Femtolensing Constraints on Primordial Black Holes

Joachim Kopp (CERN & JGU Mainz)
Solvay Workshop “The Dark Side of Black Holes” I Brussels I April 2019

In this Talk

- ☑ Introduction to Femtolensing
- ☑ Lensing of Gamma Ray Bursts (GRBs)
- ☑ Lensing of Fast Radio Bursts (FRBs)

Femtolensing

www.spacetelescope.org

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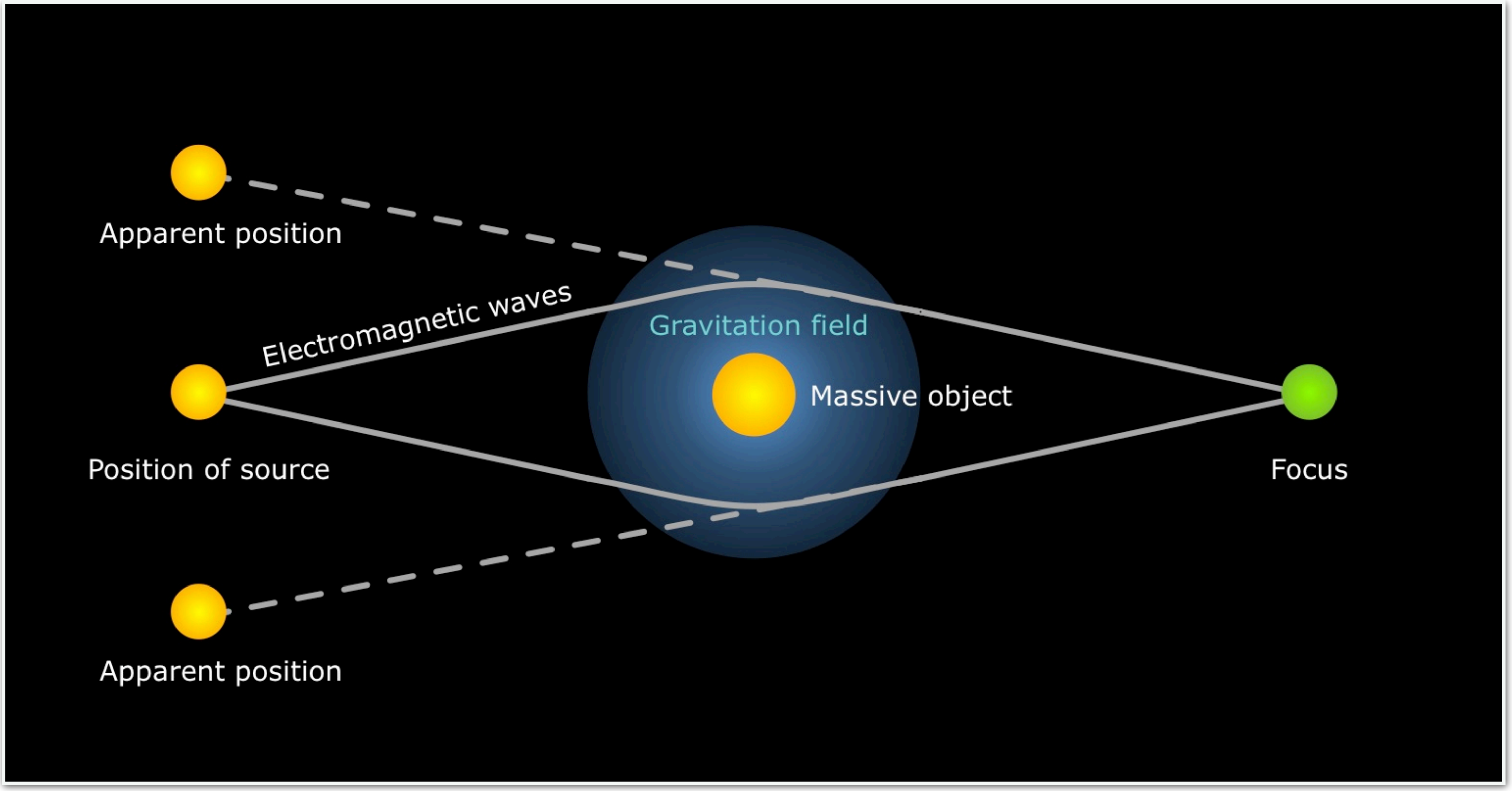
Gravitational Lensing



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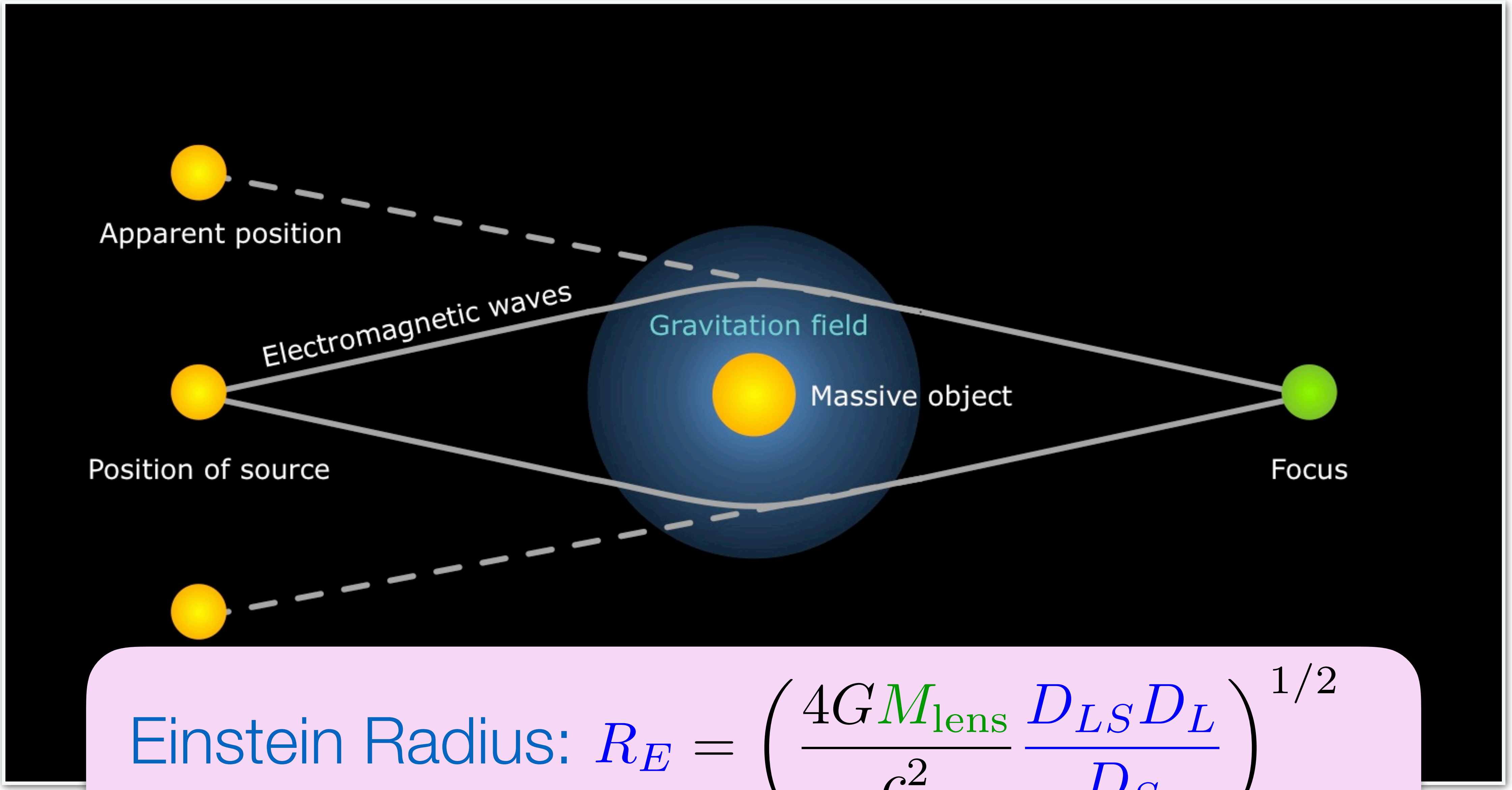
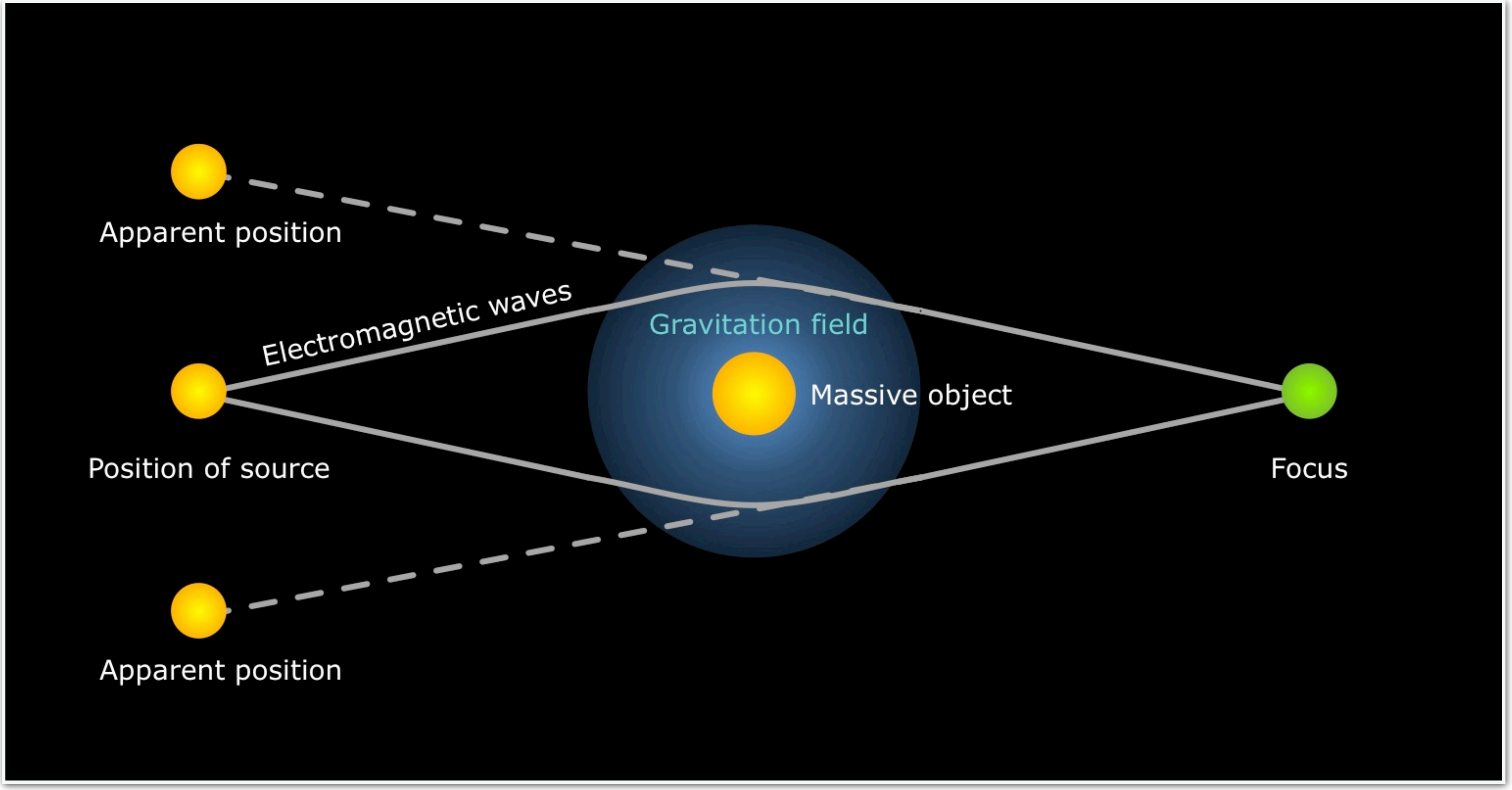


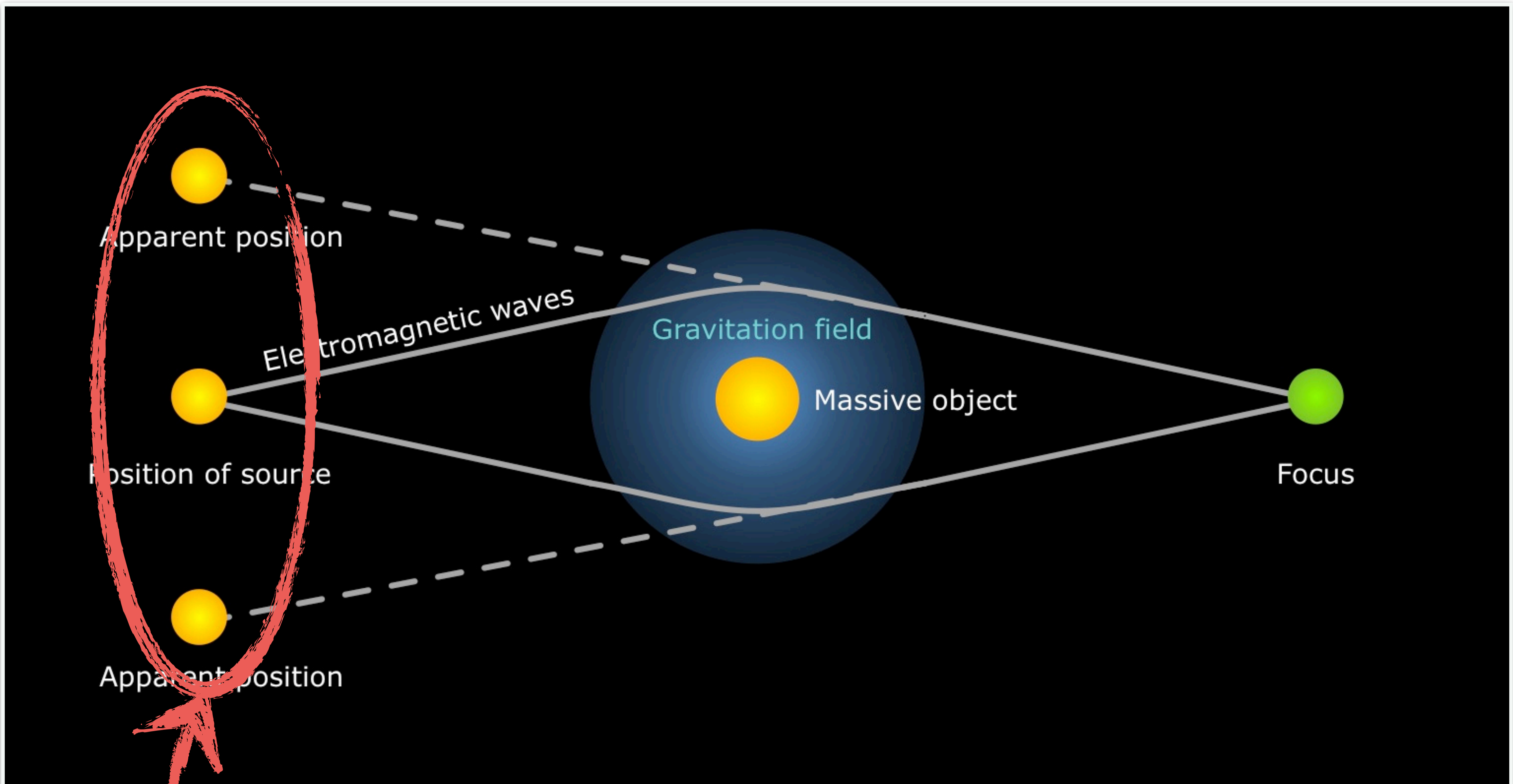
Einstein Radius: $R_E = \left(\frac{4GM_{\text{lens}}}{c^2} \frac{D_{LS} D_L}{D_S} \right)^{1/2}$

(typical distance between lensed and unlensed images)

