The Sun as a Particle Physics Laboratory

Pat Scott

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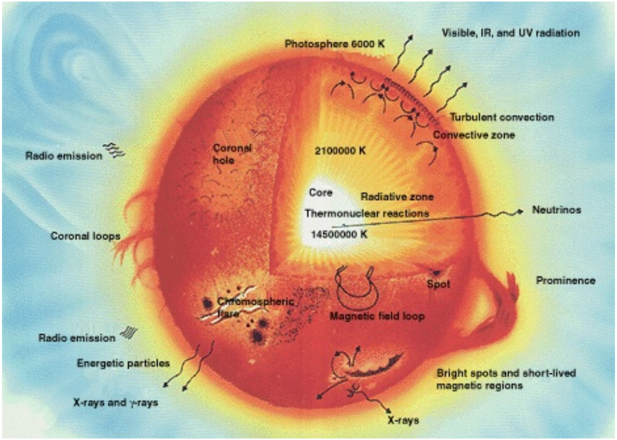
Based on:
Vincent, PS & Trampedach 1206.4315 (JCAP submitted)
PS, Savage, Edsjö & IceCube Collab. 1207.0810 (JCAP **11**:57 2012)
Silverwood, PS, Danninger, et. al. 1210.0844 (JCAP submitted)

Slides available from `www.physics.mcgill.ca/~patscott`

Outline

1. Why the Sun?
2. Solar neutrino telescope data ⟶ new physics
3. Light bosons and the solar abundance problem

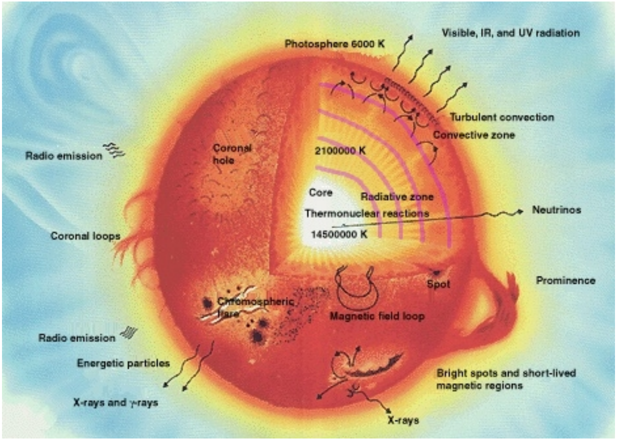
Solar observables sensitive to new physics



Solar observables sensitive to new physics

helioseismology

- solar structure
  ⟶ exotic E transport



Lopes, Silk, Cumberbatch, Casanellas, Taoso, Bottino, Frandsen et al

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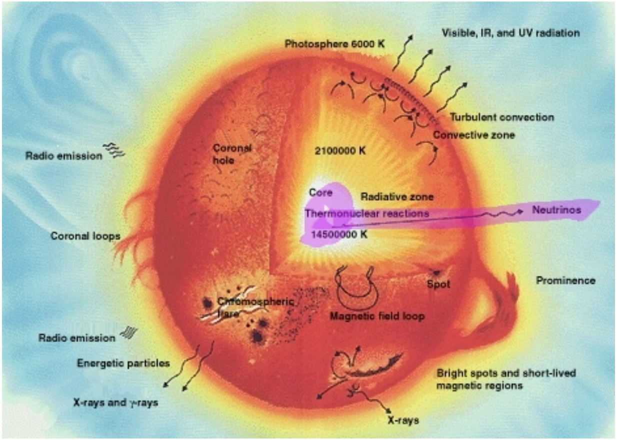
neutrinos

- neutrino properties (mixings, etc)



