Primordial Black Hole signatures from femtolensing and spectral fringe of Gamma-ray Bursts

Speaker: Po-Yen Tseng (NTHU)

Collaborator: Chang-Yu Dai (NTHU)

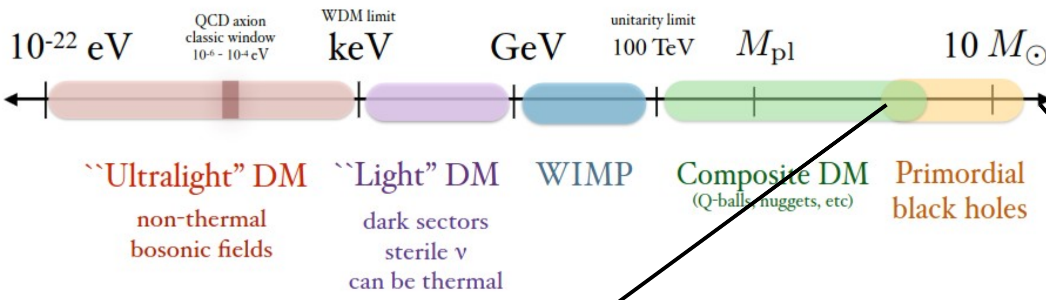
Reference:
JHEAp 53 (2026) 100635 (arXiv:2602.06407)

30th International Summer Institute on Phenomenology of Elementary Particle Physics and Cosmology (SI2026), Aug. 7-13, 2026, Japan

DM candidate

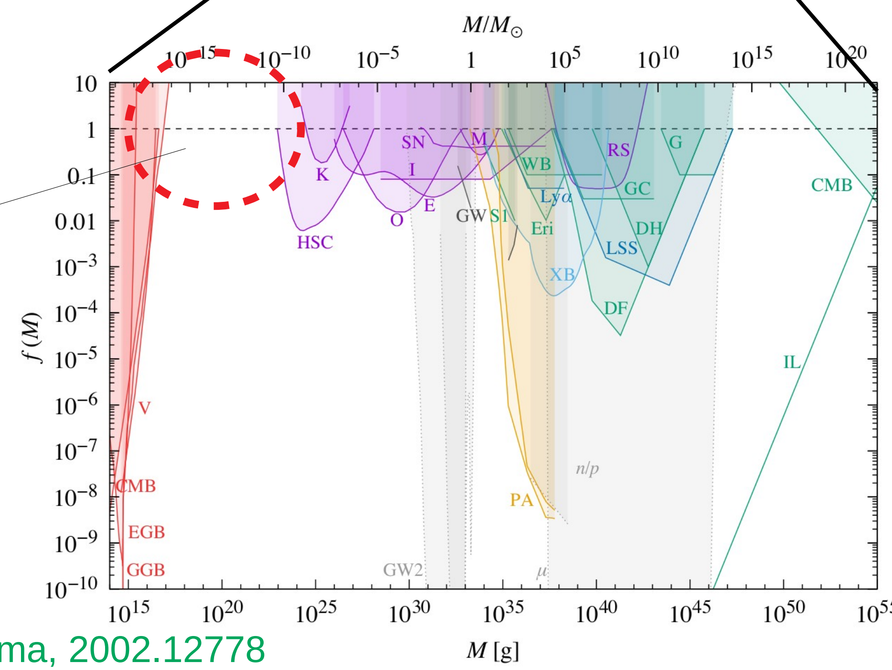
- Mass scale of dark matter:

Tongyan Lin: PoS 333 (2019) 009



PBH 1E-15~1E-10 solar mass:

PBH fraction: $f_{\rm PBH} \equiv \frac{\rho_{\rm PBH}}{\rho_{\rm DM}}$



B.Carr, K.Kohri, Y.Sendouda, and J.Yokoyama, 2002.12778

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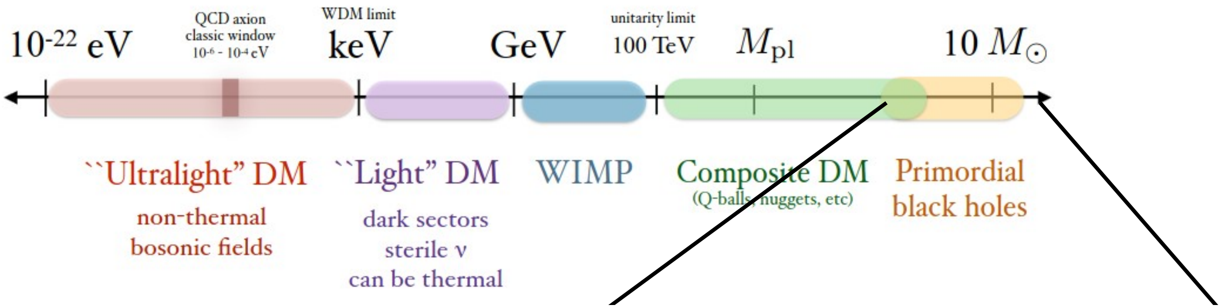

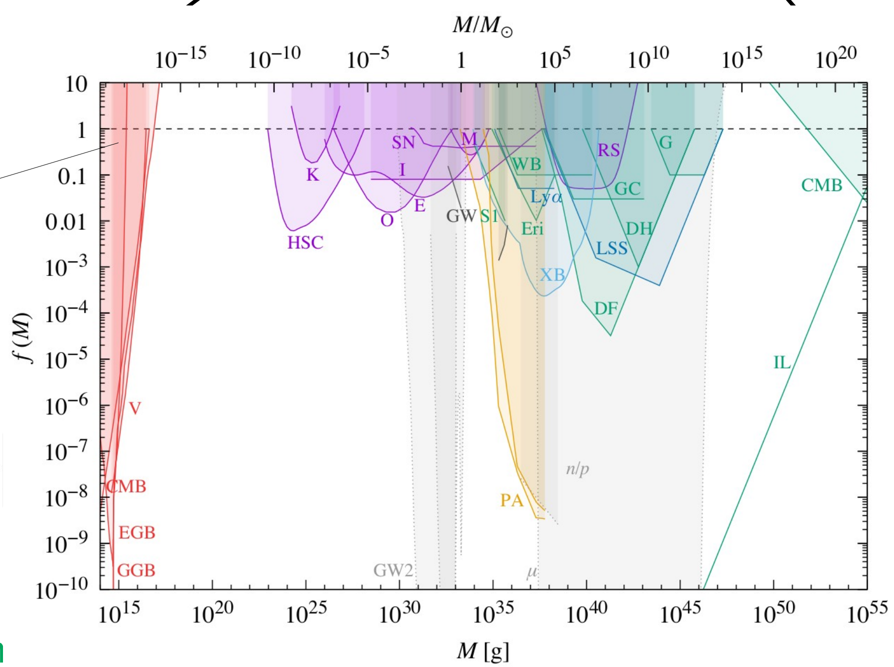

Hawking radiation:

$$T_{\rm PBH} \simeq 5.3\ \text{MeV} \times \left(\frac{10^{-18} M_\odot}{M_{\rm PBH}}\right)$$

$$\frac{d\Phi}{d\mathcal{T}} = \int_{t_\phi}^{\min(t_{\rm eva},t_0)} c\,dt[1+z(t)]\,\frac{f_{\rm PBH}\rho_{\rm DM}}{M_{\rm PBH}}\,\frac{d^2N_\chi}{d\mathcal{T}dt}$$

B.Carr, K.Kohri, Y.Sendouda, and J.Yokoyan

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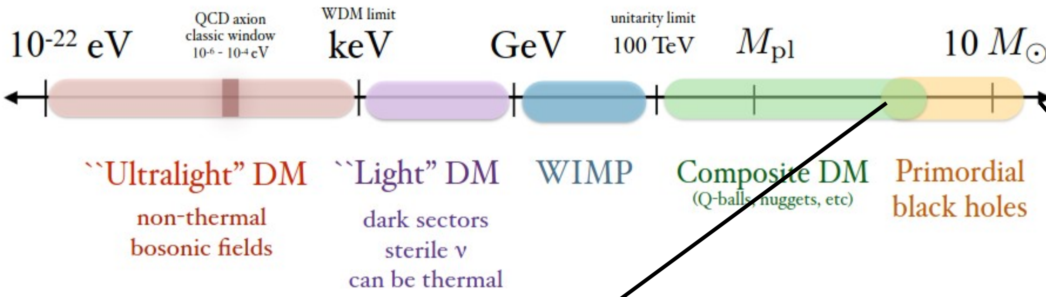
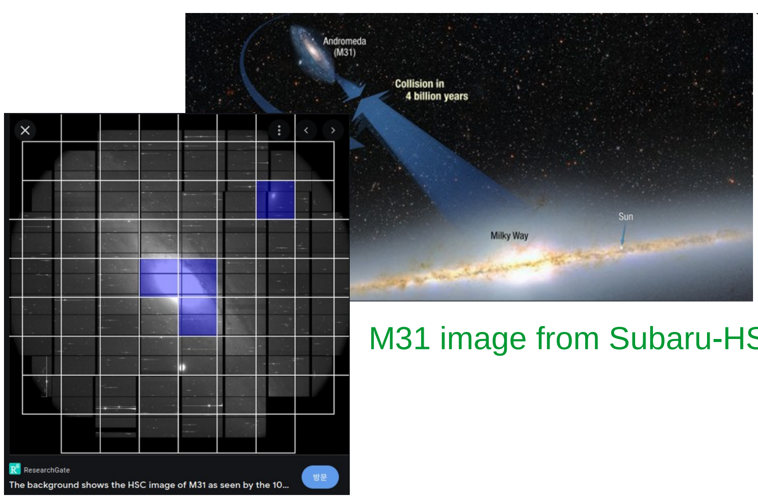
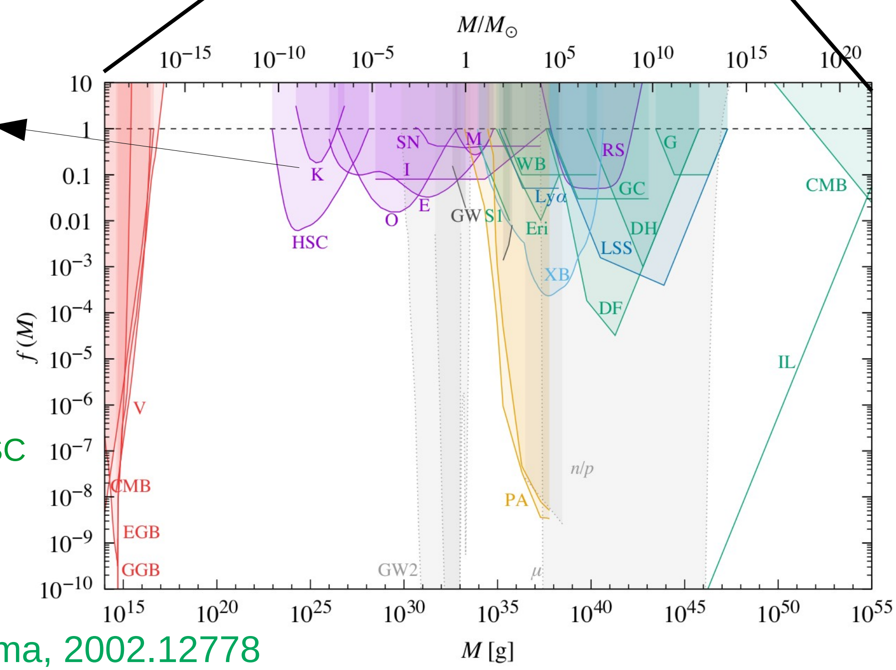


