Microlensing with extended structures

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New Techniques for Dark Matter Discovery

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Based on
arXiv:2002.08962 [astro-ph.CO]
with David McKeen and Nirmal Raj

Dark matter substructure

Two things we may agree upon…

- (Unfortunately) all of our evidence for Dark Matter is gravitational
- Many dark matter models feature substructure

Primordial BHs	Boson stars	Subhaloes	Miniclusters	Mirror stars

What else can we learn from gravitational interactions?

→ Microlensing surveys constrain primordial black holes

→ What about extended structures?

In this talk: EROS-2 and OGLE-IV surveys

Microlensing

*Micro*lensing: the lensed images are not individually resolved

Instead, there is a temporary magnification of the observed brightness

Source star in the Milky Way or Magellanic clouds

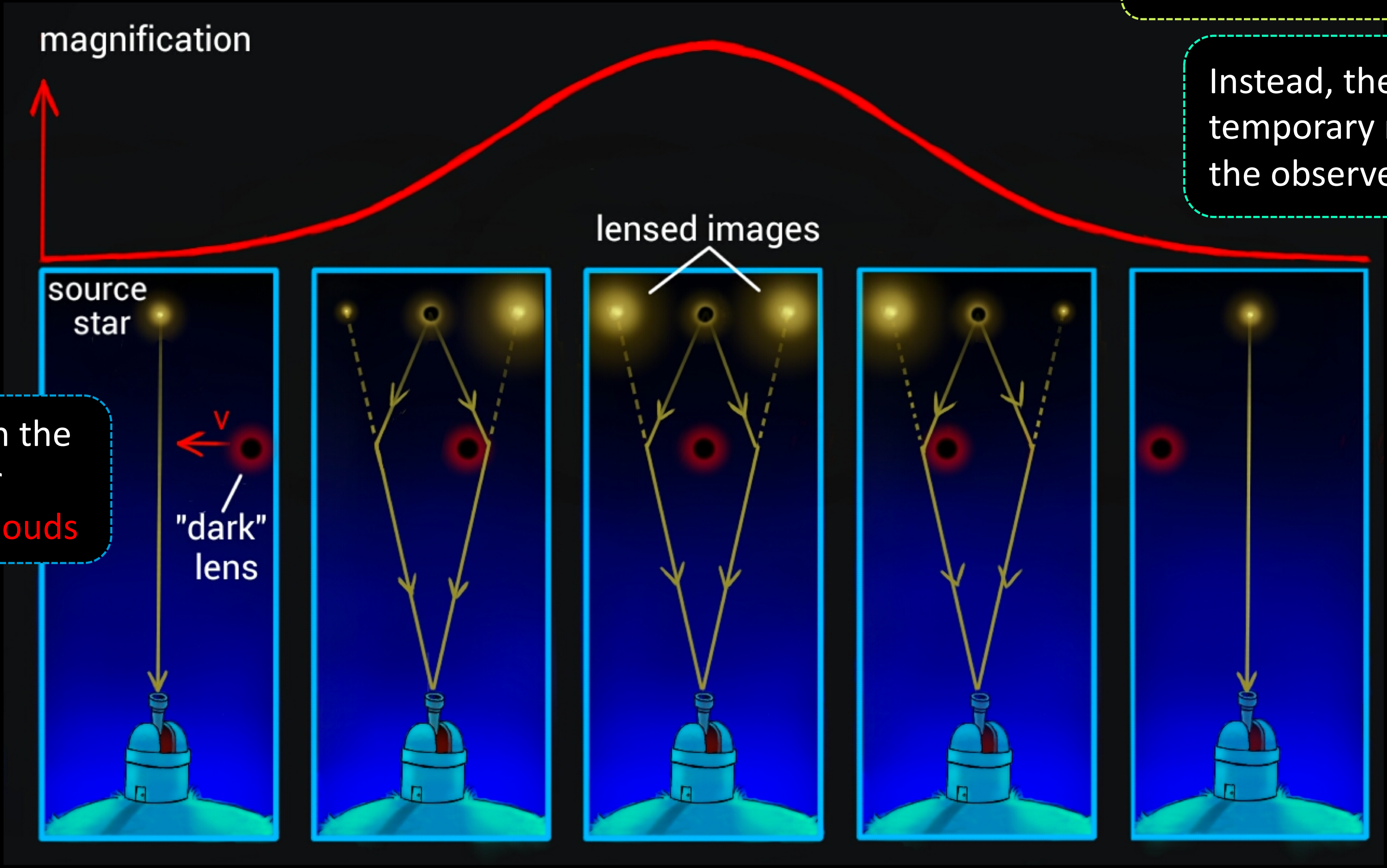
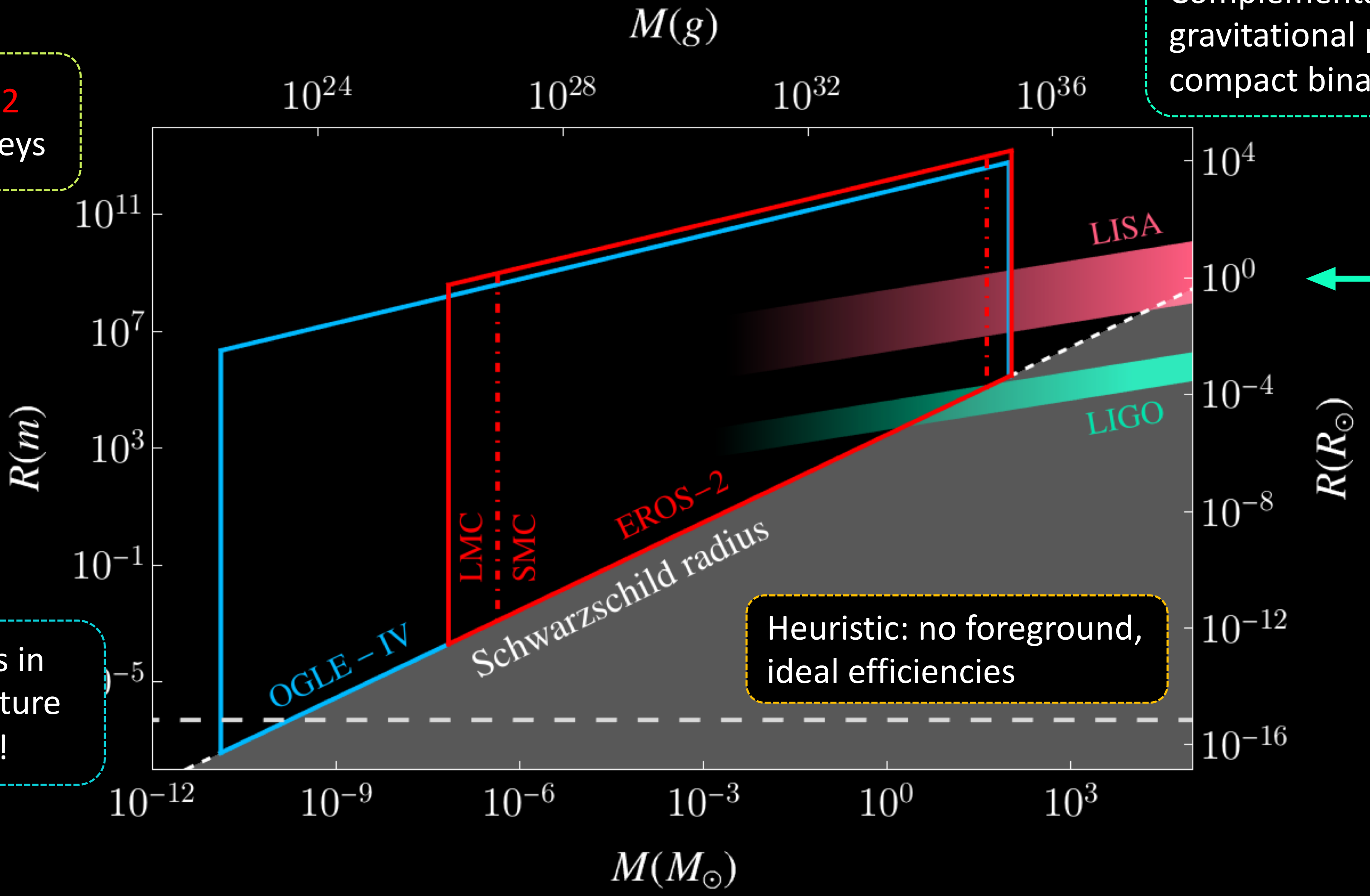