Davis, Bahcall, SNO, Super-Kamiokande, Borexino, etc

Solar observables sensitive to new physics

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  → exotic E transport

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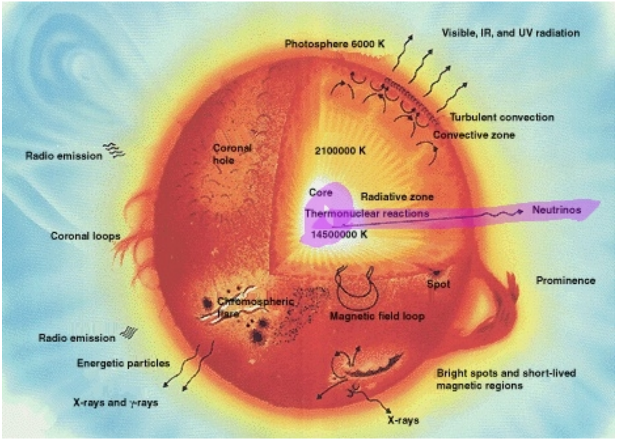
- neutrino properties (mixings, etc)
- solar core T
  → exotic E transport



Gould, Raffelt, Taoso, Lopes, Silk, Casanellas, Serenelli, et al

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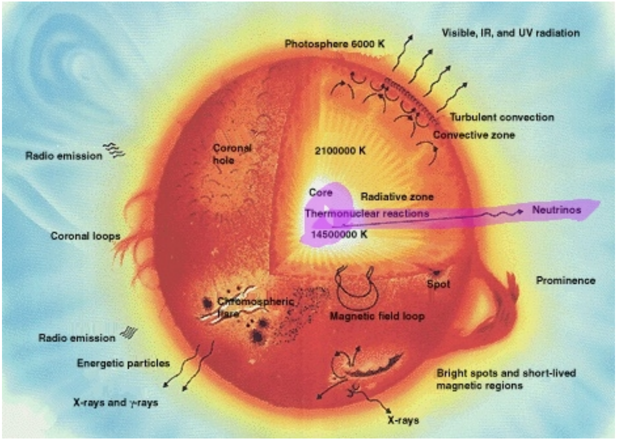
  → exotic E transport
- exotic ν production
  → dark matter annihilation



Steigmann, Silk, Olive, Gaisser, Bergström, Edsjö, PS, Savage, et al

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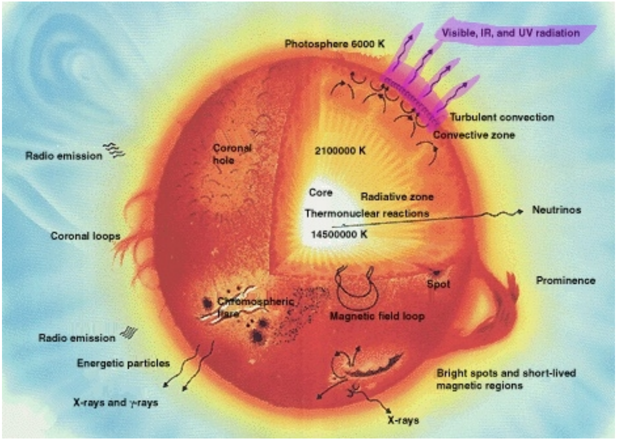
- solar spectrum
  - new opacity source/sink



Vincent, PS & Trampedach

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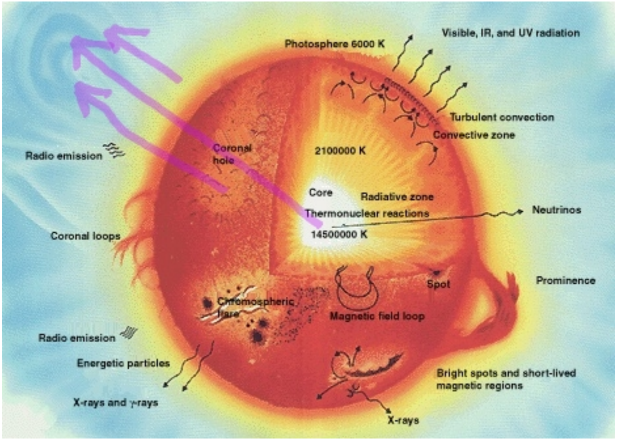
- ⟶ direct axion searches