Microlensing:



M31 image from Subaru-HSC



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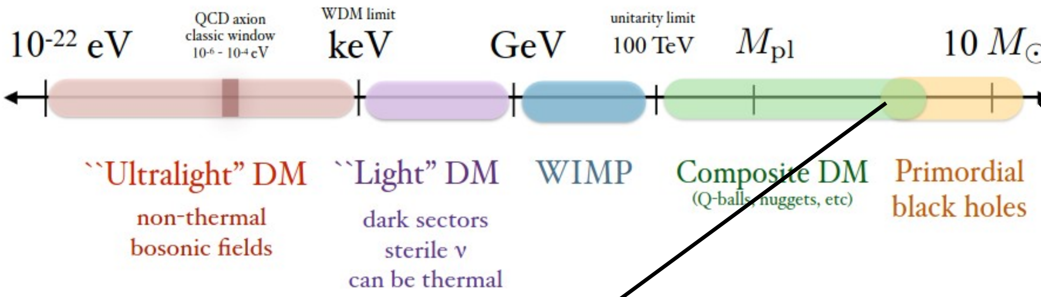
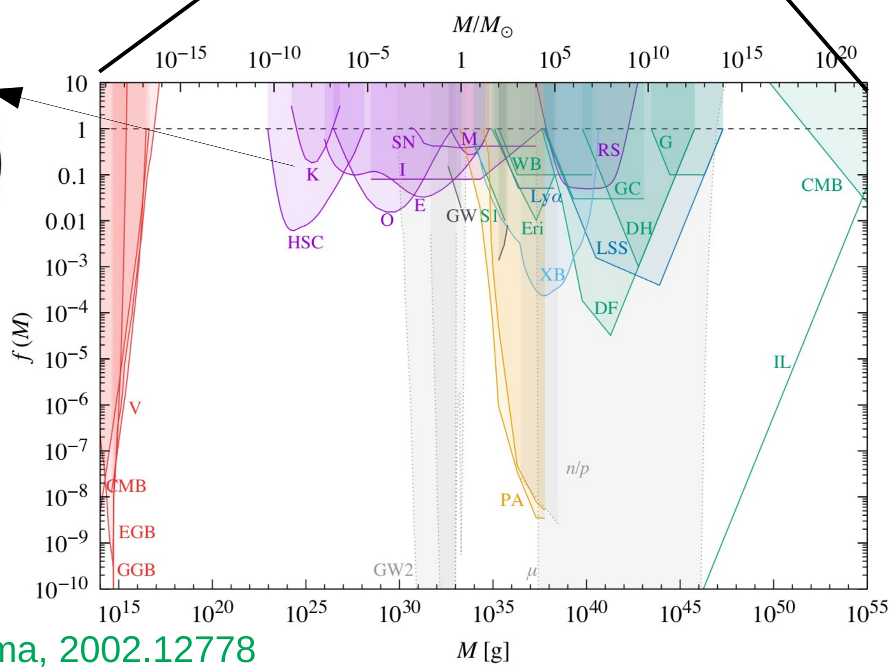


Mircrolensing:

$$R_s = 2GM \simeq 295\,\mathrm{nm}\left(\frac{M_{\rm PBH}}{10^{-10}M_\odot}\right)$$

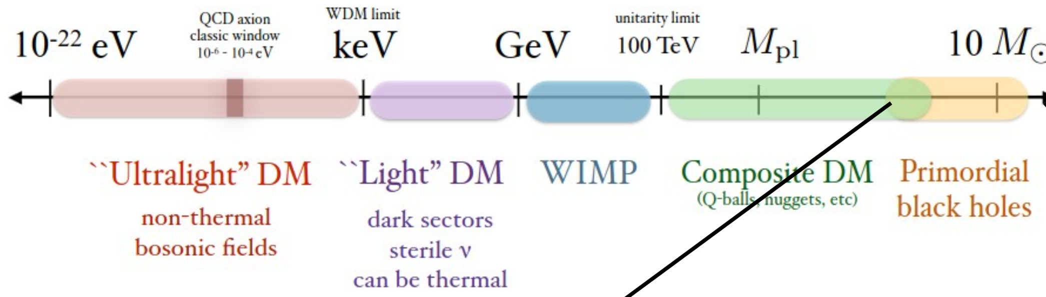


B.Carr, K.Kohri, Y.Sendouda, and J.Yokoyama, 2002.12778

DM candidate

- Mass scale of dark matter:

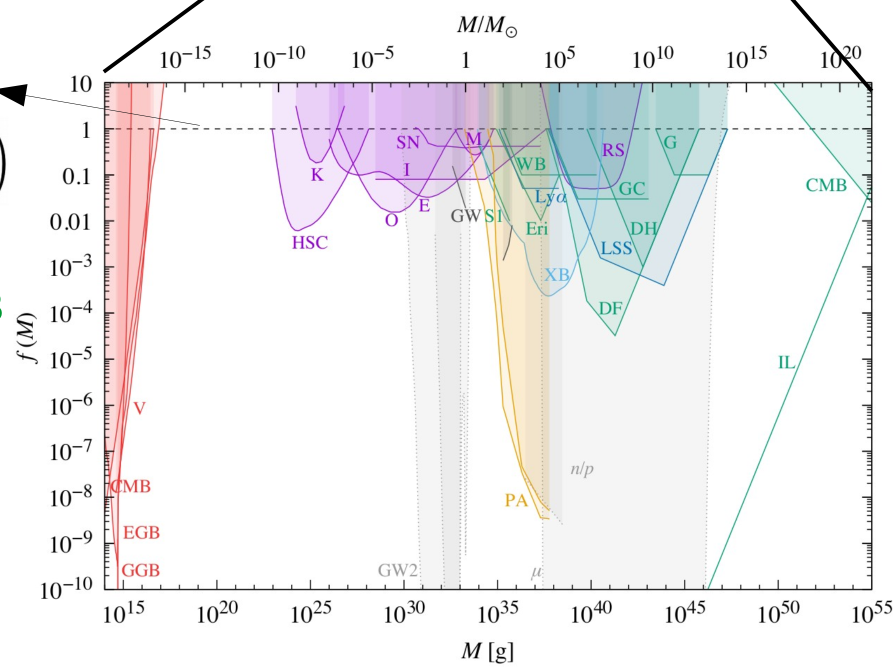
Tongyan Lin: PoS 333 (2019) 009



Femtolensing: gamma-ray

$$R_s = 2GM \simeq 295\,\mathrm{nm}\left(\frac{M_{\rm PBH}}{10^{-10}M_\odot}\right)$$

A.Gould et.al: Astrophys.J.Lett. 452, L111 (1995)
S.Jung, T.H Kim: Phys.Rev.Res. 2 (2020)1, 013113



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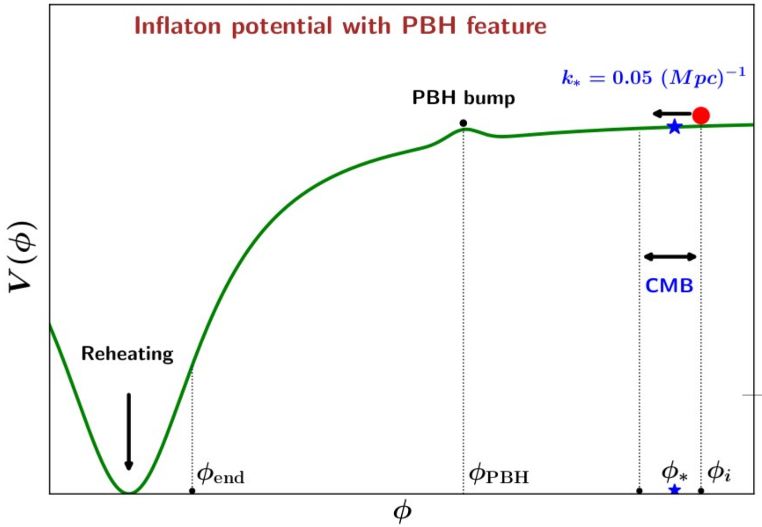
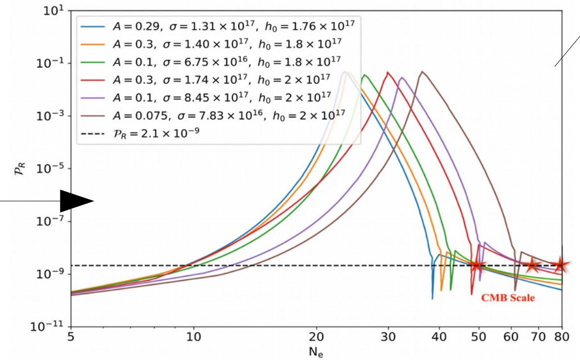
- PBH in [1E-15,1E-10] solar mass
- Gamma-ray Bursts & Swift data
- Gravitational lensing
- Numerical analysis
- Results & Discussion