Image credit: Adam Rogers, theamateurrealist.wordpress.com

Sneak peak: substructure sensitivity

In this talk: EROS-2 and OGLE-IV surveys

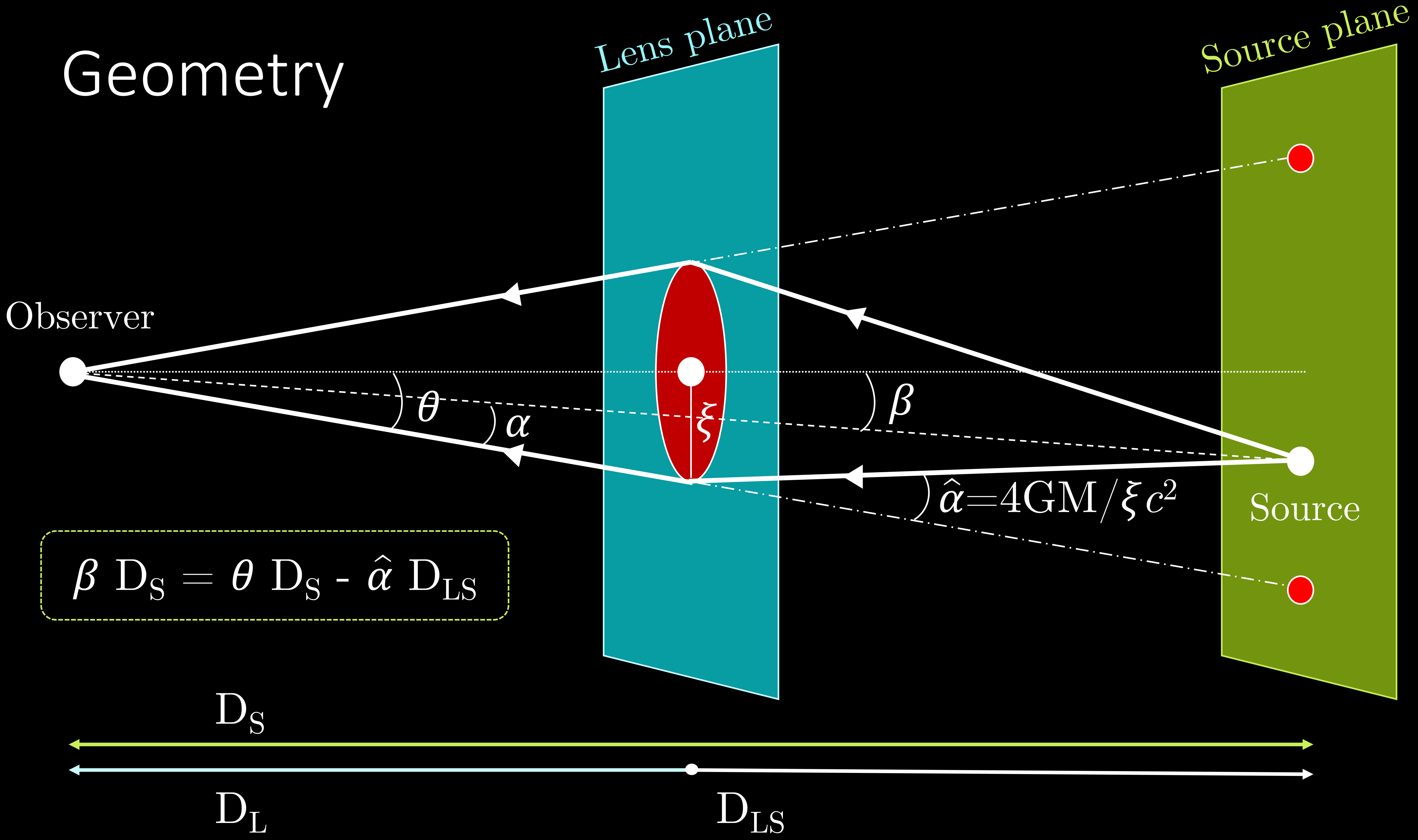
Complementary to other gravitational probes, like compact binary inspirals