Raffelt, Sikivie, CAST, et al

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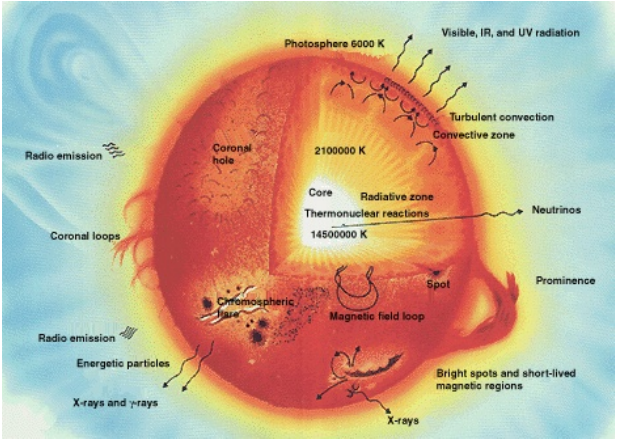

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What we know about dark matter

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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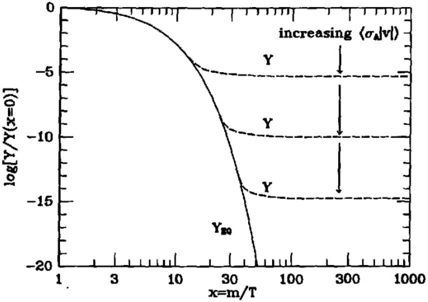
WIMPs at a glance

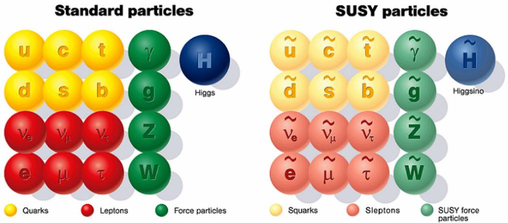
- Dark because no electromagnetic interactions
- Cold because very massive (∼10 GeV to ∼10 TeV)
- Non-baryonic and stable - no problems with BBN or CMB
- Weak-scale annihilation cross-sections *naturally* lead to a relic abundance of the right order of magnitude



(Kolb & Turner 1990)

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 → detection channel
- Many WIMPs are Majorana particles (own antiparticles) $\Longrightarrow$ self-annihilation cross-section



How to find WIMPs with neutrino telescopes

The short version:

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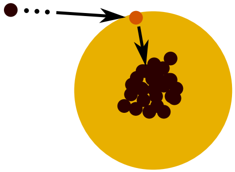

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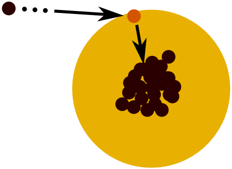

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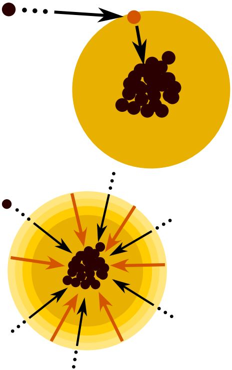

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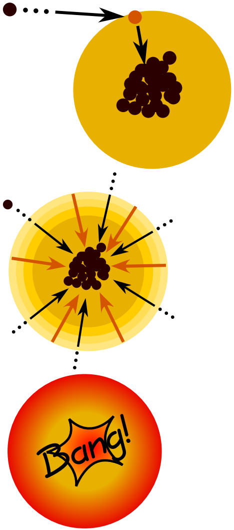

The short version:

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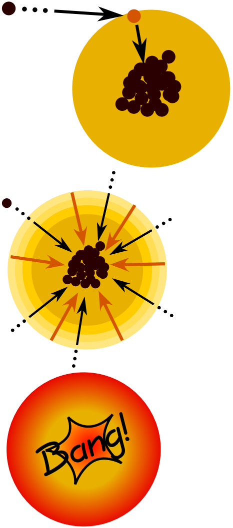

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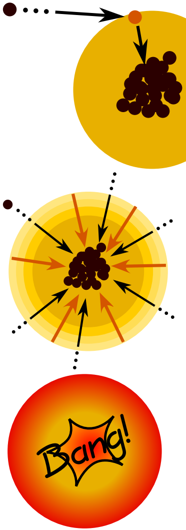

