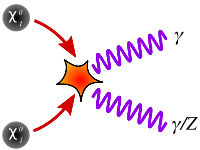
Gamma-rays from dark matter



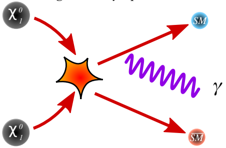
- 3 main gamma-ray channels:
  - monochromatic lines

Gamma-rays from dark matter

2 photons (or Z+photon): monochromatic lines



Internal bremsstrahlung: hard gamma-ray spectrum



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  - internal bremsstrahlung (FSR + VIB)

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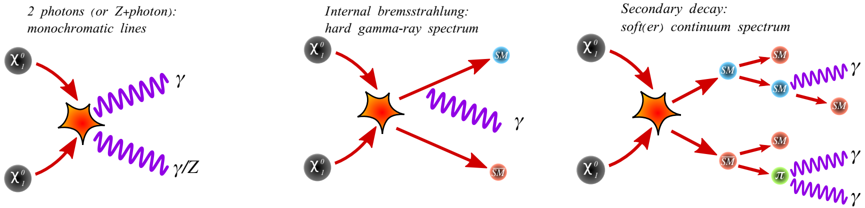

- 3 main gamma-ray channels:
  - monochromatic lines
  - internal bremsstrahlung (FSR + VIB)
  - continuum from secondary decay

Targets

- $\Phi \propto$ annihilation rate $\propto \rho^2_{\rm DM}$

Likely targets:

- Galactic centre - large signal, large BG
- Galactic halo - moderate signal, moderate BG
- dwarf galaxies - low statistics, low BG
- clusters/extragalactic diffuse - large modelling uncertainties, low signal, low BG
- dark clumps - low statistics, low BG

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Weniger, *JCAP* 2012
Hooper & Linden, arXiv:1110.0006

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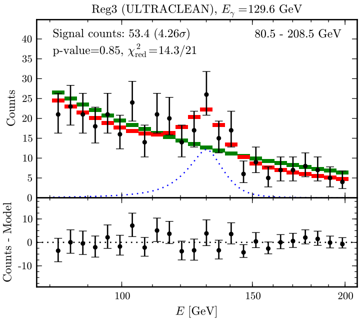

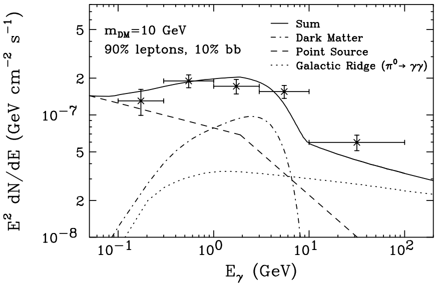

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Pierre, Siegal-Gaskins & PS arXiv:1401.7330

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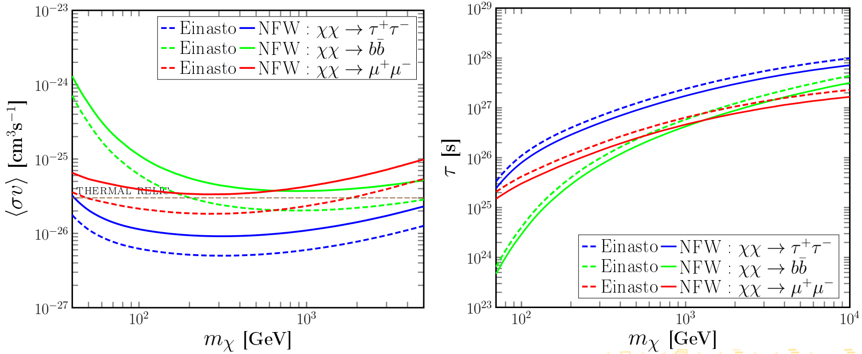

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Cline, Kainulainen, PS & Weniger *Phys Rev D* 2013