Femtolensing

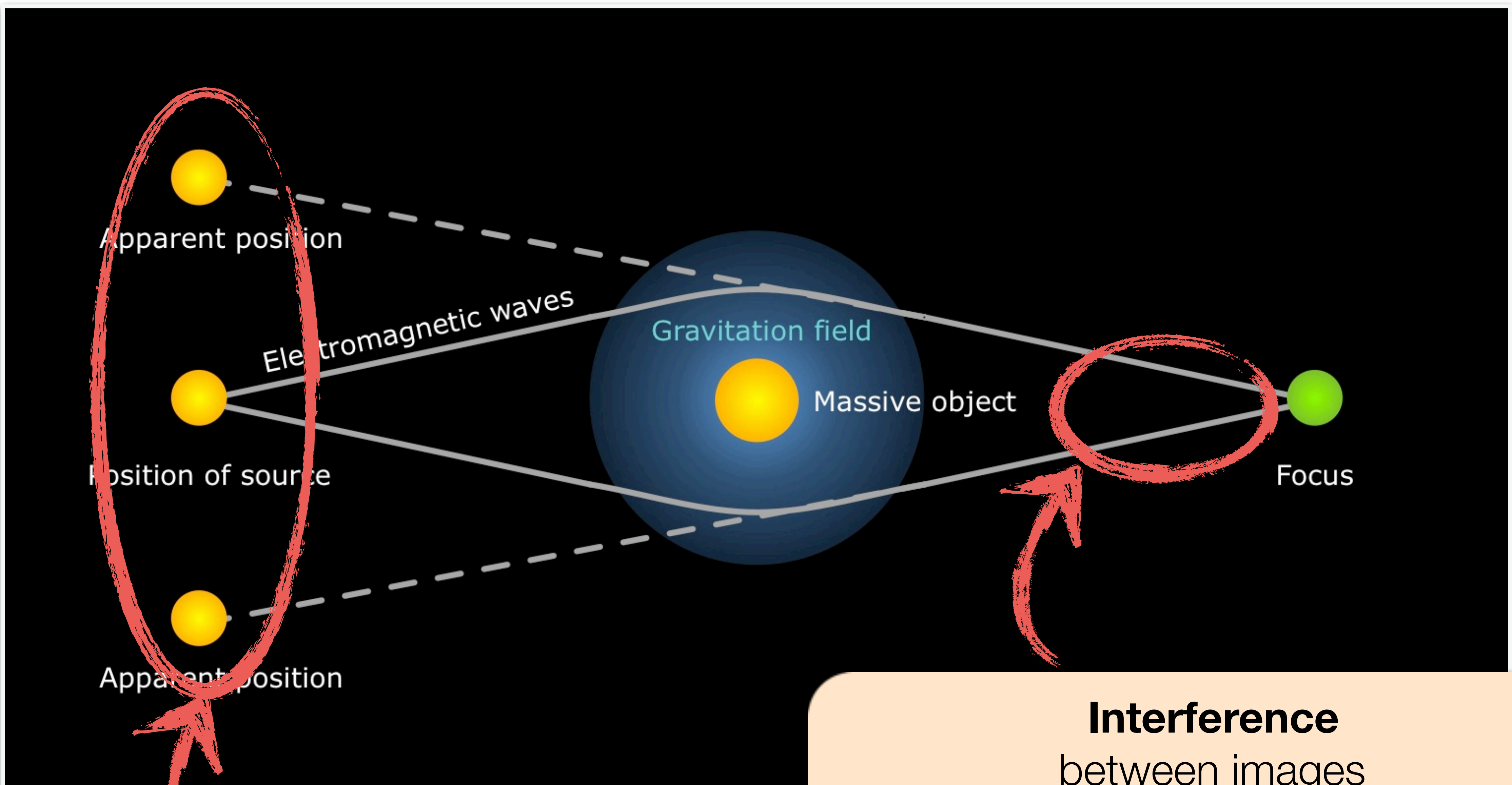


Femtolensing



Images not resolved

Femtolensing



Images not resolved

Interference
between images

$$A = A_1 e^{iEt_1} + A_2 e^{iEt_2}$$

expect wiggles in energy spectrum

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Time Delay

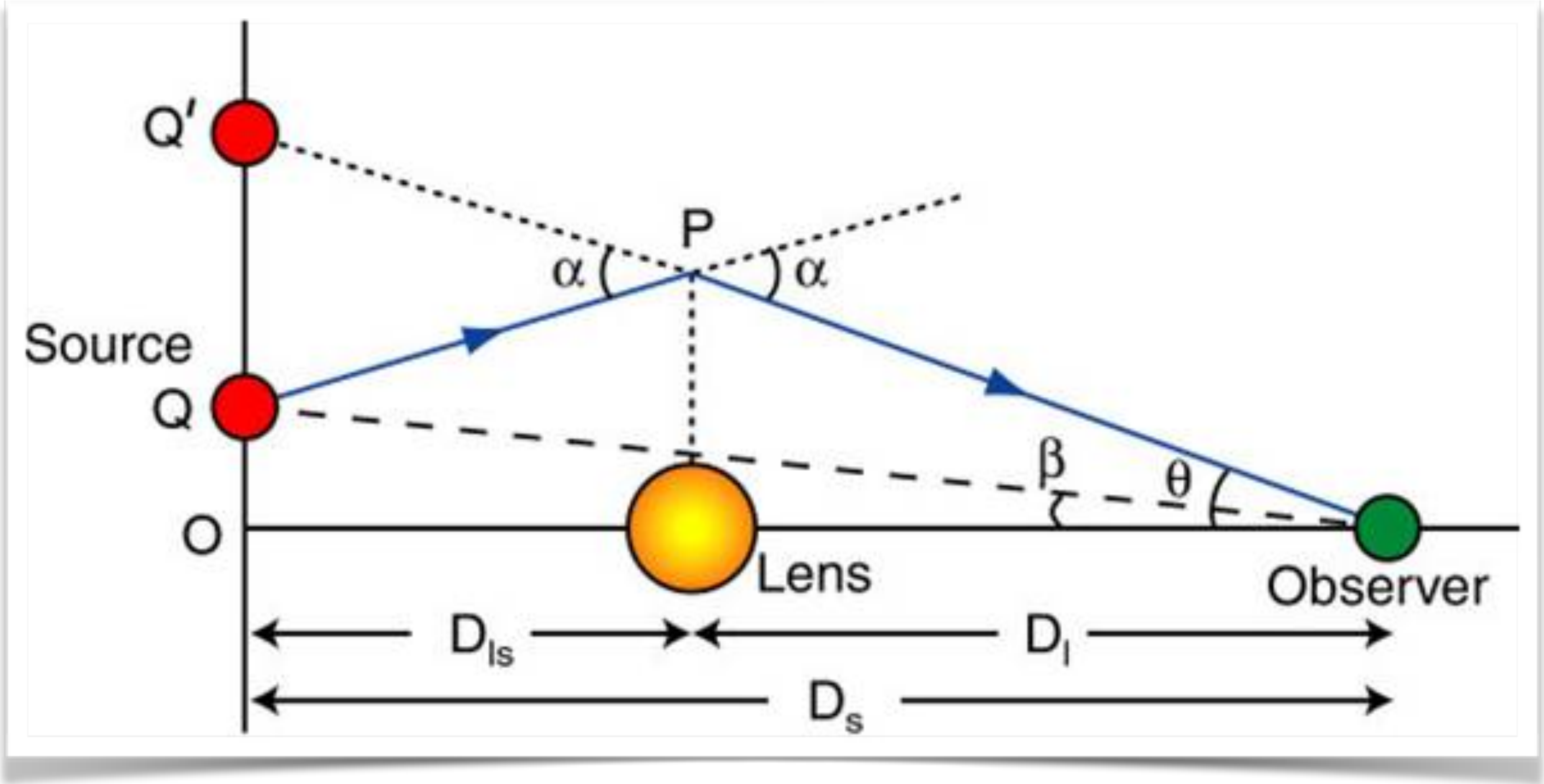
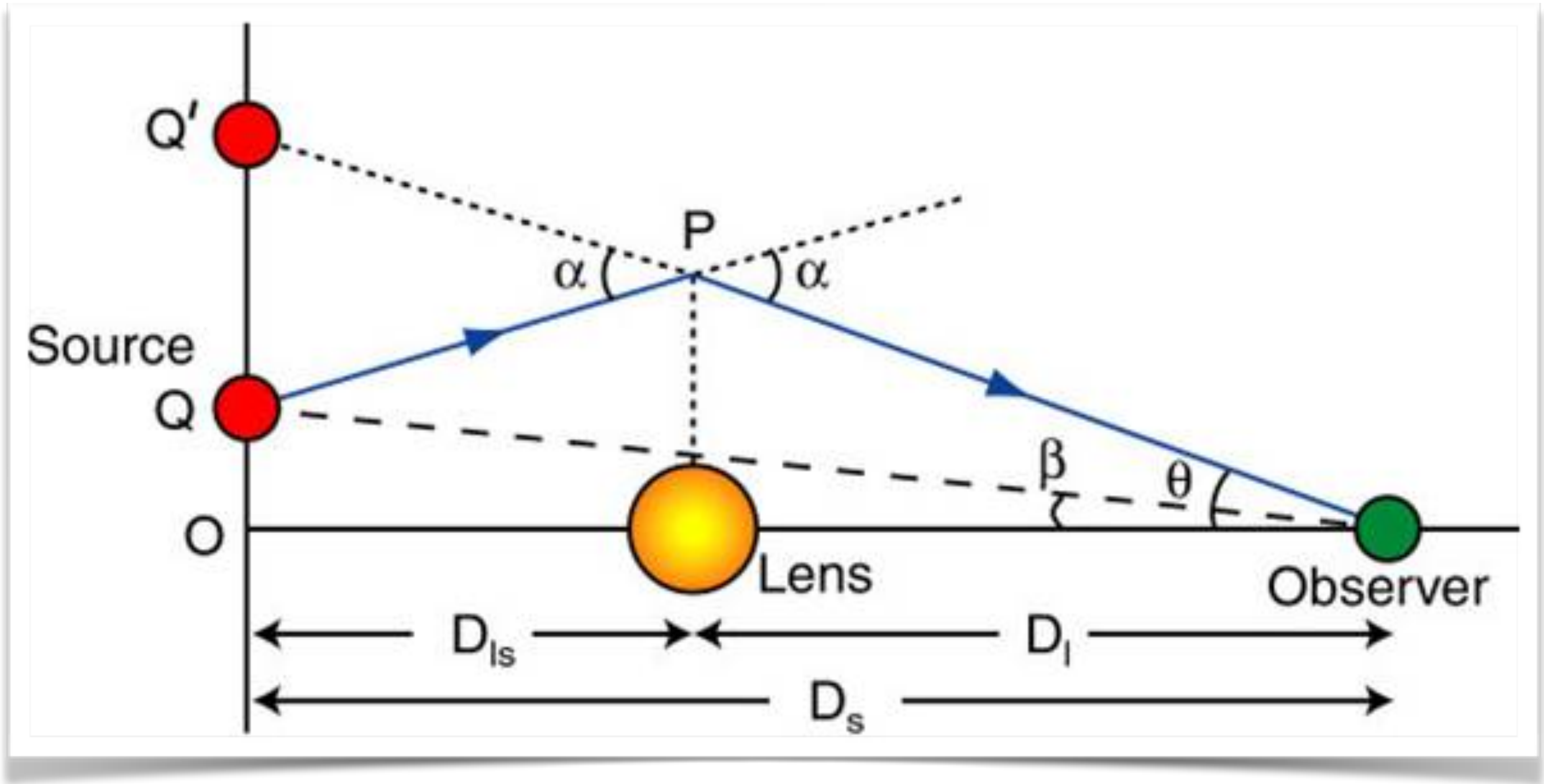


Image: University of Manchester

Time Delay:

$$\Delta t = \frac{1}{c}\frac{D_L D_S}{D_{LS}}(1+z_L)\left(\frac{|\vec{\theta}-\vec{\beta}|^2}{2} - \psi(\vec{\theta})\right)$$

Time Delay



University of Manchester

Geometric Time Delay

Time Delay:

$$\Delta t = \frac{1}{c}\frac{D_L D_S}{D_{LS}}(1+z_L)\left(\frac{|\vec{\theta}-\vec{\beta}|^2}{2}-\psi(\vec{\theta})\right)$$

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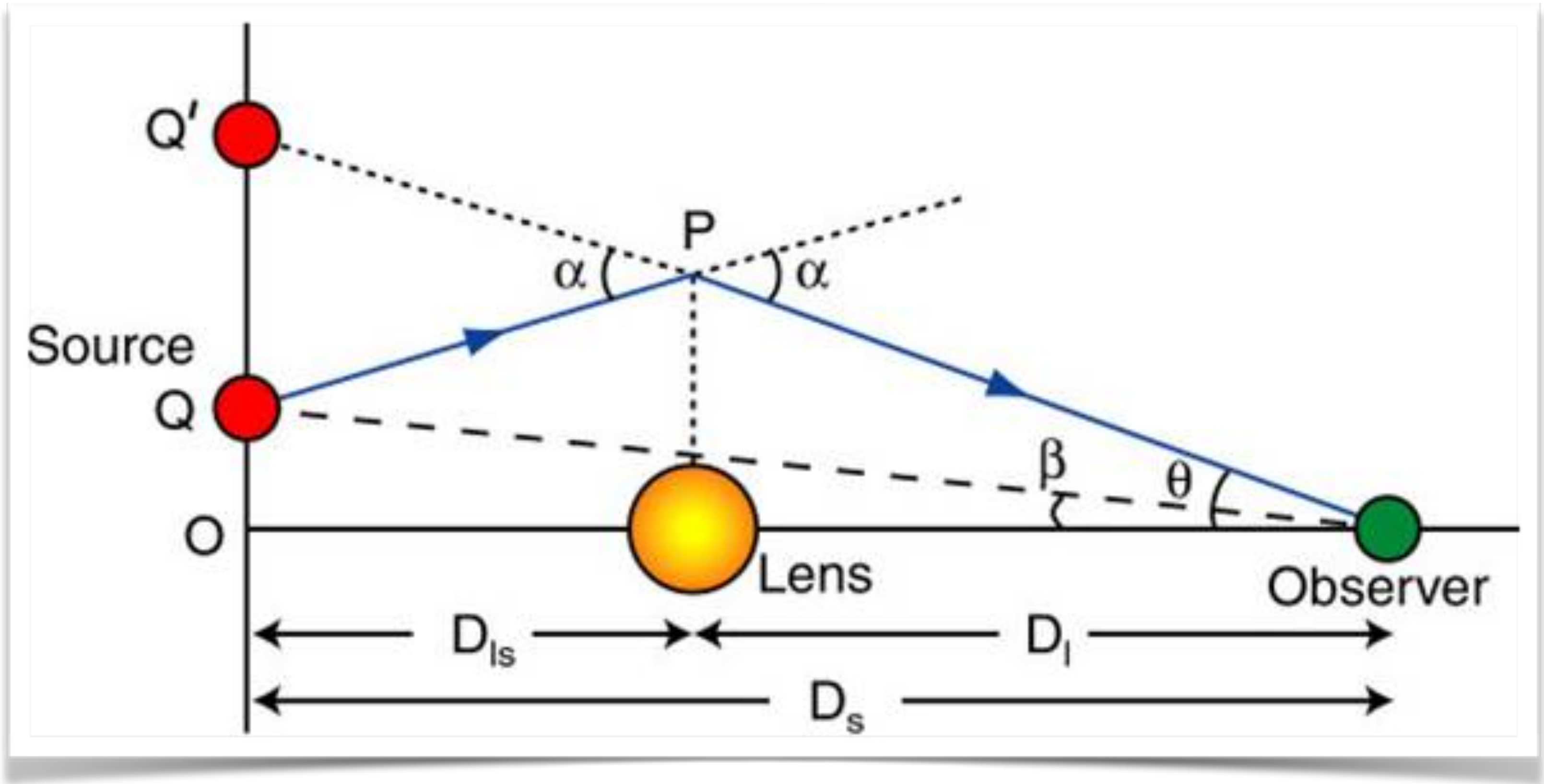

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Geometric Time Delay

Time Delay:

$$\Delta t = \frac{1}{c}\frac{D_L D_S}{D_{LS}}(1+z_L)\left(\frac{|\vec{\theta}-\vec{\beta}|^2}{2} - \psi(\vec{\theta})\right)$$

Lensing Potential

for point-like lens: $\psi(\theta) = \theta_E^2 \log\theta$

Lens Equation

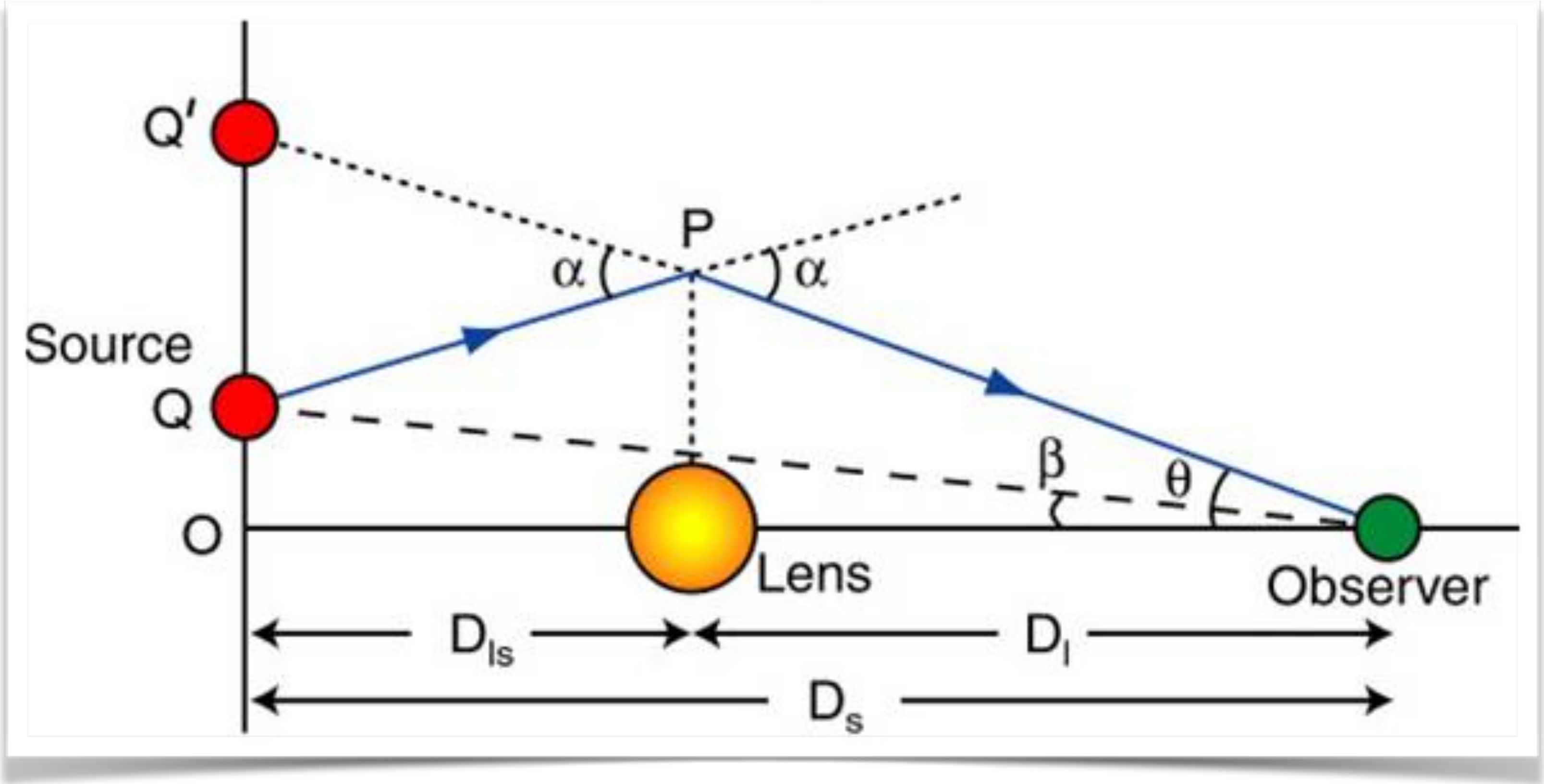

Image: University of Manchester

Lens Equation:
(in geometric optics,
from stationary point of Δt)

$$\theta - \beta = \frac{\theta_E^2}{\theta}$$

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Lens Equation

Einstein Angle
(typical angular distance between lensed and unlensed images)

$$\theta_E = \frac{R_E}{D_L} = \left(\frac{4 G_N M_{\rm lens}}{c^2} \frac{D_{LS}}{D_S D_L} \right)^{1/2}$$

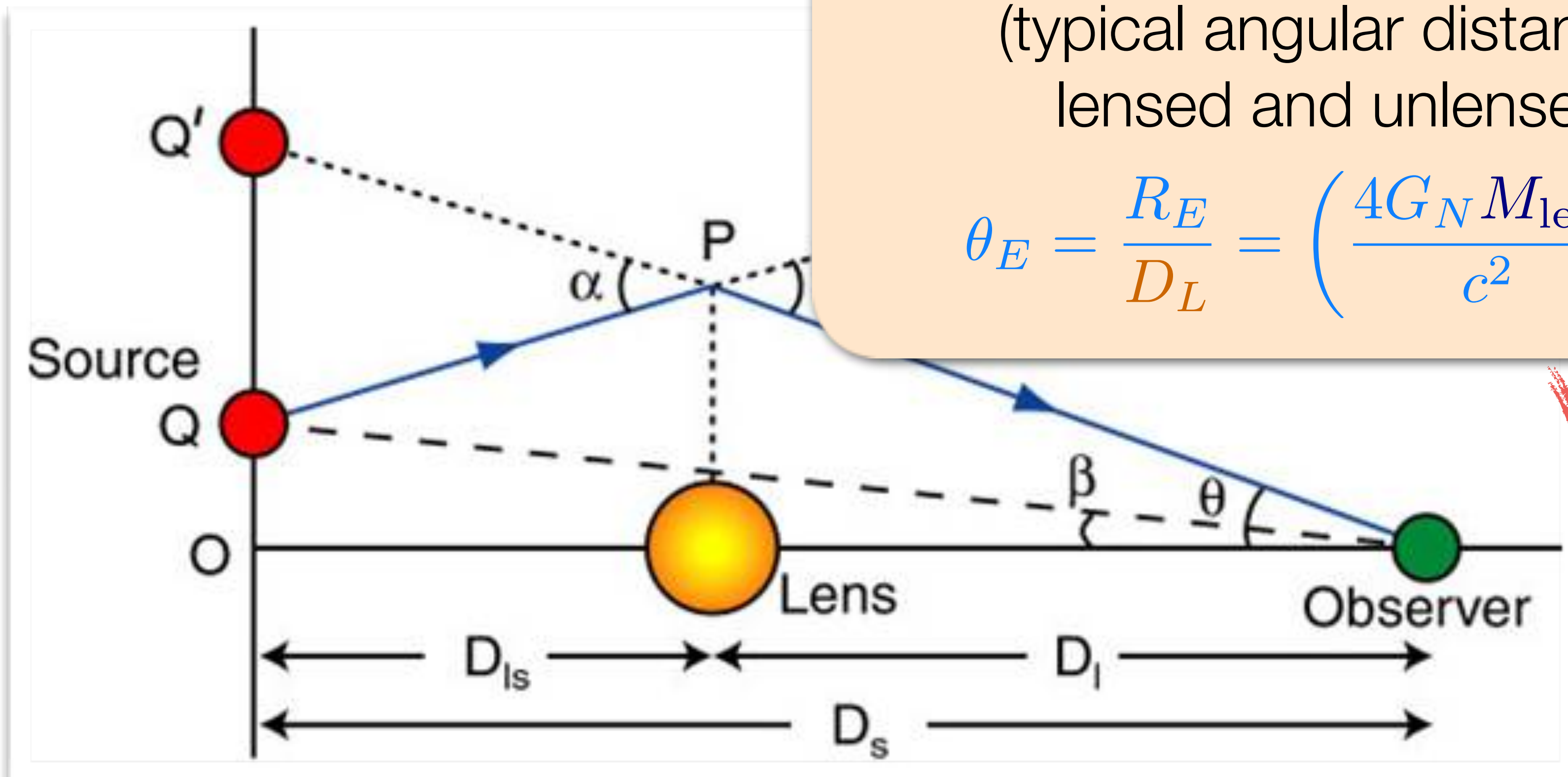


Image: University of Manchester

Lens Equation:
(in geometric optics,
from stationary point of Δt)

