PPC 2024

Breaking into the window of primordial black hole dark matter with x-ray microlensing

Based on arXiv: 2405.20365 (Submitted to Phys. Rev. Lett. [PRL])

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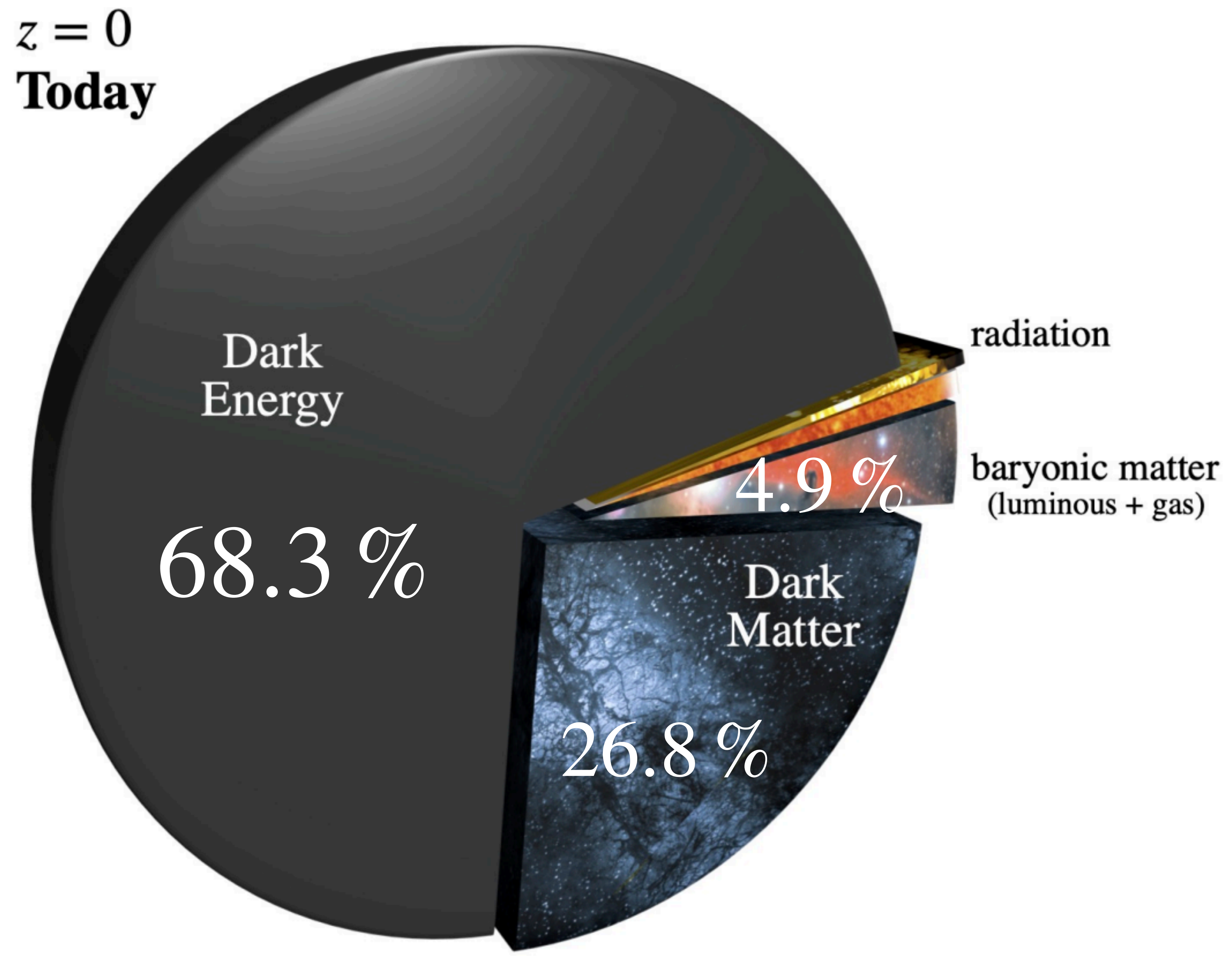
(Ph.D. student at IISc Bangalore)

Ingredients of our universe

What our universe is made up of?

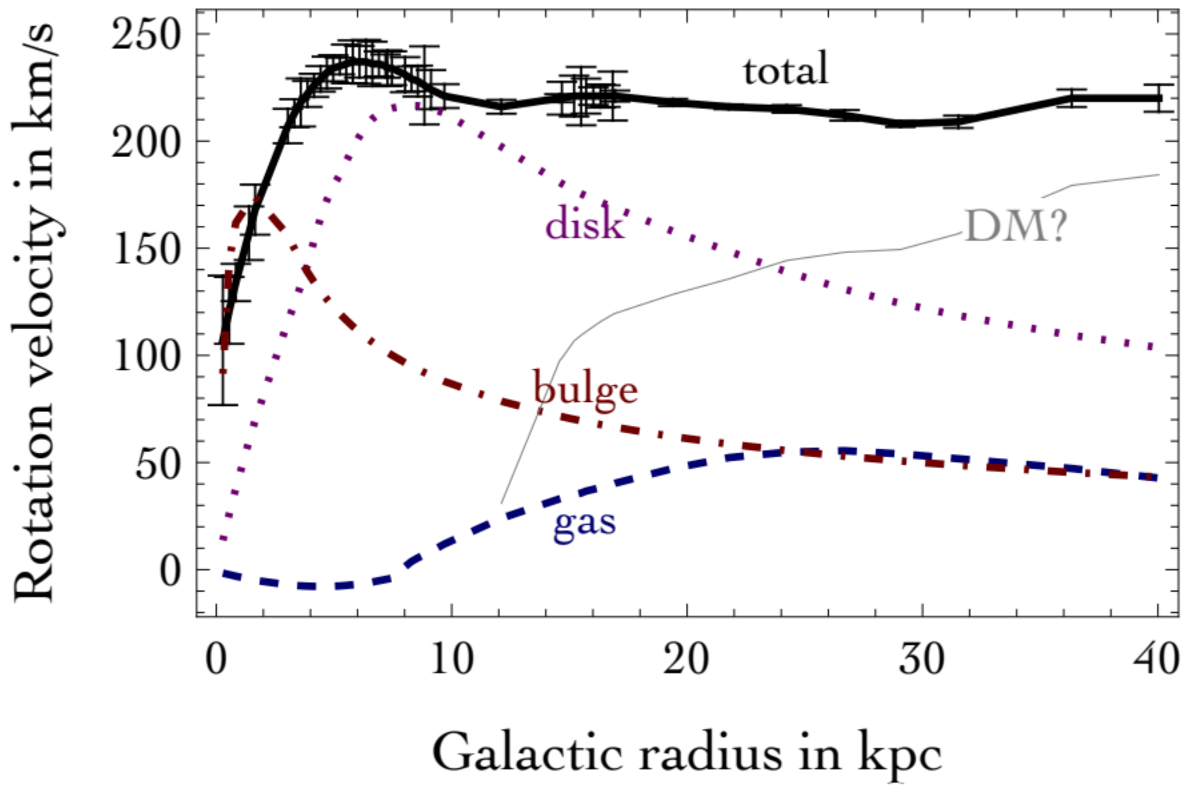
This is what CMB tells about the universe we live in

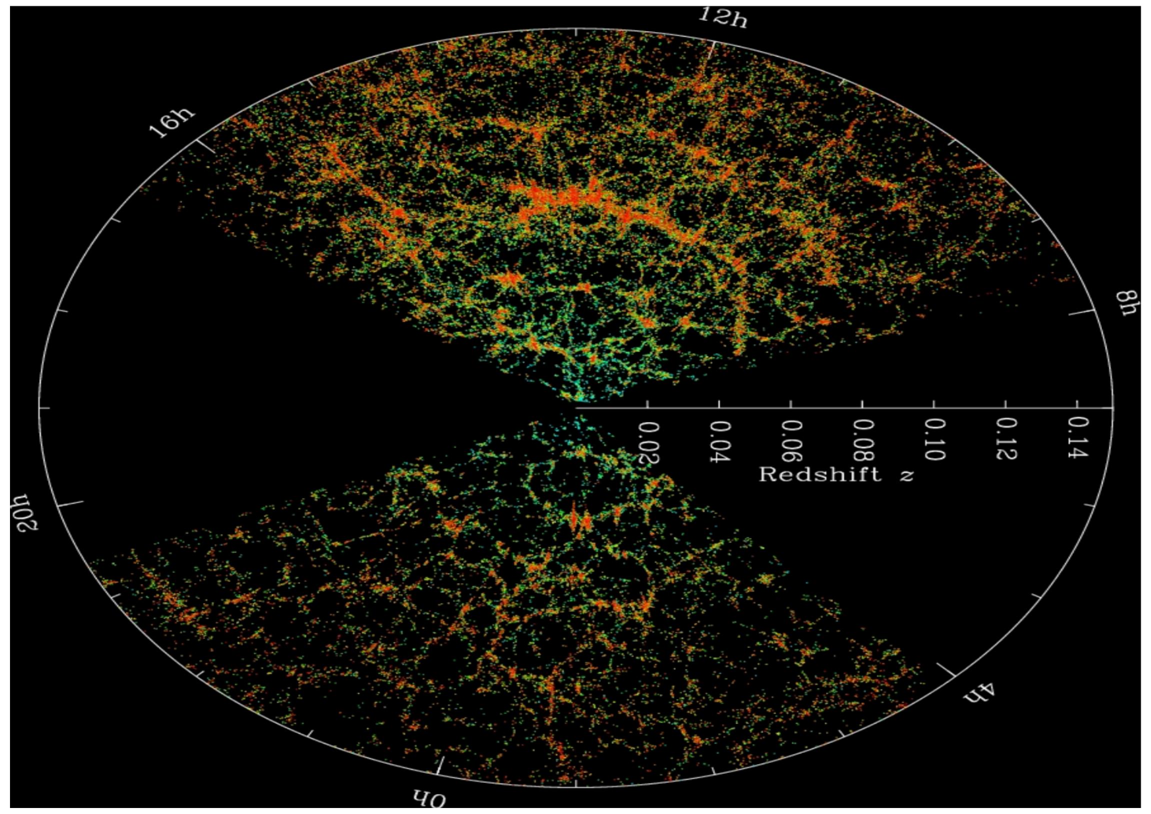


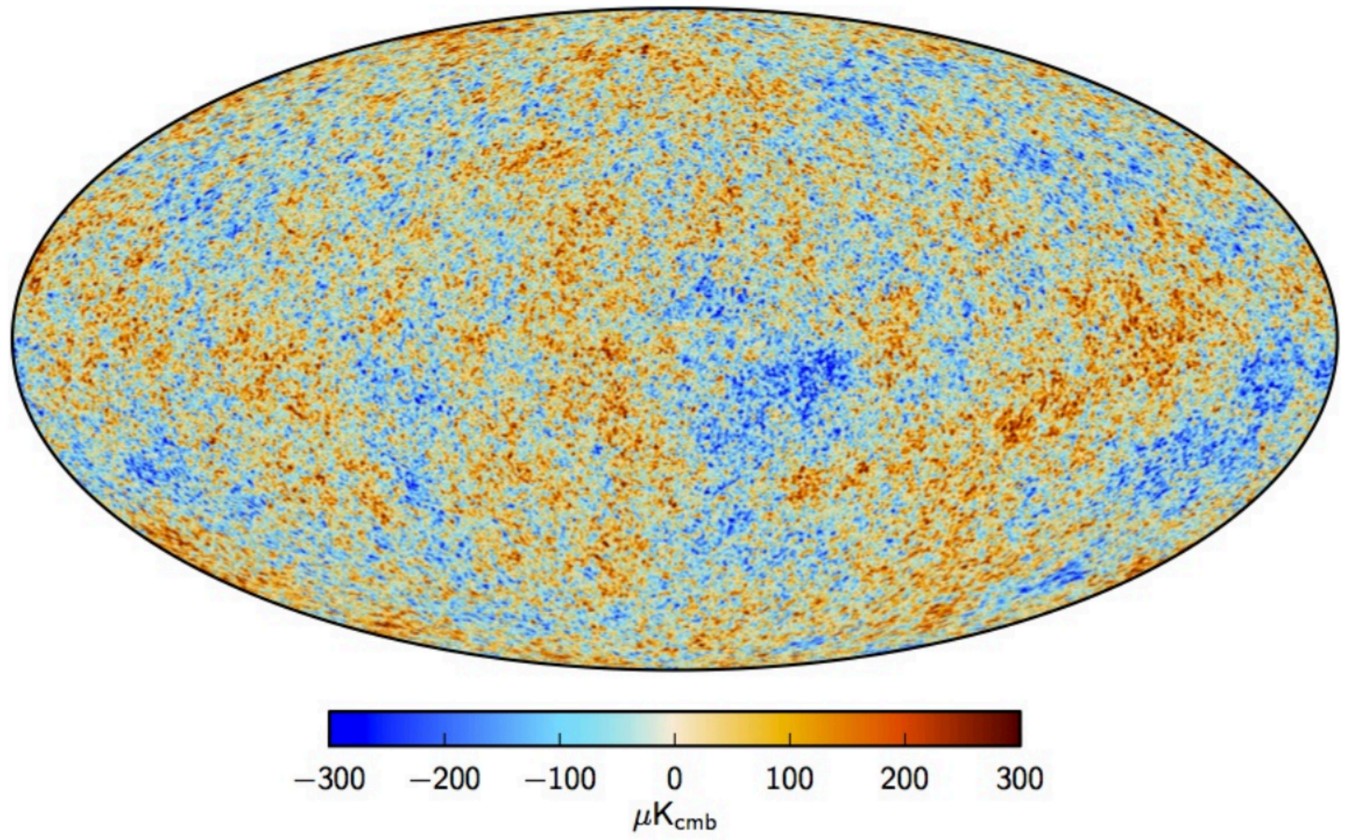
Cirelli et. al. [arXiv: 2406.01705]

Dark matter comprises ~85% of total matter in the universe!

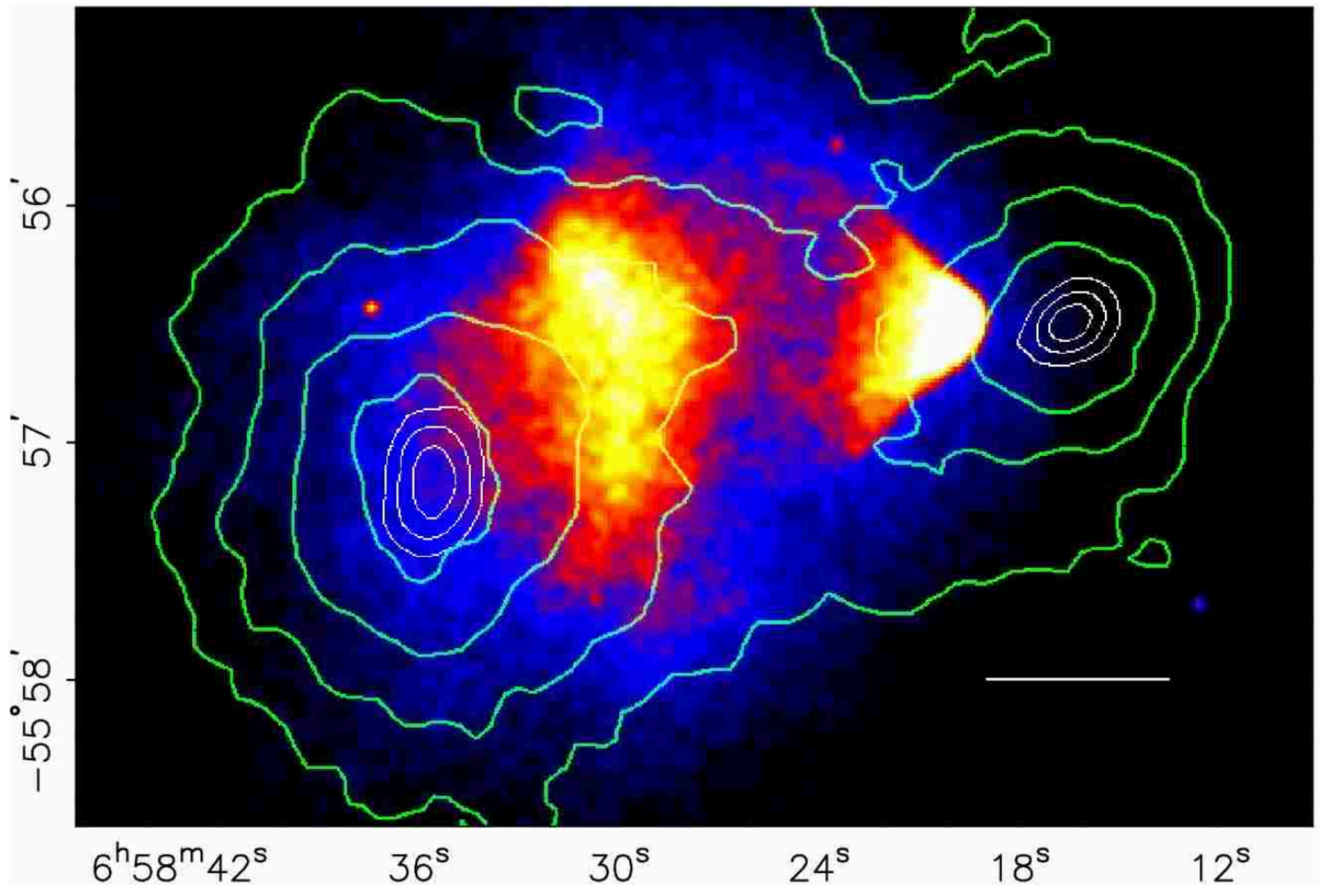
Evidences of dark matter in the universe



