Dark Matter Spikes in our Galactic Halo

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in collaboration with
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Dark Matter Spikes in ou… alo

Preliminary!

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…exas at Austin

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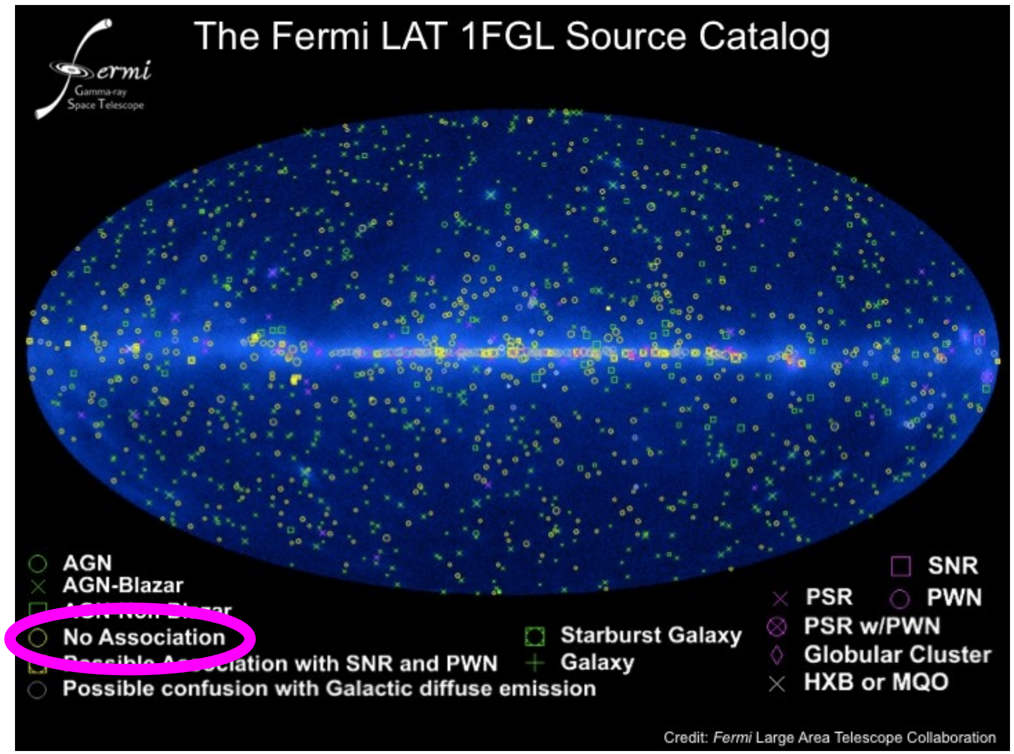
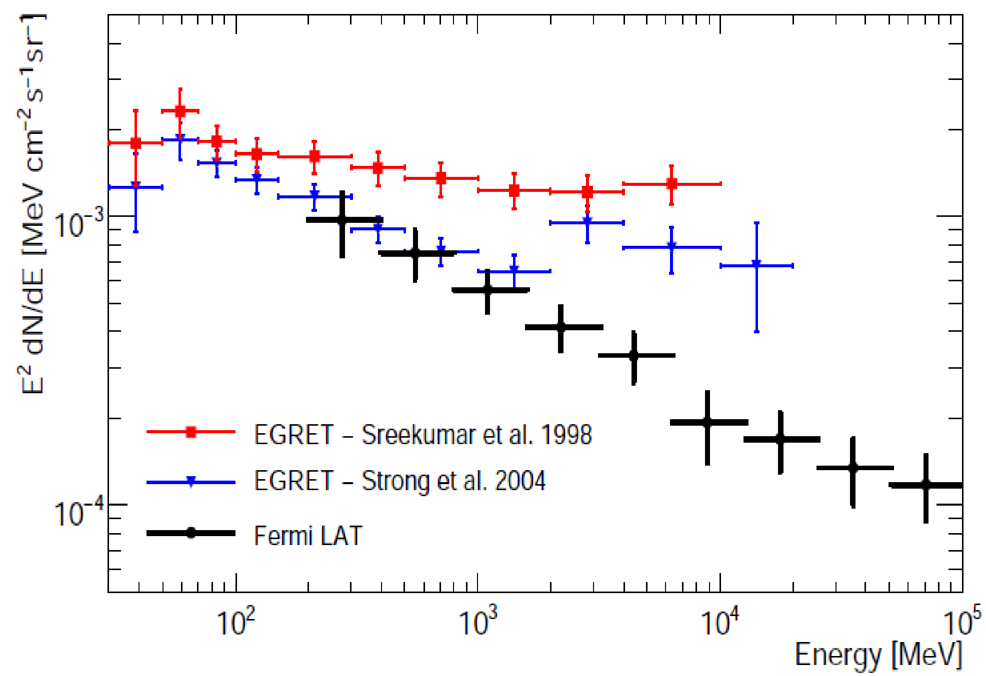
Fermi Gamma-Ray Space Telescope



Diffuse Gamma-Ray Flux



Can we use FGST data to constrain early star formation and/or models of dark matter annihilation?

The Recipe

1. Begin with dark matter minihalos in the early universe, with a dash of pristine gas.
   - The gas will collapse to form the first stars.
   - The first stars will be quite massive, and will likely collapse to black holes.
2. When an object forms near the center of minihalo, dark matter will be dragged into and around the central body, creating a dark matter "spike."
3. Evolve dark matter structures and black holes to low redshift, determining the local distribution.
4. Calculate the expected gamma-ray flux from dark matter annihilations in spikes:
   - ➔ point sources (if they are bright enough)
   - ➔ contribution the diffuse gamma-ray flux (if they are faint)

[See work by J. Silk. P. Gondolo, G. Bertone, A. Zentner, H. Zhao, M. Fornasa, M. Taoso etc.]

Nomenclature

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

Formation of the First Stars

- Population III.1:
  - $z \gtrsim 20$
  - Molecular Hydrogen cooling
- Minimum halo mass for star formation

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

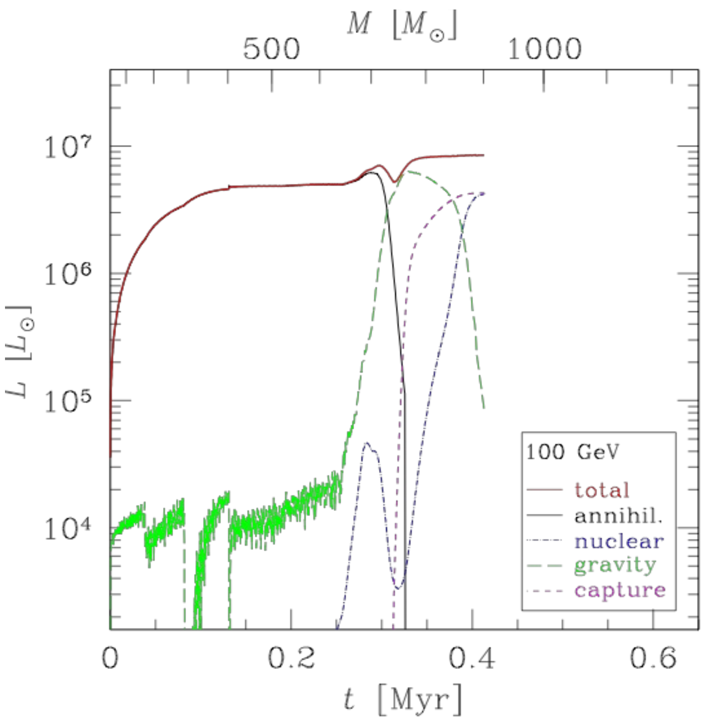
Trenti & Stiavelli (2009)

- Predicted to be quite massive
  - Theory: insufficient cooling allowed them to grow large Larson (1999)
  - Simulations: also show typical masses $\gtrsim 100\ M_{sun}$ Bromm, Coppi & Larson (1999, 2002); Abel, Bryan & Norman (2000, 2002); Nakamura & Umemura (2001); O'Shea & Norman (2007); Yoshida *et al.* (2006, 2008); etc.
- Assume they die by collapsing to black holes Heger & Woosley (2002)

Dark Stars?

