Dark archaeology: cosmology through gravitational probes of dark objects

Djuna Lize Croon (IPPP Durham)

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djuna.l.croon@durham.ac.uk | djunacroon.com

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

I call objects like these EDOs (extended dark objects)

How do we look for it?

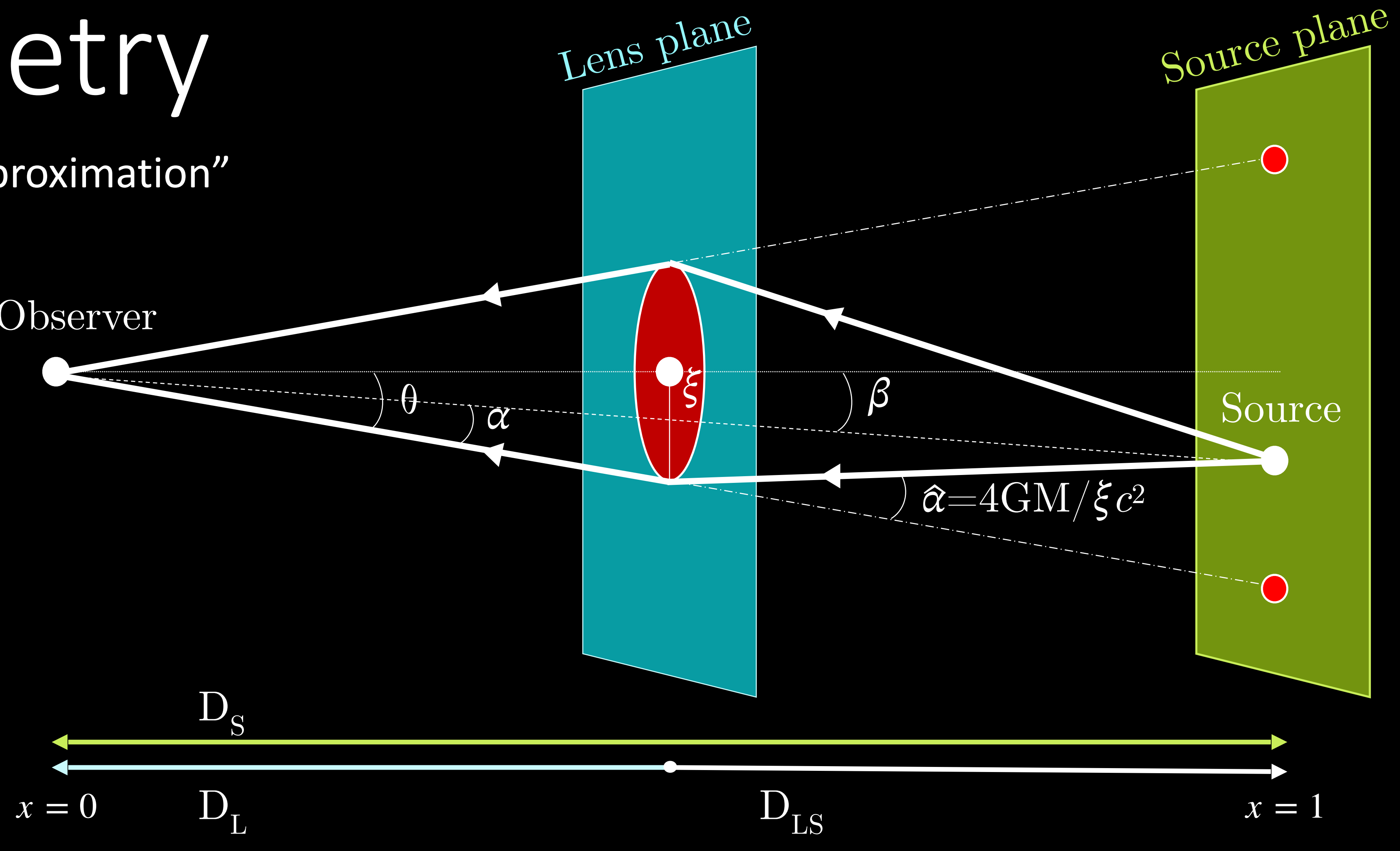
- Gravitational lensing!

What can we learn from it?

- Hints about the particle nature of DM!
- The early Universe curvature power spectrum!

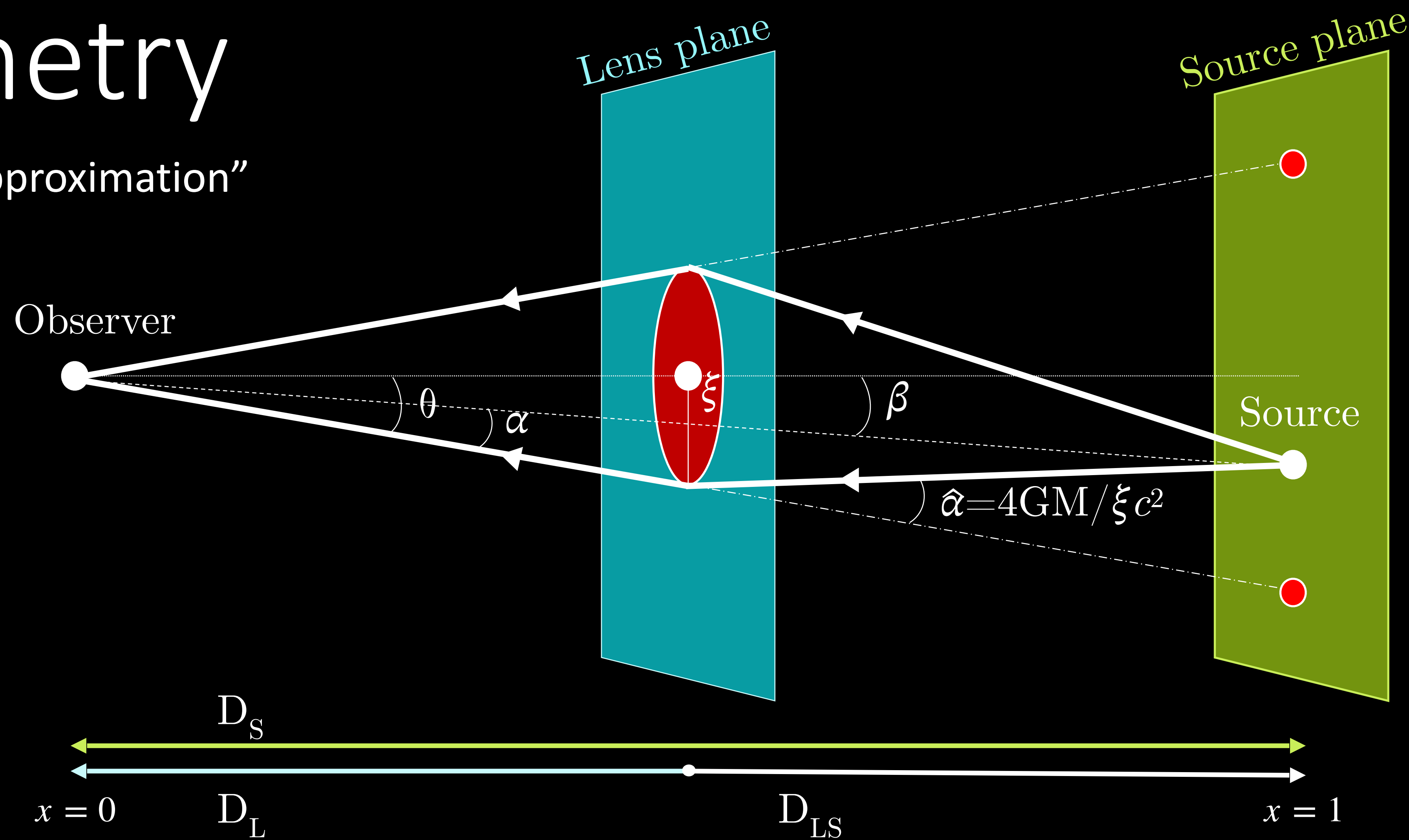
Geometry

"Thin screen approximation"



Geometry

"Thin screen approximation"

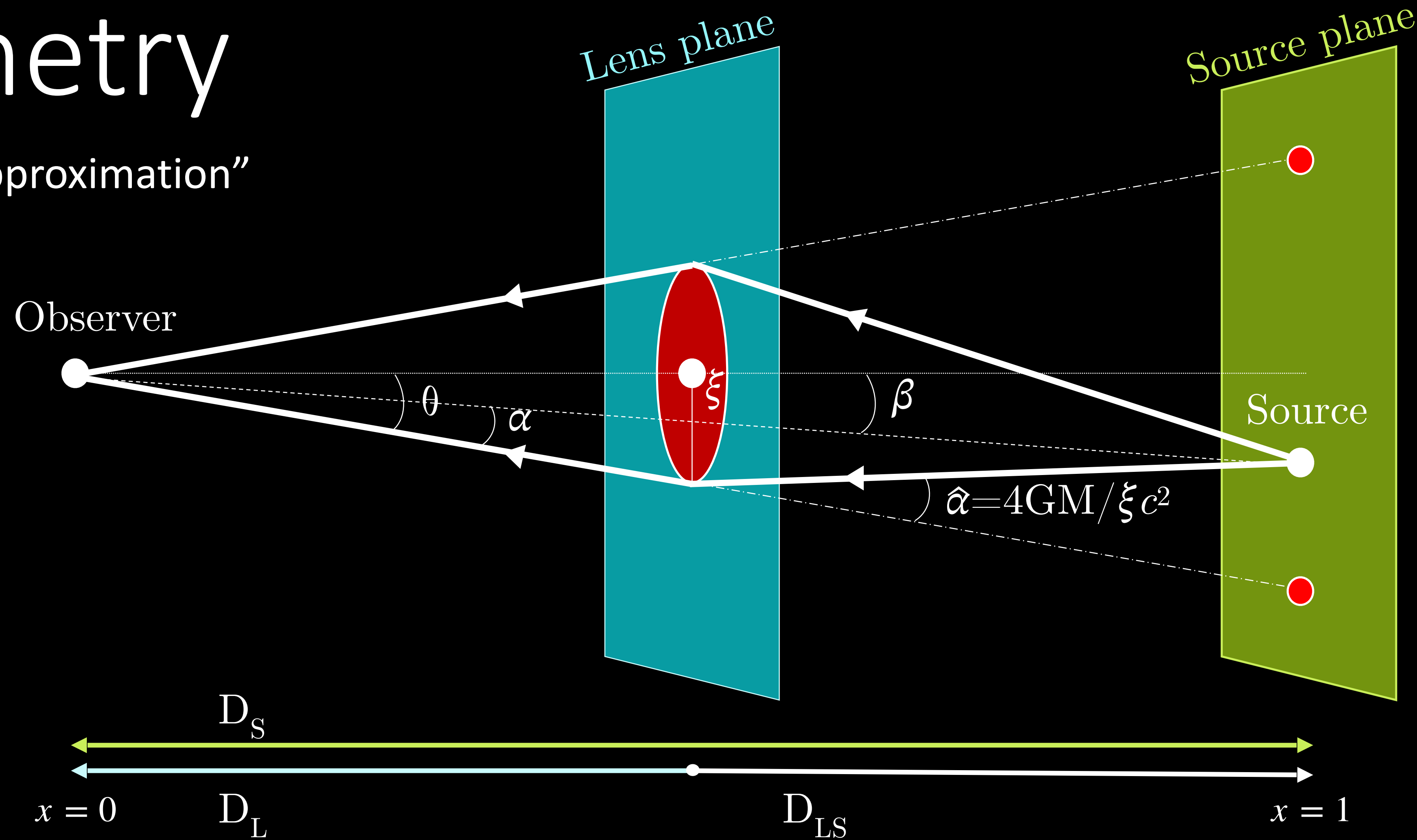


Lensing equation: $\beta = \theta - \frac{4GM(\theta)}{\theta D_L c^2} \frac{D_{LS}}{D_S}$

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

Geometry

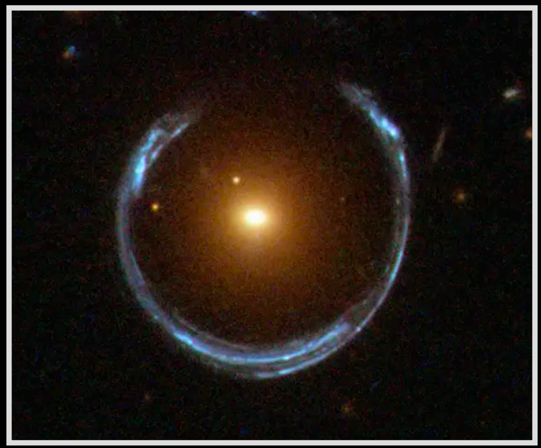
"Thin screen approximation"



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



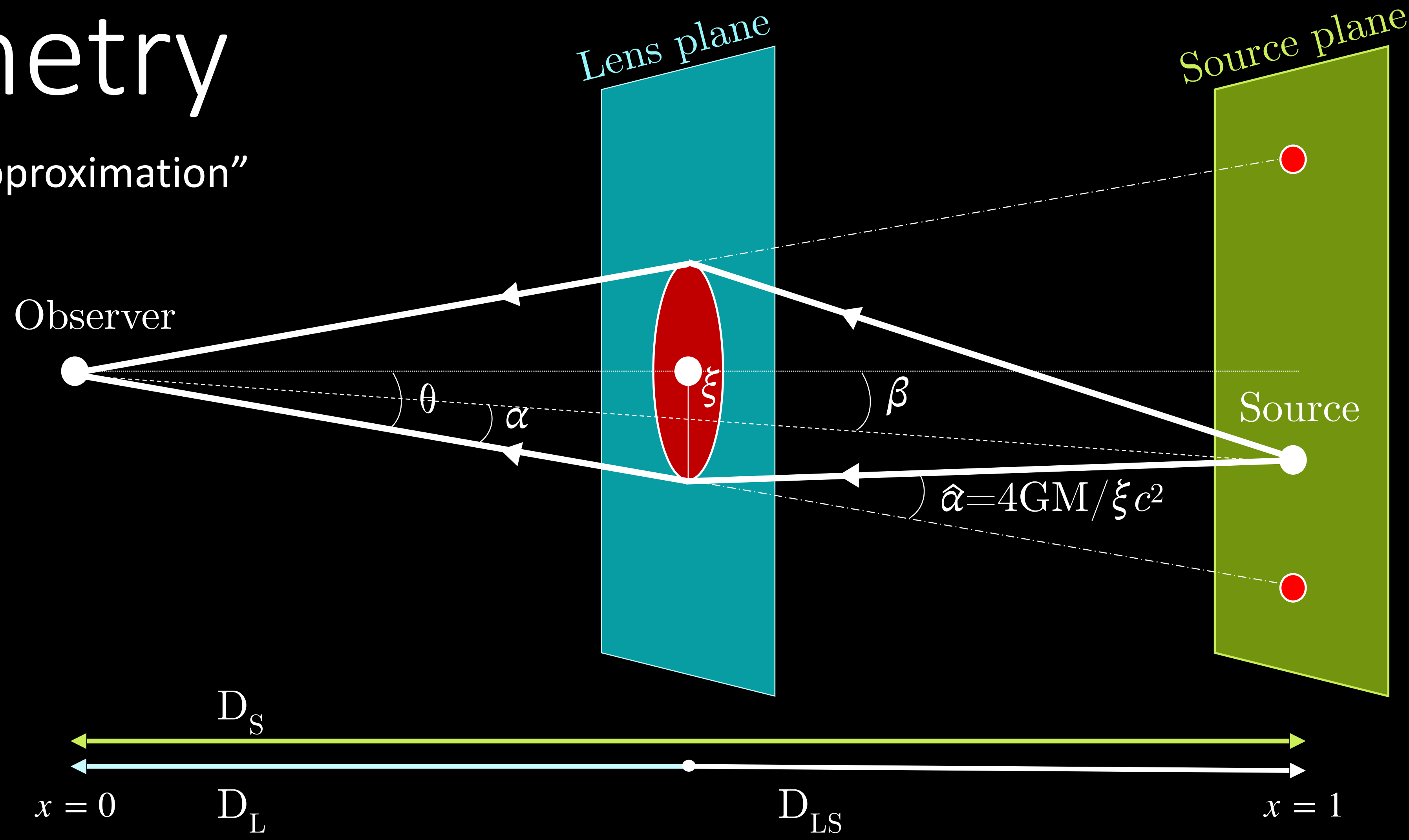
Einstein radius

$r_E = \theta_E D_L$

Near perfect Einstein Ring with the HST

Geometry

"Thin screen approximation"



Normalise everything to θ_E

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

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

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

DC, D. McKeen, N. Raj, PRD, arXiv:2002.08962 [astro-ph.CO]

