Astroparticle physics

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Outline

Session I:

- Survey: extreme energies, extreme densities.
- Relics from the early Universe: freeze-out.

Session II:

- The most energetic particles: ultra-high energy cosmic rays.

Session III:

- Gamma-ray astronomy. Indirect DM detection.
- Cosmological magnetic fields.

DM detection: astrophysical inputs

The γ-ray flux from DM annihilation goes as:

$$\Phi = \underbrace{\frac{N_i}{8\pi m_\chi^2}\langle\sigma v\rangle}_{\text{\# collisions giving gamma-rays}} \times \underbrace{\int_{\text{line of sight}} \mathrm{d}s\, \rho^2}_{\text{Amount of DM}^2}$$

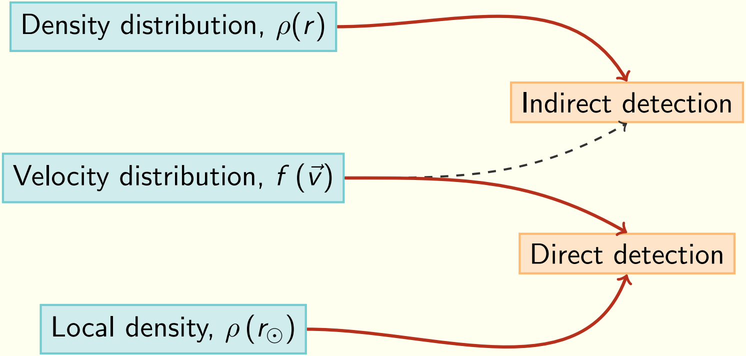
In the case of DM decays we simply replace

$$\frac{1}{2}\langle\sigma v\rangle \to \Gamma \text{ and } \frac{\rho^2}{m_\chi^2} \to \frac{\rho}{m_\chi}$$

The rate of recoil events in a direct detection experiment goes as:

$$R = \frac{\mathcal{E}\rho(r_\odot)}{m_A m_\chi}\int_0^\infty \mathrm{d}E_R\, \epsilon(E_R) \int_{v \geq v_{\min}(E_R)} \mathrm{d}^3v\, v\, f\left(\vec{v} + \vec{v}_\oplus(t)\right) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R}$$

Astrophysical inputs



Astrophysical inputs

- Gamma-rays $\rightarrow$ Mpc - npc
- Antimatter $\rightarrow$ local, kpc
- Neutrinos $\rightarrow$ local, npc

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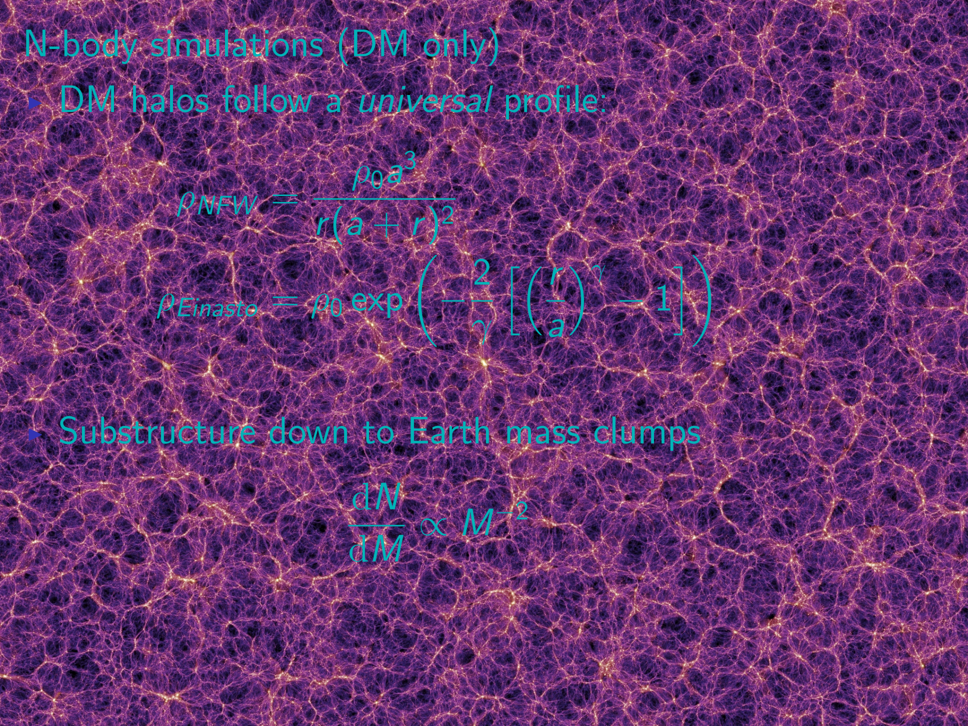


N-body simulations (DM only)

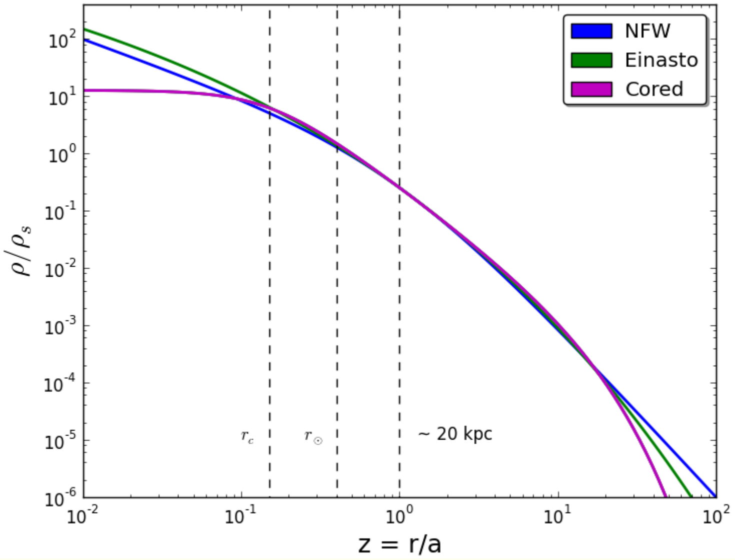
- DM halos follow a *universal* profile:

