Dark Matter Theory and New Searches

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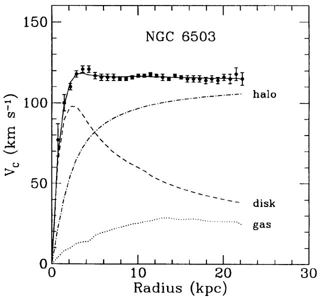
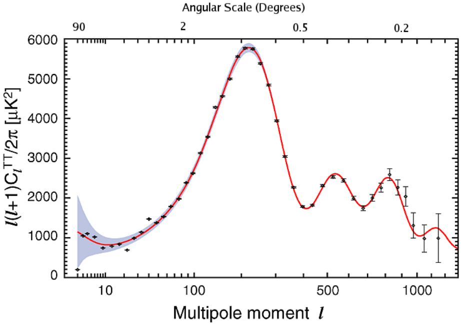
Dark matter theory overview
+ work in preparation with Kenny Ng and John Beacom

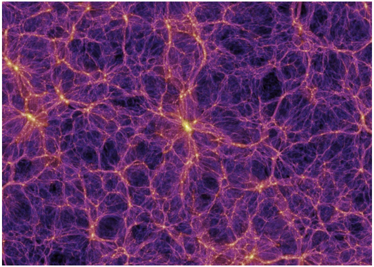
THE UNIVERSITY OF MELBOURNE

CoEPP

Abundance of evidence!







What we think we know about dark matter

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- About 5 times more abundant than baryonic matter
- Stable, or has lifetime greater than age of universe
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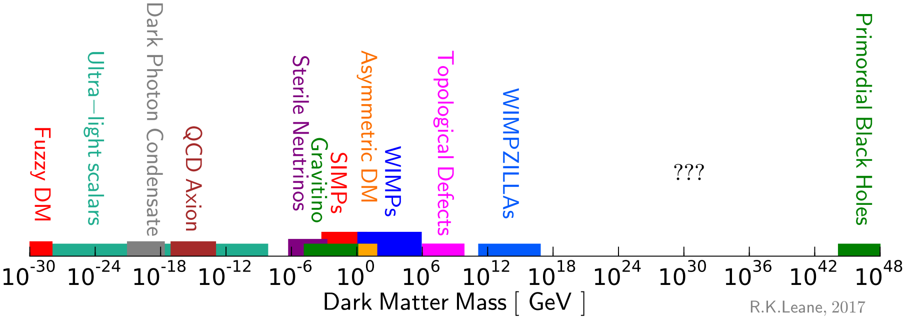
  - Dark haloes do not allow for large amounts of cooling via radiation
  - Small fraction could be allowed via dark radiation (i.e. double disk DM)
- Either non self-interacting or self-interacting
- Mostly either cold (non-relativistic) or warm (semi-relativistic)
  - Cold $\rightarrow$ missing satelites, cusp predicted but core observed
  - Warm $\rightarrow$ not enough satelites

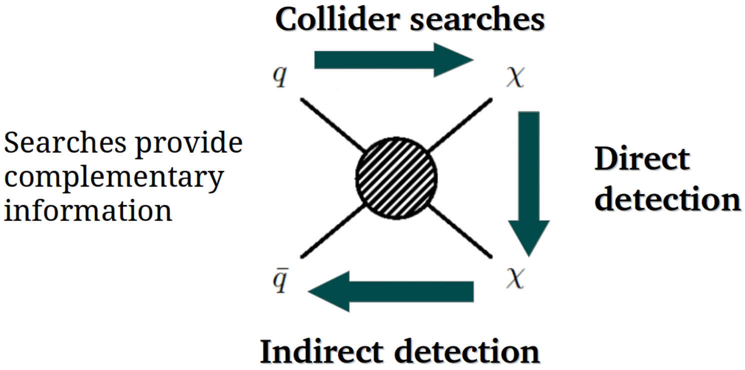
Range of dark matter candidates

Many DM masses possible. Can be roughly $10^{-31} < m_\chi < 10^{48}$ GeV!

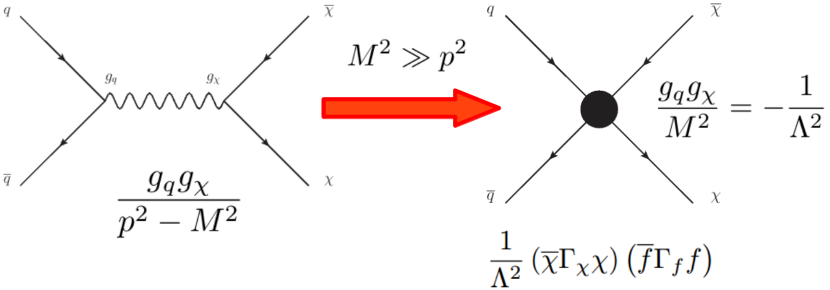


Searches for particle dark matter

- WIMP dark matter well motivated: weak scale masses and interaction strengths
- Many candidates predicted by UV theories
- Realistic detection prospects



Effective field theories for dark matter



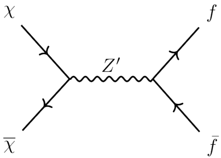
- Model independent
- Useful at low energies, i.e. direct detection
- Colliders? Need to be careful. Cutoff at new physics scale.

