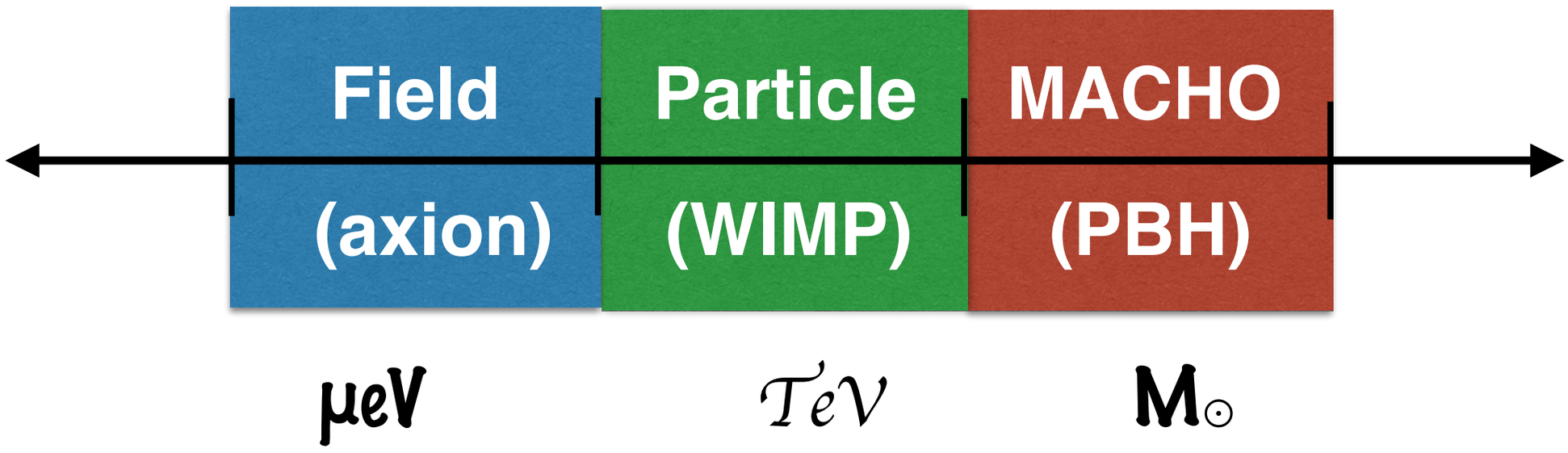
Femtolensing and Axion Miniclusters

Wei Xue

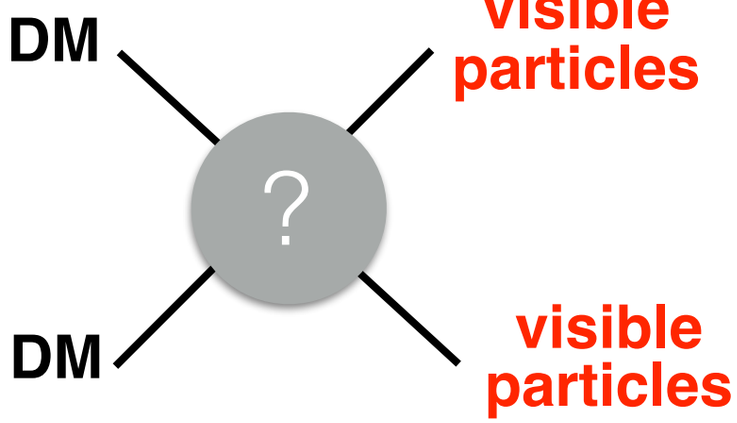
May 15, 2018

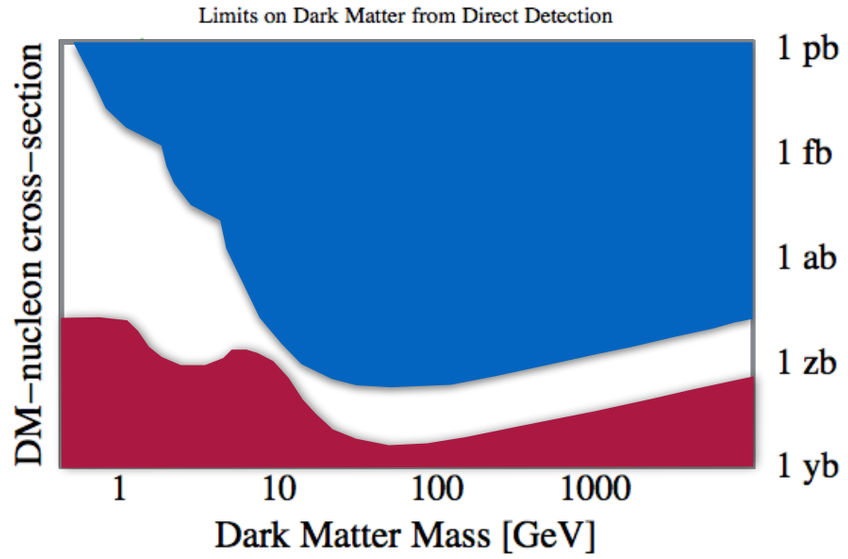
with A. Katz, S. Sibiryakov, J. Kopp

Dark Matter Window

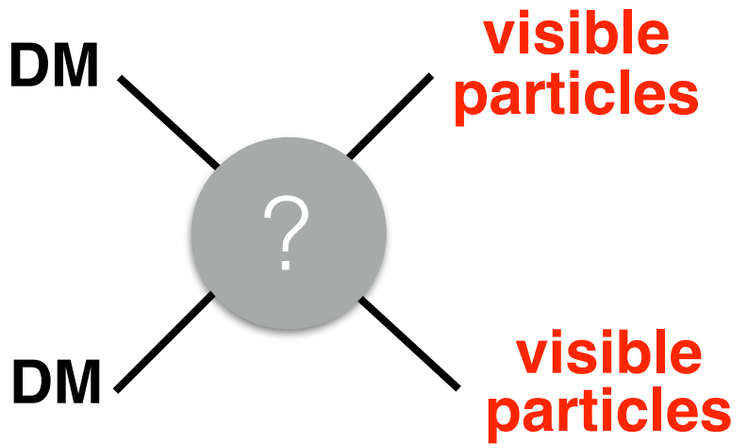


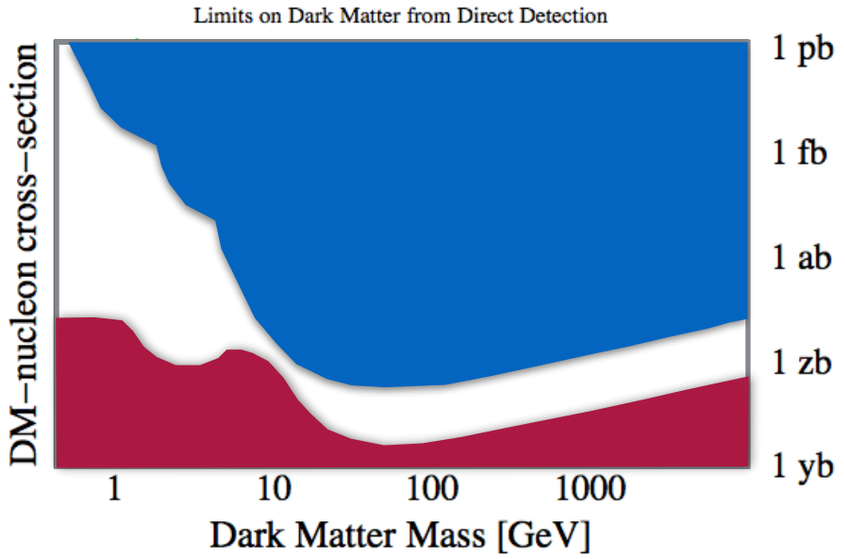
Dark Matter Search Today

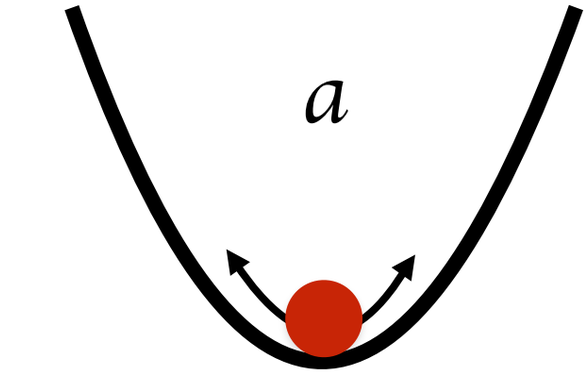


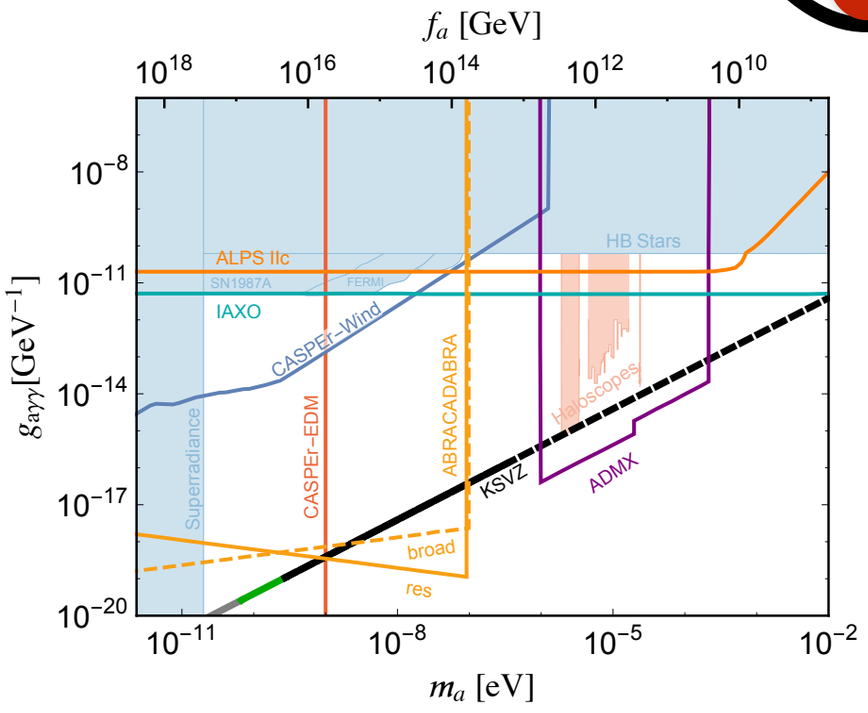


Dark Matter Search Today

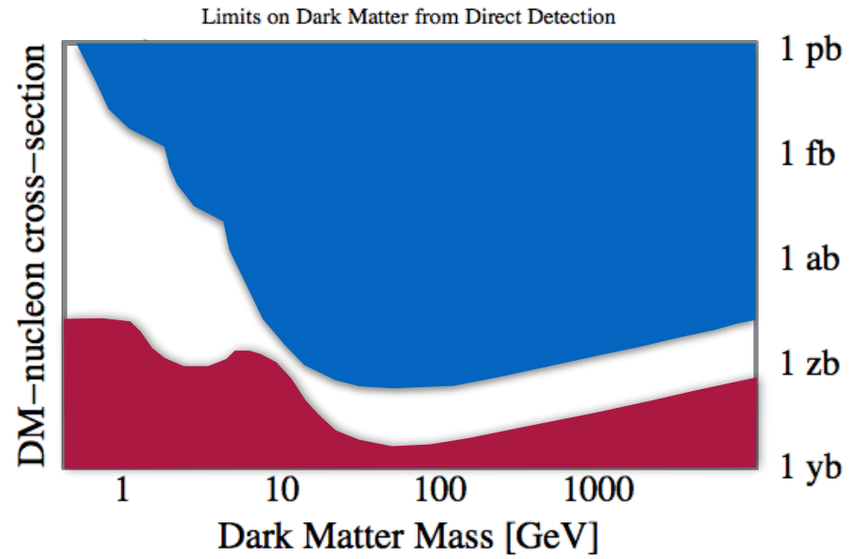


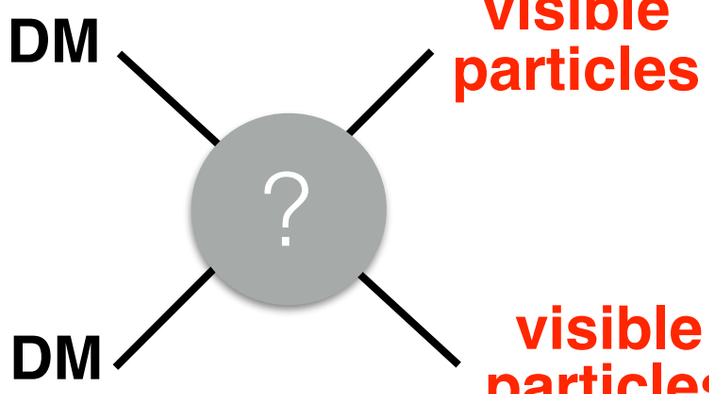


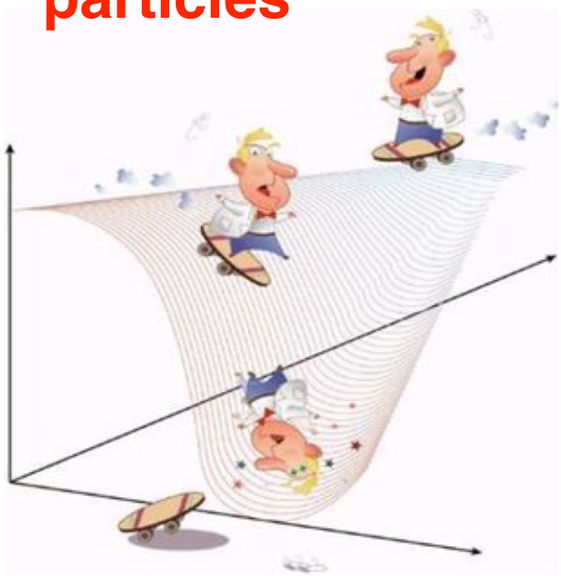


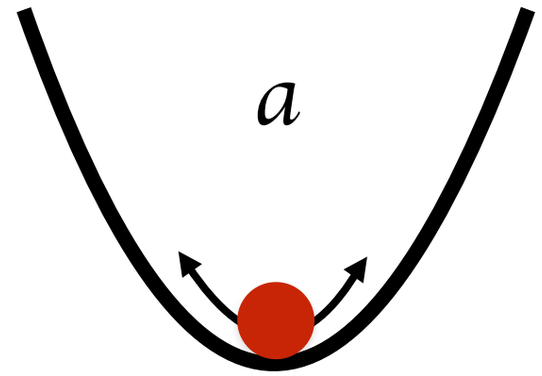


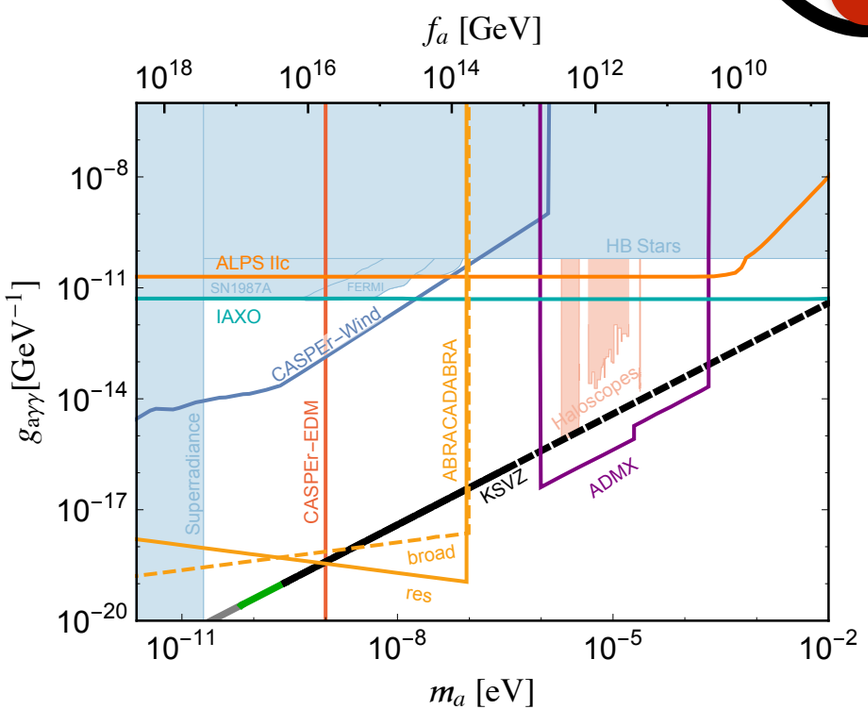
Dark Matter Search Today