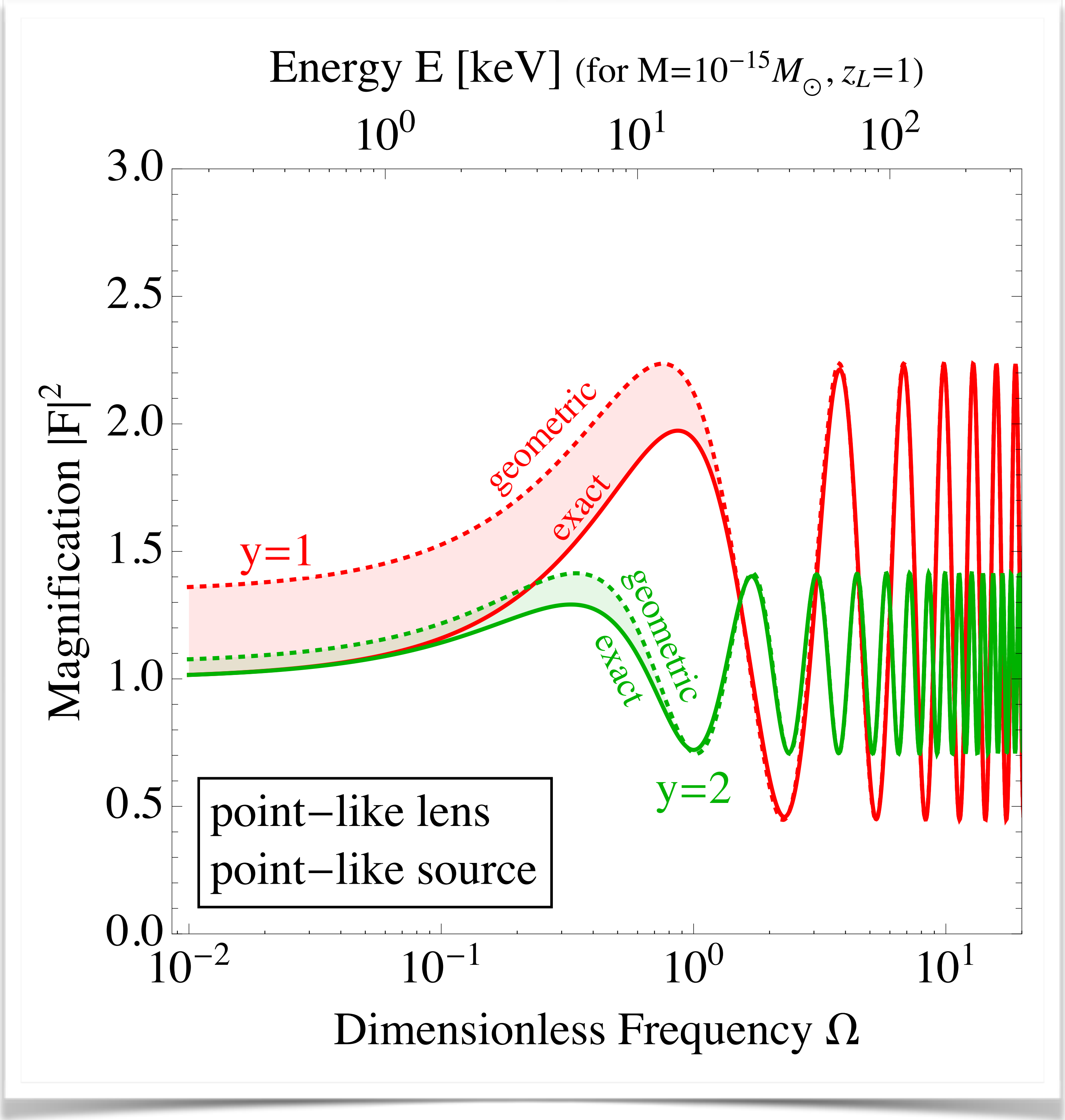
$$\theta - \beta = \frac{\theta_E^2}{\theta}$$

Wave Optics Corrections

- If $\omega \Delta t \gg 1$:
  - Stationary Phase Approximation breaks down
  - Instead of two discrete images, evaluate full Fresnel integral

$$F(\vec{\beta};\omega) = \frac{\Omega}{2\pi i}\int d^2\vec{\theta}\, e^{i\omega\Delta t(\vec{\theta},\vec{\beta})}$$

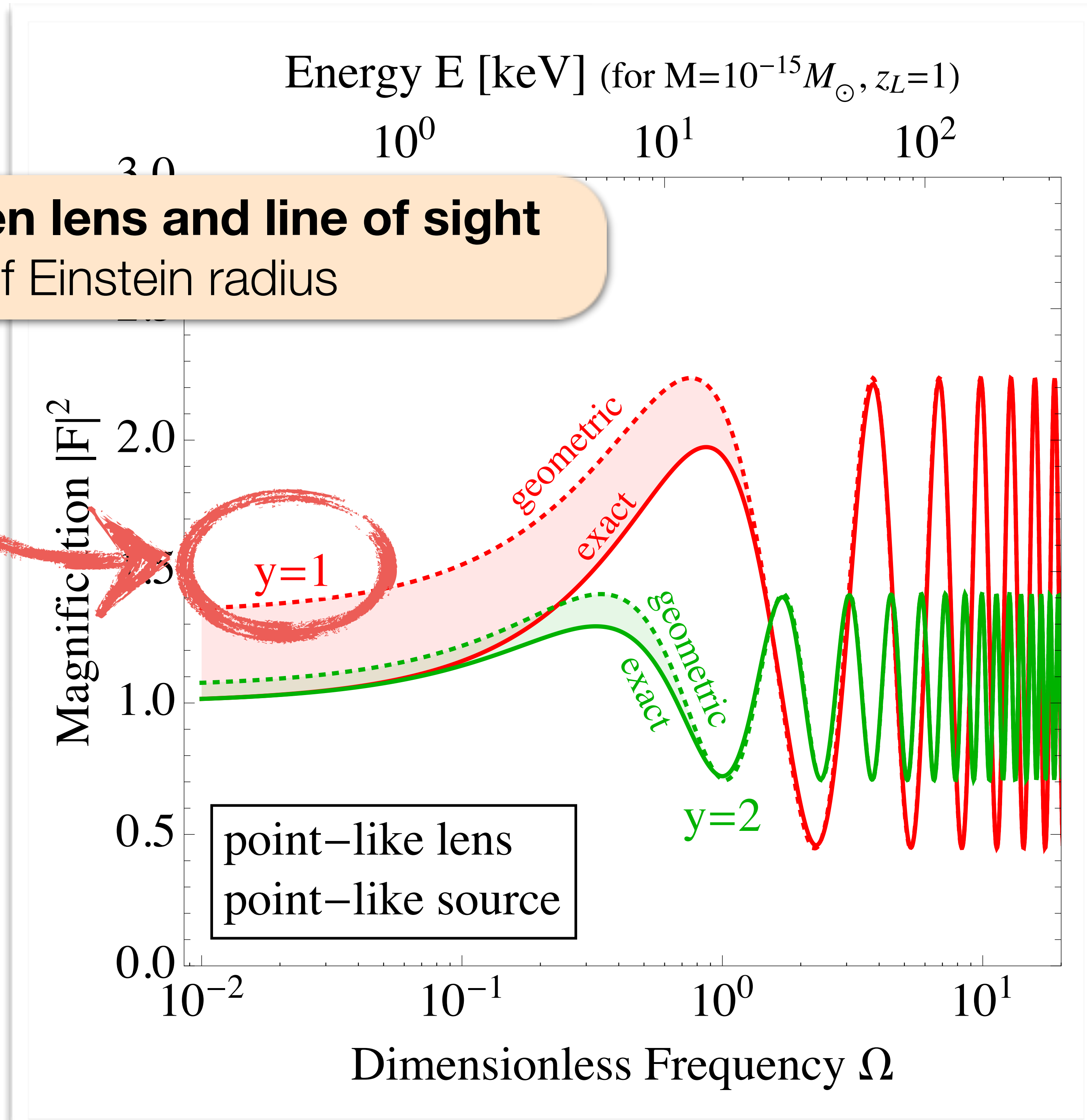
Magnification Function



Katz JK Sibiryakov Xue
arXiv:1807.11495

Magnification Function

Distance between lens and line of sight
in units of Einstein radius



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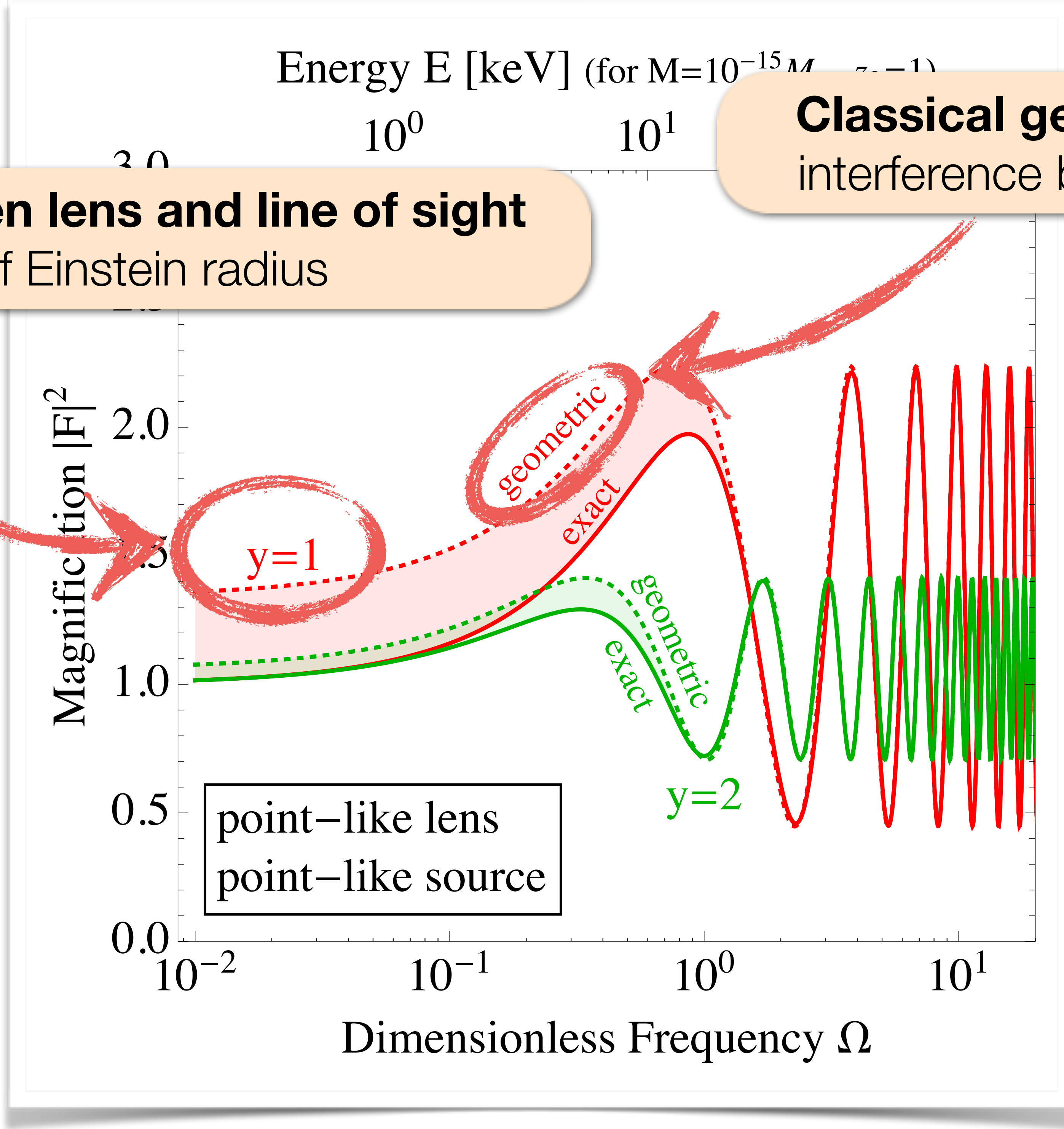

Distance between lens and line of sight
in units of Einstein radius

Classical geometric picture
interference between two rays

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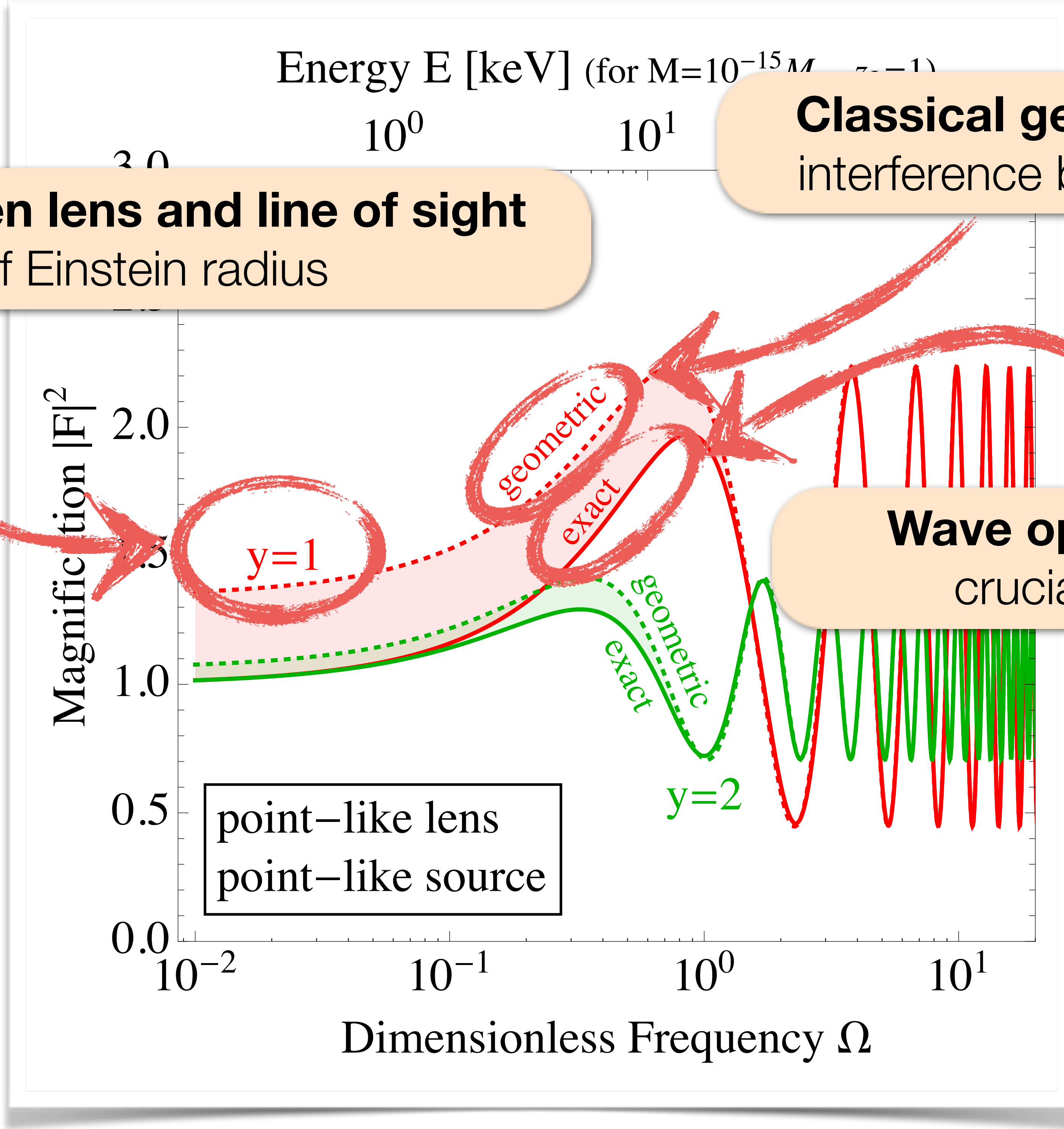
Magnification Function



Distance between lens and line of sight
in units of Einstein radius

Classical geometric picture
interference between two rays

Wave optics corrections
crucial if $\lambda \gtrsim G_N M_{lens}$

Katz JK Sibiryakov Xue
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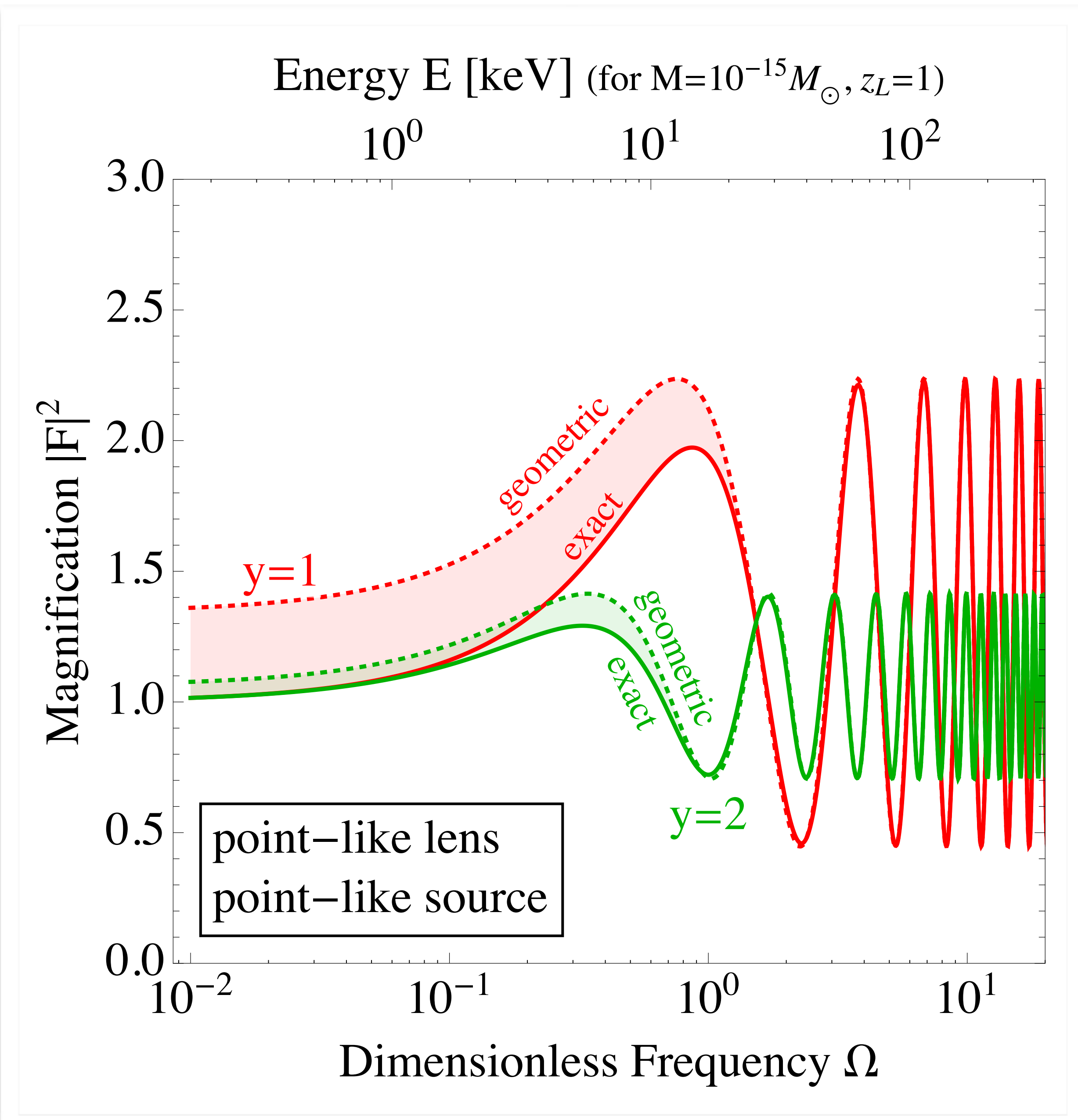
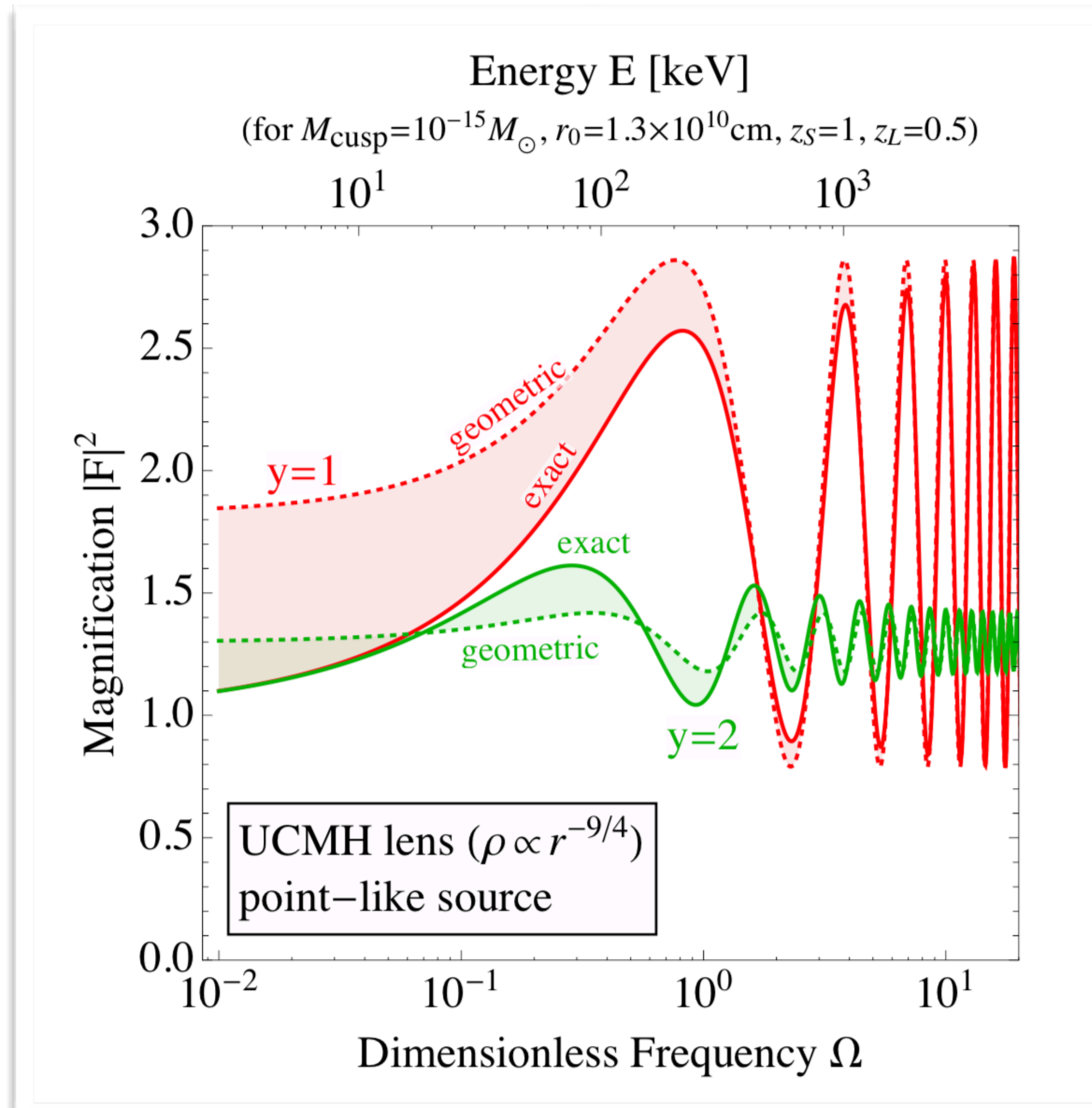
Excursion: Finite Size Lenses