Simplified models for dark matter

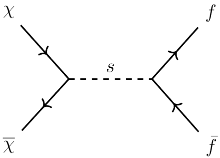
- Only lightest mediator is retained, set limits on couplings and mediators
- Allows for richer phenomenology

Benchmark Simplified Models:

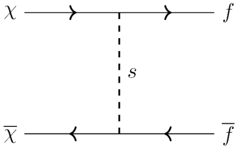
s-channel spin-1



s-channel spin-0



t-channel spin-0



Status of simplified DM models

- Not intrinsically capable of capturing full phenomenology of UV complete theories
  - Fine, but need to use when appropriate
  - Issues with gauge invariance have motivated next generation, "less simplified models"

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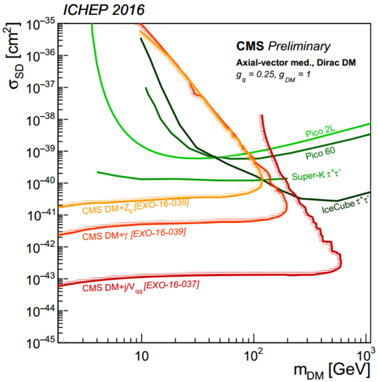
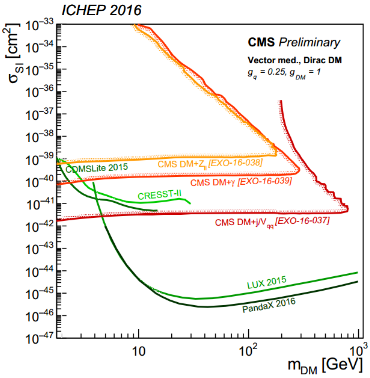




So many theories, so little time

- Good to be model independent where possible, but also need to ensure models are physically consistent, not to miss important phenomenology

- Another important avenue for discovery is finding distinctive new signatures, exploiting strengths of different experiments

Complementary probe of the DM scattering cross section

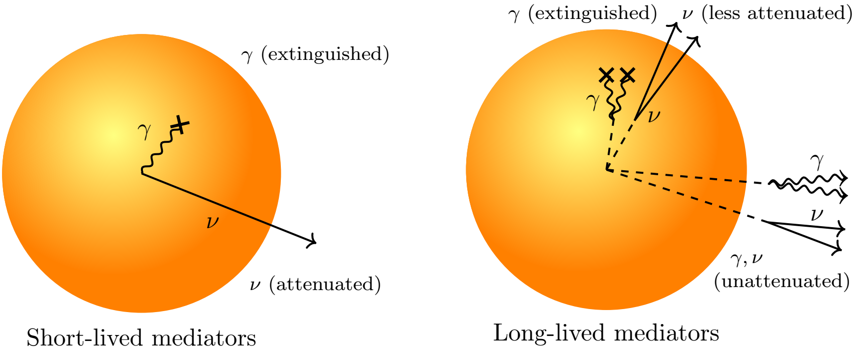
DM can be captured in the Sun by scattering with solar nuclei.

- Of possible DM annihilation modes, only neutrinos weakly interacting enough to escape
- These neutrinos are measured at SuperK and IceCube, provide probe of DM scattering cross section
- What if DM annihilates to long-lived mediators instead?

Solar signatures of long-lived dark mediators

If annihilation proceeds via long-lived dark mediators:

1. Neutrinos will be less attenuated
2. Other particles such as gamma-rays can escape



RKL, Ng, Beacom (in preparation)

Measuring gamma-rays with new Fermi-LAT data

Standard annihilation fluxes of DM to gamma-rays are enormous.
For example, if 100 GeV DM with scattering $\sigma_{\chi P}^{SD} \sim 10^{-40}\,\mathrm{cm}^2$ annihilates directly to gamma-rays, the energy flux is

$$\sim 10^{-2}\,\mathrm{GeV}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}.$$

In this region, the sensitivity of Fermi-LAT is

$$\sim 10^{-8}\,\mathrm{GeV}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}.$$

The annihilation flux is in excess of sensitivity by a factor of $\mathbf{10^6}$!

$\rightarrow$ Long-lived mediators open a window to otherwise lost DM signals, potentially large rates!

