Mapping the dark universe in colliders, stars and galaxies

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Washington University in St. Louis

Bologna, December 2011

Outline

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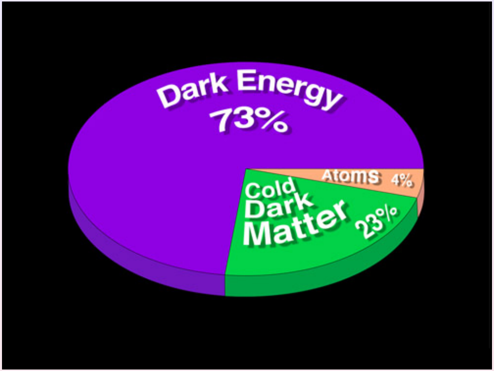
The case for dark matter



Expected in natural extensions of the SM.

Most economical explanation of:

- The rate of expansion of the universe.
- The formation of large scale structure.
- The dynamics of galaxies, clusters, …

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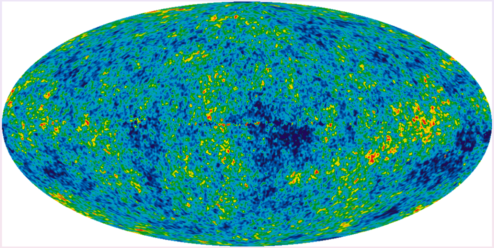

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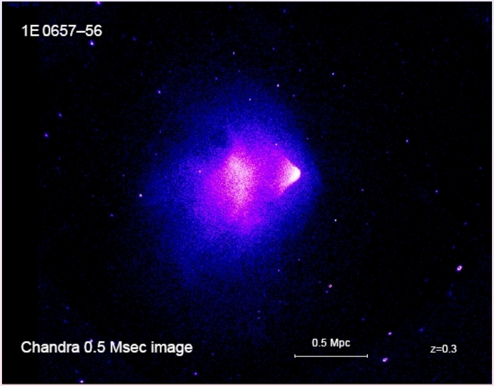

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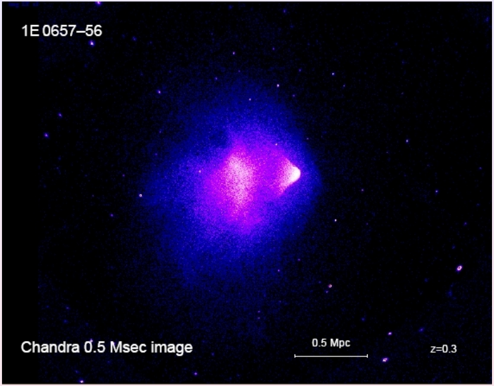

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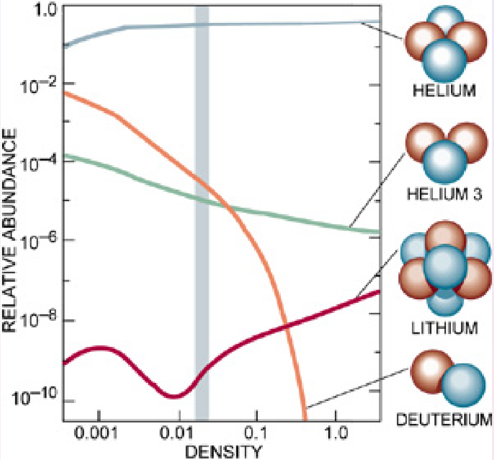
A few more oddities in the data



- There is almost no anti-matter in the universe.
- The energy density in matter and dark energy are comparable.

An example: WIMPs

Similar to a heavy neutrino, $m_\chi \approx 100$ GeV, weak-scale interactions produce observed abundance from thermal decoupling:

$$\Rightarrow < \sigma v > \approx 3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$$

The same interactions make it potentially detectable:

- $\chi\chi \rightarrow \gamma\gamma,\ \pi^0,\ e^{\pm}, \ldots$
- $\chi N \rightarrow \chi N$

Other examples include axions, MeV particles, ...

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Beyond the Standard Model Particles

The Standard Model of particle physics explains all the available data at colliders. However:

- Has a severe fine-tuning problem in the Higgs sector.
- Does not have a dark matter candidate.
- Cannot explain baryogenesis.

But, theorists have come up with (quite a few different) extensions that address this issues. *Supersymmetry, extra dimensions, . . .*

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Supersymmetry basics

The hierarchy problem is solved if there if each particle has a replica with different statistics.

