Probes of extended dark matter structures

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Catch22+2, May 2024

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Dark matter substructure

Two things we may agree upon…

- All of our evidence for Dark Matter is gravitational
- Many dark matter models feature substructure

PBHs	Boson stars	Subhalos	Miniclusters	Mirror stars

Image credit: Adam Rogers, theamateurrealist.wordpress.com

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- Microlensing can be used to probe such models

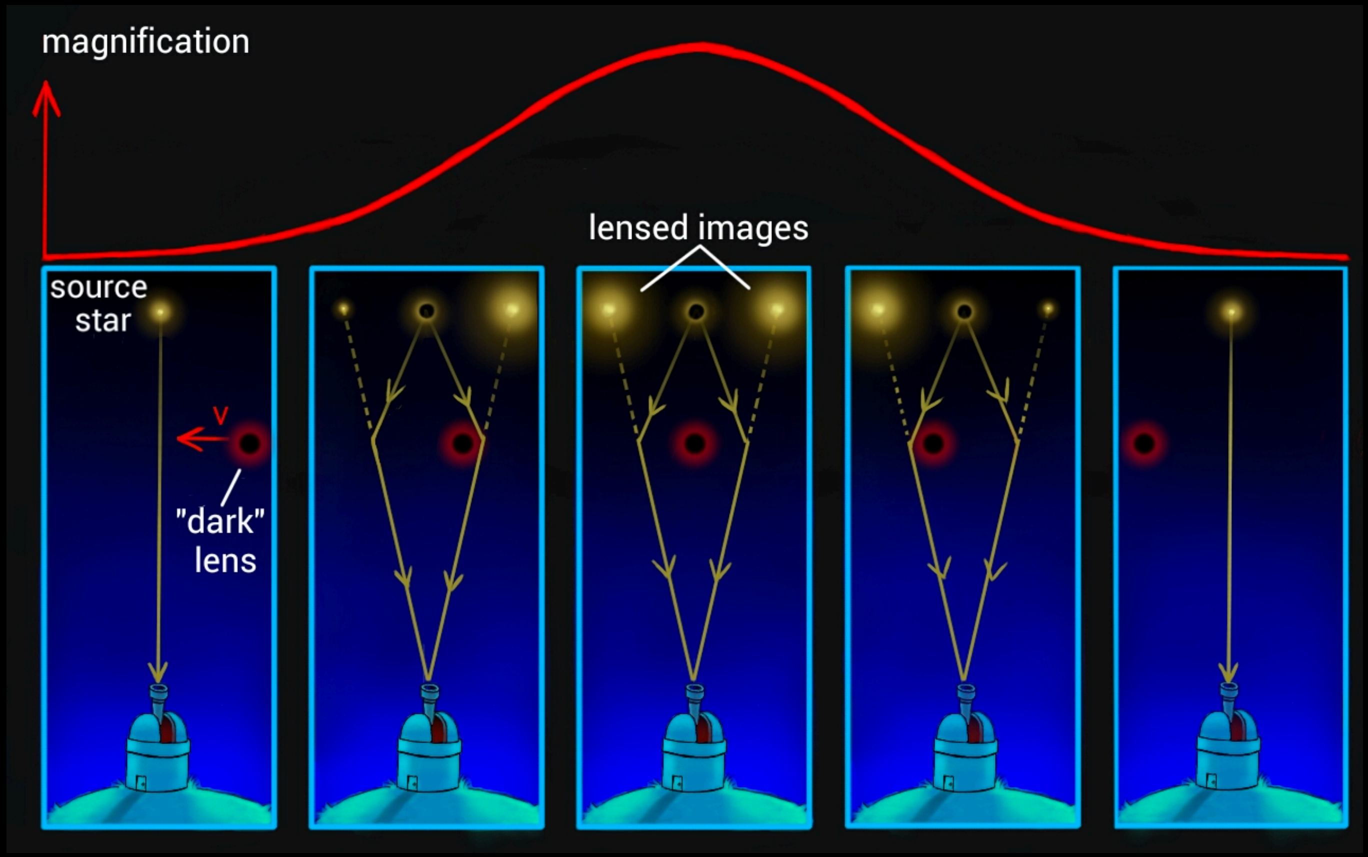
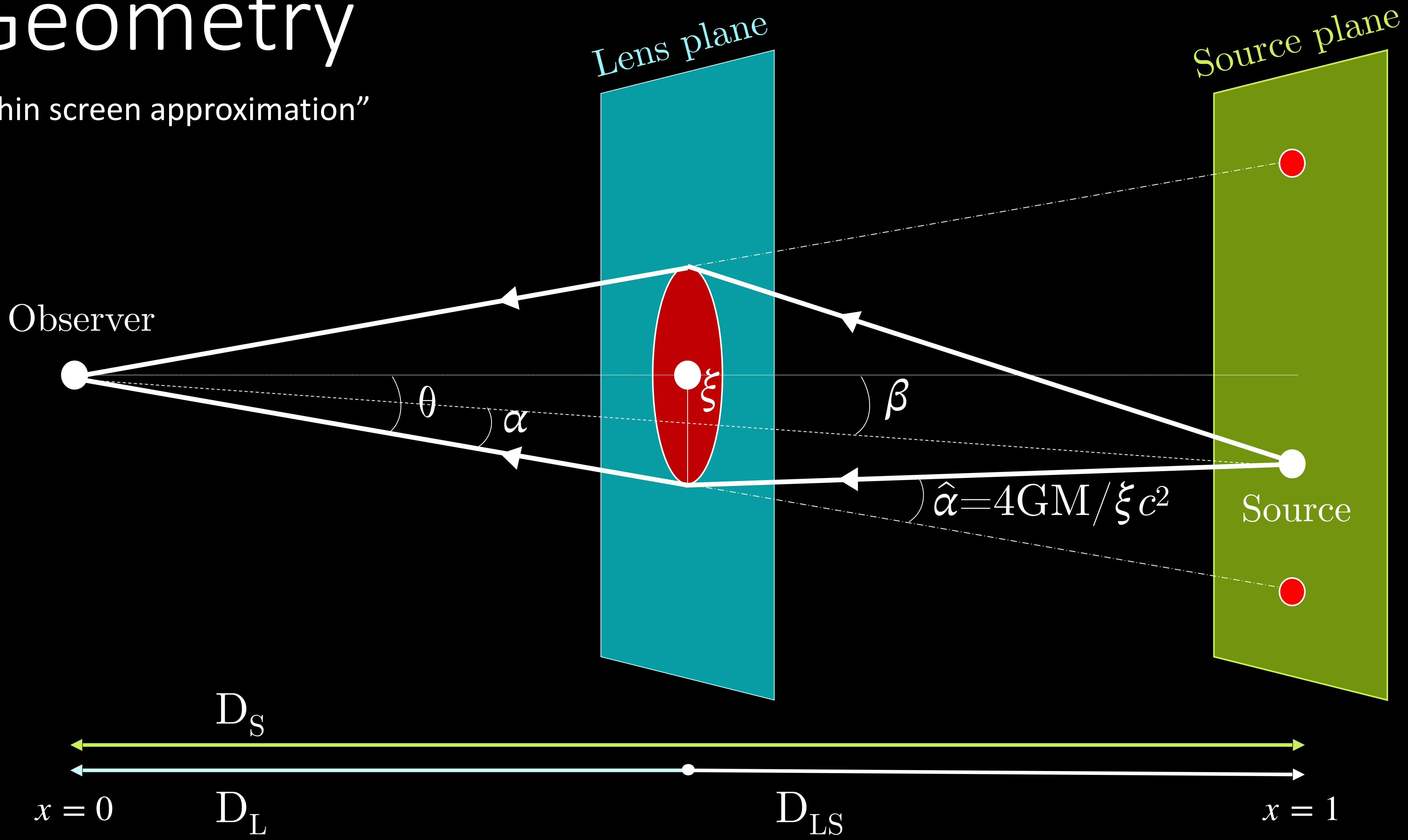


Image credit: Adam Rogers, theamateurrealist.wordpress.com

Geometry

"Thin screen approximation"



