Title: Boosting dark matter indirect detection with black holes

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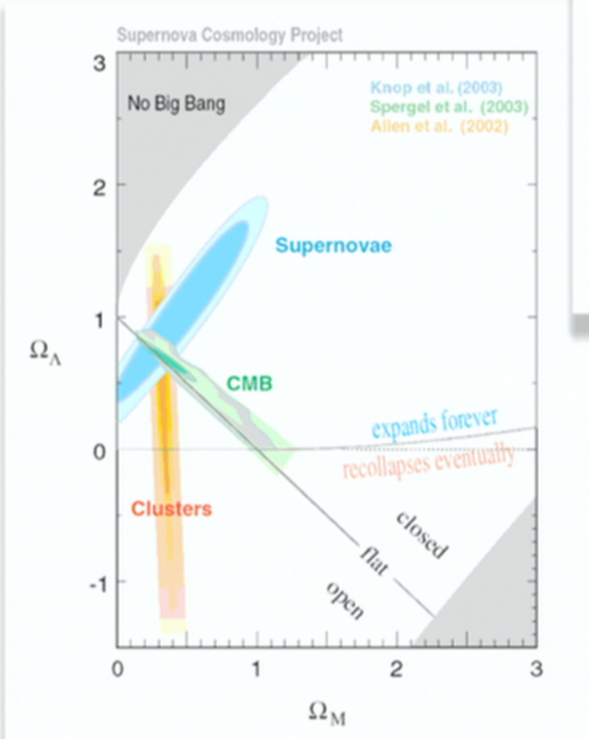
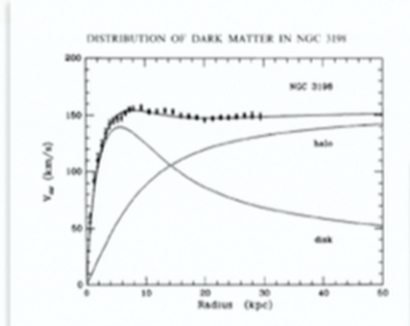
Abstract: <p> Super-massive black holes that grow at the center of dark matter halos distort the dark matter within their zone of influence into a steep density spike. This spike can give rise to strong enhancements of standard indirect detection signals, and can lead to qualitatively new windows onto the physics of the early universe. I will talk about potential dark matter signals from the Milky Way's central black hole, some astrophysical caveats, and the possible use of black holes as dark matter accelerators.</p>

Dark matter in the universe

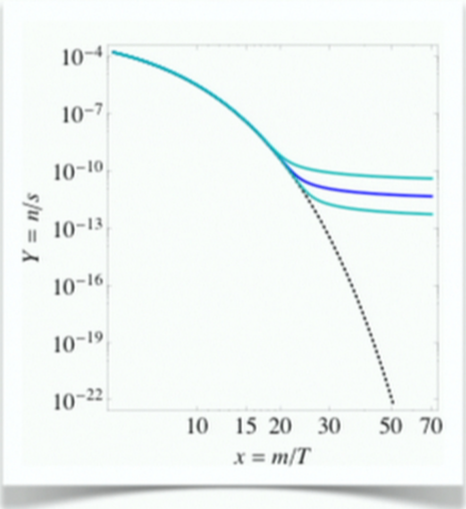


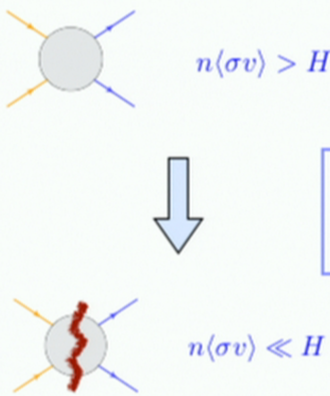


- ample gravitational evidence for dark matter
  - know present-day abundance
  - needs to be sufficiently cold
  - with limited self-interactions

Thermal freezeout: WIMP miracle

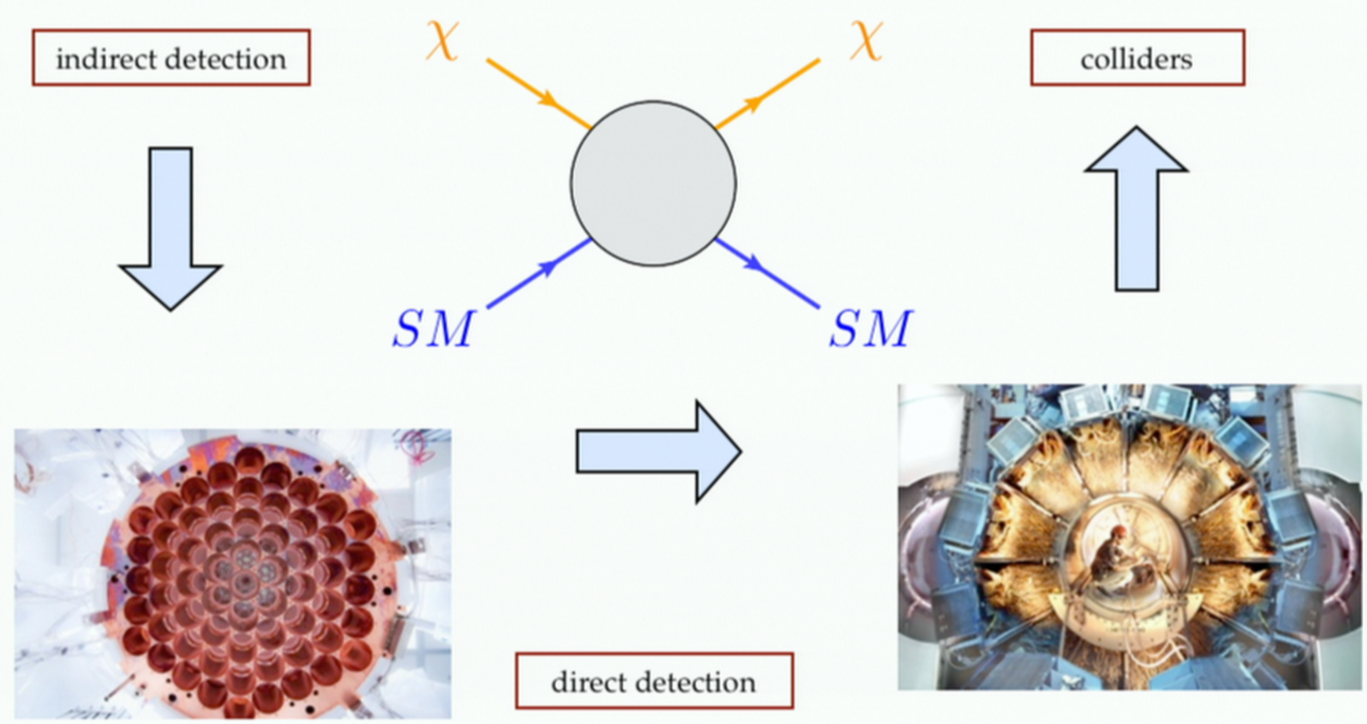
- Why should we expect DM to interact with us non-gravitationally?
- "WIMP miracle": thermal freezeout





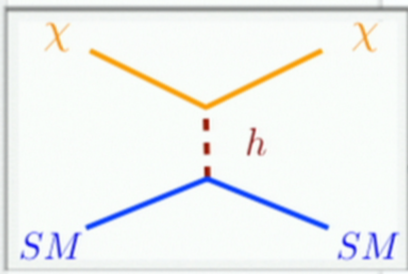
$$\Omega_{DM} \propto \frac{1}{\langle\sigma v\rangle} \sim \frac{m^2}{g^4}$$

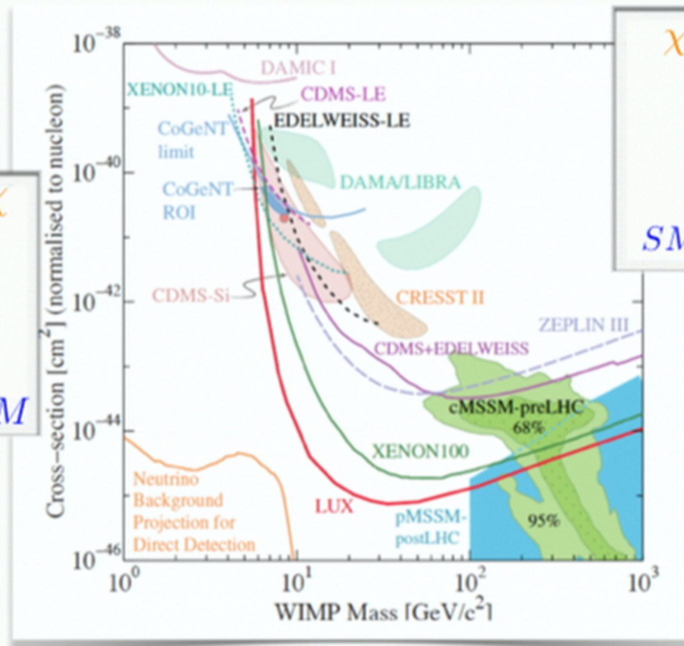
The hunt for (WIMP) dark matter

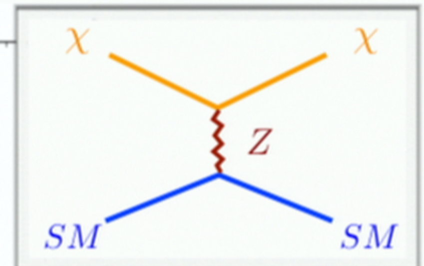


The hunt for (WIMP) dark matter

- sharply predictive; sharply (being) tested



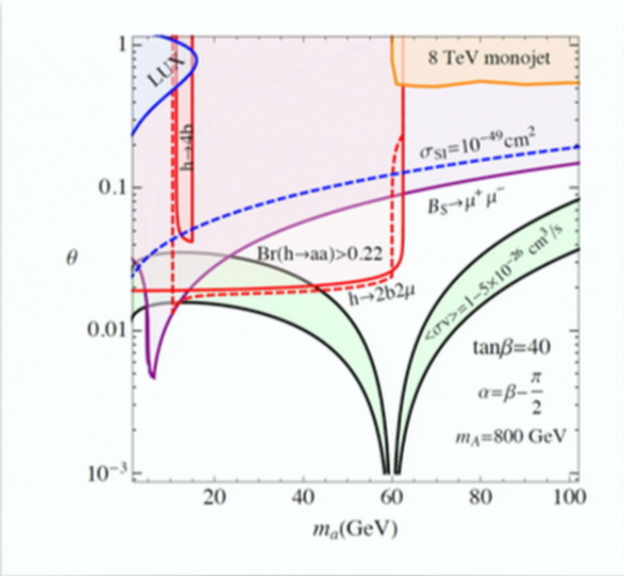


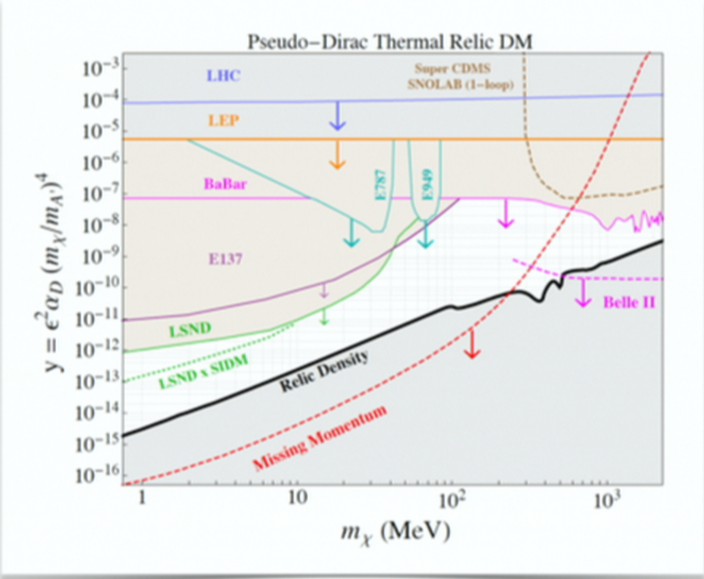


[PDG]

