Dynamics of Dark Matter at Galaxy Centers

TeV Particle Astrophysics

Fermilab, July 2005

Indirect Detection

$$\Gamma_A \propto \rho^2$$

↓

Look for "amplifiers", i.e. regions where dark matter accumulates
(galactic center, halo clumps, sun, earth…)

Annihilation Radiation

The flux can be broken into two pieces:

$$F_\gamma(E) \propto \frac{N_\gamma \langle \sigma v \rangle}{\Delta\Omega\, m_\chi^2} \cdot \int_{los} dl\, \rho^2(r)$$

Annihilation Radiation

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Particle Physics

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Dynamics

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Annihilation Radiation

The flux can be broken into two pieces:

Dynamics
+
Particle Physics

$$F_\gamma(E) \propto \frac{N_\gamma \langle \sigma v \rangle}{\Delta\Omega \, m_\chi^2} \cdot \int_{los} dl \, \rho^2(r)$$

$$\bar{J}_{\Delta\Omega} \equiv K \Delta\Omega^{-1} \int_{\Delta\Omega} d\psi \int_{los} dl\, \rho^2(r)$$

$$K^{-1} = (8.5\text{kpc})(0.3\text{GeV}/\text{cm}^3)^2$$

What to assume for $\rho(r)$?

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What to assume for *ρ*(*r*) ?

- Rotation curve – fruitless, since potential is dominated by stars, supermassive black hole
- *N*-body simulations of DM clustering – fail to resolve structures smaller than ~10^3 pc

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What to assume for $\rho(r)$?

"Standard" CDM halo: $\rho_{NFW}(r) \approx (r/R_{SUN})^{-\gamma}$, $\gamma \approx 1$

$J_{NFW} \approx 300 \quad (\Delta\Omega = 10^{-3})$

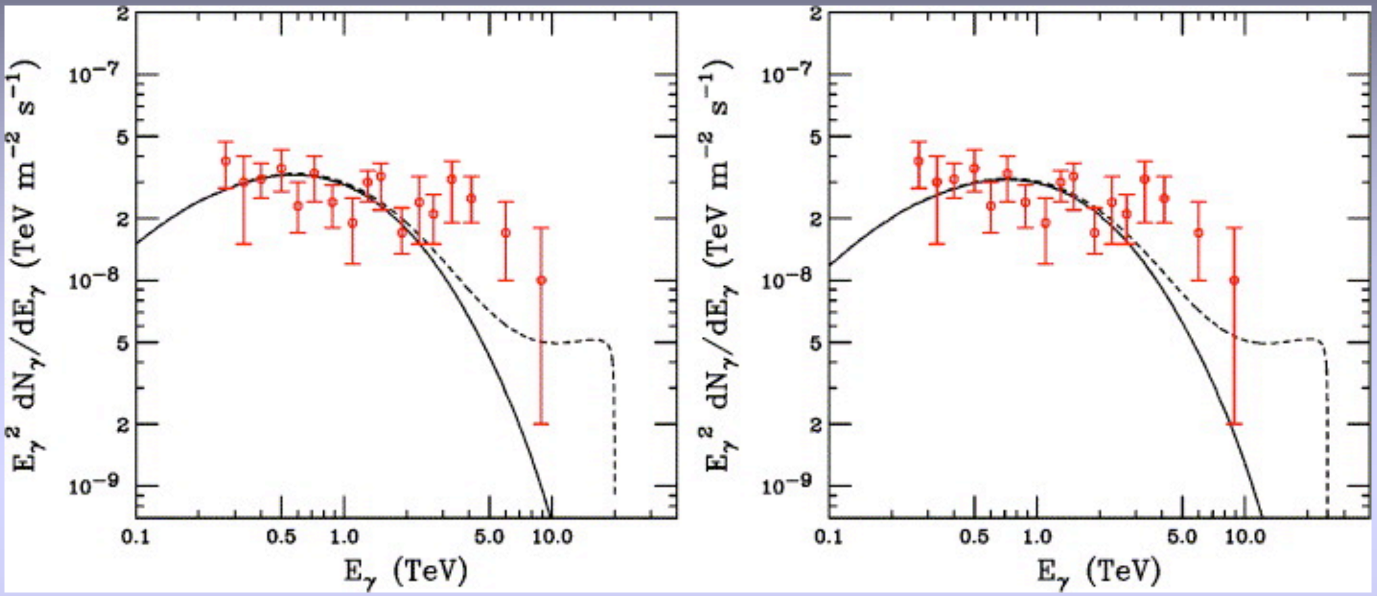
$\approx 3000 \ (\Delta\Omega = 10^{-5})$

Larger *J*-values are possible if the DM density increases more steeply toward the center than $\rho \sim r^{-1}$.

Define the boost factor *b*:

$$b \equiv J/J_{\mathrm{NFW}}$$

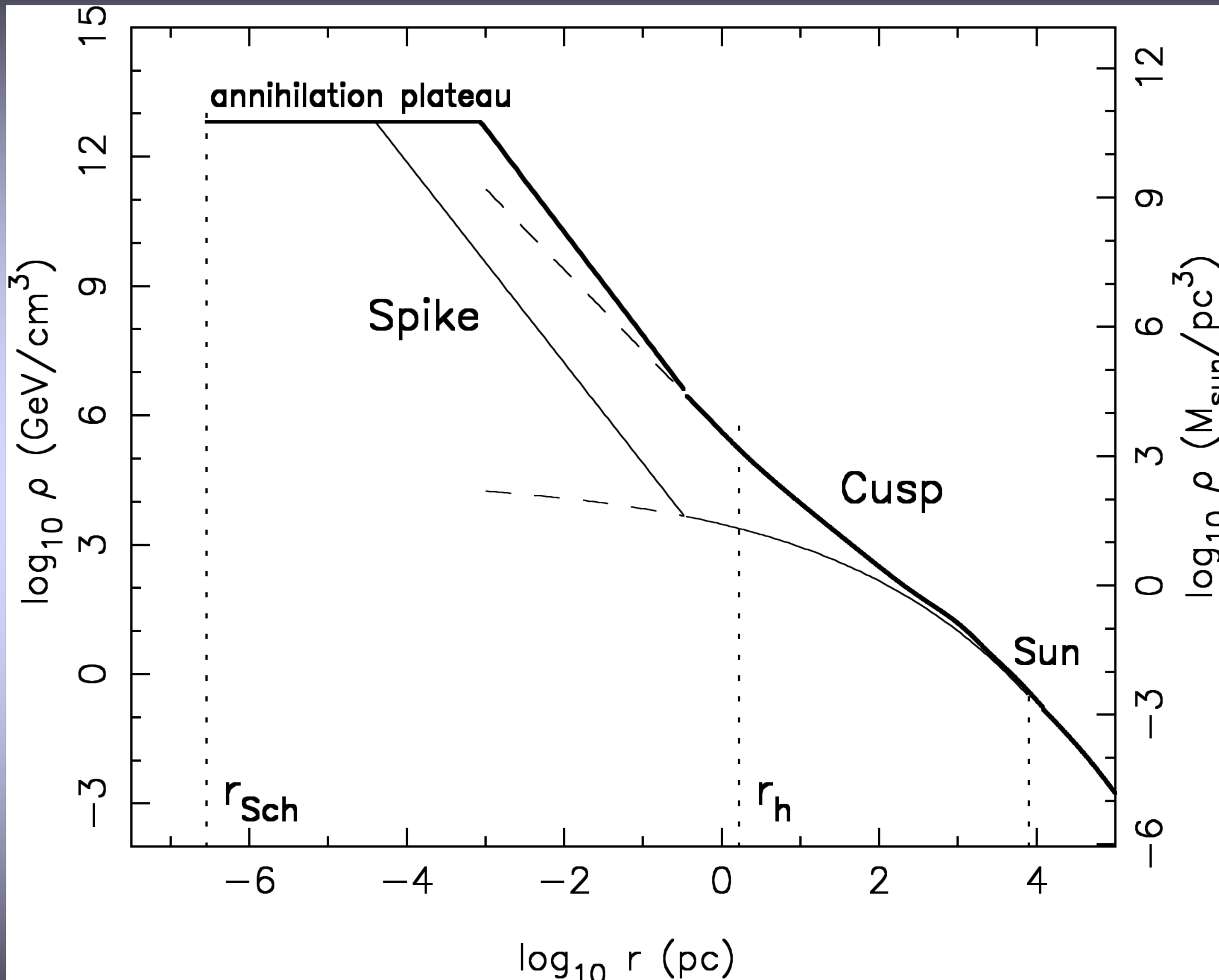
H.E.S.S. Galactic center data *(Aharonian et al 2004)*



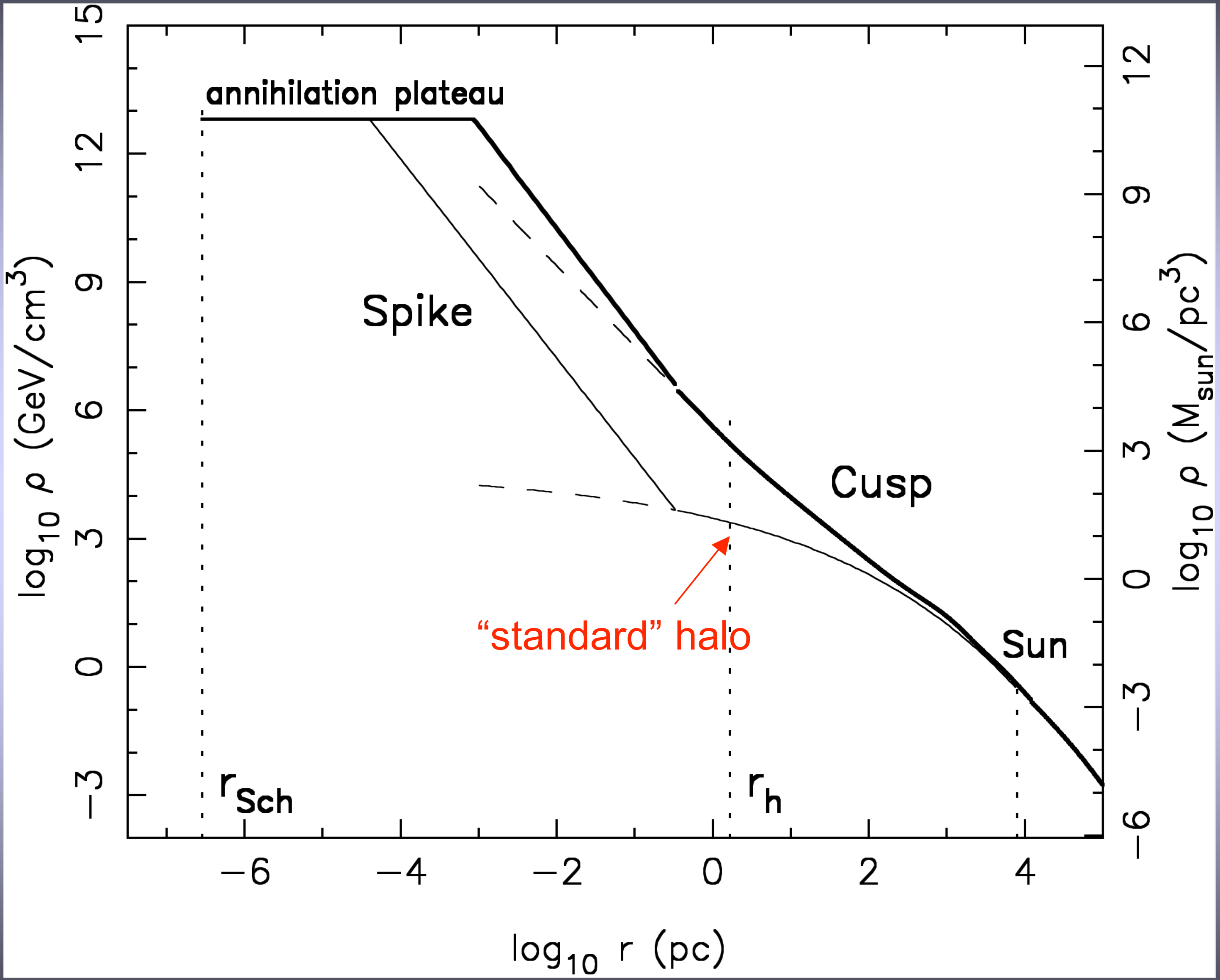
Fitting the spectrum (and other constraints) requires:

1. 20 TeV < *m* < 30 TeV
2. Boost factor $10^3 < b < 10^4$

(Horns 2005; Hooper & March-Russel 2005; Mambrini et al. 2005)



annihilation plateau
Spike
Cusp
Sun
r_{Sch}
r_h
$\log_{10} \rho$ (GeV/cm^3)
$\log_{10} \rho$ (M_{sun}/pc^3)
$\log_{10}$ r (pc)



