Dark matter and the Sun

Capture, high-energy neutrinos and introduction to the solar abundance problem

Pat Scott

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With (amongst others):
Matthias Danninger (UBC)
Aaron Vincent (IPPP Durham)
Aldo Serenelli (UAB Barcelona)

Slides available from `tinyurl.com/patscott`

Outline

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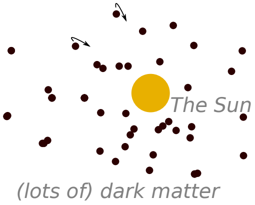
1. Getting dark matter in and out of the Sun
2. Neutrinos from solar dark matter
3. Introduction to the solar abundance problem

Capture



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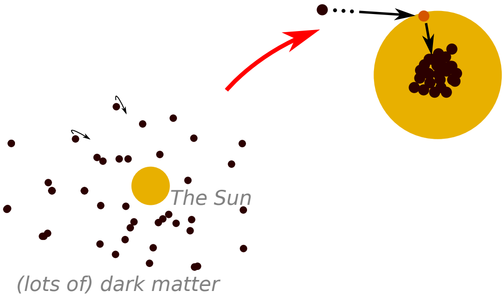

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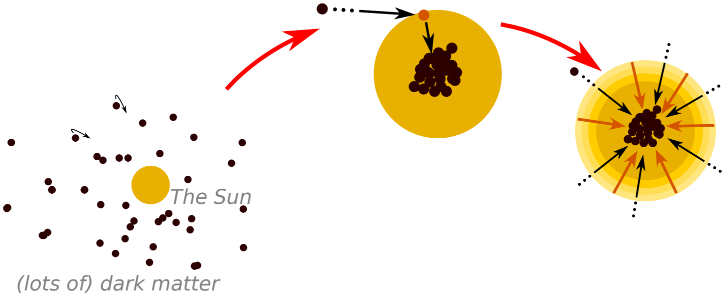

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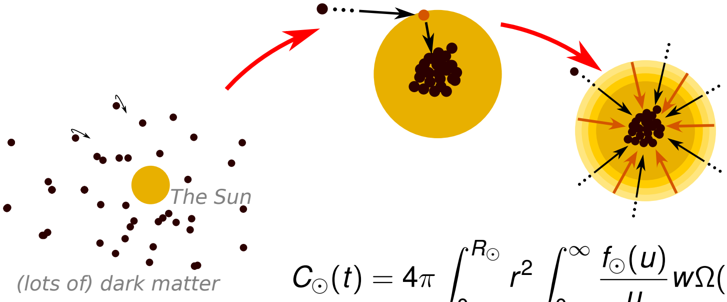
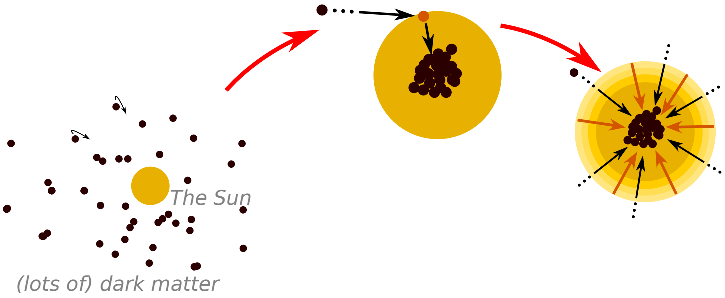


$$C_\odot(t) = 4\pi \int_0^{R_\odot} r^2 \int_0^\infty \frac{f_\odot(u)}{u} w\Omega(w)\, du\, dr. \quad (1)$$

$C_\odot$: capture rate
u: incoming DM velocity in solar frame
$f_\odot(u)$: DM velocity distribution
$\Omega(w)$: probability of DM scattering from $w \rightarrow$ below v_esc
$w(r) \equiv \sqrt{u^2 + v_\mathrm{esc}(r)^2}$

Evaporation



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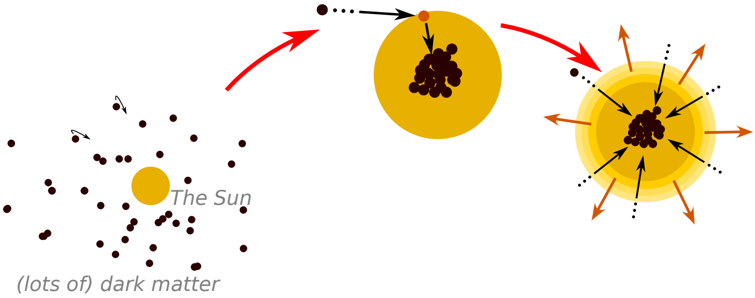