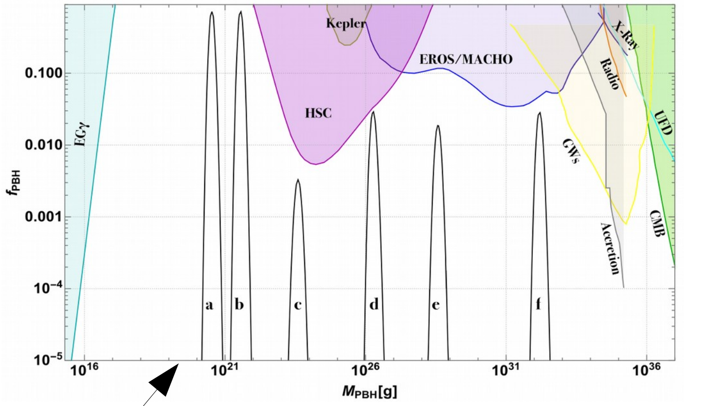
PBH formation

- Inflation with enhanced curvature perturbation
- Dark first-order phase transition



S.S.Mishra, V.Sahni: JCAP 04 (2020)007.



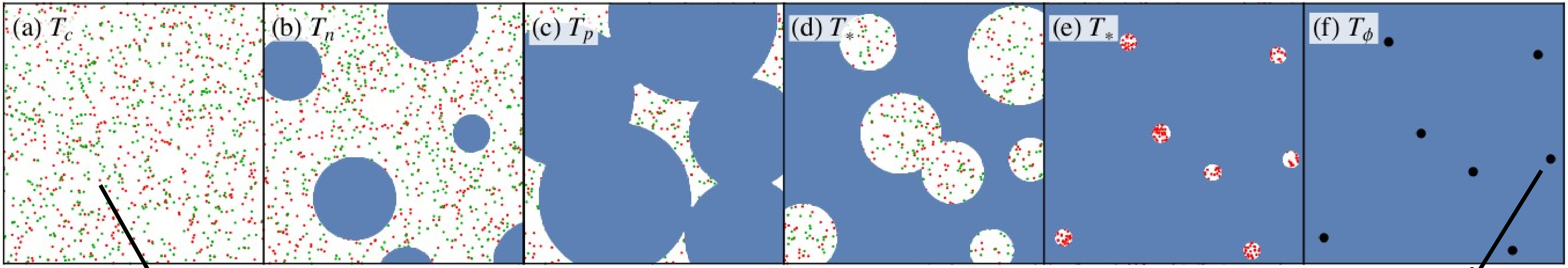


K.Cheung, C.J.Ouseph, PYT: EPJC 84 (2024) 9,906.

PBH formation

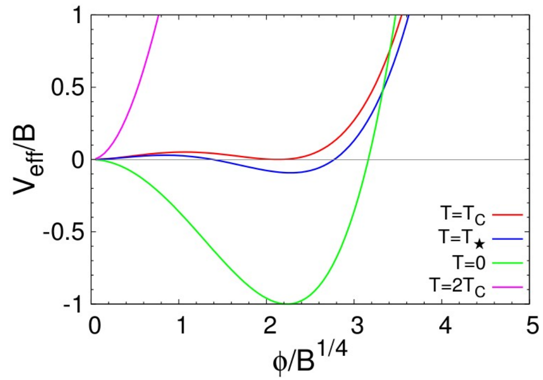
- Inflation with enhanced curvature perturbation
- Dark first-order phase transition

K.Kawana, K.P.Xie: PLB 824 (2022) 136791



χ's **Dark fermions**

Fermi Ball, PBH



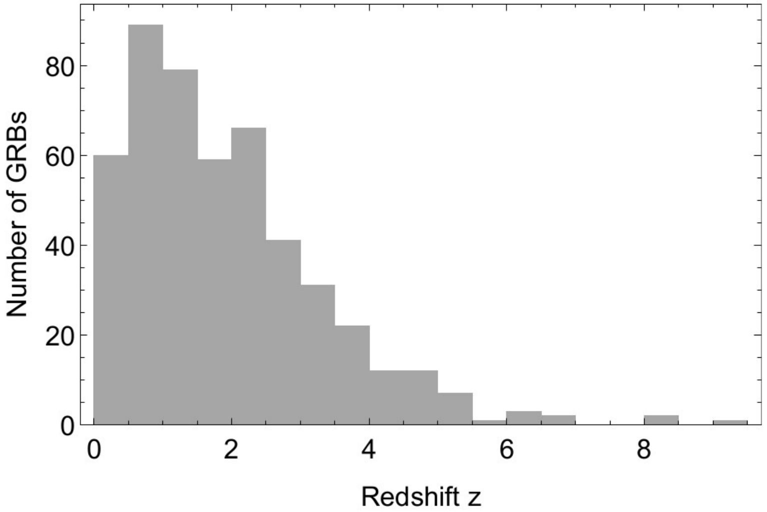
$$\mathcal{L} \supset \bar{\chi} i \partial\!\!\!/ \chi - g_\chi \phi \bar{\chi} \chi - V_{\rm eff}(\phi, T)$$

$$m_\chi \simeq g_\chi \langle \phi \rangle$$

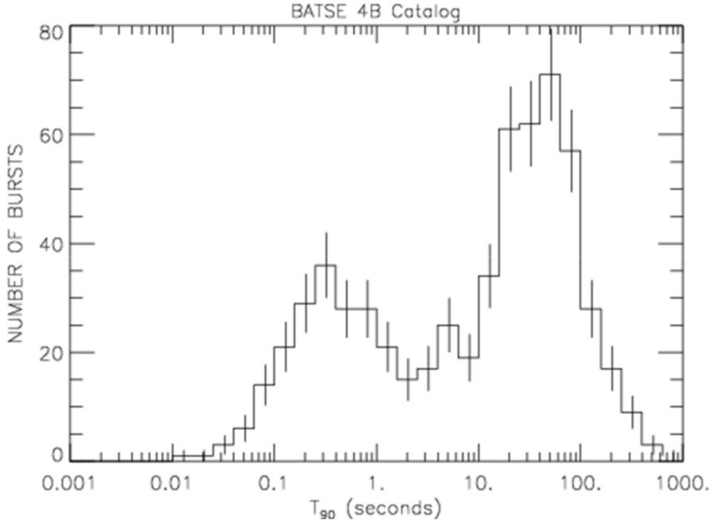
Details in Jan Tristram Acuna's talk

Gamma-ray Bursts (GRBs)

- Few thousands of GRBs have been observed, ~500 have redshift information and ~2000 have T_{90} information which is the time interval of GRB emission from 5% to 95%.



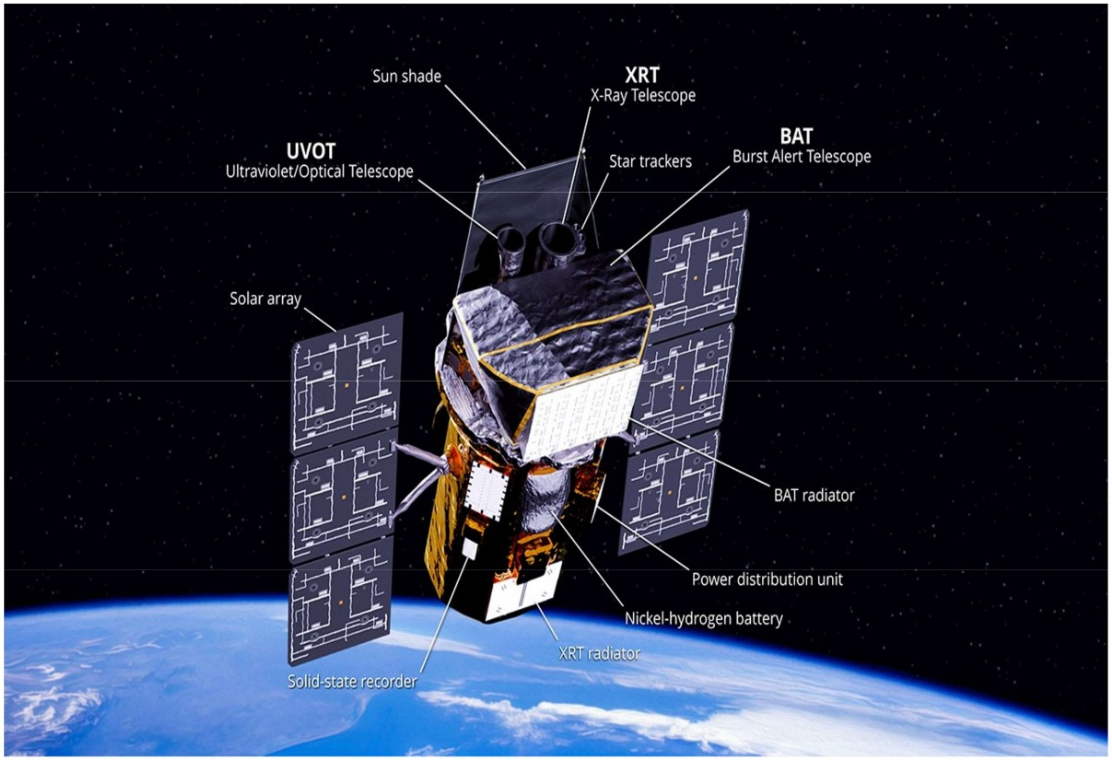
S.Jung, T.H Kim: Phys.Rev.Res. 2 (2020)1, 013113



