DARK MATTER AT THE CENTERS OF GALAXIES

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“PROBES OF DARK MATTER ON GALAXY SCALES”

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Detection of Dark Matter

Colliders

Direct Detection

Indirect Detection
The flux can be broken into two pieces:

\[ F_\gamma(E) \propto \frac{dN_\gamma}{dE_\gamma} \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \times \int_{\text{los}} \rho^2 dl \]

In the case of WIMPs, the self-annihilation cross section is revealed by the present-day mass density:

\[ \langle \sigma v \rangle \approx 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}, \]

nearly independent of \( m_\chi \).

Steigman & el. (2012)
The flux can be broken into two pieces:

$$F_\gamma(E) \propto \frac{dN_\gamma}{dE_\gamma} \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \times \int_{\text{los}} \rho^2 dl$$
Look for “amplifiers”, i.e. regions where dark matter accumulates
(galactic center, sun, earth...)

$F_\gamma \propto \rho^2$

Fornasa & Bertone (2008)
After removal of point sources and cosmic-ray photons, the Fermi/LAT flux includes an extended component centered on Sgr A* at energies $> 300$ MeV. 

Interpreted as photons from dark-matter annihilations:

- The DM density must increase faster than $r^{-1}$ toward the center
- $\langle \sigma v \rangle$ is consistent with the “thermal relic” value $3 \times 10^{-26}$ cm$^3$ s$^{-1}$
- $7$ GeV $< m_\chi < 45$ GeV
Analysis of the spectrum yields constraints on $\langle \sigma v \rangle$, $m_\chi$:

Abazajian & Manoj Kaplinghat (2011)
Supermassive Black Holes ...

- exist, with predictable masses, in bulges bigger than ~ the Milky Way's

- may exist, with uncertain masses, in some smaller galaxies (e.g. AGN)
Gravitational radius: \[ r_g = \frac{GM_\bullet}{c^2} \]
\[ \approx 5 \times 10^{-8} \left( \frac{M_\bullet}{10^6 M_\odot} \right) \text{ pc} \]

(Gravitational) influence radius:
\[ r_h = \frac{GM_\bullet}{\sigma^2} \]
\[ \approx 0.5 \left( \frac{M_\bullet}{10^6 M_\odot} \right) \left( \frac{\sigma}{100 \text{ km s}^{-1}} \right)^{-2} \text{ pc} \]

(Rotational) influence radius:
\[ r_K \approx 2 \times 10^{-3} \chi^{2/5} \left( \frac{M_\bullet}{10^6 M_\odot} \right) \left( \frac{m_\star}{M_\odot} \right)^{-1/5} \text{ pc} \]
Q: What does one expect for the density profile of DM (or stars, ...) around a SBH?

A: Pretty much anything!

If the velocity distribution is isotropic, then $\rho(r)$ must increase at least as steeply as $\rho \propto r^{-1/2}$ at $r \lesssim r_h$.

However, there are galaxies in which the stellar density profile is flatter than $\rho \propto r^{-1/2}$ ("cores"), implying an anisotropic velocity distribution.
A black hole that grows in a spherically-symmetric way pulls in matter around it:

causing the density to increase—a “density spike.”

If the growth is slow (“adiabatic”), the initial and final density profiles are uniquely related.
“Adiabatic Growth” Model

Invoking:

i) Liouville’s theorem ($f_f = f_i$)

ii) adiabatic invariance ($I = \text{const.}$)

the relation between initial and final phase-space densities is

$$f_f(E_f, L) = f_i(E_i, L)$$

$$\approx f_f(E_f)$$

where $E_f$ is related to $E_i$ through the condition

$$I_f(E_f, L) = I_i(E_i, L) \quad \text{and} \quad E_f = \frac{v^2}{2} - \frac{GM_*}{r}.$$
Peebles (1972) assumed \( f_i(E_i) = \text{const.} \)  
(e.g. the core of an isothermal sphere)

\[ \therefore f_f(E_f) = \text{const.} \]

A constant \( f \) in a \( 1/r \) potential implies

\[
\rho(r) = \int f \, d^3v = f_0 \int_0^{\sqrt{GM \cdot /r}} 4\pi v^2 \, dv
\]

\[ \propto r^{-3/2}, \quad \text{a “cusp”} \]
A “Spike” around the Black Hole?