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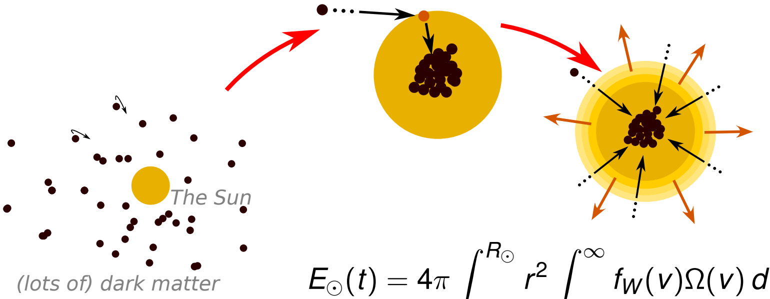
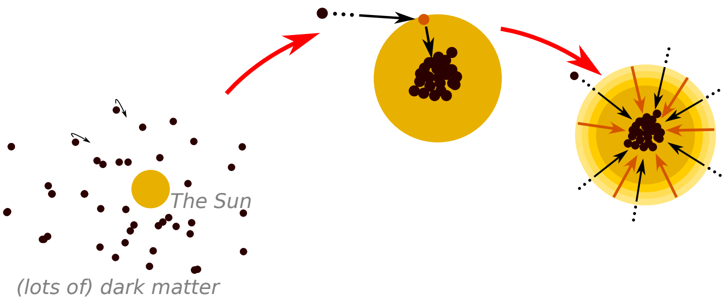


$$E_\odot(t) = 4\pi \int_0^{R_\odot} r^2 \int_0^\infty f_W(v)\Omega(v)\,dv\,dr. \tag{2}$$

$E_\odot$: evaporation rate
v: captured DM velocity inside Sun
$f_W(v)$: DM velocity distribution inside Sun
$\Omega(v)$: probability of DM scattering from $v \longrightarrow$ above $v_{\rm esc}$

Annihilation



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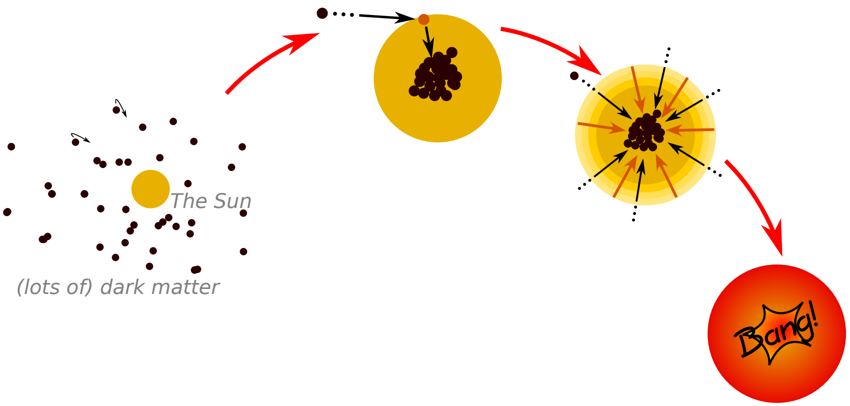

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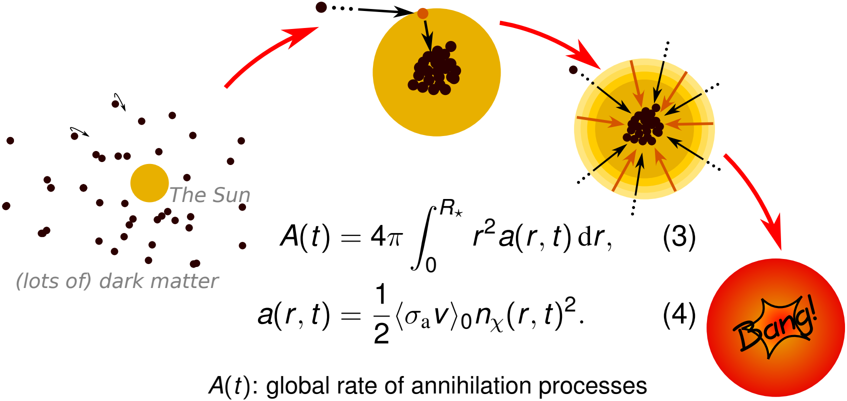
Annihilation



$$A(t) = 4\pi \int_0^{R_\star} r^2 a(r,t)\,\mathrm{d}r, \qquad (3)$$

$$a(r,t) = \frac{1}{2}\langle\sigma_\mathrm{a} v\rangle_0 n_\chi(r,t)^2. \qquad (4)$$

$A(t)$: global rate of annihilation processes
$a(r,t)$: local rate of annihilation processes
$\langle\sigma_\mathrm{a} v\rangle_0$: annihilation cross-section
$n_\chi(r,t)$: DM number density

Dark matter population master equation

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = C(t) - 2A(t) - E(t), \tag{5}$$