The hunt for (WIMP) dark matter

- Freezeout via BSM mediators can require new search strategies, but lower bound on coupling to SM gives clear target





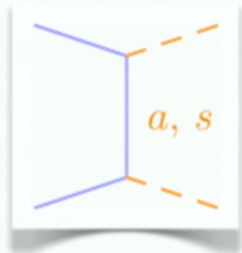
[Ipek, McKeen, Nelson; Krnjaic, Izaguirre, Shuster, Toro; ...]

Beyond WIMP dark matter

- Dark matter could be axions, super-weakly interacting particles, *Q*-balls, ...
- Dark matter could have a relic density set by dynamics in a multi-state hidden sector
  - thermal: hidden sector freezeout
  - non-thermal: e.g. asymmetric DM
- No guarantee of non-gravitational interactions with SM at terrestrially accessible rates

Hidden sector dark matter

- A simple example: hidden sector freezeout
- WIMP miracle is more generally a statement about perturbative thermal relics:



- upper bound on m: $g^2 < 4\pi$

  $\Rightarrow\ m \lesssim 40$ TeV

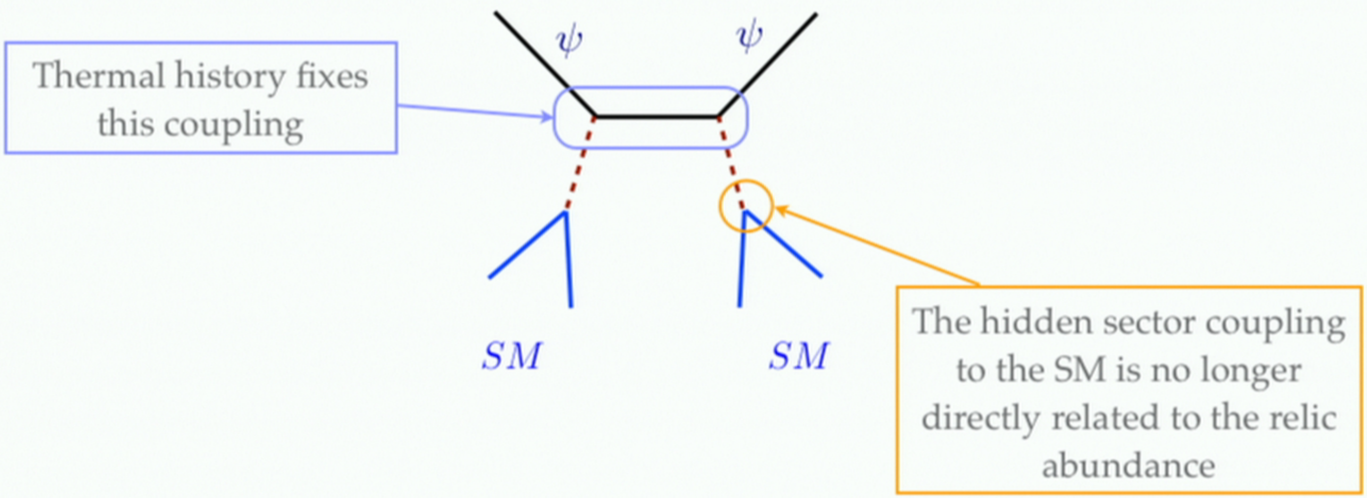
- lower bound on m: generalized Tremaine-Gunn bound,

  $\Rightarrow\ m \gtrsim$ keV

[Pospelov, Ritz, Voloshin; Das, Sigurdson; ...]

Hidden sector dark matter

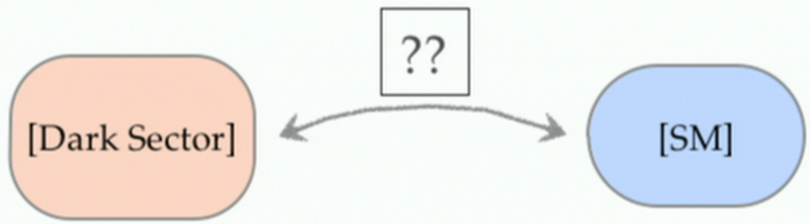
- Dark matter freezeout proceeds more or less independently of SM until mediator ultimately decays



[Pospelov, Ritz, Voloshin]

Hidden sector dark matter

- Mediator couplings to SM can be parametrically small



- Leading couplings at low energy:
  - Higgs portal $\mathcal{L}_{int} = \lambda s^2 |H|^2$
  - Vector portal $\mathcal{L}_{int} = \epsilon B_{\mu\nu} V^{\mu\nu}$
  - Axion portal $\mathcal{L}_{int} = \frac{a}{\Lambda} G_{\mu\nu} \tilde{G}^{\mu\nu}$, ...

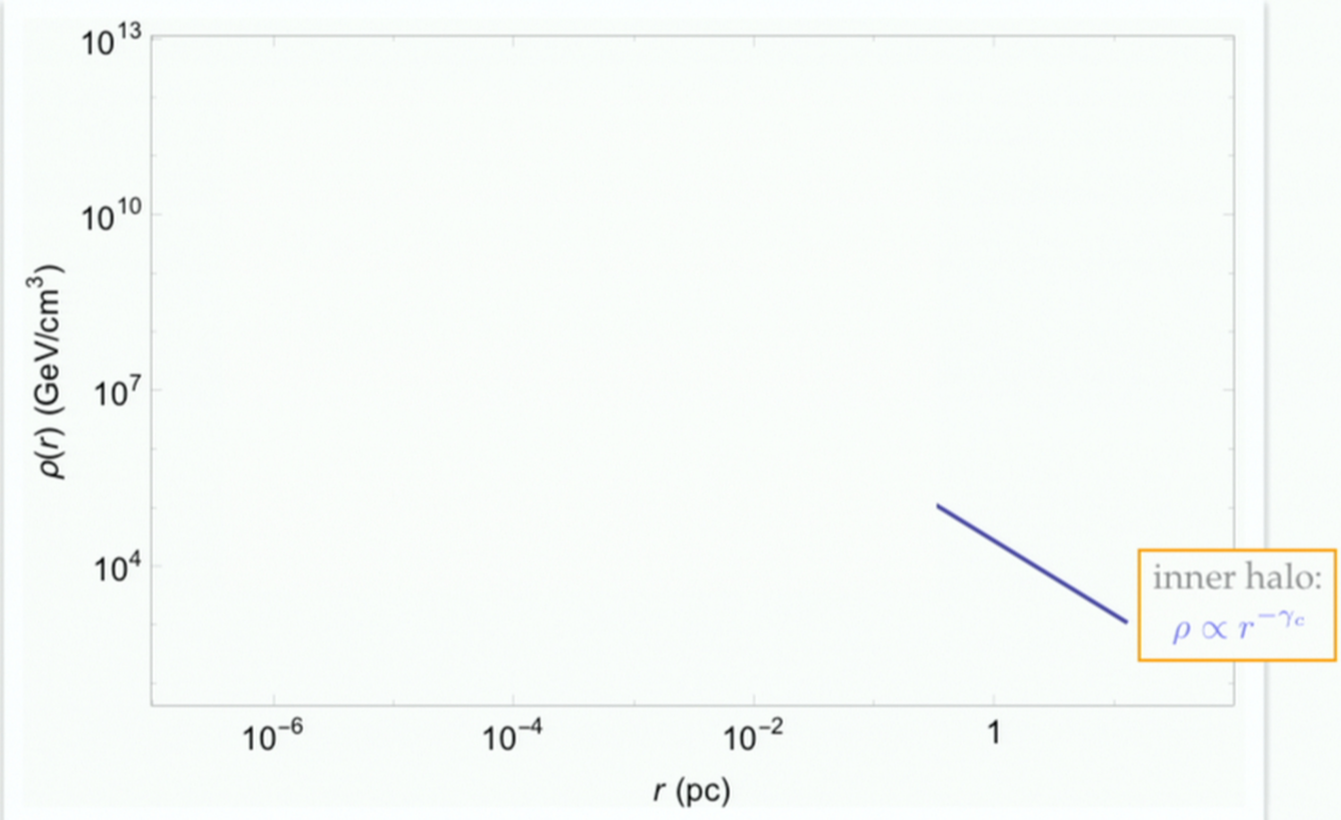
Indirect detection

$$\frac{d\Phi}{dE} = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \frac{dN}{dE} \int_{\rm los} \rho^2(r) d\ell$$