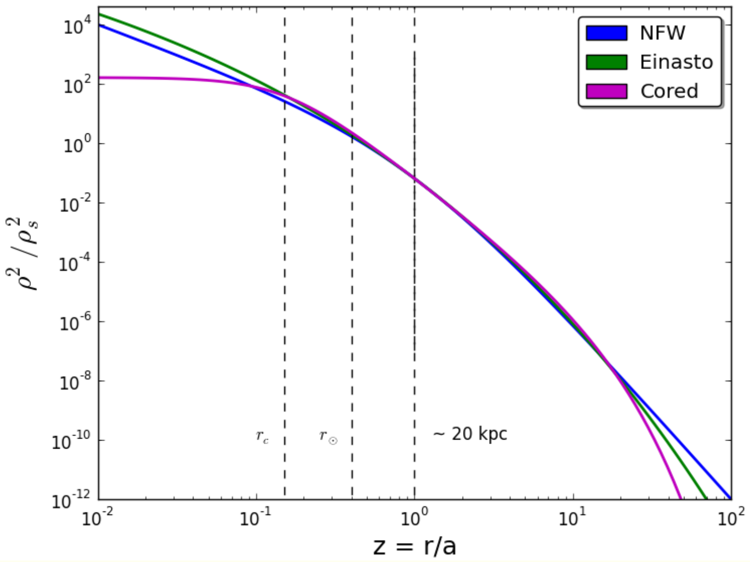
$$\rho_{NFW} = \frac{\rho_0 a^3}{r(a+r)^2}$$

$$\rho_{Einasto} = \rho_0 \exp\left(-\frac{2}{\gamma}\left[\left(\frac{r}{a}\right)^{\gamma} - 1\right]\right)$$

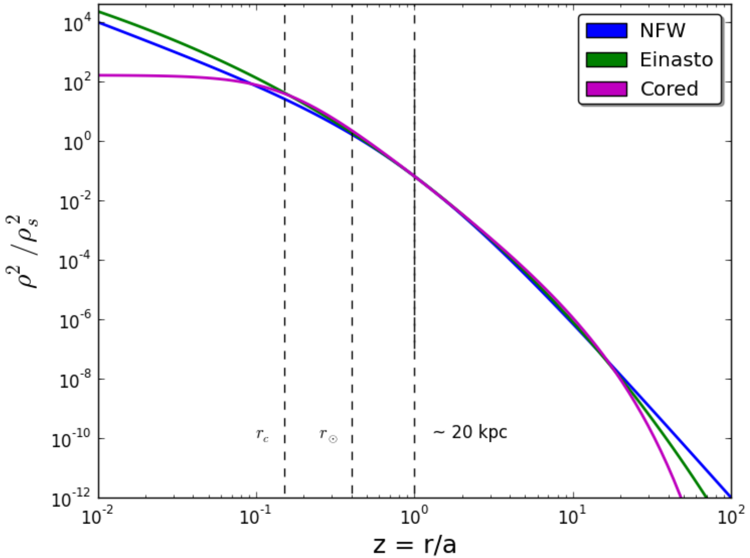
- Substructure down to Earth mass clumps

$$\frac{\mathrm{d}N}{\mathrm{d}M} \propto M^{-2}$$


NFW
Einasto
Cored
ρ/ρ_s
$z = r/a$
r_c
$r_\odot$
~ 20 kpc
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}



Is there agreement with observational data?

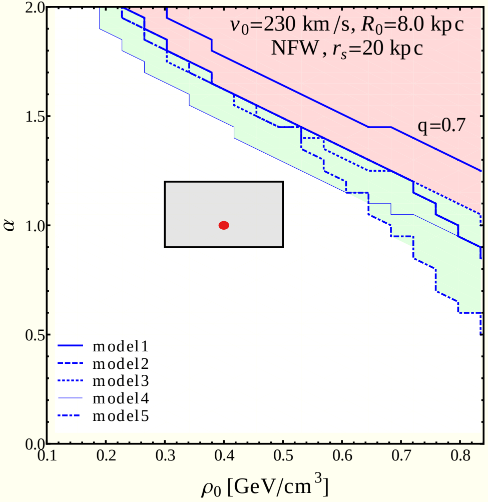


Is there agreement with observational data?

Issues at small scales:

- cusp vs core?
- too big to fail problem

Galactic Center



Iocco et al. 11

Microlensing measurements consistent with cuspy profiles, but exclude extreme adiabatically compressed ones.

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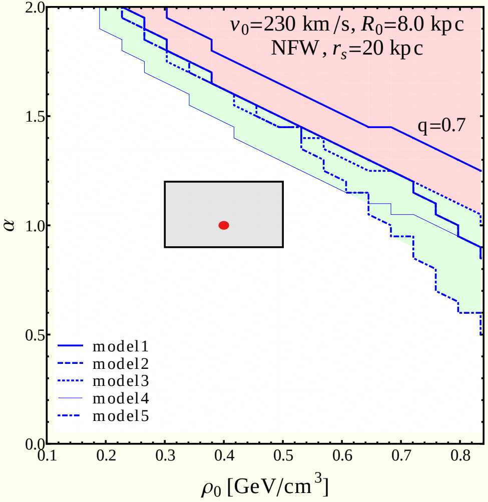

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Substructure - dSph

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

Obtaining the phase-space distribution

Assume that dark matter satisfies the colisionless Boltzmann equation,

$$\frac{\partial f}{\partial t} + \vec{v}\frac{\partial f}{\partial \vec{x}} - \frac{\partial \Phi}{\partial \vec{x}}\frac{\partial f}{\partial \vec{v}} = 0,$$

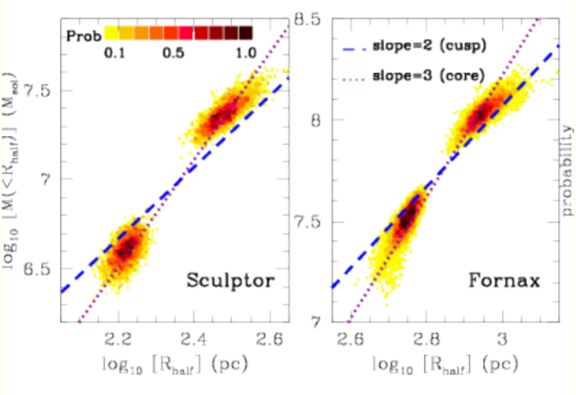
and integrate over all velocities to find the Jeans' equation:

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

If the l.o.s velocity dispersion has been measured, we can constrain the mass profile assuming a functional form for β.

Binney and Tremaine 08

Substructure - dSph



Peñ arrubia & Walker 11

Baryonic physics is unlikely to play a role, but projection effects might be important.