Many decades in both substructure mass and size!

Heuristic: no foreground, ideal efficiencies

Geometry



Lens plane
Source plane
Observer
θ
α
ξ
β
$\hat{\alpha} = 4GM/\xi c^2$
Source
$\beta \, D_S = \theta \, D_S - \hat{\alpha} \, D_{LS}$
D_S
D_L
D_{LS}

The lensing equation (point-like lenses)

- The source position β and image position θ are related by

$$\beta = \theta - \alpha$$
$$= \theta - \frac{4GM(\theta)}{\theta c^2}\frac{D_{\rm LS}}{D_{\rm S}}$$

$\beta = 0$
$M(\theta) = M$

Source behind
a point-like lens

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{\rm LS}}{D_{\rm L}D_{\rm S}}}$$

"Einstein angle" for a point-like lens

- θ_E can be used to define a lensing tube with radius $r_E = \theta_E D_L$

Magnification: $\mu = \frac{\theta}{\beta}\frac{d\theta}{d\beta} = \sum_i \mu_i = \frac{u^2+2}{u\sqrt{u^2+4}}$

$$\xrightarrow{u=1} 1.34\ .$$

Images

$u \equiv \beta/\theta_{\rm E}$ Impact parameter

Microlensing event is counted if $\mu > 1.34$

The lensing equation (extended lenses)

- For extended lenses, μ can not always be found analytically
- Define the threshold impact parameter $u_{1.34}$:

$$\mu_{\mathrm{tot}}(u \leq u_{1.34}) \geq 1.34$$

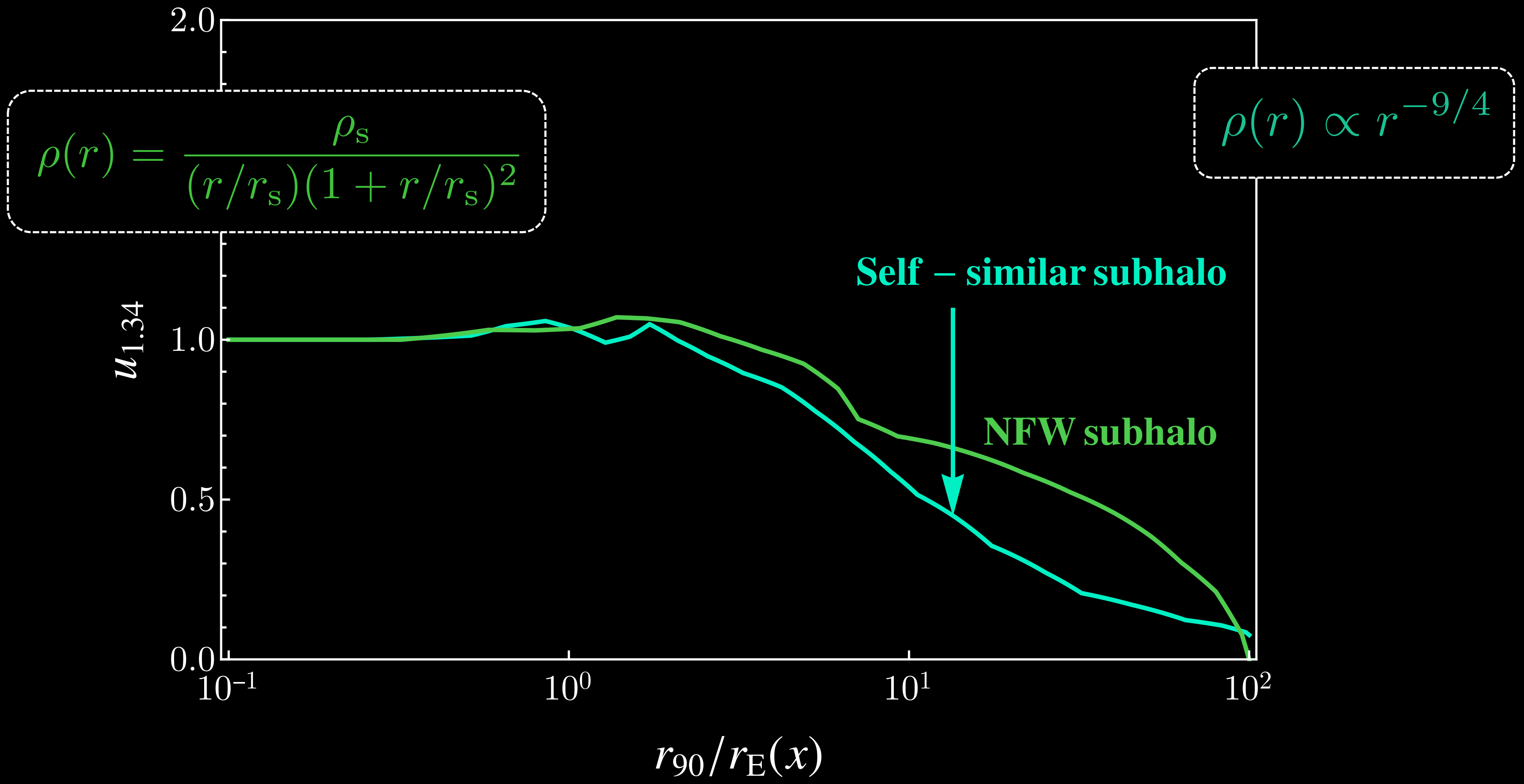
All smaller impact parameters produce a magnification above μ > 1.34