When

- $E(t) = 0$
- $C(t)$ constant
- $A(t)$ = constant $\times$ $N(t)^2$

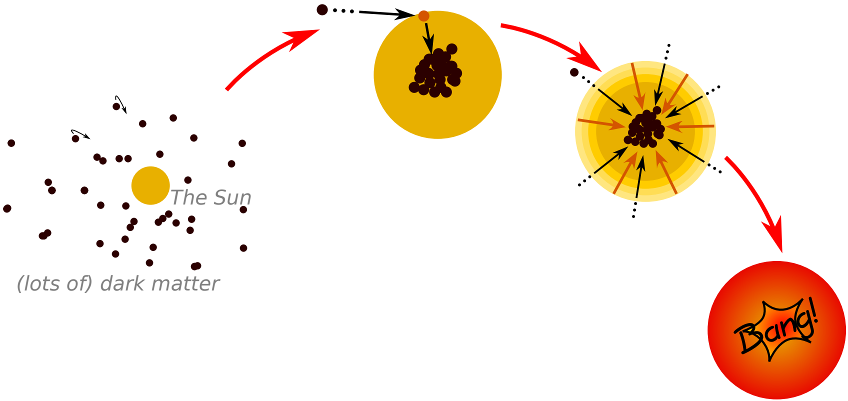
then

$$N(t) = C(t)t_\mathrm{eq} \tanh\left(\frac{t}{t_\mathrm{eq}}\right) \tag{6}$$

with equilibration time $t_\mathrm{eq} = (2AC/N^2)$.

In practice, it's usually better to just solve for N numerically as the star evolves.

Indirect detection



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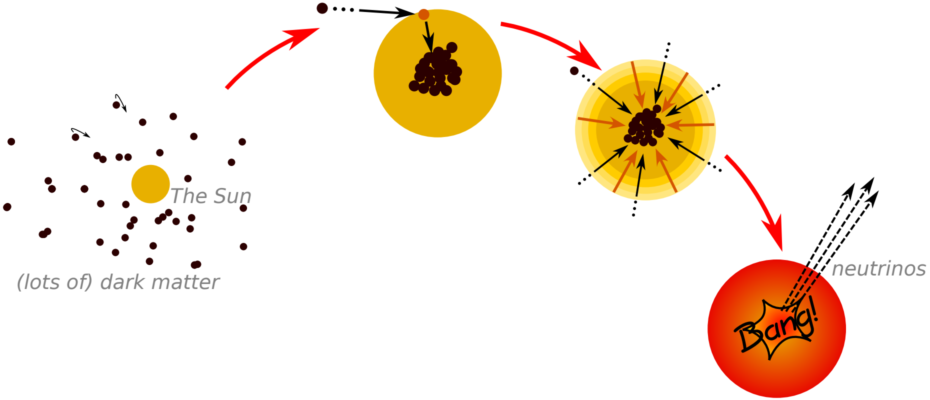

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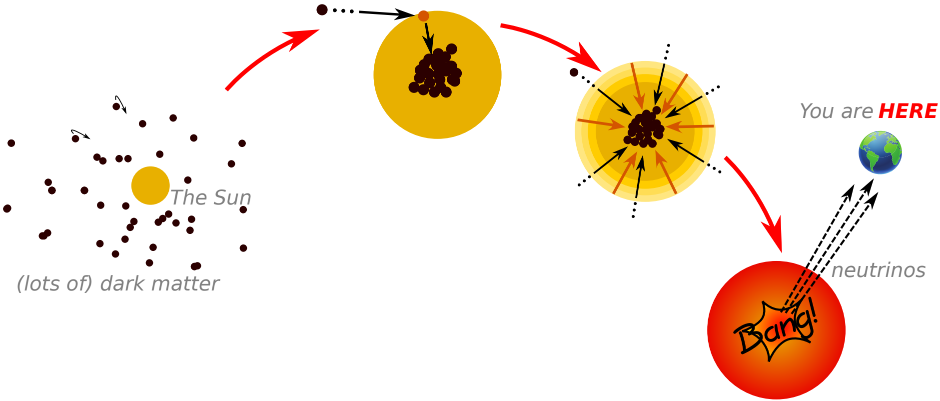