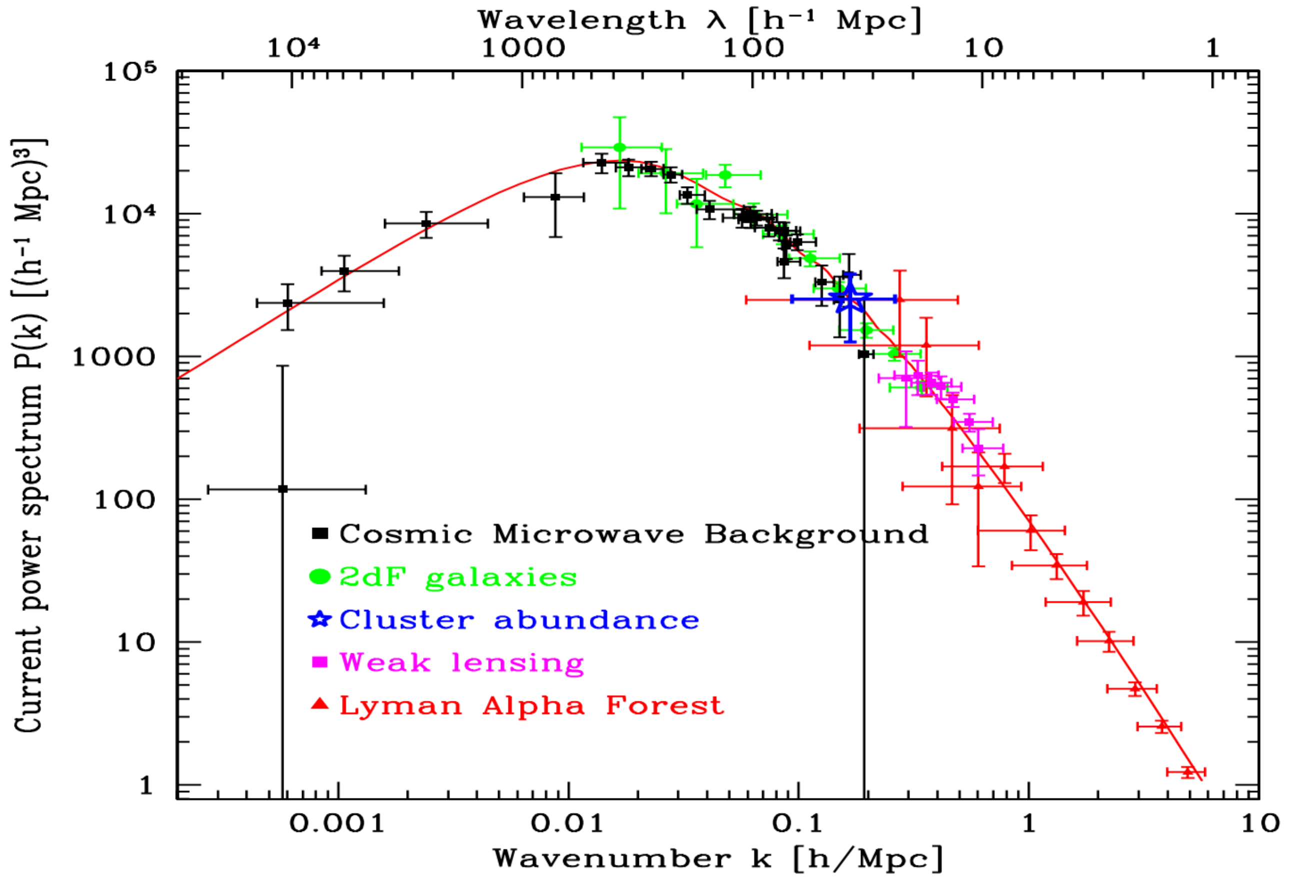


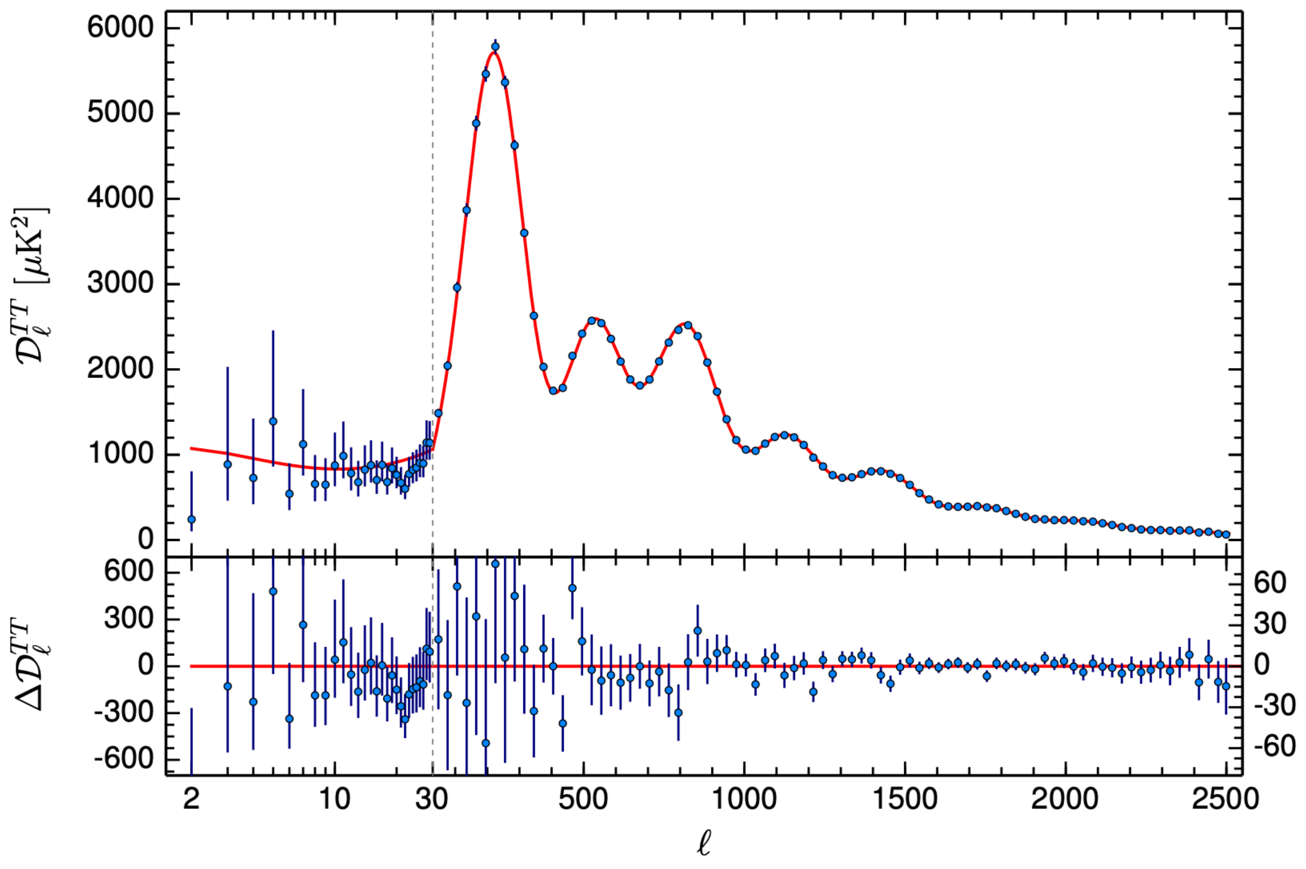


Smoking gun…Bullet cluster



Clowe et al., The Astrophysical Journal + 2006





Cirelli et. al. [arXiv: 2406.01705]

Small scale → **Large scale**

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What is Dark Matter after all?

Dark matter?

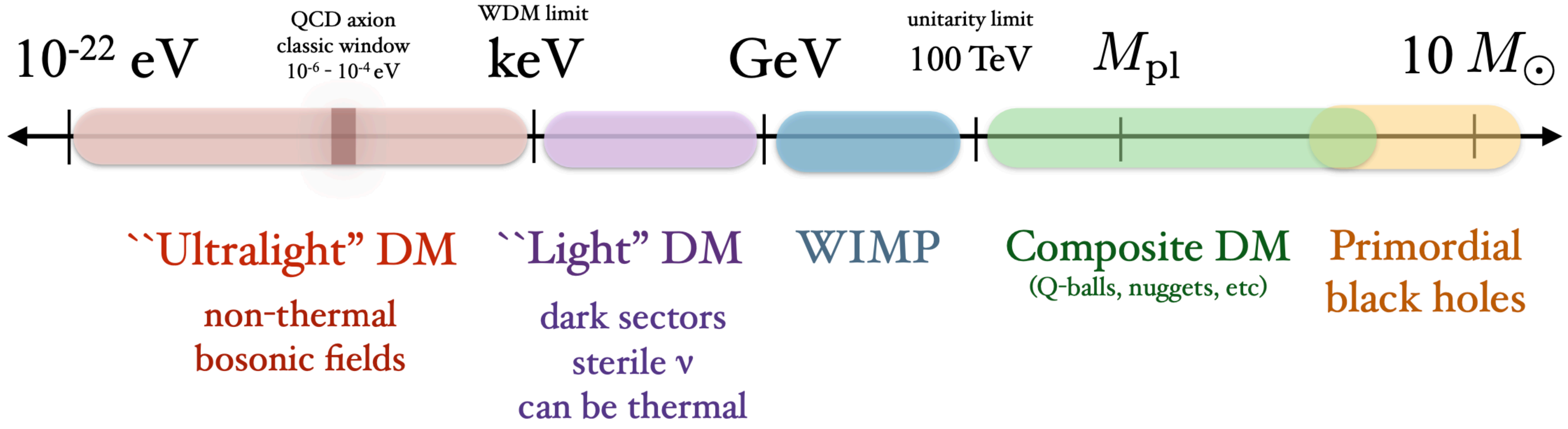
Cold, collision-less, stable

Mysterious?

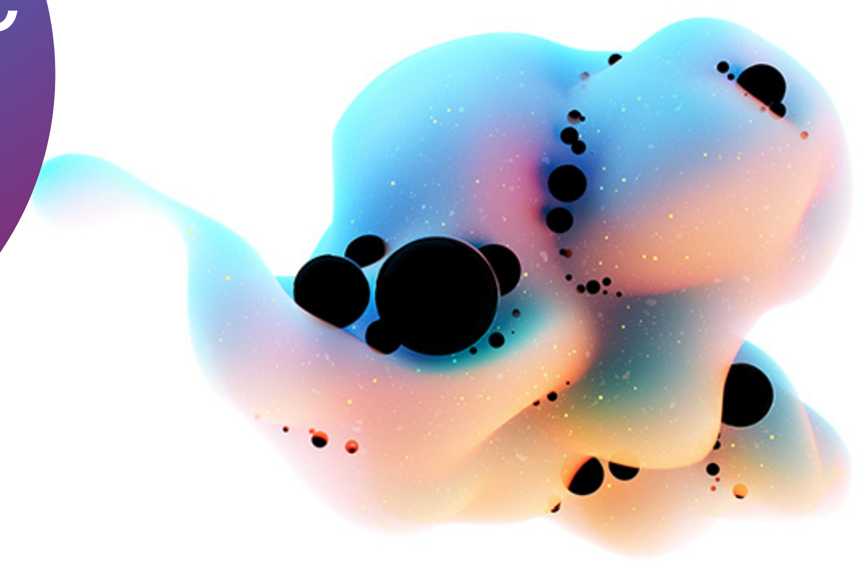
Wave or Particles

Macroscopic e.g. PBH

Mass ?
Charge?
Spin?



[Image: Tongyan Lin + 2019]



Note: $1M_{\odot} \simeq 10^{66}$ eV

~90 orders of magnitude wide parameter space for DM mass!

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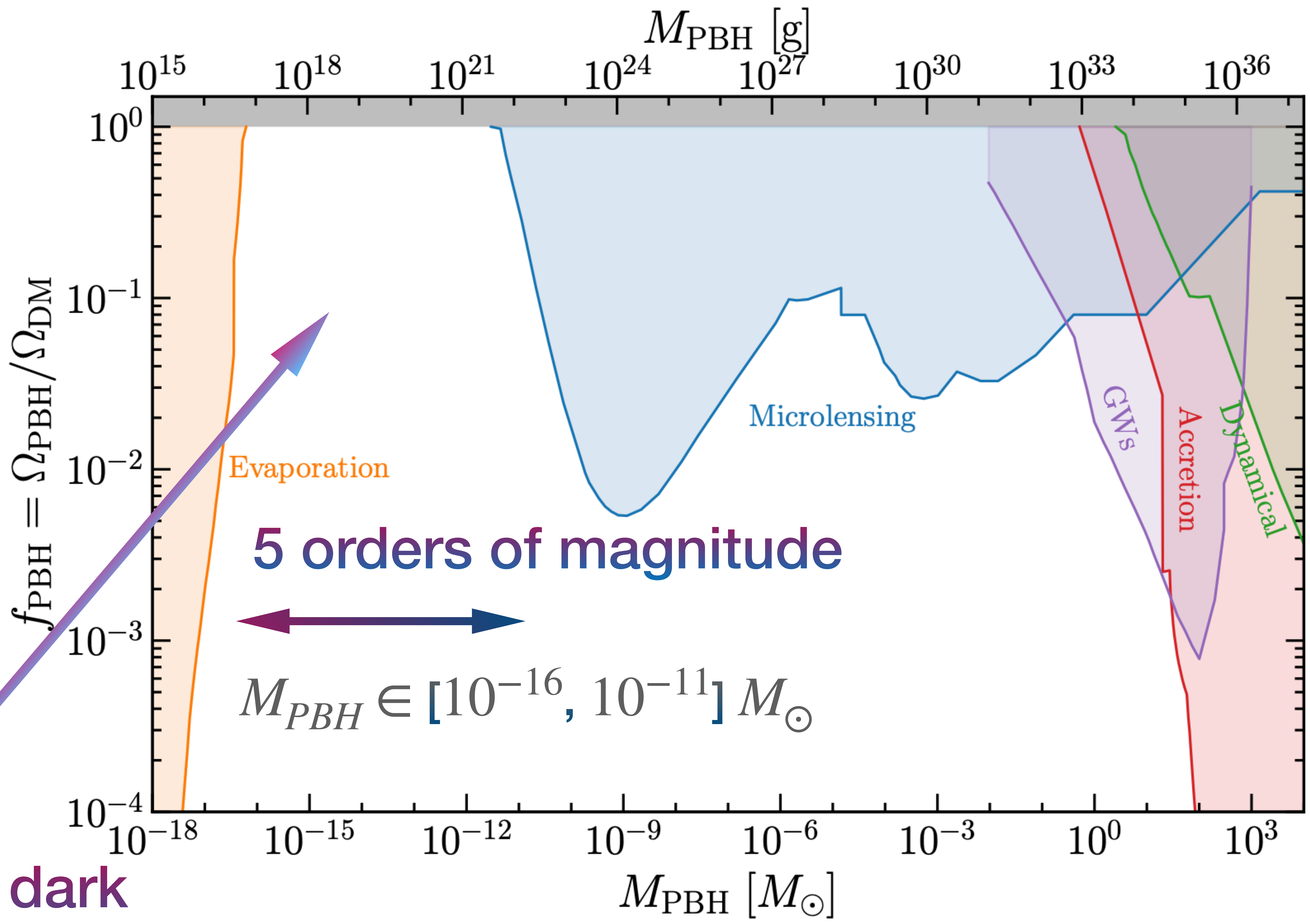
The primordial black hole dark matter window

PBHs may form due to density perturbations generated during the inflationary epoch!

1974



PBH as 100 % dark matter!?

[Oncins + 2022, arXiv:2205.14722]

The primordial black hole dark matter window

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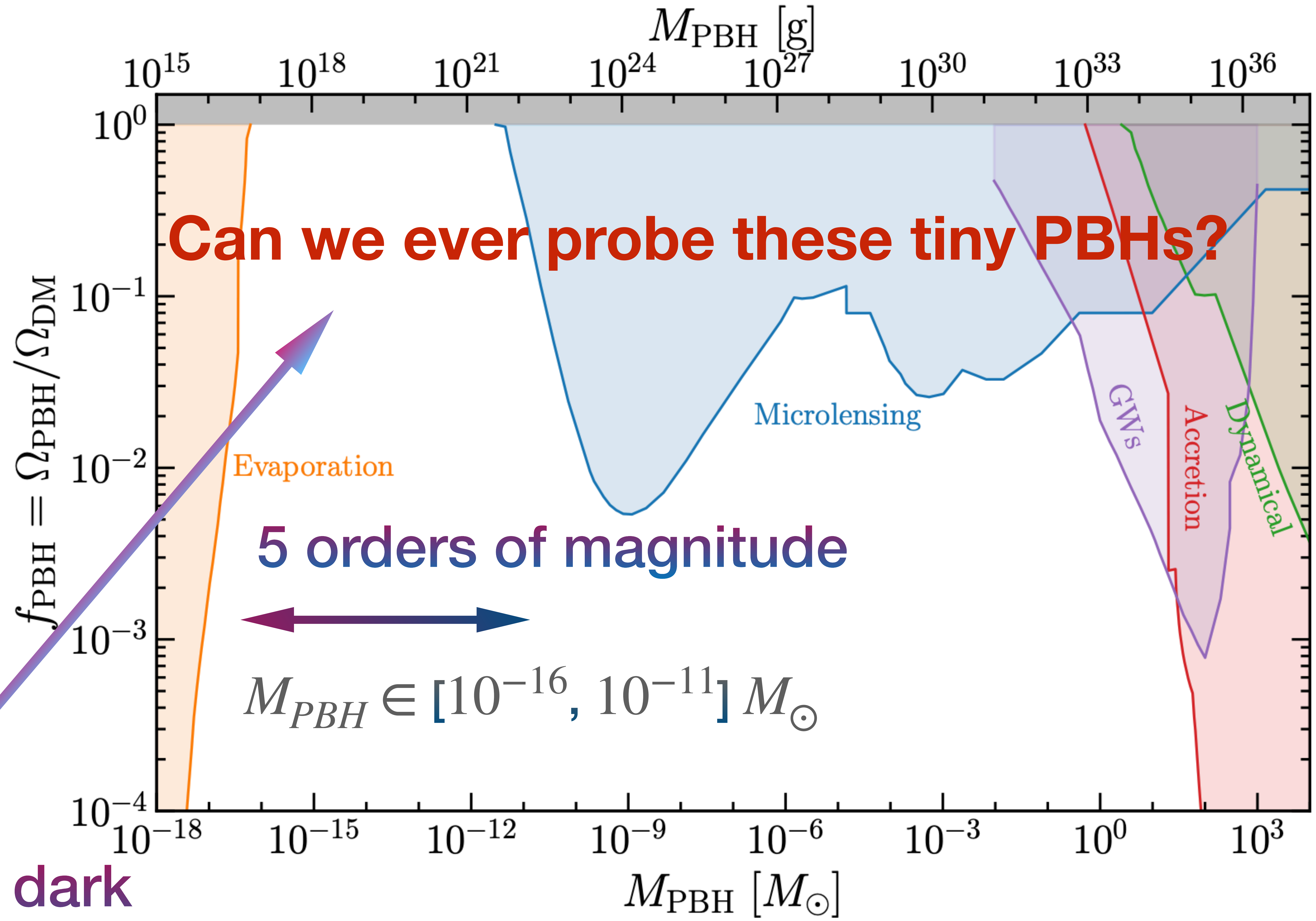
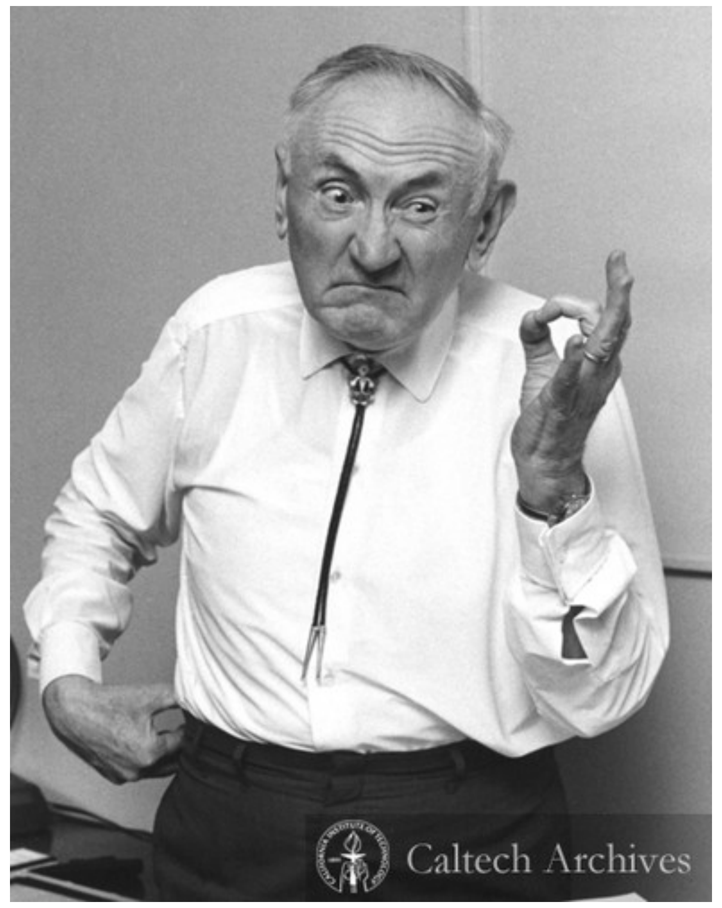