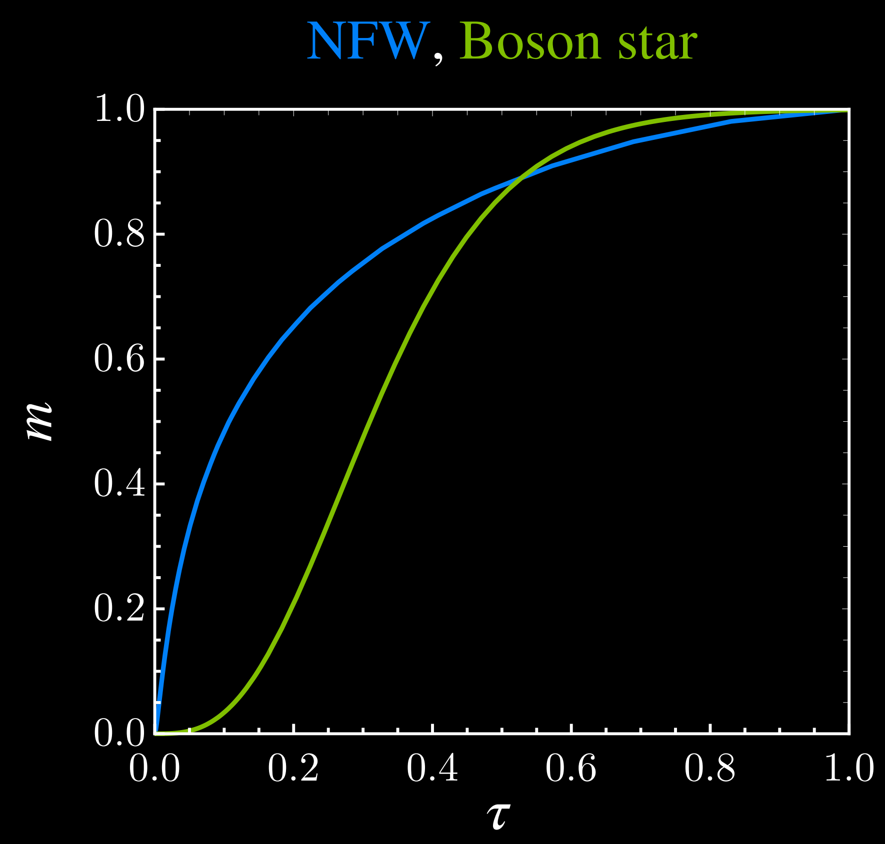
Geometry

"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: $m(\tau) = 1$



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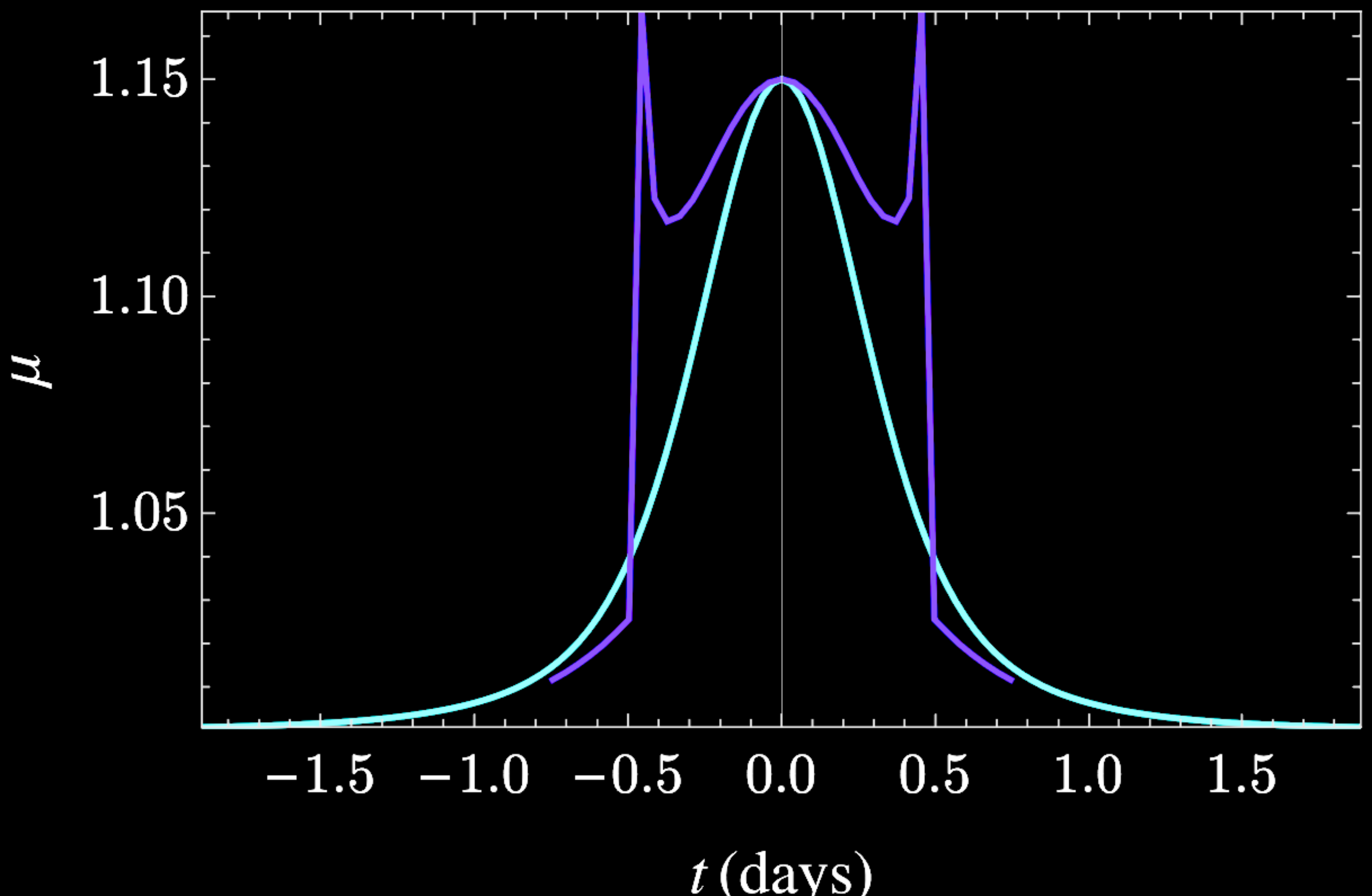
Caustic crossing

Example light curve

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

Boson star with $\tau_m = 1$

PBH (or $\tau_m = 0$)



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

Caustic crossing

Example light curve

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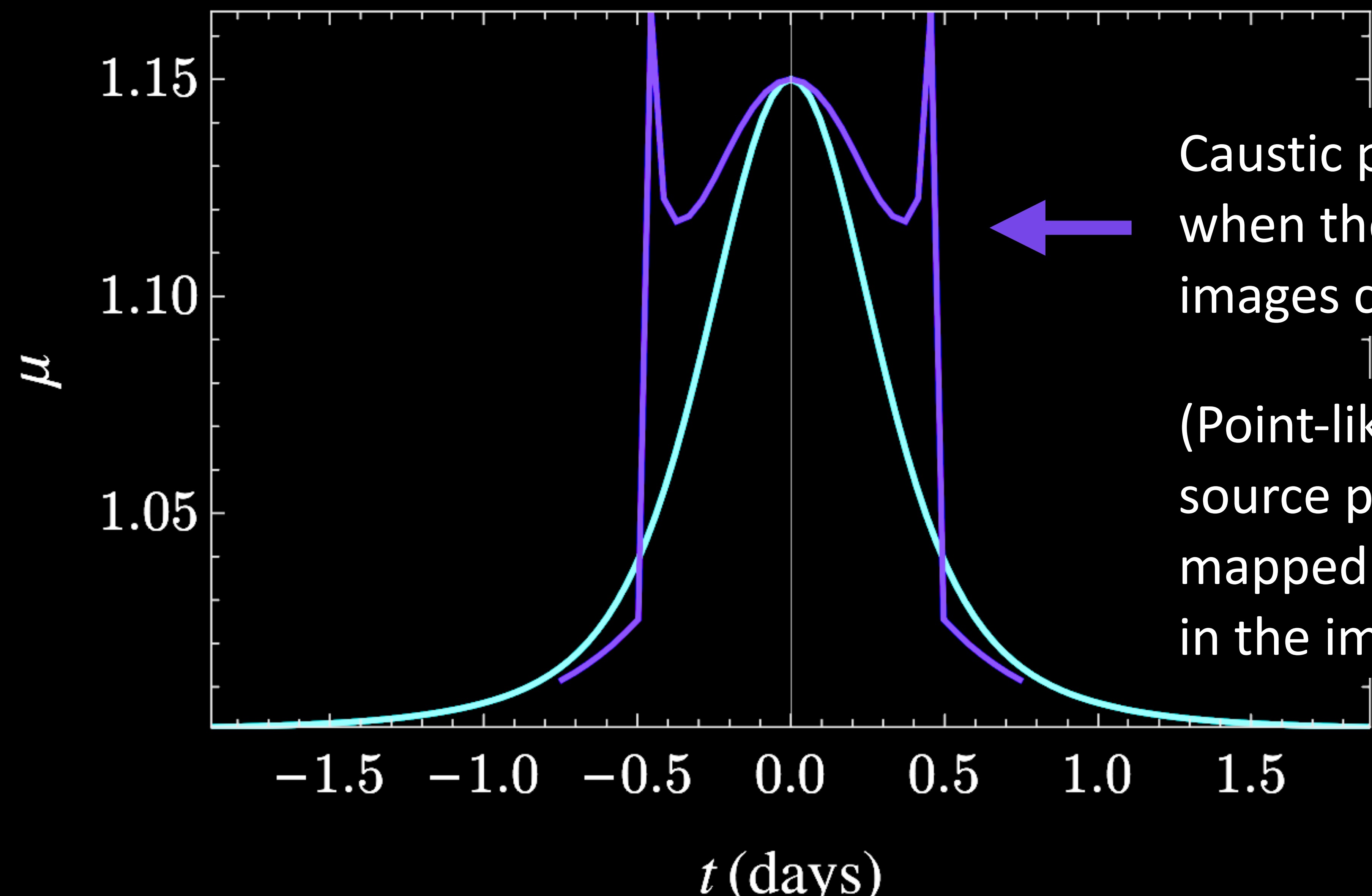


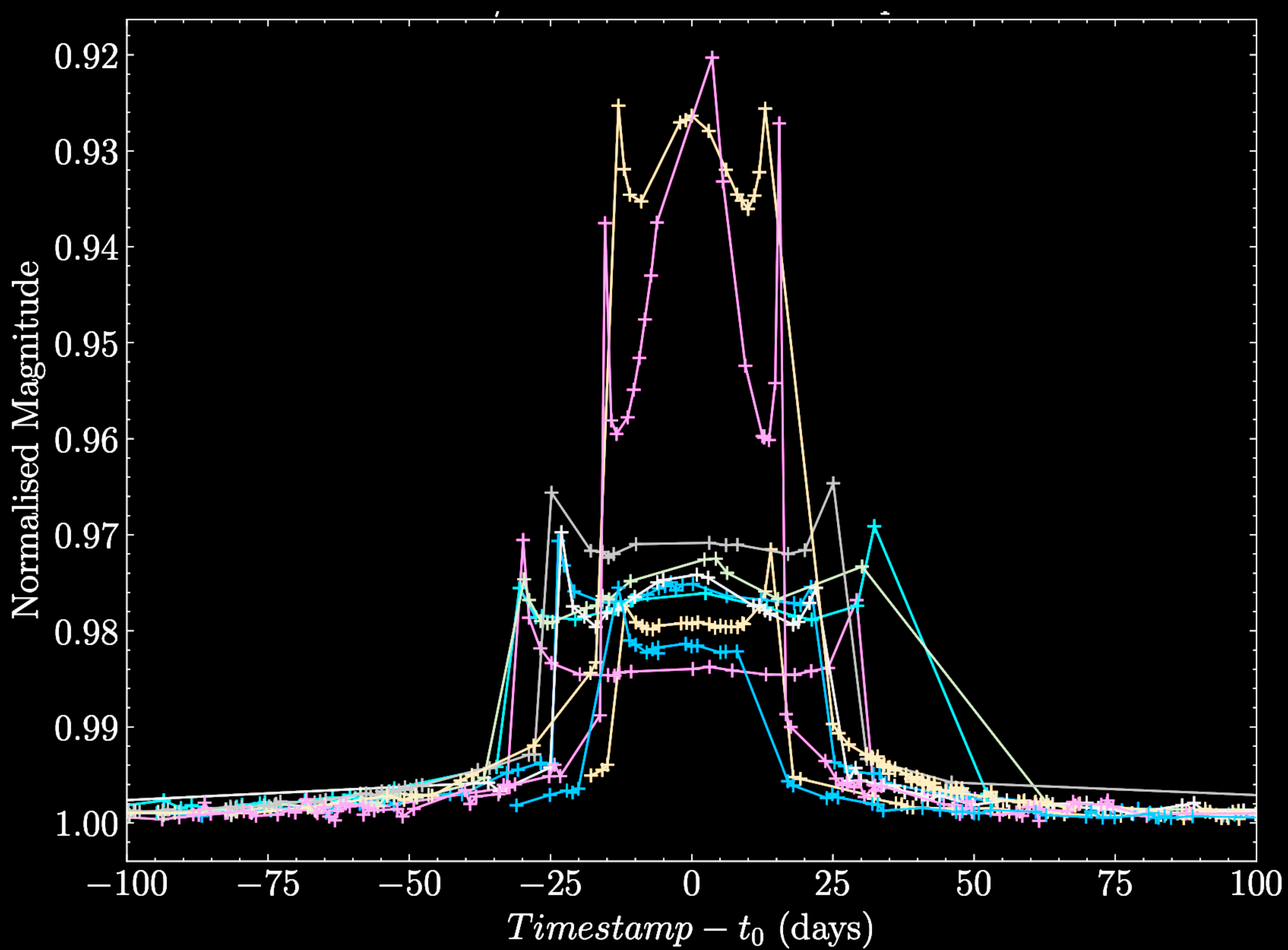
Caustic peaks arise when the number of images changes

(Point-like area in the source plane gets mapped to infinite size in the image plane)

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

Light curves with caustics

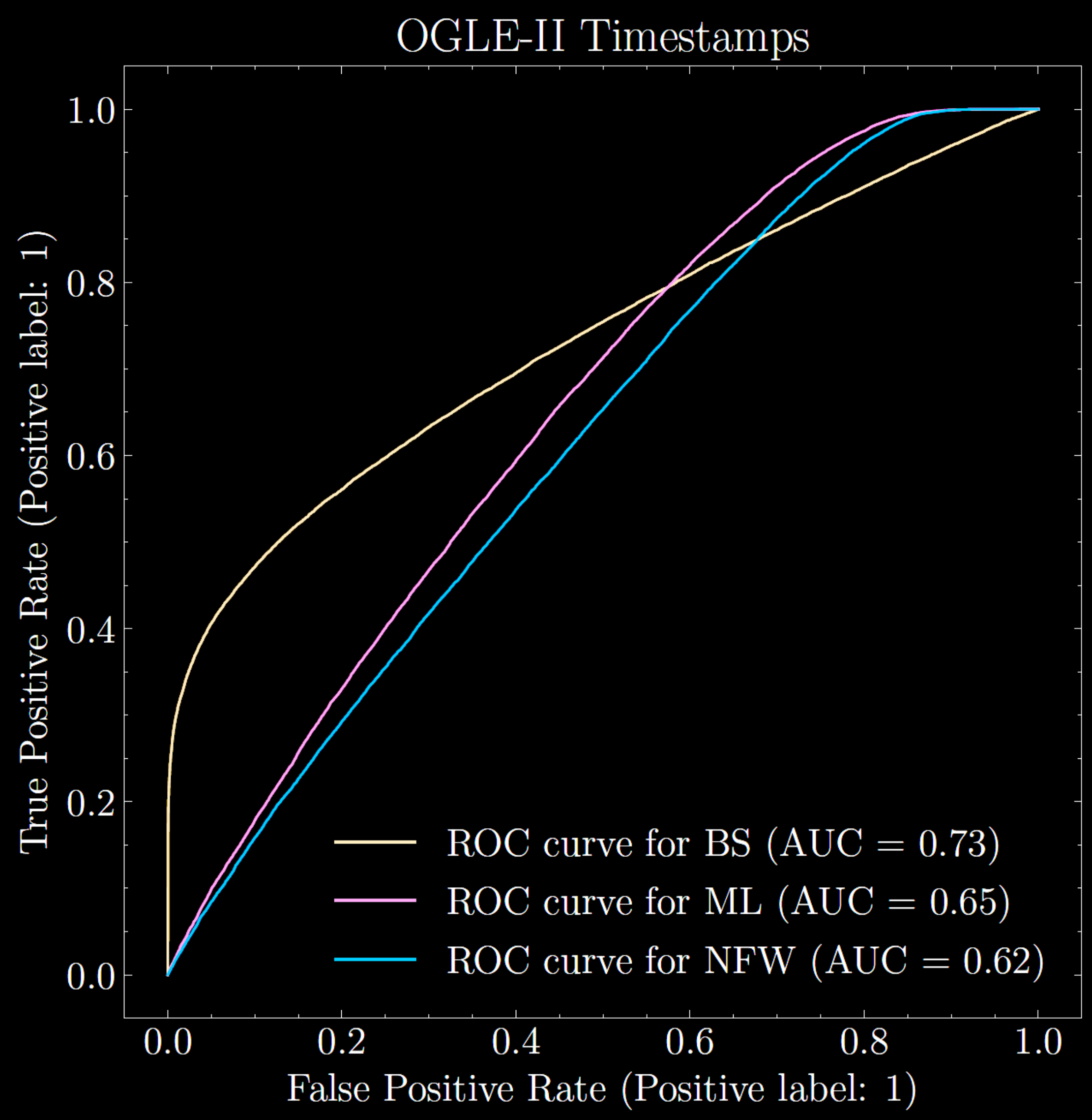
Can we look for these explicitly?