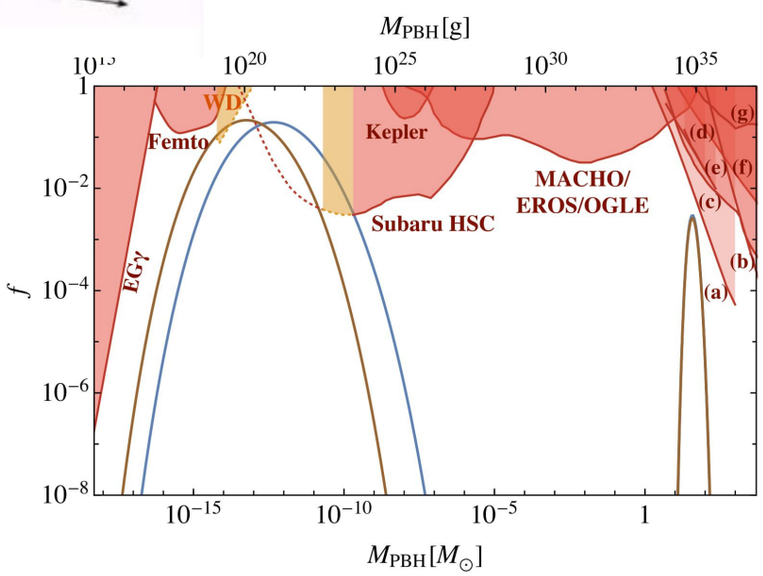




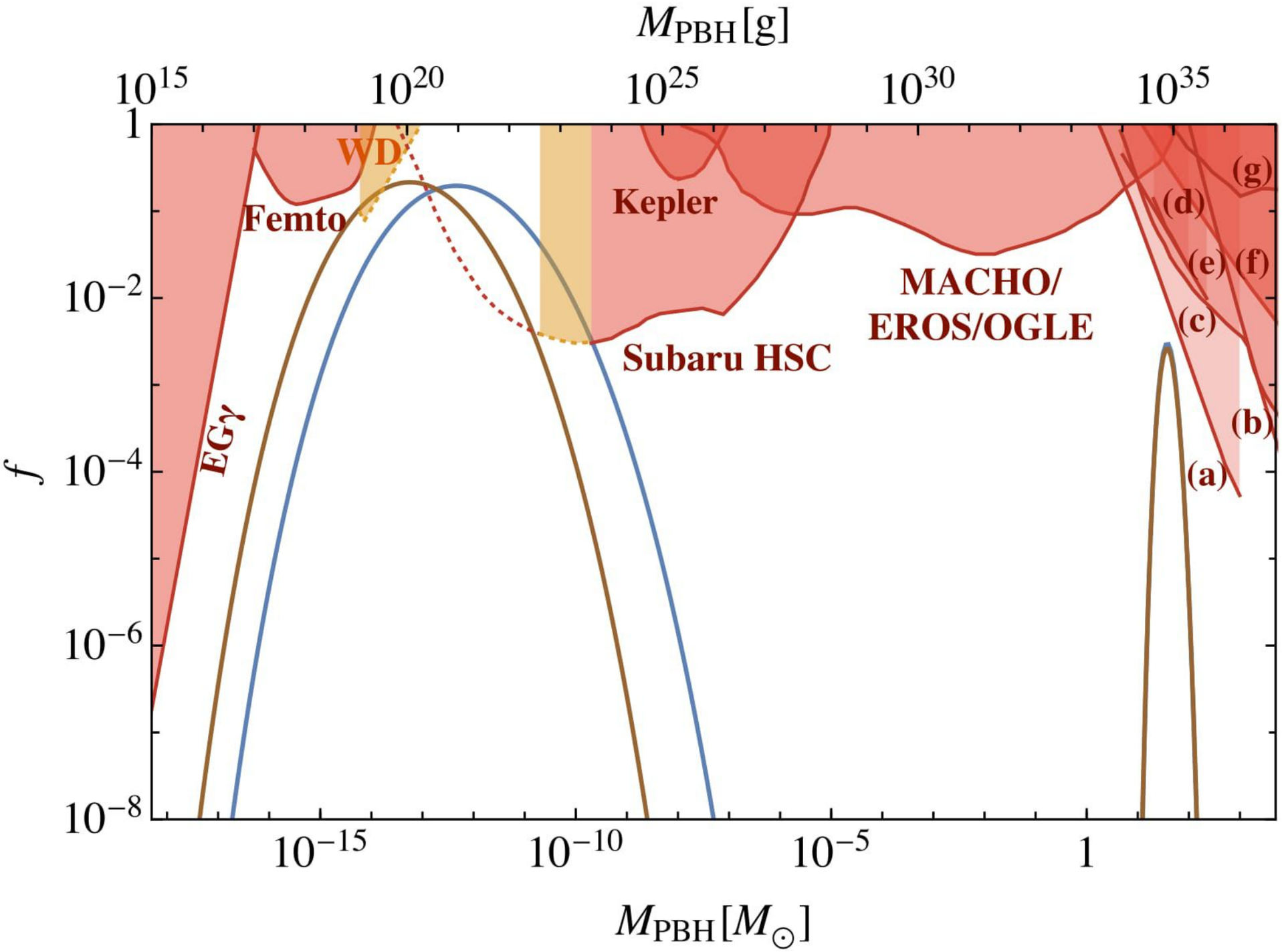




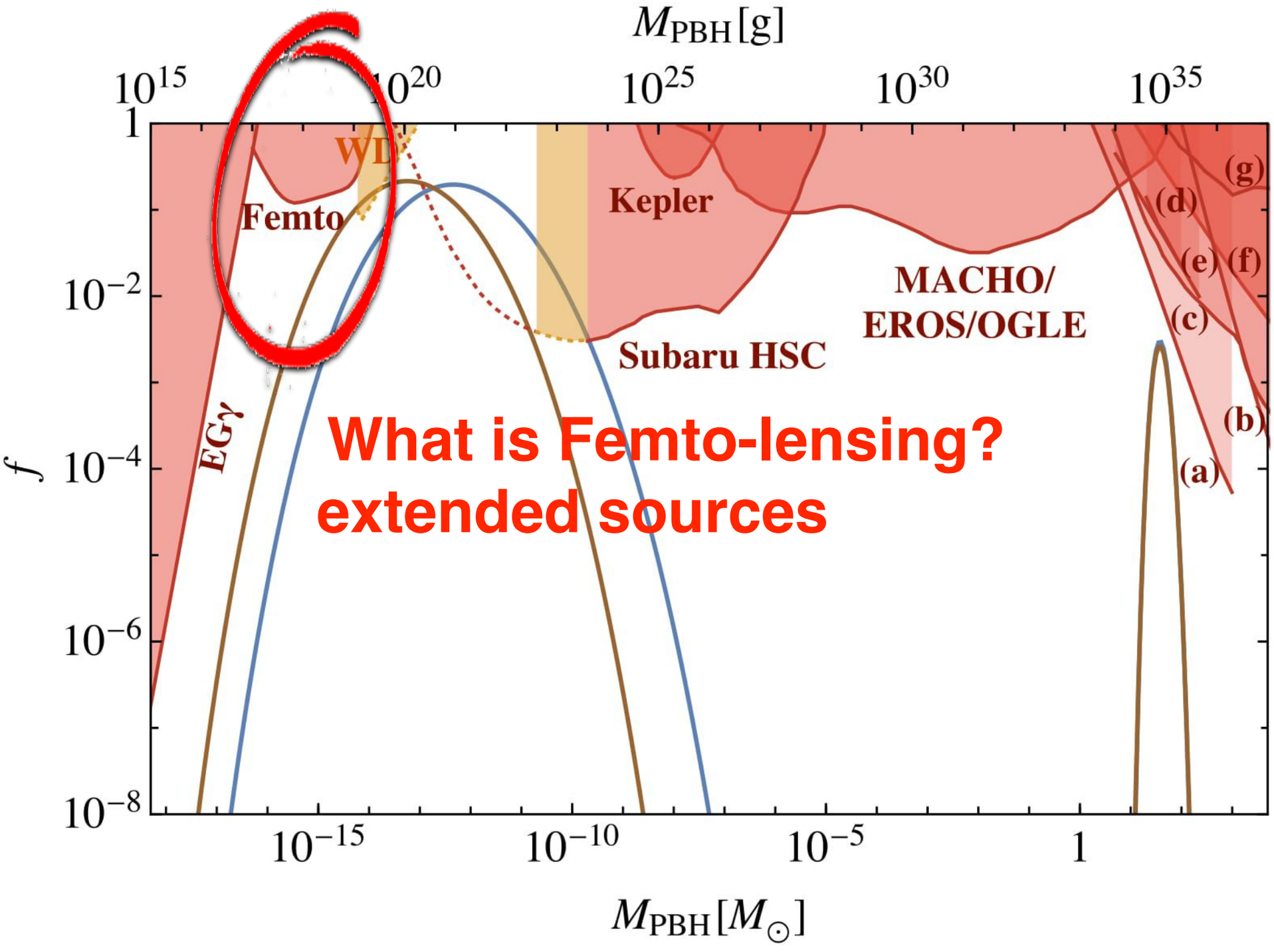




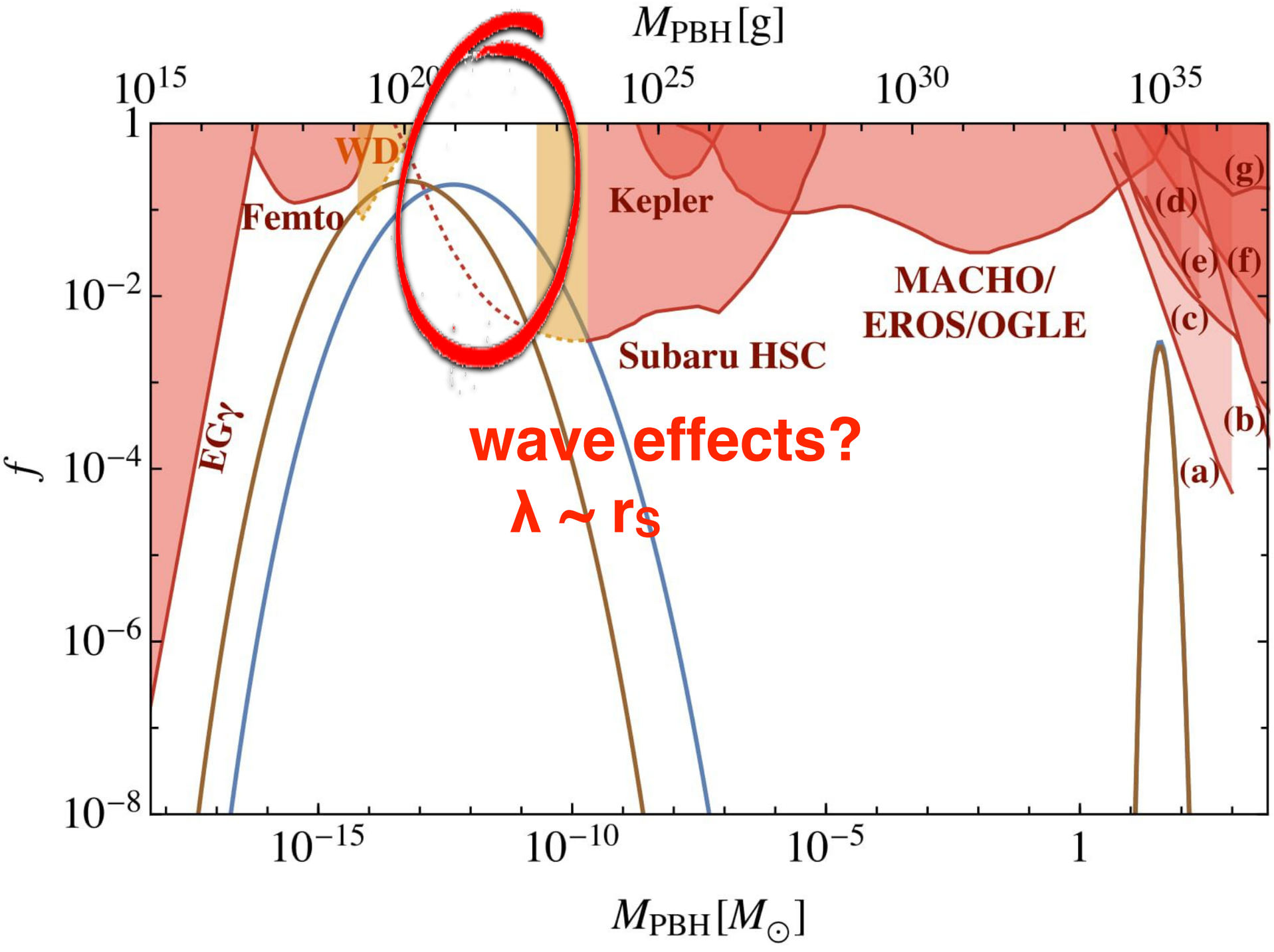
Primordial Black Hole Abundance



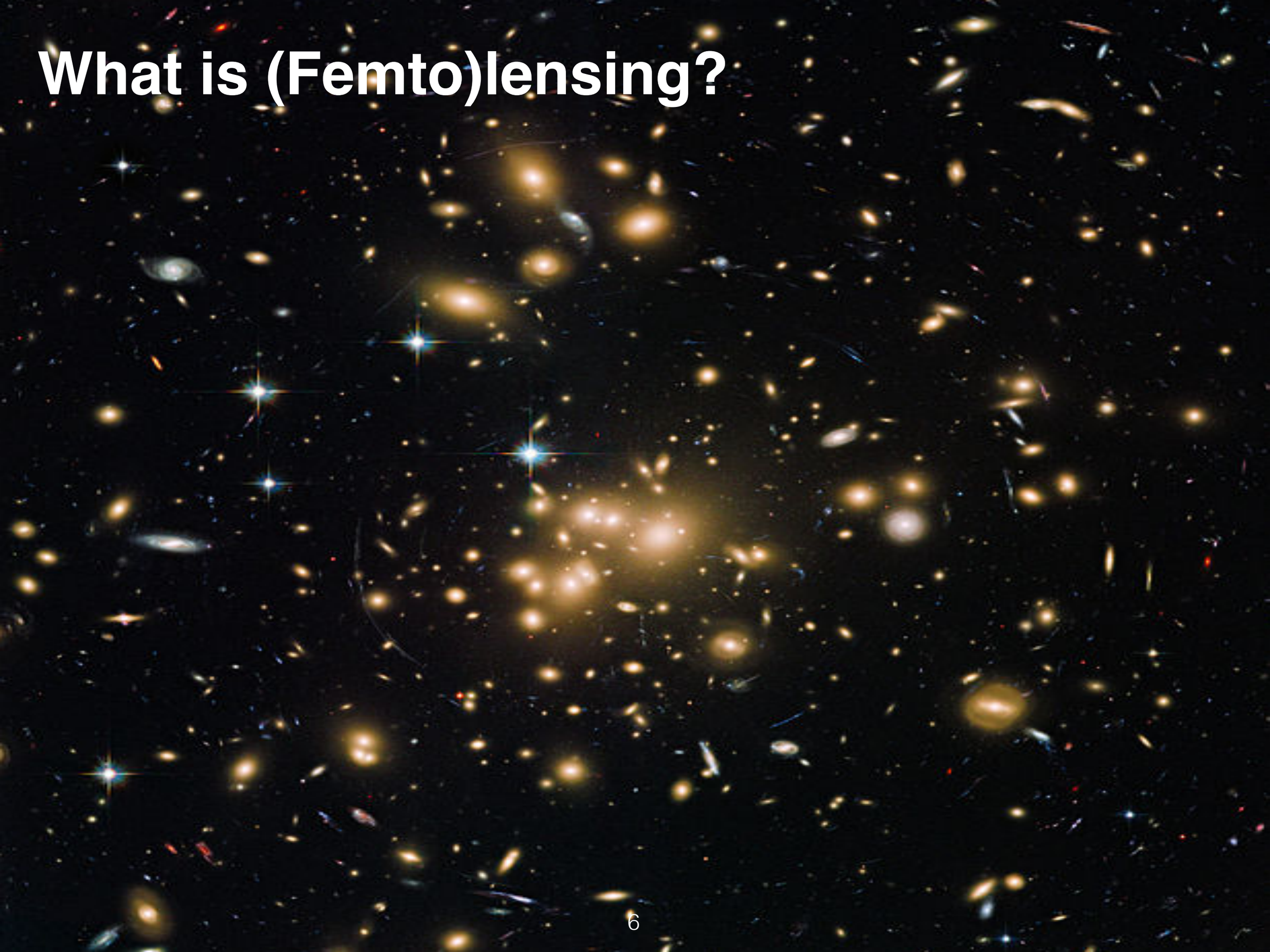
Primordial Black Hole Abundance



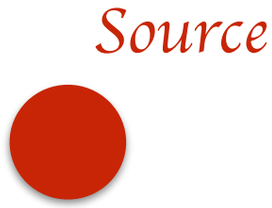
Primordial Black Hole Abundance



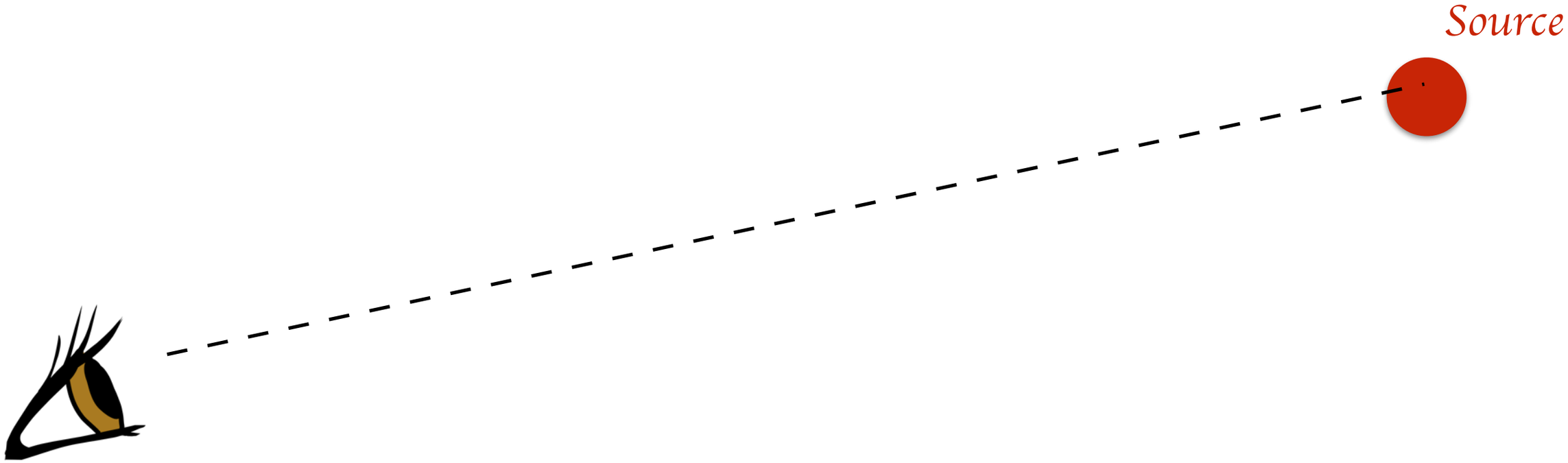
What is (Femto)lensing?



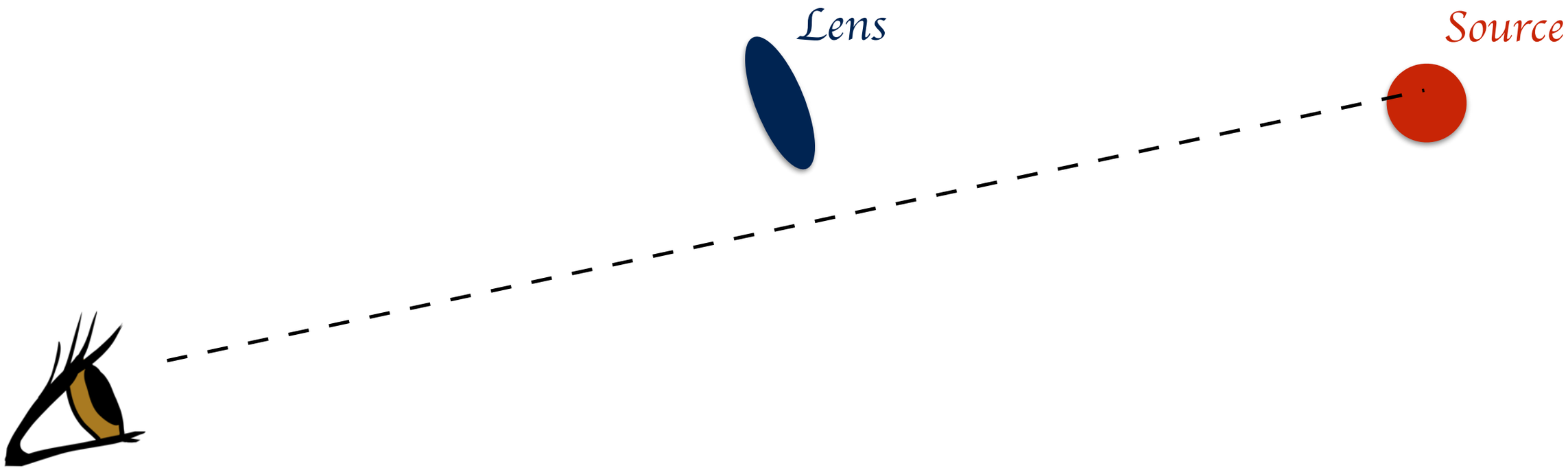
What is Lensing?



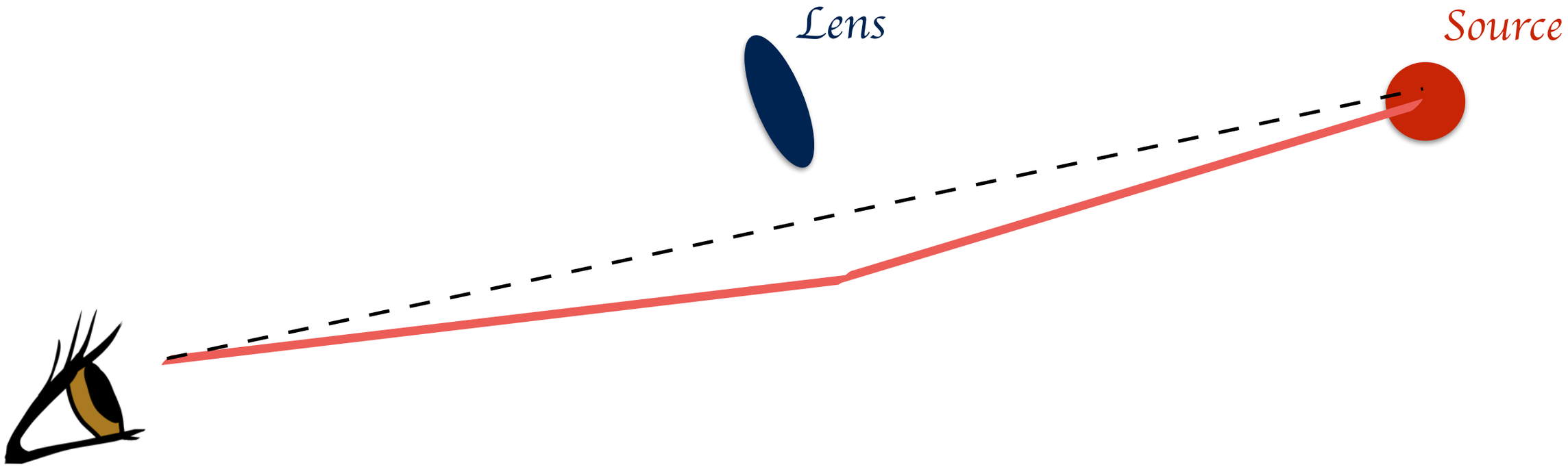
What is Lensing?



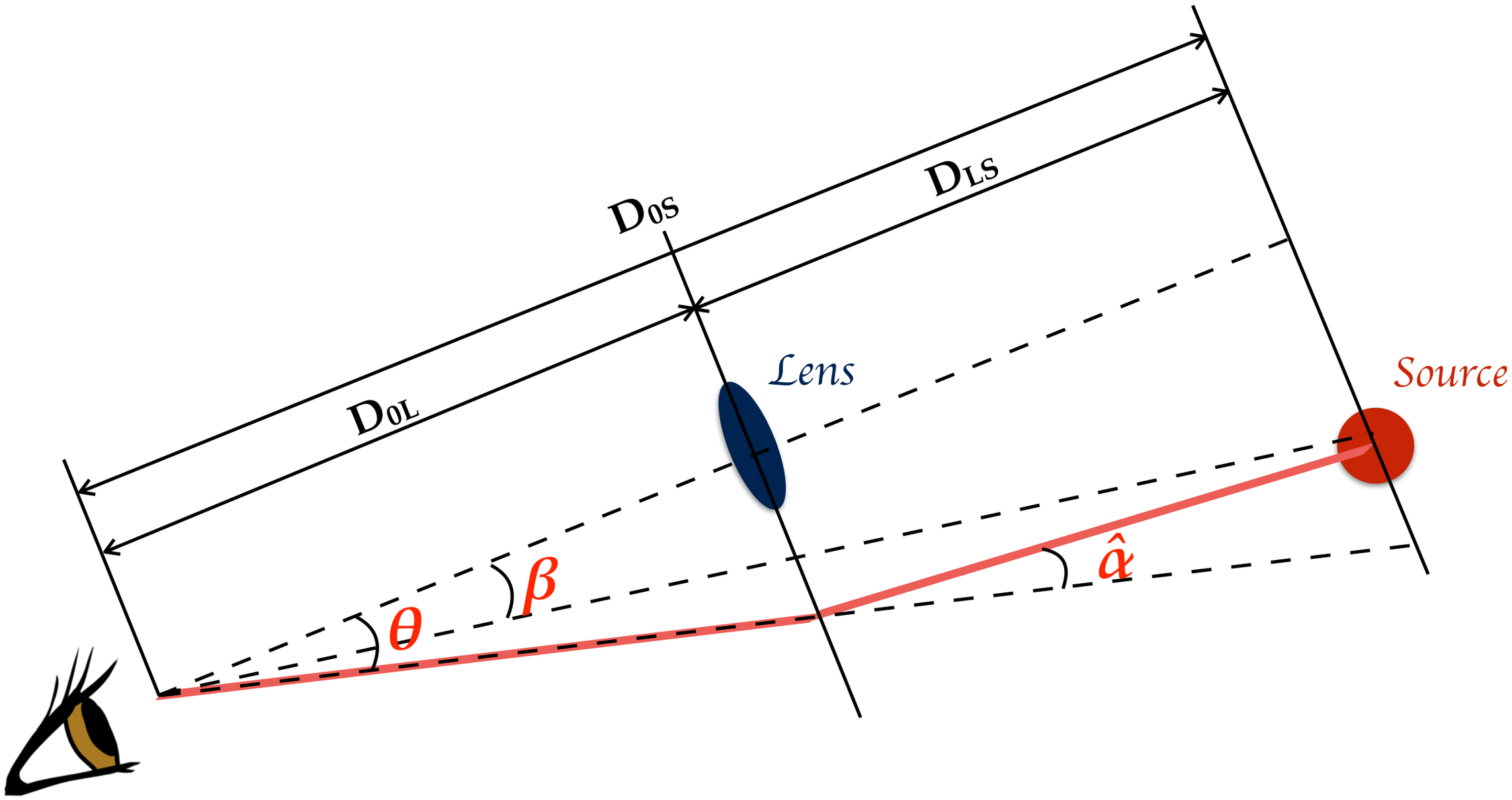
What is Lensing?



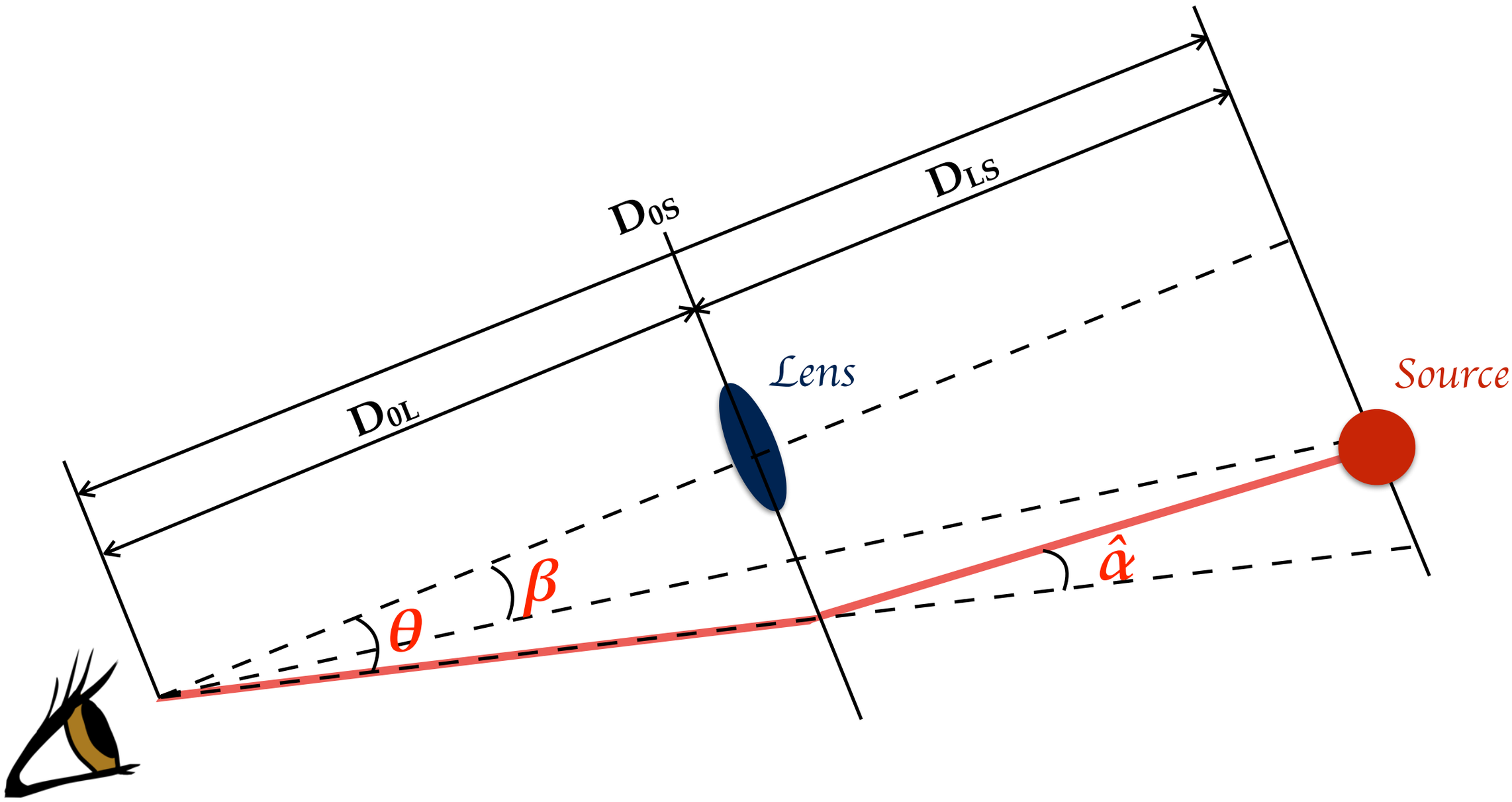
What is Lensing?



What is Lensing?