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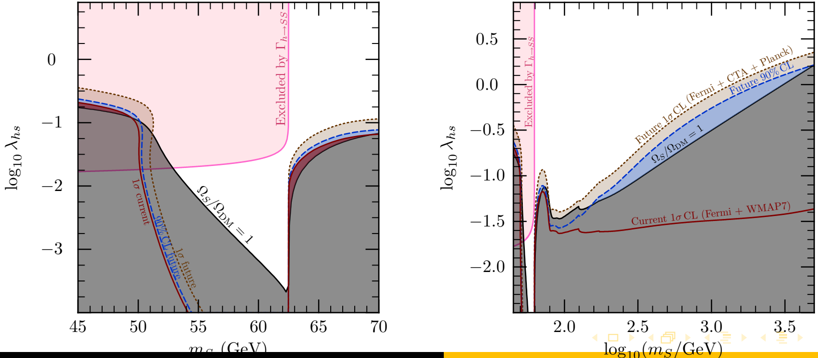

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Fermi-LAT Collab., *Phys. Rev. D* 2014

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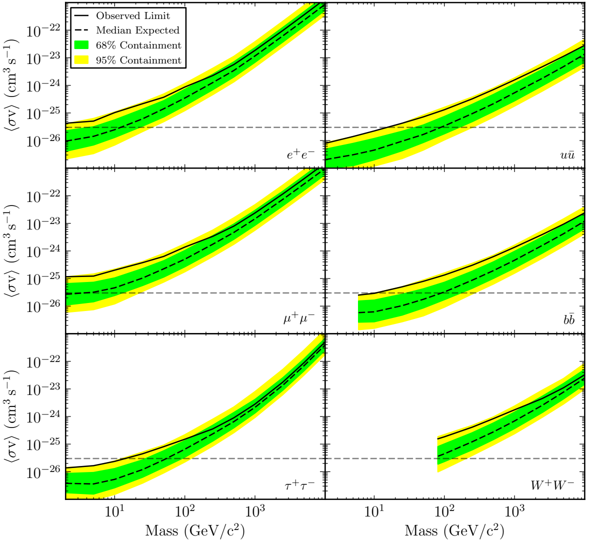

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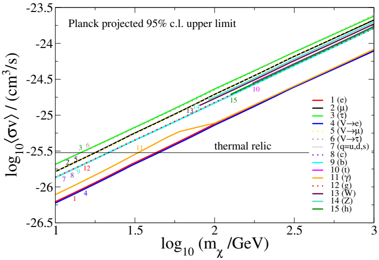
Impacts of DM annihilation on the CMB

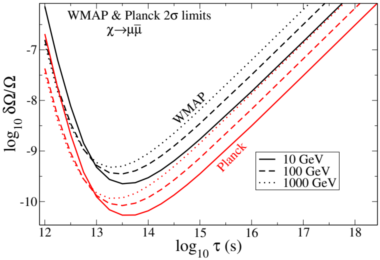
Energy injection from DM annihilation/decay at $z \sim 600$

$\longrightarrow$ Would change ionisation balance via γs and e^+e^- interaction with electrons and H

$\longrightarrow$ Changes timing + extent of recombination

$\longrightarrow$ Distortion of CMB angular power spectrum



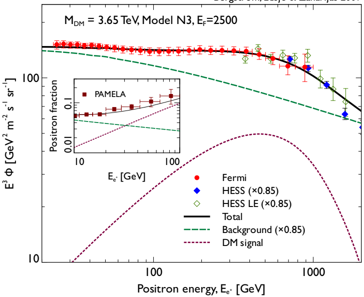


Cline & PS *JCAP* 2013

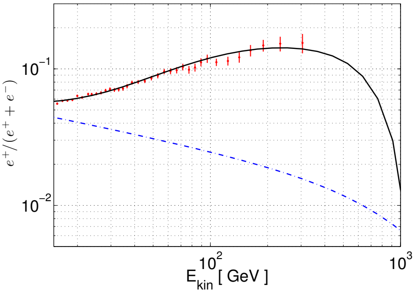
Positrons

- Excess over expected background (secondary) positron ratio observed
- First seen by PAMELA, confirmed by *Fermi* then AMS-02. Still unexplained.
- Could be evidence of dark matter

Bergström, Edsjö & Zaharijas 2009



AMS-02; De Simone et al *JCAP* 2013



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Directly detecting dark matter in the lab

