Light dark matter properties with neutrinos from the Sun

Mattias Blennow
emb@kth.se

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Collaborators: J. Edsjö, T. Ohlsson, E. Fernandez-Martinez, O. Mena, S. Agarwalla, M. Carrigan

1 Status of Dark Matter

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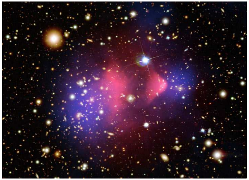
2 Dark Matter in the Sun

Beyond the Standard Model

- Hints for physics beyond the Standard Model:
    - Dark Matter (DM)
    - Dark Energy
    - Neutrino oscillations



Beyond the Standard Model

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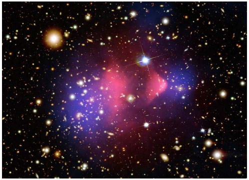

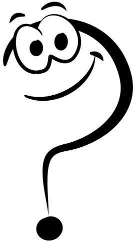

- Open questions for this talk
  - What is the nature of DM?
  - How can we detect it?
  - Can we use neutrinos?

Comparing Baryonic and Dark Matter

Baryons

Mass:

$m_N \simeq 1$ GeV

Abundance:

$n_b/n_\gamma = (6.19 \pm 0.15) \cdot 10^{-10}$

Density:

$\Omega_b \simeq 0.049$

Dark Matter

Mass:

Abundance:

Density:

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Abundance:

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$\Omega_{DM} \simeq 0.27$

$$\frac{\Omega_{DM}}{\Omega_b} \simeq 5$$

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$\Longrightarrow$ Cross section of weak strength

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$\Longrightarrow$ Cross section of weak strength

- Weakly Interacting Massive Particles (WIMPs)

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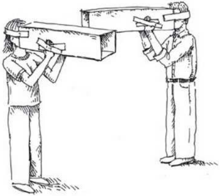
$\Longrightarrow$ Cross section of weak strength

- Weakly Interacting Massive Particles (WIMPs)
- Great! Or is it?



The WIMP miracle

Baryons

Mass:

$m_N \simeq 1$ GeV

Abundance:

$n_b/n_\gamma = (6.19 \pm 0.15) \cdot 10^{-10}$

Density:

$\Omega_b \simeq 0.046$

WIMP Dark Matter

Mass:

$m_{DM} \simeq 1$ TeV

Abundance:

$n_{DM} \simeq 10^{-3} n_b$

Density:

$\Omega_{DM} \simeq 0.23$

$$\frac{\Omega_{DM}}{\Omega_b} \simeq 5$$

The WIMP miracle!

The WIMP miracle

Baryons

Mass:

$m_N \simeq 1$ GeV

Abundance:

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NOT thermal production!

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Thermal freezout

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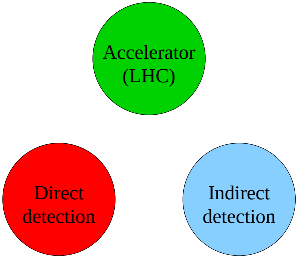
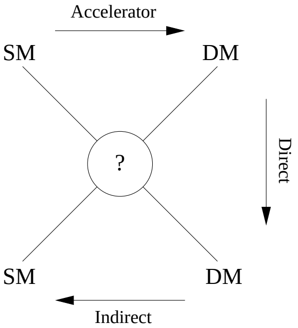
The WIMP miracle!

The three avenues



- Accelerators: LHC
- Direct detection: DAMA/LIBRA, COUPP, CoGeNT, XENON
- Indirect detection: PAMELA, AMS-02, FERMI/LAT, IceCube

The three avenues



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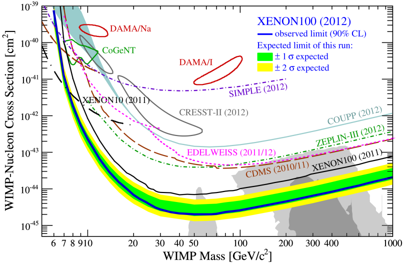
Direct detection

- Signal: Recoils from DM-SM scattering
- Many different experiments
  - DAMA/LIBRA
  - CoGeNT
  - CRESST
  - CDMS
  - XENONx