Light curves with caustics

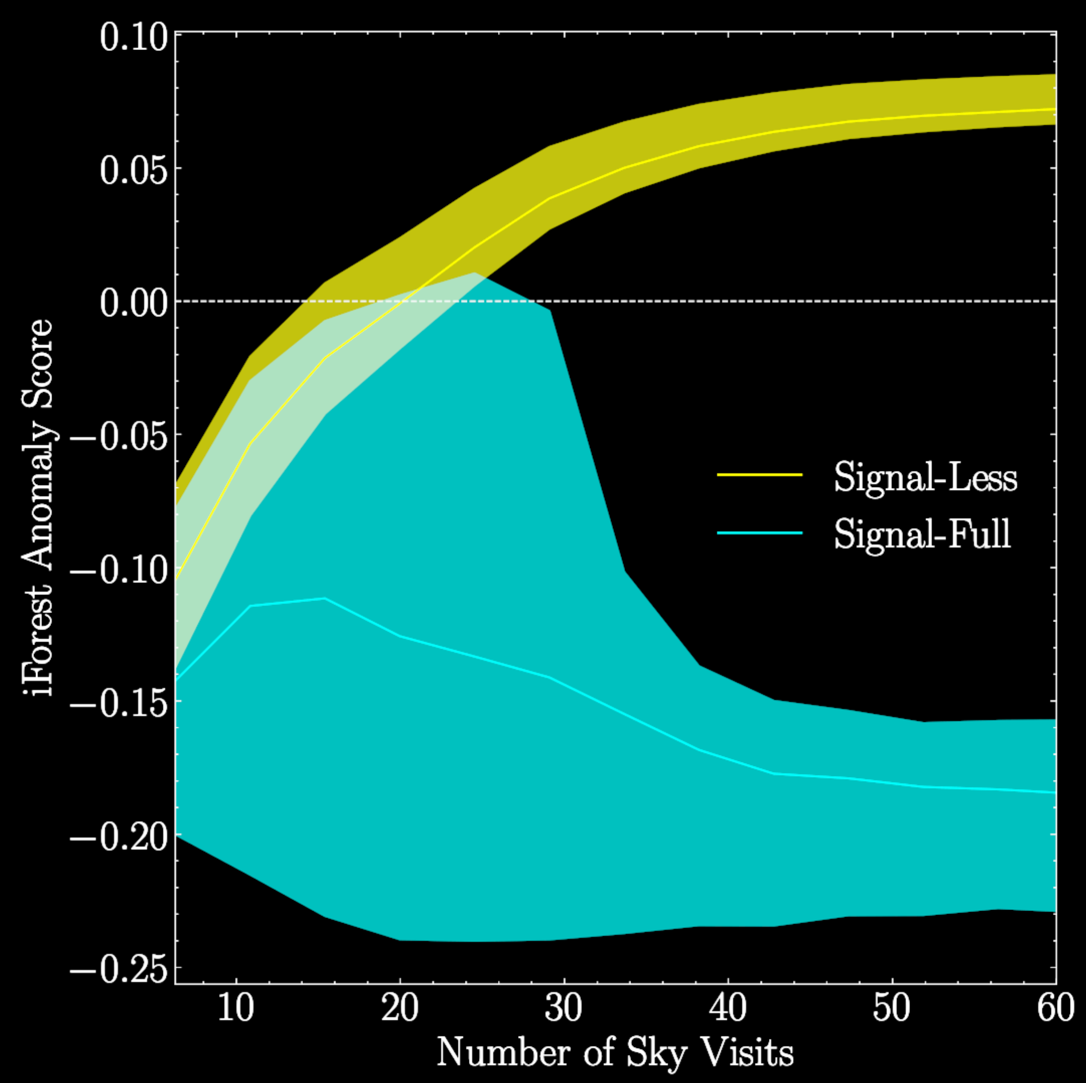
Can we look for these explicitly? Yes!

Dedicated microlensing surveys
Histogram-based gradient boosted classifier



M. Crispim-Romao, DC, PRD, arXiv:2402.00107

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



M. Crispim-Romao, DC, Godines, MNRAS, arXiv:2503.09699

Generalising PBH constraints

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

"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

DC, D. McKeen, N. Raj, PRD, arXiv:2002.08962 [astro-ph.CO]

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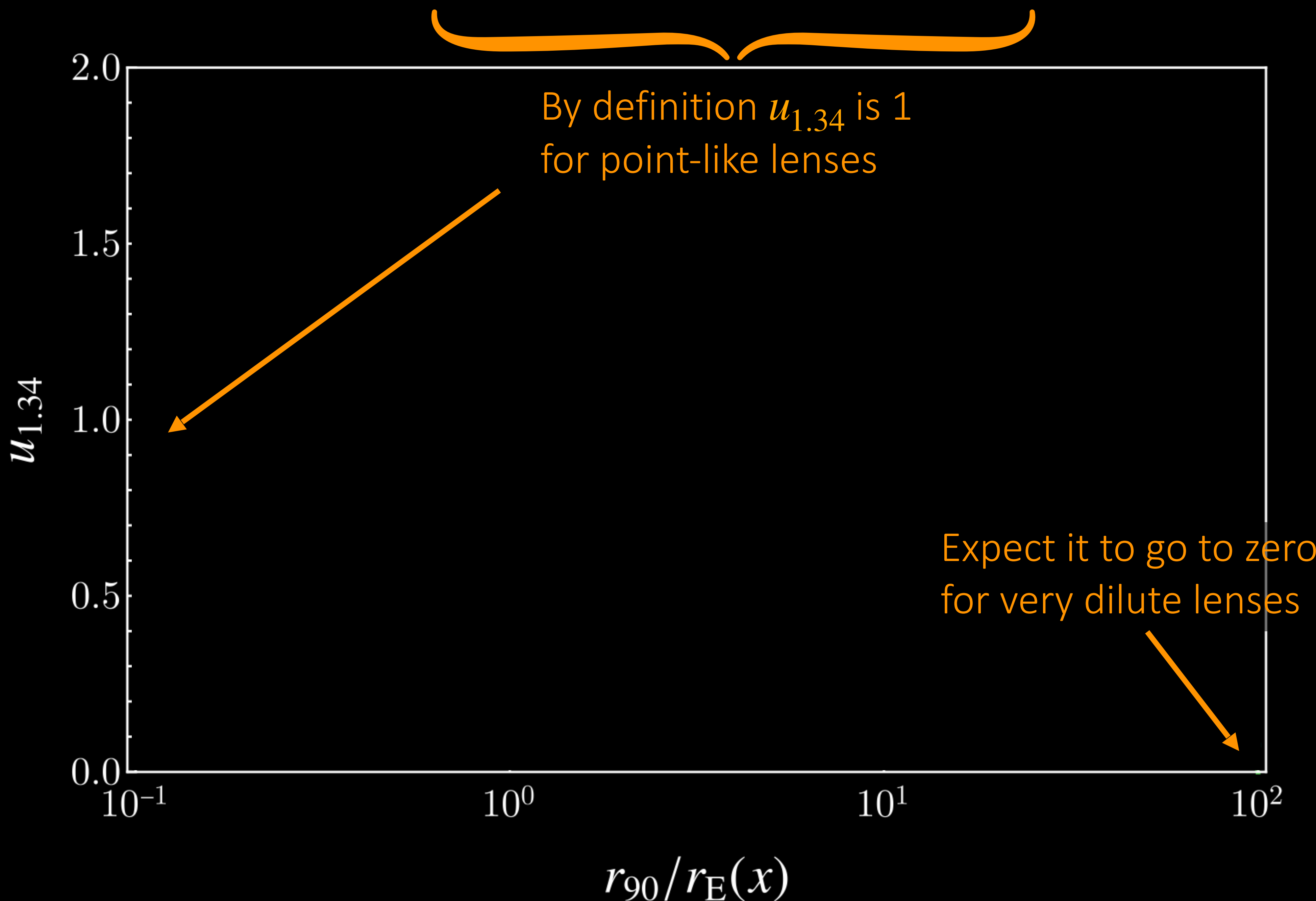

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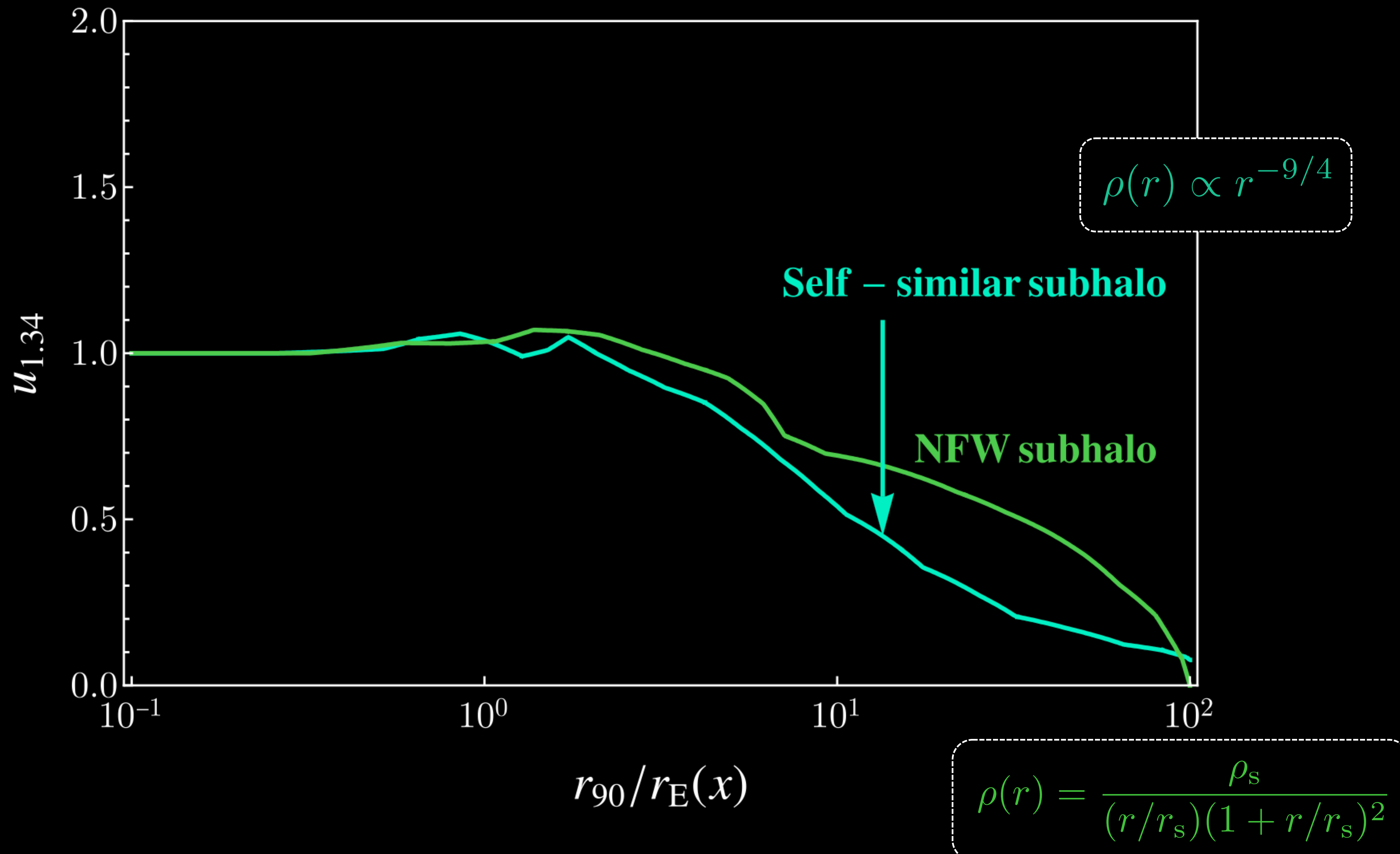

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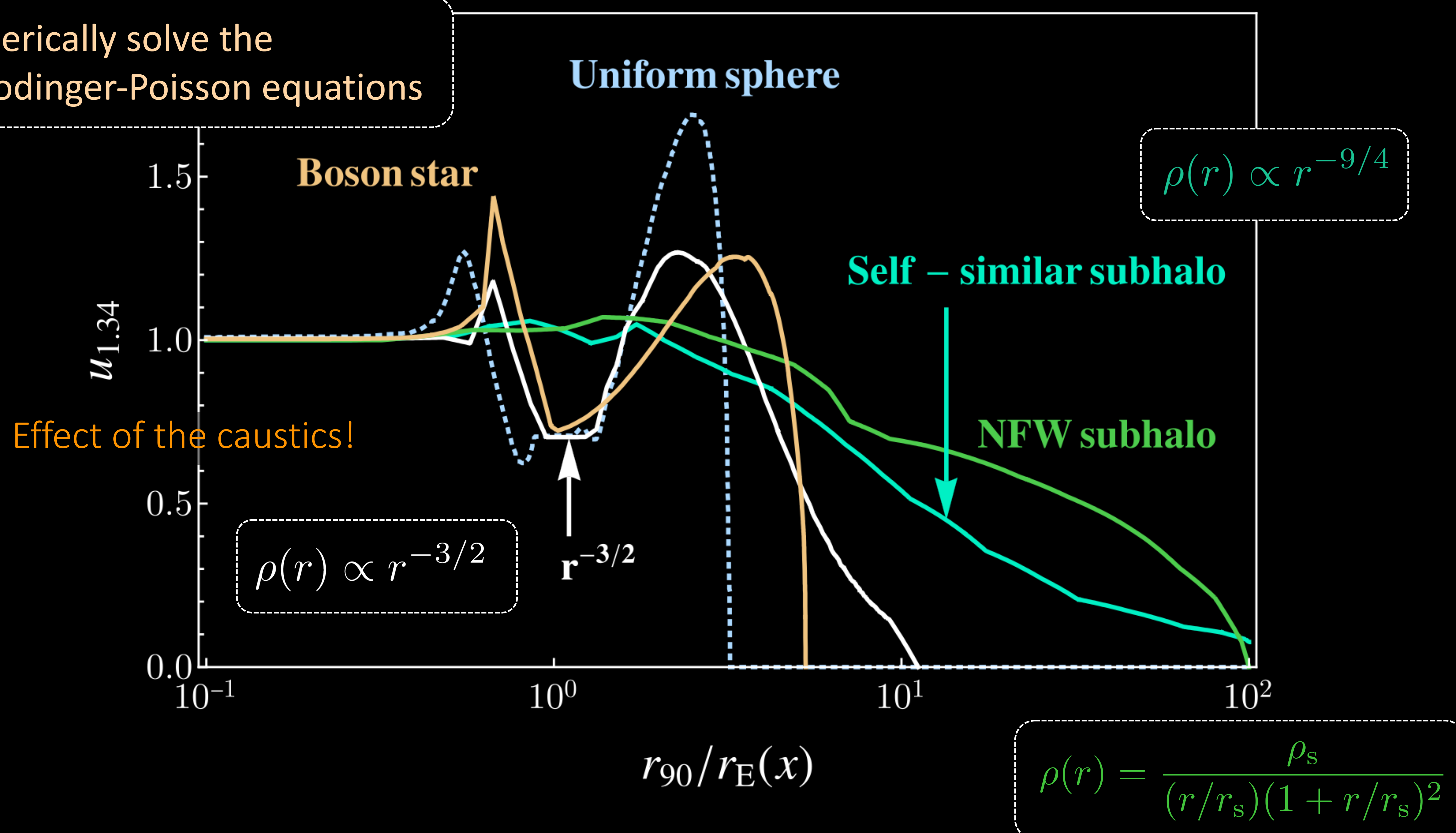
Numerically solve the Schrodinger-Poisson equations

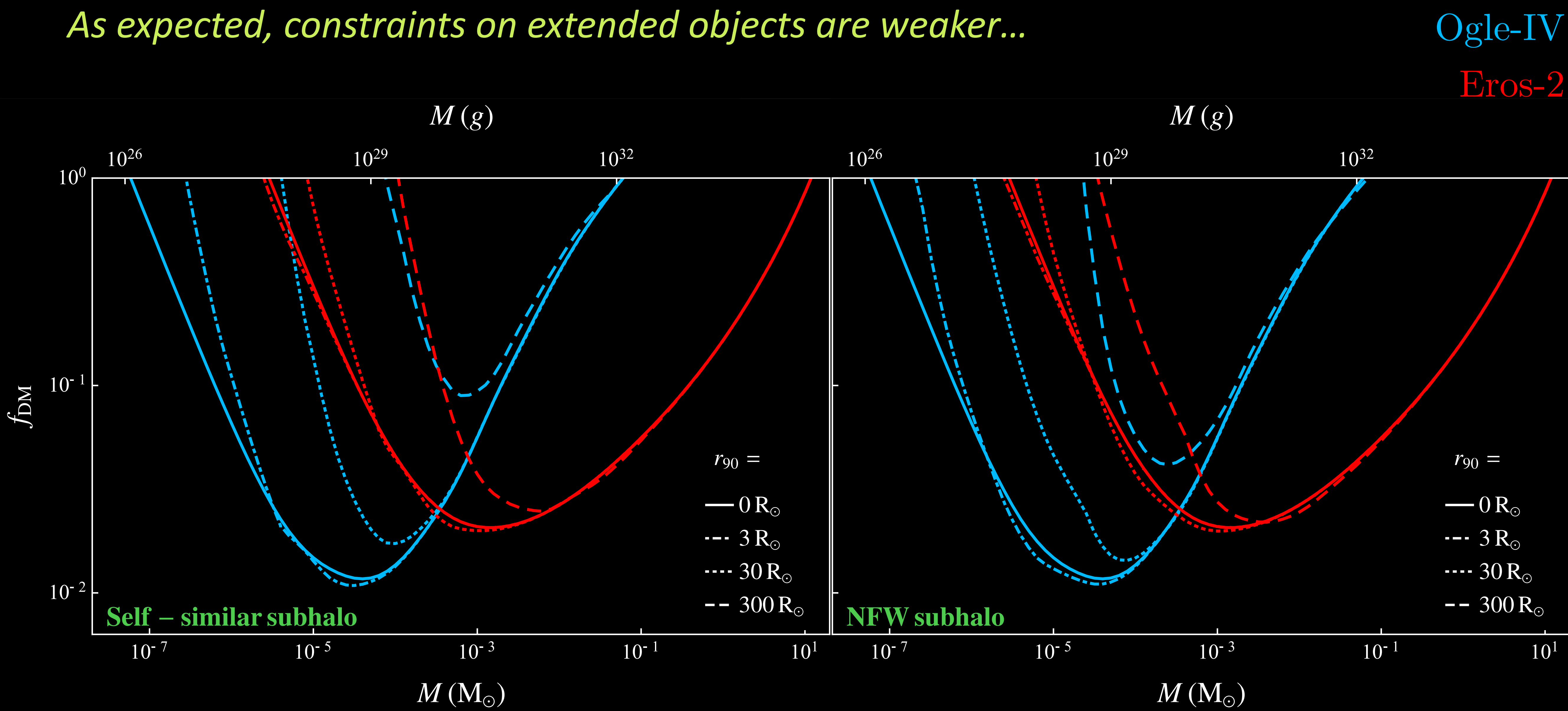


DC, D. McKeen, N. Raj, PRD, arXiv:2002.08962 [astro-ph.CO]

