Gamma-Ray Constraints on Dark Matter Spikes

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in collaboration with
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Big Questions

What is dark matter?

What were the first stars like?

The first stars formed in dark matter minihalos.

Remnant black holes

Dark matter spikes

Distributed in the Milky Way halo today

Dark matter annihilation in spikes

Gamma ray point sources

First Stars

$$50 \lesssim z \lesssim 5$$

$$m_{DM} = 10^5 - 10^8 M_\odot$$

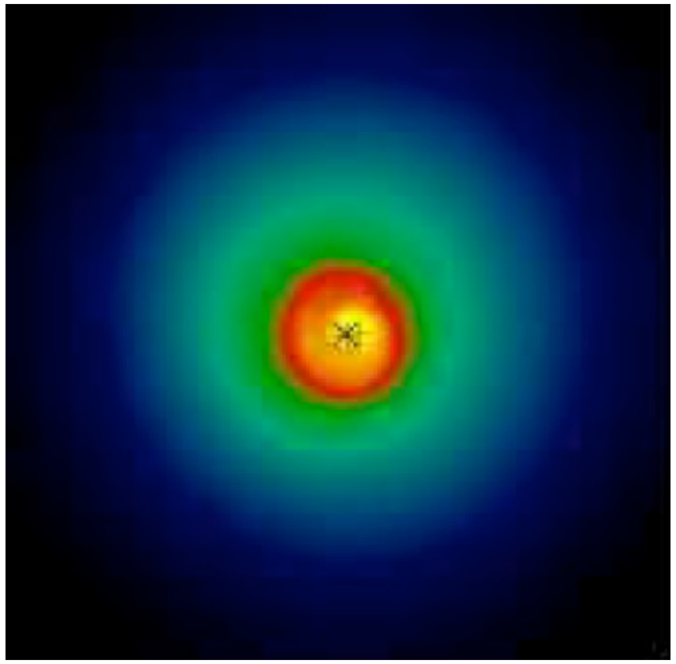
- End of dark ages
- Reionization
- Metal enrichment of IGM
- Black Holes

Nomenclature

- Population I
  - luminous, hot and young – like our Sun
- Population II
  - low metallicity relative to solar
- Population III
  - Population III.2: essentially metal-free, but gas partially ionized
  - **Population III.1**: ~zero metallicity (BBN abundances), unaffected by other astrophysical sources

Formation of the First Stars

Stacy, Greif, & Bromm (2012)



- Population III.1: first luminous objects
  - unaffected by other astrophysical objects
  - $z \gtrsim 20$
  - primordial abundances
  - H_2 cooling
- Minimum halo mass for star formation (Trenti & Stiavelli 2009)

$$M_{t_H - cool} \simeq 1.54 \times 10^5 M_\odot \left(\frac{1+z}{31} \right)^{-2.074}$$

- Massive?
- Death by core-collapse → black hole

Adiabatic Contraction

- Where a baryonic object (star, BH, etc.) forms in a dark matter halo, baryons dominate the potential
- Dark matter particles fall into potential well created by protostar
- Calculate contraction via Blumenthal, Faber, Flores, & Primack (1986): angular momentum invariant (very good approximation)
- Contracted profile: $\rho \sim r^{-1}$ (NFW) → $\rho \sim r^{-1.9}$ (spike)

Adiabatic Contraction

NFW

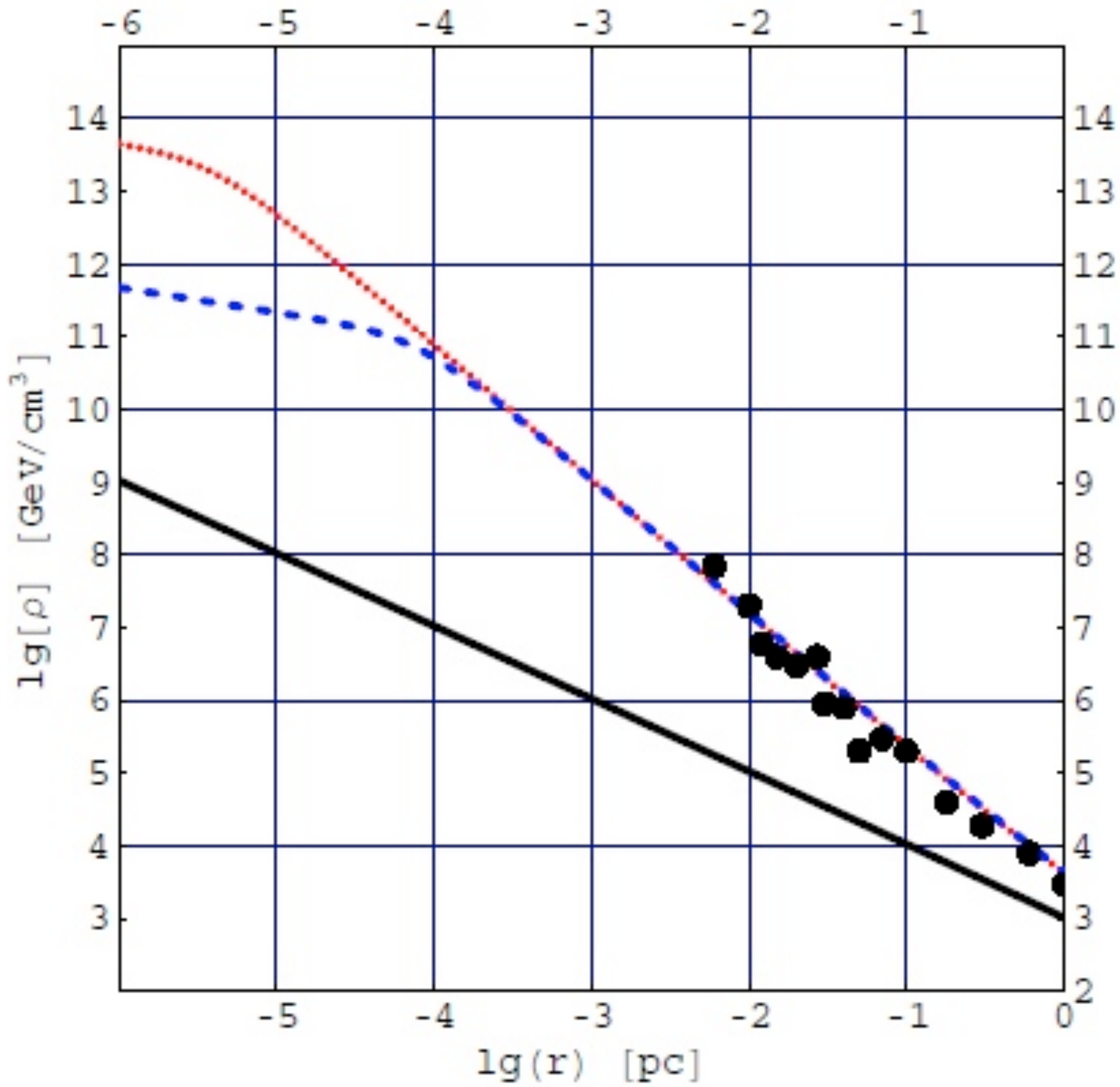
AC profile with H densities

10^{13} cm^{-3}

10^{16} cm^{-3}

- Simulation results from Abel, Bryan, & Norman (2002) for H density 10^{13} cm^{-3}

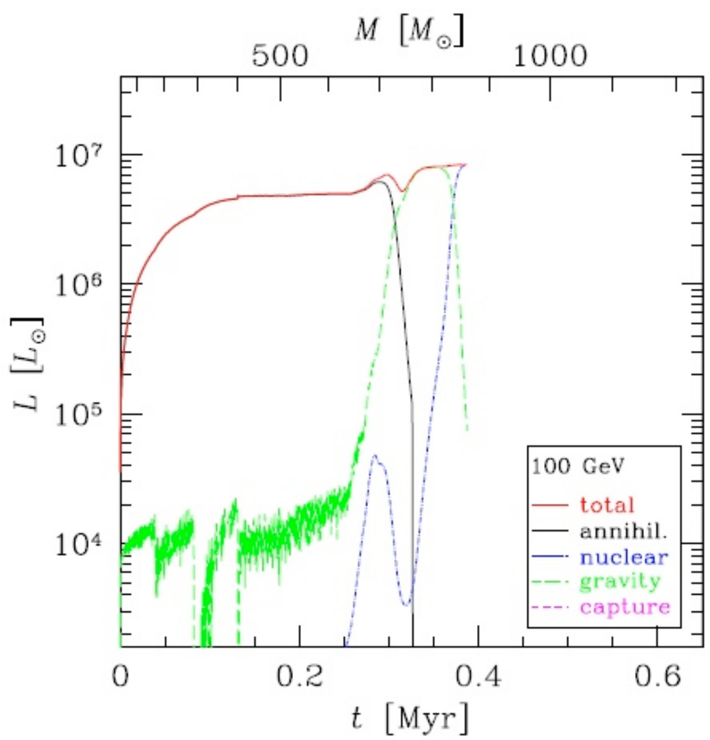
Figure from Freese *et al.* (2008)