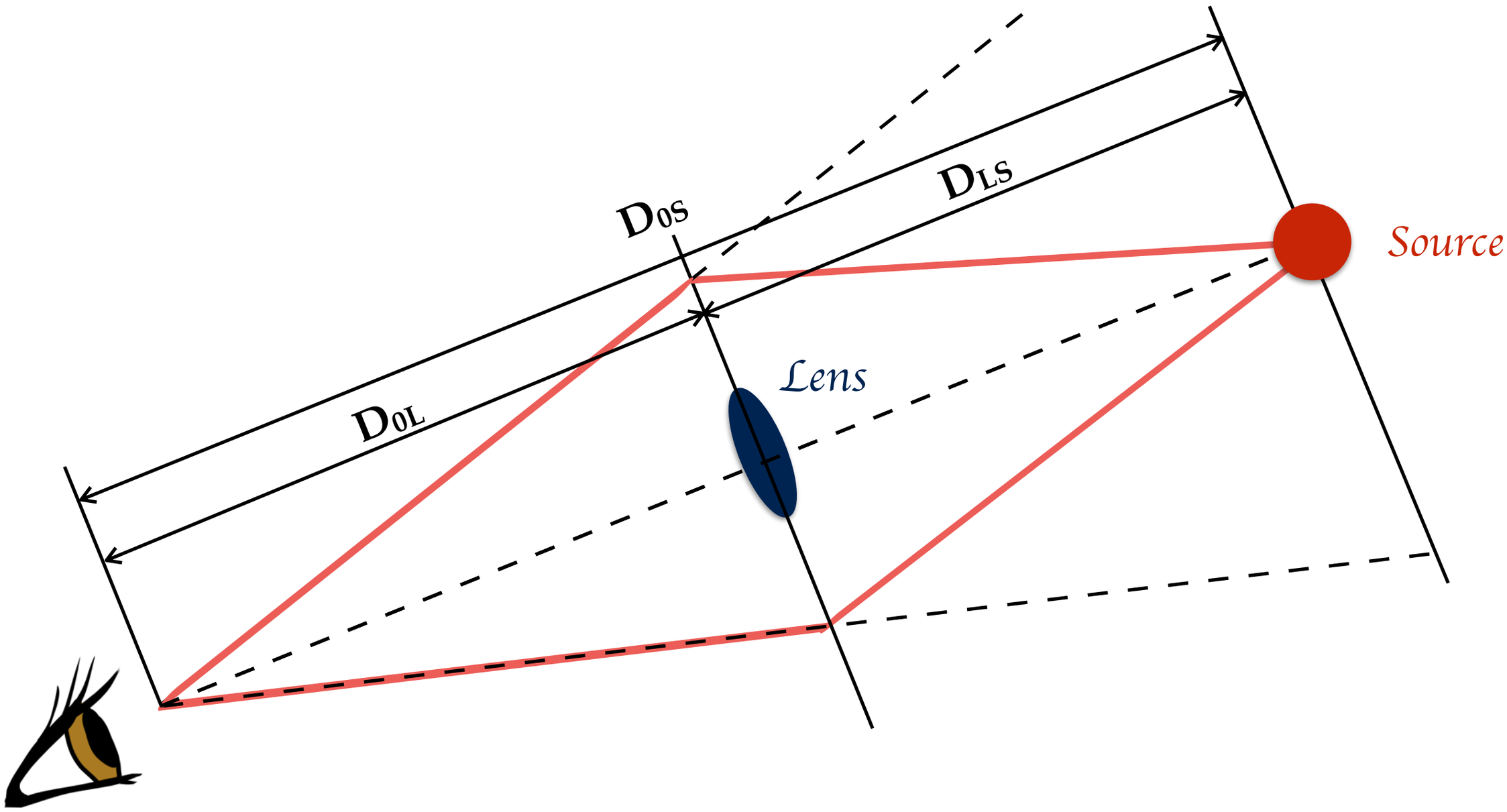


Lensing Equation

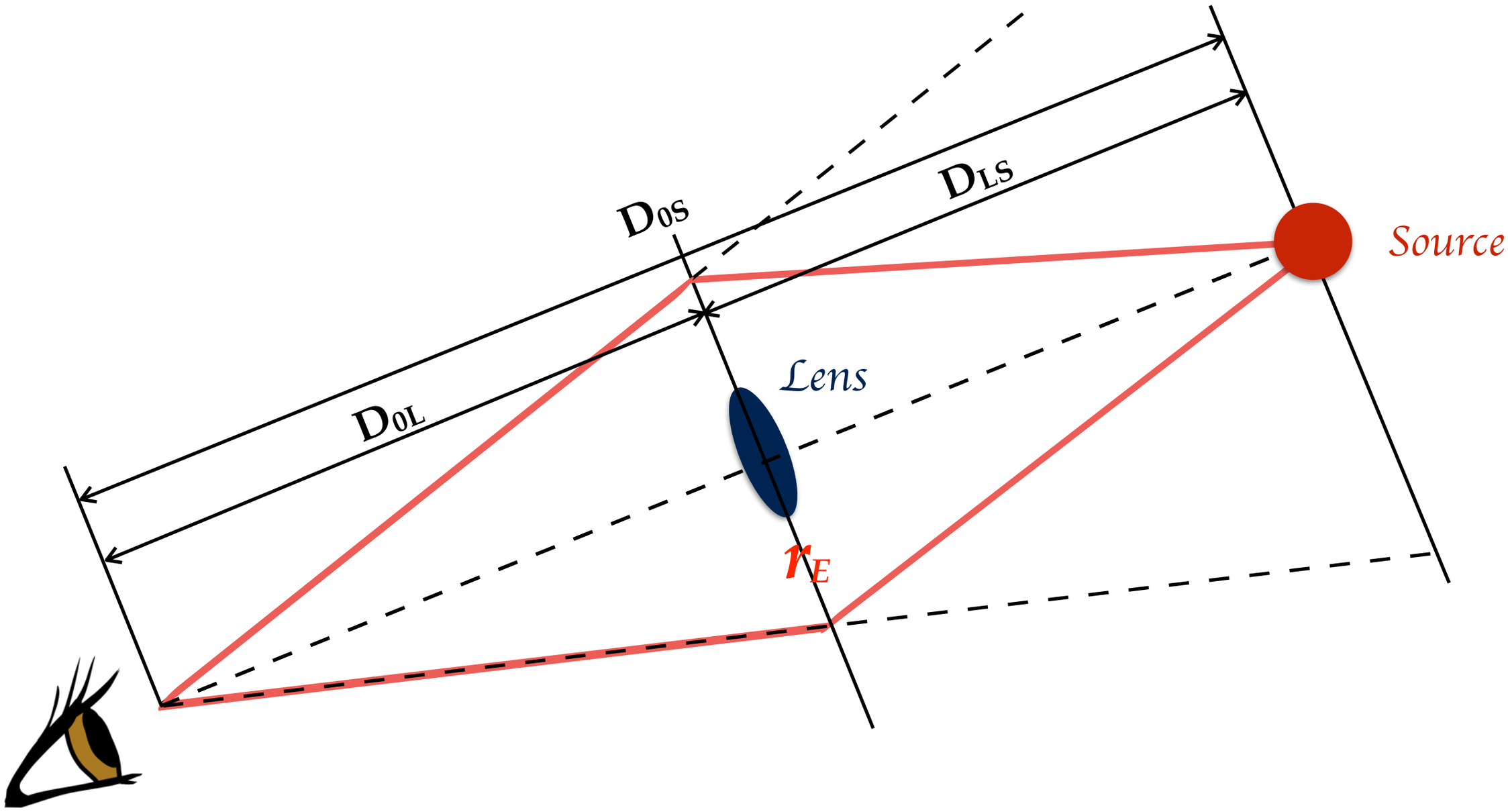


$$\theta = \beta - \hat{\alpha} \times (D_{0S}/D_{LS})$$
$$= \beta - \alpha$$

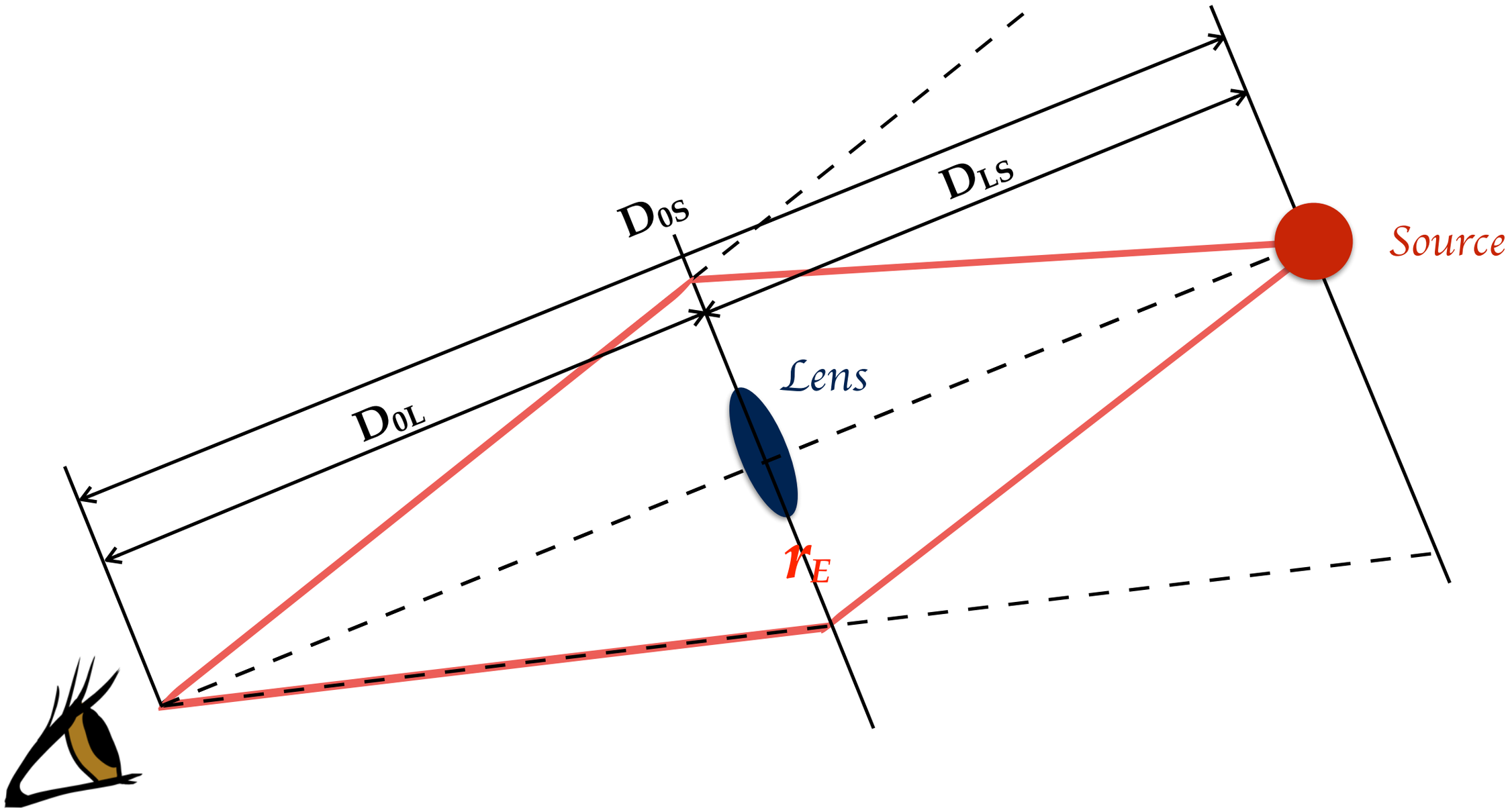
Einstein Radius r_E



Einstein Radius r_E

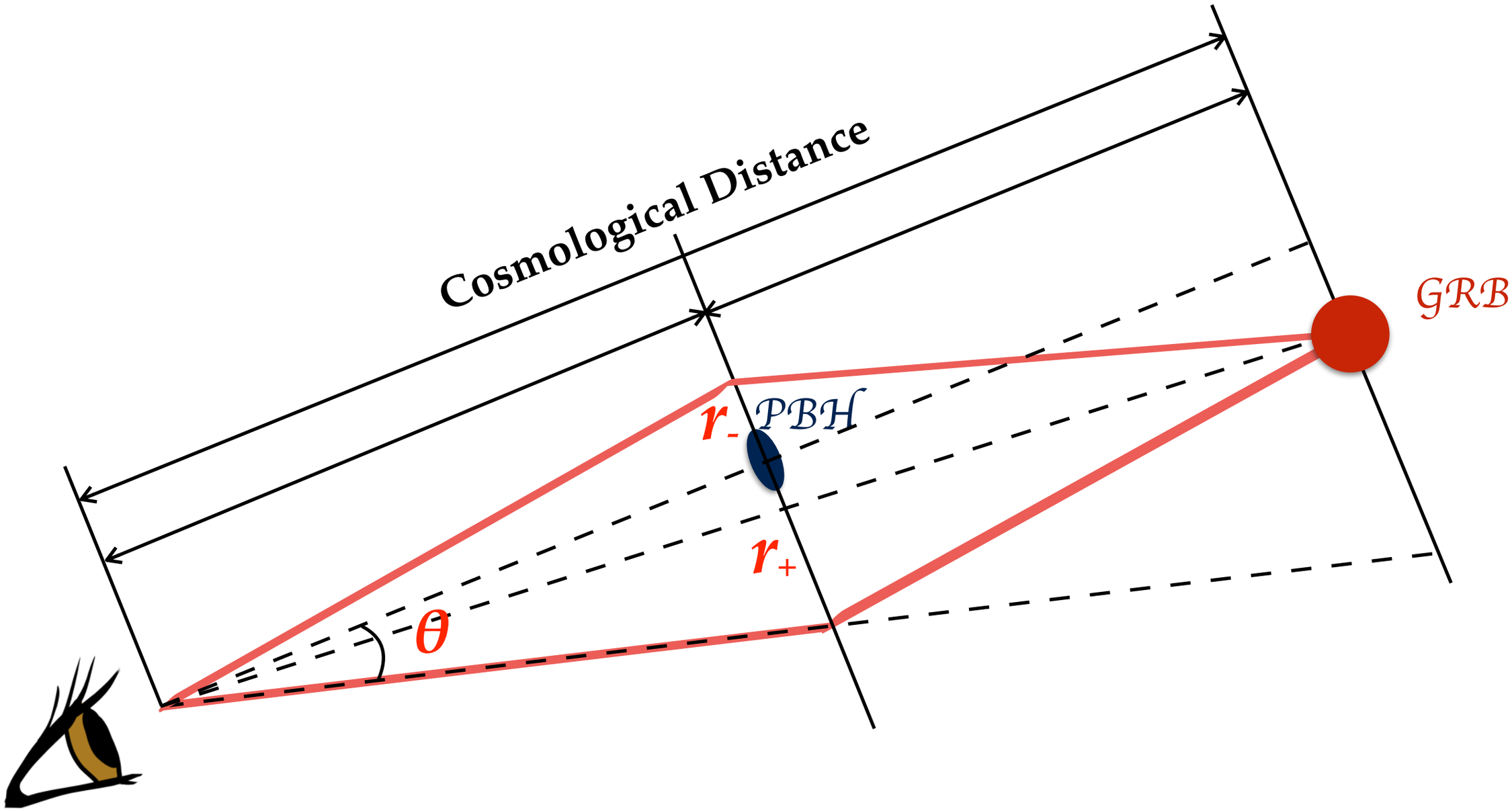


Einstein Radius r_E



$$r_E = \sqrt{\frac{4GM}{c^2}\frac{D_{OL}D_{LS}}{D_{OS}}}$$

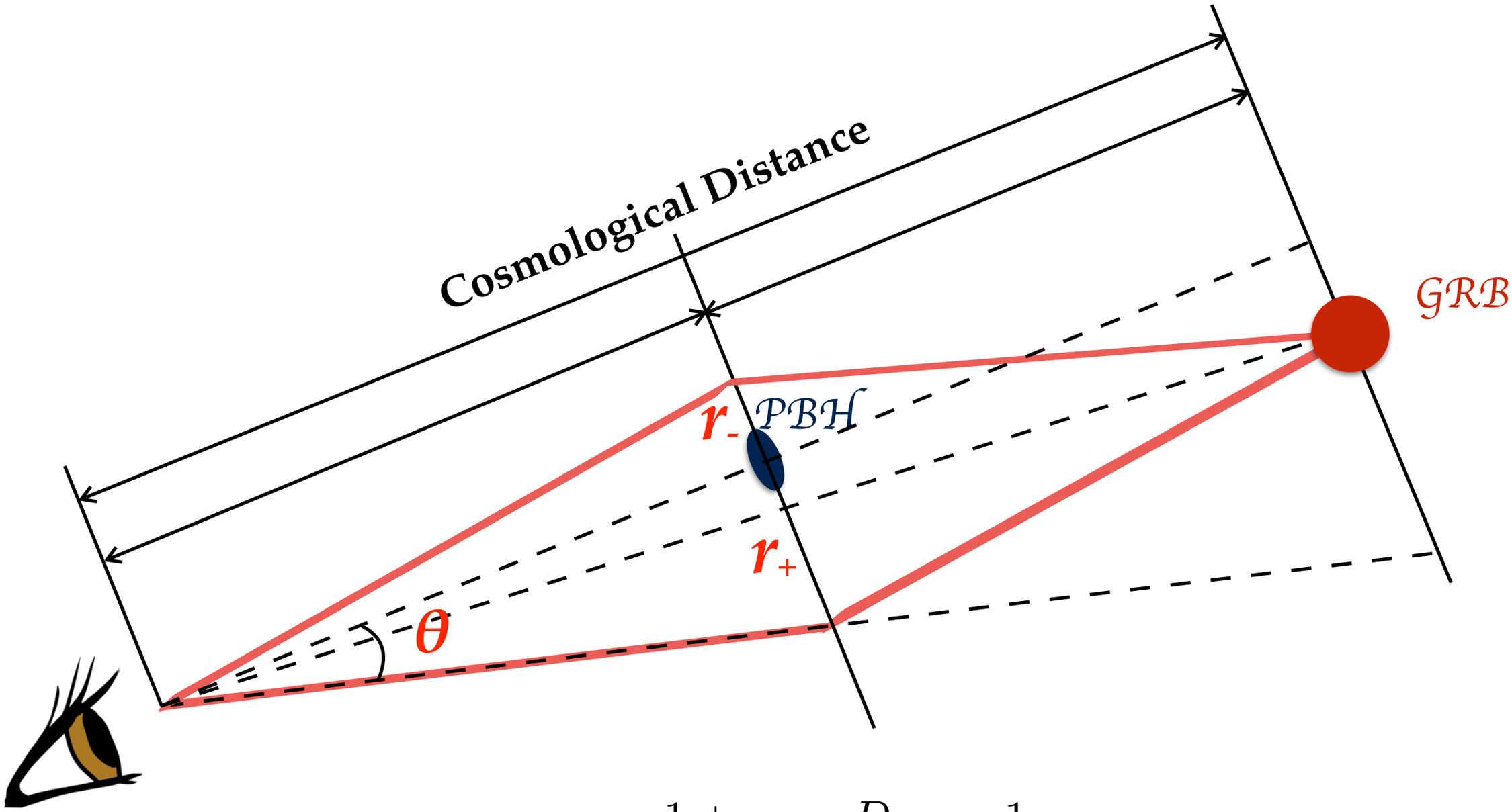
Femtolensing (unresolved images)



θ ~ *femto-arcsec*

$r_\pm$ ~ θ × *Gpc* ~ *100 km*

Time Delay $t = t_{geom} + t_{grav}$

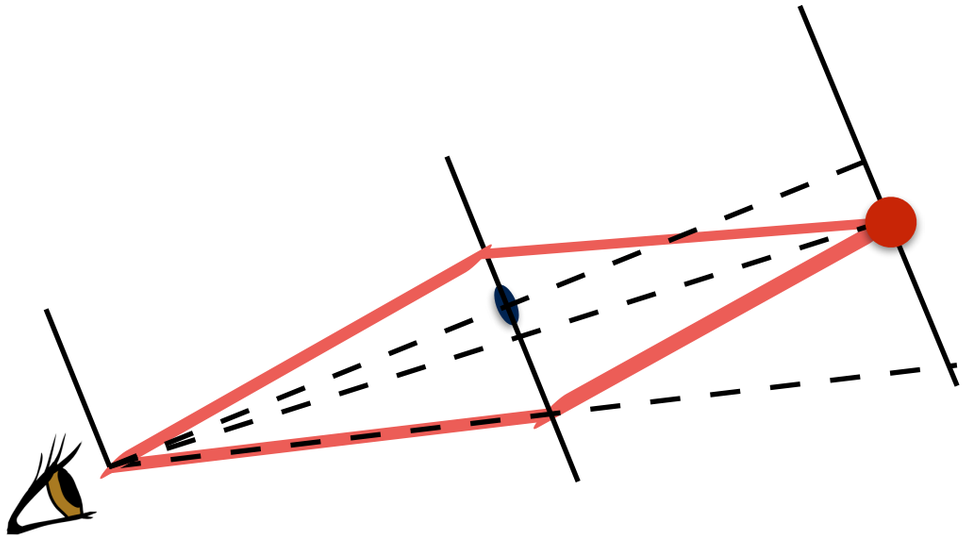


$$\delta t_{geom} = \frac{1+z_L}{c}\frac{D_{OS}}{D_{OL}D_{LS}}\frac{1}{2}(r_\pm - x_S)^2$$

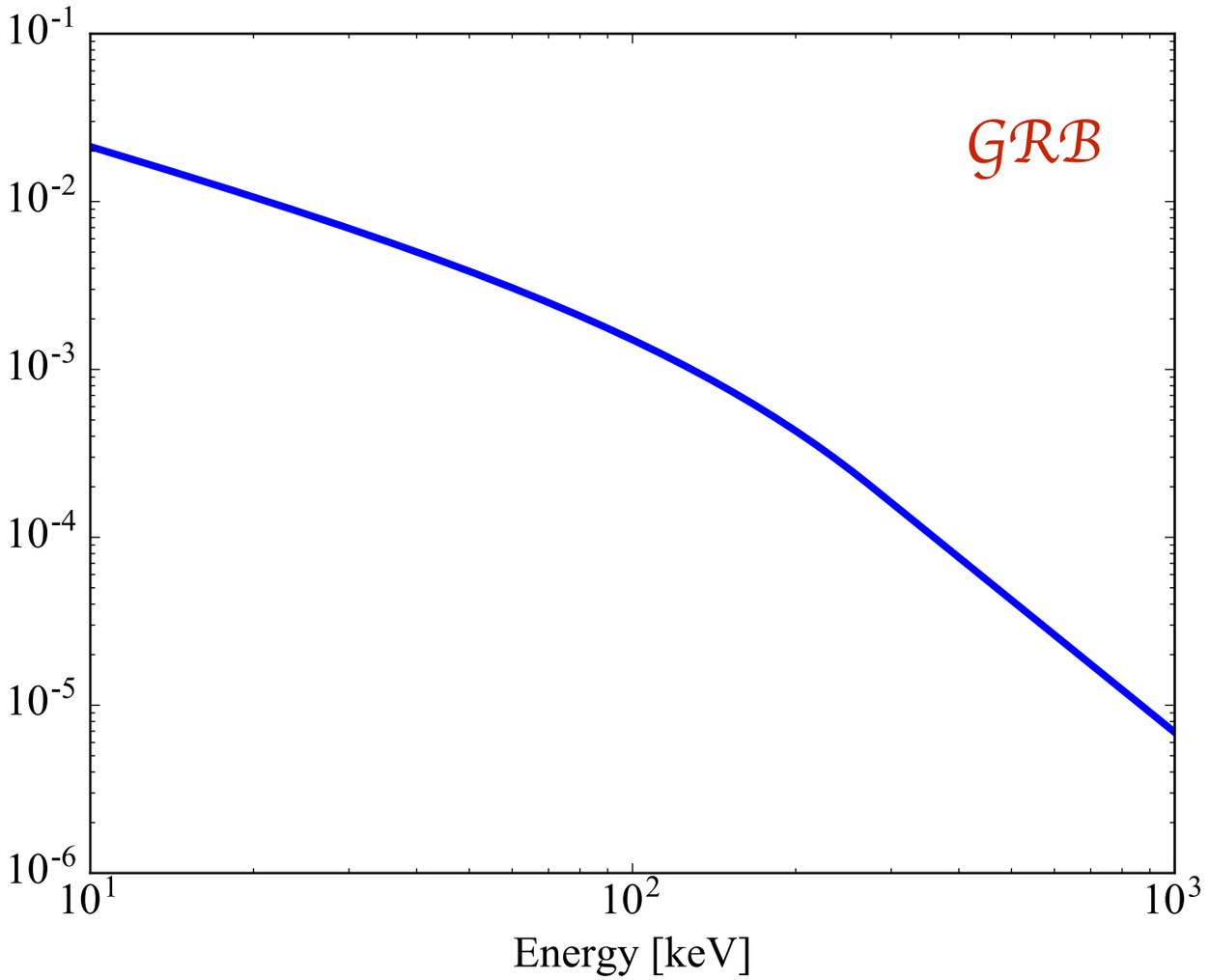
$\delta t \sim MeV^{-1}$ - keV^{-1}

Interference $\Delta\phi = E\,\delta t$

$$\delta t \sim MeV^{-1} \; - \; keV^{-1}$$

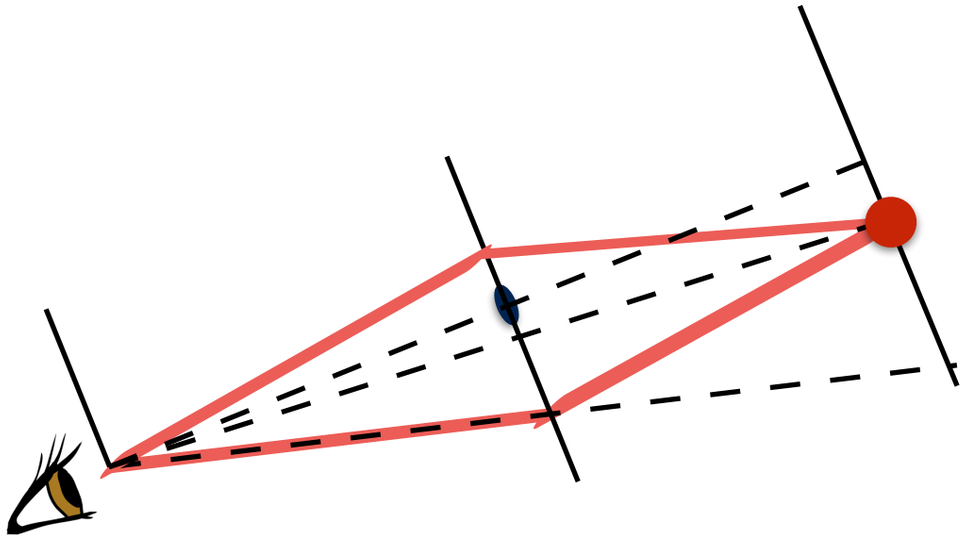


$$|A_1 + A_2|^2 \propto 1 + \mathcal{O}(1)\cos(\Delta\phi)$$

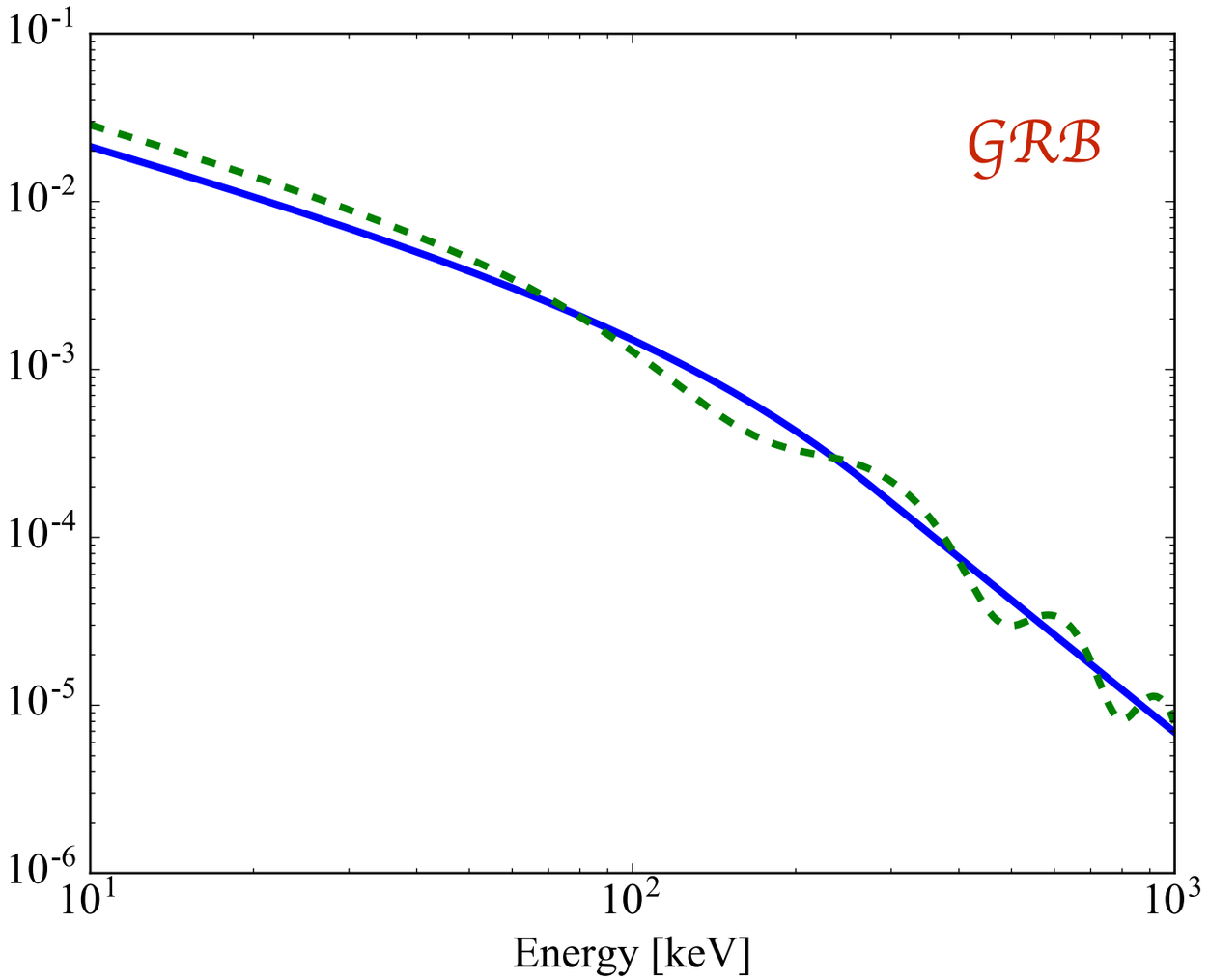


Interference $\Delta\phi = E\,\delta t$

$$\delta t \sim MeV^{-1} \; - \; keV^{-1}$$



$$|A_1 + A_2|^2 \propto 1 + \mathcal{O}(1)\cos(\Delta\phi)$$

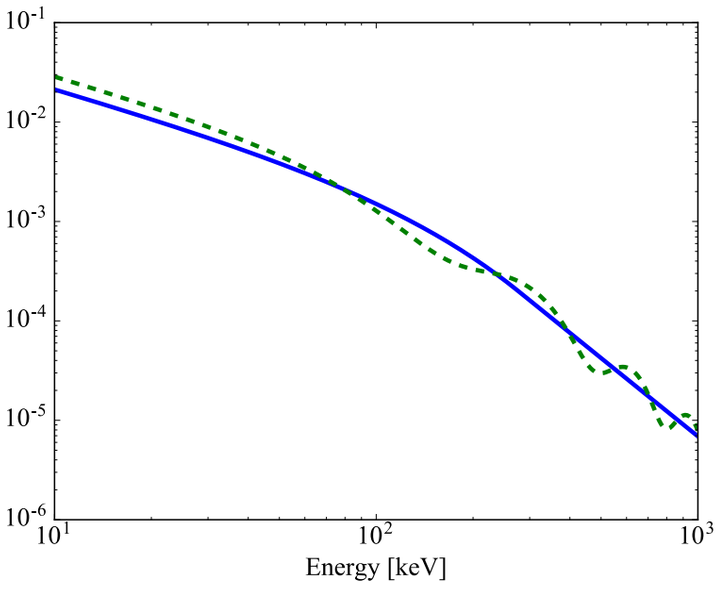


Primordial Black Hole Abundance

$$\delta t \sim keV^{-1} \xrightarrow{GRB} r_E \sim 100\ km \longrightarrow M \sim 10^{-15}\, M_\odot$$

