MICROLENSING OF X-RAY PULSARS:

A METHOD TO DETECT PRIMORDIAL BLACK HOLE DARK MATTER

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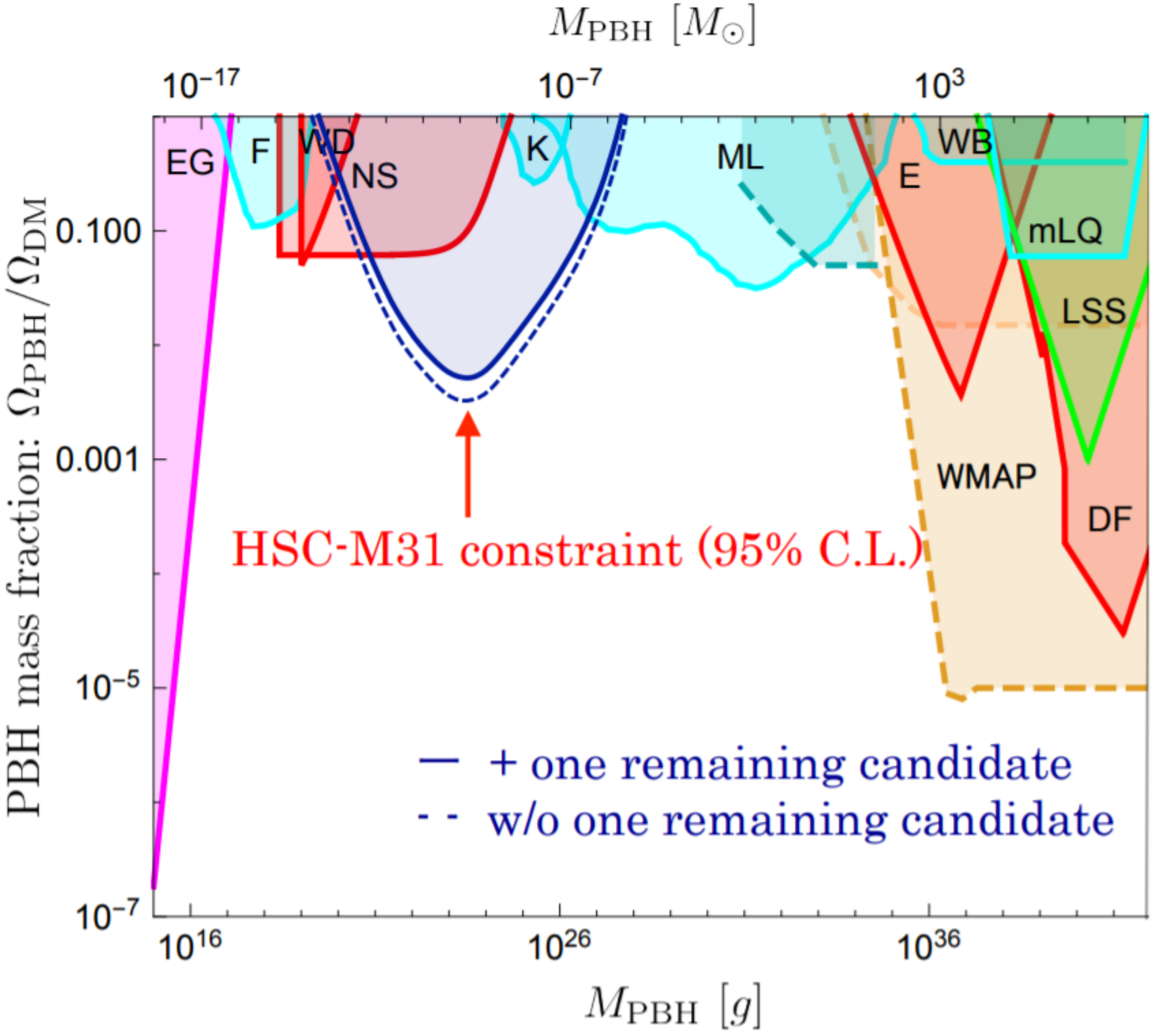
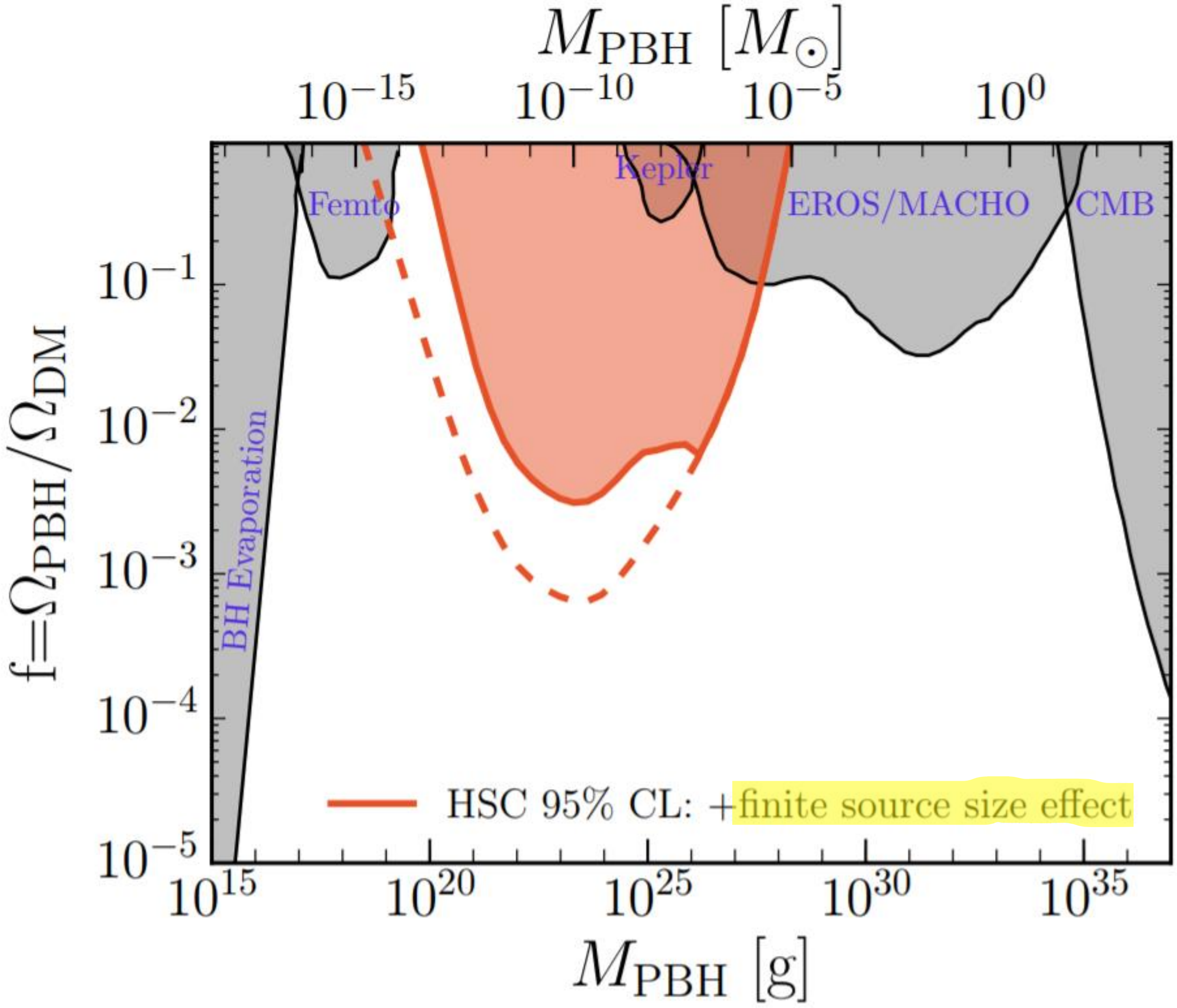
SITUATION EARLY 2017



Niikura, *et. al.* (v1: Jan 2017)

