

# Dark archaeology: cosmology through gravitational probes of dark objects

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University of Oslo, January 2026

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# Our best evidence for BSM physics

## *What on Earth is dark matter?*

- Plenty of evidence for DM!
- Likely not explained by modifications of gravity



<https://youtu.be/IEKcPfJHfNU> (see also [djunacroon.com](http://djunacroon.com))

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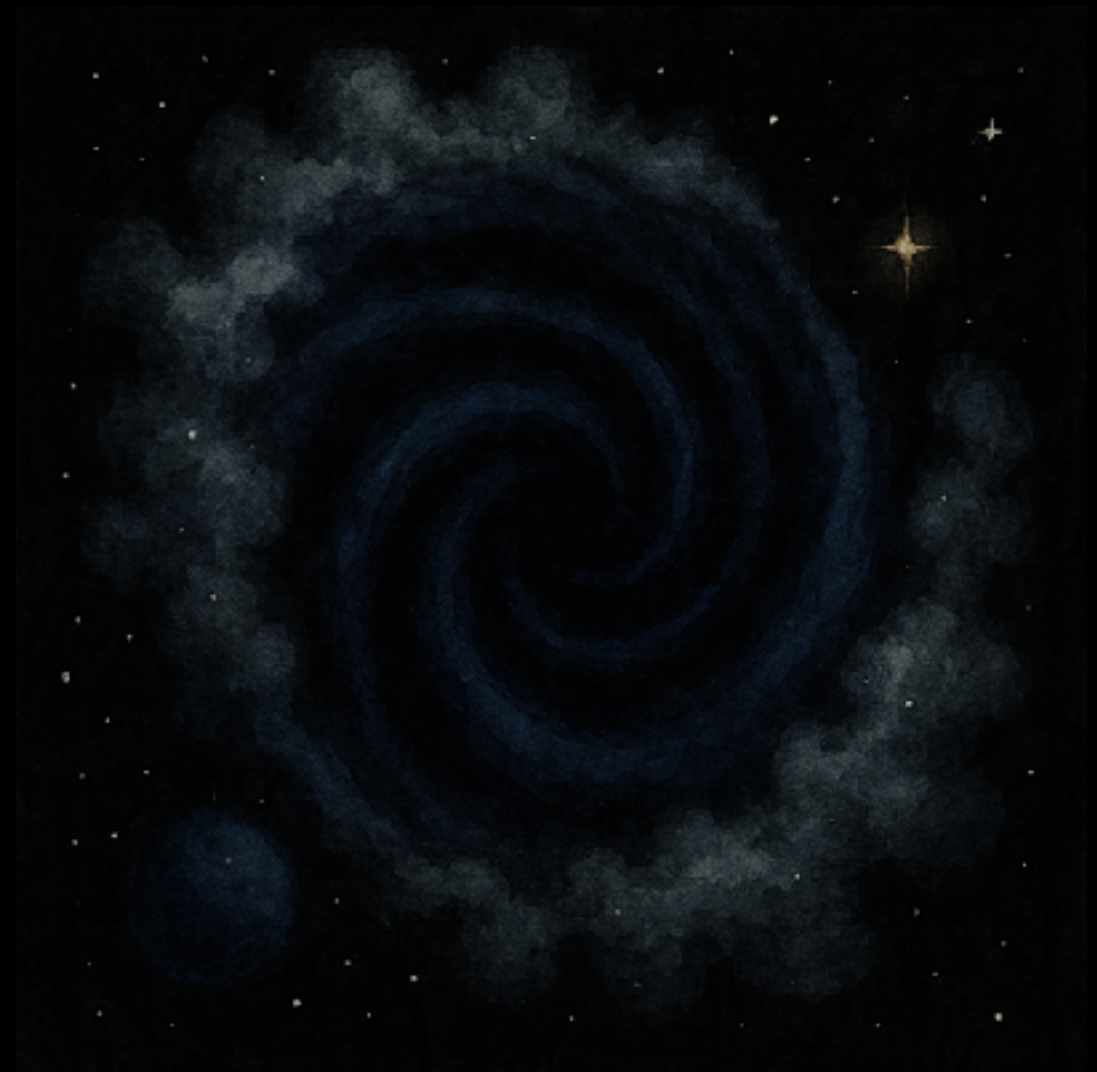
*No idea, or too many ideas, about its nature:*



# Probing dark matter substructure

*Imagine...*

- Dark matter only interacts gravitationally 🥲



# Probing dark matter substructure

*Imagine...*

- Dark matter only interacts gravitationally 🥹
- It features sub-structure! 🎉

PBHs

Boson stars

Subhalos

Miniclusters

Mirror stars



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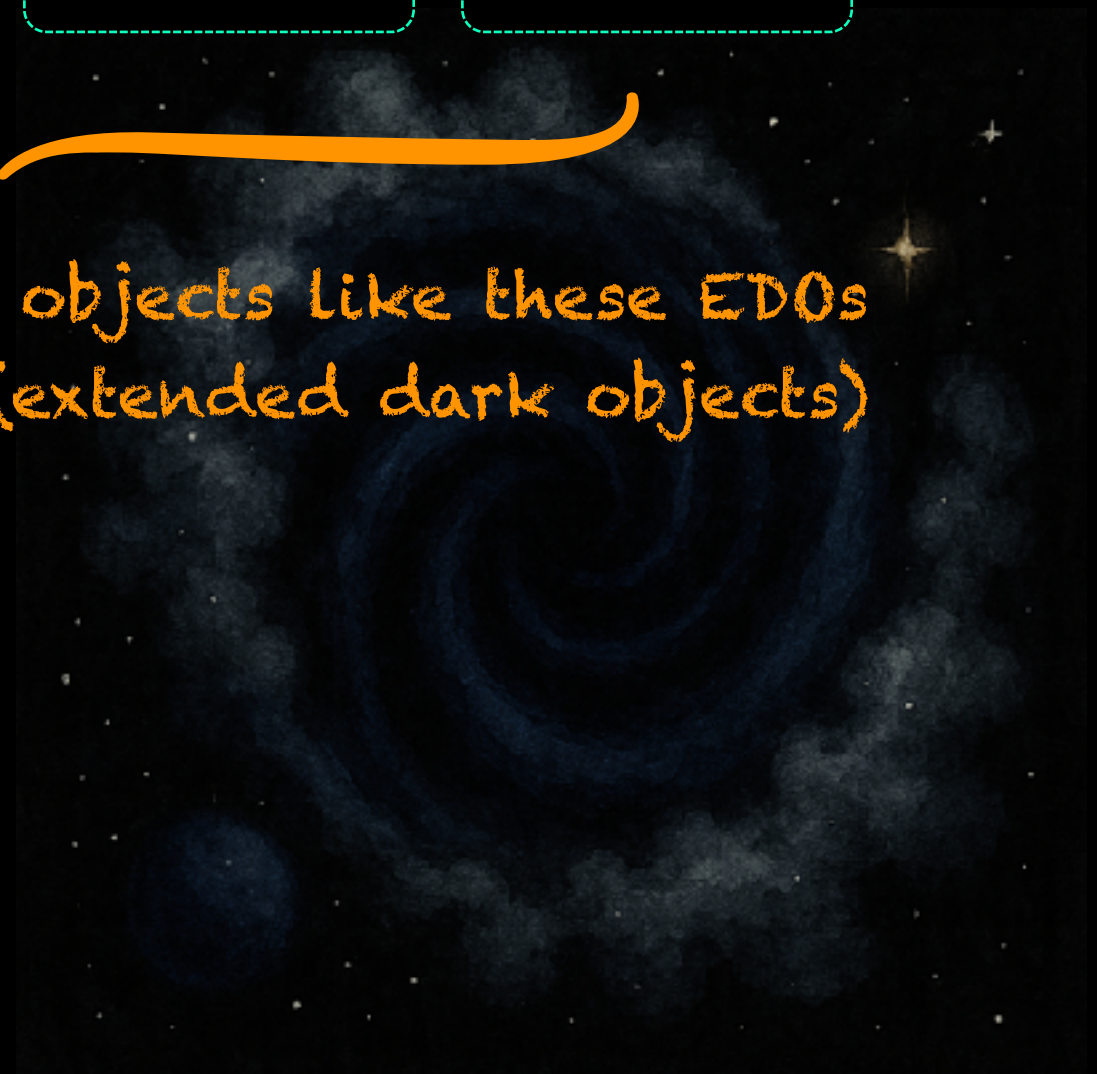
*How do we look for it?*

- Gravitational lensing!

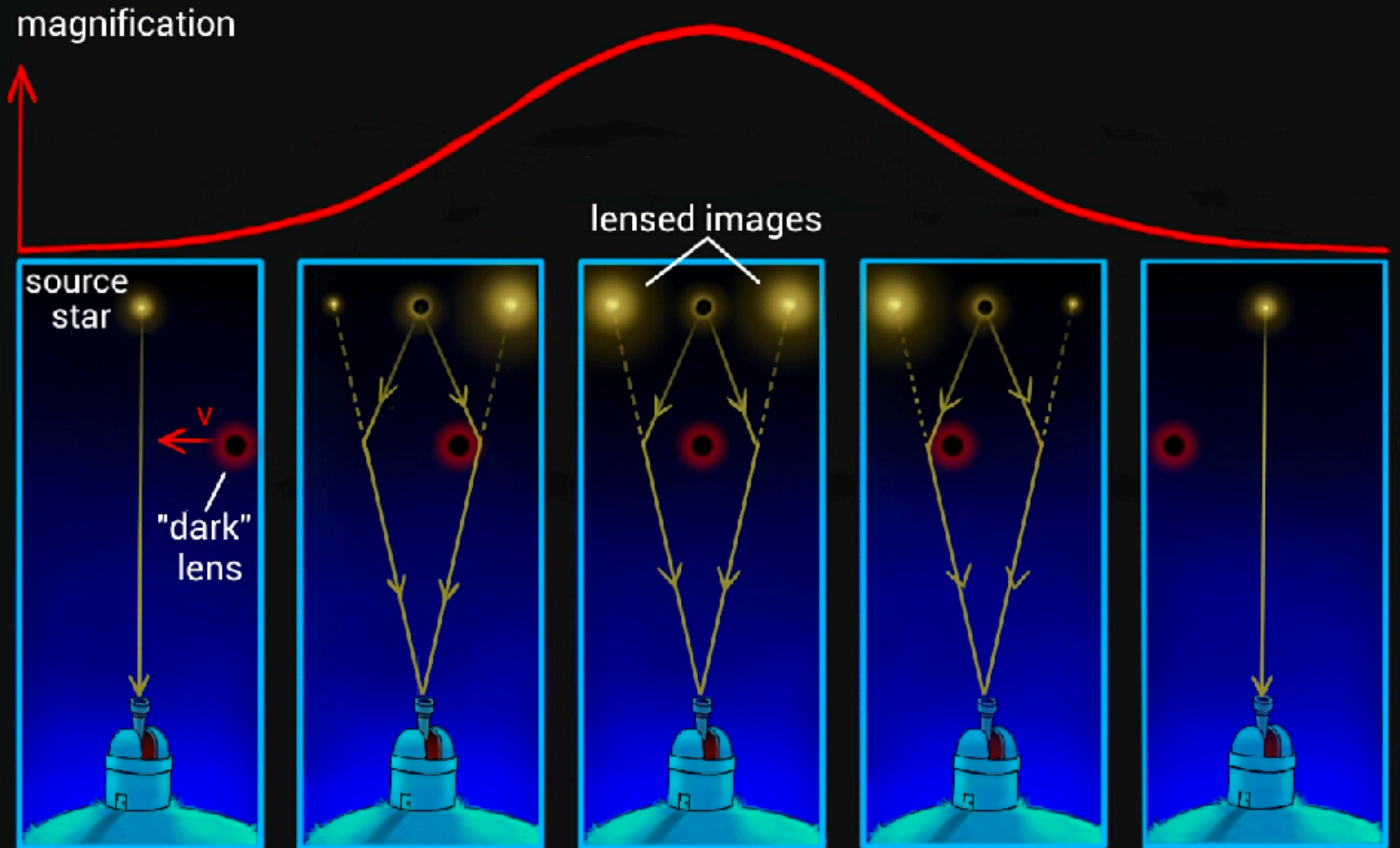
*What can we learn from it?*

- Hints about the nature of DM
- The curvature power spectrum

I call objects like these EDOs  
(extended dark objects)

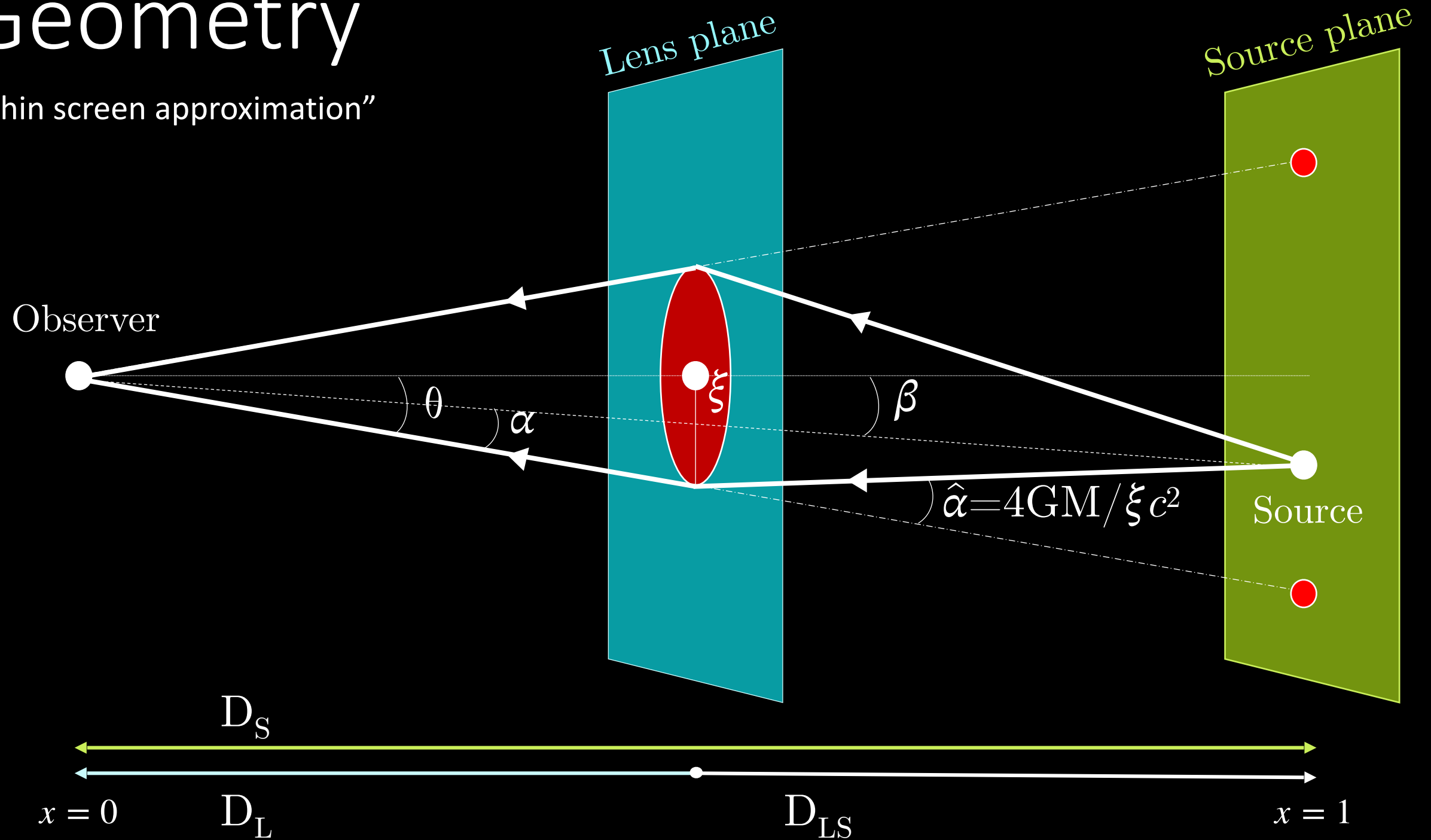


# Dark matter substructure



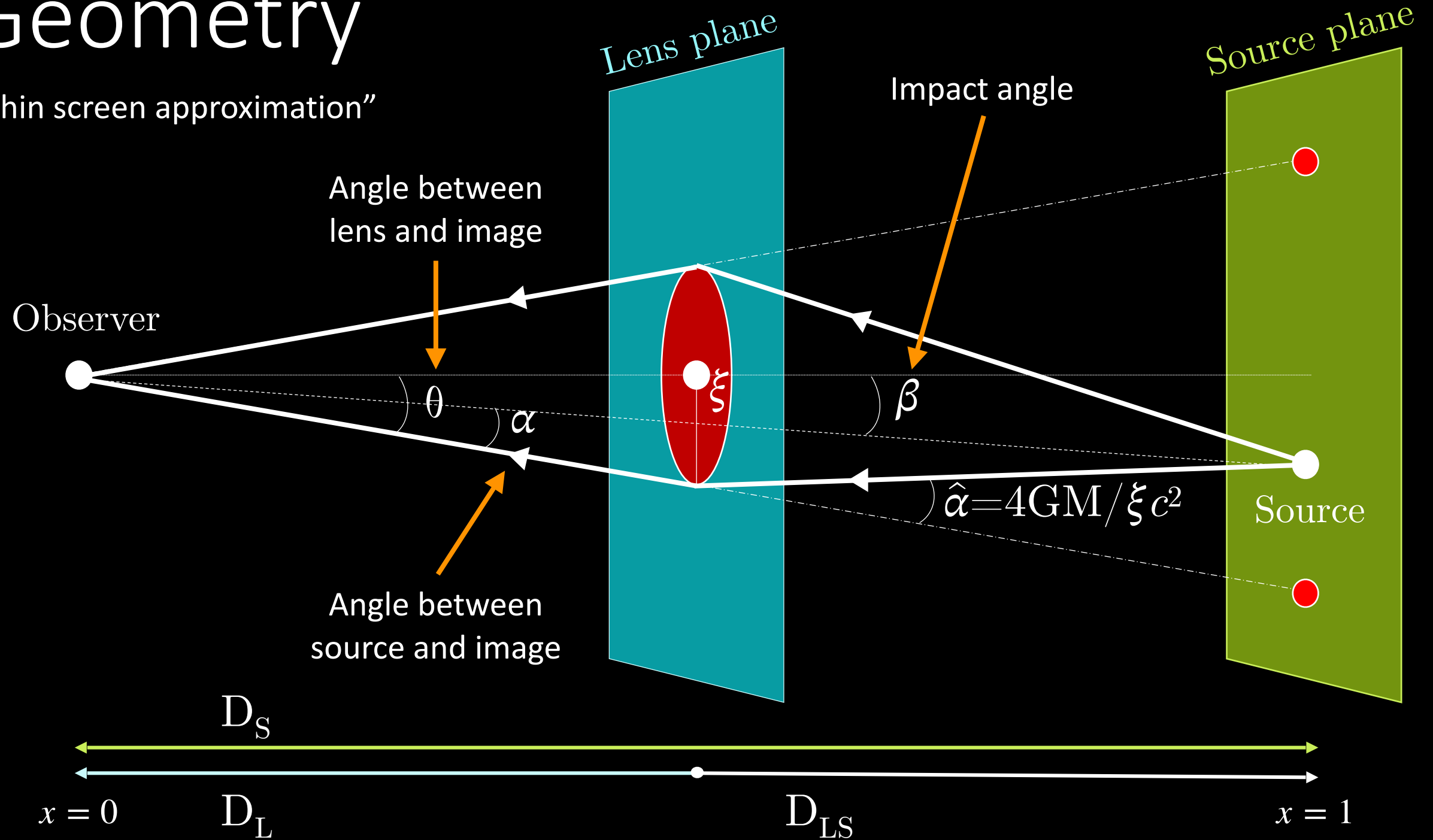
# Geometry

“Thin screen approximation”



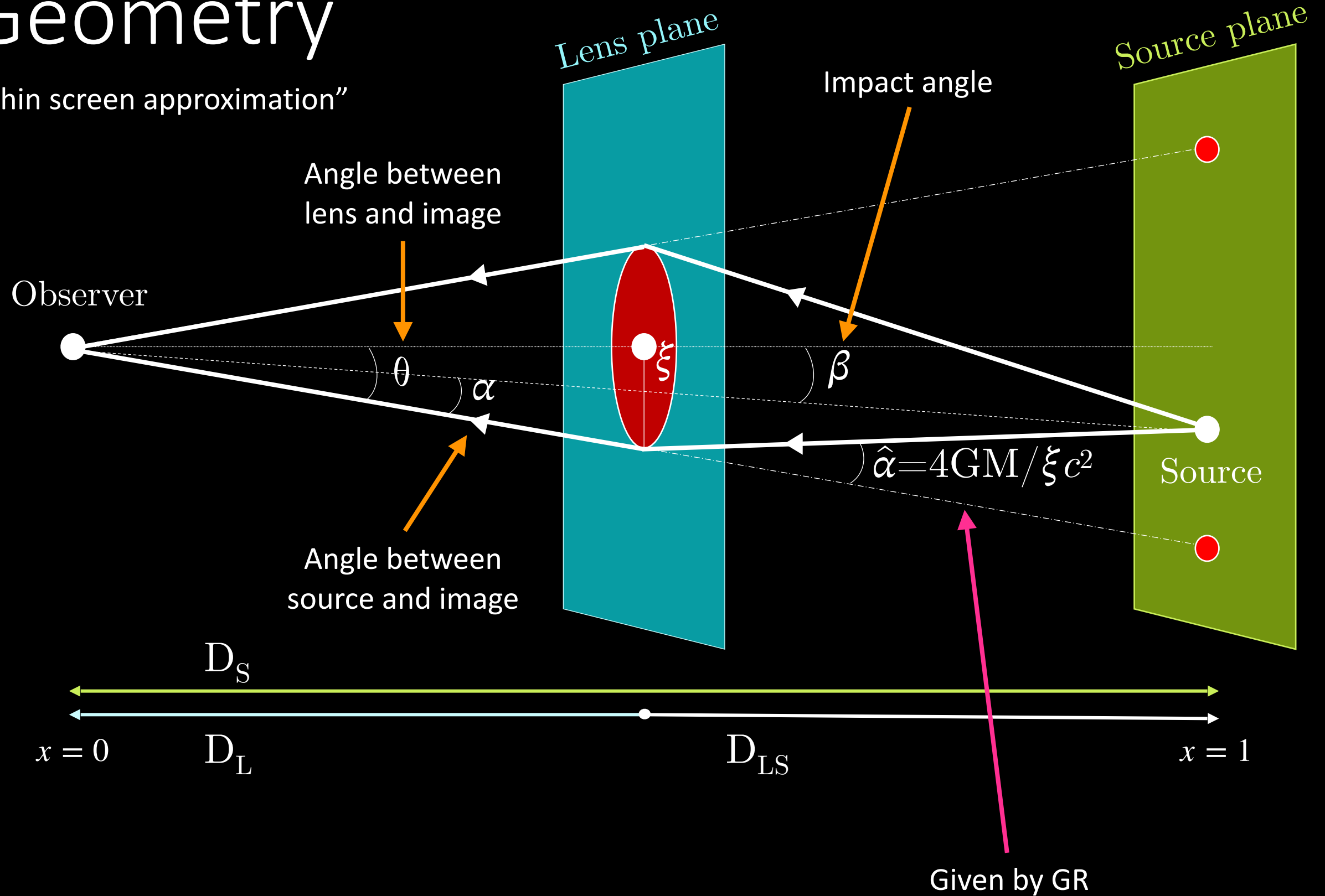
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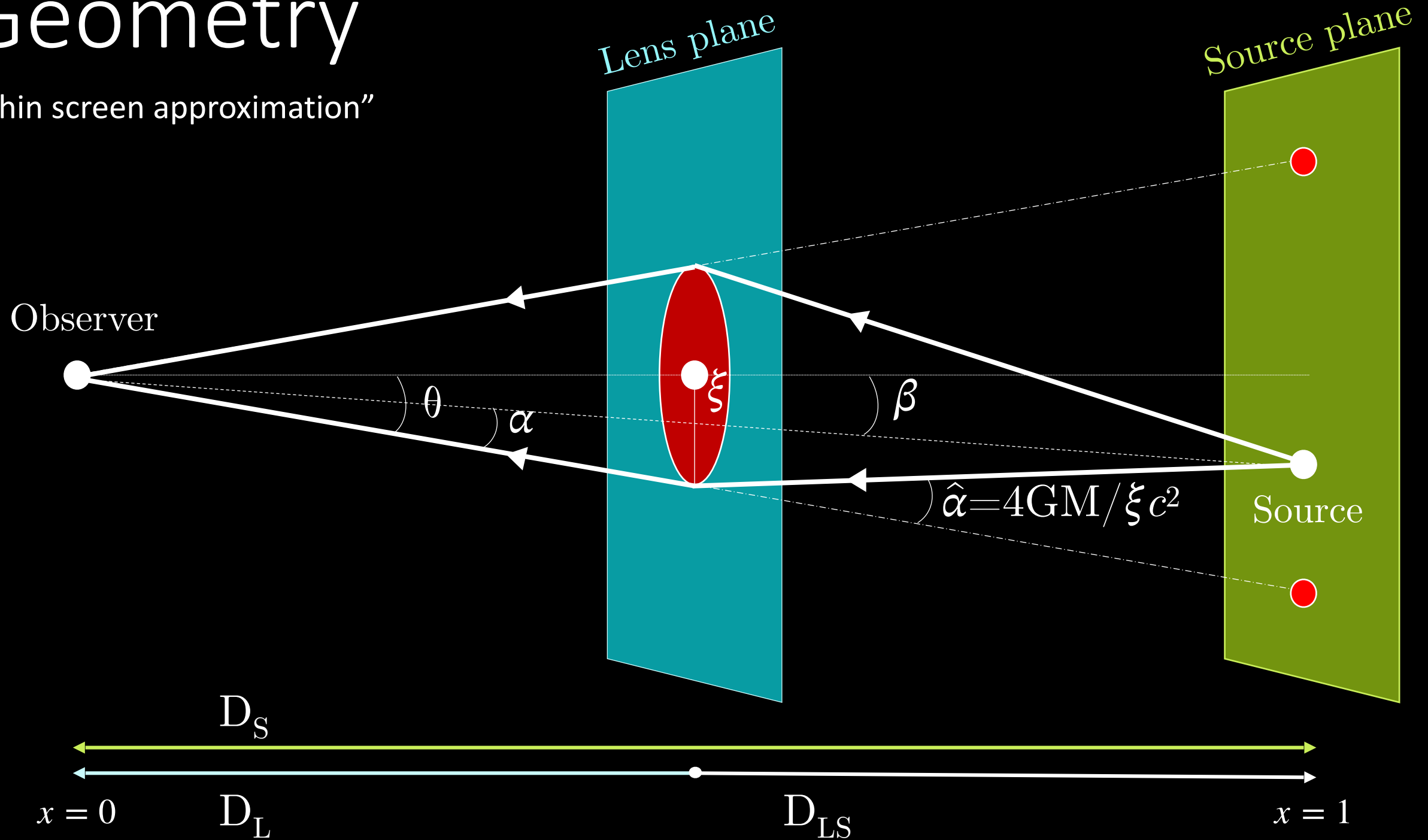
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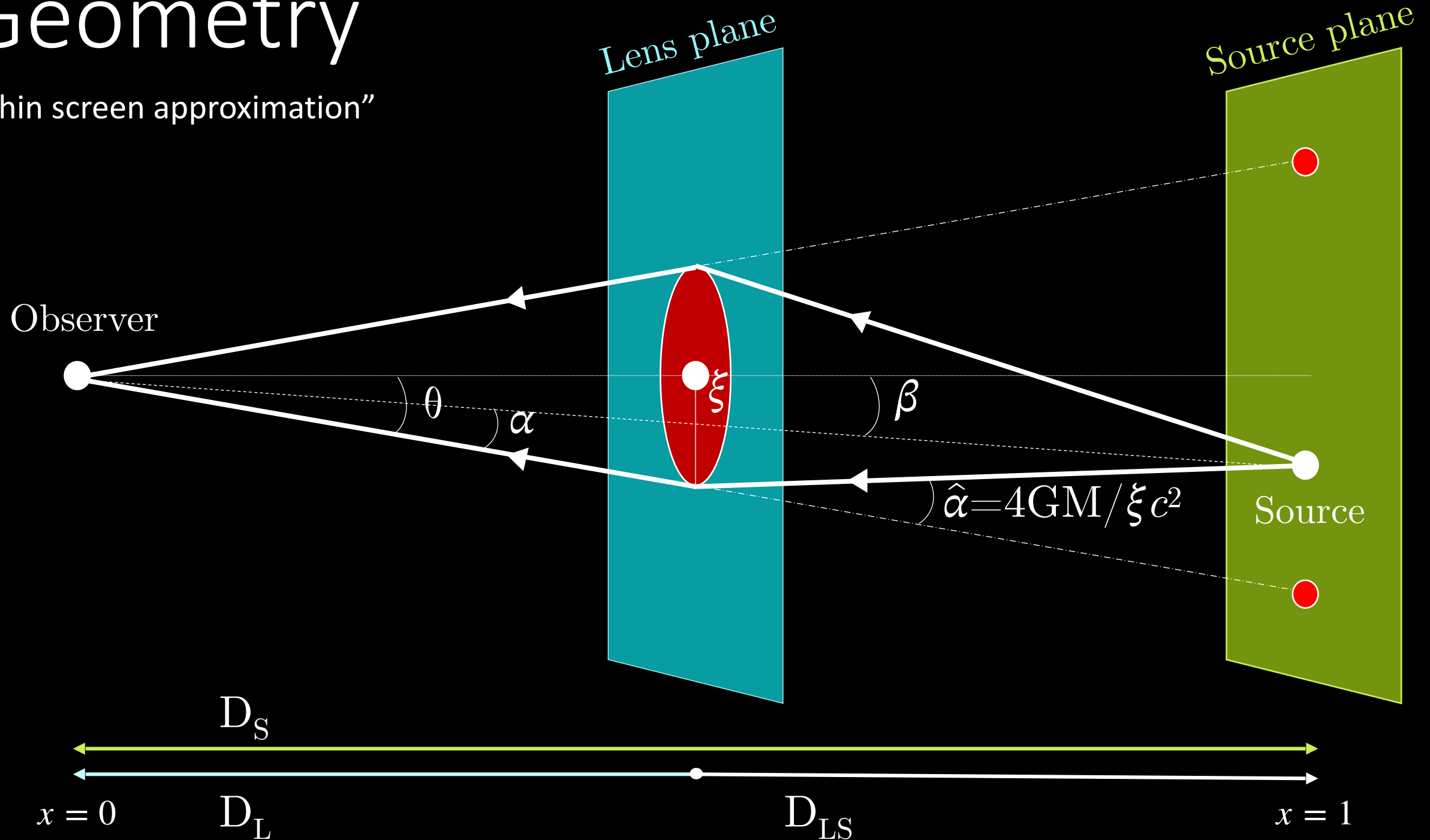