The simplest extension, MSSM, contains a copy for each SM particle, and five higgs bosons: h, H, A, $H^{\pm}$. And over a hundred parameters!

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Proton stability is an accident in the SM, but must be enforced by R-parity in the MSSM. As a consequence, the LSP is stable

$\Rightarrow$ *Dark Matter candidate*!

- The conditions for baryogenesis could be met at the electroweak phase-transition.
- Coupling constants merge at the GUT scale.

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The neutralino

Often work in a simplified framework *cMSSM*:
$M_0, M_{1/2}, A, \tan\beta, sign(\mu)$.

- The LSP can be a linear combination of super-partners of gauge and higgs bosons, called the neutralino.
- In this framework, $m_\chi \gtrsim 50$ GeV.

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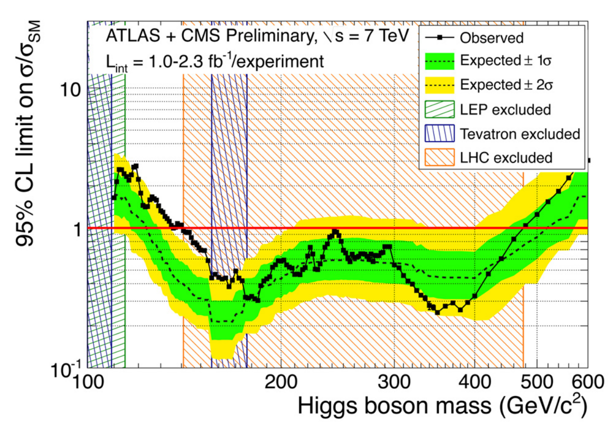

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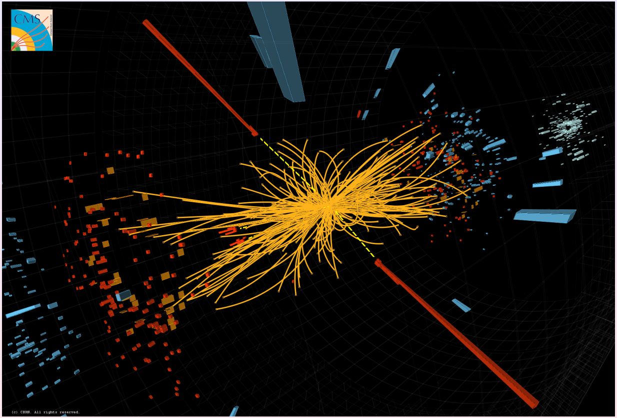

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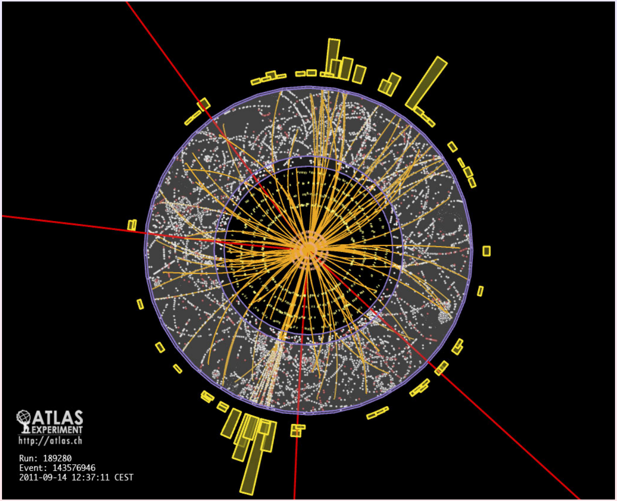

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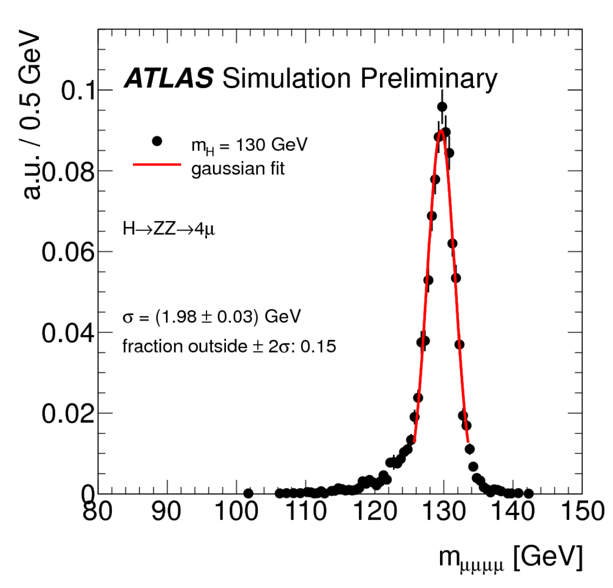