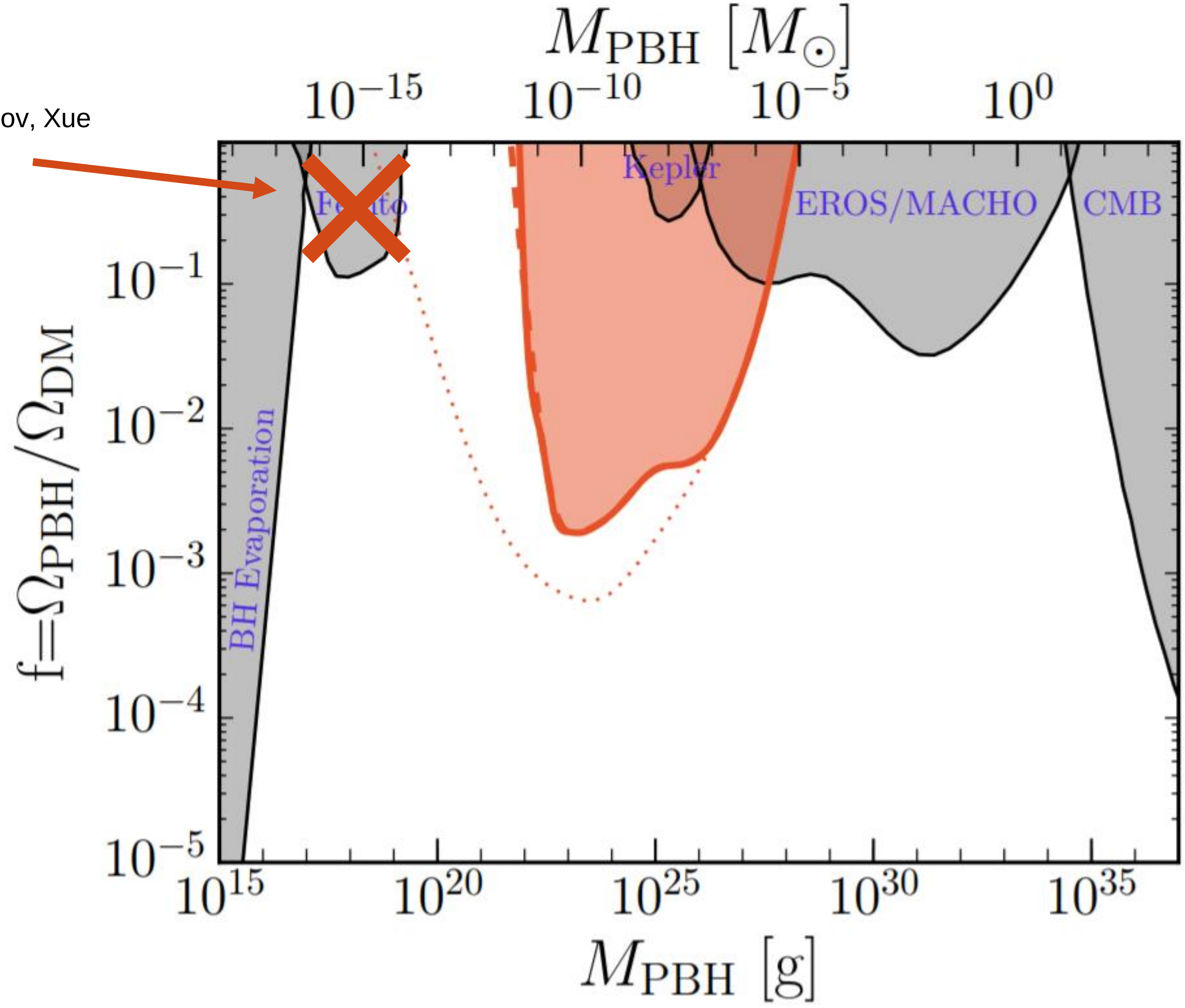
SITUATION EARLY 2018



Niikura, *et. al.* (v2: Oct 2017)

SITUATION LATE 2018

Katz, Kopp, Sibiryakov, Xue
(July 2018)



Niikura, *et. al.* (v3: Oct 2018)

Learn from this to determine a suitable lensing source.

WHAT SOURCE?

SOURCE CRITERIA

1. Emits at a large enough energy to reduce wave effects.
   Wave effects become important when

   $$E_\gamma \lesssim 1/(4G_N M) = 0.66\,\mathrm{keV} \times (10^{20}\,\mathrm{g}/M)$$

   Points towards X-rays.

2. Small geometric size compared to the Einstein radius to reduce finite source size effects.

$$r_{\mathrm{E}}(x) = \sqrt{4\,G_N\,M\,x\,(1-x)\,D_{\mathrm{OS}}} = (107\,\mathrm{km}) \times \left(\frac{\sqrt{x(1-x)}}{1/2}\right) \left(\frac{D_{\mathrm{OS}}}{50\,\mathrm{kpc}}\right)^{1/2} \left(\frac{M}{10^{19}\,\mathrm{g}}\right)^{1/2}$$

$$a_{\mathrm{S}}(x) = \frac{x R_{\mathrm{S}}}{r_{\mathrm{E}}(x)} \approx (0.1) \times \left(\frac{x}{\sqrt{x(1-x)}}\right) \left(\frac{R_{\mathrm{S}}}{20\,\mathrm{km}}\right) \left(\frac{50\,\mathrm{kpc}}{D_{\mathrm{OS}}}\right)^{1/2} \left(\frac{10^{19}\,\mathrm{g}}{M}\right)^{1/2},$$

SOURCE CRITERIA

3. Large distance from Earth to increase the optical depth (or number of possible lensing events).

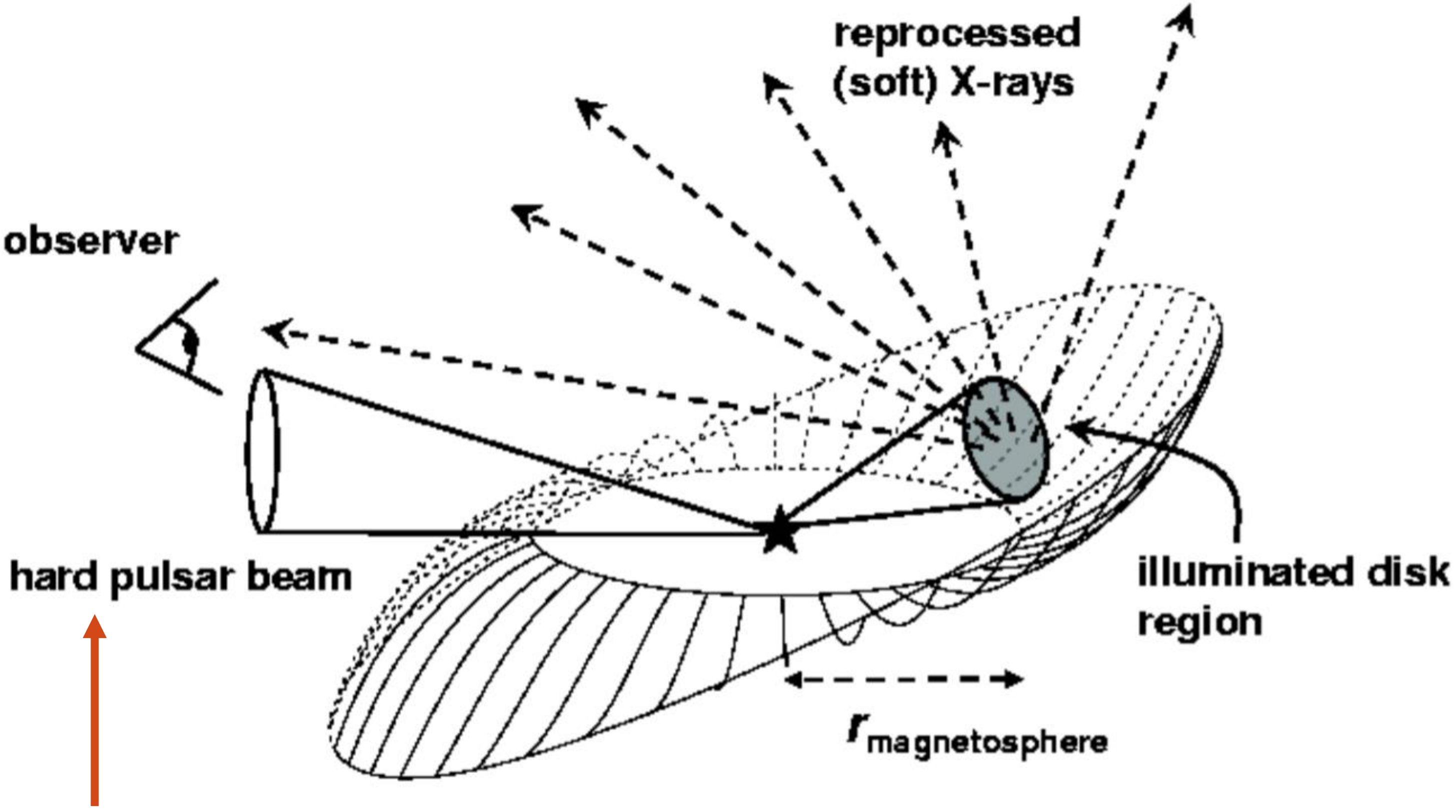
$$\tau = f_{\rm PBH} \int_0^1 dx\, D_{\rm OS}\, \frac{\rho_{\rm DM}(x\,\vec{r}_{\rm S})}{M}\, \pi\, r_{\rm E}^2(x)\, y_T^2$$