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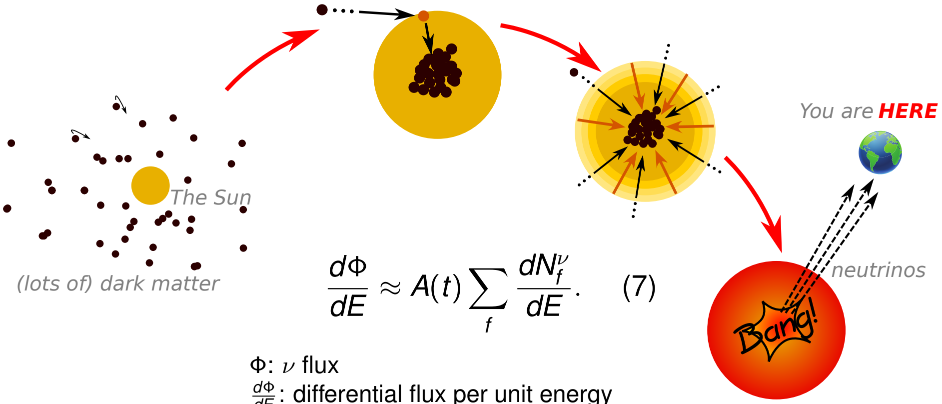
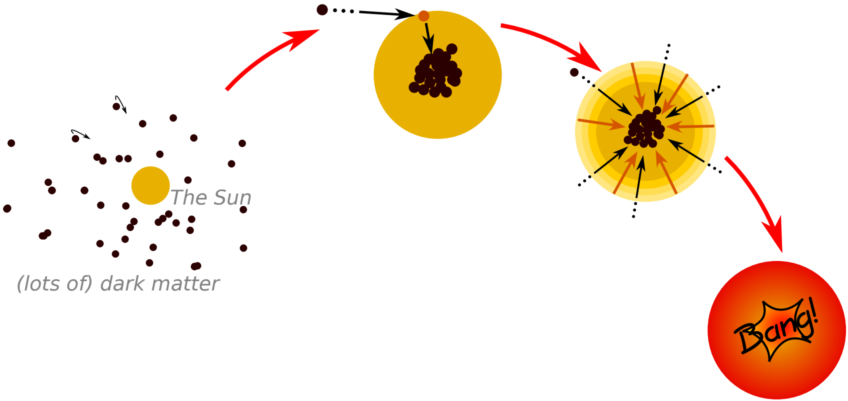


$$\frac{d\Phi}{dE} \approx A(t)\sum_f \frac{dN_f^\nu}{dE}. \qquad (7)$$

Φ: ν flux
$\frac{d\Phi}{dE}$: differential flux per unit energy
f: final state
dN^ν/dE: annihilation spectrum

Heat conduction



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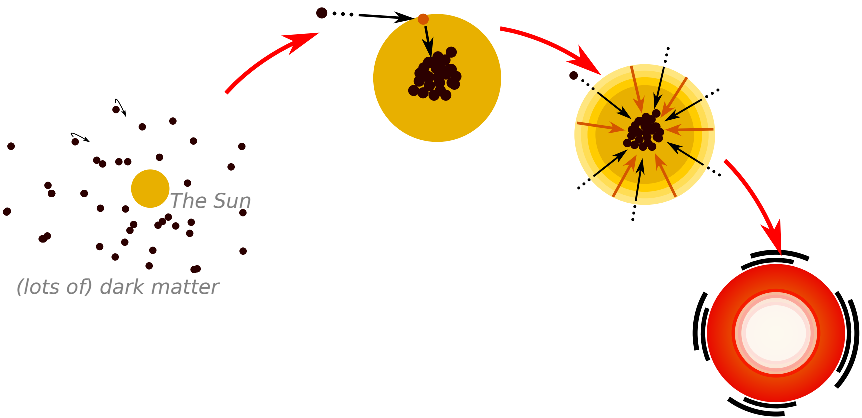

Local conductive energy transport with dark matter

Dark matter number density:

$$n_\chi(r) = n_\chi(0)\left[\frac{T(r)}{T(0)}\right]^{3/2}\exp\left[-\int_0^r \mathrm{d}r'\,\frac{k_\mathrm{B}\alpha(r')\frac{\mathrm{d}T(r')}{\mathrm{d}r'} + m_\chi\frac{\mathrm{d}\phi(r')}{\mathrm{d}r'}}{k_\mathrm{B}T(r')}\right] \qquad (8)$$

Dark matter conductive luminosity:

$$L_\chi(r) = 4\pi r^2\zeta^{2n}(r)\kappa(r)n_\chi(r)l_\chi(r)\left[\frac{k_\mathrm{B}T(r)}{m_\chi}\right]^{1/2}k_\mathrm{B}\frac{\mathrm{d}T(r)}{\mathrm{d}r}, \qquad (9)$$

Corresponding energy injection rate per unit mass of stellar material:

$$\epsilon_\chi(r) = \frac{1}{4\pi r^2\rho(r)}\frac{\mathrm{d}L_\chi(r)}{\mathrm{d}r}. \qquad (10)$$

$\phi(r)$: gravitational potential at height r in star
$T(r)$: temperature at height r
$\rho(r)$: stellar density at height r
$\zeta(r)$: $v_0/v_T(r)$ or $q_0/[m_\chi v_T(r)]$ depending on cross-section
$v_T(r)$: DM thermal velocity at height r

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Mini-Summary: Observables to watch out for

DM-nucleon scattering allows DM collisions with nuclei in the Sun

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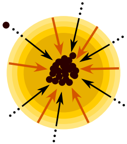
DM-nucleon scattering allows DM collisions with nuclei in the Sun
→ gravitational capture and settling the to solar core