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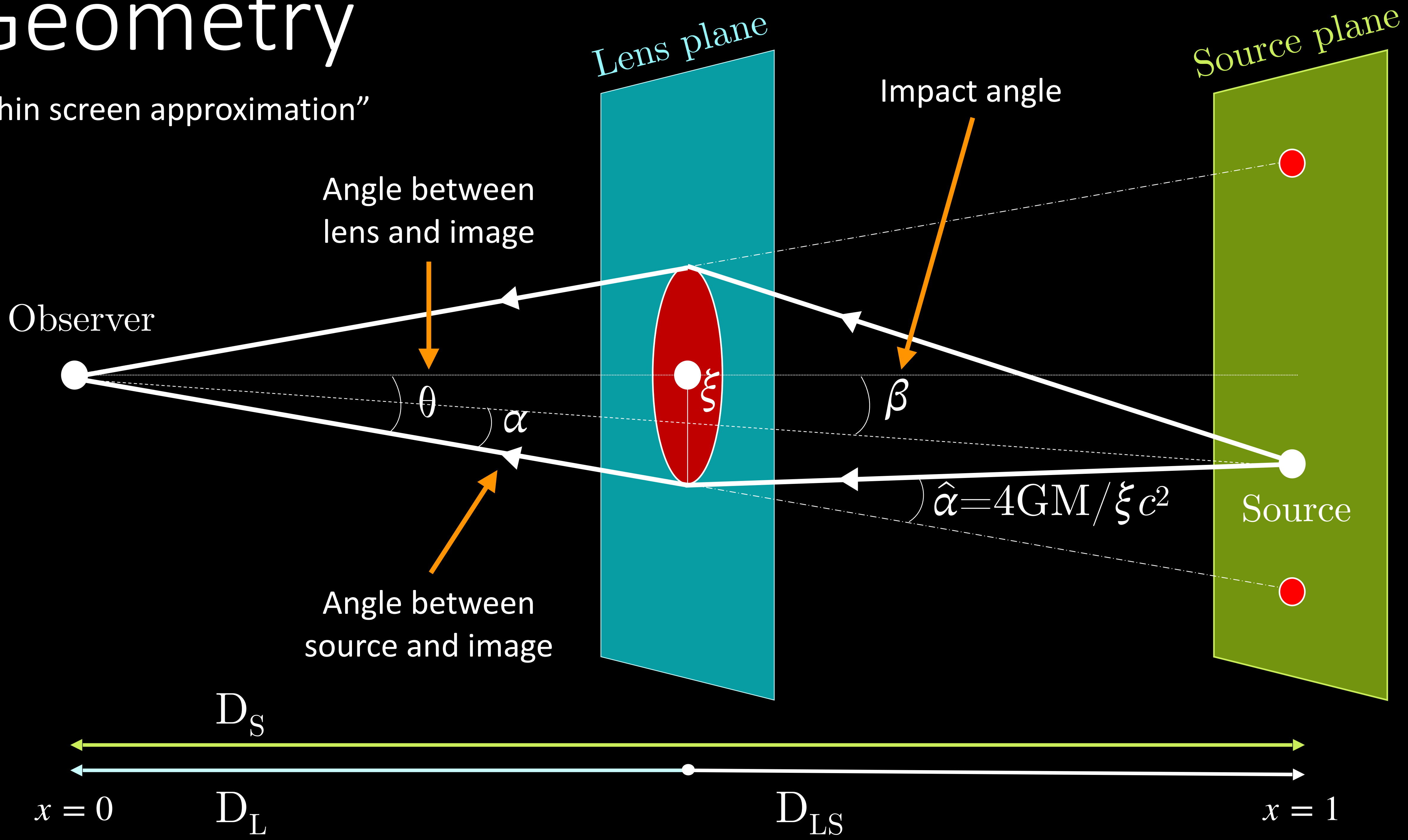

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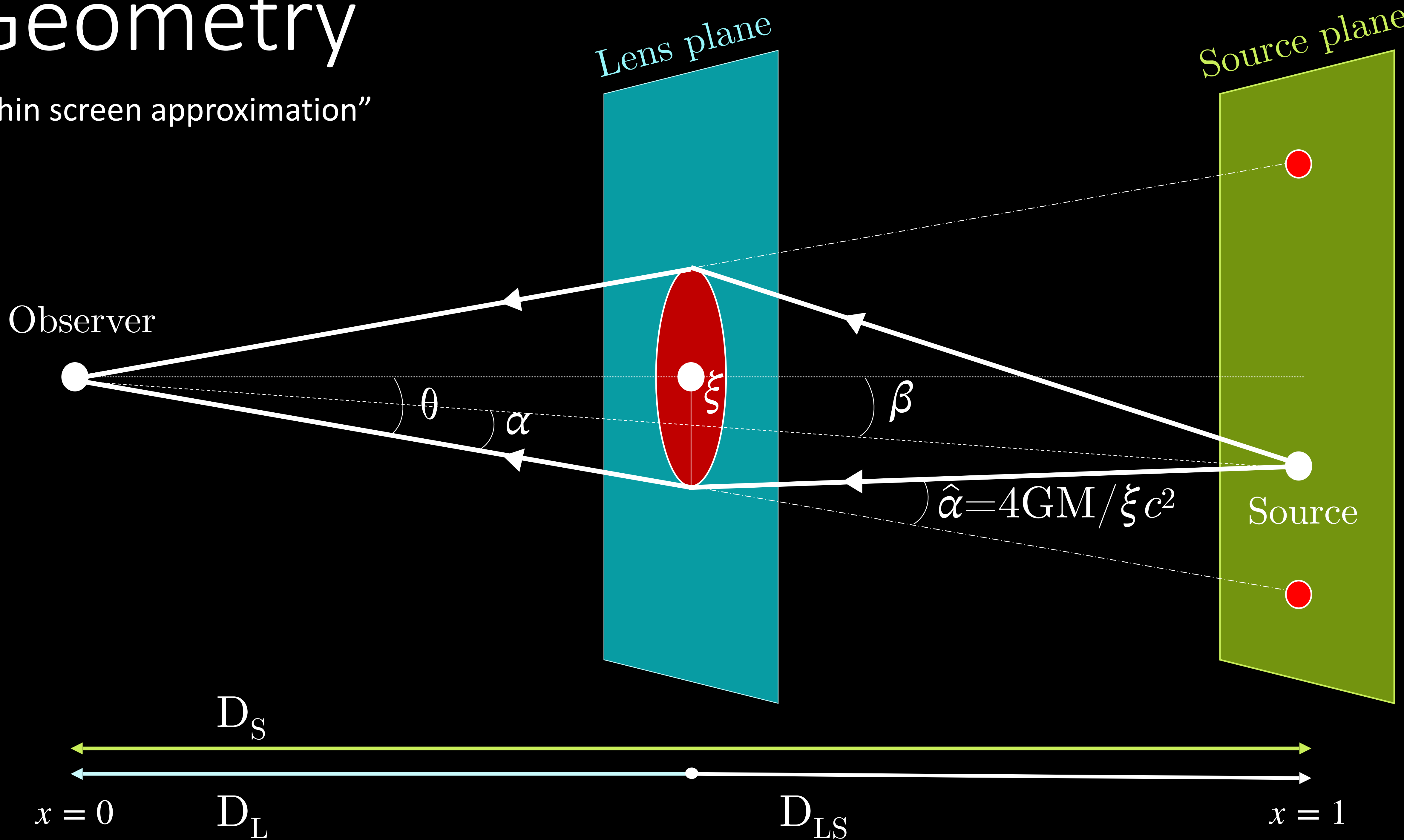
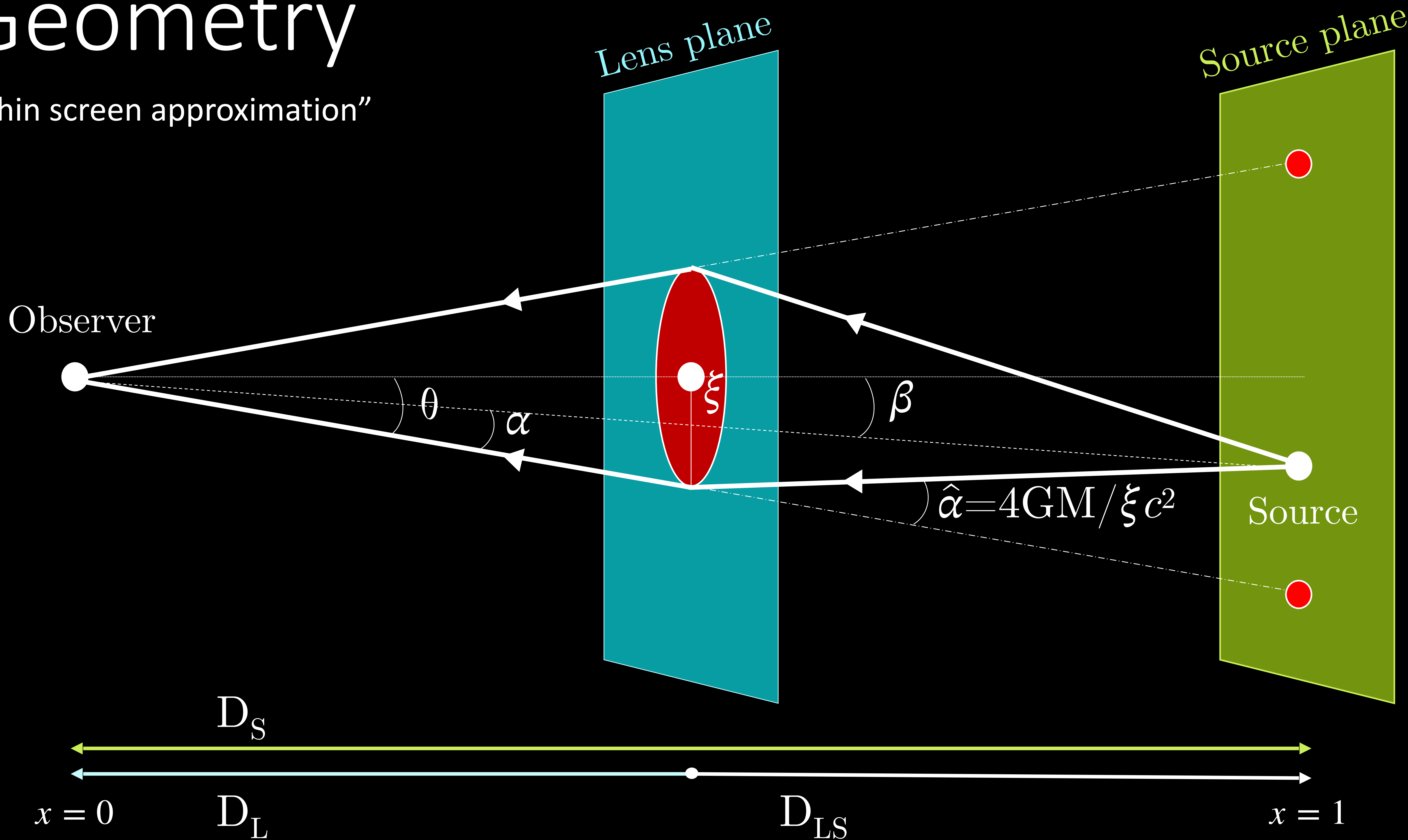