$$\begin{aligned} \langle \Delta t \rangle &= \Gamma^{-1} \approx \frac{\pi}{2}\frac{t_{\rm E}}{\tau}\, f_{\rm PBH}^{-1}\, y_T \\ &\approx (11\,\text{days}) \times f_{\rm PBH}^{-1}\, y_T^{-1} \left(\frac{\sqrt{x(1-x)}}{1/2}\right) \left(\frac{D_{\rm OS}}{65\,\text{kpc}}\right)^{1/2} \left(\frac{M}{10^{19}\,\text{g}}\right)^{1/2} \end{aligned}$$

Points towards Milky Way dwarf galaxies

4. Large, steady flux so that magnification can be easily identified.

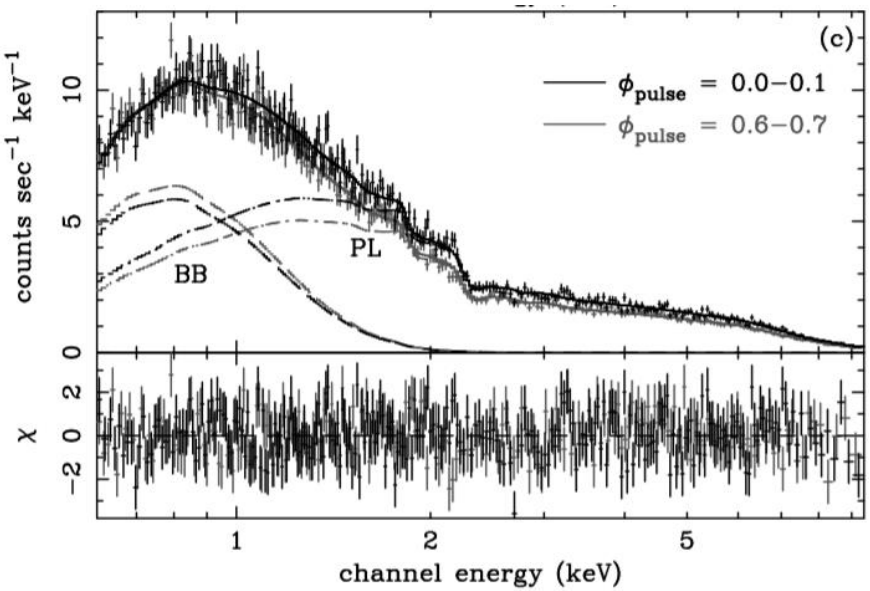
X-RAY PULSARS



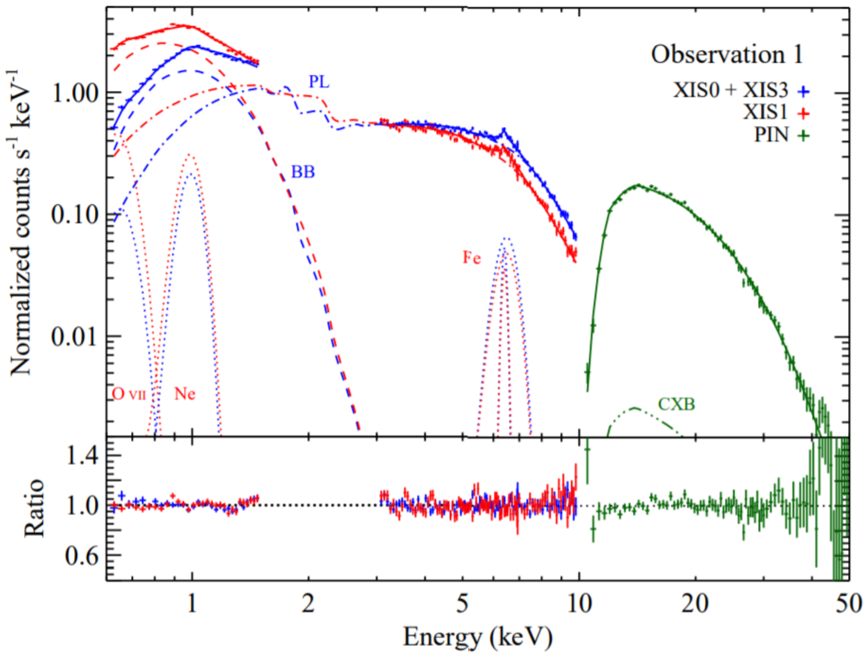
- Small source size ~10-100 km
- Dominates spectrum at high energies ≳ 2 keV

Hickox, Vrtilek (2005)

SMC X-1 AND LMC X-4 SPECTRA



Hickox, Vrtilek (2005)
XMM-Newton telescope



Hung, Hickox, Boroson, Vrtilek (2010)
Suzaku telescope

- <u>Higher energies (that reduce wave effect) correspond to smaller source size!</u>
- Distant in our halo (50-65 kpc) but bright.