- In case you "fell asleep or left" Malcolm Fairbairn's talk on Monday:
- As star began to form, DM was dragged into a growing potential well
  - DM annihilation rate enhanced ~ρ^2
  - Could DMA products "power" the star?
    1. Sufficiently high DM density for large annihilation rate
    2. Annihilation products get stuck in star
    3. Dark matter heating beats H2 cooling

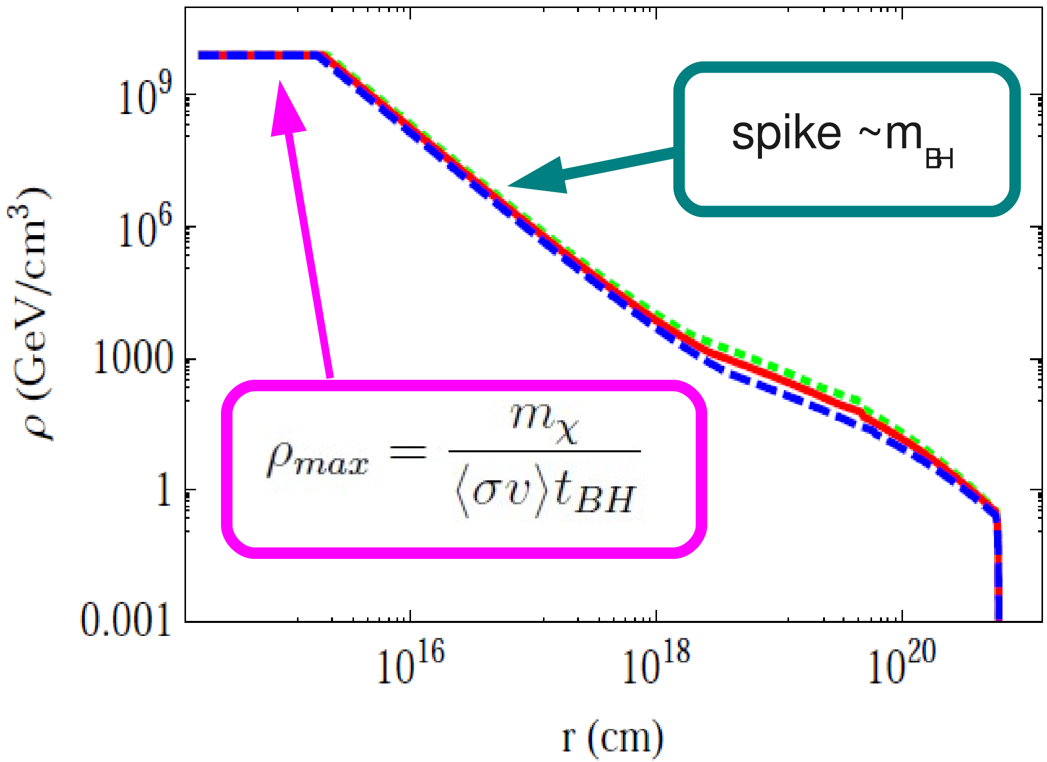
    ➔ **Answer: YES!!**
    See Spolyar *et al.* (2008+)



- Dark stars have low surface temperatures, so they might have been very large: end up as Zero Age Main Sequence stars of 500-1000 $M_\odot$ or more.

DM spikes

- With or without DS phase, we expect an enhanced DM density around the object.



- Baryons fall in, potential well deepens, DM falls in, too...
  - Start with NFW profile
  - Adiabatic contraction

DM spikes

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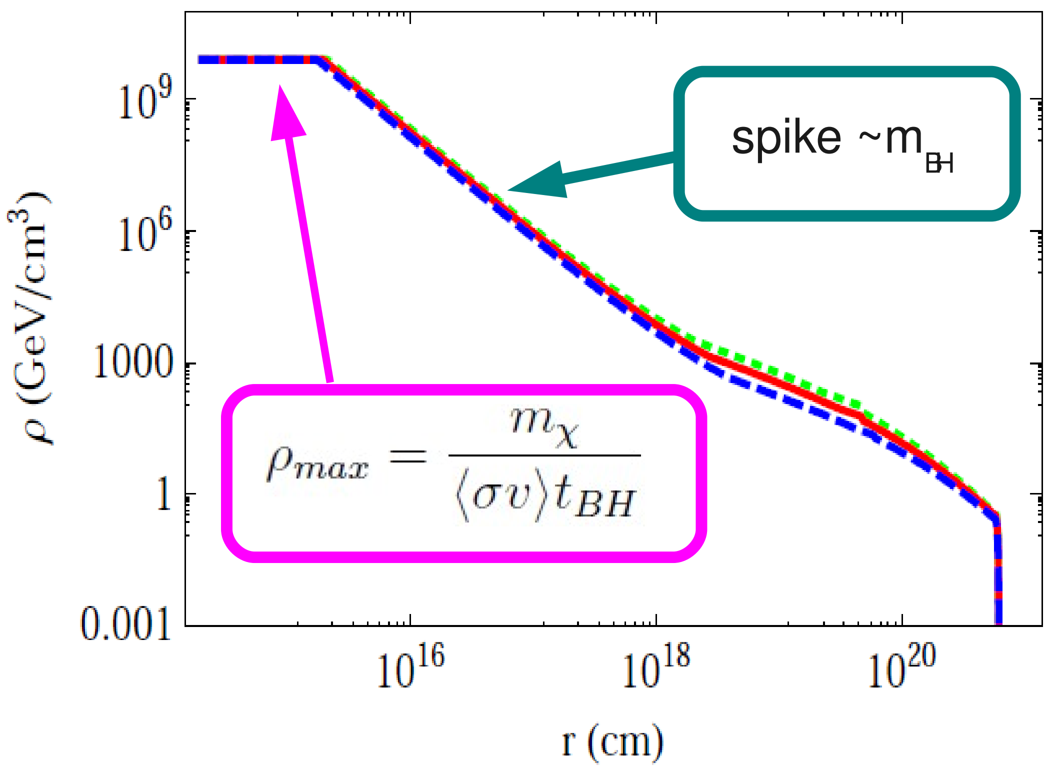