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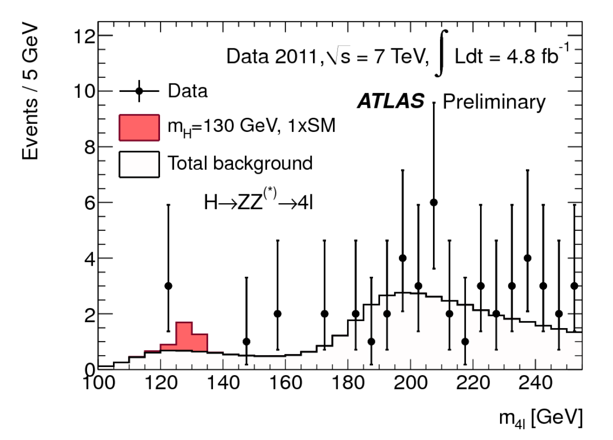

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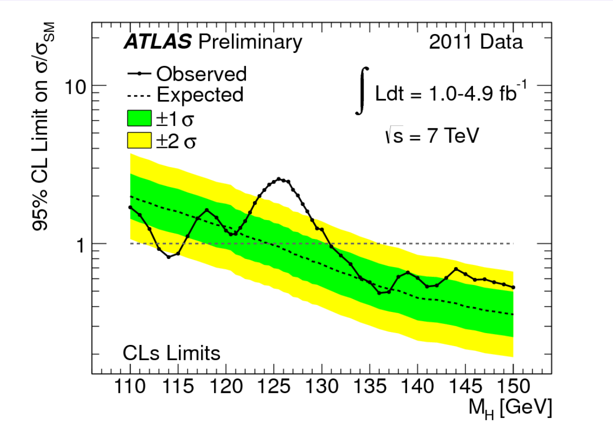

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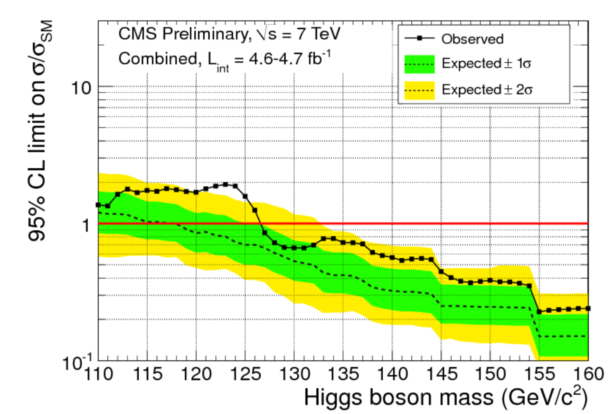

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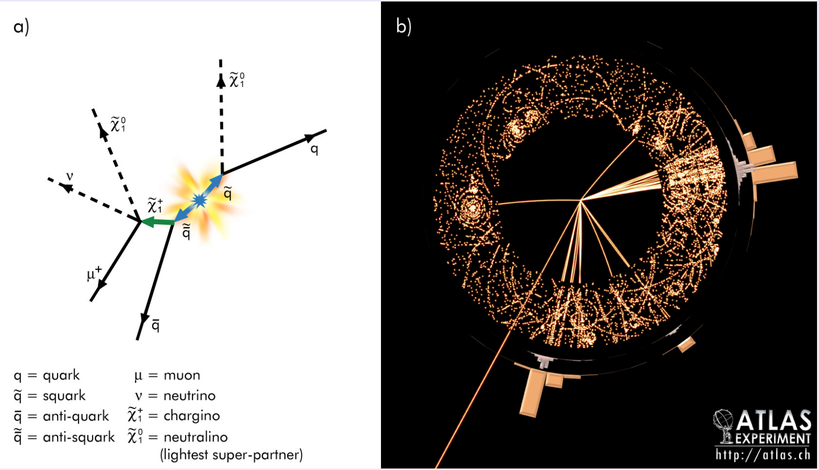