Non-pointlike compact DM candidates: ultra-compact (axion) minihalos

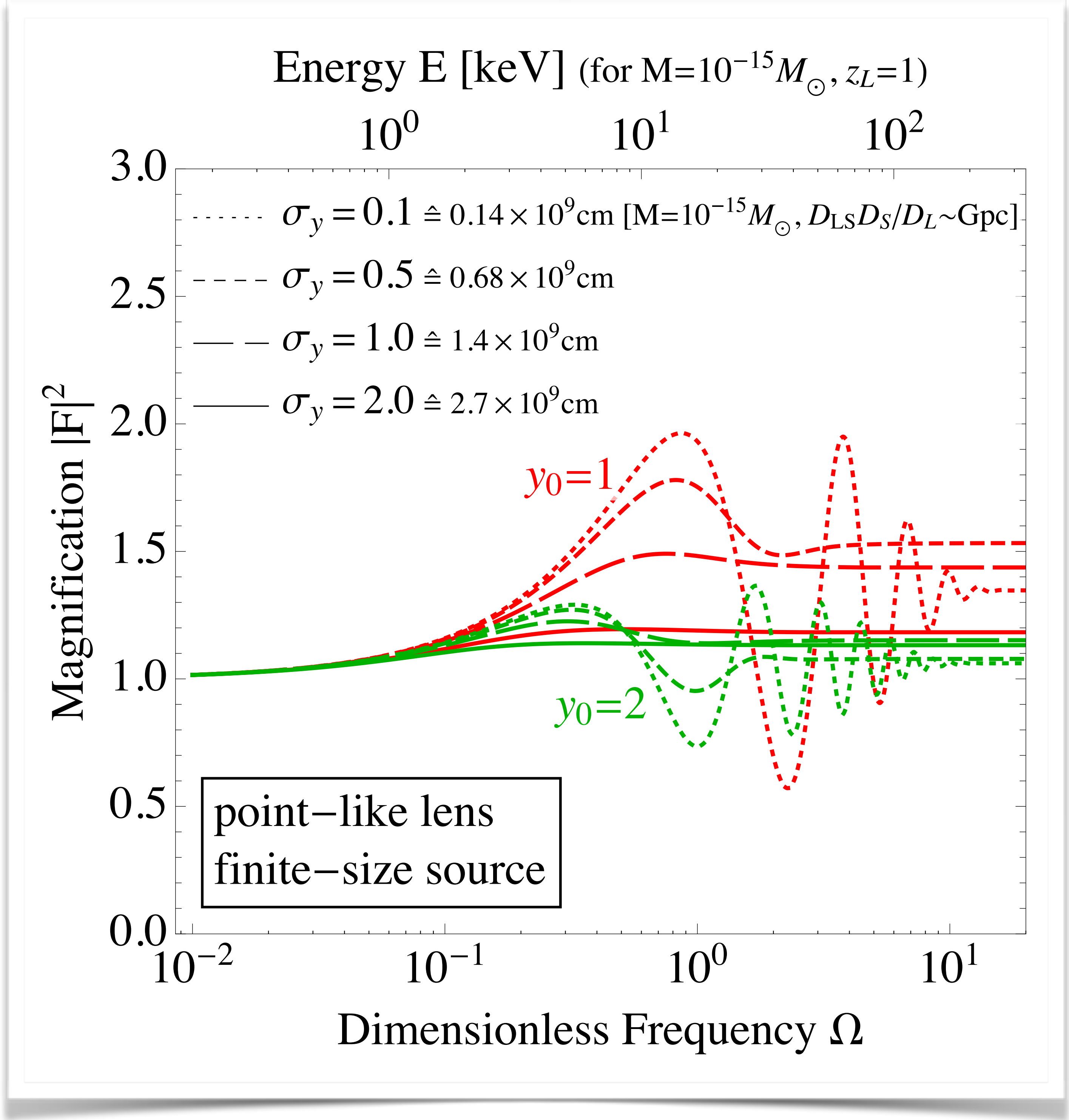
large uncertainty in mass distribution and density profile





Primordial Black Hole Constraints from Femtolensing of GRBs

Finite Size of GRB Sources



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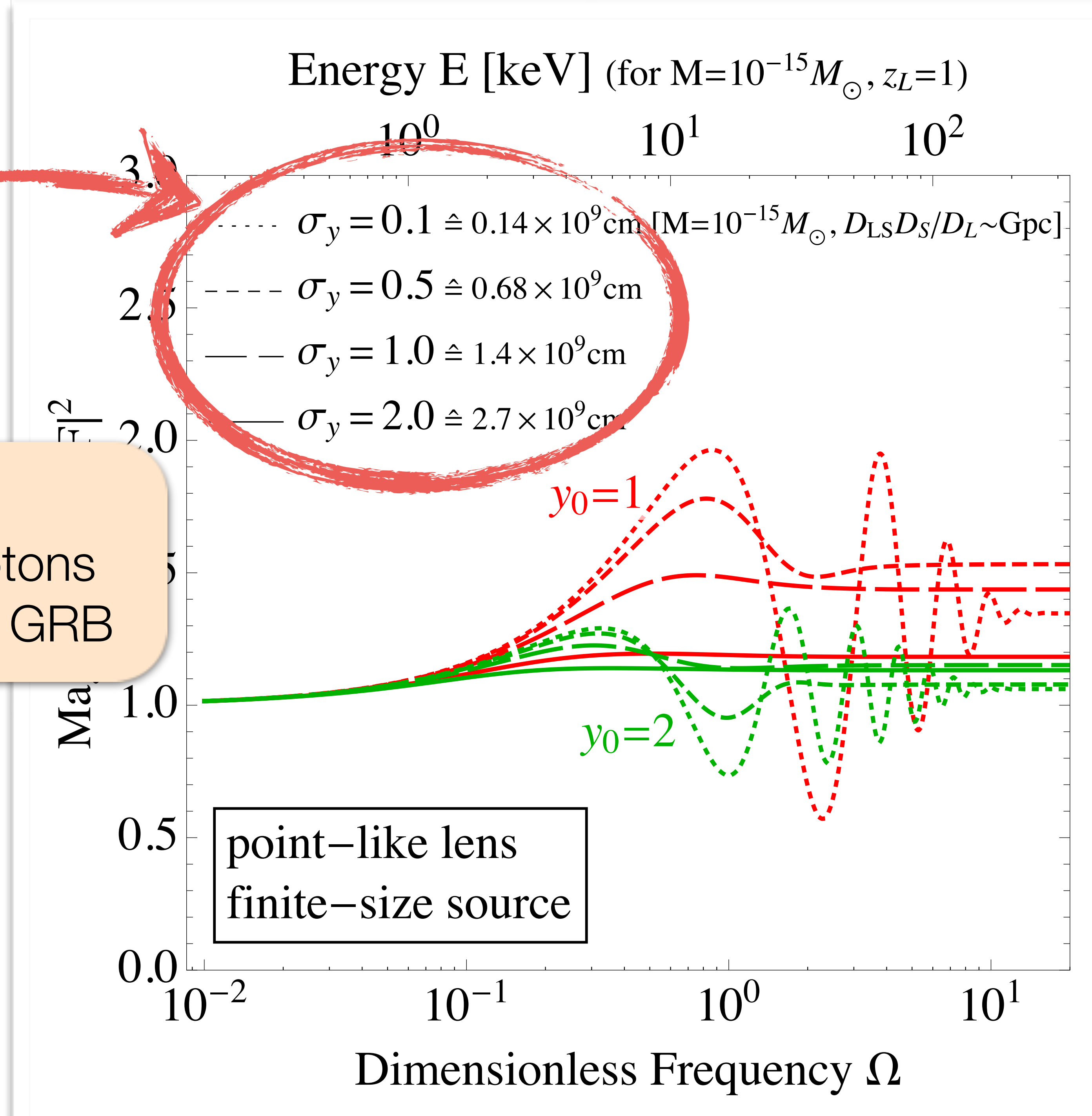

GRBs are not pointlike
small phase difference between photons emitted at different points across the GRB

Katz JK Sibiryakov Xue
arXiv:1807.11495

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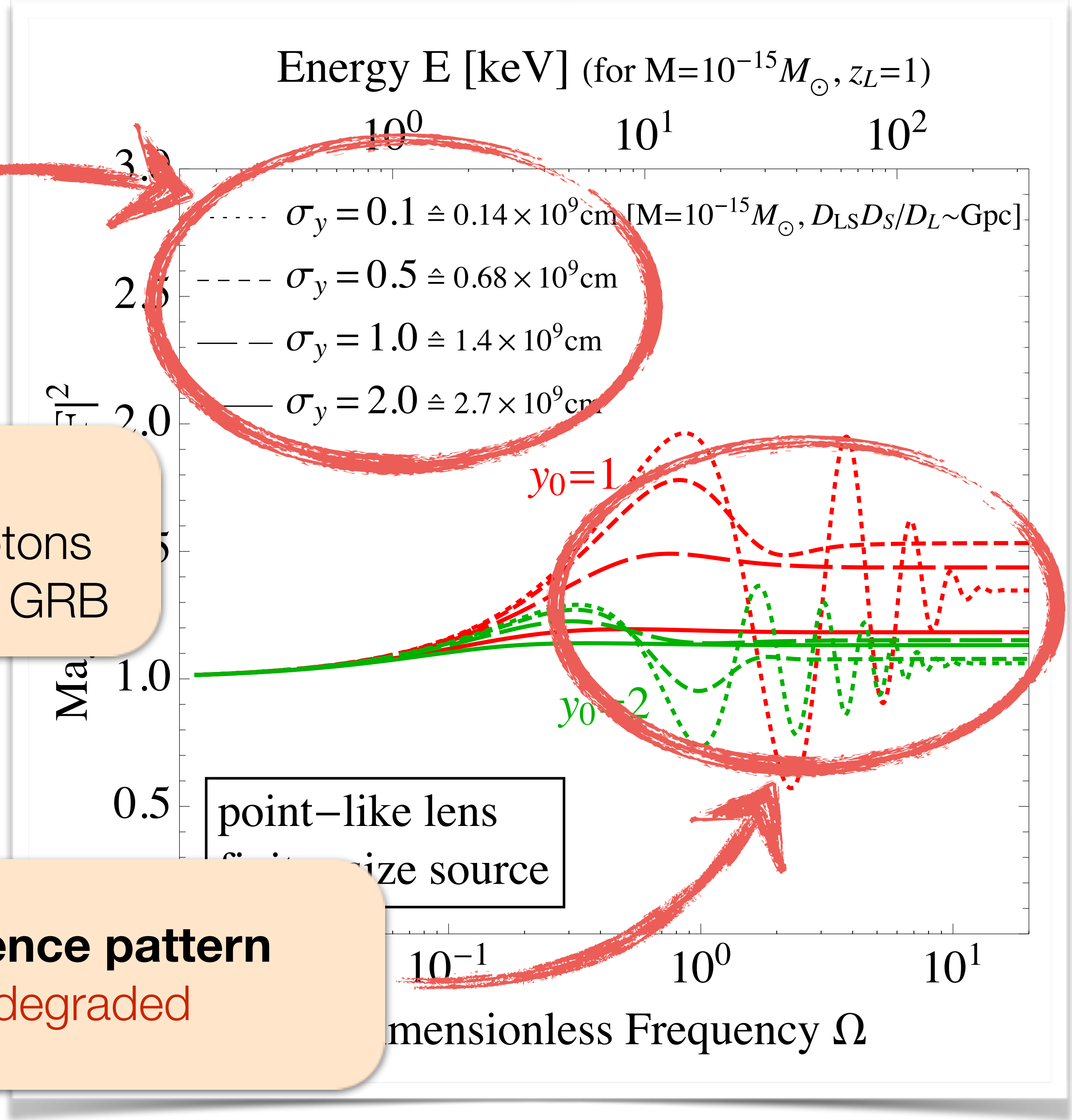


GRBs are not pointlike
small phase difference between photons emitted at different points across the GRB

Wash-out of interference pattern
sensitivity severely degraded

Katz JK Sib
arXiv:1807.1

Finite Size of GRB Sources

- γ production in GRBs:
  - e^+, e^- acceleration in relativistic shock waves

Katz JK Sibiryakov Xue, arXiv:1807.11495

- Variability time scale in rest frame for source size a_S:

$$t_\text{var} \sim a_S / c$$

- Relativistic boost γ:

$$t_\text{var} \sim (1 + z_S)\left(1 - \frac{v}{c} \cos\theta_\text{obs}\right) \gamma \, a_S / c$$

- Observation angle $\theta_\text{obs} \sim 1/\gamma$
- Observed $t_\text{var} \gtrsim 0.01$ sec (short GRB); $\gtrsim 0.1$ sec (long GRB)

$$a_S \simeq \frac{10^{11}\,\text{cm}}{1 + z_S} \times \left(\frac{t_\text{var}}{0.03\,\text{sec}}\right)\left(\frac{\gamma}{100}\right)$$

Finite Size of GRB Sources: Caveats

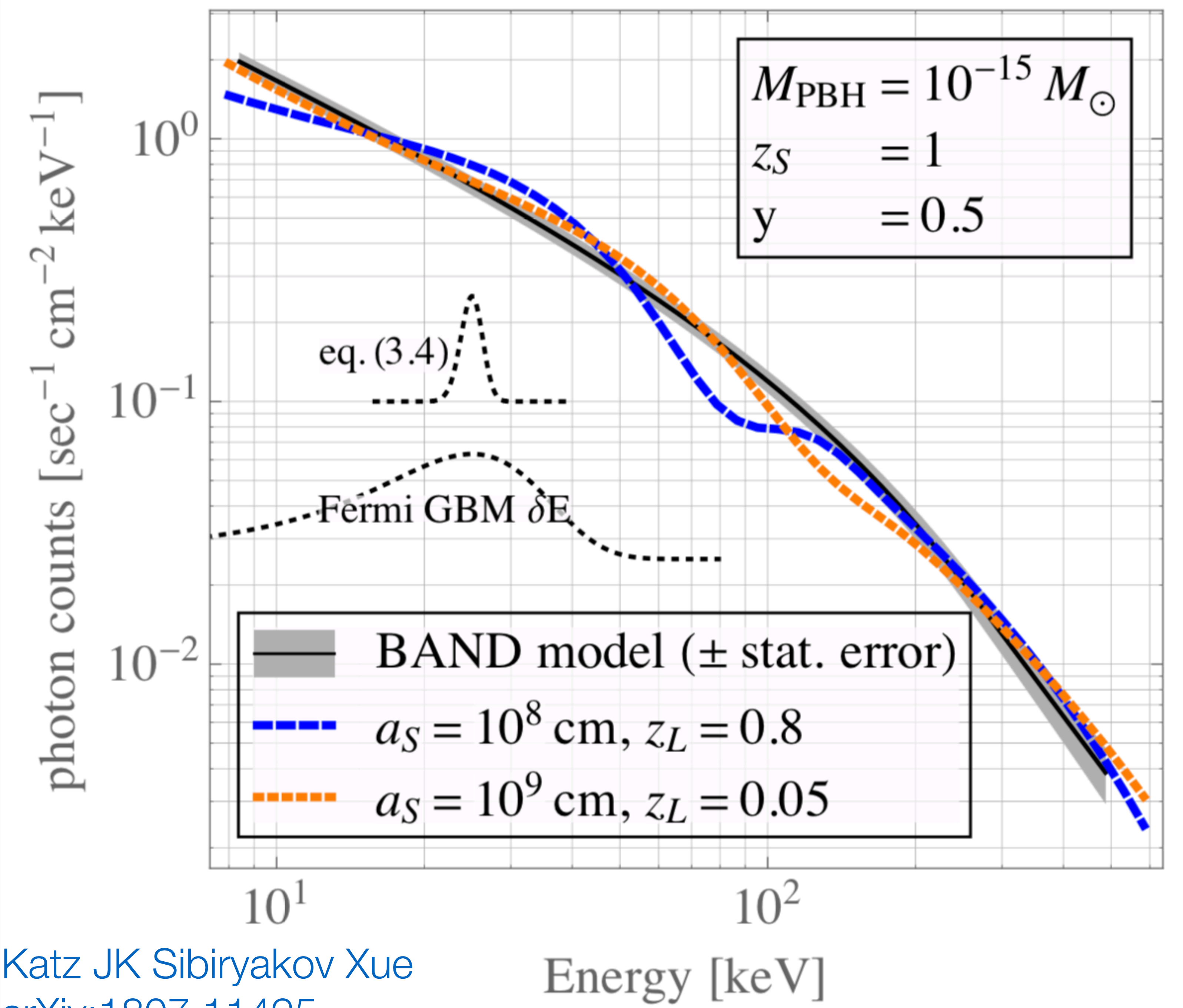
- Some GRBs with shorter variability time scale $t_{var} \lesssim 10^{-3}$ sec
  - t_{var} distributio could have a long tail → use tail form femtolensing
- Intrinsic variability might be too fast to be resolved
- Conservative estimate from optical depth requirement $\tau < 1$:

$$a_S > 1.8 \times 10^9 \left(\frac{d_S}{7\,\text{Gpc}}\right)^2 \left(\frac{f_{500}}{10^{-3}\text{sec}^{-1}\text{cm}^{-2}\,\text{keV}^{-1}}\right) \left(\frac{\gamma}{1000}\right)^{-4} \text{cm}\,.$$

- Assumptions:
  - Power law spectrum with $\alpha = -2$
  - Thomson scattering (non-relativistic in rest frame of ejecta)
  - Target e^+, e^- from pair production by γ rays
  - …