Dark matter and black holes

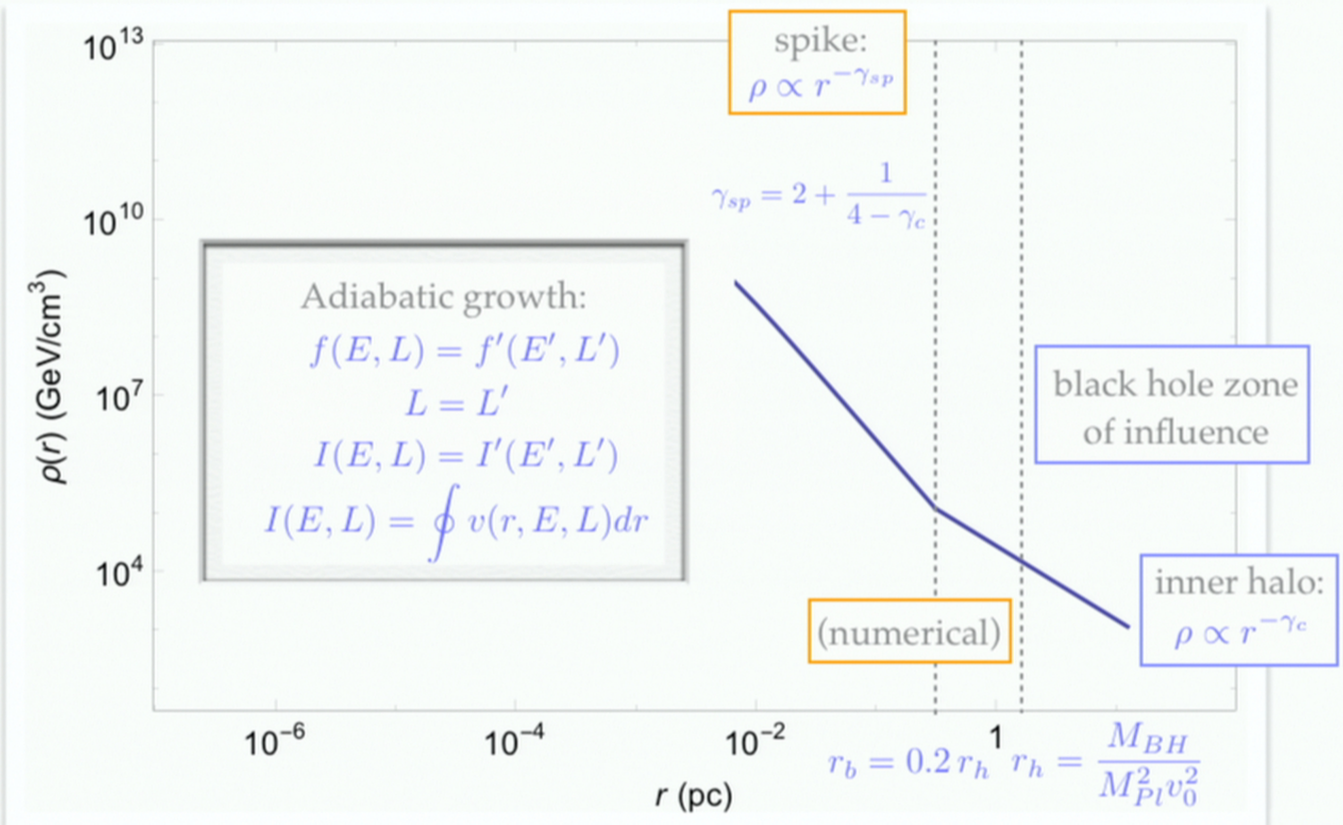
- Other astrophysical windows onto the particle physics of dark matter?
  - evolution of astrophysical objects: from stars to galaxy clusters
  - Qualitatively novel cosmic ray signals from black holes: dark matter density spikes and their consequences

Adiabatic spike solution



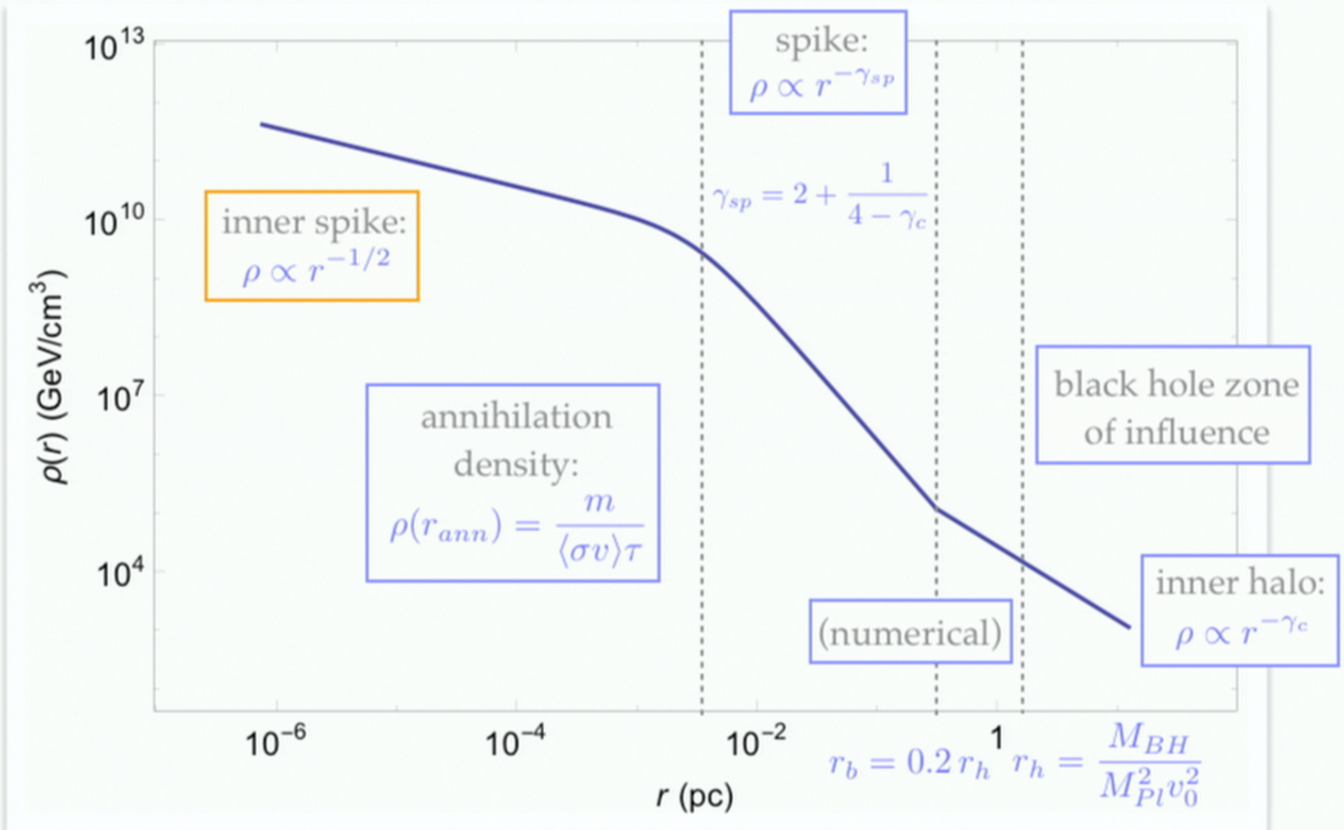
[Gondolo and Silk; Vasiliev]

Adiabatic spike solution



[Gondolo and Silk; Vasiliev]

Adiabatic spike solution



[Gondolo and Silk; Vasiliev]

A spike in the Milky Way

- Steep power law $\Longrightarrow$ strong dependence on inputs
- Input parameters:
  - $M_{BH} = 4 \times 10^6\, M_{sun}$
  - v_0
  - Inner NFW index γ_c
  - DM particle properties: ρ_{ann}

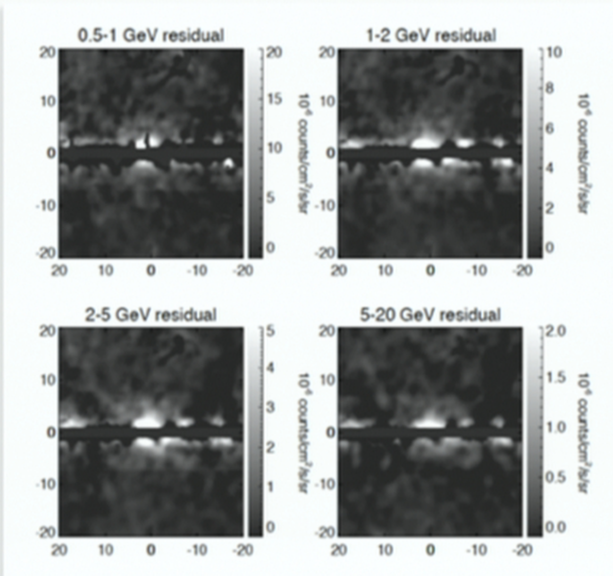
Fairly well-known: stellar orbits

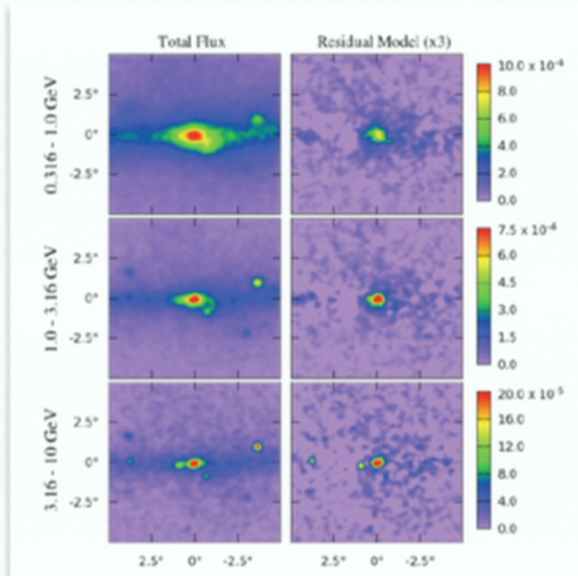
Measured from stellar population
(less precisely determined)

[Gultekin et al]

A potential signal of dark matter

- Excess in 1-10 GeV gamma rays from the Galactic center

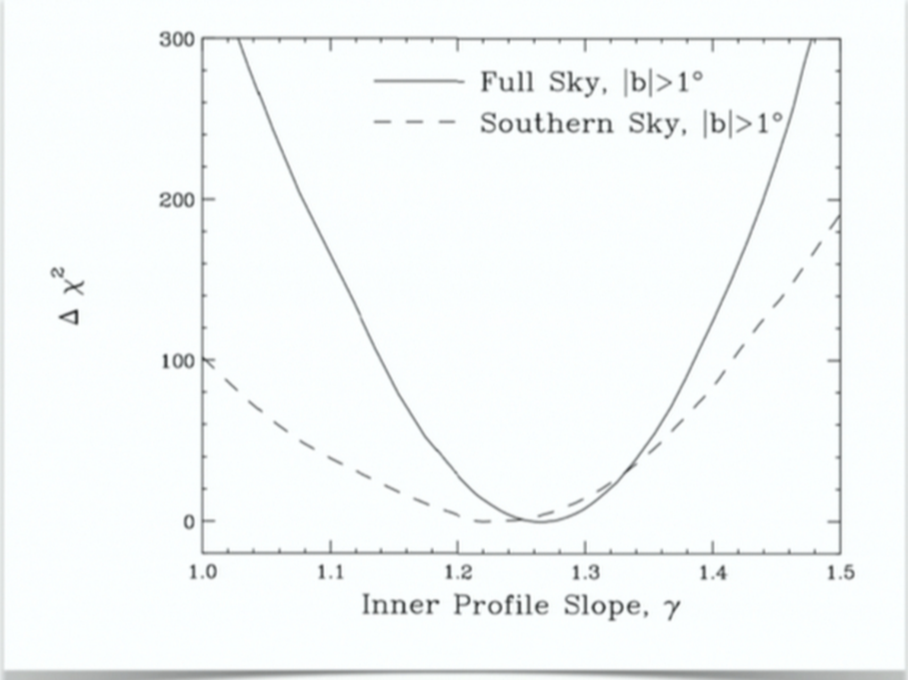




[Daylan et al.; see also Calore et al; *Fermi*; ...]