Duration of GRBs detected by BATSE

- We used to define the effective size of GRB: $a_s = c \times T_{90}$

GRBs: The Neil Gehrels Swift Observatory

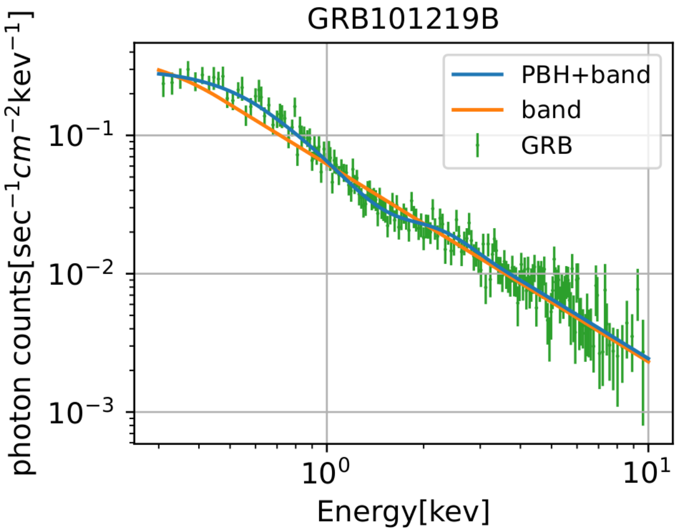


NASA’s Goddard Space Flight Center Conceptual Image Lab

Burst Alert Telescope (BAT): trigger and localize

X-Ray Telescope (XRT): 0.2-10 keV

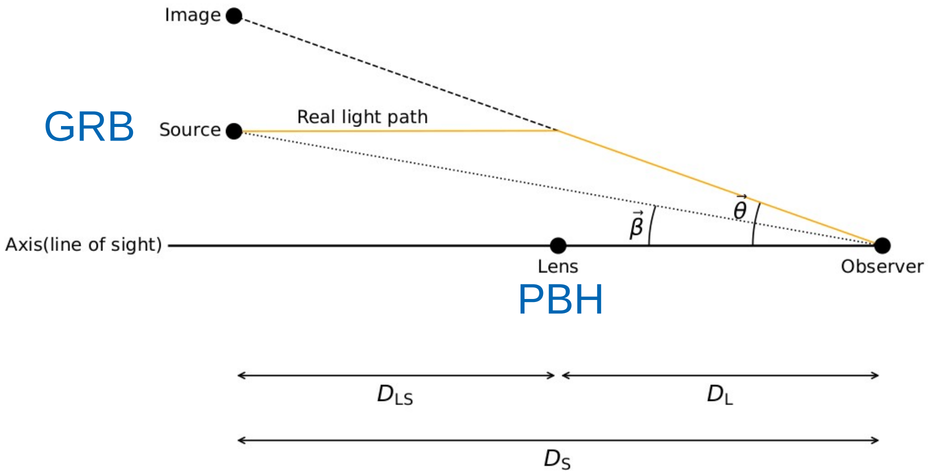
UV/Optical Telescope (UVOT): 170-650 nm



C.Y.Dai, PYT: JHEAp 53 (2026) 100635

Gravitational lensing

- We consider the PBH lensing on the GRB photon spectra.
- Geometry of gravitational lensing:



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Lensing equation: $\vec{\theta} - \vec{\beta} = \nabla\psi(\vec{\theta})$

Lensing potential is decieded by the mass distribution and Poisson equation:

$$\nabla^2\psi(\vec{\theta}) = \frac{8\pi G}{c^2}\frac{D_{LS}D_L}{D_S}\int_{-\infty}^{\infty} dz\,\rho(\sqrt{(D_L\theta)^2 + z^2})$$

Gravitational lensing: femtolensing

- We consider the PBH lensing on the GRB photon spectra.
- They will be a time delay, which causes a phase shift $\Delta\phi = \omega\Delta t$, where ω is the angular frequency of the photon.

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

- If the arrival times of the split rays cannot be distinguished by the detector, the detector will get an interference pattern.
- The intensity of the signal will be magnified and manifested in the spectrum.

A.Gould et.al: Astrophys.J.Lett. 452, L111 (1995)
S.Jung, T.H Kim: Phys.Rev.Res. 2 (2020)1, 013113

Gravitational lensing: geometric optics

- For a point-like lens, lensing equation becomes $x - y = 1/x$ normalizing $\vec{x} \equiv \vec{\theta}/\theta_E$ and $\vec{y} \equiv \vec{\beta}/\theta_E$ by Einstein angle $\theta_{\rm E} \equiv \sqrt{4GM \cdot D_{LS}/D_L D_S}$.
- This equation has two image solutions. If they produce the interference pattern, the total magnification leads to

$$\mu = \frac{y^2+2}{y\sqrt{y^2+4}} + \frac{2}{y\sqrt{y^2+4}} \sin\left[\Omega\left(\frac{y\sqrt{y^2+4}}{2} + \ln\left|\frac{y+\sqrt{y^2+4}}{y-\sqrt{y^2+4}}\right|\right)\right]$$

Dimensionless frequency: $\Omega \equiv \frac{4GM_{\rm PBH}(1+z_L)}{c^3}\omega$

Gravitational lensing: wave optics

- Energy of GRB from Swift XRT is 1-10 keV, and the mass range of PBH is 1E-15~1E-12 solar mass, so the wavelength of GRB is comparable with Schwarzschild radius of PBH.
- We need to consider wave optics.
- The magnification can be generalized by $\mu = |F|^2$

$$F(\vec{y}, \Omega) = \frac{\Omega}{2\pi i} \int d^2\vec{x}\, e^{i\Omega \Delta t(\vec{x}, \vec{y})}$$

Gravitational lensing: wave optics

- Energy of GRB from Swift XRT is 1-10 keV, and the mass range of PBH is 1E-15~1E-12 solar mass, so the wavelength of GRB is comparable with Schwarzschild radius of PBH.

- We need to consider wave optics.

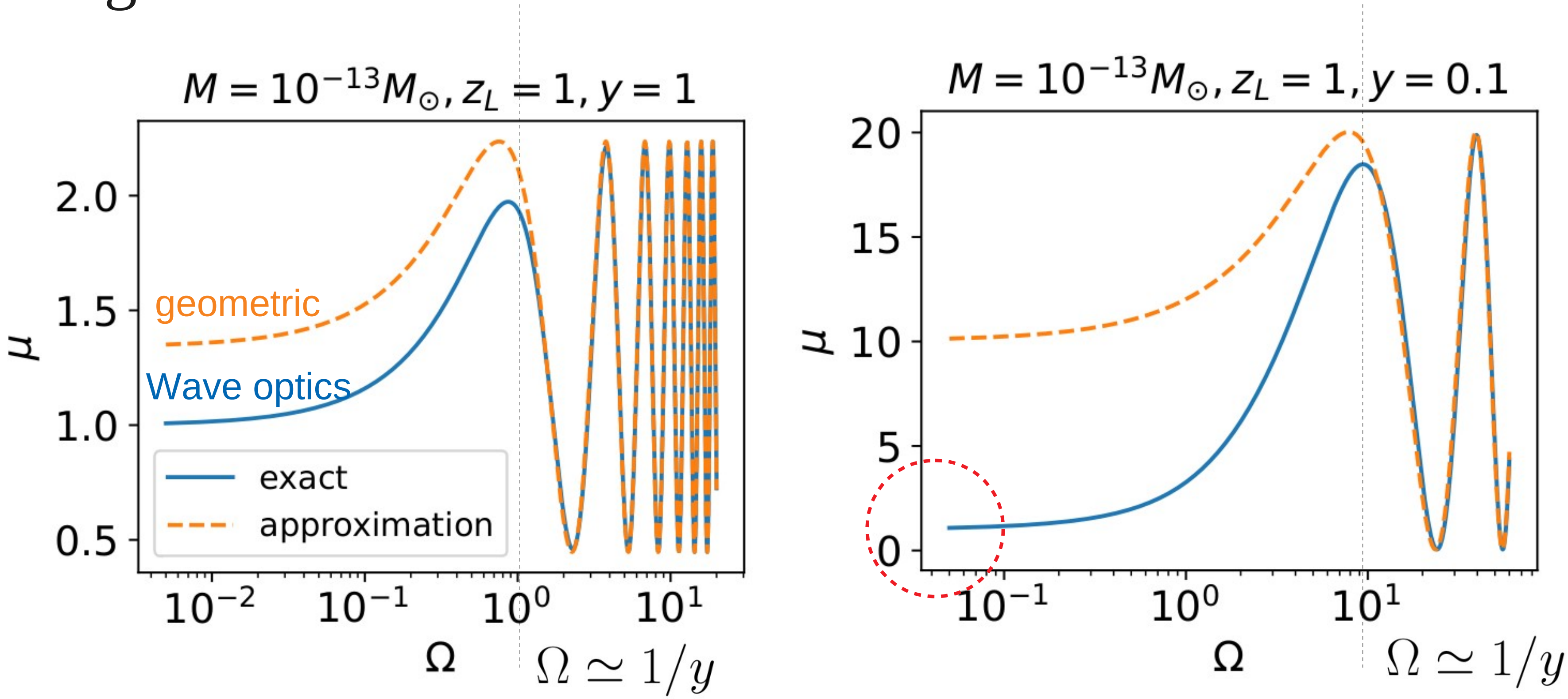
- The magnification can be generalized by $\mu = |F|^2$. In the point-like lens, the magnification can be expressed by

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

1F1: Hypergeometric function of the 1st kind

Gravitational lensing: wave optics

- Compare the geometric and wave optics for the magnification:



$\mu \to 1$ when $\Omega \to 0$

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Gravitational lensing: extended source

- We integrate over the source area πa_s^2 to obtain the magnification

$$\bar{\mu} = \frac{\int dy^2\, W(\vec{y}, \sigma_y)\mu(\vec{y}, \Omega)}{\int \; dy^2\, W(\vec{y}, \sigma_y)}$$

modeling the source with Gaussian function $W(\vec{y}, \sigma_y) = e^{\frac{-|\vec{y} - \vec{y_0}|^2}{2\sigma_y^2}}$

Normalized source size: $\sigma_y \equiv \frac{a_s}{D_s \theta_E}$

Source location: y_0

$a_s = 10^5 m$
$a_s = 10^6 m$
$a_s = 10^7 m$
$a_s = 5 \times 10^7 m$
$a_s = 10^8 m$
$a_s = T_{90} \times c$

- We require $\sigma_y \ll 1$; otherwise, the interference fringes will disappear.