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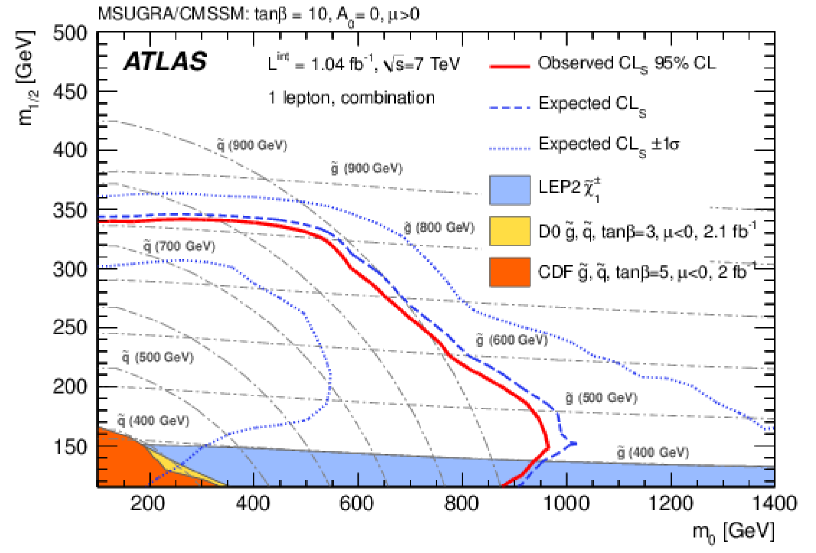

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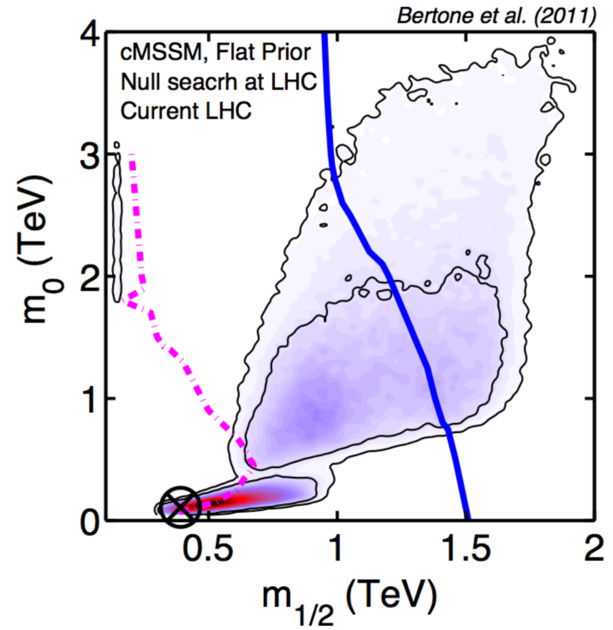
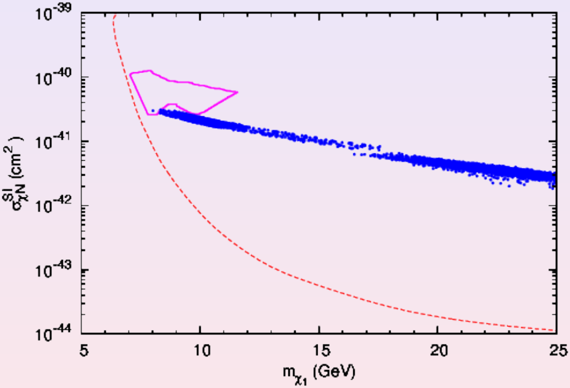


How about light WIMPs?



Calibbi et al.

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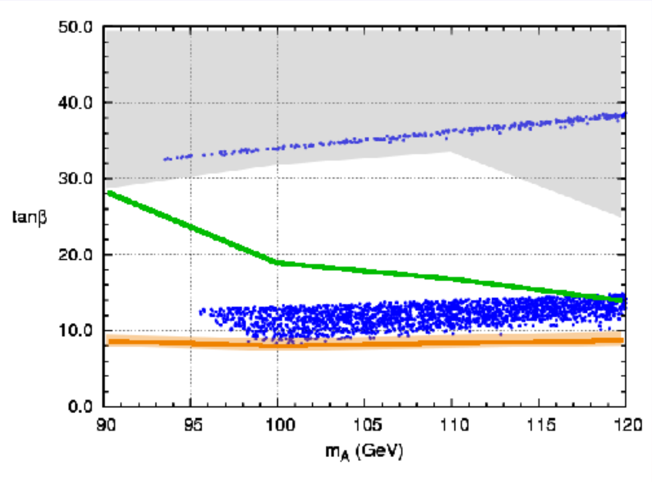

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How about light WIMPs?