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15
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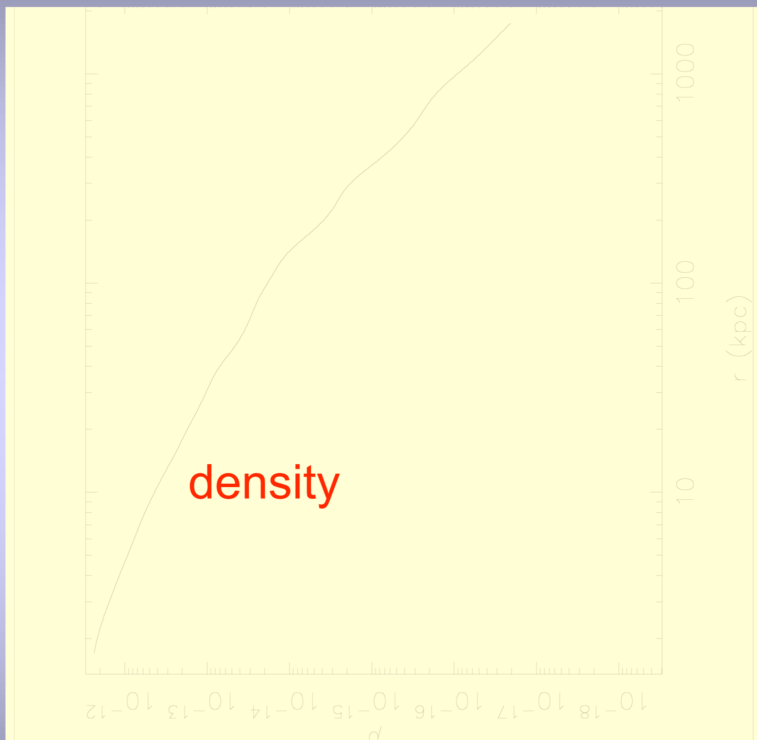
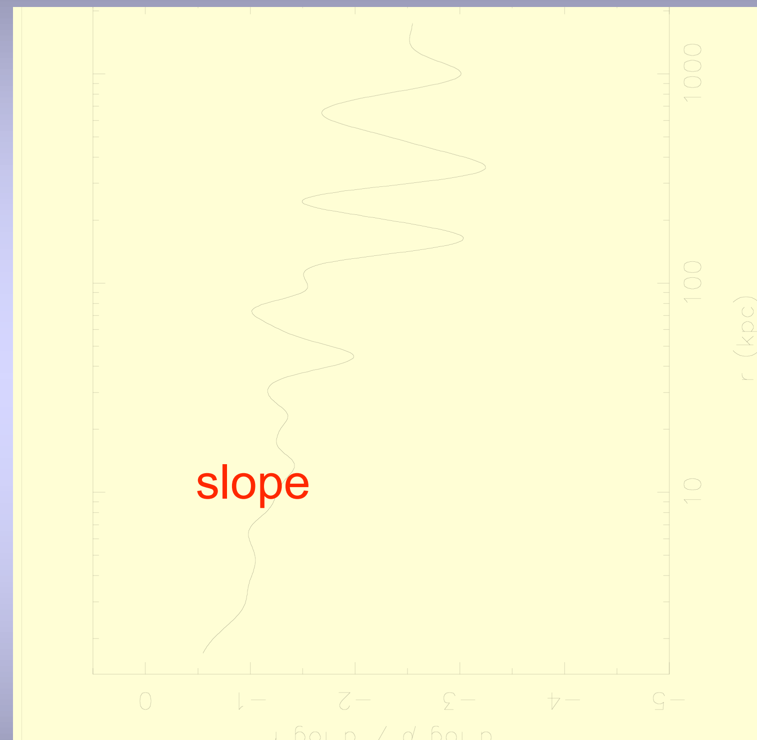
4

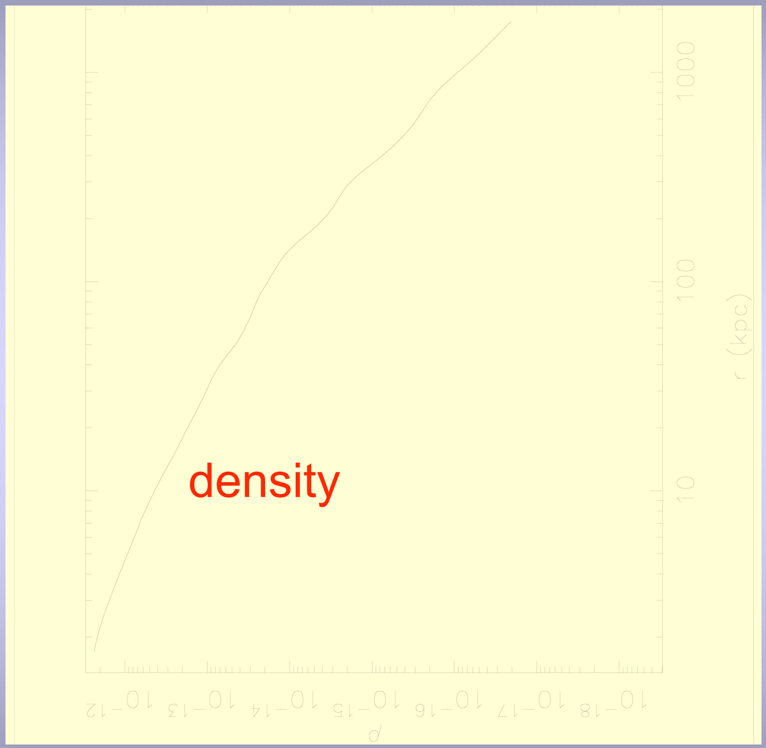
ΛCDM Halos

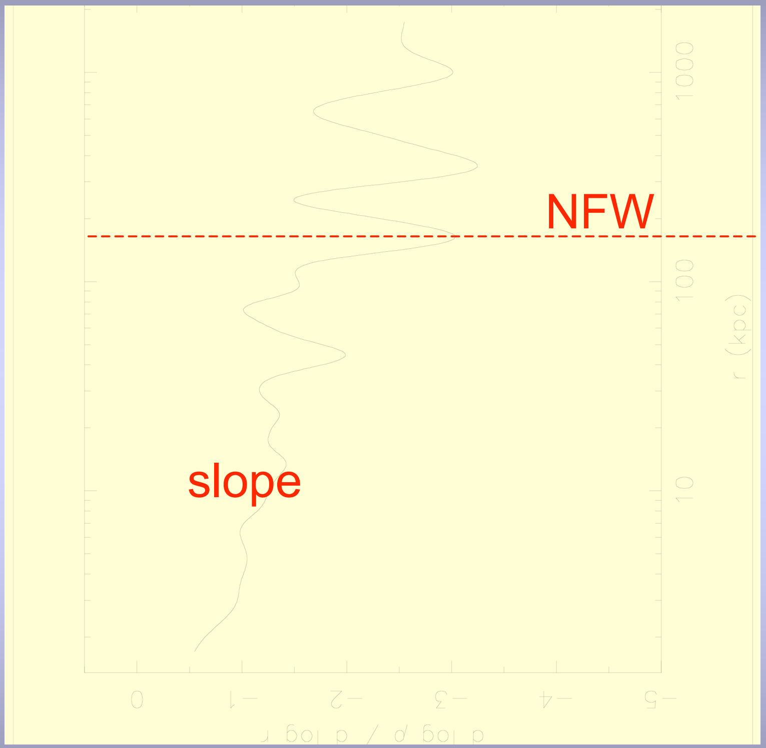




Navarro et al. 2004
Reed et al. 2005
Diemand et al. 2005
Merritt et al. 2005

ΛCDM Halos





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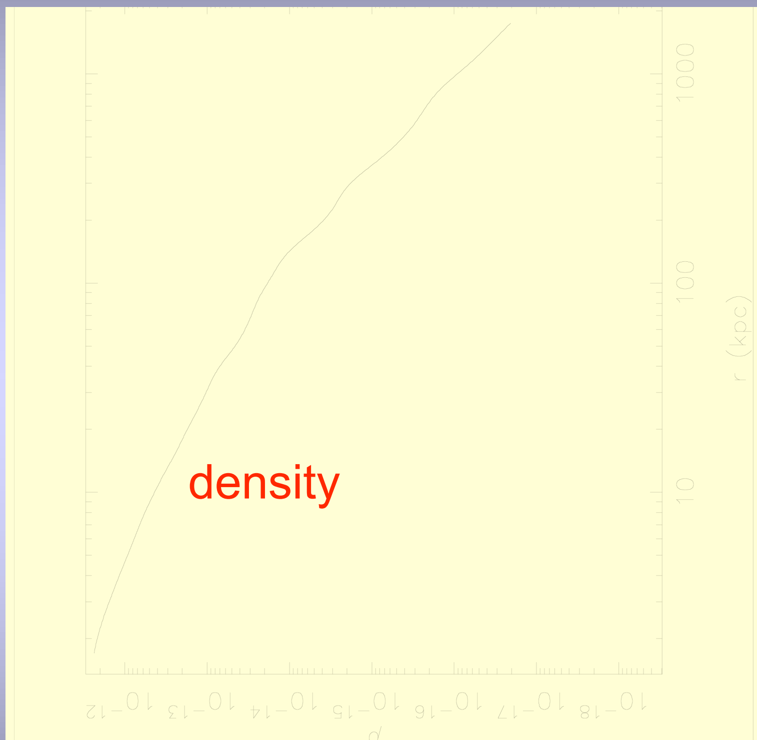

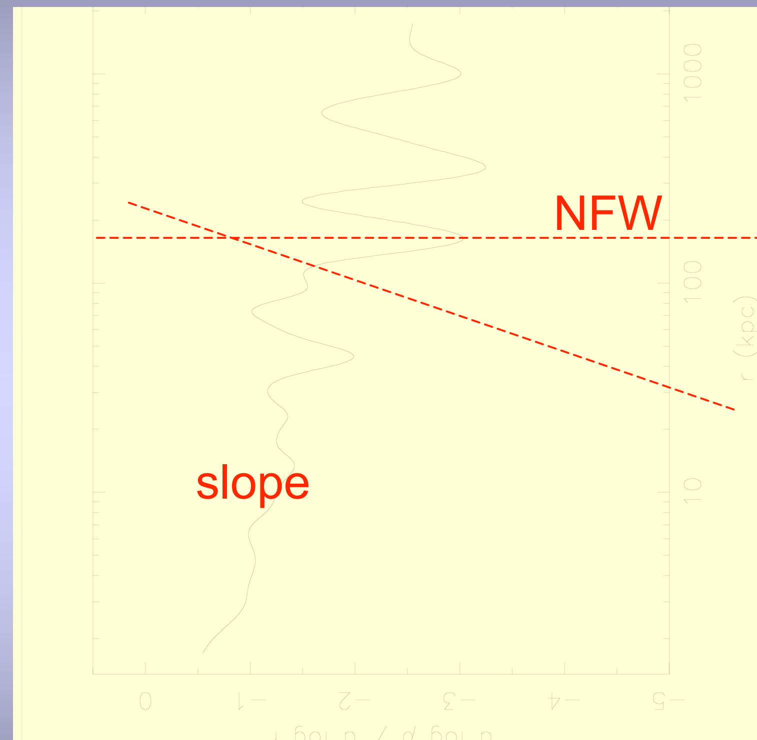

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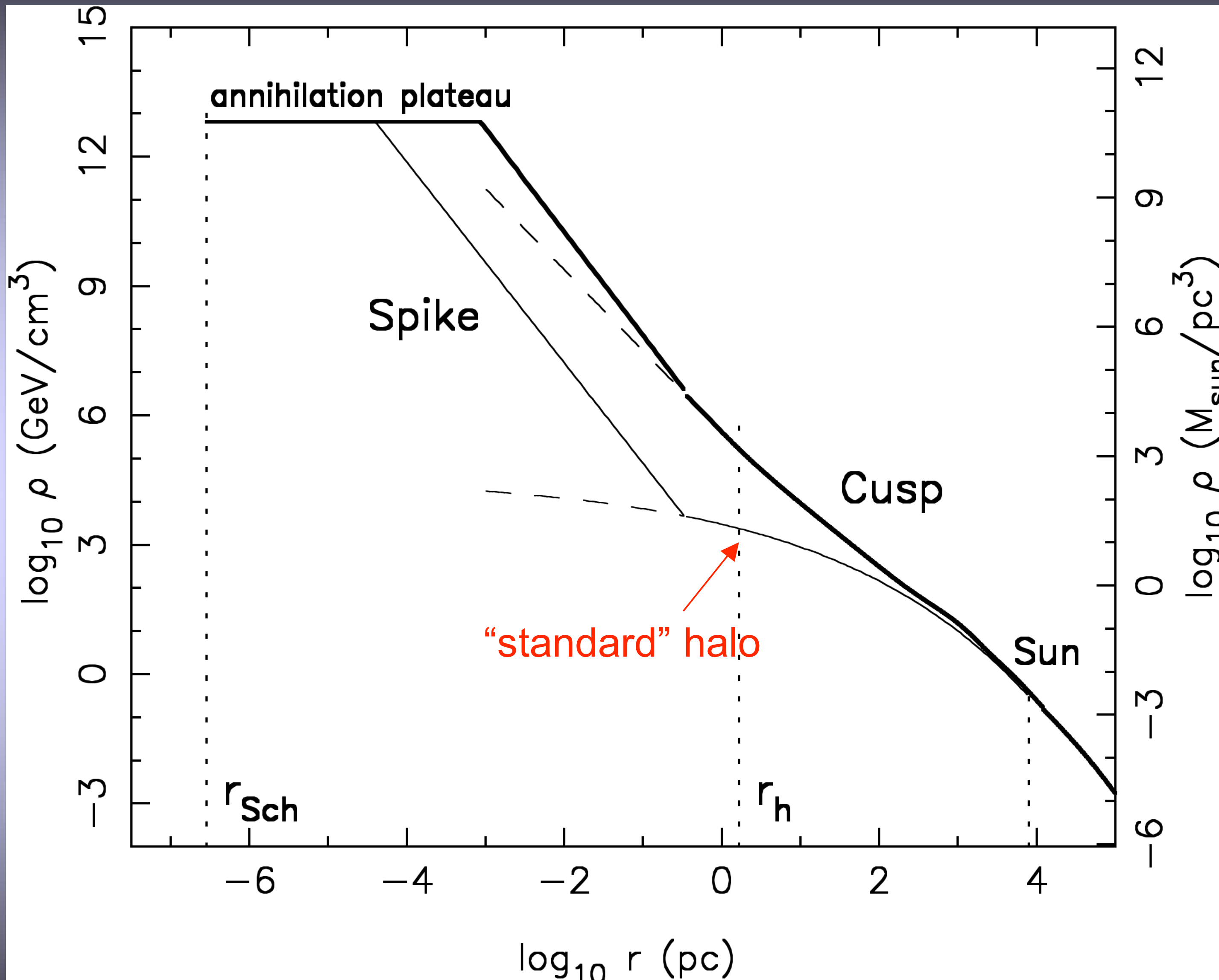