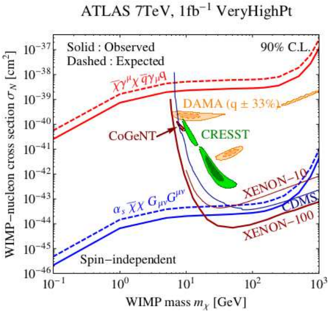


XENON100, Phys.Rev.Lett. 109 (2012) 181301

- Large nuclei → Spin independent cross-sections (scales as A^2)
- Dependent on local DM distribution

Accelerator searches

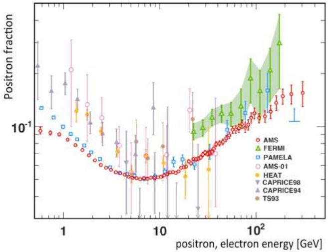
- Signal: Something missing!
- In many ways complementary to direct searches
- Typically assume effective theory
- At disadvantage for light mediator masses?



Fox, Harnik, Kopp, Tsai
Phys.Rev. D85 (2012) 056011

Indirect detection

- Signal: DM annihilation products
- Where? Almost everywhere!
    - Gamma rays (Fermi-LAT)
    - Antimatter excess in cosmic fluxes (PAMELA, AMS-02, Fermi-LAT)
    - Neutrinos from the Sun (IceCube, Super-K, etc)
- Scales as DM density squared
- Very dependent on assumptions



AMS-02 homepage

The current status (good news!)

We have several DM signals/hints!

Direct

DAMA/LIBRA, CoGeNT, CRESST
$m_{\mathrm{DM}} \simeq 10$ GeV, $\sigma \simeq 0.1$ fb

Indirect

Fermi-LAT
$m_{\mathrm{DM}} \simeq 130$ GeV
PAMELA, Fermi-LAT, AMS-02
$m_{\mathrm{DM}} \gtrsim 300$ GeV

. . . or with or with other experiments . . .

They just dont fit together . . .

The current status (bad news!)

Image from FreeDigitalPhotos.net

- All signals seem to be excluded or unlikely to be caused by DM
  - Direct detection – excluded by others (most strongly XENON100)
  - Positron excess – difficult from model perspective
  - Gamma ray excess – is it there or not?

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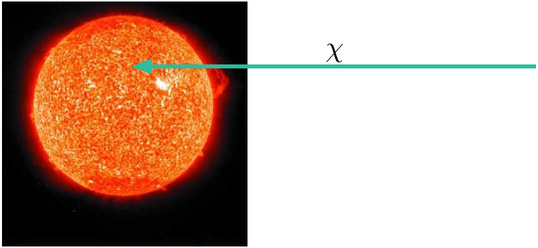
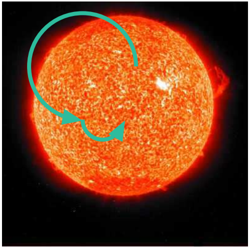
DM capture and annihilation

DM capture and annihilation



DM capture and annihilation



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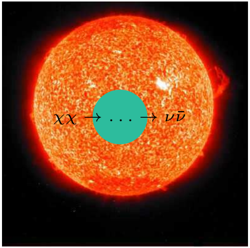
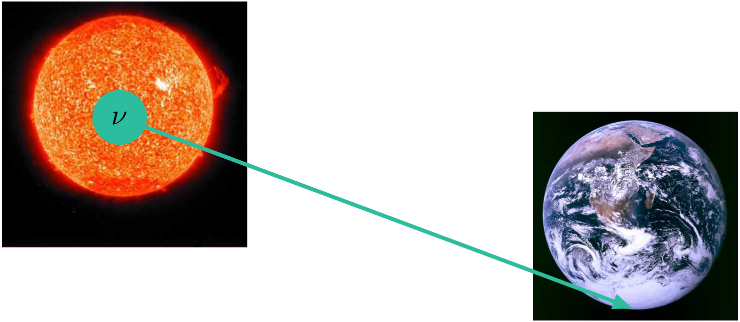