Consider models other than MSSM, probably less natural.

- WIMPs below $m_\chi \lesssim 10$ GeV affect energy transport in the Sun.
- Super-weakly interacting particles affect SN cooling rates for m_χ 1 GeV.

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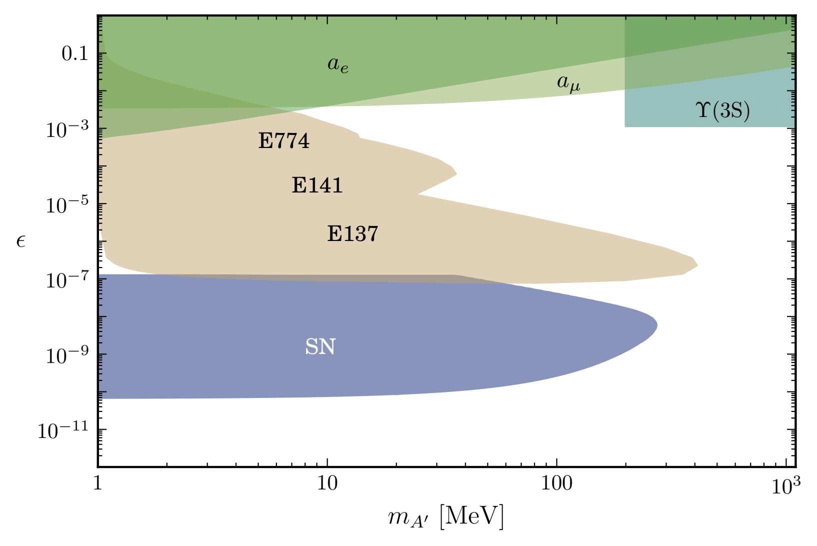
Dark photons in hidden sectors



Indirect detection

$$\chi\chi \to \gamma\gamma,\ \pi^0,\ e^{\pm},\ldots$$

$$Flux = \underbrace{\frac{<\sigma v>}{4\pi m_{dm}^2}\frac{dN_\gamma}{dE_\gamma}}_{\text{Number of SM particles}} \times \underbrace{\int_0^\infty \rho^2(r)dl}_{\text{Amount of DM}^2}$$

- *Astrophysical factor* suggests looking at GC, dwarf spheroidals, ...
- Photons and neutrinos point back to the source, while charged particles diffuse.

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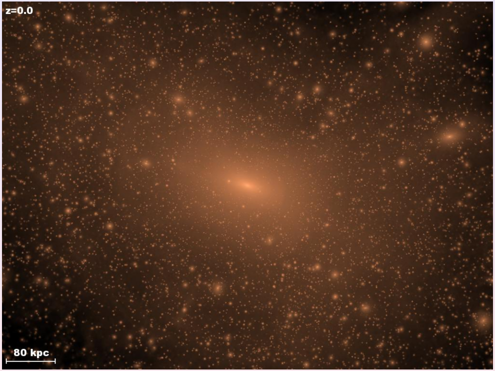
The distribution of DM: simulations



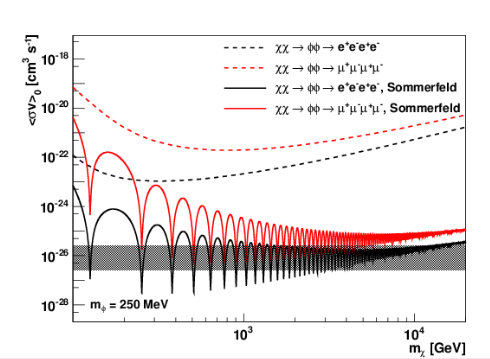
1 billion 4,100 $M_\odot$ particles. 0.5 kpc in the host halo.

The distribution of DM: observations

Jeans' equation shows that $M/L \sim 1000$. Clean systems.