annihilation plateau
Spike
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"standard" halo
Sun
r_{Sch}
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$\log_{10} r$ (pc)
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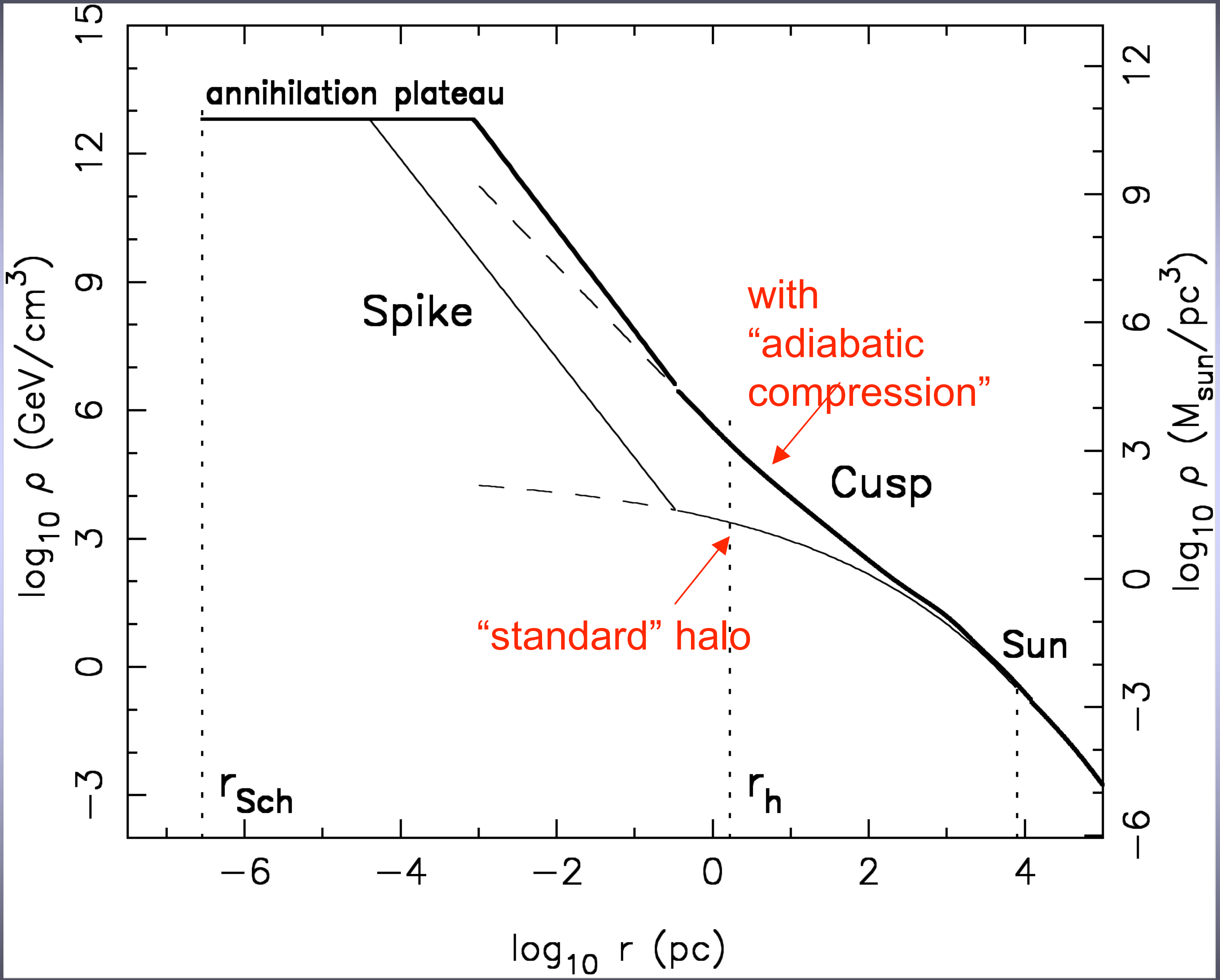
annihilation plateau
Spike
with
“adiabatic
compression”
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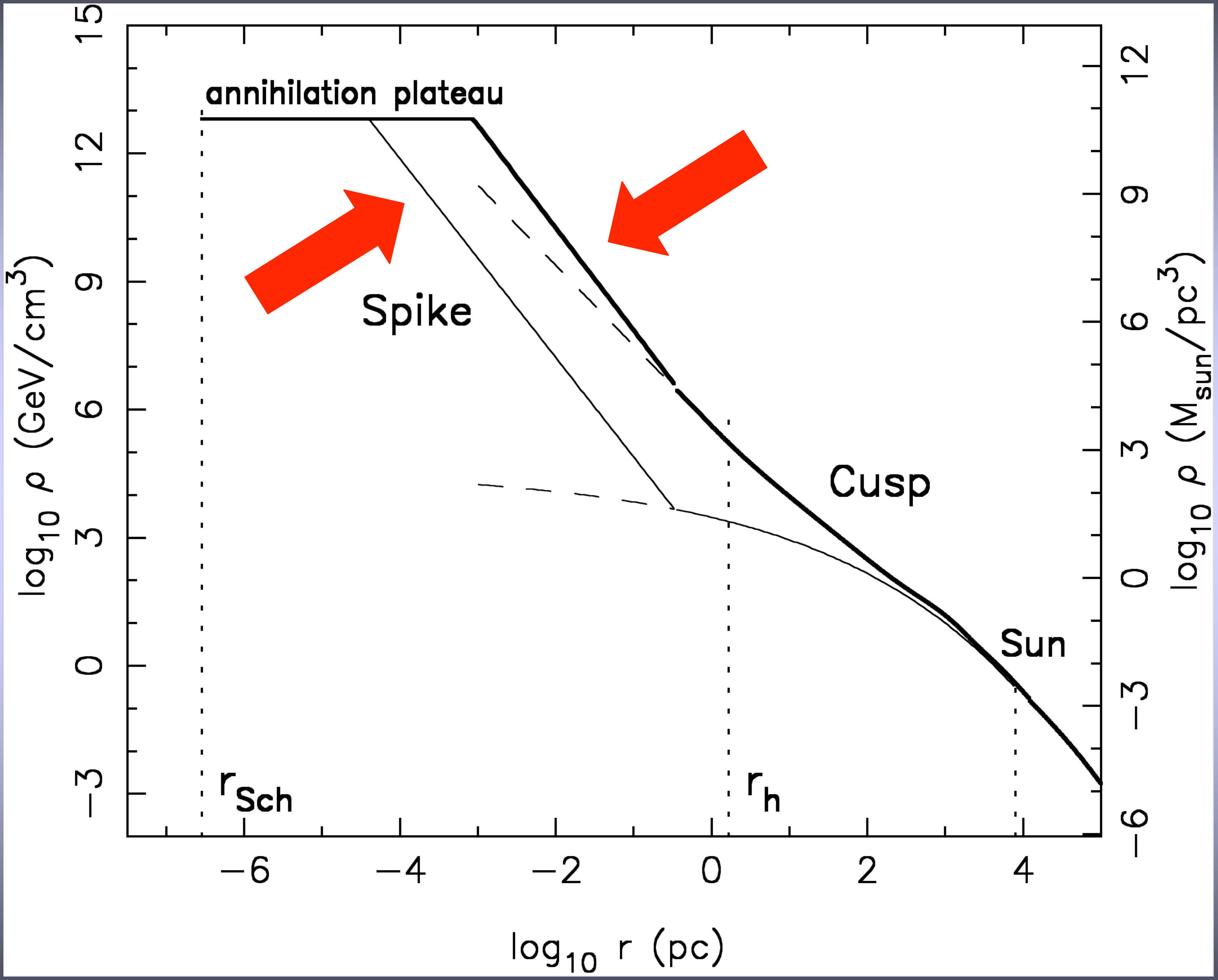

annihilation plateau
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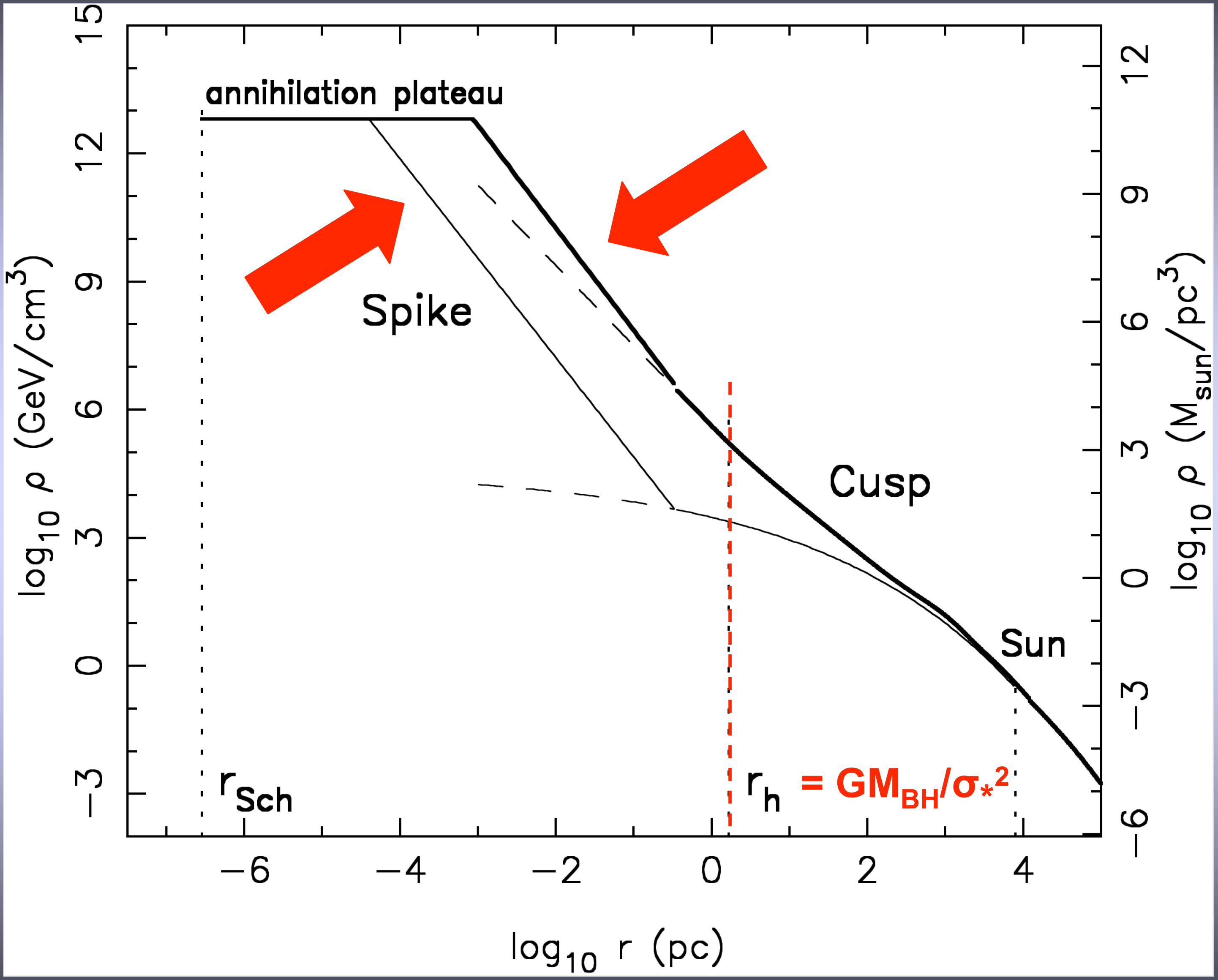

annihilation plateau
Spike
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Sun
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r_h = GM_BH/σ_*^2
log10 ρ (GeV/cm3)
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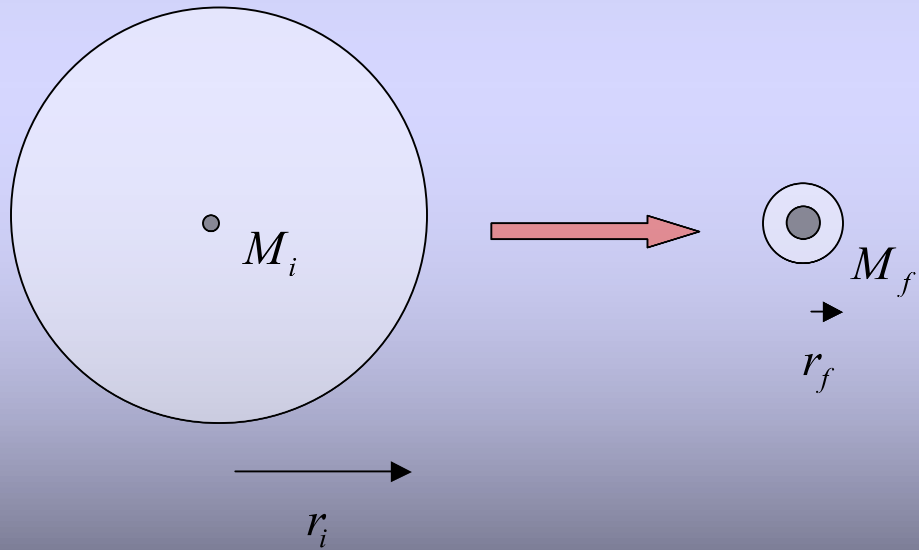
A “Spike” Around the Black Hole?

A growing black hole pulls in matter around it:



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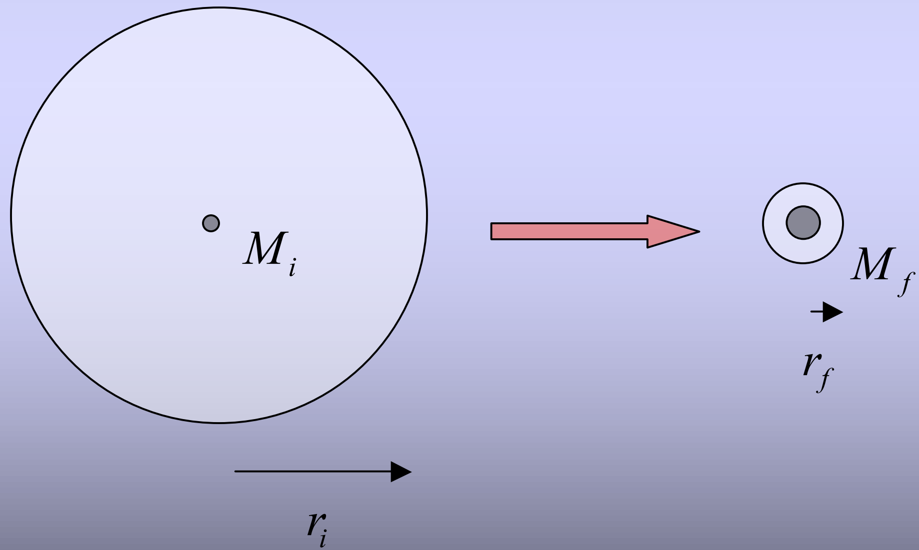