- WIMP flies in, scatters elastically off an atomic nucleus $\implies$ nucleus gets a kick
- Very small kick $\implies$ very low threshold detection required

$$\frac{dN}{dE_\mathrm{r}} = \frac{\sigma\rho}{2\mu^2 m_\chi} F^2 \int_{v_\mathrm{min}(E_\mathrm{r})}^{v_\mathrm{esc}} \frac{f(v)}{v} dv$$

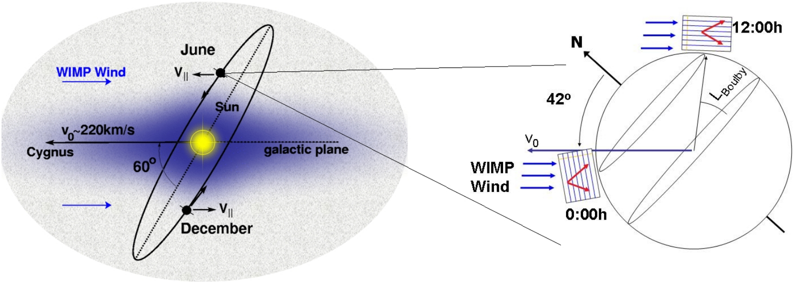
N	= number of scatterings
E_r	= nuclear recoil energy
σ	= WIMP-nucleus cross-section
ρ	= WIMP density
μ	= WIMP-nucleus reduced mass
m_χ	= WIMP mass
F	= nuclear form factor
$f(v)$	= WIMP velocity distribution
v	= WIMP velocity
$v_\mathrm{min}(E_\mathrm{r})$	= minimum v to produce recoil E_r
v_esc	= halo escape velocity (max v)

Recoil rate is degenerate in unknowns

- WIMP mass
- local WIMP density
- halo velocity distribution
- WIMP-nucleus cross-section

Daily & yearly modulation

Due to Earth's proper motion in the galaxy, we expect:



annual modulation

diurnal (day-night) modulation

Spin-dependent and -independent cross-sections

Spin-independent

- Scattering off all nucleons
- $\implies$ proportional to A^2 ($A =$ atomic weight)
- Dominates for heavy nuclei due to A^2 enhancement
- Form factor can suppress momentum transfer in very large nuclei though
- Most studied, most accessible

Spin-dependent

- Scattering only off nucleons with *net* nuclear spin (i.e. whose spins remain *unpaired*)
- $\implies$ less increase with A than spin-independent cross-section
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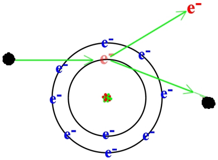
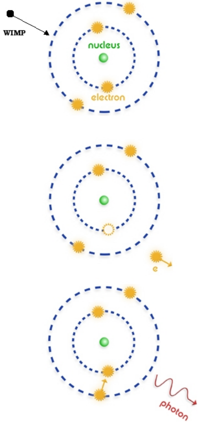
3 ways to detect recoils

Ionisation

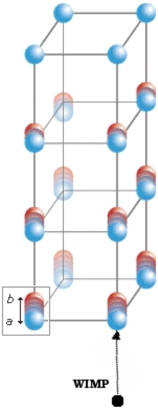


Scintillation

(just fluorescence with a quick recovery and in a transparent medium)

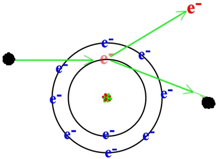


Vibration (phonons)



3 ways to detect recoils

Ionisation



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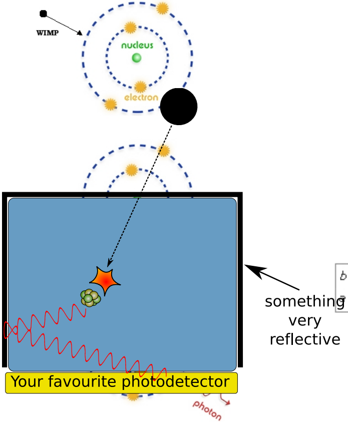