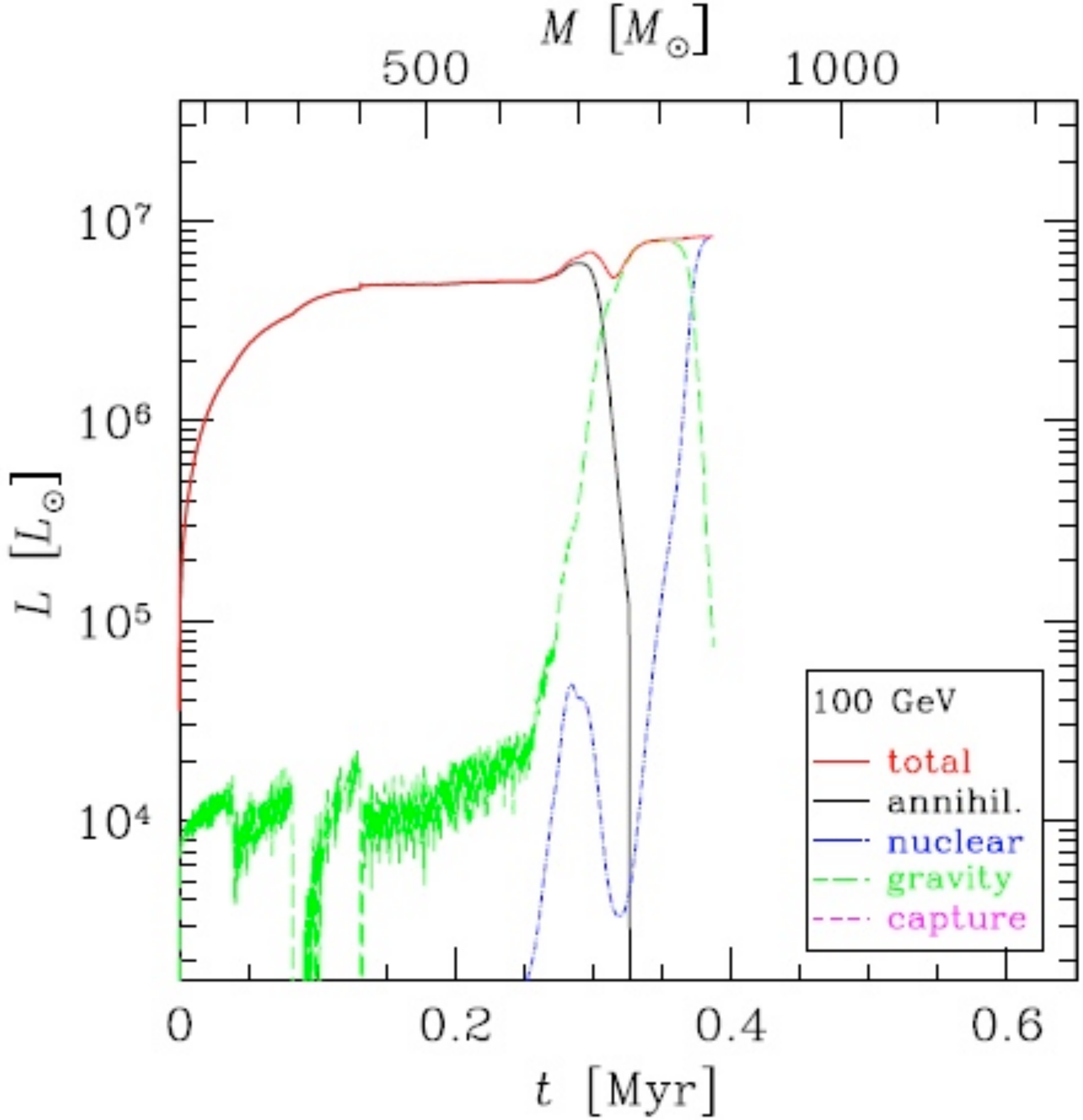
Dark Stars?

- If dark matter particles annihilate, and if the first stars formed in dark matter overdensities at high redshift $(\rho \propto (1+z)^3)$
- DMA rate enhanced: $\Gamma \propto \rho^2$
- DMA products stuck in collapsing baryonic cloud
- ***DMA "powering" the star???***

Answer: YES!!
Spolyar *et al.* (2008+)



- Conditions met for standard adiabatic contraction of DM halo



Freese et al. (2009)

Dark Star Phase

- Very high DM density (~1% dark matter)
- DM heating dominant
- How long does it last???

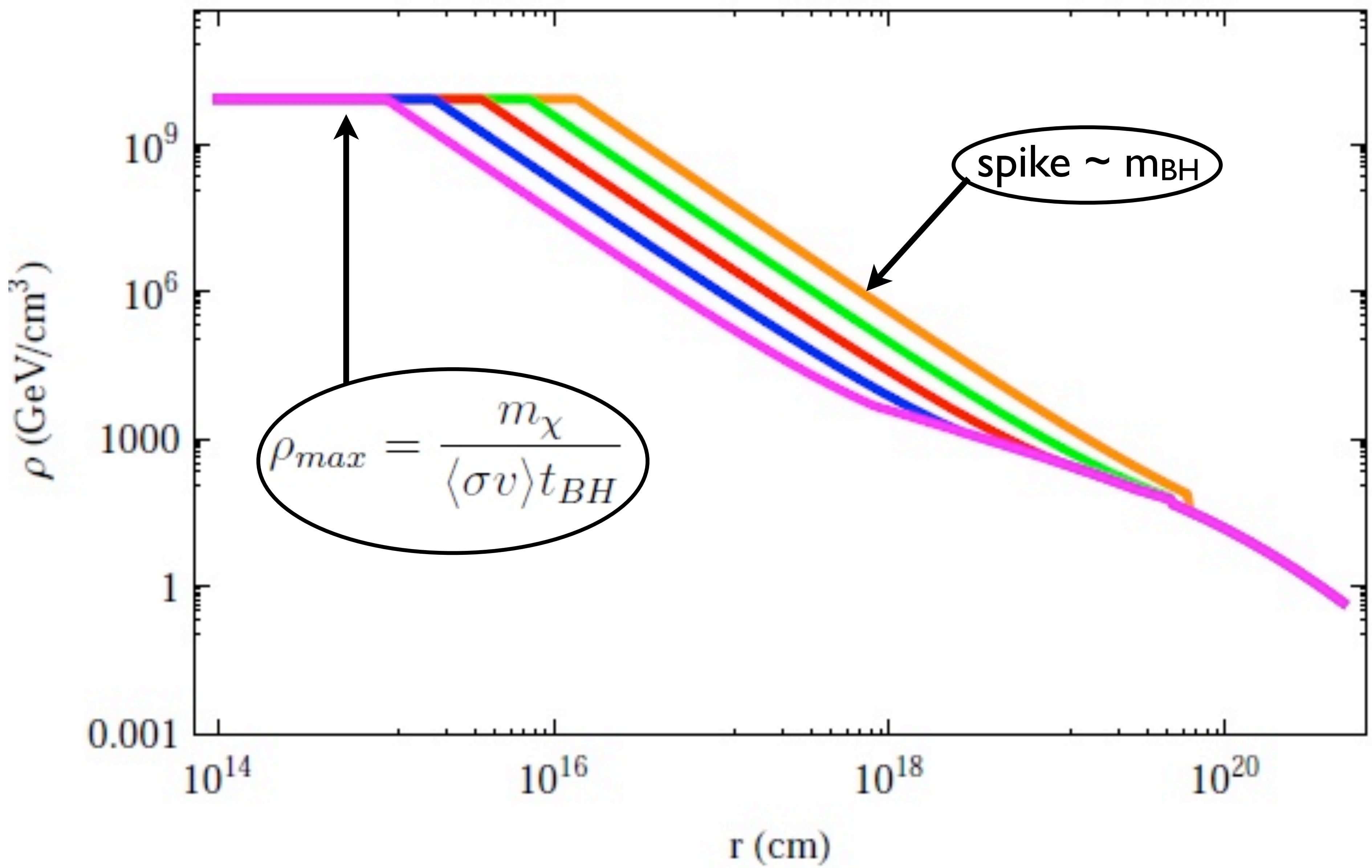
larger central baryonic object → higher spike density

$$10M_\odot < m_{BH} < 10^5 M_\odot$$

- Death by collapse to black hole (→ much larger)

DM Spikes

15% baryons, 85% DM, NFW profile → star/BH +AC DM profile



Where they are today...