Evans, FF, Sarkar 04

VERITAS



$<\sigma v>_0$ [cm^3 s^{-1}]
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
$\chi\chi \to \phi\phi \to e^+e^-e^+e^-$
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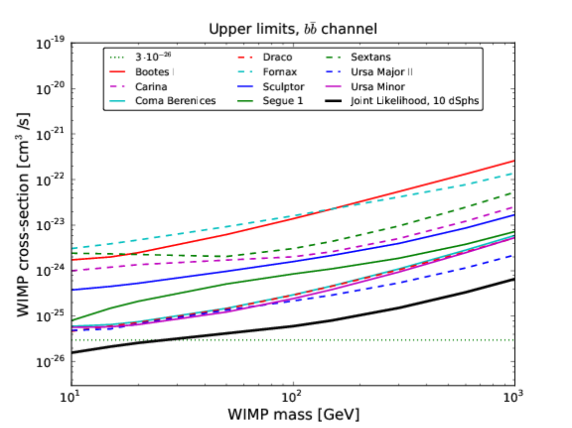
m_ϕ = 250 MeV
10^3
10^4
m_χ [GeV]

Fermi



Upper limits, $b\bar{b}$ channel
WIMP cross-section [cm^3 /s]
WIMP mass [GeV]
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^1
10^2
10^3
$3 \cdot 10^{-26}$
Bootes I
Carina
Coma Berenices
Draco
Fornax
Sculptor
Segue 1
Sextans
Ursa Major II
Ursa Minor
Joint Likelihood, 10 dSphs

The annihilation cross-section

Annihilations in the halo are non-relativistic, $v \approx 10^{-3}$.

$$\sigma v = a + b v^2 + \ldots$$

The amplitude is analytical for $k \to 0$

$$\mathcal{M} \propto \int \mathrm{e}^{ikx} V_{Born}(x)$$

Including factors of $k^l Y_l^m$ in a partial wave expansion, $\sigma \propto k^{2l-1}$

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More complicated velocity dependence

If there are new light particles mediating long-range forces between the dark matter, an enhancement occurs at low velocities:

$$\sigma \to \sigma \times \frac{\pi\alpha}{v}$$

Enhancements at low velocities, $v \sim 10^{-3}$, different than at decoupling, $v \sim 1$.

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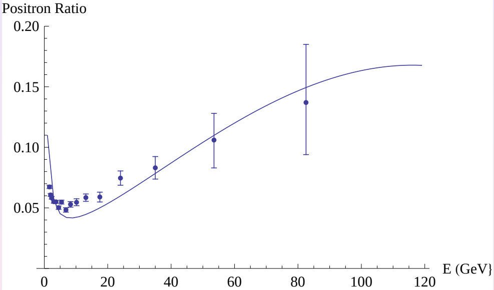

Lattanzi & Silk

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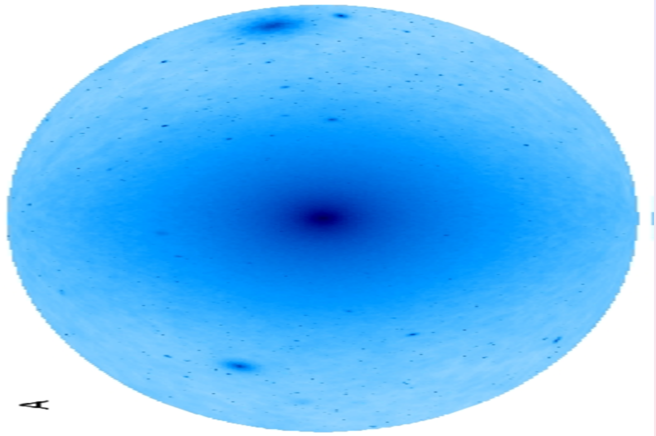

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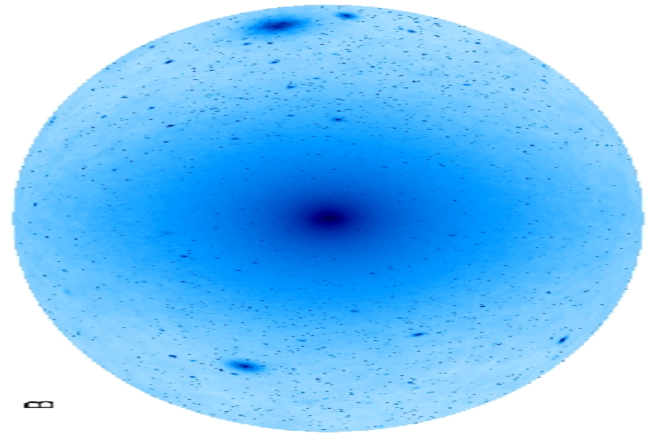

Lattanzi & Silk

What went in calculating the flux?