- As we will see, the threshold impact parameter $u_{1.34}$ depends on different properties of the lens
  - Mass profile $M(\theta)/M$
  - Characteristic size r_{90}
  - Distances in the problem

Reasonable hypothesis: dilute lenses give $u_{1.34} < 1$

Threshold impact parameter

For some lenses, as expected, the larger the lens, the smaller $u_{1.34}$

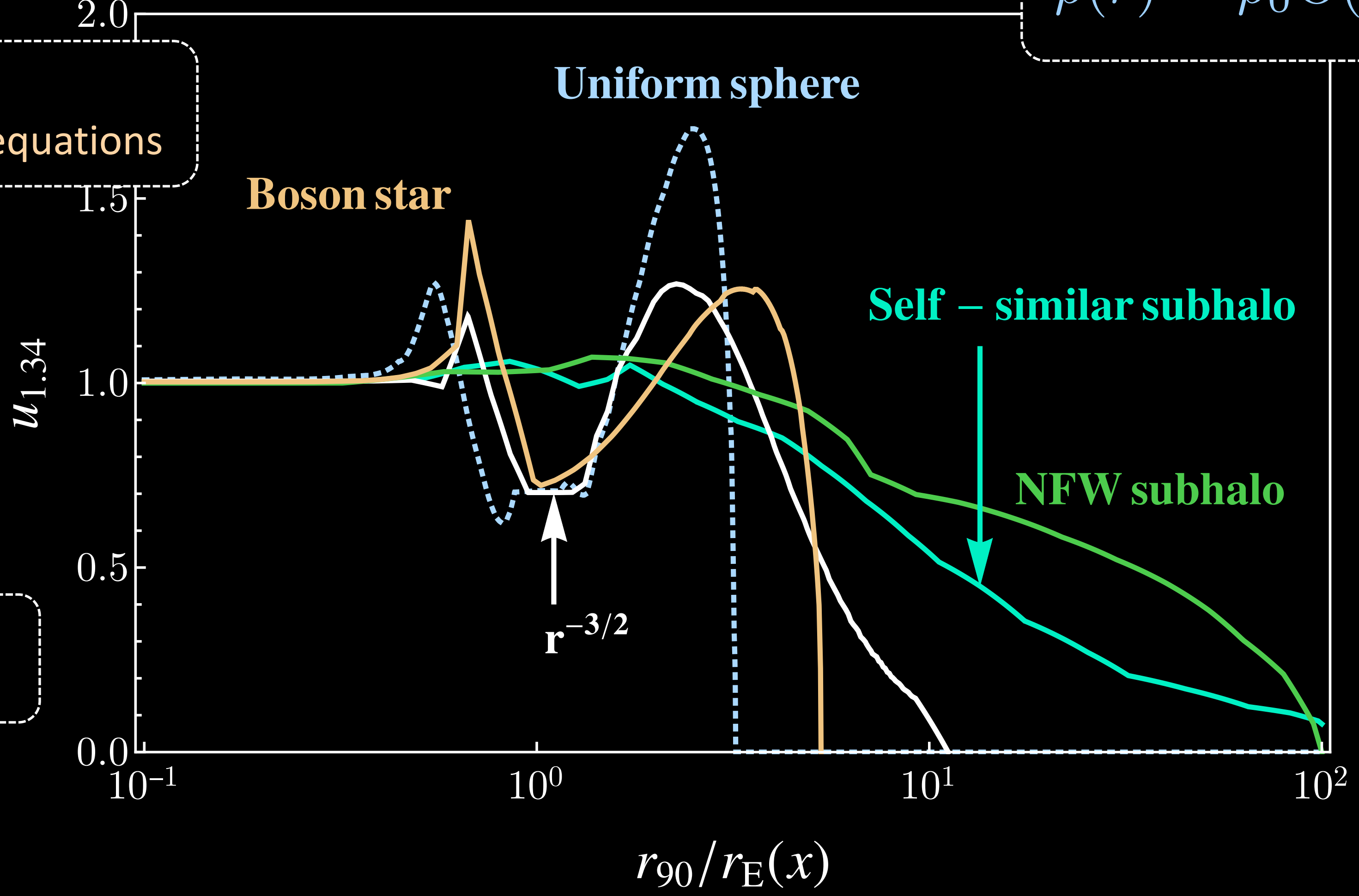


Threshold impact parameter

But for others, something else happens...

