A Galaxy and its Dark Matter Profile: a Story of Enhanced Annihilations

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arXiv:1701.00067
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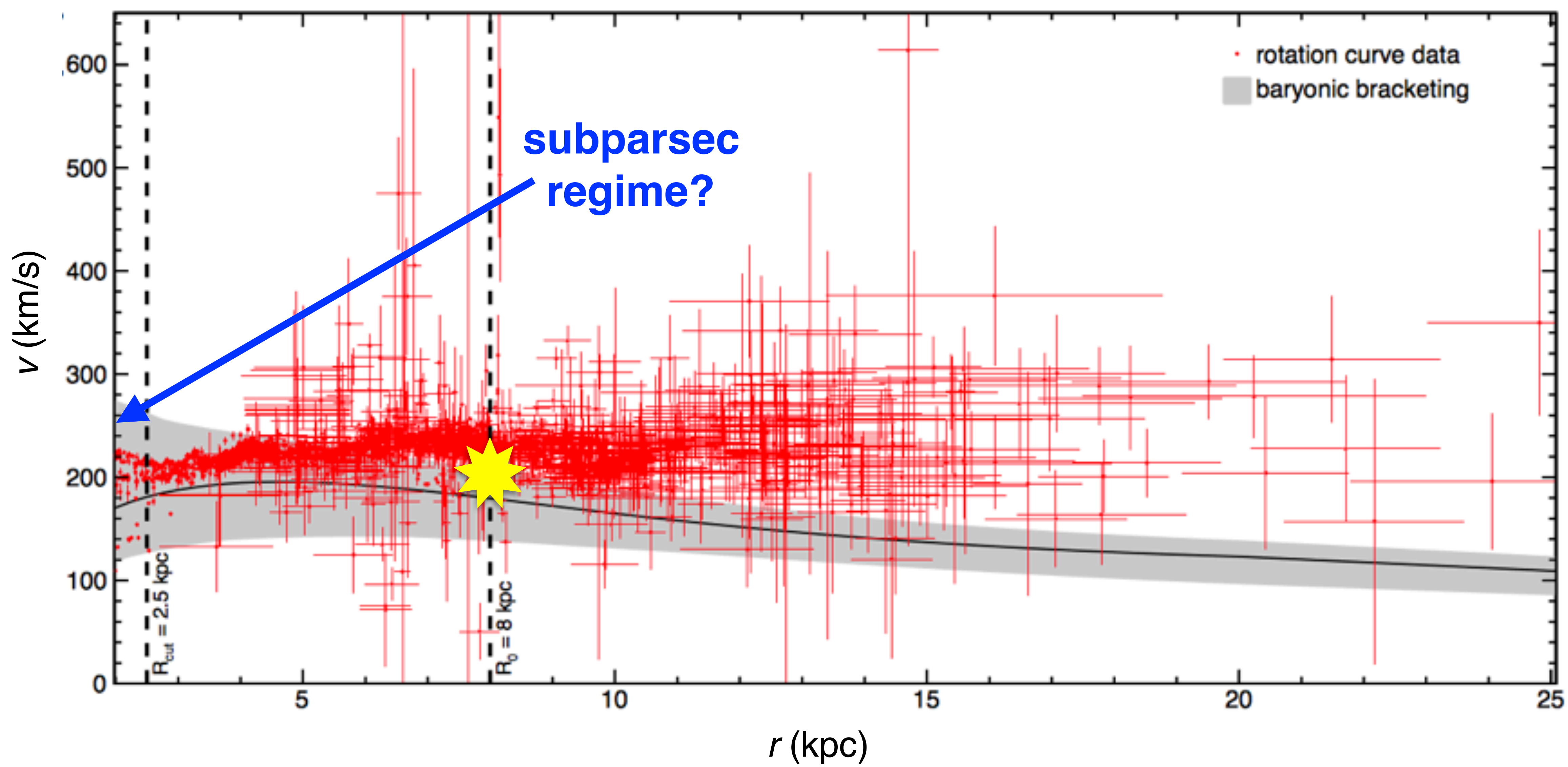
Milky Way Dark Matter

- **From observations:** compilation of rotation curve measurements, plus baryonic models indicates dark matter *inside the solar circle*

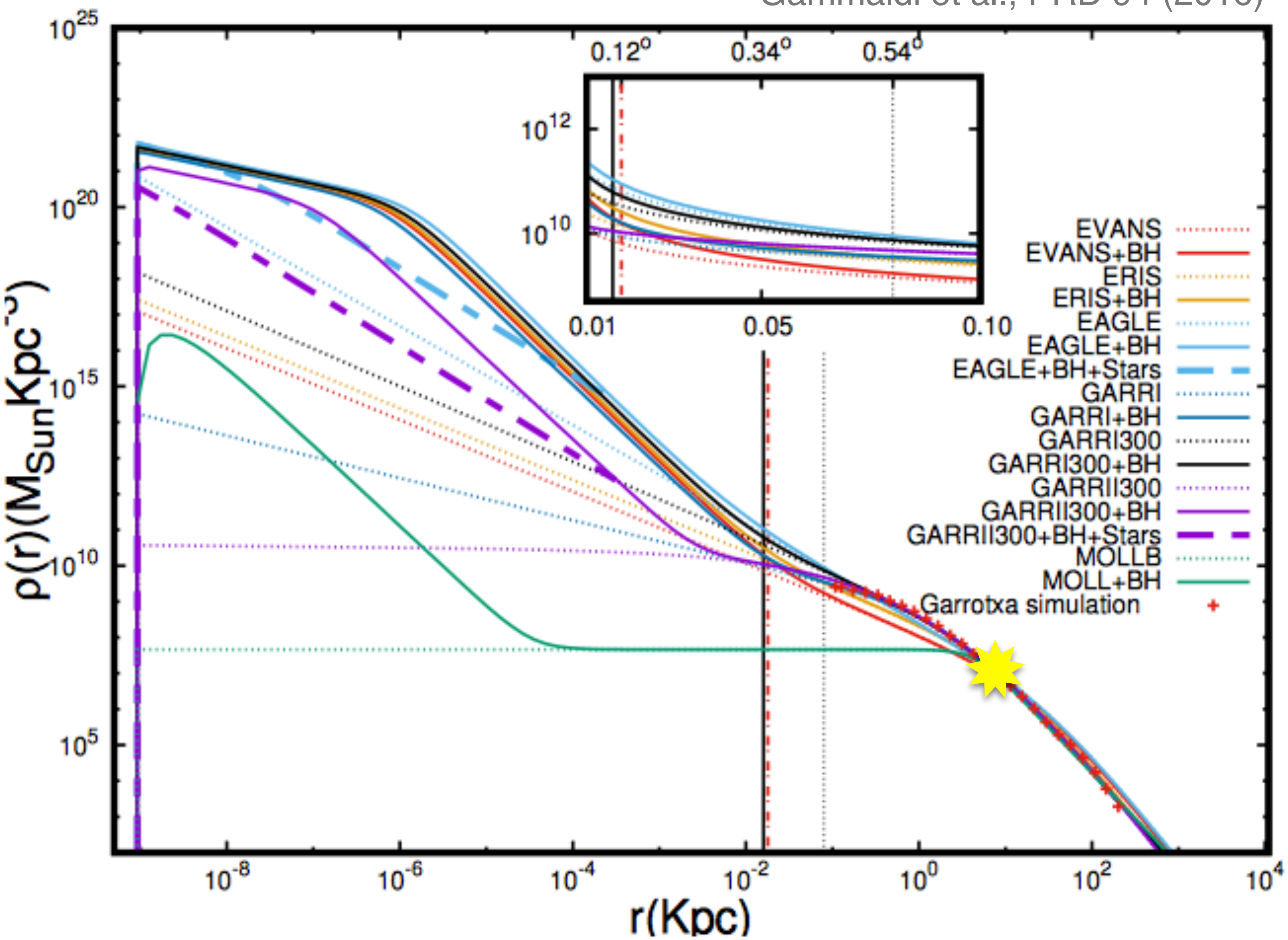
Pato, Iocco, & Bertone, JCAP 12 (2015)



Milky Way Dark Matter

- **From simulations:** State-of-the-art N-body + hydrodynamics simulations

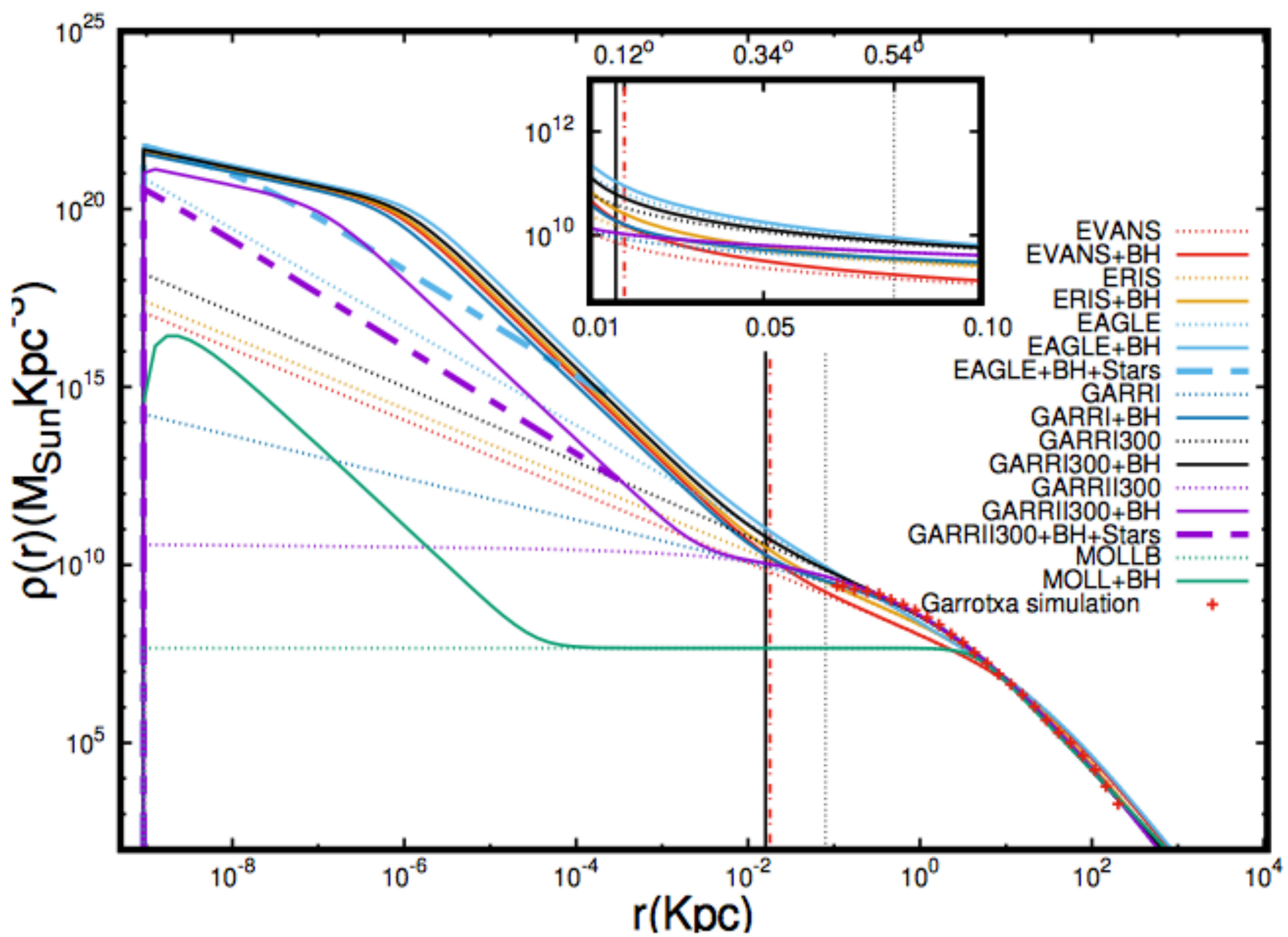
Gammaldi et al., PRD 94 (2016)