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  - Adiabatic contraction

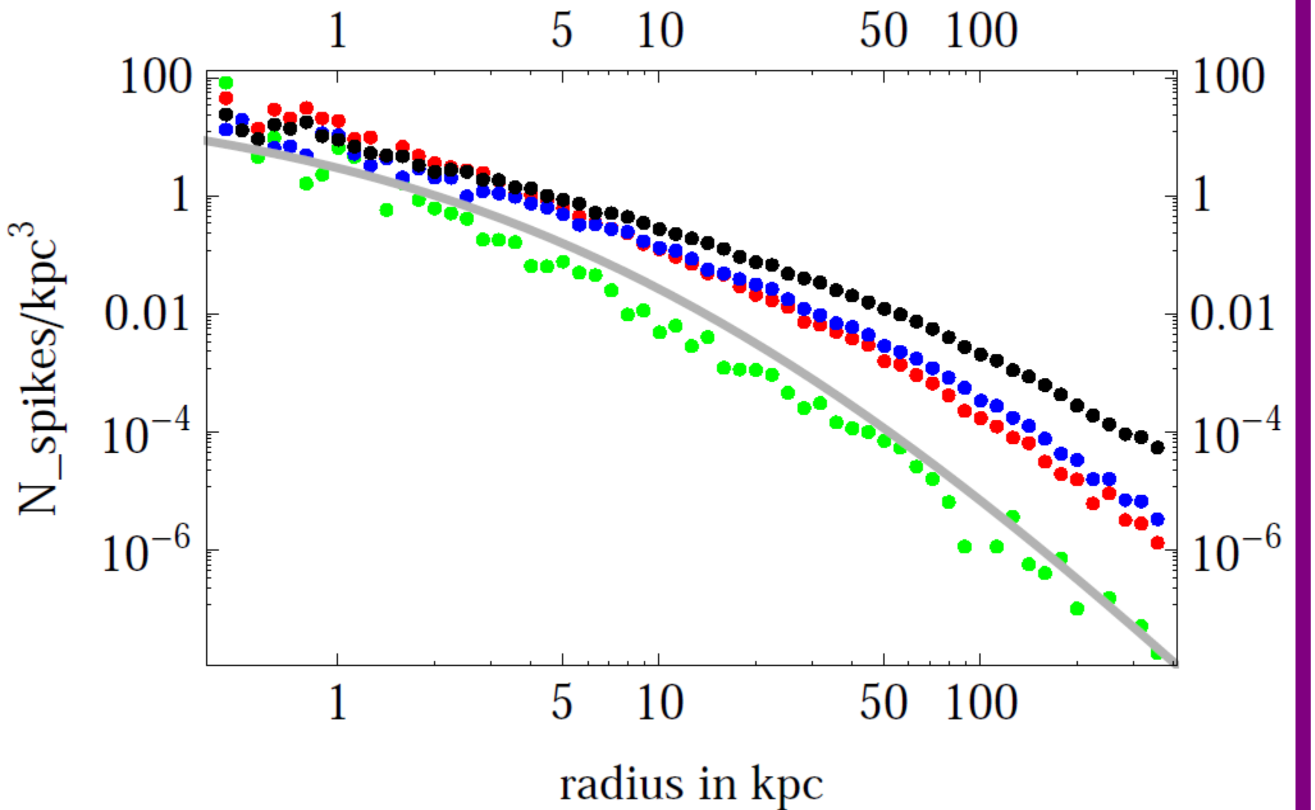
Parametrize end of Population III.1 star formation à la Greif & Bromm (2006):

Early	$z_f = 23$
Intermediate	$z_f = 15$
Late	$z_f = 11$

Remnant Distribution

- Given ranges for redshift and minihalo mass, use VL-II simulation to find the distribution today of DM spikes (assuming each hosted a star)

Early	**409**
Intermediate	**7983**
Late	**12416**
Bertone, Zentner & Silk (2005)	1027 ± 84



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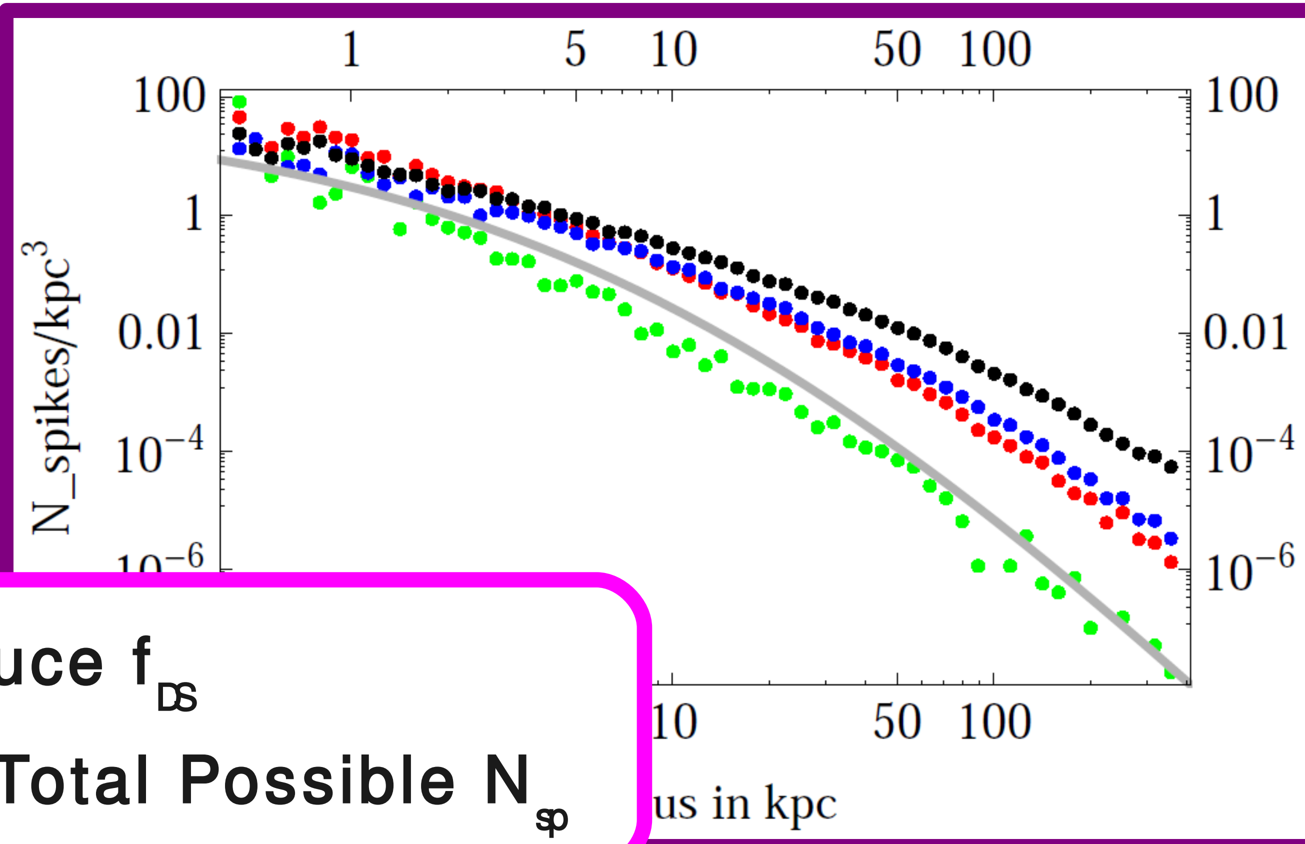


Introduce f_{DS}

Actual $N_{sp} = f_{DS} \cdot$ Total Possible N_{sp}

Signal from DM Annihilations

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

- Choose models for DM mass and annihilation channels:

Model	Mass (GeV)	Final State	Model	Mass (GeV)	Final State
b100	100	$b\bar{b}$	τ100	100	$\tau^+\tau^-$
b1T	1000	$b\bar{b}$	τ1T	1000	$\tau^+\tau^-$
W100	100	W^+W^-	μ100	100	$\mu^+\mu^-$
W1T	1000	W^+W^-	μ1T	1000	$\mu^+\mu^-$

- In fact, $\langle \sigma v \rangle = \sum_f \langle \sigma v \rangle_f = \langle \sigma v \rangle \sum_f B_f$ and $\Gamma_f = B_f \Gamma$