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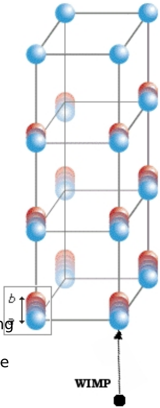

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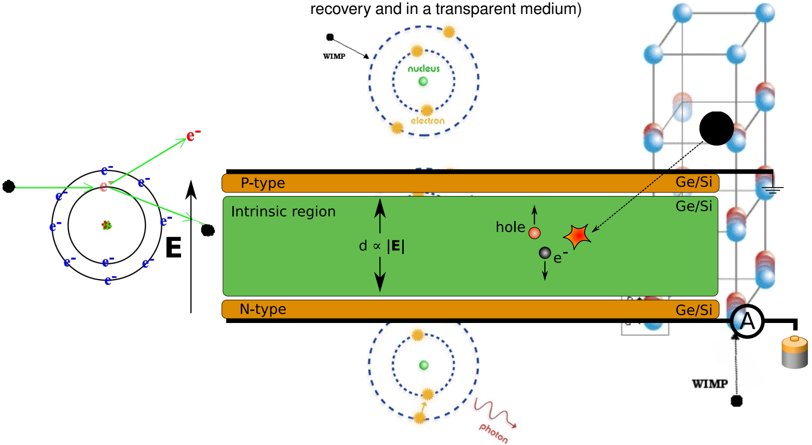
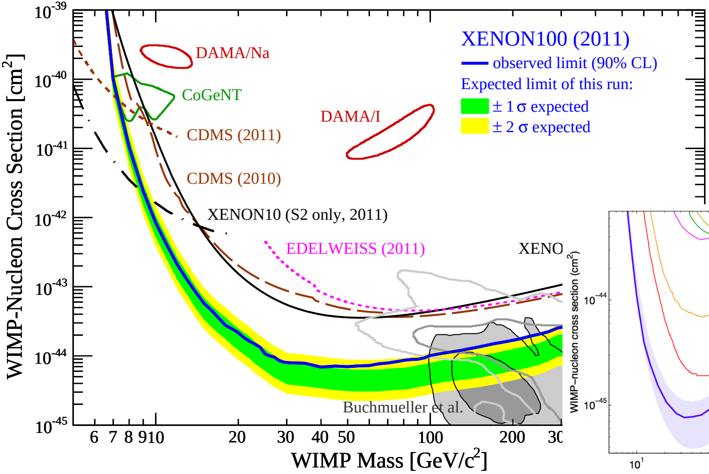
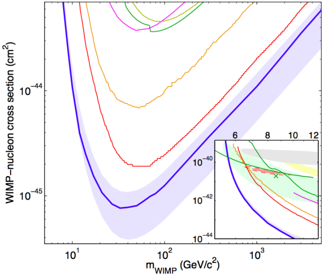


The current state of play

XENON-100, *Phys. Rev. Lett.* 2011
LUX, *Phys. Rev. Lett.* 2014

Leading spin-independent sensitivity is from LUX





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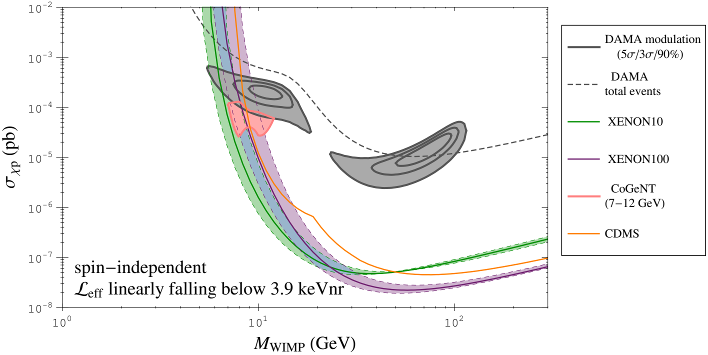