A Dark Matter Spike?

- As SMBH forms, it dominates the potential in the inner galaxy
- Dark matter particles are dragged into the deepening potential well
- If the growth of the SMBH is slow enough, conservation of dark matter angular momentum and mass yields a “spike”

Gondolo & Silk, PRL 83 1719 (1999)



Profile Form

- Roughly:

$$\rho(r) = \begin{cases} \rho(r_{core}) & 10 r_{Sch.} < r \leq r_{core} \\ \rho_0 \left(r/r_{sp}\right)^{-\gamma_{sp}} & r_{core} < r \leq r_{sp} \ , \\ \rho_0 \left(r/r_{sp}\right)^{-\gamma_c} & r_{sp} < r \ , \end{cases}$$

- Key features:
  - looks like initial (uncontracted) profile at large radii
  - density saturates at small radii: $\rho_{sat} = \frac{m_\chi}{\langle \sigma v \rangle \, \tau_{spike}}$
  - “spike” between r_{core} and r_{sp}

Spike Details

- Roughly:

$$\rho(r) = \begin{cases} \rho(r_{core}) & 10 r_{Sch.} < r \le r_{core} \\ \rho_0 \left(r/r_{sp}\right)^{-\gamma_{sp}} & r_{core} < r \le r_{sp} \ , \\ \rho_0 \left(r/r_{sp}\right)^{-\gamma_c} & r_{sp} < r \ , \end{cases}$$

- r_{sp} is related to sphere of influence of BH (~0.4 pc)

Ferrarese & Ford, Sp. Sci. Rev. (2005)

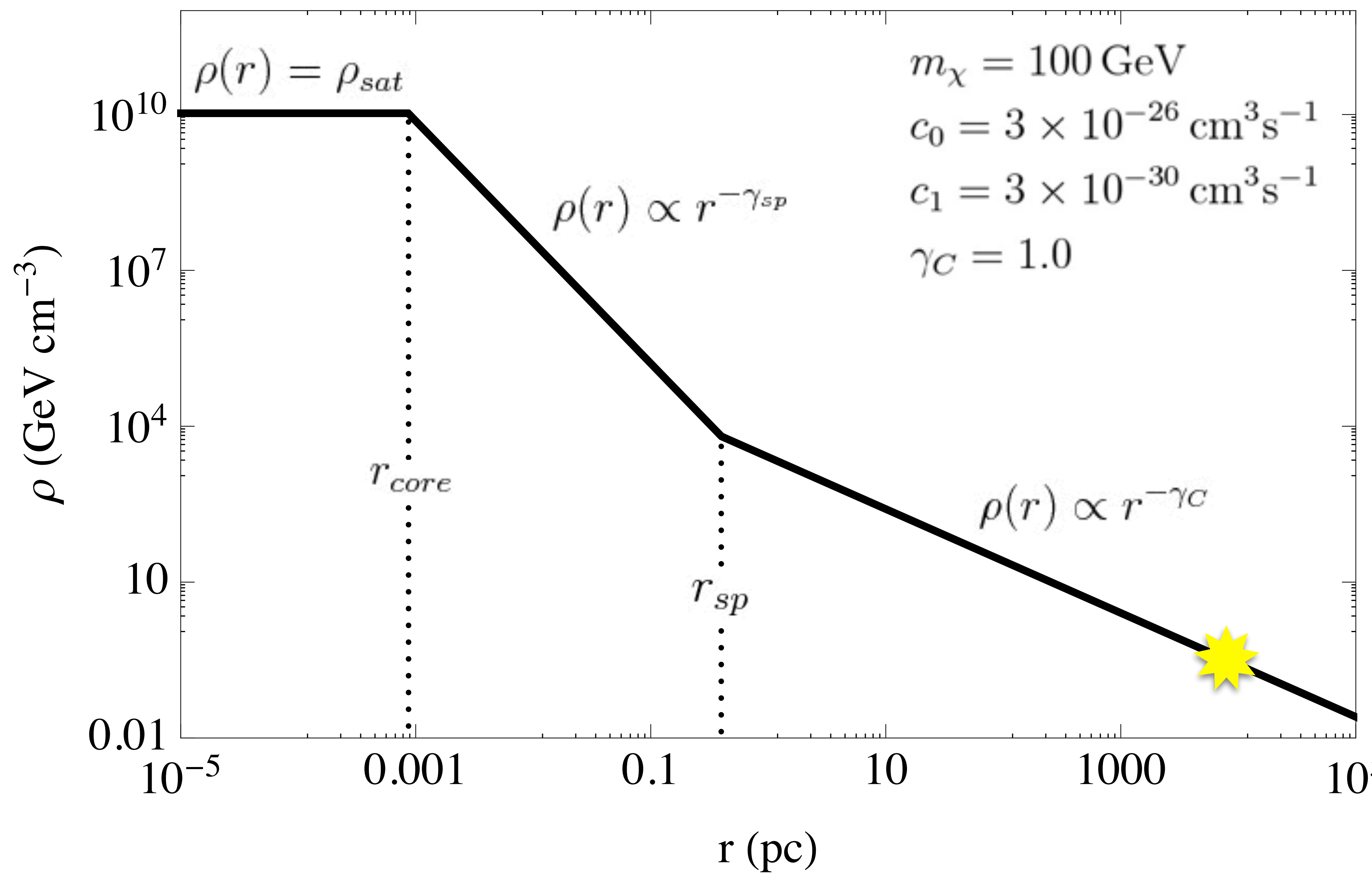
- r_{core} is the radius at which $\rho(r) = \rho_{sat.}$
  - $\rho(r_{core}) = \dfrac{m_\chi}{\langle \sigma v \rangle \tau_{spike}}$ and $\langle \sigma v \rangle = c_0 + c_1 \left(\dfrac{v^2}{c^2}\right) = c_0 + c_1 \left(\dfrac{r_{Sch.}}{2r}\right)$
  - Note $\langle \sigma v \rangle (r)$

Shelton, Shapiro, & Fields, PRL 115 (2015)

- For collisionless DM and adiabatic growth of the BH,

$$\gamma_{sp} = \frac{9 - 2\gamma_c}{4 - \gamma_c}$$

Dark Matter Spike



What is not included?

eg. Fields, Shapiro, & Shelton, PRL 113 (2014)

- Gravitational interactions between DM and baryons

★ scattering of DM on stars → “heating” of DM — eg. Gnedin & Primack, PRL 93 (2004); Vasiliev & Zelnikov, PRD 78 (2008)

- invisible compact objects
- dramatic dynamical changes (mergers, etc.) — eg. Merritt et al., PRL 88 (2002)
- DM self-interactions — Shapiro & Paschalidis (2014)
- If growth is not adiabatic (BH appears suddenly)
  - even if seed is large and then growth is adiabatic — Ullio, Zhao, & Kamionkowski (2001)
- BH off-center

➡ **all “flatten” the spike**

Spike Details

- Rough form: $$\rho(r) = \begin{cases} \rho(r_{core}) & 10 r_{Sch.} < r \leq r_{core} \\ \rho_0 \, (r/r_{sp})^{-\gamma_{sp}} & r_{core} < r \leq r_{sp} \; , \\ \rho_0 \, (r/r_{sp})^{-\gamma_c} & r_{sp} < r \; , \end{cases}$$