$$\theta D_S = \beta D_S - \hat{\alpha} D_{LS} \rightarrow \beta = \theta - \alpha = \theta - \hat{\alpha} \frac{D_{LS}}{D_S} = \theta - \frac{4GM(\theta)}{\theta D_L c^2} \frac{D_{LS}}{D_S}$$

Lensing equation

# Geometry

"Thin screen approximation"



$$\theta D_S = \beta D_S - \hat{\alpha} D_{LS} \rightarrow \beta = \theta - \alpha = \theta - \hat{\alpha} \frac{D_{LS}}{D_S} = \theta - \frac{4GM(\theta)}{\theta D_L c^2} \frac{D_{LS}}{D_S}$$

$$\beta = 0 \rightarrow \theta \equiv \theta_E = \sqrt{\frac{4GM}{c^2} \frac{D_{LS}}{D_L D_S}}$$

Einstein radius

$$r_E = \theta_E D_L$$

Near perfect Einstein  
Ring with the HST



# The Einstein radius

Lensing equation:  $\beta = \theta - \frac{4GM(\theta)}{\theta D_L c^2} \frac{D_{LS}}{D_S}$

$$\beta = 0 \rightarrow \theta \equiv \theta_E = \sqrt{\frac{4GM}{c^2} \frac{D_{LS}}{D_L D_S}}$$

Magnification:  $\mu = \frac{\theta}{\beta} \frac{d\theta}{d\beta} = \sum_i \mu_i$

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Normalise everything to  $\theta_E$

- $u \equiv \beta/\theta_E$
- $\tau \equiv \theta/\theta_E$
- $m(\tau) \equiv M(\theta_E \tau)/M$

Lensing equation:  $u = \tau - \frac{m(\tau)}{\tau}$

Magnification:  $\mu = \left| 1 - \frac{m(\tau)}{\tau^2} \right|^{-1} \left| 1 + \frac{m(\tau)}{\tau^2} - \frac{1}{\tau} \frac{dm(\tau)}{d\tau} \right|^{-1}$

# Geometry

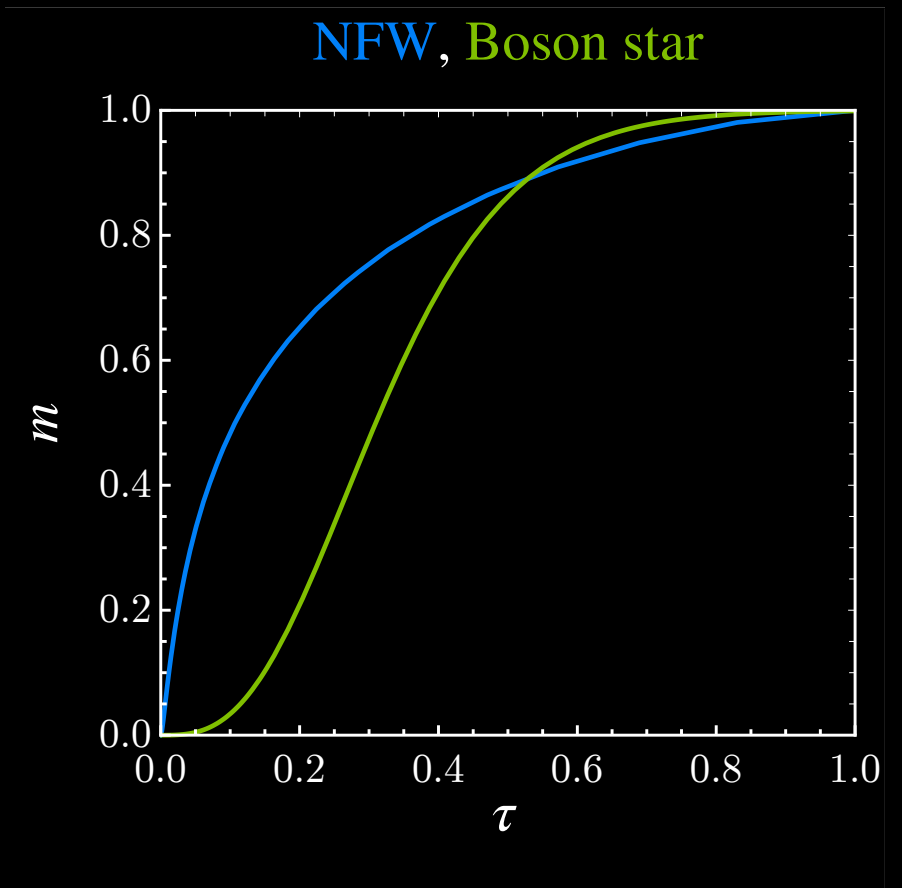
“Thin screen approximation”

$$m(\tau) = \frac{\int_0^\tau d\sigma \sigma \int_0^\infty d\lambda \rho(r_E \sqrt{\sigma^2 + \lambda^2})}{\int_0^\infty d\gamma \gamma^2 \rho(r_E \gamma)}$$

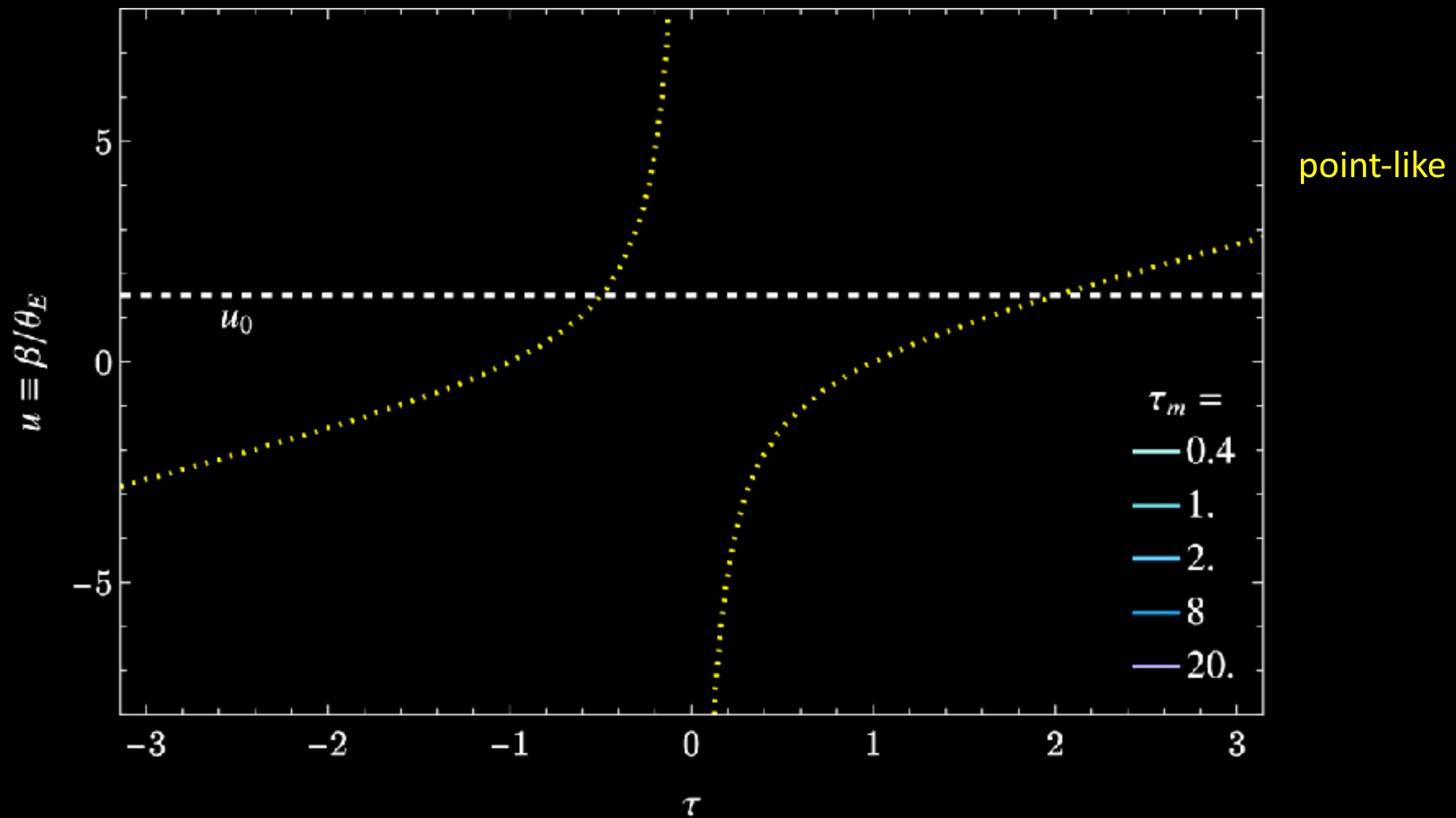
Projected lens mass distribution  
Point-like lenses:  $m(\tau) = 1$

Lensing equation:  $u = \tau - \frac{m(\tau)}{\tau}$

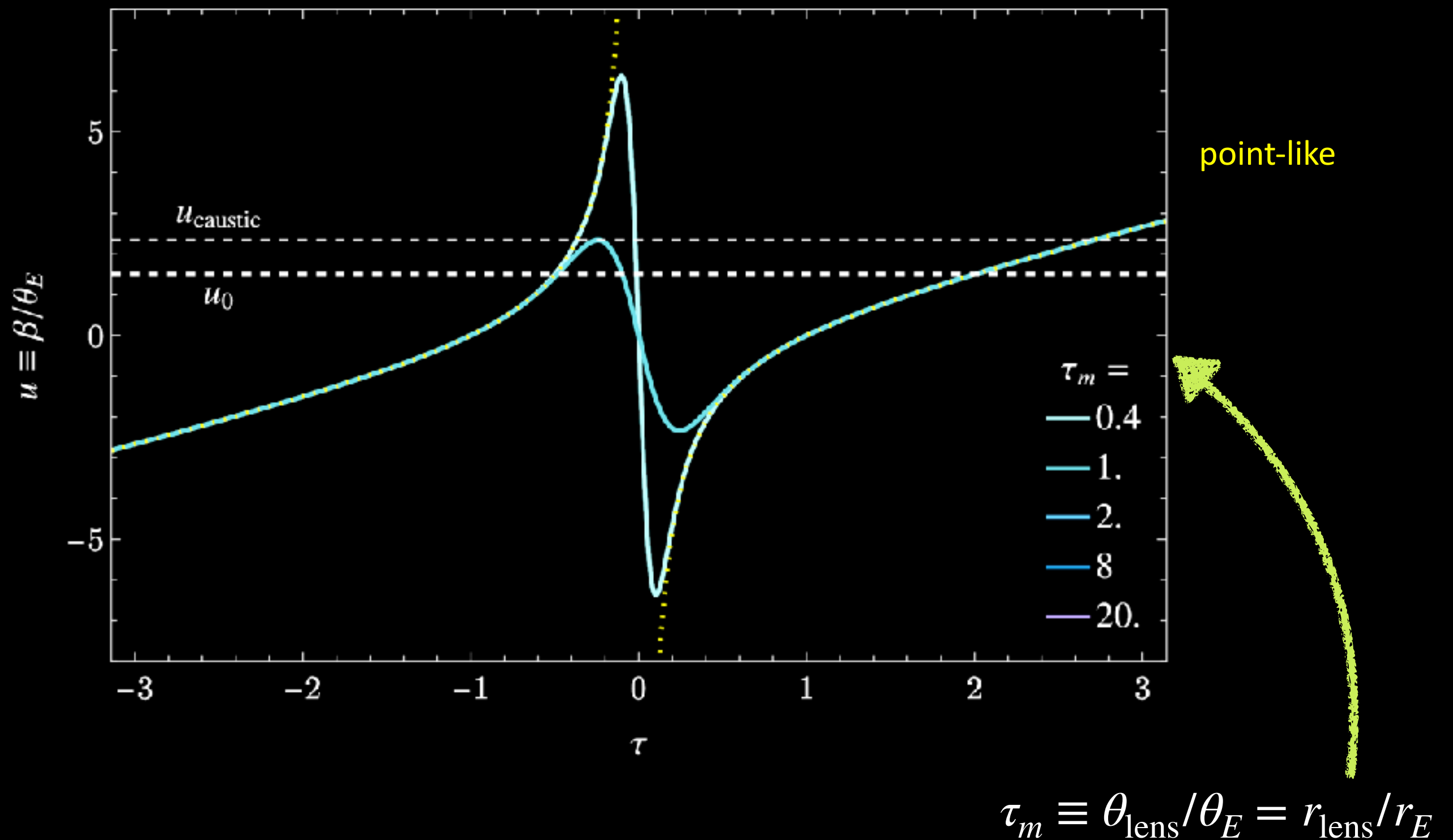
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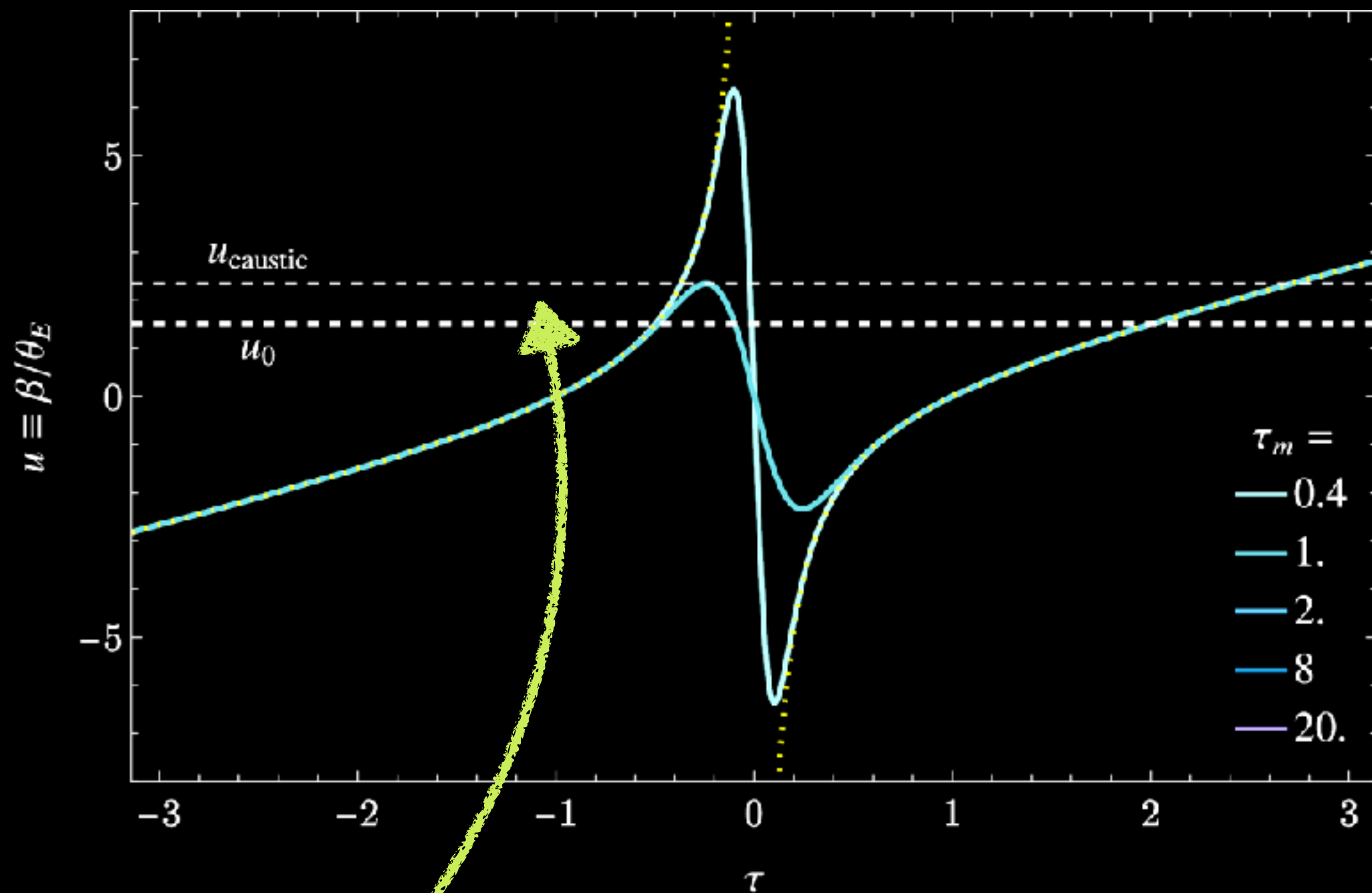
# Solving the lens equation $u = \tau - \frac{m(\tau)}{\tau}$



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point-like

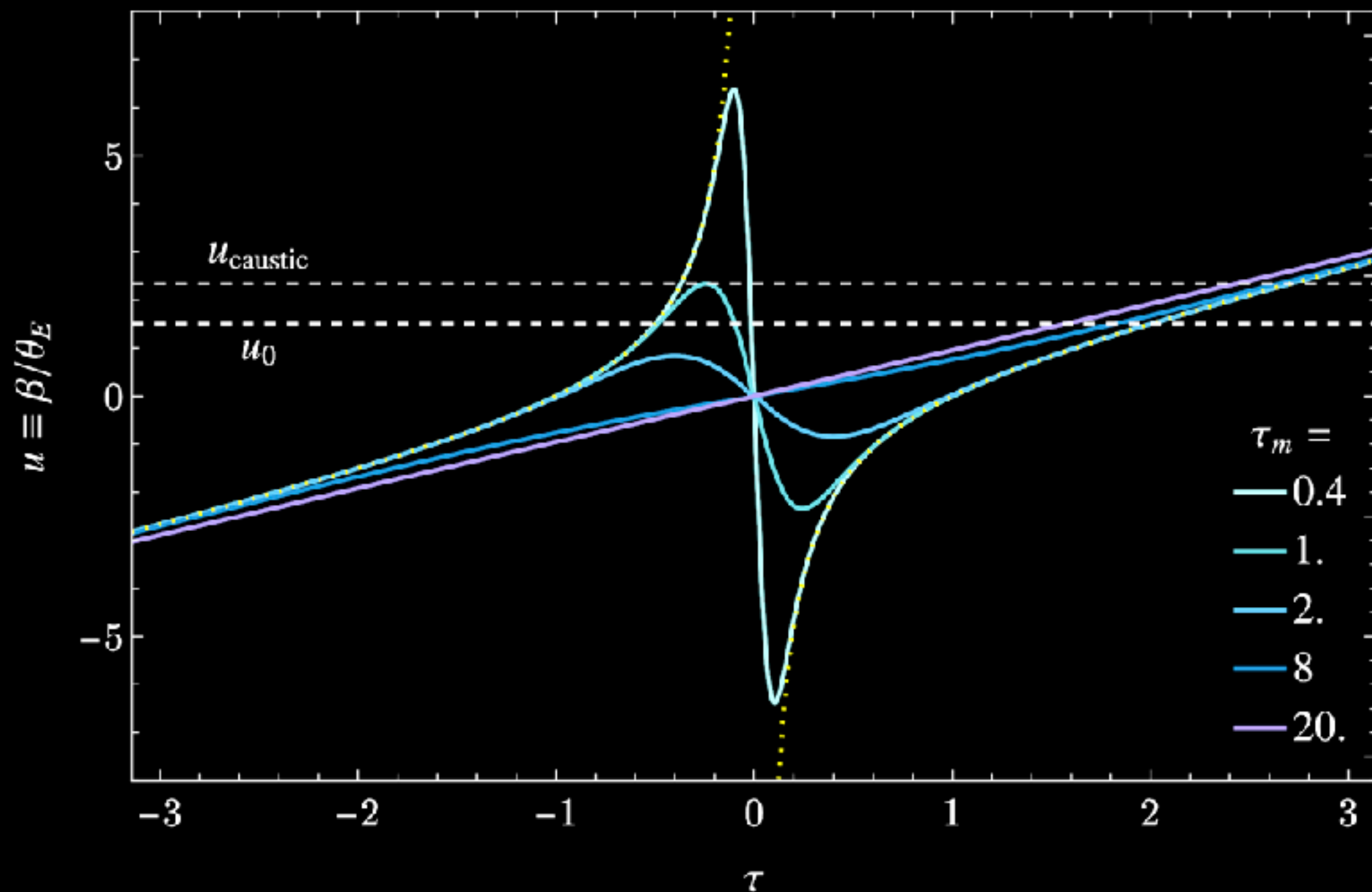
3 solutions, one with negligible  $\mu_i$