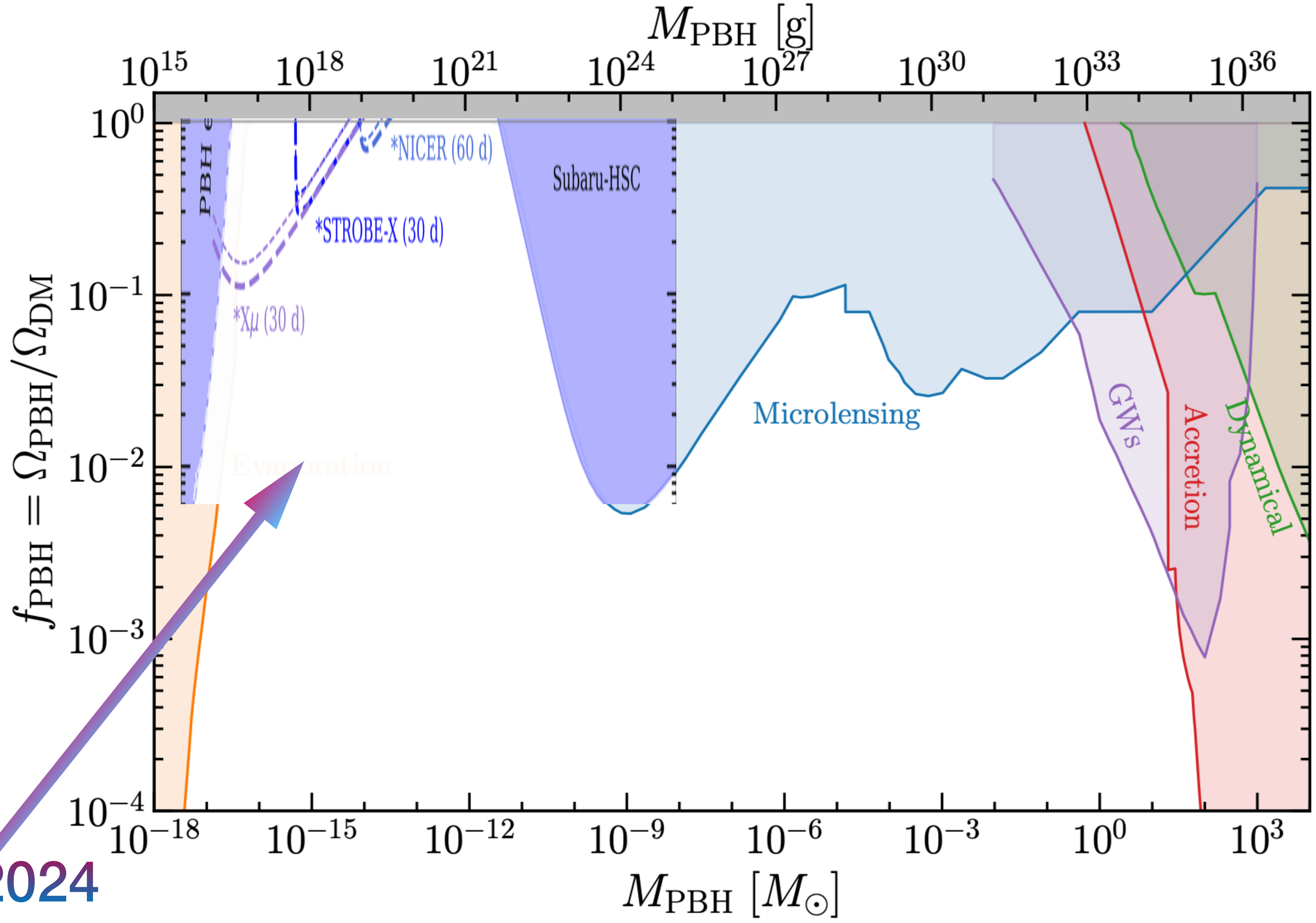
PBH as 100 % dark matter!?

[Oncins + 2022, arXiv:2205.14722]

The primordial black hole dark matter window

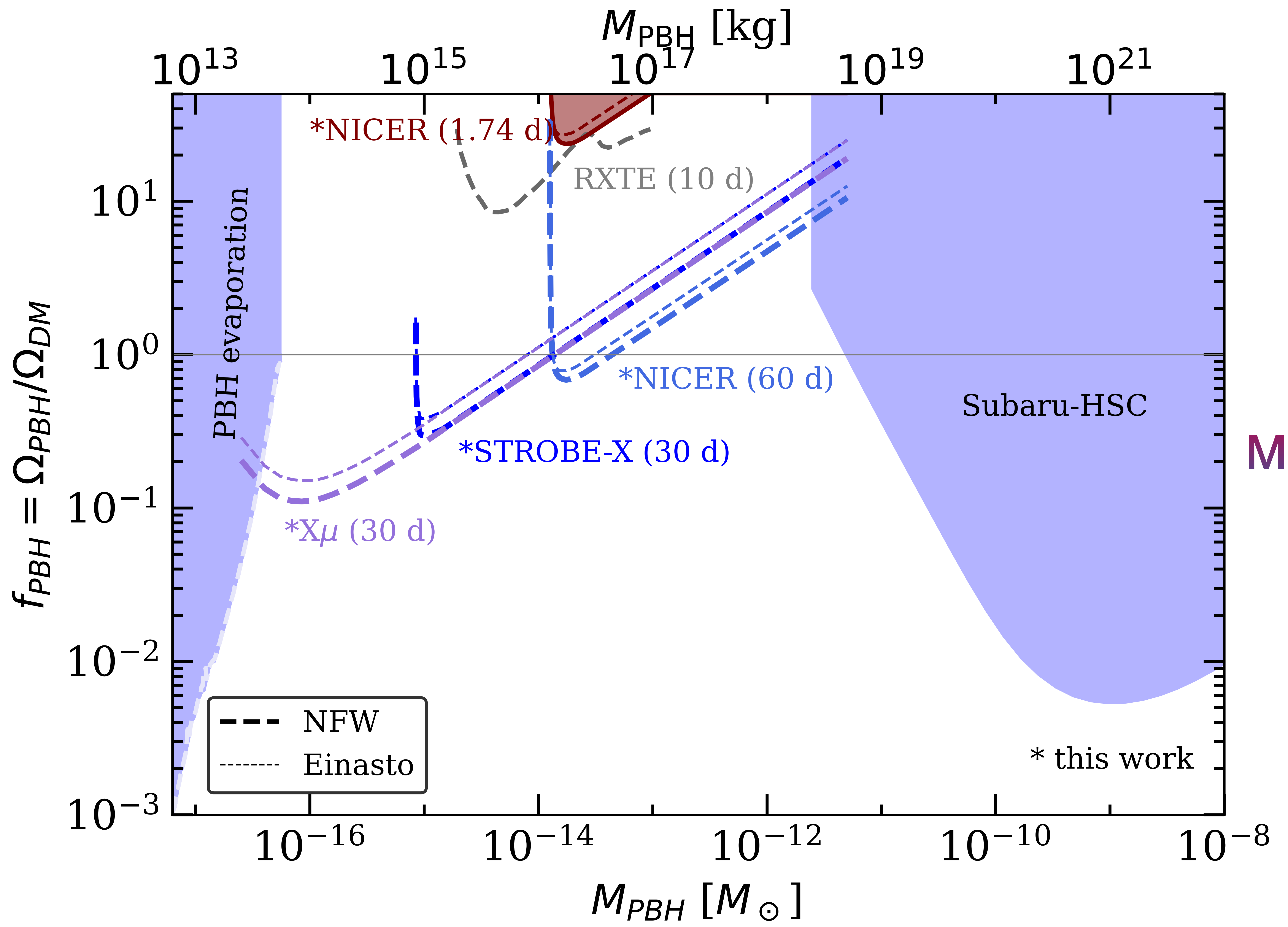
Current and future x-ray telescopes can probe this window!





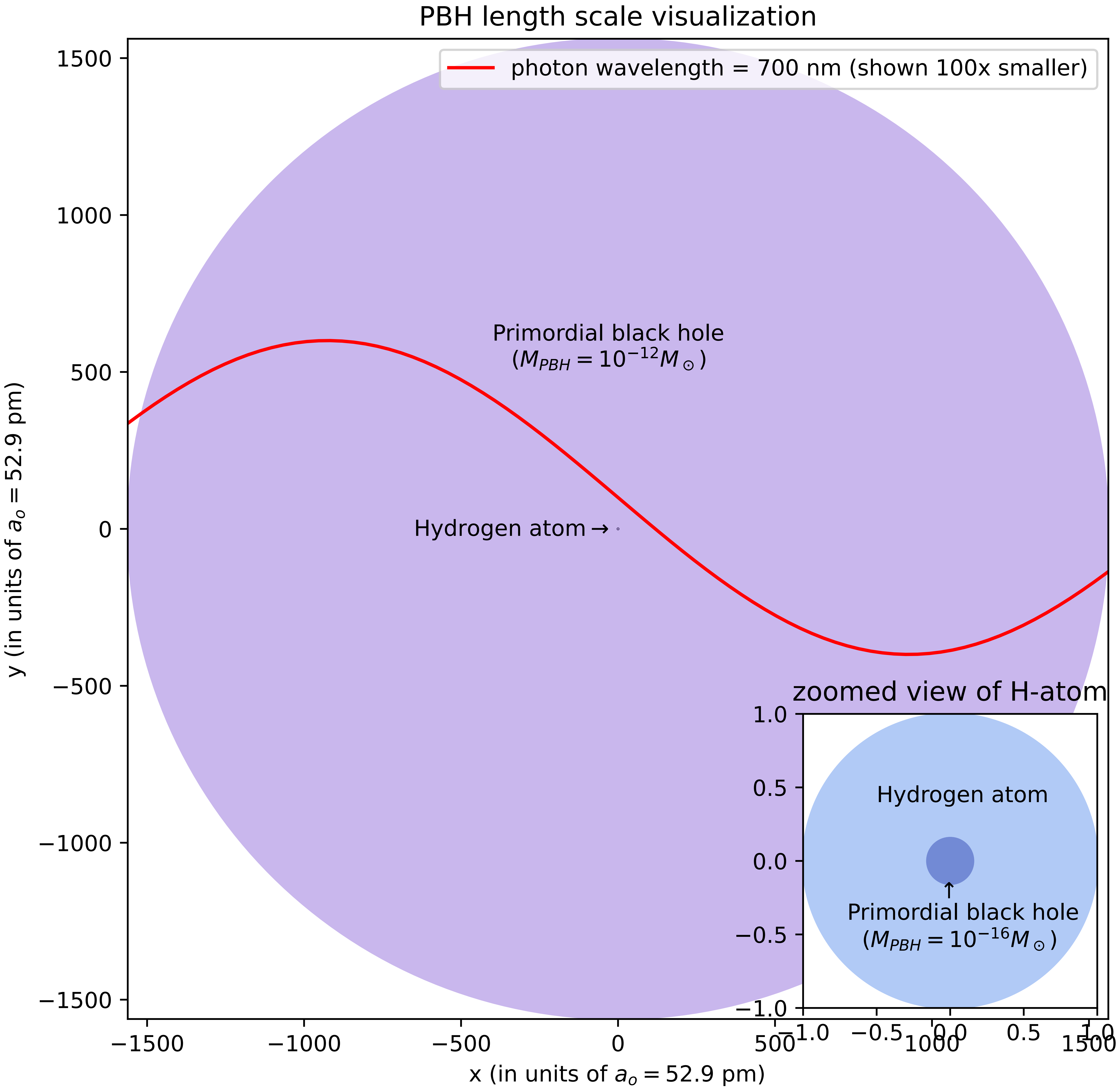
Manish Tamta et. al. + 2024
arXiv:2405.20365