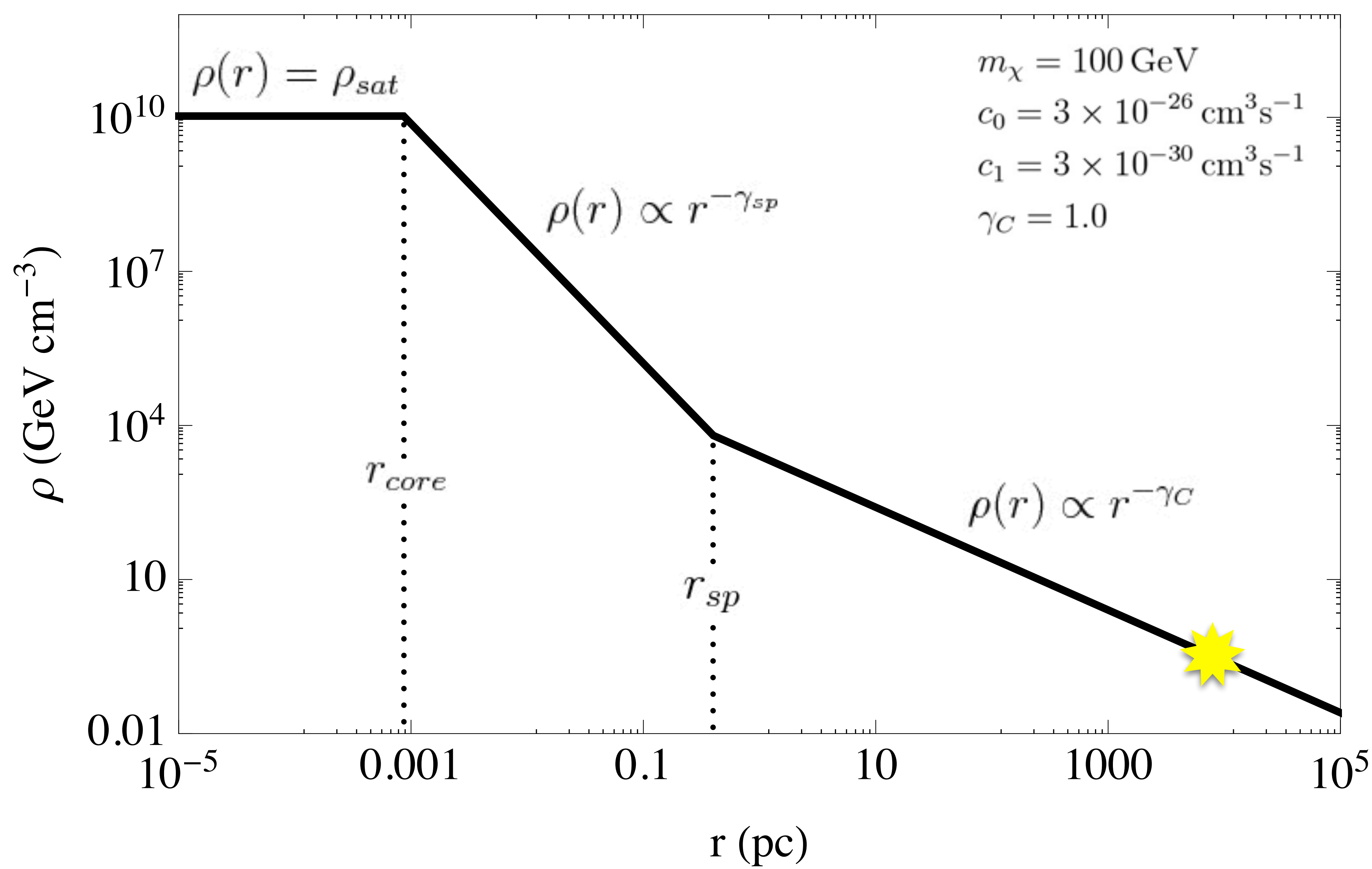
- Stars near the BH have much larger KE than DM, so tend to “heat up” the DM, which flattens the spike:
  - $\rho(r,t) \approx \rho(r,0) \, e^{-\tau/2}$ with $\tau = \tau_{spike}/t_{heat}$ Merritt, PRL (2004)
  - $t_{heat} \approx \mathcal{O}(1) \, \mathrm{Gyr}$ (?) Bertone & Merritt (2005); Vasieliev & Zelnikov (2008)
  - $t_{heat} \propto m_{BH}^2 \, \sigma^{-3} \, \tilde{m}_\star^{-1} \, [\ln(0.4 N_\star)]^{-1}$ Merritt, PRL (2004)
- another way of thinking of this is that it changes r_{sp}

$$r_{sp}(t) = r_{sp}(0) \times \exp\left(\frac{-\tau}{2(\gamma_{sp} - \gamma_c)}\right)$$

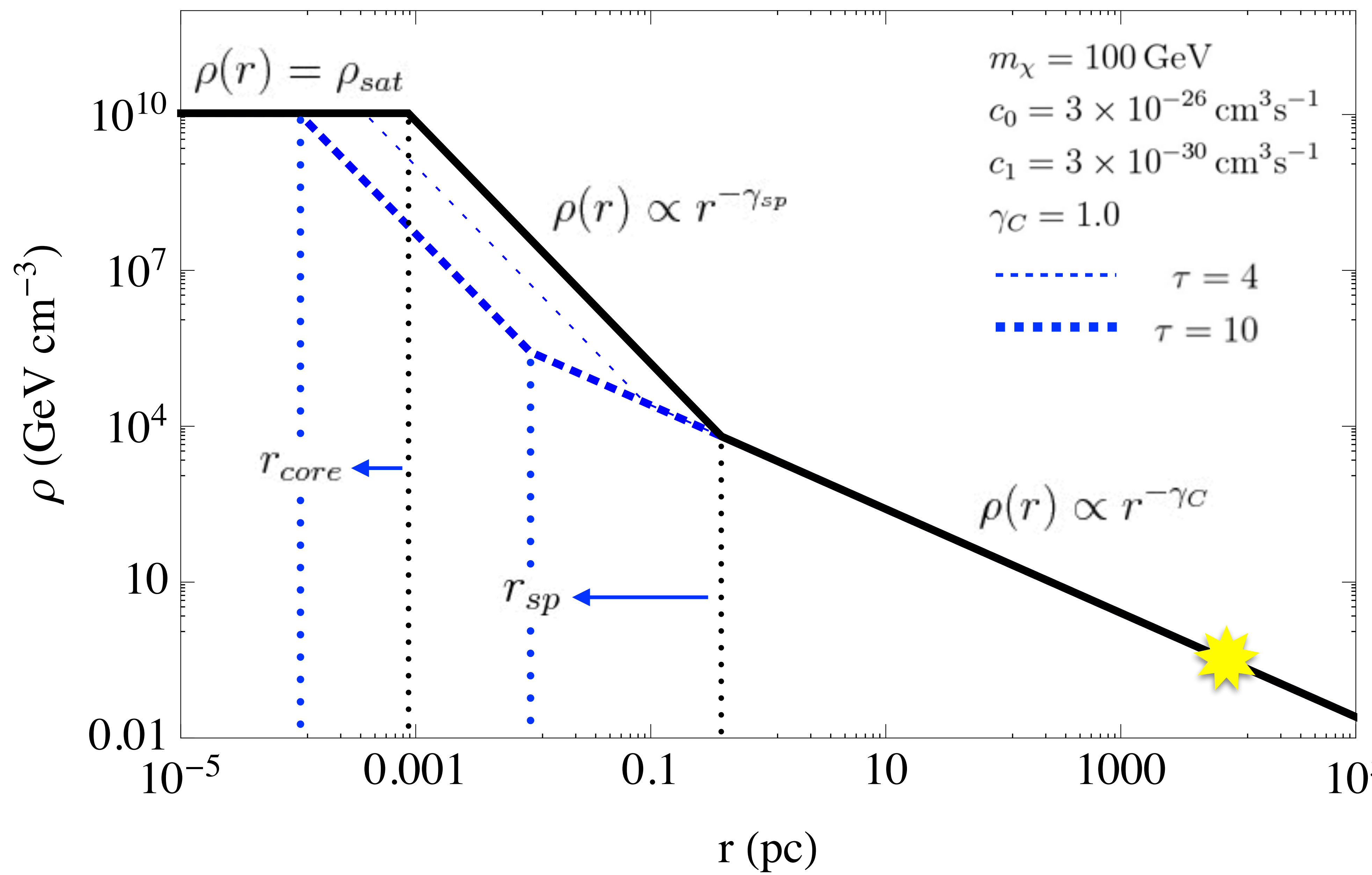
“depleted”

“idealized”

Dark Matter Spike



Dark Matter Spike



DM Annihilations in the Spike

$$\frac{d\Phi_\gamma}{d\Omega\, dE} = \frac{1}{2}\frac{r_\odot}{4\pi}\left(\frac{\rho_\odot}{M_{\rm DM}}\right)^2 \int_{\rm l.o.s.} \frac{ds}{r_\odot}\left(\frac{\rho(r(s,\theta))}{\rho_\odot}\right)^2 \sum_f \langle\sigma v\rangle_f \frac{dN_\gamma^f}{dE}$$

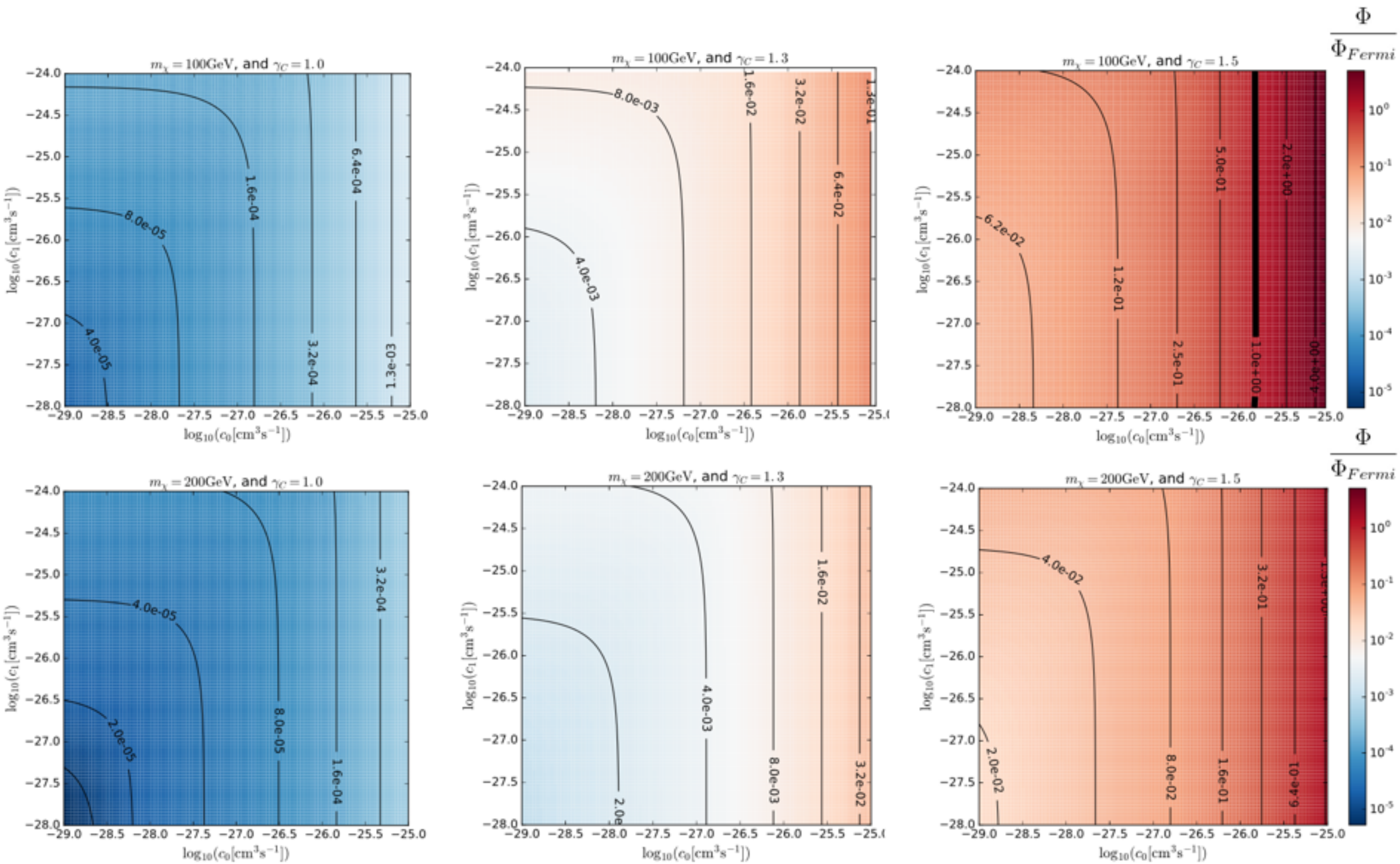
$$r(s,\theta) = (r_\odot^2 + s^2 - 2\, r_\odot\, s\cos\theta)^{1/2}$$