$$\theta D_S = \beta D_S - \hat{\alpha} D_{LS} \rightarrow \underbrace{\beta = \theta - \alpha = \theta - \hat{\alpha}\frac{D_{LS}}{D_S} = \theta - \frac{4GM(\theta)}{\theta c^2}\frac{D_{LS}}{D_S}}_{\text{Lensing equation}}$$

Geometry

"Thin screen approximation"



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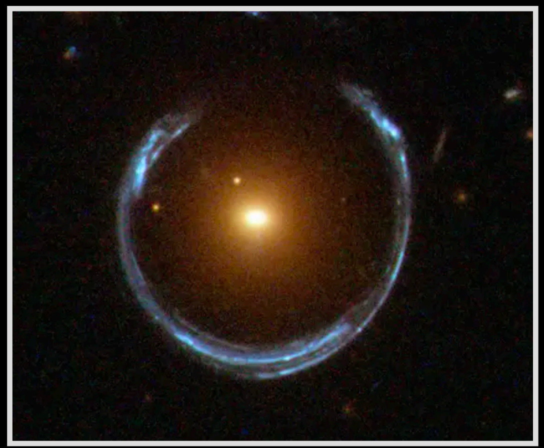
$$\beta = 0 \rightarrow\ ,\ \theta \equiv \theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_L D_S}}$$

Einstein radius

$r_E = \theta_E D_L$



Near perfect Einstein Ring with the HST

The lensing tube

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

The lensing tube

normalised impact parameter $u \equiv \beta/\theta_E$

- Magnification: $\mu = \dfrac{\theta}{\beta}\dfrac{d\theta}{d\beta} = \sum \mu_i = \dfrac{u^2+2}{u\sqrt{u^2+4}} \rightarrow 1.34$

point-like lens

$u \rightarrow 1$

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point-like lens $\quad u \to 1$

- θ_E defines a lensing tube with radius $r_E = \theta_E D_L$

- Defining $\tau \equiv \theta/\theta_E$, $m(\tau) \equiv M(\theta_E \tau)/M$,

$$u = \tau - \frac{m(\tau)}{\tau} \quad \text{with} \quad \mu = \left|1 - \frac{m(\tau)}{\tau^2}\right|^{-1} \left|1 + \frac{m(\tau)}{t^2} - \frac{1}{\tau}\frac{dm(\tau)}{d\tau}\right|^{-1}$$

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

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Projected lens mass distribution

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

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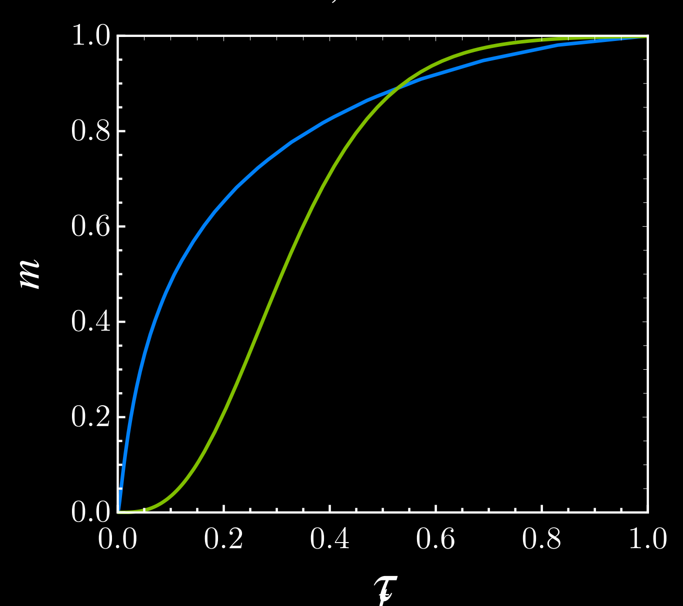
NFW, Boson star