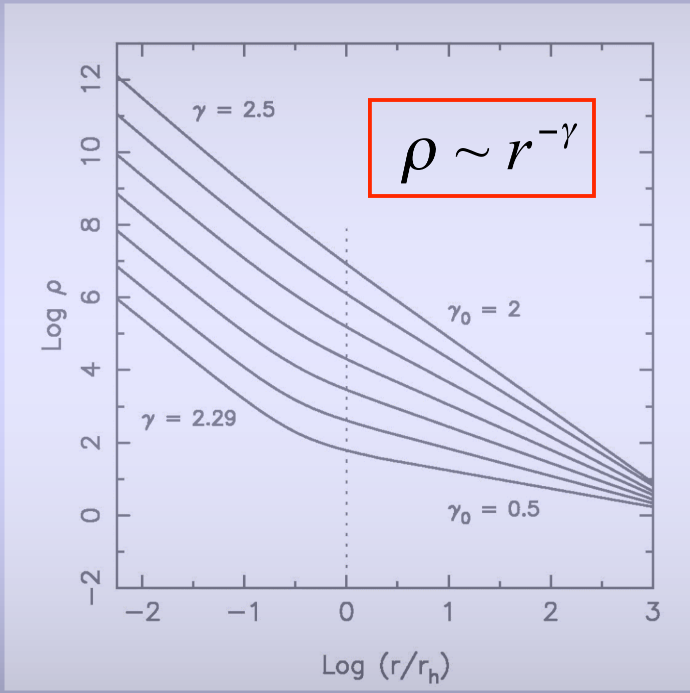

Peebles 1972,
Young 1980, …,

Gondolo & Silk 1999

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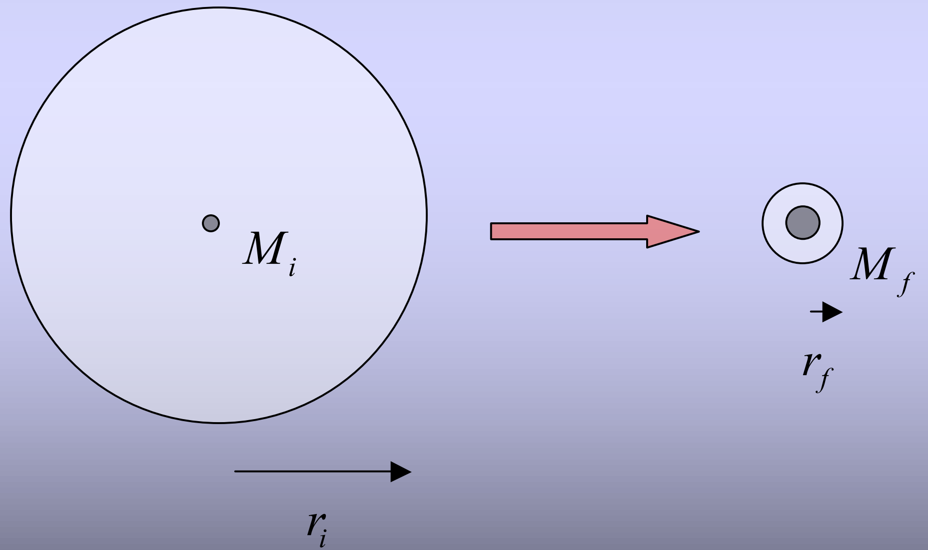

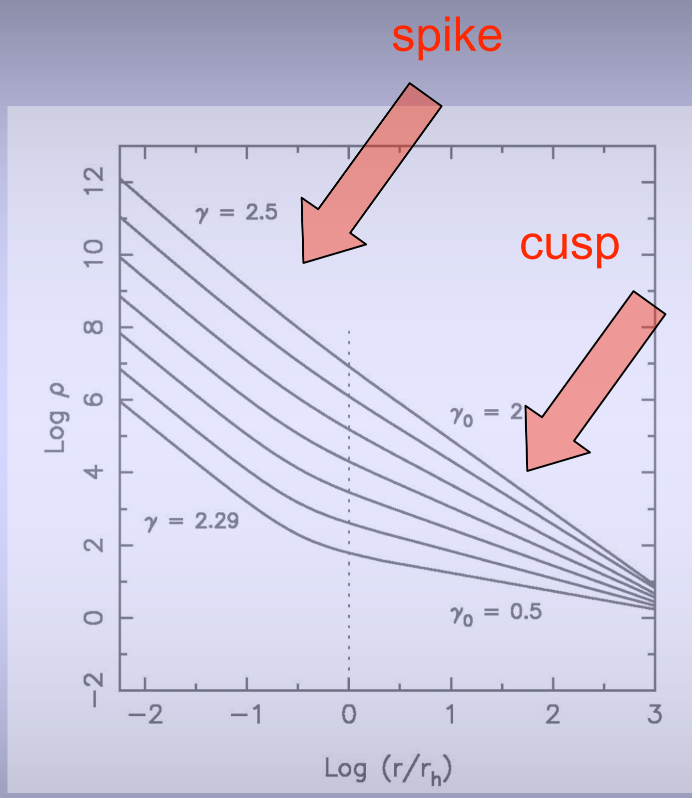

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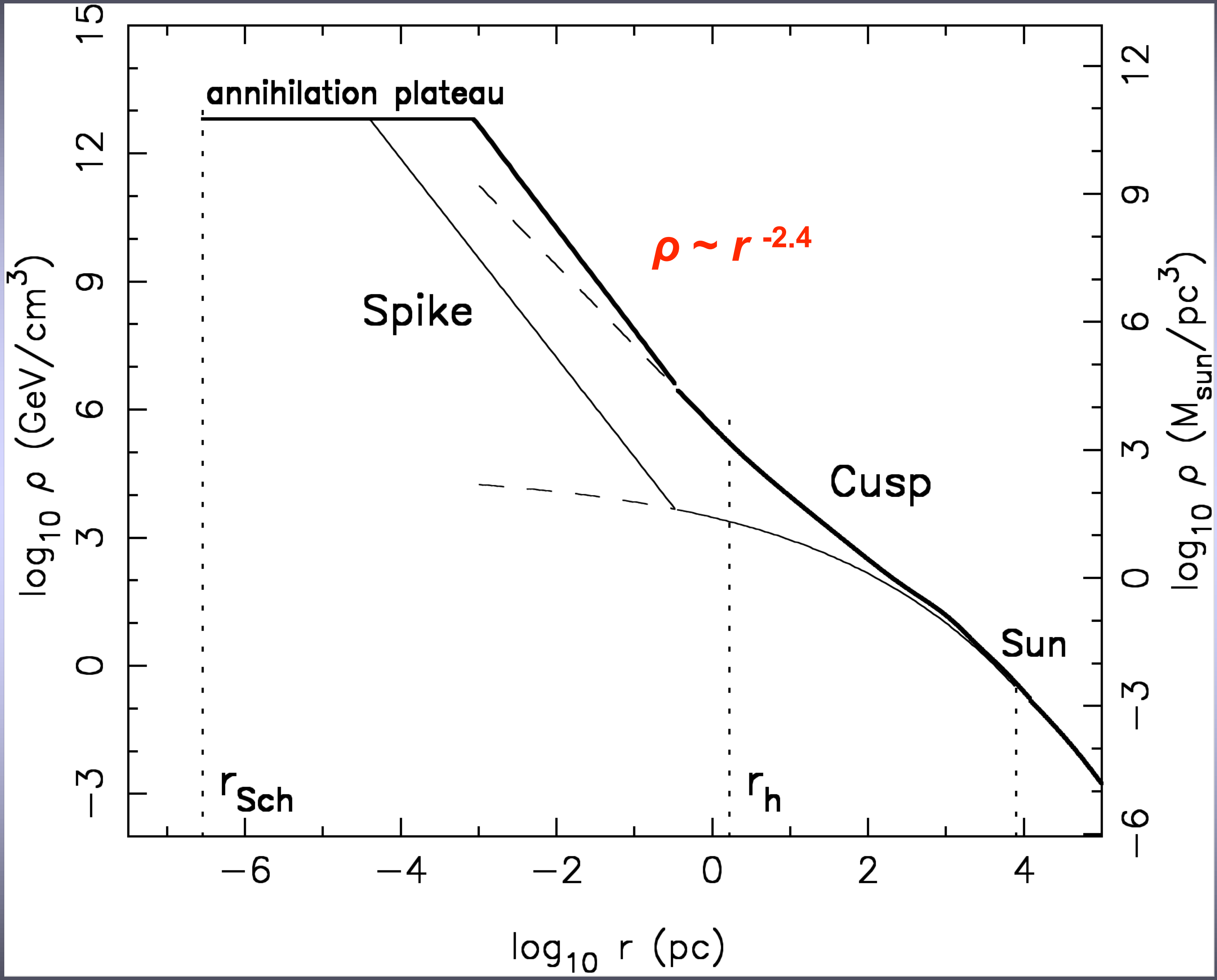

annihilation plateau
ρ ~ r -2.4
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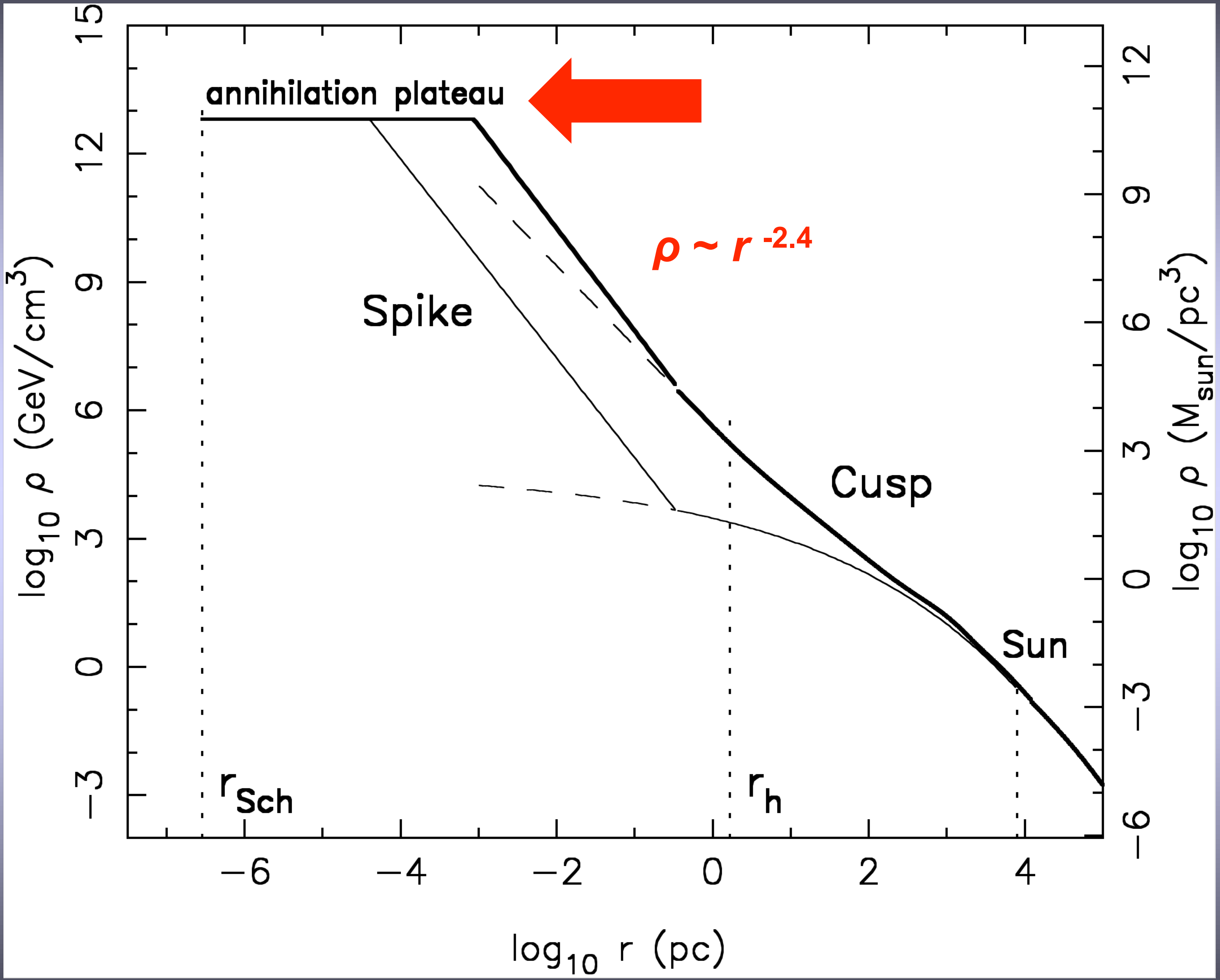

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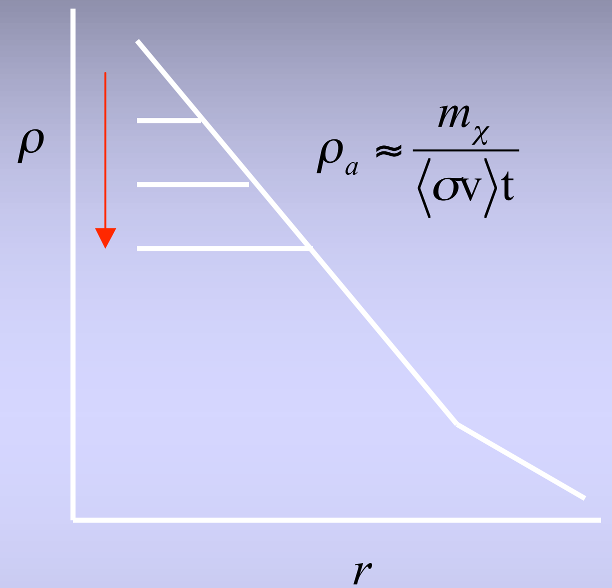
$$\frac{\partial\rho}{\partial t} \approx -\rho \times n\langle\sigma v\rangle \approx -\rho^2 \frac{\langle\sigma v\rangle}{m}$$

$$\frac{1}{\rho} \approx \frac{1}{\rho_0} + \frac{\langle\sigma v\rangle t}{m}, \qquad \rho \rightarrow \frac{m}{\langle\sigma v\rangle t}$$



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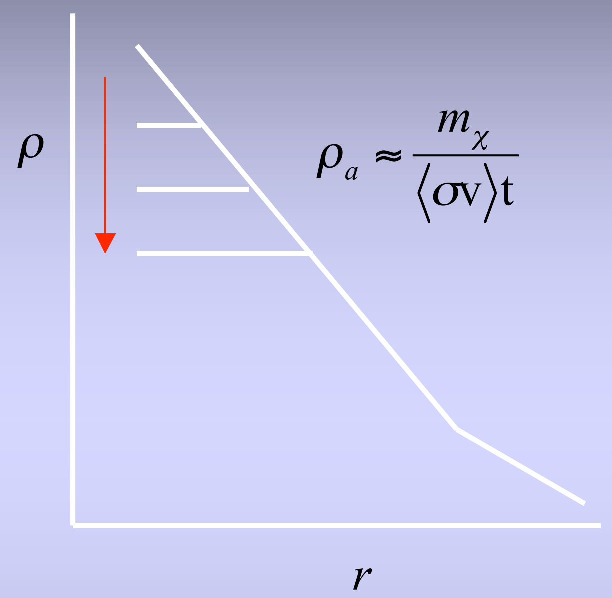

In a spike with inner truncation:

r_a = radius at which annihilation time equals galaxy lifetime,

$\rho_a \approx m_\chi/\langle\sigma v\rangle t$,

the J-factor is determined by r_a and ρ_a:

$$\overline{J}_{\Delta\Omega} \approx \frac{4\pi}{3}\frac{J_0}{\Delta\Omega}\frac{\rho_a^2 r_a^3}{R_\odot^2}\left\{1+\frac{3}{2\gamma_{sp}-3}\left[1-\left(\frac{r_a}{r_{sp}}\right)^{2\gamma_{sp}-3}\right]\right\}$$

$$\approx \frac{4\pi}{3}\frac{J_0}{\Delta\Omega}\frac{\rho_a^2 r_a^3}{R_\odot^2}\frac{1}{1-3/(2\gamma_{sp})}$$

$$\approx \frac{10}{\Delta\Omega}\left(\frac{\rho_a}{\rho_\odot}\right)^2\left(\frac{r_a}{R_\odot}\right)^3$$

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$$\approx \frac{10}{\Delta\Omega} \left(\frac{\rho_a}{\rho_\odot} \right)^2 \left(\frac{r_a}{R_\odot} \right)^3$$

Using the "benchmark" models of Battaglia et al. (2004), one finds boost factors in the range:

$3 \times 10^5 < b < 3 \times 10^7$.