Katz JK Sibiryakov Xue, arXiv:1807.11495

Lensed GRB spectra



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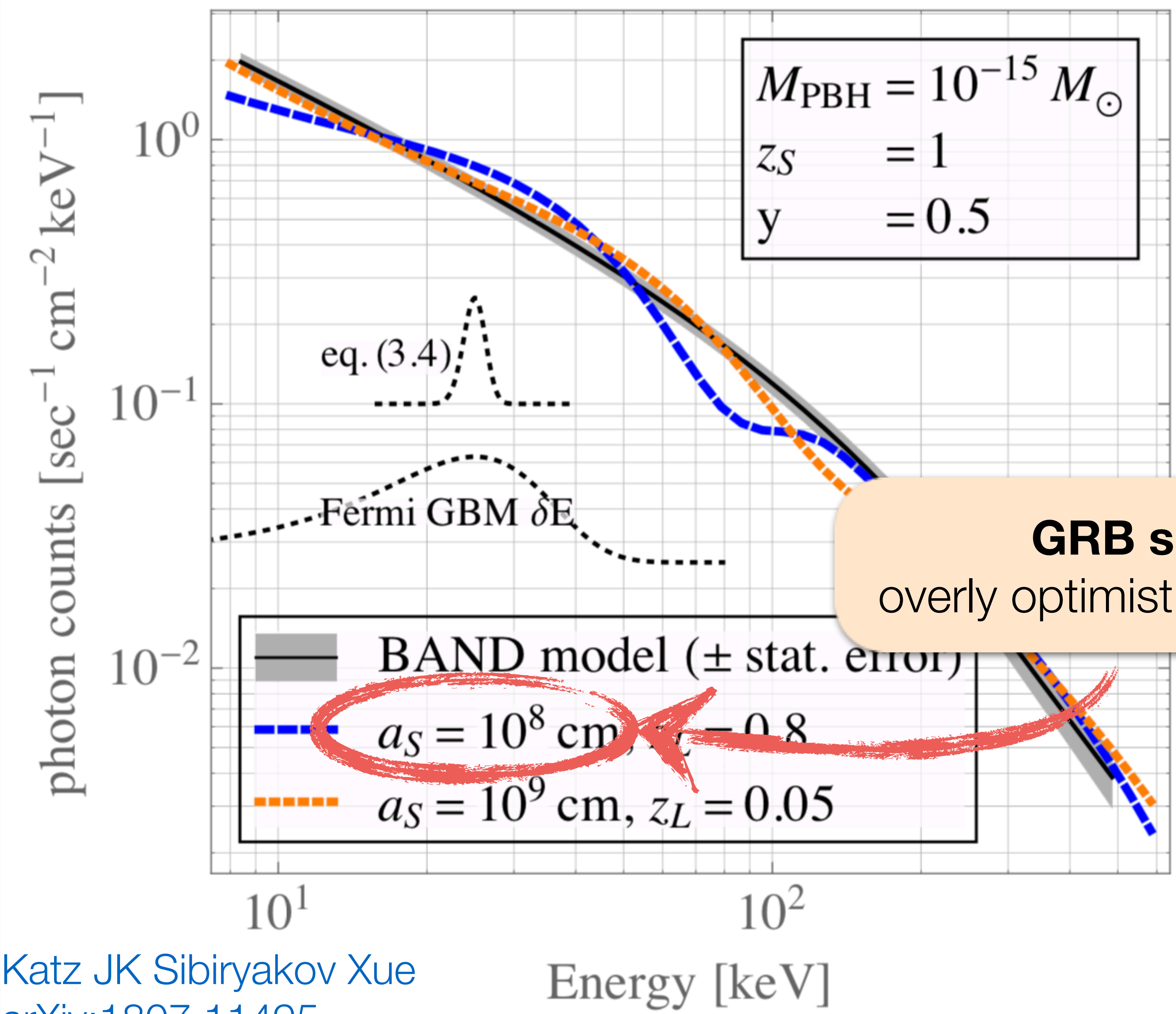
Lensed GRB spectra



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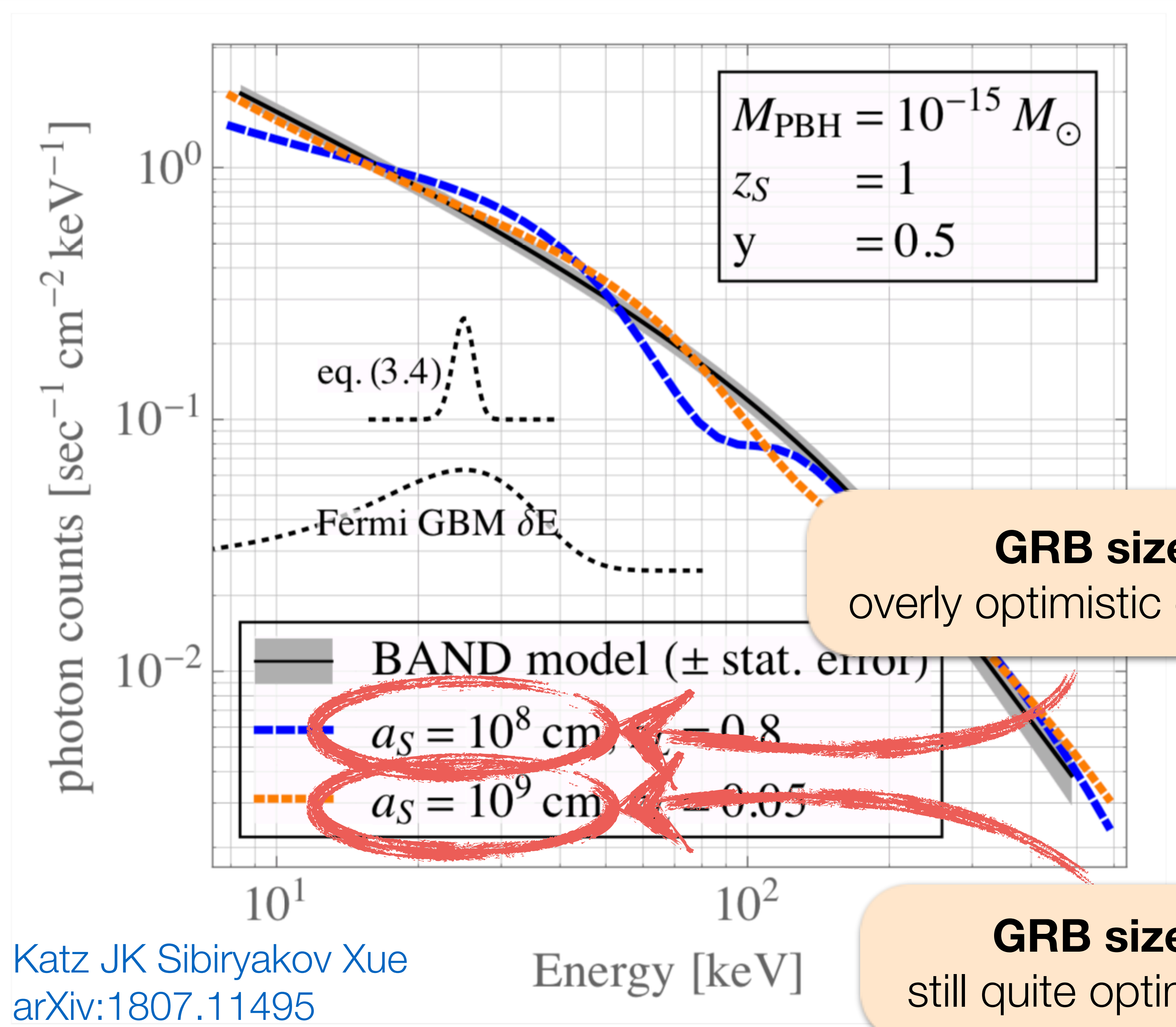
GRB size
overly optimistic estimate

Lensed GRB spectra



Katz JK Sibiryakov Xue
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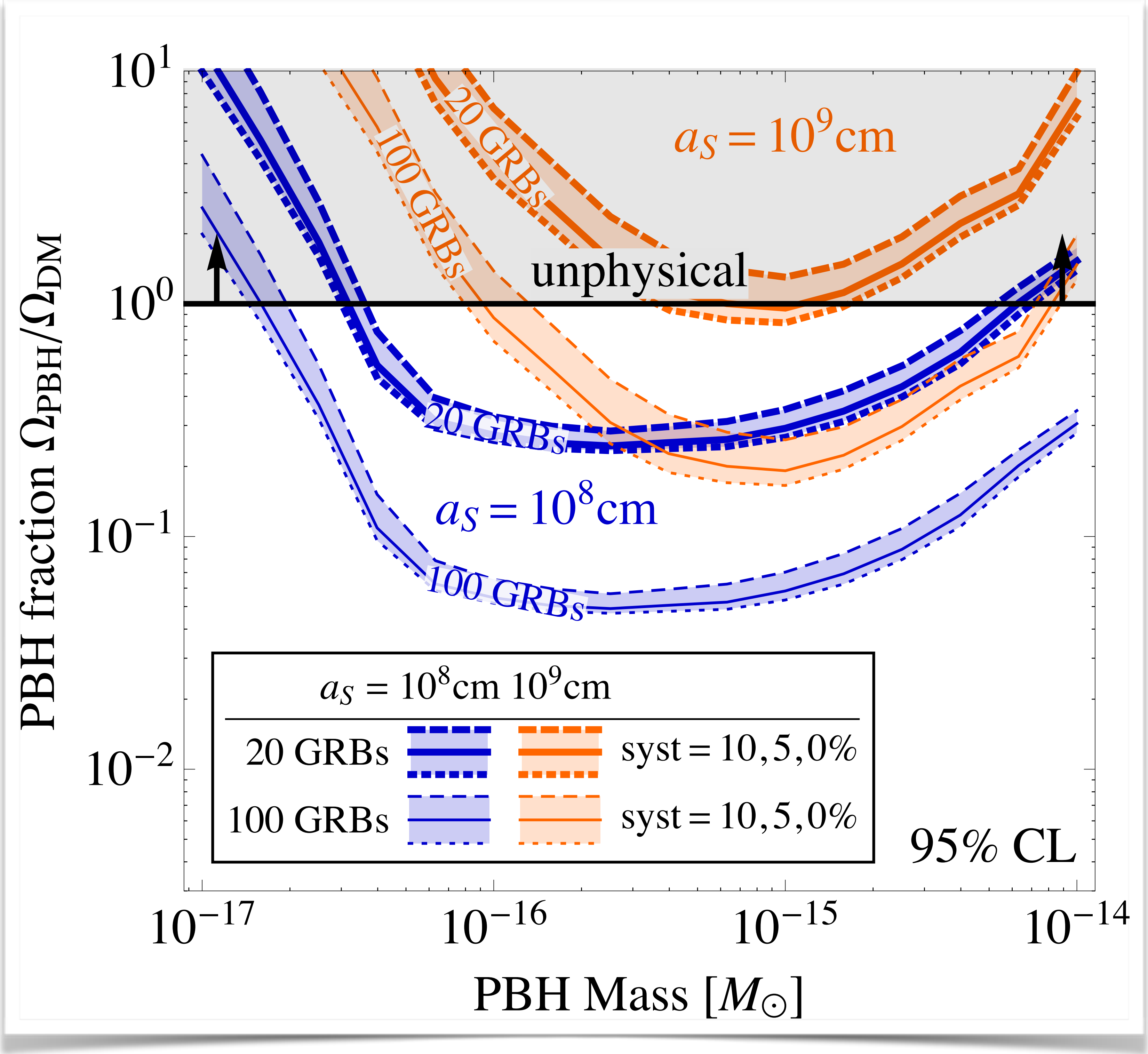
GRB size
overly optimistic estimate

GRB size
still quite optimistic

Sensitivity Estimates



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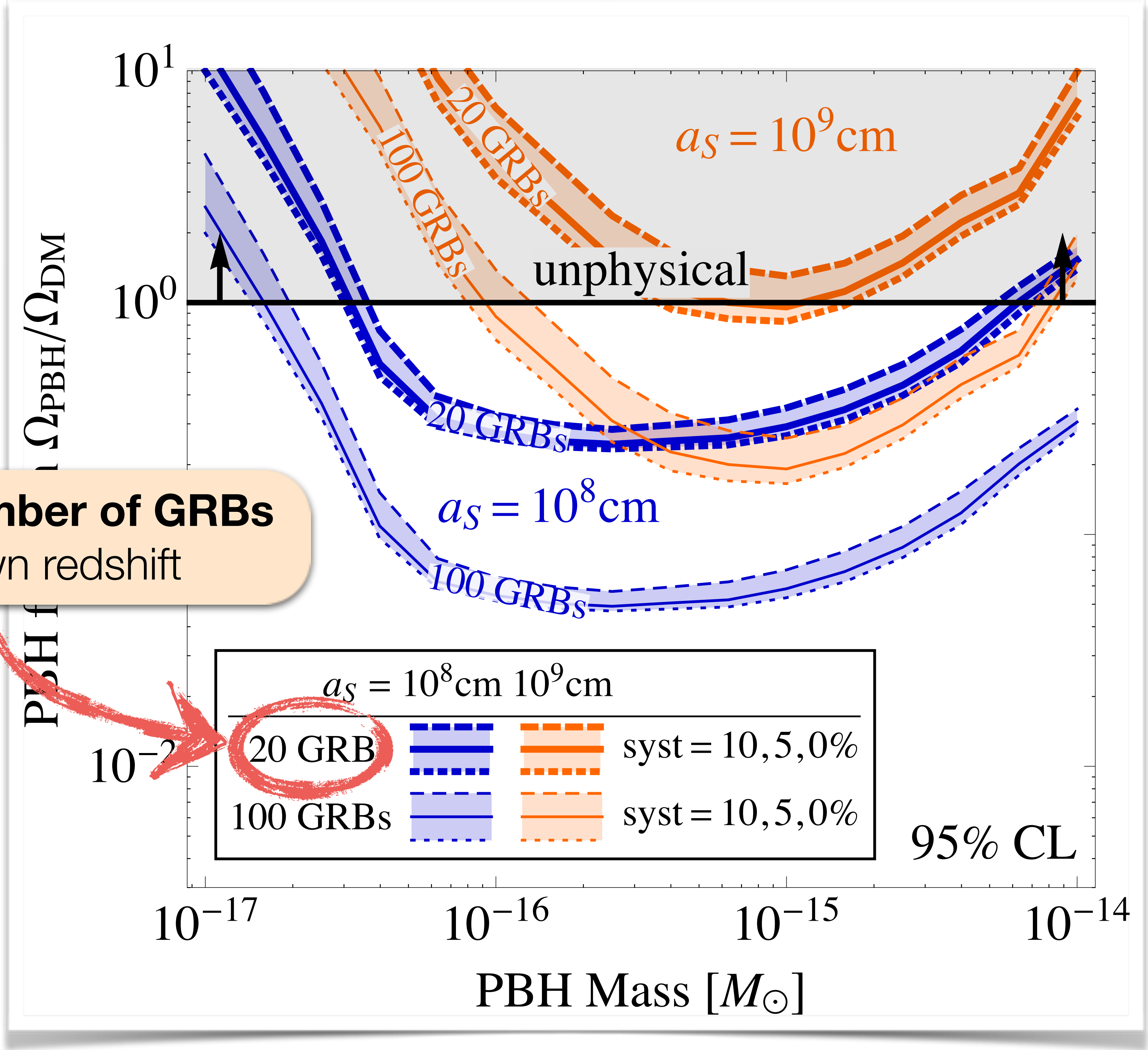

~ current number of GRBs
with known redshift

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arXiv:1807.11495

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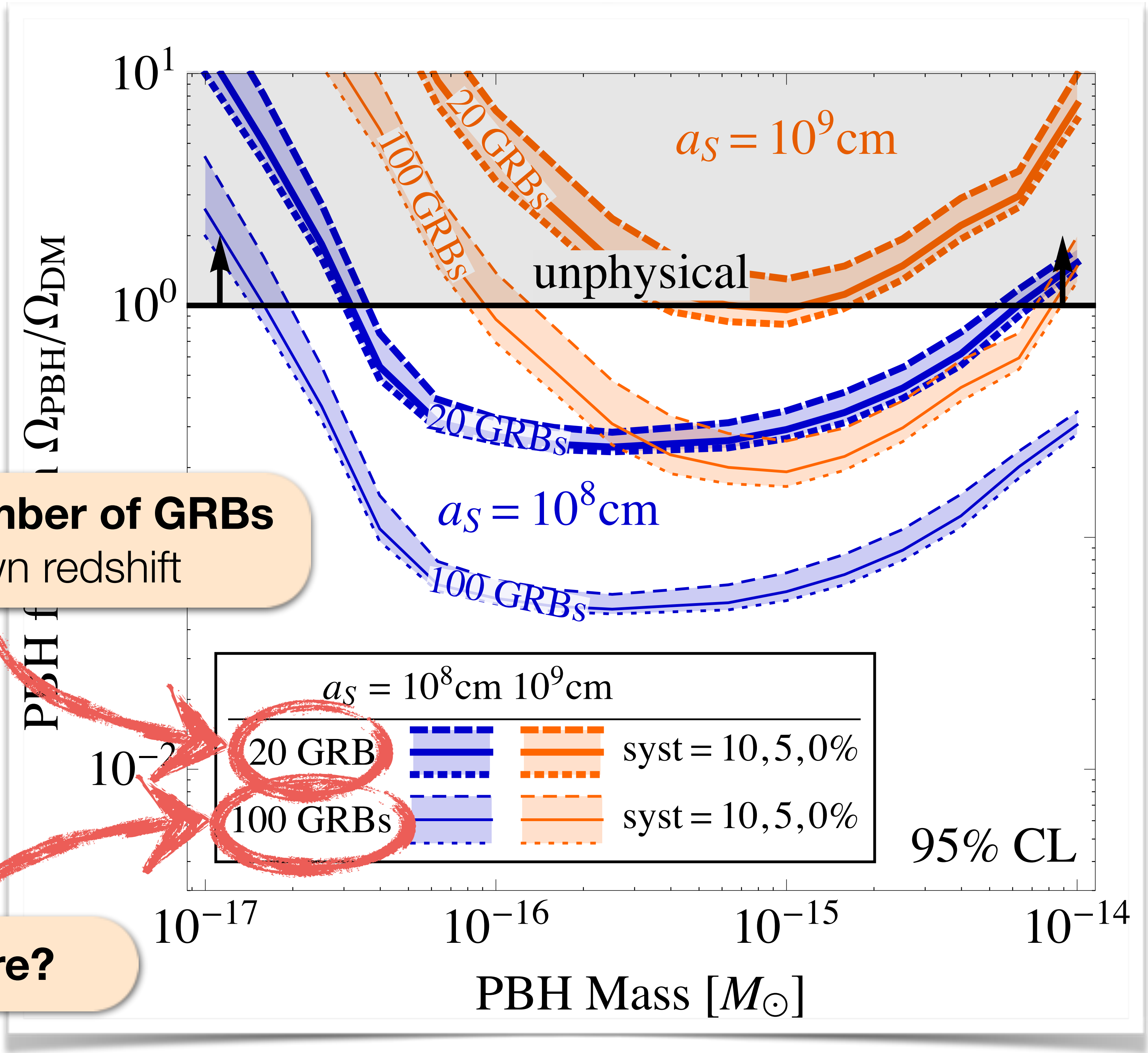

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Future?