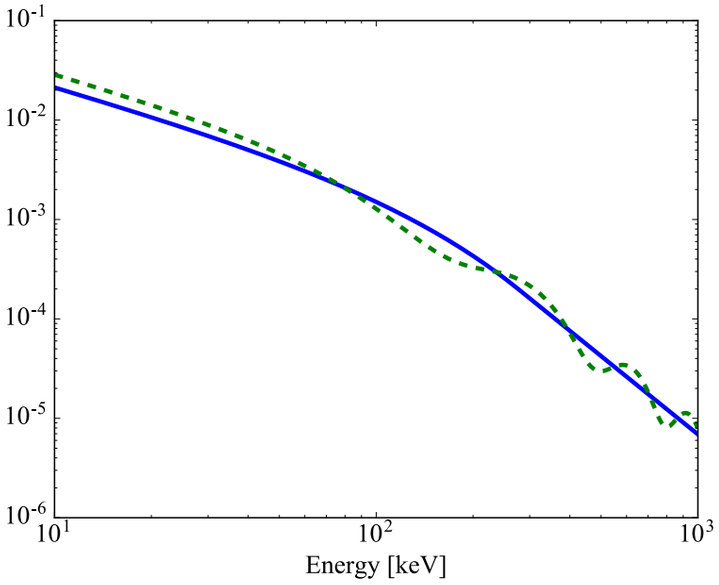
Primordial Black Hole Abundance

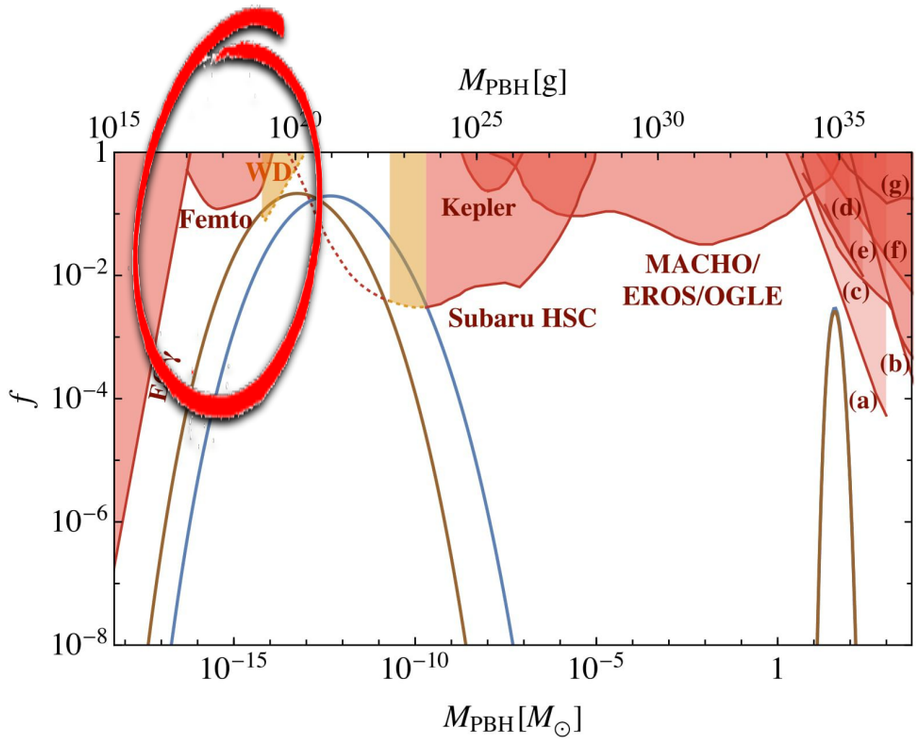
$$\delta t \sim keV^{-1} \xrightarrow{GRB} r_E \sim 100\ km \longrightarrow M \sim 10^{-15}\, M_\odot$$



Primordial Black Hole Abundance

$\delta t \sim keV^{-1}$ —GRB→ $r_E \sim 100\ km$ ⟶ $M \sim 10^{-15}\ M_\odot$

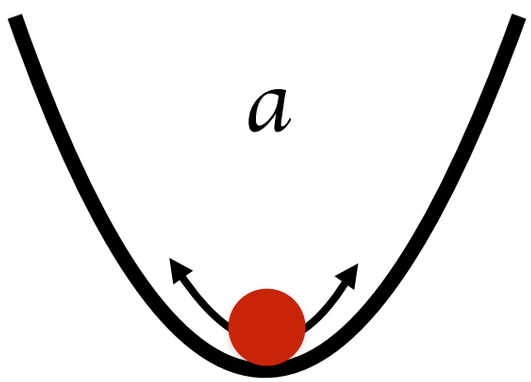




Minihalos and femtolensing?

- does femtolensing work for minihalos?
  - is it the similar as PBH?
- Lens
  - how the (axion) minihalos forms?
  - what is the minihalo density profile?
  - What is the typical image radius, time delay?
    $r_0 > r_E$
- Sources
  - How do we detect it?

Axion Minihalos



QCD axion minihalos

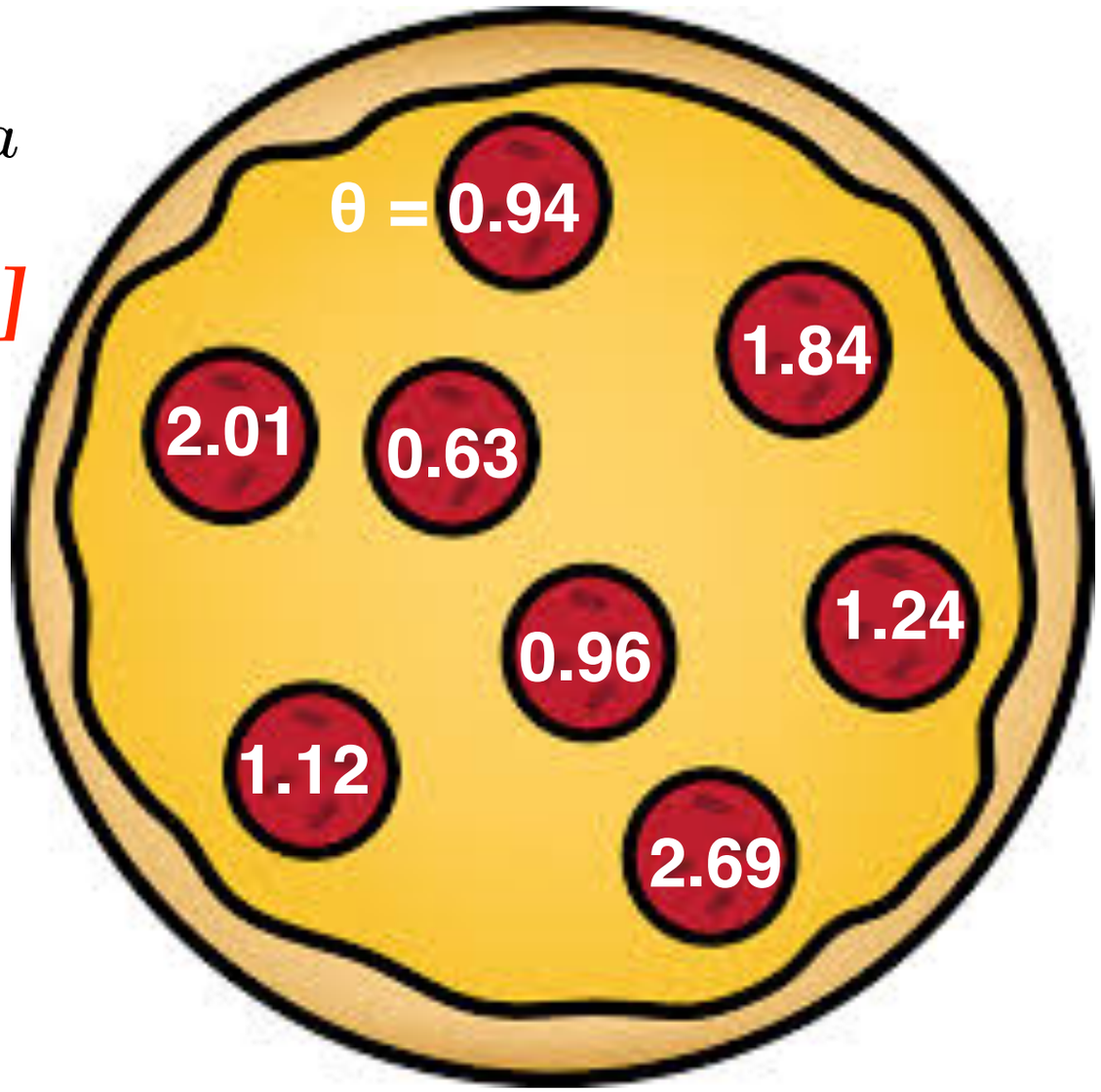
$T < f_a \sim 10^{12}\ GeV$

- PQ symmetry breaking after inflation

$m_a = 0$

$\theta_i = \phi_i / f_a$

θ *in* $[-\pi, \pi]$



QCD axion minihalos

$T \sim GeV$

- axion mass induced by QCD instantons

$$\rho_a \sim \Lambda^4_{QCD}\, \theta^2$$

- $\mathcal{O}(1)$ density fluctuation

$$\delta\rho_a / \rho_a \sim 1$$

- tiny density fluctuation (radiation dominant universe)

$$\delta\rho_a / \rho_{Total} \ll 1$$

QCD axion minihalos

$$T \sim eV$$

- matter-radiation equality, density fluctuations

$$\delta\rho_a / \rho_{Total} \sim 1$$

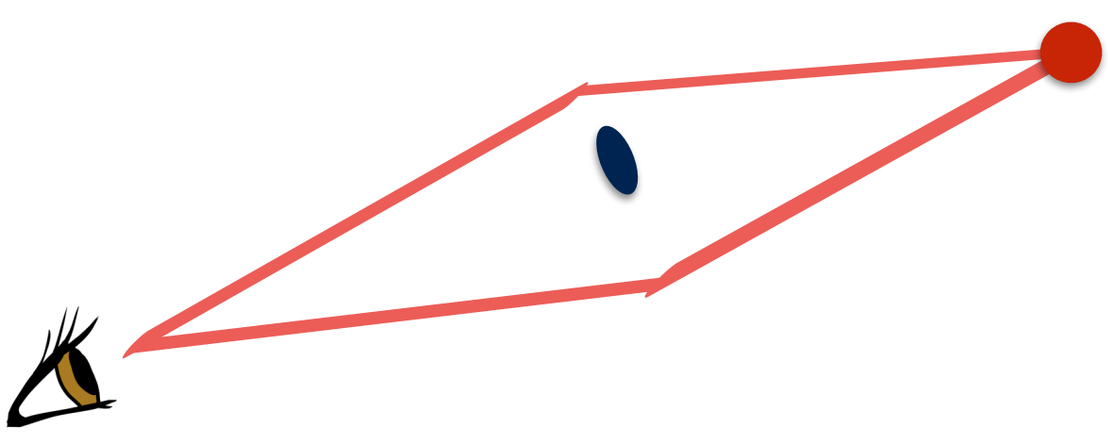
- axion minihalos form by gravity

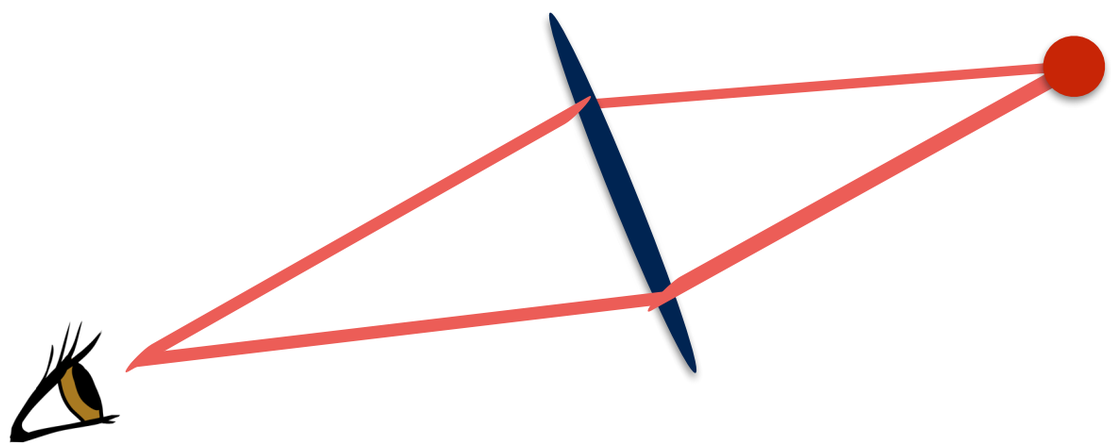
- typical mass and size

$$r_0 \sim 10^9\ m\ ,\ \ M \sim 10^{-12}\ M_\odot$$

Minihalos and Femtolensing

Lens





Minihalo Density Profiles

- free-falling profile

$$\rho_{ff} = \rho_0 \left(r_0/r\right)^{9/4}$$

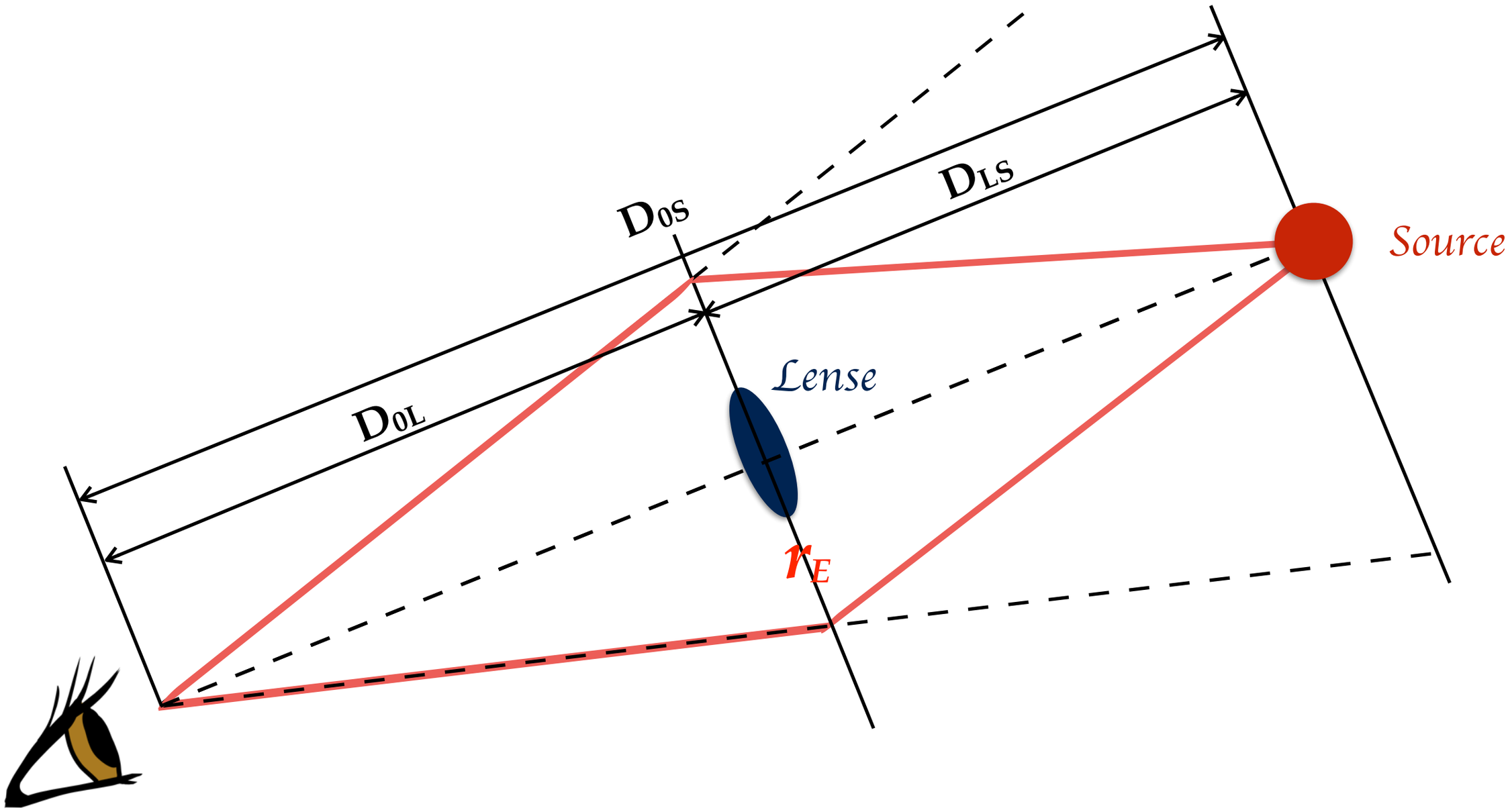
- isothermal profile

$$\rho_{iso} = \rho_0 \left(r_0/r\right)^{2}$$

- NFW profile

$$\rho_{NFW} = \frac{\rho_0}{\left(r/r_0\right)\left(1 + r/r_0\right)^2}$$

Einstein Radius r_E

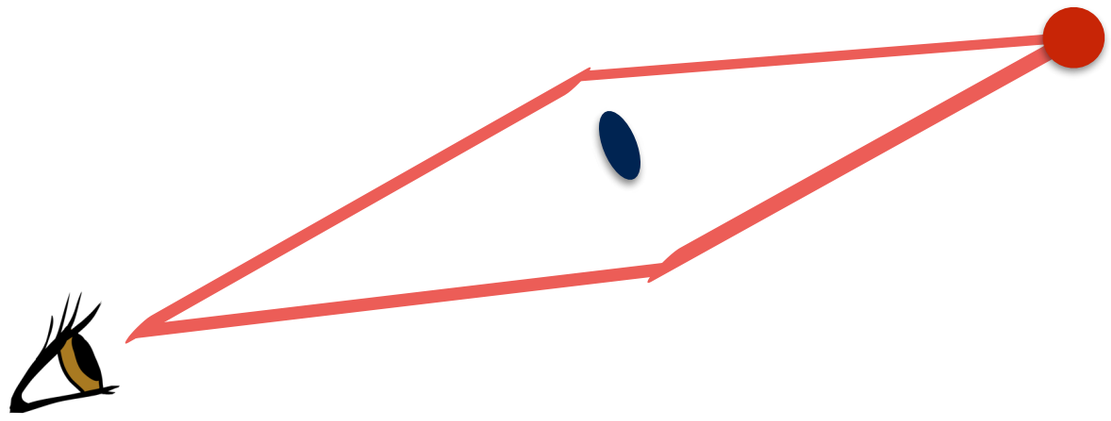


$$r_E = \sqrt{\frac{4GM}{c^2}\frac{D_{OL}D_{LS}}{D_{OS}}}$$

Point Mass or not?