(Bertone & Merritt 2005)

But: Do / did the spike (ever) exist?

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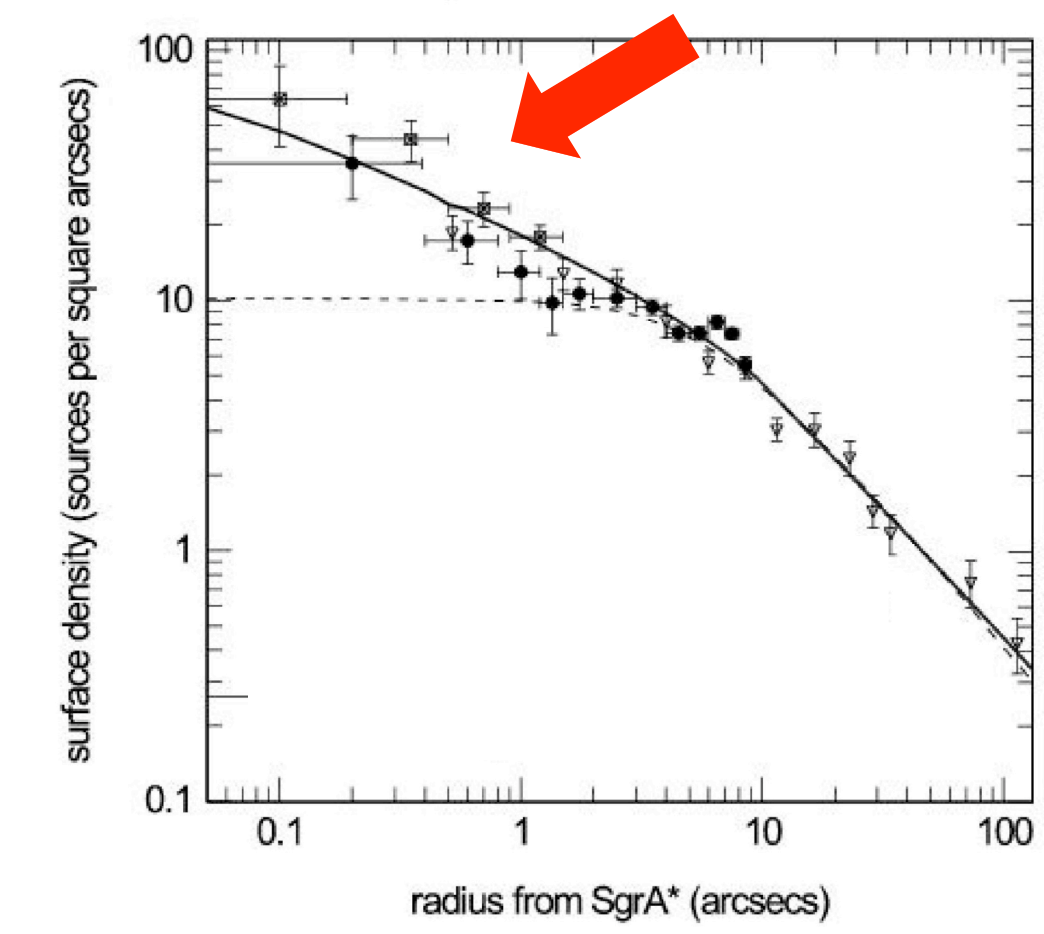
One thing we know for sure: there is a spike in the stars!



$\rho \approx r^{-\gamma}$,
$1.5 < \gamma < 1.7$

Genzel et al. 2003

Is the stellar spike due to growth of the SBH?

No – another mechanism is more likely.

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No – another mechanism is more likely.

In one relaxation time:

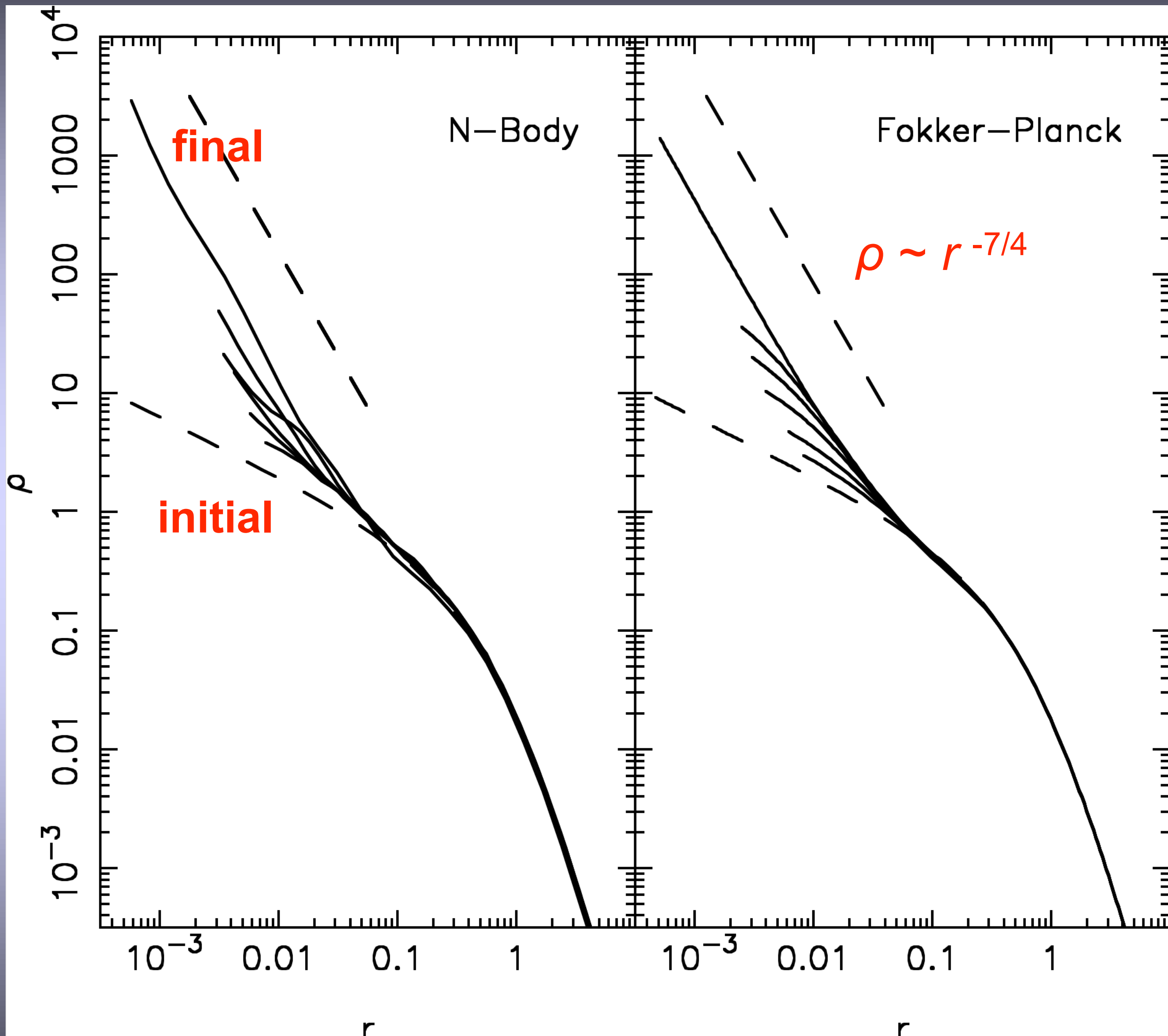
$$T_r \approx \frac{0.065 \mathrm{v}_*^3}{G^2 m_* \rho_* \ln\Lambda} \approx 1.4\times 10^9 \,\mathrm{yr}$$

a cusp/spike in the stars grows around the SBH.

The steady-state density profile is:

$$\rho \sim r^{-7/4}, \quad r < 0.2 r_h \approx 0.5 \text{ pc}.$$

(Bahcall & Wolf 1976)



Growth of a Bahcall-Wolf spike.

Preto, Merritt & Spurzem 2004

What (if anything) does the existence of the stellar spike imply for the existence of a DM spike?

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Consider two possible scenarios:

1. Both stellar and DM spikes have been present for ~10^{10} yr.
2. One or both spikes were destroyed, e.g. by a binary BH .

What (if anything) does the existence of the stellar spike imply for the existence of a DM spike?

Consider two possible scenarios:

1. Both stellar and DM spikes have been present for ~10^{10} yr.
2. One or both spikes were destroyed, e.g. by a binary BH.

In scenario #2, we have as constraint the current existence of the stellar spike.

Scenario #1: The stellar and DM spikes are "old".

The dark matter spike evolves dynamically:

Physical mechanisms:

1. **Scattering off of stars** ("heating")

--Takes place on a ~relaxation time scale:

$$T_{heat} = \frac{4\sqrt{3}}{27}\frac{M_\bullet}{m_*}\left(\frac{GM_\bullet}{r_h^3}\right)^{-1/2}\frac{1}{\ln\Lambda} \approx 1.0\times10^9\,\mathrm{yr}$$

-- Redistributes dark matter to larger radii, lowers density

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2. **Self-annihilation**

-- Limits density near center to $\approx \frac{m_\chi}{\langle\sigma v\rangle}\frac{1}{T}$

3. Capture by the black hole

-- Important at radii $r \le 1\mathrm{pc}$

-- Capture rate dominated by particles scattered onto low-angular-momentum orbits

Scenario #1: The stellar and DM spikes are “old”.

Evolution of the spike can be described by the Fokker-Planck equation.

Let ***f(E)*** be the phase-space density of dark-matter particles:

$$\frac{\partial f}{\partial t} = -\frac{1}{4\pi^2 p}\frac{\partial F_E}{\partial E} - f(E)\nu_{coll}(E) - f(E)\nu_{loss}(E)$$

$$F_E(E) = D_{EE}(E)\frac{\partial f}{\partial E},$$

$$D_{EE}(E) = \text{energy diffusion coefficient}$$

$$\nu_{coll}(E) = \left\langle m_\chi^{-1}\rho\sigma \mathrm{v}\right\rangle_{\text{orbit-averaged}}$$

$$\nu_{loss}(E) = \text{scattering rate into black hole}$$

Scenario #1: The stellar and DM spikes are “old”.

Plots show evolution of dark matter spike over 10^{10} yr at the Galactic center, due to:

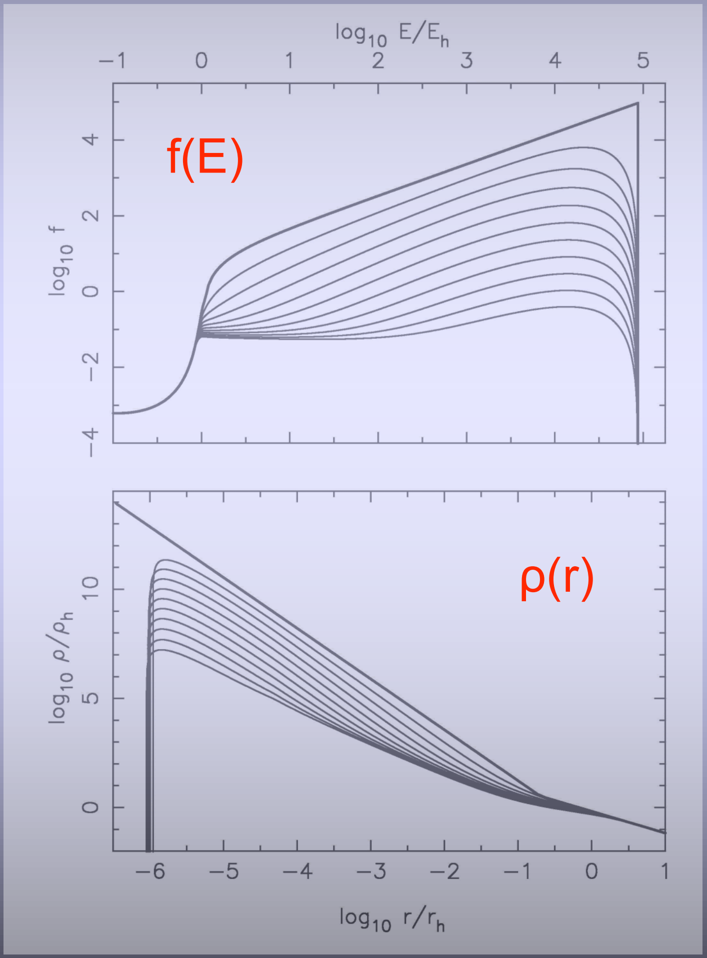
-- heating by stars

-- capture in the black hole

Initial density profile: $\rho \sim r^{-2.3}$

Final density profile: $\rho \sim r^{-1.8}$

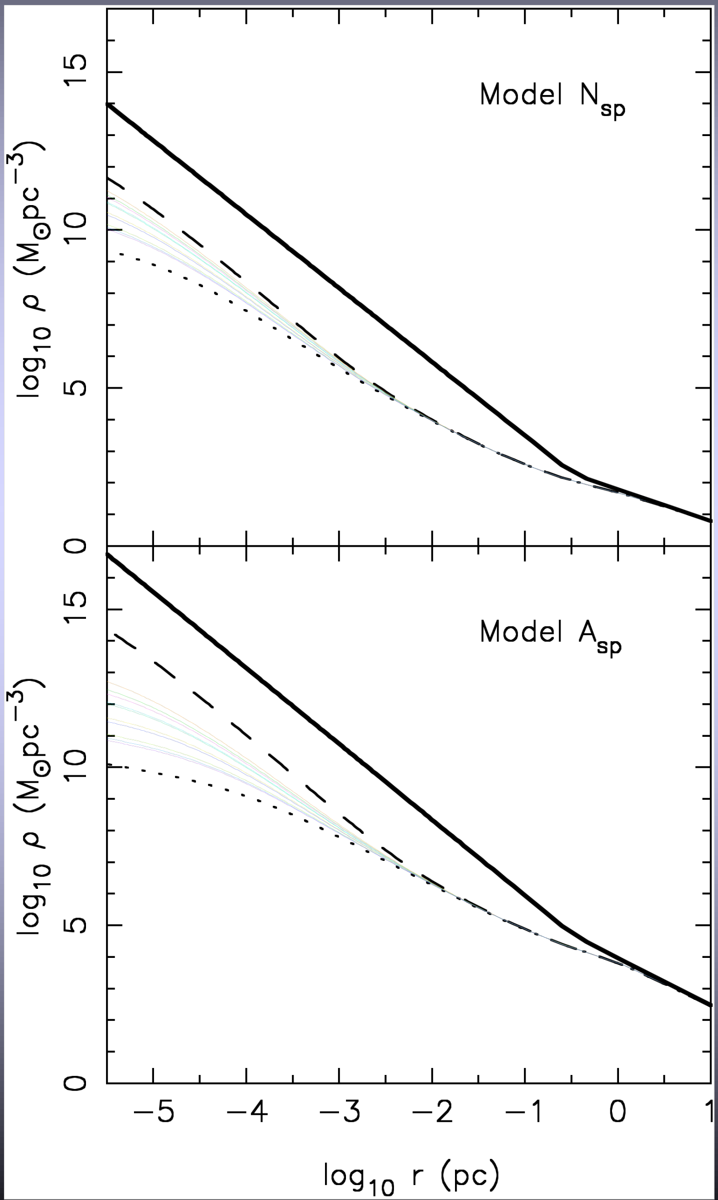
Merritt 2004



Scenario #1: The stellar and DM spikes are “old”.