3 solutions, all contributing  $\mu_i$

→ at  $u_{\text{caustic}}$ , number of solutions jumps from 1 to 3

$$\tau_m \equiv \theta_{\text{lens}}/\theta_E = r_{\text{lens}}/r_E$$

# Solving the lens equation $u = \tau - \frac{m(\tau)}{\tau}$



point-like

3 solutions, one with negligible  $\mu_i$

3 solutions, all contributing  $\mu_i$

1 solution of the point-like case

1 solution, larger  $\mu_i$  than point-like

1 solution,  $\mu_i \rightarrow 0$

$$\tau_m \equiv \theta_{\text{lens}}/\theta_E = r_{\text{lens}}/r_E$$

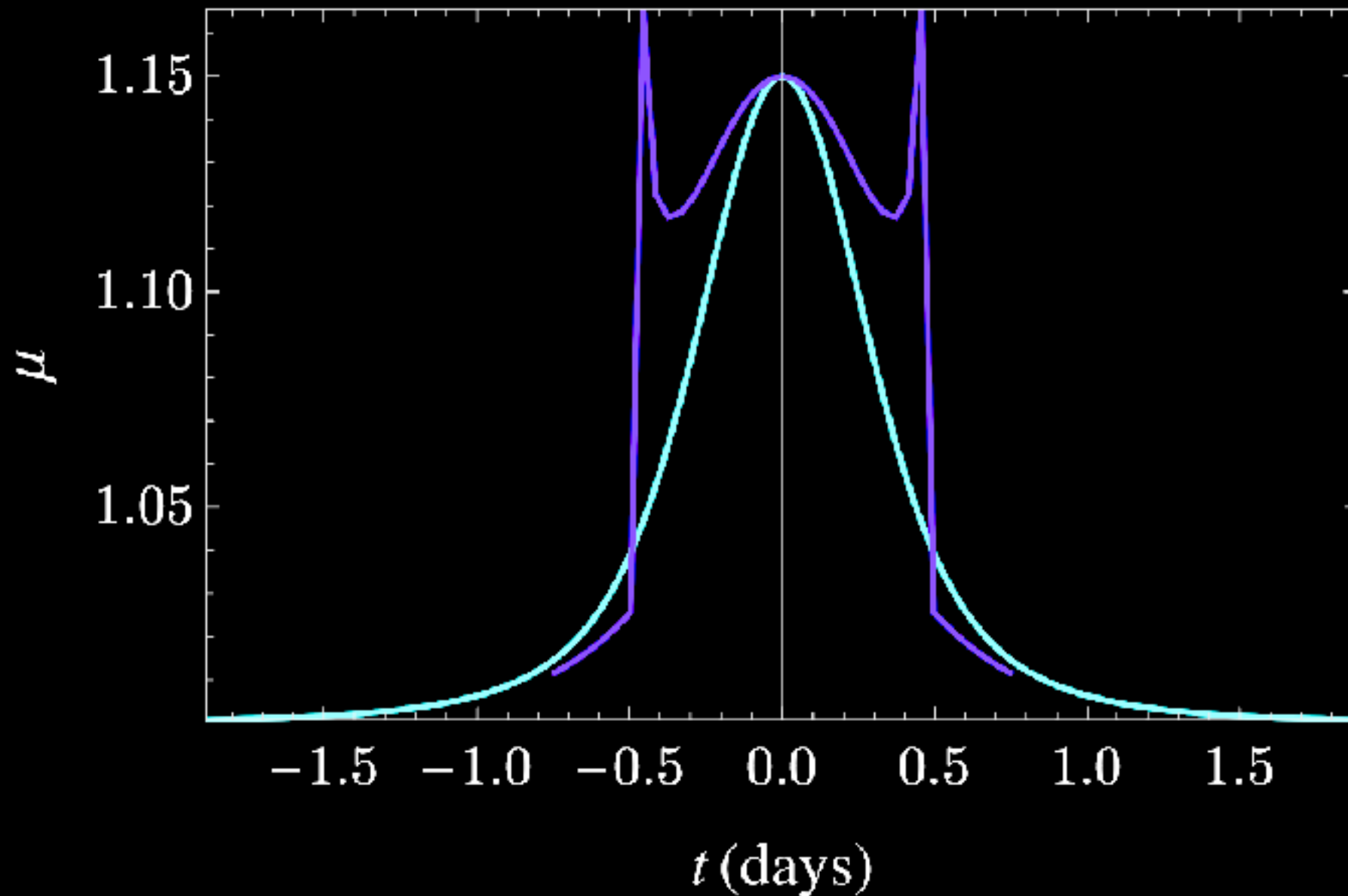
# Caustic crossing

*Example light curve*

*with  $\tau_m \equiv \theta_{\text{lens}}/\theta_E = r_{\text{lens}}/r_E$*

Boson star with  $\tau_m = 1$

PBH (or  $\tau_m = 0$ )



Point-like lens:  $m(\tau) = 1 \rightarrow \mu = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}$

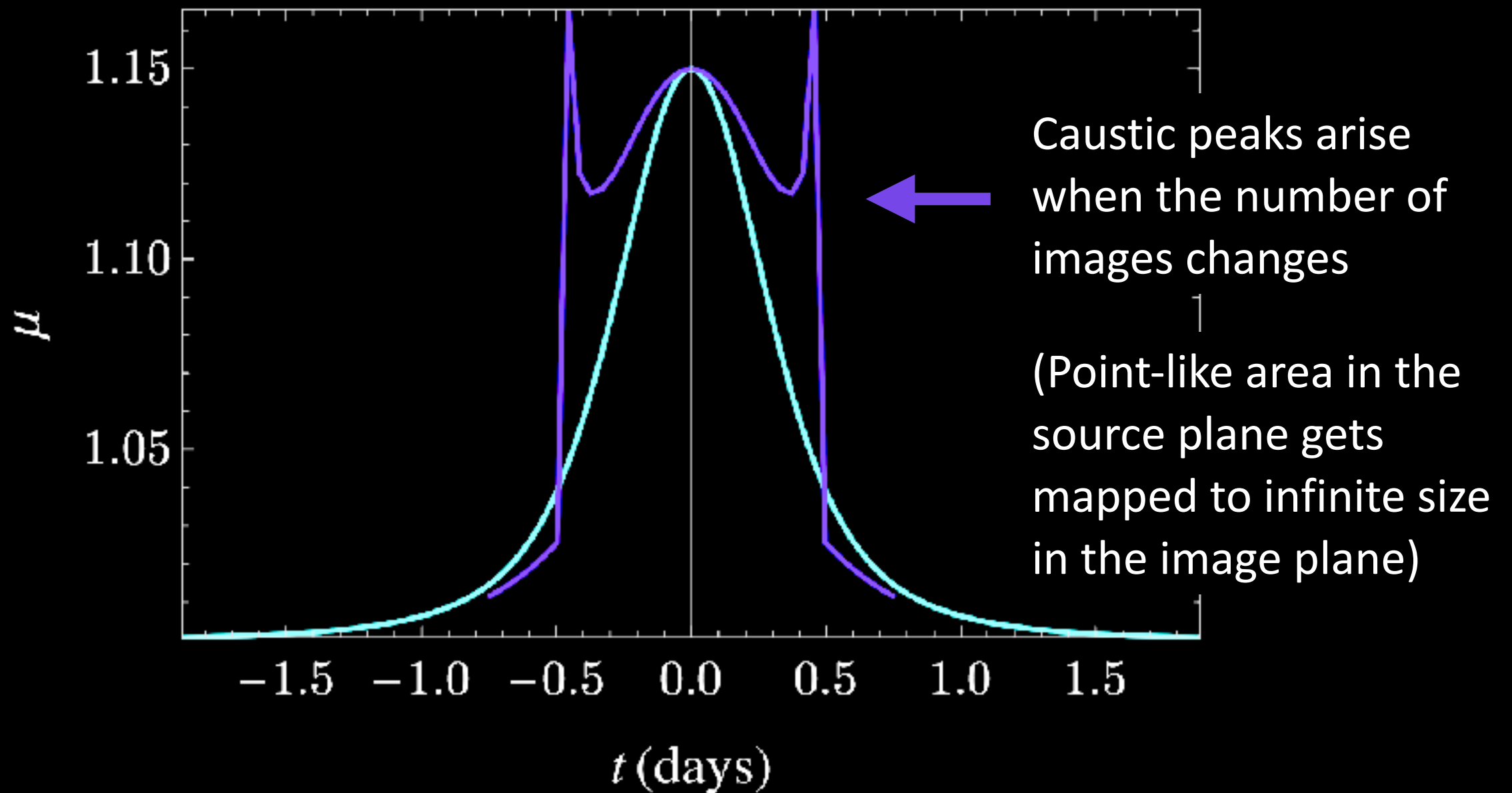
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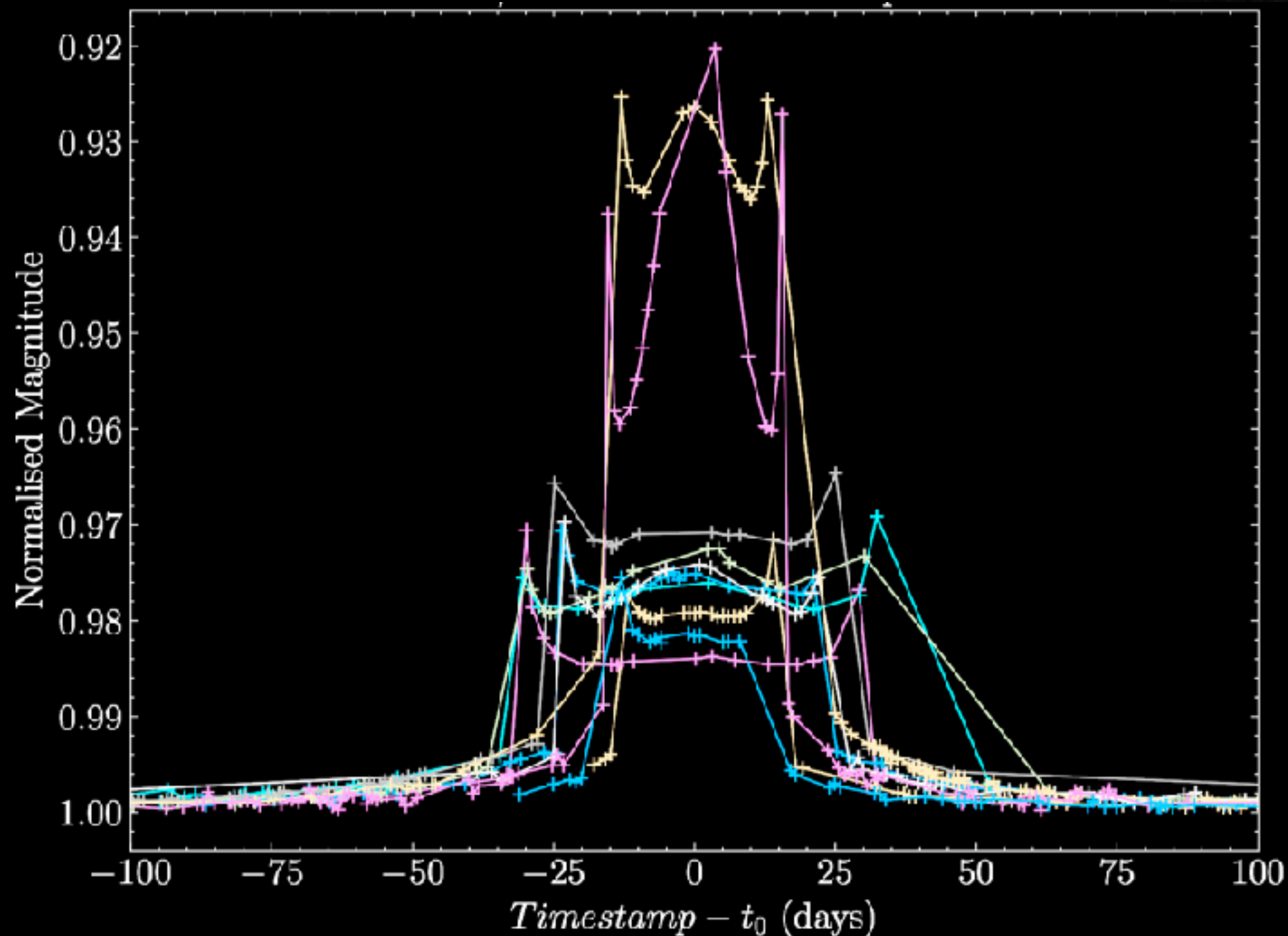
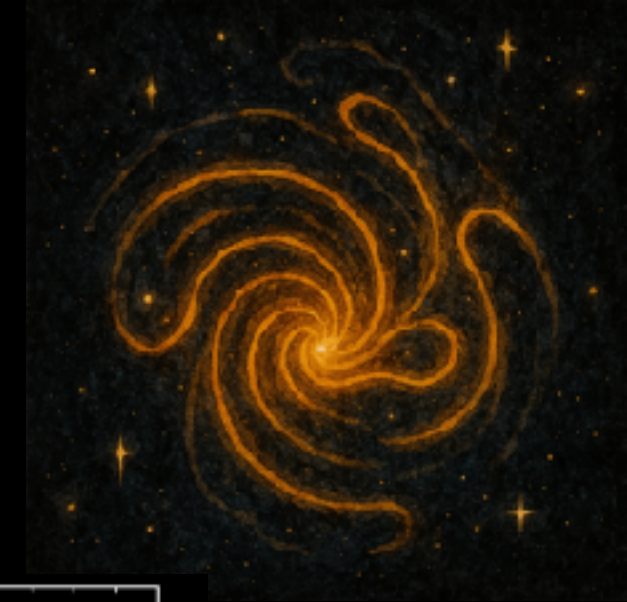
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# Light curves with caustics

*Can we look for these explicitly?*



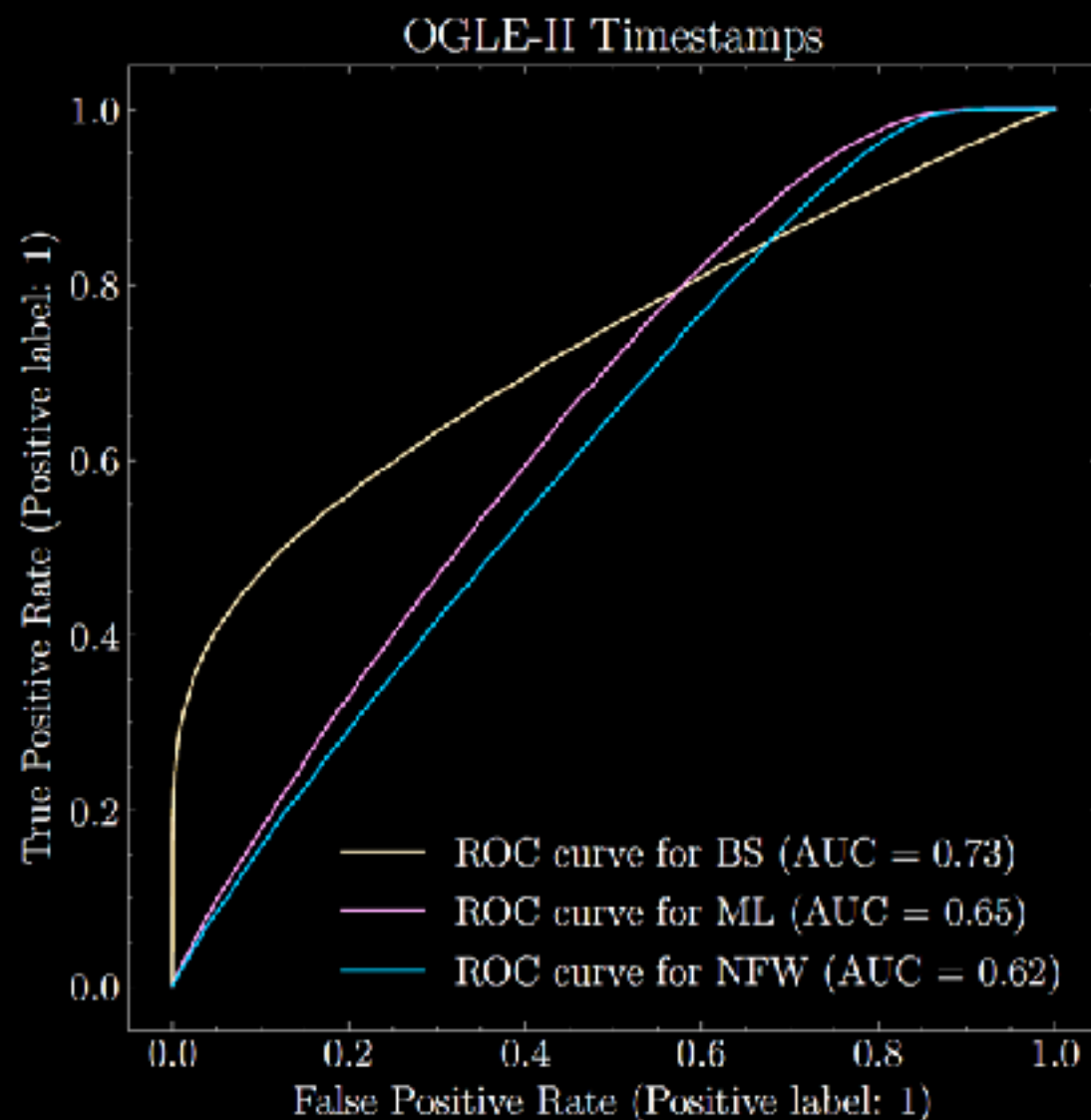
# Light curves with caustics

*Can we look for these explicitly? Yes!*



*Dedicated microlensing surveys*

*Histogram-based gradient boosted classifier*

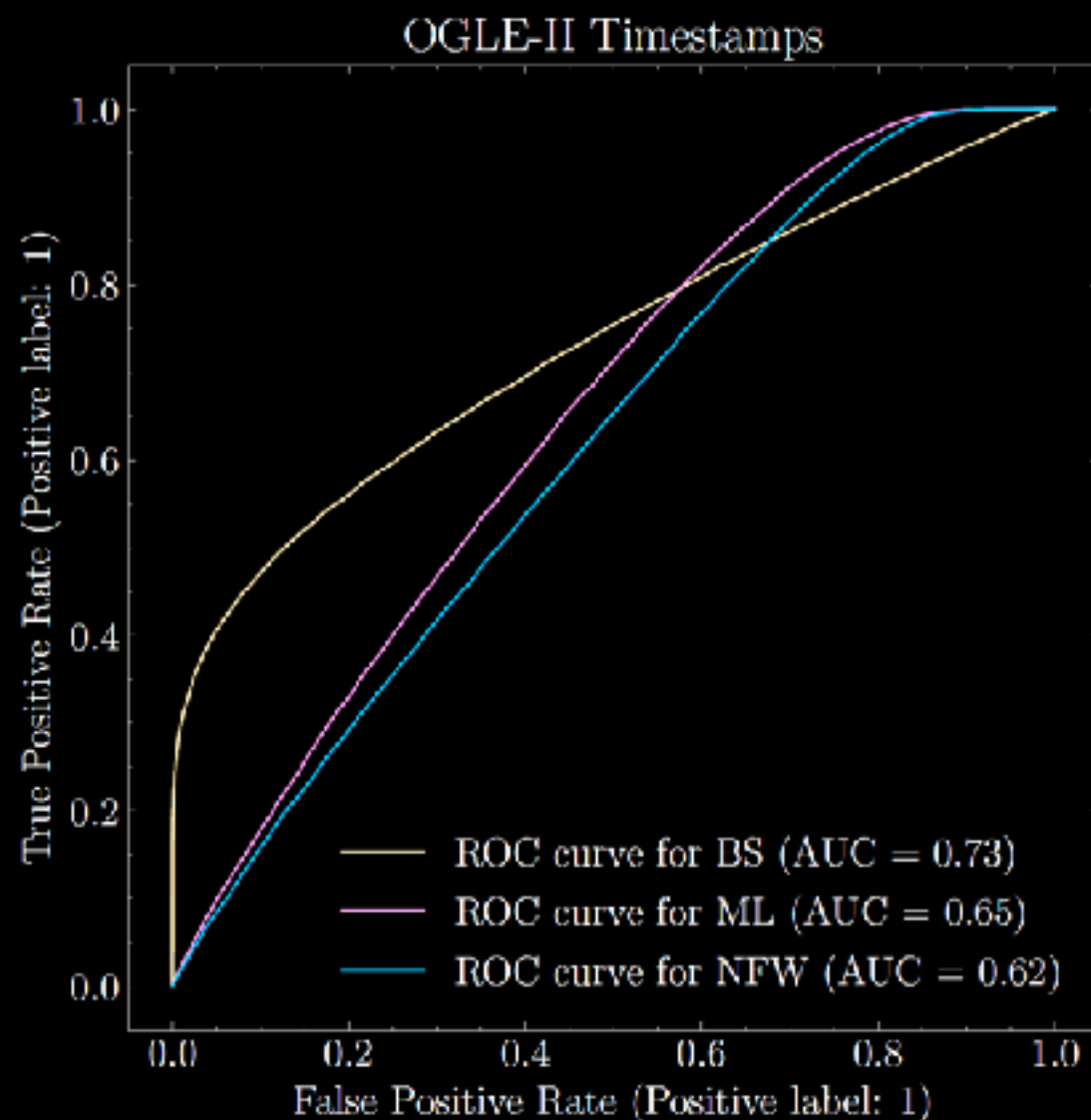


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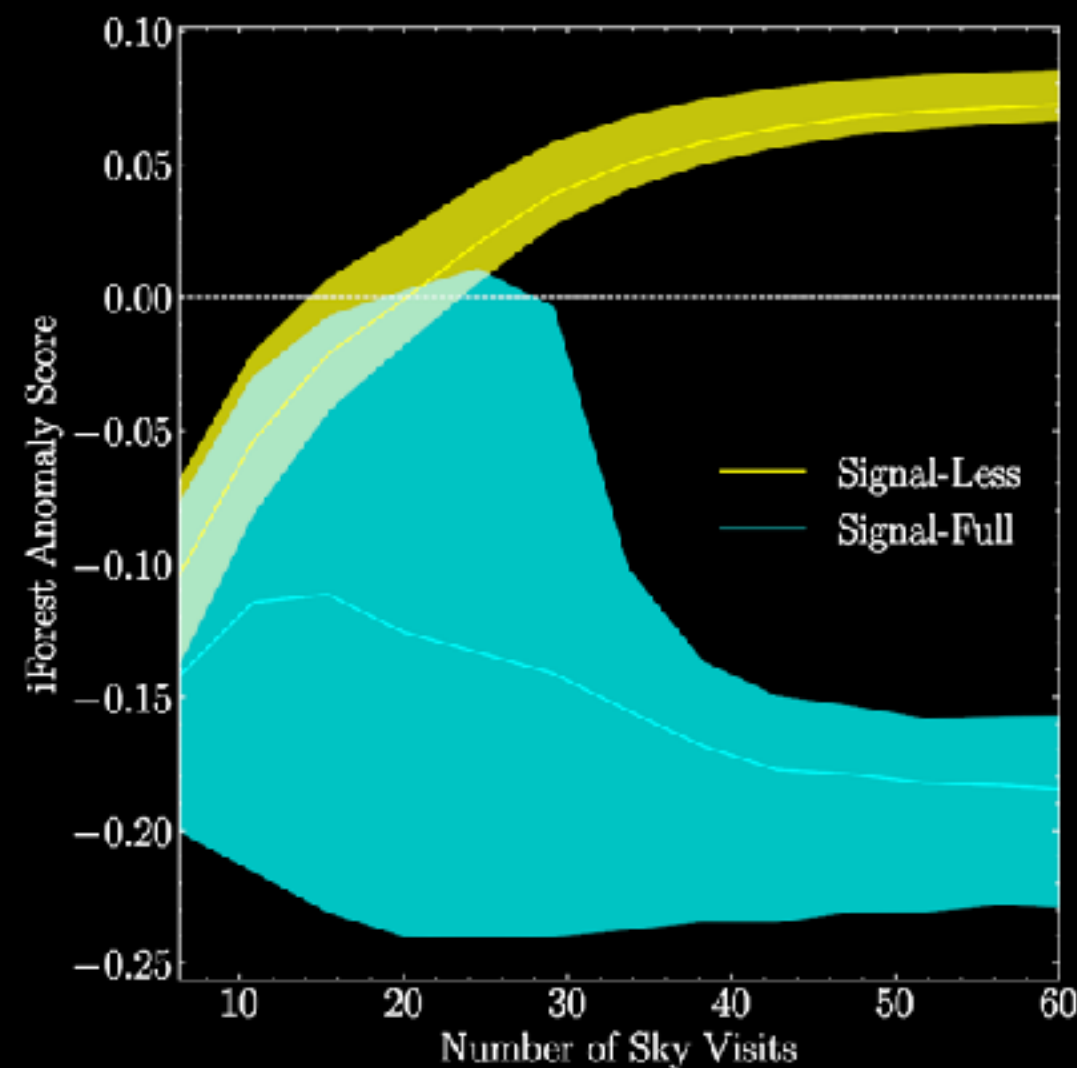
*Can we look for these explicitly? Yes!*



*Dedicated microlensing surveys*  
*Histogram-based gradient boosted classifier*



*LSST: more stars, irregular cadence*  
*Anomaly detection for early identification*



# Generalising PBH constraints

Define  $u_{1.34}$  by  $\mu_{\text{tot}}(u \leq u_{1.34}) > 1.34$

*“Efficiency” of extended lenses*

All smaller impact parameters produce  
a magnification above  $\mu > 1.34$

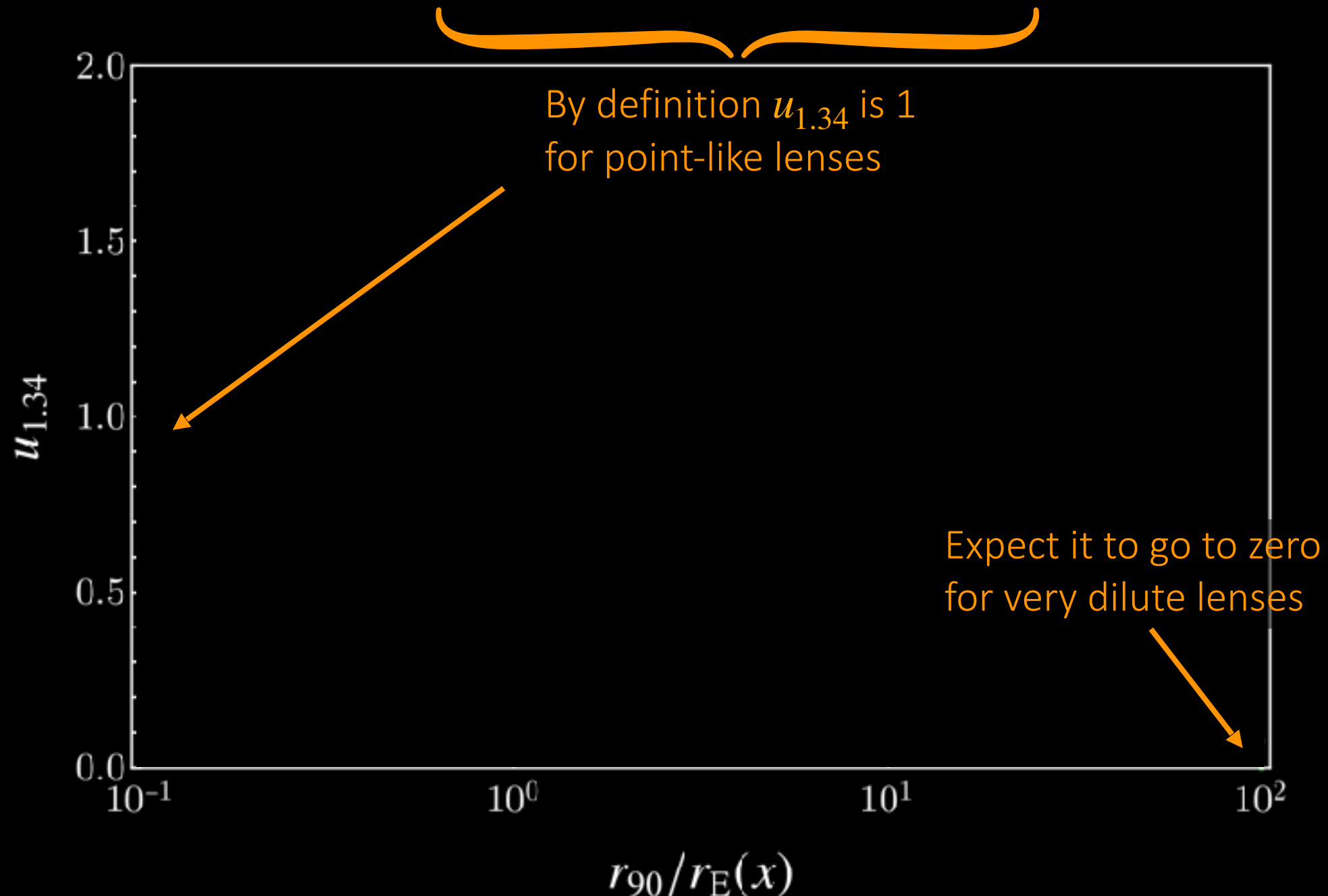
By definition  $u_{1.34}$  is 1  
for point-like lenses