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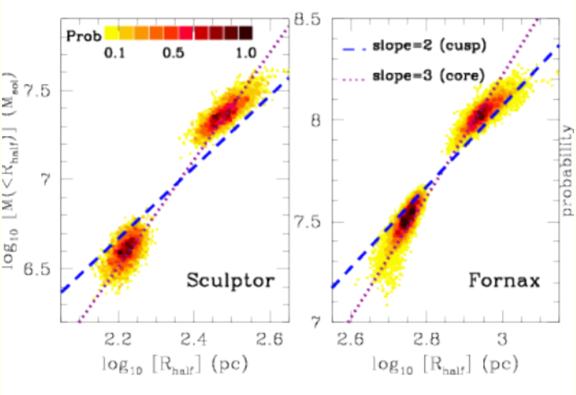

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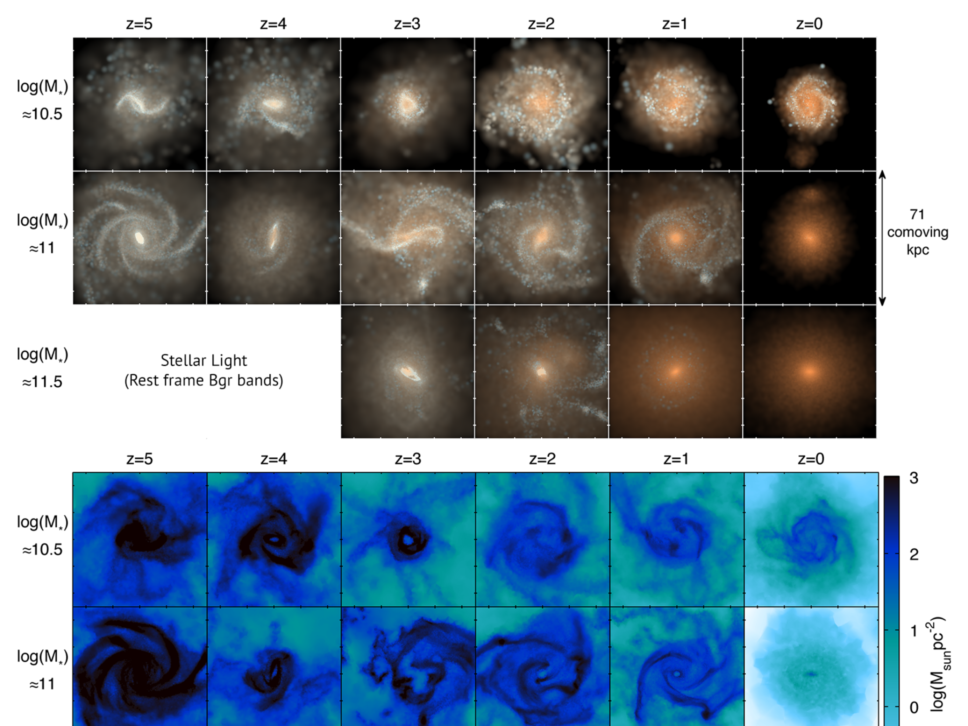
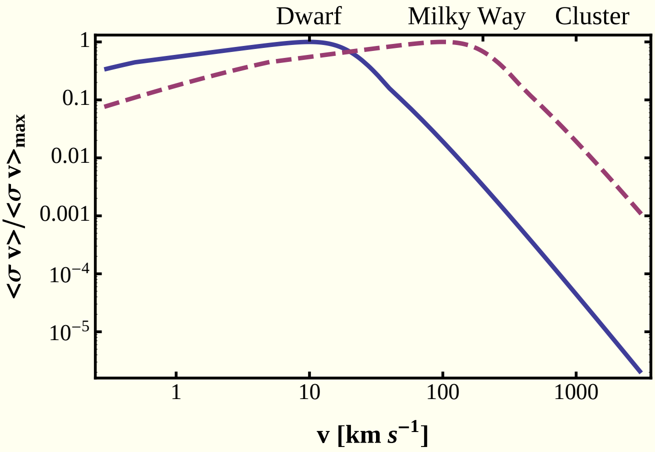
Adding baryons:

- Adiabatic compression makes halos more cuspy.
- Feedback from SNe, AGN activity, . . . can create cores.

Central regions are still uncertain.


z=5
z=4
z=3
z=2
z=1
z=0
log(M*) ≈10.5
log(M*) ≈11
log(M*) ≈11.5
71 comoving kpc
Stellar Light
(Rest frame Bgr bands)
z=5
z=4
z=3
z=2
z=1
z=0
log(M*) ≈10.5
log(M*) ≈11
3
2
1
0
log(M_sun pc^-2)

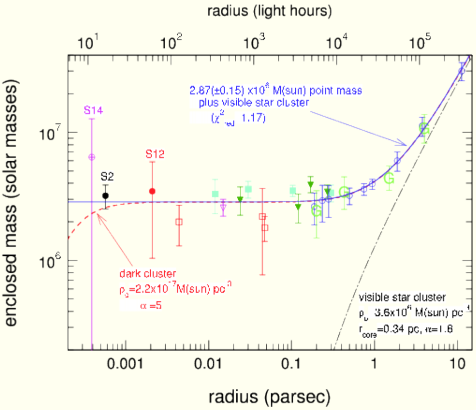
Velocity dependent cross-section



Weiner & Loeb 10

Taking into account the central black hole

- Will focus on the super-massive BH at the center of the Galaxy.
- Similar effects will occur in the cores of AGNs, or in IMBHs.



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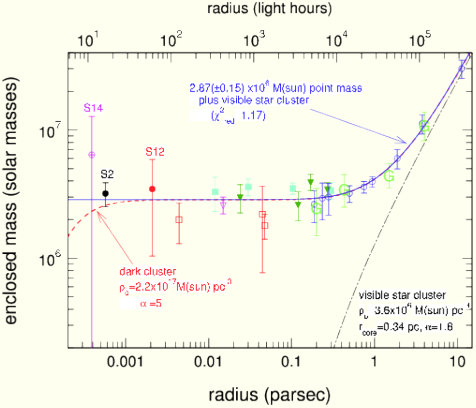
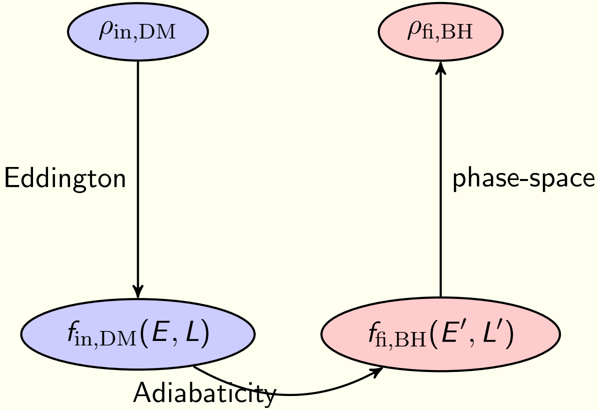
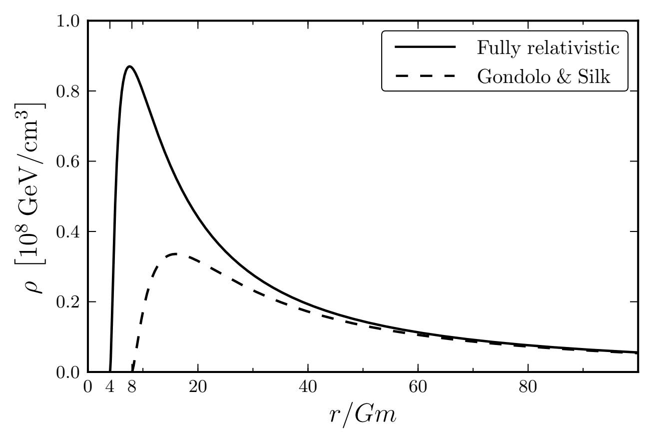