GRB spectrum

- We adopt the BAND model to parameterize the original GRB energy spectrum:

$$f_{\rm BAND}(E) = \begin{cases} A(\frac{E}{E_0})^{\alpha_1} e^{-\frac{E}{E_0}}, \; E \leq (\alpha_1 - \alpha_2)E_0 \\ A(\alpha_1 - \alpha_2)^{\alpha_1 - \alpha_2} (\frac{E}{E_0})^{\alpha_2} e^{\alpha_2 - \alpha_1}, \; \text{otherwise} \end{cases}$$

D.BAND et.al : Astrophys. J. 413, 281-292 (1993)

- Therefore, the PBH modified intensity is given by $\bar{\mu} \times f_{\rm BAND}$

Numerical analysis

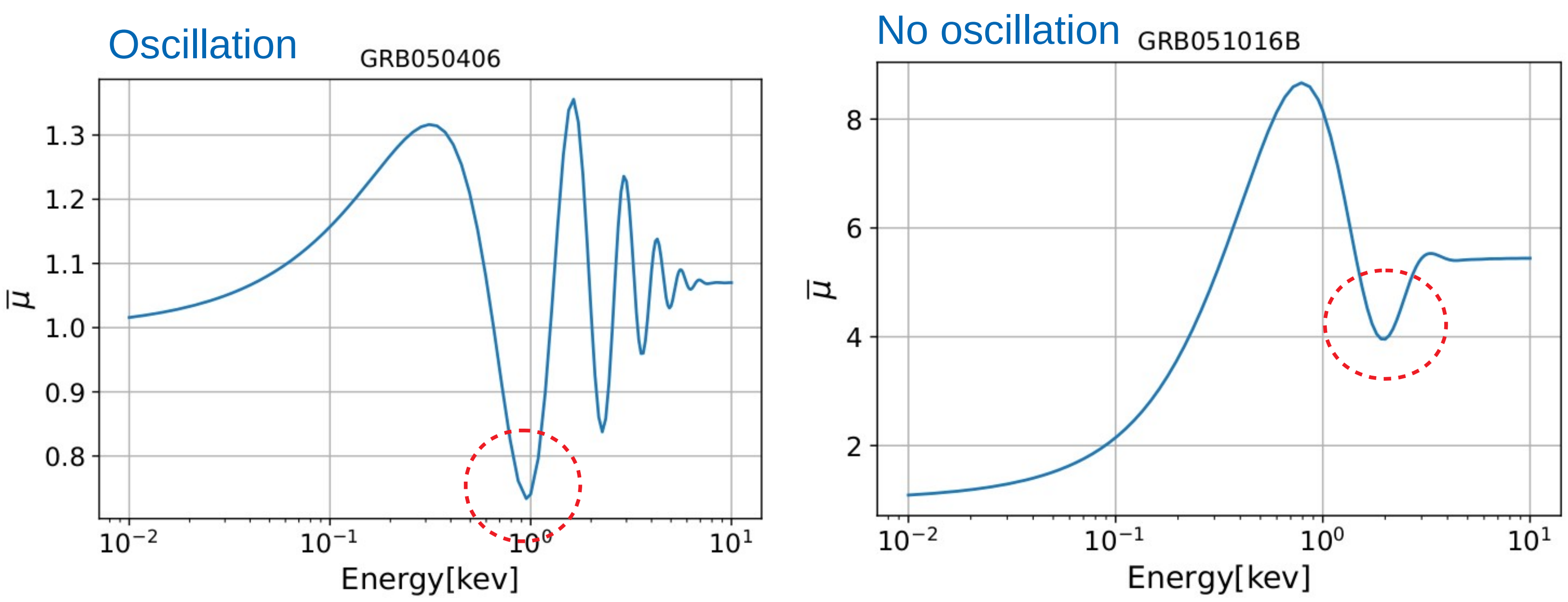
- We adopt 106 GRB spectra data from Swift XRT, in which they provide the additional duration T_{90} and redshift z_S.
- For fitting, we have seven parameters: three relate to PBH and four relate to the BAND model:

$$0.1 \le A/A^{\rm Xspec} \le 10\,, \quad 0.1\,{\rm keV} \le E_0 \le 2E_0^{\rm Xspec}$$
$$-1 \le \alpha_1 \le 1\,, \quad 2\alpha_2^{\rm Xspec} \le \alpha_2 \le -0.5$$
$$10^{-10} \le z_L \le z_S\,, \quad 10^{-17} \le M_{\rm PBH}/M_\odot \le 10^{-12}\,, \quad 0.1 \le y_0 \le 5$$

- Additional conditions:
  1. $\sigma_y \equiv \frac{a_s}{D_S \theta_E} \ll 1$
  2. $\Omega\left(\frac{\tilde{y}\sqrt{\tilde{y}^2+4}}{2} + \ln\left|\frac{\tilde{y}+\sqrt{\tilde{y}^2+4}}{\tilde{y}-\sqrt{\tilde{y}^2+4}}\right|\right) < 2\pi \times 10$
  3. $\lim_{\Omega\to 0} \overline{\mu} = 1$

Numerical analysis: oscillation pattern

- Once we find the best fit, the first local minimum of $\bar{\mu}$ is used to determine the oscillation property:



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Numerical analysis: classification

- Among 106 GRBs, we performed two fitting scenarios:

  I) BAND model only, II) BAND+PBH.

- GRBs are classified into six groups:

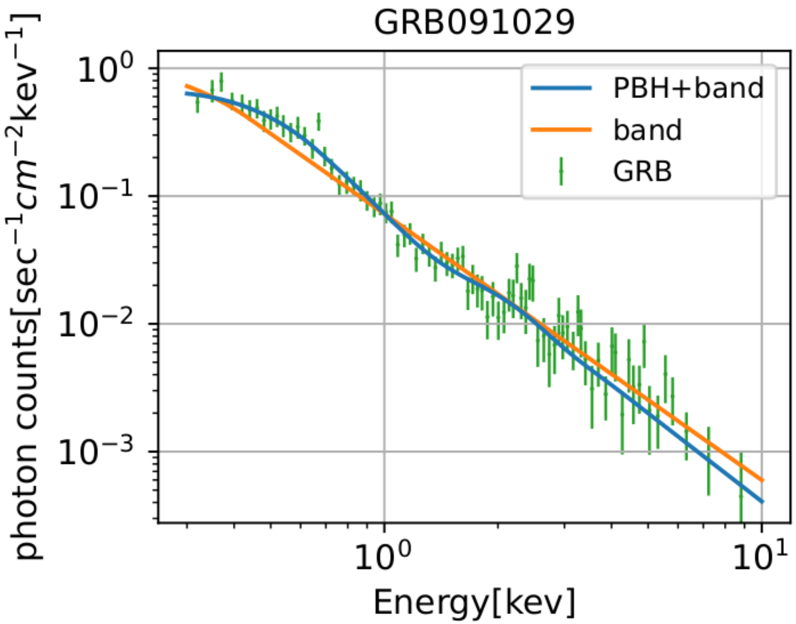
PBH improve the fitting — PBH does not improve

	Goodness of fit decrease by over 0.05	Goodness of fit decrease by less than 0.05	Goodness of fit increase
Oscillation	21	11	14
No oscillation	42	13	5

$$\text{Goodness of fit} \equiv \chi^2_{\rm min}/\text{d.o.f}$$

Numerical analysis: oscillation pattern

- Two examples of GRBs show oscillation pattern:

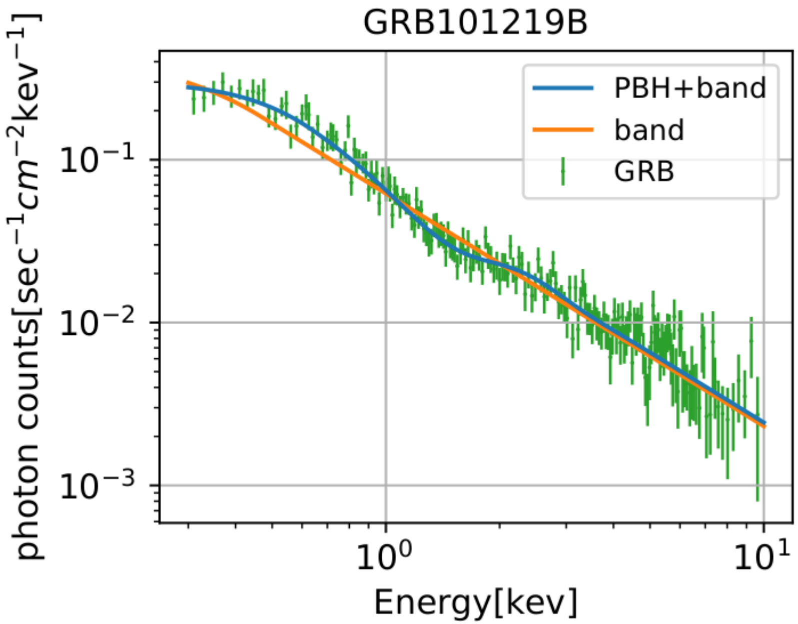


$D_S = 1.6 \times 10^6$ kpc

$M_{\rm PBH} = 2.33 \times 10^{-14} M_\odot$

$D_L = 11$ kpc

$y_0 = 2.1$



$D_S = 1.3 \times 10^6$ kpc

$M_{\rm PBH} = 2.95 \times 10^{-14} M_\odot$

$D_L = 11$ kpc

$y_0 = 1.6$

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Constraints on PBH abundance

- We selected 85 GRBs and derive the upper limit for PBH fractional abundance $f_{\rm PBH} \equiv \rho_{\rm PBH}/\rho_{\rm DM}$.
- Computing the optical depth τ , then the no-lensing probability for single GRB is given by $P_1 = e^{-\tau}$.
- For N GRBs, it becomes $P_{\rm null}(f_{\rm PBH}) = \Pi_{i=1}^{N} P_{1,i} = \Pi_{i=1}^{N} e^{-\tau_i}$, and we set $P_{\rm null} = 0.05$ to find the upper limits of $f_{\rm PBH}$.