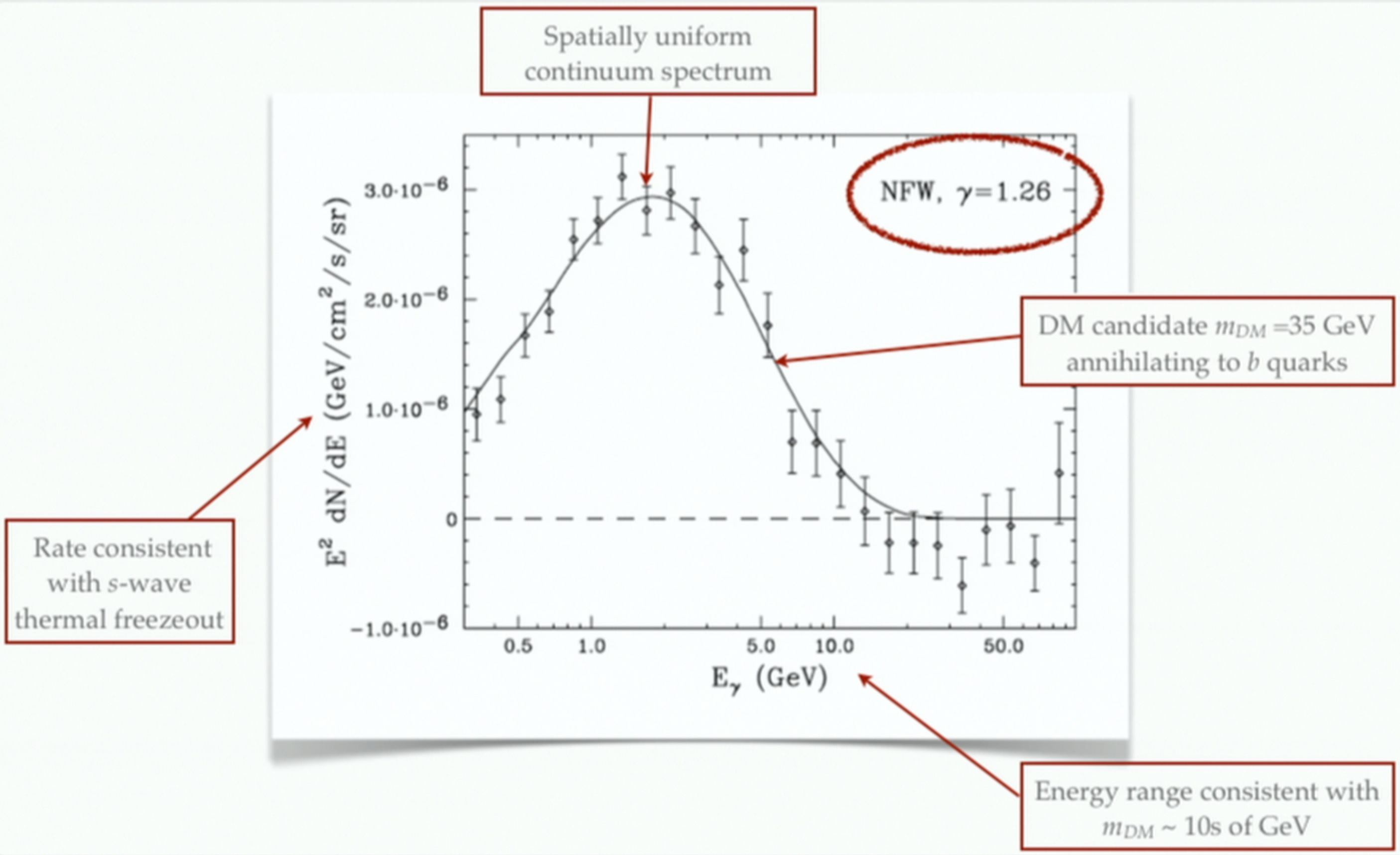
A potential signal of dark matter

- well-fit by DM annihilations in an NFW halo with $\gamma_c \approx 1.2$



[Daylan et al.]

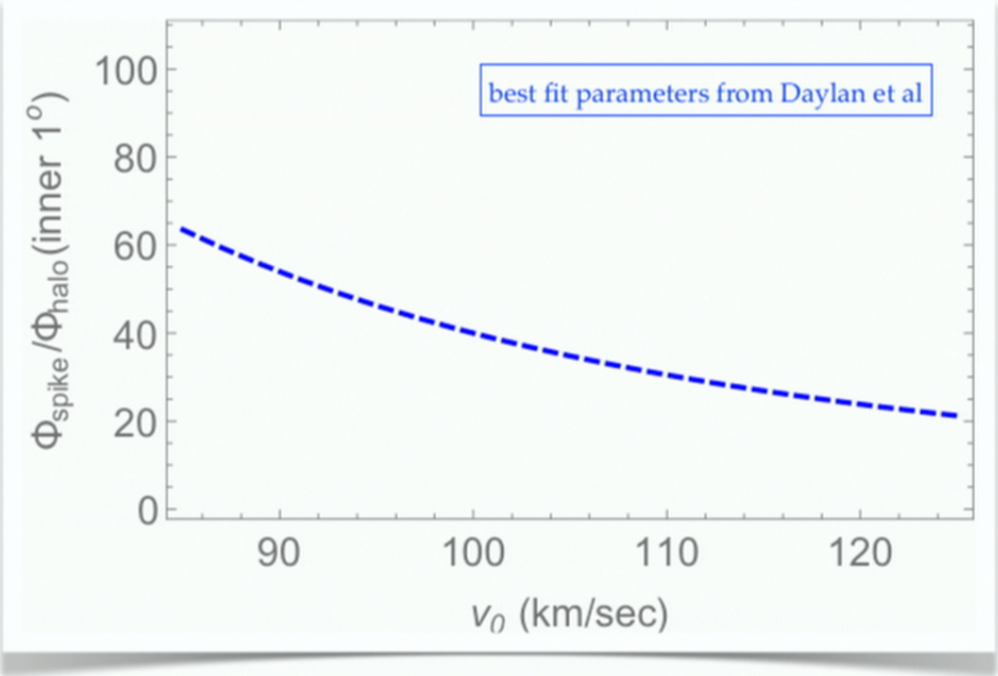
A potential signal of dark matter



[Daylan et al.]

Parametric dependence

- Sensitive parameter dependence in spike to halo ratio



[Fields, Shapiro, JS]

Parametric dependence

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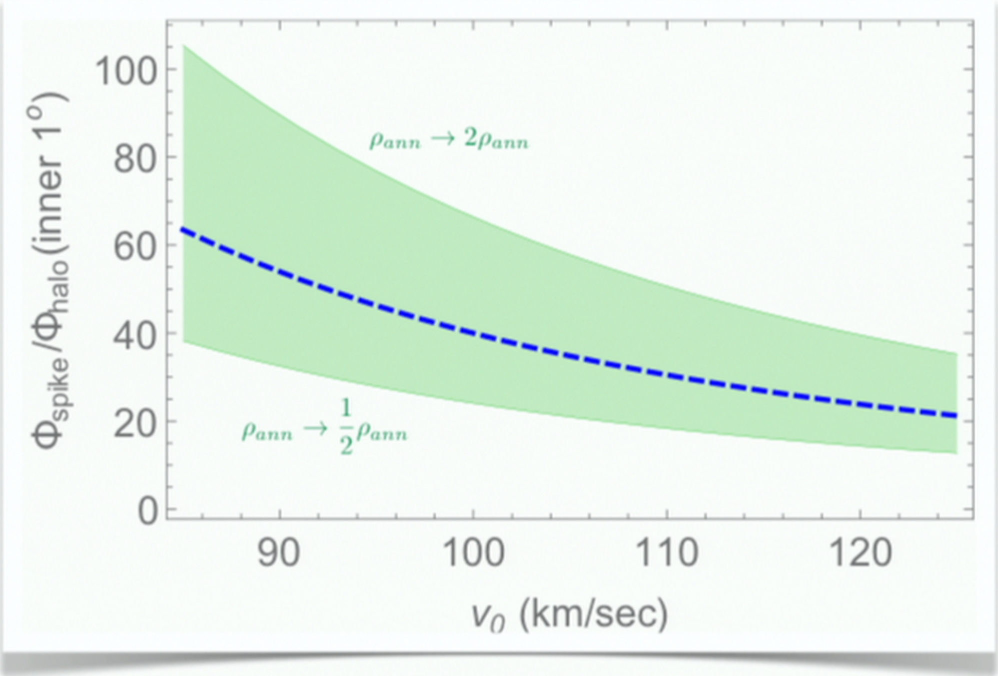
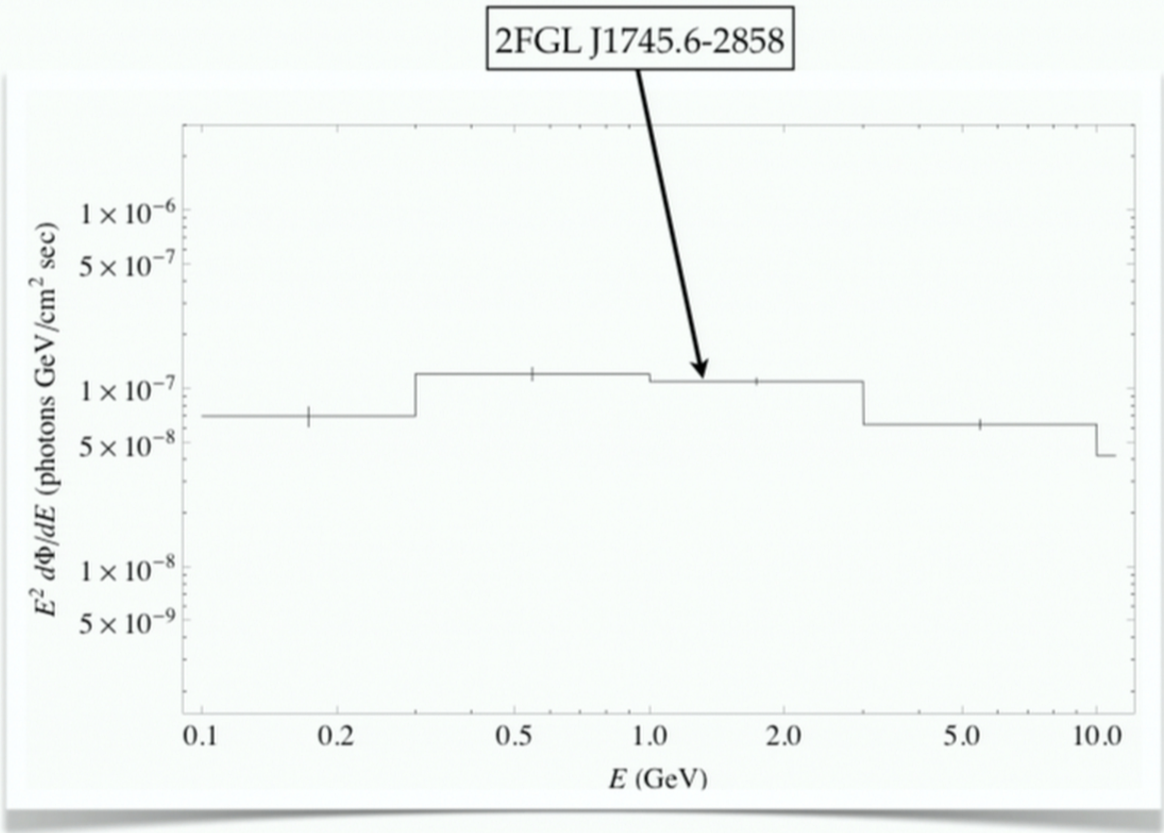