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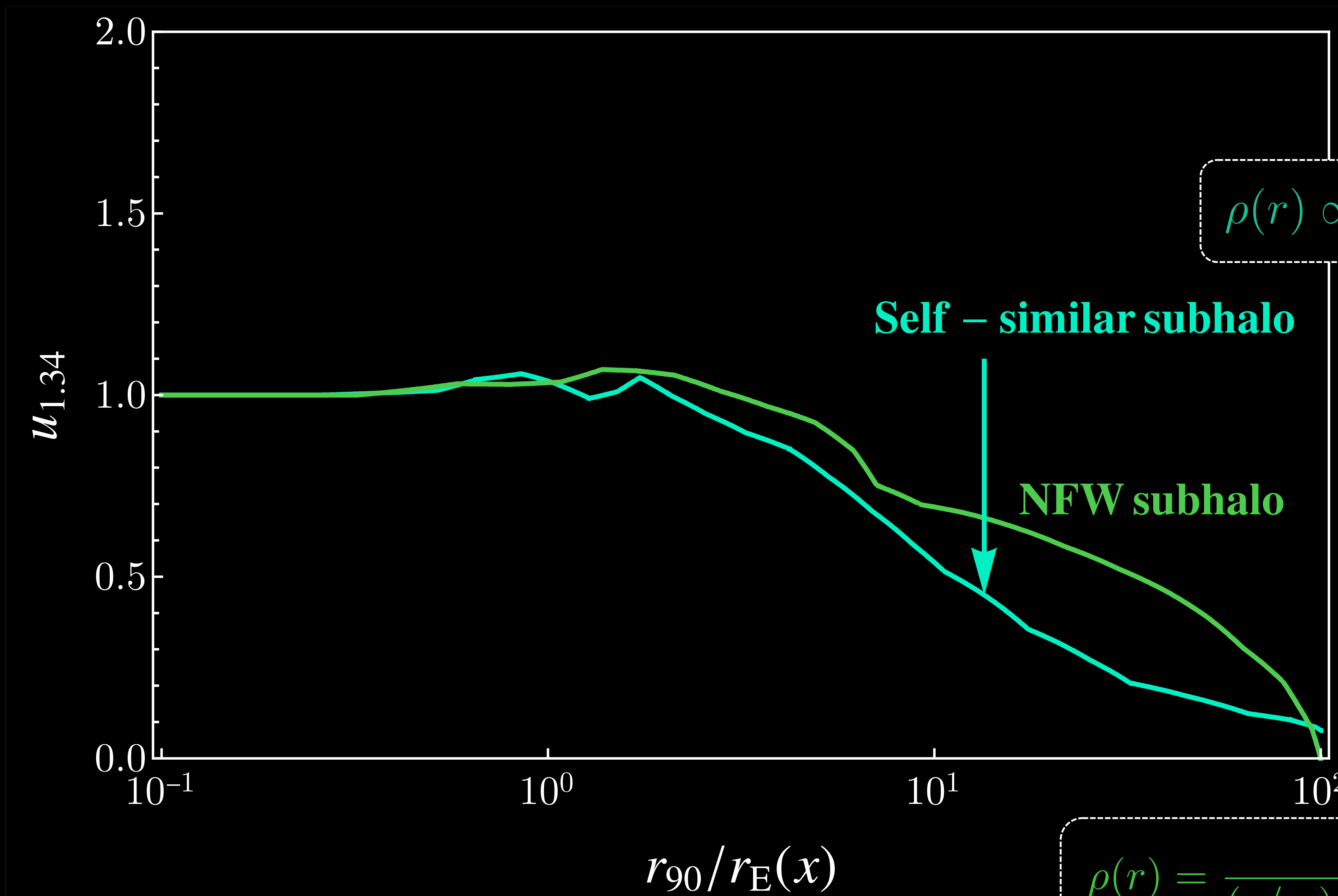
DC, D. McKeen, N. Raj, PRD, arXiv:2002.08962 [astro-ph.CO]

Threshold impact parameter

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

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



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

$$\rho(r) = \frac{\rho_{\rm s}}{(r/r_{\rm s})(1+r/r_{\rm s})^2}$$

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

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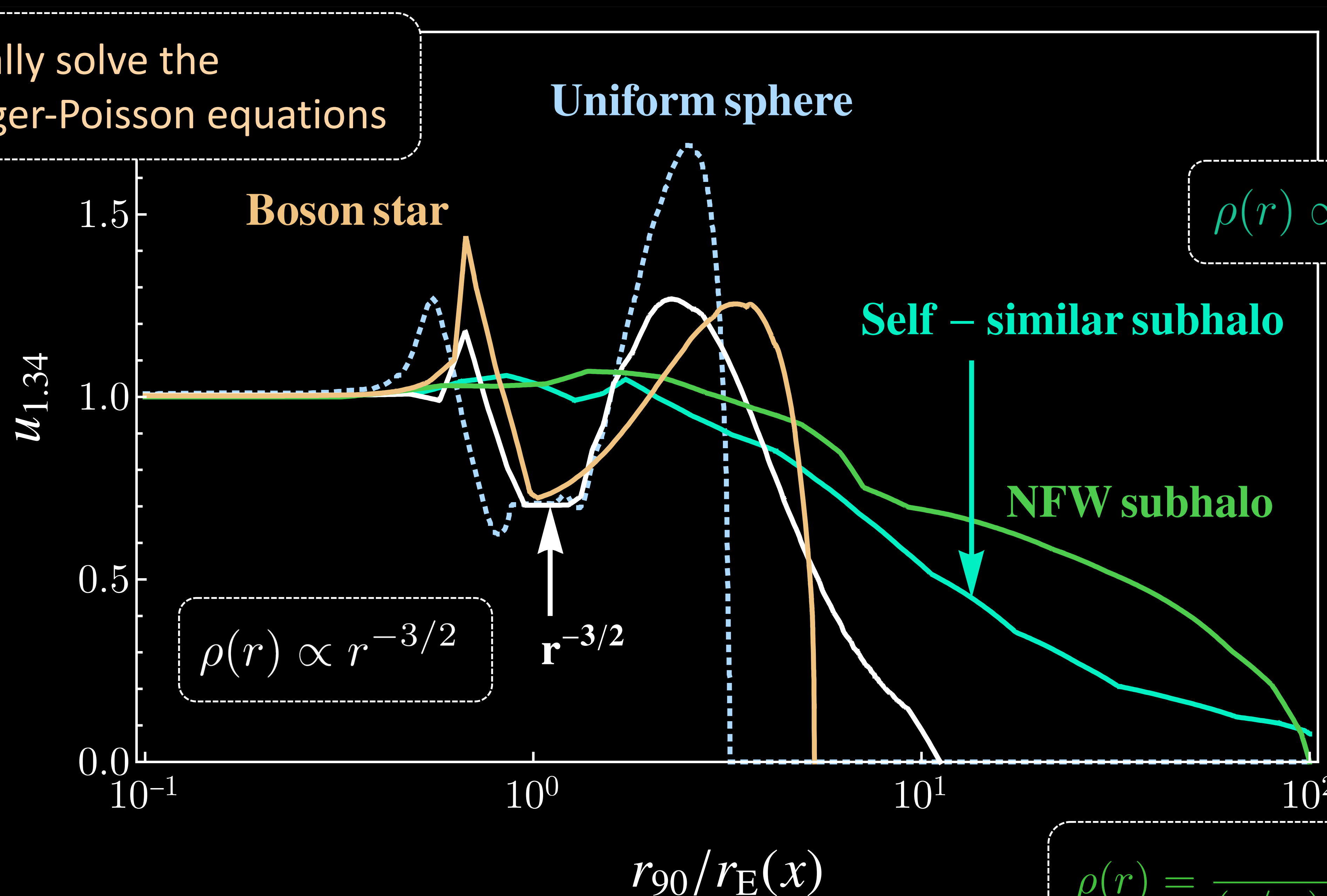
Numerically solve the Schrodinger-Poisson equations