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…

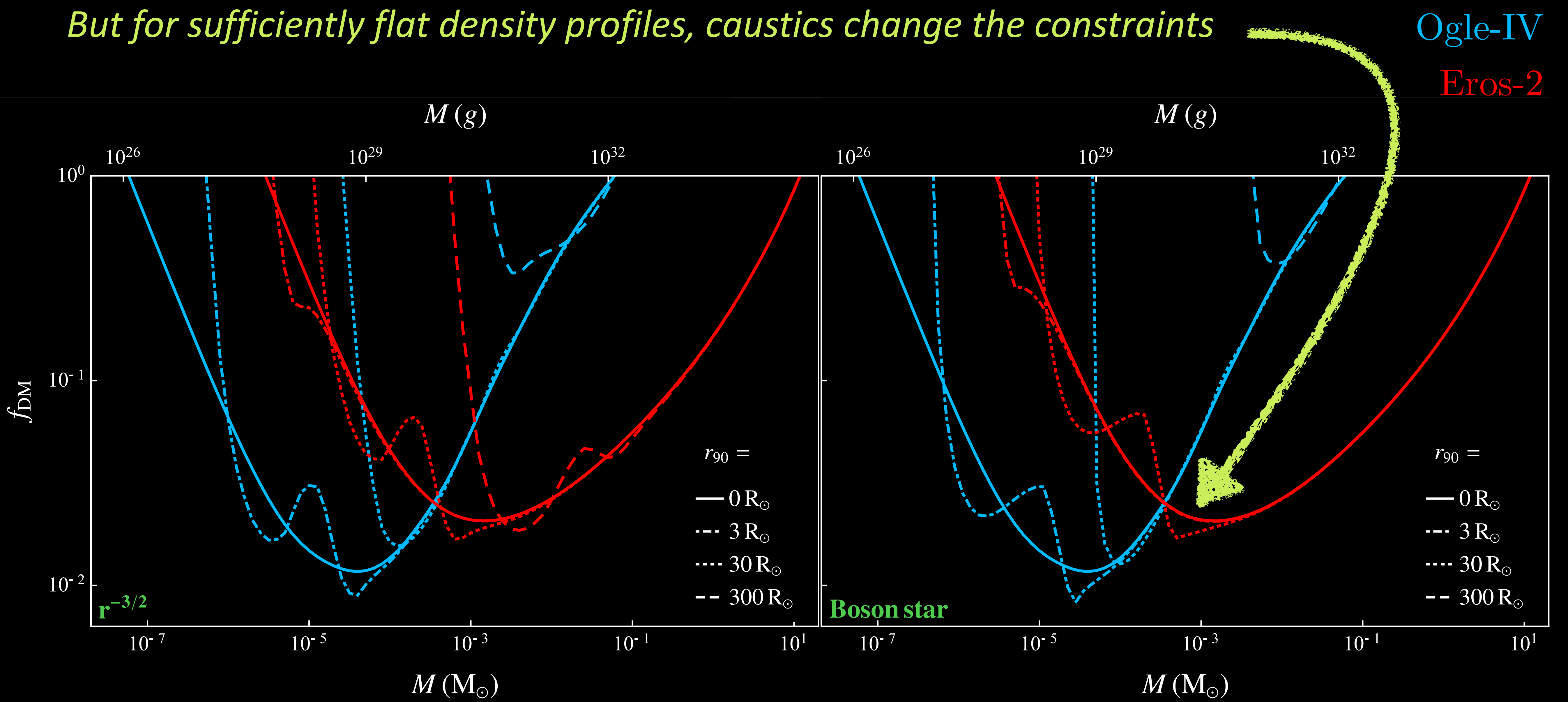


DC, D. McKeen, N. Raj, PRD, arXiv:2002.08962 [astro-ph.CO]

Constraints on DM fraction

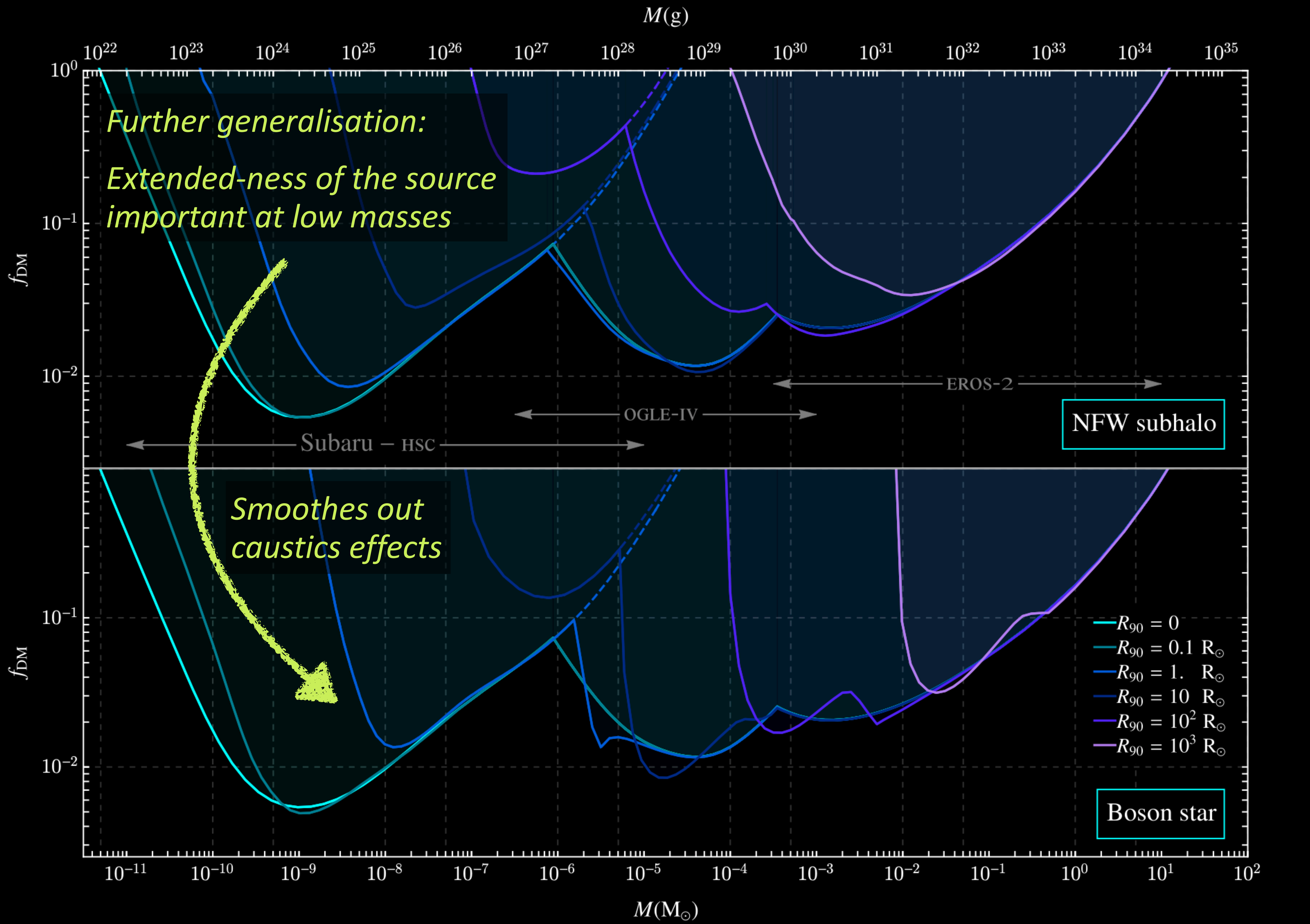
Using the differential event rate, find constraints given expected number of (non-observed) events. Generalised for extended objects using an <u>extended lens efficiency</u>.

But for sufficiently flat density profiles, caustics change the constraints

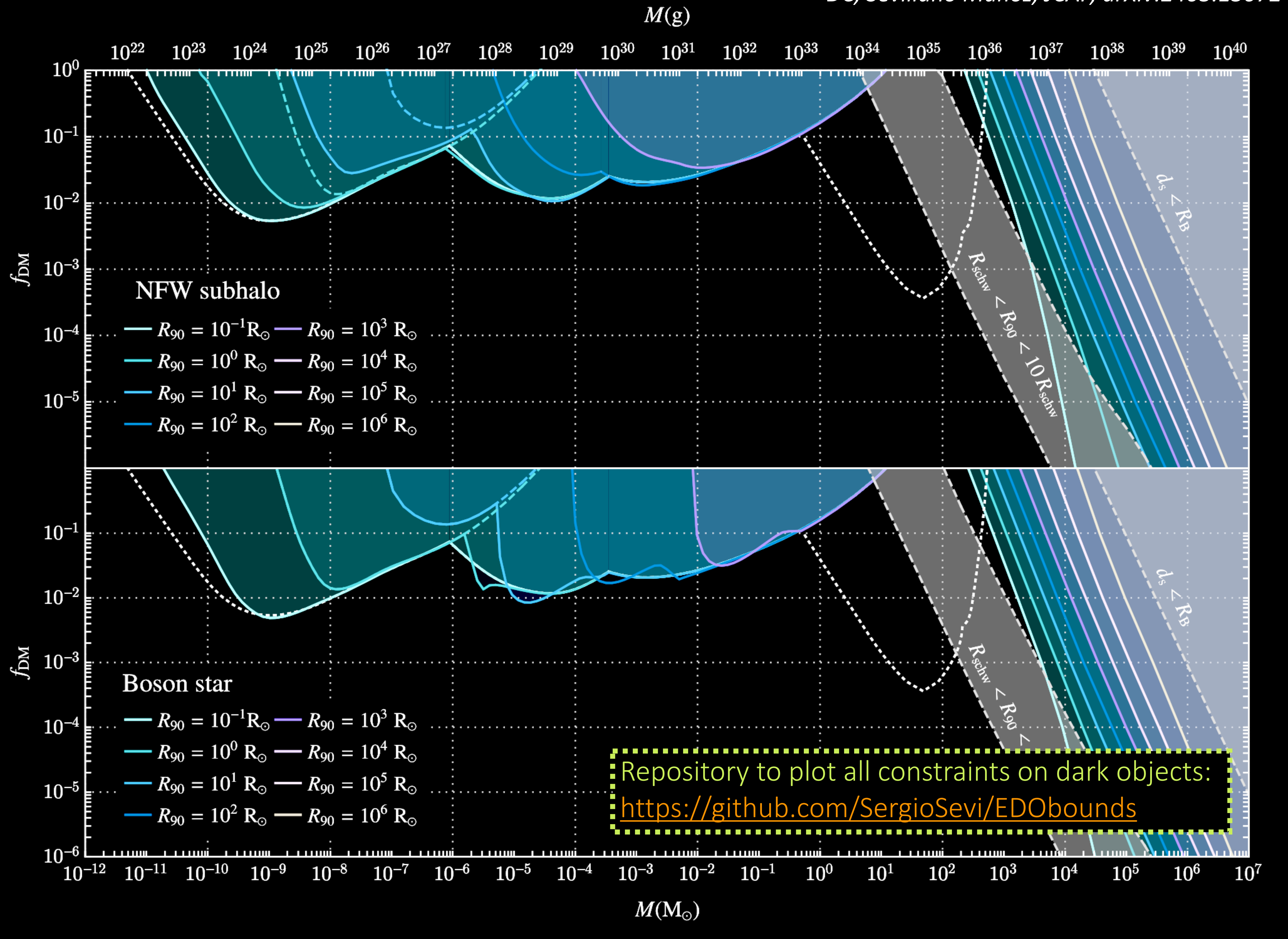


DC, D. McKeen, N. Raj, PRD, arXiv:2002.08962 [astro-ph.CO]

DC, D. McKeen, N. Raj, Z. Wang, PRD, arXiv:2007.12697 [astro-ph.CO]



DC, Sevillano Muñoz, JCAP, arXiv:2403.13072



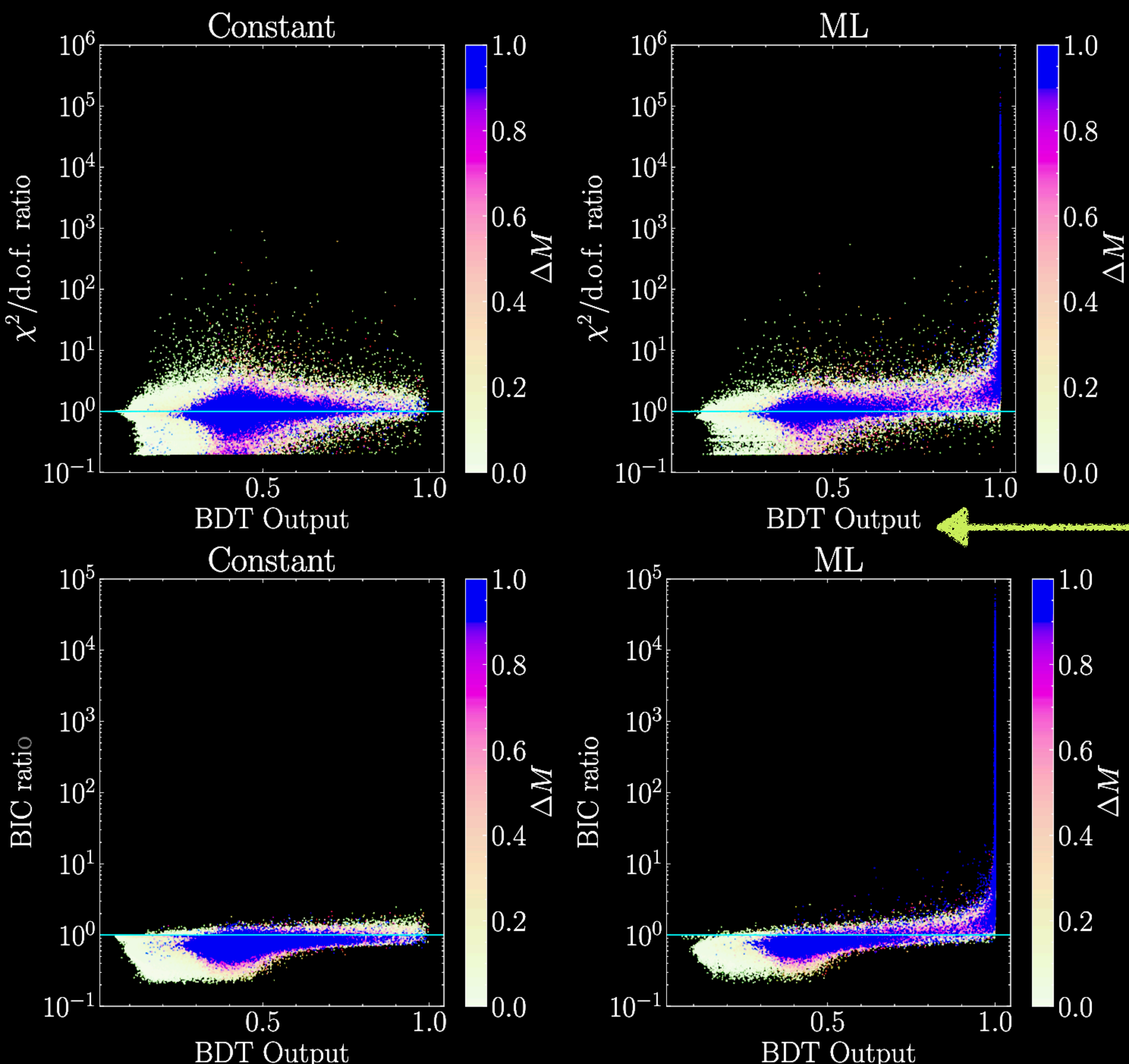
Repository to plot all constraints on dark objects:
https://github.com/SergioSevi/EDObounds