- Flux will contribute to GC point source
- Fermi-LAT GC point source is 3FGL source J1745.6-2859c (Sgr A*)
  - Integrated flux from 1 to 100 GeV is

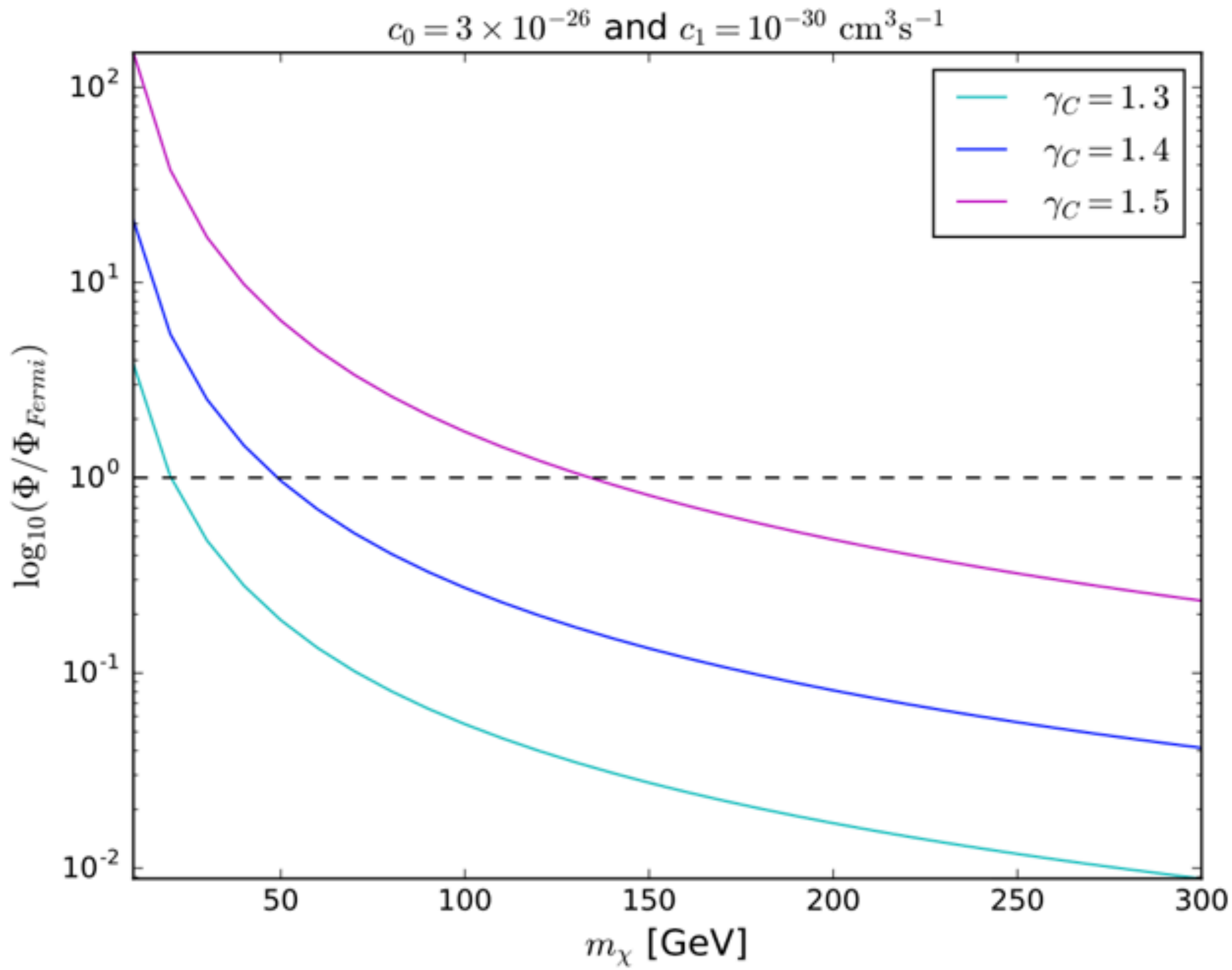
$$\Phi_{\rm Fermi} = 2.18 \times 10^{-8}\ \text{photons/cm}^2\text{s}$$

- Note: we take $\int_{1\,{\rm GeV}}^{100\,{\rm GeV}} \frac{dN_\gamma^f}{dE} dE = 1$. Flux scales with integrated photon count.
  - Subnote: The spectrum may be important: Fermi's PSF is highly energy-dependent below 10 GeV! This is not included.

Depleted Spike - Complete Picture



Observational Reach



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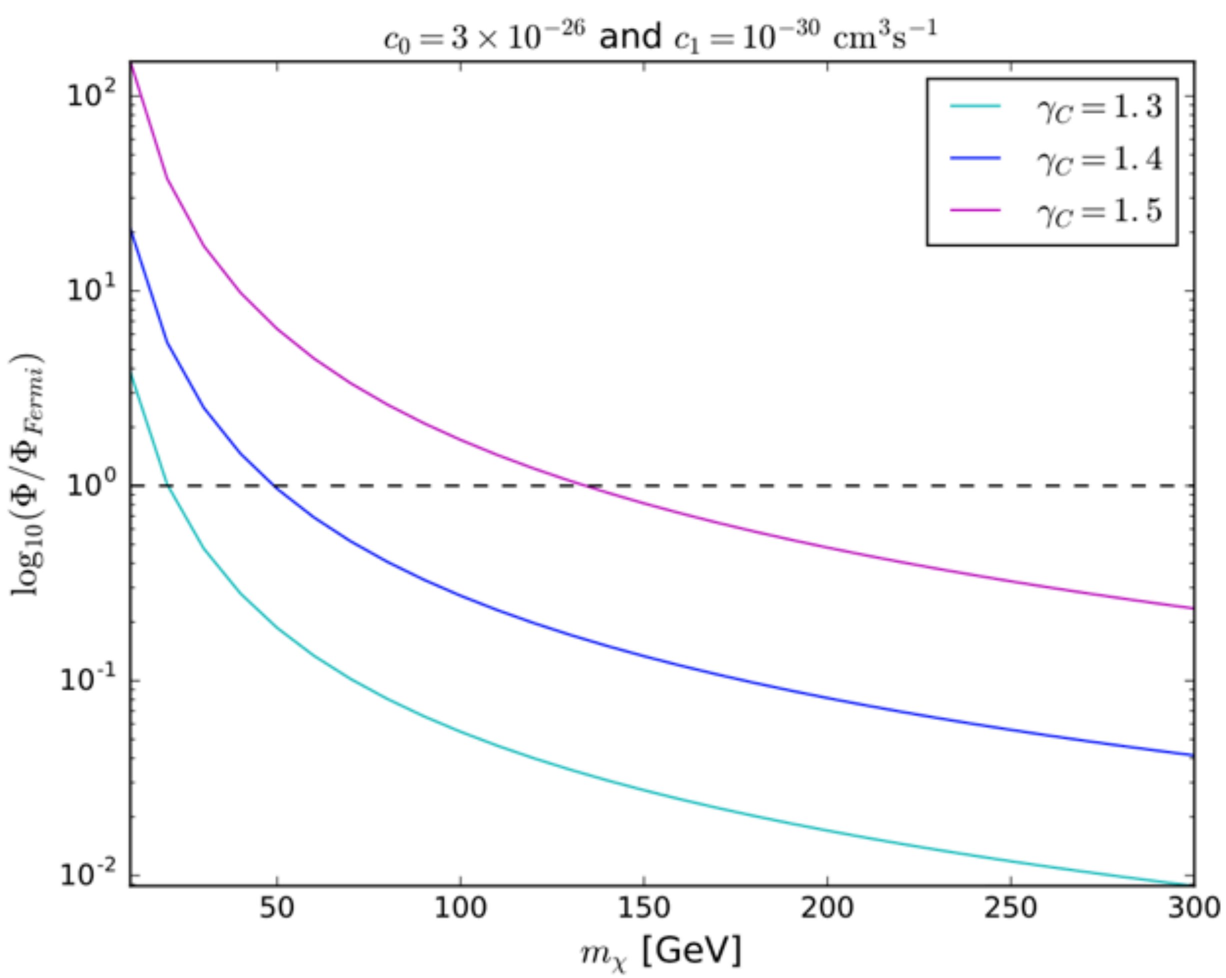
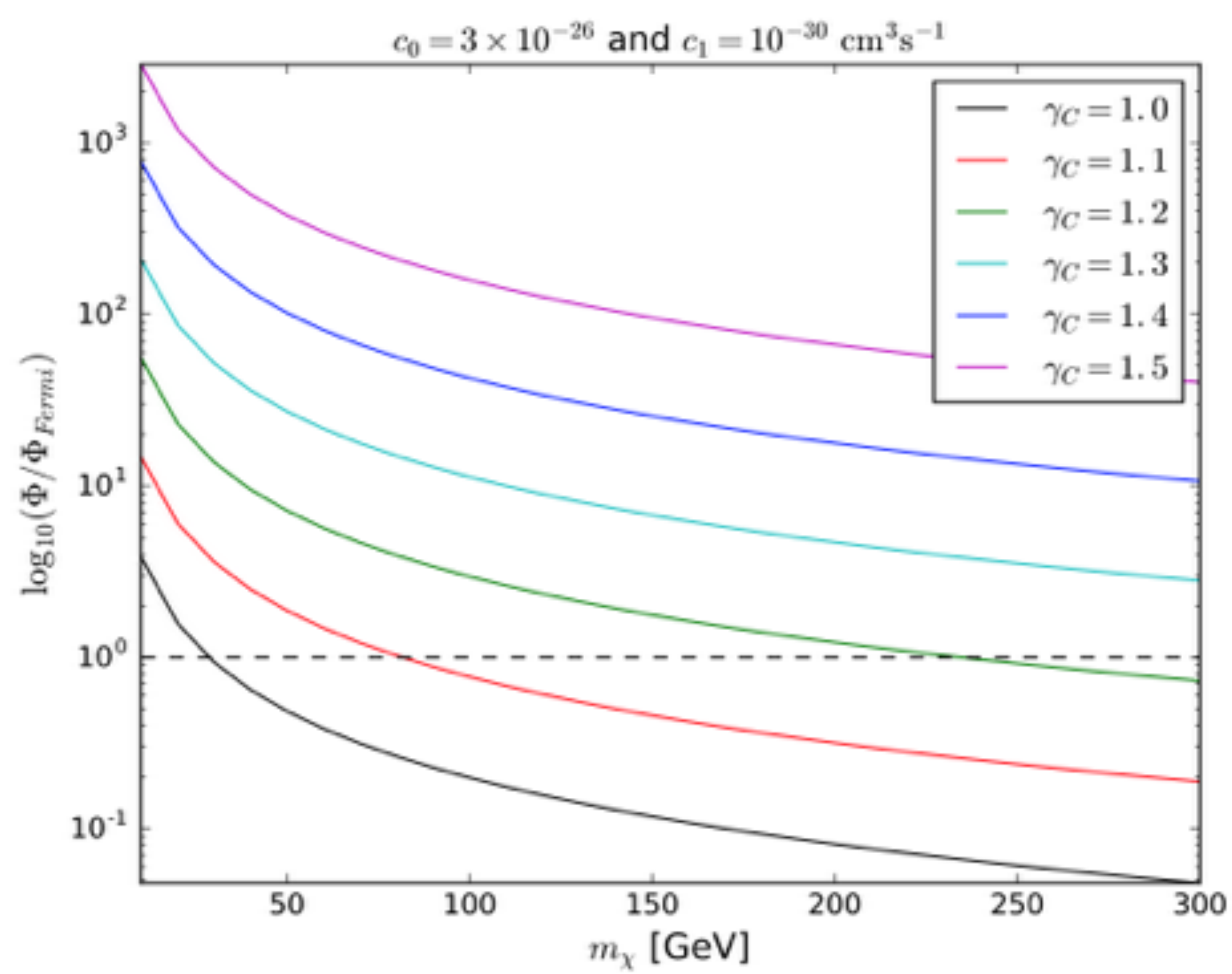