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DM-nucleon scattering allows DM collisions with nuclei in the Sun
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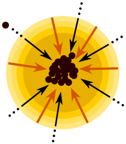


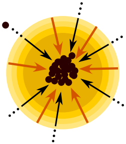
Mini-Summary: Observables to watch out for

DM-nucleon scattering allows DM collisions with nuclei in the Sun

⟶ gravitational capture and settling the to solar core

⟶ 1. observable: high-*E* neutrinos from annihilation

⟶ 2. nuclear scattering inside the Sun



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DM-nucleon scattering allows DM collisions with nuclei in the Sun
⟶ gravitational capture and settling the to solar core
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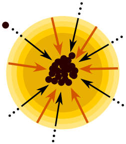
  ⟶ 2. nuclear scattering inside the Sun
    ⟶ additional energy transport



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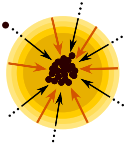
  - ⟶ additional energy transport
    - ⟶ modified solar structure



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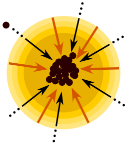
→ 1. observables: (helioseismology)

– sound speed
– oscillation frequencies
– convective zone depth
– surface helium frac.



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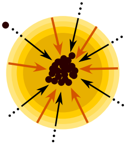
      - → 2. different core temperature



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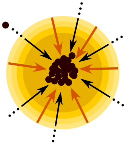

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        → 2. different core temperature

          → observable: solar neutrino rates

WIMPS

$\langle \sigma v \rangle \neq 0$

$\sigma_{\rm nuc} \neq 0$

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Mini-Summary: Observables to watch out for

DM-nucleon scattering allows DM collisions with nuclei in the Sun

$\longrightarrow$ gravitational capture and settling the to solar core

- $\longrightarrow$ 1. ~~observable: high-E neutrinos from annihilation~~
- $\longrightarrow$ 2. nuclear scattering inside the Sun
  - $\longrightarrow$ additional energy transport
    - $\longrightarrow$ modified solar structure
      - $\longrightarrow$ 1. observables: (helioseismology)
        - – sound speed
        - – oscillation frequencies
        - – convective zone depth
        - – surface helium frac.
      - $\longrightarrow$ 2. different core temperature
        - $\longrightarrow$ observable: solar neutrino rates

ADM

$\langle \sigma v \rangle \sim 0$

$\sigma_{\rm nuc} \neq 0$

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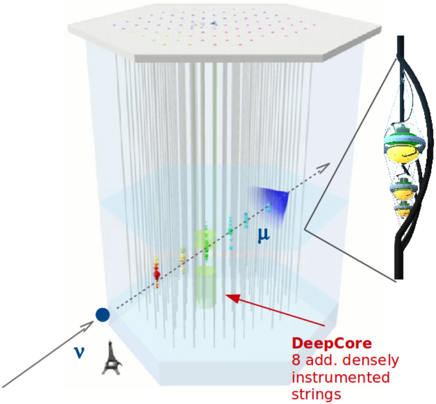
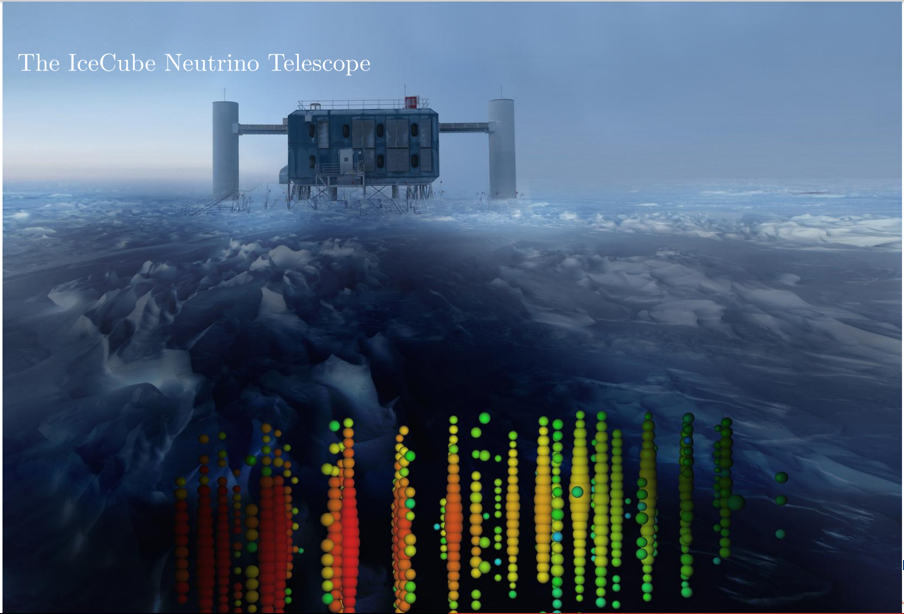
The IceCube Neutrino Observatory

- 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)