LSST by Rubin: projections

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

Typically used

BIC



BDT

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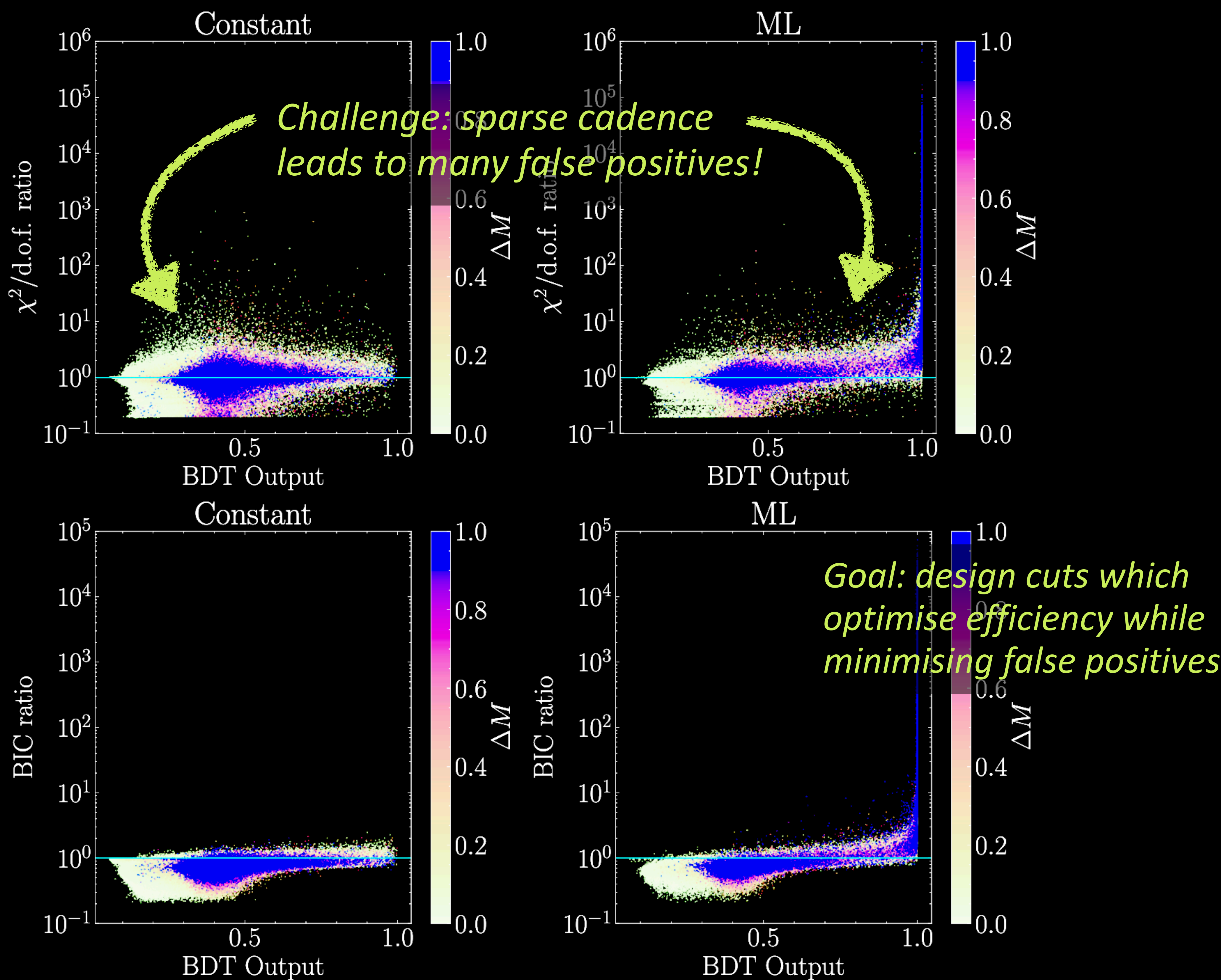
Miguel Crispim-Romao, DC, Benedict Crossey, Daniel Godines, PRD, arXiv:2506.20709



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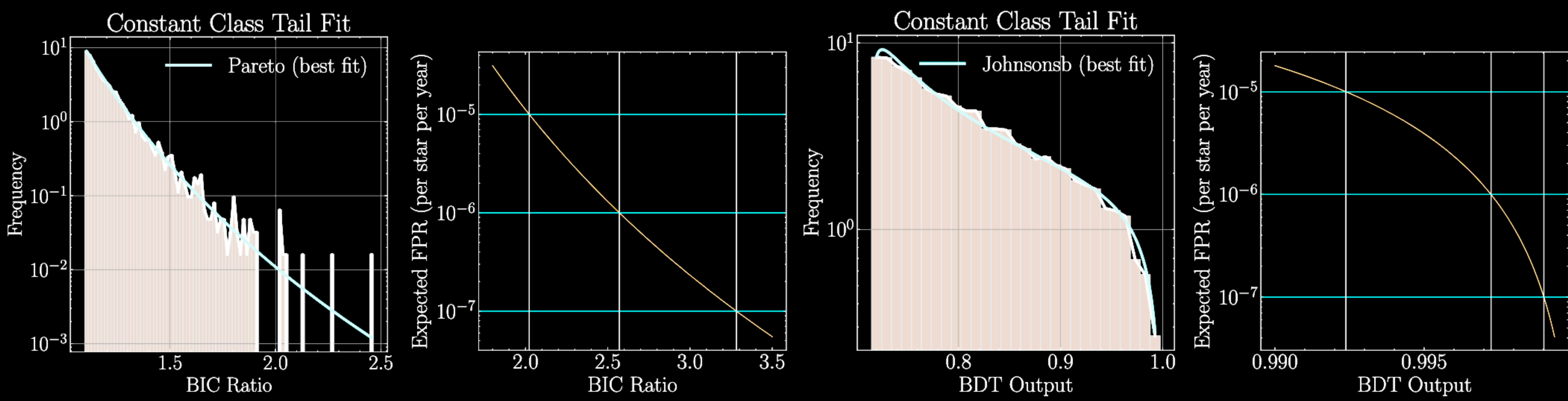


For competitive constraints, need FPR $< 10^{-7}$

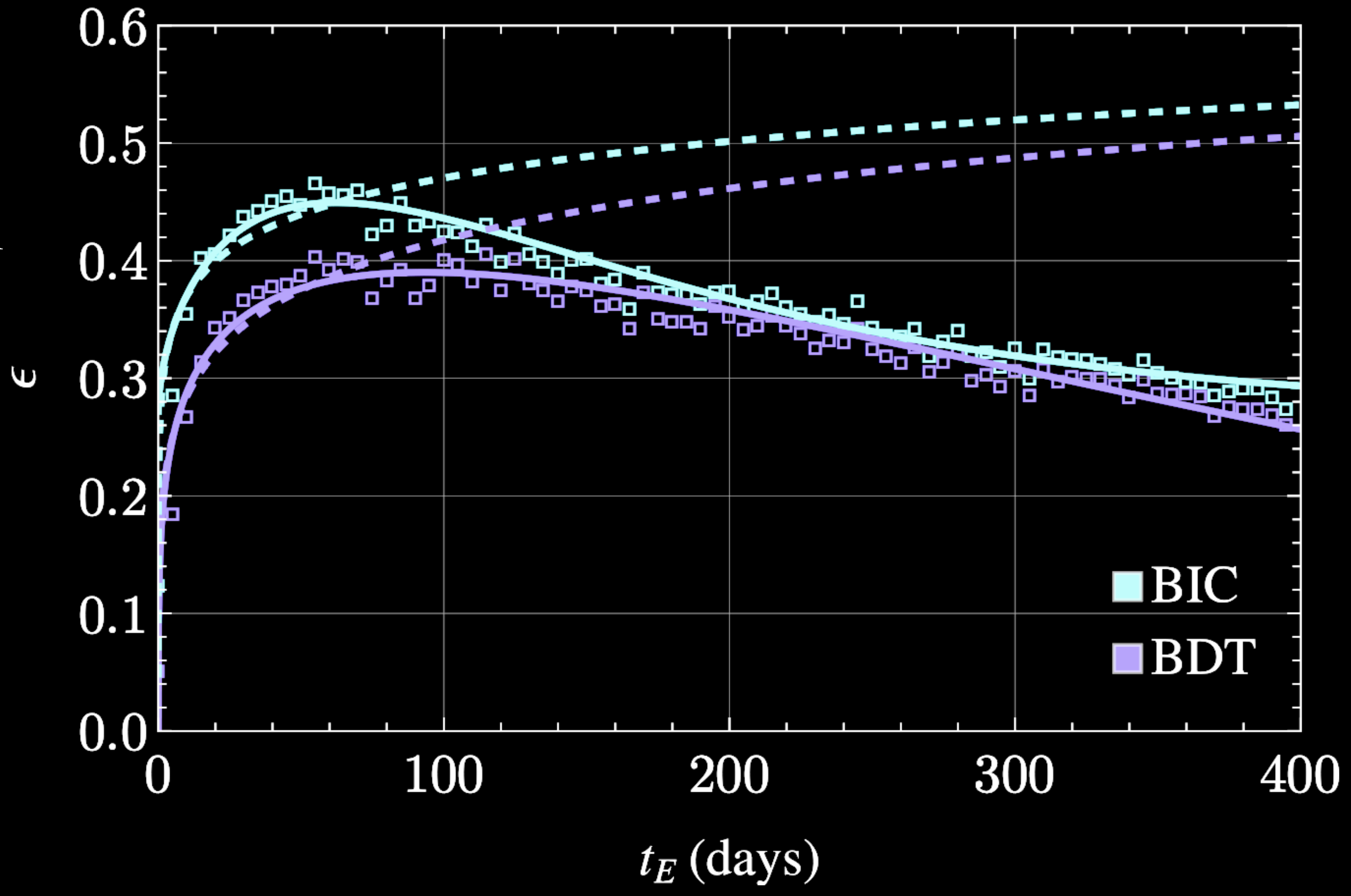
cut	FPR	$\bar{\epsilon}$
BIC ratio > 3.28	10^{-7}	0.38
BDT > 0.999	10^{-7}	0.34
χ^2/d.o.f. ratio > 10	3.5×10^{-4}	0.30
χ^2/d.o.f. ratio > 10, $\tilde{u}_0 < 1$	1.1×10^{-4}	0.20

LSST by Rubin: projections

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

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

$$\epsilon \equiv N_{>\text{cut}}/N_{\text{total}}$$



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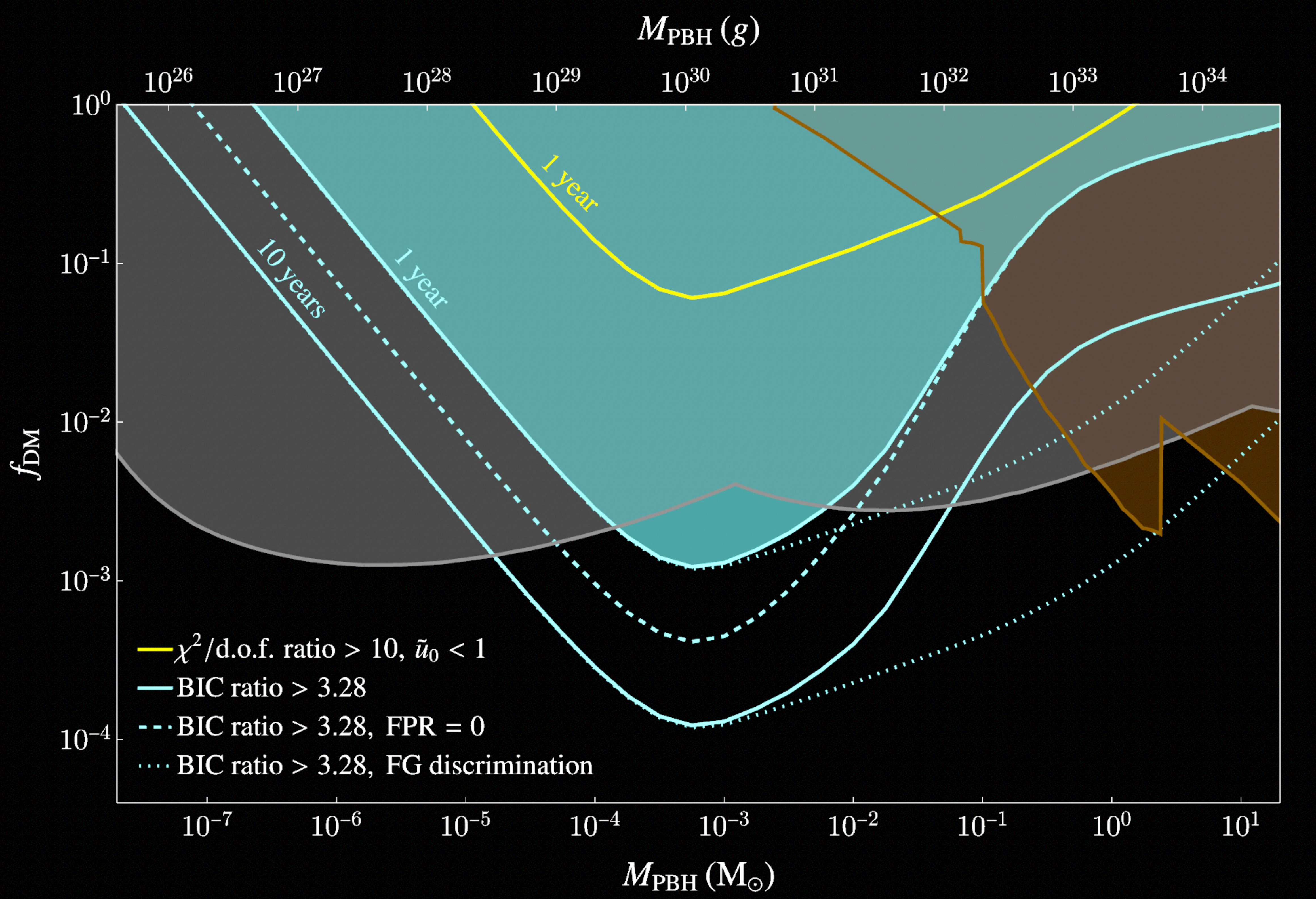
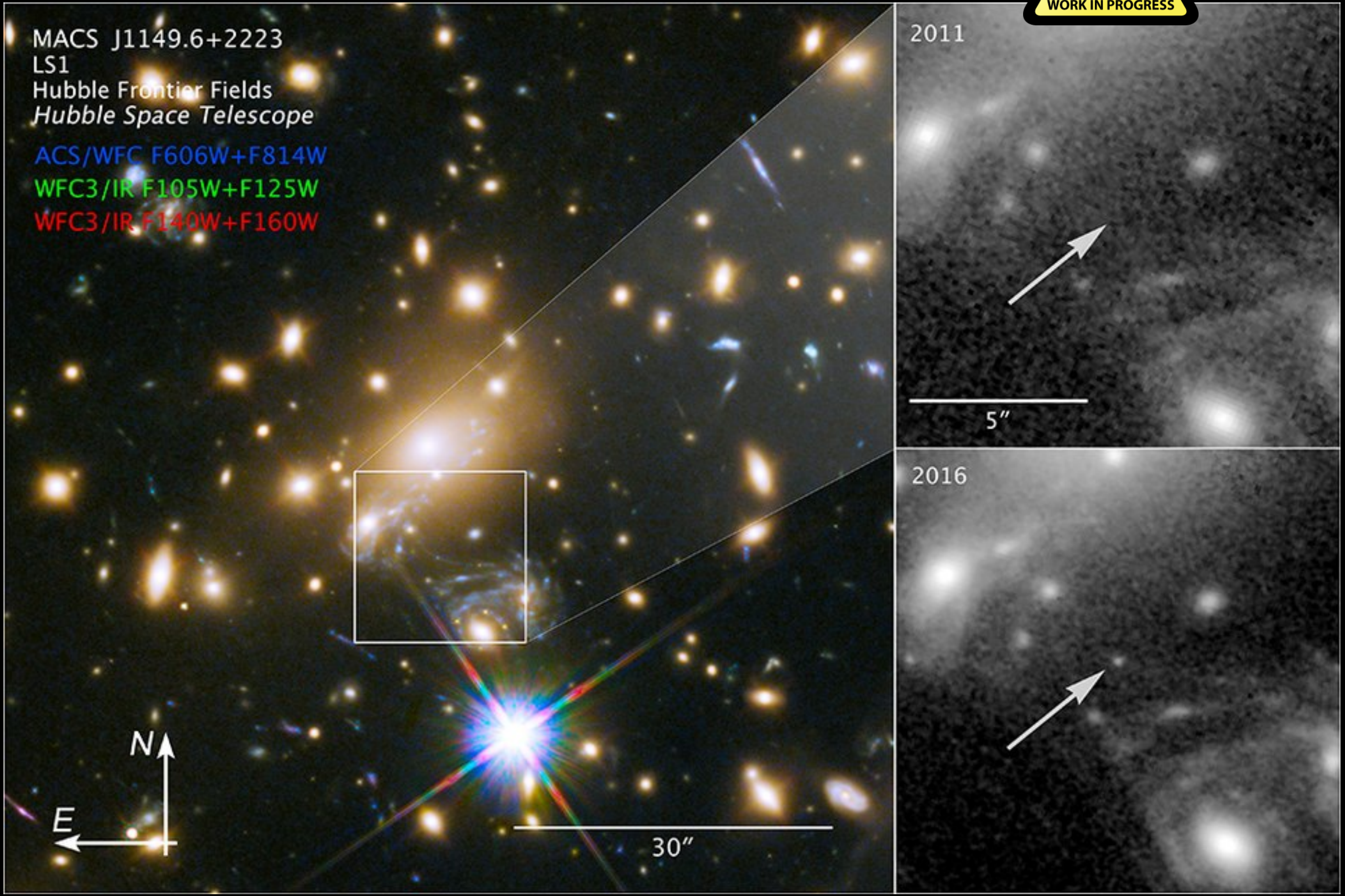