X-ray telescope sensitivities for PBH dark matter detection/exclusion



Manish Tamta et. al.
+ 2024

$X\mu$: used the SED of Crab-like pulsar in SMC



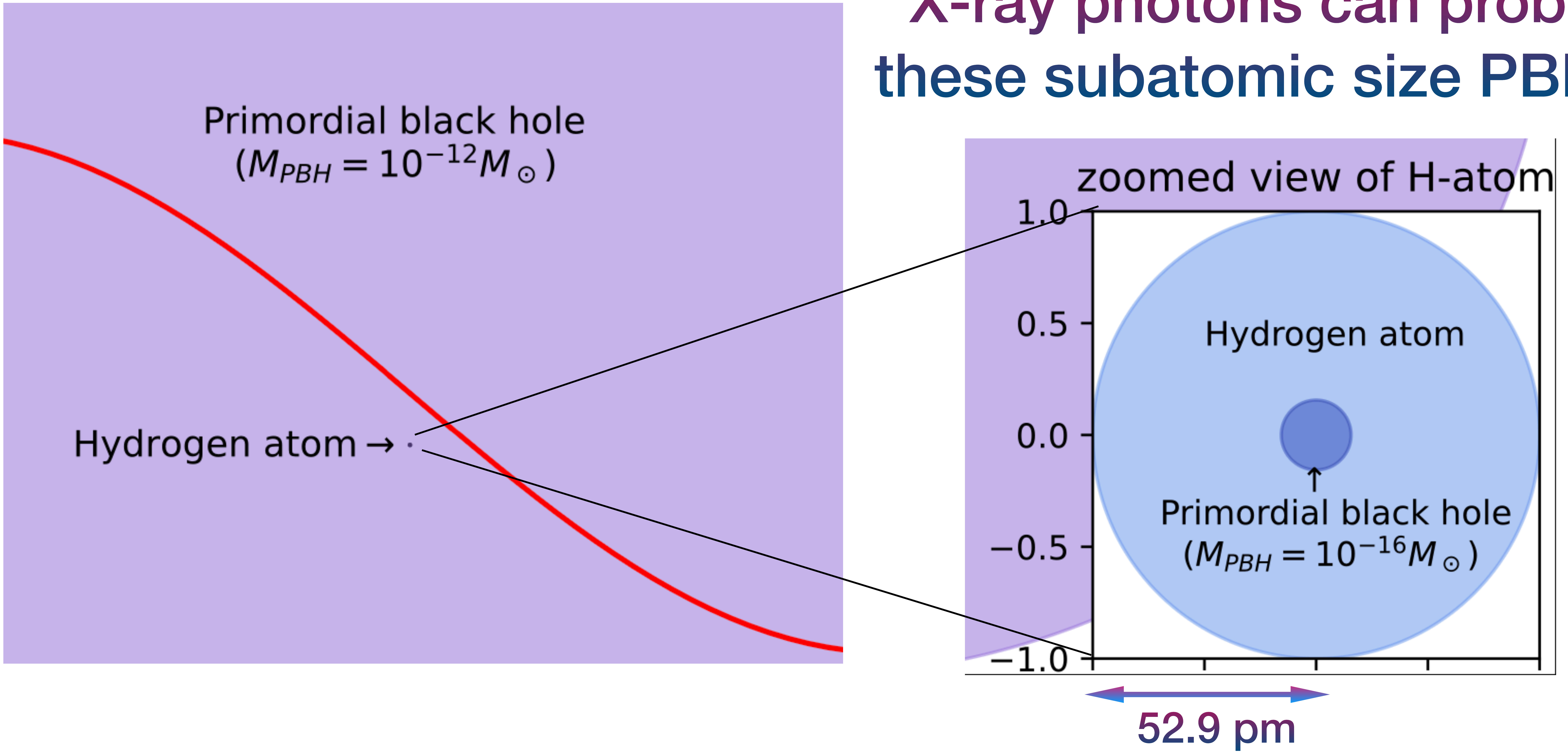
Mass/length scales involved

$$M_{PBH} \in [10^{-16}, 10^{-11}]\, M_\odot$$

$$R_{Schw} \in [2.9 \times 10^{-13}, 2.9 \times 10^{-8}]\, m$$

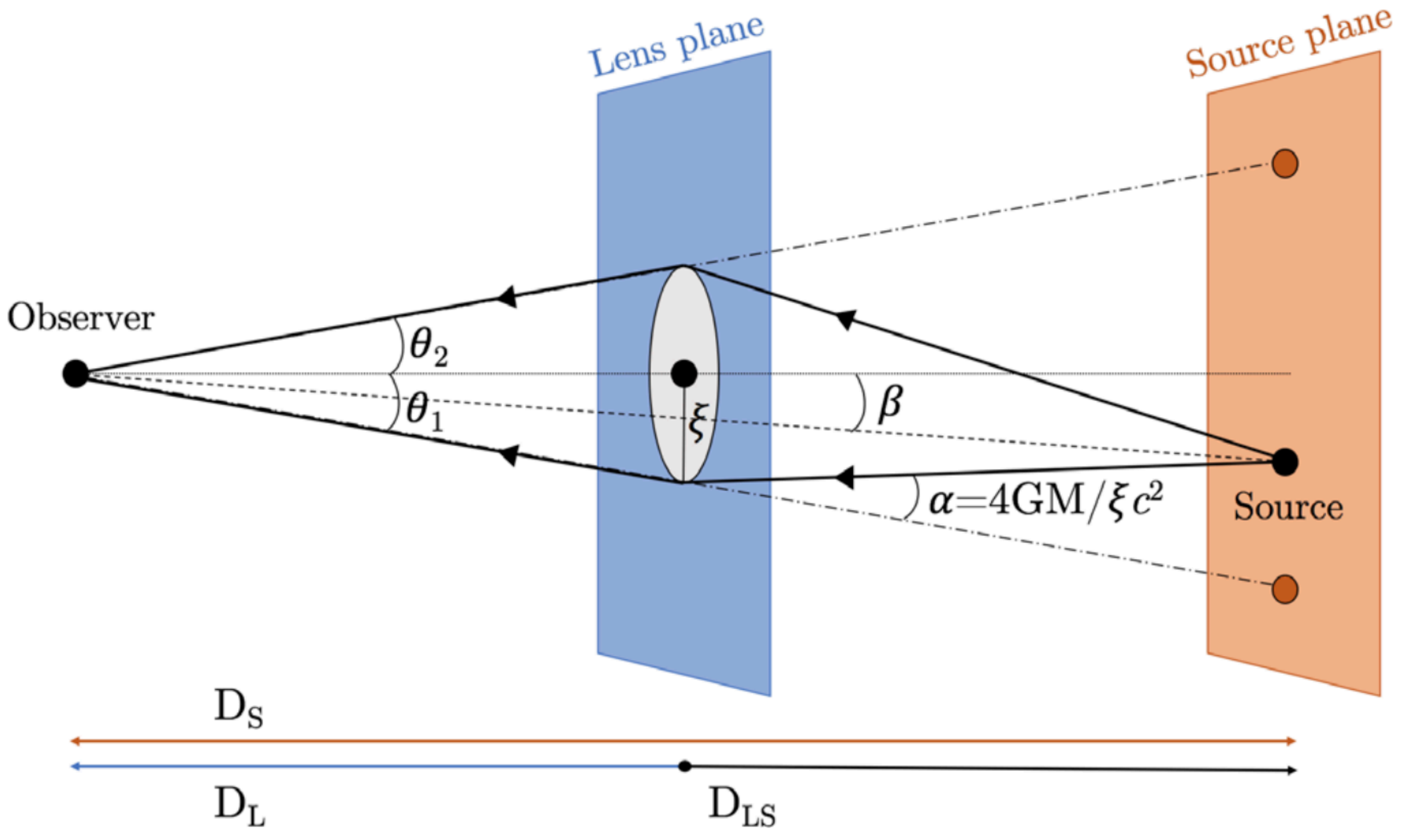
Manish Tamta + 2024

X-ray photons can probe these subatomic size PBHs

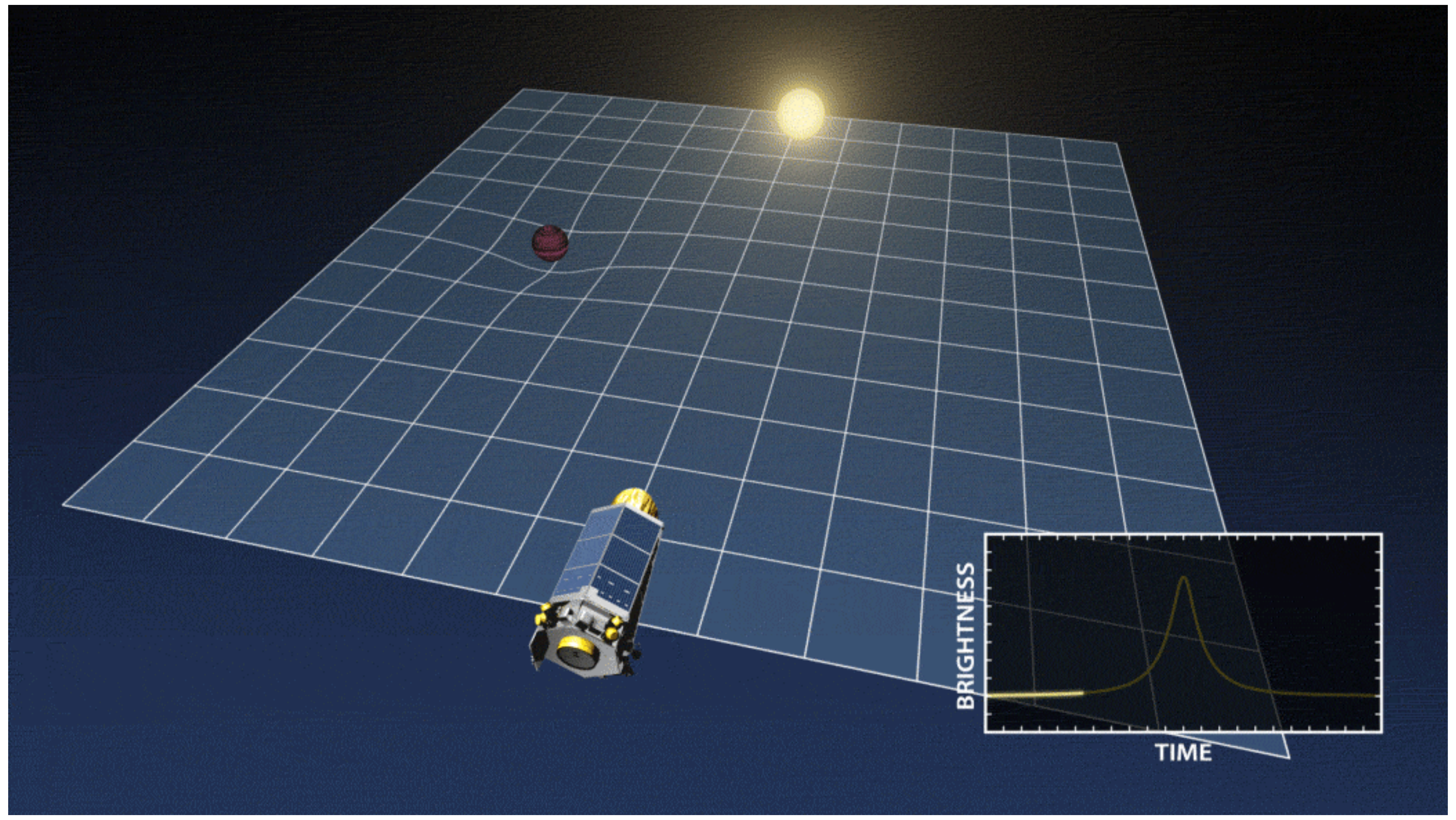


What is gravitational microlensing

Lens equation: $\vec{\beta} = \vec{\theta} - \vec{\alpha}$



Croon, McKeen, Raj + 2020



$$\hat{\alpha} = \frac{4GM}{c^2\xi} = \frac{2R_{Schw}}{\xi}$$

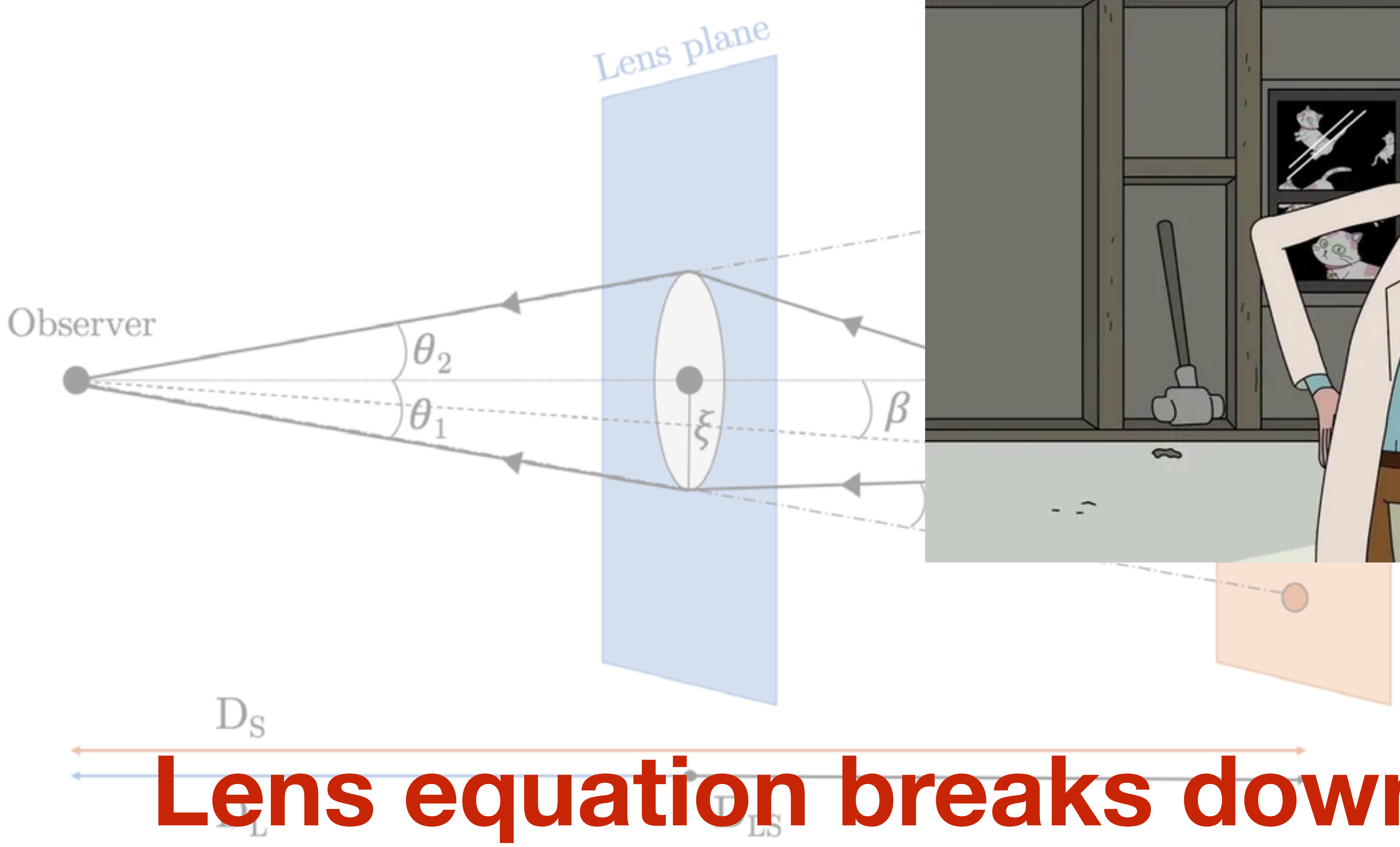
Magnification due to a point lens

$$\mu = \frac{\theta}{\beta}\frac{d\theta}{d\beta} = \frac{y^2+2}{y\sqrt{y^2+4}}$$

$$y \equiv \frac{\beta}{\theta_E}$$

Need for wave optics microlensing

Lens equation: $\vec{\beta} = \vec{\theta} - \vec{\alpha}$



$$\hat{\alpha} = \frac{\quad}{c^2\xi} = \frac{2R_{Shcw}}{\xi}$$

Lens equation breaks down when microlensing happens in the wave regime!

Croon, McKeen, Raj + 2020

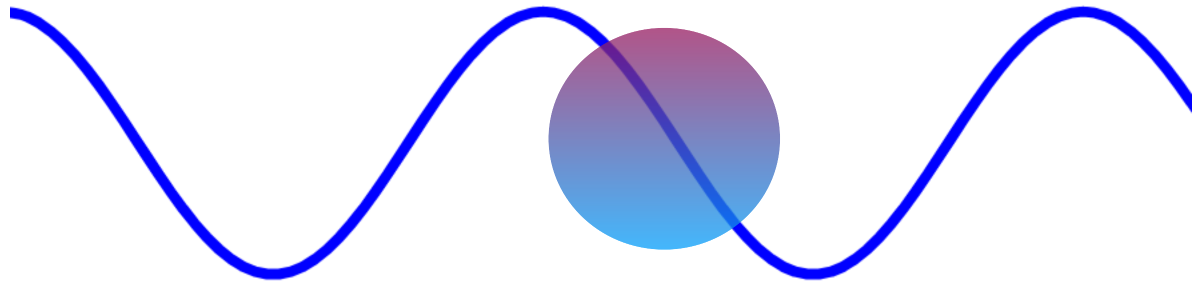
$$\mu = \frac{\theta}{\beta}\frac{d\theta}{d\beta} = \frac{y^2+2}{y\sqrt{y^2+4}}$$

Wave regime lensing and Parameter w

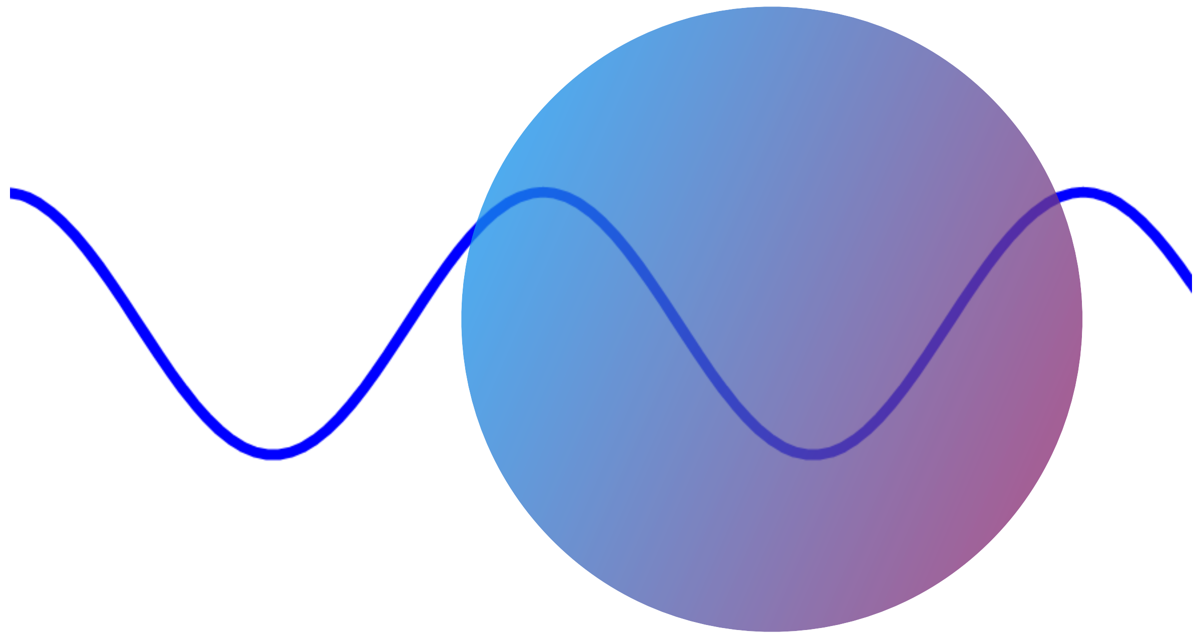
$$w \equiv \frac{4GME_\gamma}{\hbar c^3} = \frac{2R_{schw}E_\gamma}{\hbar c}$$

Dimensionless frequency

Wave regime: if $w \lesssim y^{-1}$



Geometric optics regime: when $w >> y^{-1}$



Note that y is impact parameter!

Theory of gravitational microlensing in the wave regime+FSE

Pulsar

Wave-effects

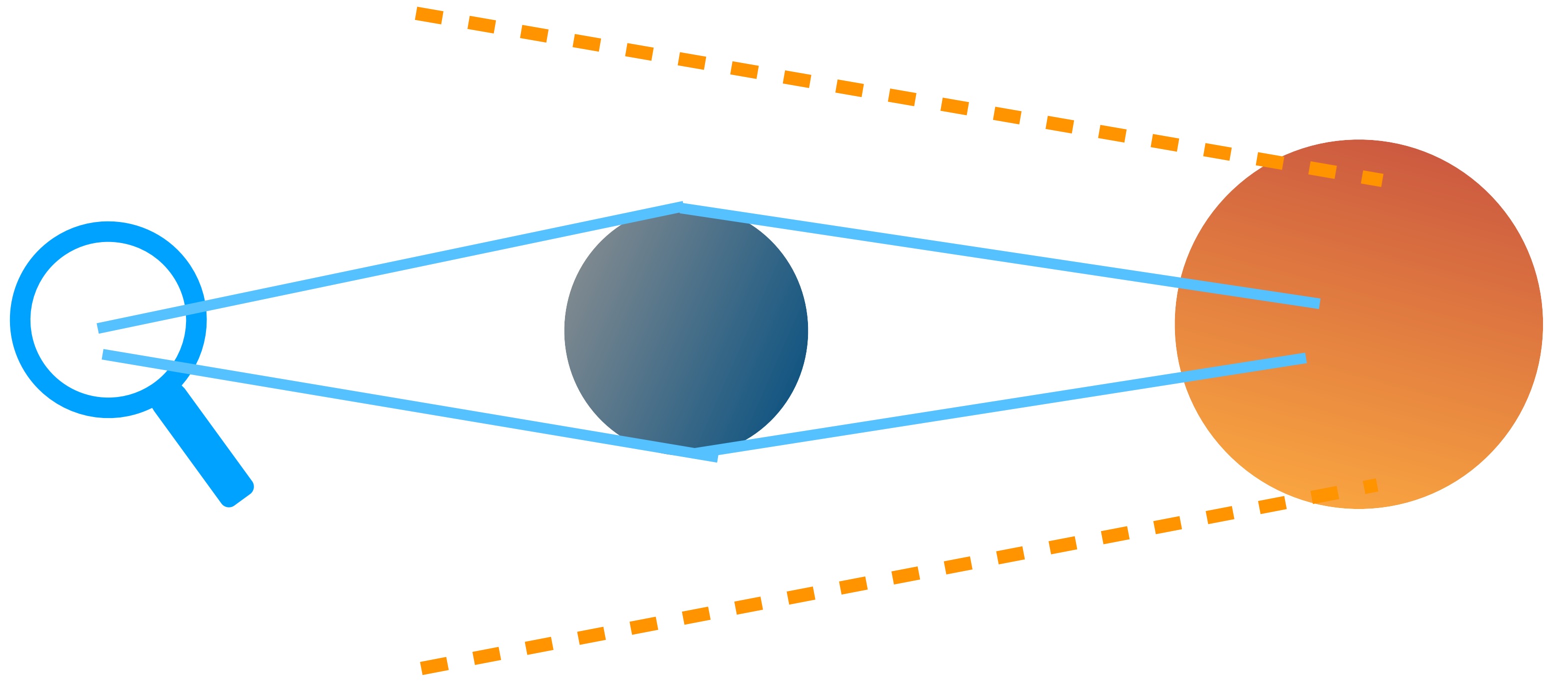
$$\bar{\mu}_E(y, a_s(x)) = \frac{1}{\mathcal{N}} \int_{E_{min}}^{E_{max}} dE \mathscr{A}(E)\mathscr{F}(E) a_s^{-2} e^{-\frac{y^2}{2a_s^2}} \frac{\pi w}{1-e^{-\pi w}} \int_0^\infty r e^{\frac{-r^2}{2a_s^2}} I_0(yr/a_s^2) \left| {}_1F_1\left(\frac{\imath w}{2}, 1; \frac{\imath w r^2}{2}\right)\right|^2 dr$$

Detector

Finite extent of the source

$$a_S = \frac{x R_S}{r_E}$$

where $\mathcal{N} = \int_{E_{min}}^{E_{max}} dE \mathscr{A}(E)\mathscr{F}(E)$



Frequency dependent magnification!