Particle Mass = 4.1 x 10^3 $M_\odot$

Diemand et al. (2008)

Identifying Candidate Halos

- Mass range $$M_{t_H-cool} \simeq 1.54 \times 10^5 M_\odot \left(\frac{1+z}{31}\right)^{-2.074}$$

$$M_{t_H-cool} < M_{DM} < 10^7 M_\odot$$

- Redshift range

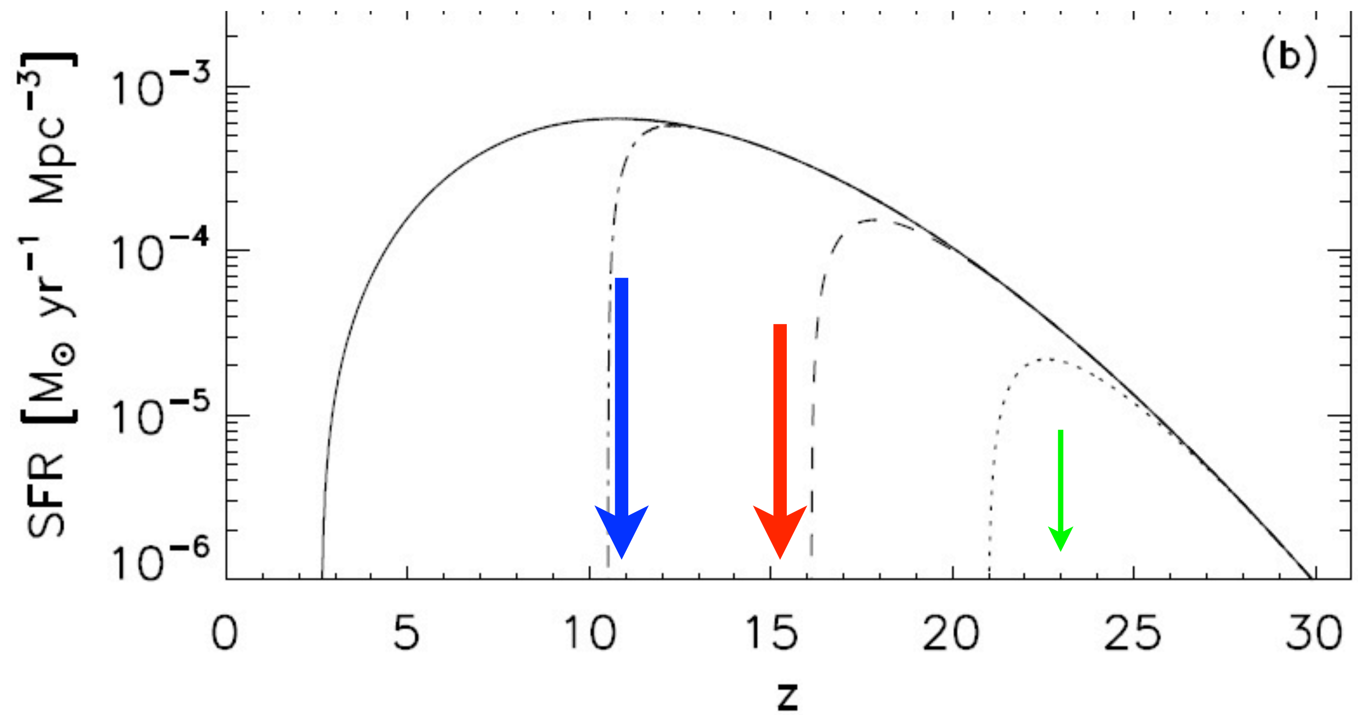
Greif & Bromm (2006)

Early $z_f = 23$

Intermediate $z_f = 15$

Late $z_f = 11$

Star Formation Rate



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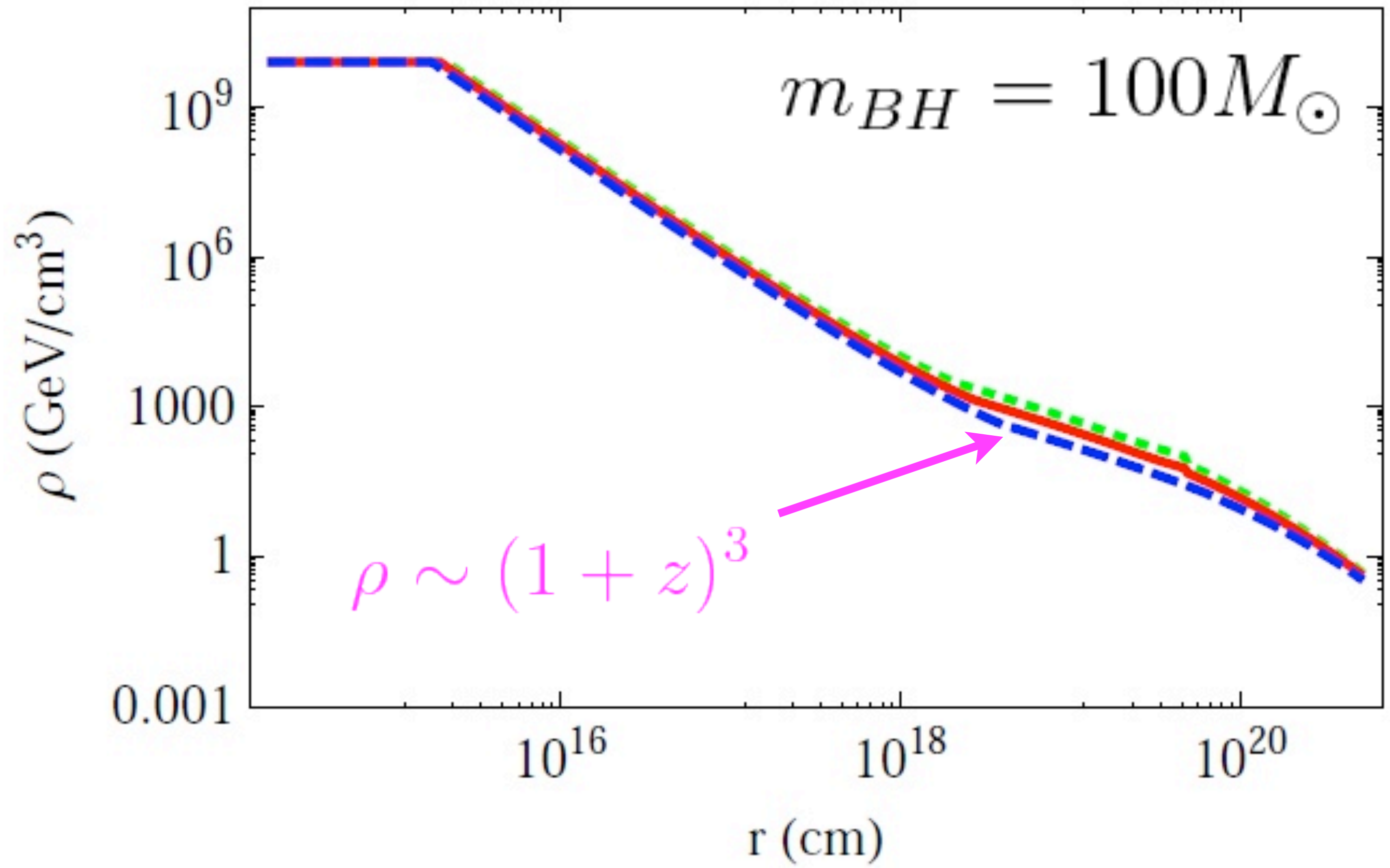
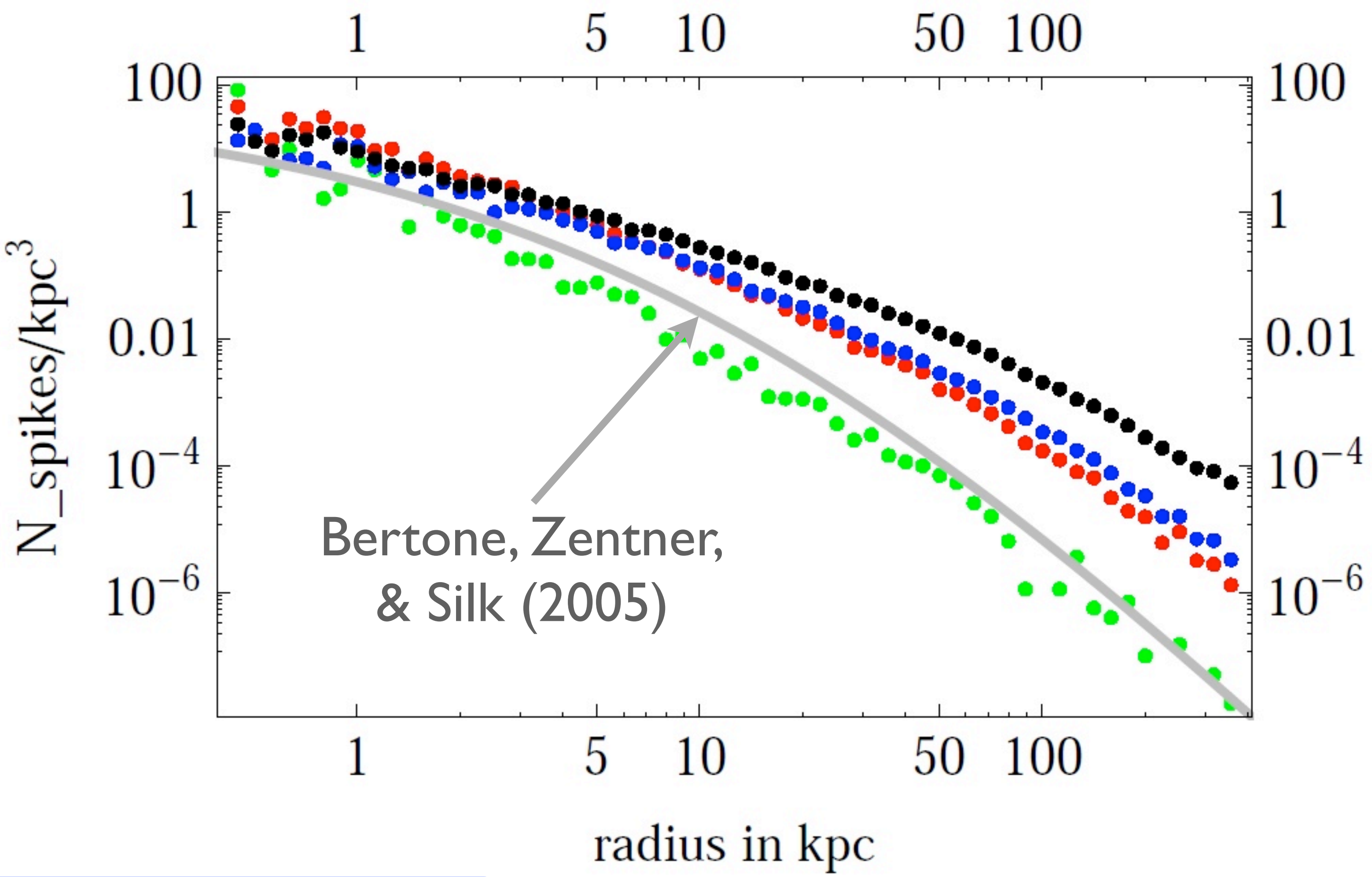