DeepCore
8 add. densely instrumented strings

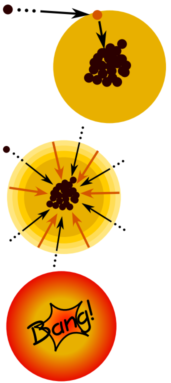
The IceCube Neutrino Telescope



Neutrino telescope likelihoods: `nulike`

Unbinned ν telescope likelihood $\Longrightarrow$ full event-level angular and energy info

$$\mathcal{L}_\mathrm{unbin} \equiv \mathcal{L}_\mathrm{num}(n_\mathrm{tot}|\theta_\mathrm{tot}) \prod_{i=1}^{n_\mathrm{tot}} (f_\mathrm{S}\mathcal{L}_{\mathrm{S},i} + f_\mathrm{BG}\mathcal{L}_{\mathrm{BG},i})$$



Strategy: precompute partial likelihoods for each event, then reweight with the ν spectrum at Earth for each model

- precompute step uses `nusigma` with CTEQ6-DIS PDFs to get charged current $\nu - n$ and $\nu - p$ cross-sections as function of x and y
- like step input: neutrino spectrum at Earth (from DarkSUSY or whatever else you want to use)
- like step output: num predicted events, likelihood
- → fully model-independent = future-proof for global fits

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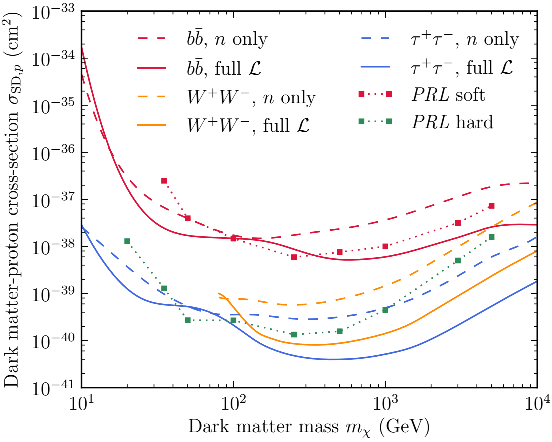

IceCube Collab. (contacts: PS + M. Danninger) arXiv:1601.00653, *JCAP* 2016
`nulike`: model-independent unbinned limit calculator for generic BSM models
Publicly available at nulike.hepforge.org

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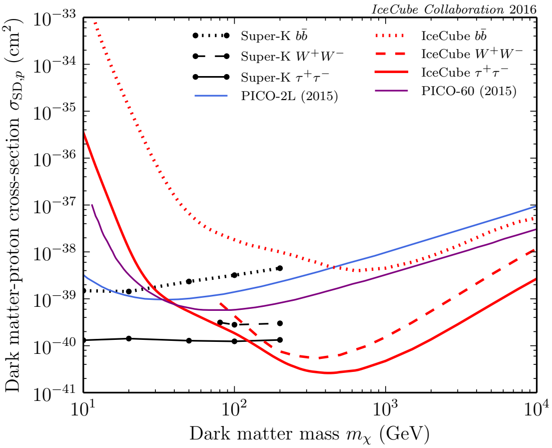

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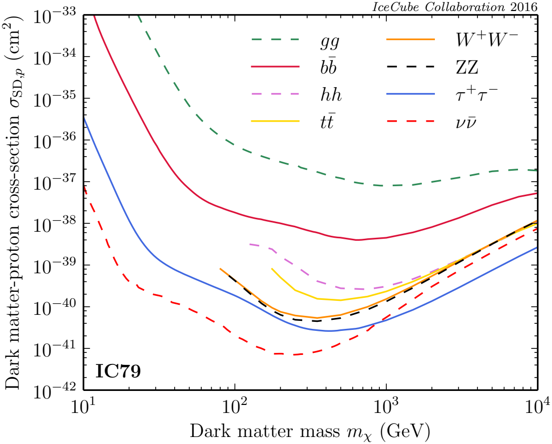

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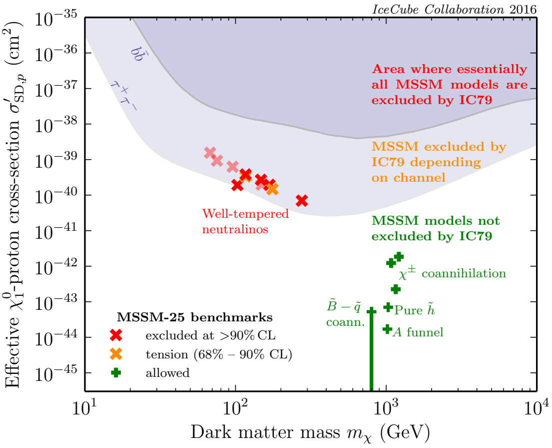

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A word on how (not) to interpret indirect detection in BSM models