$$r_E = \sqrt{\frac{4GM}{c^2}\frac{D_{OL}D_{LS}}{D_{OS}}}$$

- black hole $r_0 \ll r_E$
  point mass



- free-falling, isothermal, NFW profile $r_0 < r_E$
  point mass

- free-falling, isothermal, NFW profile $r_0 > r_E$
  solve the lensing equation

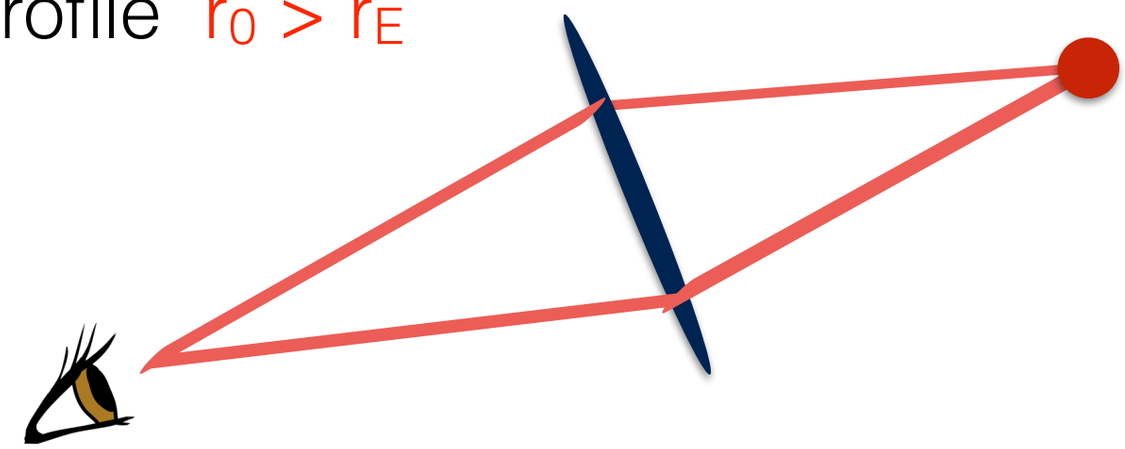


image positions $r_0 > r_E$

ξ_0 length scale in the lens plane

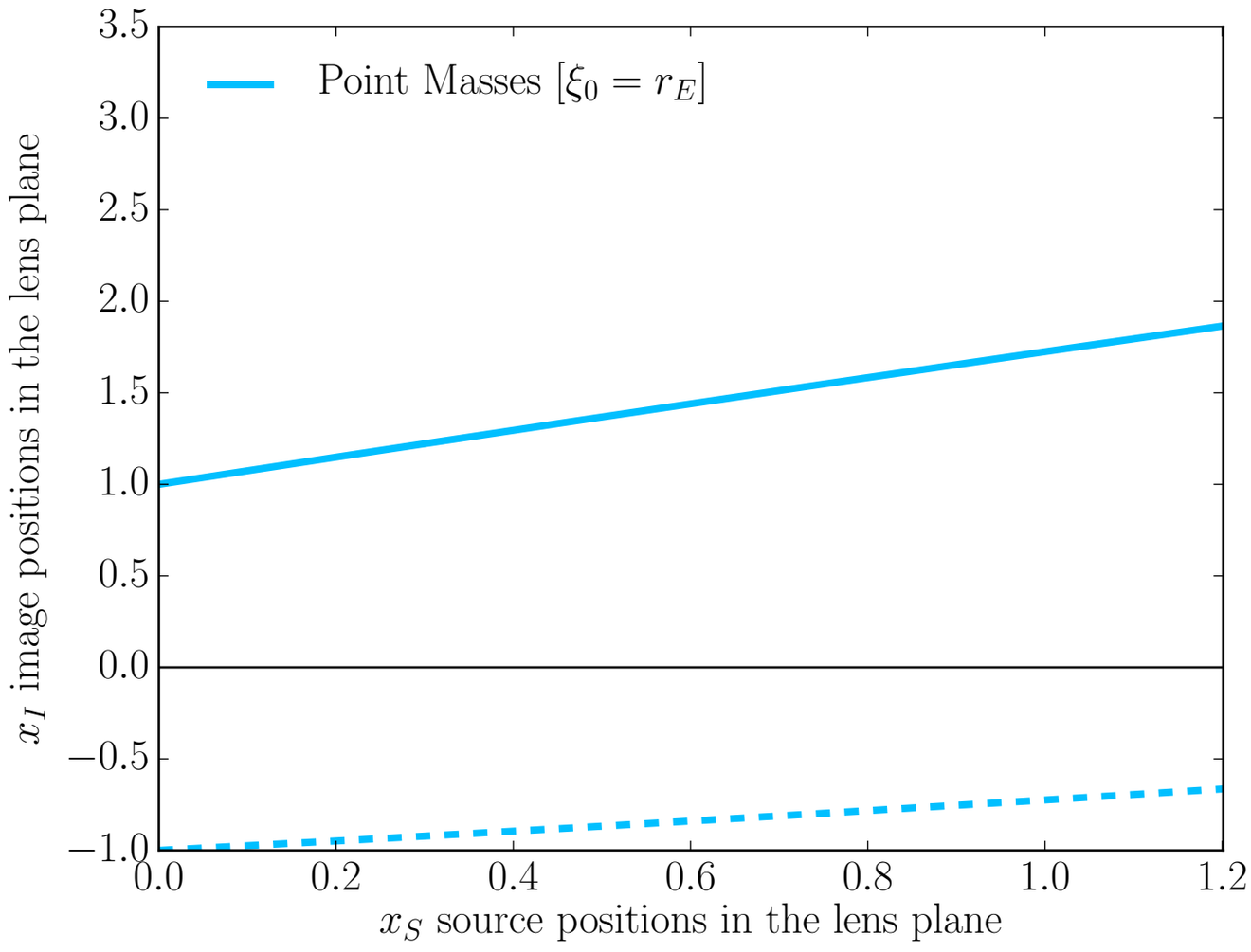


image positions $r_0 > r_E$

ξ_0 length scale in the lens plane

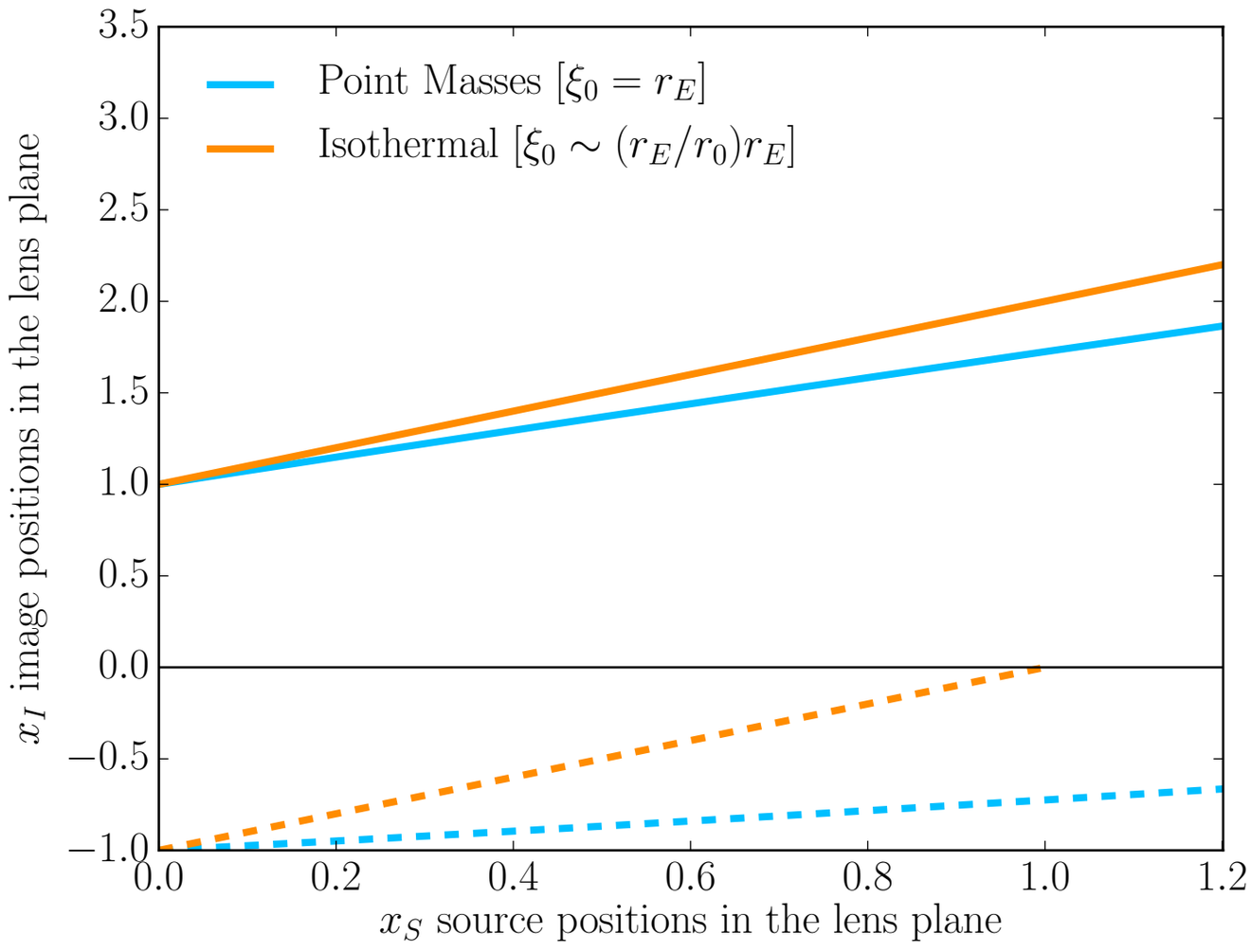
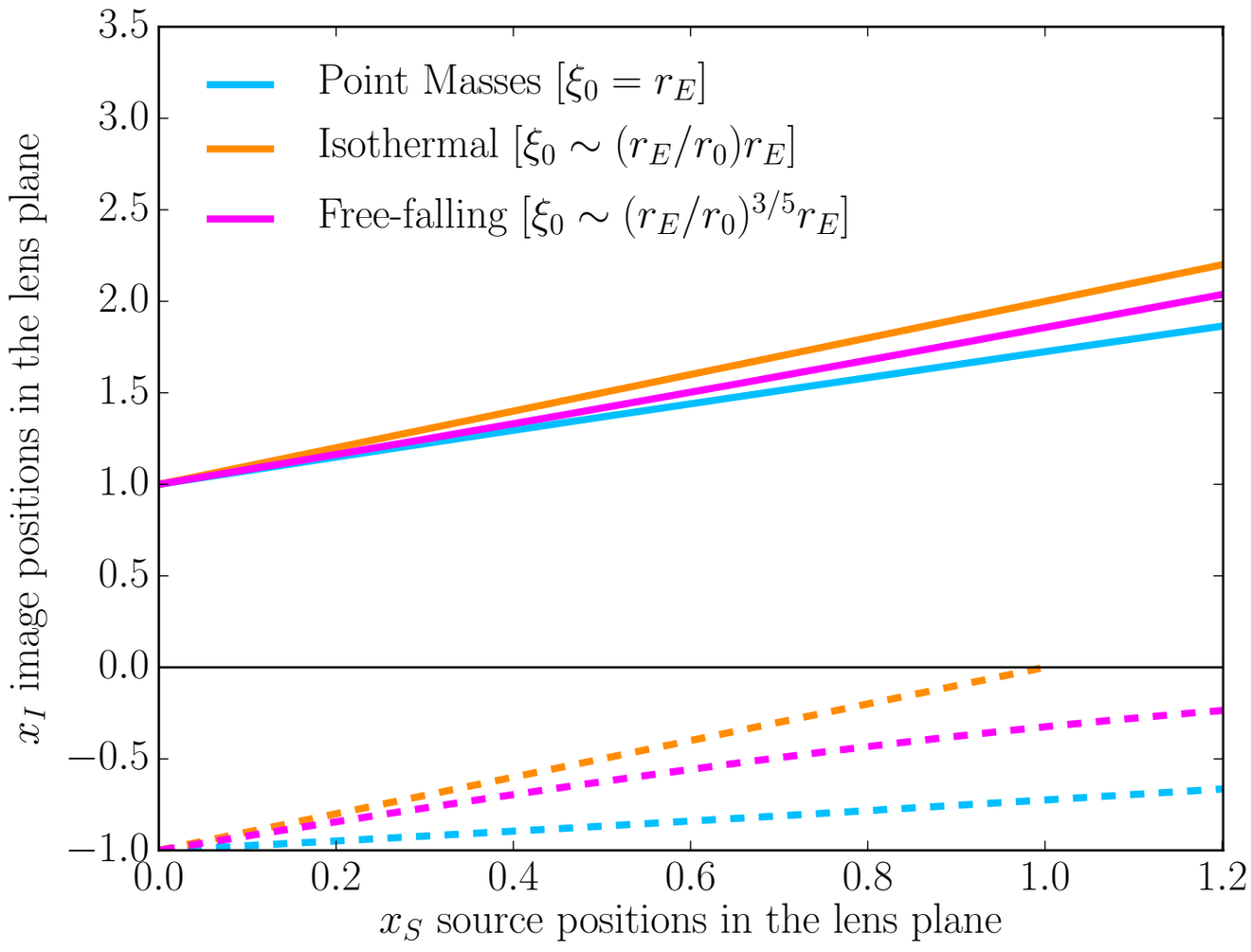


image positions $r_0 > r_E$

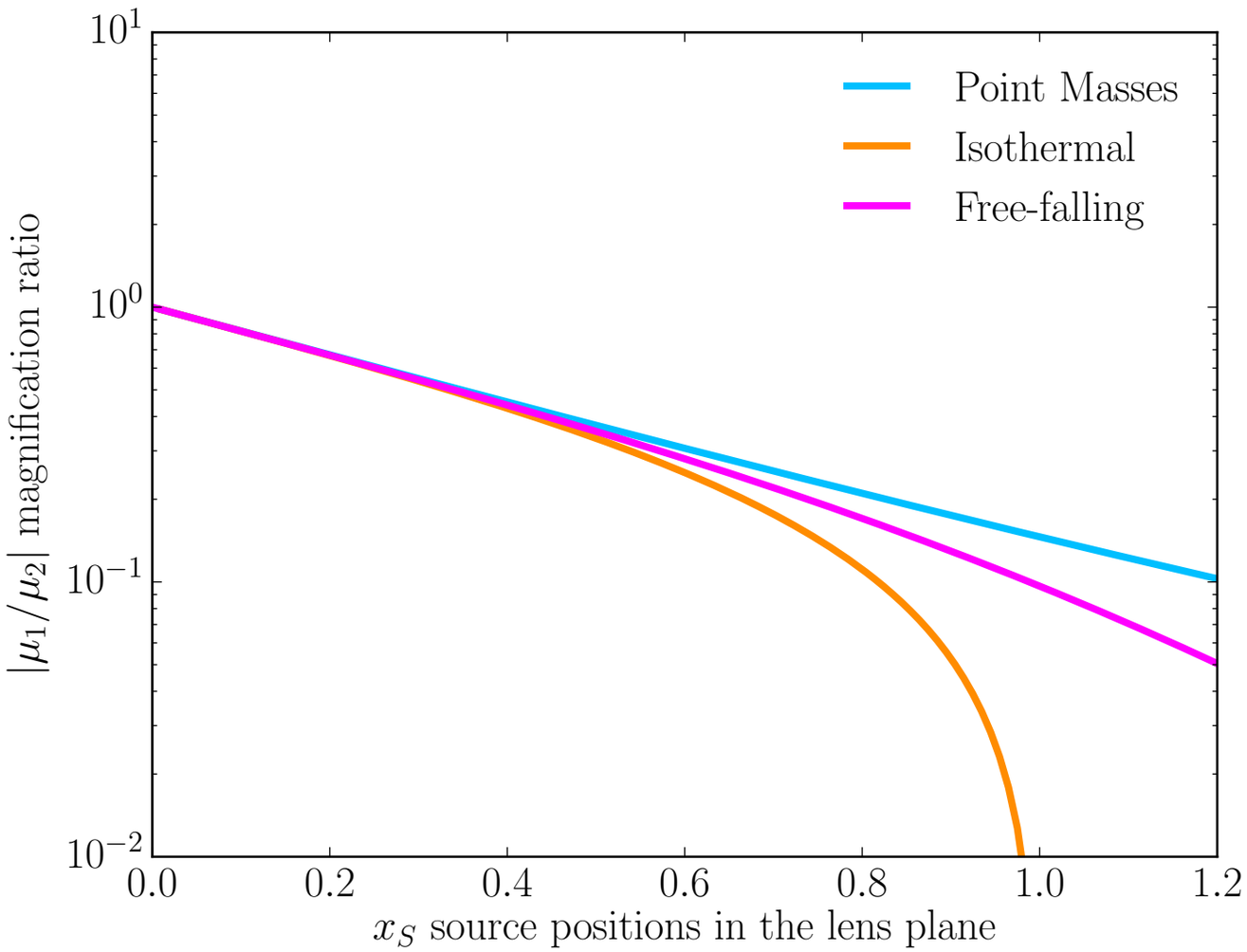
ξ_0 length scale in the lens plane



Magnification Ratio

ξ_0 length scale in the lens plane

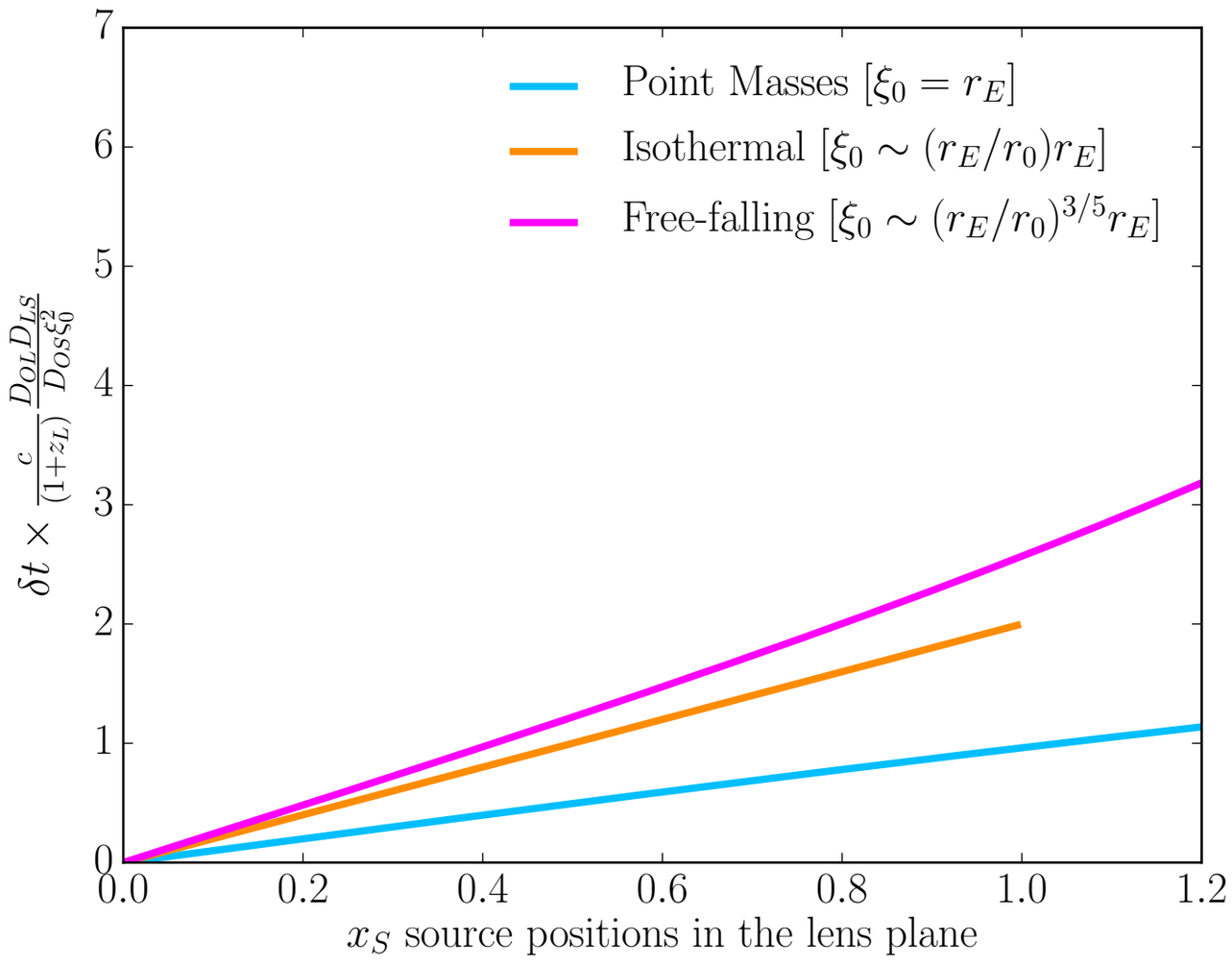
$$|A_1 + A_2|^2 \propto 1 + \mathcal{O}(1)\cos(\Delta\phi)$$ ***$\Delta\phi = E\,\delta t$***



Time Delay

ξ0 length scale in the lens plane

$$\delta \mathbf{t} = \mathcal{O}(1)\frac{1+z_L}{c}\frac{D_{OS}}{D_{OL}D_{LS}}\xi_0^2$$



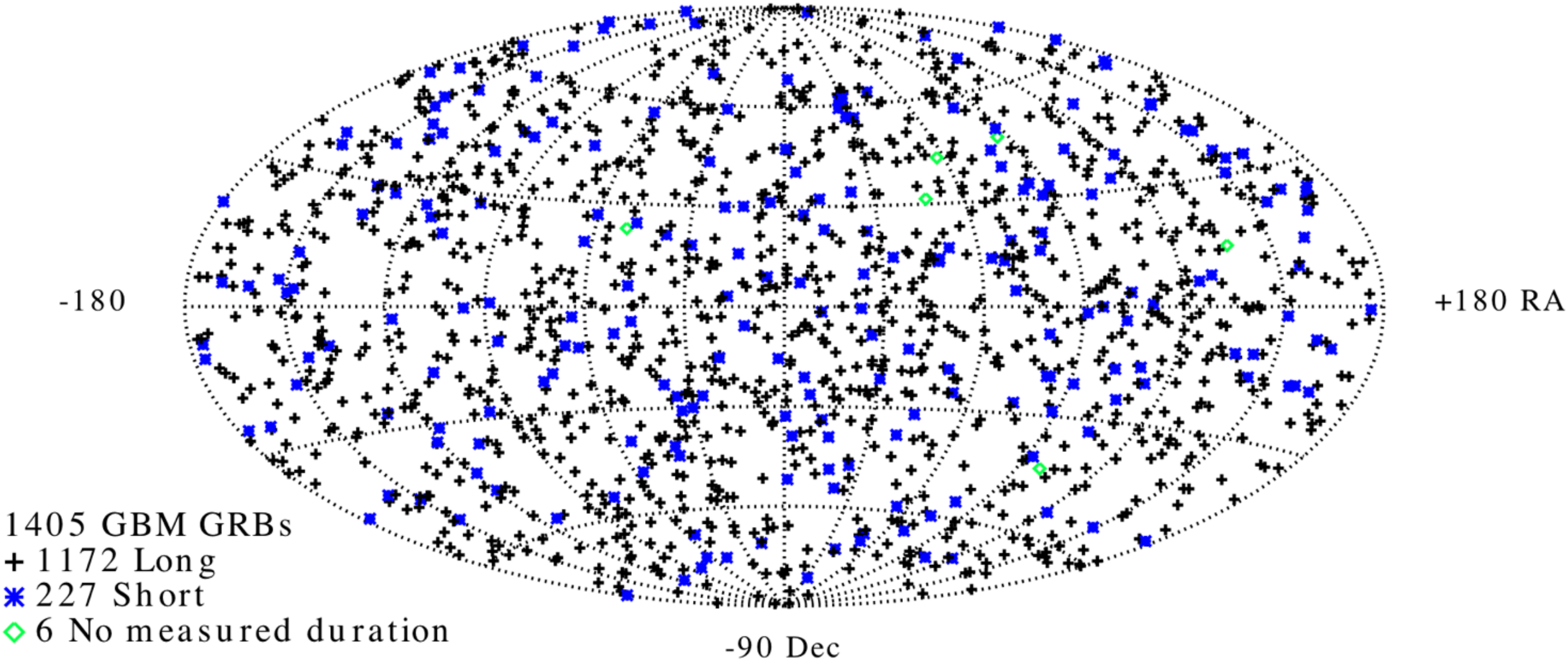
$$|A_1 + A_2|^2 \propto 1 + \mathcal{O}(1)\cos(\Delta\phi)\ \boldsymbol{\Delta\phi = E\ \delta t}$$

Summary

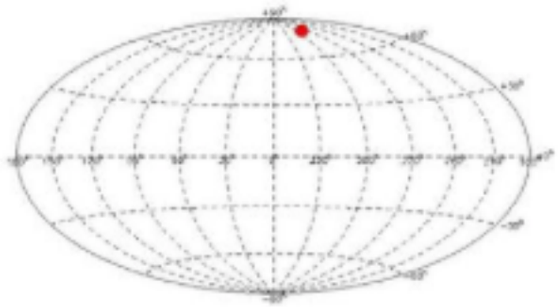
	Density	***image radius***	***time delay***
Point Mass	δ	r_E	$\propto r_E^2$
isothermal	$\rho_0(r_0 / r)^2$	$(r_E/ r_0)\, r_E$	$\propto (r_E/ r_0)^2 r_E^2$
free-falling	$\rho_0(r_0 / r)^{9/4}$	$(r_E/ r_0)^{3/5}\, r_E$	$\propto (r_E/ r_0)^{6/5} r_E^2$
general	$\rho_0(r_0 / r)^n$	$(r_E/ r_0)^{(3-n)/(n-1)}\, r_E$	$\propto (r_E/ r_0)^{2(3-n)/(n-1)} r_E^2$

Minihalos and Femtolensing Sources

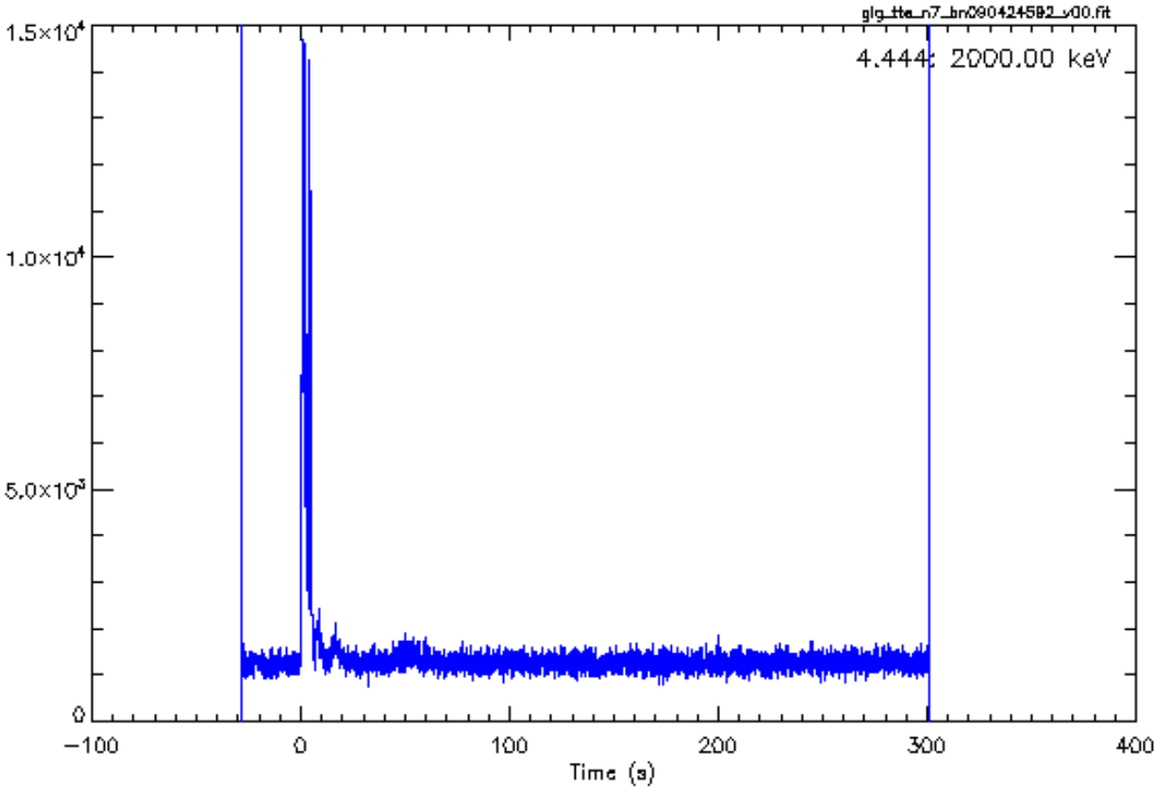
Fermi GBM GRBs in first six years of operation