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

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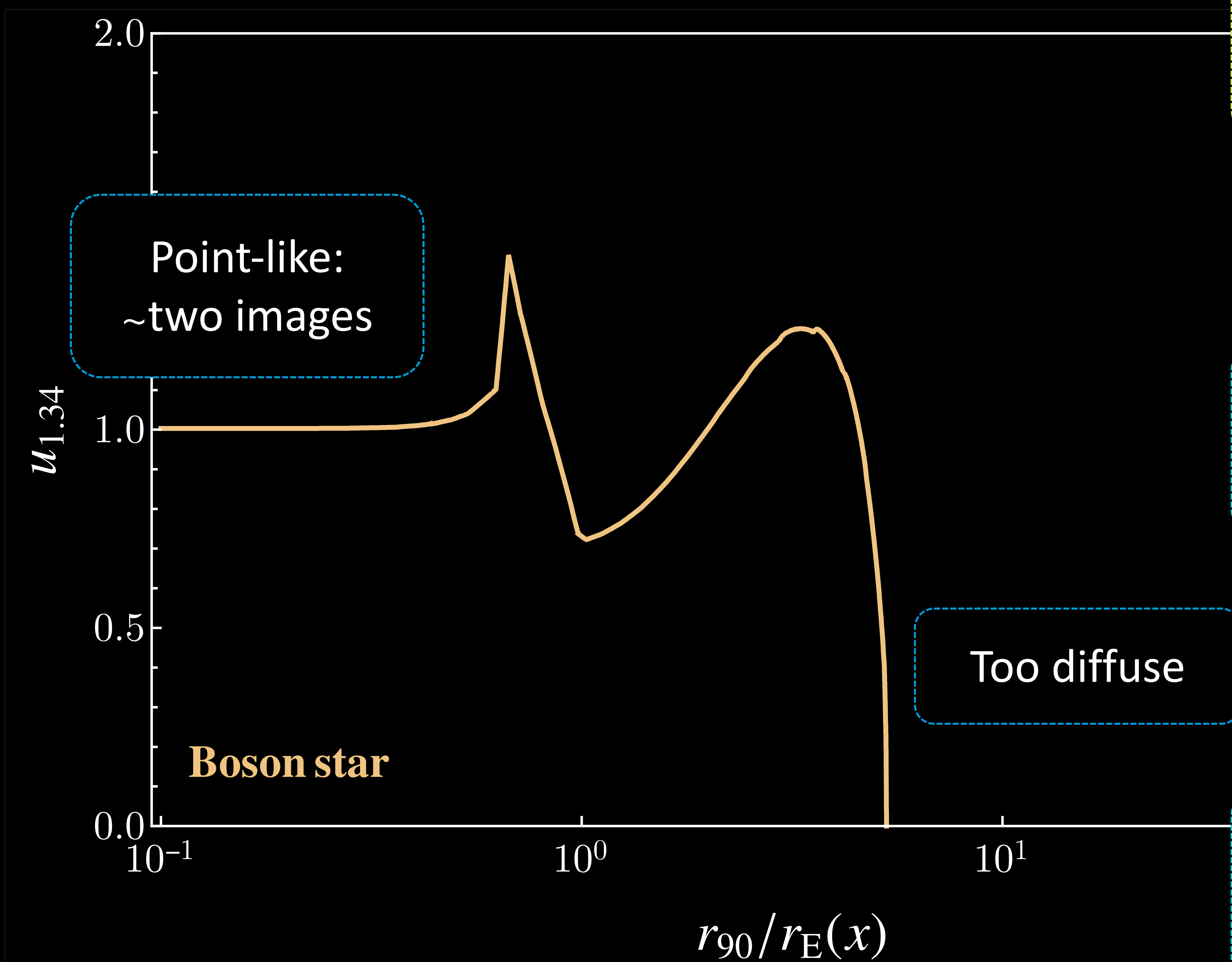
DC, D. McKeen, N. Raj, PRD, arXiv:2002.08962 [astro-ph.CO]

Caustics

What's going on here?



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

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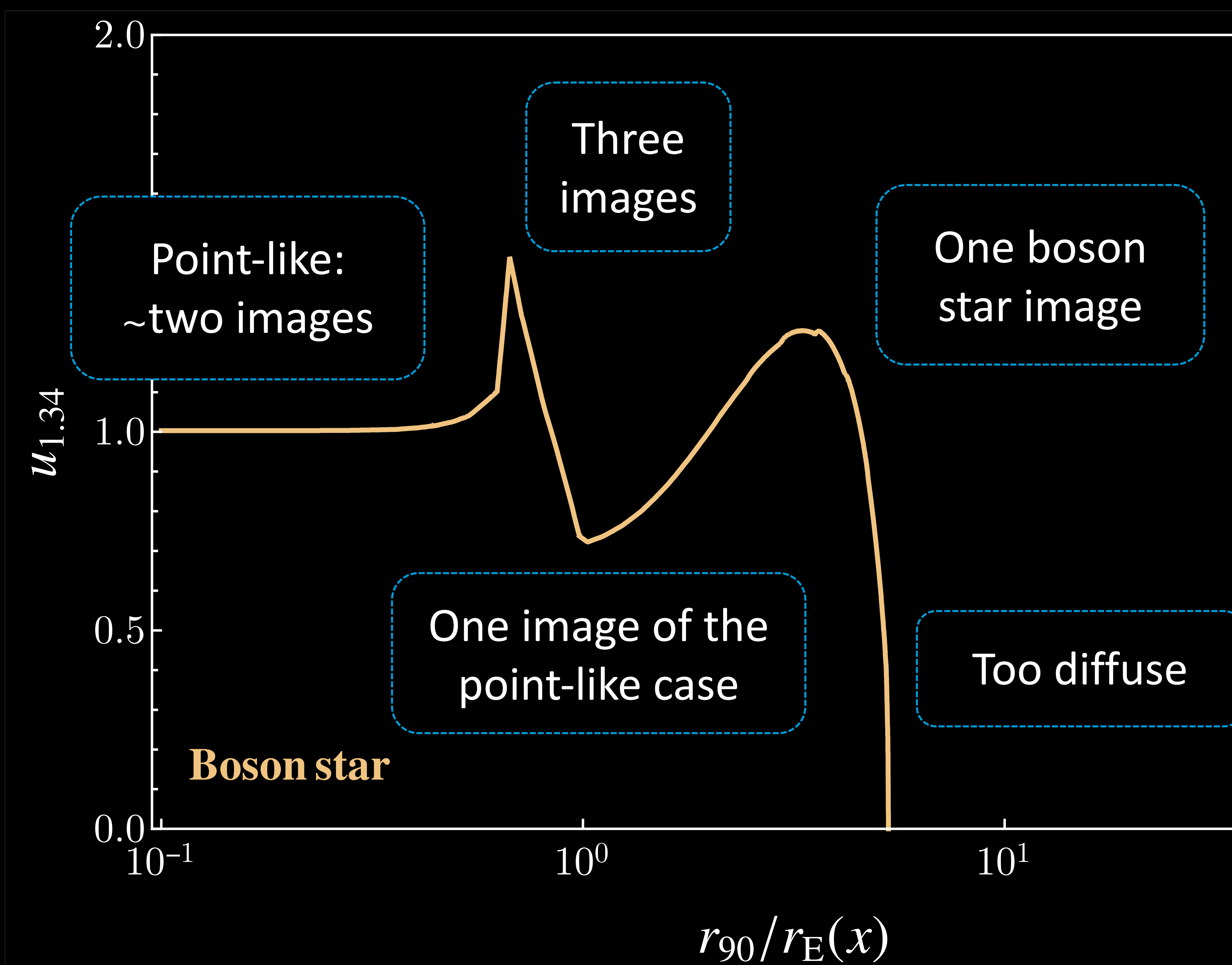