Numerically solve the Schrodinger-Poisson equations

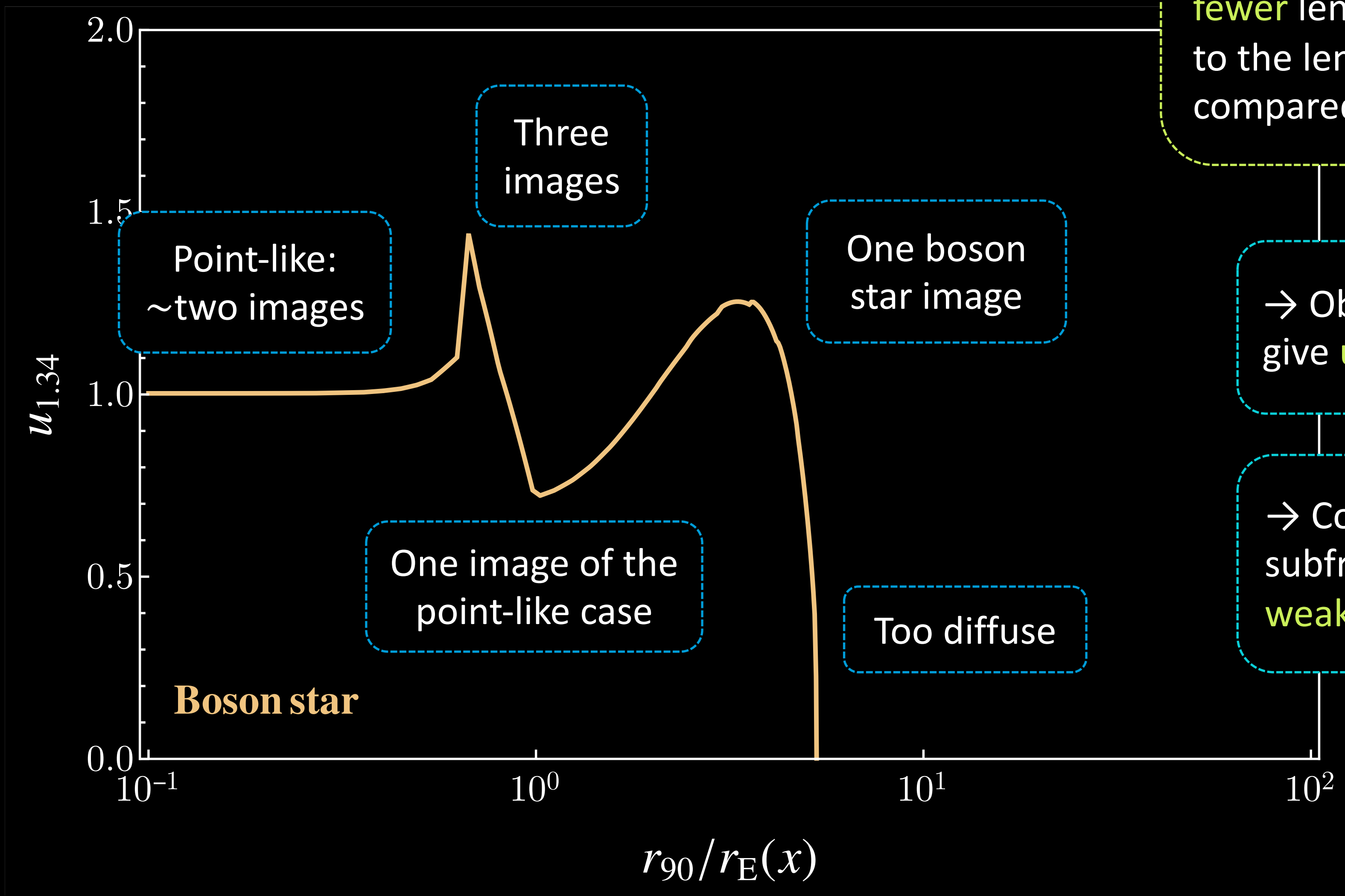
$$\rho(r) = \rho_0 \Theta(r_m - r)$$



$$\rho(r) \propto r^{-3/2}$$

Caustics

What's going on in this plot?