Constraints on PBH abundance

- We selected 85 GRBs and derive the upper limit for PBH fractional abundance $f_{\rm PBH} \equiv \rho_{\rm PBH}/\rho_{\rm DM}$.
- Computing the optical depth τ ,

$$\tau = \int_0^{z_s} \frac{dz_L}{H(z_L)} \sigma(D_L) \frac{\rho_{PBH}}{M_{\rm PBH}} (1+z_L)^2$$

$$\rho_{\rm DM} = \begin{cases} \frac{\rho_{\rm s}}{(r/r_s)(1+r/r_s)^2}, & \text{inside the Milky Way} \\ 1.3 \times 10^{-6}\ {\rm GeV/cm^3}, & \text{extragalactic} \end{cases}$$

$$r \equiv \sqrt{R_{\rm Sol}^2 - 2R_{\rm Sol}D_{\rm L}\cos(l)\cos(b) + D_{\rm L}^2}$$

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- We selected 85 GRBs and derive the upper limit for PBH fractional abundance $f_{\rm PBH} \equiv \rho_{\rm PBH}/\rho_{\rm DM}$.
- Computing the optical depth τ ,

$$\tau = \int_0^{z_s} \frac{dz_L}{H(z_L)} \sigma(D_L) \frac{\rho_{PBH}}{M_{\rm PBH}} (1+z_L)^2$$

- The lensing cross section is given by $\sigma(D_L) = \pi(y_{\rm max}\theta_E D_L)^2$, where $y_{\rm max}$ obtained by solving

$$-2\ln\left(\frac{L_0(\vec{\mu_s}|y=y_{\rm max})}{L_0(\vec{\mu_s}|y=\infty)}\right) = \alpha$$

$y_{\rm max}$:maximal distance at which the PBH produces a distinguishable lensing effect

Constraints on PBH abundance

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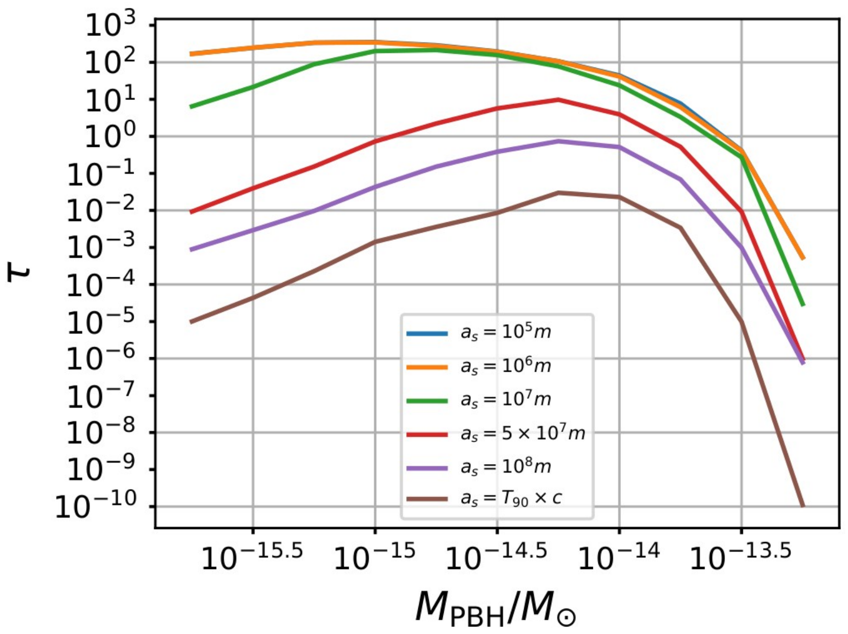
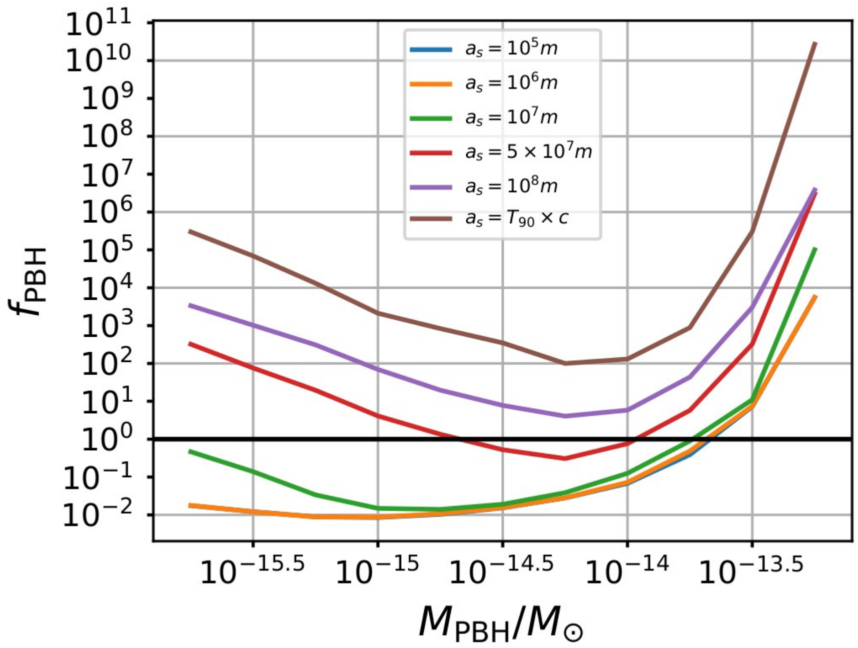
- Computing the optical depth τ ,





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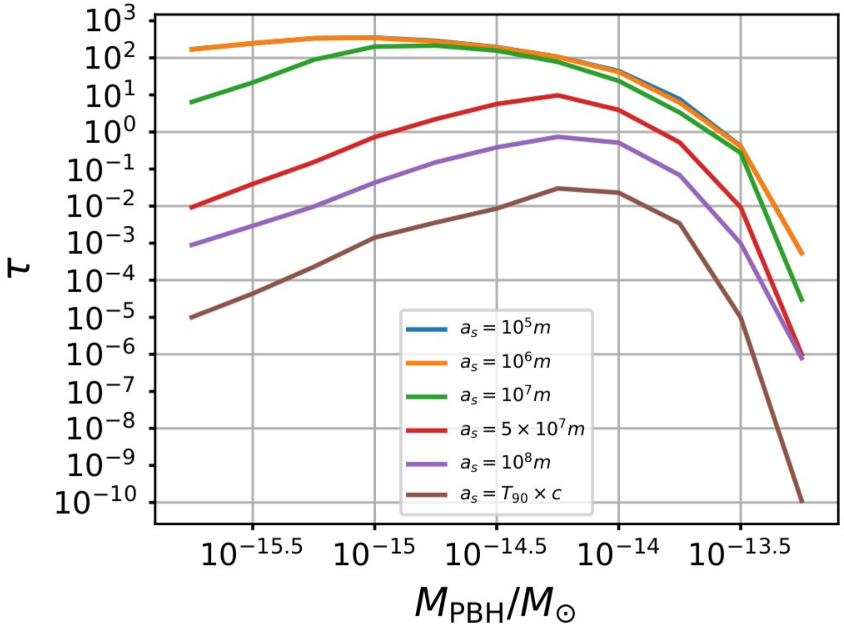
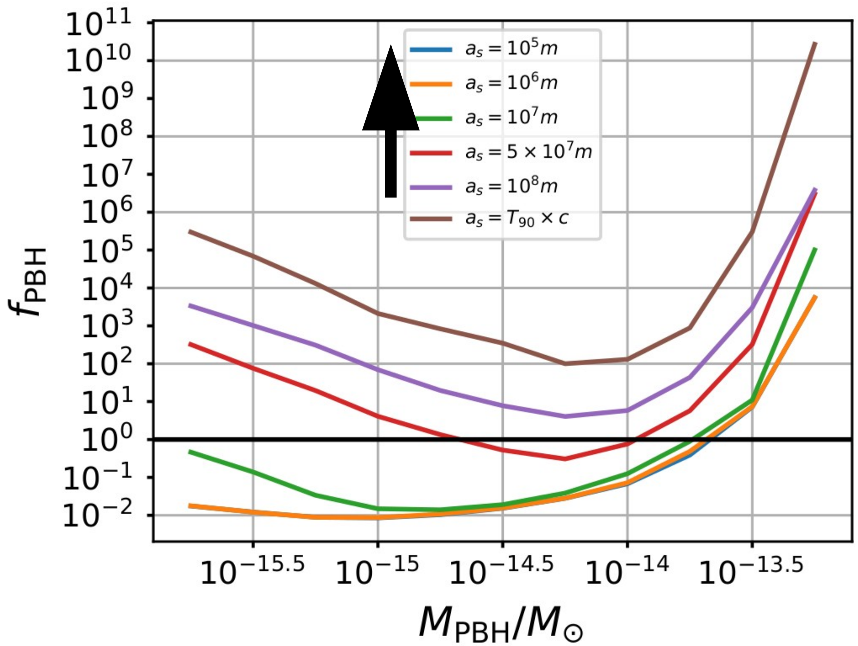
Constraints on PBH abundance

- We selected 85 GRBs and derive the upper limit for PBH fractional abundance $f_{\mathrm{PBH}} \equiv \rho_{\mathrm{PBH}}/\rho_{\mathrm{DM}}$.