Spike Distribution

- Assuming each candidate host halo did host a first star:
- *But probably not every candidate halo did.*



$$\text{Actual } N_s = f_S \times (\text{Total Possible } N_s)$$

What is f_S?

$$f_S = f_S^0 \left(1 - f_{merged}(f_S^0, m_{BH})\right)$$

- f_S: fraction of all potential DM spikes to survive until *z=0*
- f_S^0: fraction of candidate minihalos to have hosted first stars (DM spikes)
- f_{merged}: fraction of DM spikes destroyed in mergers

- Estimates show $f_{merged} < 0.5$ in all cases.
- Only significant for $m_{BH} \gtrsim 10^4 M_\odot$ and $f_S^0 \approx 1$.
- In most cases, $f_{merged} \to 0$ and $f_S \to f_S^0$.

What can we learn?

Dark Matter

m

$\langle \sigma v \rangle$

final states

First Stars

z

IMF (Dark Star phase?)

SFR ($f_S \rightarrow f_S^0$)

- Assume dark matter model
  ➜ limits on star formation history
- Assume star formation history
  ➜ limits on dark matter

From a Single Spike

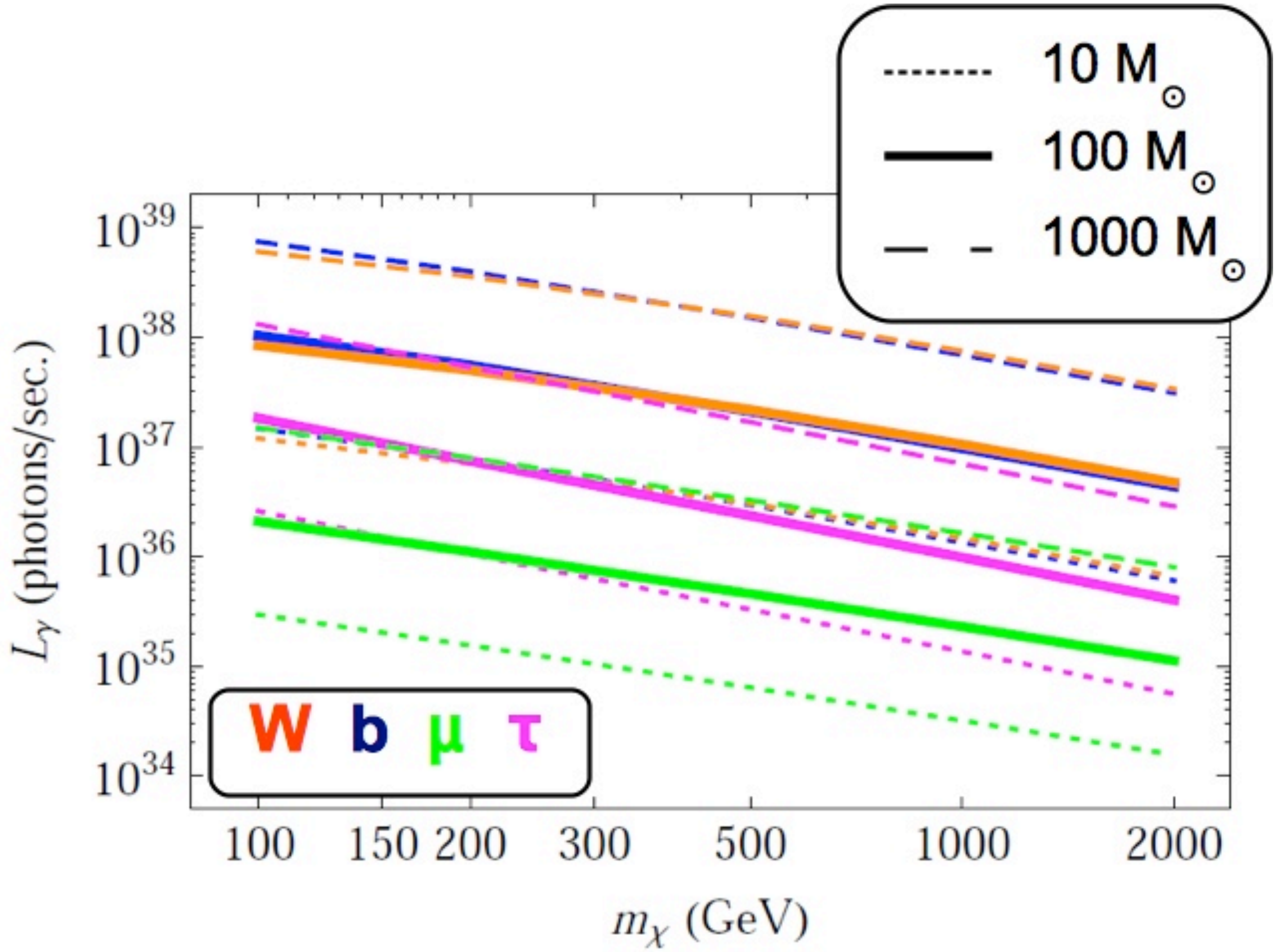
- Annihilation Rate

$$\Gamma = \frac{\langle \sigma v \rangle}{2m_\chi^2} \int_{r_{min}}^{r_{max}} dr\, 4\pi r^2\, \rho_{DM}^2$$

$$\langle \sigma v \rangle = 3 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}$$

- Luminosity

$$\mathcal{L} = \int dE \sum_f \frac{dN_f}{dE} \Gamma_f$$

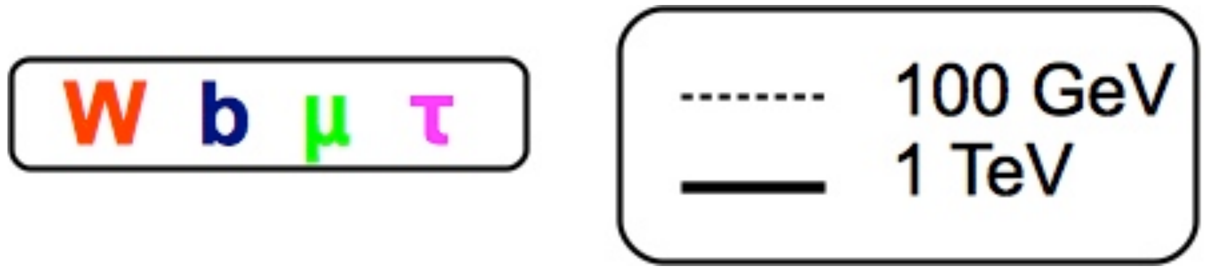


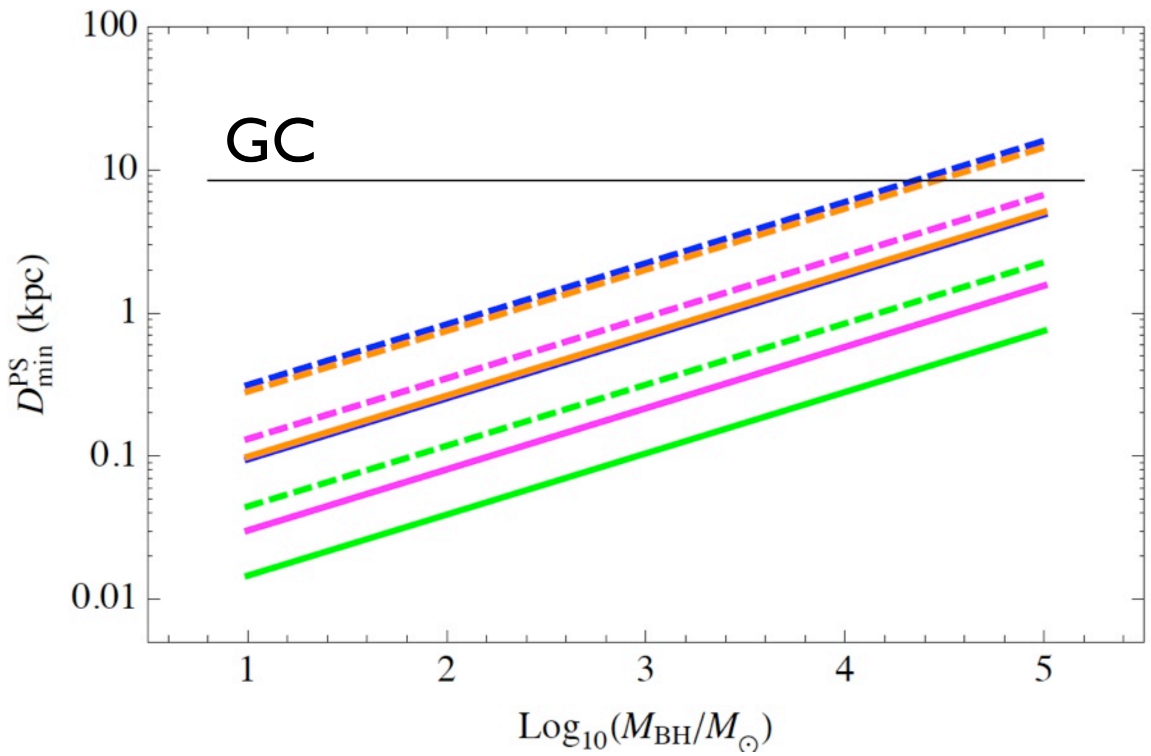
- Larger WIMP mass -> fewer WIMPs -> lower luminosity
- Larger BH mass -> higher spike density -> higher luminosity