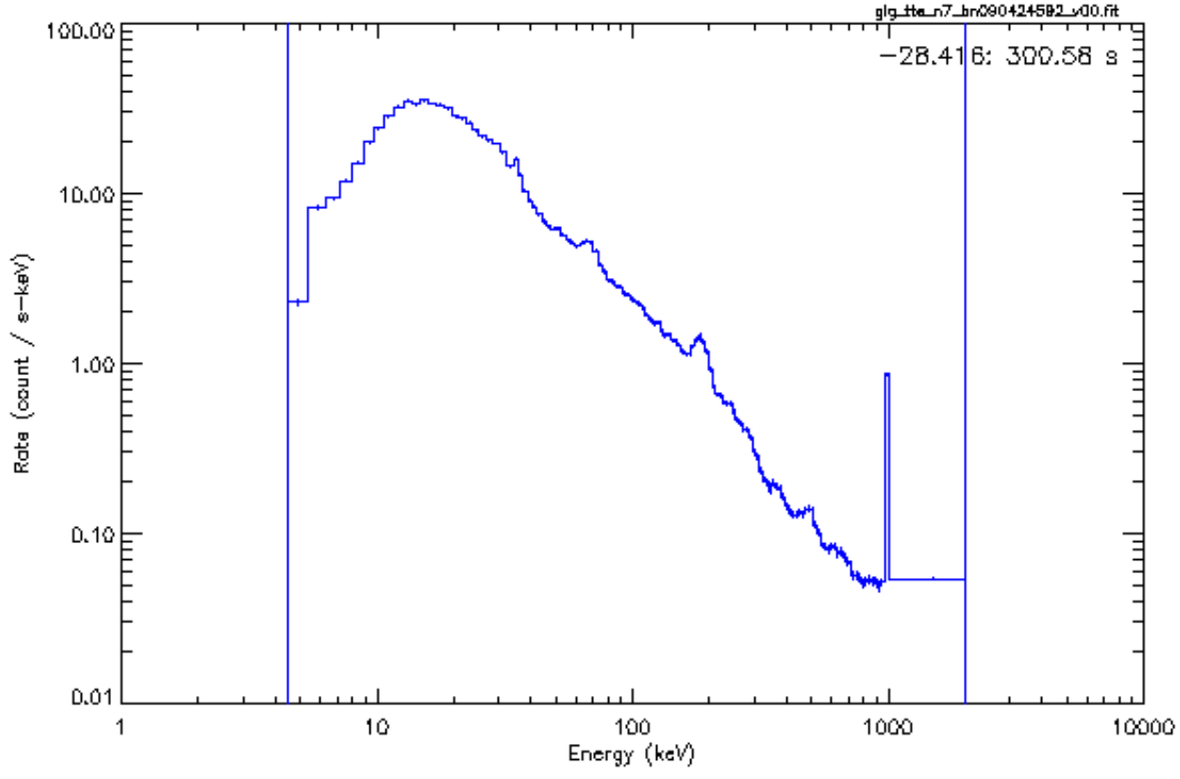


GRB090424

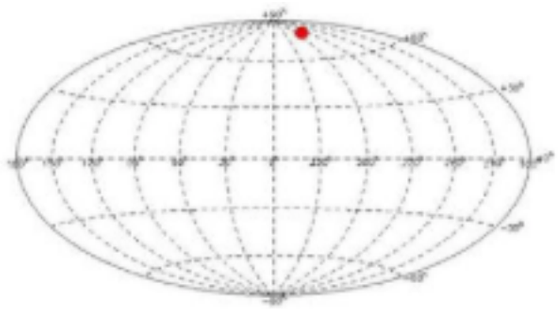


- Redshift measured (70 GRB observed)
- $z_S = 0.544$

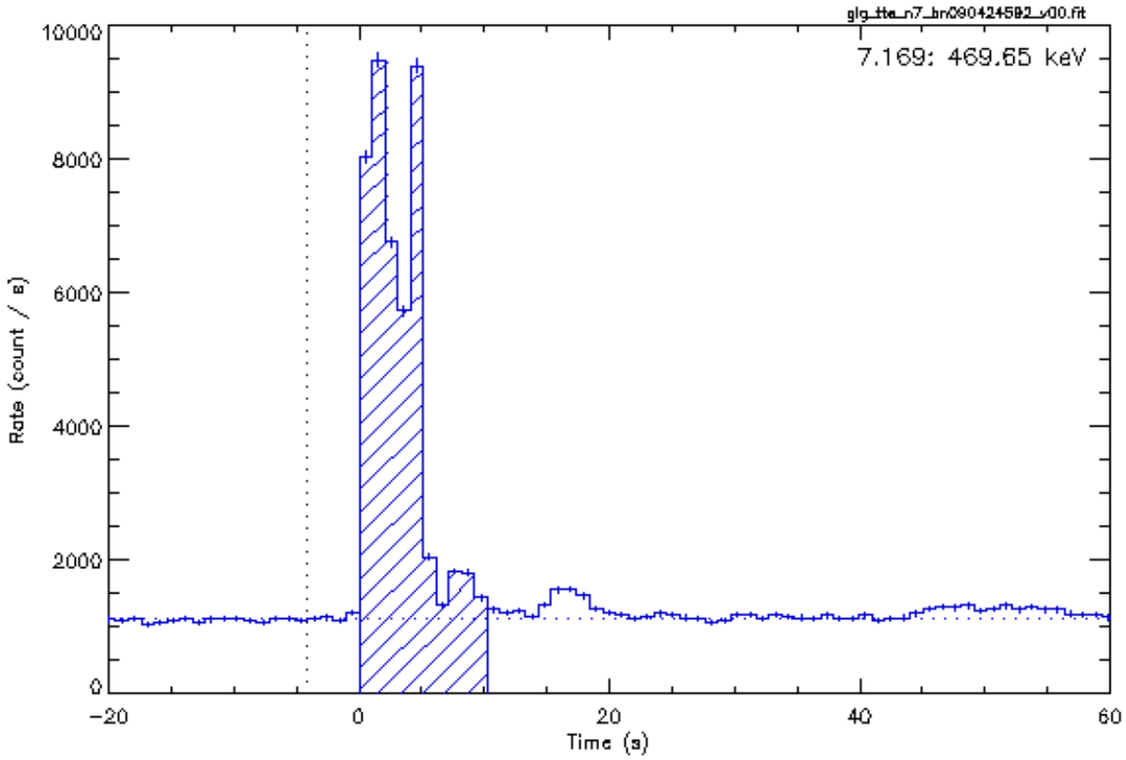


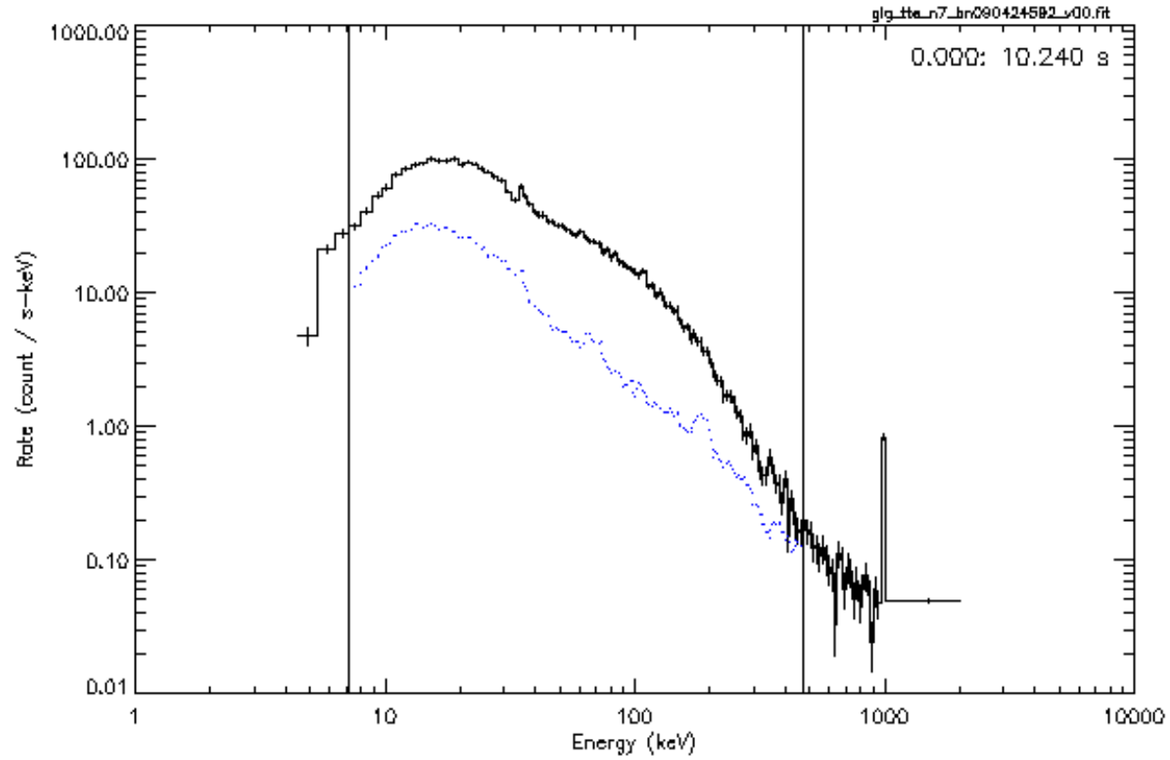


GRB090424

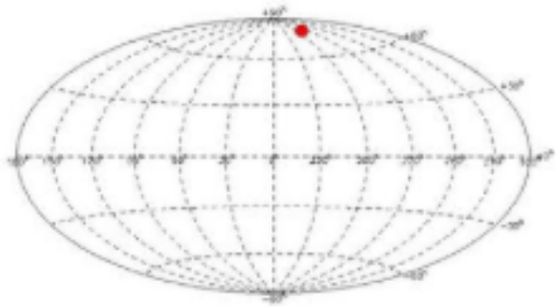


- First 10 s
- background subtraction

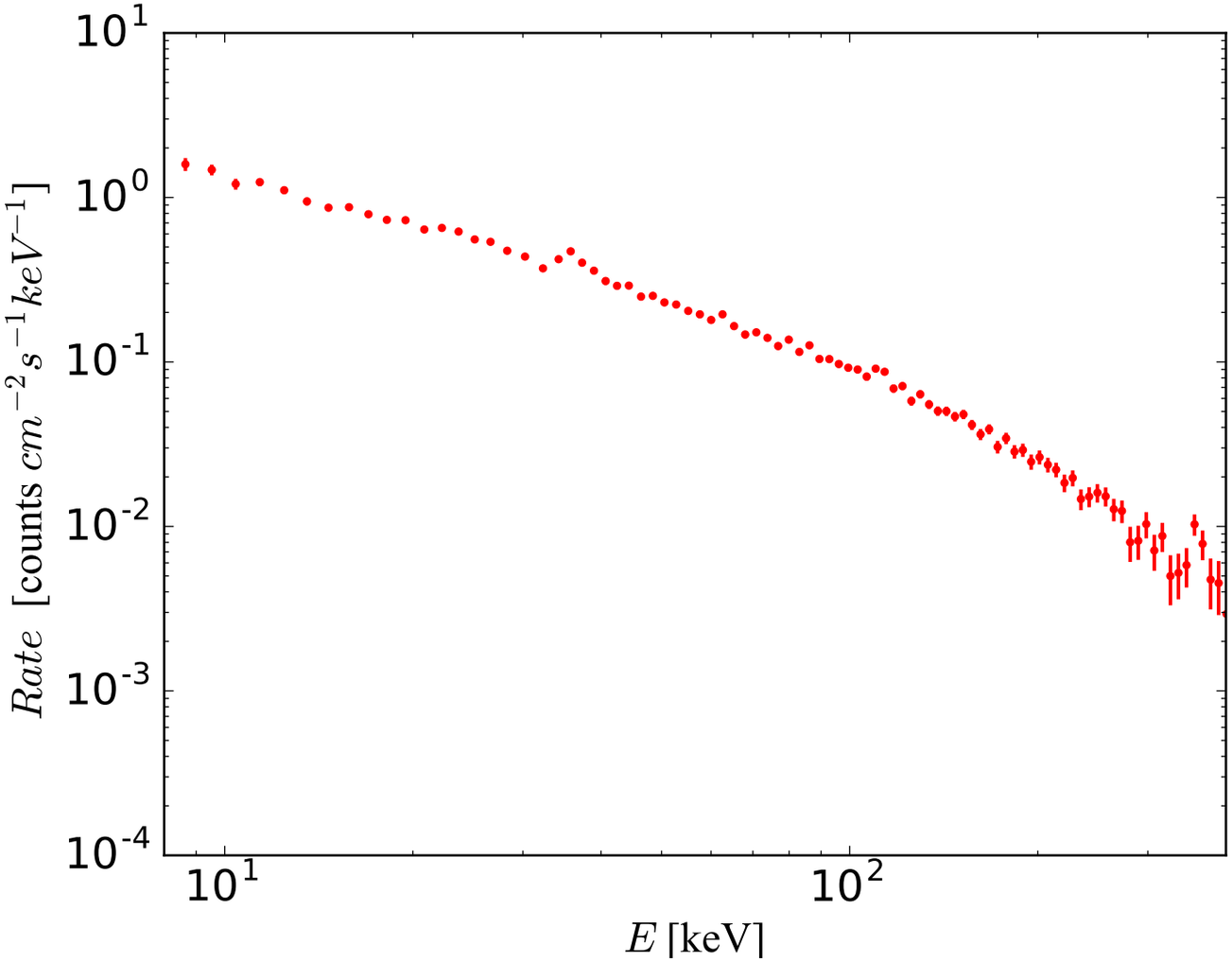




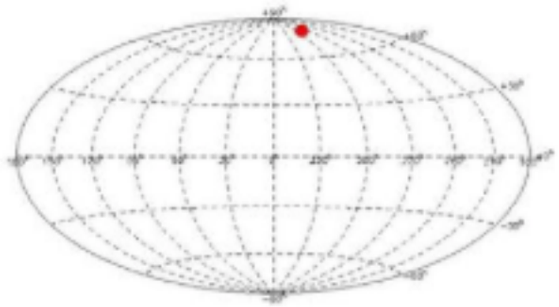
GRB090424



- fit $$\sigma = \pi \left(r_{s,max}^2 - r_{s,min}^2 \right)$$

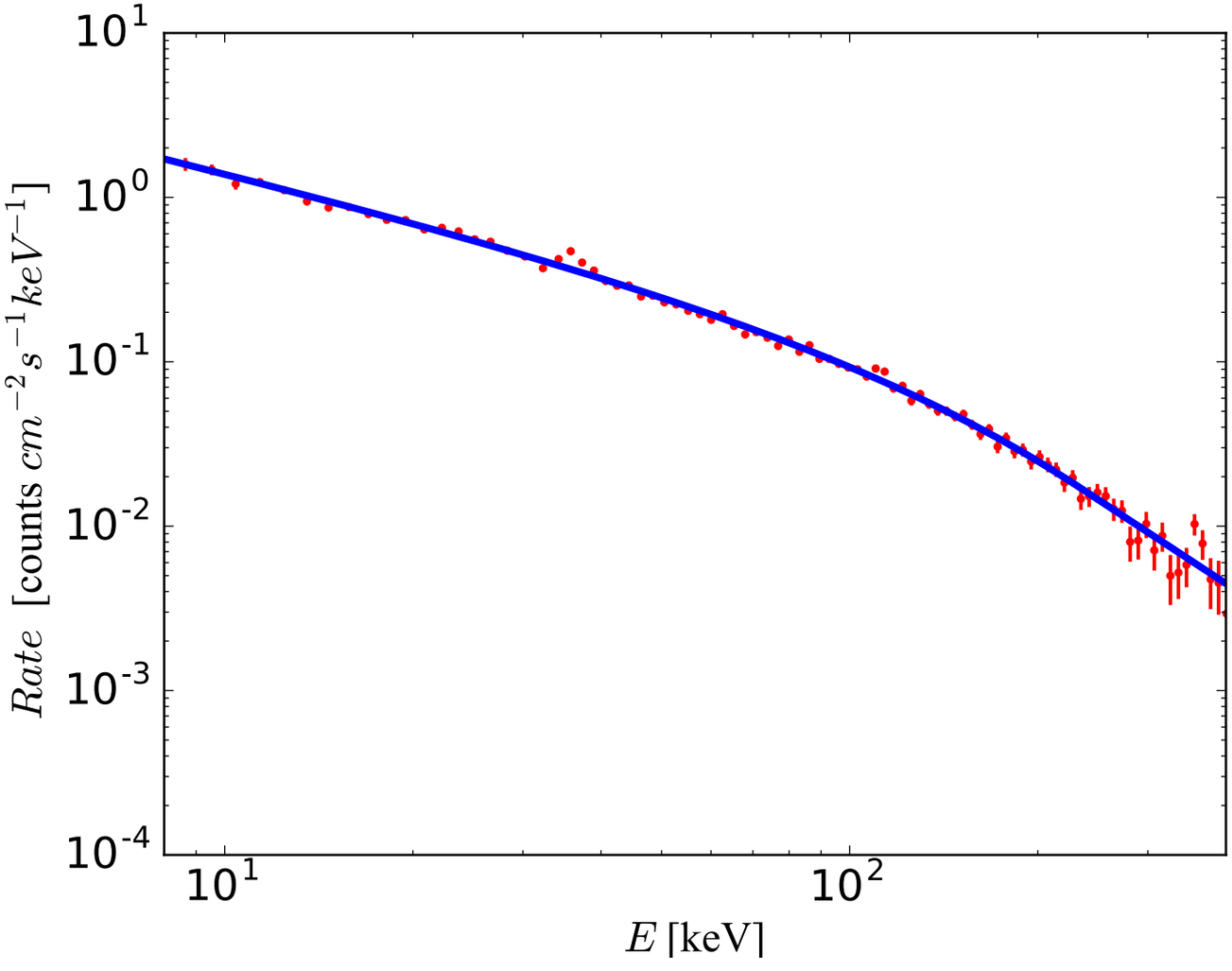


GRB090424

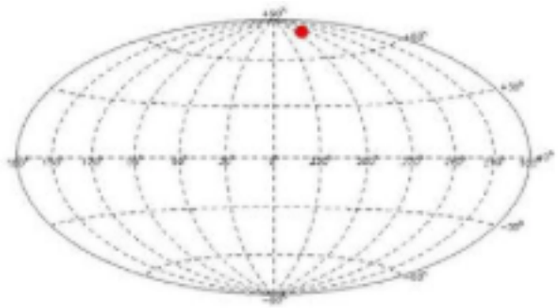


- fit

$$\sigma = \pi \left(r_{s,max}^2 - r_{s,min}^2 \right)$$

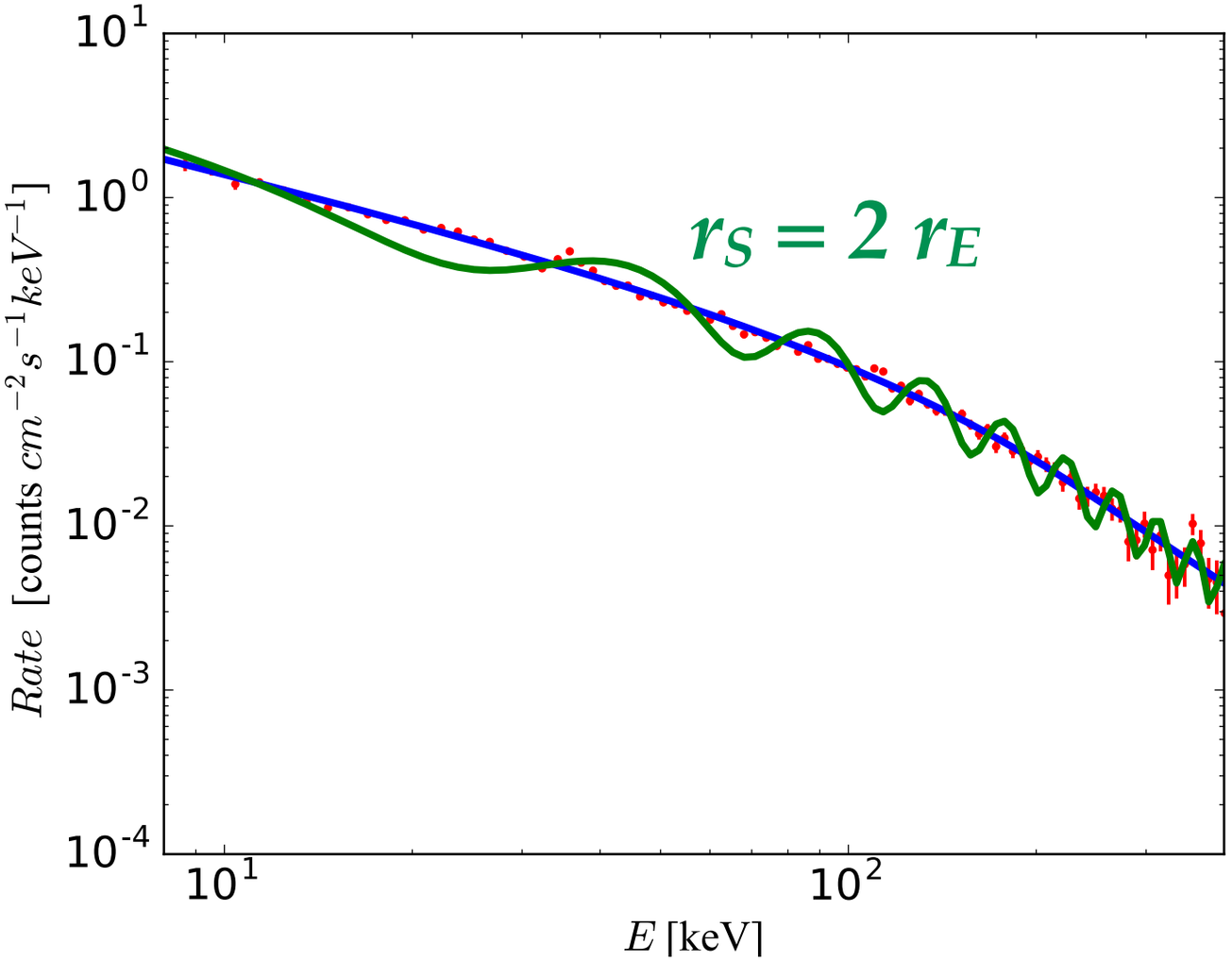


GRB090424

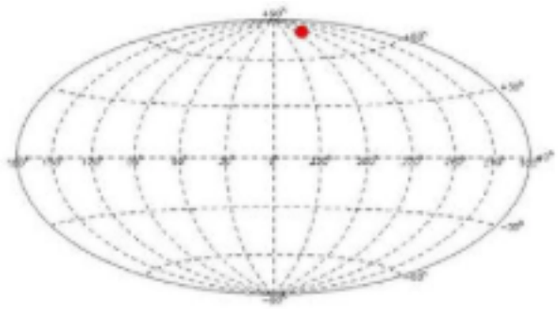


- fit $$\sigma = \pi \left(r_{s,max}^2 - r_{s,min}^2 \right)$$

M= 10^{-15} M$_\odot$

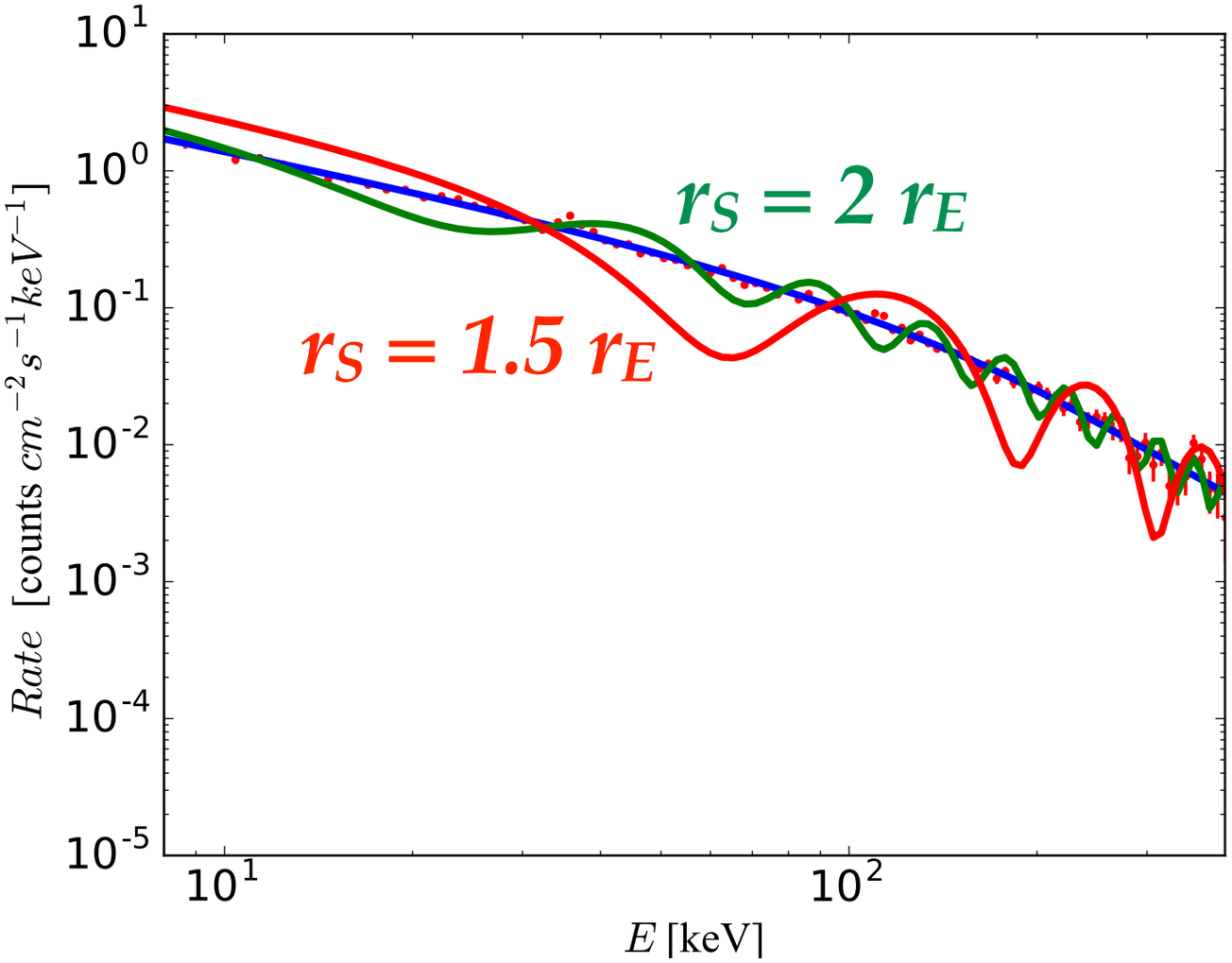


GRB090424



- fit $\sigma = \pi \left(r_{s,max}^2 - r_{s,min}^2 \right)$

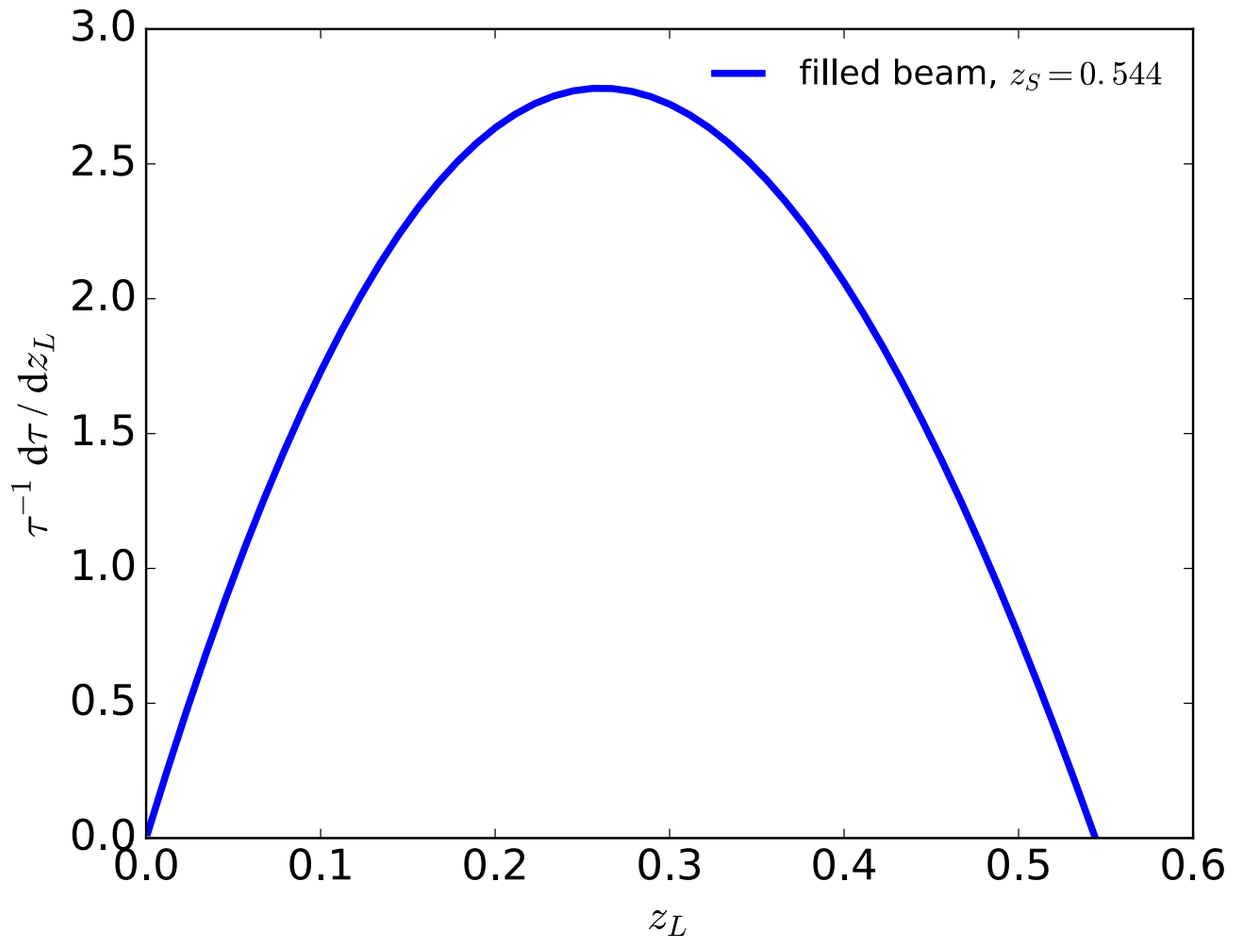
M= 10^{-15} M$_\odot$



Optical Depth

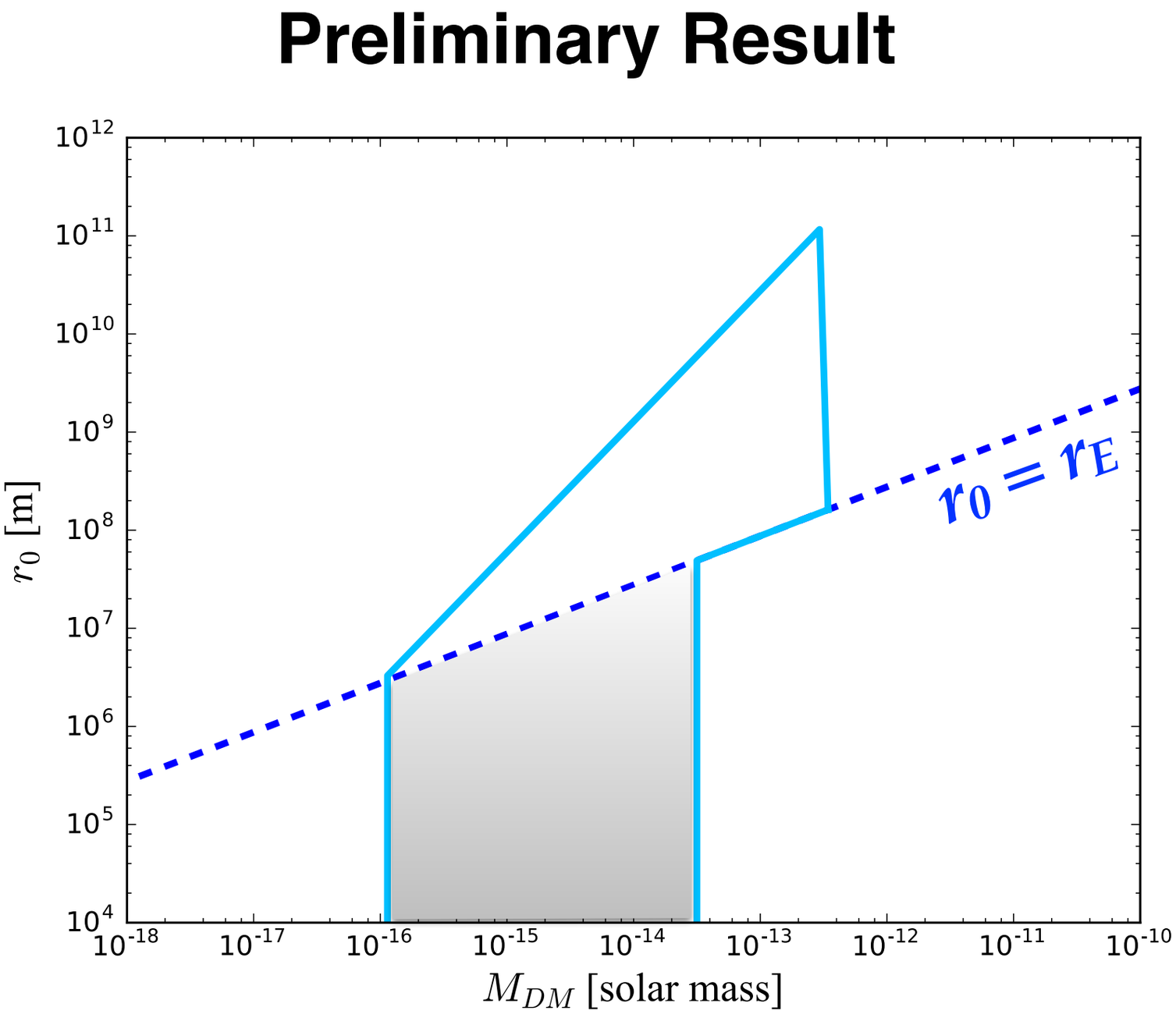
$$\sigma = \pi \left(r_{s,max}^2 - r_{s,min}^2 \right)$$

$$d\tau = \frac{\rho_{halo}}{M_{halo}} (1 + z_L)^3 \sigma \frac{cdt}{dz_L} dz_L$$