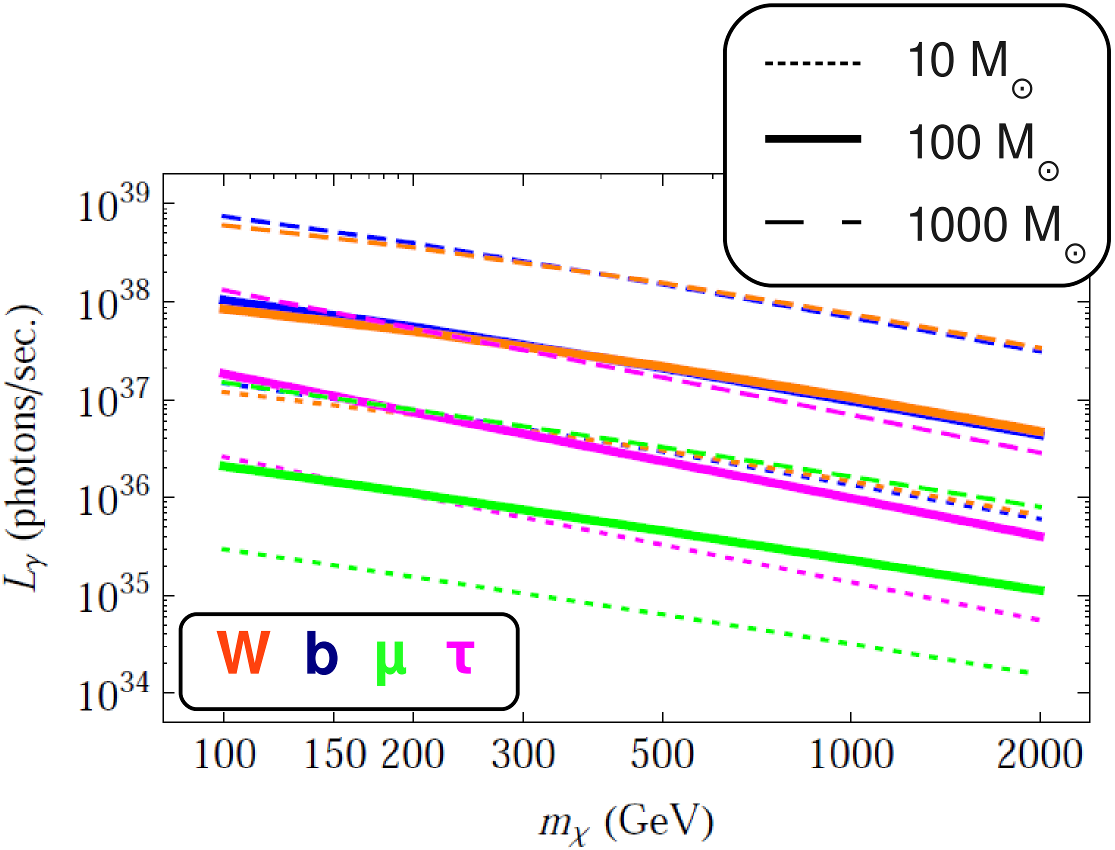
From a Single Spike

- Luminosity

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

- Flux from a single spike

$$\frac{d\Phi_f}{dE} = \frac{\Gamma_f}{4\pi D^2} \frac{dN_f}{dE}$$



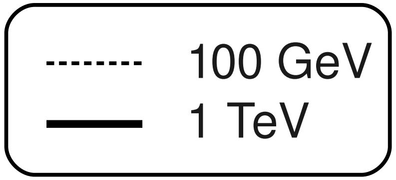
$$\frac{d\Phi_f}{dE} = \frac{B_f \langle \sigma v \rangle}{2m_\chi^2} \frac{dN_f}{dE} \int_0^{\theta_{max}} d\theta \, 2\pi \sin\theta \int_0^{s_{max}} ds \, \rho_{DM}^2(r)$$

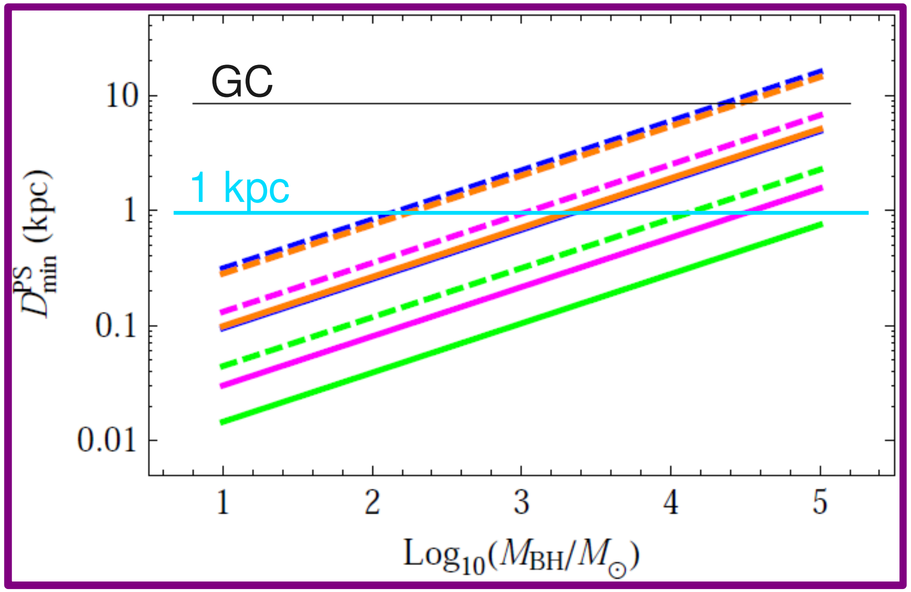
$$\begin{cases} r = \sqrt{D^2 + s^2 - 2sD\cos\theta} \\ \Delta\Omega = 2\pi(1 - \cos\theta_{max}) \end{cases}$$

Diffuse vs. Point Source Flux

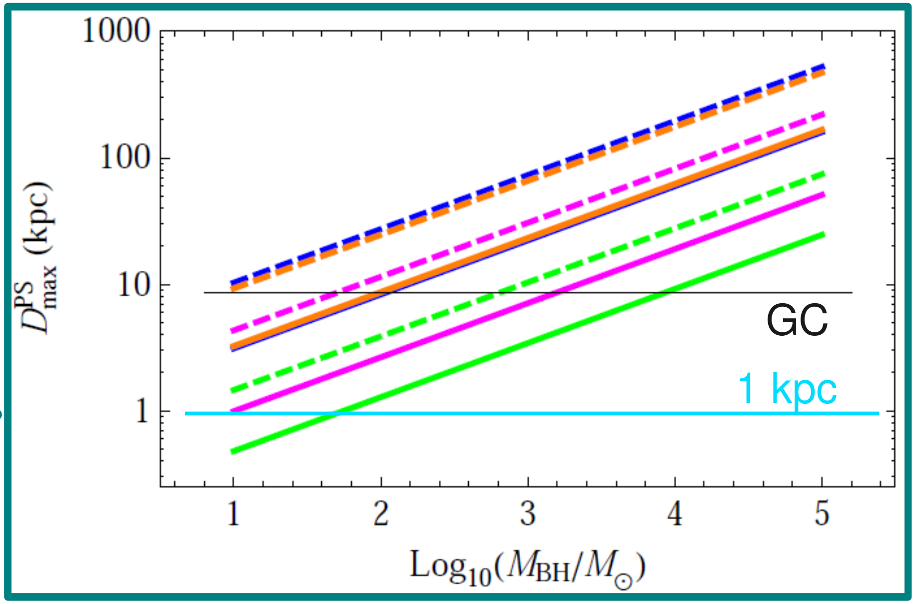
- **Two ways they could show up:** (FSC and EGB both Abdo *et al.* 2010)
- DM spikes may already show up as point sources in the FGST catalog!
  - Brightest one can't be brighter than the brightest observed source (unidentified?) → minimal distance, *DminPS*
  - If a source is far enough away [dim enough], 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, the won't be identifiable as point sources, and would contribute to the diffuse EGB.
  - ➔ Does the expected diffuse flux from all non-PS spikes overproduce the FGST-measured EGB?