Point Sources vs. Diffuse Flux

- DM spikes may already show up as point sources in the FGST catalog.
  - Brightest one can't be brighter than the brightest observed source → minimal distance, *DminPS*
  - If a source is far enough away [dim enough], FGST won't be able to pick it out as a point source → maximal distance for point sources, *DmaxPS*
  - How many point sources are there? Does the number predicted by VL2 agree with the number of unassociated FGST sources? What can we learn about the number of these objects that formed in the early universe?
- If spikes are dim enough [far enough away], they won't be identifiable as point sources, and would contribute to the diffuse gamma-ray flux.
  - Does the expected diffuse flux from all non-PS spikes overproduce the FGST-measured diffuse flux?

Point Sources?



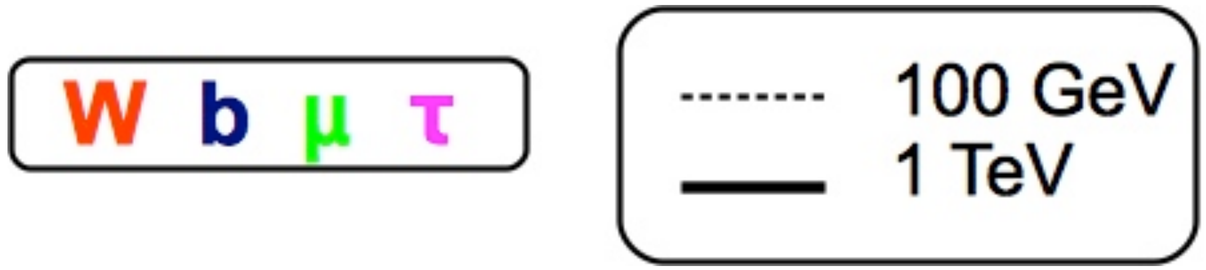


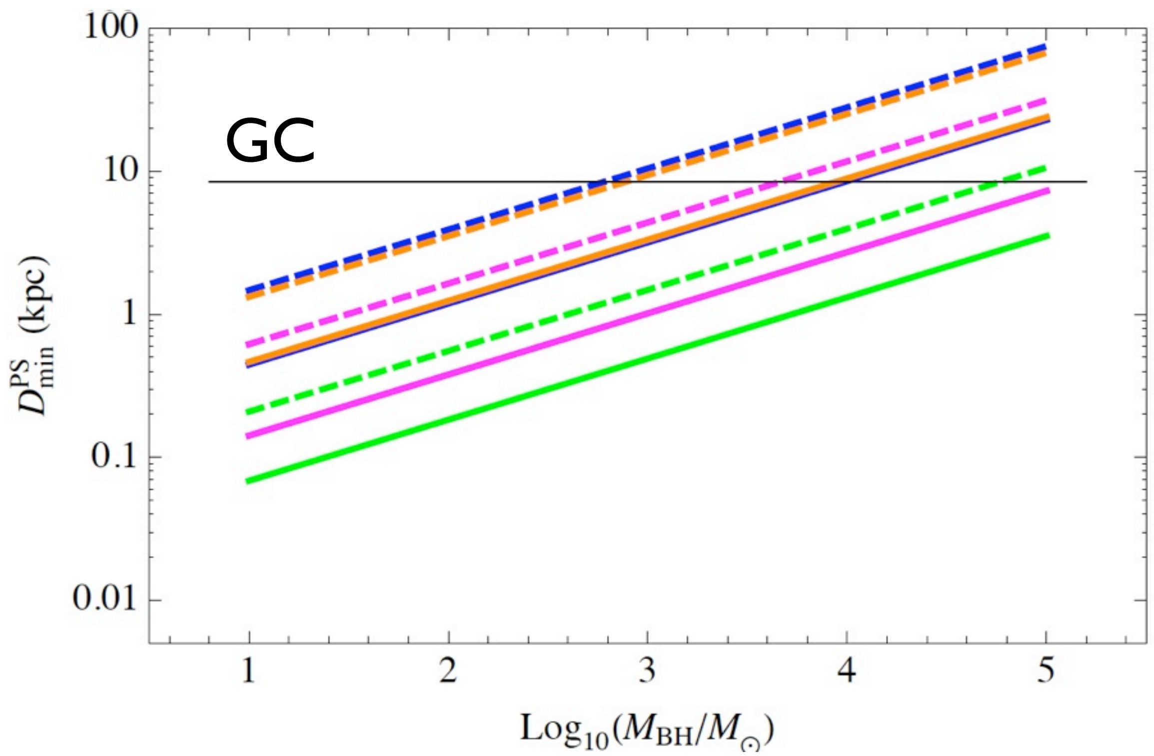
DminPS: minimum distance at which a PS can be located so that it's not brighter than the brightest FGST point source

Known Knowns and Known Unknowns

- Brightest gamma-ray point source?
  - Vela
  - Is the brightest DM spike along our LoS to Vela?
    - Probably not.
- Brightest unassociated gamma-ray point source?
  - *n*FGL J*blah.blah*
  - Could this be a DM spike?
    - Maybe (but probably not).

Point Sources?





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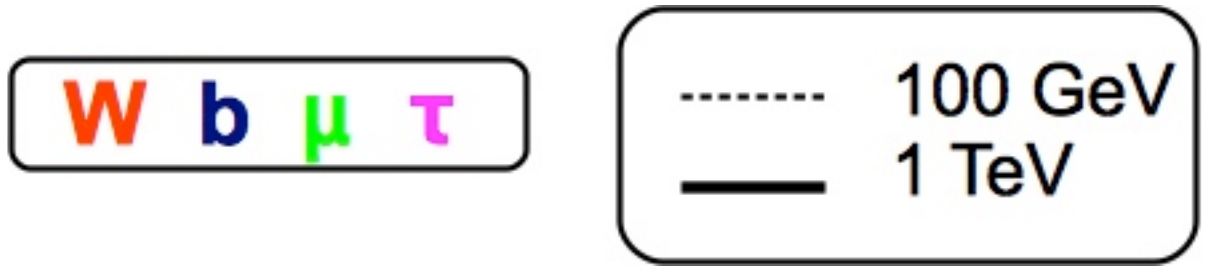
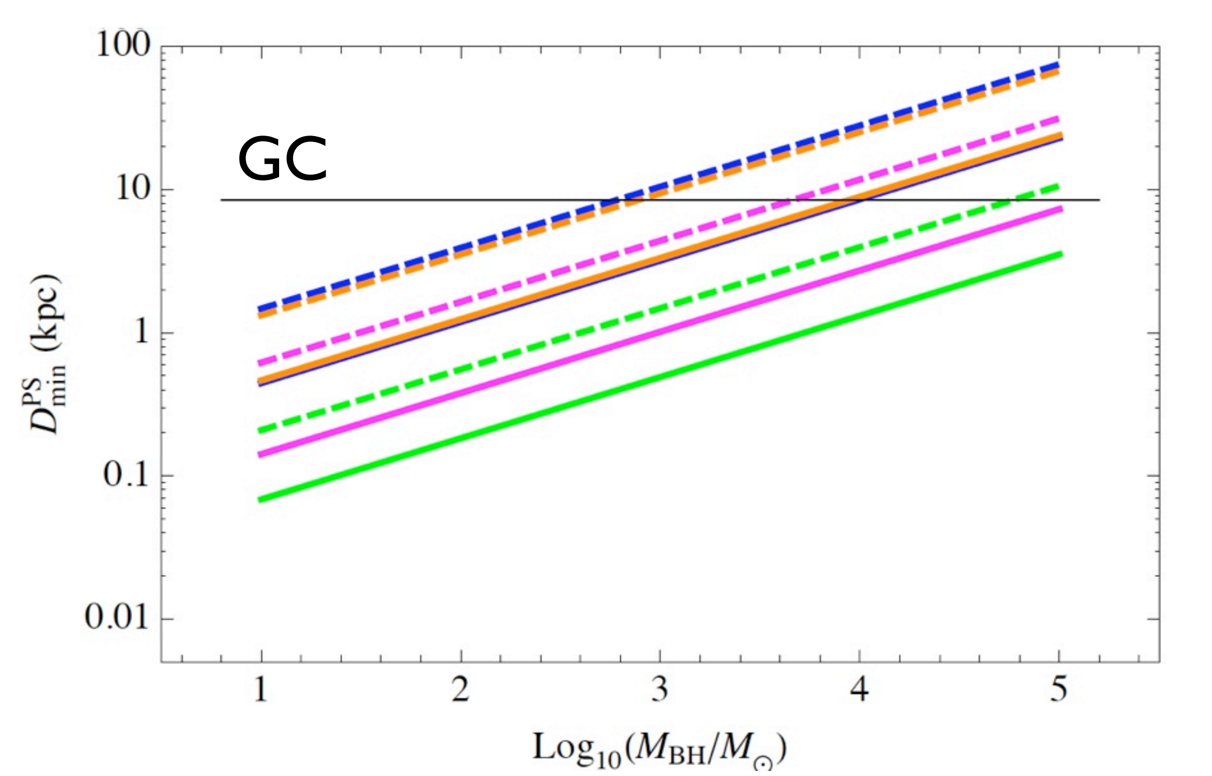
Point Sources?