Idealized Spike

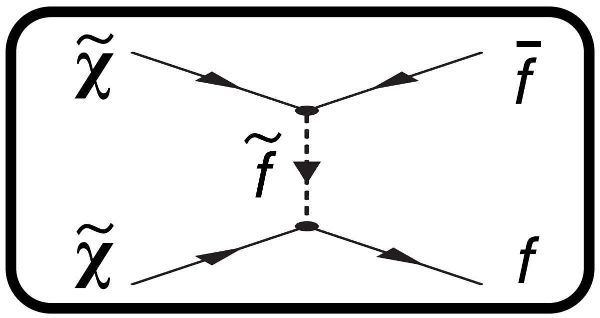


An Interesting Example

Fukushima, Kelso, Kumar, Sandick, & Yamamoto, (2014)

- singlet DM coupled to SM fermions via charged scalars

  ➜ ***bino* DM** ➜**b quarks** ➜ **b *squarks***



- s-wave annihilation is chirality suppressed ~ m_f^2/m_χ^2
- p-wave is velocity-suppressed ($v^2 \approx 0.1$) at freeze-out
- Solution: L-R mixing eliminates chirality-suppression

$$\mathcal{L}_{\text{int}} = \lambda_L e^{i\phi/2} \widetilde{f}_L^* \, \overline{\chi} P_L f + \lambda_R e^{-i\phi/2} \widetilde{f}_R^* \, \overline{\chi} P_R f + \text{c.c}$$

$$\begin{pmatrix} \tilde{f}_1 \\ \tilde{f}_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \tilde{f}_L \\ \tilde{f}_R \end{pmatrix}$$

- Four mass parameters: $m_\chi, \; m_{\tilde{f}_1}, \; m_{\tilde{f}_2}, \; m_f$
- Yukawas, $|\lambda_{L,R}|$, CPV phase, ϕ , scalar mixing angle, α

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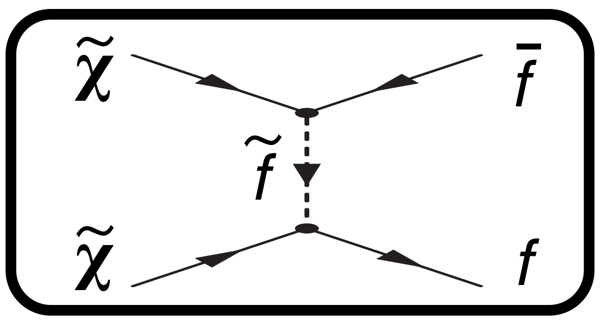

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100 GeV 105 GeV decoupled m_b

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SUSY zero

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  → ***bino* DM** →**b quarks** → **b *squarks***

See Also:

- DM abundance & lepton dipole moments (light sleptons), PRD (2014)
- Direct DM det. (light squark mediators) w/ Kelso, Kumar, & Stengel, PRD (2015)
- Direct DM det. (anapole moment) w/ Sinha & Teng, JHEP (2016)
- Indirect DM det. (dwarf galaxies) w/ Kumar, Teng, & Yamamoto, PRD (2016)

$$\mathcal{L}_{\text{int}} = \lambda_L e^{i\phi/2} \widetilde{f}_L^* \, \overline{\chi} P_L f + \lambda_R e^{-i\phi/2} \widetilde{f}_R^* \, \overline{\chi} P_R f + \text{c.c}$$