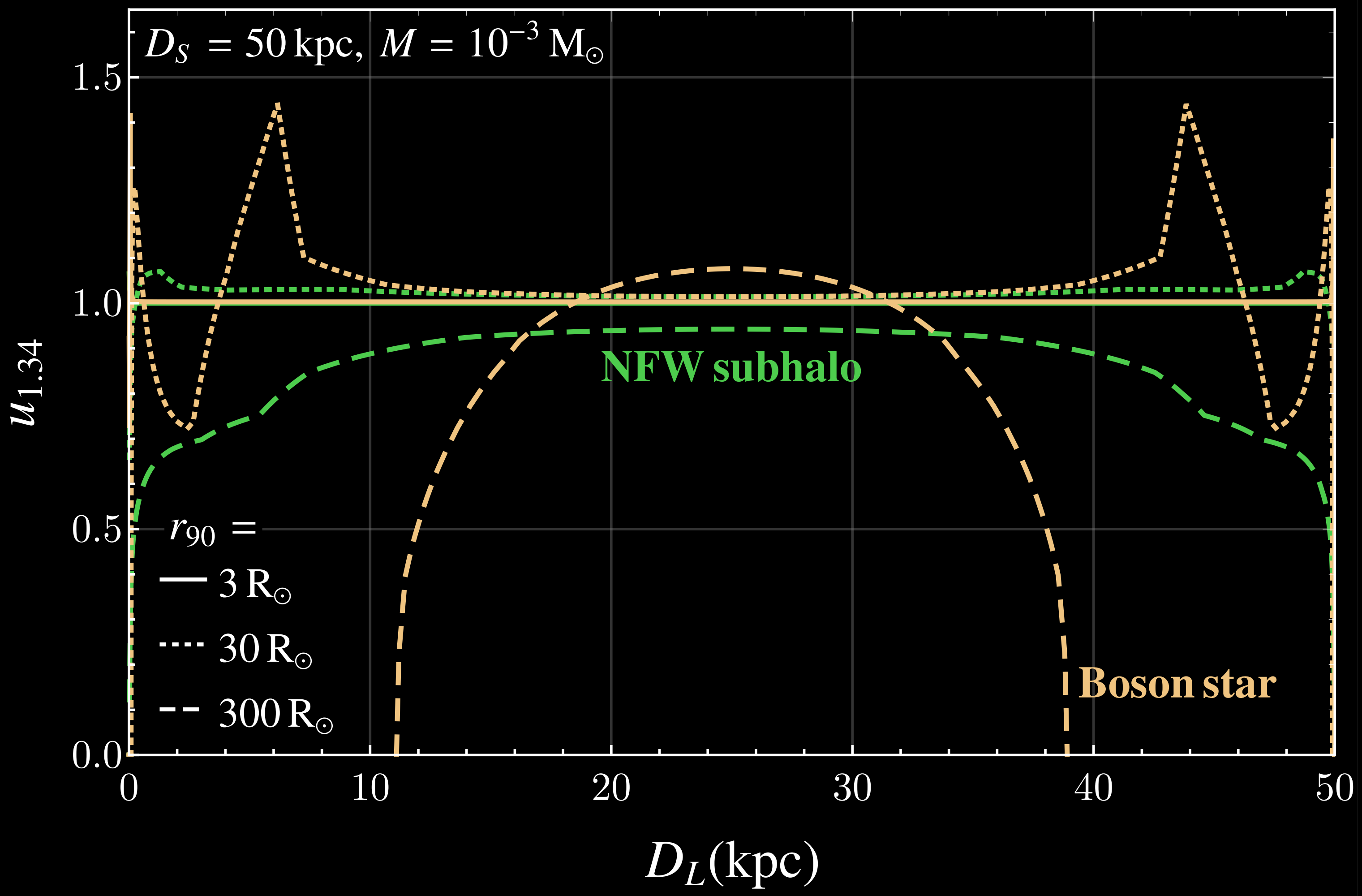
Sufficiently flat density profiles can give more or fewer lens images (solutions to the lens equation) compared to a point-like lens

→ Objects such as boson stars may give unique microlensing signals

→ Constraints on the dark matter subfraction may be stronger or weaker than for point-like lenses

Caustics

Consequence: the Einstein tube is not a tube; not ellipsoidal



→ Depending on the source, experiments may be more or less sensitive to extended objects compared to point sources in different locations

Constraining extended objects

The differential event rate contains all the essential physics

$$\frac{d^2\Gamma}{dx\,dt_{\mathrm{E}}} = \varepsilon(t_{\mathrm{E}})\frac{2D_{\mathrm{S}}}{v_0^2 M} f_{\mathrm{DM}}\,\rho_{\mathrm{DM}}(x)\,v_{\mathrm{E}}^4(x)\,e^{-v_{\mathrm{E}}^2(x)/v_0^2}$$

Efficiency of the experiment: $\varepsilon(t_{\mathrm{E}})$

v_0: $220\ \mathrm{km/s}$

Fraction of Ω_{DM}: f_{DM}

Halo profile: isothermal (ρ_{DM})

$$v_{\mathrm{E}}(x) \equiv 2u_{1.34}(x)r_{\mathrm{E}}(x)/t_{\mathrm{E}}$$

Constraining extended objects

The total number of expected events depends on the experiment

$$N_{\mathrm{events}} = N_\star T_{\mathrm{obs}} \int_0^1 dx \int_{t_{\mathrm{E,min}}}^{t_{\mathrm{E,max}}} dt_{\mathrm{E}} \frac{d^2\Gamma}{dx\, dt_{\mathrm{E}}}$$