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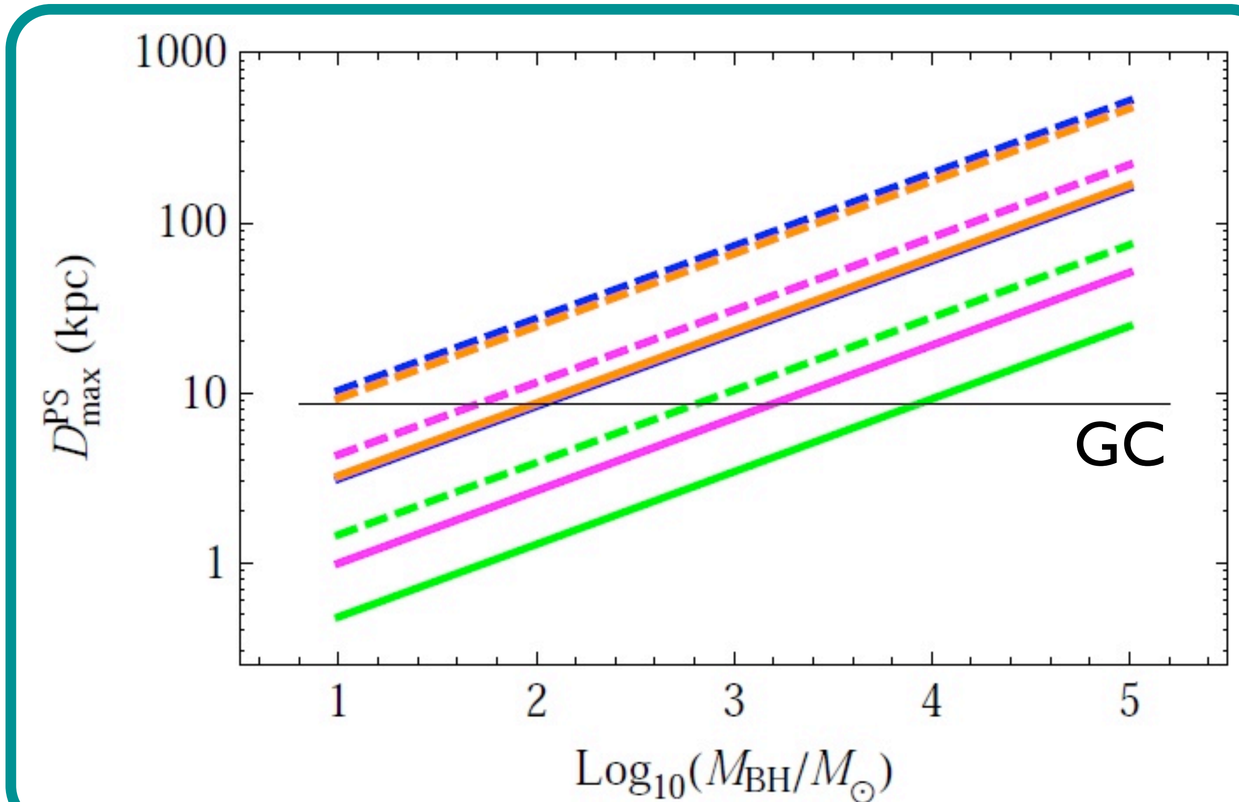


DmaxPS: maximal distance at which a PS would be bright enough to have been identified by FGST in the first year of operation

Diffuse Flux

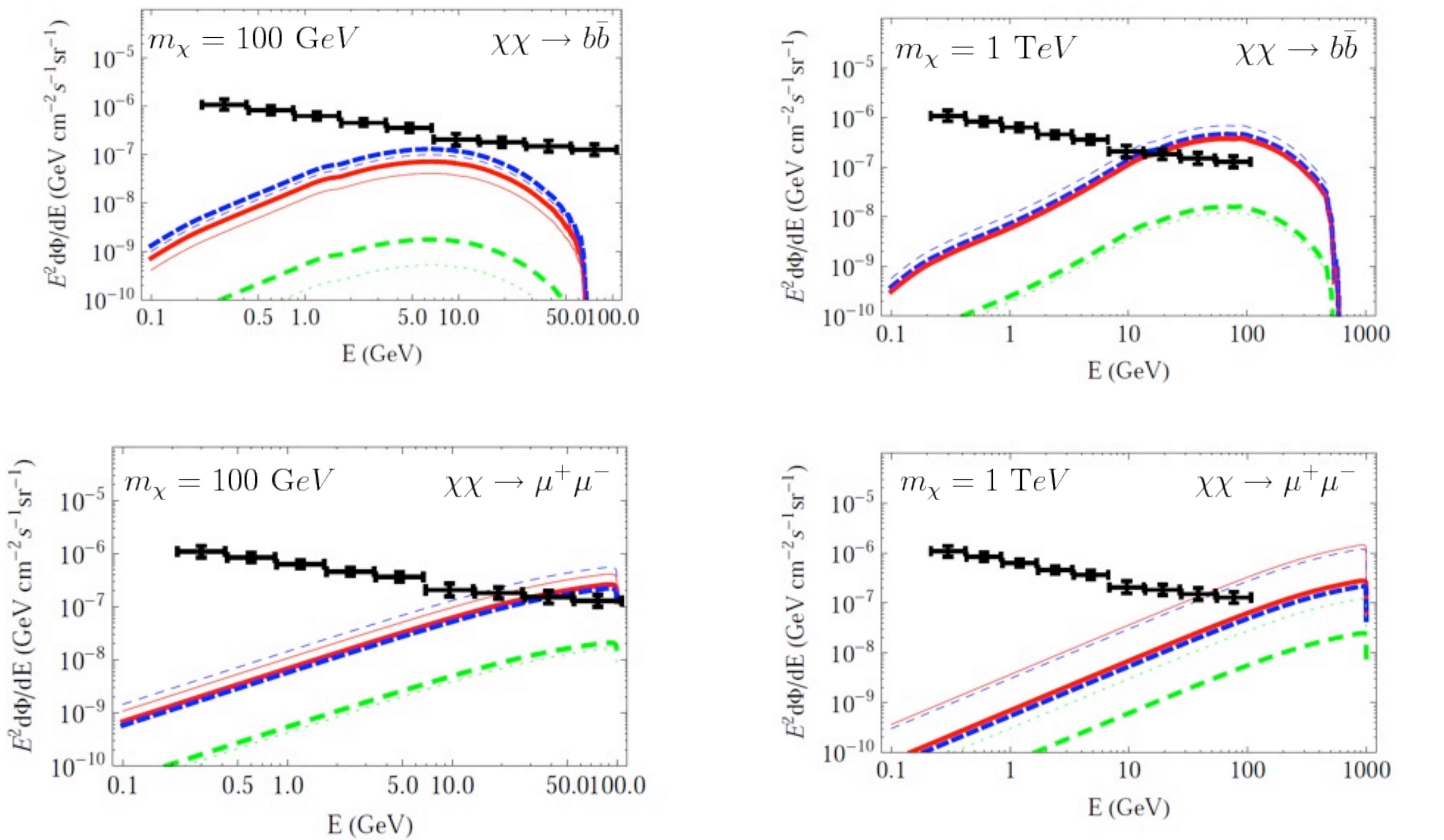
- All DM spikes that are not bright enough to have been identified as point sources in the First Source Catalog are contributing to the diffuse gamma-ray flux, also measured by FGST.
- We will use the diffuse flux to constrain f_ς, so we do NOT want to overestimate the number of spikes contributing to the diffuse flux.
- Require that diffuse spikes result in < 20 events per year above 1 GeV in FGST (~2-3σ fluctuation on the diffuse background)

The Fermi LAT Collaboration finds that ~16% of the isotropic diffuse flux can be attributed to unresolved 4-5σ point sources (with fluxes that are large enough that they would have been resolved but for selection effects). Astrophys.J. 720, 435 (2010)