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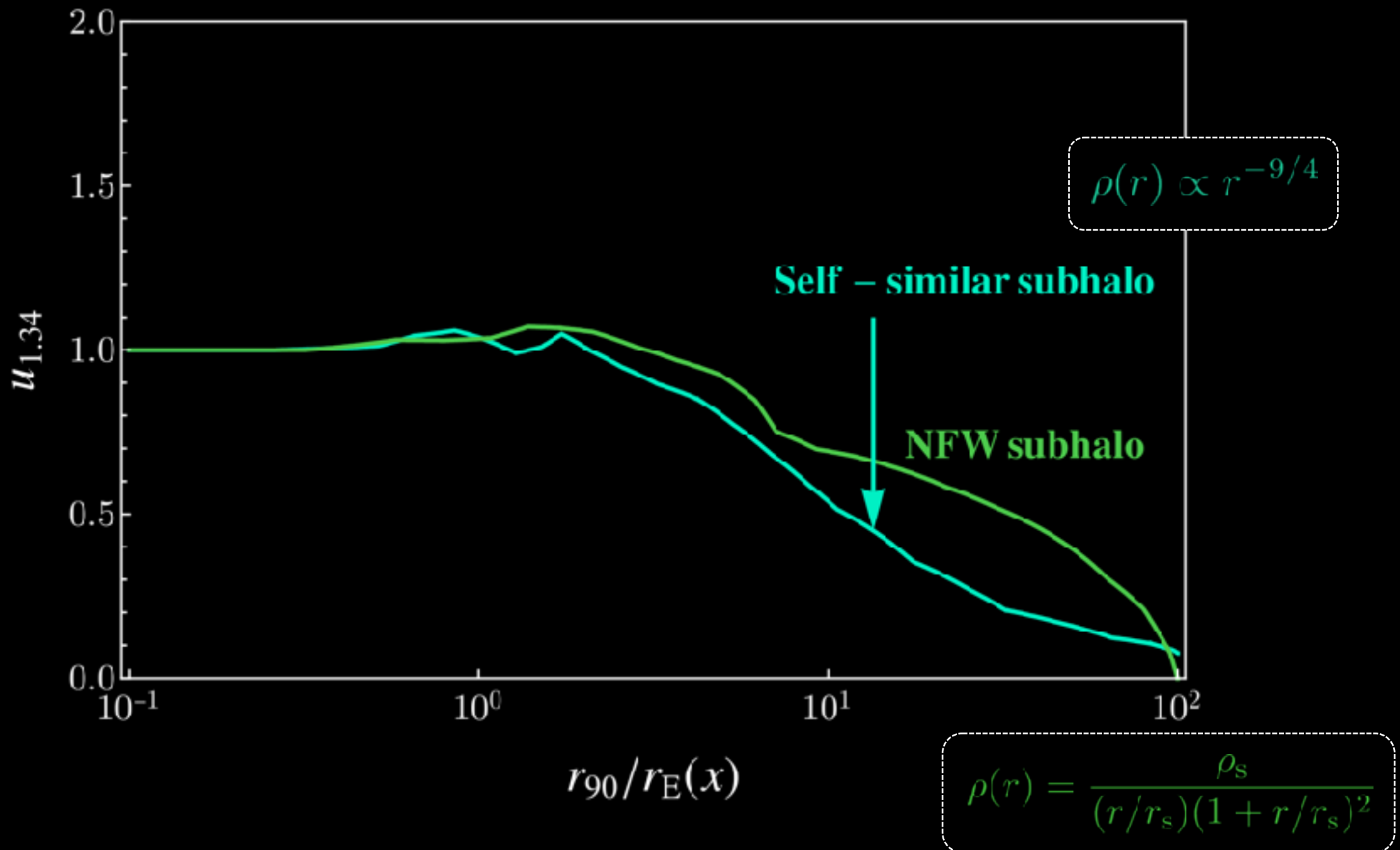


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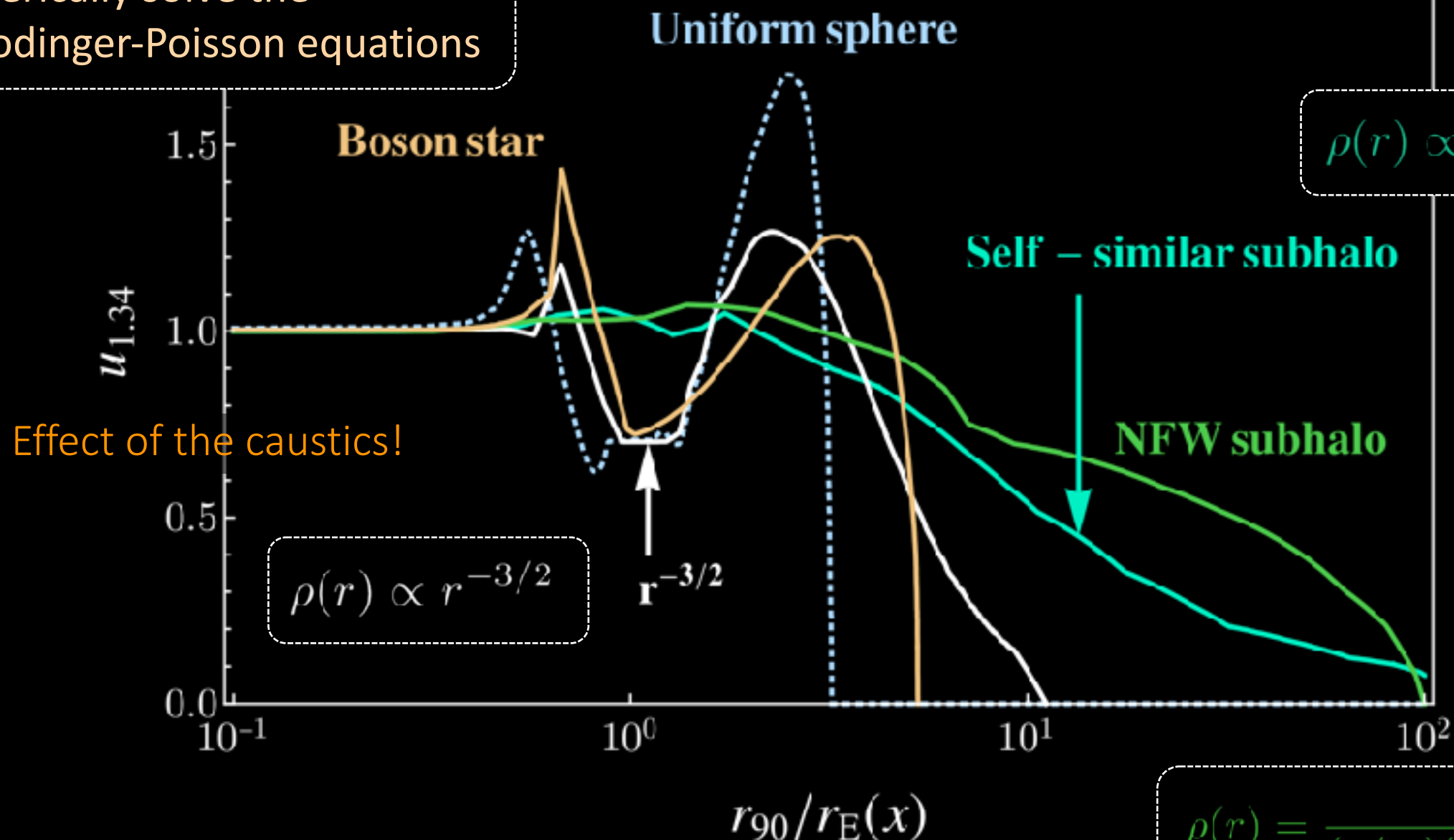
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“Efficiency” of extended lenses

All smaller impact parameters produce a magnification above  $\mu > 1.34$

Numerically solve the Schrodinger-Poisson equations



$$\rho(r) \propto r^{-9/4}$$

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

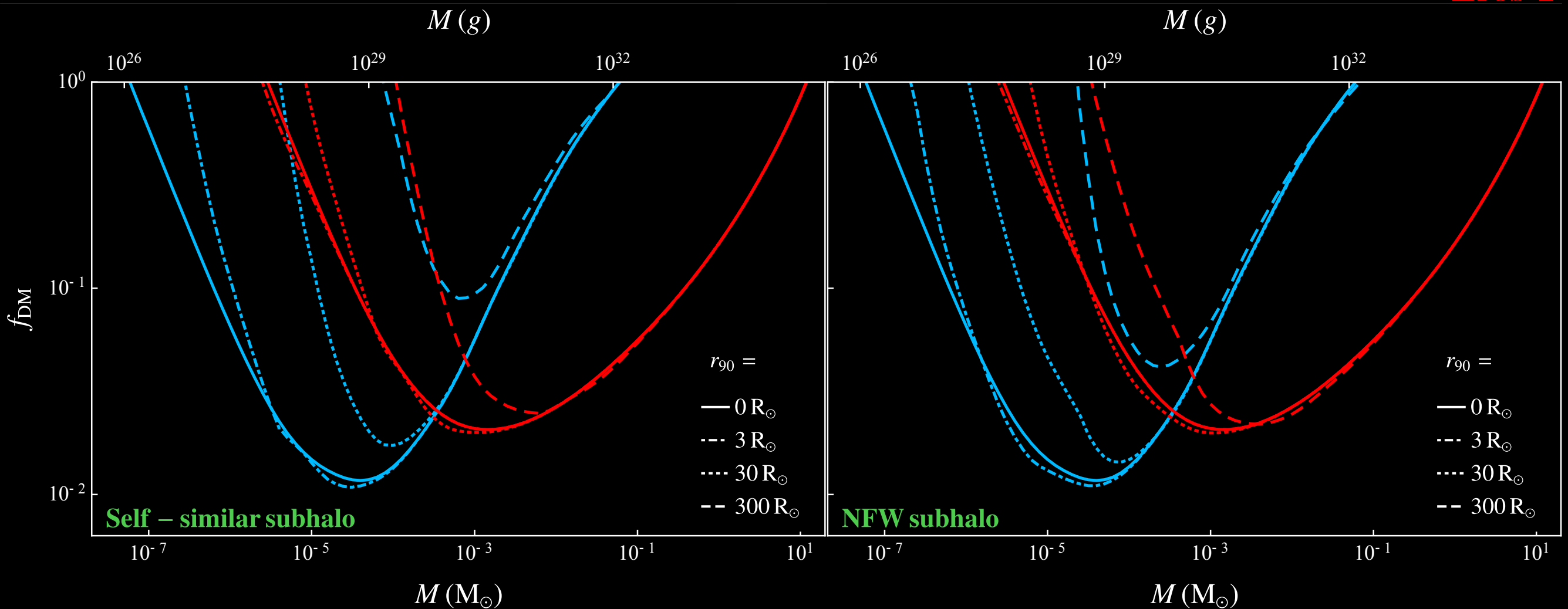
# Constraints on DM fraction

*Using the differential event rate, find constraints given expected number of (non-observed) events. Generalised for extended objects using an extended lens efficiency.*

*As expected, constraints on extended objects are weaker...*

Ogle-IV

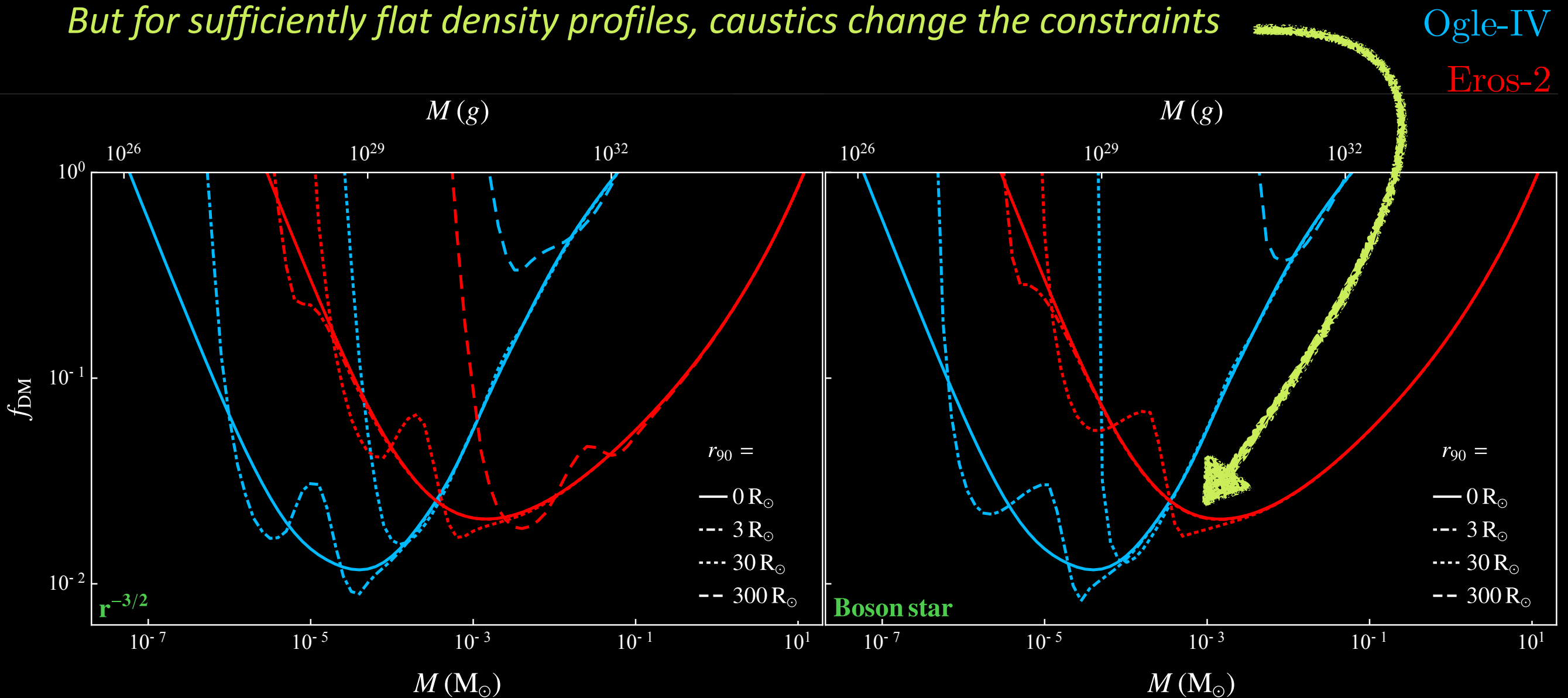
Eros-2

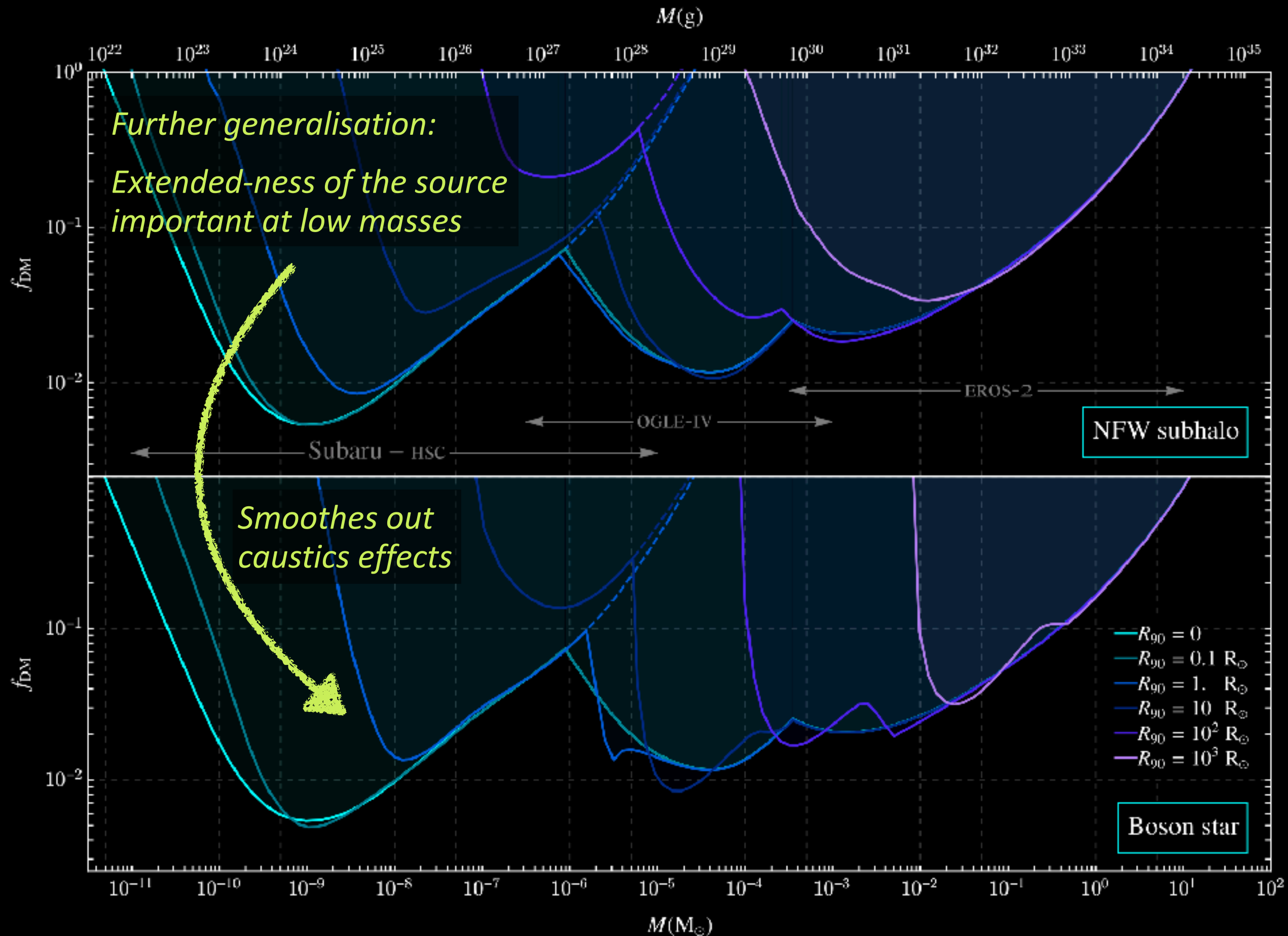


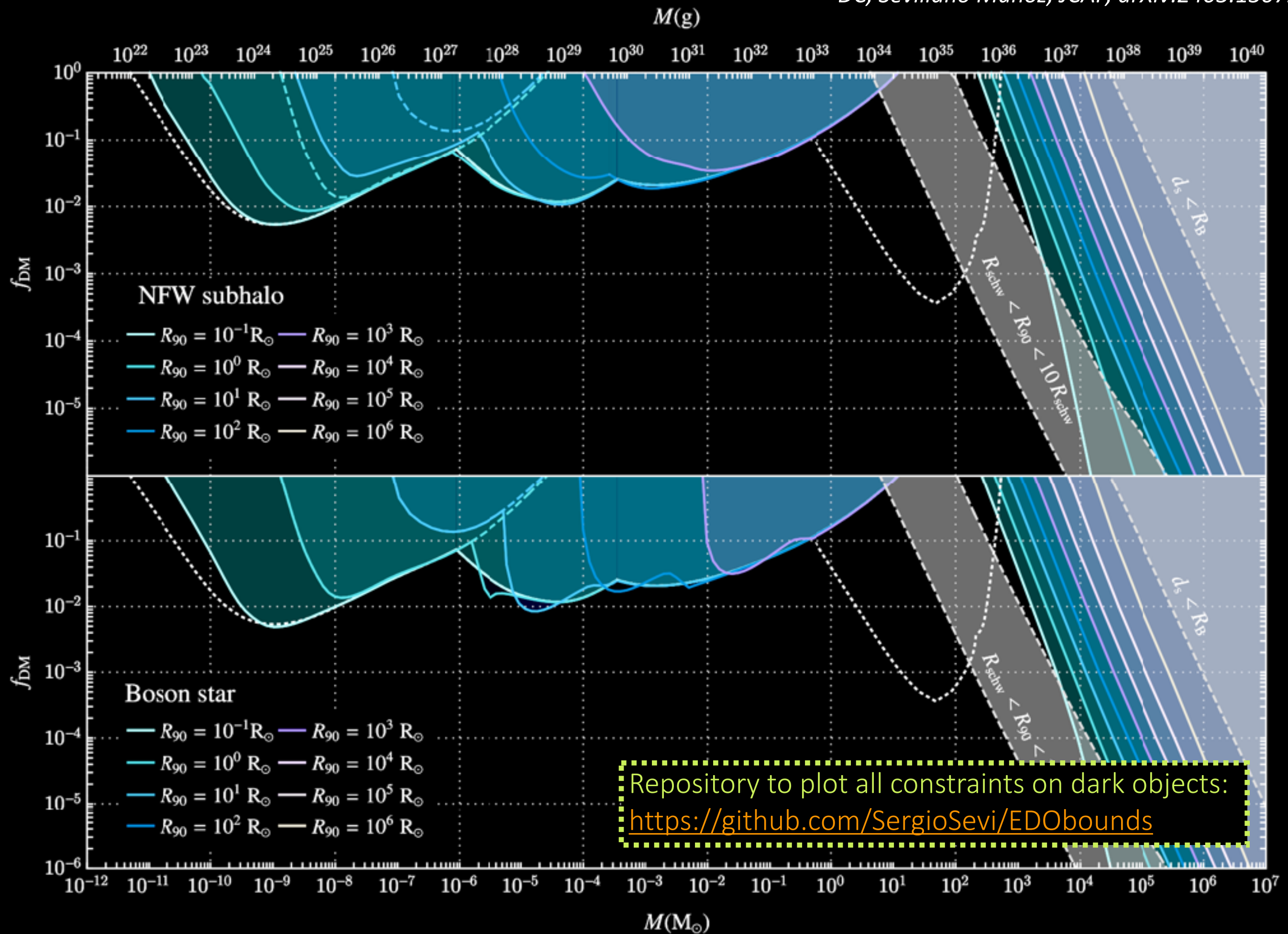
# Constraints on DM fraction

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*But for sufficiently flat density profiles, caustics change the constraints*







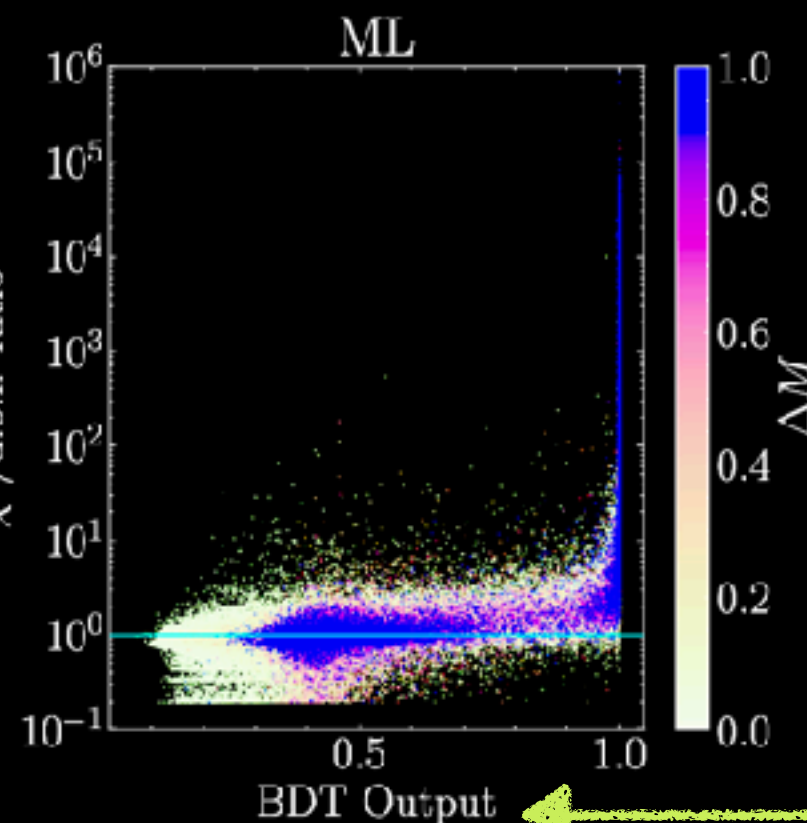
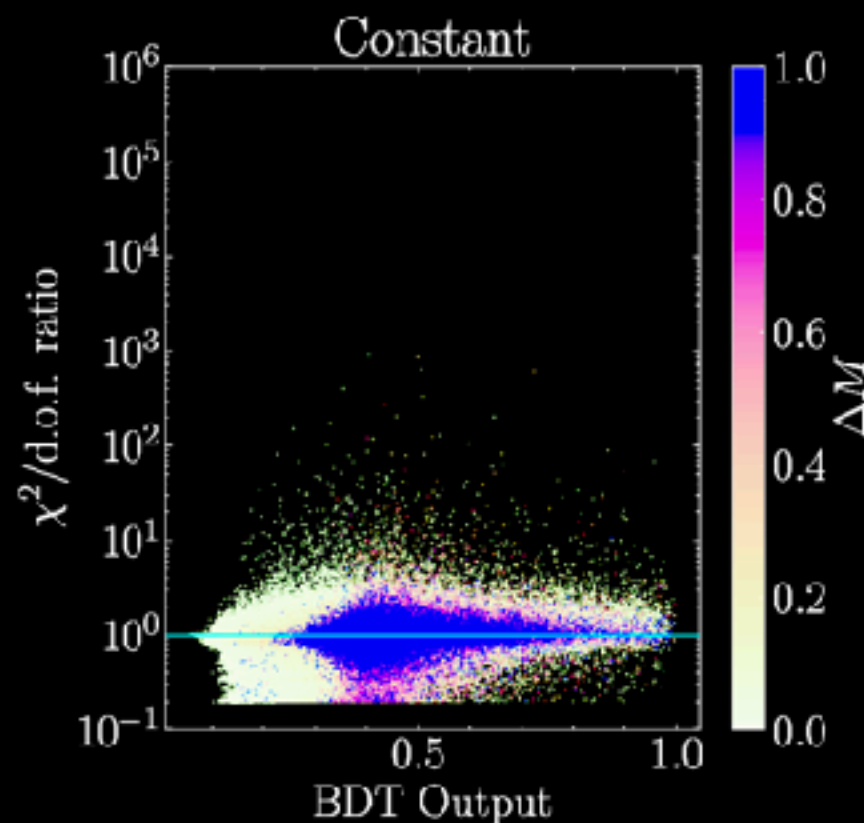
# LSST by Rubin: projections