Adiabatic growth of a BH

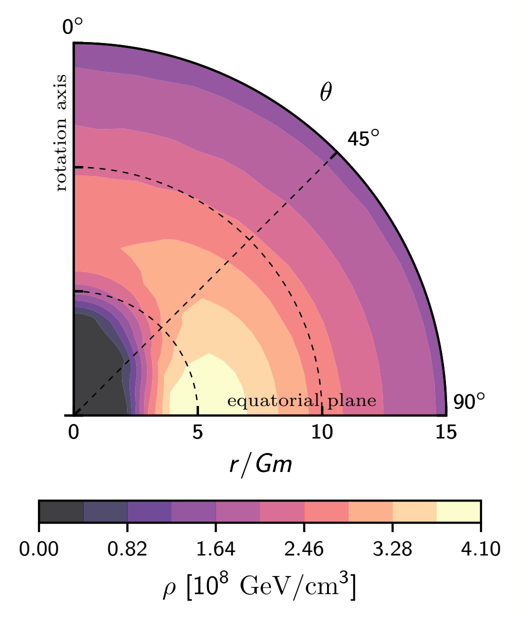


Full GR calculation

For a constant phase-space distribution:

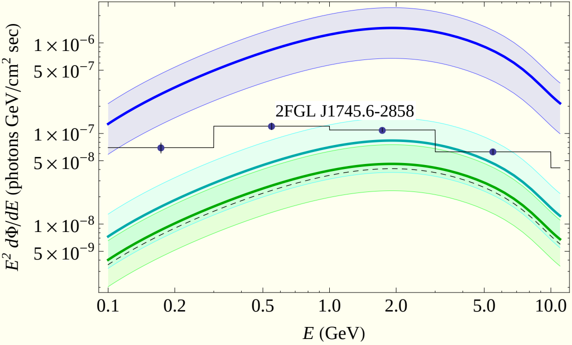


L. Sadeghian, FF, C.M. Will '13



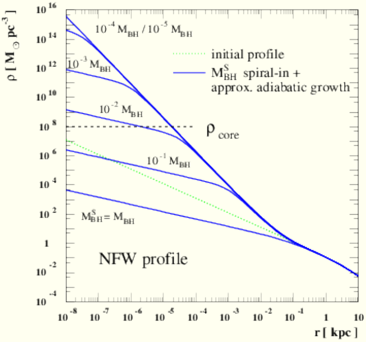
F.F., A. Medeiros, C.M. Will '17

The GC excess



Fields, Shapiro & Shelton, 1406.4856

Caveats



Bertone, Hooper & Silk, Phys. Rep. 2004

Astrophysical processes might deplete the spike in certain galaxies, but they are not universal. Integrated effects will persist and can affect the interpretation of LIGO signal.

Nishikawa, Kovetz, Kamionkowski, Silk '17

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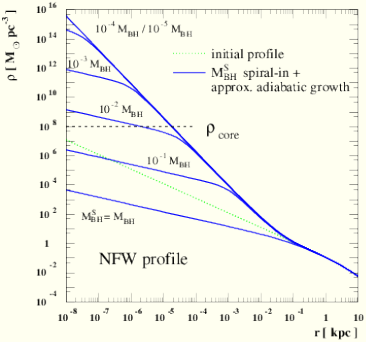

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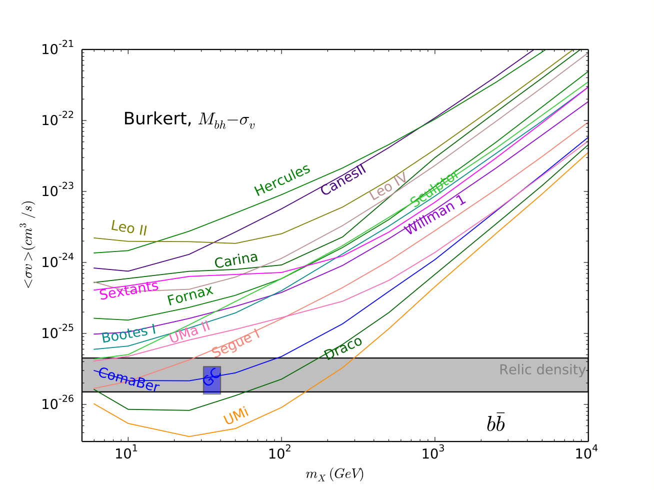
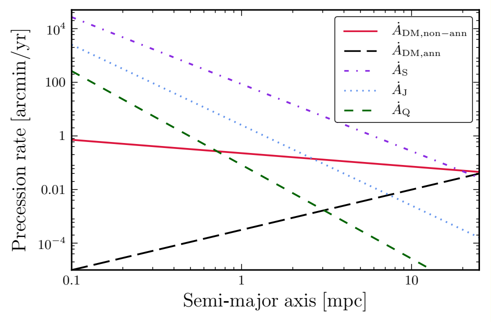
Limits from dwarf spheroidals



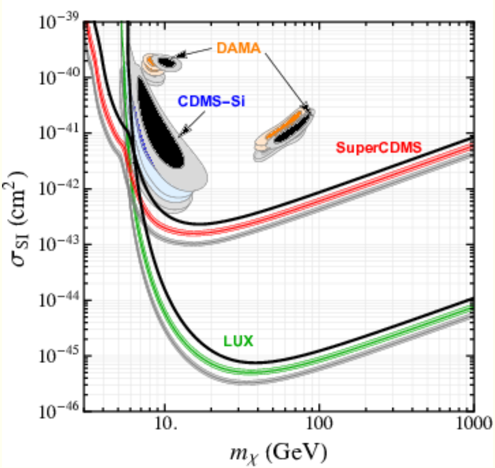
Gonzalez-Morales, Profumo & Queiroz, 1406.2424

Decaying vs annihilating DM



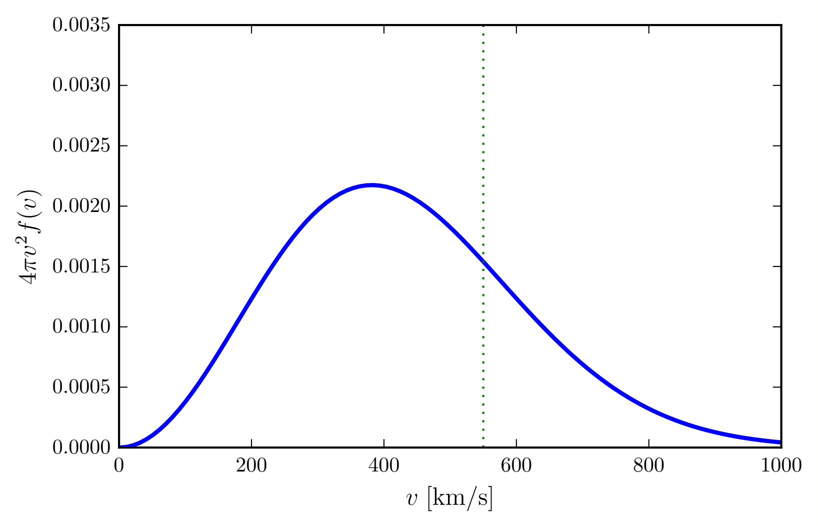
The orbits of S-stars can be used to constrain the existence of a plateau induced by annihilations.