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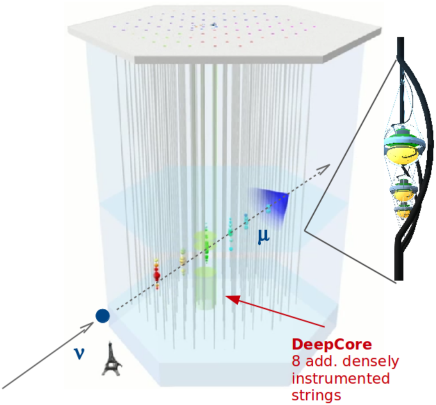
6. Look for Čerenkov radiation from the muons in **IceCube**, ANTARES, etc

The IceCube Neutrino Observatory

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



What can the muon signal tell me?

Roughly:

Number – how much annihilation is going on in the Sun
$\Longrightarrow$ info on $\sigma_{\rm SD}$, $\sigma_{\rm SI}$ and $\langle\sigma v\rangle$
Spectrum – sensitive to WIMP mass m_χ and branching fractions *BF* into different annihilation channels *X*
Direction – how likely it is that they come from the Sun

In model-independent analyses a lot of this information is either discarded or not given with final limits

Goal:

Use as much of this information on $\sigma_{\rm SD}$, $\sigma_{\rm SI}$, $\langle\sigma v\rangle$, m_χ and $BF(X)$ as possible to directly constrain specific points and regions in WIMP model parameter spaces ($+$LHC$+$DD$+\ldots$)

What can the muon signal tell me?

The focus here is supersymmetry (SUSY) – but this is really just a framework, applicable to any model.

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All IceCube data used are available at http://icecube.wisc.edu/science/data/ic22-solar-wimp (and in DarkSUSY, for convenience)

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SUSY Scanning with IceCube – Simple Likelihood

Simplest way to do anything is to make it a counting problem…

Compare observed number of events n and predicted number θ for each model, taking into account error σ_ϵ on acceptance:

$$\mathcal{L}_{\rm num}(n|\theta_{\rm BG}+\theta_{\rm sig}) = \frac{1}{\sqrt{2\pi}\sigma_\epsilon}\int_0^\infty \frac{(\theta_{\rm BG}+\epsilon\theta_{\rm sig})^n e^{-(\theta_{\rm BG}+\epsilon\theta_{\rm sig})}}{n!}\frac{1}{\epsilon}\exp\left[-\frac{1}{2}\left(\frac{\ln\epsilon}{\sigma_\epsilon}\right)^2\right]\mathrm{d}\epsilon\,. \tag{1}$$

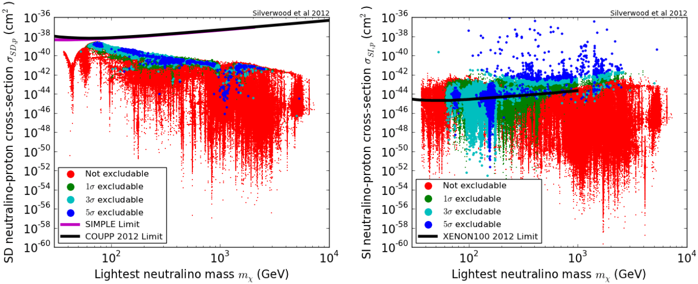
Nuisance parameter ϵ takes into account systematic errors on effective area, from theory, etc. $\sigma_\epsilon \sim 20\%$ for IceCube.