But if the initial density profile is a **power-law**:

$$\rho_i(r) \propto r^{-\gamma_0}, \quad f_i(E_i) \propto E_i^{-\beta}, \quad \beta = \frac{6 - \gamma_0}{2(2 - \gamma_0)}$$

the final density is (almost) a power-law:

$$\rho_f(r) \propto r^{-\gamma}, \quad \gamma = 2 + \frac{1}{4 - \gamma_0}$$

$$0 \leq \gamma_0 \leq 2, \quad 2.25 \leq \gamma \leq 2.5.$$
The (initial) central density can be expanded:

\[ \rho_i(r) = \rho_0 \times \left( 1 + C_1 r + C_2 r^2 + \ldots \right) \]

For the isothermal sphere, \( C_1 = 0 \).

For the power-law model, \( C_1 \neq 0 \), even when \( \gamma_0 = 0 \).

In fact, the central phase-space density diverges:

\[ f_i(E) \propto \left[ E - \Phi(0) \right]^{-1}. \]

Quinlan & al. (2005)
But: was the initial density a power-law?

A better fit appears to be

\[ \frac{d \ln \rho}{d \ln r} = -2 \left( \frac{r}{r_0} \right)^\alpha \]

i.e.

\[ \rho(r) \propto \exp \left( -Ar^\alpha \right) \]

the "Einasto model."

Navarro & al. (2004)
D. M. & al. (2005)
Stadel & al. (2009)
Replacing the NFW halo by an Einasto halo has two consequences.

1. The (initial) density near the SBH is reduced, by a factor

\[
\frac{\rho_{\text{Einasto}}}{\rho_{\text{NFW}}} \approx \frac{e^{2/\alpha}}{4} \frac{r_\bullet}{r_{-2}}
\]

\[
\frac{r_\bullet}{r_{-2}} \approx \frac{(1 - 100) \text{ pc}}{(10 - 100) \text{ kpc}} \quad \approx 10^{-5} - 10^{-2}
\]

\[
\therefore \quad 0.01 \lesssim \left| \frac{\rho_{\text{Einasto}}}{\rho_{\text{NFW}}} \right|_{r_\bullet} \lesssim 1
\]
2. The Einasto model has

\[ \rho(r) = \rho_0 \exp(-Ar^\alpha) \]

\[ = \rho_0 \times (1 + C_1 r^\alpha + C_2 r^{2\alpha} + \ldots) \]

and its central phase-space density diverges.

But.... no one has worked out the implications for the adiabatic-growth model! (yet)
These results for “collisionless” cusps can be greatly modified by “collisional” effects, including:

1. Close interaction of DM particles with a binary SBH during a merger (“slingshot ejection”)

2. Close interaction of DM with stars (“scattering”)

3. DM-DM interactions (“self-annihilations”)

Self-Annihilations

The annihilation rate per DM particle is

$$\Gamma = n \langle \sigma v \rangle$$

∴ The DM density drops at a rate

$$\dot{\rho} = m_\chi \dot{n} = -m_\chi n \Gamma = -\frac{\rho^2}{m_\chi} \langle \sigma v \rangle$$

Setting $\dot{\rho} \times t_H \approx -\rho$, $t_H \approx 10$ Gyr, implies a maximum $\rho$:

$$\rho \lesssim \frac{m_\chi}{\langle \sigma v \rangle t_H}$$

$$\lesssim 3 \times 10^9 \frac{\text{GeV}}{\text{cm}^3} \left( \frac{m_\chi}{10 \text{ GeV}} \right) \left( \frac{\langle \sigma v \rangle}{10^{-26} \text{cm}^3 \text{s}^{-1}} \right)^{-1} \left( \frac{t_H}{10 \text{ Gyr}} \right)$$
Halo compressed by baryons (bulge)
Halo compressed by black hole ("spike")
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Galaxies merge

Binary SBH forms

Binary *ejects stars/DM* via the “gravitational slingshot”
Evidence for “Cusp Destruction”

The brightest galaxies **always** have central cores:
Observed “mass deficits” are:

\[ 1 \, M_\odot \lesssim M_{\text{def}} \lesssim 2 \, M_\odot , \]

consistent with the predictions of the merger model.