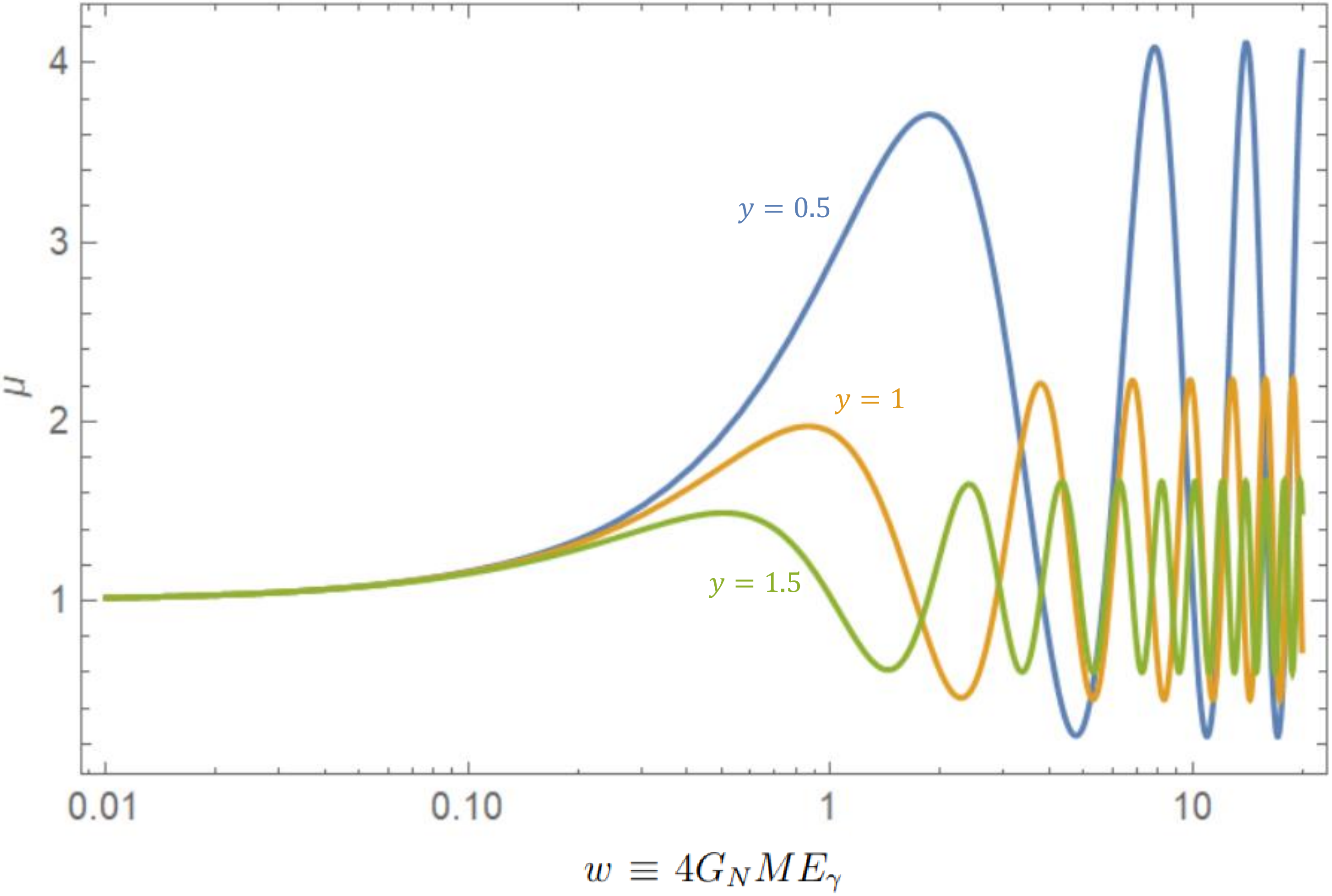
LENSING

WAVE EFFECT

Tangential separation between source and lens:

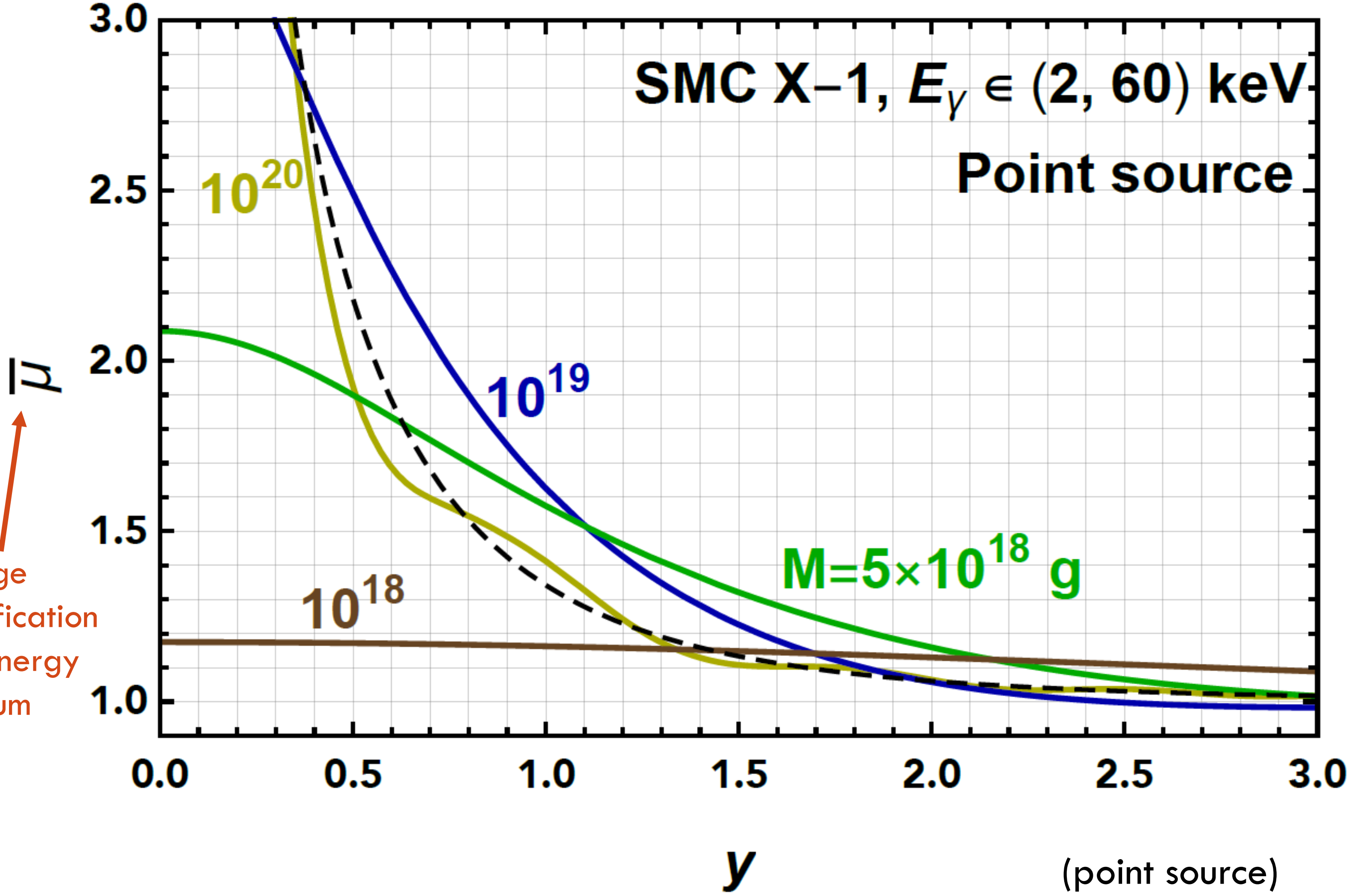
$y(x) \equiv d_s(x)/r_{\mathrm{E}}(x)$

Magnification



(point source)

WAVE EFFECT



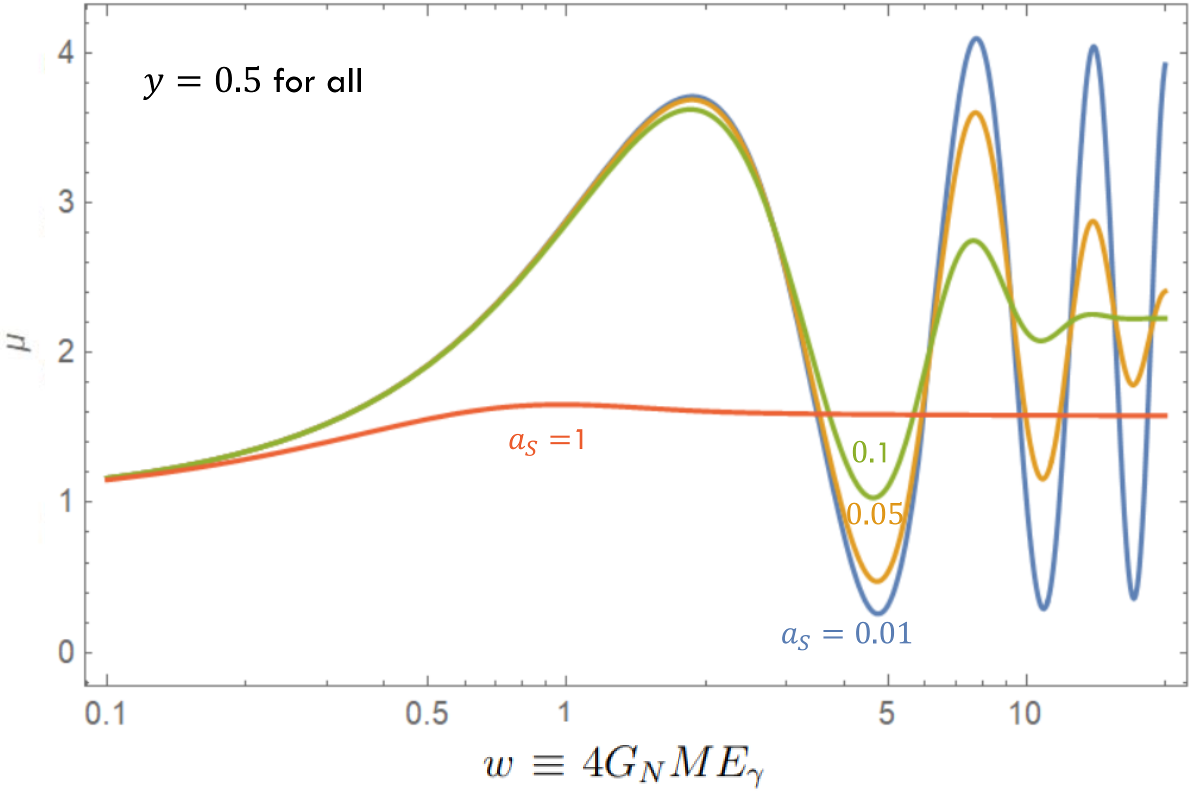
Average magnification over energy spectrum