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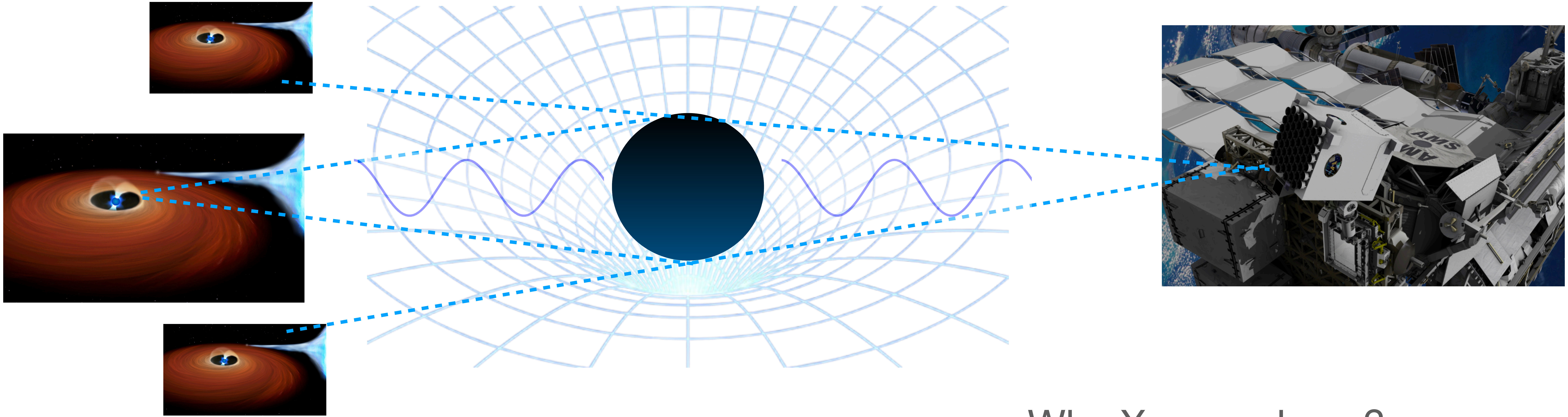
X-ray microlensing can probe subatomic size PBHs

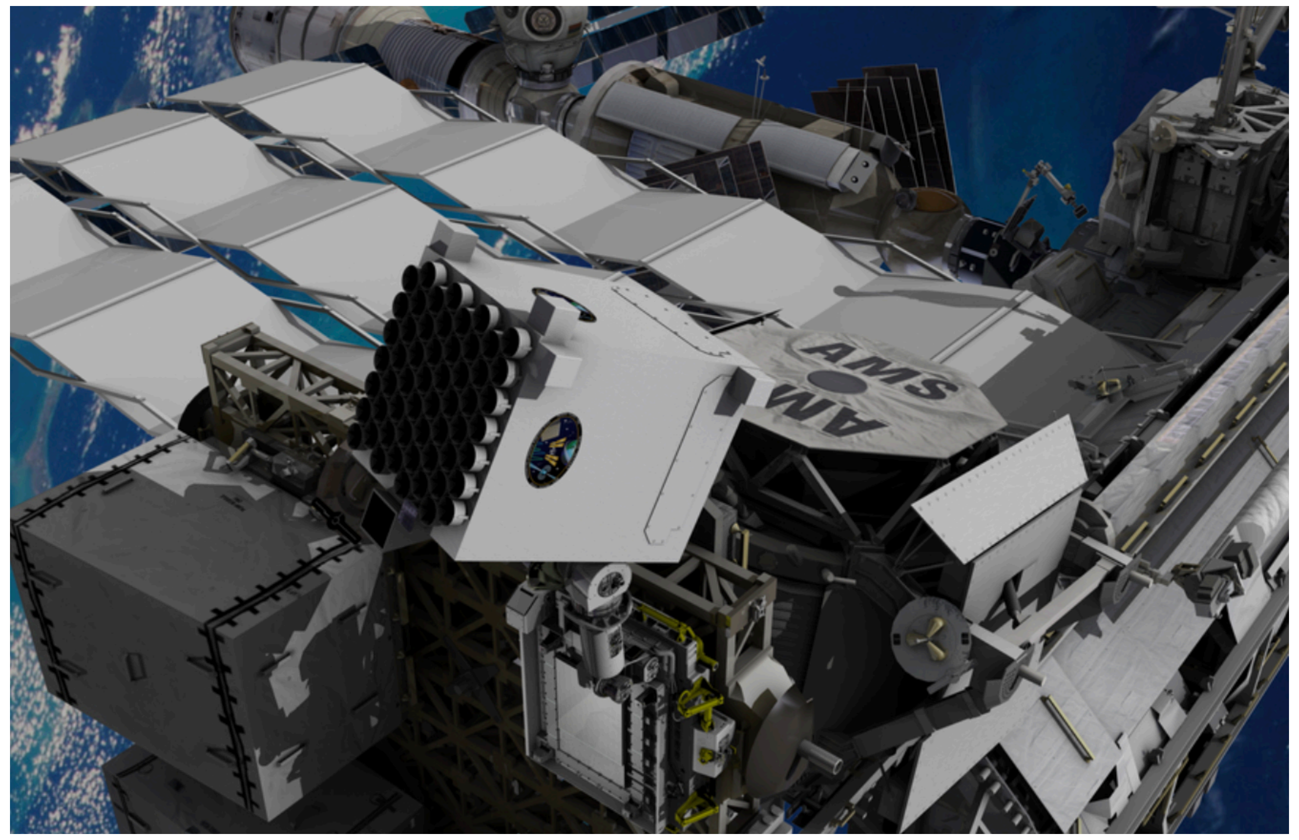


Yang Bai et. al. + 2019

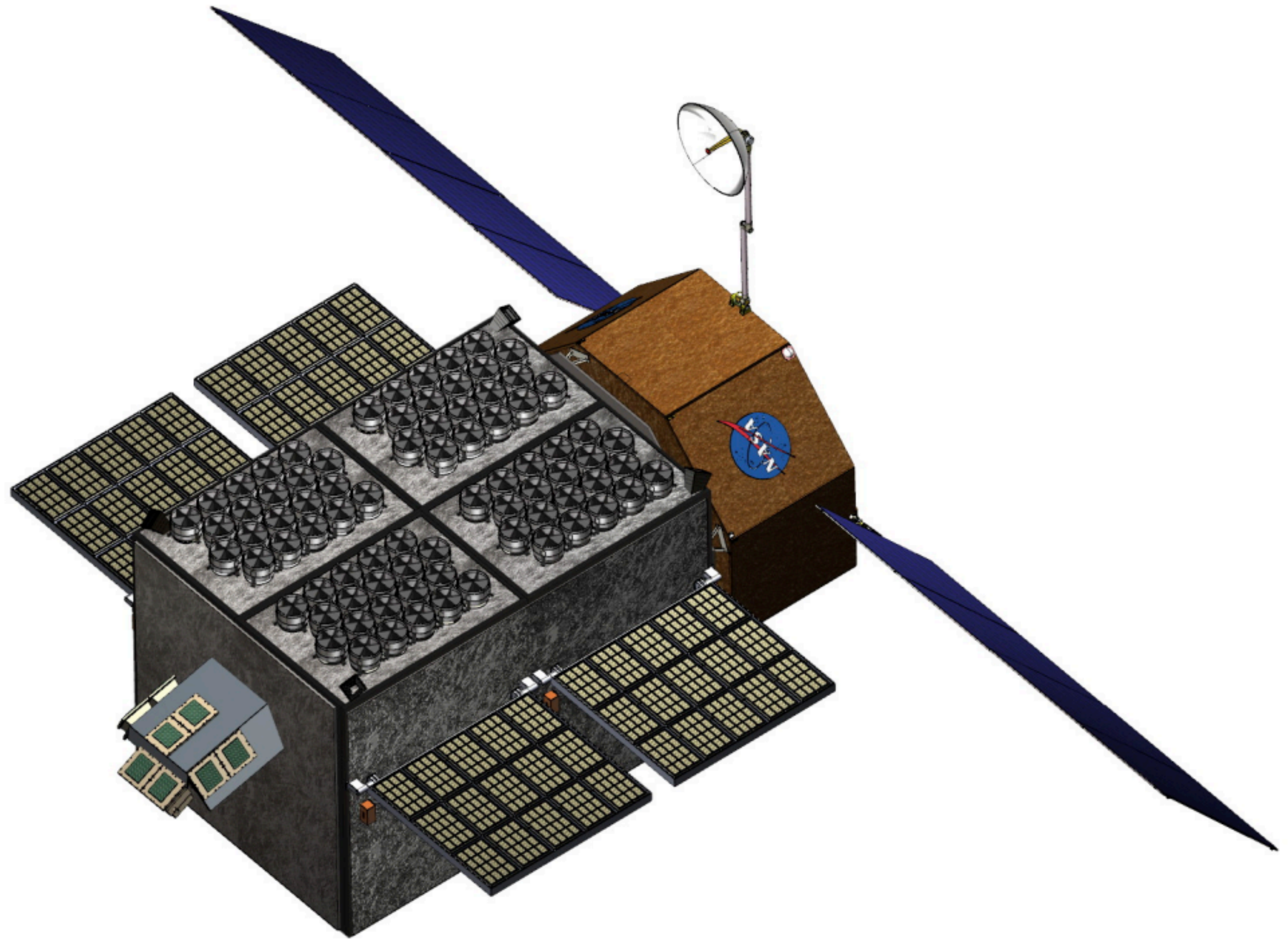
Why X-ray pulsars?

- Less variability and persistent x-ray emission
- Higher photon counts

Telescopes and pulsars for x-ray microlensing

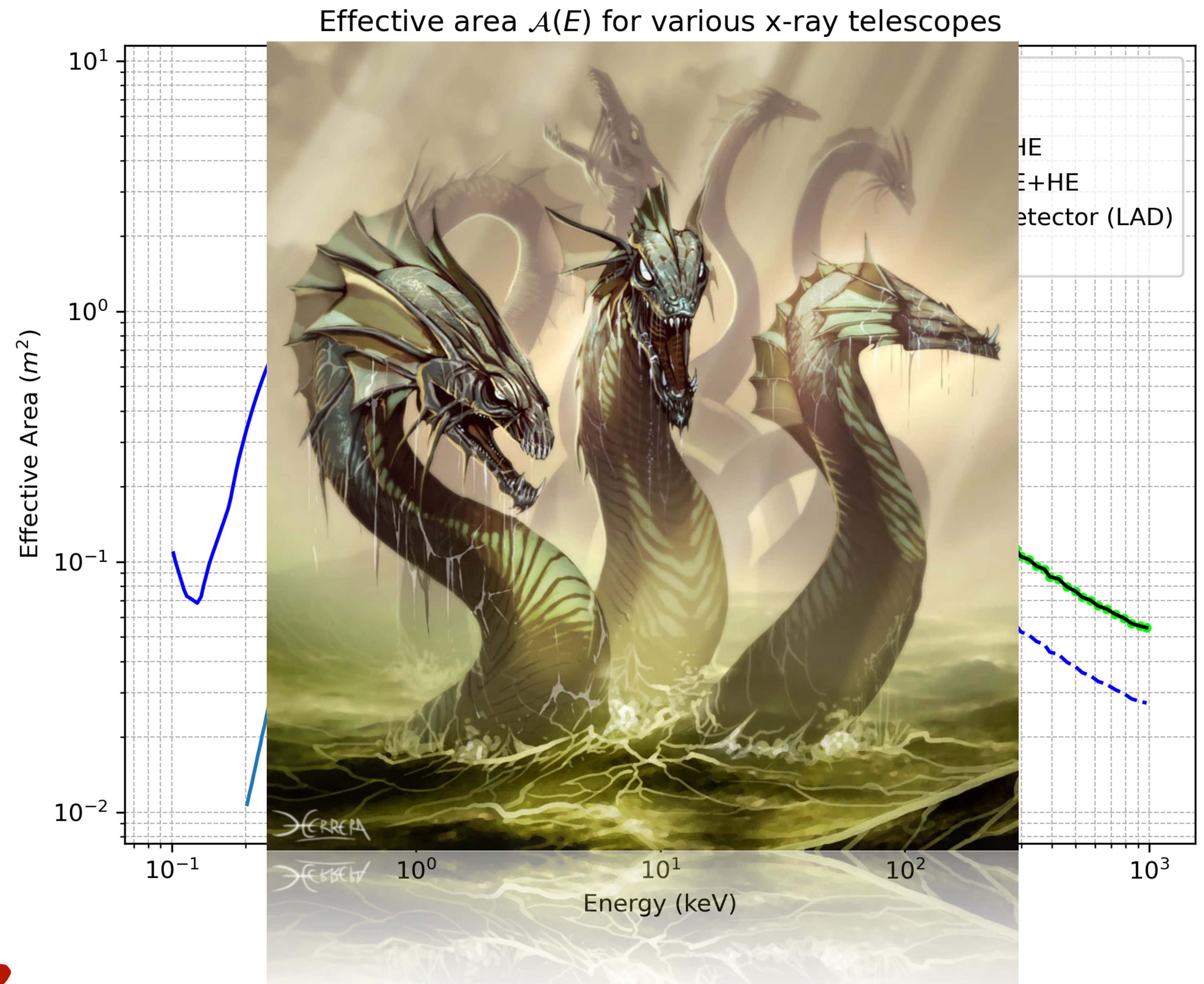


NASA's NICER
https://svs.gsfc.nasa.gov/



STROBE-X
arXiv:1903.03035

Expected launch: 2031



$X\mu$

Let's hope for such telescopes in the near future :)

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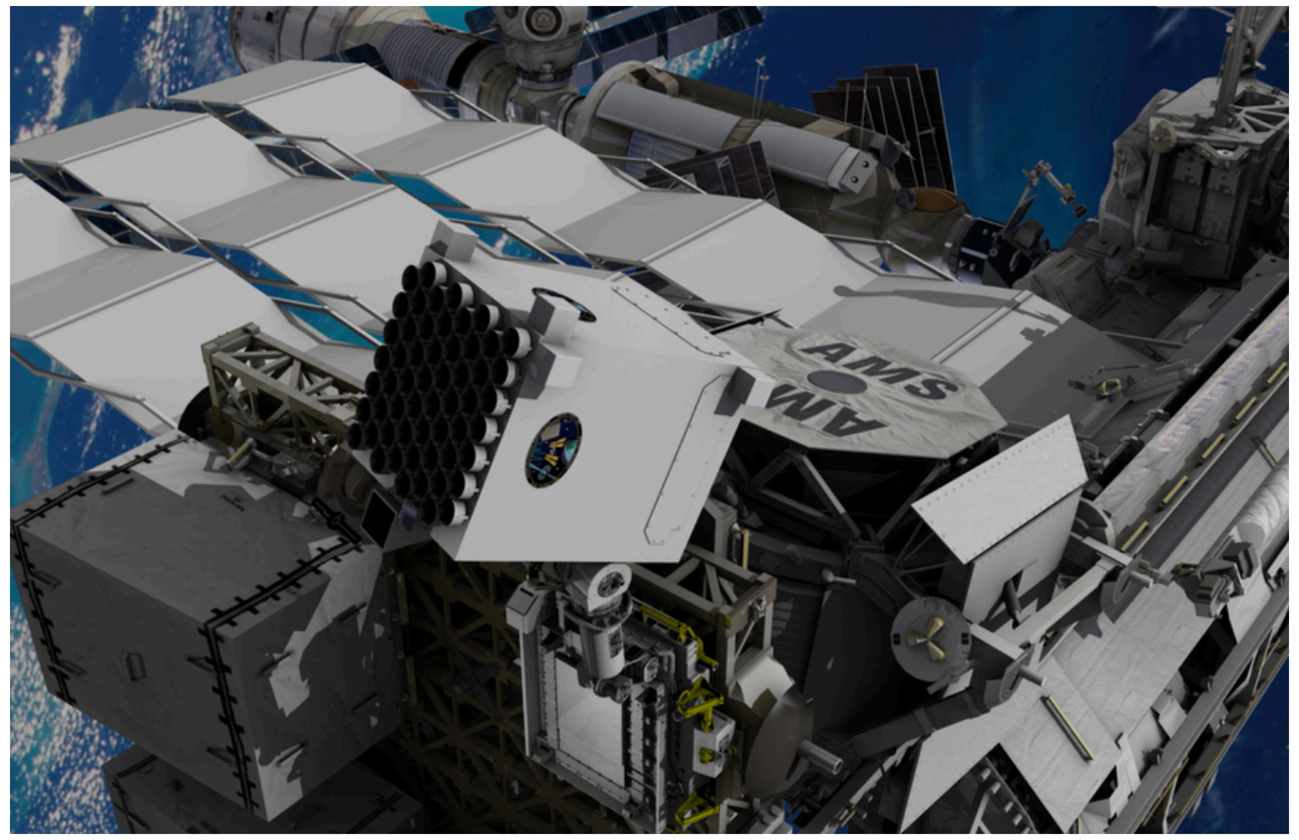
Telescopes and pulsars for x-ray microlensing