Plots show initial and final dark matter profiles, including all three processes.

Colored lines: various choices for <σ*v*>/m, from the “benchmark” models of Battaglia *et al*. (2004)



Bertone & Merritt 2005

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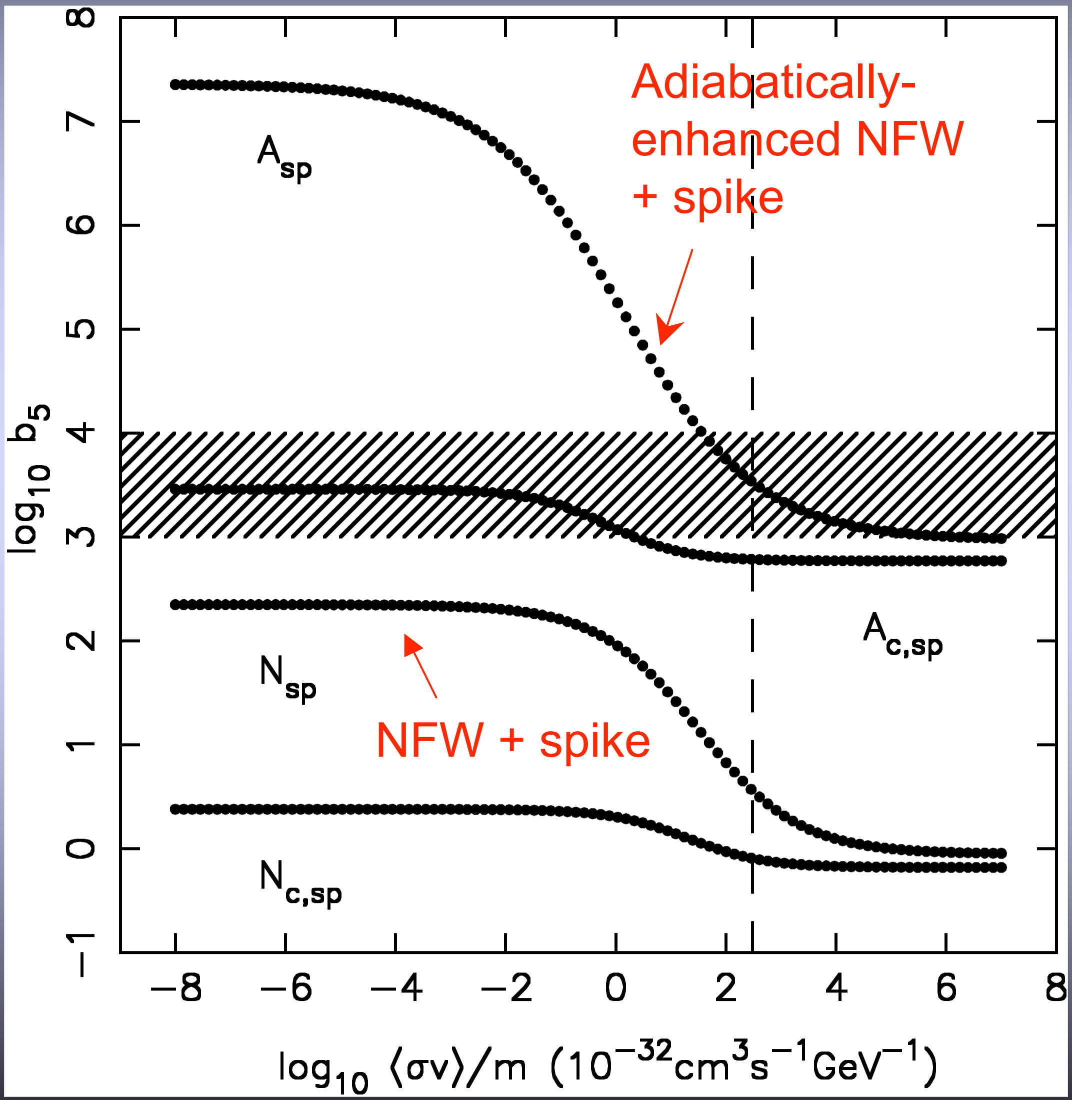

Boost factors for DM spikes, ***after 10^{10} yr of evolution***, including self-annihilations.

Bertone & Merritt 2004

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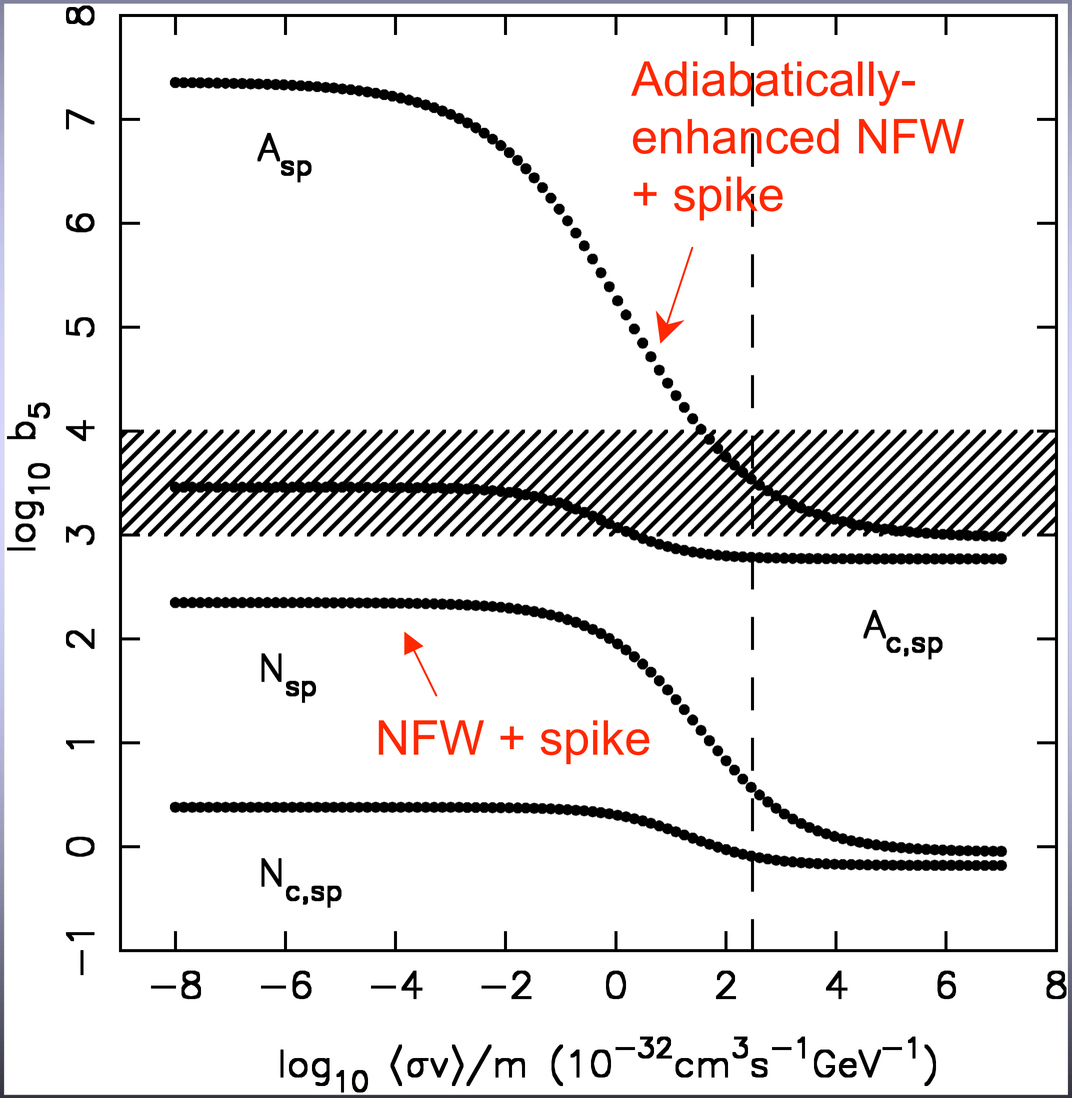


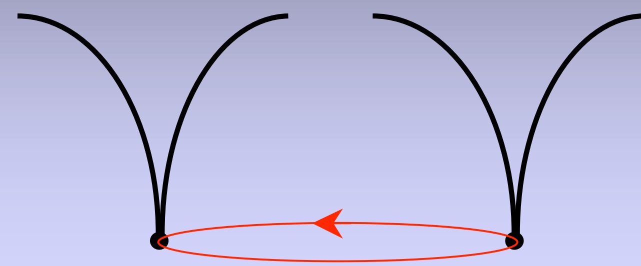
Boost factors for DM spikes, ***after 10^{10} yr of evolution,*** including self-annihilations.

Conclusion: Even an "evolved" spike can have large boost factors, $b > 10^3$.

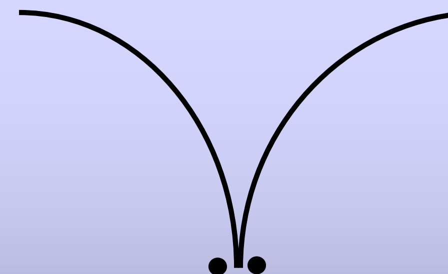
Bertone & Merritt 2004

Scenario #2: The DM spike was destroyed.

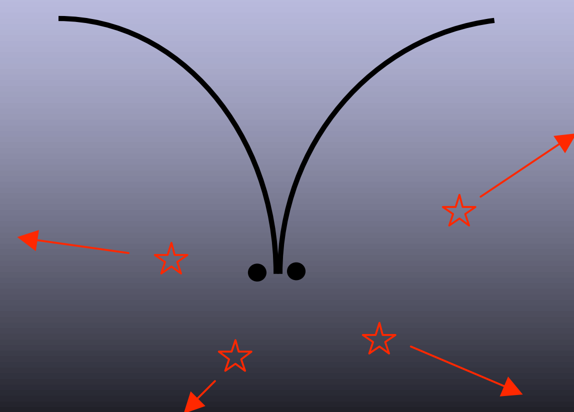
Galaxies merge



Binary BH forms



Binary ejects stars/DM via the "gravitational slingshot"



Spike Destruction by Binary BHs

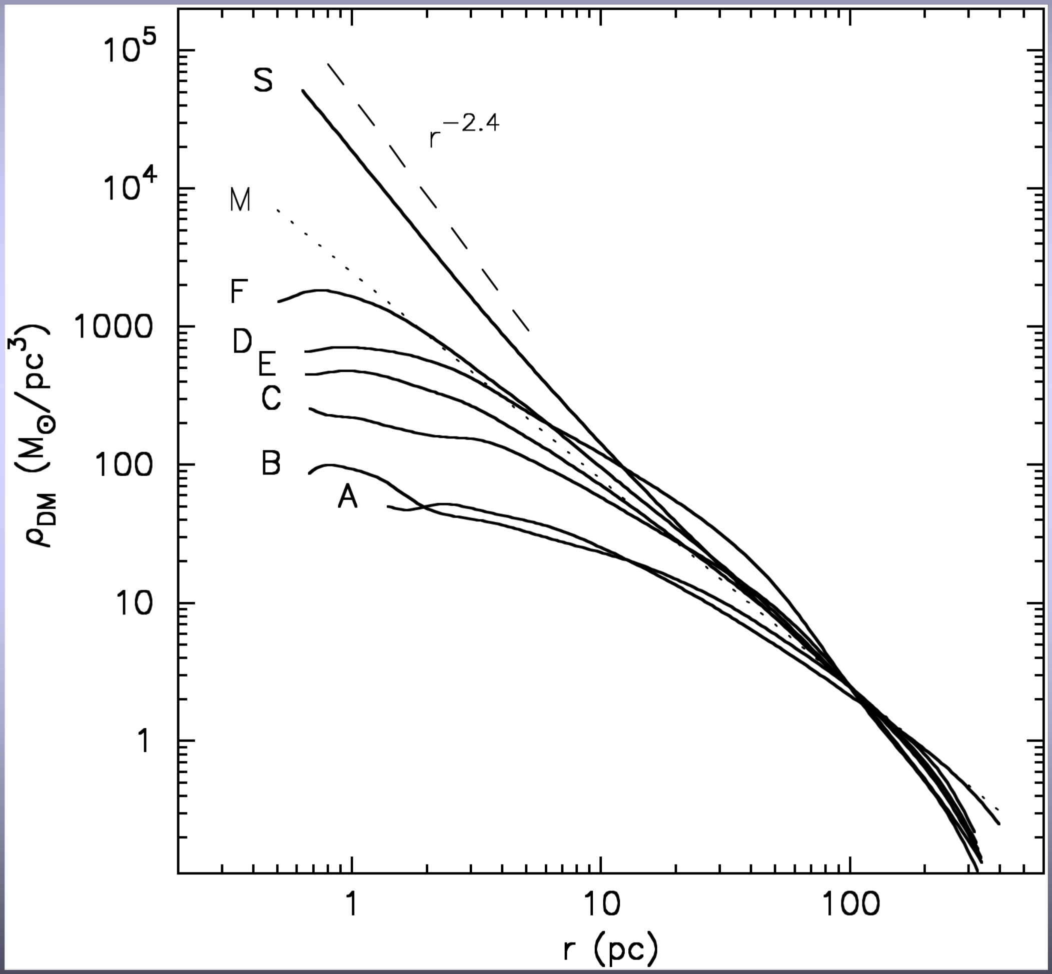
N-body simulations of spike disruption by binary black holes.