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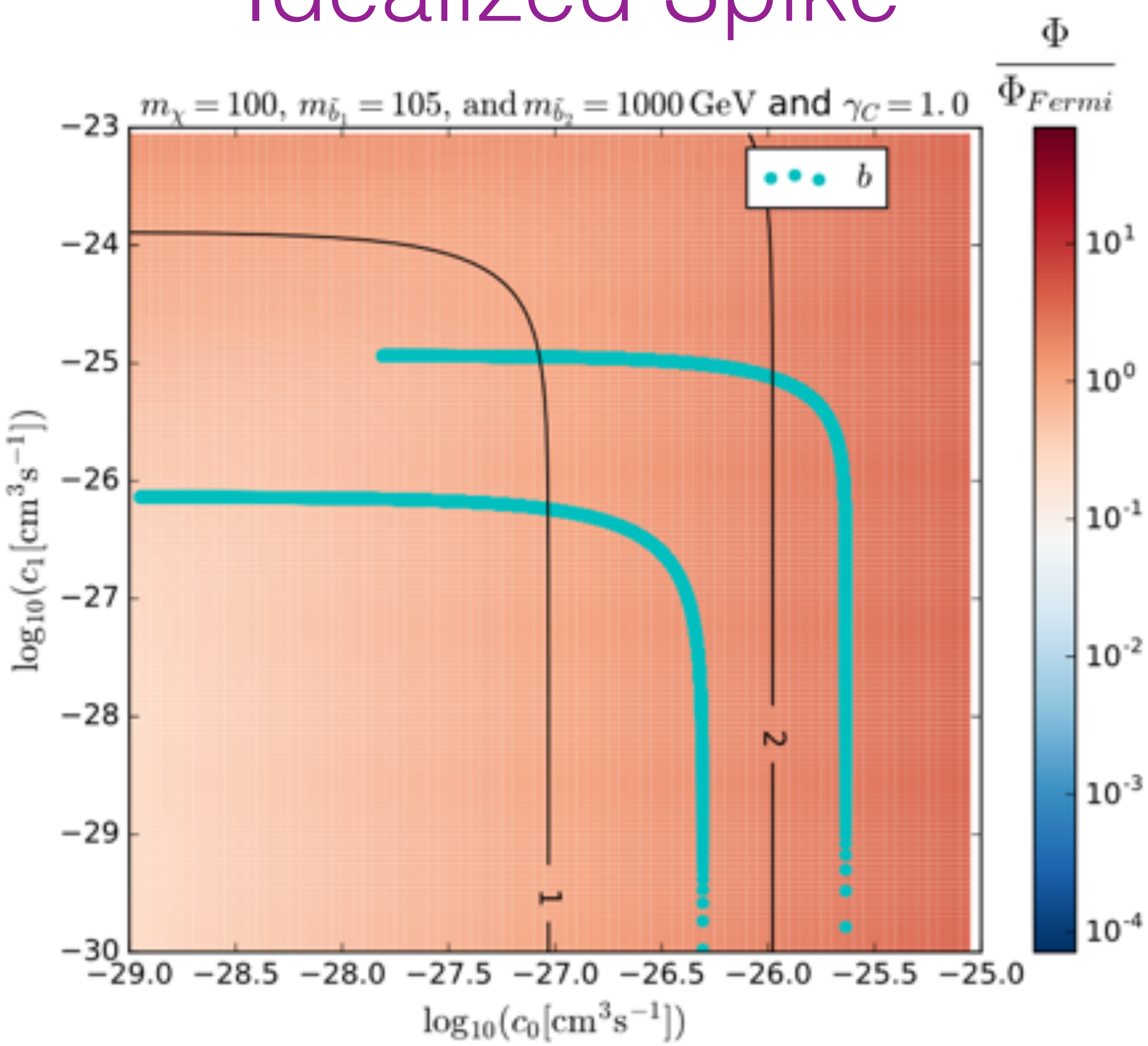
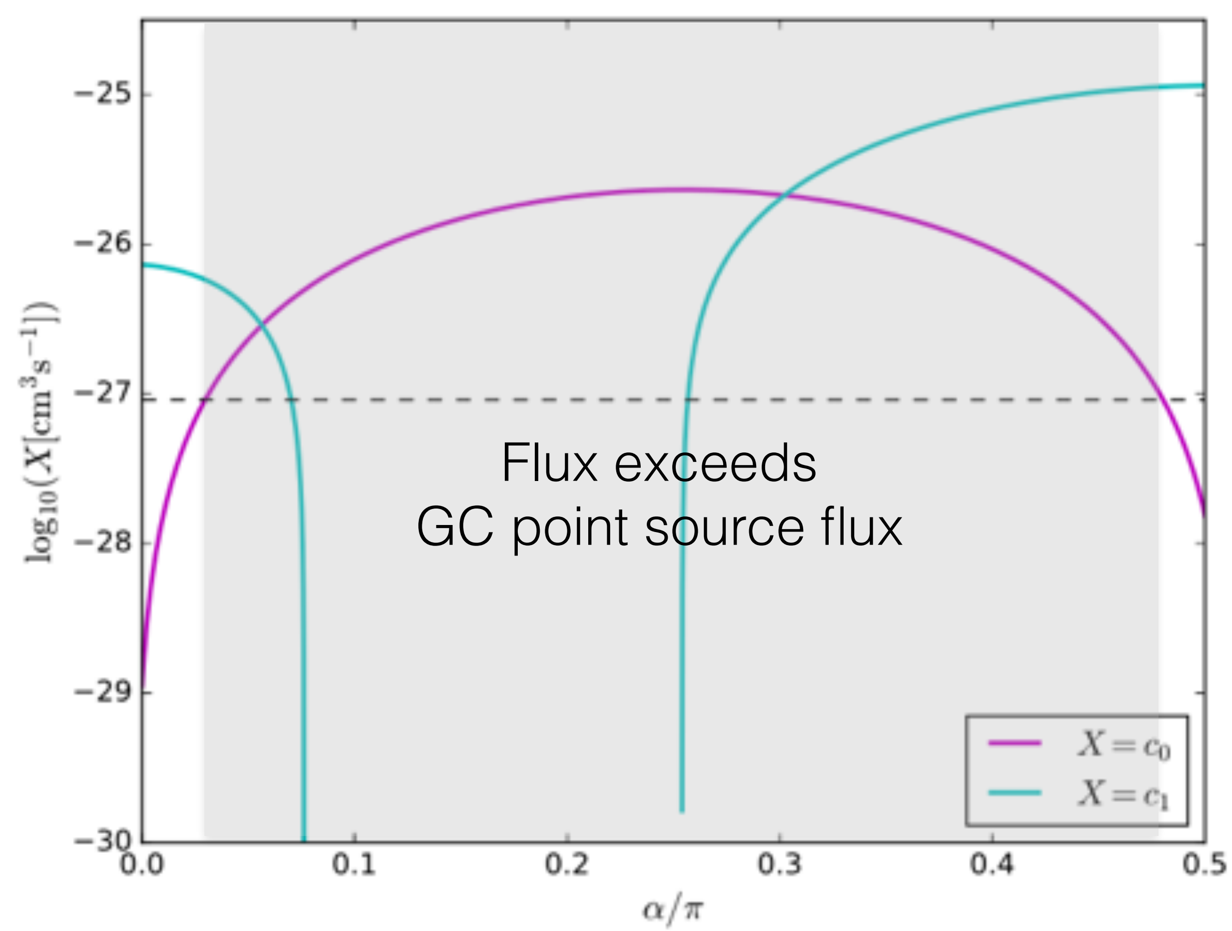
An Interesting Example

Idealized Spike





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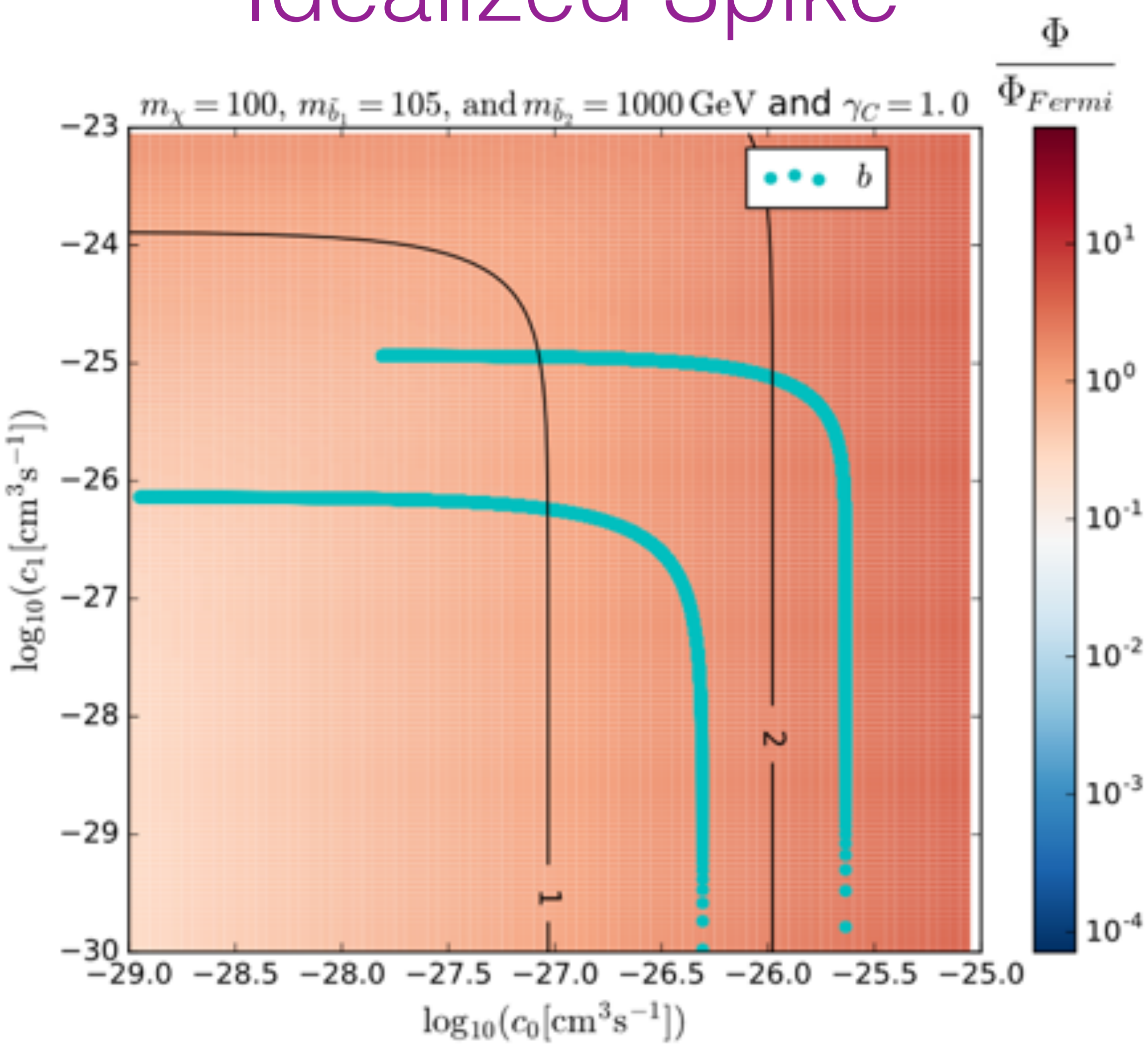
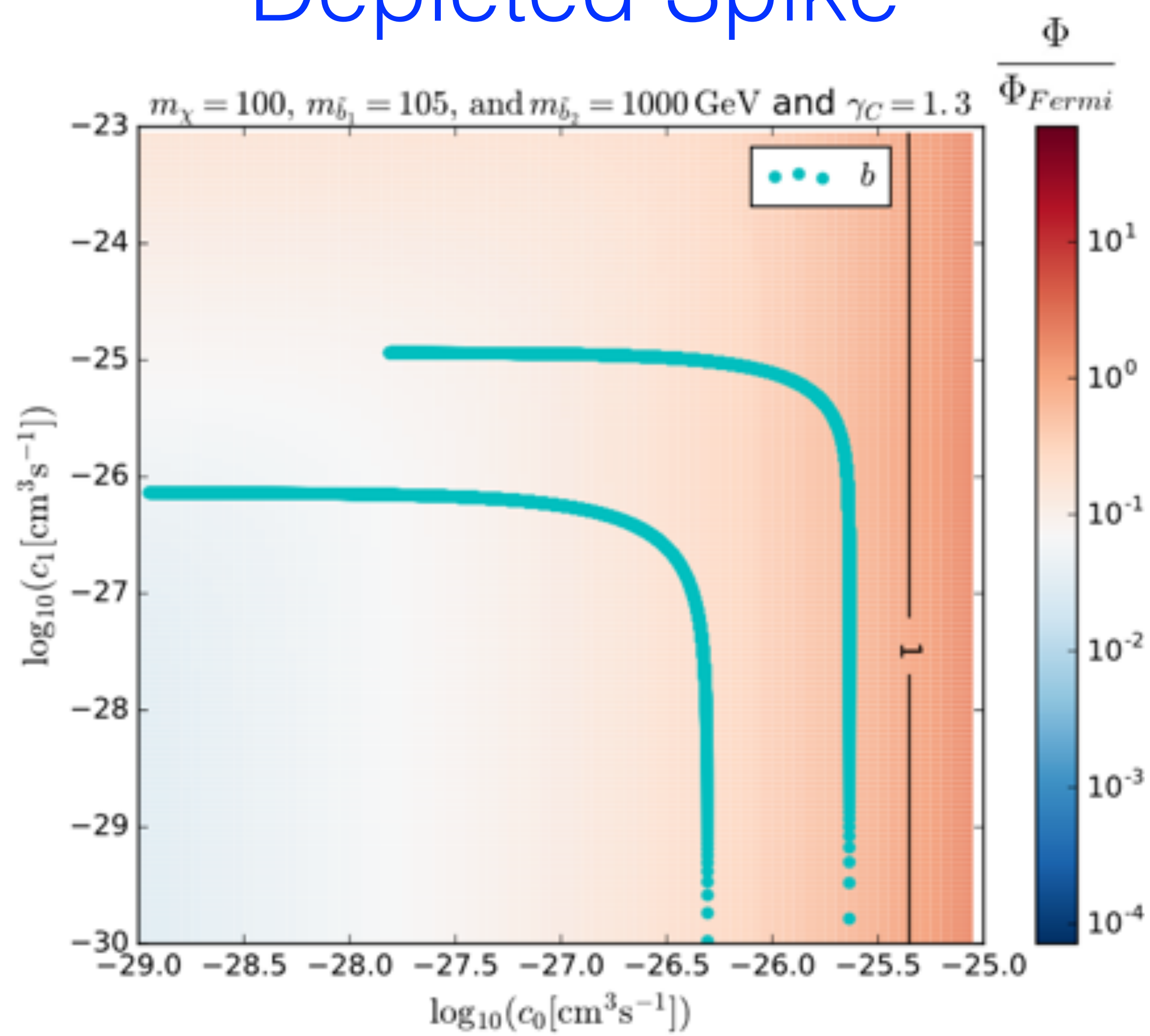
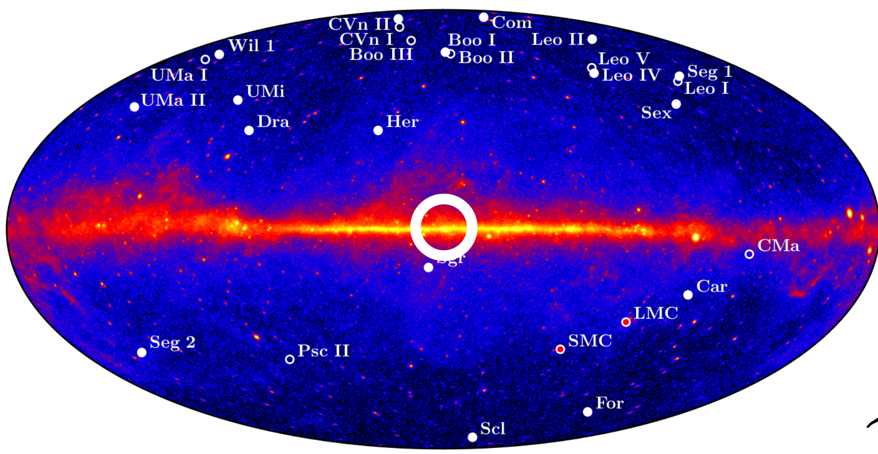