How about $f(v)$?

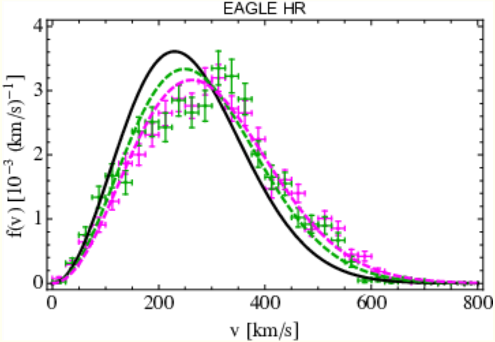


Bozorgnia *et al.* 1601.04707

The Standard Halo Model



The velocity distribution from simulations



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Use Eddington's formula:

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

Caveats: we are assuming $\beta = 0$.

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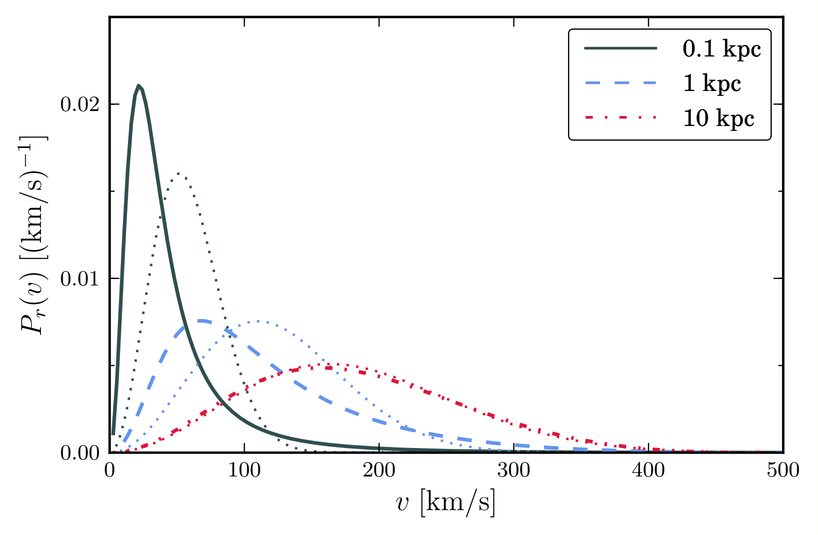
For an NFW profile



A halo-independent bound

Assume that DM is distributed as a single stream with fixed velocity $\vec{v_0}$ with respect to the solar frame,

$$f_{\vec{v_0}}(\vec{v}) = \delta\left(\vec{v} - \vec{v_0}\right).$$

Given an upper limit, $R_{\max}$, from the null results of a direct detection experiment we obtain a bound on the cross section by requiring that

$$R_{\vec{v_0}} \leq R_{\max}$$

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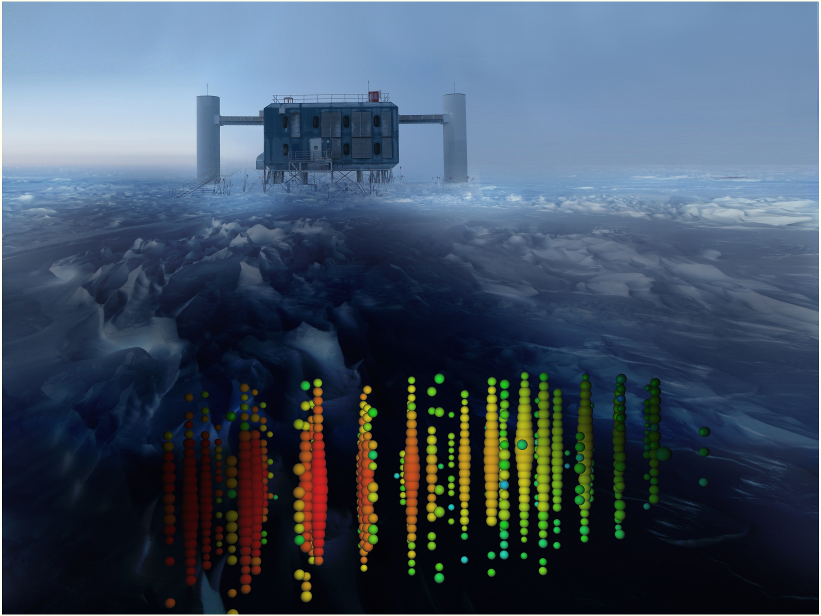
Neutrino telescopes



Neutrino telescopes

- DD experiments are insensitive to slowly moving WIMPs. But, these can be efficiently captured in the Sun.
- They probe the WIMP population in a complementary way: neutrino searches are sensitive to slow moving DM particles.
- Hence, for every stream speed v_0 there is a finite upper bound for the cross-section, σ_*.

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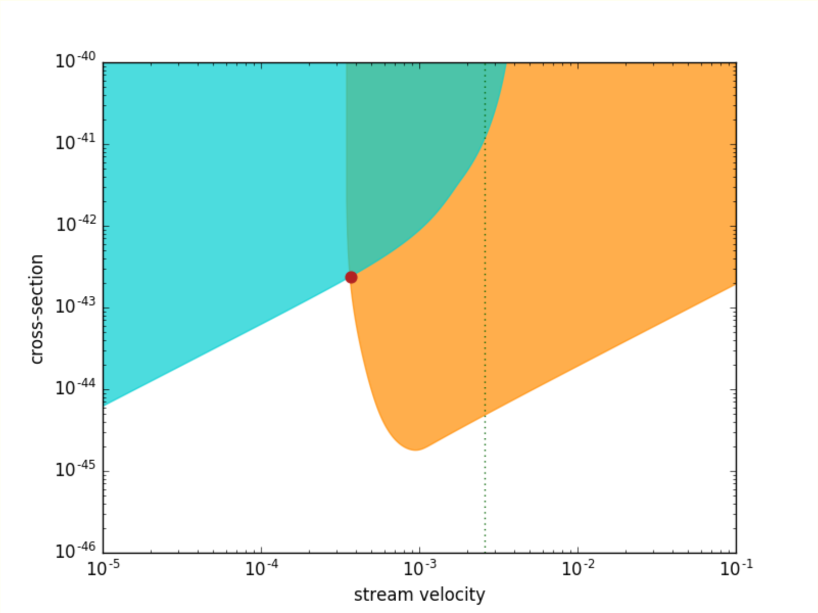
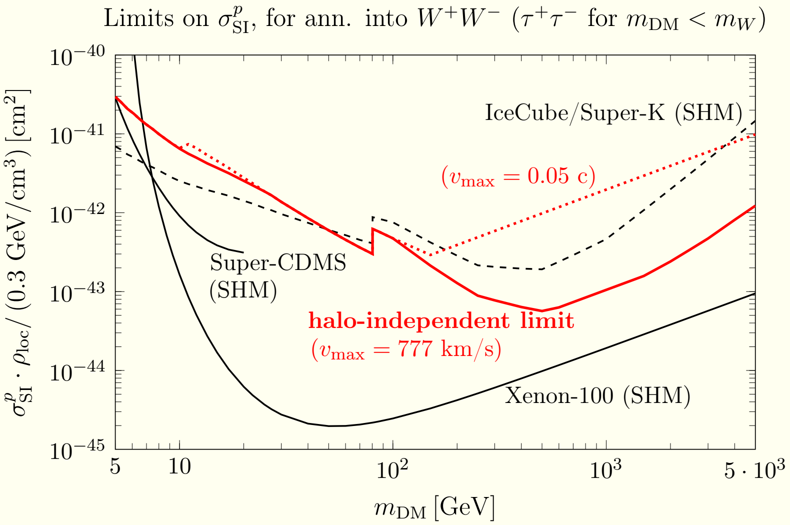