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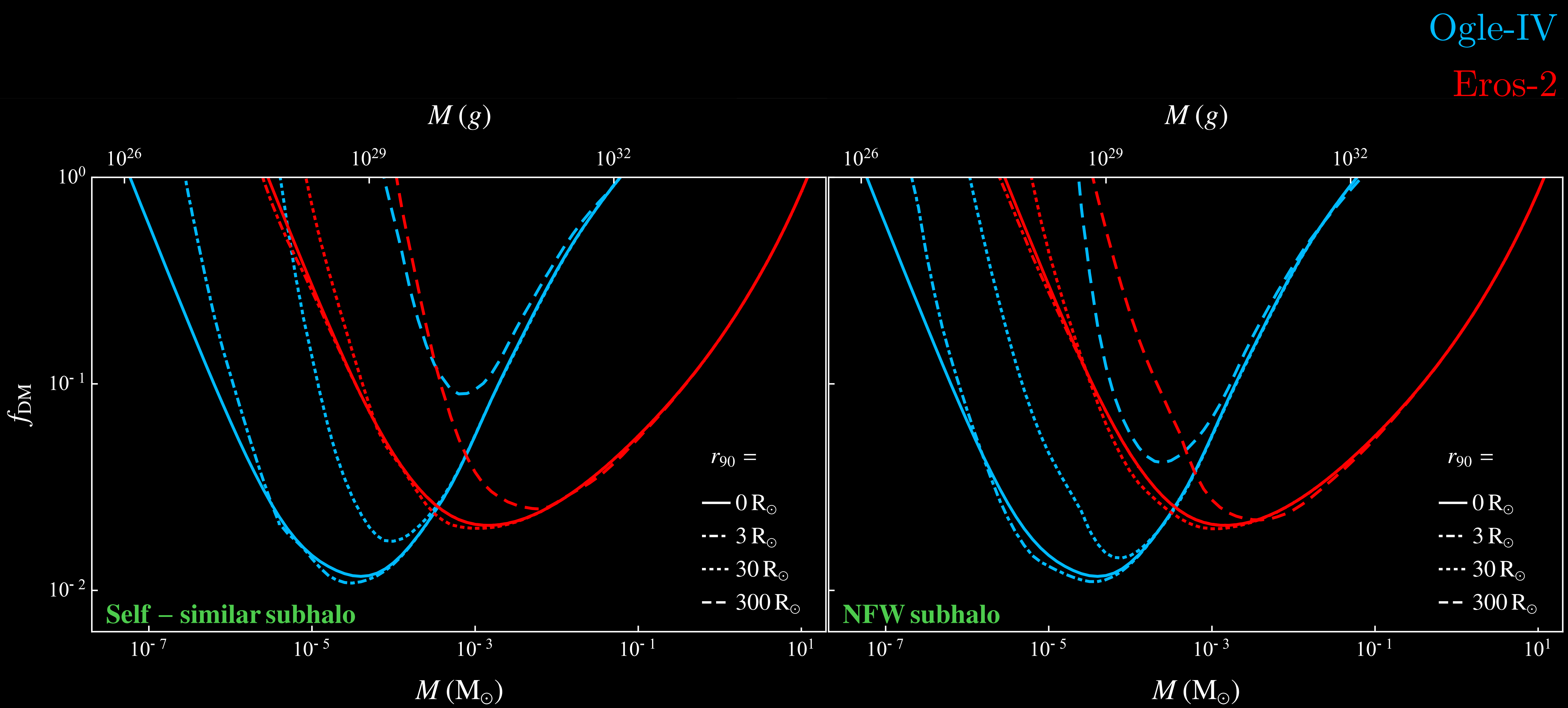
→ Constraints on the dark matter subfraction may be stronger or weaker than for point-like lenses

Constraints on DM fraction

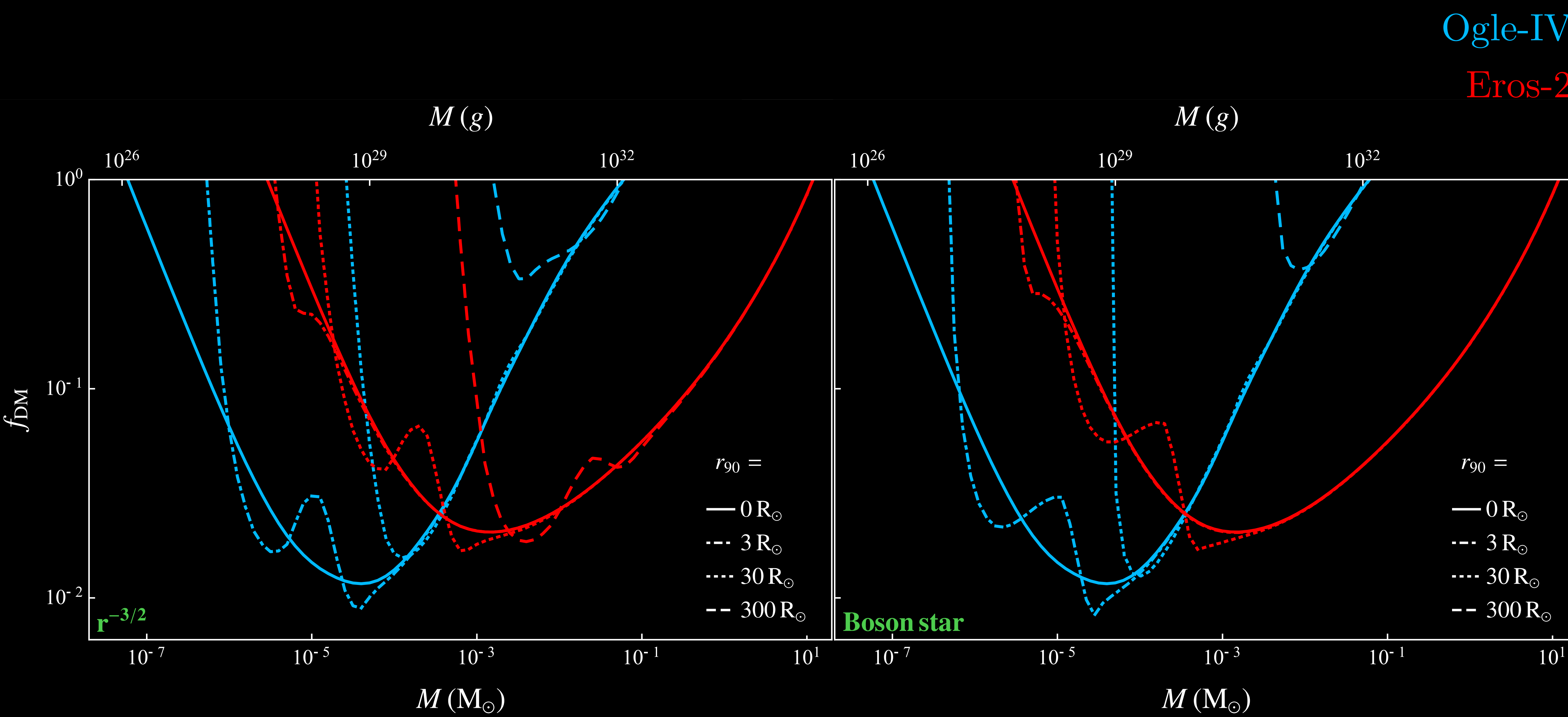
Generally, constraints on extended objects are weaker…



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

Constraints on DM fraction

But for sufficiently flat density profiles, caustics change the constraints



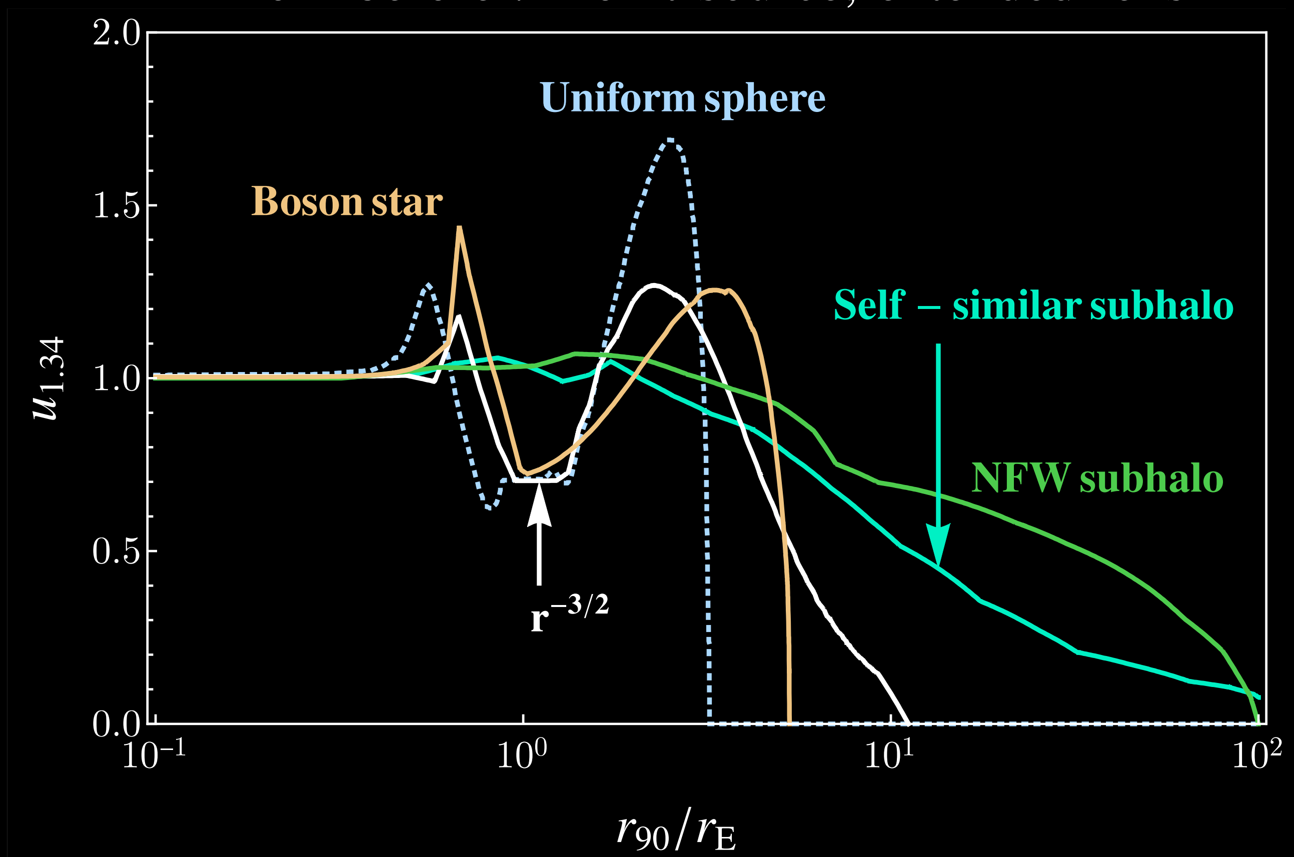
DC, D. McKeen, N. Raj, PRD, arXiv:2002.08962 [astro-ph.CO]