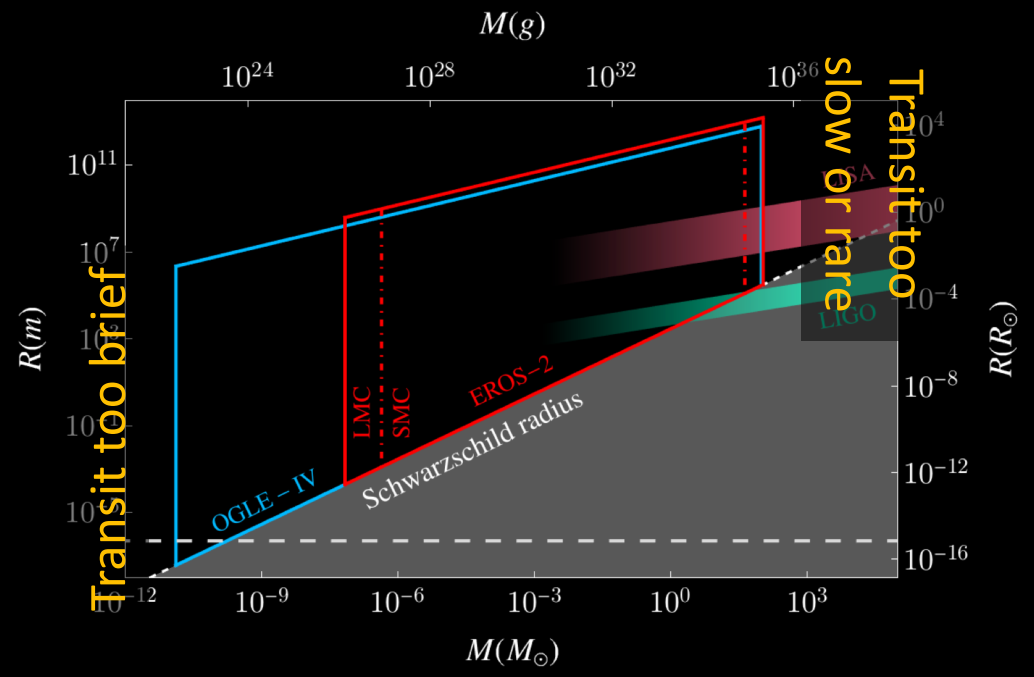
Maximum and minimum transit time

Number of observed stars

EROS-2 LMC: 5.49×10^6
OGLE-IV: 4.88×10^7

Observation time

EROS-2 LMC: 2500 days
OGLE-IV: 1826 days



Obtaining constraints

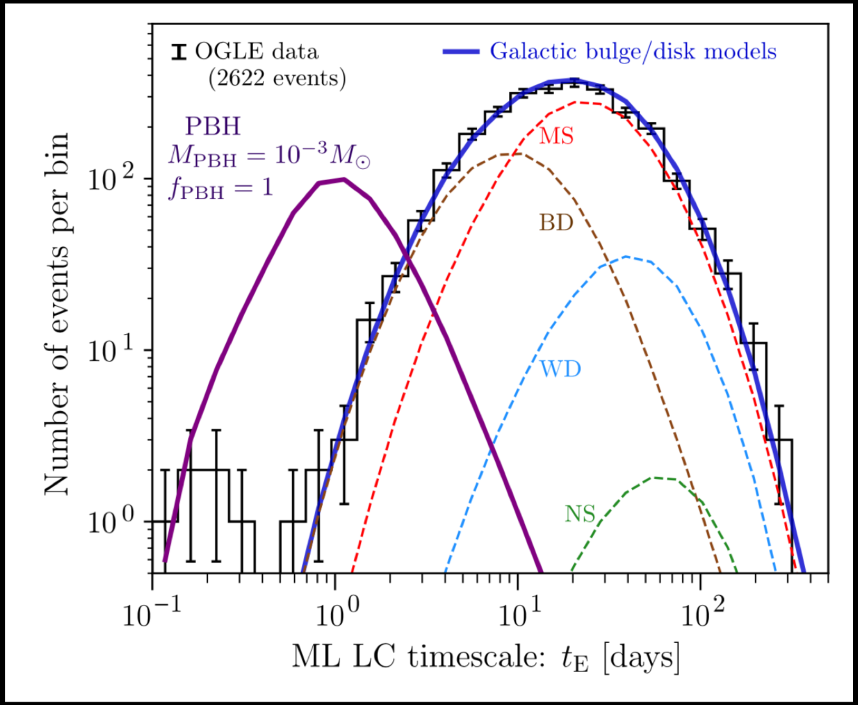
To obtain limits, we have to account for the observed events

- EROS-2: 3.9 events at 90% CL
- OGLE-IV: $\mathrm{O}(1000)$ astrophysical events, $\kappa = 4.61$ at 90% CL

Bin events in $\mathrm{t_E}$

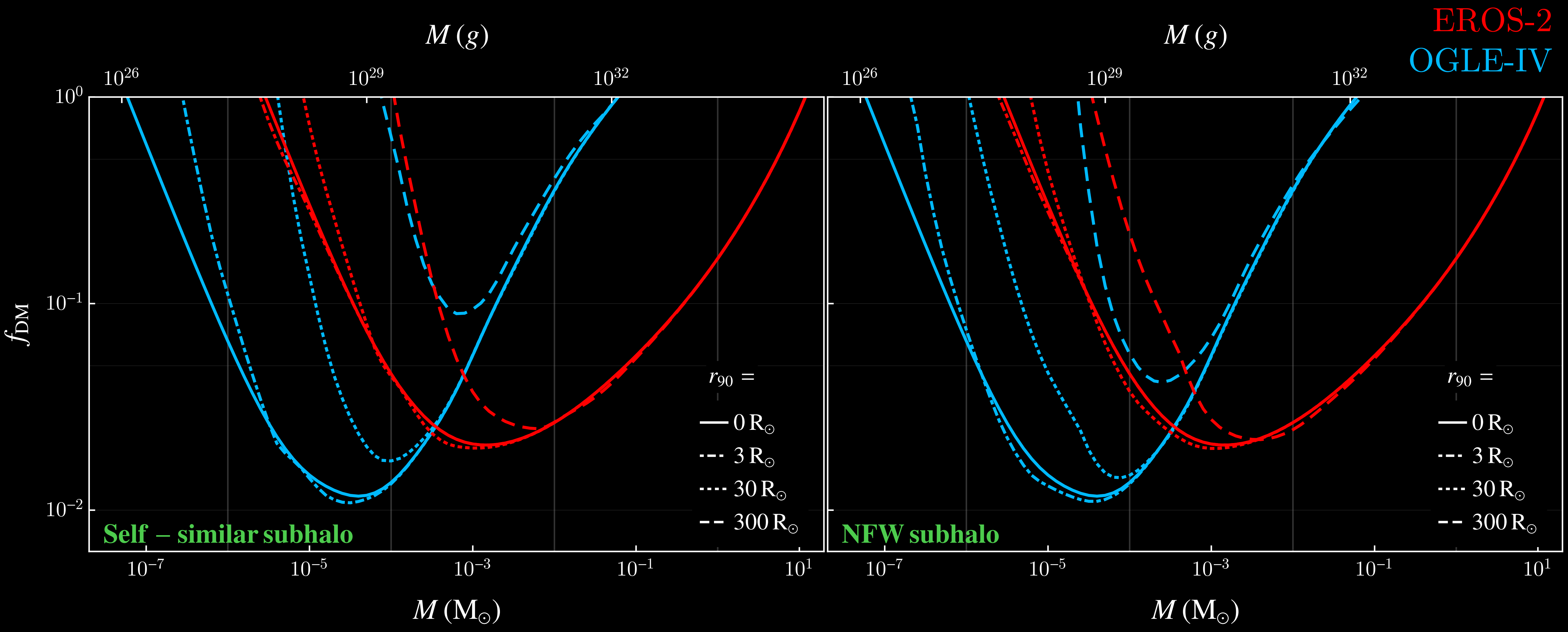
$$\kappa = 2\sum_{i=1}^{N_{\rm bins}}\left[N_i^{\rm FG} - N_i^{\rm SIG} + N_i^{\rm SIG}\ln\frac{N_i^{\rm SIG}}{N_i^{\rm FG}}\right]$$