DM capture and annihilation



Capture

$$\frac{dC_{\odot,i}}{dV} = \frac{\rho_\chi\, \rho_{\odot,i}(r)}{2m_\chi \mu_i^2}\, \sigma_i \int_0^\infty du\, \frac{f(u)}{u} \int_{E_{R,\min}}^{E_{R,\max}} dE_R\, |F(E_R)|^2 \tag{1}$$

$$\frac{f(u)}{u} = \frac{1}{\sqrt{\pi}\, v_\odot^2} \left(e^{-(u-v_\odot)^2/v_\odot^2} - e^{-(u+v_\odot)^2/v_\odot^2} \right) \tag{2}$$

$$C_\odot = 4\pi \sum_i \int_0^{R_\odot} dr\, r^2\, \frac{dC_{\odot,i}}{dV} \tag{3}$$

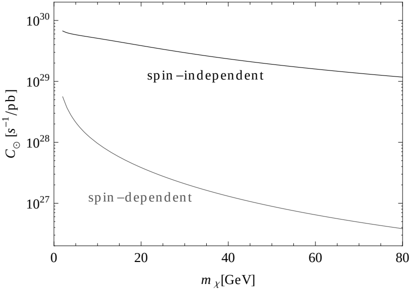
Capture

- Proportional to σ_p
- Proportional to local DM density
- Depends on the DM mass
- Depends on $v_\odot$

We assume:

$v_\odot = 220$ km/s

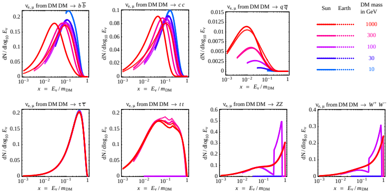
$\rho_{\mathrm{DM}} = 0.3$ GeV/cm^3



Kappl, Winkler, Nucl.Phys. B850 (2011) 505-521

Annihilation

- Several different annihilation channels possible (depending on m_{DM})
  - Quarks ($q\bar{q}$)
  - Leptons ($\ell^+\ell^-$, $\nu\bar{\nu}$)
  - Weak mediators (W^+W^-, ZZ)
  - Gluons (gg)



Cirelli, et al., Nucl.Phys. B727 (2005) 99-138

- Some do not give neutrinos
- For the others we can compute the spectrum
- Not dependent on annihilation cross section(!) but sensitive to branching ratios

Propagation to the Earth

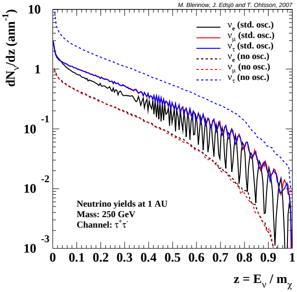
Do we need to consider neutrino oscillations? What is $\Delta m_{31}^2 L$?

- Sun-Earth, $\sim 3.5 \cdot 10^5$ GeV
- Perhelion-aphelion, $\sim 10^4$ GeV
- Day-night, ~ 30 GeV

On the other hand

- Detectors have finite resolution
- Typically oscillation effects are washed out

See:
Cirelli, et al., Nucl. Phys. B727, 99 (2005)
MB, Edsjö, Ohlsson, JCAP 0801 (2008) 021
Esmaili, Farzan, Phys.Rev. D81 (2010) 113010



MB, Edsjö, Ohlsson, JCAP 0801 (2008) 021

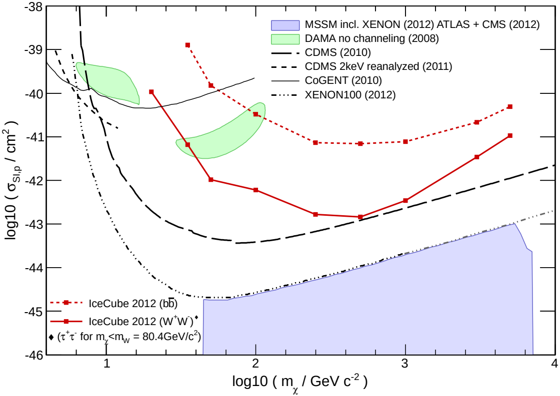
WimpSim

MonteCarlo for neutrino telescope studies: **WimpSim**
MB, Edsjo, Ohlsson, JCAP 0801 (2008) 021
http://copsosx03.physto.se/wimpsim/