(point source)

FINITE SOURCE SIZE EFFECT

Point source magnification weighted by Gaussian source intensity profile:

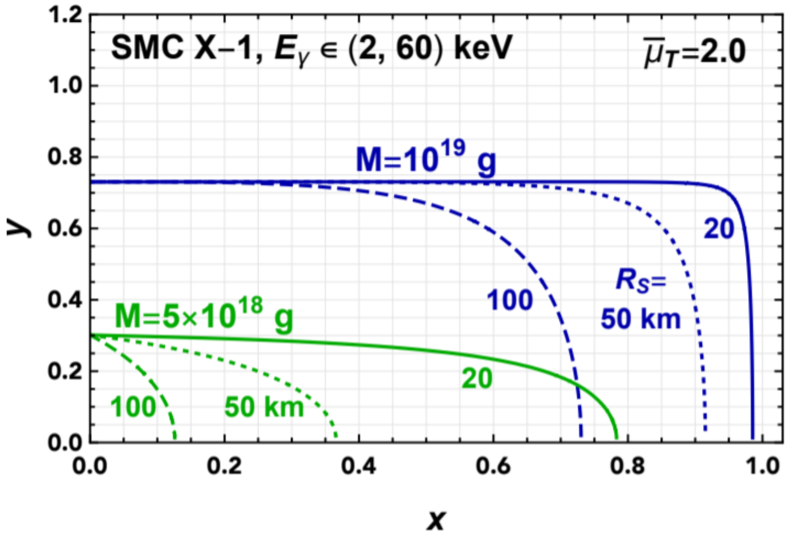
$$\bar{\mu}(w, a_S, r_S) = \frac{\int_{-\infty}^{\infty} W(\vec{y})\mu(w,y)d^2y}{\int_{-\infty}^{\infty} W(\vec{y})d^2y} \qquad W(\vec{y}) = \exp\left(-\frac{|\vec{y}-\vec{Y}|^2}{2a_S^2}\right)$$

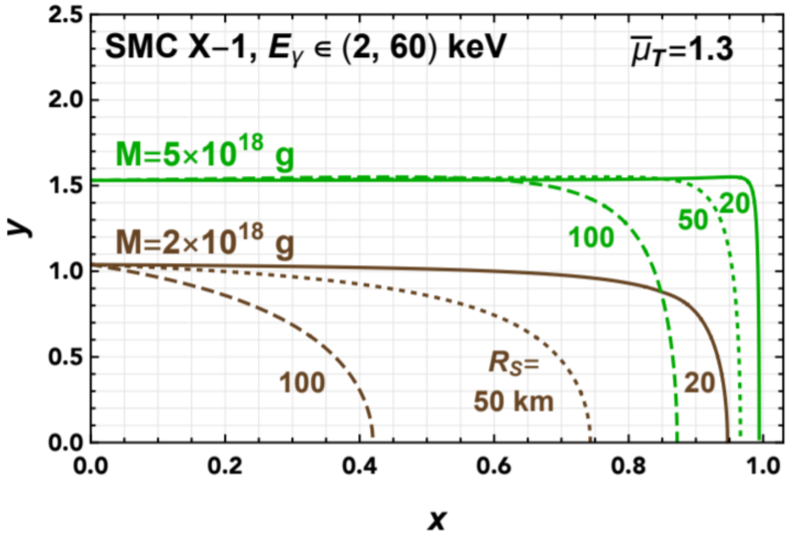


$$\left\{ a_S(x) = \frac{x R_S}{r_E(x)} \right\}$$

FINITE SOURCE SIZE EFFECT

Below the curves: $\bar{\mu} > \bar{\mu}_T$



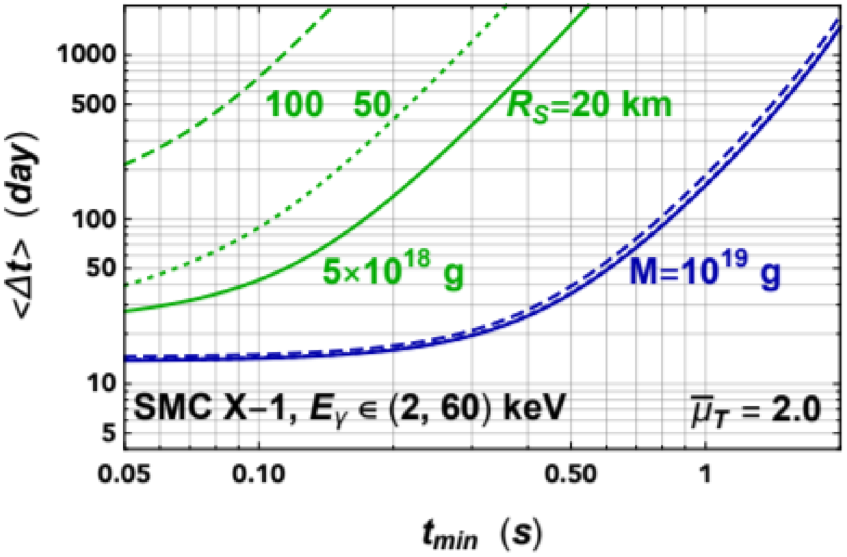


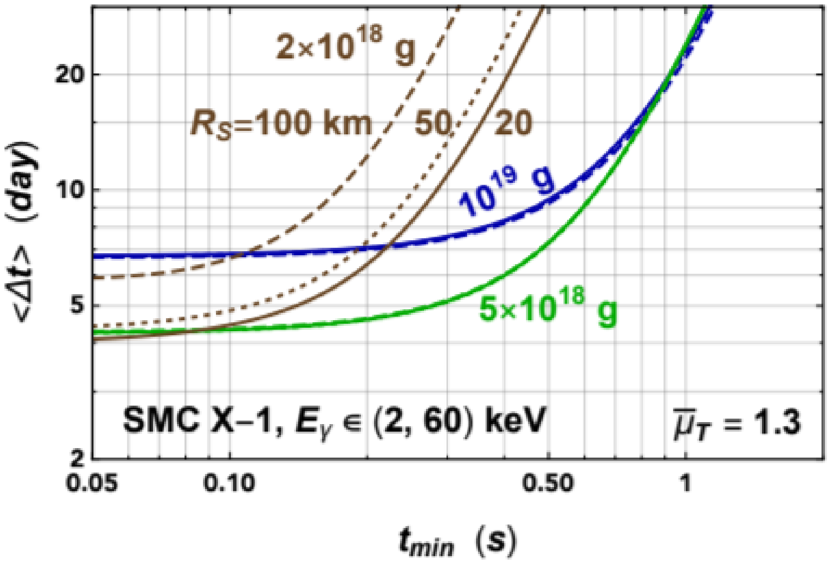
Ratio of radial distance to lens and source: D_L / D_S