The averaged cross-section

$$\langle \sigma v \rangle \to S(v) \langle \sigma v \rangle$$

But, the flux is

$$\Phi = Rate \times v_{rel}$$

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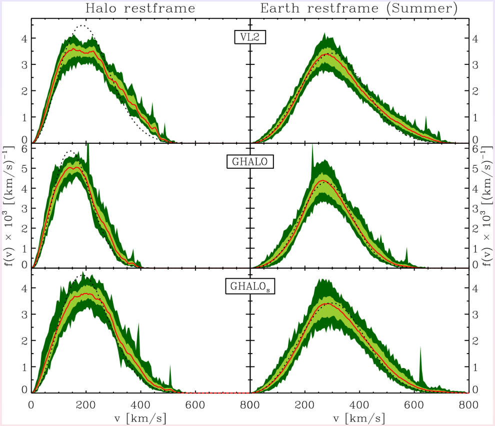
Since DM is assumed to be heavy, use Maxwell-Boltzmann?



Kuhlen et al.

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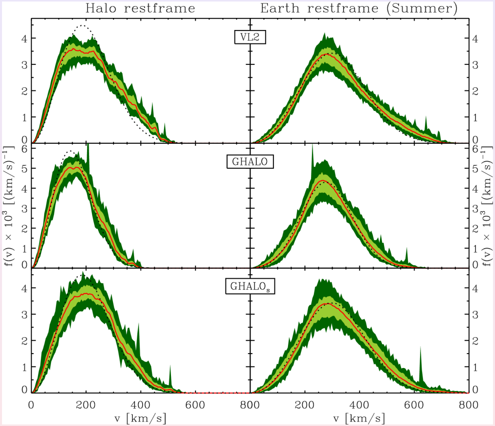

Kuhlen et al.

How should we calculate the fluxes?

$$Flux \propto \int dv_{rel} dl f_{pair}(v_{rel}) \sigma v_{rel}$$

Where,

$$f_{\mathrm{sp}}(\vec{v}_1) f_{\mathrm{sp}}(\vec{v}_2) \mathrm{d}\vec{v}_1 \mathrm{d}\vec{v}_2 = f_{\mathrm{pair}}(\vec{v}_{\mathrm{cm}}, \vec{v}_{\mathrm{rel}}) \mathrm{d}\vec{v}_{\mathrm{cm}} \mathrm{d}\vec{v}_{\mathrm{rel}}. \quad (1)$$

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Obtaining the phase-space distribution

Assume that dark matter satisfies the colisionless Boltzmann equation,

$$\frac{\mathrm{df}}{\mathrm{dt}} = 0$$

Very hard to solve! Only a few exact solutions known, found finding integrals of motion (*singular isothermal sphere*, Hernquist, Jaffe, ...).

Taking velocity moments we obtain the Jeans' equation:

$$v_c^2 = \frac{GM(r)}{r} = -\bar{v_r^2}\left(\frac{d\log\nu}{d\log r} + \frac{d\log \bar{v_r^2}}{d\log r} + 2\beta\right).$$

Necessary condition, useful to obtain density profiles from observational data.

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Eddington's formula

Gives the phase space distribution, if we know the density profile:

$$f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2} \int_0^{\mathcal{E}} \frac{\mathrm{d}\Psi}{\sqrt{\mathcal{E} - \Psi}} \frac{\mathrm{d}^2\rho}{\mathrm{d}\Psi^2}. \tag{2}$$

Choose profile, $1/r/(r + r_s)^2$, $\exp(-(r/r_s)^1/N)$, $1/(r^2 + r_c^2)$; generate 10^3 velocities at each sampled distance.

Numerically, we change integration variables to r, and precalculate the potential on a grid.

Check that $\rho(r) \equiv \int \mathrm{d}^3\mathbf{v}\, f(\mathcal{E})$.