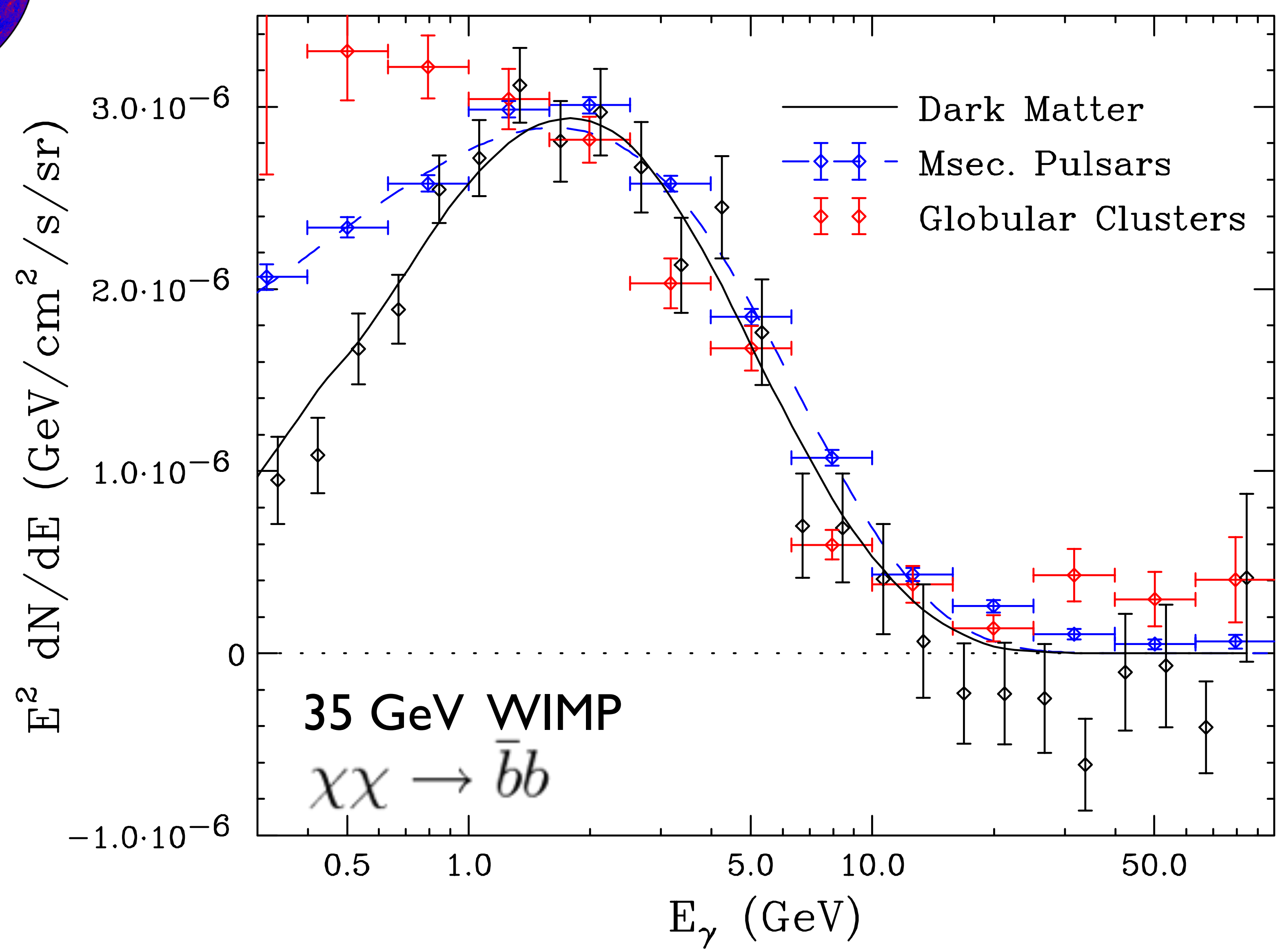
Depleted Spike



Galactic Center γ-ray Excess



Cholis, Linden, & Hooper (2014)



- The energy spectrum, morphology, and annihilation rate are all consistent with thermal WIMP dark matter w/ an NFW-like profile.
- Fermi Collab.: "Peaked profiles with long tails (NFW, NFW contracted) yield the most significant improvements in the data-model agreement."

Fermi GC Excess?

Depleted Spike

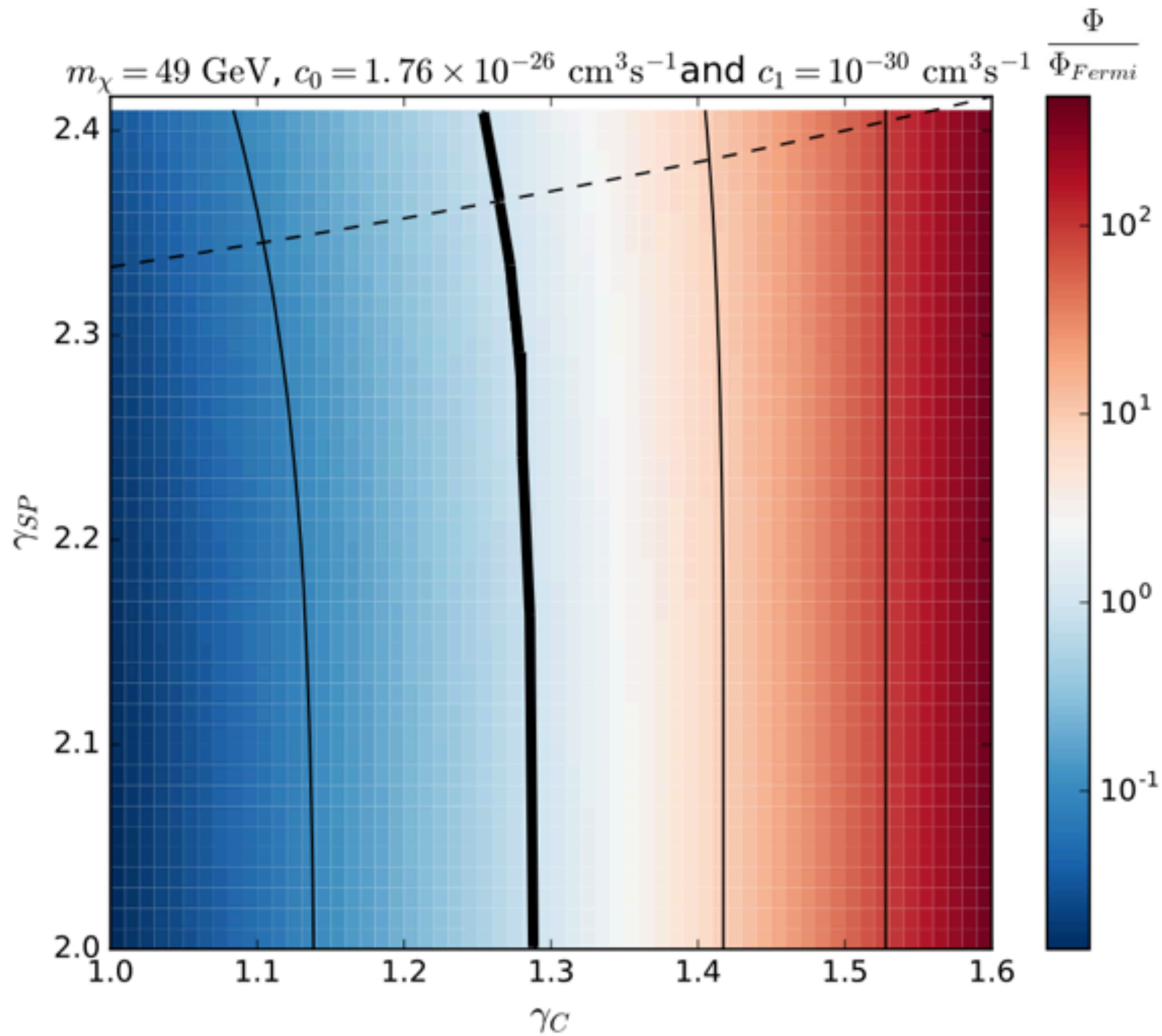
- GC excess fit by

$$\chi\chi \rightarrow b\bar{b}$$
$$m_\chi = 49\,\mathrm{GeV}$$
$$c_0 = 1.76 \times 10^{-26}\,\mathrm{cm^3 s^{-1}}$$