*Sparse cadence leads to  
unique challenges*

*Miguel Crispim-Romao, DC, Benedict Crossey, Daniel Godines, PRD, arXiv:2506.20709*

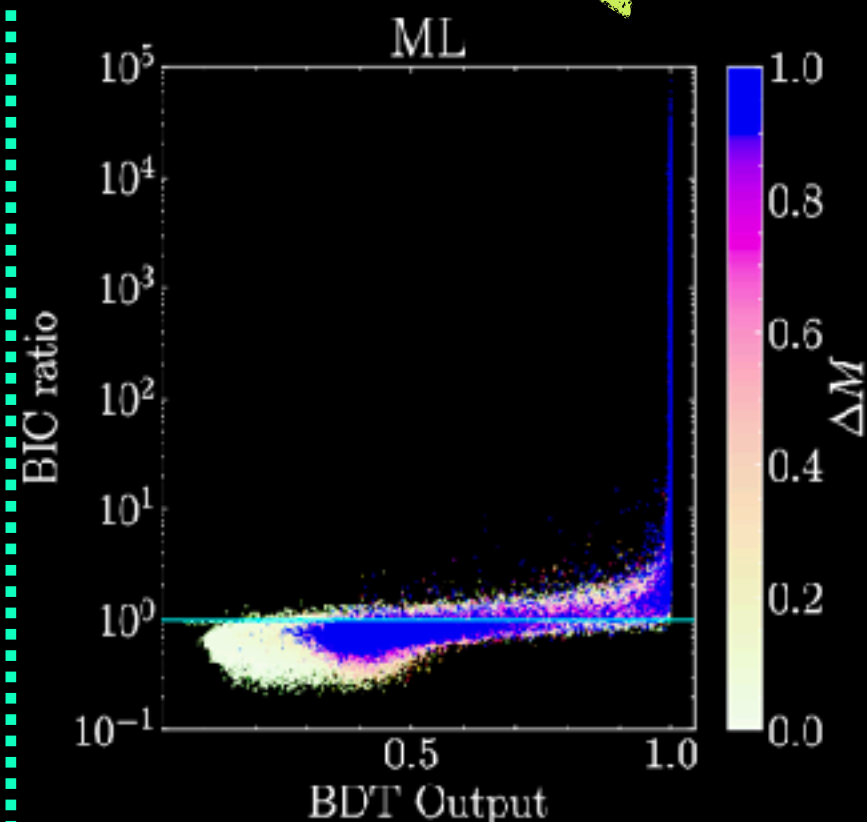
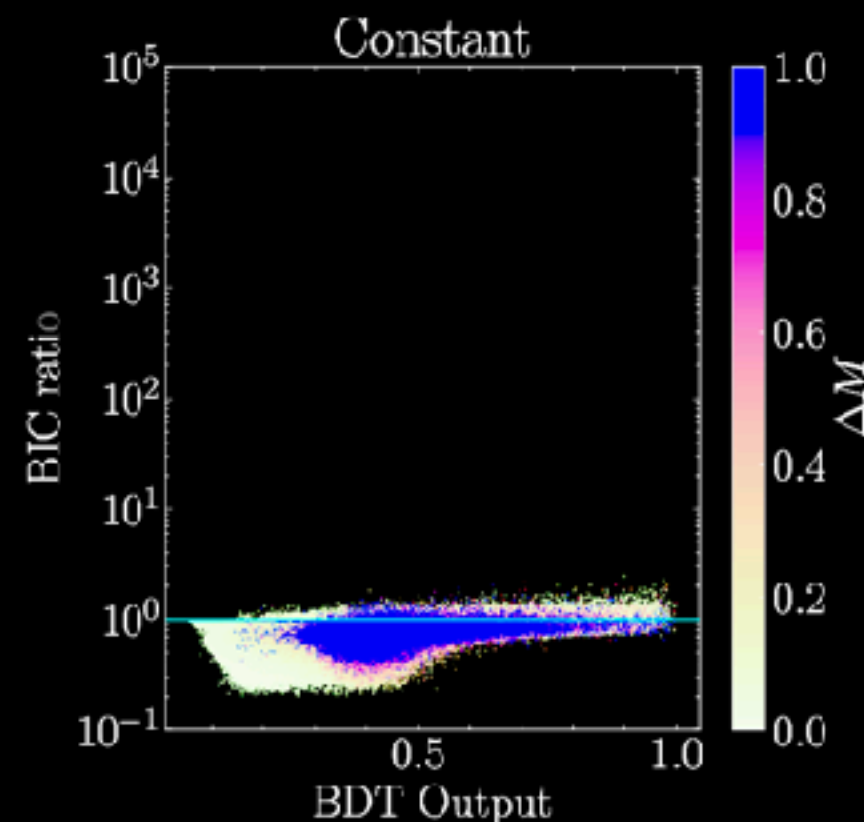
Signal-less

*Typically used*



Signal

*BIC*

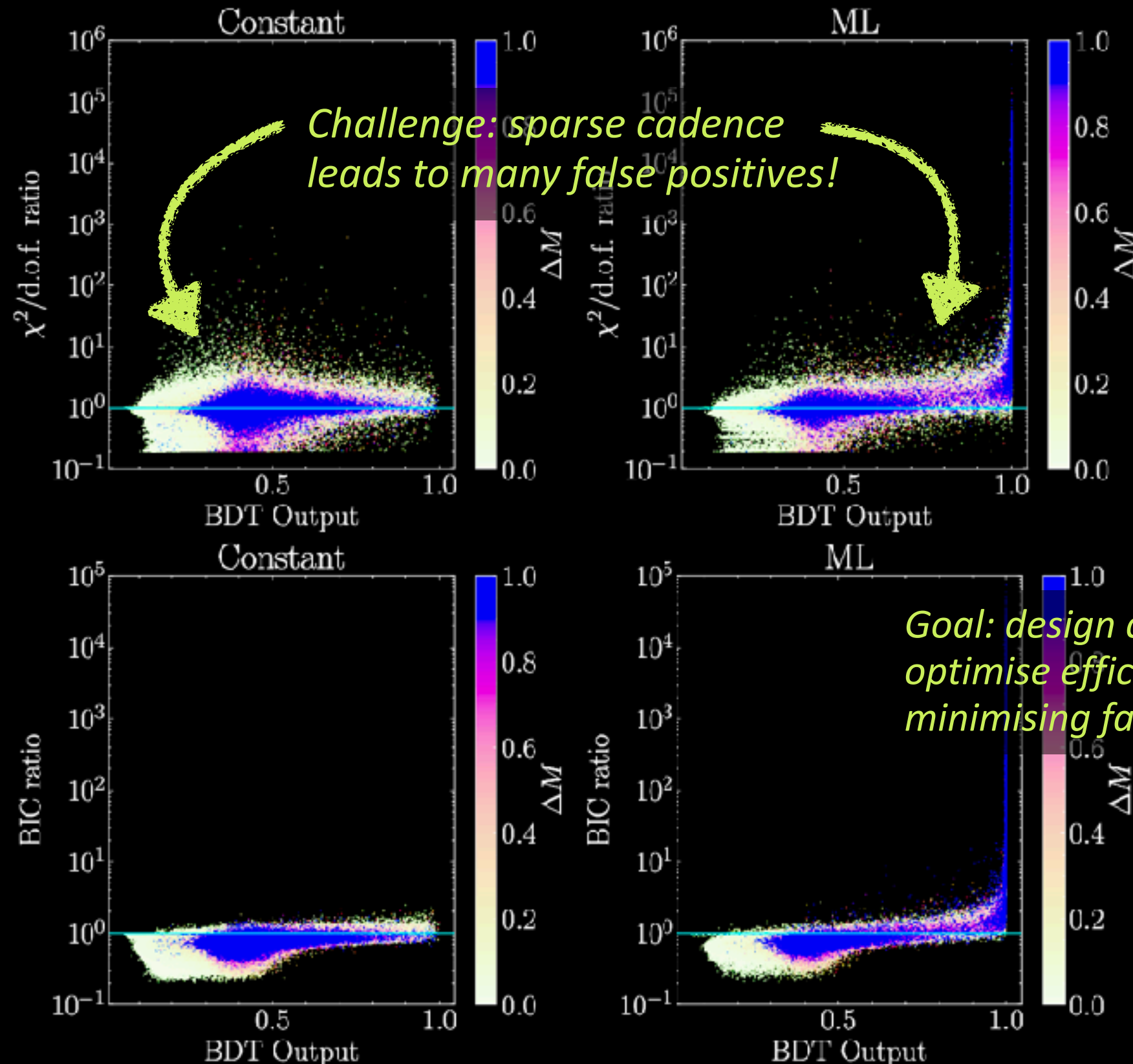


*BDT*

# LSST by Rubin: projections

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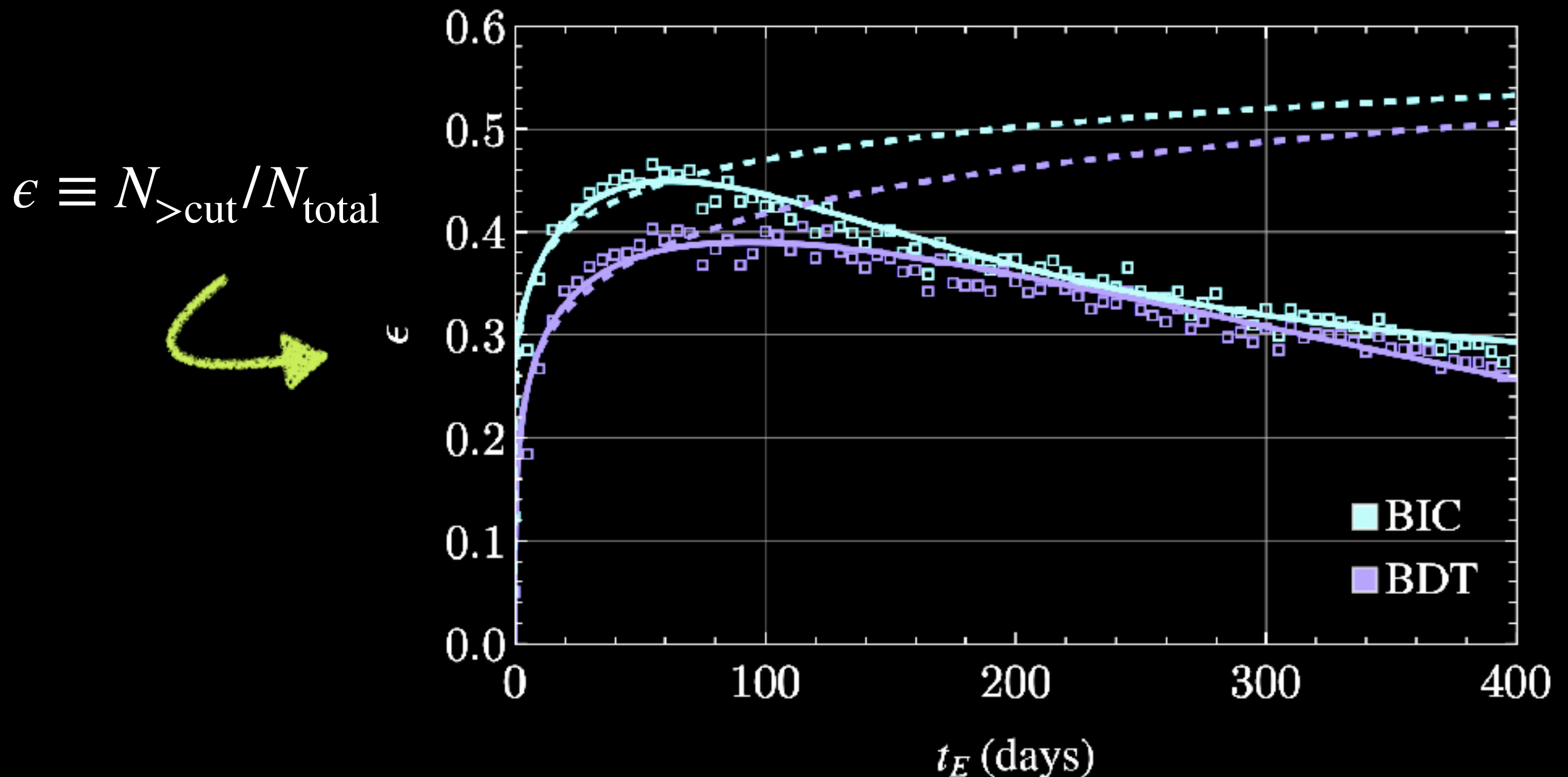
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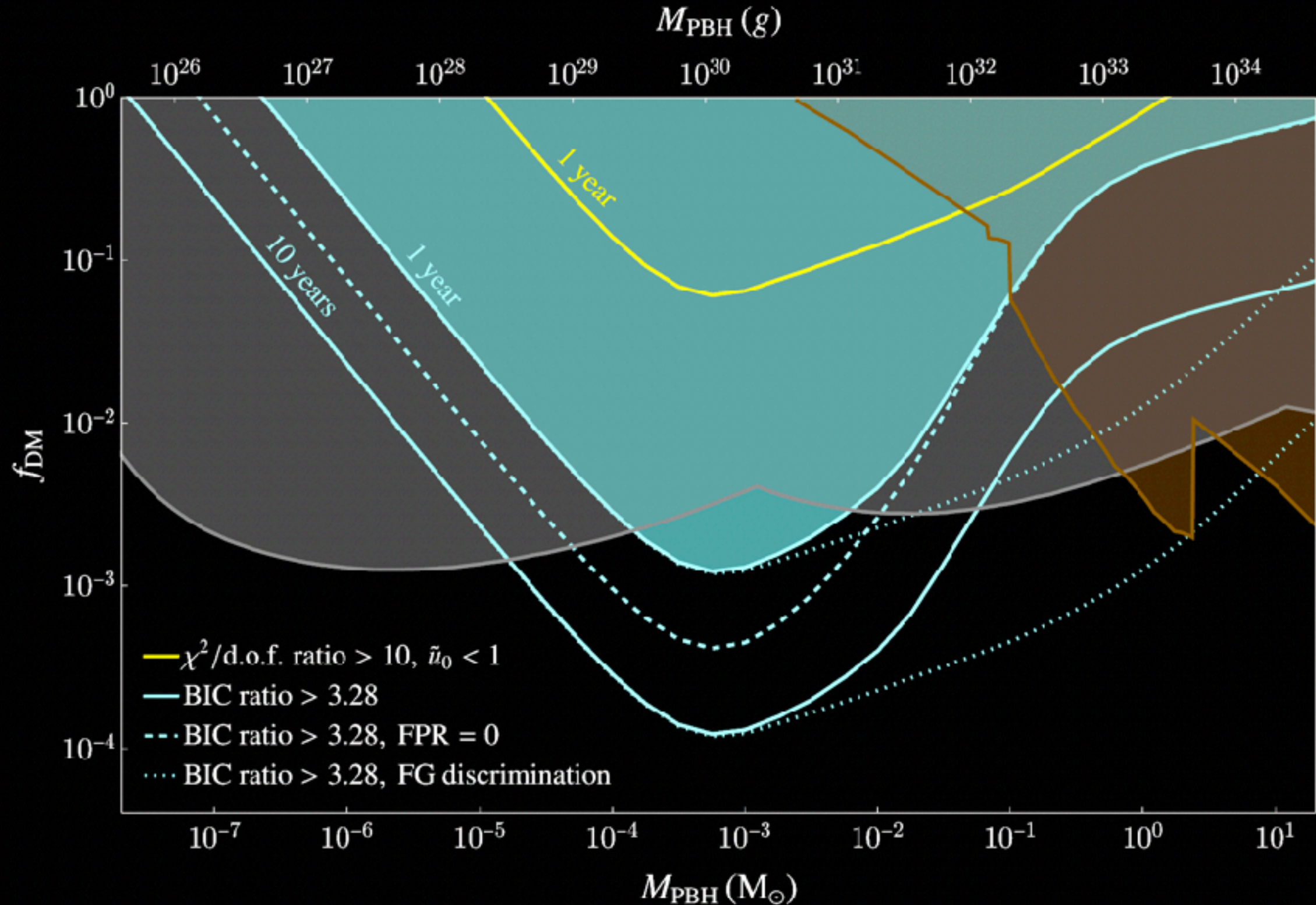
*Miguel Crispim-Romao, DC, Benedict Crossey, Daniel Godines, PRD, arXiv:2506.20709*

Define a cut in false positives — what fraction of events is identified?

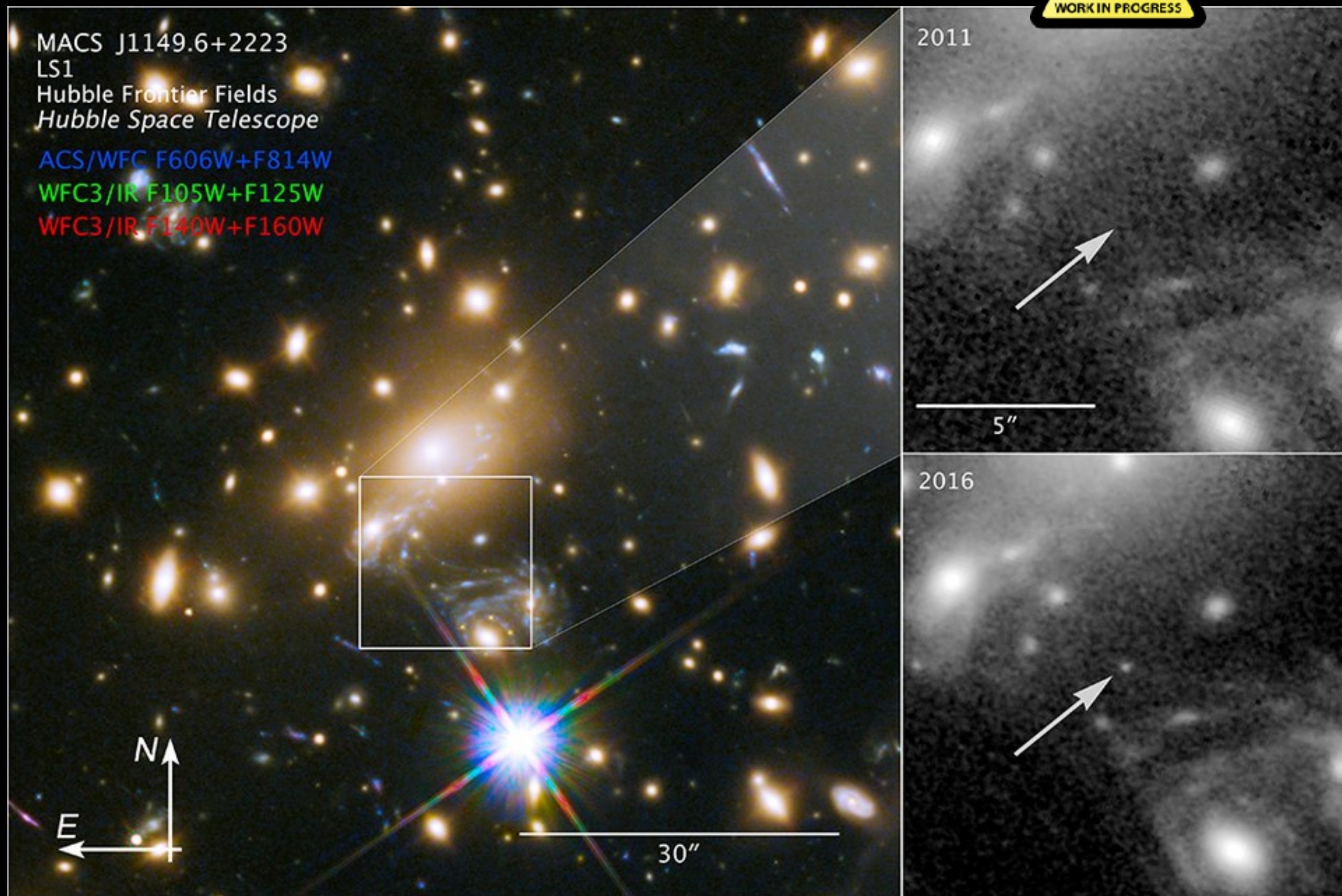


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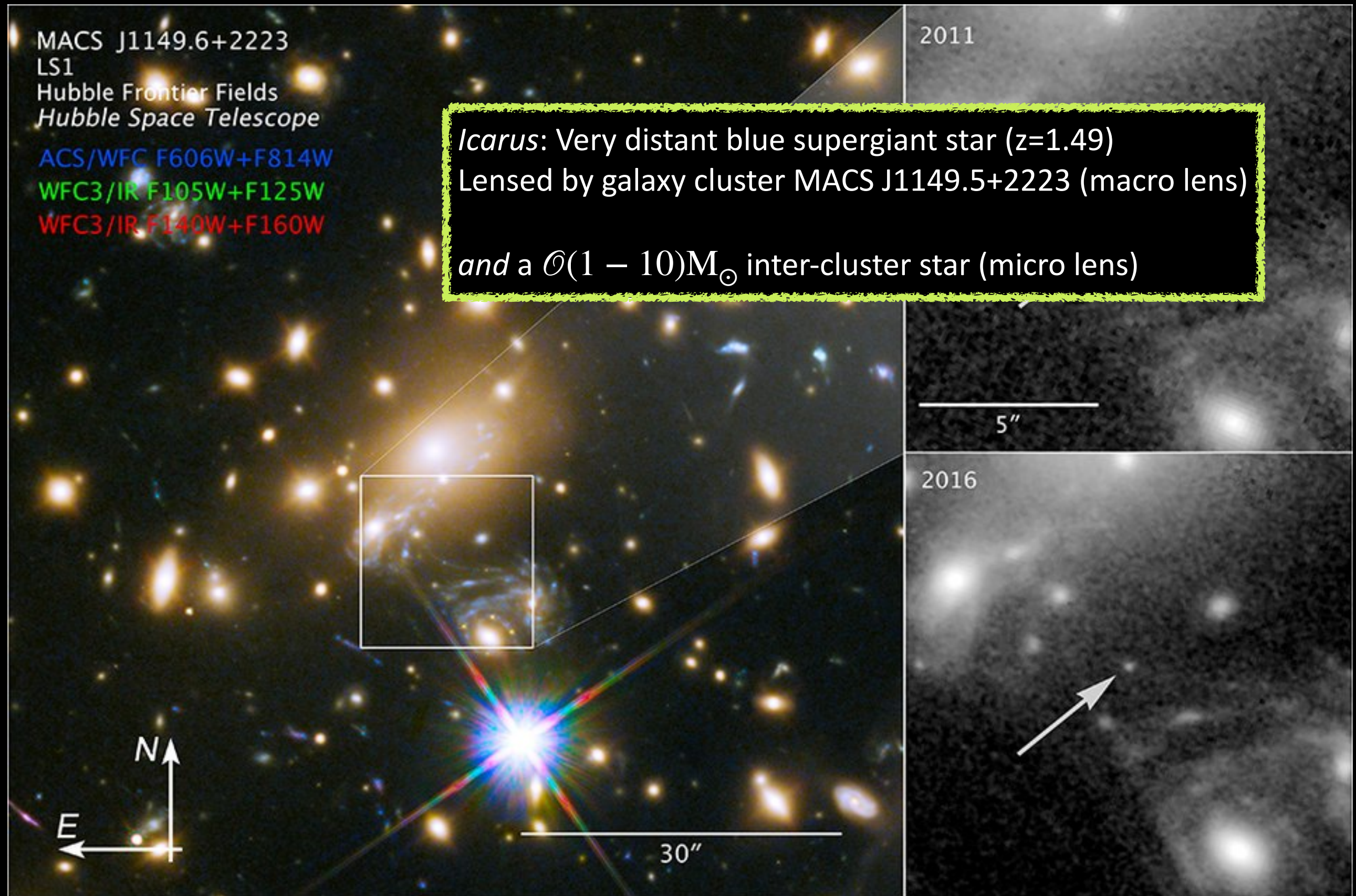
*Miguel Crispim-Romao, DC, Benedict Crossey, Daniel Godines, PRD, arXiv:2506.20709*



# Caustic crossings in giant arcs



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$$u_1 = \frac{\tau_1}{\mu_r} - \frac{\tau_1}{\tau^2}$$
$$u_2 = \frac{\tau_2}{\mu_t} - \frac{\tau_2}{\tau^2}$$

*Oguri et al, PRD,*  
*arXiv:1710.00148*

tangential and radial  
macro-magnifications

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Oguri et al, PRD,  
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tangential and radial  
macro-magnifications



$$u_1 = \frac{\tau_1}{\mu_r} - \frac{\tau_1}{\tau^2}m(\tau)$$

$$u_2 = \frac{\tau_2}{\mu_t} - \frac{\tau_2}{\tau^2}m(\tau)$$

DC, Crossey, Diego, Kavenagh,  
Palencia, arXiv:25XX.XXXX

Local convergence



Mean convergence



-Tangential shear

$$\mu^{-1} = \left| \left( \frac{1}{\mu_r} - \frac{m'(\tau)}{2\tau} \right) \left( \frac{1}{\mu_t} - \frac{m'(\tau)}{2\tau} \right) - \left( \frac{m'(\tau)}{2\tau} - \frac{m(\tau)}{\tau^2} \right)^2 + \left( \frac{1}{\mu_r} - \frac{1}{\mu_t} \right) \left( \frac{m'(\tau)}{2\tau} - \frac{m(\tau)}{\tau^2} \right) \cos 2\phi \right|$$

$m(\tau) = 0 \rightarrow$  recover macro-lens only result  $\mu^{-1} = (\mu_t \mu_r)^{-1}$   
 $m(\tau) = 1 \rightarrow$  recover point-like result