As source size decreases, optical depth saturate to an upper limit

- Computing the optical depth τ ,





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Constraints on PBH abundance

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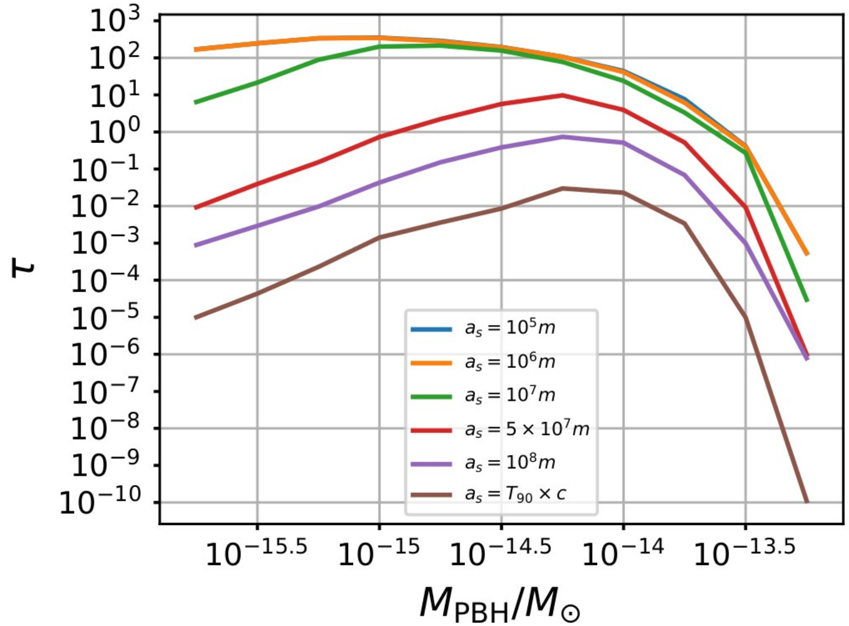
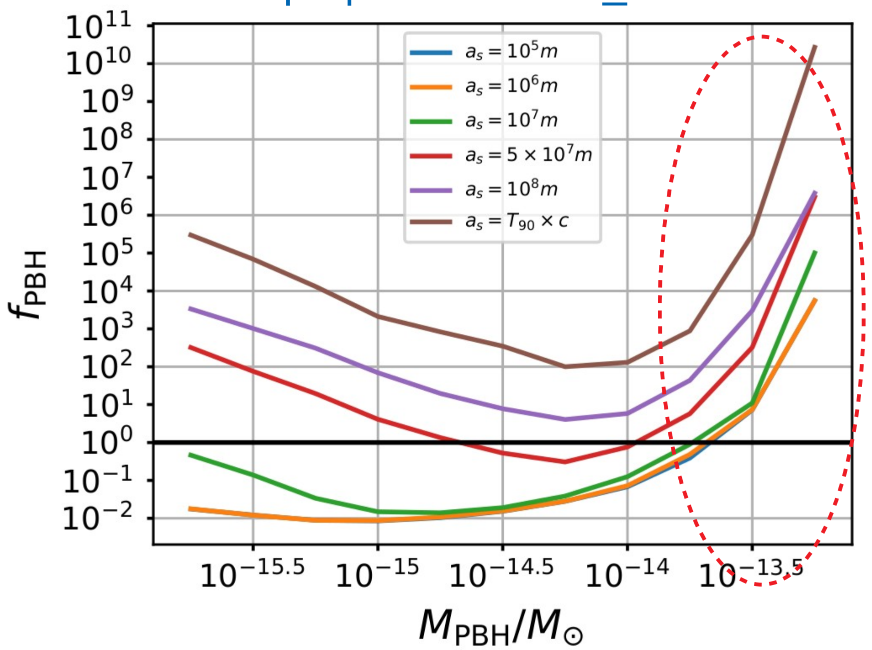
- Computing the optical depth τ ,

Optical depth is inversely proportional to M_PBH.





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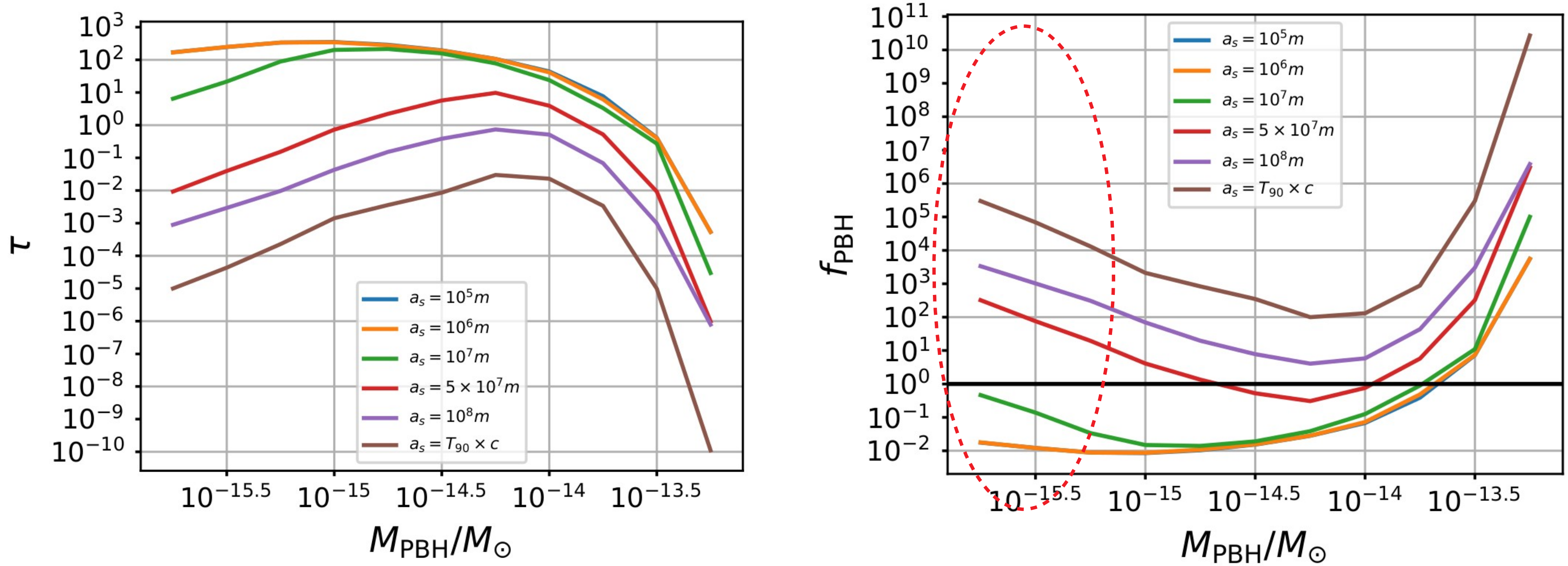
Constraints on PBH abundance

- We selected 85 GRBs and derive the upper limit for PBH fractional abundance $f_{\rm PBH} \equiv \rho_{\rm PBH}/\rho_{\rm DM}$.

We imposed the condition: $\sigma_y \ll 1$

- Computing the optical depth τ ,

$$\sigma_y \equiv \frac{a_s}{D_s \theta_E} \qquad \theta_{\rm E} \equiv \sqrt{4GM \cdot D_{LS}/D_L D_S}$$



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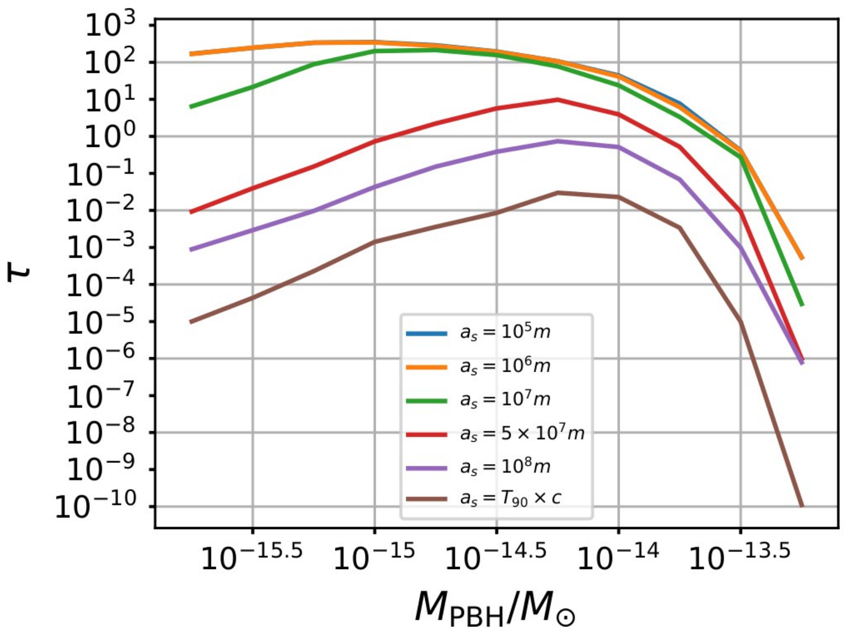
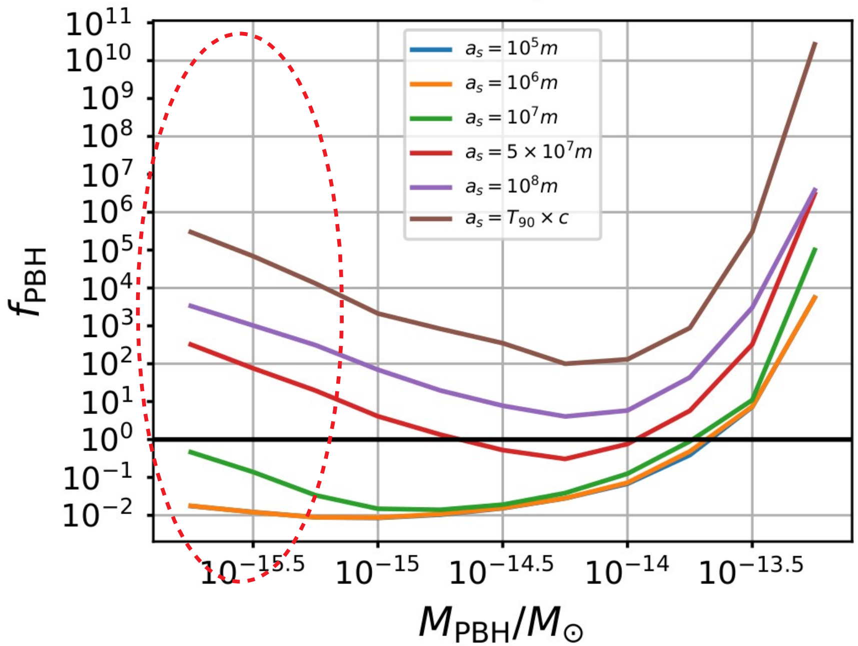
$$\Omega \equiv \frac{4GM_{\rm PBH}(1+z_L)}{c^3}\omega$$