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Searches in gamma-ray and neutrino channels

Gamma-rays:

- Current limits use Fermi data on solar gamma-rays
  - 2011 and 2015 analyses
- Future sensitivity with water cherenkov telescopes HAWC and LHAASO
  - HAWC has data, sensitive to very high ($>$TeV) gamma-rays
  - LHAASO upcoming, also extremely sensitive to very high ($>$TeV) gamma-rays

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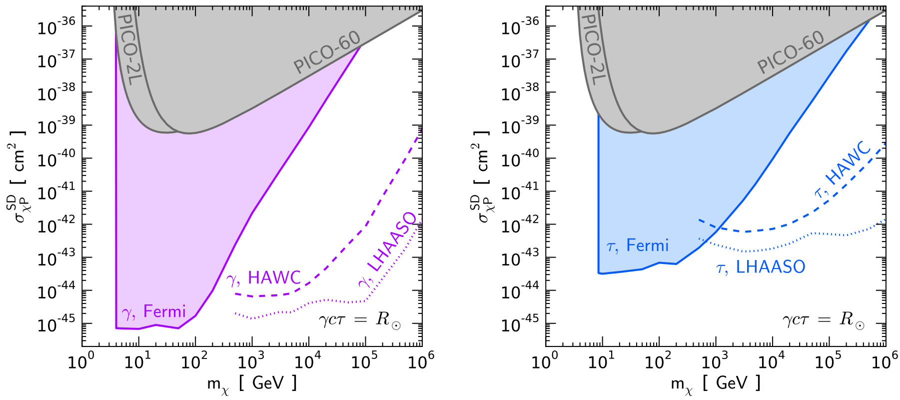
Neutrinos:

- Best gain for long-lived mediators is at higher (>TeV) energies
  - Less neutrino absorption by the solar matter
  - Less cooling of the secondaries (pions, muons etc)
- Use gigaton neutrino telescopes IceCube and KM3Net

DM scattering cross section limits: Gamma-rays

Can outperform direct detection exps by several orders of magnitude!



$$\chi\chi \to YY \to 2\,(\mathrm{SM} + \mathrm{SM}) \to ...\gamma...$$

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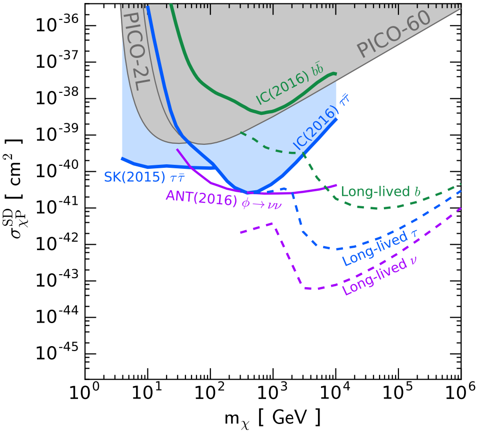
DM scattering cross section limits: Neutrinos

Outperforms both direct detection exps and neutrino telescopes



$$\chi\chi \to YY \to 2\,(\,\mathrm{SM}+\mathrm{SM}\,) \to \ldots\nu\ldots$$

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Conclusions

- Exploiting complementary of searches key for DM discovery, as well as common elements to many theories
- DM annihilation to long-lived mediators in the Sun provides probe of DM scattering cross section
- Can outperform direct detection exps by several orders of magnitude
- Potential signal can be tested at both direct and indirect detection exps
  - Further, gamma-ray and neutrino telescopes can allow for cross-check between different indirect detection channels

Exciting time with new searches with TeV gamma-ray telescopes and observatories, and new data from neutrino telescopes!

Backup slides

Long-lived dark mediator flux

$$E^2 \frac{d\Phi}{dE} = \frac{\Gamma_{\mathrm{ann}}}{4\pi D_\oplus^2} \times E^2 \frac{dN}{dE} \times \mathrm{Br}(\mathrm{Y} \to \mathrm{SM}) \times P_{\mathrm{surv}}, \tag{1}$$

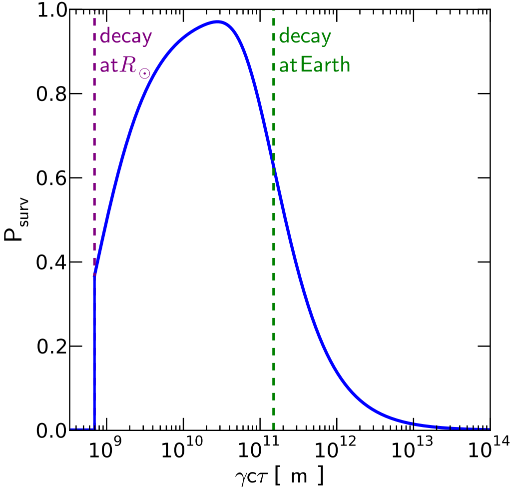
where

- $D_\oplus = 1$ A.U. is the distance between the Sun and the Earth
- $E^2 dN/dE$ is the particle energy spectrum per DM annihilation
- $\mathrm{Br}(\mathrm{Y} \to \mathrm{SM})$ is the branching fraction of the mediator Y to SM particles
- P_{surv} is the probability of the signal surviving to reach the detector, given by
$$P_{\mathrm{surv}} = e^{-R_\odot/\gamma c\tau} - e^{-D_\oplus/\gamma c\tau}. \tag{2}$$