EVENT RATE

$$\frac{d\Gamma}{d\hat{t}} = f_{\rm PBH} \times 2 \int_0^{x_{\rm max}} dx \, D_{\rm OS} \, \frac{\rho_{\rm DM}(x\,\vec{r}_{\rm S})}{M} \int_0^{y_T(x)} \frac{dy}{\sqrt{y_T(x)^2 - y^2}} \, \frac{v_r^4}{v_c^2} \, e^{-v_r^2/v_c^2}$$

$$\langle \Delta t \rangle = \left(\int_{t_{\rm min}}^{\infty} \frac{d\Gamma}{d\hat{t}} \right)^{-1}$$





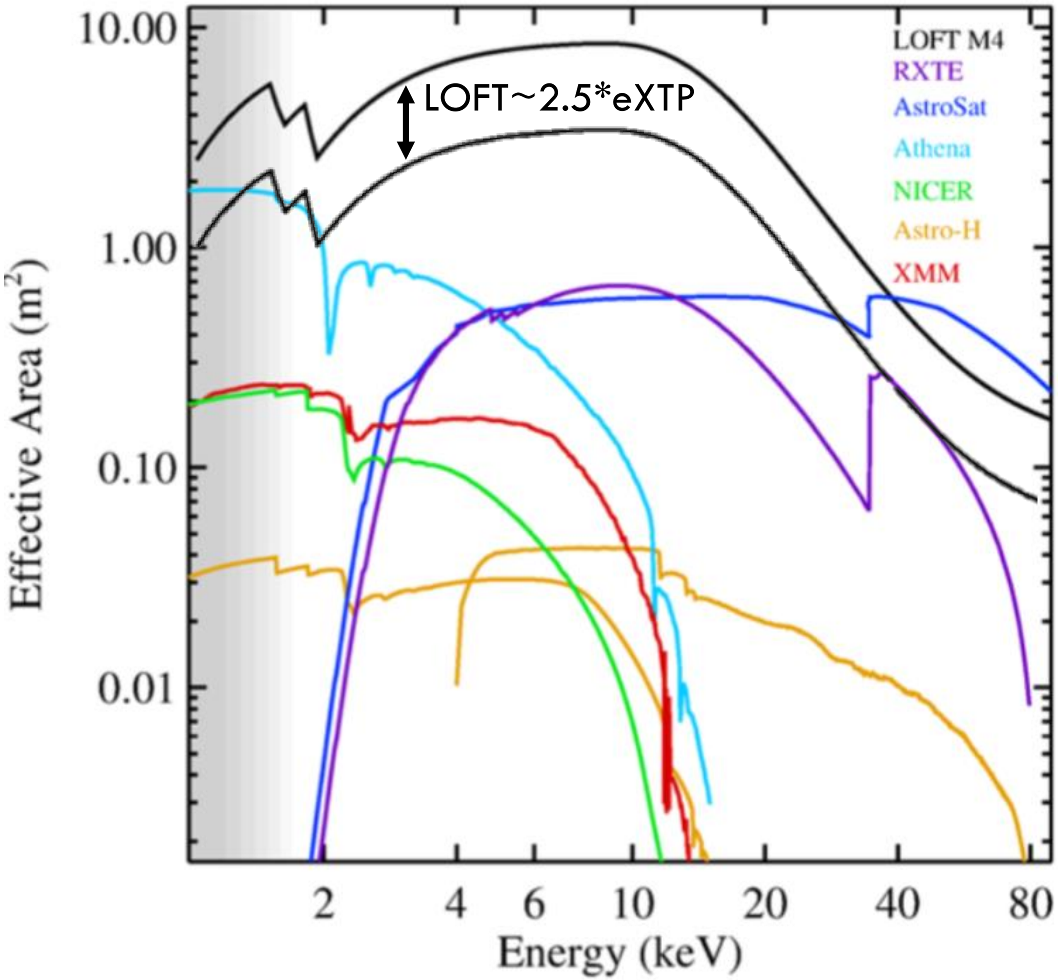
SETTING EXCLUSION BOUNDS

- Remove fluctuations due to pulse period from data.
- Require a few consecutive time bins with flux statistically significantly larger than expected by random fluctuations in source/instrument.

  (Make this stringent enough to essentially eliminate background from statistical fluctuations).
- Larger t_{bin} means lower lensing rate, but also smaller statistical fluctuations.

  We select the value of t_{bin} that gives the strongest bound at each mass.
  (This selection is *a priori*, so no trial factor)

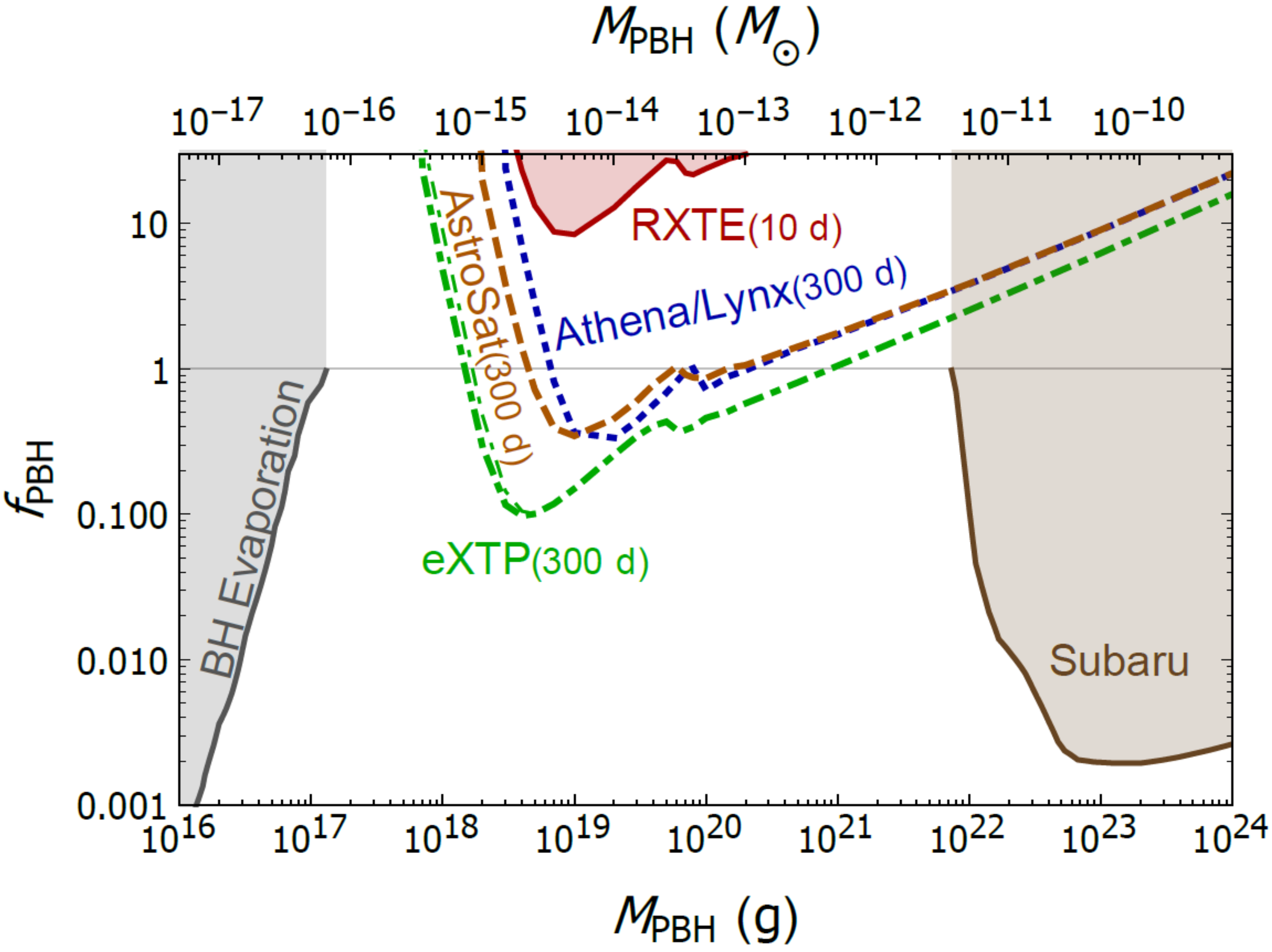
CURRENT AND FUTURE TELESCOPES



LOFT collaboration (2018)