A,B: m_1/m_2 = 1:1

C: m_1/m_2 = 1:3

…

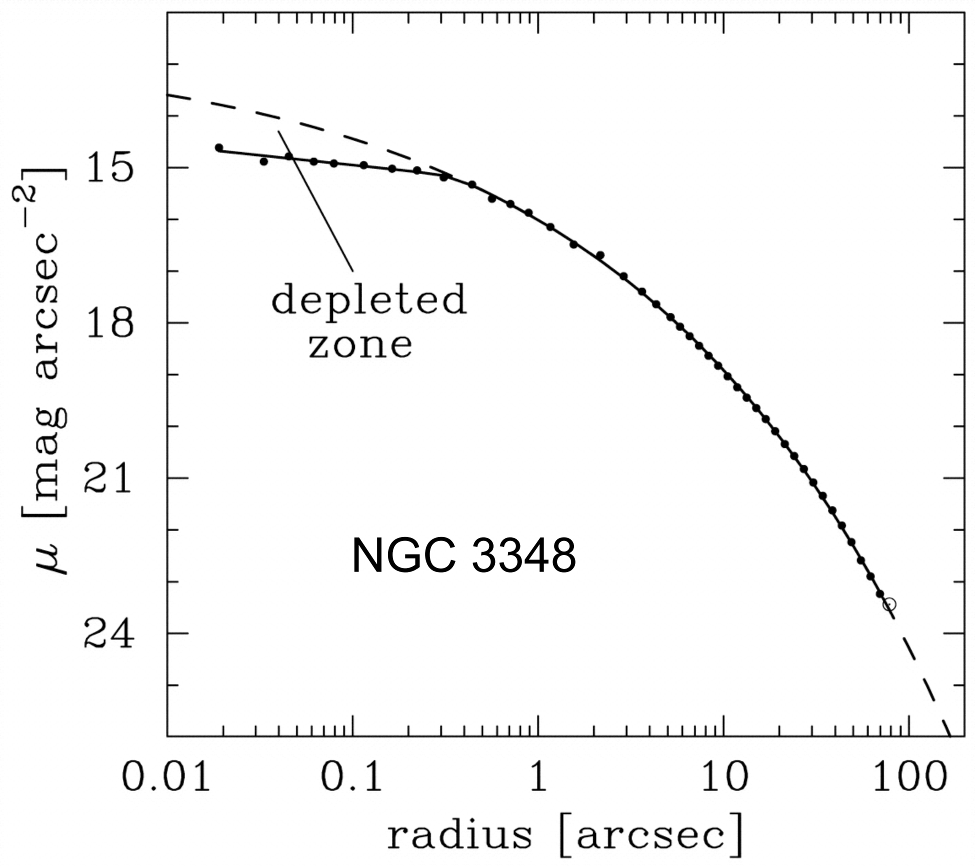
F: m_1/m_2 = 1:10



Merritt et al. 2002

Evidence for *Stellar* Spike Destruction

"Depleted zones" are observed at the centers of many (bright) galaxies.



A. Graham 2004

Evidence for *Stellar* Spike Destruction

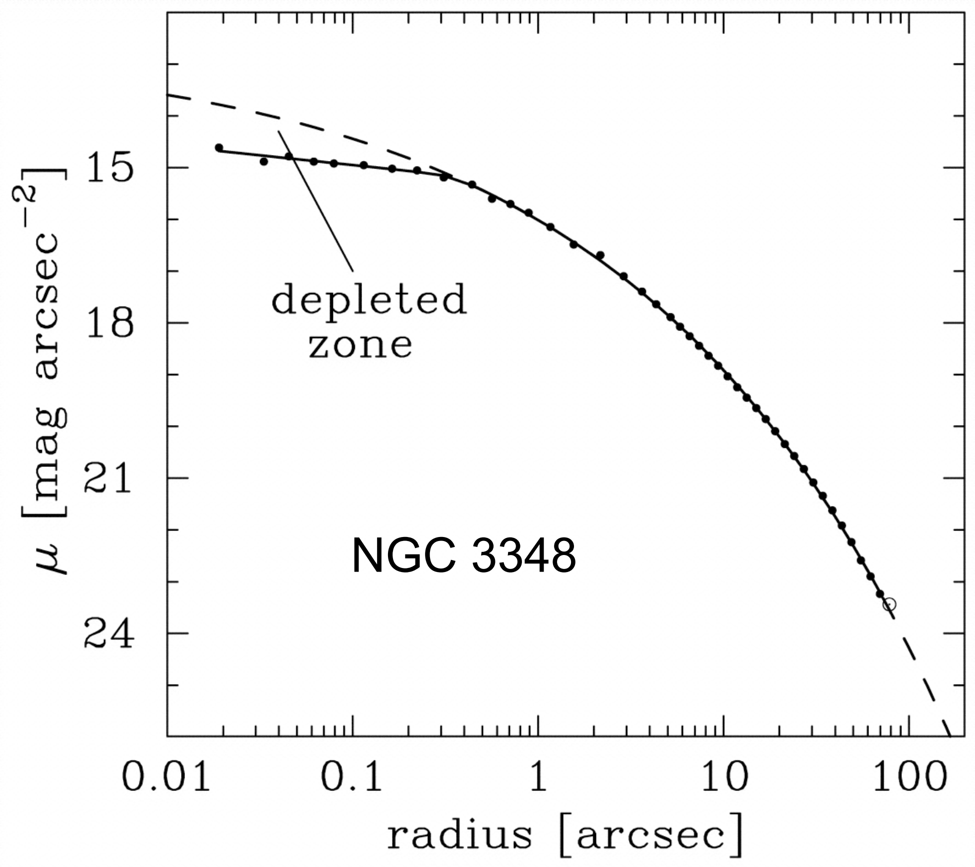
"Depleted zones" are observed at the centers of many (bright) galaxies.

But, Milky Way does not have a "depleted zone"!

Either:

a) Milky Way bulge never merged

b) Stellar spike re-grew, post-merger

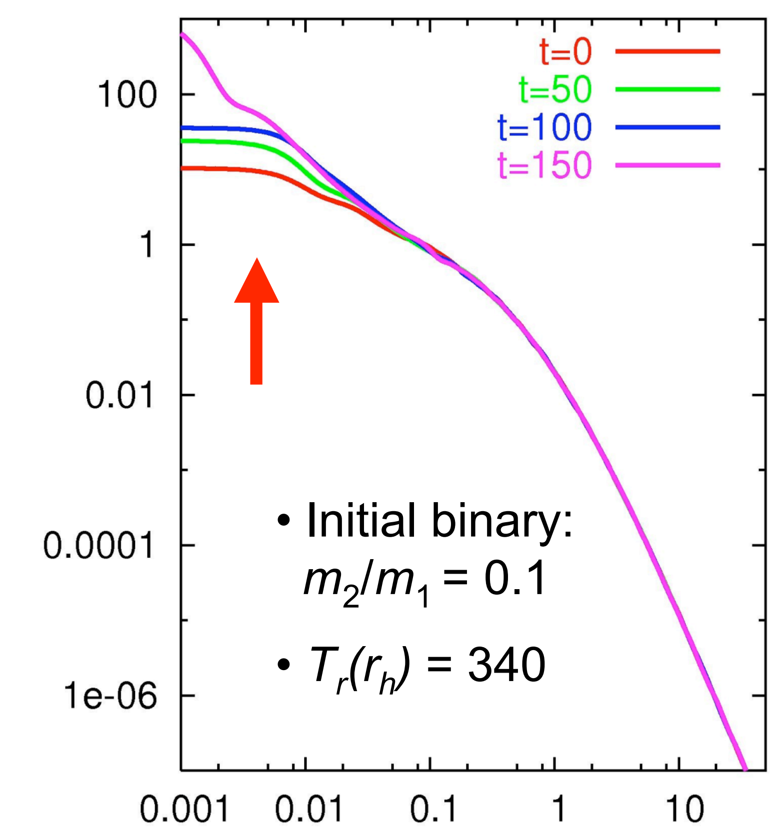


A. Graham 2004

(Stellar) Spike Regeneration

A stellar spike can re-generate after being destroyed by a BBH, via the Bahcall-Wolf mechanism.

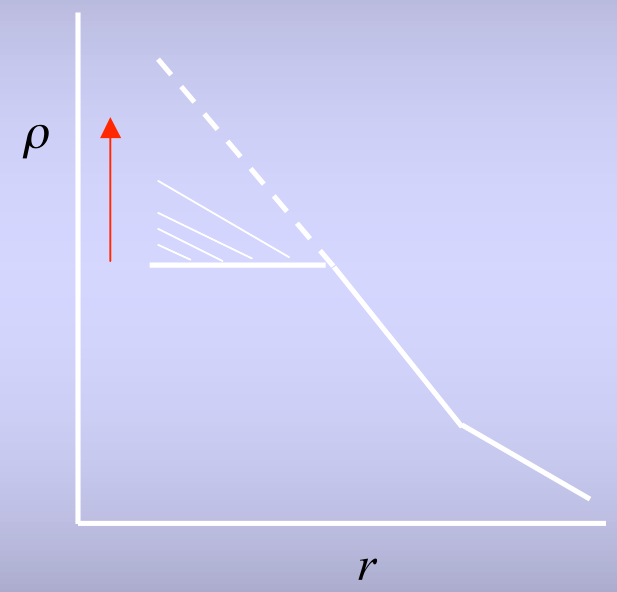
Requirement: The relaxation time is < 10^{10} yr after the merger.



Szell & Merritt 2005

(Dark Matter) Spike Regeneration

What happens to the DM after the stellar spike has re-formed?



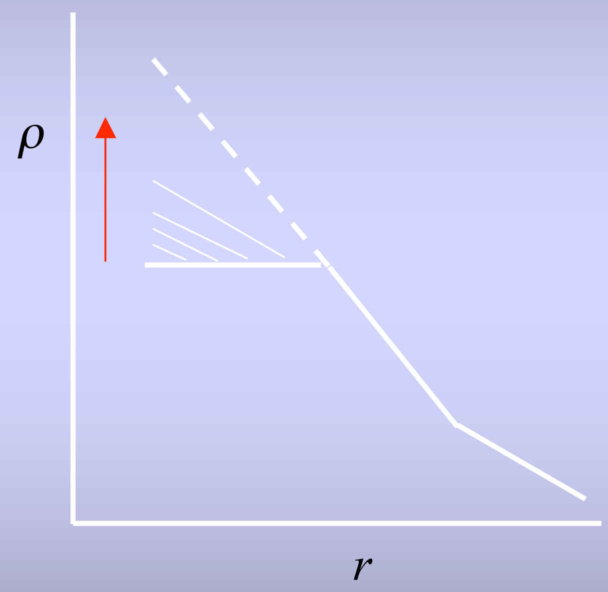
(Dark Matter) Spike Regeneration

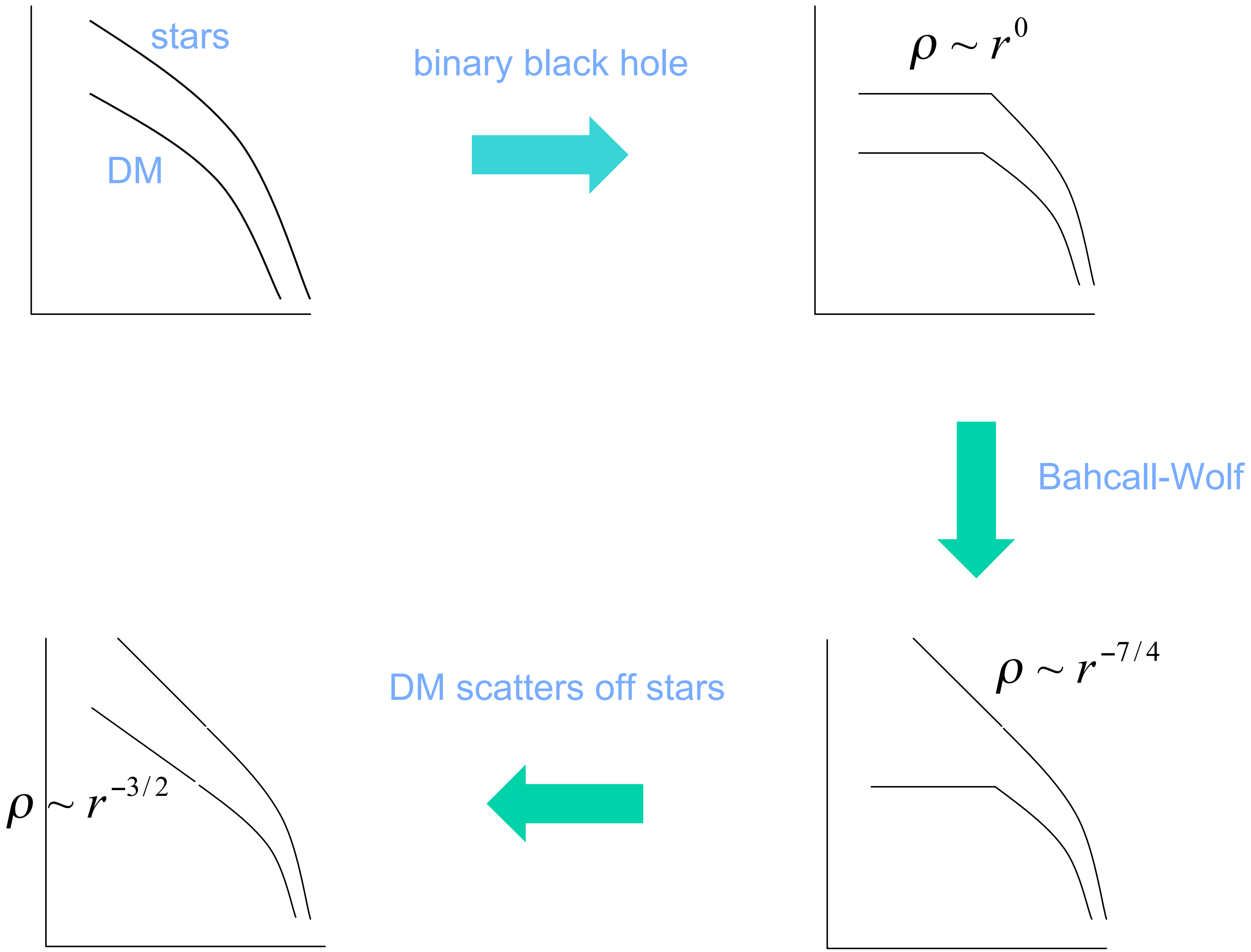
What happens to the DM after the stellar spike has re-formed?