Point Sources





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



DmaxPS: maximal distance at which a PS will likely be bright enough to be identified by FGST

Number of Point Sources

- FGST: 1451 sources, 630 not associated with other objects
  - **368 unassociated with |b|>10°**

	b100			b1T		
$m_{BH}/M_\odot$	Early	Int.	Late	Early	Int.	Late
10	195 (70)	1117 (649)	557 (387)	~ 2 (~ 2)	21 (17)	14 (11)
10^2	304 (151)	3247 (2263)	2935 (2186)	147 (45)	586 (372)	281 (215)
10^3	380 (213)	5715 (4283)	6754 (5305)	284 (135)	2788 (1895)	2340 (1708)
10^4	381 (217)	7237 (5548)	10608 (8486)	372 (207)	5213 (3870)	5866 (4575)
10^5	158 (128)	5918 (4831)	10946 (8946)	392 (224)	7069 (5402)	9998 (7980)

	μ100			μ1T		
$m_{BH}/M_\odot$	Early	Int.	Late	Early	Int.	Late
10	< 1 (< 1)	~ 2 (~ 2)	~ 1 (~ 1)	$\ll 1$ ($\ll 1$)	$\ll 1$ ($\ll 1$)	$\ll 1$ ($\ll 1$)
10^2	~ 5 (~ 4)	42 (34)	26 (22)	< 1 (< 1)	~ 1 (~ 1)	~ 1 ($\lesssim 1$)
10^3	195 (69)	1132 (658)	578 (400)	~ 3 (~ 2)	28 (23)	18 (15)
10^4	305 (152)	3278 (2288)	2987 (2229)	172 (56)	846 (493)	390 (287)
10^5	380 (214)	5752 (4314)	6836 (5374)	294 (143)	3013 (2074)	2629 (1939)

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10^5	158 (128)	5918 ([illegible]	[illegible]	[illegible]	[illegible]	[illegible] (7980)

Brightest unidentified source is only 1/22 as bright as Vela.
→ Could be an enhancement in *DminPS* by a factor of 4.7,
and therefore fewer sources between *DminPS* and *DmaxPS*.

	[illegible]			**μ1T**		
$m_{[illegible]}$	[illegible]	[illegible]	[illegible]	Early	Int.	Late
[illegible]	[illegible]	[illegible]	[illegible] (~ 1)	$\ll 1$ ($\ll 1$)	$\ll 1$ ($\ll 1$)	$\ll 1$ ($\ll 1$)
1[illegible]	[illegible]	[illegible]	26 (22)	< 1 (< 1)	~ 1 (~ 1)	~ 1 ($\lesssim 1$)
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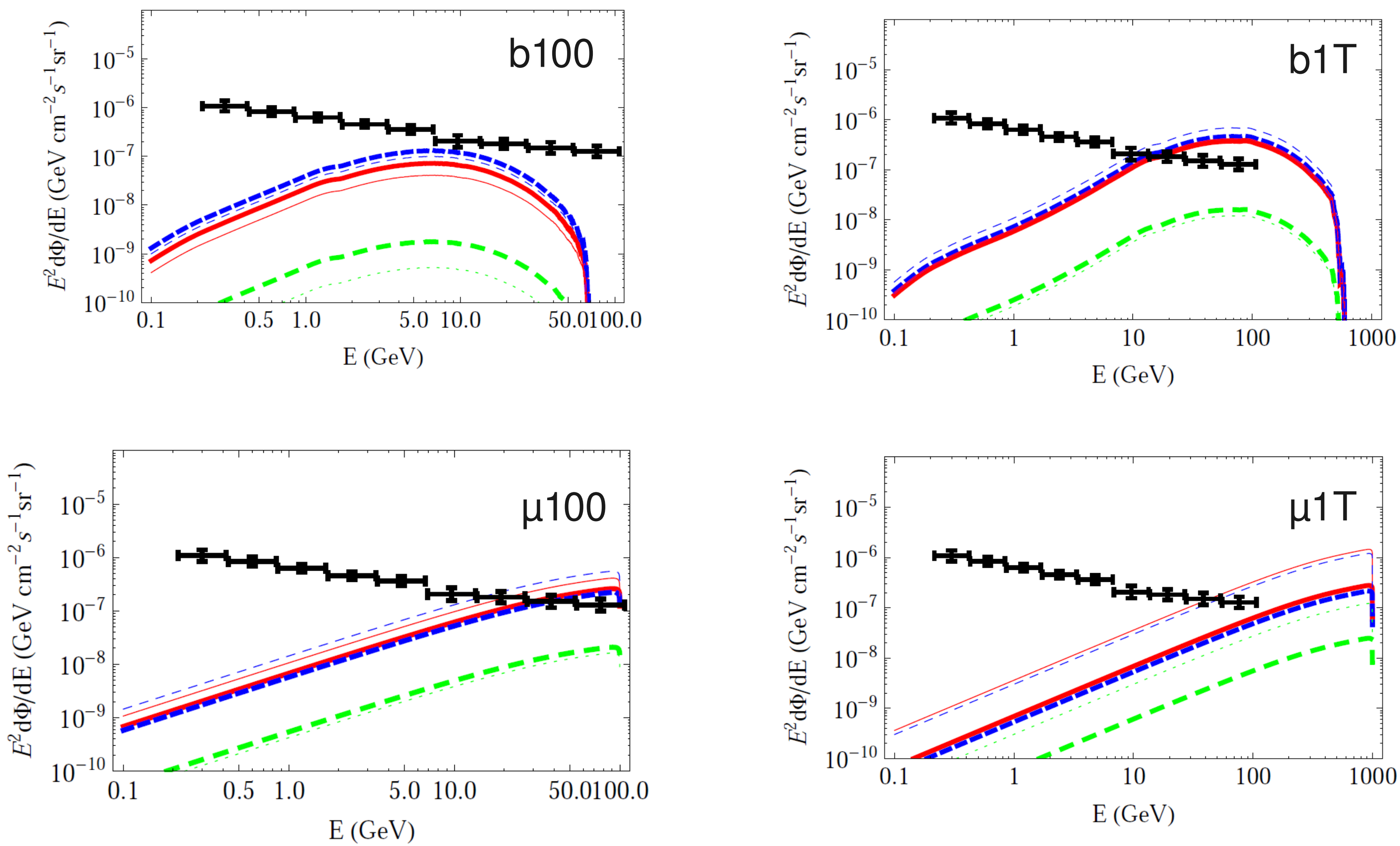
Diffuse Flux

$f_{DS} = 1$

100 $M_\odot$ (thick line)

1000 $M_\odot$ (thin line)



Constraining f_{DS}

- With diffuse flux ("Diffuse Constraint"):

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

Require that diffuse flux does not exceed the EGB by more than 3σ.