- Addition to DarkSusy
- Dark matter capture
- Annihilations
- Oscillation and absorbtion
- Event based
- Gives different types of fluxes at a detector as output

In use in the neutrino telescope community

Current limits (spin independent)



IceCube Collaboration, Phys.Rev.Lett. 110 (2013) 131302

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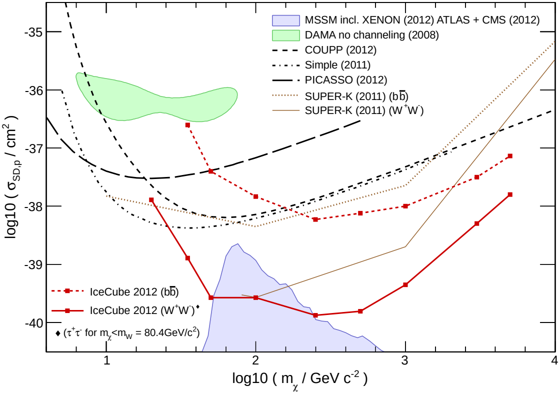
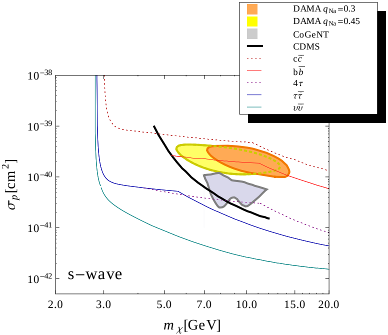
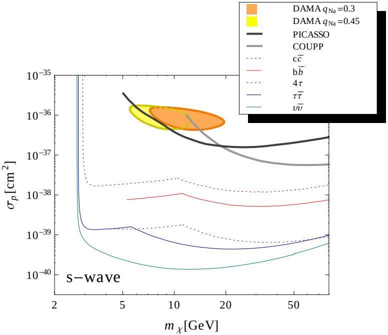


IceCube Collaboration, Phys.Rev.Lett. 110 (2013) 131302

Low DM mass region (Super-K)





Kappl, Winkler, Nucl.Phys. B850 (2011) 505-521

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What do we need?

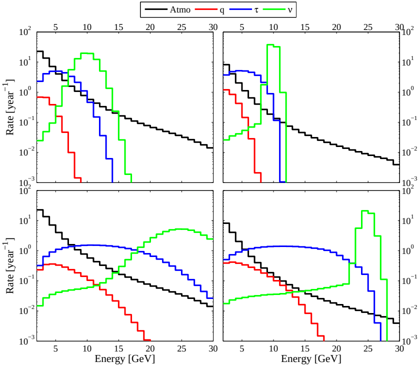
If Super-K works, what about the next generation of neutrino detectors? What do we need?

- Volume!
    - Not competing with IceCube - different mass regime
- Low threshold
    - We need to see the spectrum
    - Preferably significantly lower than $m_{\rm DM}$
- High resolution
    - In energy → spectral information
    - In angle → background suppression

Volume

- More volume = More statistics
- IceCube = 1 km^3 = 1 Gton
- Future neutrino experiment $\simeq$ 0.1 Mton
- Denser instrumentation = lower threshold

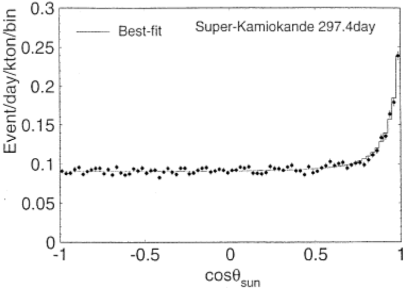
Low threshold



I will get back to this figure

Resolution

- Energy
  - Would like to do more than counting
  - Mass determination
  - Annihilation branching ratios
- Angle
  - Background rejection (atmospheric)
  - Compare to "ordinary" solar ν



Dar, Shaviv, Phys.Rept. 311 (1999) 115-141

Candidates

- Good news: If you can do atmospherics, you (probably) can do this
- Consider some detectors discussed for future LBL experiments
    - Liquid Argon (LAr) TPC – LBNO / LBNE
    - Magnetic Iron Calorimeter (MIND) – INO
    - Water Cherenkov – Hyper-K