Need mediator Y to have sufficiently long lifetime τ or boost factor $\gamma = m_\chi/m_Y$, leading to a decay length L that exceeds the radius of the Sun, $R_\odot$, as

$$L = \gamma c\tau > R_\odot. \tag{3}$$

Signal survival probability



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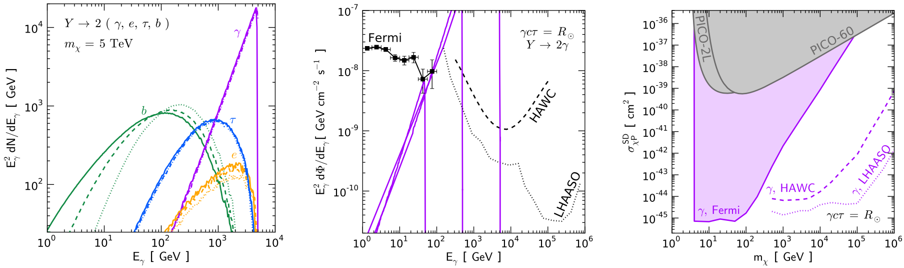
Gamma-ray limit procedure



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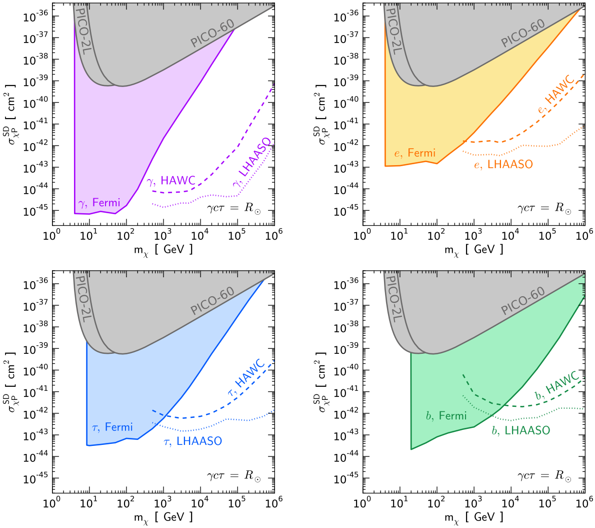

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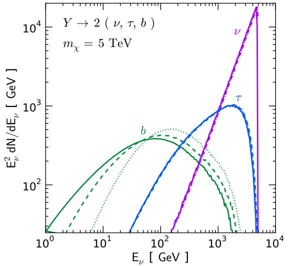
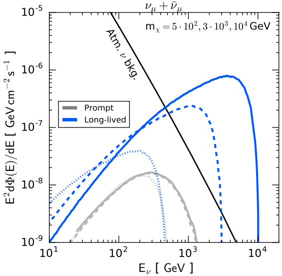
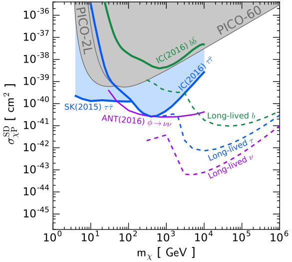
Neutrino limit procedure







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Long-lived dark mediator constraints

- **BBN:** The observed relic abundance of SM particles by BBN implies any new mediator must have lifetime τ which satisfies $\tau < 1$s.
- **CMB:** DM annihilation to SM products in the early universe is constrained by the CMB.
- **Supernovae:** Particularly for low mass mediators ($<$GeV), from mediator decay and supernova cooling.
- **Colliders:** If the dark sector is secluded, may be negligible. Otherwise, Belle, BaBar, ATLAS and CMS
- **Beam Dump/Fixed Target experiments:** Most relevant when the mediator has $\sim$sub-GeV mass. E137, LSND and CHARM
- **Other indirect detection signals:** Fermi-LAT and DES measurements of dSphs at low DM mass, and large positron signals can be constrained by AMS-02
- **Thermalization and Unitarity:** Issues with thermalization for > 10 TeV DM, and unitarity issues over $\mathcal{O}(100)$ TeV DM mass. Furthermore bound state effects at high DM mass.

Capture rate