- With point source population ("Point Source Constraint"):

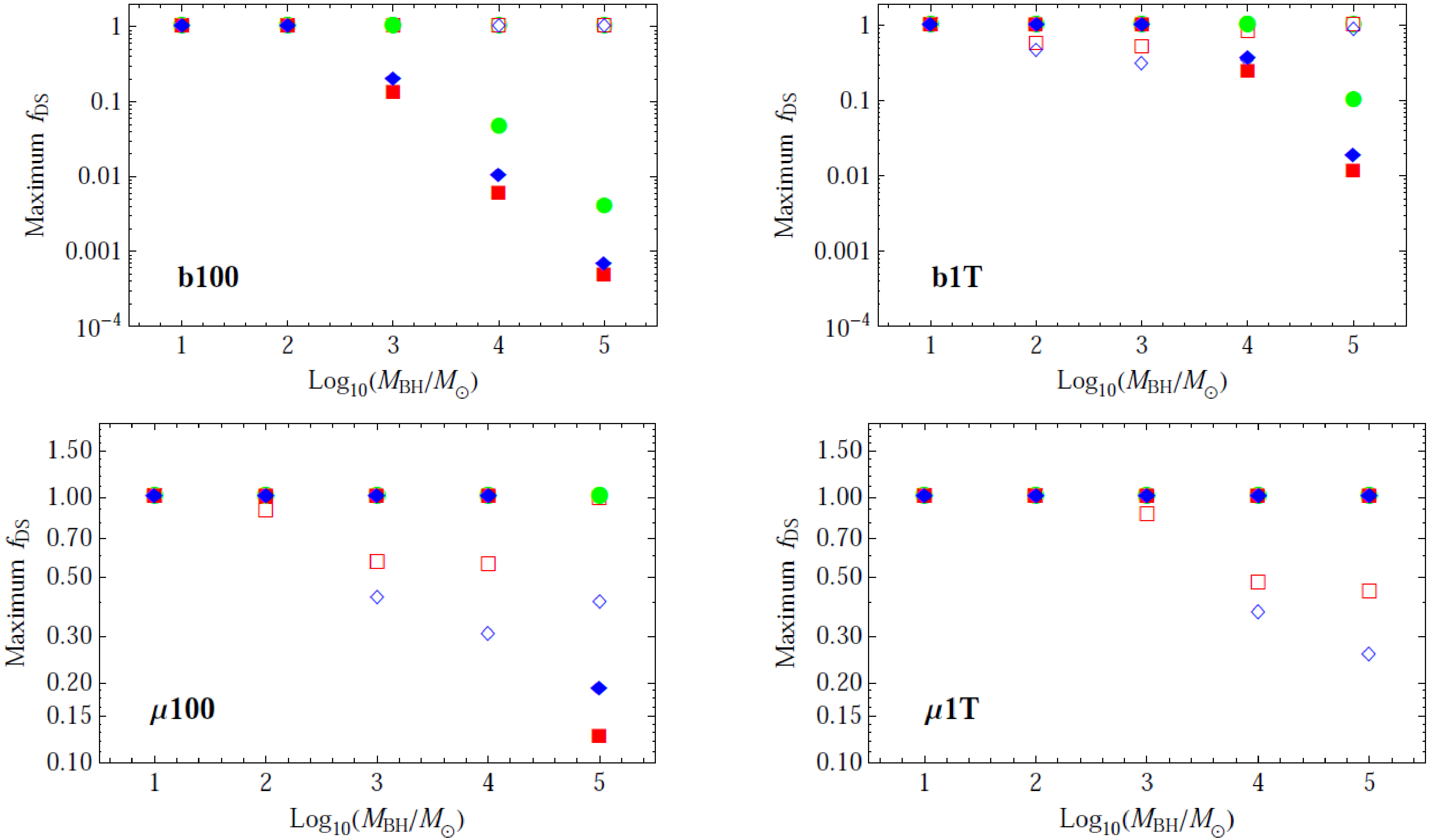
$$N_{sp}(R, f_{DS}) = f_{DS} \times N_{sp}(R, f_{DS} = 1)$$

$$\int_0^{D_{min}^{PS}} ds \int_{allsky} d\Omega \, N_{sp}(R, f_{DS}) \leq 1$$

Require an expectation of < 1 spike within *DminPS* of our solar system.

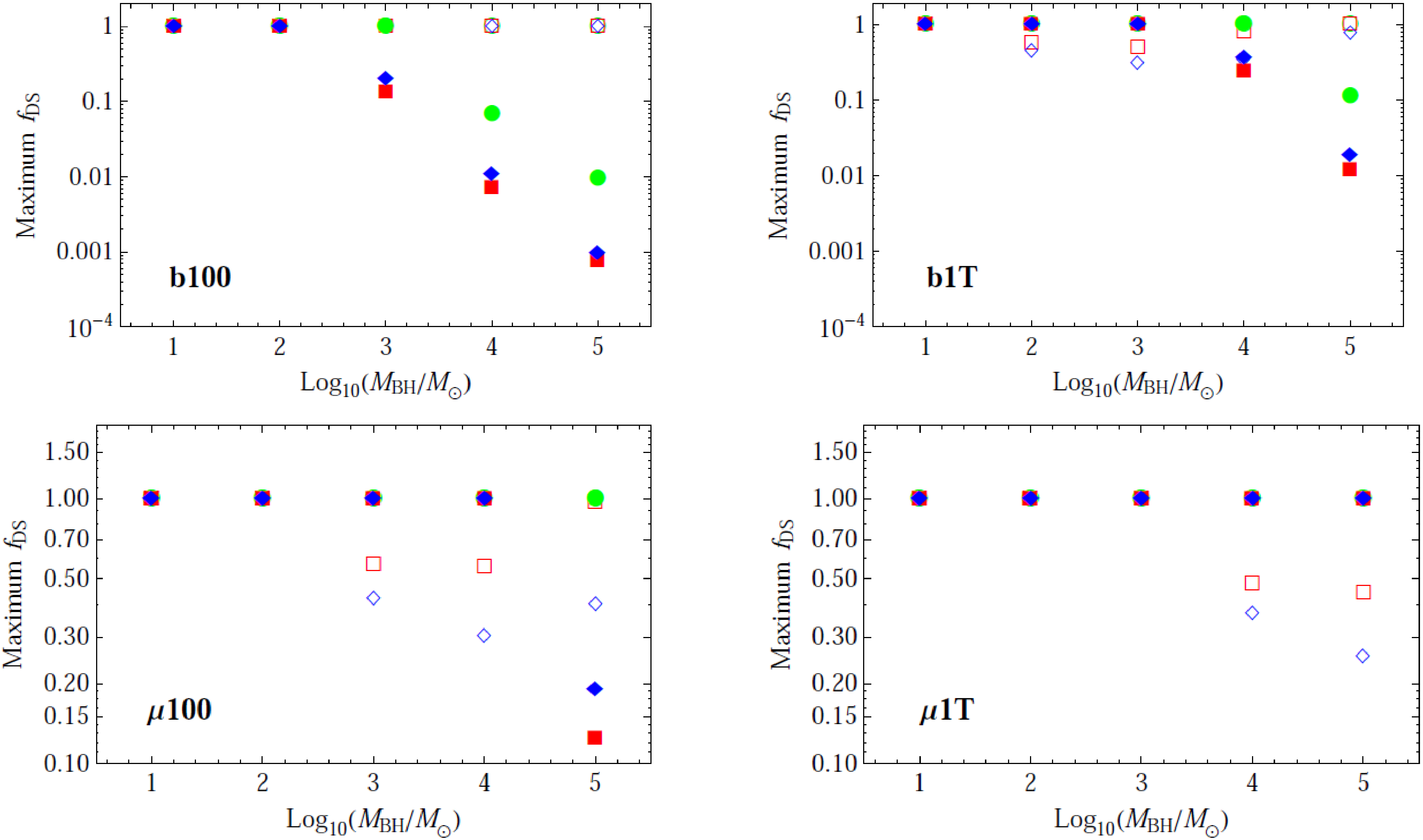
Constraining f_{DS}

diffuse → open   point source → filled



Excluding inner 5 kpc!!

diffuse → open   point source → filled



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Conclusions

- **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).**
  - Low Luminosity Spikes:
    - most contribute to diffuse flux, but not enough for a Diffuse Constraint
    - close ones not bright enough for a Point Source Constraint
  - Increasing Luminosity:
    - Diffuse Constraint kicks in
    - distance at which spikes can be identified as point sources increases, so some spikes in the distribution are bright (close) enough
  - High Luminosity:
    - most spikes in our Galactic halo are bright point sources (Point Source Constraint)
    - few are so far away that they contribute to the diffuse flux (no Diffuse Constraint)
  - If Population III.1 star formation is short, limits are weak.
- **Fermi may have already seen some of these things!**
  - Probably not more than 20-60 according to Buckley & Hooper (2010)

Next?