Diffuse Flux

$m_{BH} = 100 M_\odot$ $m_{BH} = 1000 M_\odot$

$z_f = 15$ $z_f = 11$



Constraining *fs*

$$N_{sp}(R, f_{DS}) = f_{DS} \times N_{sp}(R, f_{DS} = 1)$$

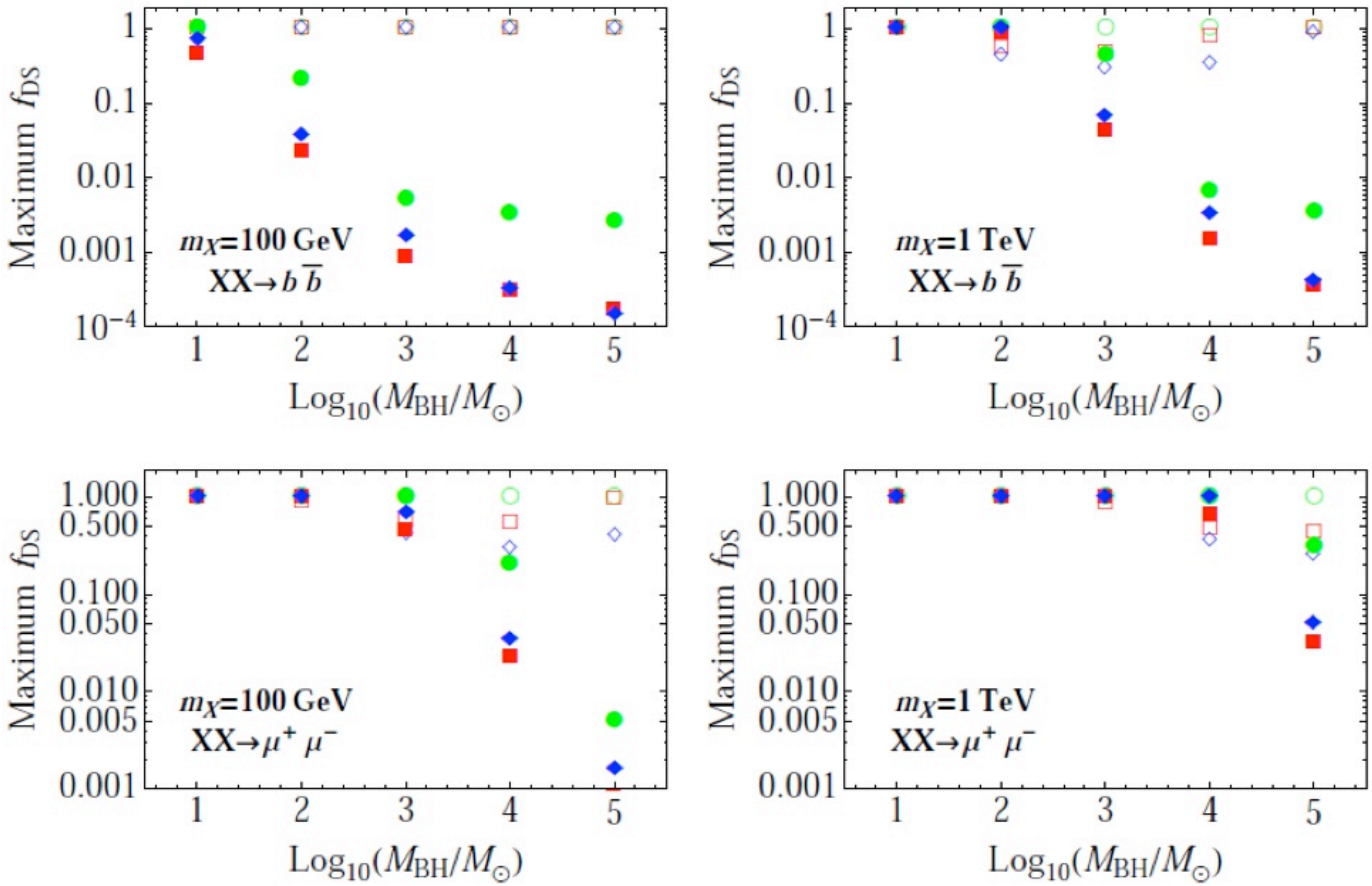
$$\Phi_i(f_{DS}) = f_{DS} \times \Phi_i(f_{DS} = 1)$$

- With diffuse flux (“Diffuse Constraint”):
  - Require that diffuse flux does not exceed EGB by more than 3σ
- With point source luminosity (“Point Source Constraint”):
  - Require an expectation of <1 spike within *DminPS*