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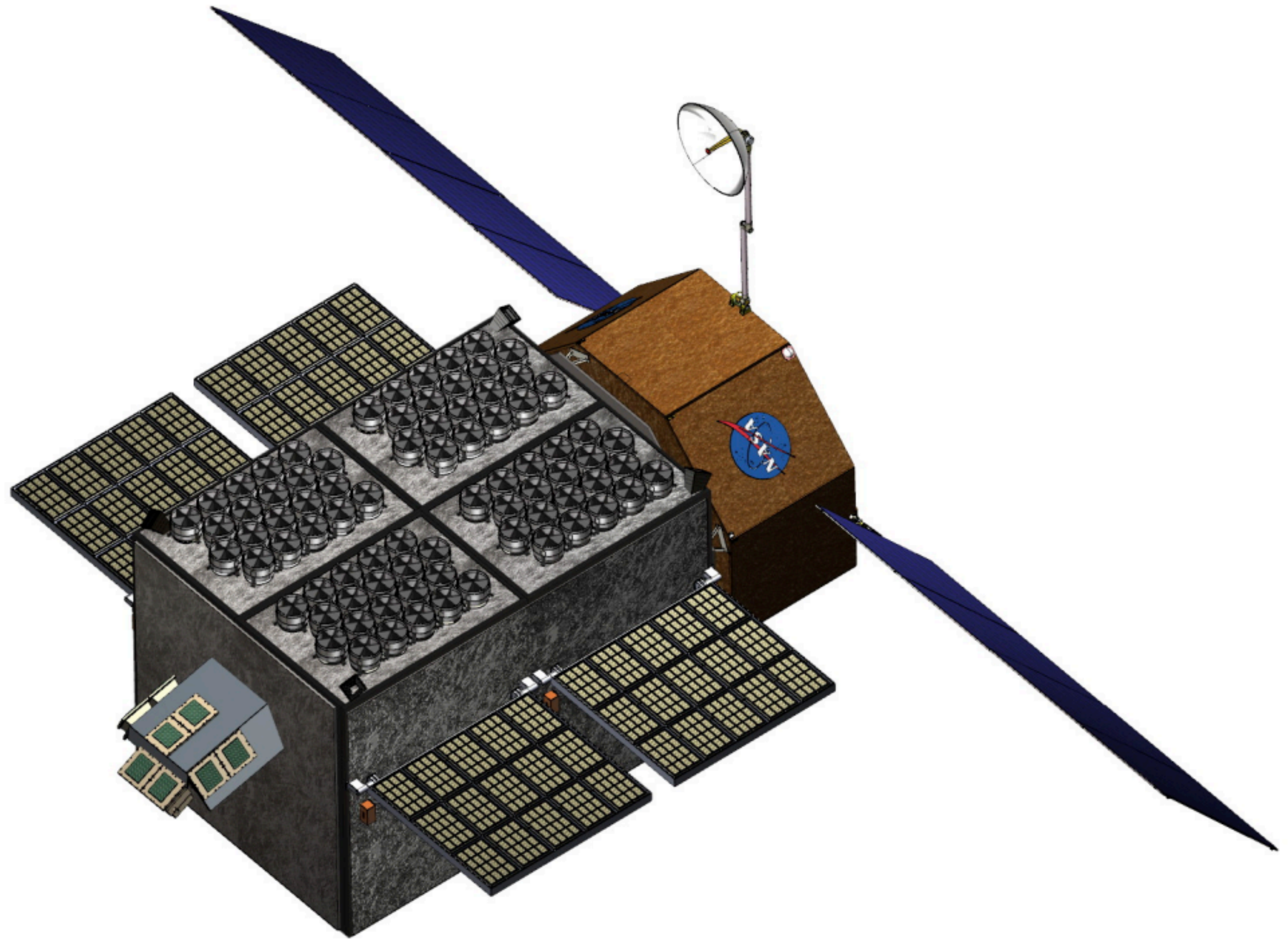

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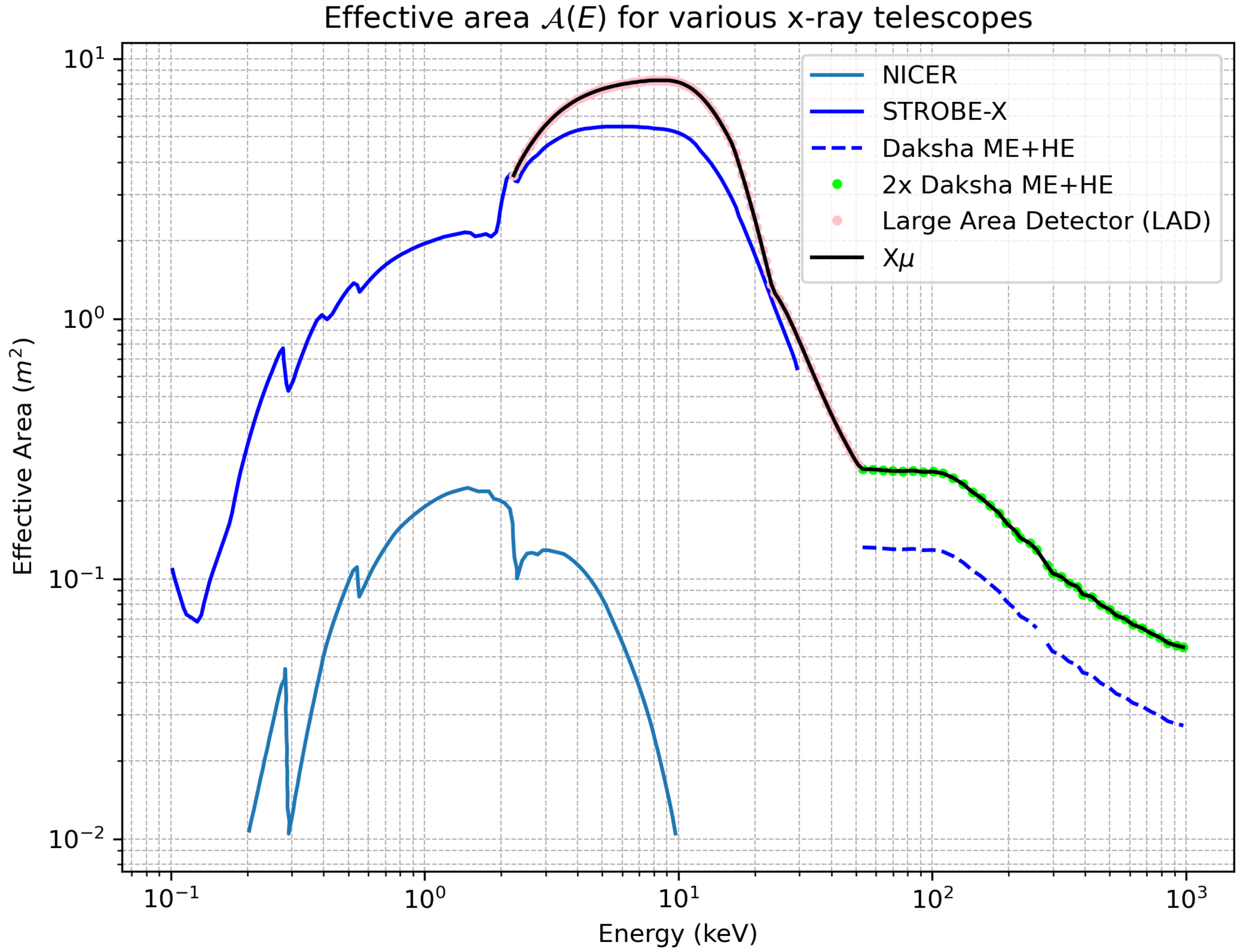
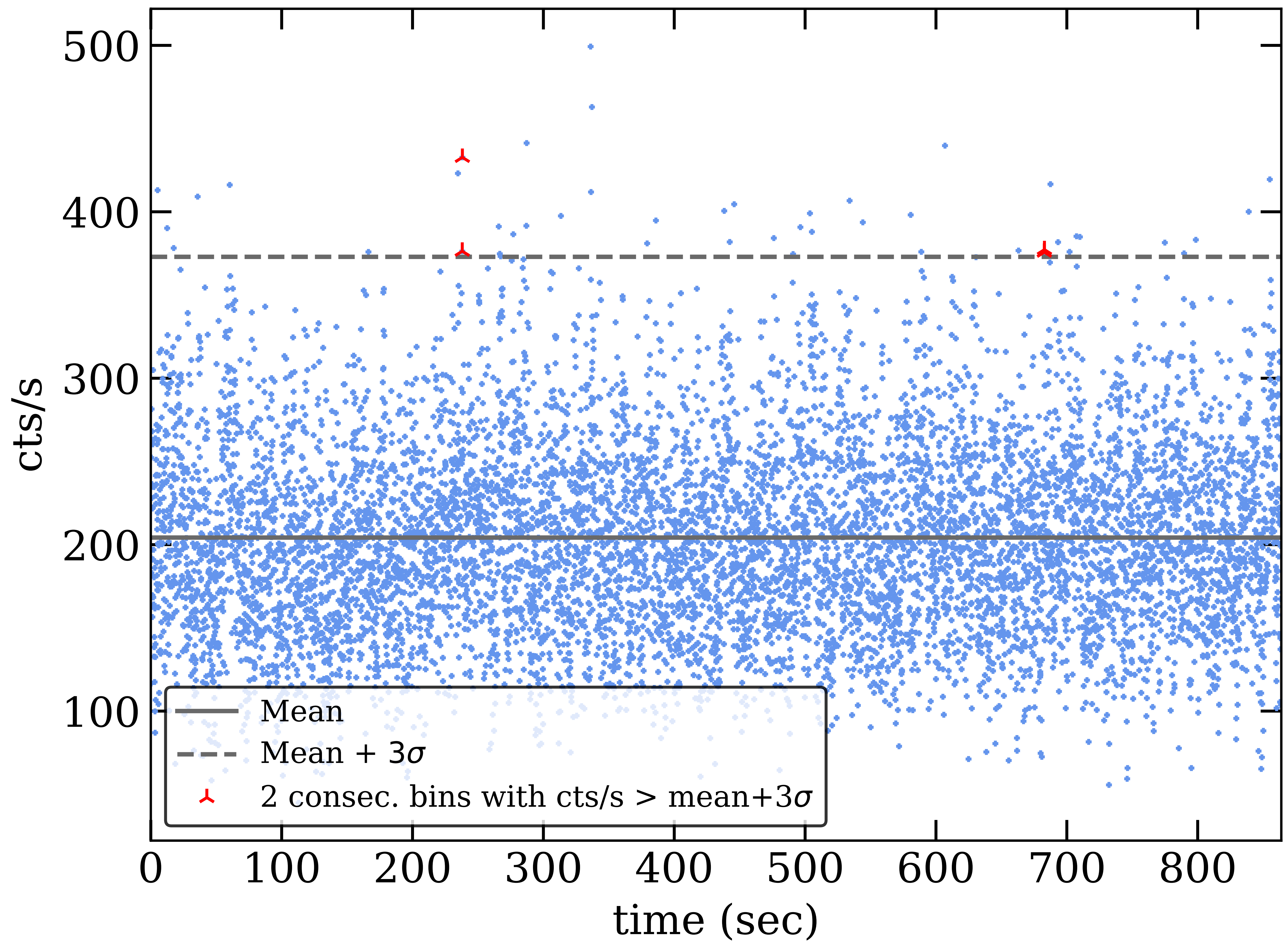


$X\mu$

x-ray pulsar	net exposure (days)	D_S (kpc)	(ℓ, b)	σ_B/B
SMC X-1	1.74	64 [28]	$(300.41°, -43.56°)$	0.28
Cyg X-2	5.47	11 [29]	$(87.33°, -11.32°)$	0.02
Vela X-1	4.46	2 [30]	$(263.06°, 3.93°)$	0.25
Crab pulsar	4.76	2 [31]	$(184.56°, -5.78°)$	0.01

Statistical way of interpreting X-ray pulsar light curve



How to identify a true microlensing event in the light curve?

Excess x-ray photon counts at 3σ level for 3 consecutive time bins is a detection!

+

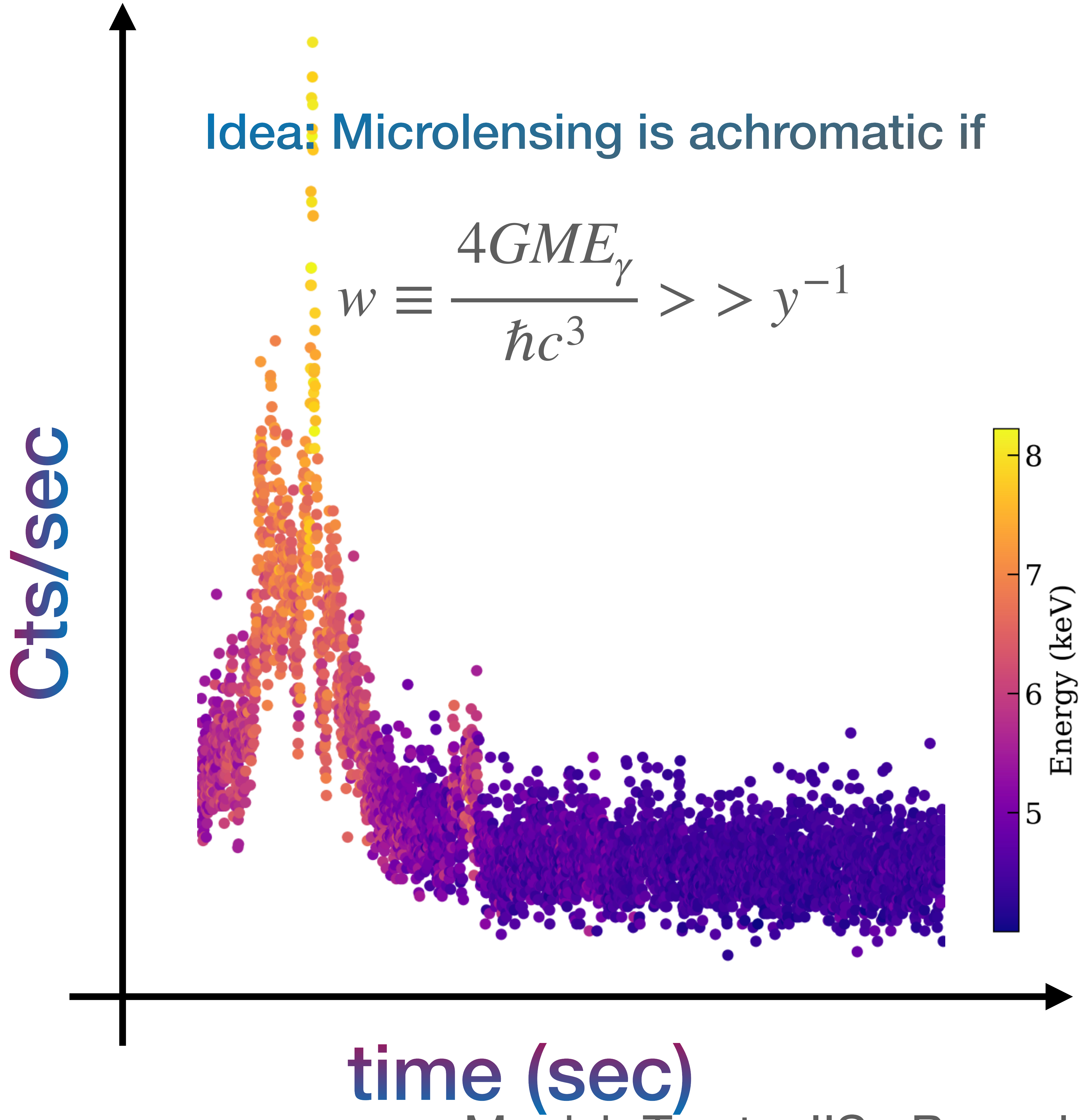
Achromaticity $(w \gtrsim y^{-1})$

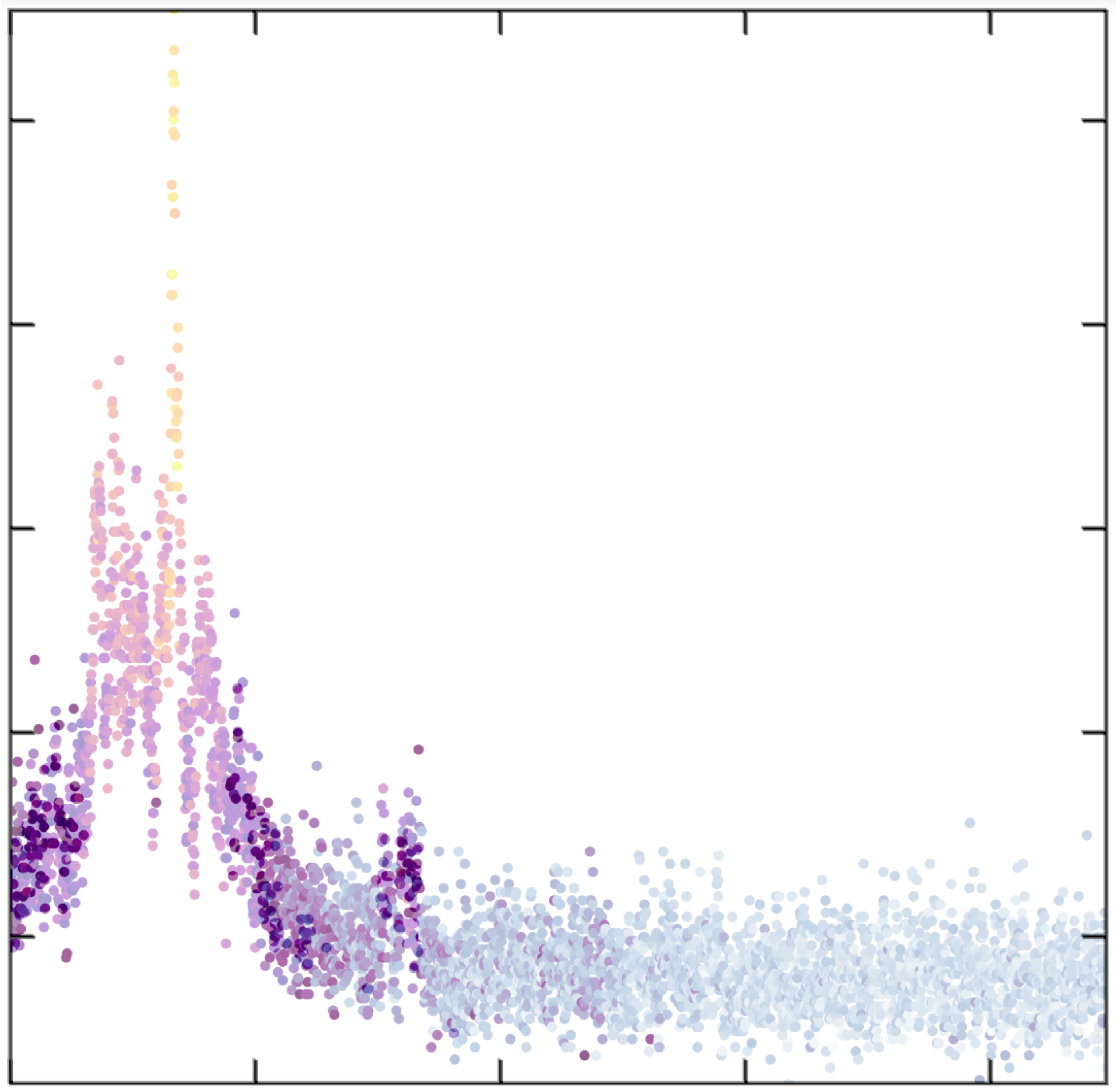
$$\mathbb{P}(N_\sigma) = [1 - \Phi(N_\sigma = 3)]^{N_{consec}=3} = 2.5 \times 10^{-9}$$