Savage, Gelmini, Gondolo, Freese
Phys. Rev. D 2011

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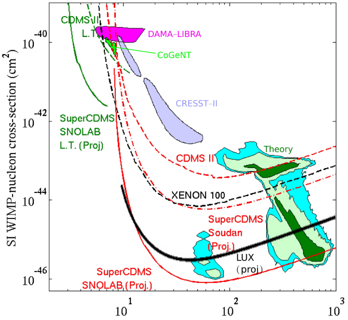
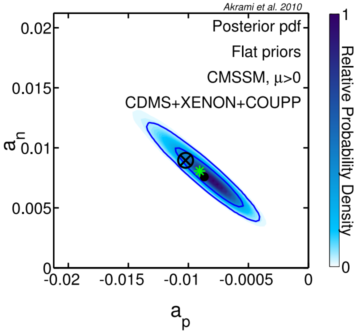
- $\rightarrow$ exciting, but tricky

Hitting the ton scale

Future experiments should shed much more light on the situation





XENON-1T, LZ (LUX/ZEPLIN) and SuperCDMS will cover vast areas of parameter space

Akrami, Savage, PS et al, *JCAP* 2010

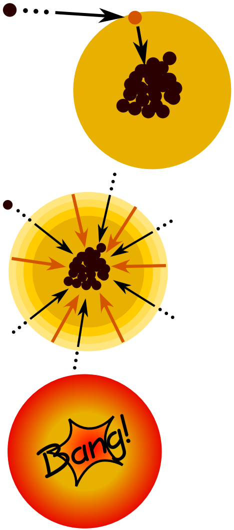
Outline of Lecture 2

1. Background and models
   - Introduction
   - Models and requirements
2. Production of dark matter
3. Detection of dark matter
   - Indirect detection
   - Direct detection
   - Impacts of dark matter on stars **(optional)**

Reminder:

The cartoon version:

1. Halo WIMPs crash into the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core
4. Annihilate with each other, producing neutrinos
5. Propagate+oscillate their way to the Earth, convert into muons in ice/water
6. Look for Čerenkov radiation from the muons in **IceCube**, ANTARES, etc



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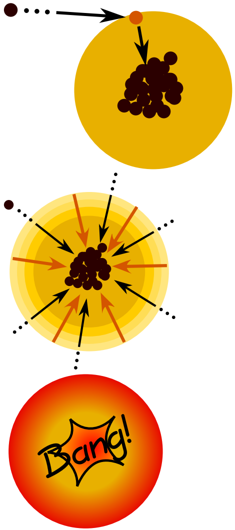

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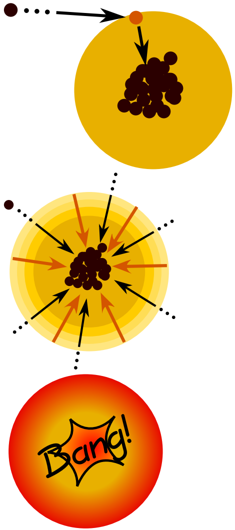

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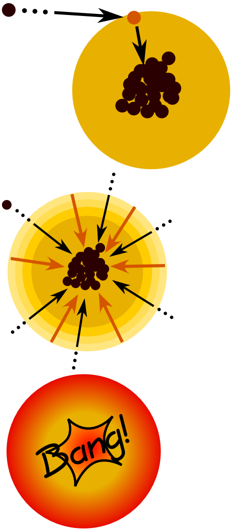

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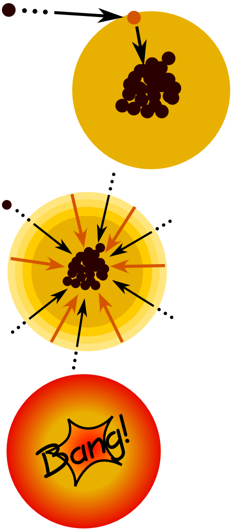
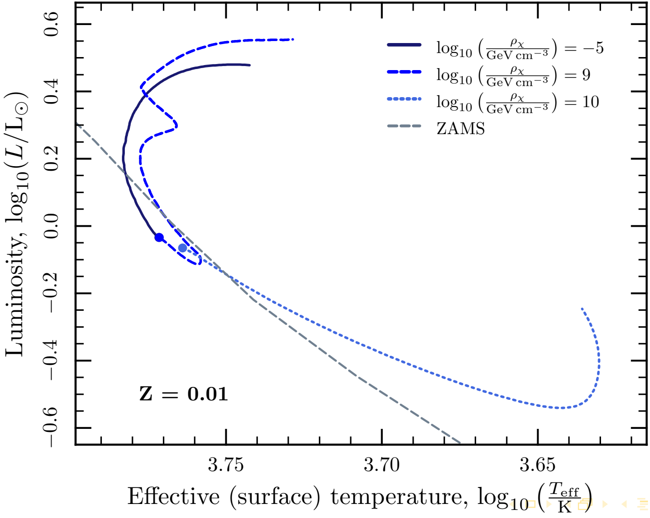
5. Particles dump their energy in the stellar core
6. Stellar structure responds, star evolves accordingly