Constraining *fs*

Diffuse → Open   Point Source → Filled

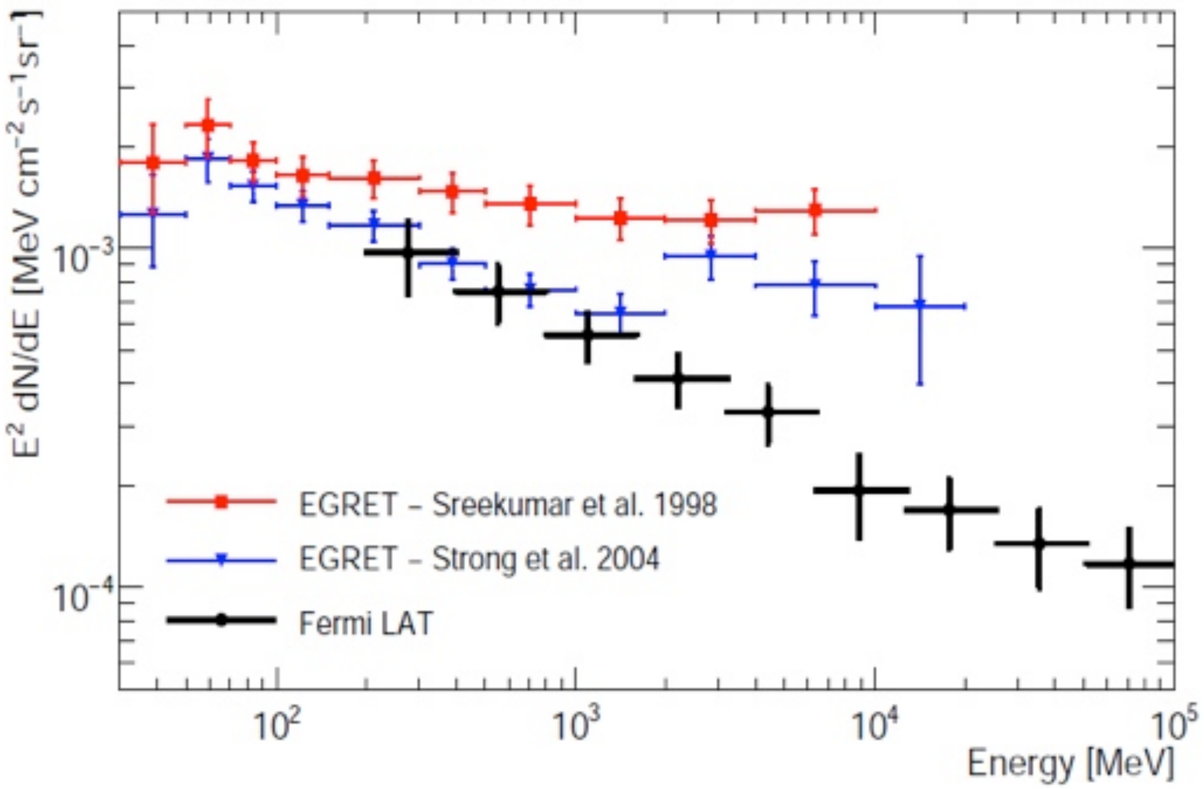
$z_f = 15$ $z_f = 11$



Light WIMPs

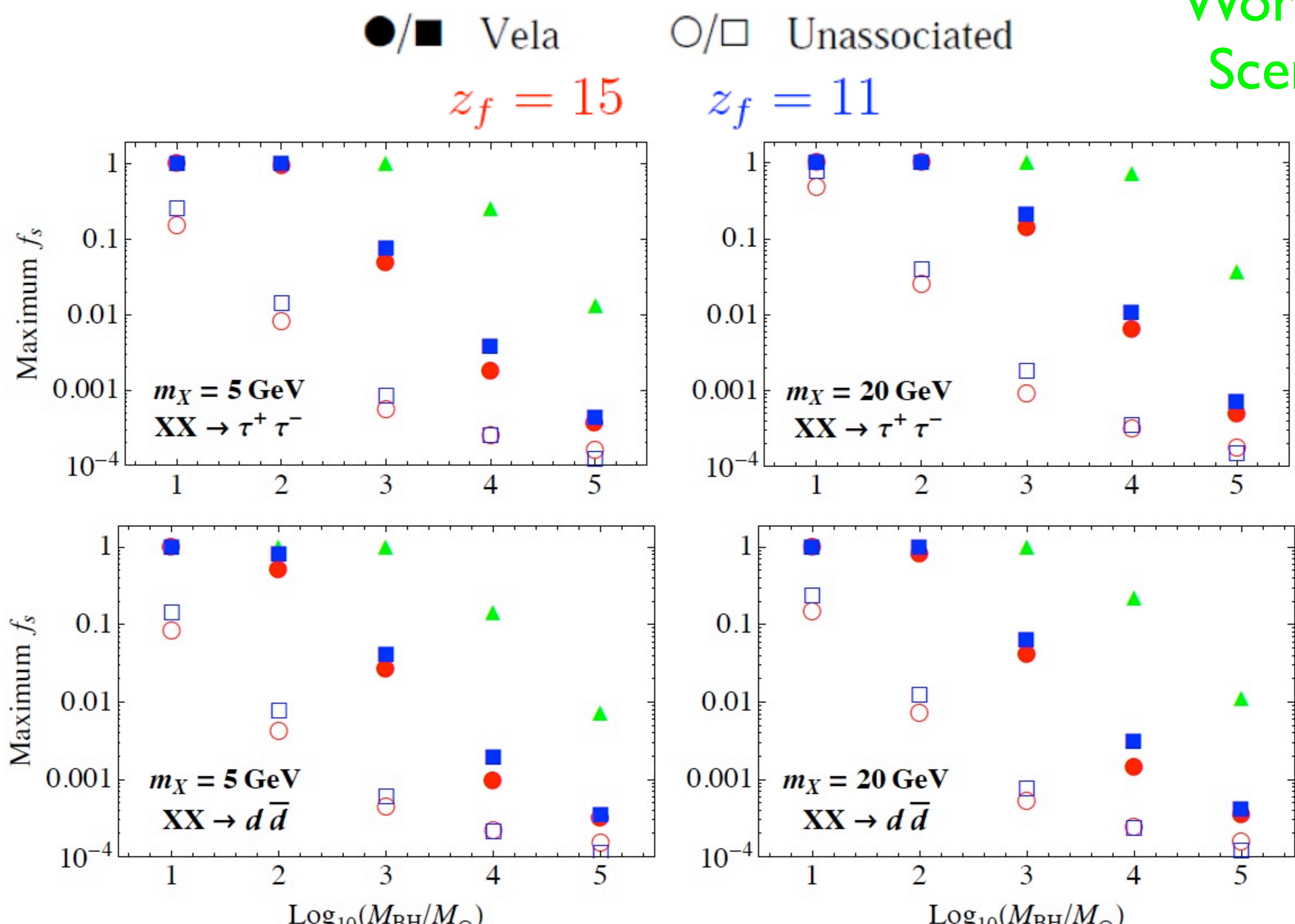
- Lose the highest energy photons.
  - No diffuse constraint
- $\Gamma_{ann} \propto n^2$.
  - larger annihilation rate
  - PS constraint improves

Abdo *et al.* (2010)



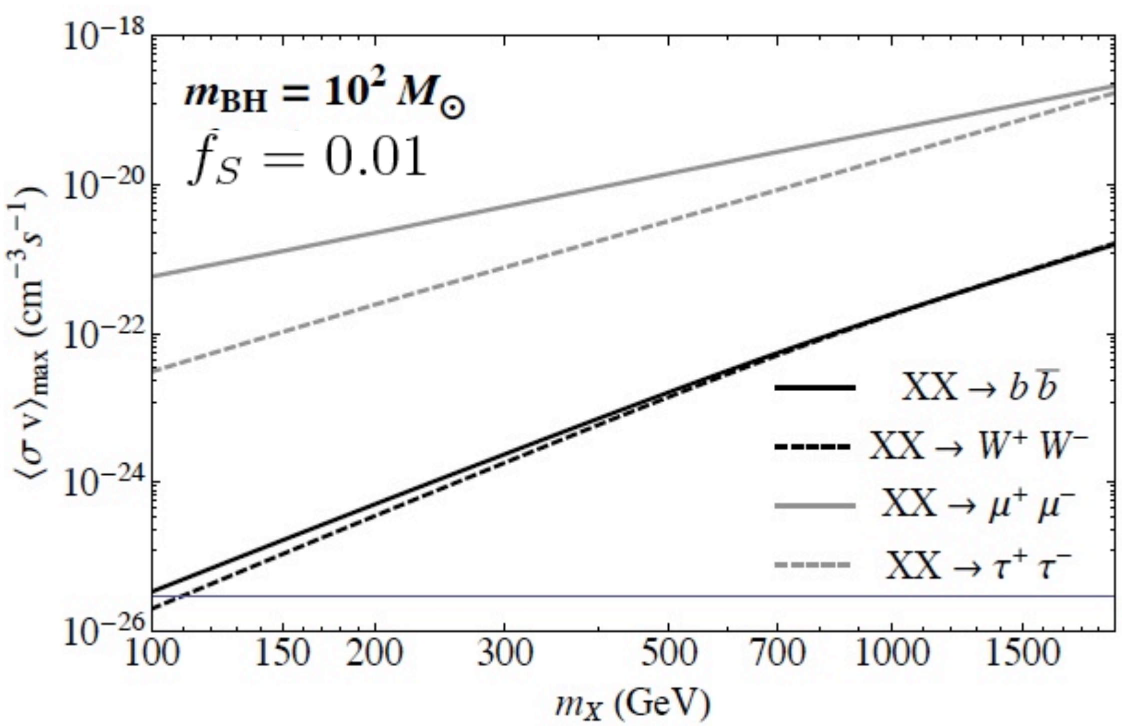
Light WIMPs

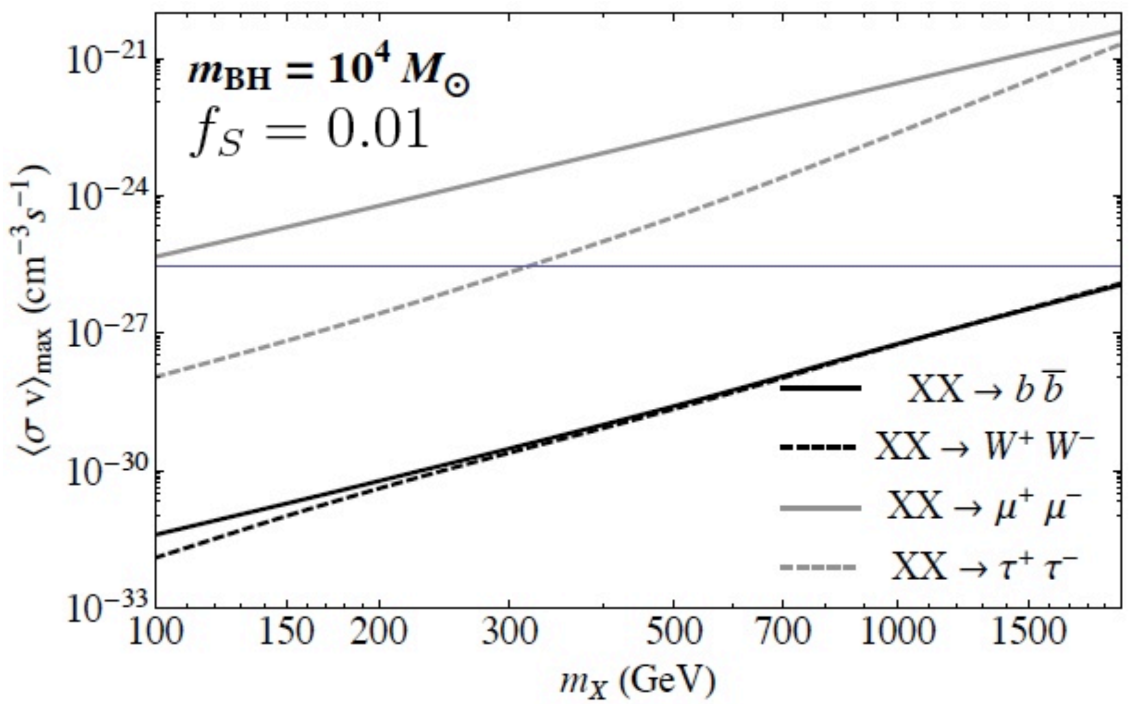
Worst Case Scenario!!



Non-Thermal DM

- What can we learn about dark matter if we know something about the formation history? Sandick & Watson (2011)
  - Fix f_S and m_{BH}.
  - Find maximum possible annihilation cross section.





Wrapping Up

- We have placed conservative limits on the fraction of minihalos in the early universe that could have hosted formation of Population III.1 stars (robust w.r.t. uncertainties about inner halo dynamics).
  - For standard WIMPs:
    - The smallest black holes considered (10 solar mass) are largely unconstrained for 100+ GeV dark matter.
    - For annihilation to quarks or gauge bosons, even 100 solar mass black holes are somewhat constrained.
    - The most massive black holes considered here are strongly constrained for most dark matter annihilation models.

Wrapping Up

- We have placed conservative limits on the fraction of minihalos in the early universe that could have hosted formation of Population III.1 stars (robust w.r.t. uncertainties about inner halo dynamics).
    - If dark matter is light:
        - typical black hole size is < 100 solar masses (i.e. no Dark Star phase)
        - and/or dark matter annihilates primarily to $\mu^+\mu^-$ or other final states that result in low gamma-ray luminosity
        - and/or the annihilation cross section today is far below thermal
        - and/or that an extremely small fraction of minihalos in the early universe that seem to be suitable to host the formation of the first stars actually were

Take Home Message

- We have placed conservative limits on the fraction of minihalos in the early universe that could have hosted formation of Population III.1 stars (robust w.r.t. uncertainties about inner halo dynamics).

- Serious tension between naïve models and data
- Gamma ray data actually has a lot to say about early star formation and dark matter.