Katz JK Sibir...
arXiv:1807.11495

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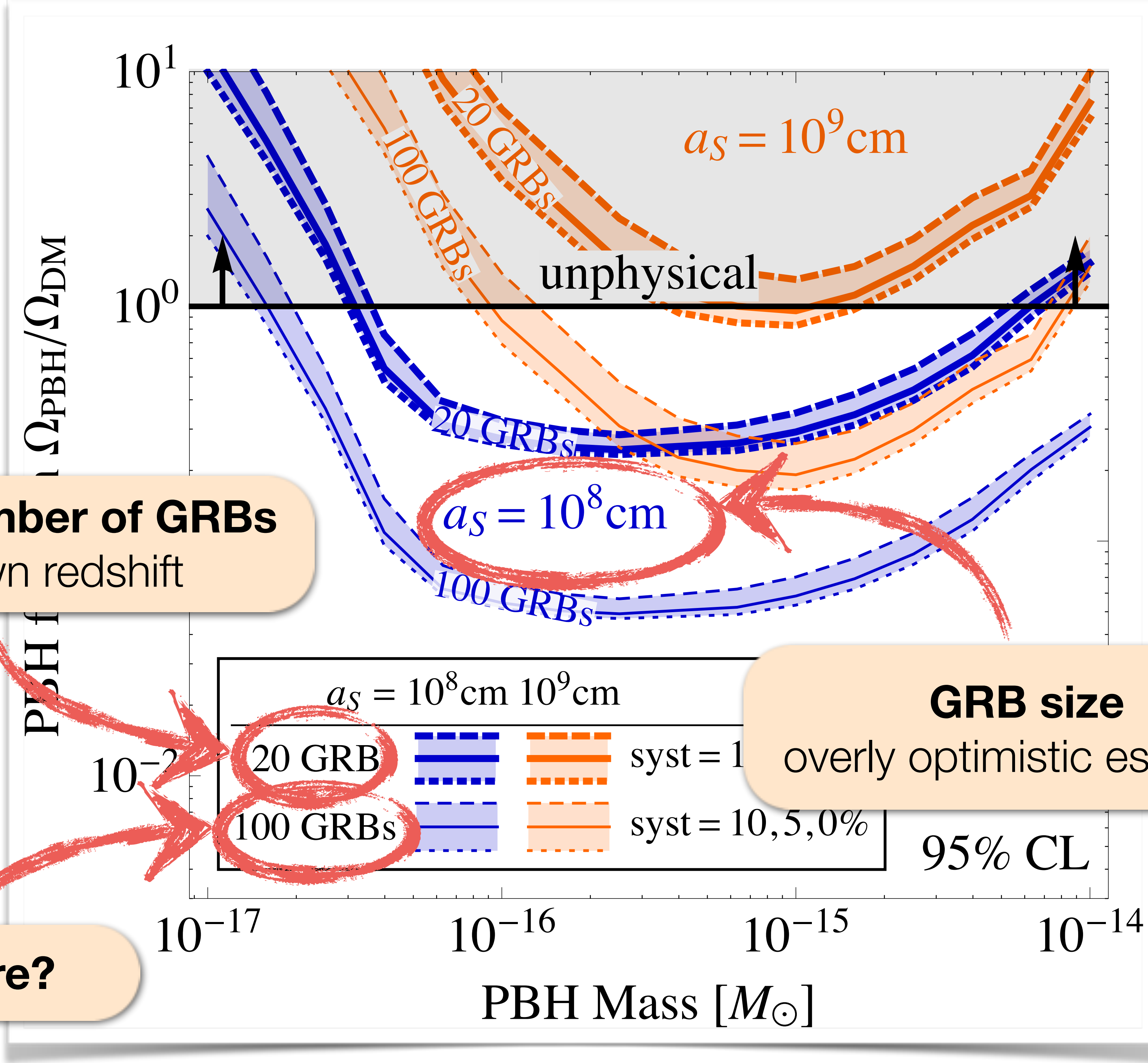

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Future?

Katz JK Sibir[...]
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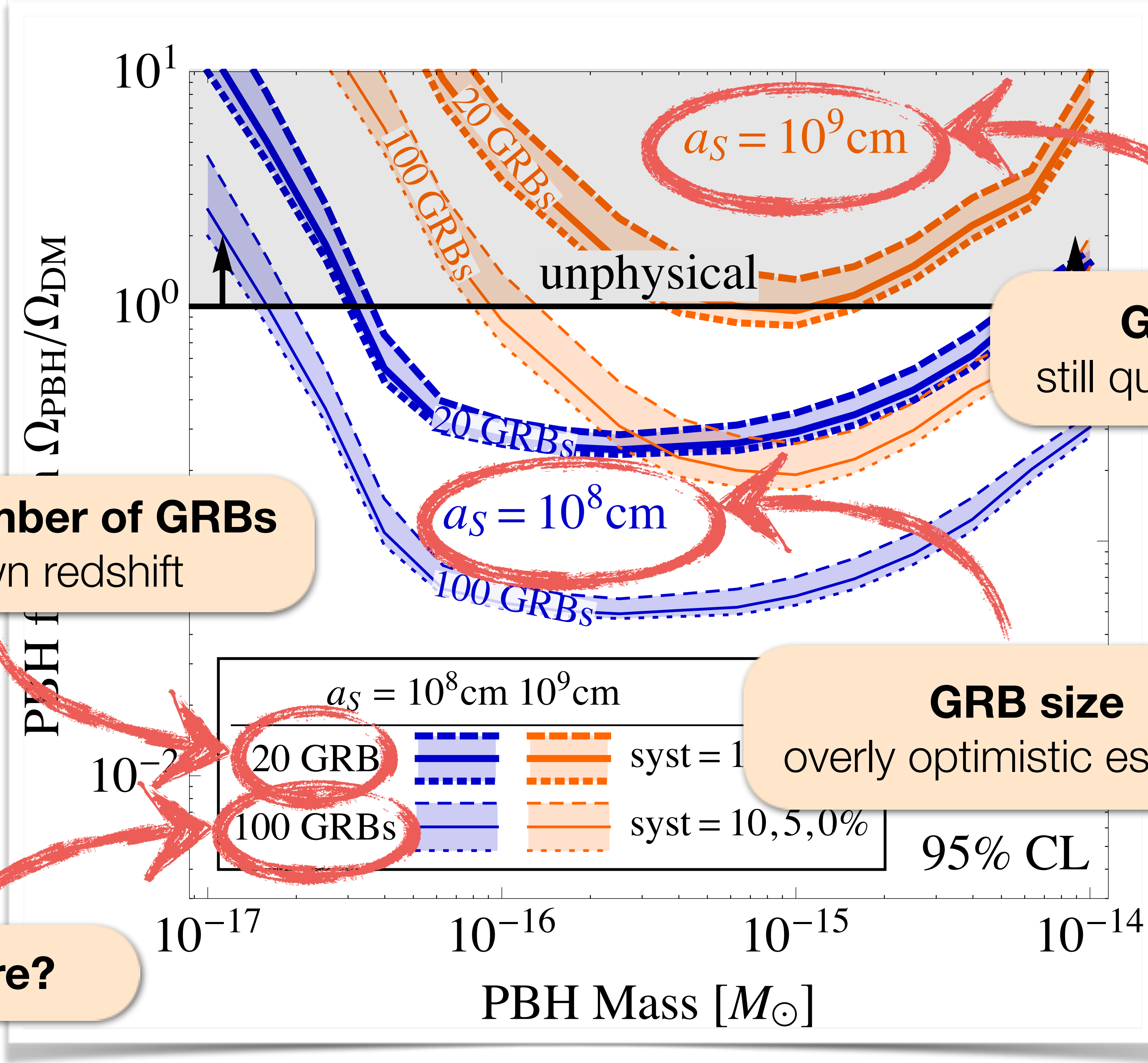

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Future?

Katz JK Sibir...
arXiv:1807.11495

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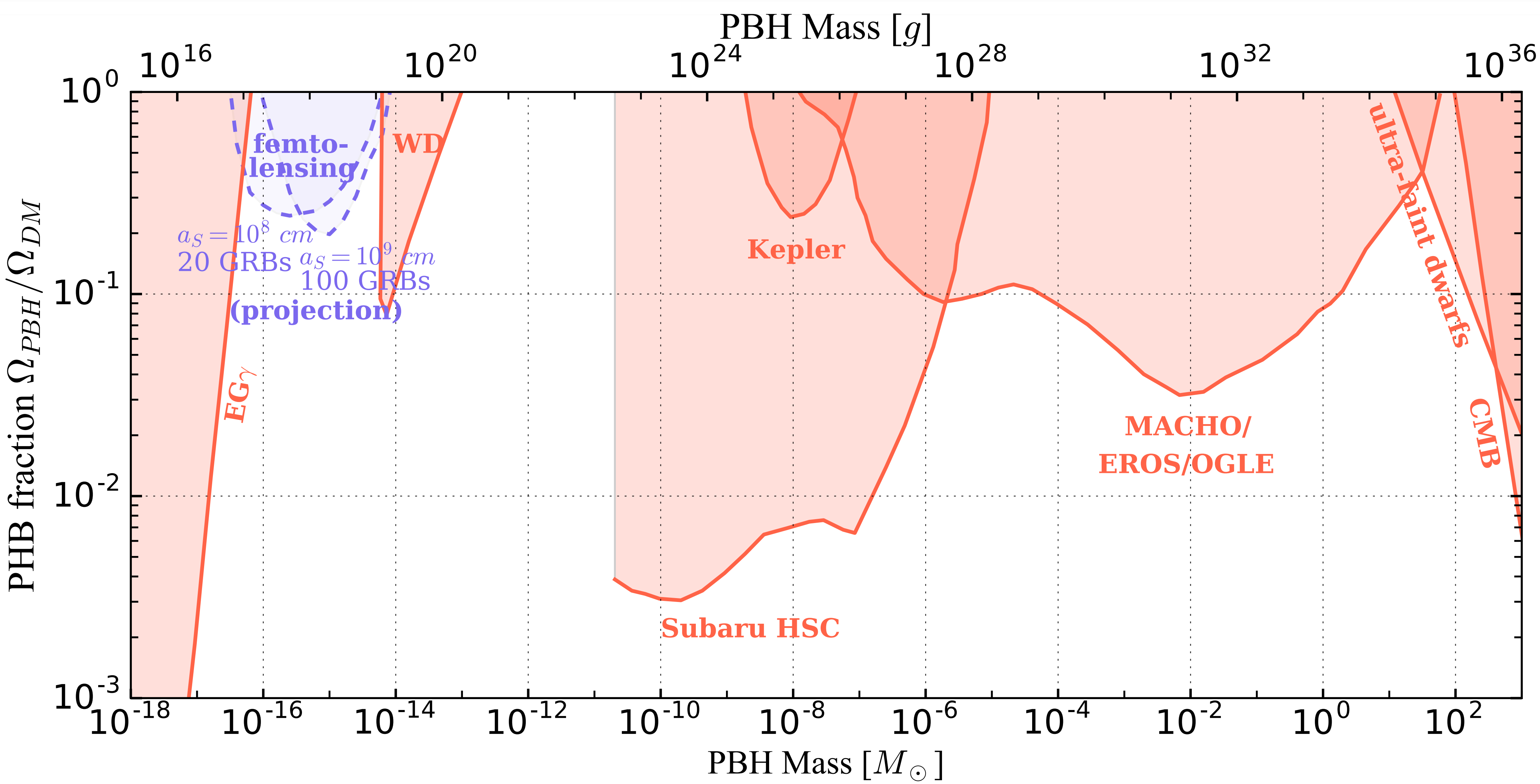
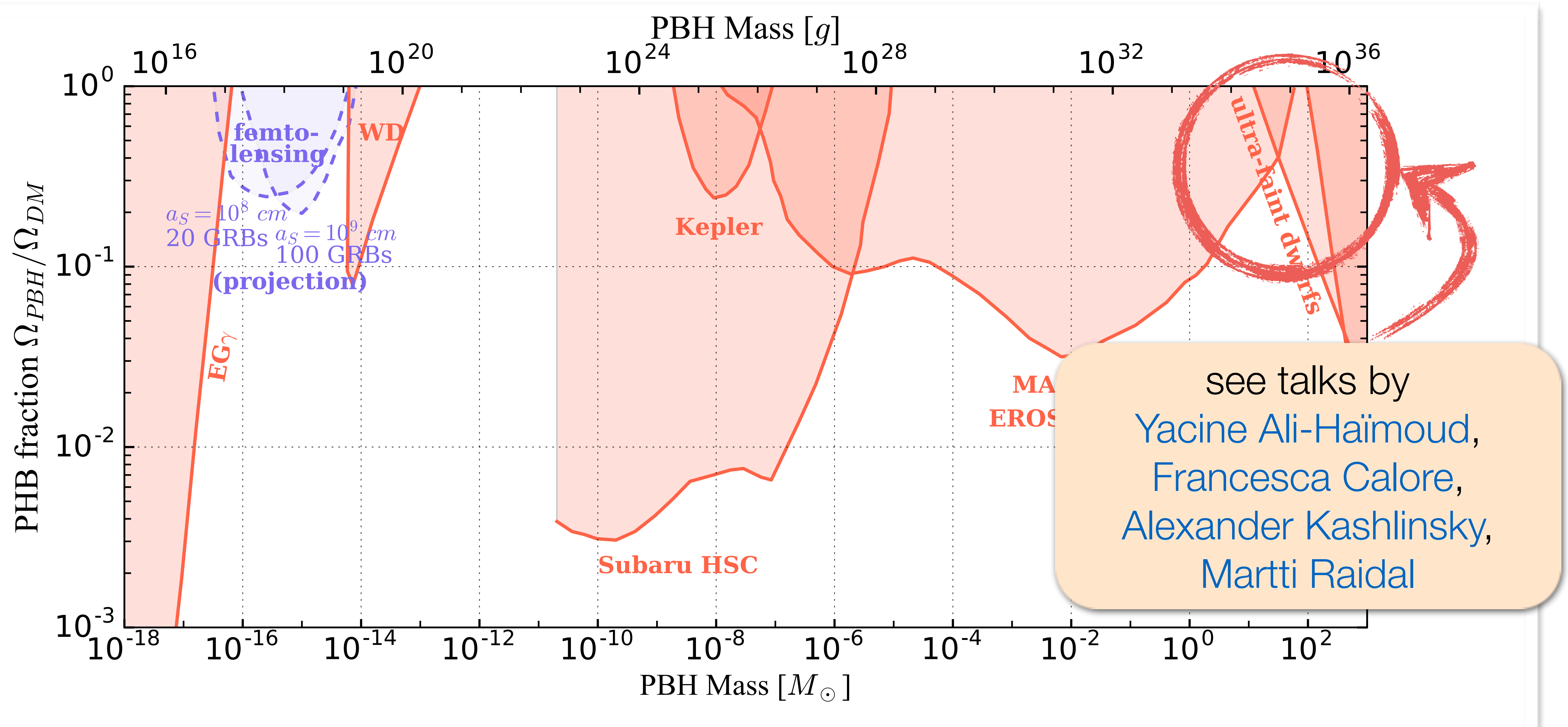
PBH Parameter Space



Katz JK Sibiryakov Xue
arXiv:1807.11495

Assuming δ-like PBH mass distribution, see Licia Verde's talk for caveats

PBH Parameter Space



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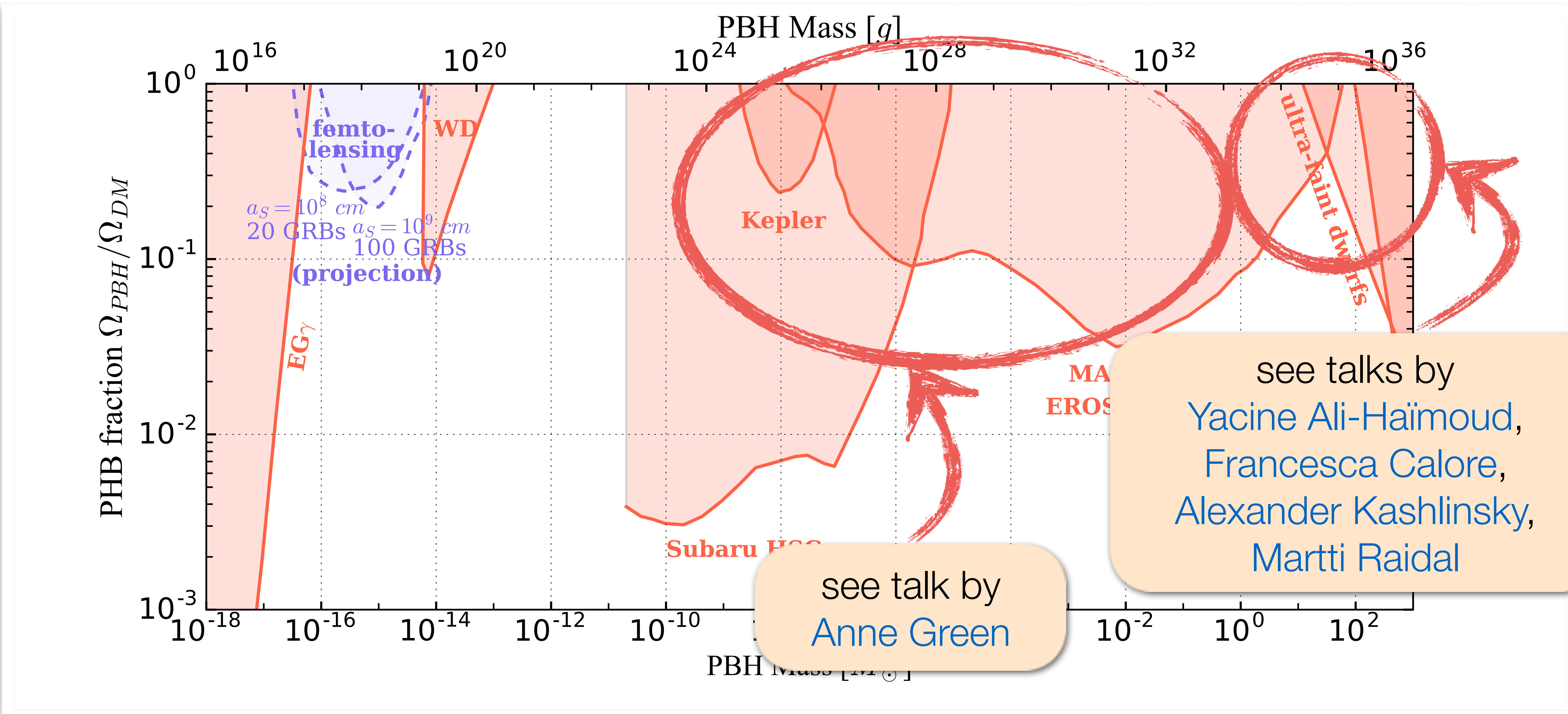

see talk by
Anne Green

see talks by
Yacine Ali-Haïmoud,
Francesca Calore,
Alexander Kashlinsky,
Martti Raidal

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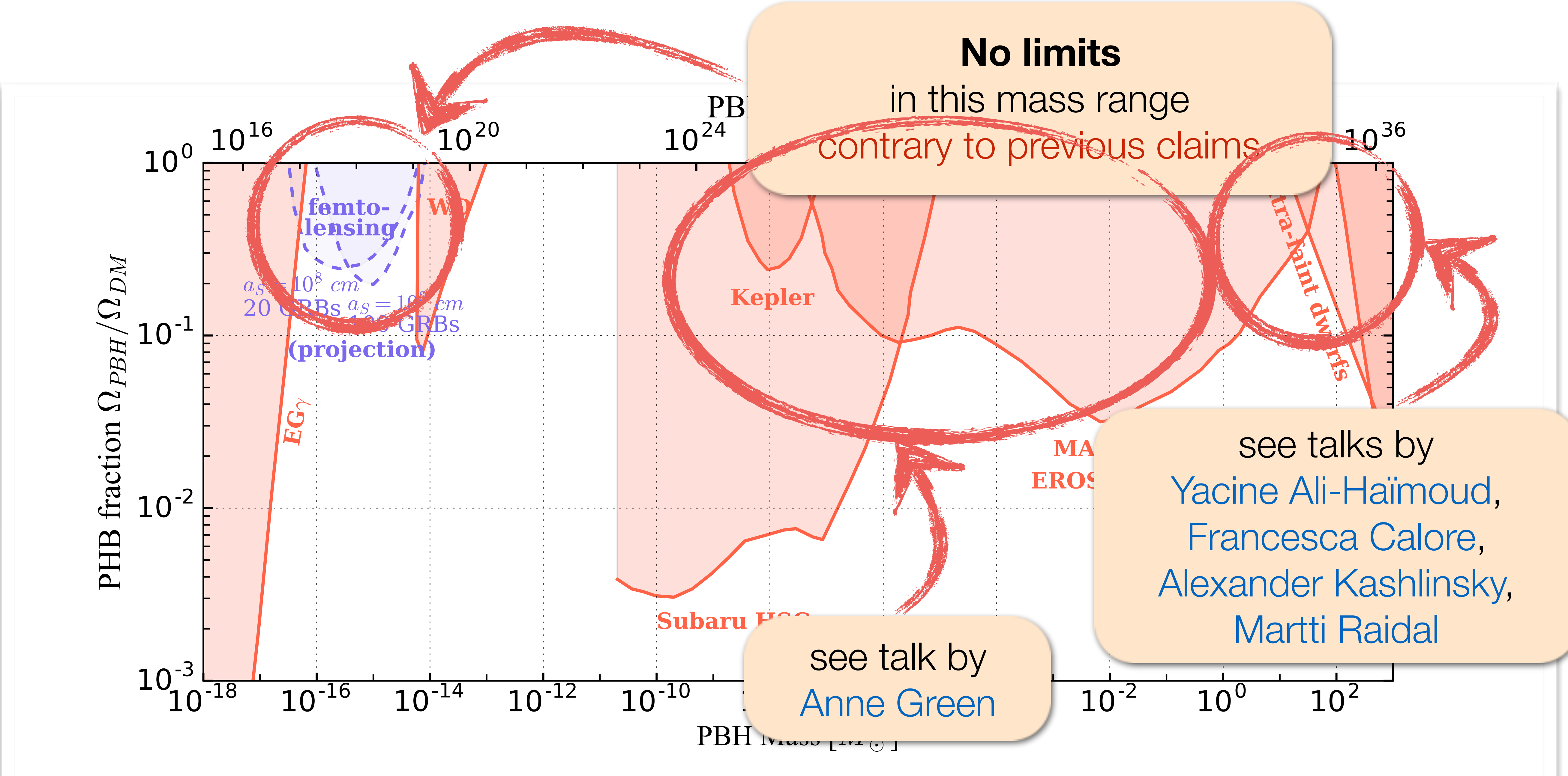