Calore, Cholis, & Weniger, JCAP 1503 (2015)

- Only a conflict if γ_C is large (even for LARGE γ_{sp})
- Contours are ~vertical!

➡ Heating timescale is critical…

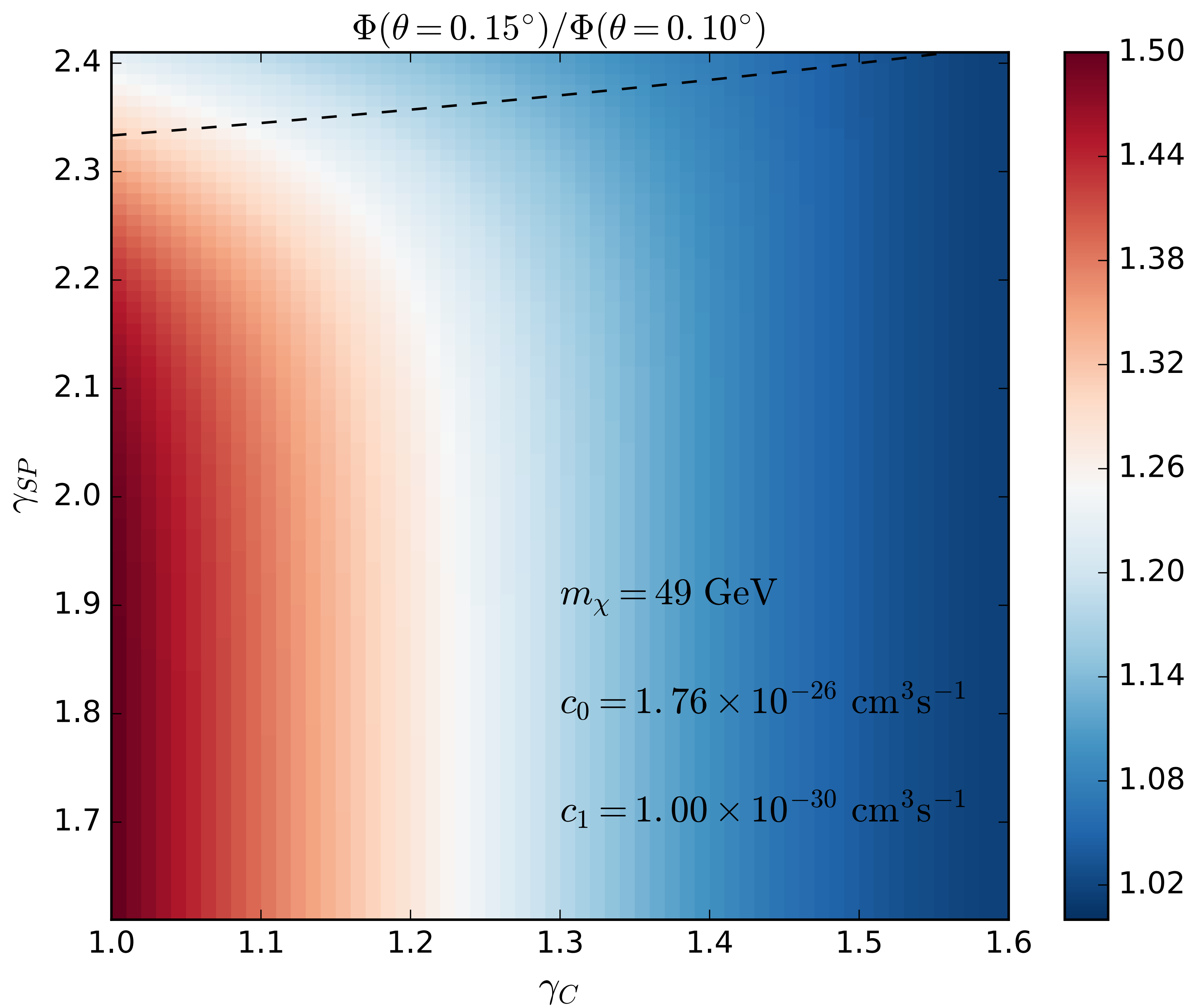


Summary

- Is/was there a spike? **Maybe.**
- Depleted or not? **Can't tell**
  - If spike is not depleted, pretty strong constraints can be placed on DM models, tension with dark matter explanation of GC excess (see also Fields Shapiro, & Shelton PRL 2014).
  - If spike is depleted, it may not be a “spike” at all anymore, and it really doesn’t help us say much about dark matter.
- **Bottom line: Modeling of astrophysical processes that influence the dark matter distribution is key!**
- Future: Use dark matter to learn about our galaxy (?)

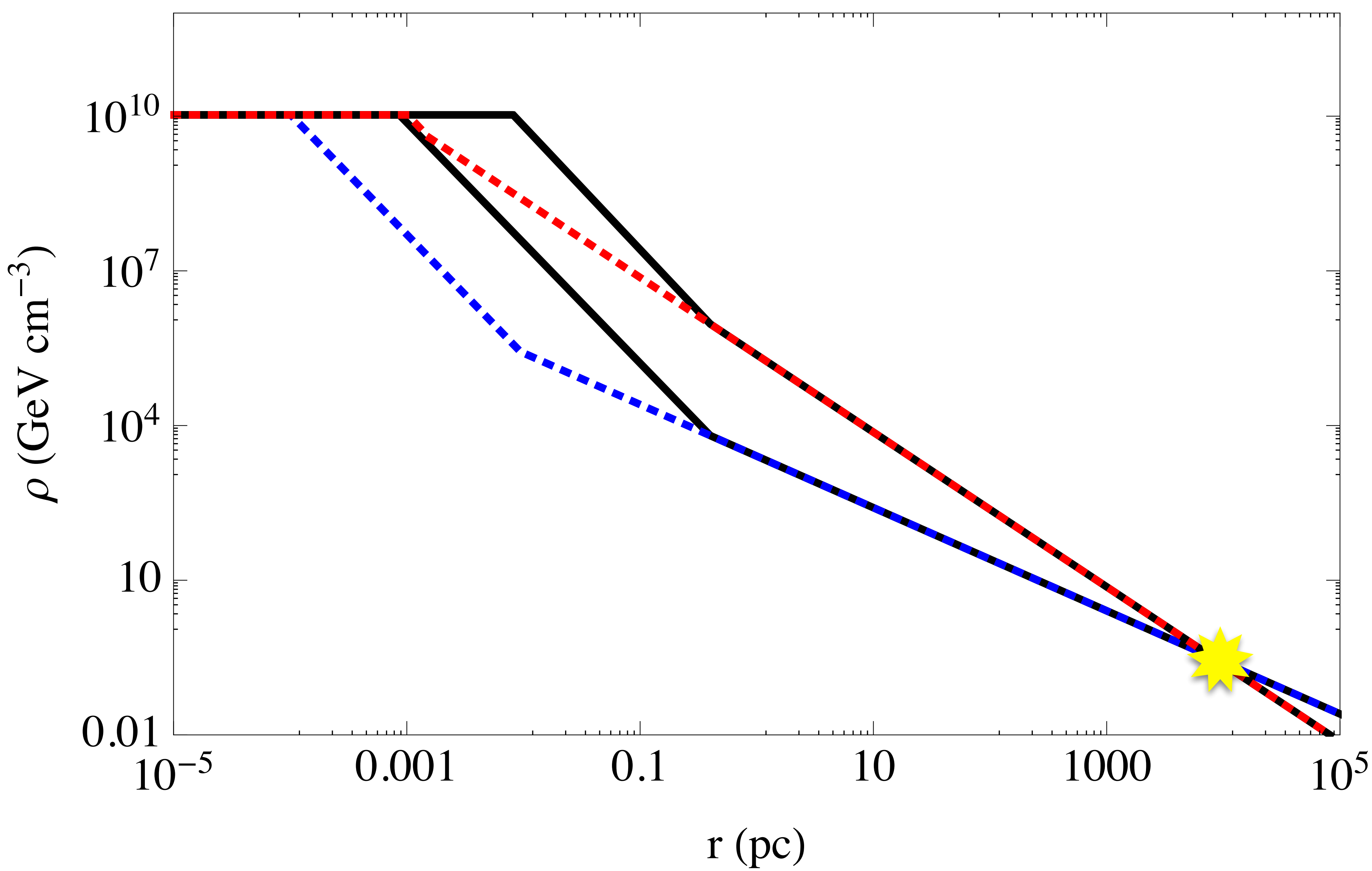
Extra Slides

Depleted Spike:
Is it a point source?



It really only looks like a point source for large g_sp (which also causes large r_sp). Otherwise, what you're seeing is probably just the fact that the profile falls quickly for large gamma_c.

Does it look like a spike?



Core and Spike Radii