Wave optic effect:

$$F(y,\Omega) = -i\Omega e^{i\Omega y^2/2} \int_0^\infty J_0(\Omega xy) x e^{i\Omega(\frac{1}{2}x^2 - \psi(x))}\, dx$$

- Computing the optical depth τ ,





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Summary

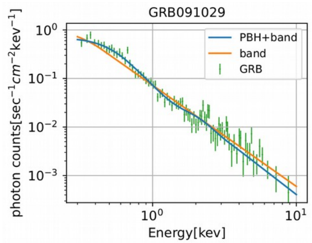
- We analyzed 106 GRBs from Swift XRT spectrum data, fitting with BAND model + PBH femtolensing.
- 21 GRBs show feature of lensing oscillation and their goodness of fit are improved including PBH femtolensing. This result is too optimistic.
- The other 85 GRBs, we used to derive the constraints on the PBH abundance. It is unable to exclude PBH dark matter with [1E-15~1E-10] solar mass with conservative GRB sizes.

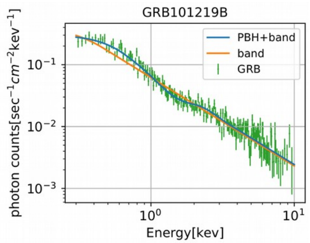
Thank you for your attention!

Back up

Numerical analysis: oscillation pattern

- Two examples of GRBs show oscillation pattern:

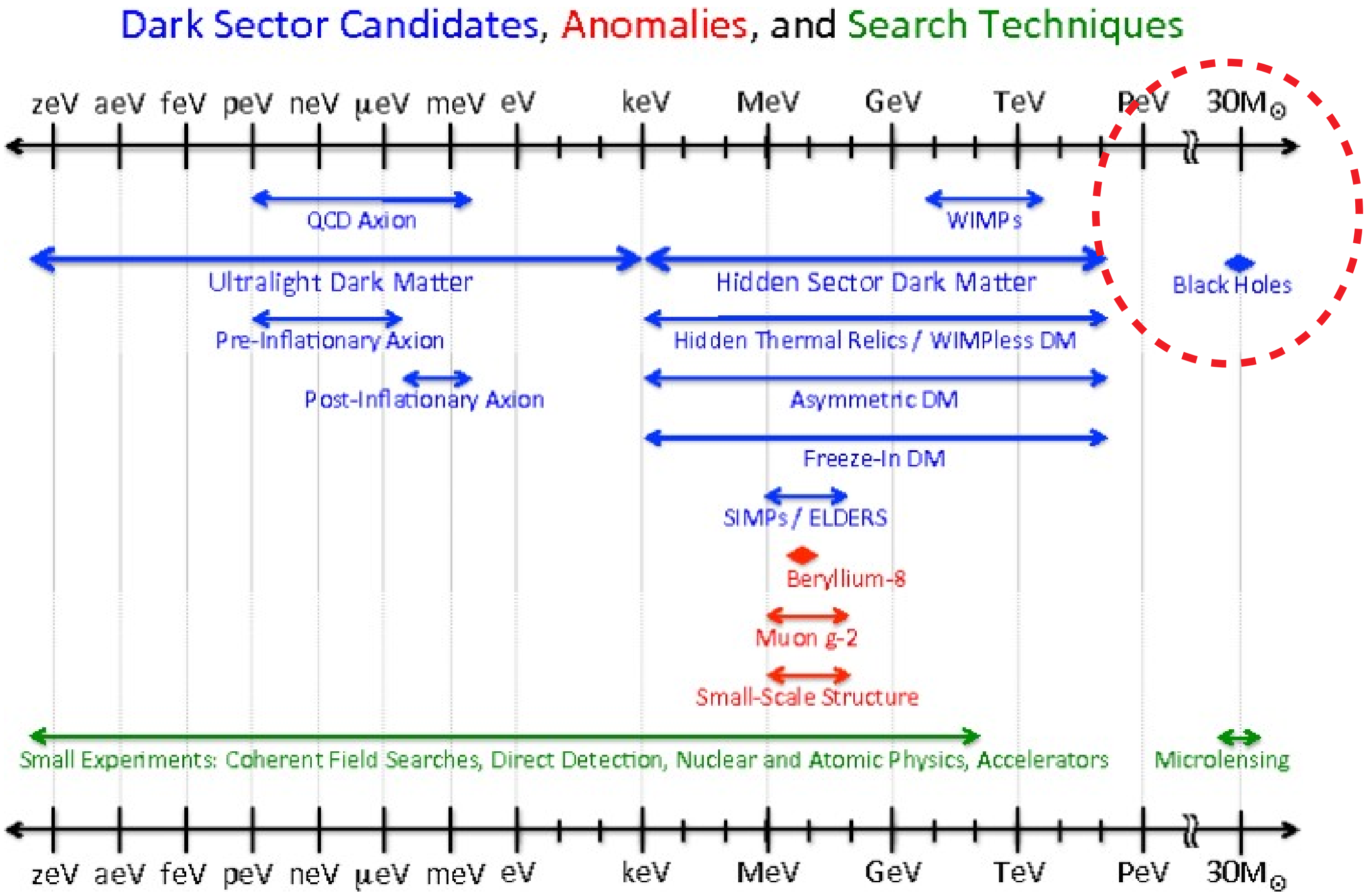




GRB	T_{90}	z_S	A[a]	E_0[b]	α_1	α_2	$M_{\rm PBH}/M_\odot$	z_L	y_0	$\chi^2_{\rm BAND/PBH}$	$\chi^2_{\rm BAND/PBH}$/d.o.f	P-value [45]
050406	5.4	2.44	67.76	0.16	1.00	-2.31	-	-	-	51.57	0.77	0.13
			71.02	0.19	1.10	-2.31	3.73×10^{-14}	3.36×10^{-5}	1.90	45.90	0.72	
051221A	1.4	0.547	24.52	0.35	0.96	-1.89	-	-	-	129.31	0.97	7.95×10^{-3}
			25.70	0.42	1.06	-1.89	2.33×10^{-14}	5.82×10^{-5}	1.90	117.47	0.90	
060604	95	2.1357	1.71	0.79	0.10	-2.34	-	-	-	225.62	1.03	2.66×10^{-5}
			1.23	0.91	9.18×10^{-2}	-2.58	1.84×10^{-14}	5.95×10^{-7}	2.10	201.75	0.93	
060707	66.2	3.43	3.98×10^{-6}	15000.00	-1.91	-13.39	-	-	-	21.47	0.93	0.23
			9.73×10^{-6}	30000.00	-1.72	-10.71	2.95×10^{-14}	5.95×10^{-7}	1.90	17.21	0.86	
061021	46.2	0.3463	995.89	0.18	1.00	-1.97	-	-	-	144.01	1.27	7.49×10^{-5}
			492.14	0.18	0.90	-1.78	1.84×10^{-14}	5.95×10^{-7}	2.60	122.30	1.11	
080604	82	1.416	456.02	0.19	1.00	-1.86	-	-	-	97.15	0.96	5.03×10^{-2}
			1113.64	0.20	1.20	-1.86	1.46×10^{-14}	1.09×10^{-6}	2.60	89.34	0.91	
091020	34.6	1.71	68.35	0.39	0.88	-1.89	-	-	-	141.59	0.88	1.19×10^{-3}
			151.93	0.39	1.05	-1.89	1.84×10^{-14}	4.06×10^{-6}	2.60	125.70	0.80	
091029	39.2	2.752	1946.13	0.14	1.00	-2.08	-	-	-	103.53	1.33	1.38×10^{-7}
			2704.14	0.19	1.20	-2.29	2.33×10^{-14}	2.57×10^{-6}	2.10	68.80	0.92	
101219B	34	0.5519	11.87	0.25	0.43	-1.43	-	-	-	230.94	1.26	2.15×10^{-15}
			10.31	0.33	0.51	-1.43	2.95×10^{-14}	2.57×10^{-6}	1.60	159.56	0.89	

DM candidate

- Range of DM mass:



CERN document Server: US:Cosmic Visions: New ideas in dark matter 2017

PBH: memory burden effect

- The mass window for PBH DM candidate with various k:

V.Thoss, A.Burkert, K.Kohri: 2402.17823