Extended sources: $r_E = \theta_E D_L \sim r_S$

Same procedure as before, but now $u_{1.34}$ is a function of both r_{90} and r_S

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

From before : Point source, extended lens



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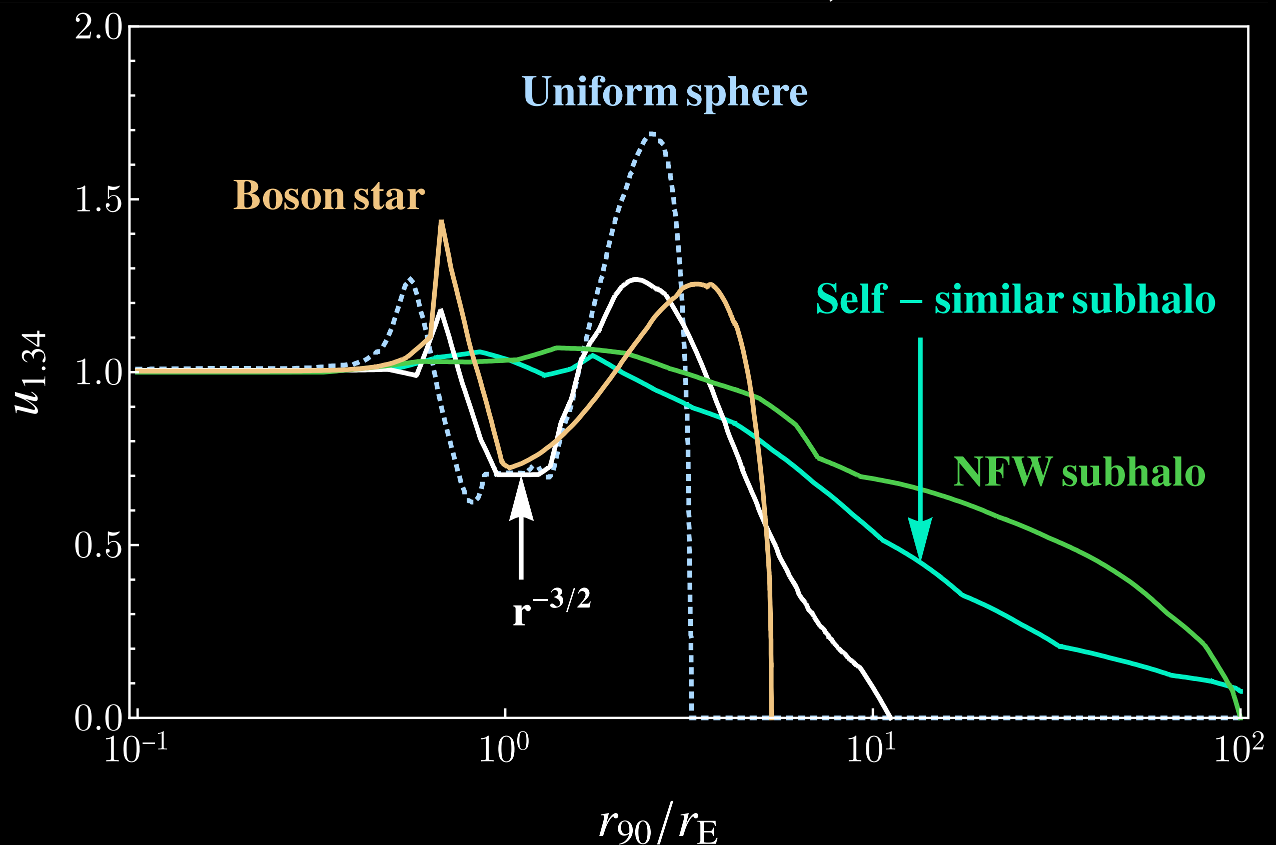
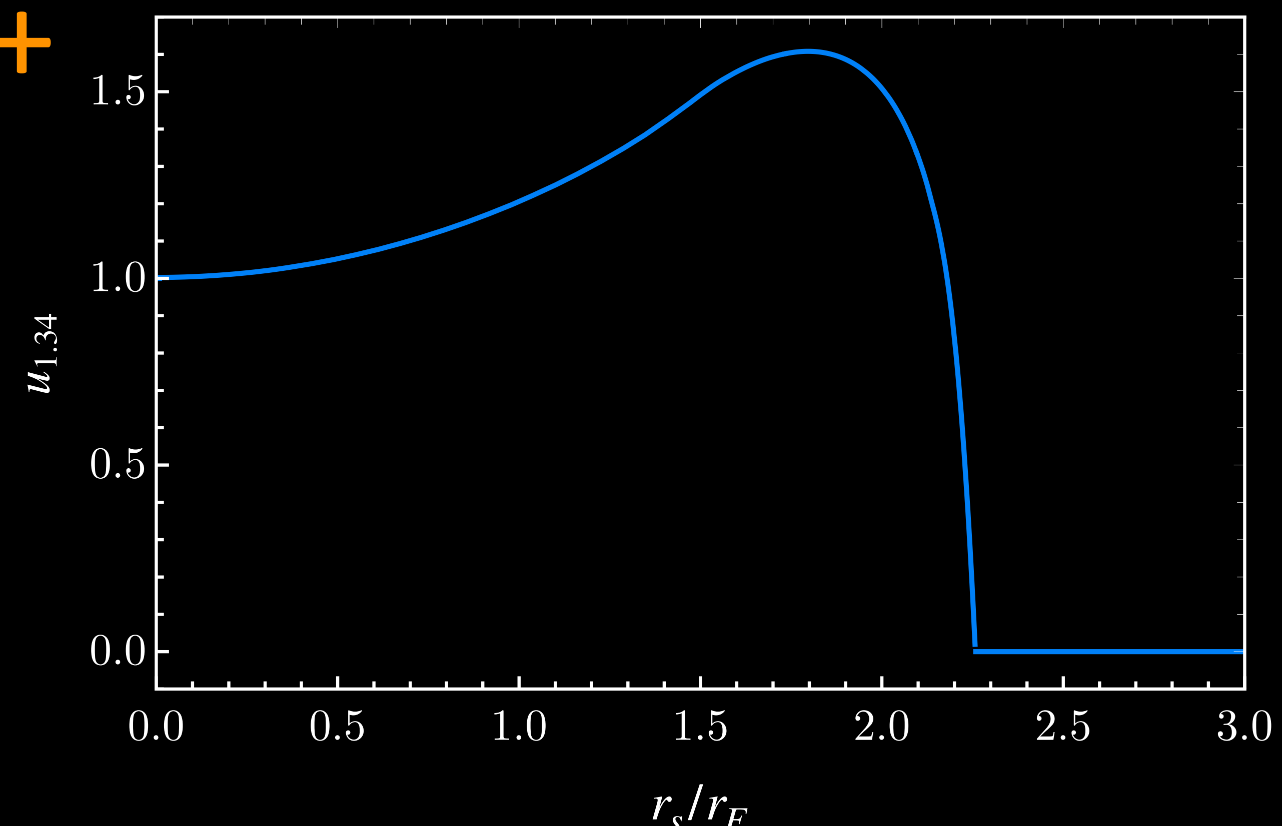