$$N_i^{\rm SIG} \equiv N_i^{\rm FG} + N_i^{\rm DM}$$



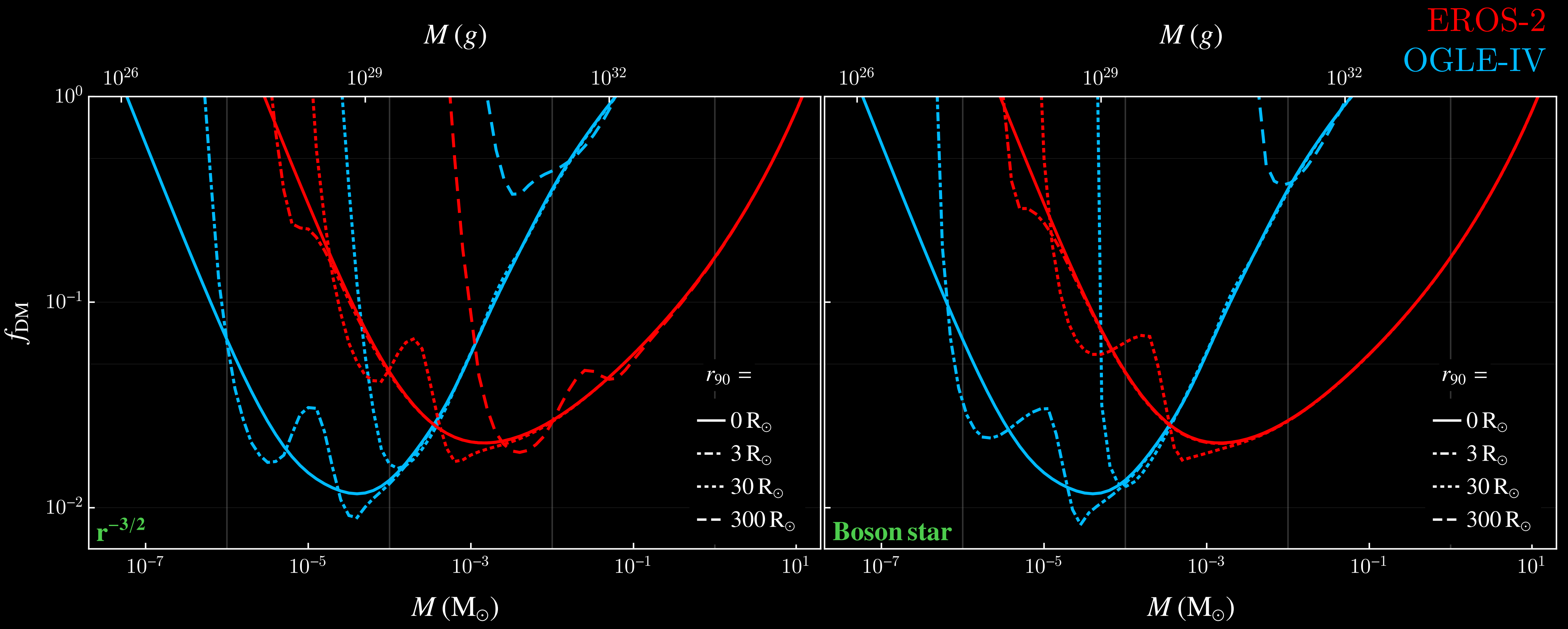
Constraints on DM fraction

Generally, constraints on extended objects are weaker…



Constraints on DM fraction

But for sufficiently flat density profiles, caustics change the constraints



To conclude,

- Many dark matter models feature substructure such as miniclusters, microhaloes, and Bose Einstein condensates
- All of our current evidence for Dark Matter is gravitational

- Microlensing provides a way to look for dark matter substructure of a large range of sizes and masses

  →Extended objects may give unique microlensing signatures

- We *will* learn more about dark matter through gravity!

Thank you!

…ask me anything you like!

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