N-body merger simulations, of haloes with initial “spikes”.

A, B : $m_1/m_2 = 1:1$

C : $m_1/m_2 = 1:3$

... 

F : $m_1/m_2 = 1:10$

D. M. et al. (2002)

Destruction of DM Spikes by Binary SBHs
N-body merger simulations, of haloes with initial “spikes”.

\[
\frac{d\Phi_\gamma}{d\Omega} = \sum_i N^i_\gamma \frac{\sigma_i v}{4\pi M^2_\chi} \int_\psi \rho^2 dl
\]

\[
J(\psi) = \frac{1}{8.5 \text{kpc}} \left( \frac{1}{0.3 \text{GeV/cm}^3} \right)^2 \int_\psi \rho^2 dl
\]

D. M. et al. (2002)
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Scattering of DM by Stars

Gravitational interactions transfer energy from stars (heavy) to DM particles (light).

A steady-state is reached when the phase-space density of the DM is constant.

Near the SBH, the corresponding configuration-space density is

$$\rho(r) = \int f d^3v = f_0 \int_0^{\sqrt{GM*}/r} 4\pi v^2 dv \propto r^{-3/2}$$

Cusp “Regeneration”

stars

\[ \rho \propto r^{-7/4} \]

DM

\[ \rho \propto r^{-3/2} \]

Q: Which galaxies are likely to have short, central relaxation times?

A: Galaxies with nuclear star clusters (NSCs)
Half-mass relaxation times:

\[ t_{rh} \approx 2 \times 10^5 \left( \frac{r_{eff} \text{ (pc)}}{\text{yr}} \right)^{3/2} \left( \frac{N}{\text{pc}} \right)^{1/2} \left( \frac{m_*/M_\odot}{\text{yr}} \right)^{1/2} \]

of NSCs fall below 10 Gyr in galaxies with \(-M_B \lesssim 17\).

At least some NSCs also host SBHs (e.g. N4395), although the fraction is uncertain.  Seth & al. (2008)
Half-mass relaxation times:

\[ t_{rh} \approx 2 \times 10^5 \frac{[r_{\text{eff}} \text{ (pc)}]^{3/2} N^{1/2}}{[m_*/M_\odot]^{1/2}} \text{ yr} \]

of NSCs fall below 10 Gyr in galaxies with \(-M_B \lesssim 17\).

In the Galactic center, the (local) relaxation time appears to be \( > 10 \) Gyr everywhere.

D. M. (2009)
Cusp Observability

Would a relatively weak, $\rho \propto r^{-3/2}$ cusp imply a substantial increase in the annihilation signal?

$$\int \rho(r)^2 r^2 dr = \left\{ \int_{r<r_h} + \int_{r>r_h} \right\} \rho(r)^2 r^2 dr$$

$r < r_h$:
$$\int_{r<r_h} \rho(r)^2 r^2 dr \approx 3 \rho(r_h)^2 r_h^3$$

$r > r_h$:
$$\int_{r>r_h} \rho(r)^2 r^2 dr$$

depends on (i) the halo model; (ii) how much of the galaxy is imaged.
Relative contribution to annihilation signal from DM at $r < r_h$ vs. $r > r_h$ in various halo models.

\[ D. M., Harfst & Bertone (2007) \]

\[ \therefore \text{Only for the Einasto halos is there a significant increase due to the } \rho \propto r^{-3/2} \text{ cusp.} \]
What About the Milky Way?

- Relaxation time < 10 Gyr
- May never have experienced “major” merger

∴ Try models with initial “spikes”; see how they evolve, due to:

i) self-annihilations
ii) star-DM scattering
iii) capture by SBH
\[ J \propto \int \rho^2 \, dl \]

**Density**

- **scattering only**
- **annihilations only**
- **both**

Vasiliev & Zelnikov (2008)
Conclusions

1. All factors mitigate against high DM densities near the centers of bright galaxies.

2. Fainter galaxies -- if they contain NSCs & SBHs -- can have short enough relaxation times for $r^{-3/2}$ cusps to spontaneously regenerate.

3. For certain halo models, the regenerated cusps imply substantially larger DM annihilation signals.

4. Particle physicists who are modelling $\gamma$ rays from the Galactic Center should adopt the dynamical models!