More complicated version also uses arrival direction and energy of every individual neutrino

Example: SUSY Scanning with IceCube – IN/OUT-type scans

Detection reach of full IceCube+DeepCore experiment in 25-parameter version of supersymmetry

Compared to direct detection experiments:



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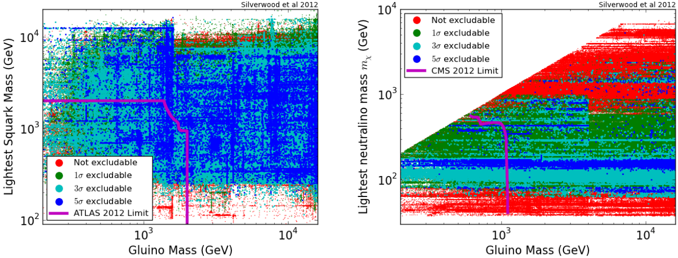
Compared to limits from the Large Hadron Collider:



SUSY Scanning with IceCube – Statistics 101

Why simple IN/OUT analyses are not enough:. . .

- Only partial goodness of fit, no measure of convergence, no idea how to generalise to regions or whole space.
- Frequency/density of models in IN/OUT scans means essentially nothing.
- More information comes from a **global statistical fit.**

$\Longrightarrow$ **parameter estimation exercise**

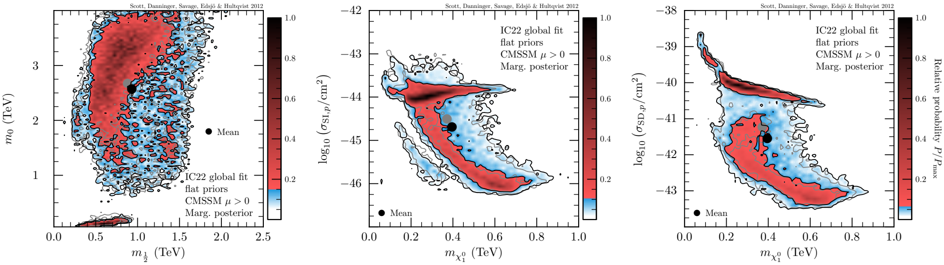
Composite likelihood made up of observations from all over:

- dark matter relic density from WMAP
- precision electroweak tests at LEP
- LEP limits on sparticle masses
- *B*-factory data (rare decays, $b \to s\gamma$)
- muon anomalous magnetic moment
- LHC searches, direct detection (only roughly implemented for now)

Example: SUSY Scanning with IceCube – Global Fits

CMSSM, IceCube-22 events

m_0–$m_{1/2}$ and $m_{\chi_1^0}$–nuclear scattering cross-sections



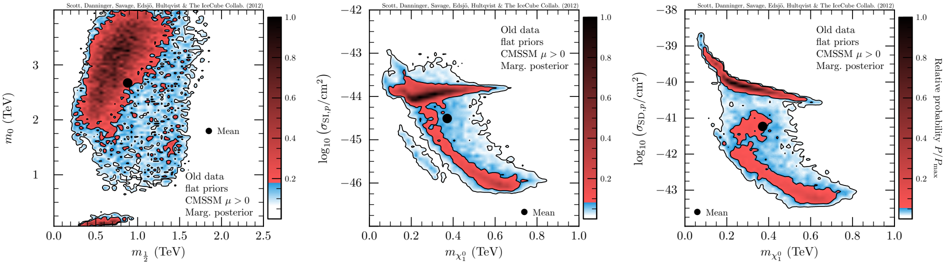
Contours indicate 1σ and 2σ credible regions

Grey contours correspond to fit *without* IceCube data

Shading+contours indicate **relative** probability only, not overall goodness of fit