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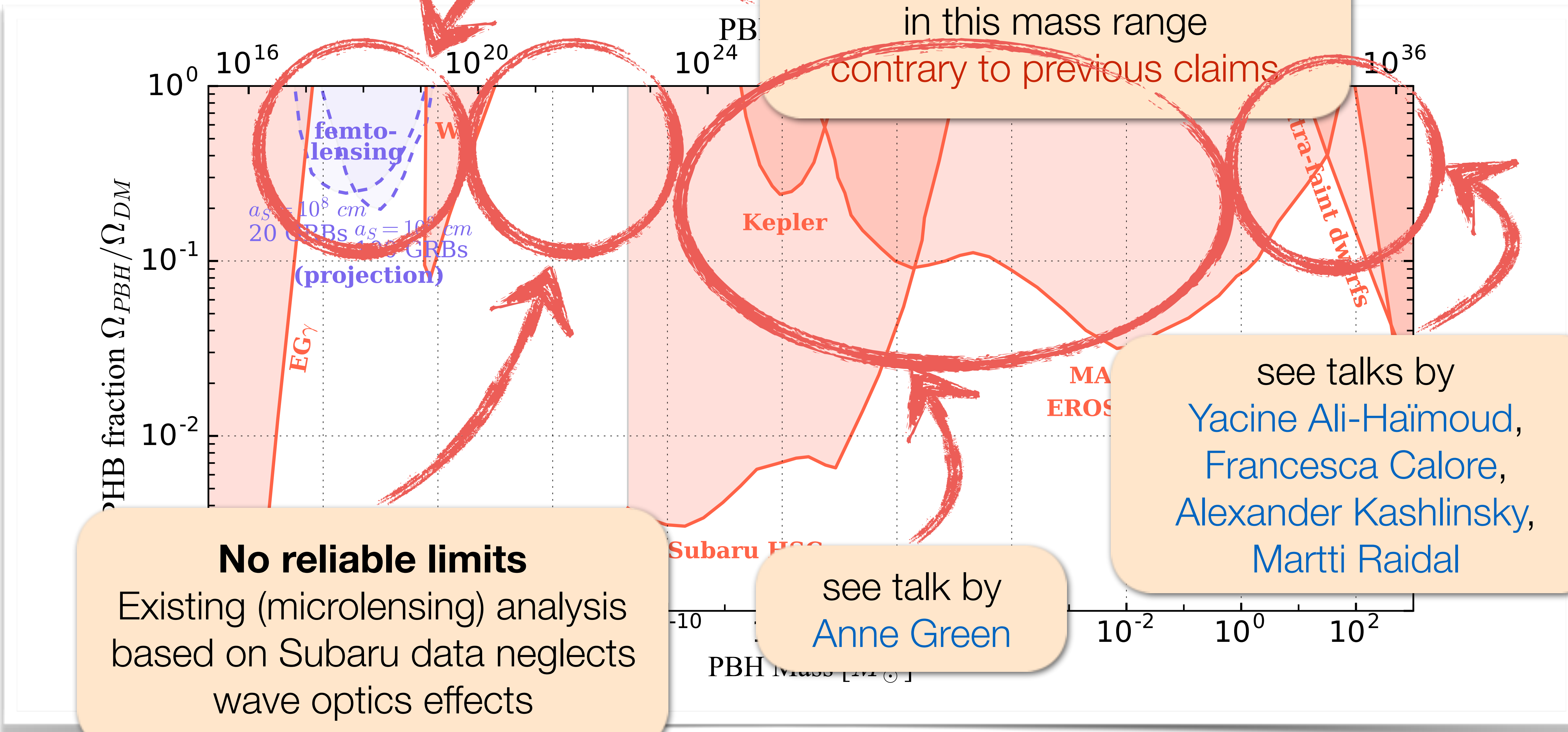

No limits
in this mass range
contrary to previous claims

No reliable limits
Existing (microlensing) analysis based on Subaru data neglects wave optics effects

see talk by
Anne Green

see talks by
Yacine Ali-Haïmoud,
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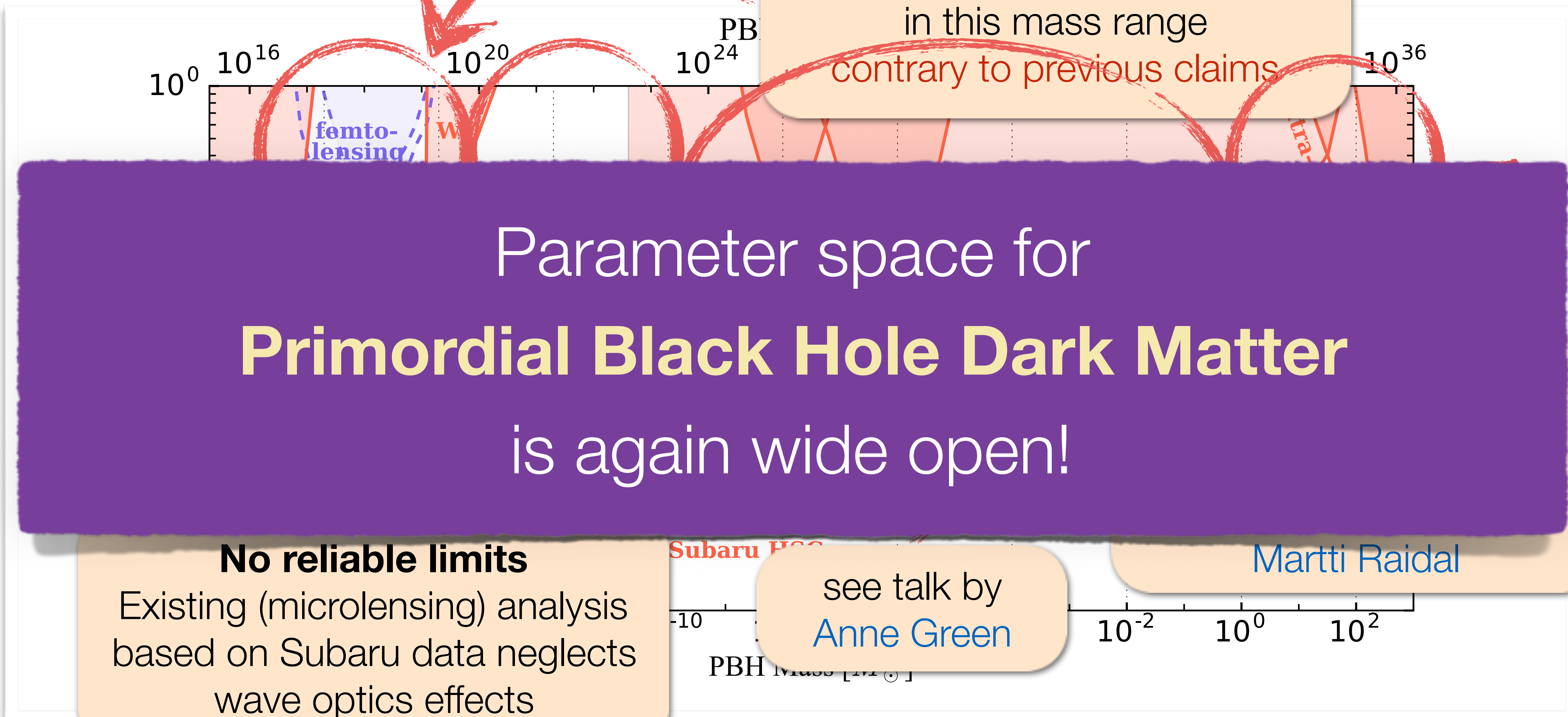
PBH Parameter Space



No limits
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Parameter space for
Primordial Black Hole Dark Matter
is again wide open!

Martti Raidal

No reliable limits
Existing (microlensing) analysis based on Subaru data neglects wave optics effects

see talk by
Anne Green

Katz JK Sibiryakov Xue
arXiv:1807.11495

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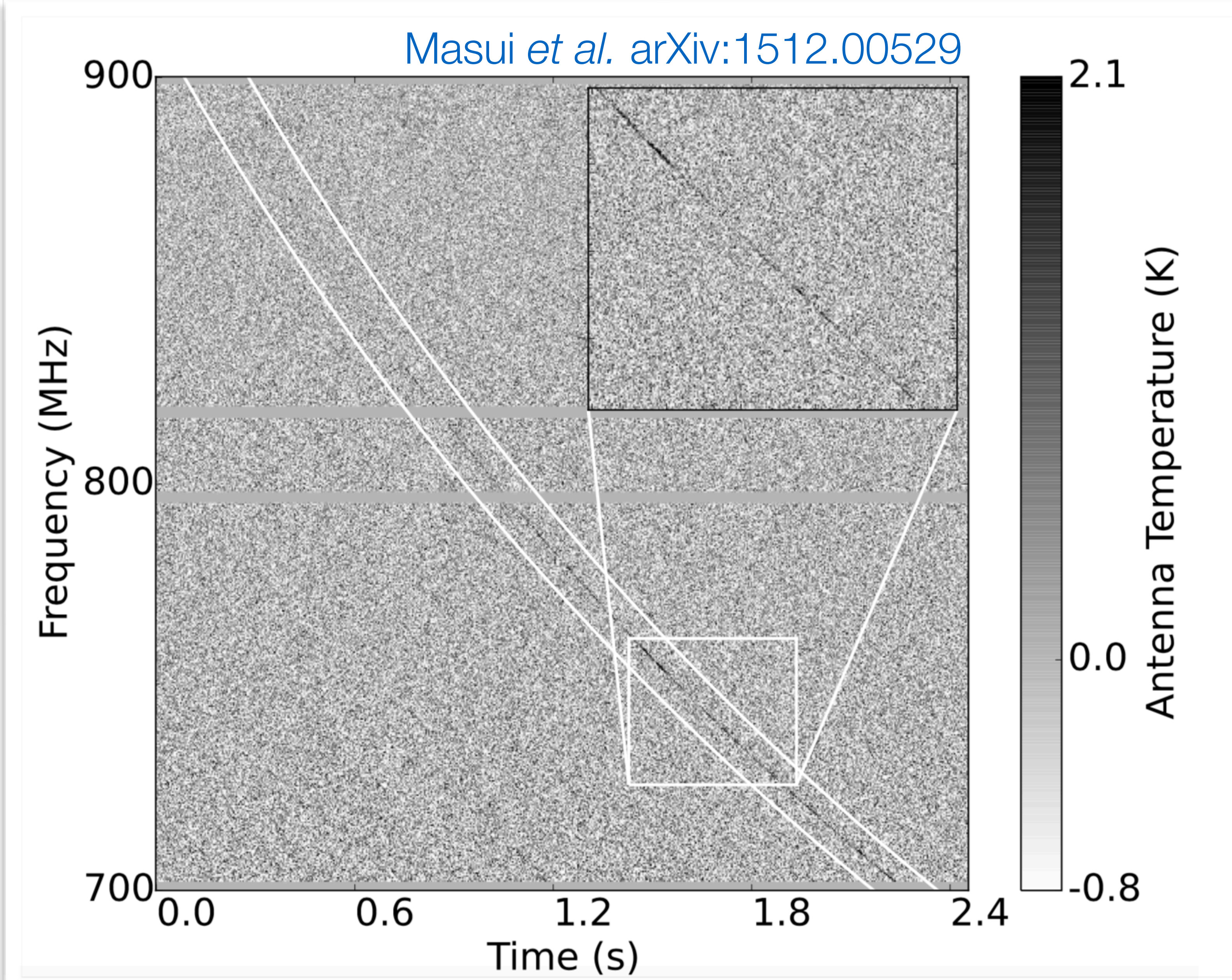
Femtolensing of FRBs

Fast Radio Bursts

- Short (~ms) burst of radio waves
- At $\mathcal{O}$(Gpc) distance
  (inferred from dispersion)
- Some repeaters
- Mechanism unknown



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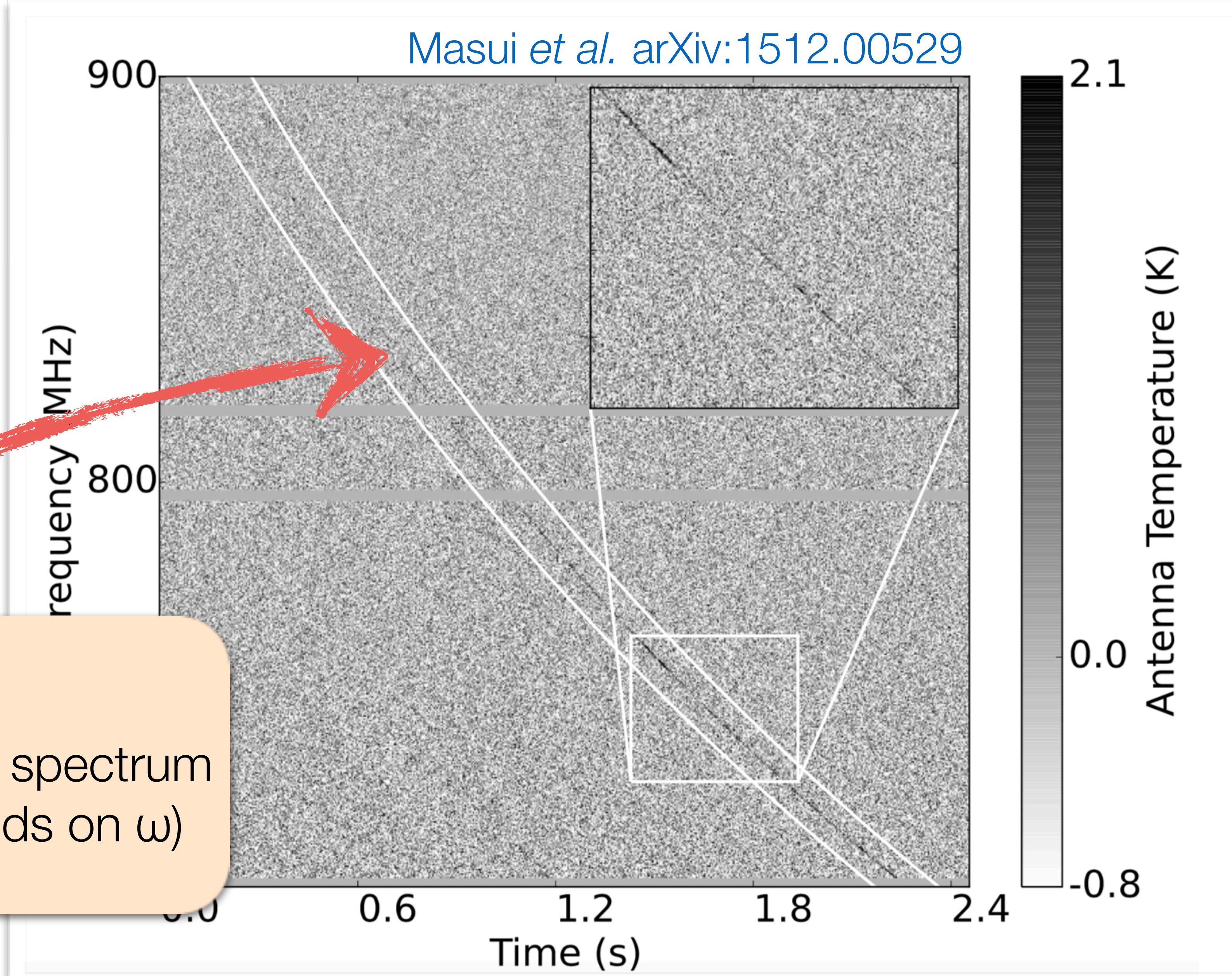

Dispersion
Burst moves through the frequency spectrum
(speed of light in ISM / IGM depends on ω)

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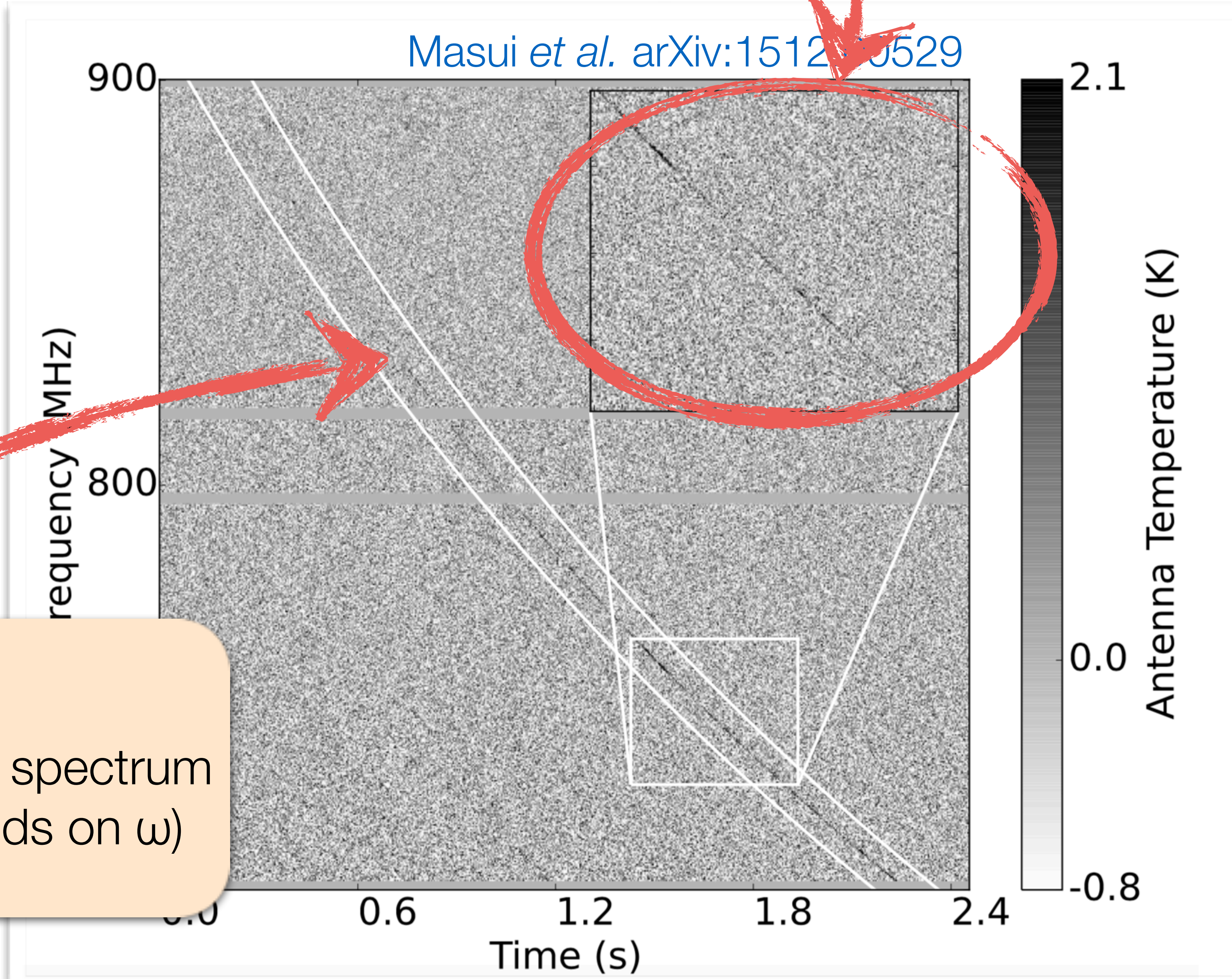
Fast Radio Bursts

Scintillation
interference between waves traveling along different paths through turbulent ISM / IGM.