Stellar evolution with dark matter annihilation



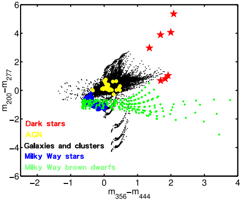
Finding 'dark stars'

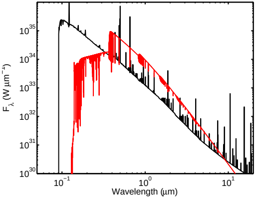
- Finding dark stars near the Galactic Centre seems quite possible - not S stars, but low-mass counterparts
- Best candidates have low masses, elliptical orbits
- VLT/ELT/TMT/GMT observations should reach the required sensitivity in next few yrs
- DarkStars stellar evolution code publicly available from http://www.fysik.su.se/~pat/darkstars

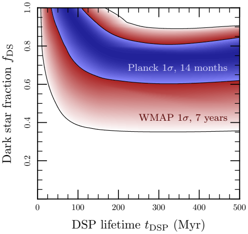
PS, Fairbairn, Edsjö, *MNRAS* 2009
Fairbairn, PS, Edsjö, *Phys. Rev. D* 2008

Finding ‘dark stars’

- First stars also good targets
- Collapsing gas steepens the potential, draws in dark matter
- Heating from annihilation can overcome gas cooling and delay collapse
- Maybe visible with JWST (if lensed), or by impacts on reionisation







PS, Venkatesan, Roebber et al *ApJ* 2011
Zackrisson, PS, Rydberg et al *ApJ* 2010; *MNRAS Lett.* 2010
Spolyar, Freese, Gondolo, *Phys. Rev. Lett.* 2008; Iocco et al, *MNRAS* 2008

Solar abundances and dark matter

- New solar composition is 33% lower in metals than 20 years ago
  - New composition uses state-of-the-art 3D hydro code, improved radiative transfer, non-LTE line formation, best observations, best atomic data, *very* careful line selection
  - Kills agreement with helioseismology ☹
- Something is missing!! Opacities wrong, weird accretion history (related to planets??), gravity waves, 3D effects or similar missing in interior code. . . or new physics?

Vincent, PS, *JCAP* in press
Serenelli, Basu, Ferguson, Asplund, *ApJL* 2009
Asplund, Grevesse, Sauval, PS, *Ann Rev A&A* 2009

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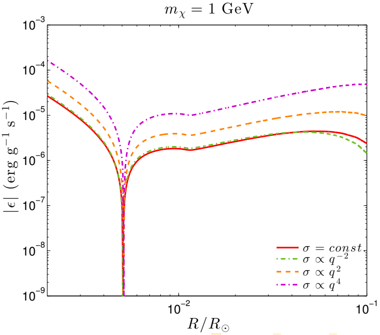
Possible solution from momentum-dependent DM?



Vincent, PS, *JCAP* in press
Serenelli, Basu, Ferguson, Asplund, *ApJL* 2009
Asplund, Grevesse, Sauval, PS, *Ann Rev A&A* 2009

Summary

- The identity of dark matter can be probed in many complementary ways
- Dark matter production in the early Universe places strong constraints on its identity
- Indirect detection generally probes masses and annihilation channels
- Direct detection probes masses and interactions with quarks
- Different probes can (and should) be put together into global fits to gain a consistent picture – tomorrow.

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