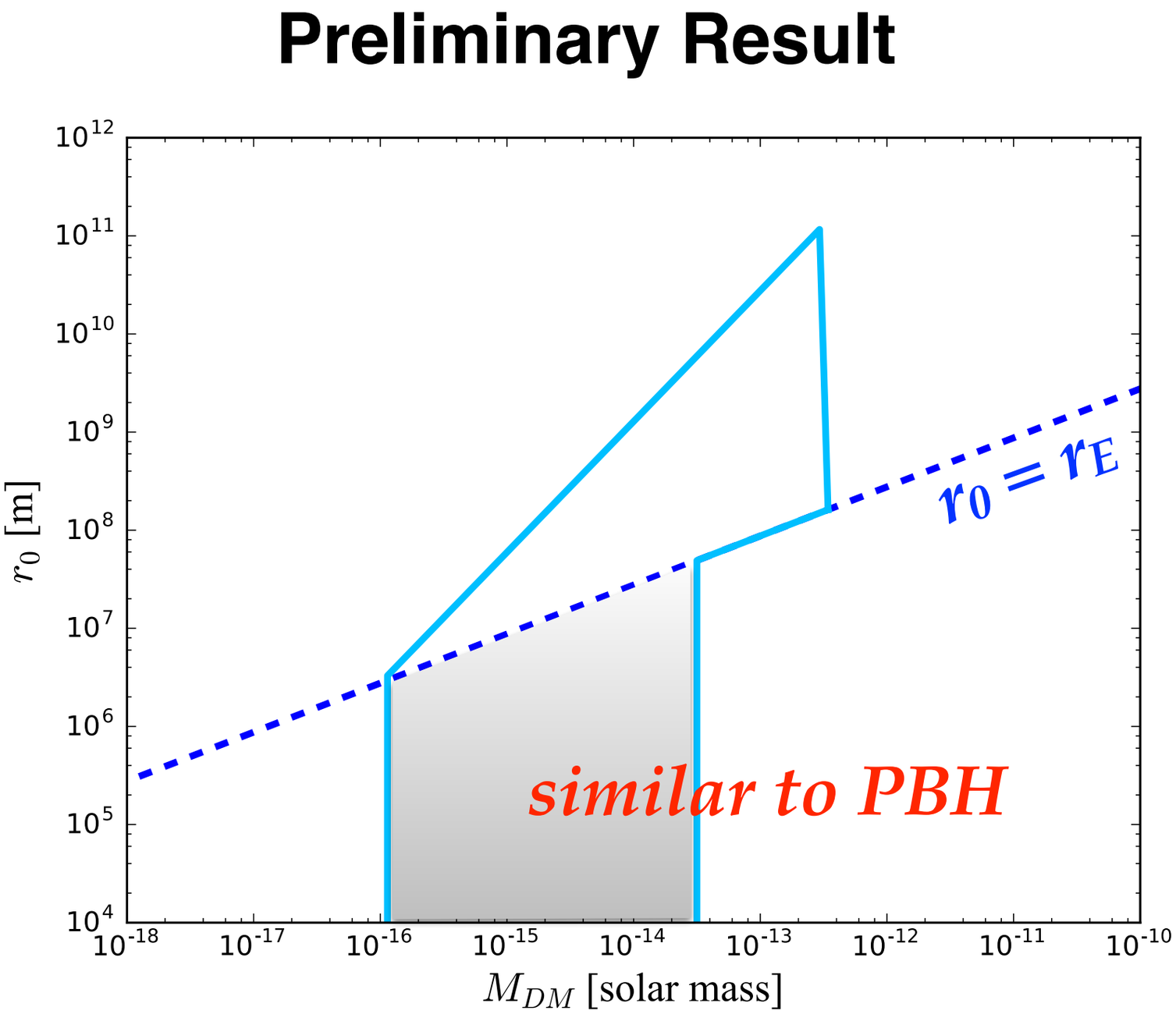
Constraints (free-falling profile)

$\xi_0 \sim (r_E/r_0)^{3/5}\, r_E$



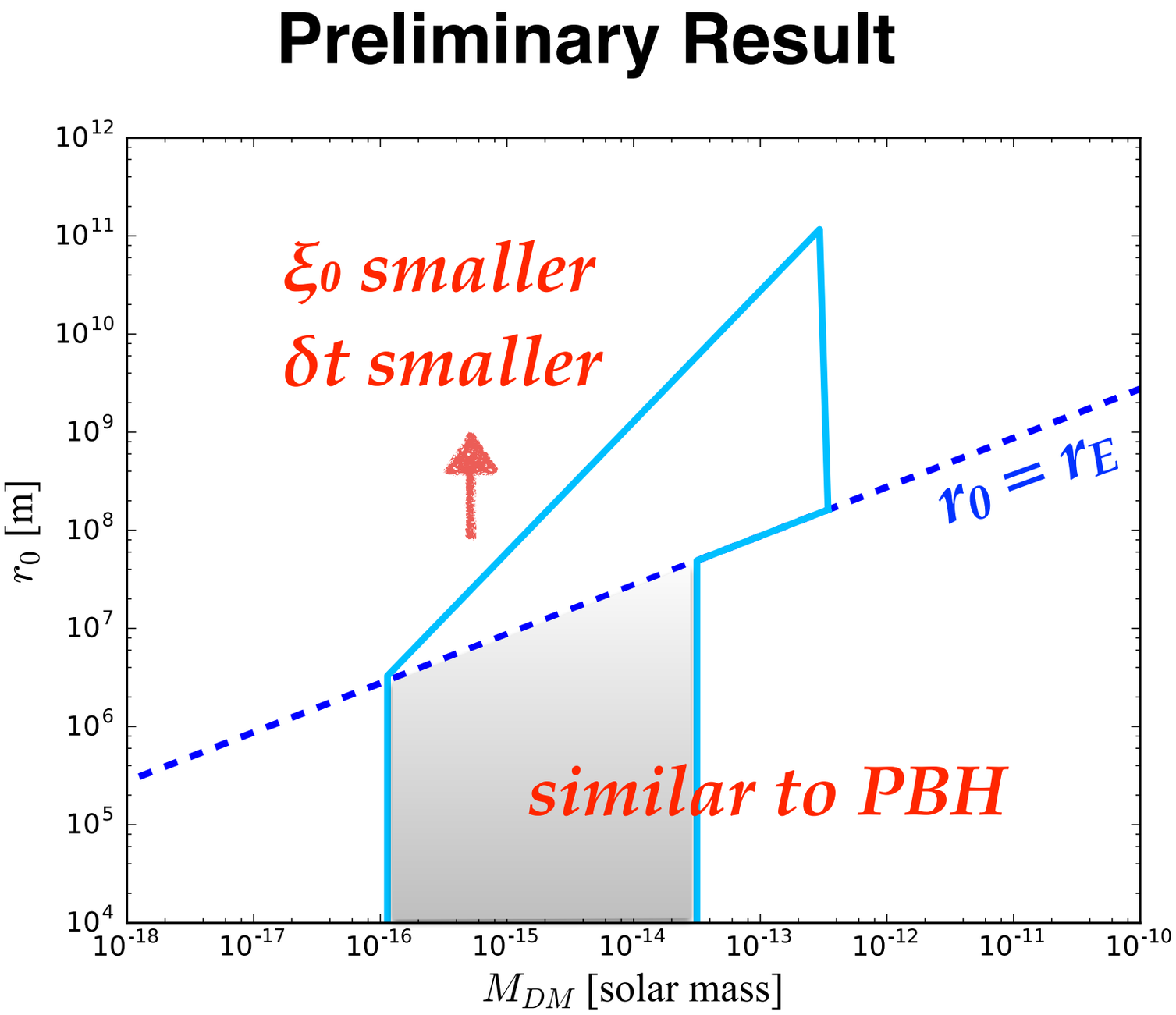
Constraints (free-falling profile)

$\xi_0 \sim (r_E/r_0)^{3/5}\, r_E$



Constraints (free-falling profile)

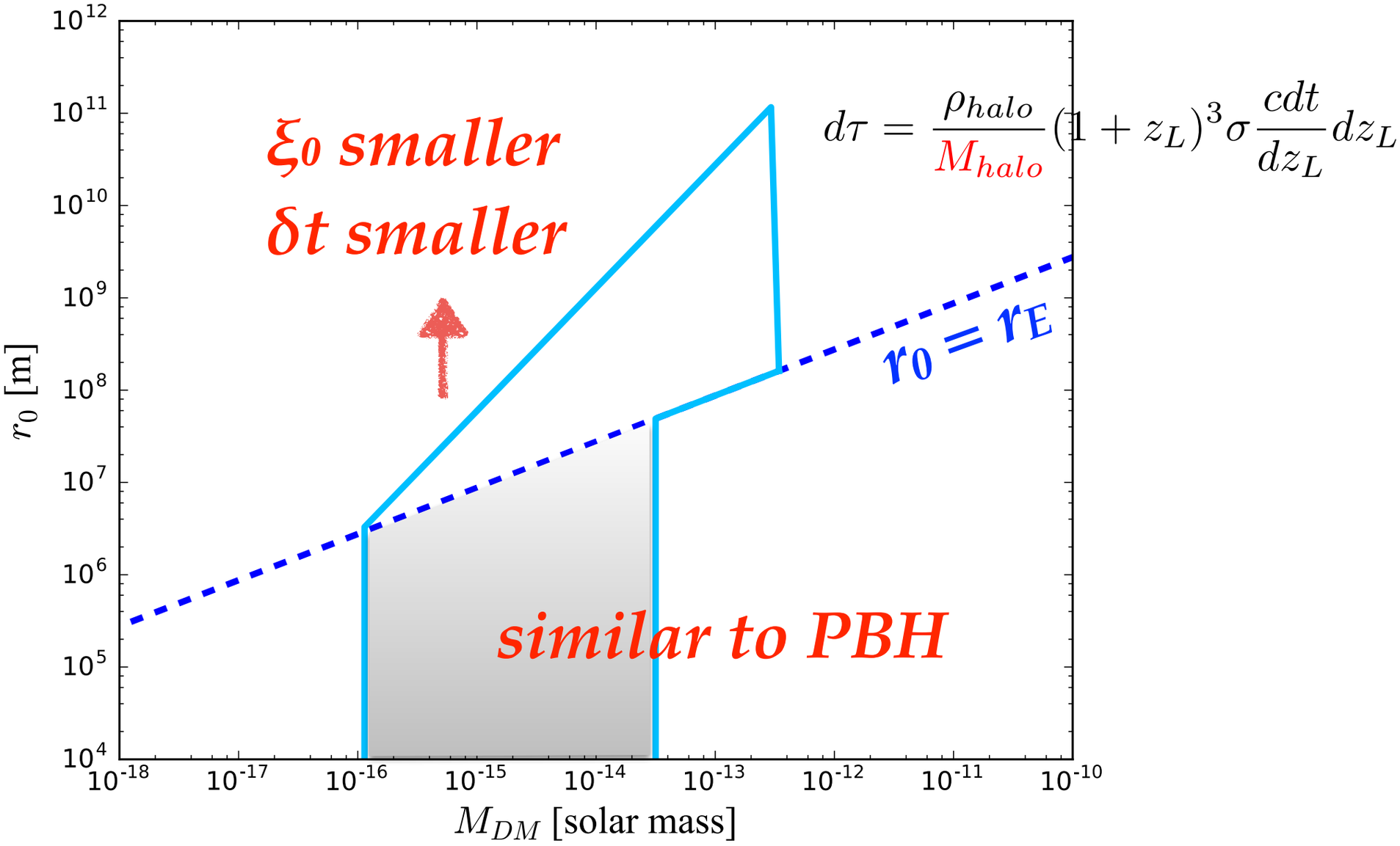
$\xi_0 \sim (r_E/r_0)^{3/5}\, r_E$



Constraints (free-falling profile)

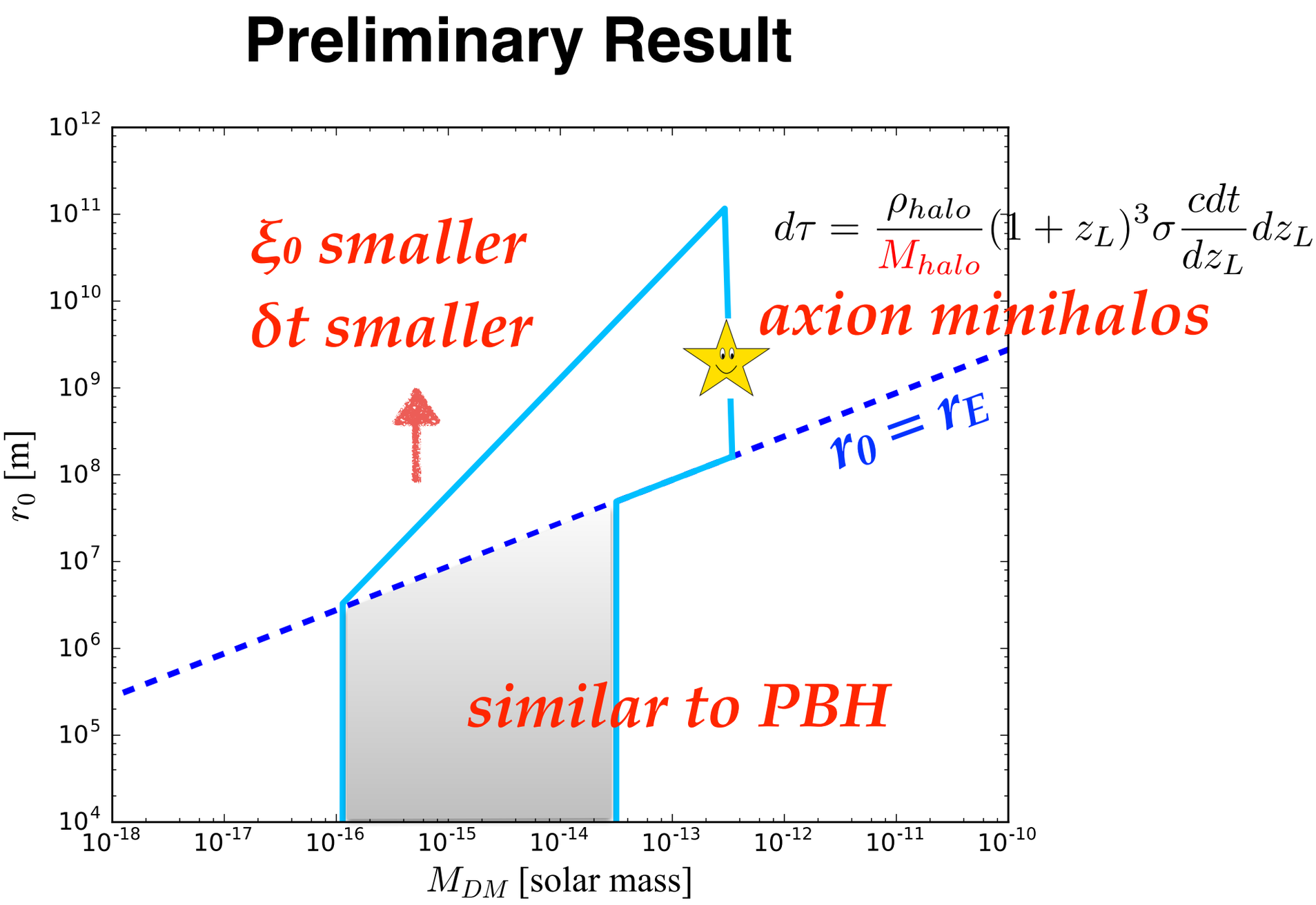
$\xi_0 \sim (r_E/r_0)^{3/5}\, r_E$

Preliminary Result



Constraints (free-falling profile)

$\xi_0 \sim (r_E/r_0)^{3/5}\, r_E$



Wave Optics
vs
Geometric Optics

Not always two images

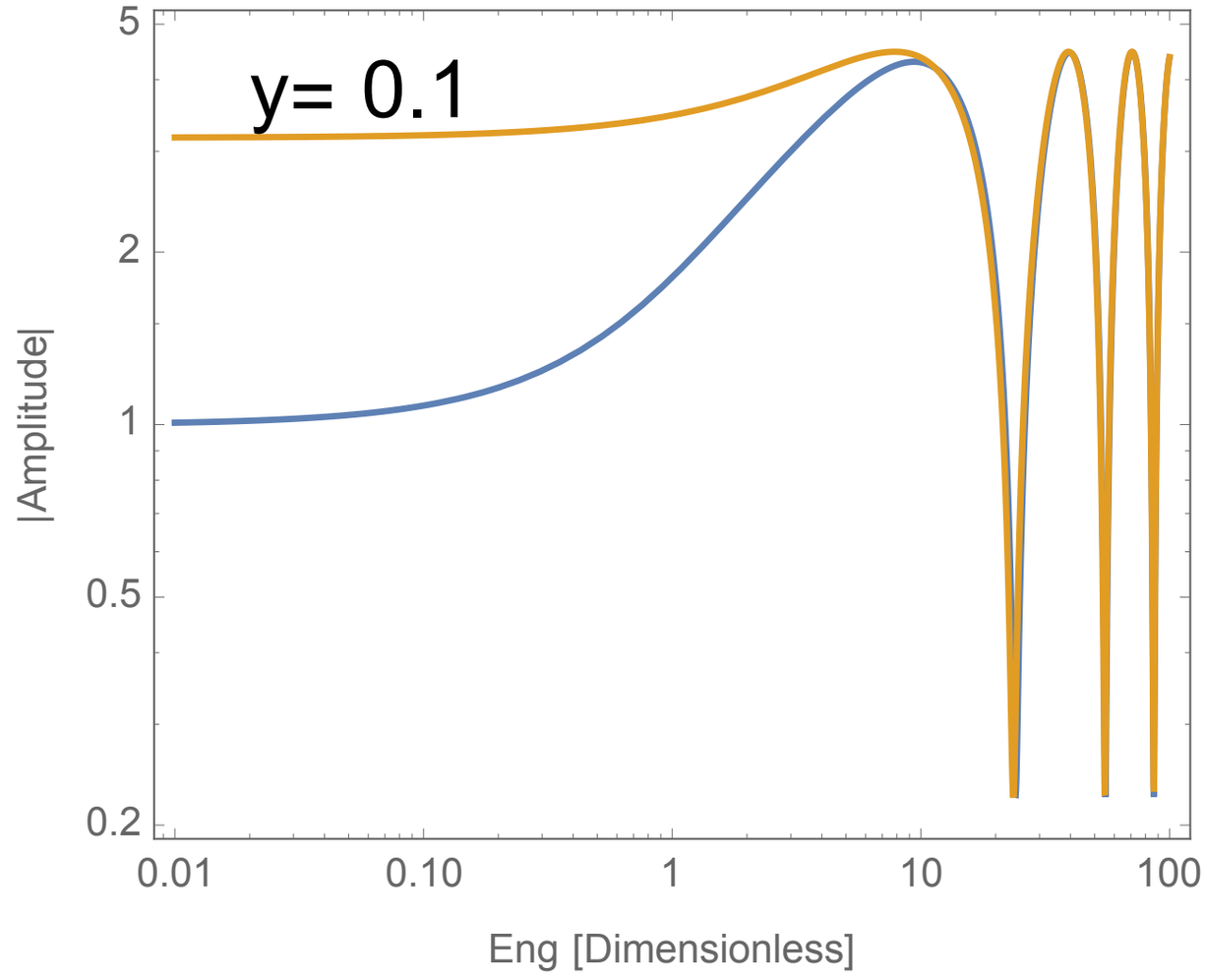
- Full lensing equation

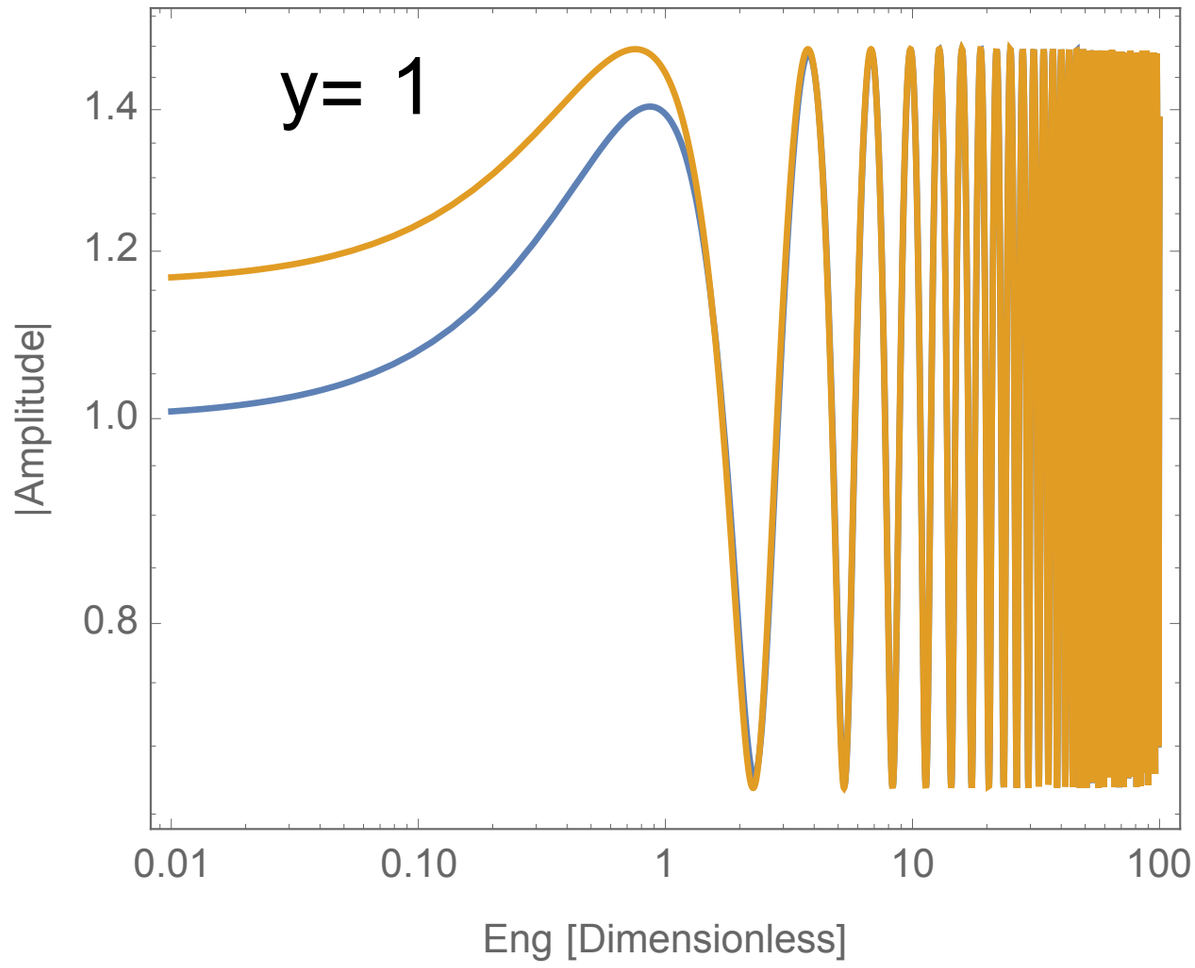
$$E \int d^2x \exp\left[iE\Delta t\right]$$