A new diagnostic for x-ray microlensing

Idea: Microlensing is achromatic if

$$w \equiv \frac{4GME_\gamma}{\hbar c^3} >> y^{-1}$$





Split the light curve into multiple energy windows

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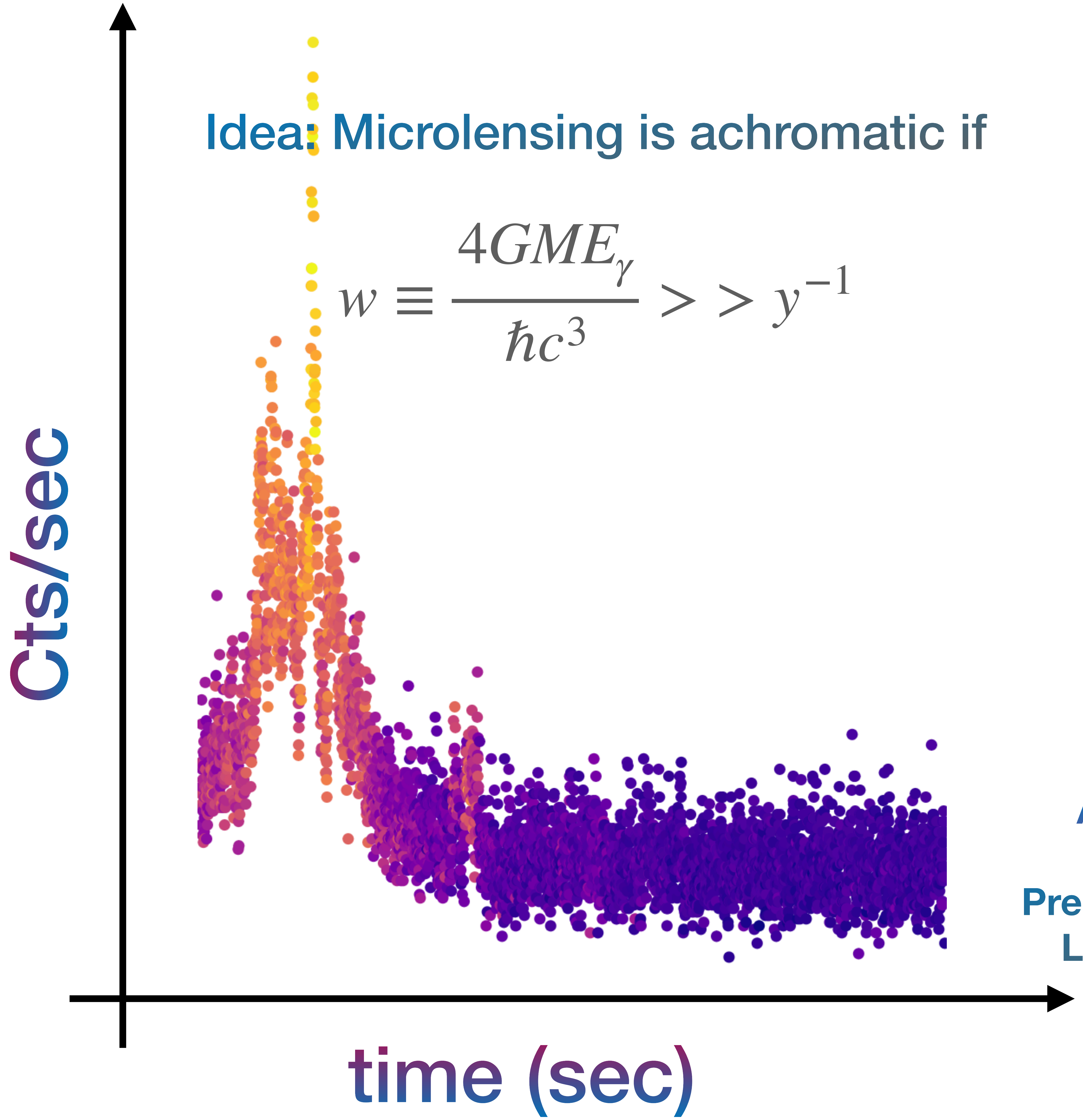

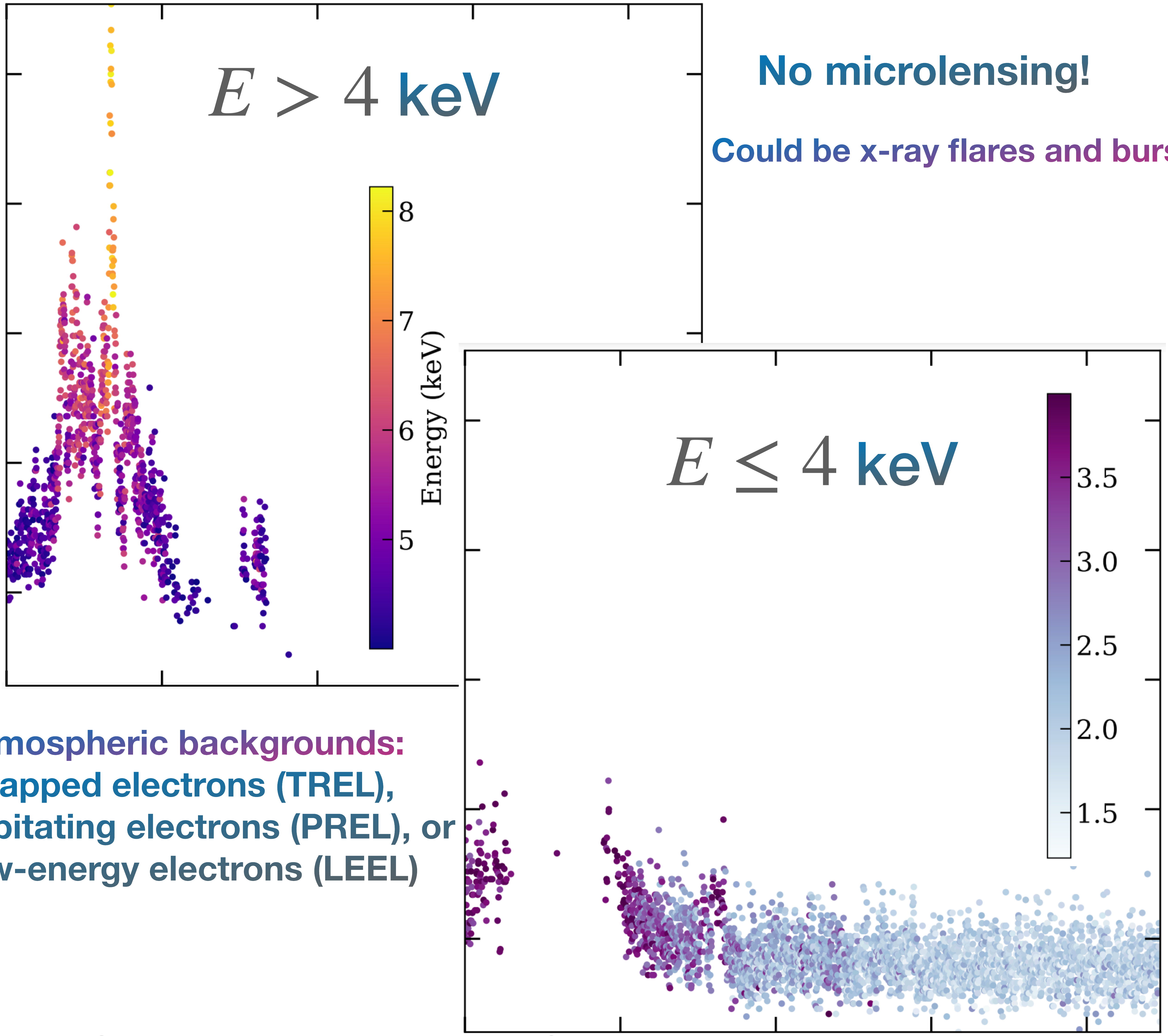

No microlensing!

Could be x-ray flares and bursts

Atmospheric backgrounds:
Trapped electrons (TREL),
Precipitating electrons (PREL), or
Low-energy electrons (LEEL)

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Microlensing Event Rate

$$\frac{d\Gamma}{dt_E} = f_{PBH}\frac{2D_s}{Mv_0^2}\int_0^1 dx\rho_{dm}(x)v_E^4(x)e^{-v_E^2/v_0^2} \times \int_0^{y_T(x)} \frac{dy}{\sqrt{y_T^2 - y^2}} \times \mathbb{P}(n_\sigma)$$

Local DM density

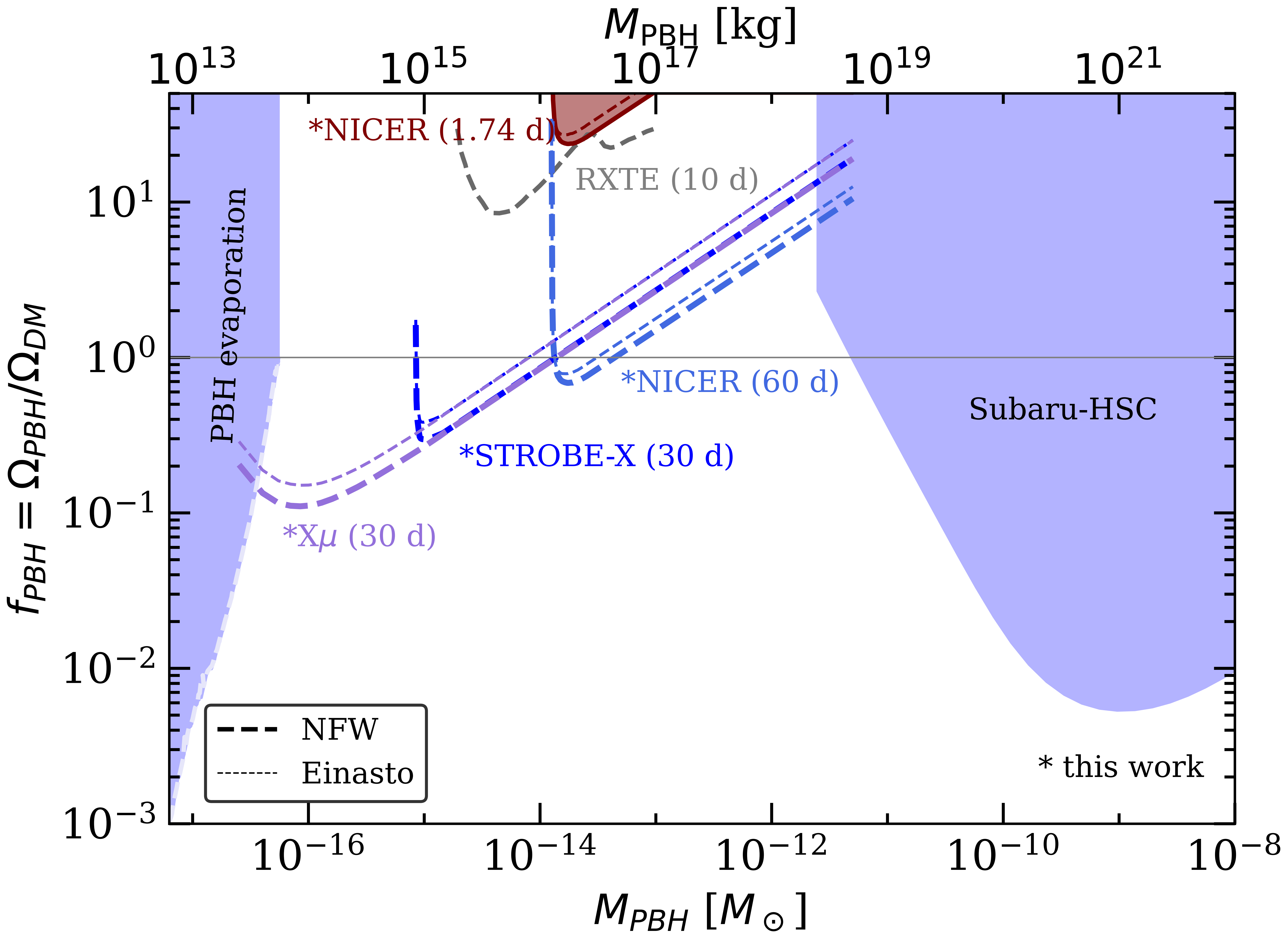
$$v_E \equiv 2r_E\sqrt{y_T^2 - y^2}/t_E$$

Remember

$$d\Gamma \sim 1/\sqrt{M}$$

Total # of microlensing events: $N_{ev} = f_{PBH}\sum_i T_{obs}^i \int_{t_{min,i}}^{t_{max,i}} dt_E \frac{d\Gamma_i}{dt_E}$

X-ray telescope sensitivities for PBH dark matter detection/exclusion



Xμ: used the SED of Crab-like pulsar in SMC

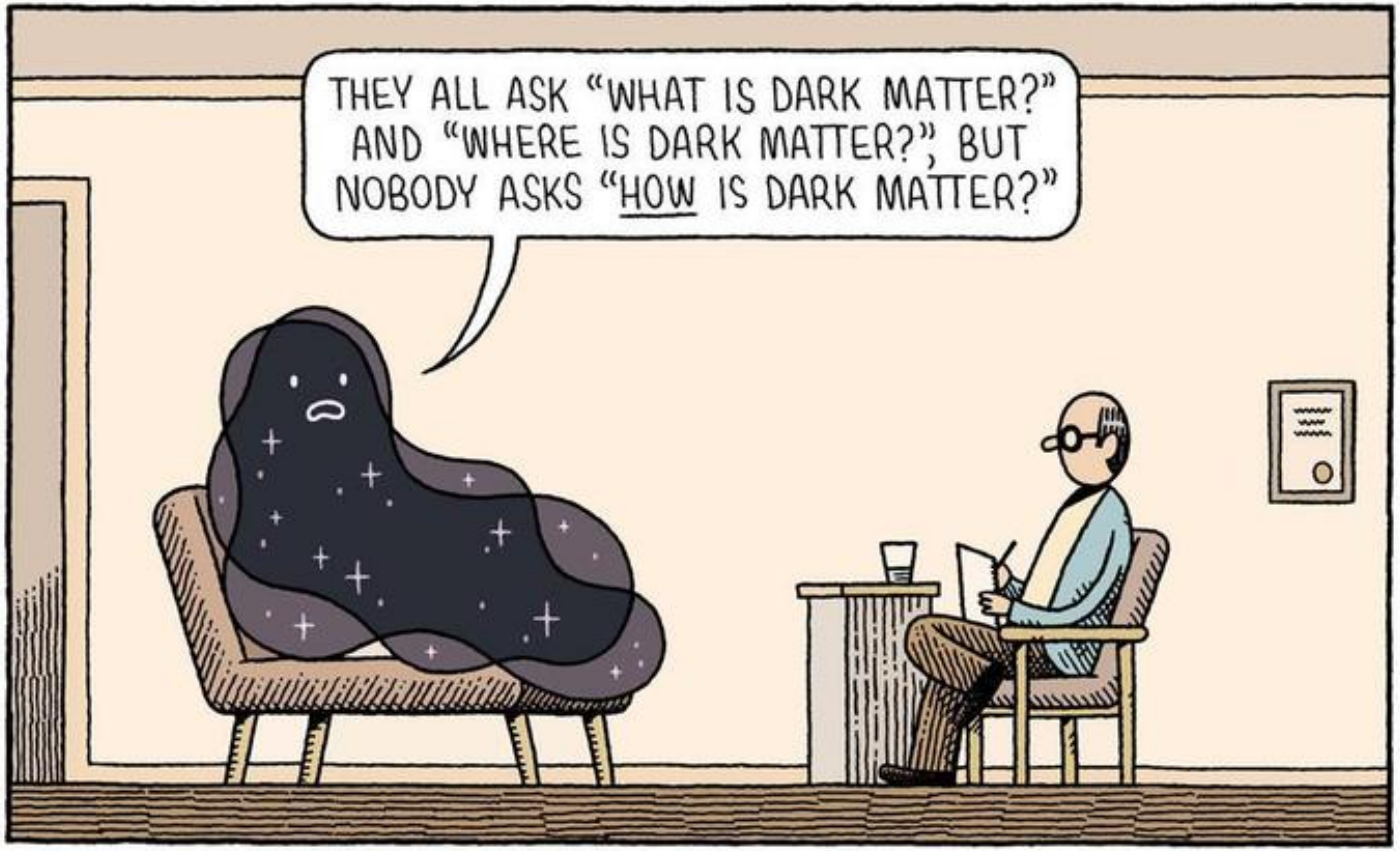
Take Home

- Primordial black holes (PBHs) in the mass range $10^{-16} - 10^{-11} M_{\odot}$ may constitute 100% dark matter.

- **WO microlensing of bright x-ray pulsars** provide the most robust and immediately implementable opportunity to uncover PBH dark matter.