# Caustic crossings in giant arcs

Point-like lens

Animation by Ben Crossey

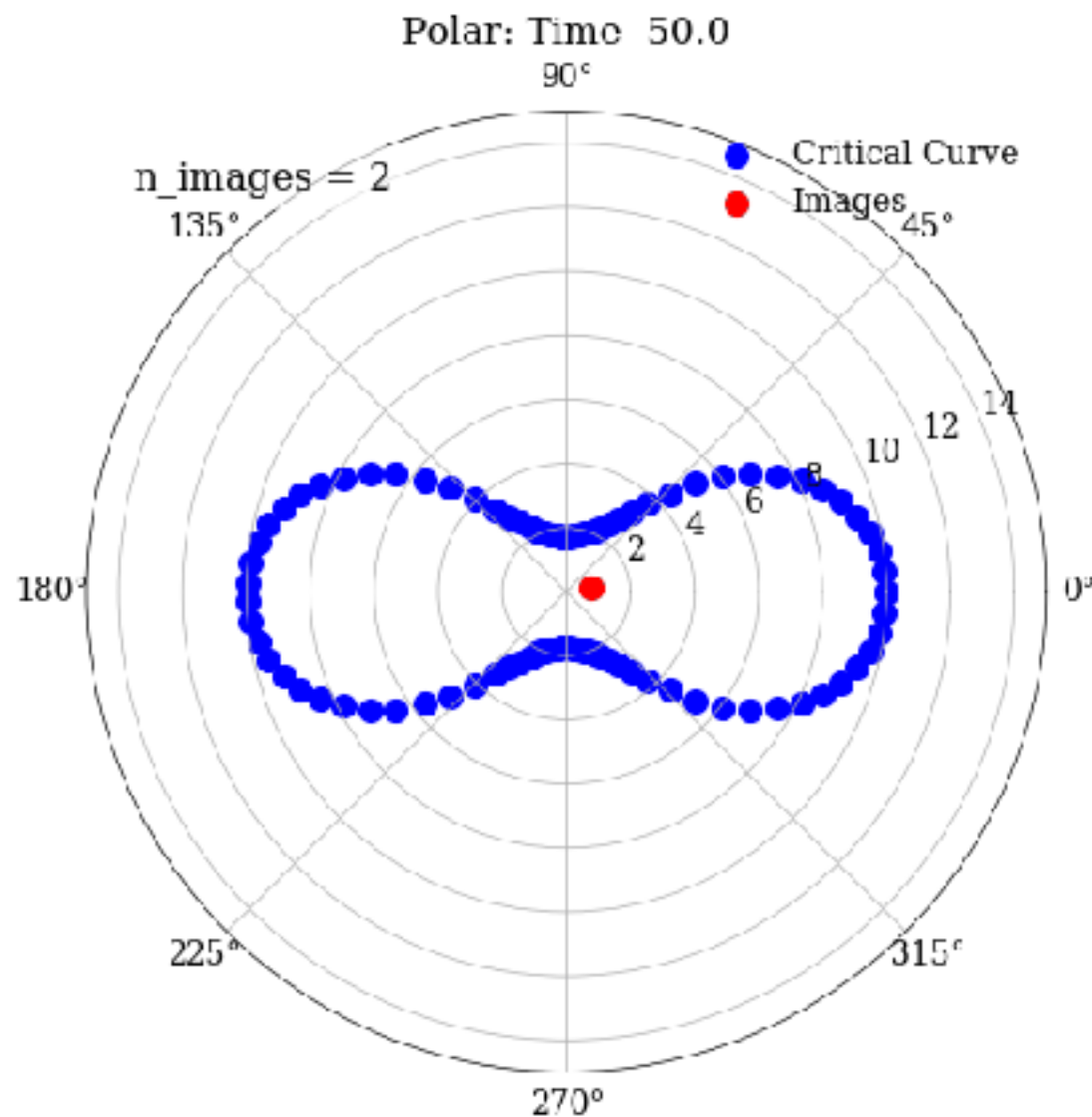
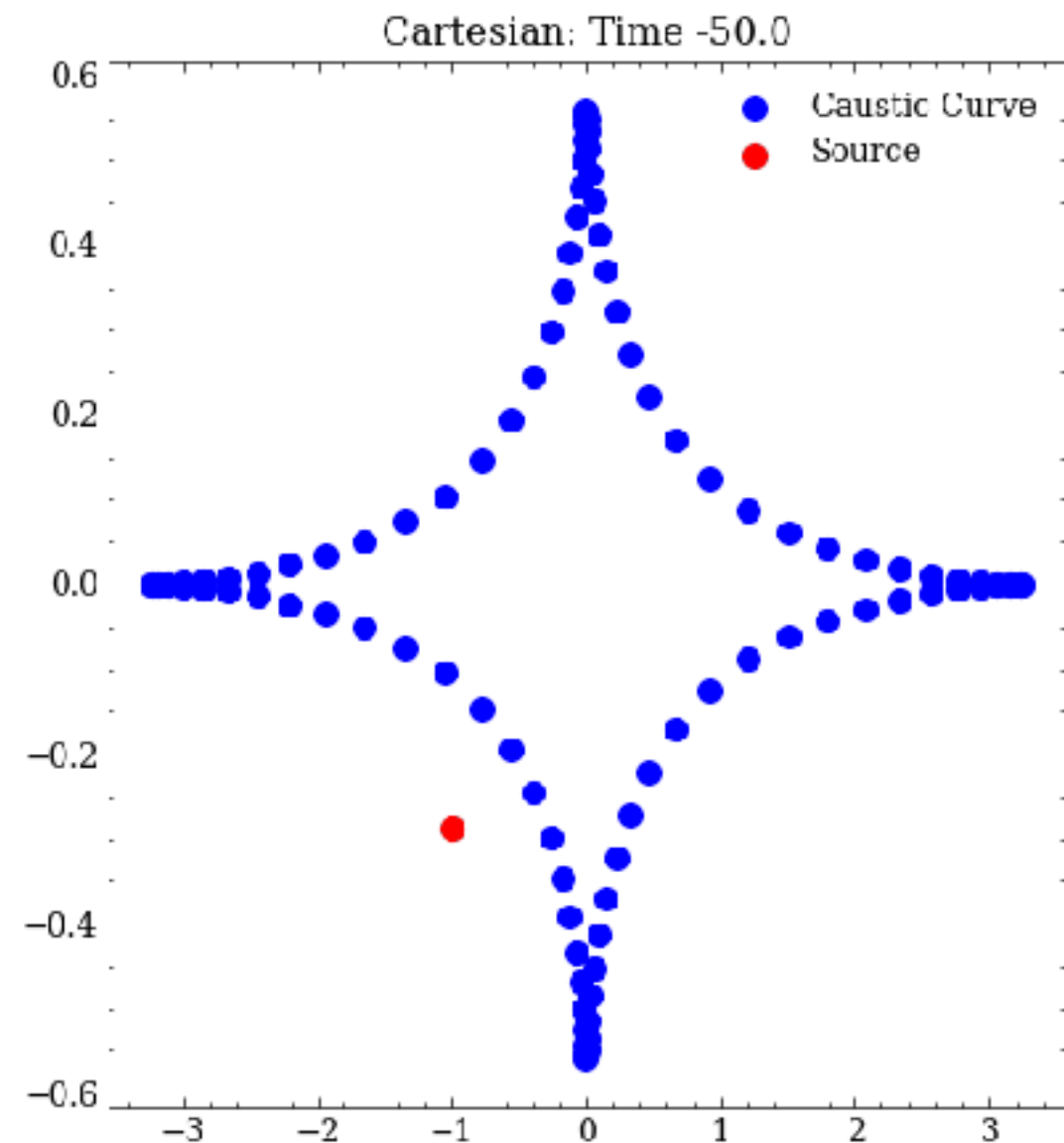


Image plane: critical curves



Source plane: caustic curves

# Caustic crossings in giant arcs

Boson star with  $\tau_m = 2$

Animation by Ben Crossey

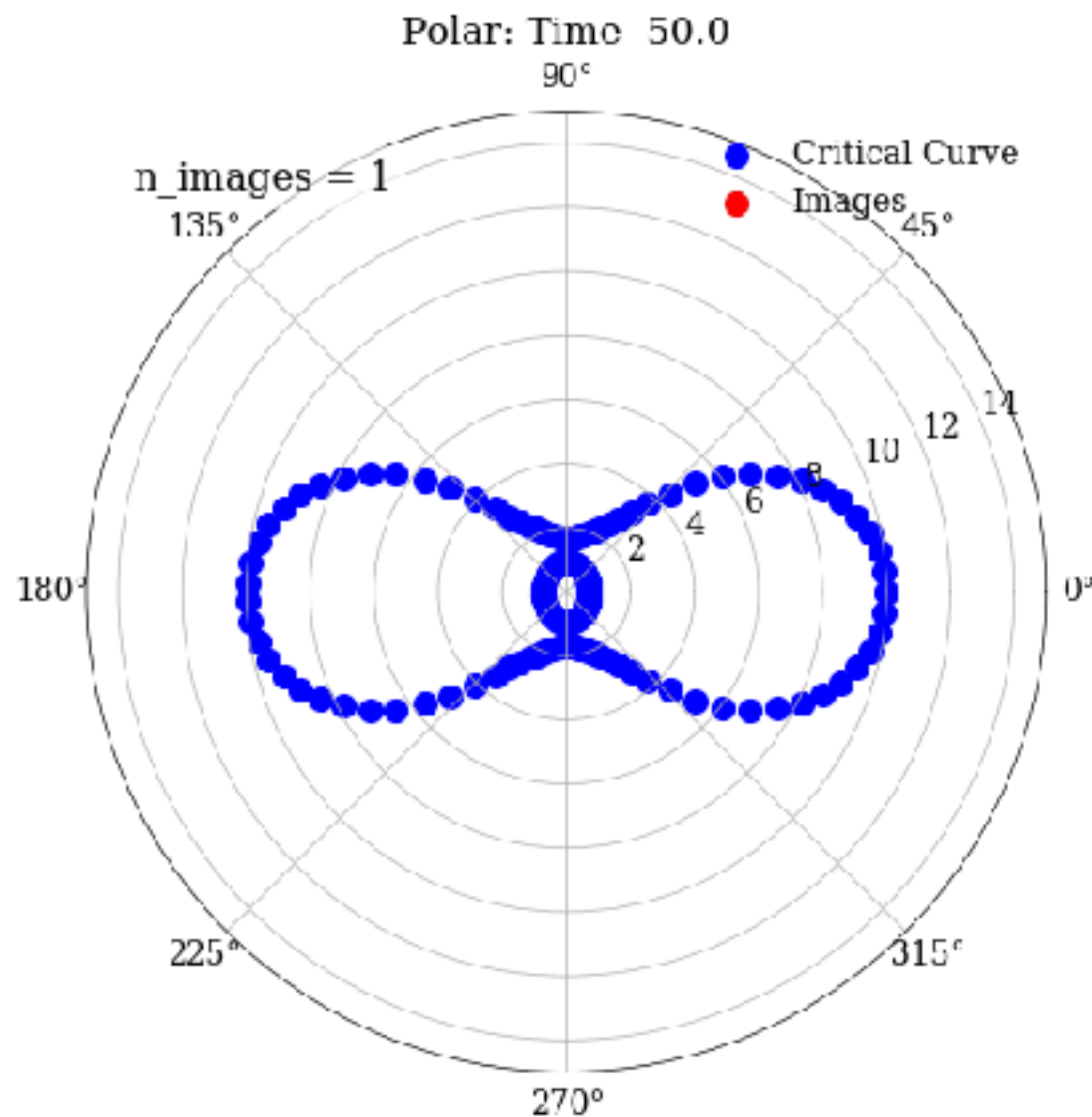
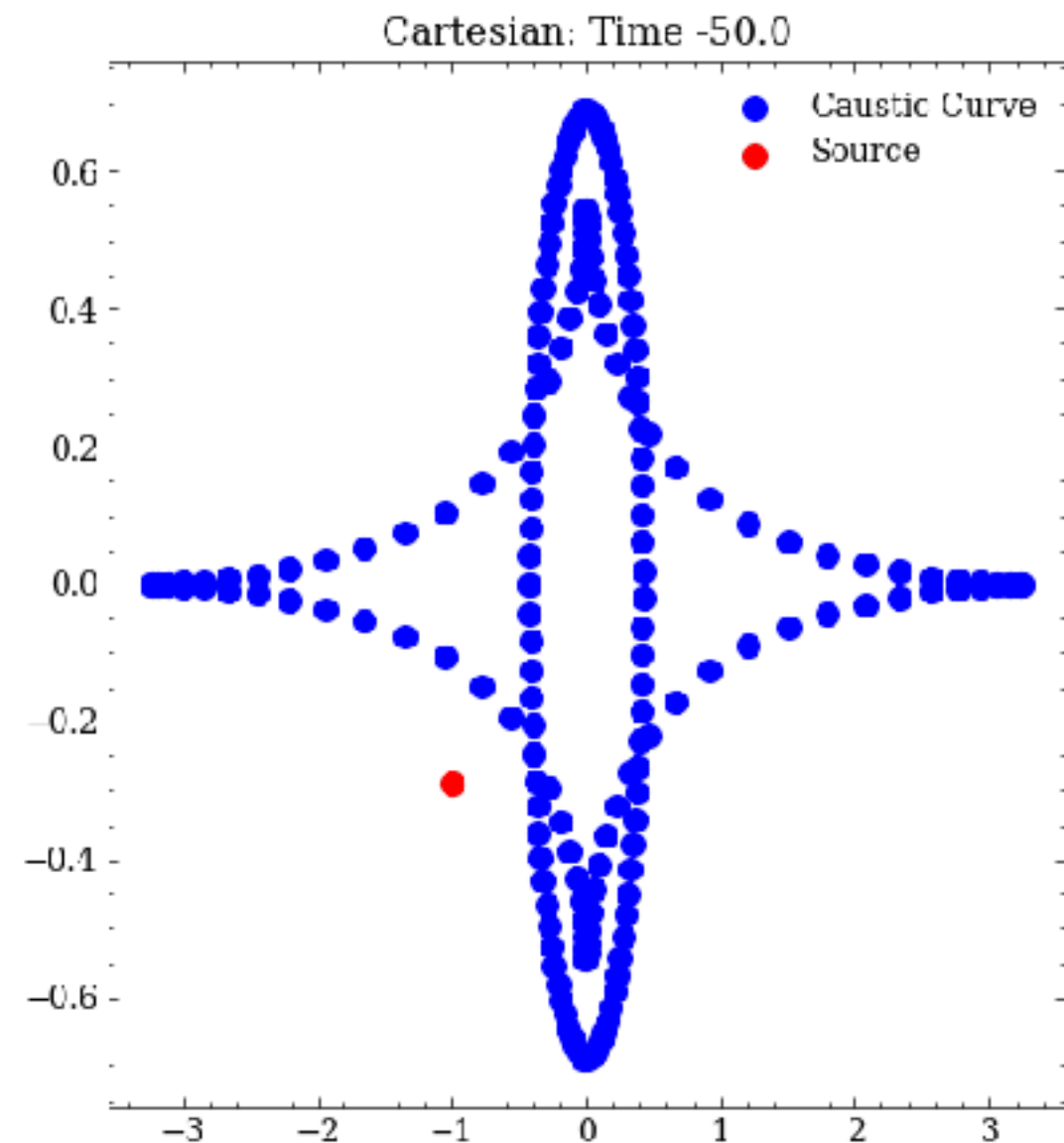


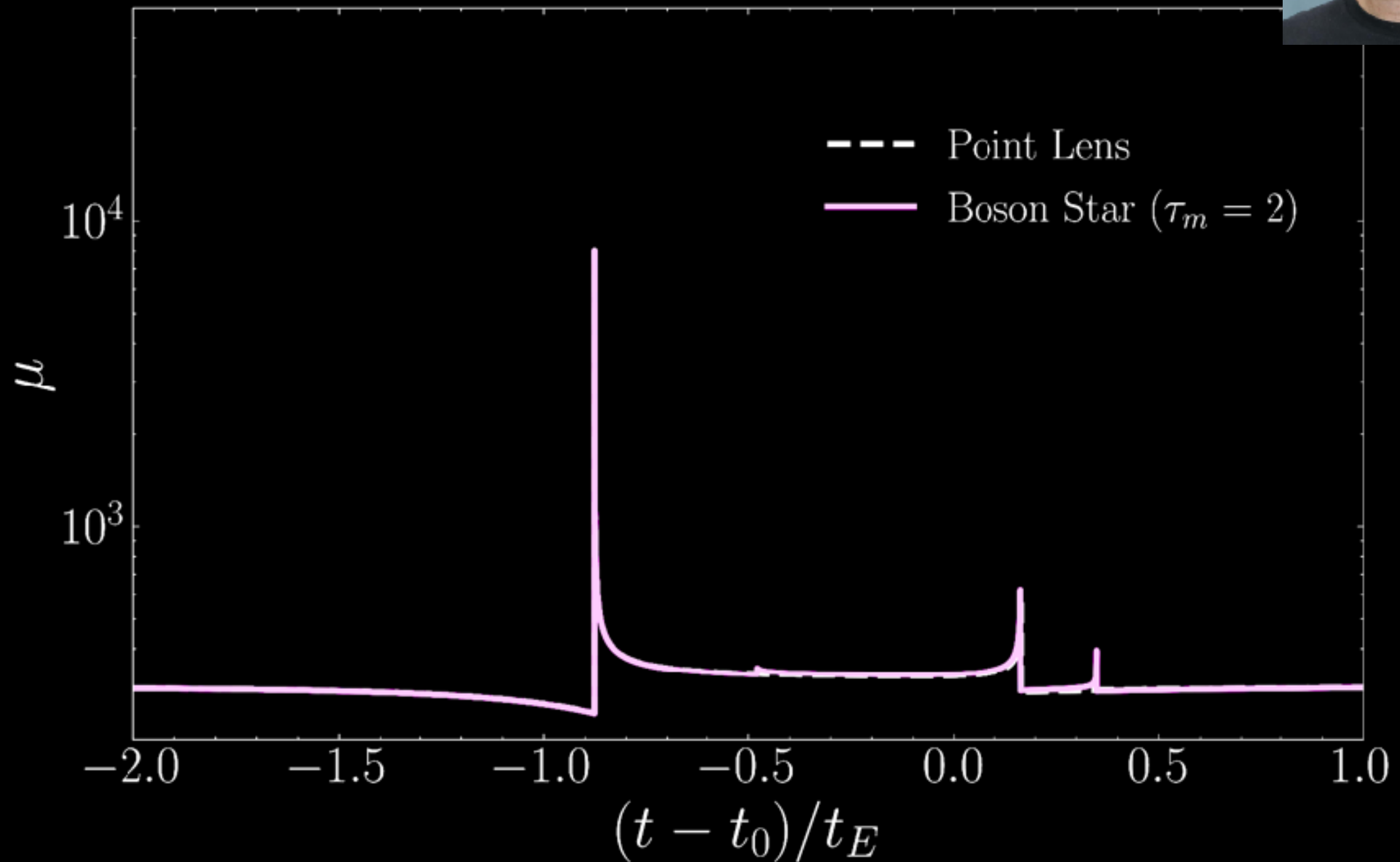
Image plane: critical curves



Source plane: caustic curves

# Caustic crossings in giant arcs

Boson star with  $\tau_m = 2$



# Caustic crossings in giant arcs

Boson star with  $\tau_m = 22$

Animation by Ben Crossey

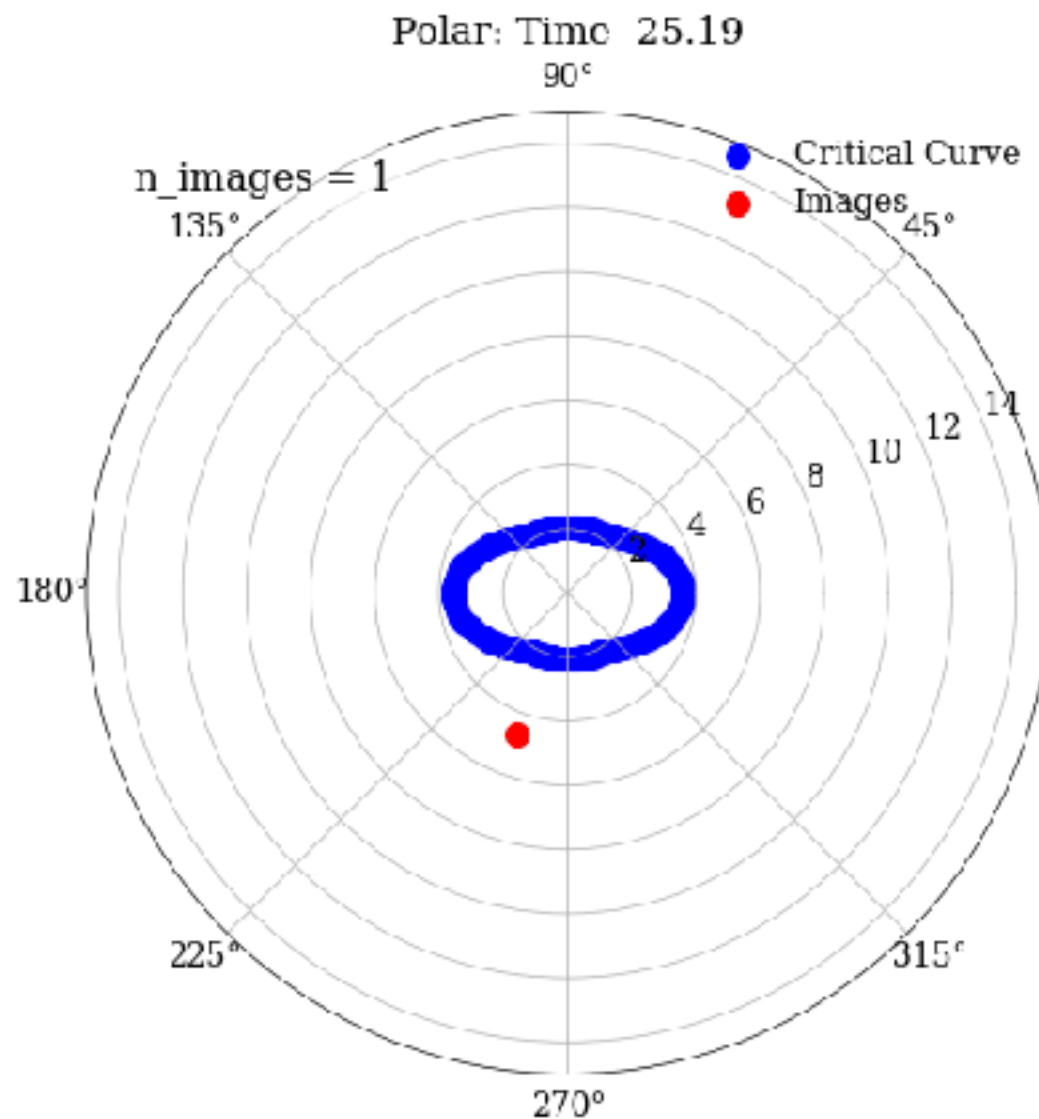
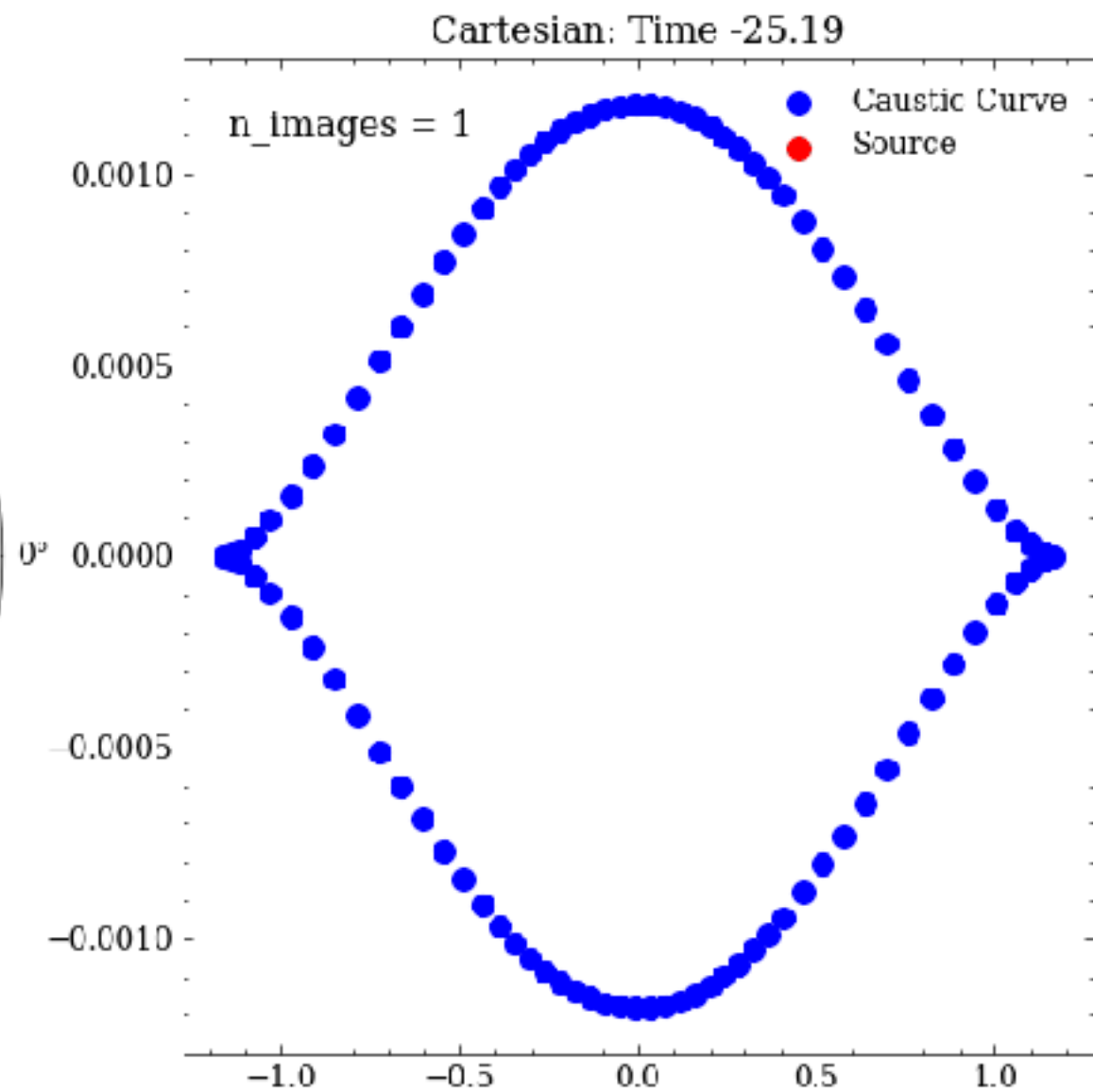