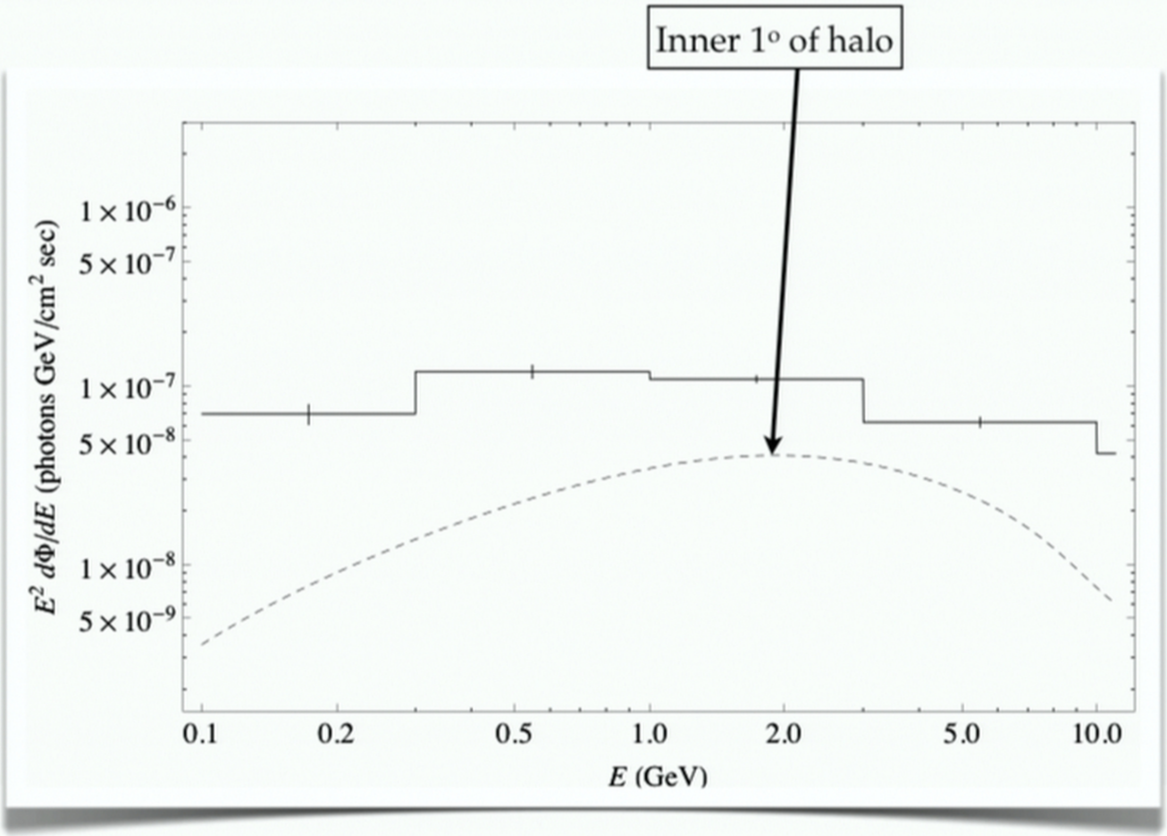
[Fields, Shapiro, JS]

The point source at the galactic center



[Second Fermi Point Source Catalog]

The point source at the galactic center



[Fields, Shapiro, JS]

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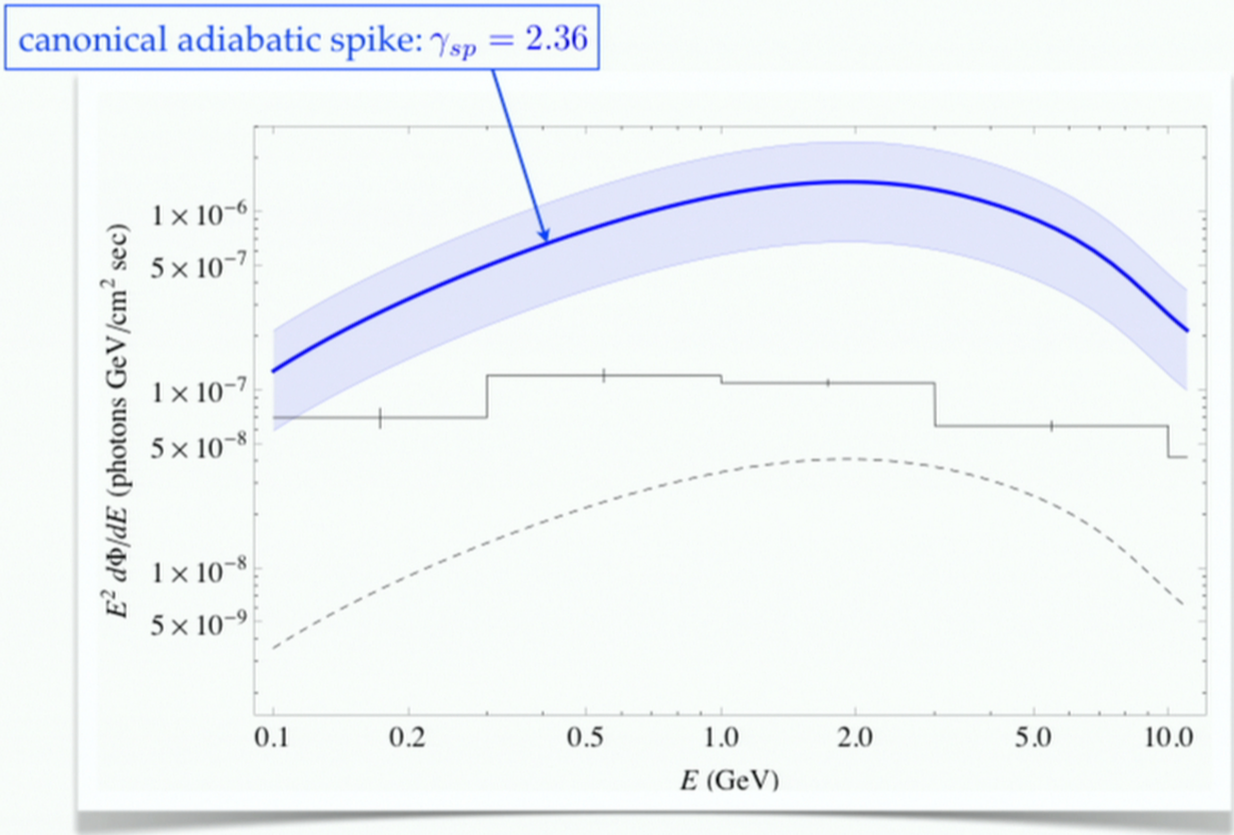

[Fields, Shapiro, JS]

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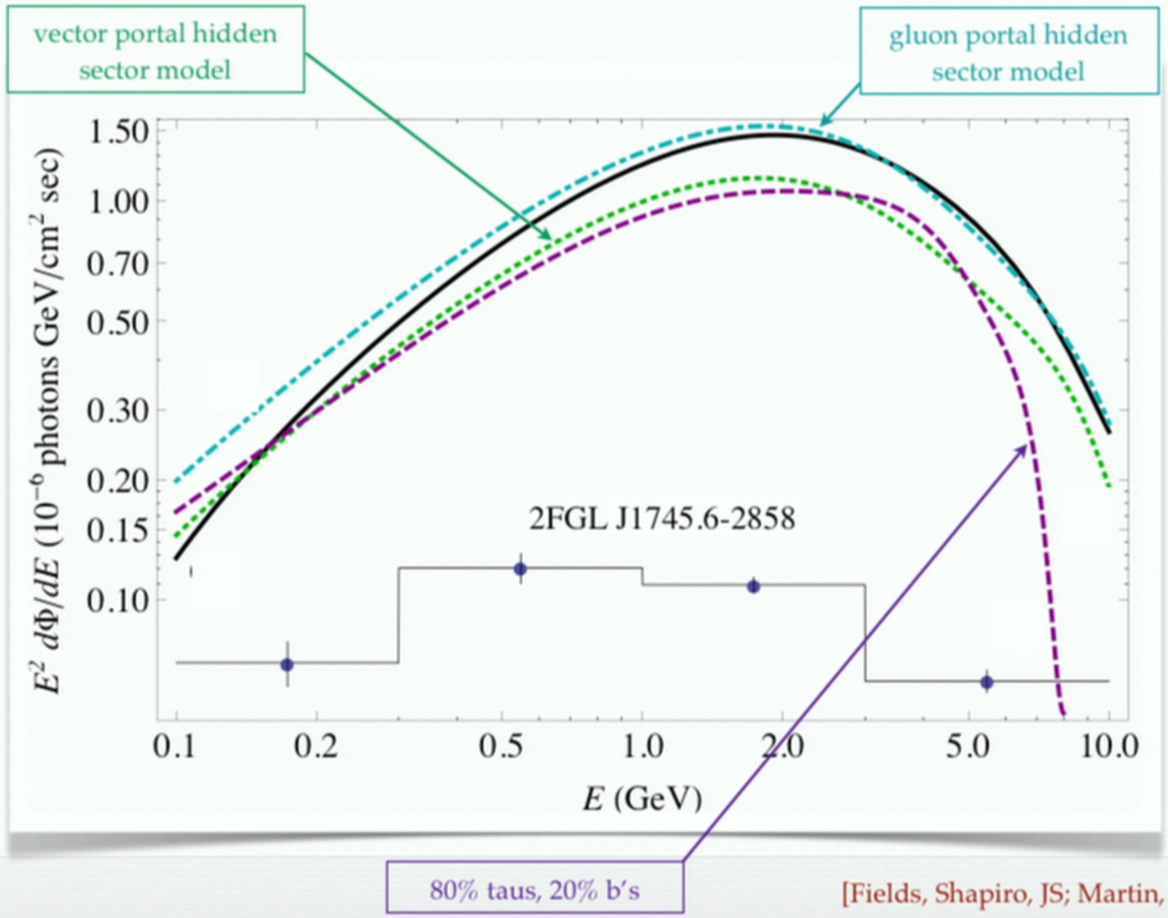