Caustic crossings in giant arcs



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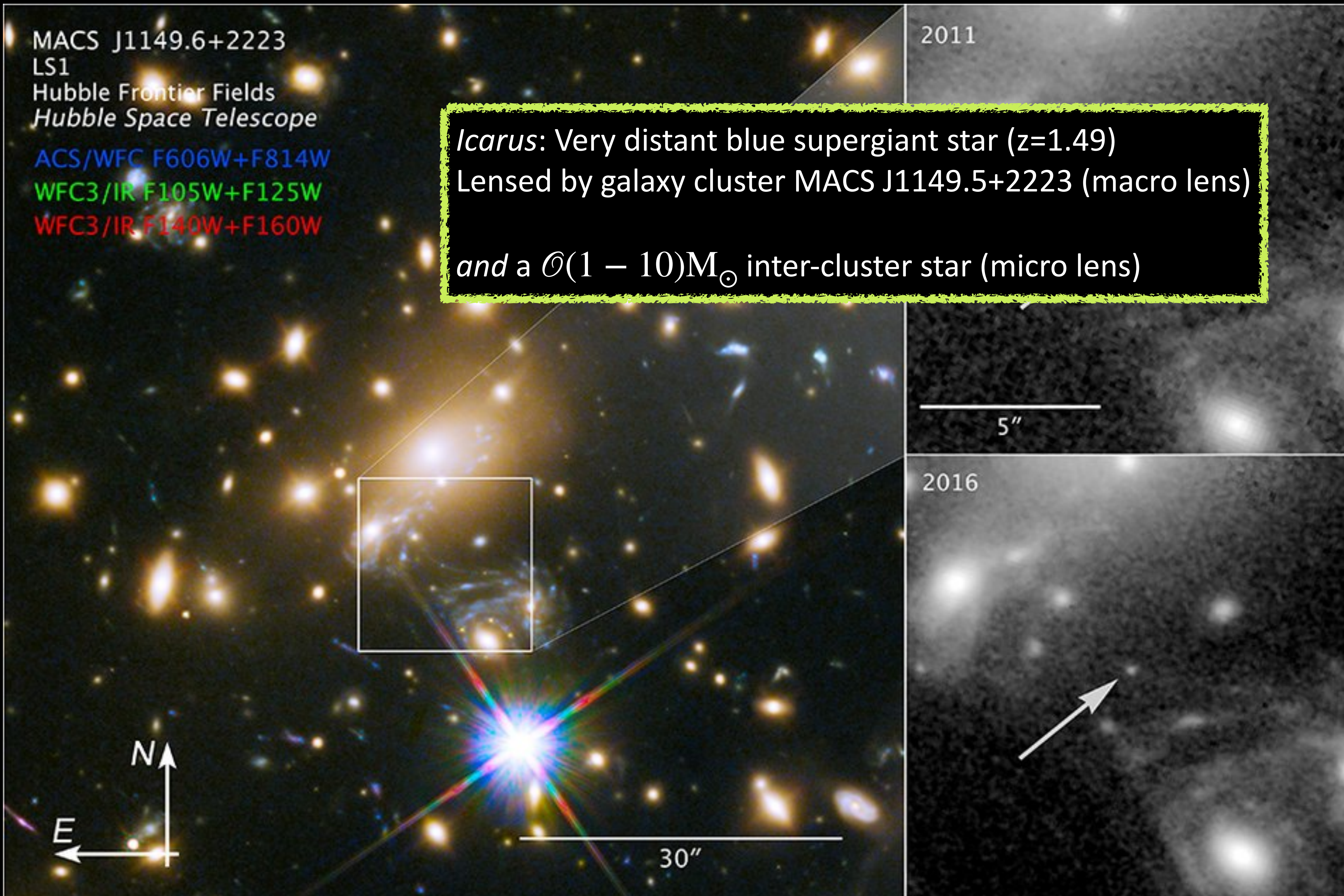
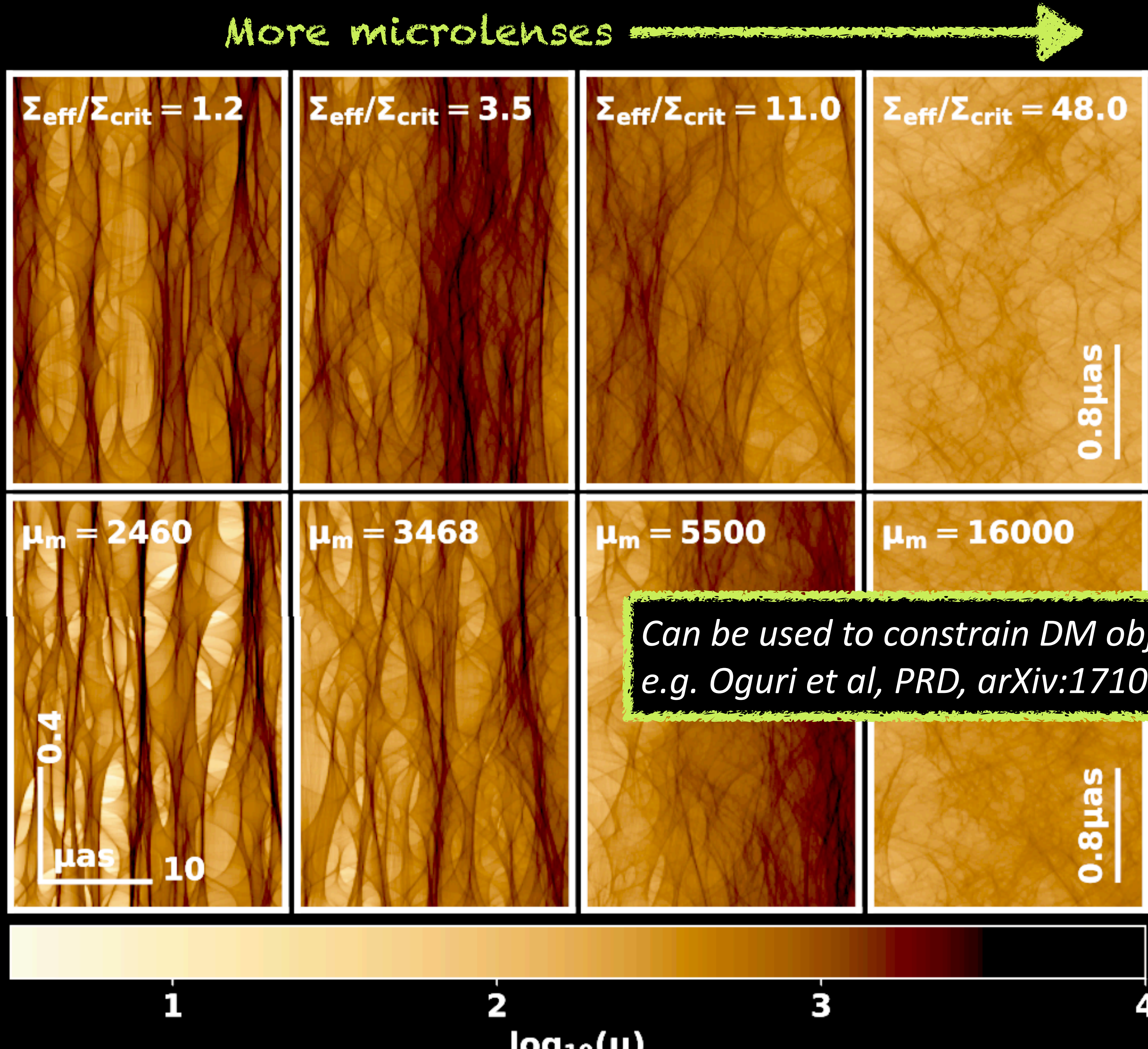


Icarus: Very distant blue supergiant star (z=1.49)
Lensed by galaxy cluster MACS J1149.5+2223 (macro lens)

and a $\mathcal{O}(1-10)\mathrm{M}_{\odot}$ inter-cluster star (micro lens)

Caustic crossings in giant arcs



Can be used to constrain DM objects!
e.g. Oguri et al, PRD, arXiv:1710.00148

Image: Palencia, Diego, Kavenagh, Martinez, A&A, arXiv:2307.09505

Caustic crossings in giant arcs

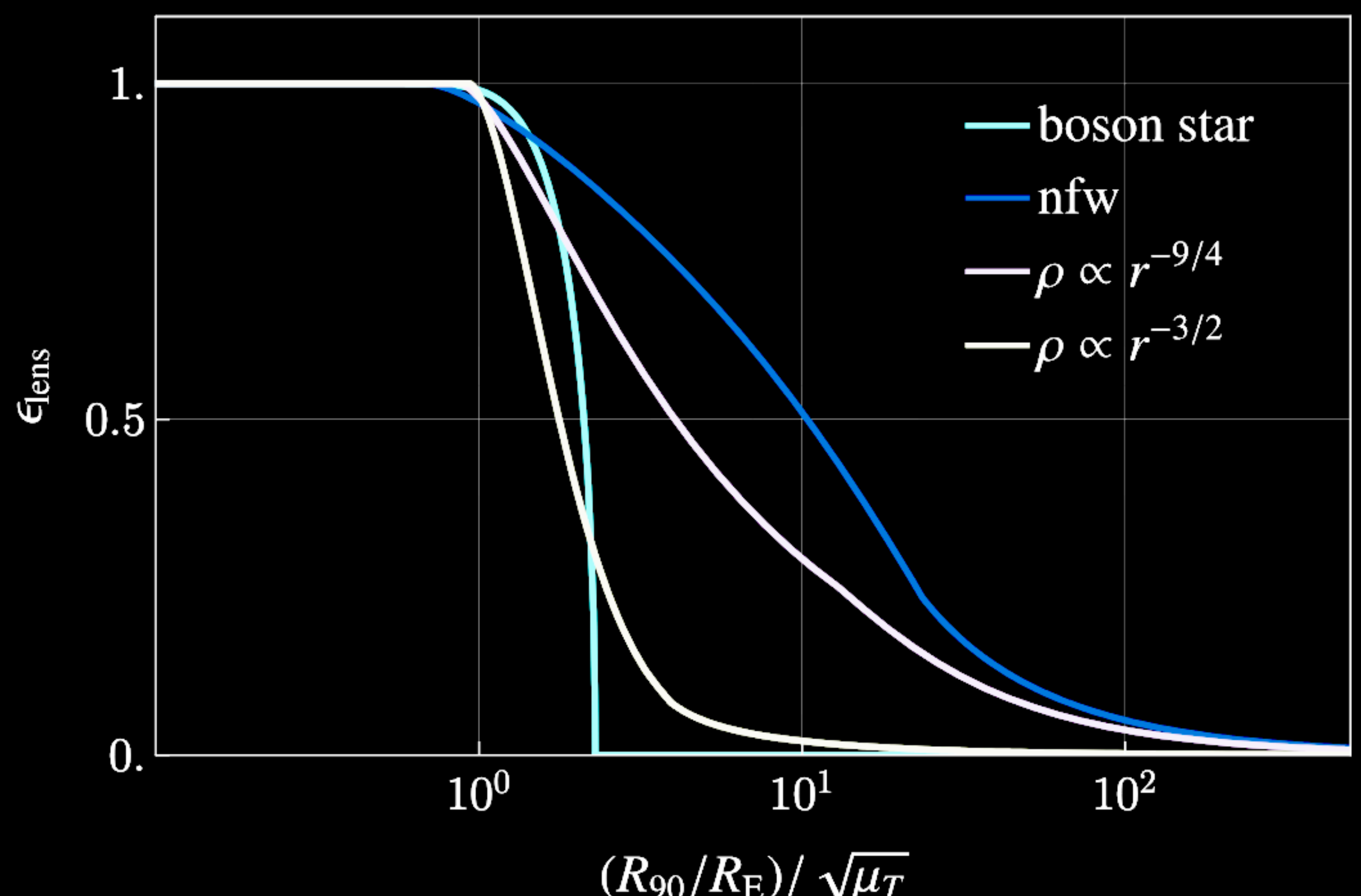
In a macro-lens background, Einstein radius of a microlens effectively boosted by $\sqrt{\mu_t}$

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

→ define an extended lens efficiency $\epsilon_{\rm lens}^2 - m\left(\epsilon_{\rm lens}\sqrt{\mu_t}\right) = 0$

such that for $m(\tau) = 1$, $\epsilon_{\rm lens} = 1$

this is the one of the roots of μ^{-1}



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

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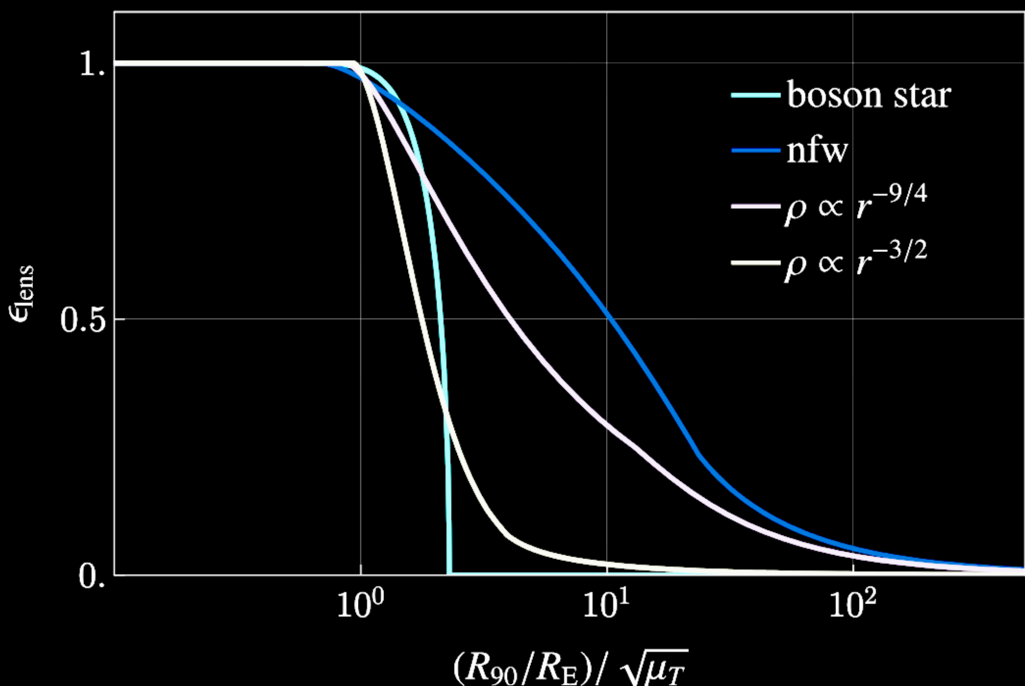

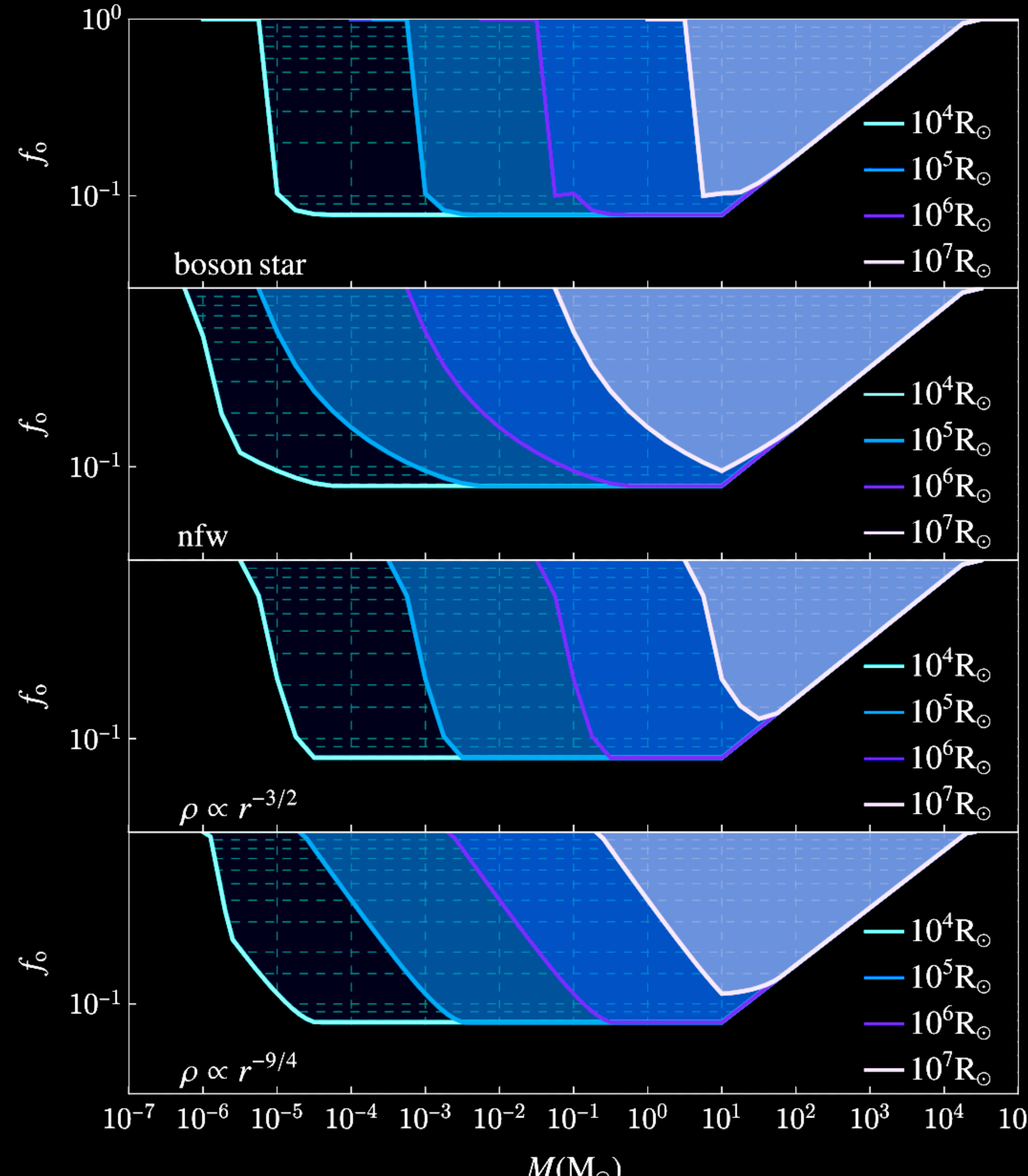

Using this efficiency, generalise Icarus constraints

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

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

Bringmann, DC, Sevillano Muñoz, arXiv:2506.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. PTAs and WIMPs (= model-dependent)