10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
cross-section
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
stream velocity

Comparison with model dependent limits



FF, A Ibarra, S Wild 15

Magnetic fields are ubiquitous in the Universe

Starting in 1949 . . .

- Large scale magnetic fields have been detected in galaxies and clusters (μG). Lyman-α systems at $z \sim 2.5$ show evidence of B-fields in Faraday rotation measurements.
- B-fields appear to have similar magnitudes for the same type of objects regardless of location in the universe. *Common primordial seeds?*
- Important to understand formation and evolution of structure.
- Could provide a window to processes in the Early Universe.

How were these fields generated?

Small field seeds get amplified via dynamo mechanisms.

- Seeds of astrophysical or cosmological origin?

  Hoyle 1958

- Can we fit the observed intensity and coherence length?
- How large should the initial seeds be for the B-fields to have enough time to grow?

Is there any observational support for this idea?

Standard observational techniques

B-fields are difficult to observe . . .

- Faraday rotation measurements sensitive to $B_{|}$.
- Synchrotron radiation can probe $B_{\perp}$.

Typically require independent knowledge of n_e.

Effects can show up in the CMB.

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B-fields and the electroweak phase-transition

Once electroweak fields become massive, they leave behind the only massless field in the spectrum, the photon.

At the time of the electroweak phase-transition, sphaleron processes occur that violate baryon number, CP violation is also present.

A sphaleron can be seen as two linked Z-strings. The leftover magnetic field lines will be linked.

$\Rightarrow$ Magnetic Helicity

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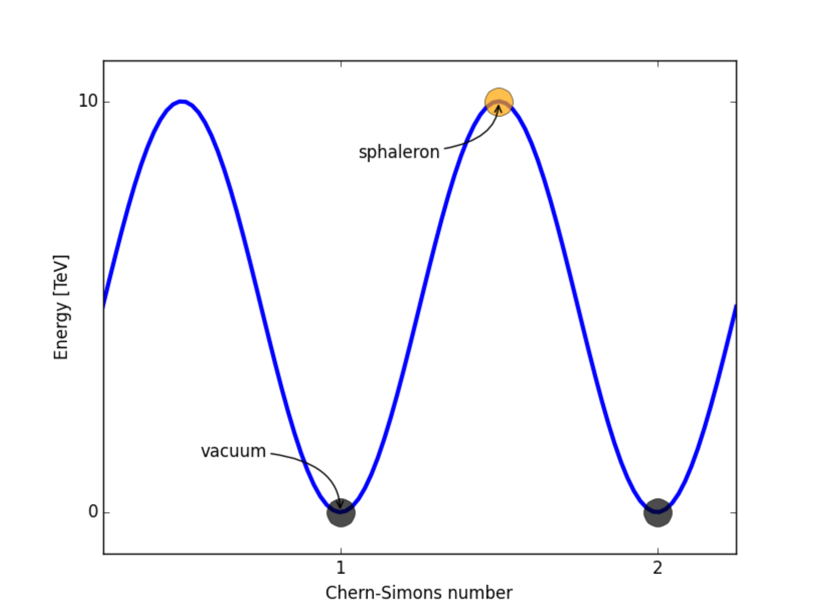
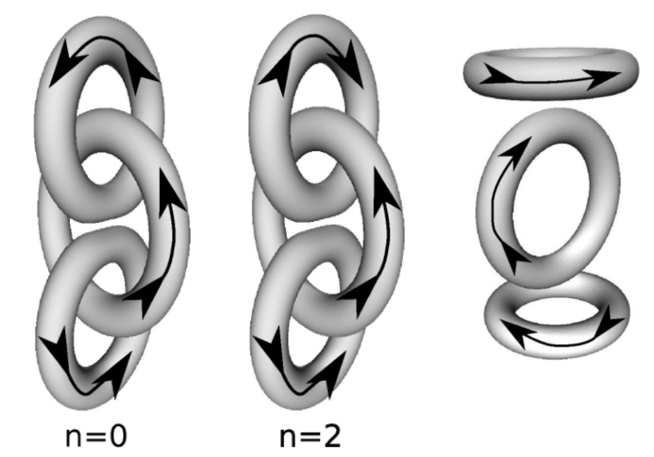
$$\Rightarrow \text{Magnetic Helicity}$$

Helicity from sphaleron decay



Helicity from sphaleron decay



Why is helicity important?

$$h = \frac{1}{V} \int_V d^3x \, \boldsymbol{A} \cdot \boldsymbol{B}$$

- Discriminate astrophysical vs. cosmological seeds.
- Provides a window to processes in the early universe.
  - Leptogenesis vs ew baryogenesis

    `Long, Sabancilar, Vachaspati, 2013`
  - Relate ρ_B to ρ_b.
- For turbulent non-diffusive evolution, MHD studies show that inverse cascade increases coherence length by $\eta^{2/3}$.