- saddle point approximation → geometric optics

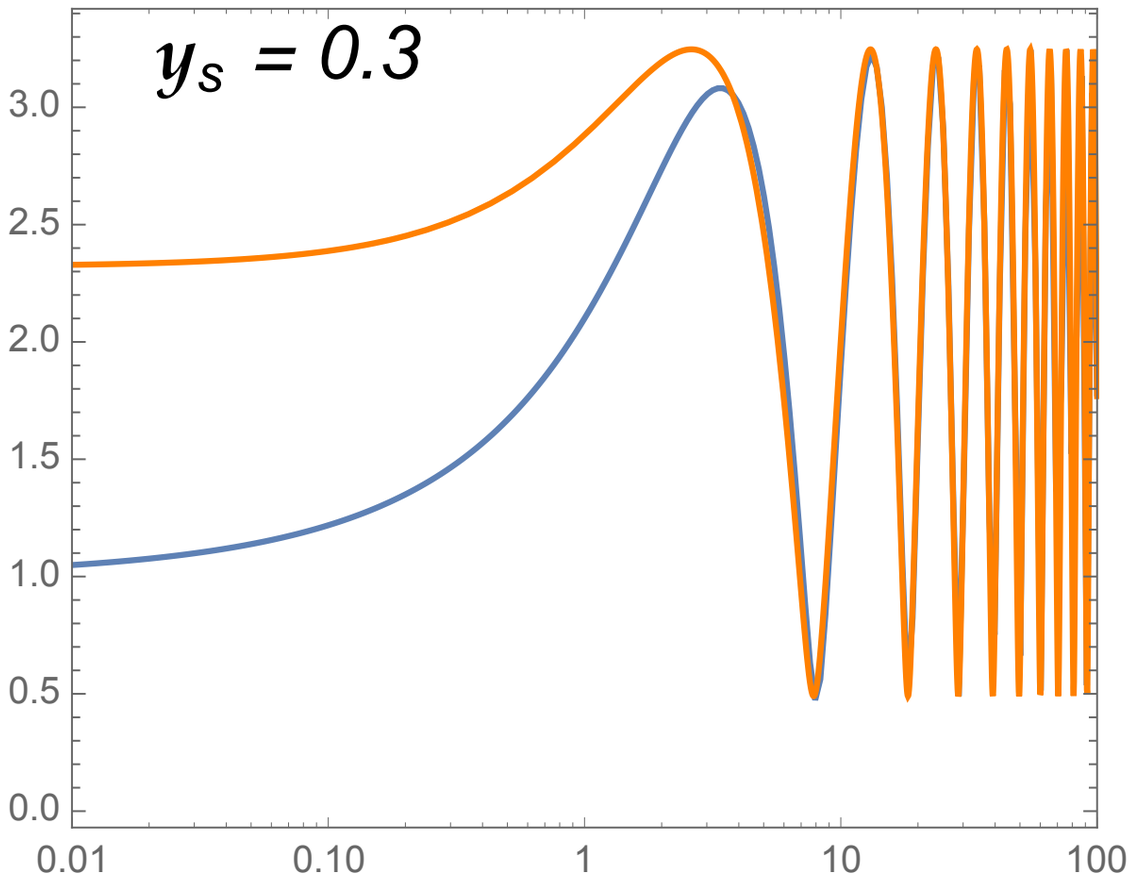
$$\theta = \beta - \alpha$$

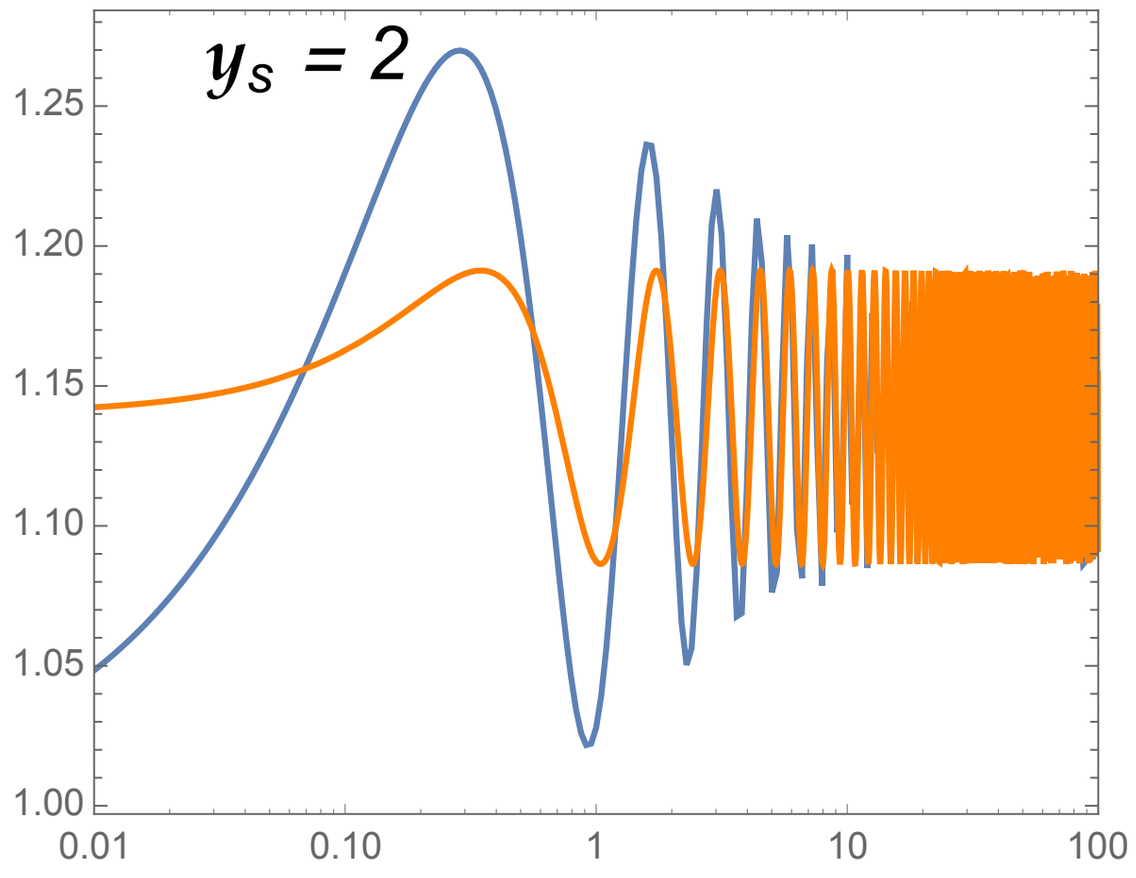
PBH


y= 0.1
|Amplitude|
5
2
1
0.5
0.2
0.01
0.10
1
10
100
Eng [Dimensionless]


y= 1
|Amplitude|
1.4
1.2
1.0
0.8
0.01
0.10
1
10
100
Eng [Dimensionless]

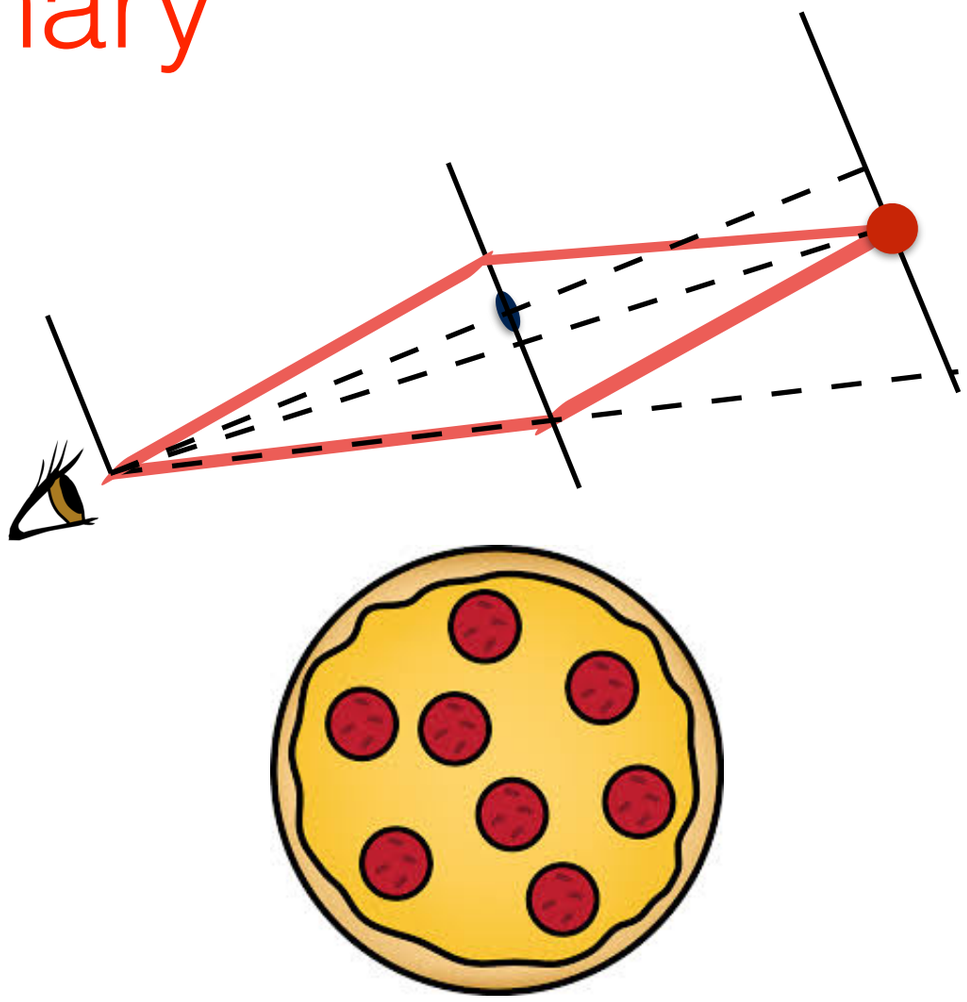
free-falling profile





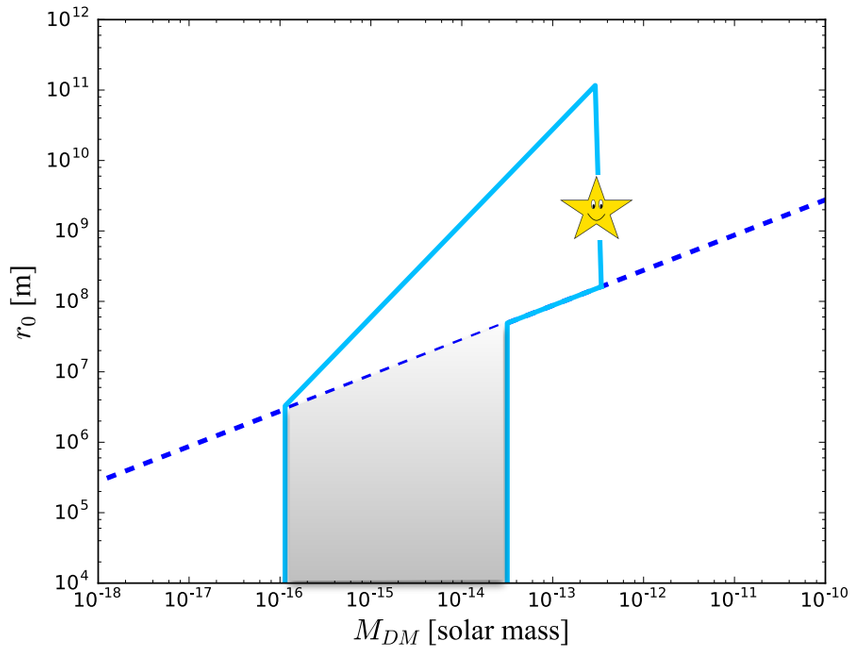
Summary

- femtolensing (unresolved) and PBH



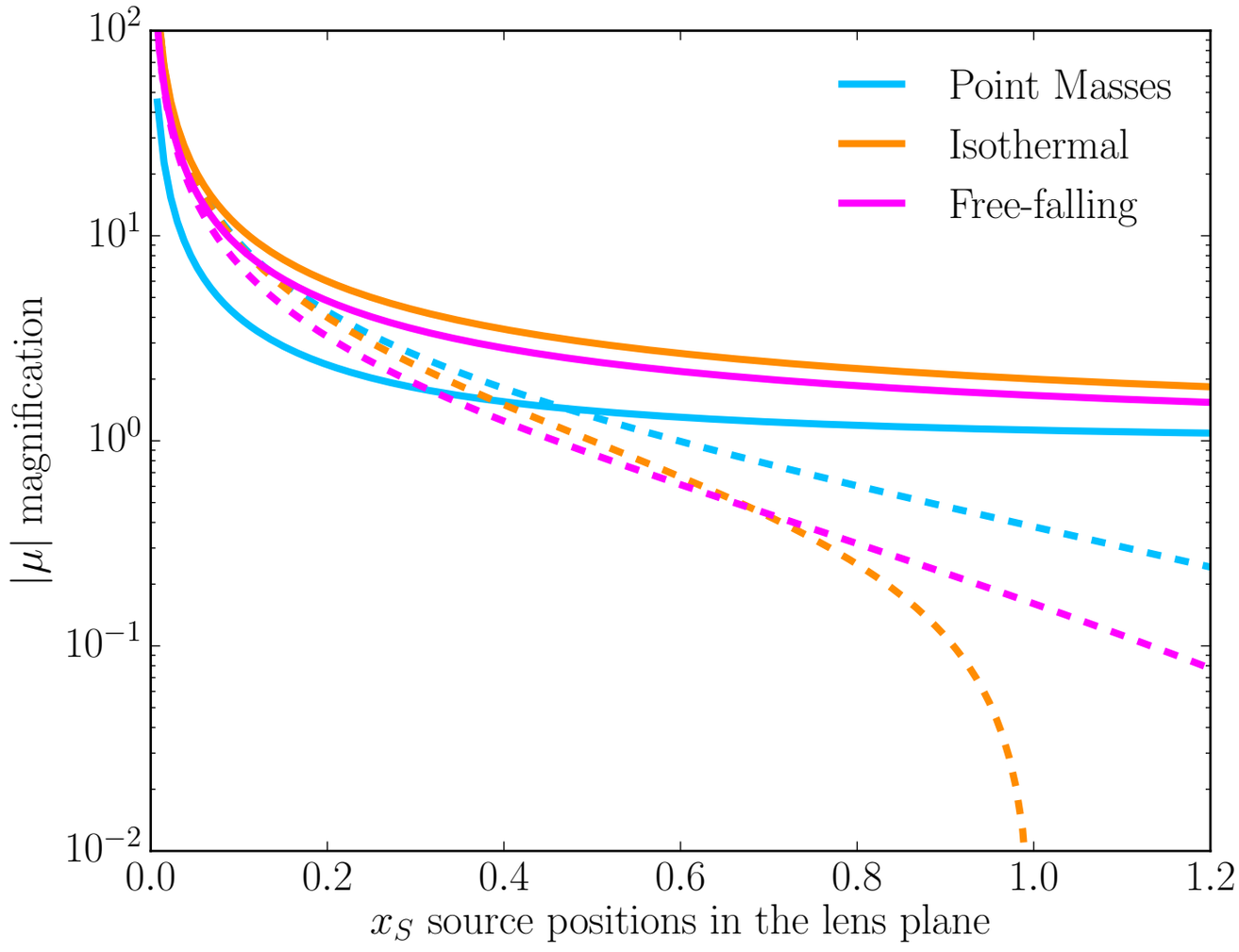
- axion minihalos

- Fermi GBM data GRB



Magnification

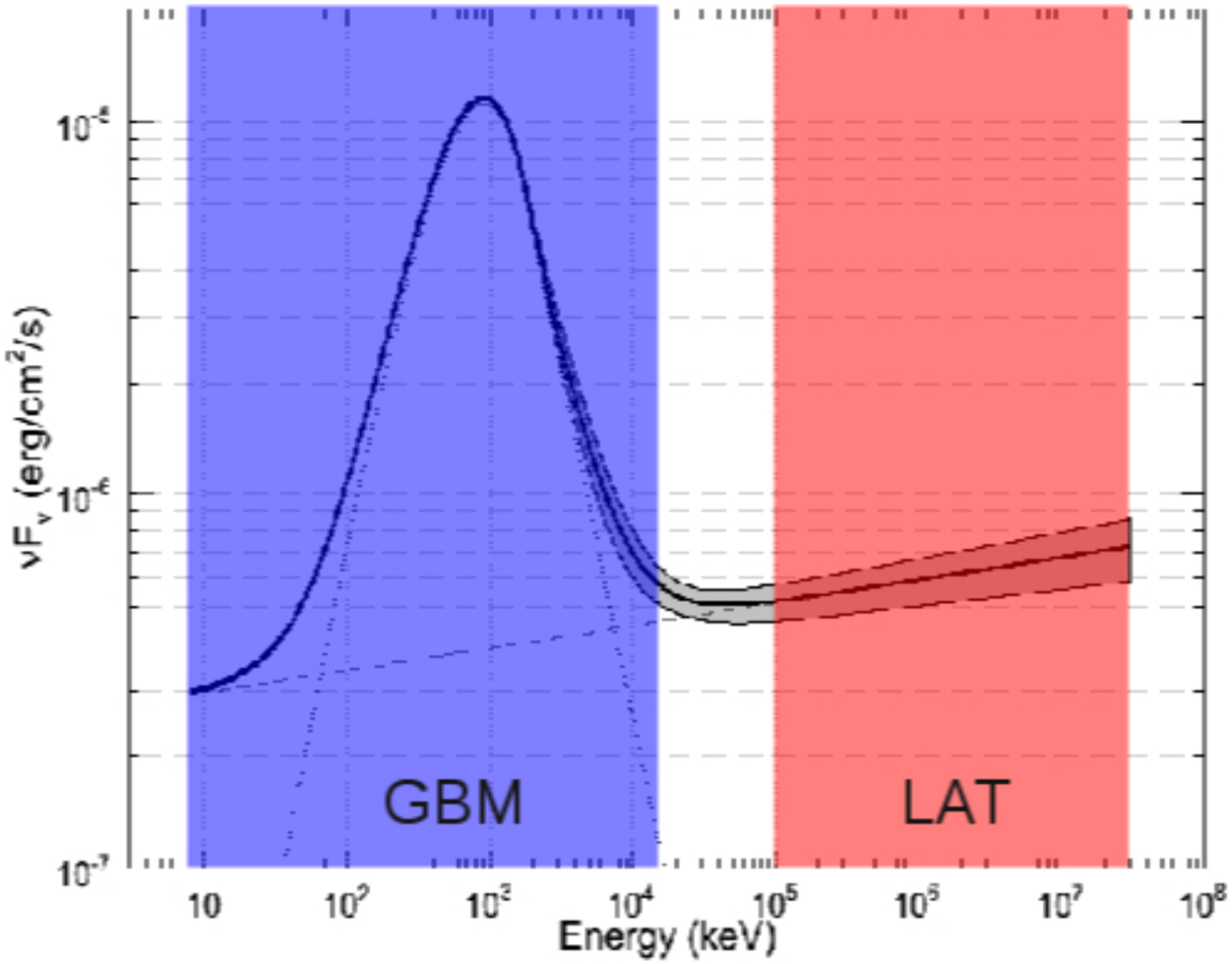
ξ_0 length scale in the lens plane



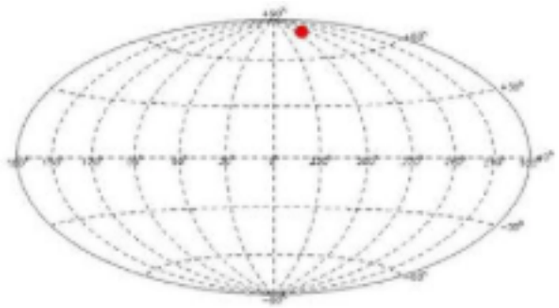
$$|A_1 + A_2|^2 \propto 1 + \mathcal{O}(1)\cos(\Delta\phi)$$ ***$\Delta\phi = E\,\delta t$***

The Gamma Ray Burst Monitor (GBM)

- 12 low-energy NaI crystal scintillators
- 2 high-energy BGS
- energy 8 keV - 40 MeV

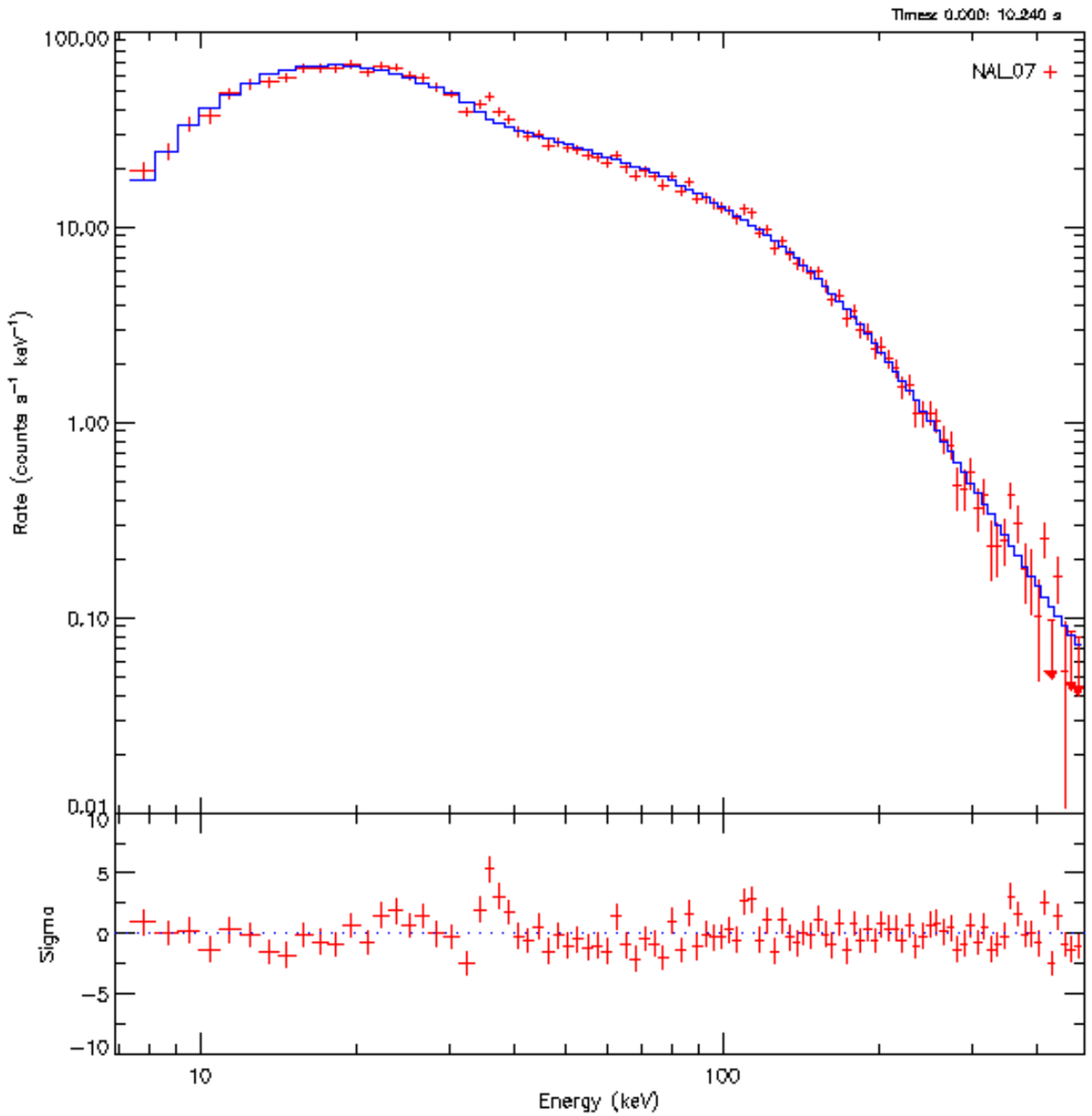


GRB090424



- fit

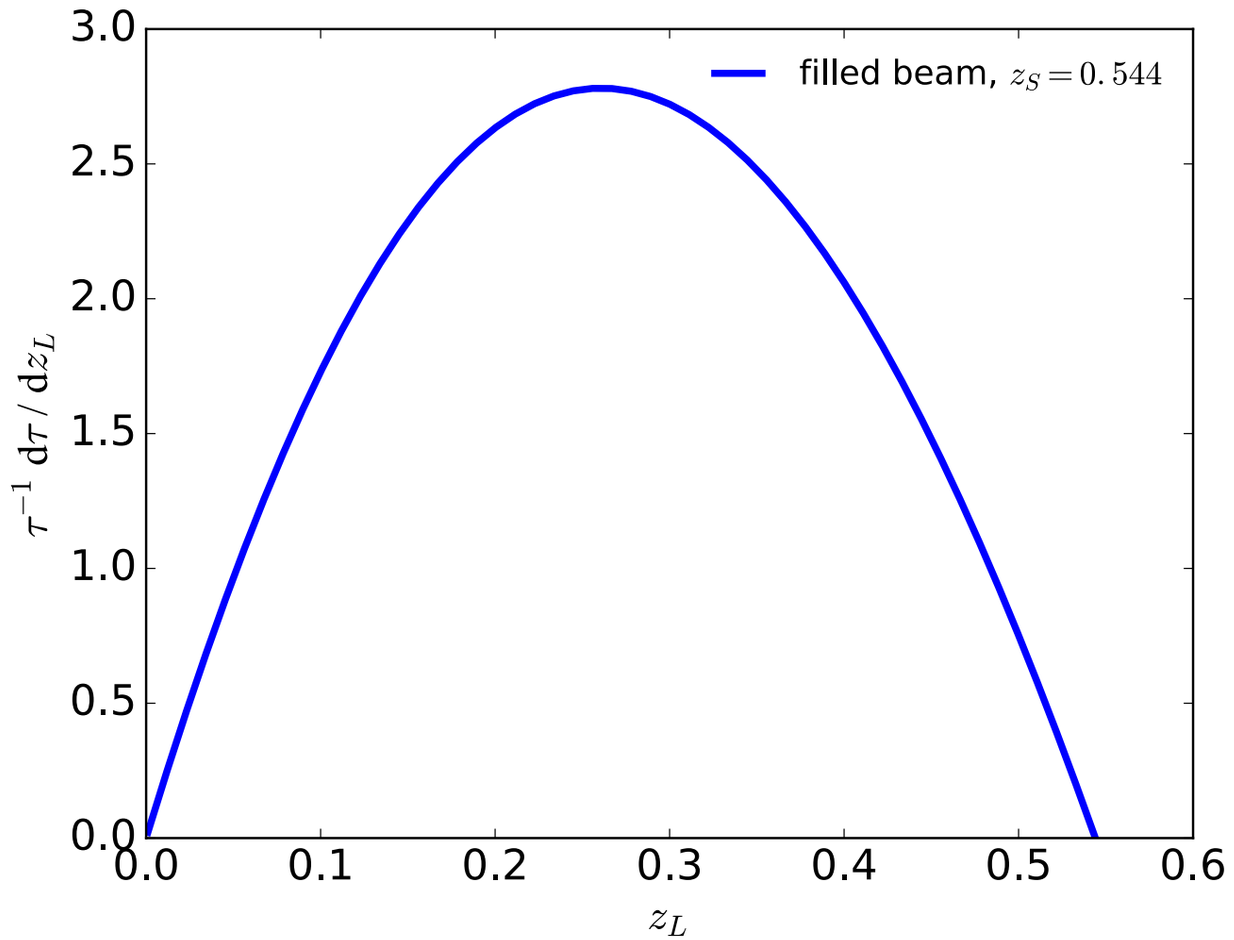
$$\sigma = \pi \left(r_{s,max}^2 - r_{s,min}^2 \right)$$



Optical Depth

$$\sigma = \pi \left(r_{s,max}^2 - r_{s,min}^2 \right)$$

$$d\tau = \frac{\rho_{halo}}{M_{halo}} (1 + z_L)^3 \sigma \frac{cdt}{dz_L} dz_L$$



PBH

$\delta t \sim keV^{-1}$ —GRB→ $r_E \sim 100\ km$ ⟶ $M \sim 10^{-15}\ M_\odot$

free-falling

$\delta t \sim keV^{-1}$ —GRB→ $\xi_0 \sim 100\ km$ ⟶ $M > 10^{-15}\ M_\odot$

$\xi_0 \sim (r_E/r_0)^{3/5}\ r_E$