Simulation setup

- Results are based on a MarkovChain Monte Carlo study
- Consider the following experiment
  - LAr (34 kton, 100 kton)
  - MIND (100 kton)
- Consider the following parameters

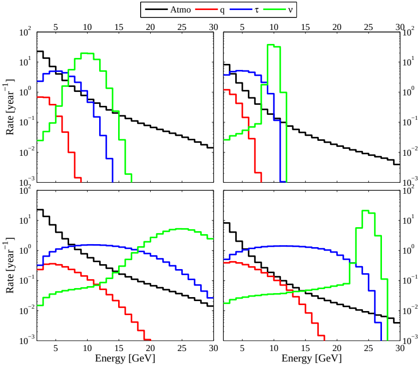
$$m_{\mathrm{DM}}, \sigma \mathrm{Br}_\nu, \sigma \mathrm{Br}_\tau, \sigma \mathrm{Br}_q$$

$(\sigma \mathrm{Br}_x = \sigma_{\mathrm{SD}} \, \mathsf{BR}(\chi\chi \to x\bar{x}))$

- Good convergence, $8 \cdot 10^5$ samples

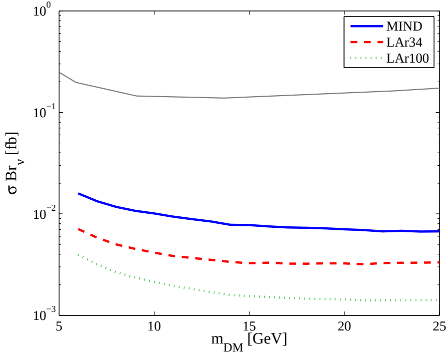
Spectra @ detectors

- $\sigma_{\mathrm{SD}} = 1$ fb
- Background includes angular cut (could be refined)
- For details on assumptions, see original reference



MB, Carrigan, Fernandez-Martinez, arXiv:1303.4530

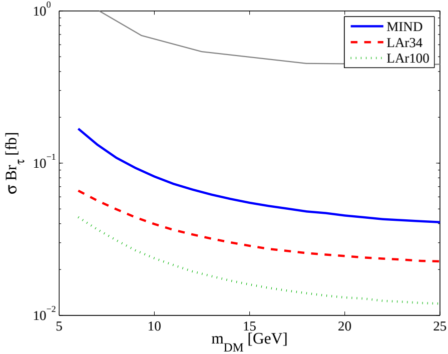
Sensitivity $(\chi\chi \to \nu\bar{\nu})$



MB, Carrigan, Fernandez-Martinez, arXiv:1303.4530

- Gray line, Super-Kamiokande from
Kappl, Winkler, Nucl.Phys. B850 (2011) 505-521
- 1–2 order of magnitude improvement

Sensitivity $(\chi\chi \to \tau^+\tau^-)$



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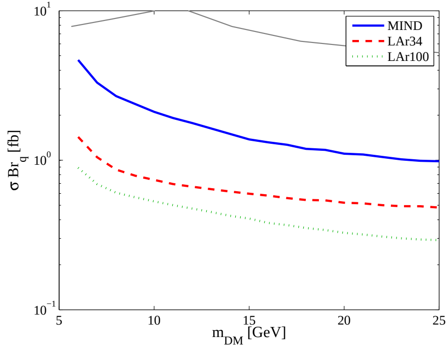

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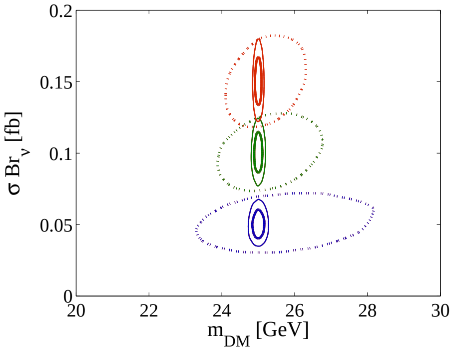
Branching ratios and mass