Example: SUSY Scanning with IceCube – Global Fits

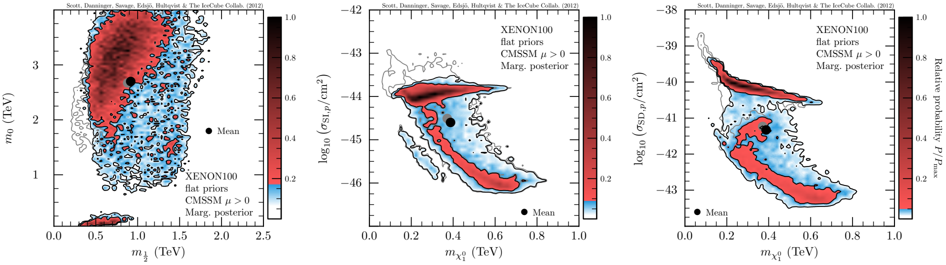
Base Observables



Example: SUSY Scanning with IceCube – Global Fits

Base Observables + XENON-100

Grey contours correspond to Base Observables *only*



Example: SUSY Scanning with IceCube – Global Fits

Base Observables + XENON-100 + CMS 5 fb^{-1}

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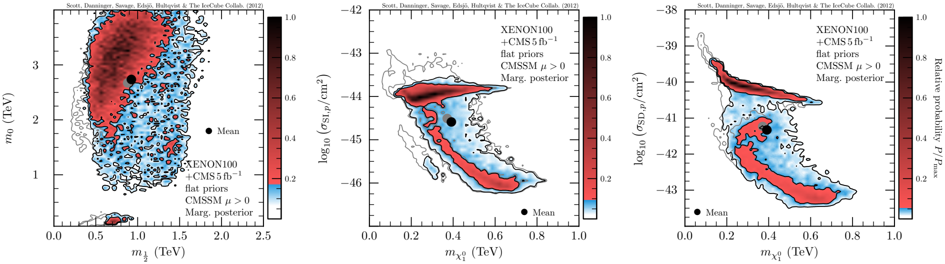

Example: SUSY Scanning with IceCube – Global Fits

Base Observables + XENON-100 + CMS 5 fb^{-1} + IC22×100

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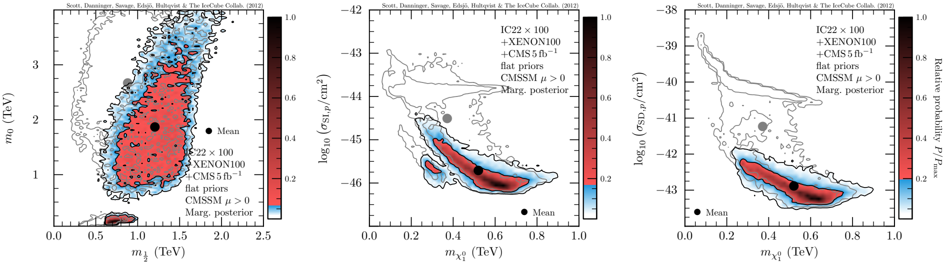
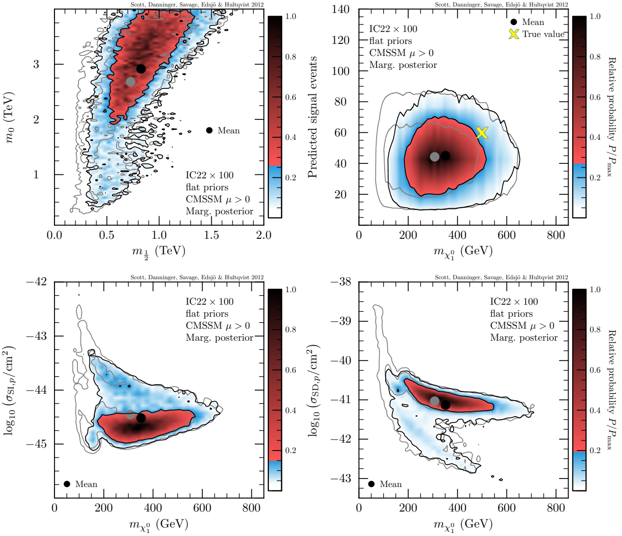


CMSSM, IceCube-22 with 100× boosted effective area
(kinda like IceCube-86+DeepCore)

Example: Model Recovery



CMSSM,
IceCube-22×100
signal reconstruction
60 signal events,
500 GeV, $\chi\chi \rightarrow W^+W^-$