- ☑ Short (~ms) burst of radio waves
- ☑ At $\mathcal{O}$(Gpc) distance (inferred from dispersion)
- ☑ Some repeaters
- ☑ Mechanism unknown



Dispersion
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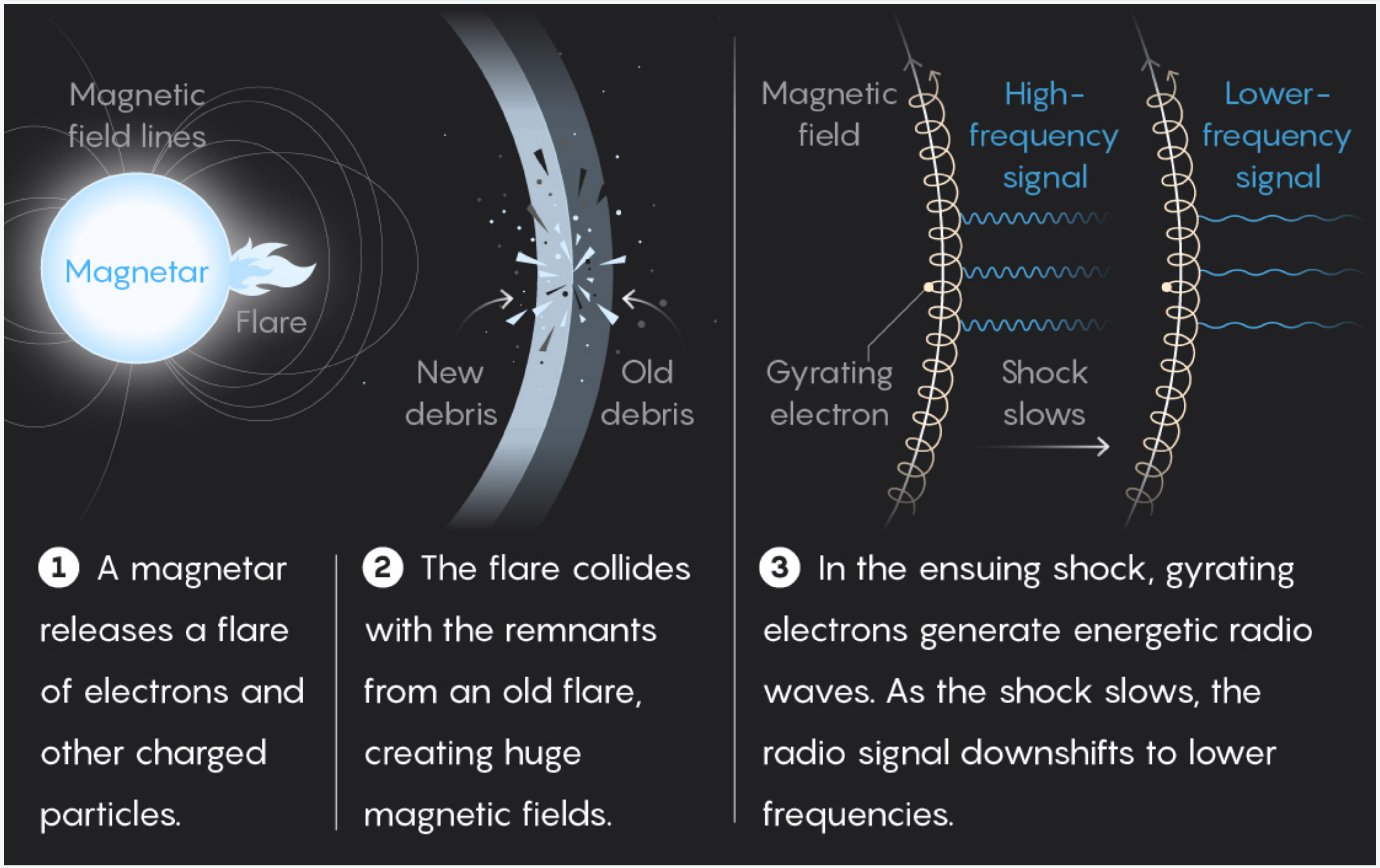
One of $\mathcal{O}(50)$ proposed FRB mechanisms



see arXiv:1810.05836
for a review of mechanisms

Image: Quanta Magazine
based on Metzger Margalit Sironi arXiv:1902.01866

Femtolensing of FRBs

- Remember:

$$\Delta t \simeq \frac{1}{c}\frac{D_L D_S}{D_{LS}}(1+z_L)\theta_E^2\left(\frac{|\vec{\theta}-\vec{\beta}|^2}{2}-\psi(\vec{\theta})\right) \sim 4G_N M_{\rm lens}$$

- Leads to $\mathcal{O}(2\pi)$ phase shifts for $f \sim$ GHz if $M_{\rm lens} \sim 10^{-4}\, M_{\rm sun}$
- Many new FRBs expected from SKA → high statistics
- But: easily confused with *scintillation*

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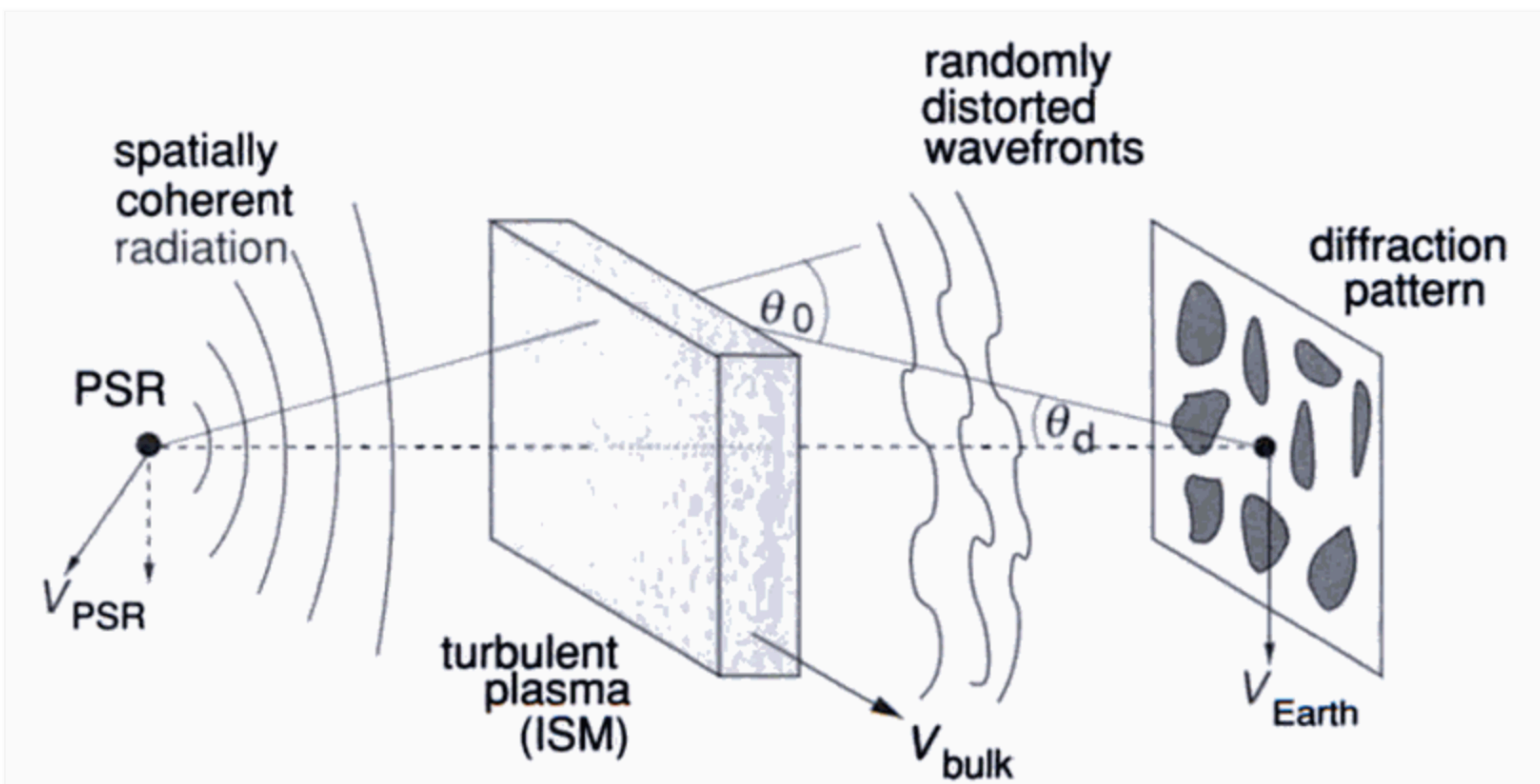
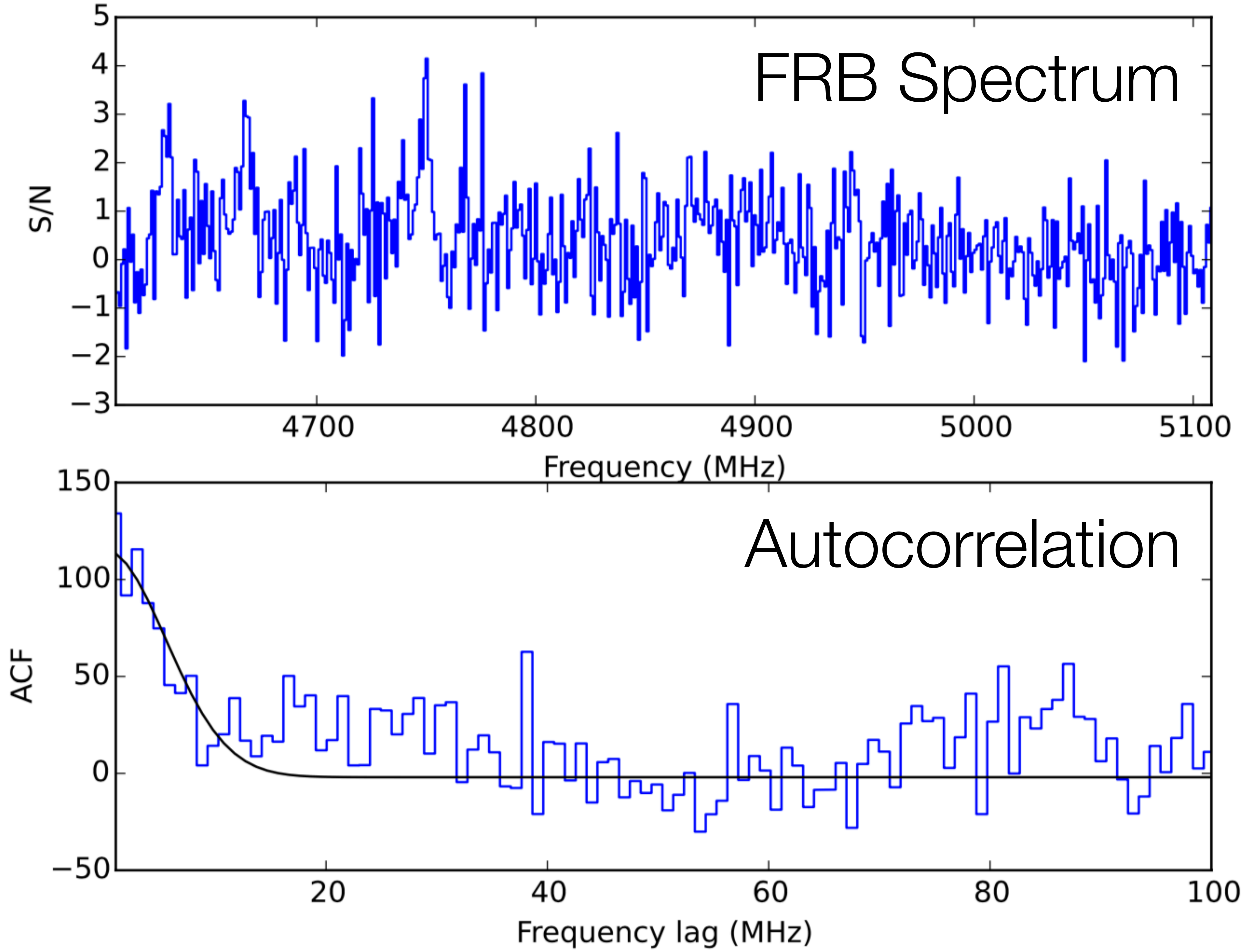
Scintillation

- many different lines of sight to the source because of refraction / diffraction in turbulent ISM / IGM
- leads to random interference patterns



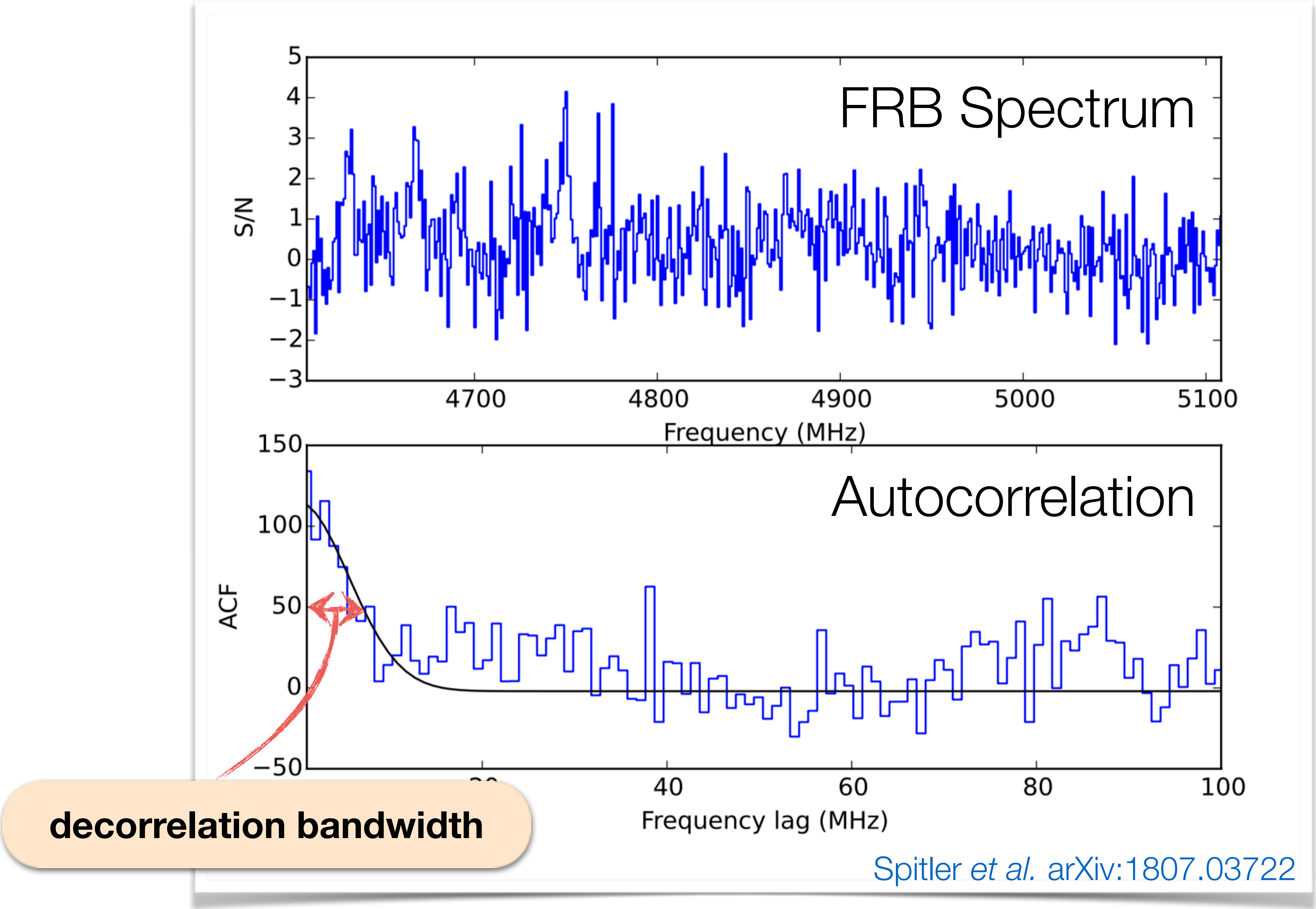
Lorimer Kramer 2004

Scintillation



Spitler *et al.* arXiv:1807.03722

Scintillation



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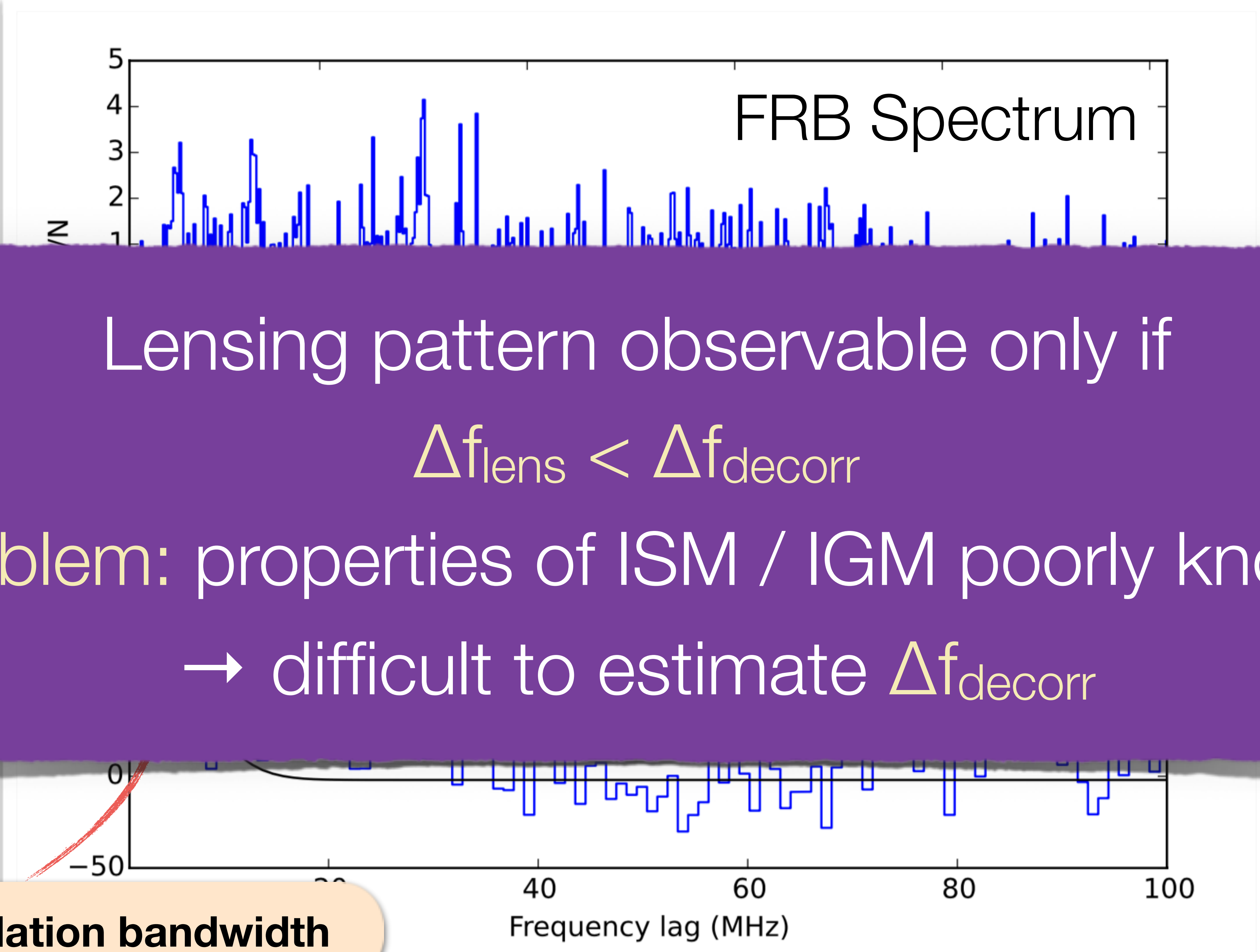
Scintillation



Lensing pattern observable only if

$\Delta f_{lens} < \Delta f_{decorr}$

Problem: properties of ISM / IGM poorly known

→ difficult to estimate Δf_{decorr}

decorrelation bandwidth

Spitler *et al.* arXiv:1807.03722

Summary

Summary

- ☑ Femtolensing is an interesting tool to constrain PBHs
- ☑ GRB lensing
  - for $M_{PBH} \sim 10^{-14}$—10^{-16} M_{sun}
  - must include wave optics corrections
  - must consider finite source size
  - no constraints with current data (contrary to previous claims)
- ☑ FRB lensing
  - FRBs are cool!
  - for $M_{PBH} \sim 10^{-4}$ M_{sun}
  - need to disentangle lensing from scintillation
  - limited by poor understanding of turbulent interstellar and intergalactic medium

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Thank You !