Clark, Lewis, Scott, MNRAS, arXiv:1509.02938
Bringmann, Scott, Akrami, PRD, arXiv:1110.2484

- But we now have far more gravitational probes…

The primordial power spectrum

- Assume a generalised power spectrum

- EDOs formed with

$$\frac{R(z_c)}{\mathrm{pc}} = 0.019\left(\frac{1000}{z_c+1}\right)\left(\frac{M(z_c)}{M_\odot}\right)^{1/3} \text{ with } M(z_c) = \frac{z_{\mathrm{eq}}+1}{z_c+1}M_i$$

Bringmann, DC, Sevillano Muñoz, arXiv:2506.XXXX

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

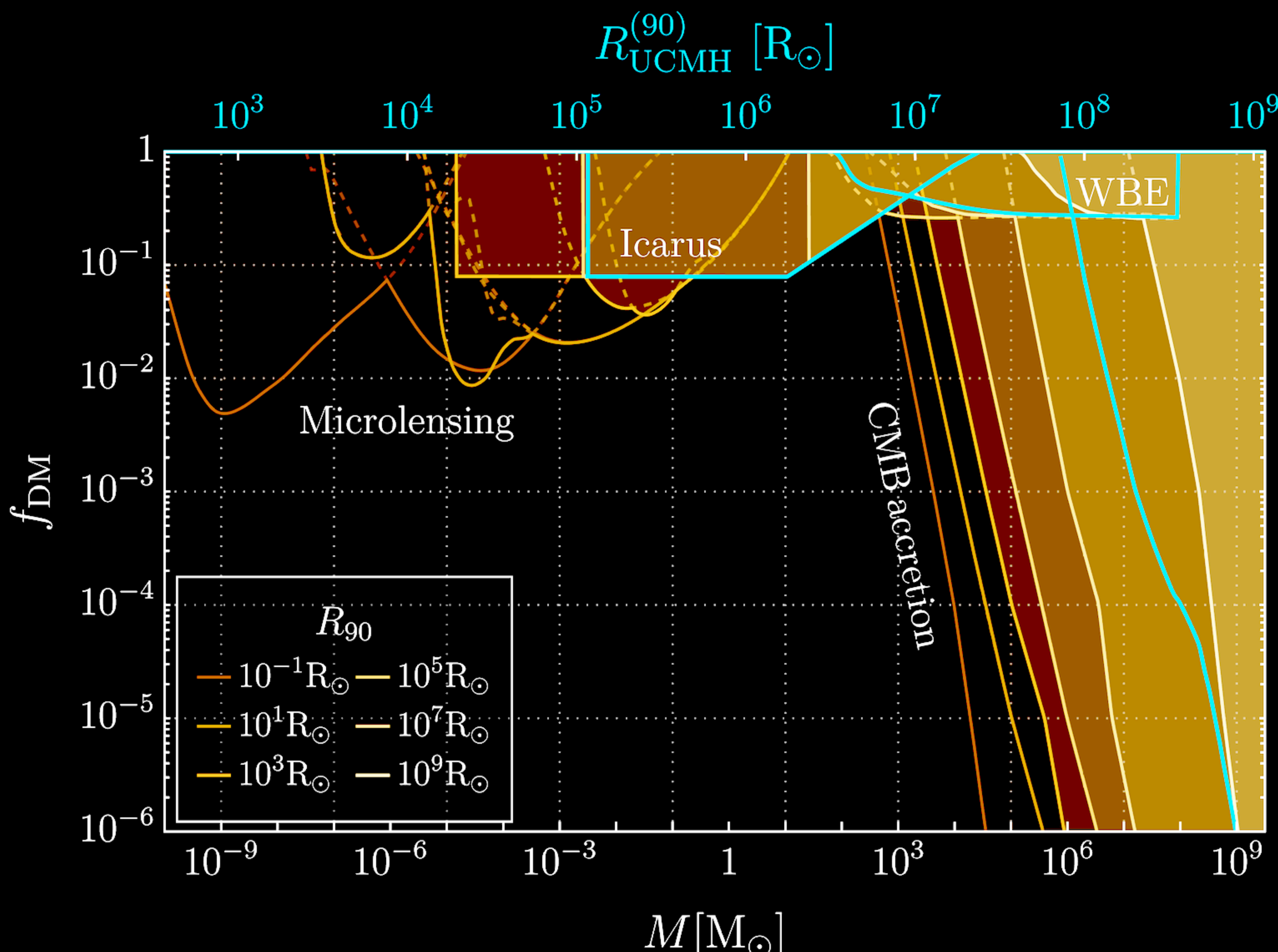
- $f_{\text{DM}} < 1$ for
  - CMB accretion (generalised to larger EDOs)
  - Wide binary evaporation
  - "ICARUS" microlensing (generalised from PBHs to EDOs)

DC, Sevillano Muñoz, JCAP, arXiv:2403.13072

Ramirez and Buckley, MNRAS, arXiv:2209.08100

Bringmann, DC, Sevillano Muñoz, arXiv:2506.XXXX

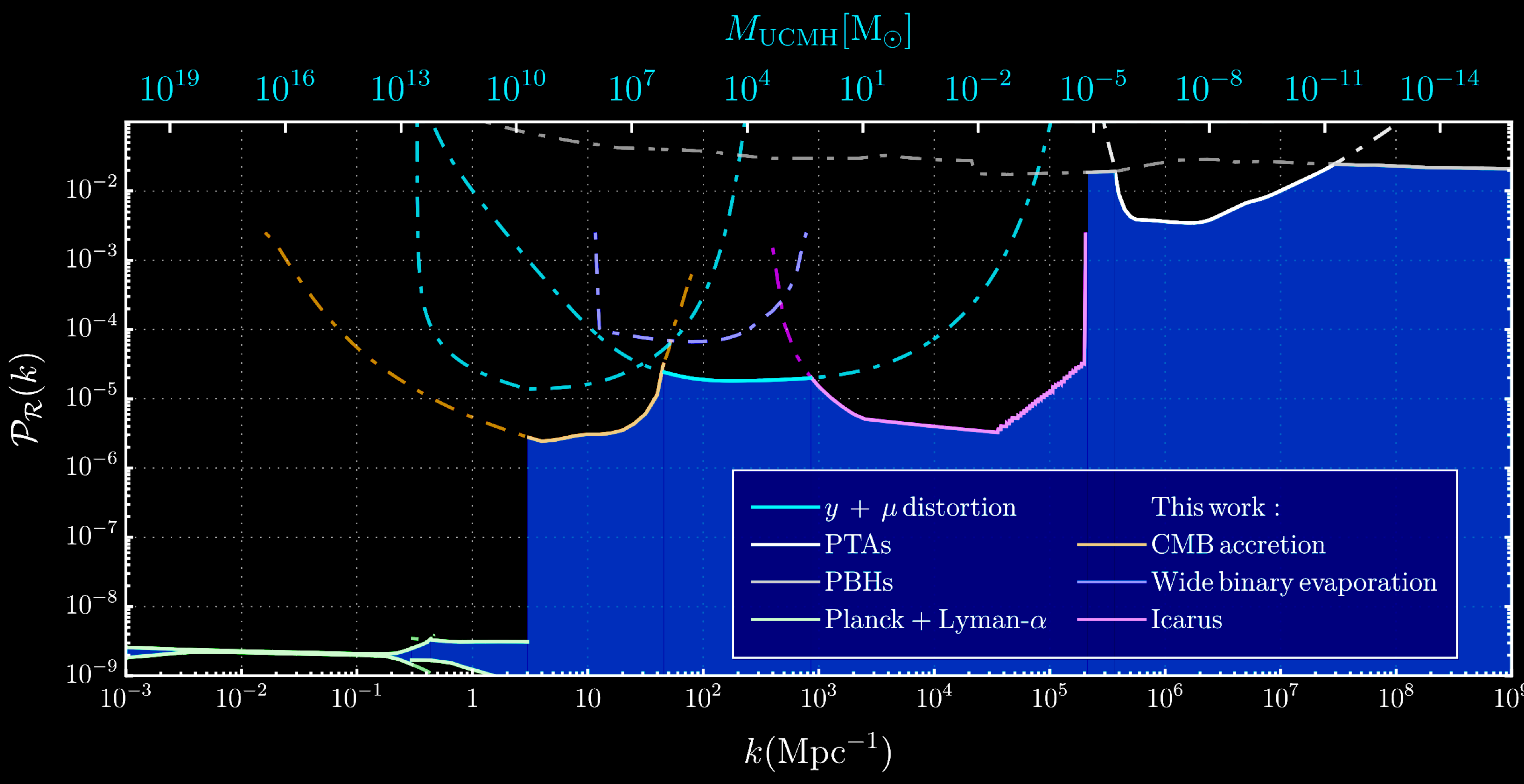
The primordial power spectrum



Bringmann, DC, Sevillano Muñoz, arXiv:2506.XXXX

The primordial power spectrum

for UCMH collapsing at z_c, $\frac{R(z_c)}{\mathrm{pc}} = 0.019\left(\frac{1000}{z_c+1}\right)\left(\frac{M(z_c)}{M_\odot}\right)^{1/3}$ with $M(z_c) = \frac{z_{eq}+1}{z_c+1}M_i$



To conclude,

- All of our current evidence for Dark Matter is gravitational; many dark matter 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,

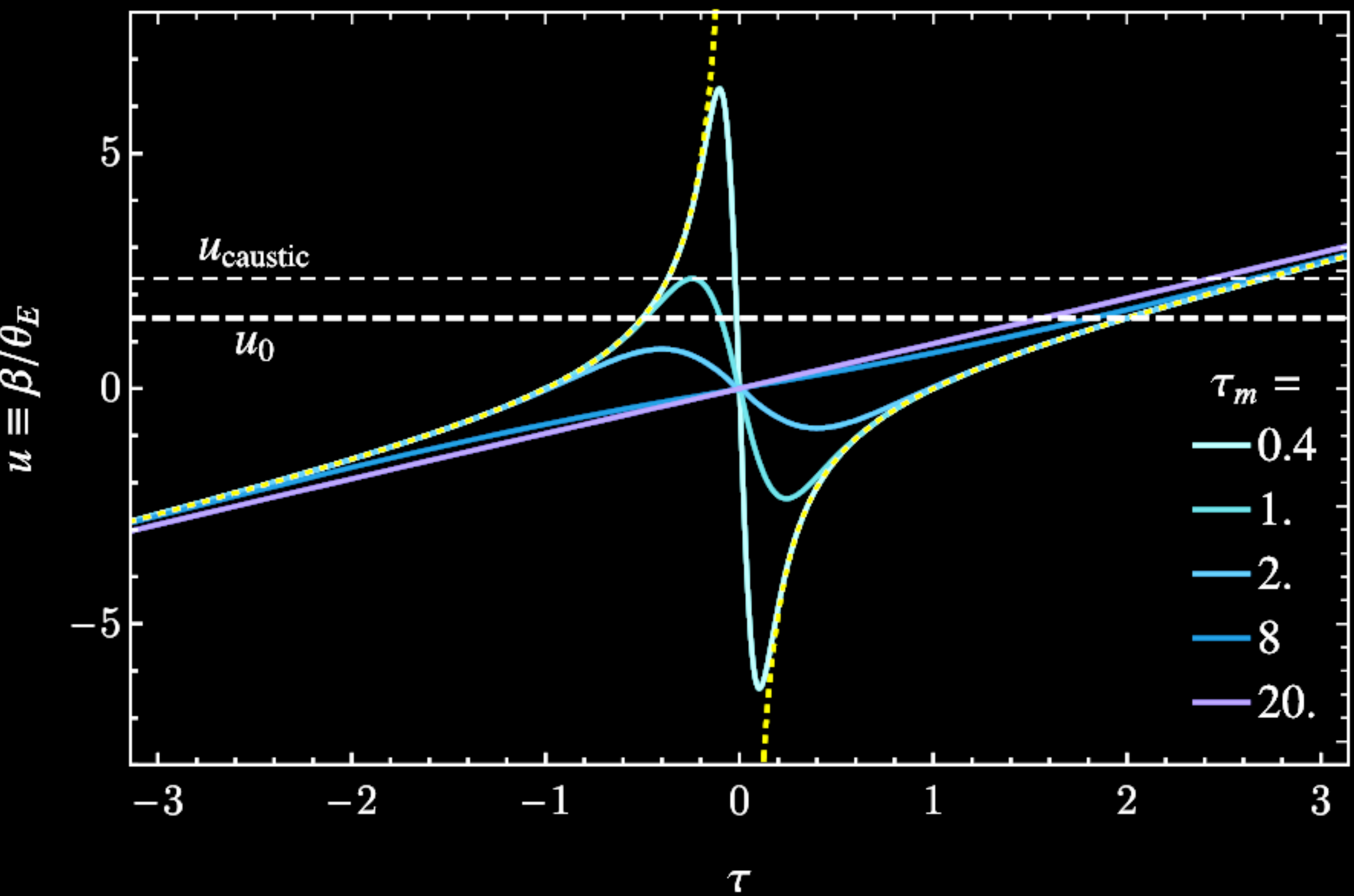
- All of our current evidence for Dark Matter is gravitational; many dark matter models feature substructure
- Microlensing provides a way to look for dark matter substructure of a large range of sizes and masses
  - →Extended objects may give unique microlensing signatures
  - →Non-observation can be used to derive constraints
- Caustic crossings in giant arcs are an opportunity to probe lenses with an even bigger radius
- Non-observations of UCMH can be used to constrain the curvature power spectrum on CMB-inaccessible scales

Thank you!

…ask me anything you like!

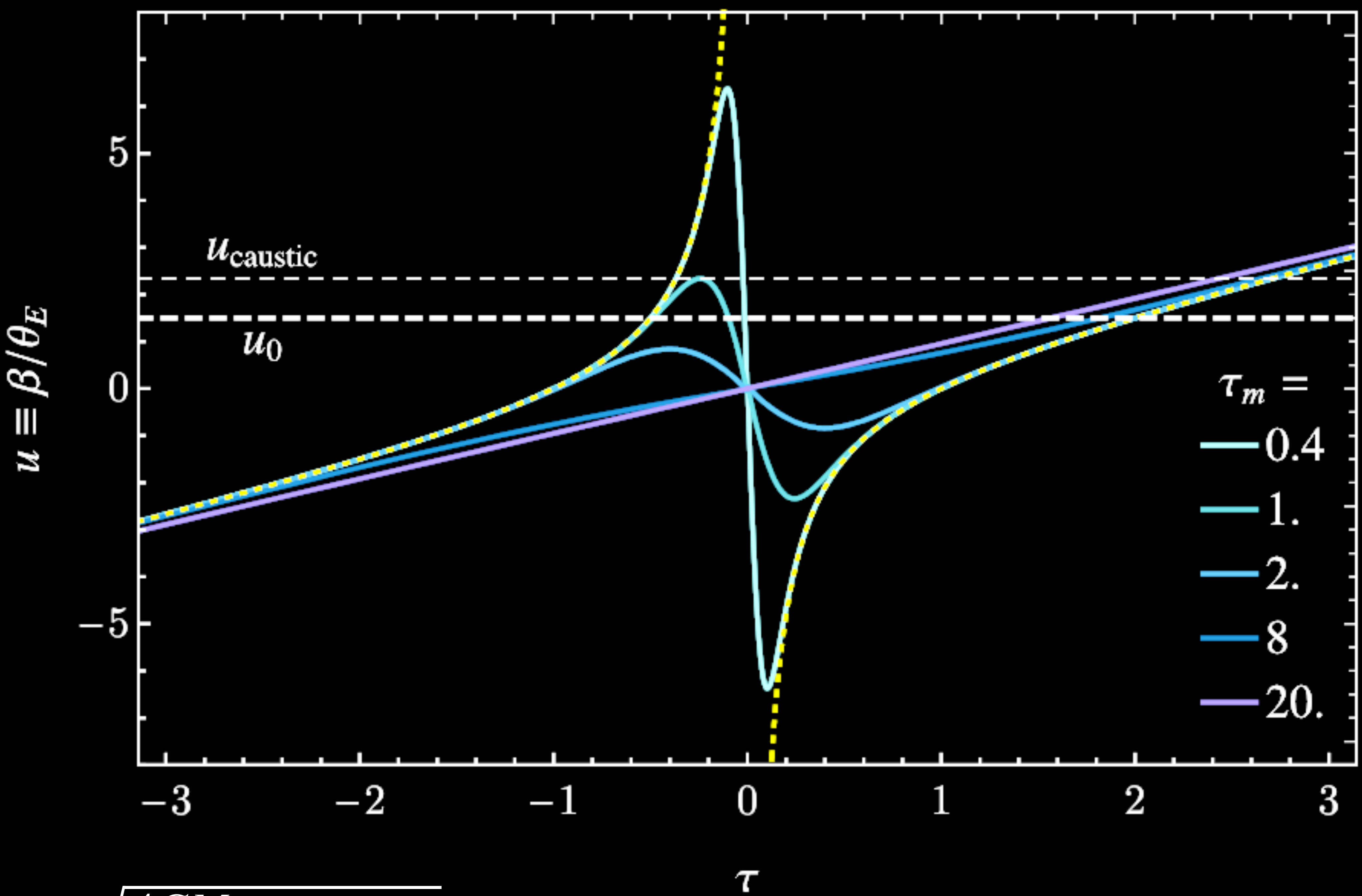
djuna.l.croon@durham.ac.uk | djunacroon.com