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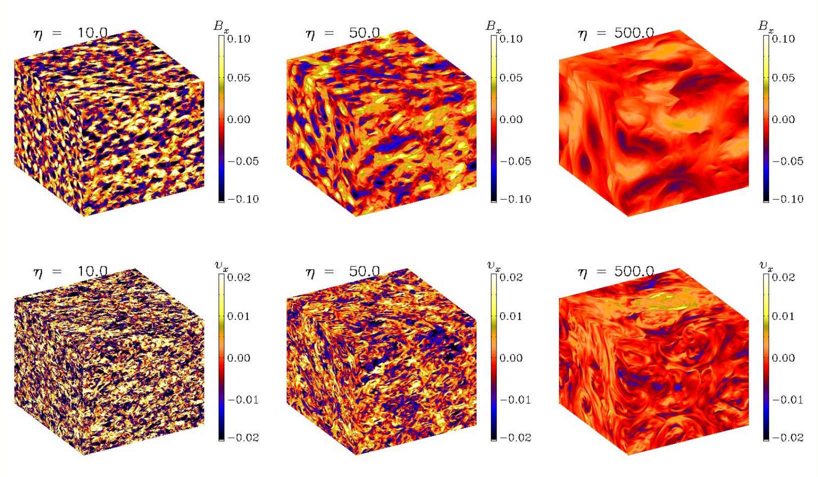
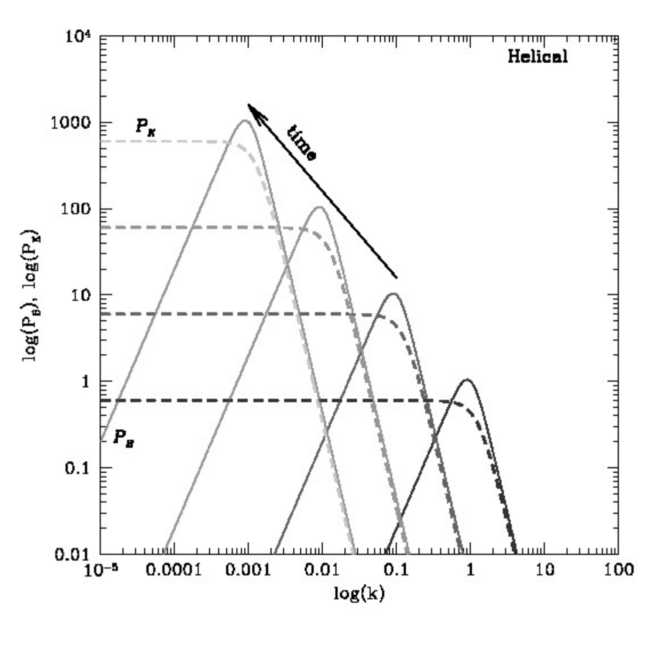
Evolution



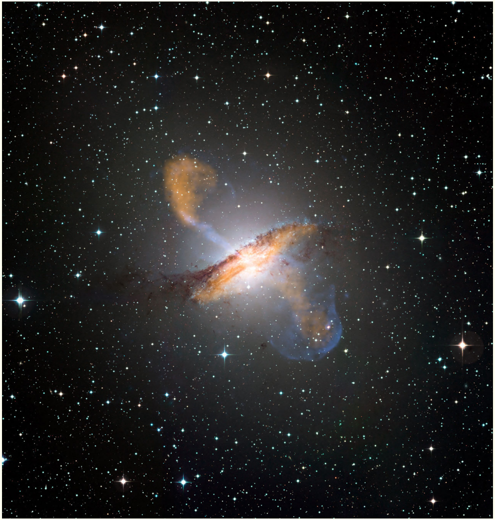
η = 10.0
B_x
0.10
0.05
0.00
−0.05
−0.10
η = 50.0
B_x
0.10
0.05
0.00
−0.05
−0.10
η = 500.0
B_x
0.10
0.05
0.00
−0.05
−0.10
η = 10.0
v_x
0.02
0.01
0.00
−0.01
−0.02
η = 50.0
v_x
0.02
0.01
0.00
−0.01
−0.02
η = 500.0
v_x
0.02
0.01
0.00
−0.01
−0.02

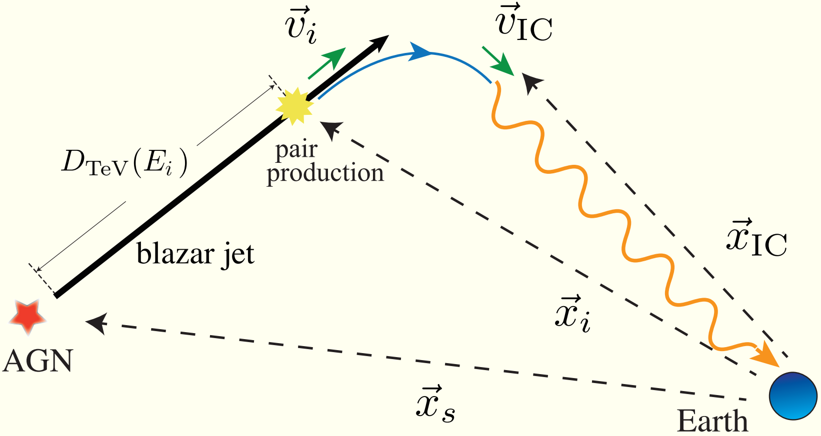
Evolution



Helical
time
P_K
P_B
10^4
1000
100
10
1
0.1
0.01
10^{-5}
0.0001
0.001
0.01
0.1
1
10
100
log(k)
$\log(P_B)$, $\log(P_K)$

We can use a distant blazar as a candle





$\vec{v}_i$
$\vec{v}_{\rm IC}$
$D_{\rm TeV}(E_i)$
pair
production
blazar jet
$\vec{x}_{\rm IC}$
$\vec{x}_i$
AGN
$\vec{x}_s$
Earth

The trip of a TeV γ-ray

1. Pair-production on an EBL photon:

$$D_{\mathrm{TeV}}(E_{\mathrm{TeV}}) \sim 80 \frac{\kappa}{(1+z_s)^2} \,\mathrm{Mpc}\, \left(\frac{E_{\mathrm{TeV}}}{10\ \mathrm{TeV}}\right)^{-1}. \quad (2)$$

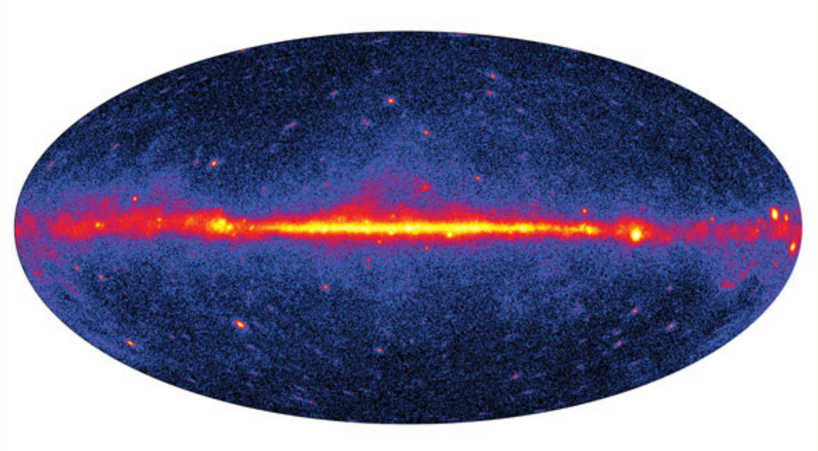
2. During its life as an $e^{\pm}$ samples the magnetic field in the void for

$$D_e \sim 30\,\mathrm{kpc}\, \frac{1}{(1+z_{\gamma\gamma})^4} \left(\frac{E_{\mathrm{TeV}}}{10\ \mathrm{TeV}}\right)^{-1} \quad (3)$$