One expects the DM spike to re-grow as well, as DM particles are scattered off of stars.

The steady-state form should be $\rho \sim r^{-3/2}$.

(Bahcall & Wolf 1977; Gnedin & Primack 2004)




stars
DM
binary black hole
$\rho \sim r^{0}$
Bahcall-Wolf
$\rho \sim r^{-7/4}$
DM scatters off stars
$\rho \sim r^{-3/2}$

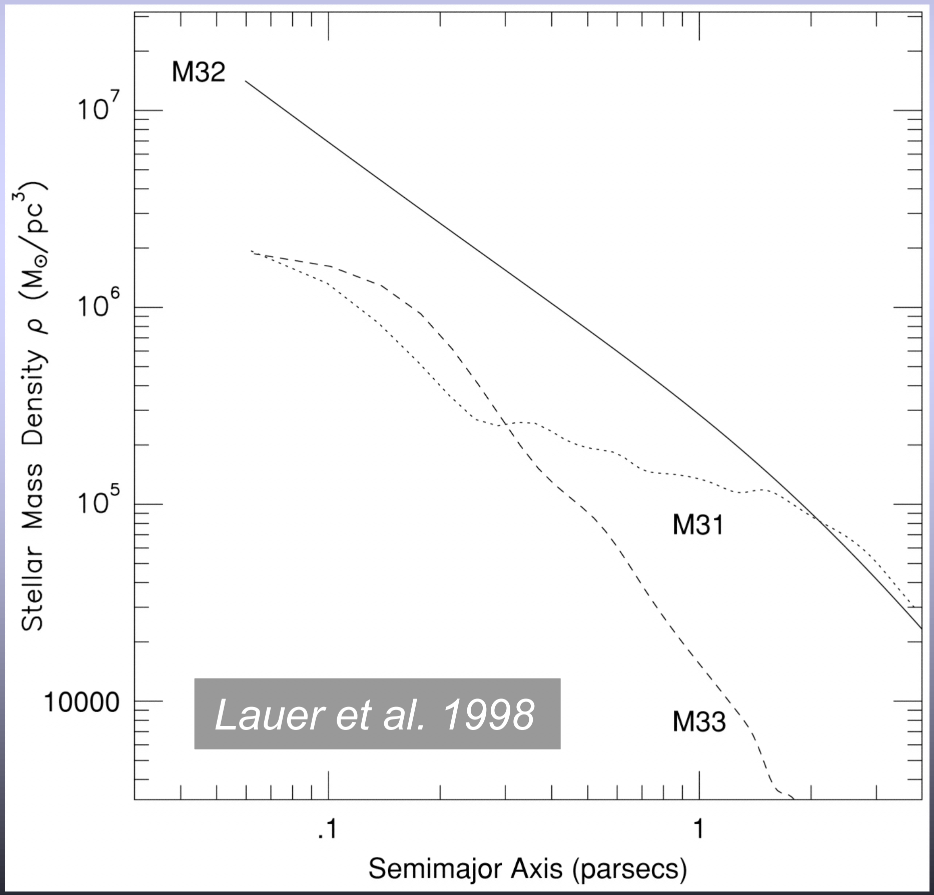
External Galaxies

What do we expect for the DM distribution at the centers of other galaxies?

External Galaxies

What do we expect for the DM distribution at the centers of other galaxies?

Stellar cusps like that in the MW are seen at the centers of the other Local Group spheroids: M31, M32, M33, N205.

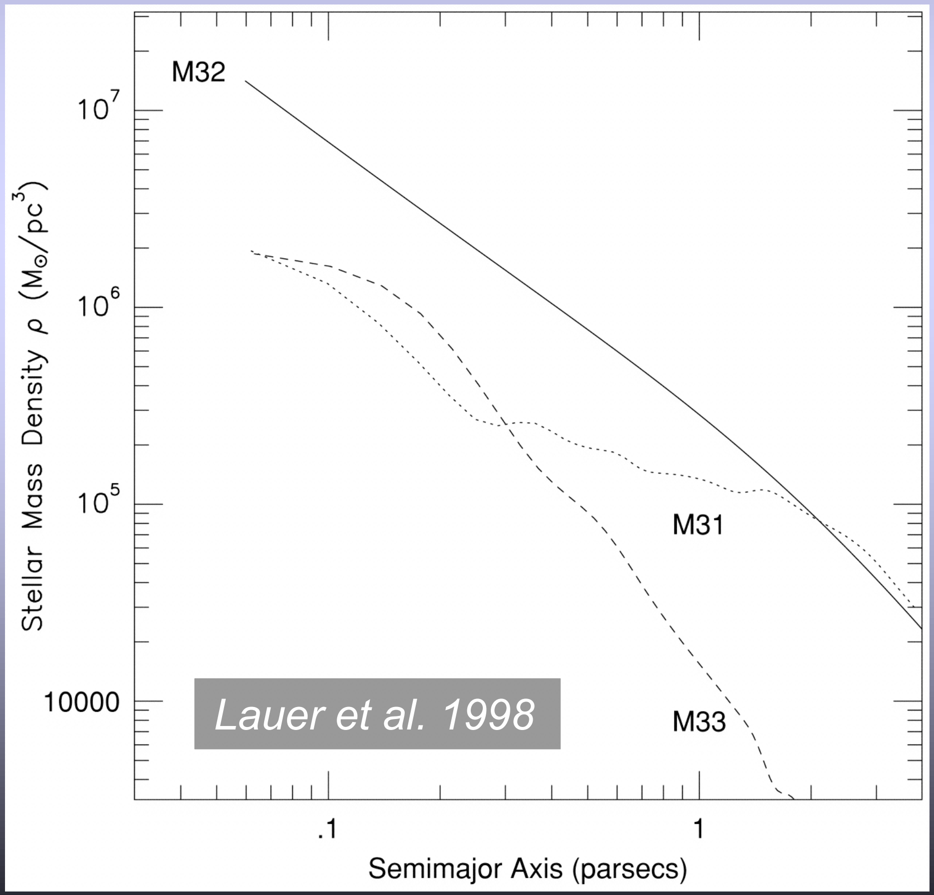


External Galaxies

What do we expect for the DM distribution at the centers of other galaxies?

Stellar cusps like that in the MW are seen at the centers of the other Local Group spheroids: M31, M32, M33, N205.

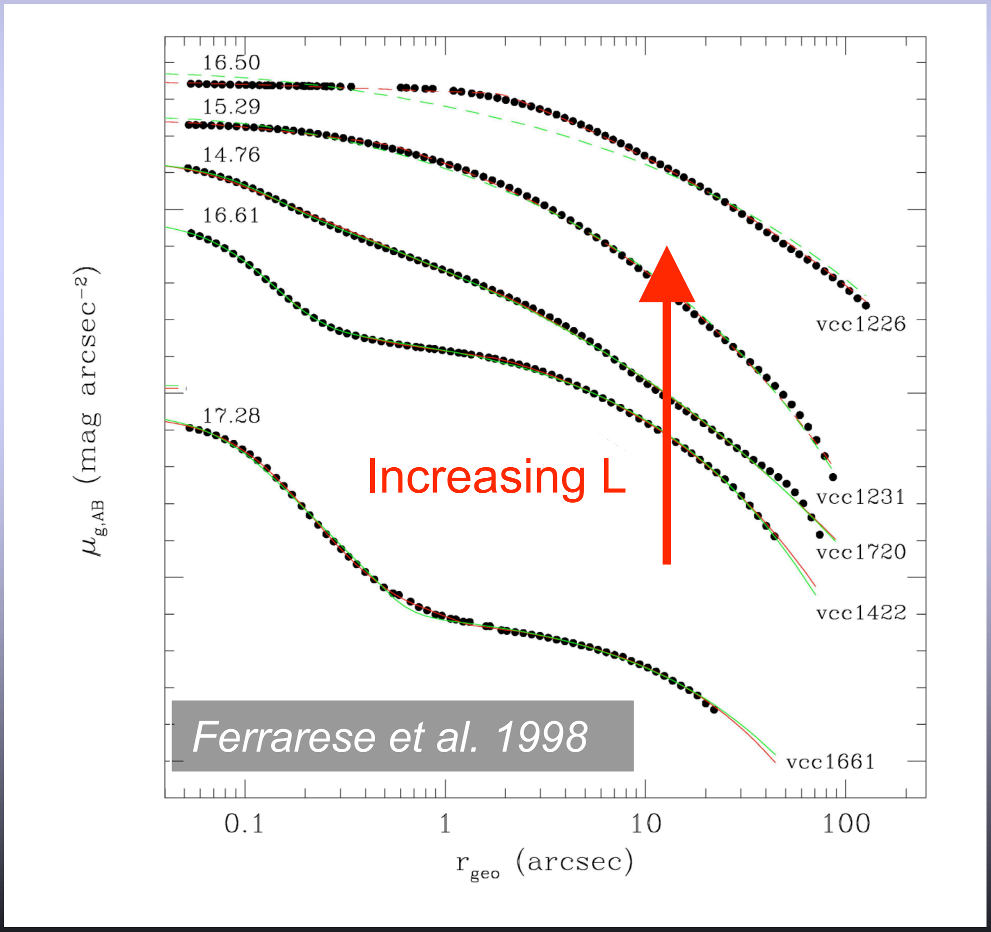
Plausibly, the DM distribution in these (faint) galaxies is similar to that in the Milky Way.



External Galaxies

What do we expect for the DM distribution at the centers of other galaxies?

Bright galaxies tend to have cores = low stellar density.

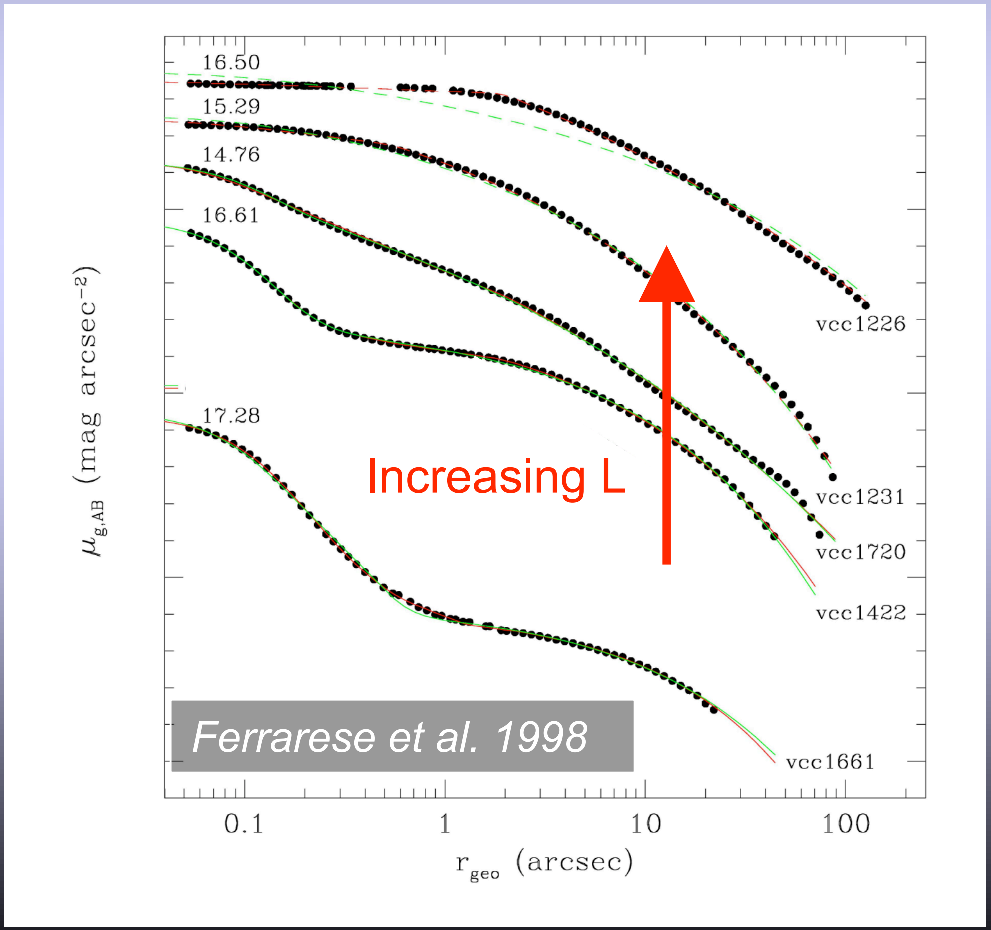


External Galaxies

What do we expect for the DM distribution at the centers of other galaxies?

<u>Bright</u> galaxies tend to have <u>cores</u> = low stellar density.

DM spikes seem unlikely in these galaxies.



Conclusions

• Co-existence of DM and baryons (stars, BH) implies evolution of DM distribution on interesting time scales.

• Very cuspy/spiky ($b \approx 10^3$) DM profiles can persist, in spite of dynamical processes that tend to destroy them.

• Existence of a stellar spike is prima-facie (though not rock-solid) evidence for a DM spike. ***More work needed!***

• DM spikes are unlikely in large / bright galaxies.

END

Stellar Density Profile at the Galactic Center

Schoedel et al. 2005

Stellar counts near the Galactic center **are consistent** with the Bahcall-Wolf steady-state form,

$$\rho \sim r^{-7/4} \quad \Sigma \sim R^{-3/4}$$

within $\sim r_h$:

$$r_h \equiv GM_{bh}/\sigma^2 \approx 40'' .$$

Similarly steep cusps are seen at the centers of the other LG spheroids: M31, M32, N205

(Lauer et al. 1998; Valluri et al. 2005)