Grey contours correspond to reconstruction *without* energy information

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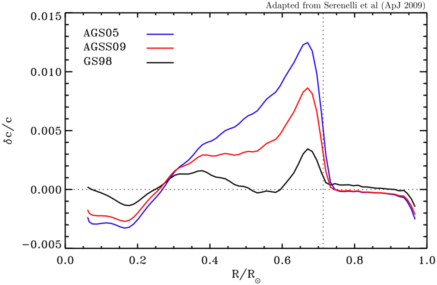
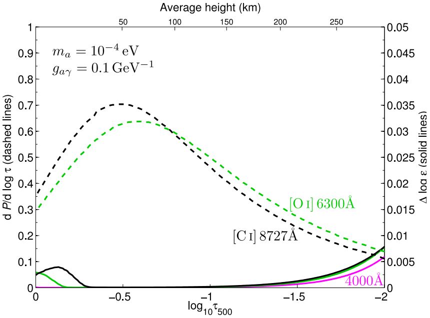
The solar abundance problem

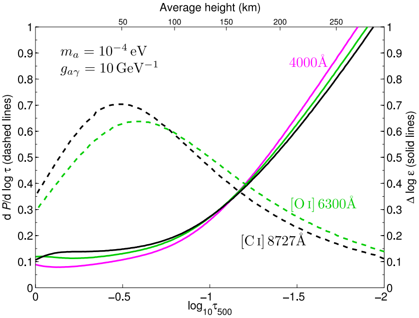
- Latest solar photospheric abundances (Asplund, Grevesse, Sauval & PS: AGS05, AGSS09) factor of ∼2 less than old ones (Grevesse & Sauval: GS98)
- Best atomic data, highly accurate observations, new 3D modelling, NLTE corrections, improved agreement with solar neighbourhood $\Longrightarrow$ highly reliable
- Messes up inferred sound speed profile, helium abundance and depth of convection zone from helioseismology
- Many solutions attempted in the last decade; none really successful


Adapted from Serenelli et al (ApJ 2009)

Axions, ALPs and impacts on solar abundances

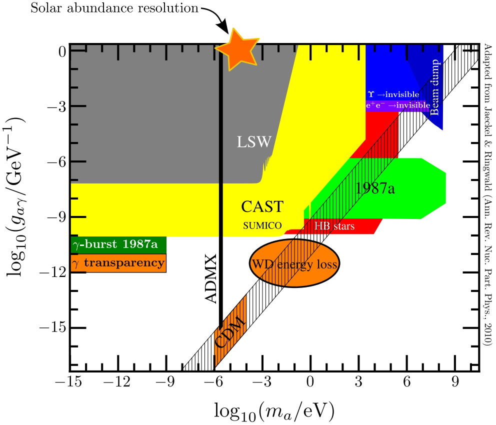
- What if the problem was due to impacts of new particles in the photosphere on spectral line formation?
- e.g. effective reduction in opacity due to conversion of photons to axion-like particles (which are not absorbed)





Allowed parameter space

- Unfortunately, this is experimentally ruled out – by a long way:



Adapted from Jaeckel & Ringwald (Ann. Rev. Nuc. Part. Phys., 2010)

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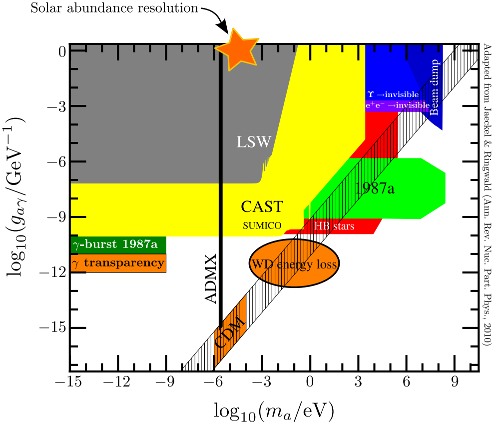

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- What about similar models of light bosons? Chameleons? Hidden photons?