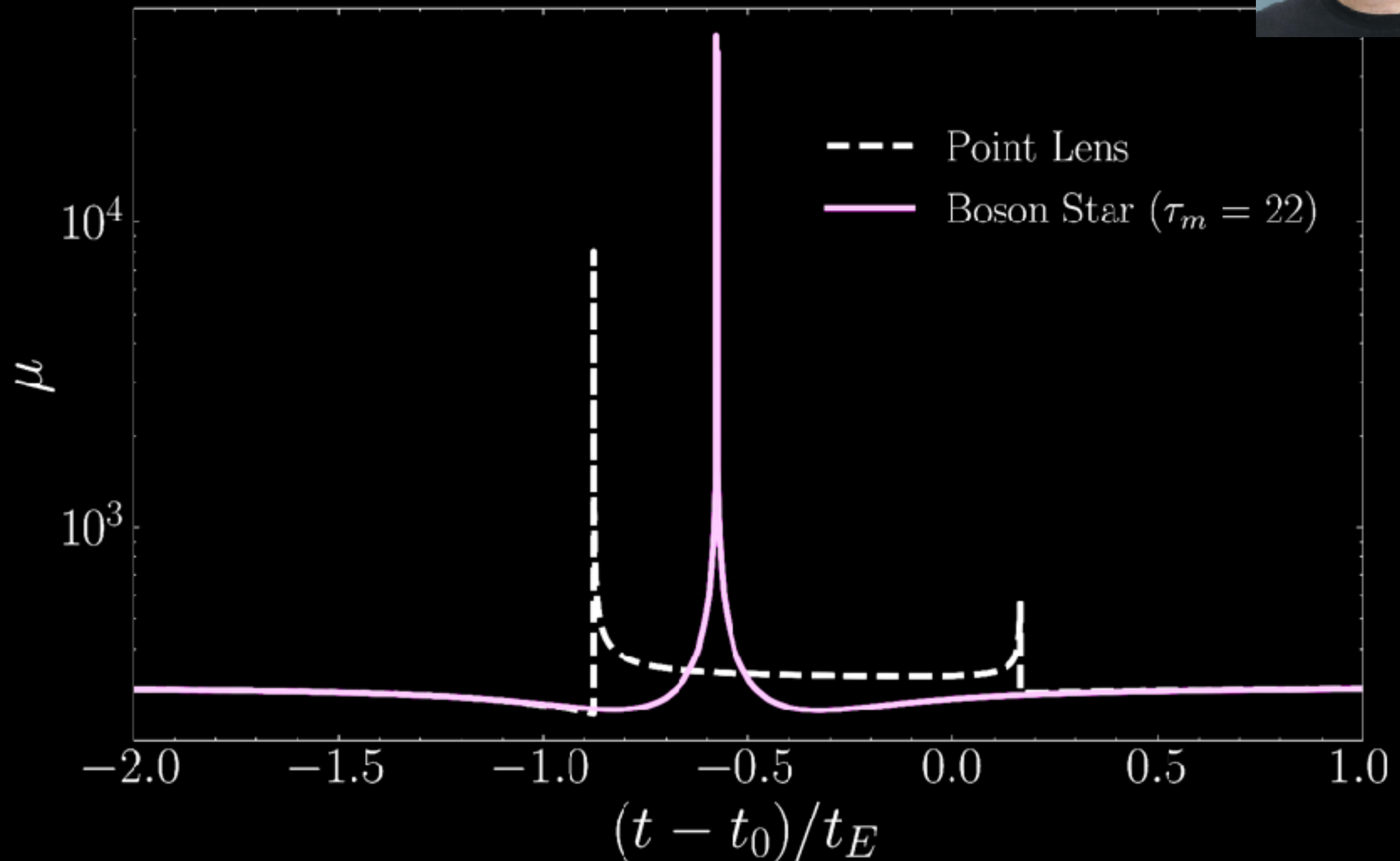
Image plane: critical curves



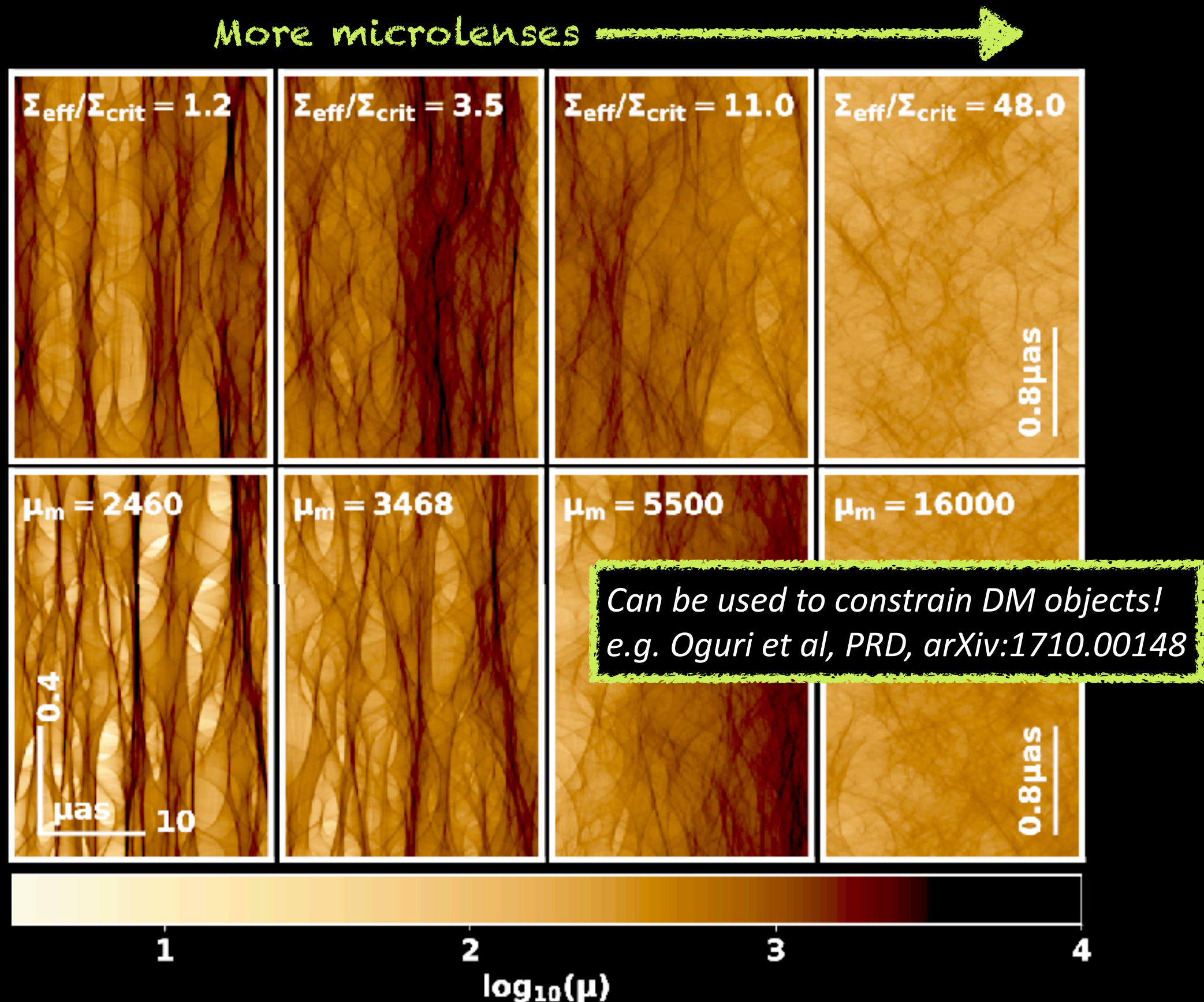
Source plane: caustic curves

# Caustic crossings in giant arcs

Boson star with  $\tau_m = 22$



# Caustic crossings in giant arcs

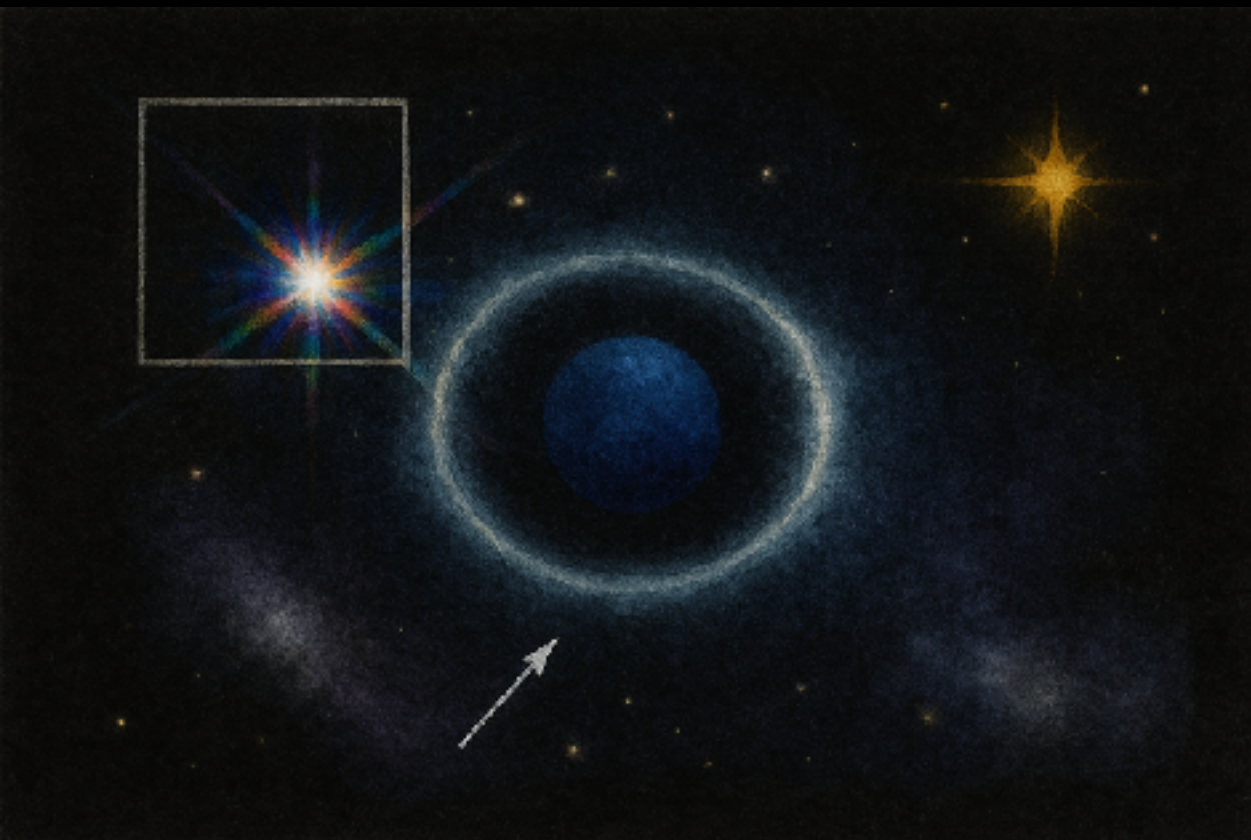


# Caustic crossings in giant arcs

In a macro-lens background, Einstein radius of a microlens effectively **boosted by**  $\sqrt{\mu_t}$

*e.g. Diego et al., ApJ, arXiv:1706.10281*

Einstein radius already large as  $\propto \sqrt{\text{distance}}$

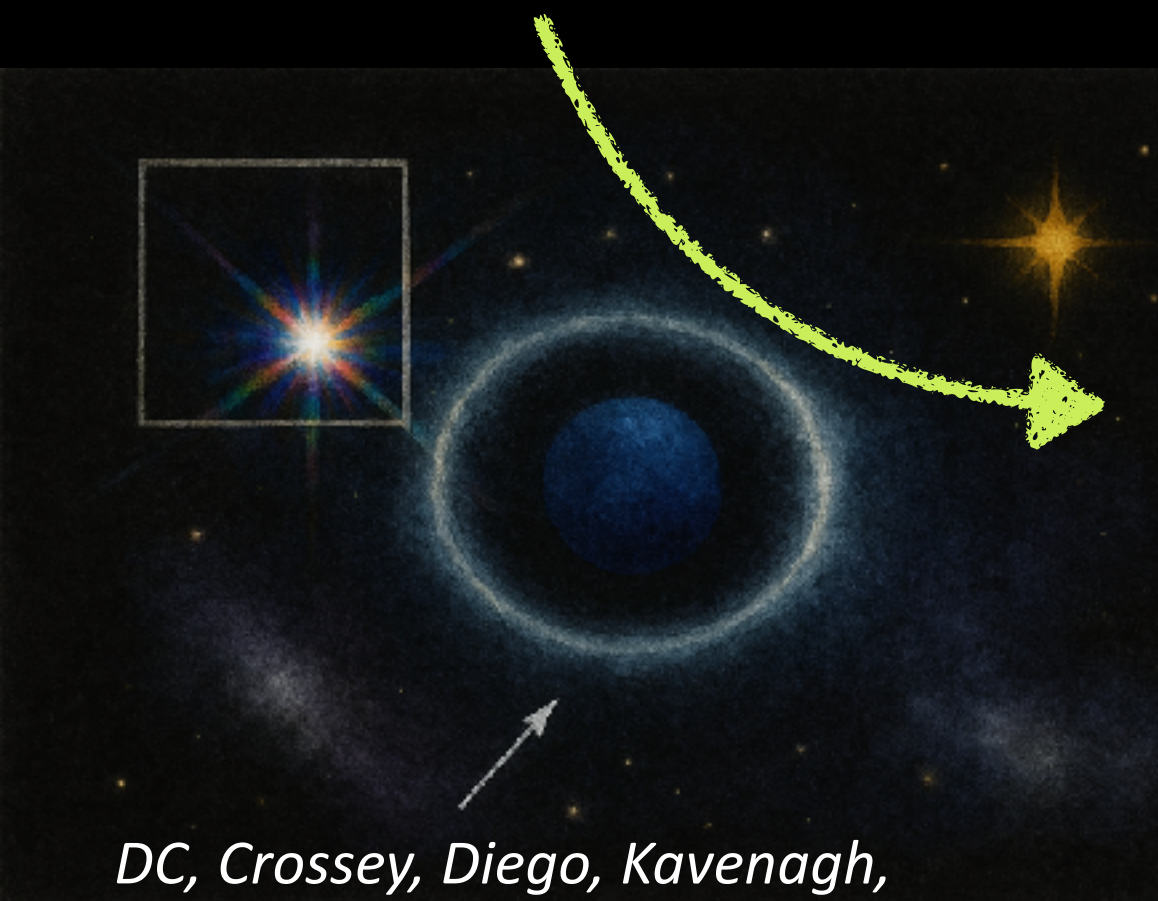


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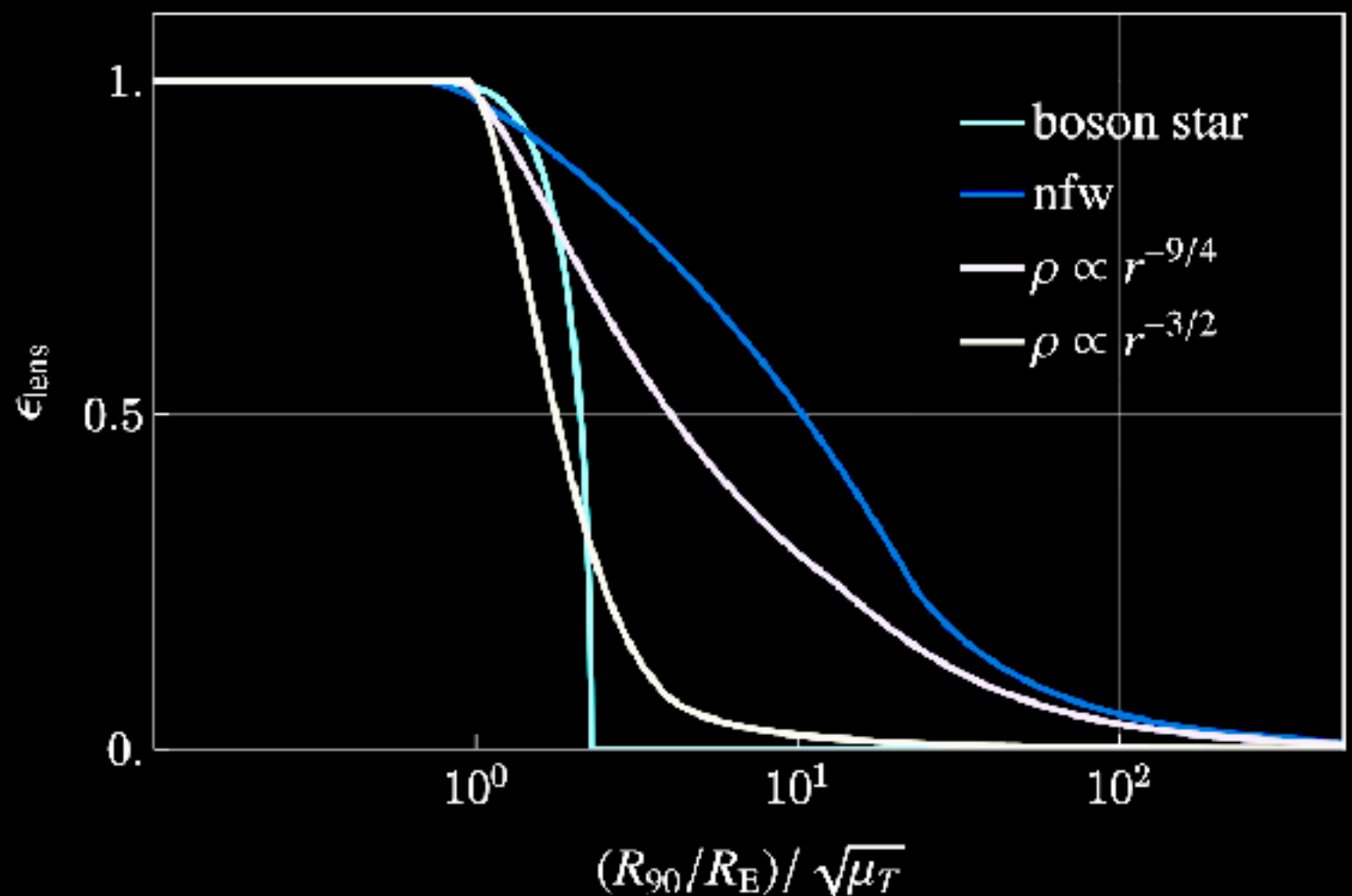
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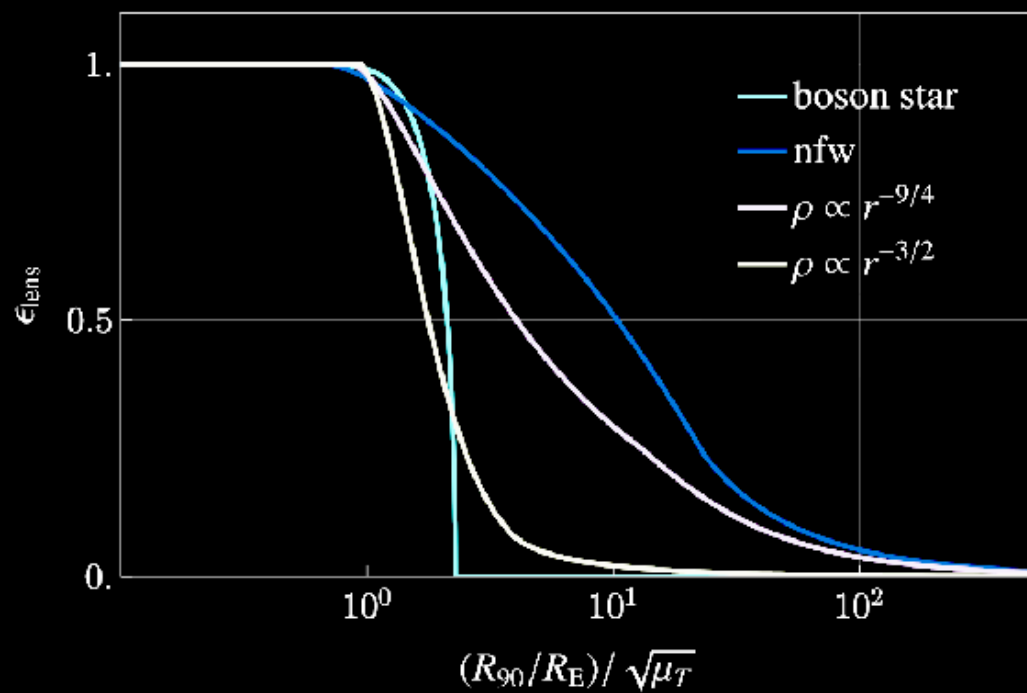
→ define an extended lens **efficiency**  $\epsilon_{\text{lens}}^2 - m \left( \epsilon_{\text{lens}} \sqrt{\mu_t} \right) = 0$   
 such that for  $m(\tau) = 1$ ,  $\epsilon_{\text{lens}} = 1$  this is the one of the roots of  $\mu^{-1}$



*DC, Crossey, Diego, Kavenagh,  
 Palencia, arXiv:25XX.XXXX*



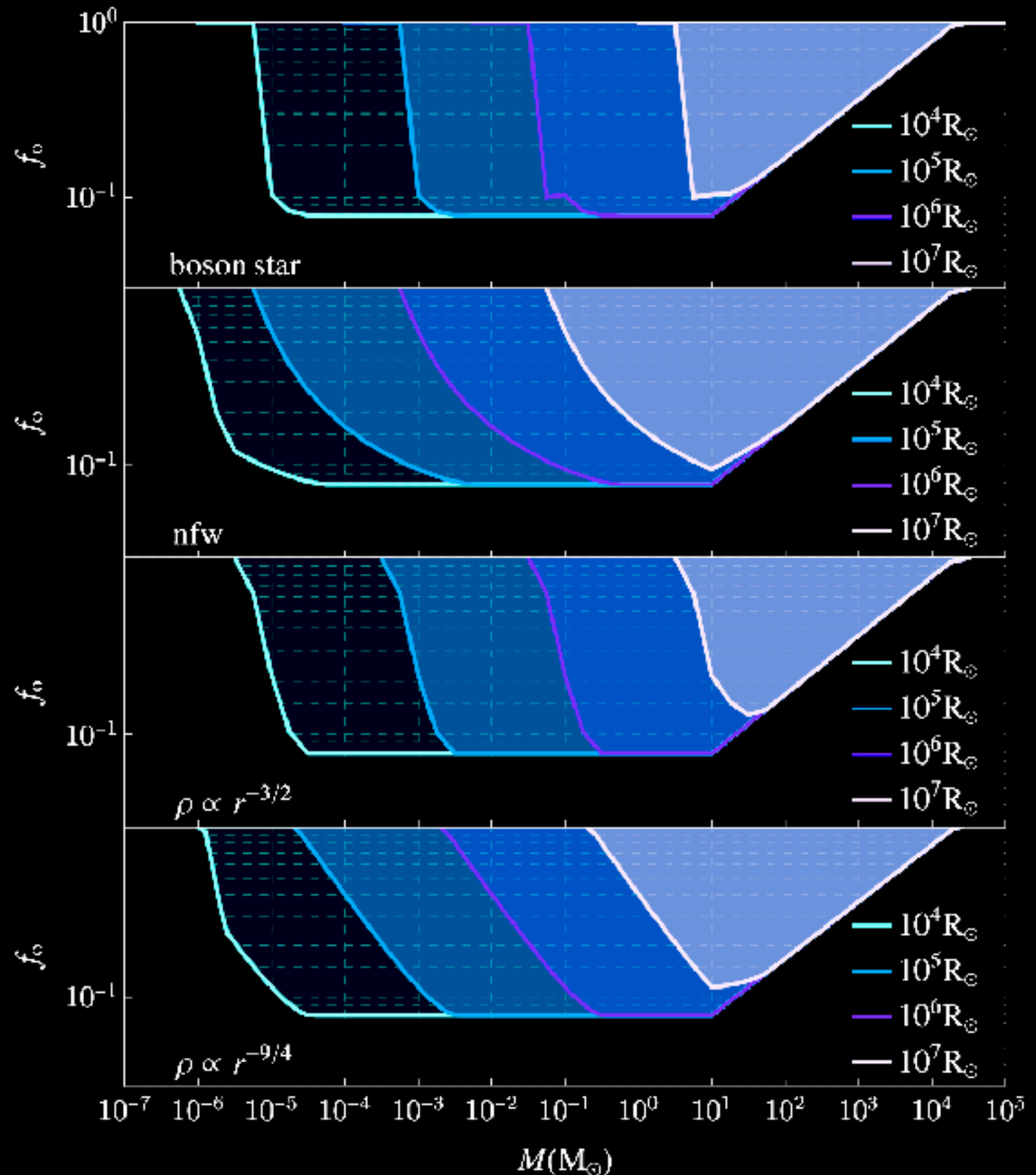
# Caustic crossings in giant arcs



Using this efficiency,  
generalise Icarus constraints

Not competitive for PBHs, but  
sensitive to much more dilute EDOs  
than galactic microlensing

DC, Crossey, Diego, Kavenagh,  
Palencia, arXiv:25XX.XXXX

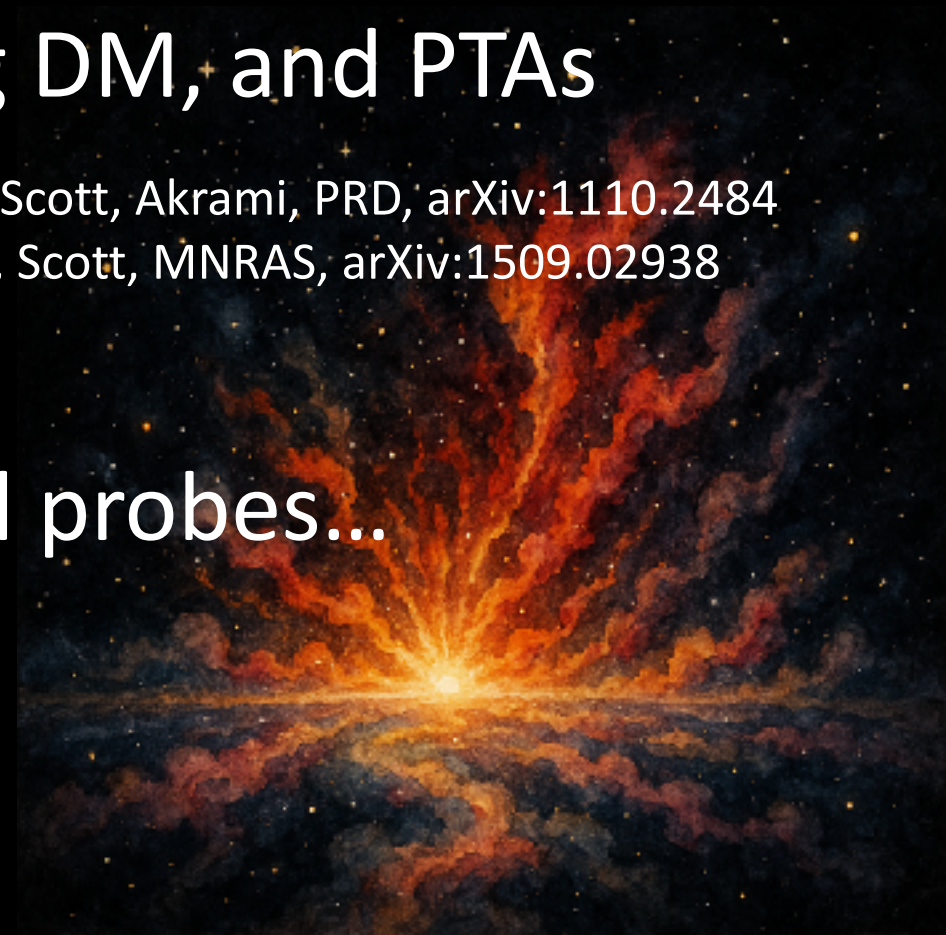


# EDOs and the early Universe

- Ultracompact mini haloes (UCMH,  $\rho \sim r^{-3/2}$ ) are formed from the collapse of **primordial overdensities**
- The non-observation of UCMH can therefore be used to draw conclusions about the **primordial power spectrum**
- This has been done for e.g. annihilating DM, and PTAs
- But we now have far more gravitational probes...