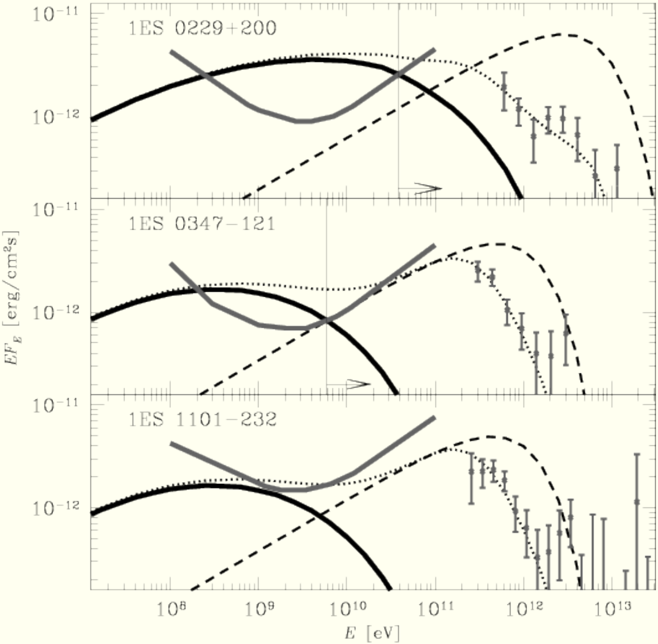
3. A secondary γ-ray is produced via IC of CMB photons:

$$E_\gamma \sim 80\,\mathrm{GeV}\, \left(\frac{E_{\mathrm{TeV}}}{10\ \mathrm{TeV}}\right)^{2} \quad (4)$$

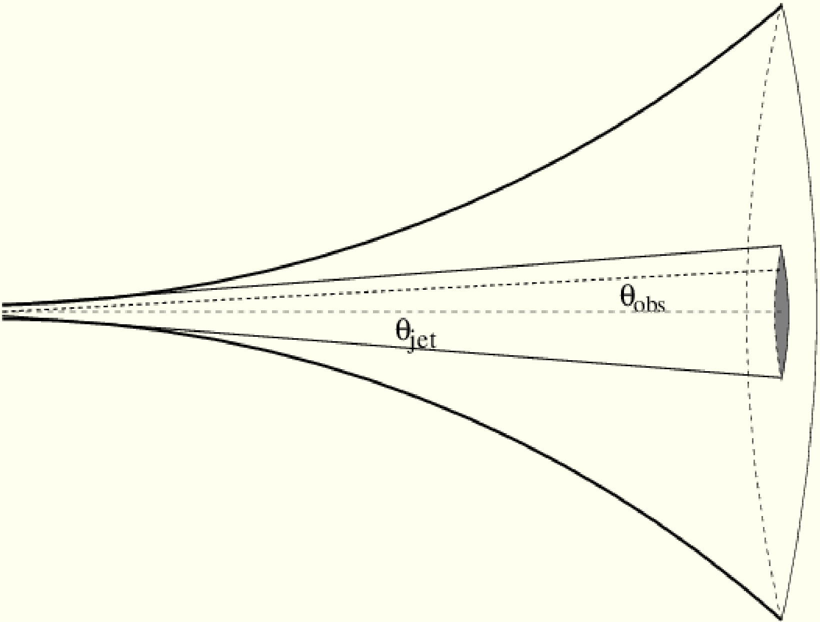
Tool: high-energy γ-rays



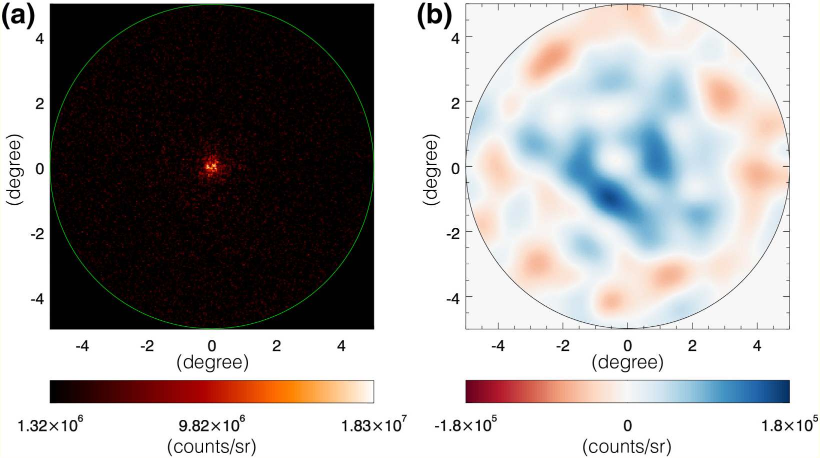
Spectrum constraints



Halo around an AGN

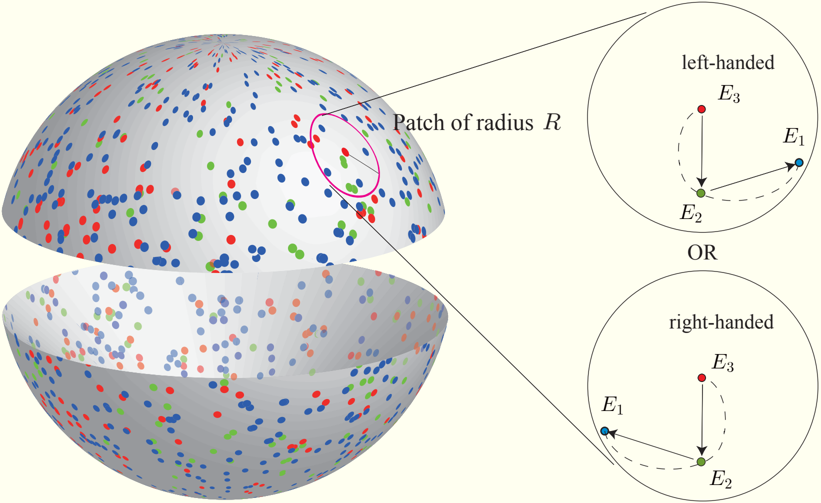


Halo around an AGN



Chen, FF, Buckley 15

Measuring helicity



Summary

- There is evidence for the presence of B-fields in voids from pair halos around AGNs and from the energy spectrum of sources undected by Fermi.
- Hints for a helical component.

B-fields can also be generated from a second order phase transition if winding in gauge fields is present.

`Zhang, FF, Vachaspati 17`