- Indirect limits always presented in terms of hard process final states
- Actual experiments do not measure those final states – they detect one type of SM particle produced later: γs, νs, etc
- Limits as presented cannot be combined and applied to models with mixed final states (= all non-toy models)
- Proper treatment of indirect detection for BSM searches requires full phenomenological recast abilities
  $\rightarrow$ full experimental *and* theoretical treatment at the same time

GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org

- Fast definition of new datasets and theoretical models
- Plug and play scanning, physics and likelihood packages
- Extensive model database – not just SUSY
- Extensive observable/data libraries
- Many statistical and scanning options (Bayesian & frequentist)
- *Fast* LHC likelihood calculator
- Massively parallel
- Fully open-source

ATLAS	A. Buckley, P. Jackson, C. Rogan, M. White,
LHCb	M. Chrząszcz, N. Serra
Belle-II	F. Bernlochner, P. Jackson
Fermi-LAT	J. Conrad, J. Edsjö, G. Martinez, P. Scott
CTA	C. Balázs, T. Bringmann, J. Conrad, M. White
HESS	J. Conrad
IceCube	J. Edsjö, P. Scott
XENON/DARWIN	J. Conrad, R. Trotta
Theory	P. Athron, C. Balázs, T. Bringmann, J. Cornell, J. Edsjö, B. Farmer, T. Gonzalo, S. Hoof, F. Kahlhoefer, A. Krislock, A. Kvellestad, M. Pato, F. Mahmoudi, J. McKay, A. Raklev, R. Ruiz, P. Scott, R. Trotta, C. Weniger, M. White

27 Members, 9 Experiments, 4 major theory codes, 10 countries

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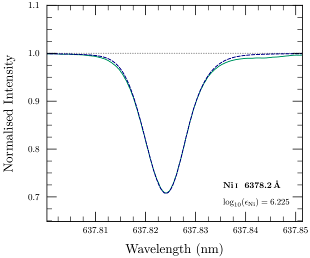
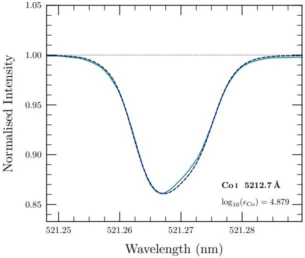
Solar abundances

- Latest solar photospheric abundances (Asplund, Grevesse, Sauval & PS: AGS05, AGSS09) factor of $\sim$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
- $Z = 0.017$ (GS98) $\rightarrow$ $Z = 0.013$ (AGSS09)

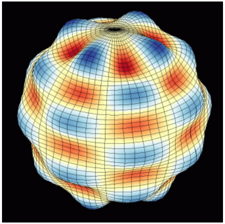




PS, Grevesse, Asplund et al *A&A* 2015

Helioseismology

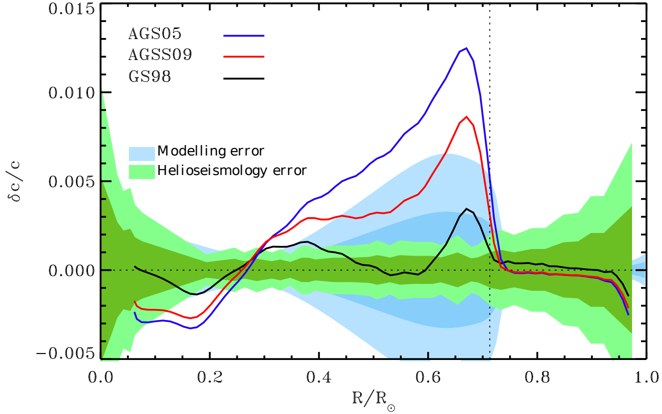
- Change Z
  $\rightarrow$ change temperature and density of interior
  $\rightarrow$ change frequencies of oscillations.
- Observe central frequency of a line Doppler shifting
  $\rightarrow$ reconstruct oscillation modes
  $\rightarrow$ compare to predictions from solar models



Credit: U Birmingham

Sound speed

Adapted from Serenelli et al (ApJ 2009)



Depth of the convection zone and surface helium

- Derivative of temperature gradient changes abruptly at base of convection zone
  → gives characteristic oscillation frequency signature
- Surface helium has implications for initial Y and thus overall molecular weight required to match observed $L_\odot$

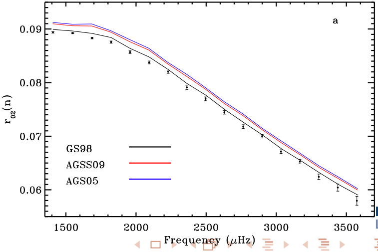
	$R_{\rm CZ}$	$Y_{\rm S}$
Observed	0.713 ± 0.001	0.2485 ± 0.0034
GS98	0.712 ± 0.002	0.243 ± 0.003
AGSS09	0.723 ± 0.002	0.232 ± 0.003

Small frequency separations

- Considering frequency difference ratios cancels many modelling systematics
- Particular combinations of frequencies are especially sensitive probes of the core