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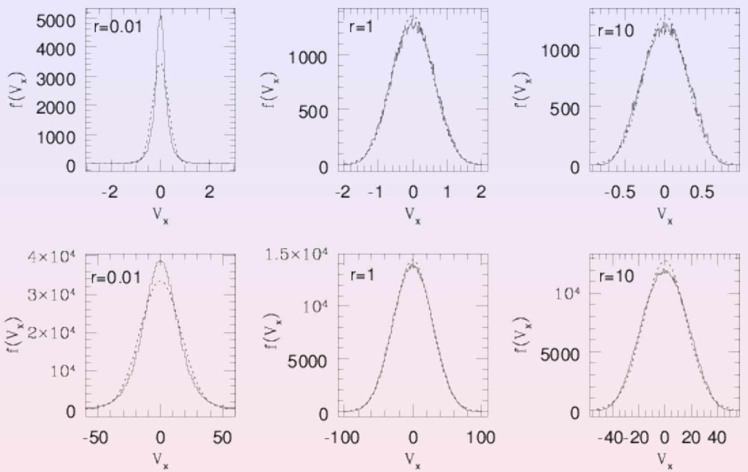
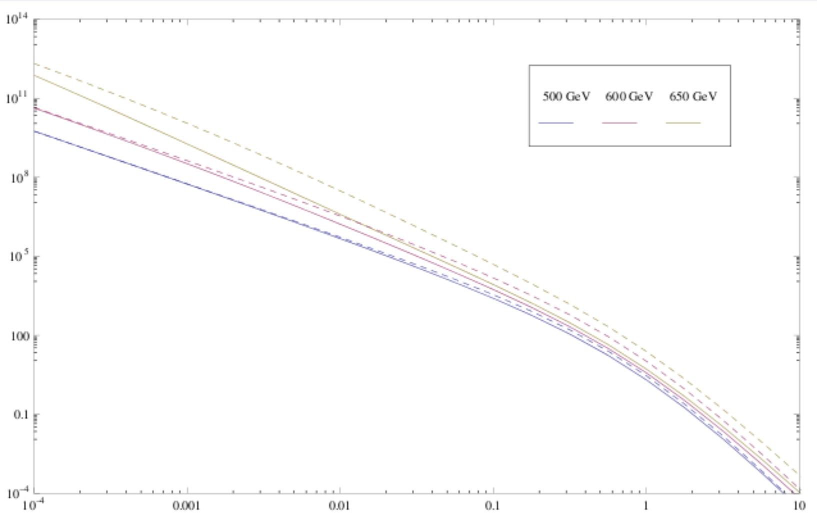
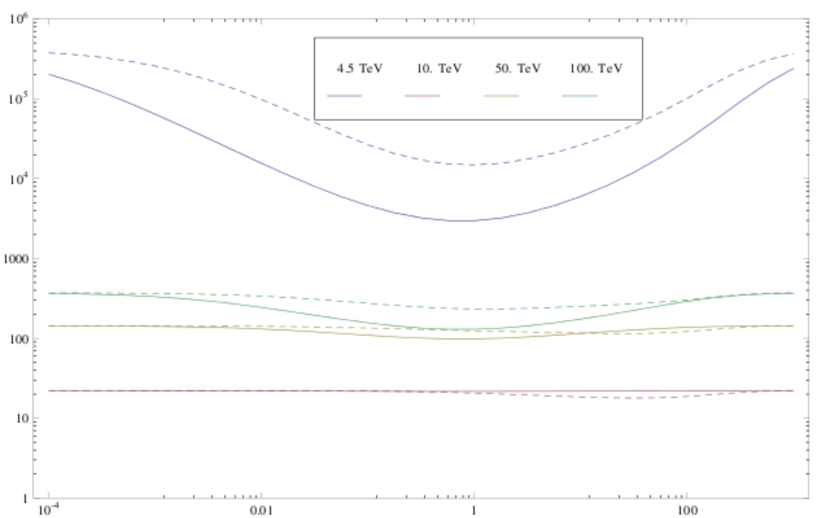


Kazantzidis, Magorrian & Moore



10^{14}
10^{11}
10^{8}
10^{5}
100
0.1
10^{-4}
10^{-4}
0.001
0.01
0.1
1
10
500 GeV
600 GeV
650 GeV

FF & Hunter



4.5 TeV
10. TeV
50. TeV
100. TeV
10^6
10^5
10^4
1000
100
10
1
10^{-4}
0.01
1
100

FF

& Hunter

Results

- We find that non-gaussianity can usually, but not always, be neglected. Jeans' treatment is good enough.
- Enhancements up to a factor of 40, compared to standard calculation.
- Will have to re-evaluate constraints from the Galactic Centre.

Conclusions

- Recent results at the LHC constrain a sizable part of neutralino phase space, but don't tell us much about the nature of dark matter.
- Gamma-ray and neutrino fluxes might depend on the velocity distribution, which might deviate from the naive Maxwell-Boltzmann approximation.
- Constraints on Sommerfeld enhanced models from IC, synchroton or diffuse backgrounds have to be re-evaluated.
- The velocity distribution also affects direct detection rates.