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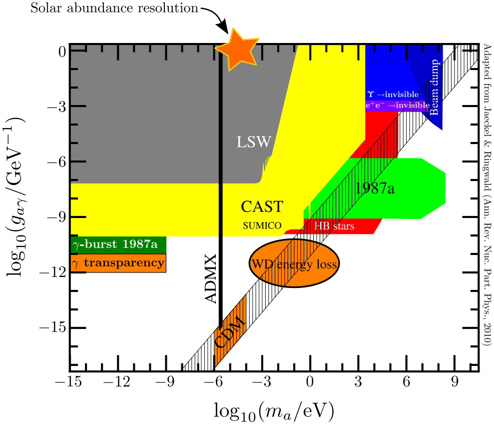

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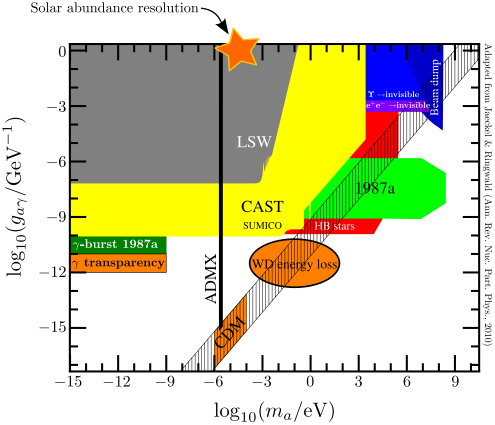

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- Requirements and limits can be recast → necessary parameter combinations also well ruled out
- $\Longrightarrow$ Light bosons cannot impact solar photospheric abundances

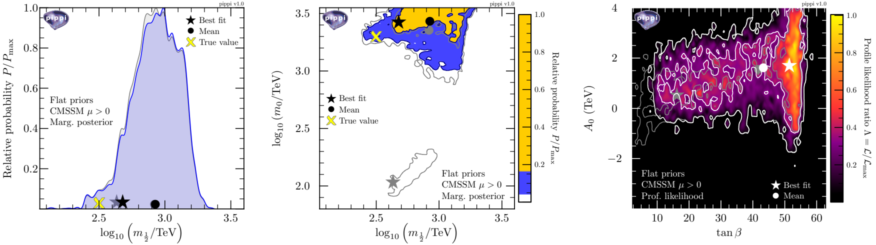
Closing remarks

- The Sun is just as useful for particle physicists as astronomers
- Neutrino searches for WIMP annihilation in the solar core are a prime example
    - Event-level neutrino likelihood extensions and real IceCube data are available in DarkSUSY 5.0.6
    - Direct SUSY analyses of IC79 data are in progress
    - Many models exist that only IC86 will be sensitive to
    - The codes can be used equally well for non-SUSY BSM scenarios too
- Axions, ALPs, chameleons or hidden photons are not the solution to the solar abundance problem. . .
- . . . but the problem is definitely at the stage of being ‘fair game’ for new physics!!

Outline

Advertisement

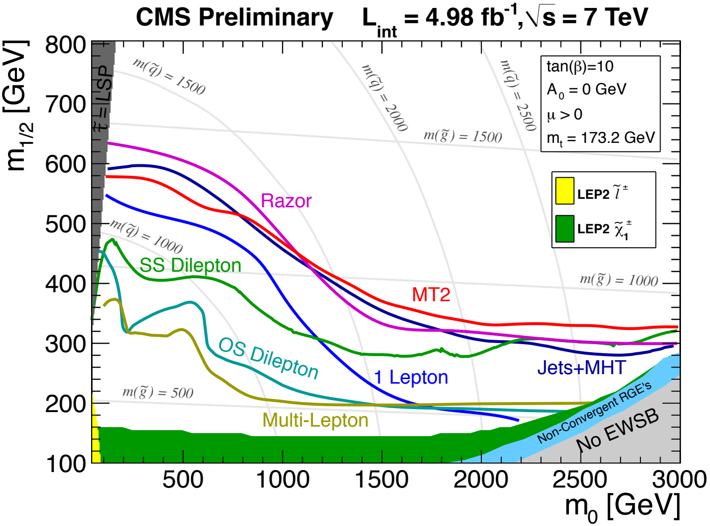
If you liked the plots in this talk…



Pippi – parse it, plot it
PS 1206.2245 (Eur. Phys. J Plus **127**:138 2012)
http://github.com/patscott/pippi

Generic pdfLaTeX sample parser, post-processor & plotter

CMS 5 fb^{-1} analyses



XENON-100 100-day analysis