$\chi\chi \to \nu\bar{\nu}$, $m_{\rm DM} = 25$ GeV

- Sub-GeV precision in $m_{\rm DM}$ for LAr (solid and dashed)
- GeV precision for MIND (dotted)
- Precision worse for lower signal (expected)

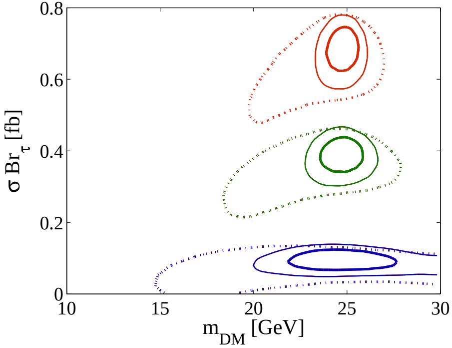


MB, Carrigan, Fernandez-Martinez, arXiv:1303.4530

Branching ratios and mass

$\chi\chi \to \tau^+\tau^-$, $m_{\mathrm{DM}} = 25$ GeV

- Mass determination still fair
- Requires larger branching
- First signs of degeneracy (MIND)

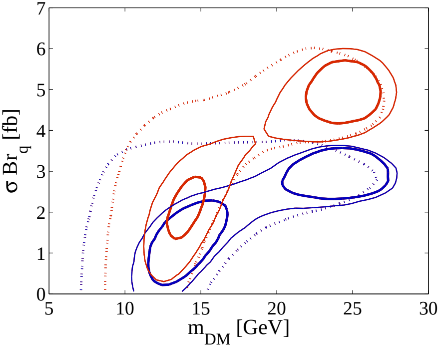


MB, Carrigan, Fernandez-Martinez, arXiv:1303.4530

Branching ratios and mass

$\chi\chi \to q\bar{q}$, $m_{\rm DM} = 25$ GeV

- Bad mass resolution
- Very large branching
- Degenerate!



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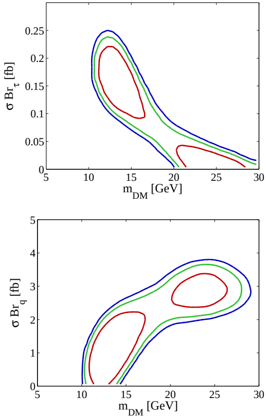
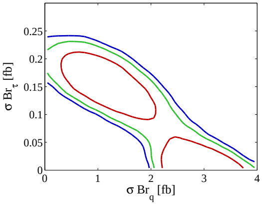
Origin of the degeneracy



34 kton LAr



MB, Carrigan, Fernandez-Martinez,
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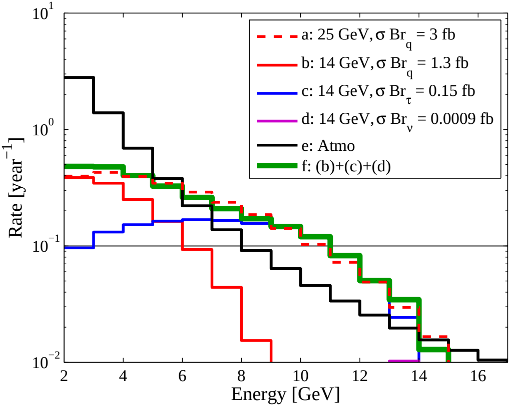
- Lower mass, different branching
- Mainly $\sigma\mathrm{Br}_q$–$\sigma\mathrm{Br}_\tau$ degeneracy

Degeneracy as seen in the spectrum



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Summary

- Dark Matter, just like neutrinos, point to beyond-SM physics
- Detection prospects: Accelerator, Direct, Indirect
- Indirect neutrino signals from the Sun
- Neutrino telescopes, but “small” detectors can compete at low masses!
- Study for future long baseline detectors
- Discussed degeneracy in determination of parameters

Conclusions

- Indirect detection of neutrinos from the Sun offers a complement to direct detection and accelerators
- The framework for implementation and analysis is well developed, as is the underlying theory
- Can span a wide range of Dark Matter masses
- Contstraints can be pushed down in the low mass regime by LBL detectors – or we make a discovery