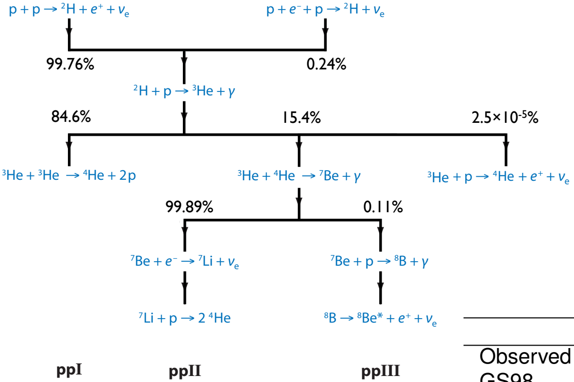
$$r_{02}(n) = \frac{\nu_{n,0} - \nu_{n-1,2}}{\nu_{n,1} - \nu_{n-1,1}}; \quad r_{13}(n) = \frac{\nu_{n,1} - \nu_{n-1,3}}{\nu_{n+1,0} - \nu_{n,0}}, \qquad (11)$$

ν: oscillation frequency
n, l: radial order, angular degree of mode



Serenelli et al. *ApJ* 2009

Solar neutrinos



$p + p \rightarrow {}^2H + e^+ + \nu_e$

$p + e^- + p \rightarrow {}^2H + \nu_e$

99.76%

0.24%

${}^2H + p \rightarrow {}^3He + \gamma$

84.6%

15.4%

2.5×10^{-5}%

${}^3He + {}^3He \rightarrow {}^4He + 2p$

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$

99.89%

0.11%

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow 2\,{}^4He$

${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

ppI

ppII

ppIII

Haxton, Robertson, Serenelli *Ann. Rev. A&A* 2012

$$\Phi({}^7\mathrm{Be}) \propto T_c^{10}$$

$$\Phi({}^8\mathrm{B}) \propto T_c^{24}$$

	$\Phi({}^7\mathrm{Be})$	$\Phi({}^8\mathrm{B})$
Observed	$4.80(1 \pm 0.05)$	$5.16(1 \pm 0.02)$
GS98	$5.00(1 \pm 0.07)$	$5.58(1 \pm 0.14)$
AGSS09	$4.56(1 \pm 0.07)$	$4.59(1 \pm 0.14)$

- AGSS09 abundances mess up inferred sound speed profile, helium abundance, depth of convection zone and small frequency separations
- Many solutions attempted in the last decade:
    - Accretion of low-metallicity gas
    - Bulk opacity modifications
    - Line broadening in opacities
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- Better agreement with Sun and direct detection if $\sigma \propto q^n v^m$ (Vincent, PS, Serenelli, *PRL*, *JCAP*, 2015-16 →Aaron)

Imperial College London

How not to solve the solar abundance problem

Recent papers claim solar wind prefers high abundances, and solves solar abundance problem

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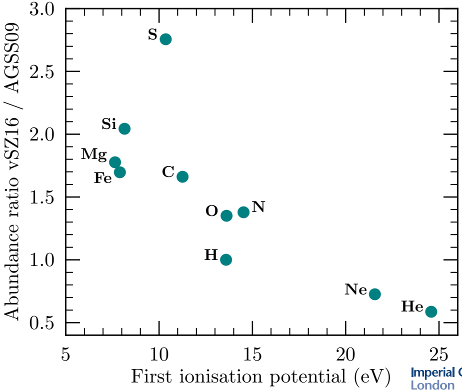

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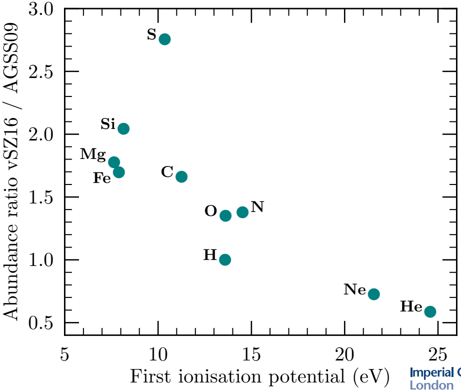

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How not to solve the solar abundance problem

Q2. Do solar models with wind composition solve the solar abundance problem?

	$\chi^2_{\rm GS98}$	$\chi^2_{\rm AGSS09}$	$\chi^2_{\rm vSZ16}$
$Y_{\rm S}$	1.4	13.5	34.2
$R_{\rm CZ}$	0.15	14.8	0.60
$Y_{\rm S} + R_{\rm CZ}$	1.6	64.8	47.3
$\{c_i\}$	46.4	111.2	359.3
$\Phi(^8{\rm B})$	0.44	1.18	19.0
$\Phi(^7{\rm Be})$	0.28	0.45	15.0
Combined	65.5	186.1	489.1

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- $\rightarrow$ suggests/constrains the existence of certain ADM models ($\rightarrow$Aaron)