PROJECTED 95% EXCLUSION

DM fraction in PBHs

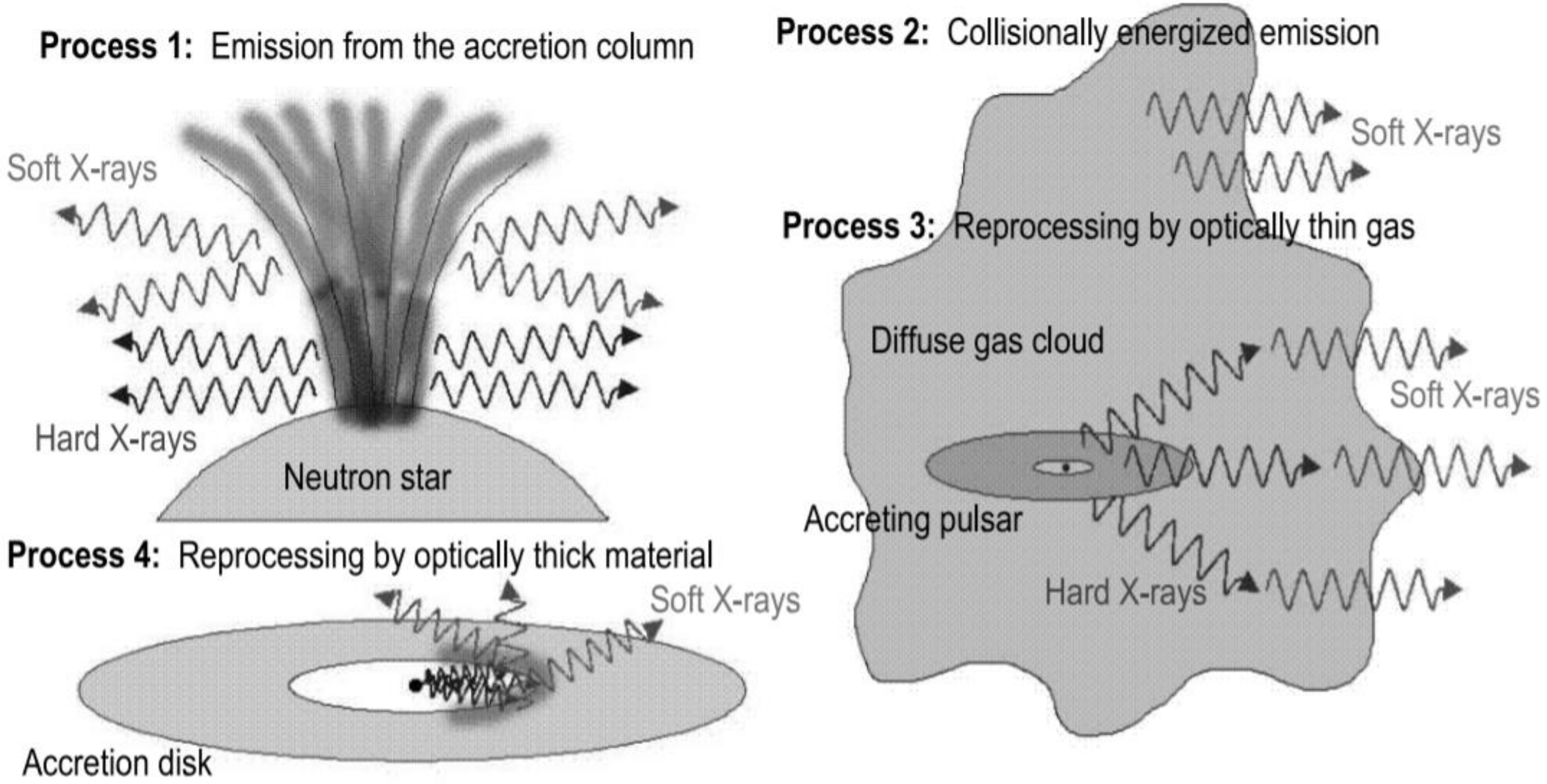


SUMMARY

- Wave effects and source size effects on lensing (along with astrophysical uncertainties related to neutron star capture) opened a window for PBHs/MACHOs to comprise all of dark matter.
- We propose probing this window by searching for lensing of X-ray pulsars.
  These sidestep wave and finite source effects because they emit at high energies from compact regions.
- With enough observation time, much of this window can be probed.

BACKUP

OTHER X-RAY PULSAR SOFT EMISSION



Hickox, Narayan, Kallman (2004)

WAVE EFFECT

$$\mu(w,y) = \frac{\pi\, w}{1-e^{-\pi\, w}} \left| {}_1F_1\left(\frac{i}{2}\, w, 1; \frac{i}{2}\, w\, y^2\right)\right|^2 ,$$

Where:

$$w \equiv 4G_N M E_\gamma$$

$$y(x) \equiv d_s(x)/r_{\text{E}}(x)$$

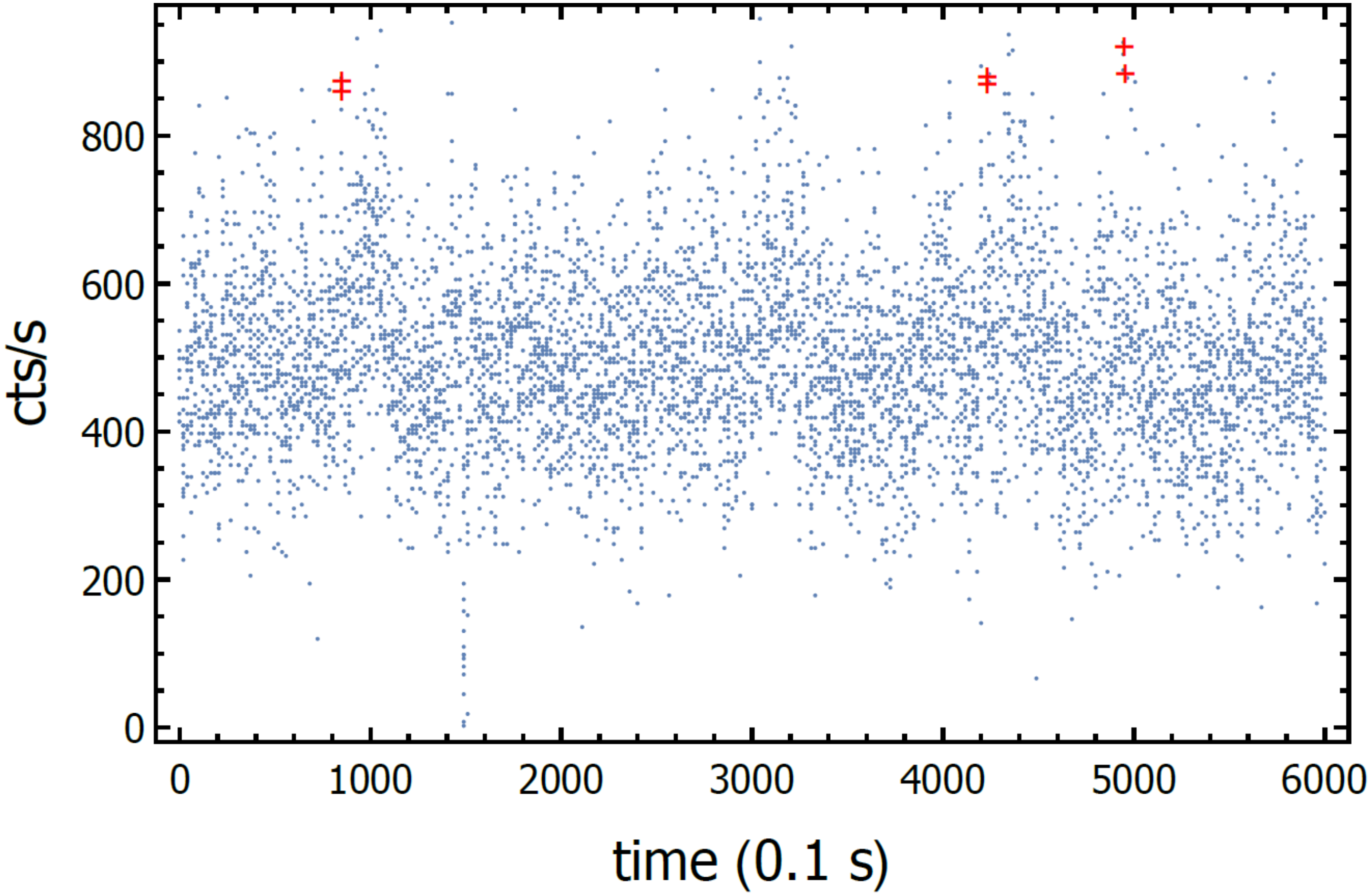
Tangential separation between source and lens