[Fields, Shapiro, JS; Martin, JS, Unwin]

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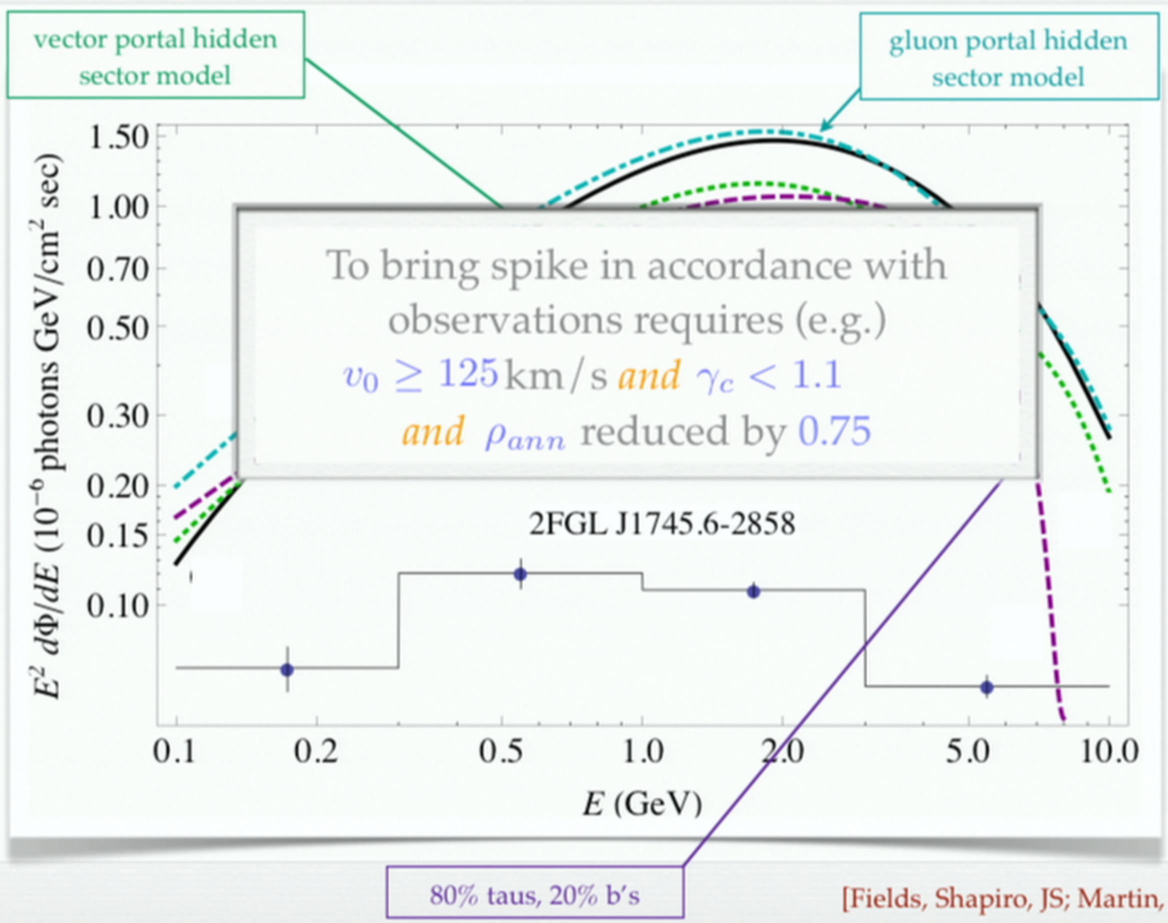
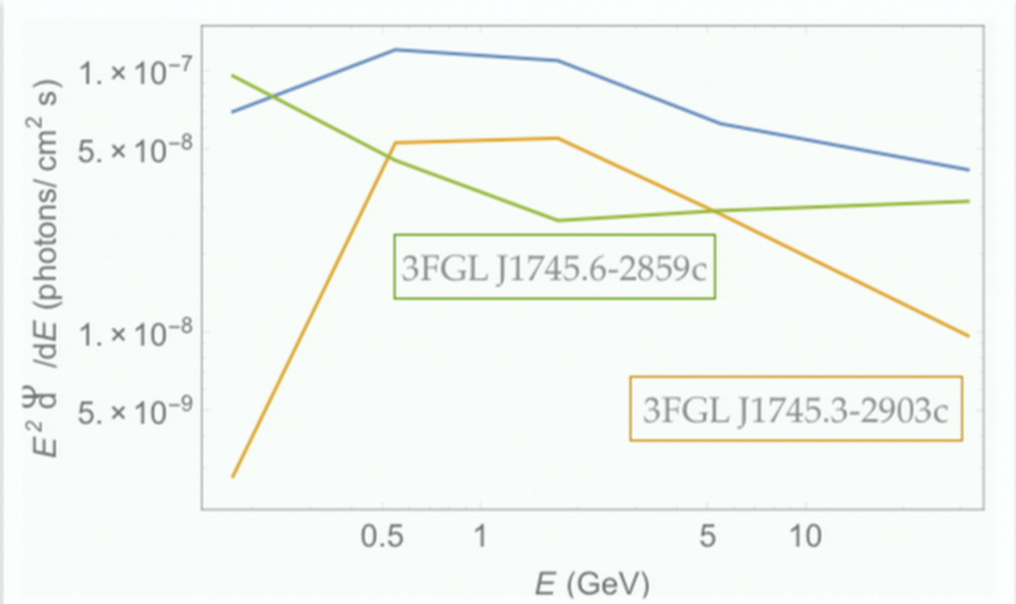


[Fields, Shapiro, JS; Martin, JS, Unwin]

The point source at the galactic center

- Updated Fermi point source catalog makes an adiabatic black hole spike even less likely:



[Third Fermi Point Source Catalog]

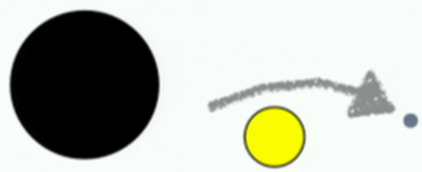
Alternatives to an adiabatic spike

- Non-adiabatic formation history:
  - Sudden origin in merger of two smaller black holes
- growth in a cored halo
  - possible result of strong baryonic feedback
- off-center formation
- Strong self-interactions
- stellar heating

[Ullio, Zhao, Kamionkowski; Shapiro and Paschalidis; Merritt; Gnedin and Primack; ...]

Stellar heating

- Canonical adiabatic spike solution
  - neglects baryonic population
  - assumes phase space densities are conserved
- Gravitational scattering off a sufficiently dense central stellar population:



  - Hierarchy m_χ / m_* results in transfer of energy to DM population
  - limiting solution $\propto r^{-3/2}$
  - relaxation timescale $\propto 1/\rho_*$

[Merritt; Gnedin and Primack]

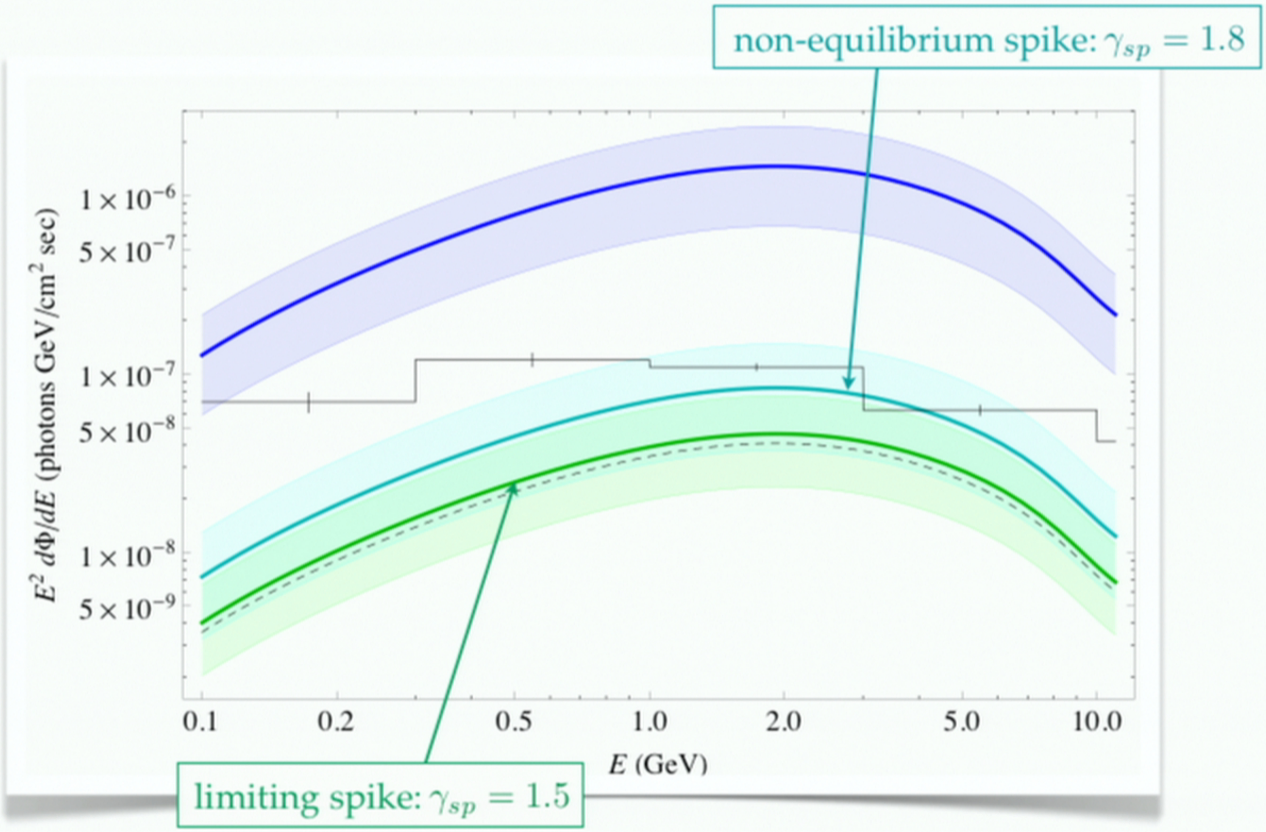
Stellar heating

- Is this mechanism operating in the Milky Way?