Bringmann, Scott, Akrami, PRD, arXiv:1110.2484

Clark, Lewis, Scott, MNRAS, arXiv:1509.02938



# The primordial power spectrum

- Assume a generalised power spectrum

- EDOs formed with

$$\frac{R(z_c)}{\text{pc}} = 0.02 \left( \frac{1000}{z_c + 1} \right) \left( \frac{M(z_c)}{M_\odot} \right)^{1/3} \quad \text{with } M(z_c) = \frac{z_{\text{eq}} + 1}{z_c + 1} M_i$$

Effective radius where UCMH density has dropped to  $3 \times$  the background density



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This means not all EDO constraints map to primordial power spectrum constraints

- $f_{\text{DM}} < 1$  for

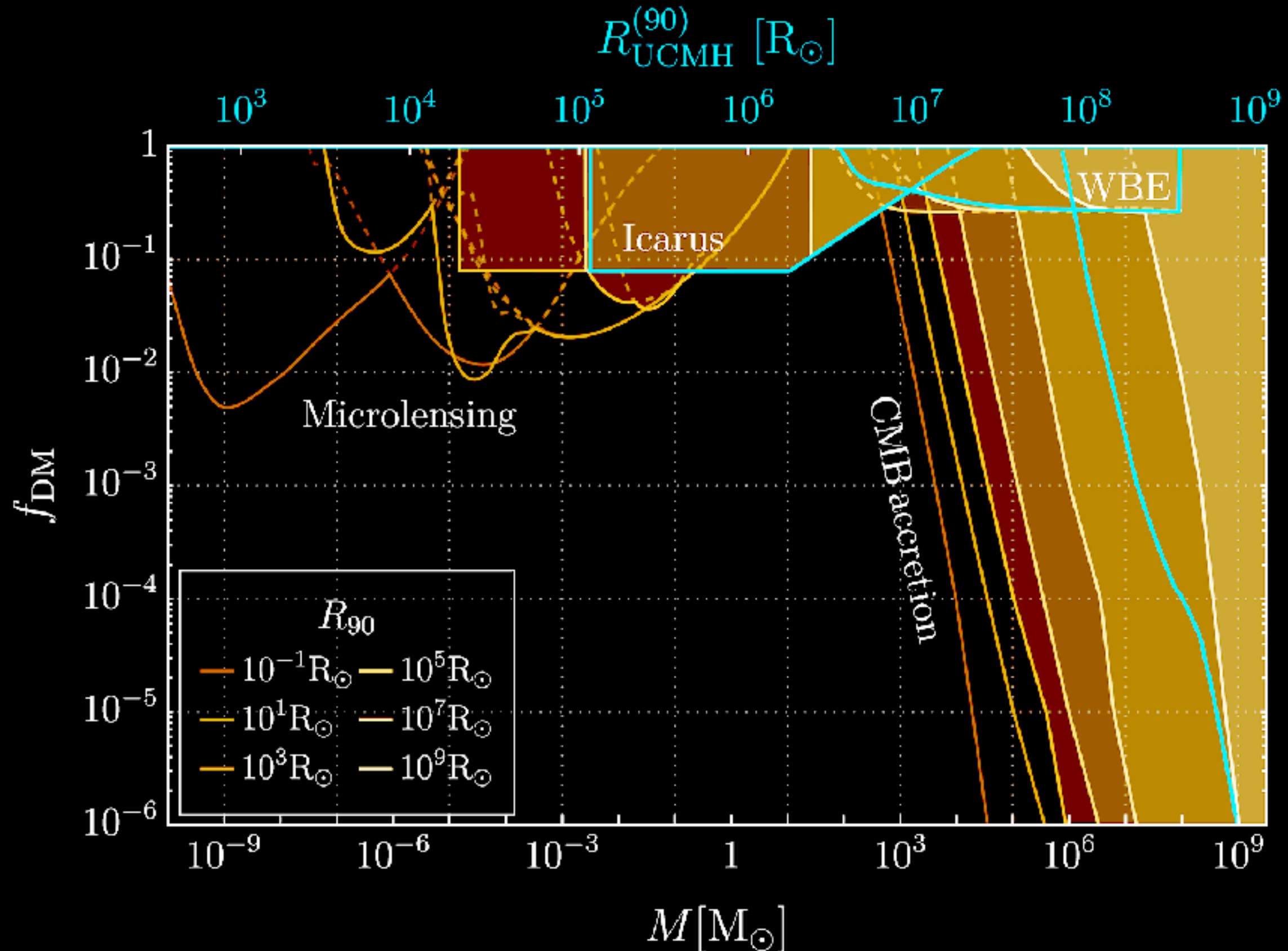


- CMB accretion (generalised to larger EDOs)
- Wide binary evaporation
- “ICARUS” microlensing (generalised from PBHs to EDOs)

DC, Sevillano Muñoz, JCAP,  
arXiv:2403.13072

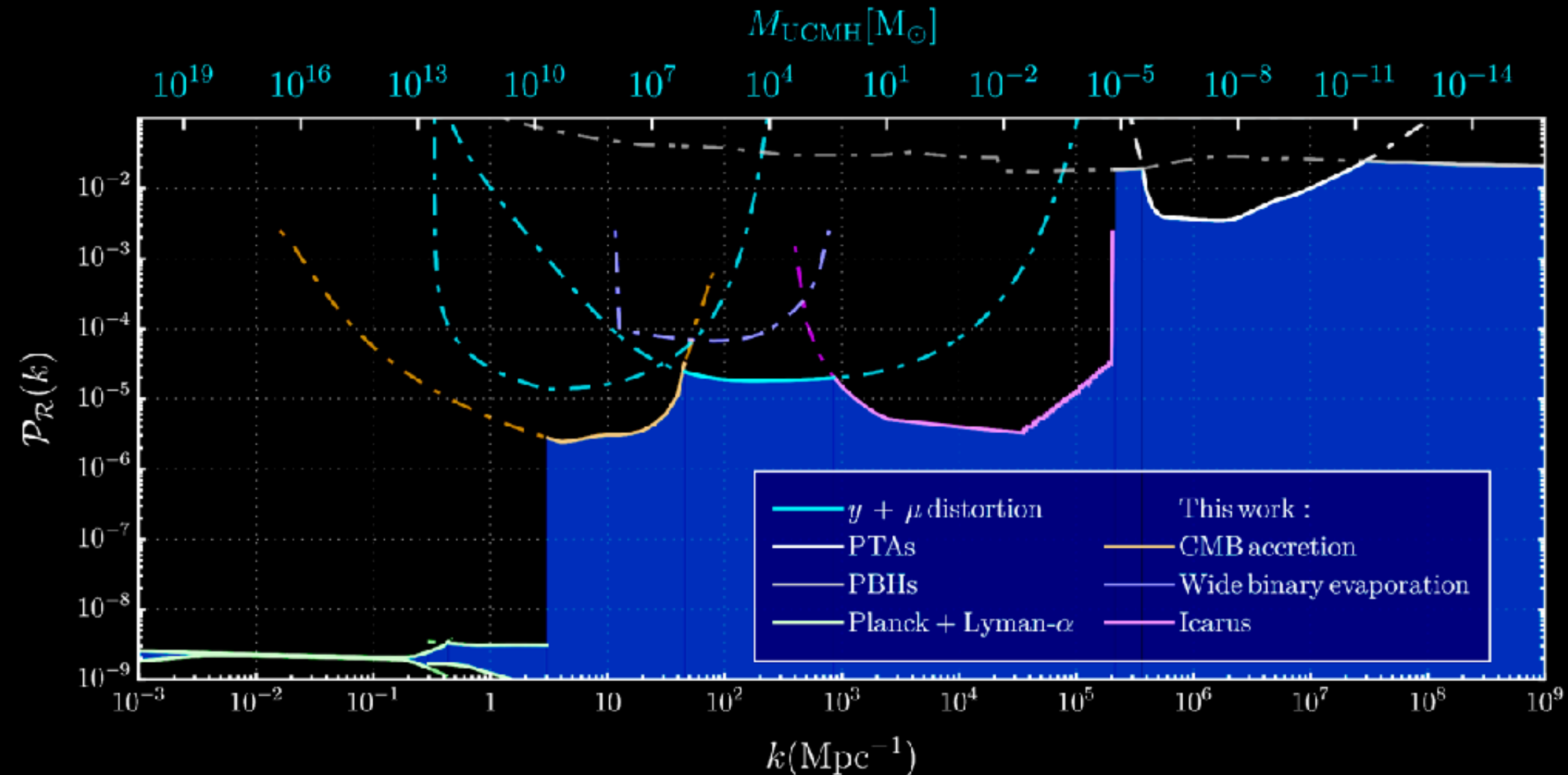
Ramirez and Buckley, MNRAS,  
arXiv:2209.08100

# The primordial power spectrum



# The primordial power spectrum

$$\text{for UCMH collapsing at } z_c, \quad \frac{R(z_c)}{\text{pc}} = 0.02 \left( \frac{1000}{z_c + 1} \right) \left( \frac{M(z_c)}{M_\odot} \right)^{1/3} \quad \text{with } M(z_c) = \frac{z_{\text{eq}} + 1}{z_c + 1} M_i$$



# To conclude,

- All of our current evidence for dark matter is gravitational; many models feature substructure
- 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**
  - Non-observation can be used to derive **constraints**



# To conclude,

- All of our current evidence for dark matter is gravitational; many models feature substructure
- 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**
  - Non-observation can be used to derive **constraints**
- Caustic crossings in giant arcs can probe lenses with even bigger radii
- Non-observations of UCMH constrain the **curvature power spectrum** on CMB-inaccessible scales



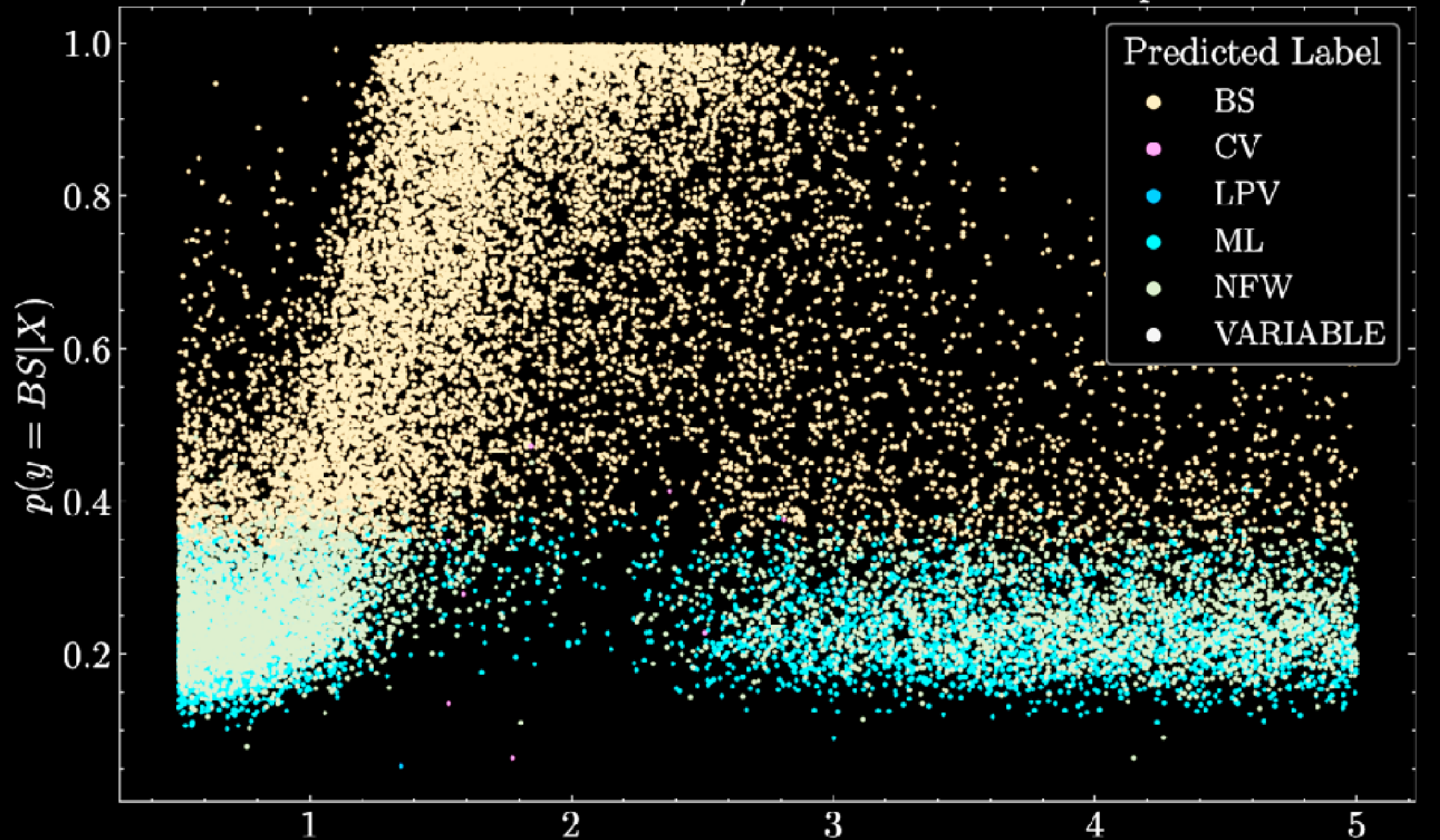
Thank you!

...ask me anything you like!

[djuna.l.croon@durham.ac.uk](mailto:djuna.l.croon@durham.ac.uk) | [djunacroon.com](http://djunacroon.com)

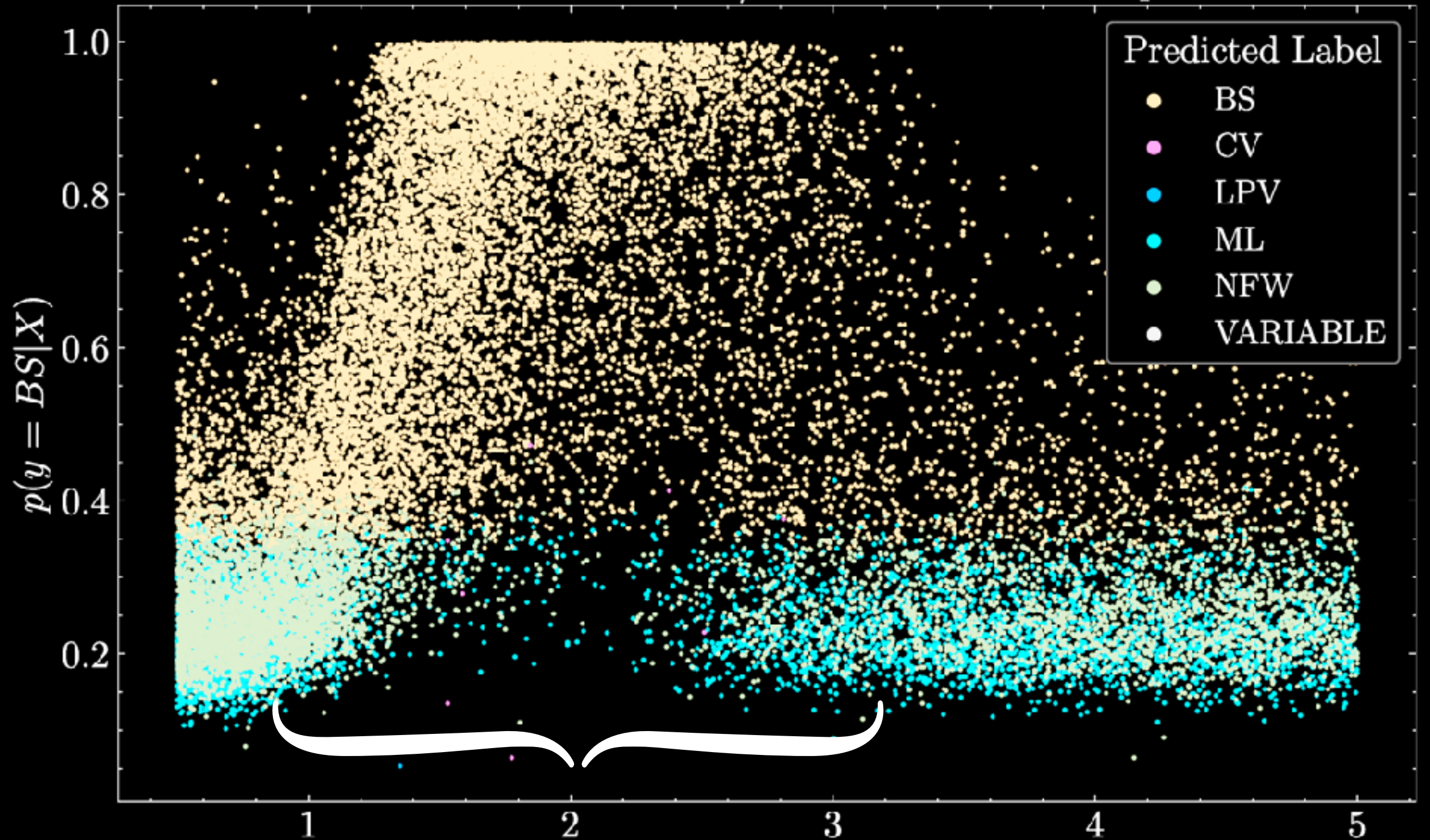


## Boson Star Events w/ OGLE-II Timestamps

 $\tau_m$ 

$$\tau_m \equiv \theta_{\text{lens}}/\theta_E = r_{\text{lens}}/r_E$$

## Boson Star Events w/ OGLE-II Timestamps

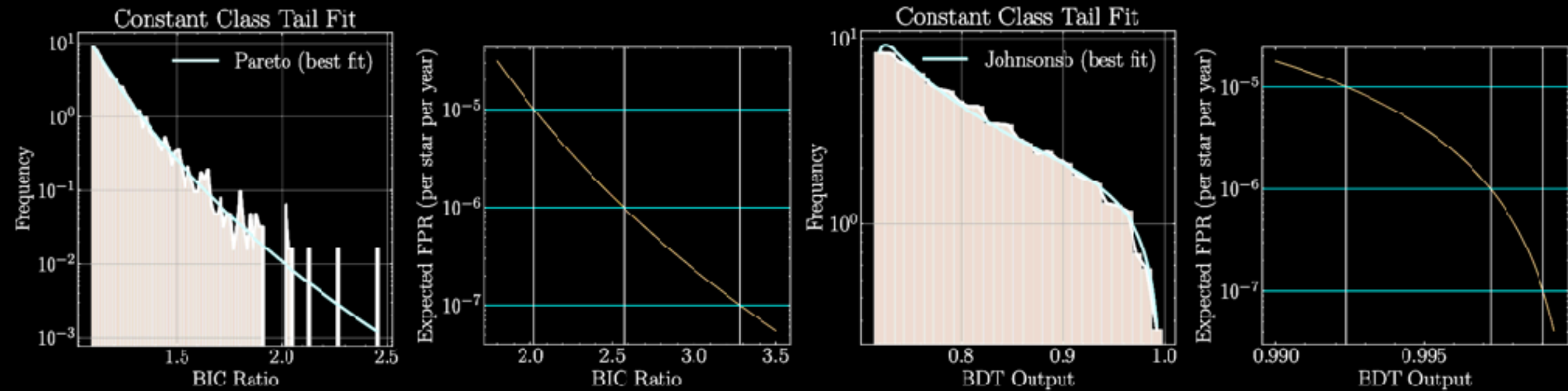


Indeed, the most probable  
detections are for  $0.8 < \tau_m < 3$

$$\tau_m \equiv \theta_{\text{lens}}/\theta_E = r_{\text{lens}}/r_E$$

# LSST by Rubin: projections

Miguel Crispim-Romao, DC, Benedict Crossey, Daniel Godines, PRD, arXiv:2506.20709



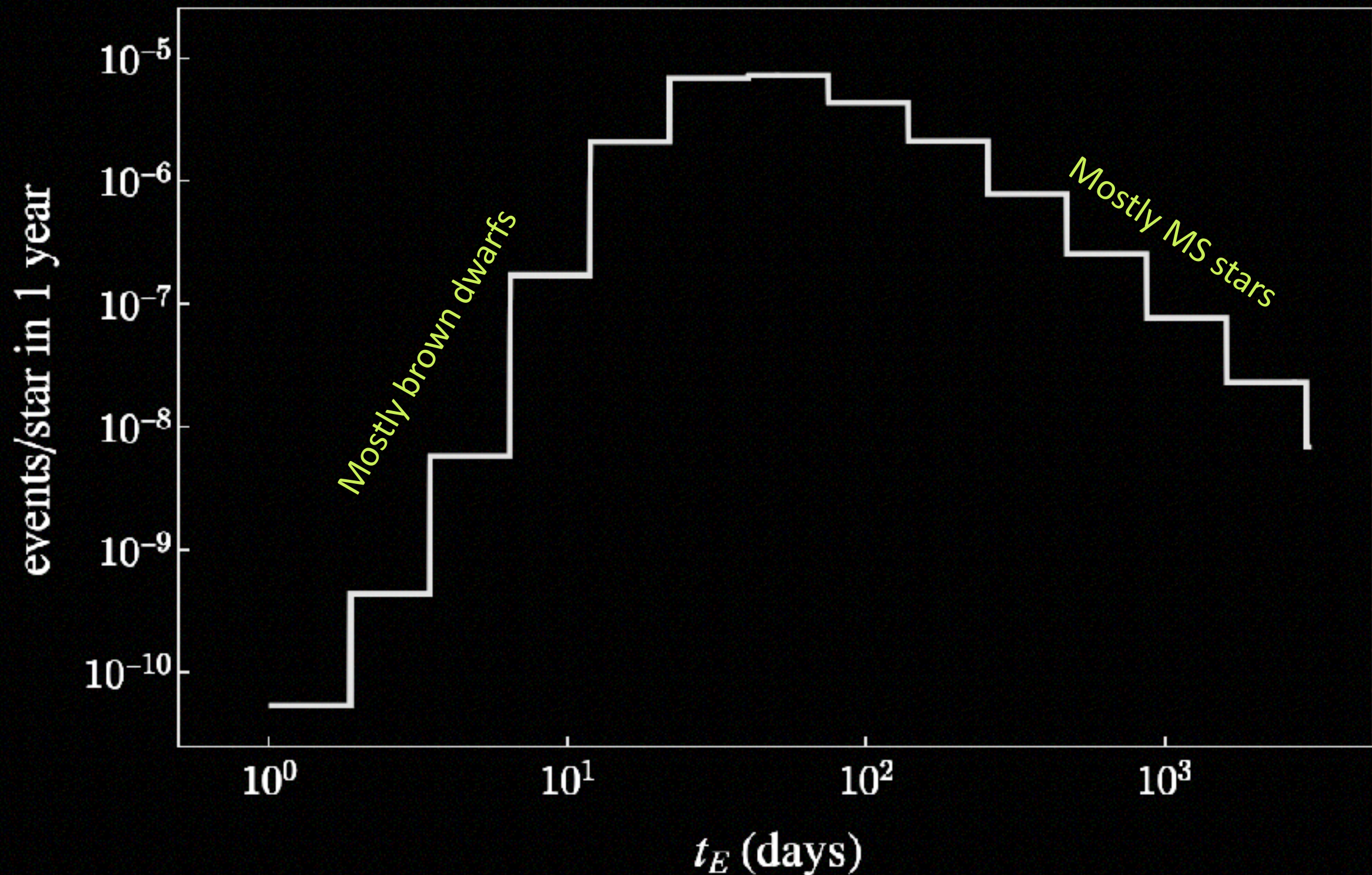
For competitive constraints,  
need  $FPR < 10^{-7}$

| cut                                                | FPR                  | $\bar{\epsilon}$ |
|----------------------------------------------------|----------------------|------------------|
| BIC ratio $> 3.28$                                 | $10^{-7}$            | 0.38             |
| BDT $> 0.999$                                      | $10^{-7}$            | 0.34             |
| $\chi^2/\text{d.o.f. ratio} > 10$                  | $3.5 \times 10^{-4}$ | 0.30             |
| $\chi^2/\text{d.o.f. ratio} > 10, \tilde{u}_0 < 1$ | $1.1 \times 10^{-4}$ | 0.20             |

# LSST by Rubin: projections

*Miguel Crispim-Romao, DC, Benedict Crossey, Daniel Godines, PRD, arXiv:2506.20709*

Foreground



# The primordial power spectrum

- Primordial curvature perturbations with amplitude  $\mathcal{P}_{\mathcal{R}}(k)$  determine the variance  $\sigma_{\chi,H}(R)$  of CDM density fluctuations at horizon entry
  - If  $\delta_{\chi}(R)$  exceeds a threshold  $\delta_{\chi}^{\min}(R) \sim 10^{-3}$ , the region collapses into an UCMH (much smaller than for PBHs)
  - If  $\sigma_{\chi,H}(R)$  is too large many regions will exceed  $\delta_{\chi}^{\min}(R)$

# The primordial power spectrum

- Primordial curvature perturbations with amplitude  $\mathcal{P}_{\mathcal{R}}(k)$  determine the variance  $\sigma_{\chi,H}(R)$  of CDM density fluctuations at horizon entry
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  - If  $\sigma_{\chi,H}(R)$  is too large many regions will exceed  $\delta_{\chi}^{\min}(R)$
- From  $f_{\text{DM}}$  we **work backward**:
  - $f_{\text{DM}}$  sets a max collapse probability  $\beta_{\max}(R)$  at redshift  $z_c$
  - In Gaussian theory,  $\beta(R) \sim \exp[-\delta_{\min}^2/(2\sigma^2(R))]$ . Thus  $\beta_{\max}$  fixes the largest allowable  $\sigma(R)$
  - Since  $\sigma^2(R)$  is essentially an integral over  $\mathcal{P}_{\mathcal{R}}(k)$  around  $k \sim 1/R$ , limiting  $\sigma(R) \Rightarrow$  upper limit on  $\mathcal{P}_{\mathcal{R}}(k)$