Expression in various limits:

$$\mu^{\max} = \pi\, w/(1-e^{-\pi w}) \qquad\qquad y = 0$$

$$\mu(w,y) = \begin{cases} 1 + \frac{\pi\, w}{2} + \frac{w^2}{12}(\pi^2 - 3y^2) & \text{for} \quad w \ll 1 \\ \frac{1}{y\sqrt{4+y^2}} \left\{ 2 + y^2 + \underbrace{2\sin\left[w\left(\frac{1}{2} y\sqrt{4+y^2} + \log\left| \frac{\sqrt{4+y^2}+y}{\sqrt{4+y^2}-y} \right| \right) \right]}_{\text{Averages to 0 for large } w} \right\} & \text{for} \quad w \gtrsim y^{-1} \end{cases}$$

SAMPLE RXTE DATA



Red crosses: 2 consecutive events 3σ above mean (much less stringent than actual lensing candidate selection)

STATISTICS

Probability for a *particular* set of N_{consec} consecutive bins above a given threshold ought to satisfy (for zero statistical background):

$$p \ll \frac{t_{\rm bin}}{t_{\rm obs}} = 1.16 \times 10^{-7} \times \left(\frac{10 \text{ days}}{t_{\rm obs}}\right)\left(\frac{t_{\rm bin}}{0.1 \text{ s}}\right)$$

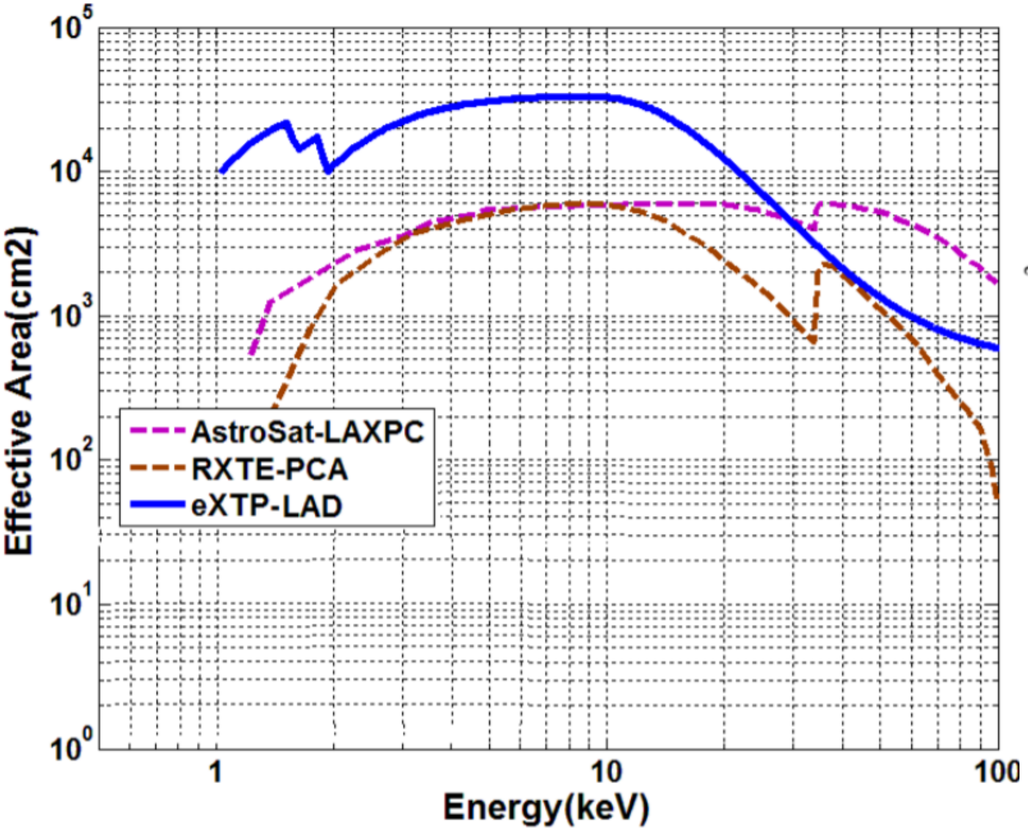
E.g., for Gaussian data with a threshold N_σ (number of standard deviations above the mean)

$$p = [1 - \Phi(N_\sigma)]^{N_{\rm consec}}$$

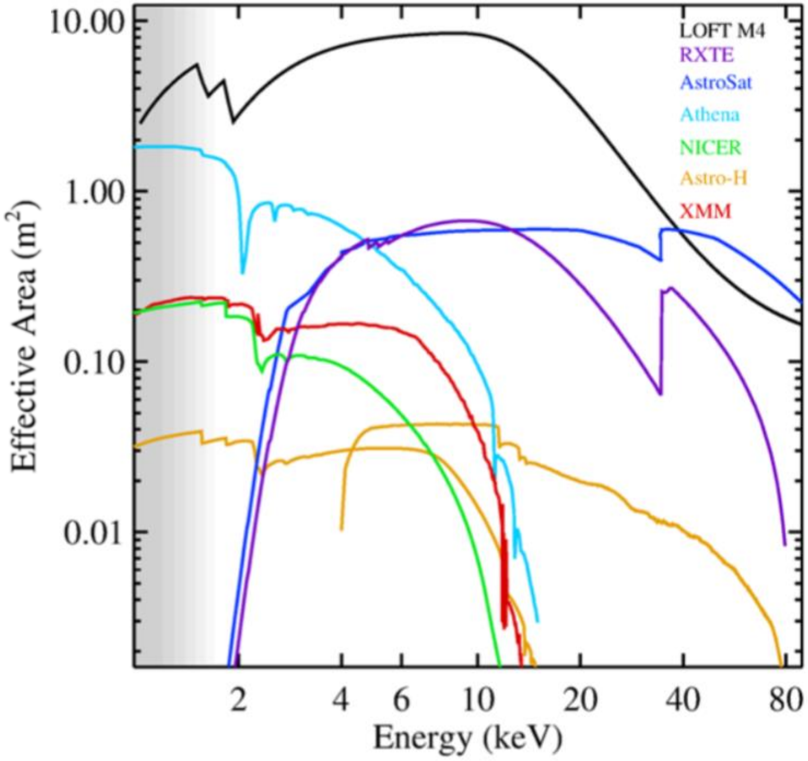
Requirement on $\bar{\mu}_T$ if unlensed points are n_σ standard deviations above/below the mean

$$\overline{\mu}_T = \left(1 \,+\, N_\sigma \,\times\, \frac{\sigma_{\rm B,fid}/{\rm B}_{\rm fid}}{\sqrt{({\rm B}/{\rm B}_{\rm fid})(t_{\rm bin}/t_{\rm bin,fid})}}\right) \Big/ \left(1 \,+\, n_\sigma \,\times\, \frac{\sigma_{\rm B,fid}/{\rm B}_{\rm fid}}{\sqrt{({\rm B}/{\rm B}_{\rm fid})(t_{\rm bin}/t_{\rm bin,fid})}}\right)$$

CURRENT AND FUTURE TELESCOPES



eXTP collaboration (2016)



LOFT collaboration (2018)