- If so: relaxation timescale likely somewhat longer than age of Milky Way

[Merritt x 2; Gnedin and Primack]

The point source at the galactic center



[Fields, Shapiro, JS]

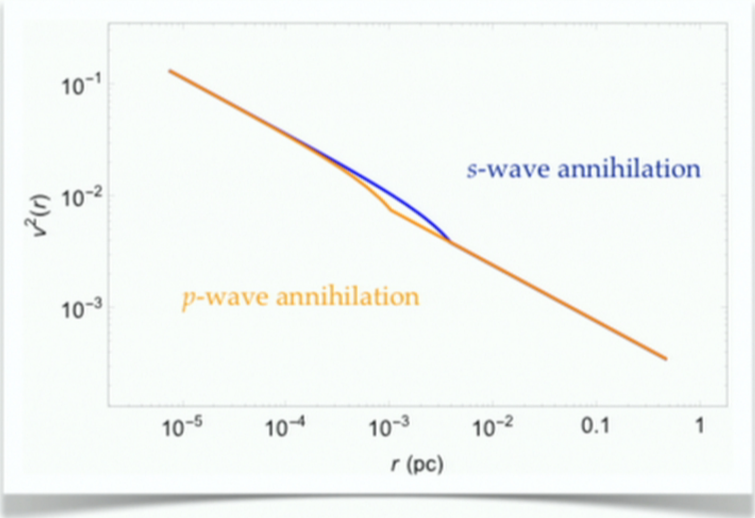
Black holes as dark matter accelerators

- Power law density in BH zone of influence requires power-law growth in velocity dispersion:

$$P = \rho \langle v^2 \rangle$$

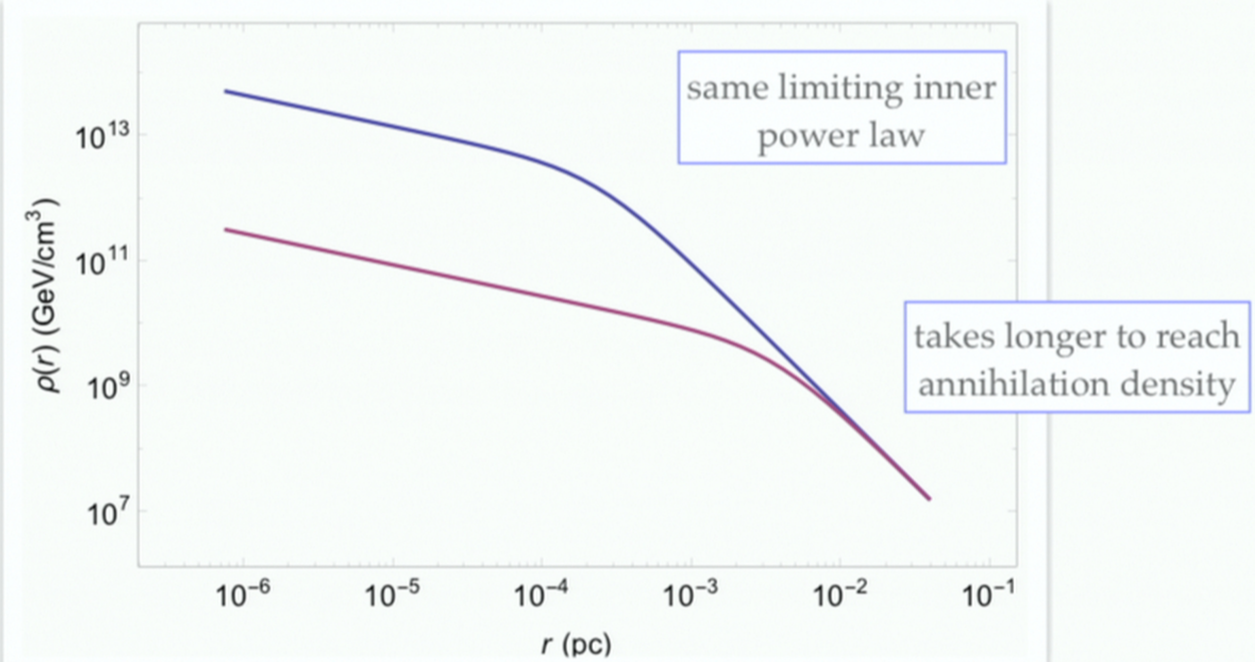
$$\frac{dP}{dr} = -\frac{M_{BH}}{M_{Pl}^2 r^2} \rho$$

$$\langle v^2(r) \rangle = \frac{M_{BH}}{M_{Pl}^2 r} \frac{1}{\gamma + 1}$$



Black holes as dark matter accelerators

- A p-wave spike in the Milky Way:



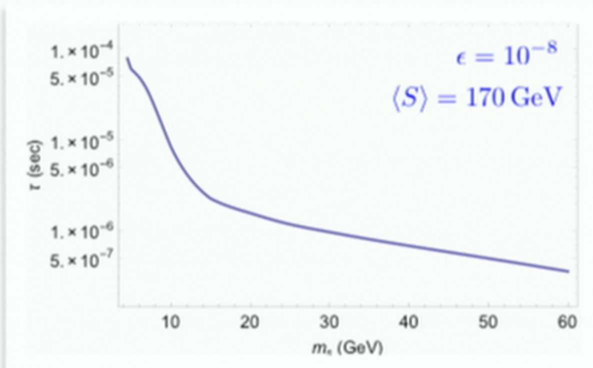
[Fields, Shapiro, JS]

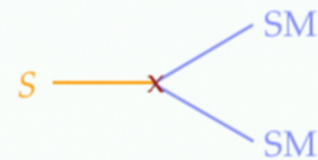
A stealthy dark matter model

- A simple model of dark matter:

$$\mathcal{L}_{int} = -yS\bar{\chi}\chi + \frac{\mu_s^2}{2}S^2 - \frac{\lambda_s}{4!}S^4 + \frac{\epsilon}{2}S^2|H|^2$$

- S gets a vev: Higgs portal mixing
  - Cosmologically prompt decay (provided s not too light):



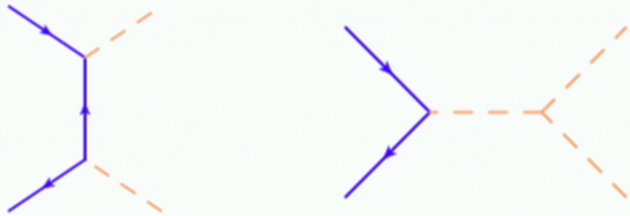


$$\theta_h = \frac{\epsilon\langle S\rangle v_h}{m_h^2 - m_s^2}$$

[Fields, Shapiro, JS]

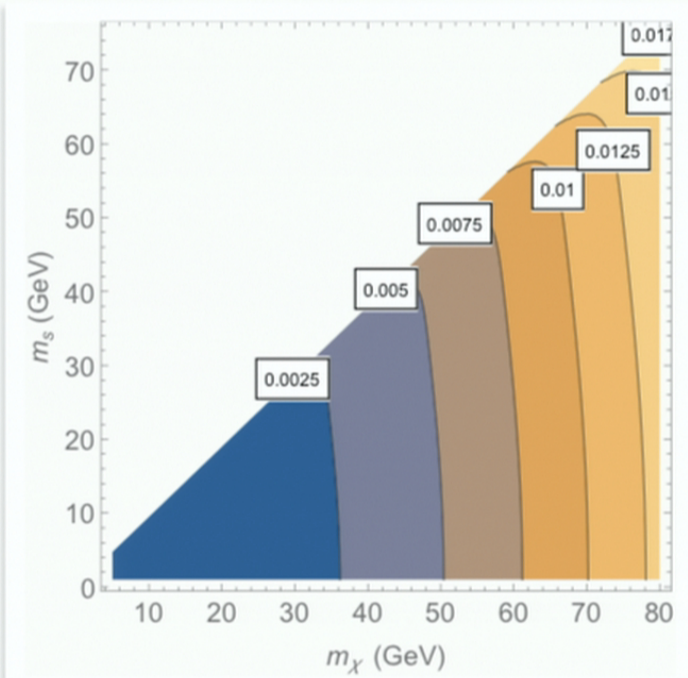
A stealthy dark matter model

- Freezeout is velocity-suppressed
  - Free parameters: m_χ, m_s, y
  - Freezeout ($\epsilon \ll y, \lambda_s$):



$$\langle \sigma v \rangle = \frac{y^4 v^2}{m_\chi^2} \sqrt{1 - \frac{m_s^2}{m_\chi^2}} f(m_s/m_\chi)$$

A stealthy dark matter model

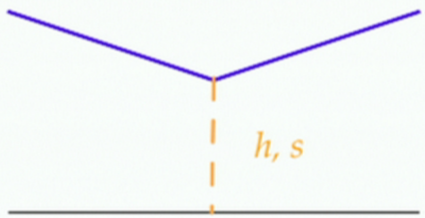


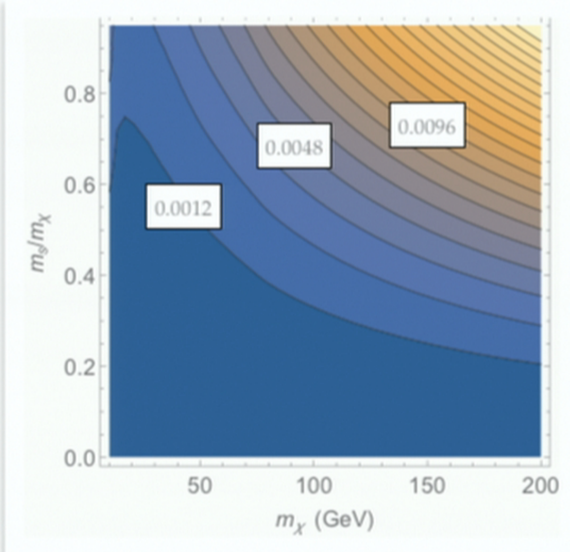
Approximate value of y^4 needed
to obtain $\Omega_{DM}h^2 = 0.112$.