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



point-like

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

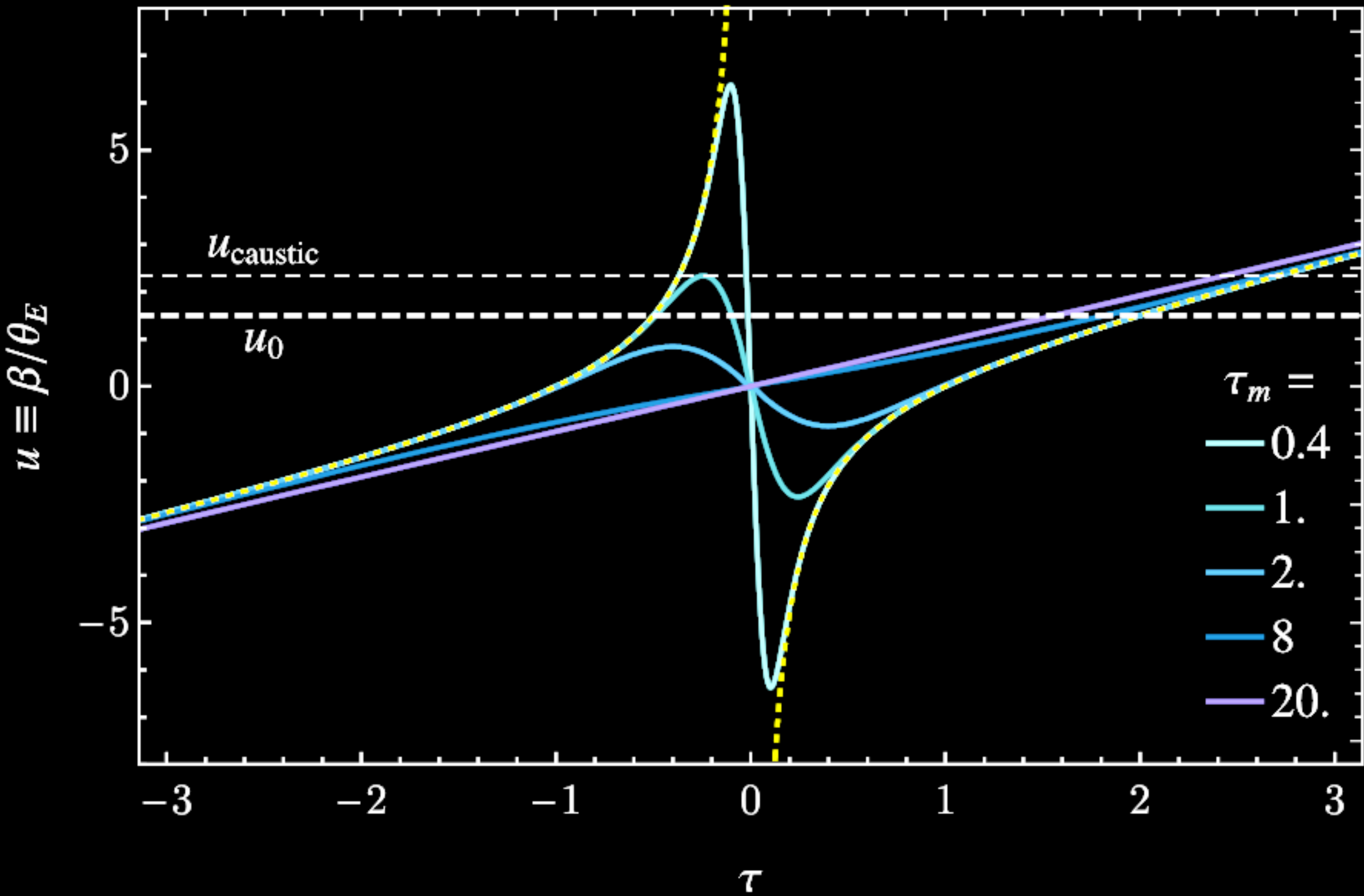


point-like

$$r_E = \sqrt{\frac{4GM}{c^2} D_S (1-x)x}$$

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

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



point-like

3 solutions, one with negligible μ_i

3 solutions, all contributing μ_i

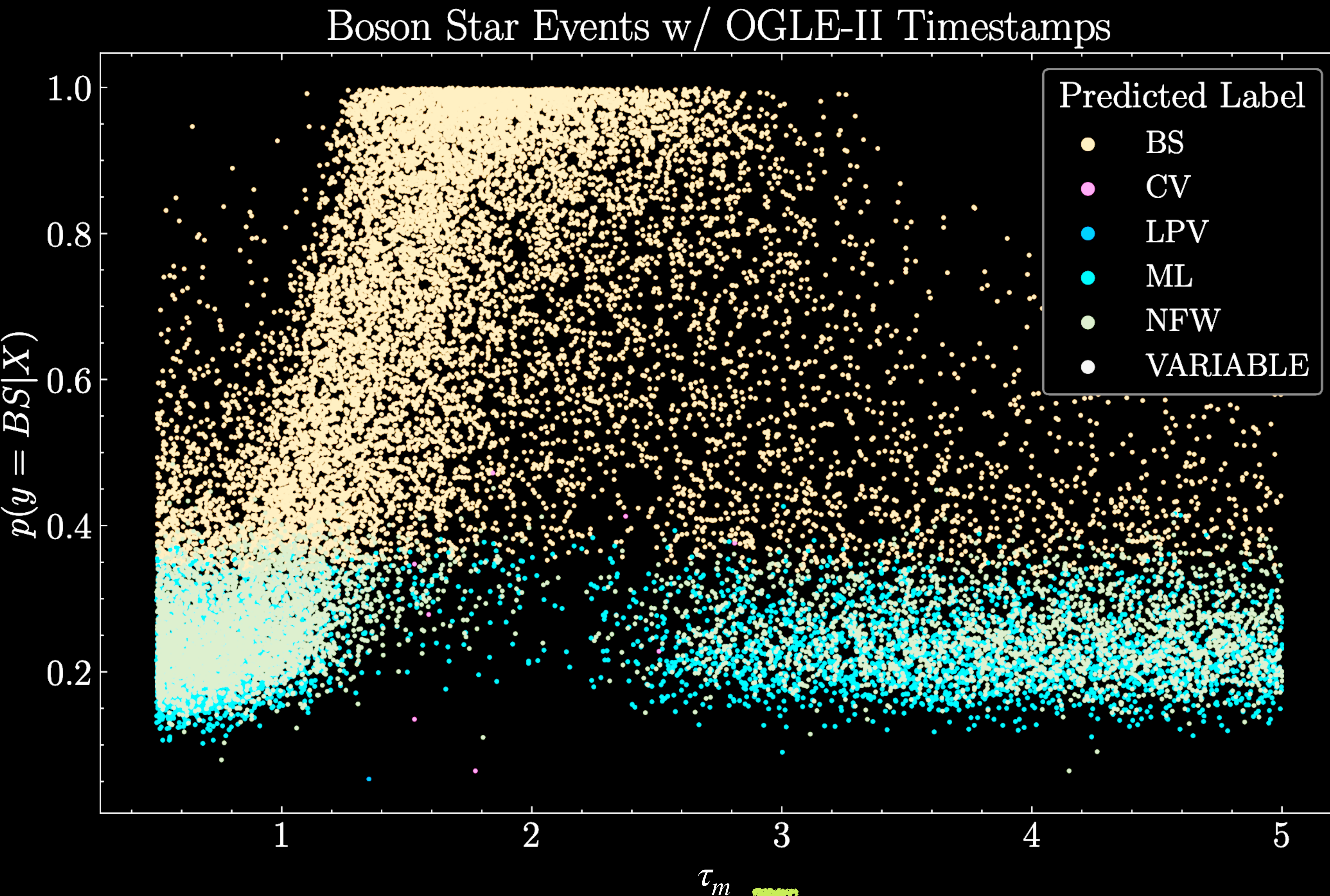
1 solution of the point-like case

1 solution, larger μ_i than point-like

1 solution, $\mu_i \to 0$

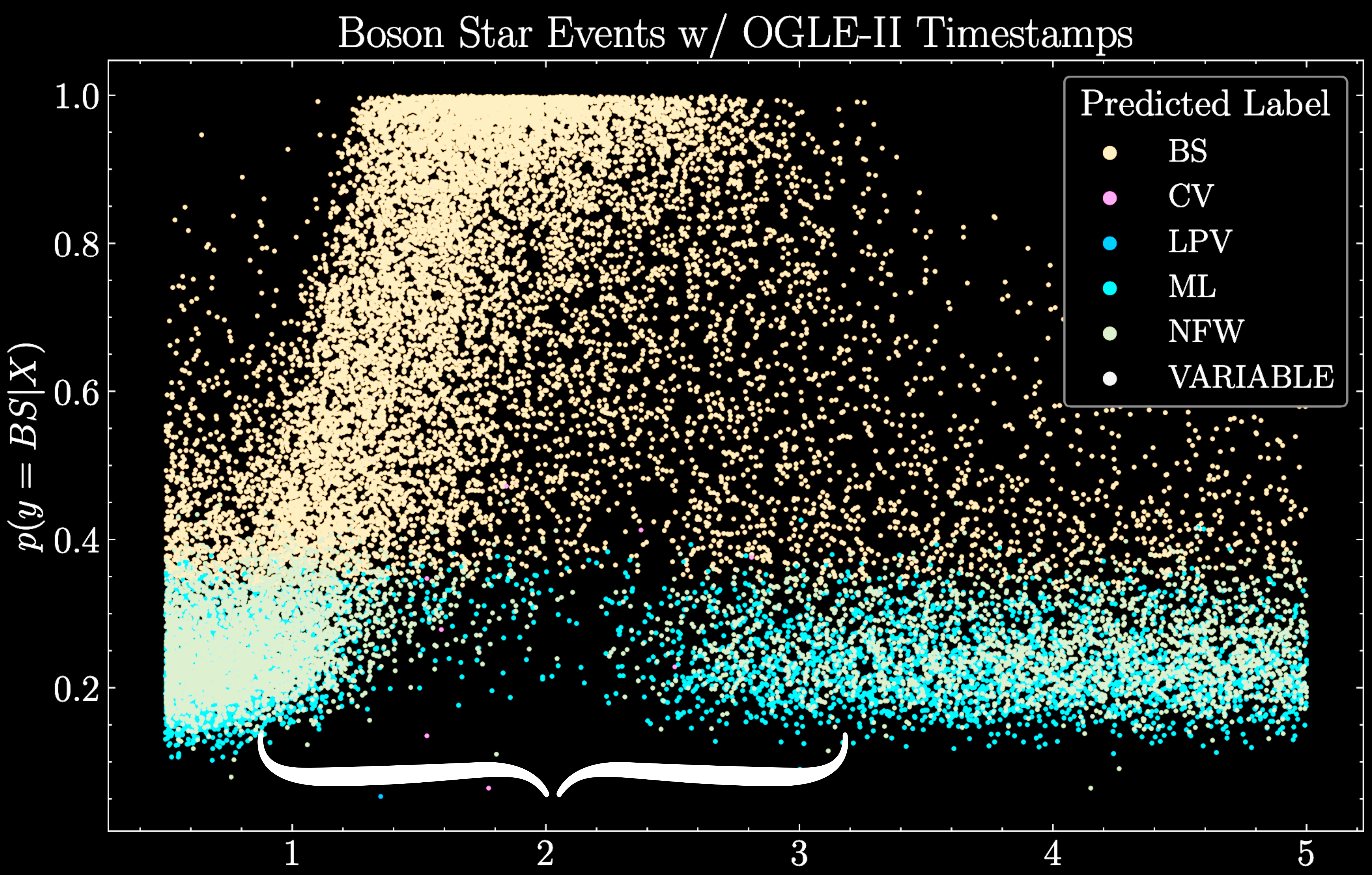
→ at u_{caustic}, number of solutions jumps from 1 to 3

Miguel Crispim-Romao, DC, PRD, arXiv:2402.00107



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

Miguel Crispim-Romao, DC, PRD, arXiv:2402.00107

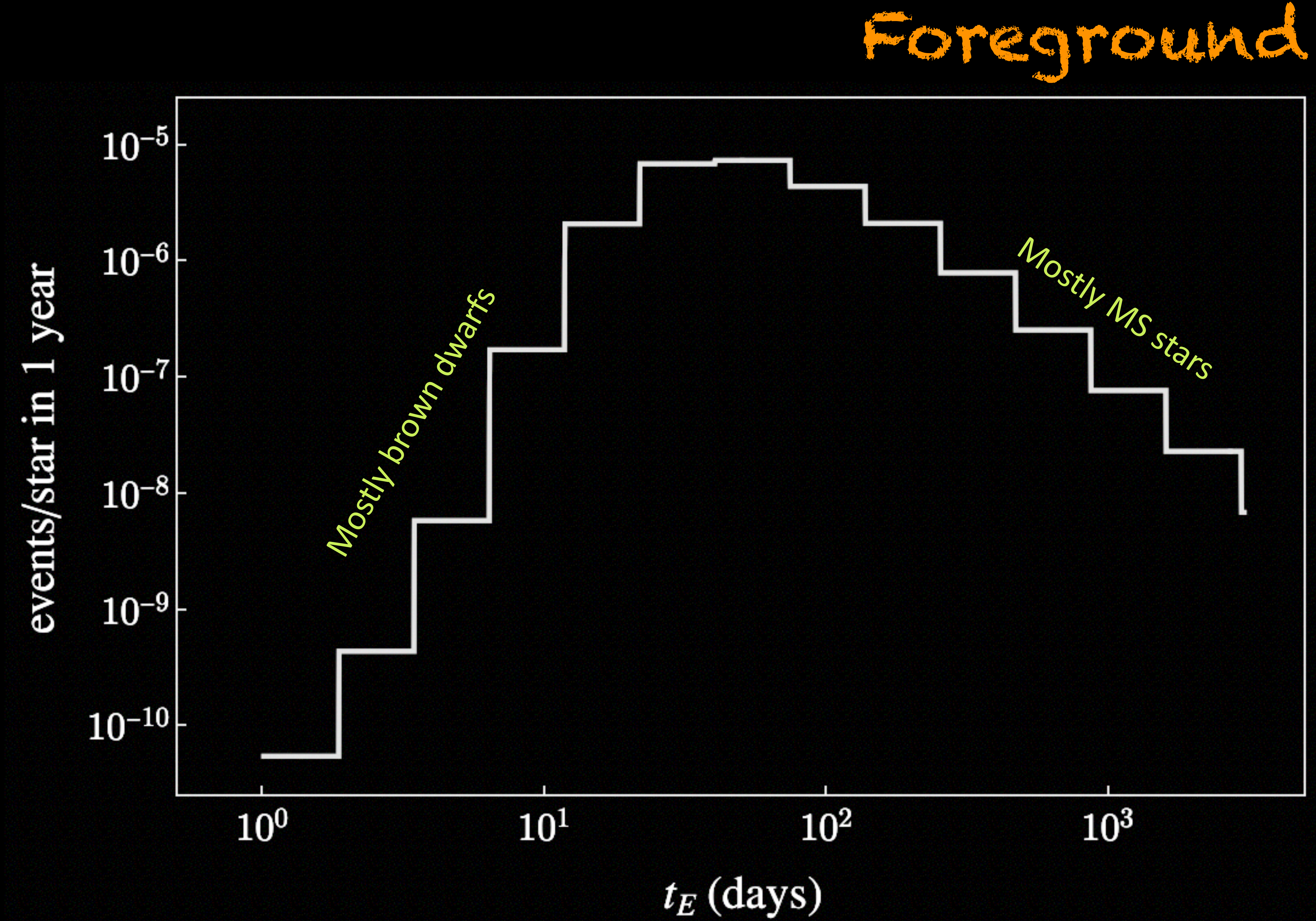


Indeed, the most probable detections are for $0.8 < \tau_m < 3$

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

LSST by Rubin: projections

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



Bringmann, DC, Sevillano Muñoz, arXiv:2506.XXXX

The primordial power spectrum

- Primordial curvature perturbations with amplitude $\mathscr{P}_{\mathscr{R}}(k)$ 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 $\delta_\chi^{\min}(R)$

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  - If $\delta_\chi(R)$ exceeds a threshold $\delta_\chi^{\rm min}(R) \sim 10^{-3}$, the region collapses into an UCMH
  - If $\sigma_{\chi,H}(R)$ is too large many regions will exceed $\delta_\chi^{\rm min}(R)$
- From $f_{\rm DM}$ we work backward:
  - $f_{\rm DM}$ 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 β_{max} fixes the largest allowable $\sigma(R)$
  - Since $\sigma^2(R)$ is essentially an integral over $\mathscr{P}_{\mathscr{R}}(k)$ around $k \sim 1/R$, limiting $\sigma(R) \Rightarrow$ upper limit on $\mathscr{P}_{\mathscr{R}}(k)$