Convert the constraint on the fraction of star-forming minihalos to a limit on the Population III.1 Star Formation Rate.

Check agreement with electron and positron data from PAMELA and Fermi.

Could upcoming neutrino experiments be sensitive to these scenarios (diffuse flux and/or point sources)?

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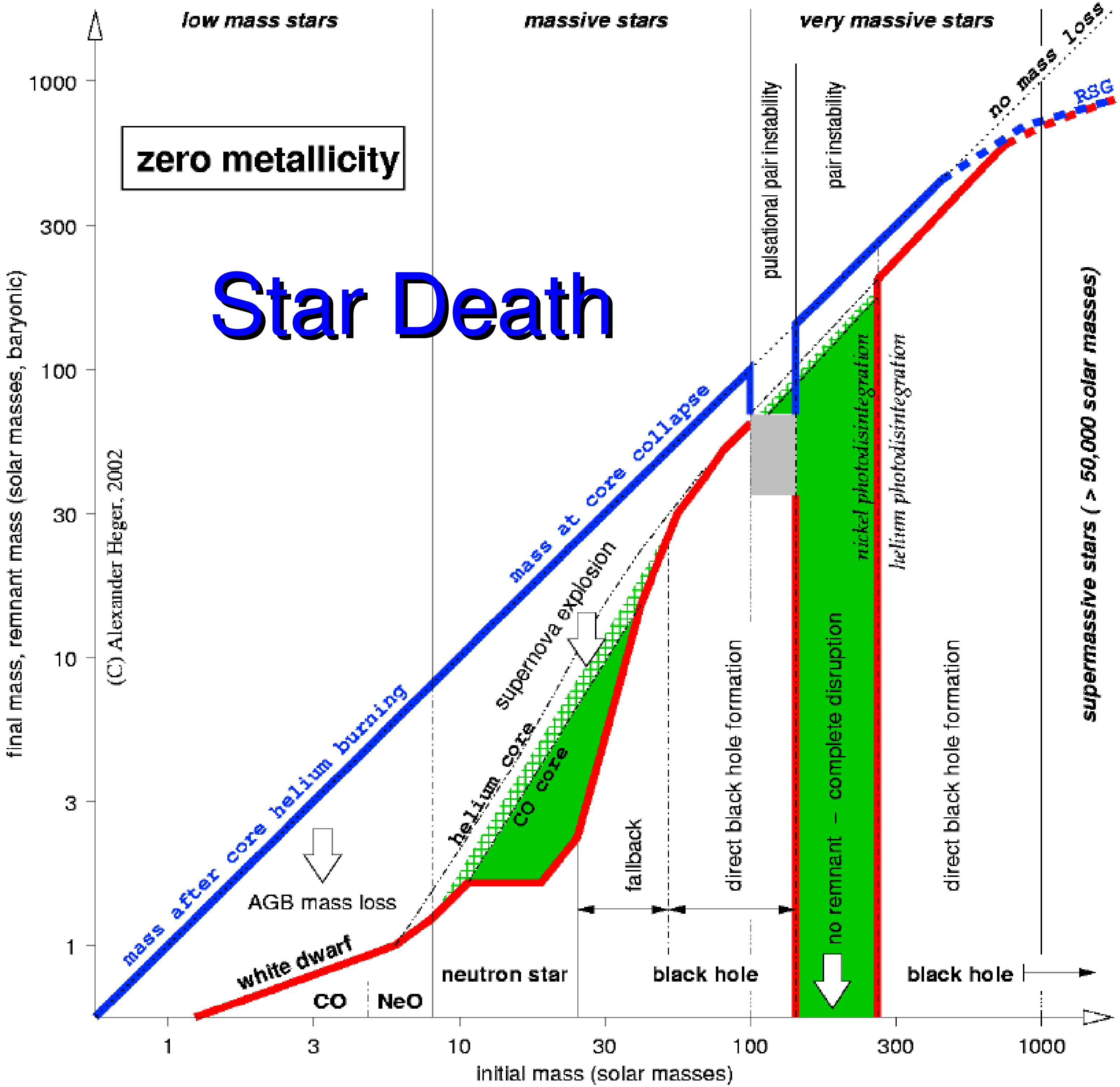
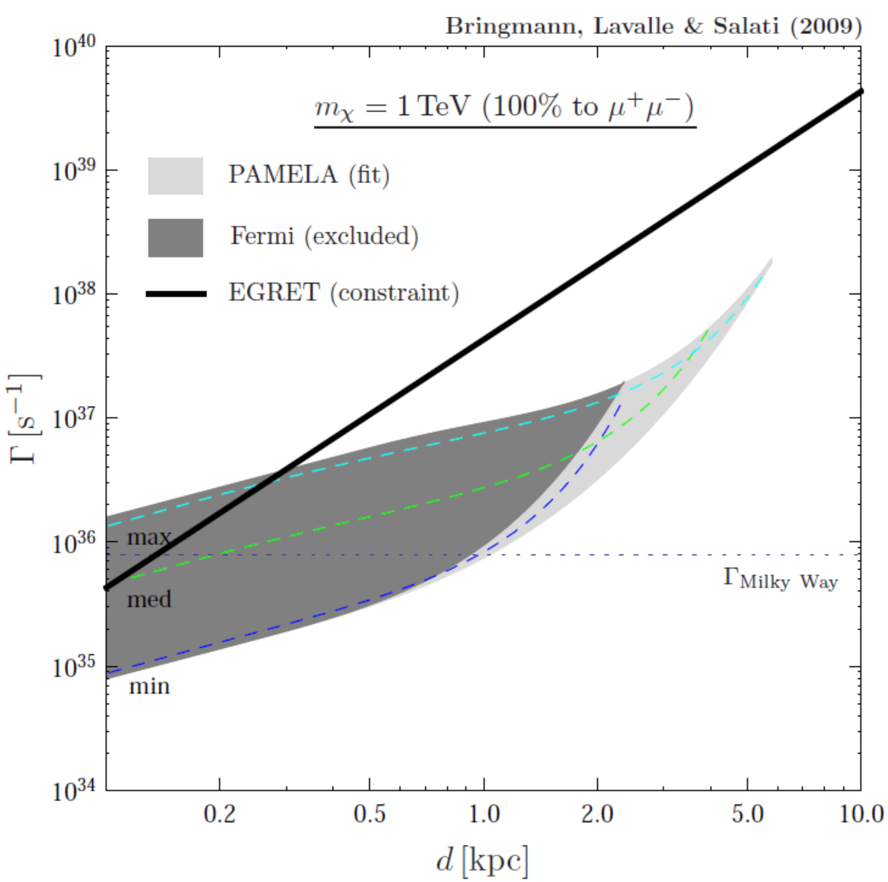