[Fields, Shapiro, JS]

A stealthy dark matter model

- For $\epsilon \ll 1$, direct detection signals are out of reach:
  - LUX, Xenon now probing thermal SM Higgs portal models
  - additional suppression by θ_h puts signal out of reach





LUX constraints on epsilon

[Fields, Shapiro, JS]

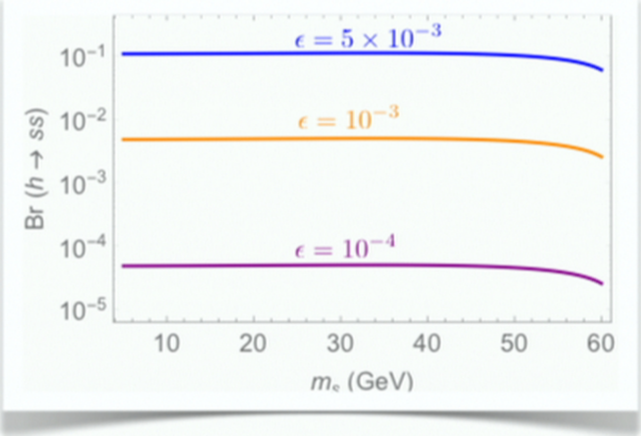
A stealthy dark matter model

- ...as is direct production at colliders

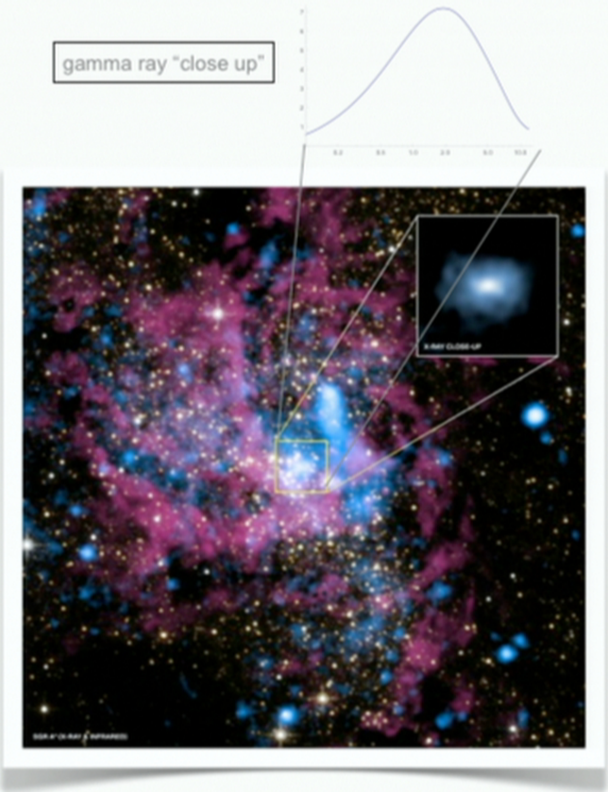
$$\mathcal{L}_{hs^2} = \epsilon v \frac{m_h^2 + 2m_s^2}{m_h^2 - m_s^2}$$

$$\mathcal{L}_{h\chi\chi} = \theta y h \bar{\chi}\chi$$

- best prospect: Higgs decays kinematically allowed
  - tough signal: $h \to 2s \to 4b$



A stealthy dark matter model

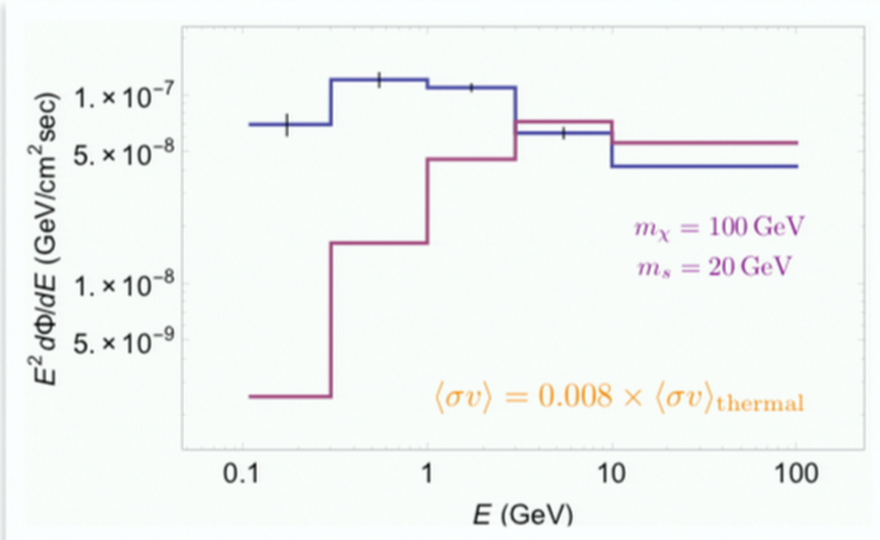


- But this model can be seen: a point source localized at a central black hole

[X-ray: NASA/UMass/D.Wang et al., IR: NASA/STScI]

The Milky Way point source

- 95% CL limits from Sagittarius A*: supersaturation

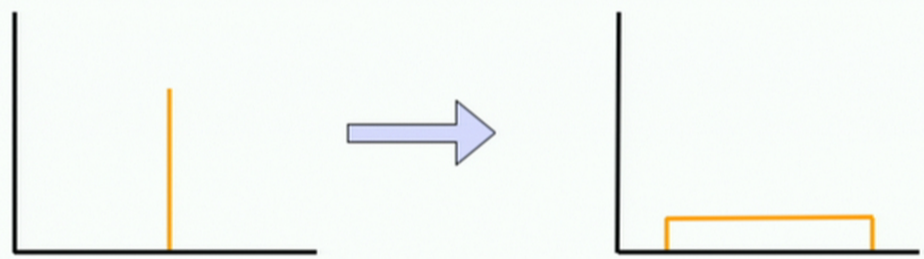


- Fine print: HDECAY, Pythia 8; $\gamma_c = 1$

[Second Fermi Point Source Catalog; Fields, Shapiro, JS]

Gamma ray boxes

- Given enormous uncertainties, need sharp kinematic feature to be confident of detection
  - gamma ray lines → gamma ray boxes



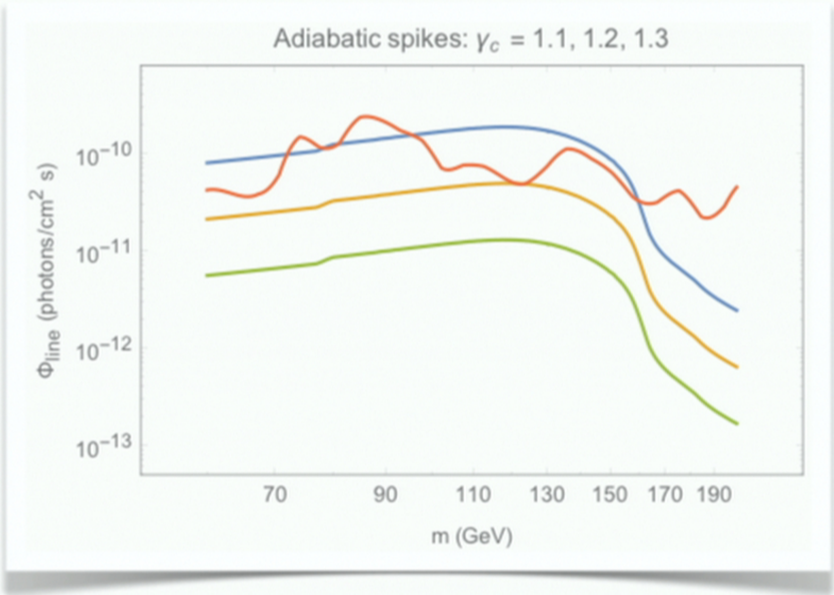
$$\frac{m_{DM}}{2} \qquad\qquad \frac{m_{DM}}{2}\left(1 \pm \sqrt{1 - \frac{m_{med}}{m_{DM}}}\right)$$

  - Prospects depend on m, γ_c; also couplings of mediator

[Ibarra, Lopez Gehler, Pato; ...]

Gamma ray boxes

- One *Fermi* line search which does not mask point sources:

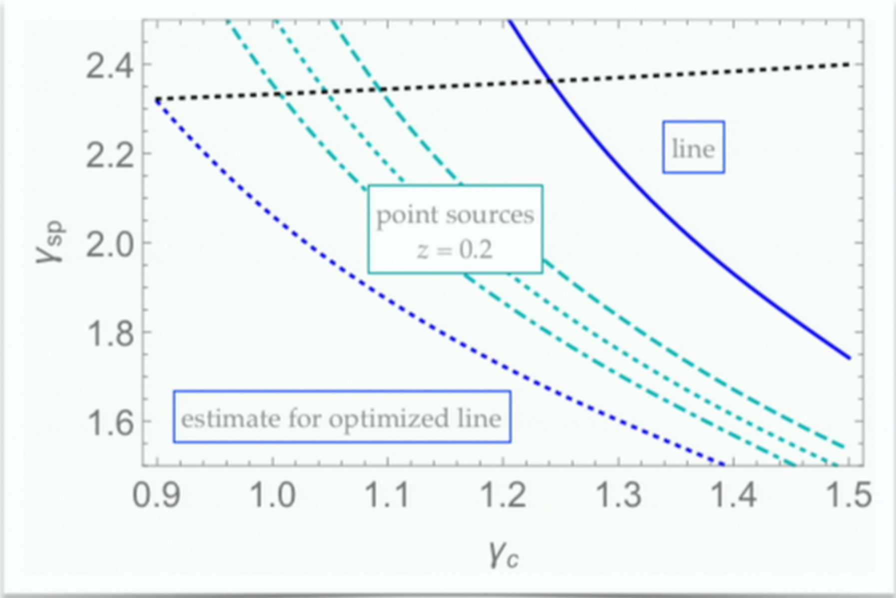


  - Higgs-like branching ratio from HDECAY, LHC HXSWG

[Ackermann et al. (Fermi Collaboration); Fields, Shapiro, JS]

Search sensitivity

- Regions of combined spike and halo parameter space sensitive to thermal cross-section:



$m_\chi = 110\,\text{GeV}$

[Fields, Shapiro, JS]

Another stealthy dark matter model

- Light pseudo-scalar decaying with O(1) BR to photons:

$$\mathcal{L}_{int} = -m\bar{\chi}\chi - \frac{1}{2}m_a^2 a^2 - iya\bar{\chi}\gamma^5\chi + \frac{a}{\Lambda}F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

  - if gluonic decay modes present, expect again ~$O(10^{-3})$ BR to boxes

- Terrestrial signals again easily dialed away

  - additional halo/spike signals from subdominant *s*-wave process $\chi\chi \to aaa$; can be kinematically impossible

Conclusions

- Super-massive black holes are dark matter observatories
  - spike emission probes different combination of particle parameters, galactic dynamics than does halo emission: new information
  - pick at most one: DM interpretation of the GC excess *or* an adiabatic spike at the center of the Milky Way
- Dark matter accelerators: window onto freezeout
  - Can observe/limit *p*-wave freezeout in broad range of well-motivated Galactic/BH scenarios
  - Many other applications: e.g. dark matter in nearly-degenerate multiplets, coannihilation *(in progress)*