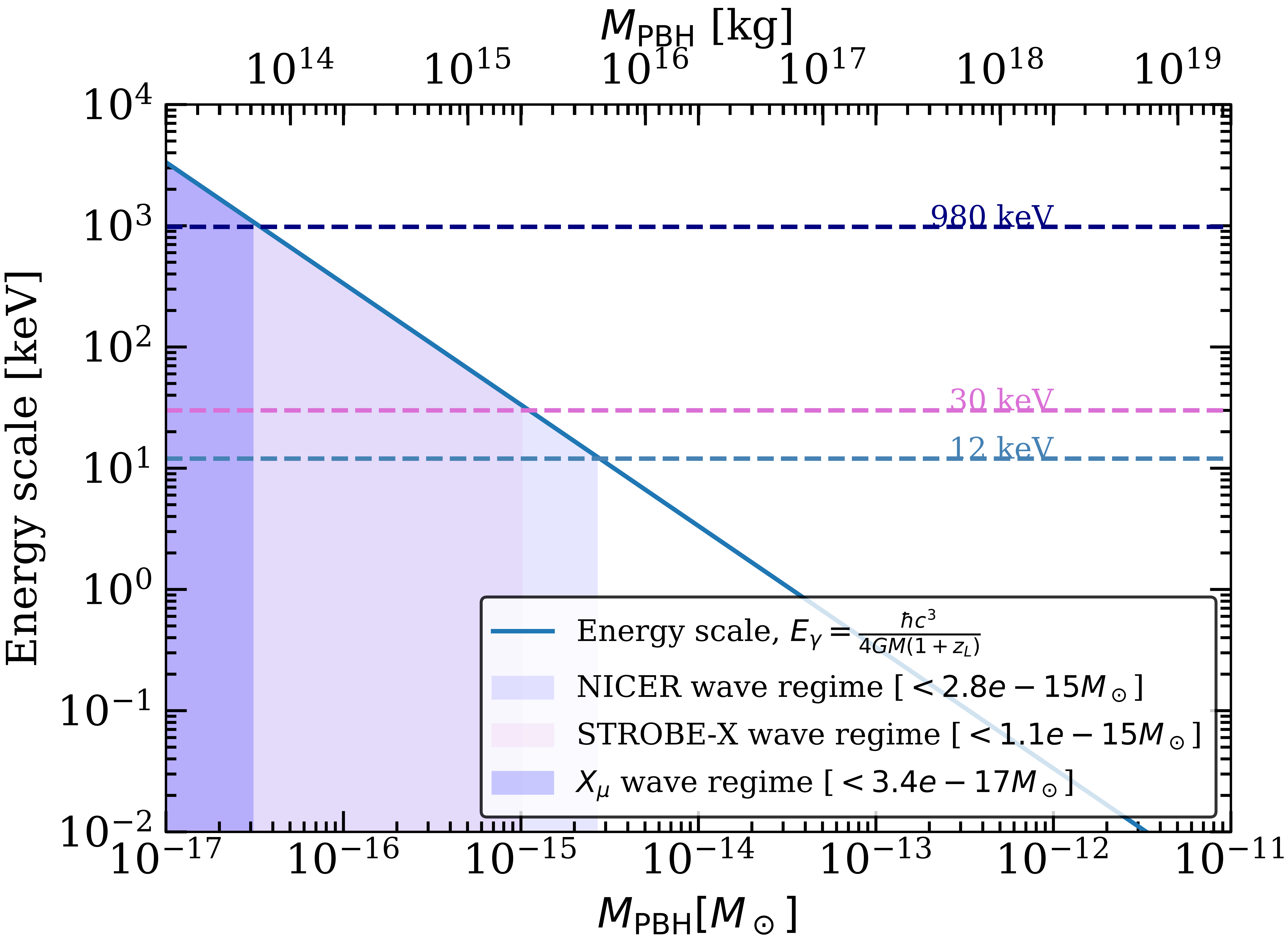
Take Home

- Primordial black holes (PBHs) in the mass range $10^{-16} - 10^{-11} M_\odot$ may constitute 100% dark matter.
- **WO microlensing of bright x-ray pulsars** provide the most robust and immediately implementable opportunity to uncover PBH dark matter.
- **NICER telescope** can probe this window near $10^{-14} M_\odot$ with **just two months** of exposure on the **x-ray pulsar SMC-X1**!
- PBH evaporation limit at around $10^{-16} M_\odot$, may be probed with a minimal microlensing setup involving **hard x-ray pulsars**!



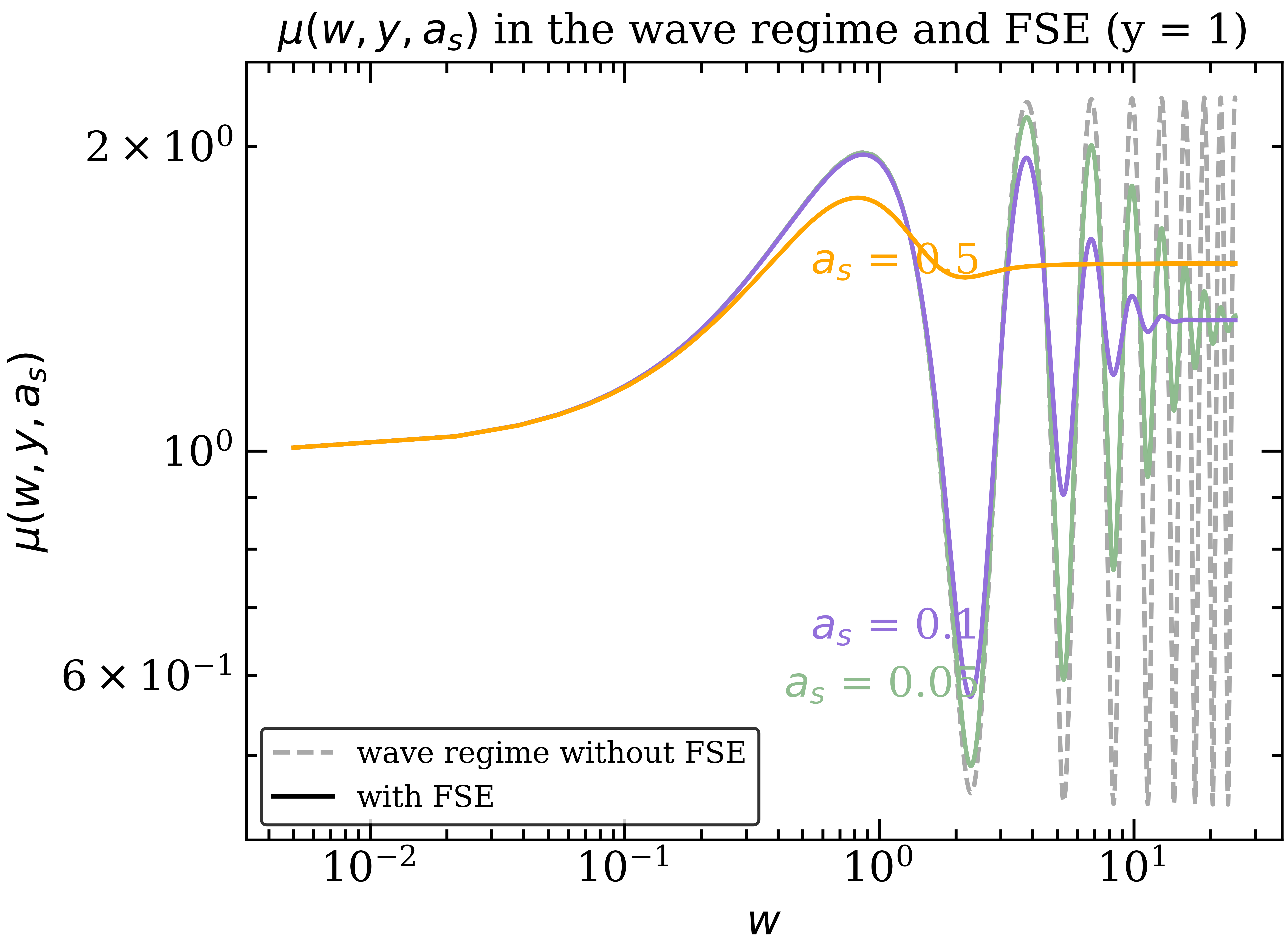
TOM GAULD for NEW SCIENTIST

Thank you for listening :)



PBH masses that can be probed

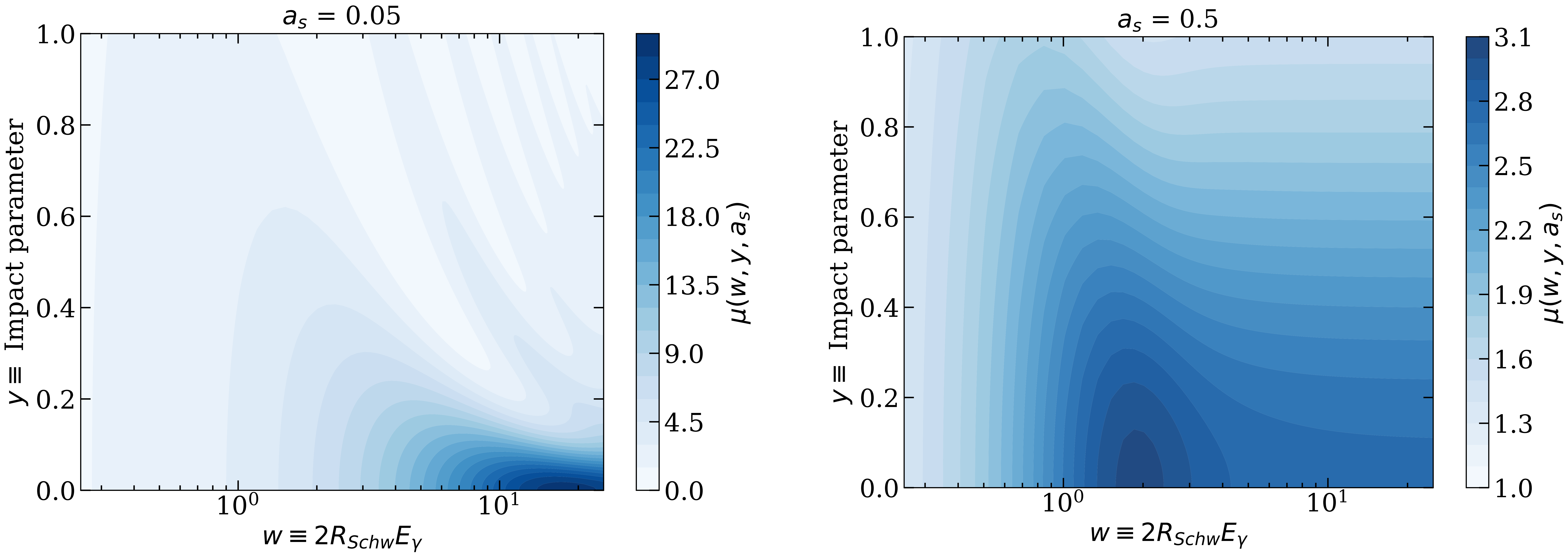
Buffer slides: Frequency dependent magnification



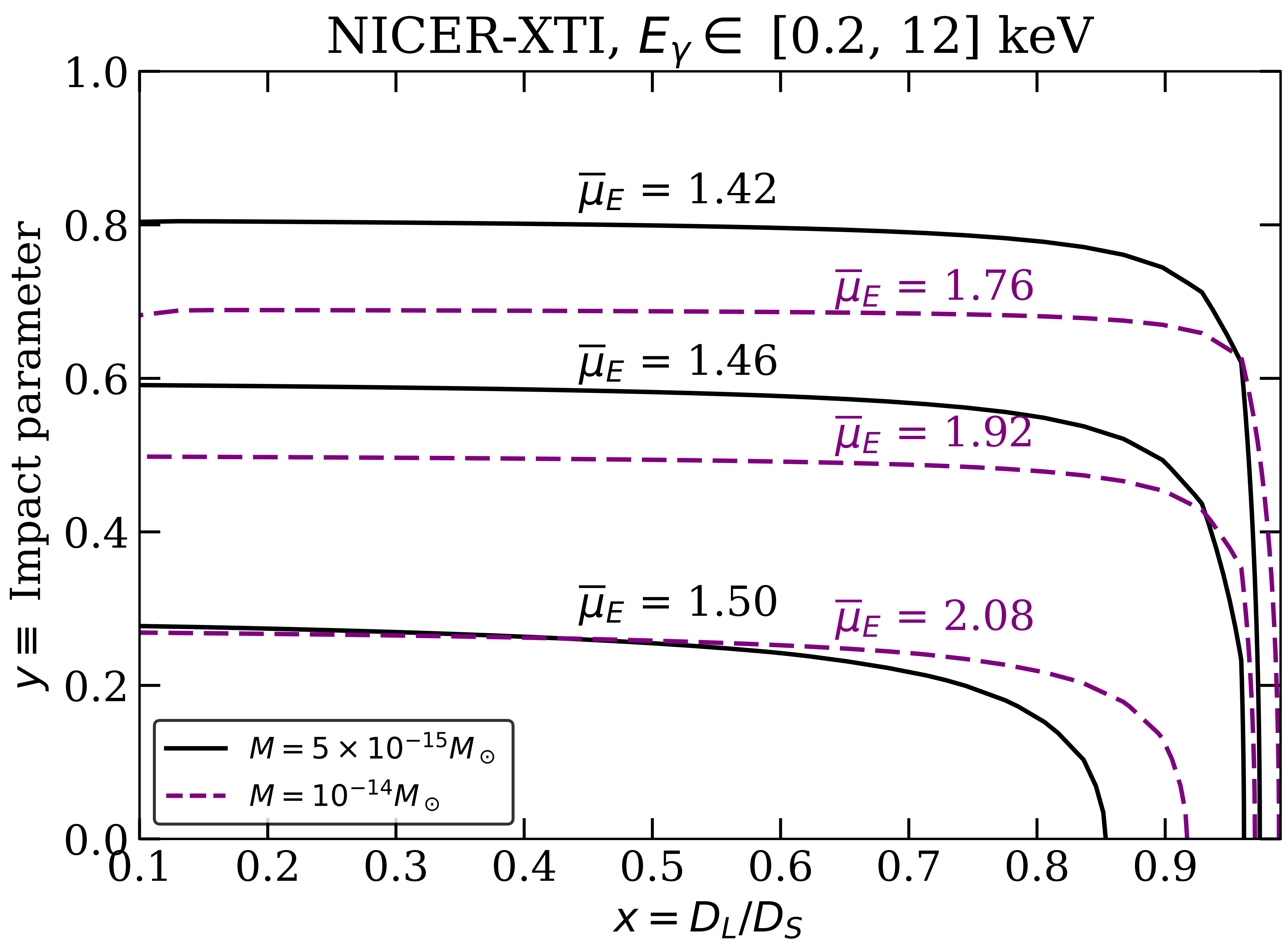
Microlensing magnification
in the wave regime
+
finite extent of the source

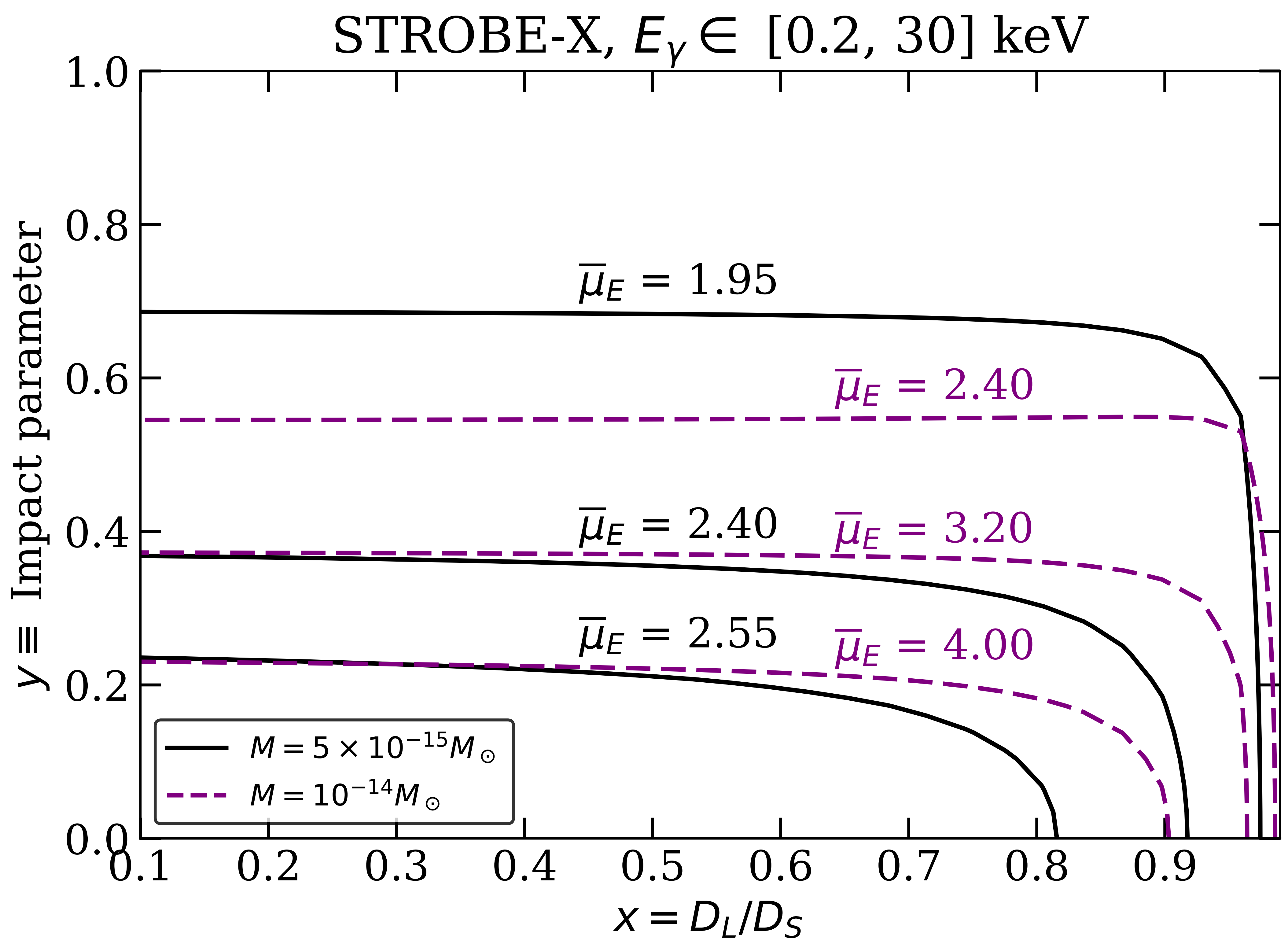
$$a_S = \frac{xR_S}{r_E}$$

Buffer slides: Magnification factor $\mu(w, y, a_s(x))$ in w-y space



Buffer slides: Detector and pulsar specific energy averaged magnification





Buffer slides: Statistical way of interpreting X-ray pulsar light curve

Threshold magnification:

$$\mu_{thresh} = \frac{1 + N_\sigma \sigma_B / B}{1 + n_\sigma \sigma_B / B}$$

Detection criterion:

$$\bar{\mu}_E \gtrsim \mu_{thresh}$$

$N_\sigma - N_{consec}$ criterion:

$N_\sigma = 3$ and $N_{consec} = 3$ with $n_\sigma = -1$ are optimal choices.

- Remark: $\mathbb{P}(n_\sigma = 0) = 0.13$; low event acceptance
- $\mathbb{P}(n_\sigma = -1) = 0.596$; optimal yet significant choice
- $\mathbb{P}(n_\sigma = -2) = 0.93$; too aggressive choice

Buffer slides: Condition for time binning of light curve

- Killing the Look elsewhere effect

$$\mathbb{P}(N_\sigma) < \frac{t_{\rm bin}}{t_{\rm exp}}$$

$$\mathbb{P}(N_\sigma) = [1 - \Phi(N_\sigma = 3)]^{N_{consec}=3} = 2.5 \times 10^{-9}$$

$$\frac{t_{\rm bin}}{t_{\rm exp}} = 1.9 \times 10^{-8} \left(\frac{t_{\rm bin}}{0.1\ \rm s}\right)\left(\frac{60\ \rm days}{t_{\rm exp}}\right)$$