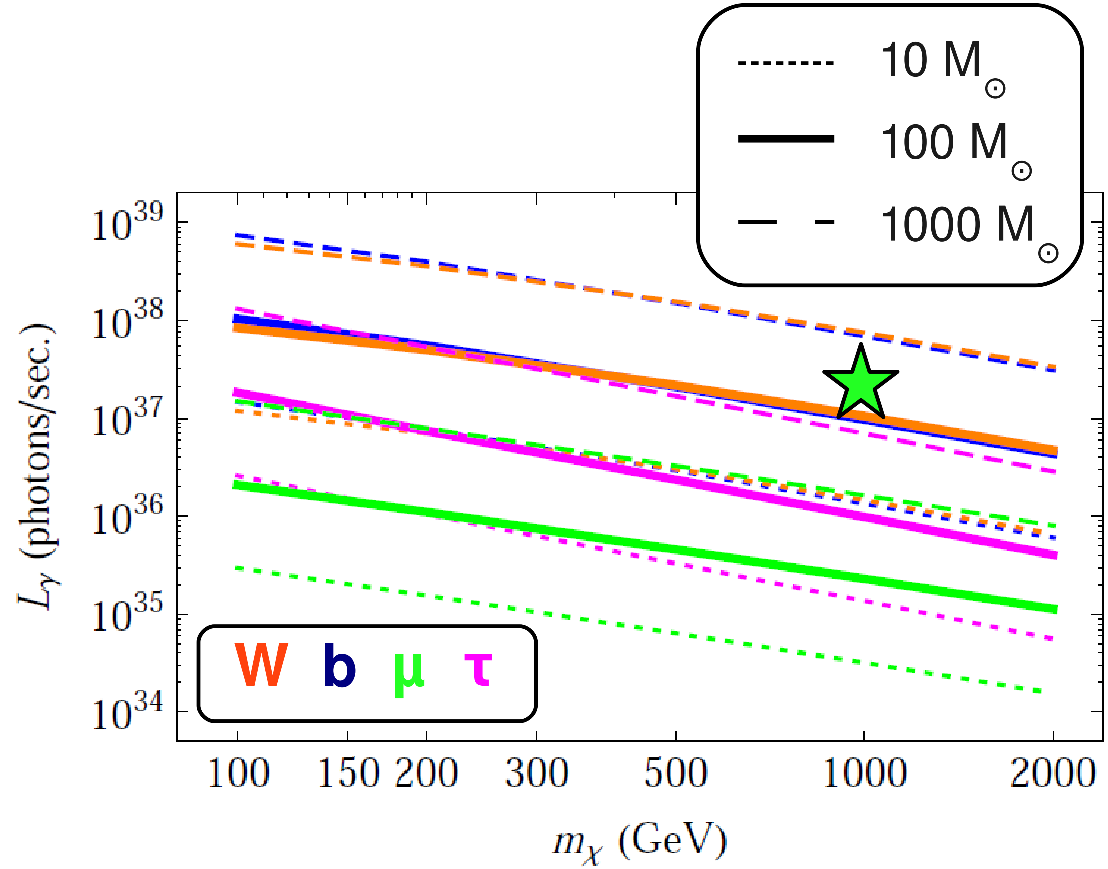
Star Death
zero metallicity
low mass stars
massive stars
very massive stars
pulsational pair instability
pair instability
no mass loss
RSG
mass after core helium burning
mass at core collapse
supernova explosion
helium core
CO core
AGB mass loss
white dwarf
CO
NeO
neutron star
fallback
direct black hole formation
no remnant – complete disruption
nickel photodisintegration
helium photodisintegration
direct black hole formation
black hole
black hole
supermassive stars (> 50,000 solar masses)
(C) Alexander Heger, 2002
final mass, remnant mass (solar masses, baryonic)
initial mass (solar masses)
1000
300
100
30
10
3
1
1
3
10
30
100
300
1000

Photons are not the only DMA products.

Positrons

- DM annihilations in a nearby spike could be causing PAMELA positron excess. Hooper, Stebbins & Zurek (2009)

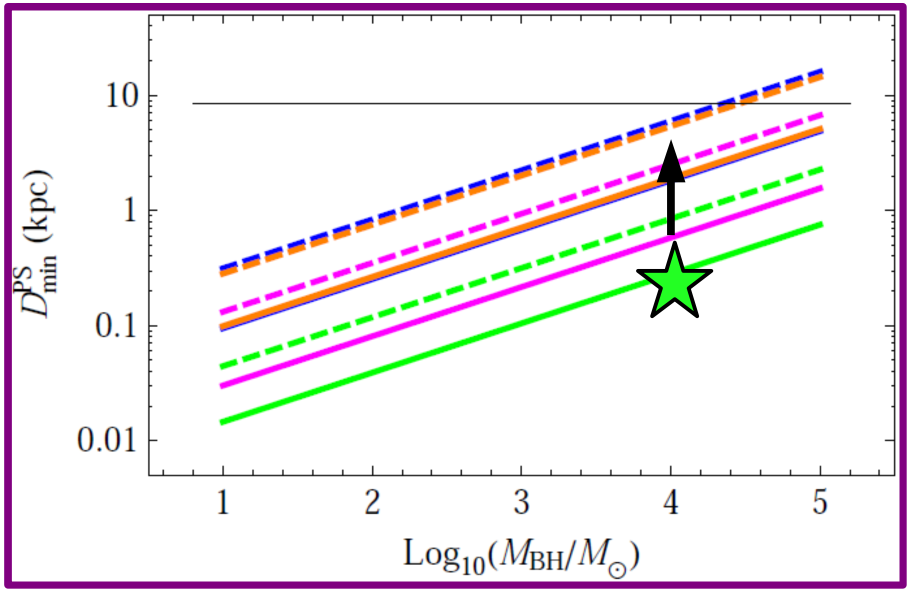




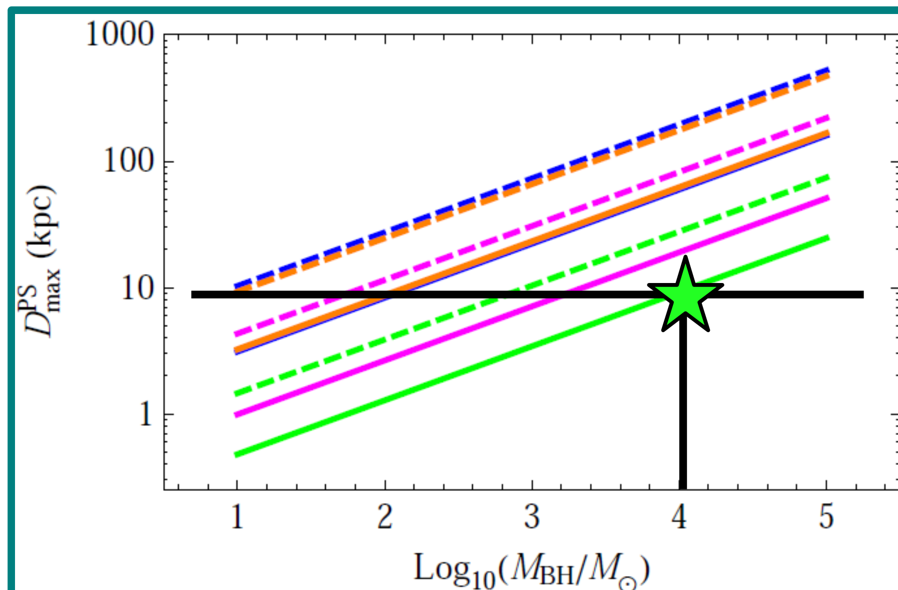
Positrons: Is the distance compatible?

W b μ τ

100 GeV
1 TeV



DminPS: For 1 TeV WIMPs annihilating to muons in the spike around a 10,000 solar mass black hole, the spike can't be closer than a few hundred parsecs.



DmaxPS: The spike would be bright enough to have been identified as a point source, since it must be within a few kpc of our solar system. This spike would probably be in the FGST catalog!

Neutrino Flux from DM Spikes

- Neutrinos: not brighter than Super-Kamiokande point source flux limit [note: not full-sky].