+

Point-like lens, extended source



For point-like lenses, see for example,
Witt and Mao, Astrophys. J (1994);
Montero-Camacho, Fang, Vasquez, Silva, Hirata, [JCAP, arXiv:1906.05950];
Smyth, Profumo, English, Jeltema, McKinnon, Guhathakurta [PRD, arXiv:1910.01285];

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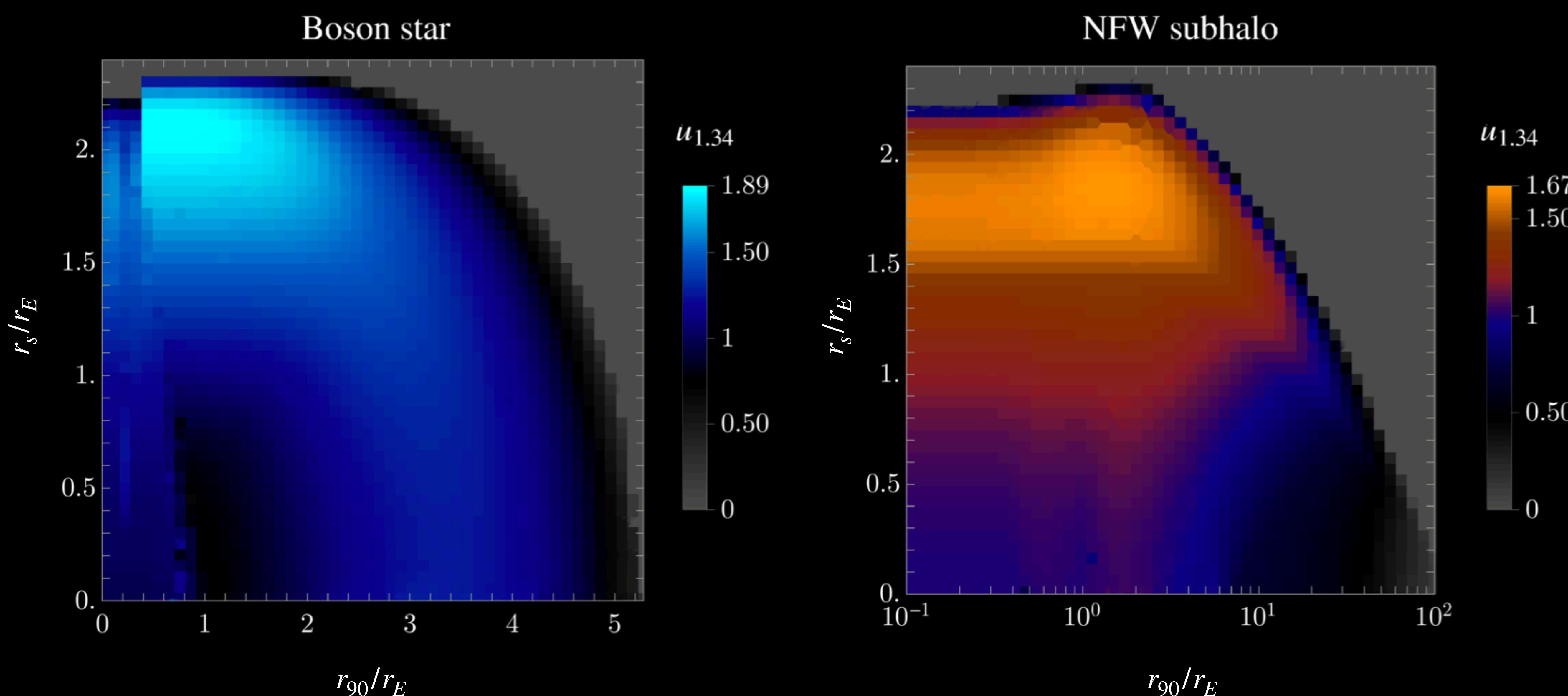
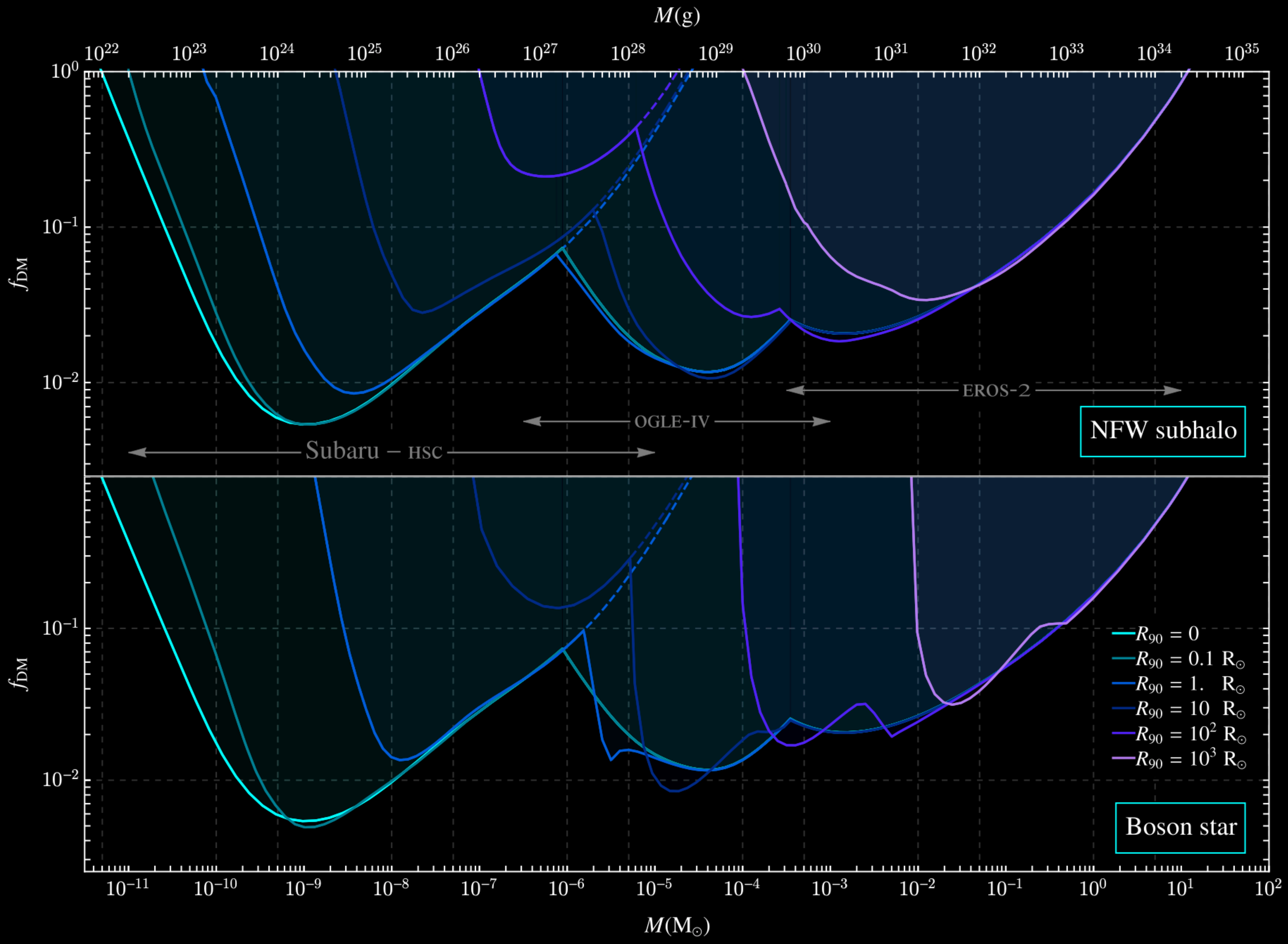
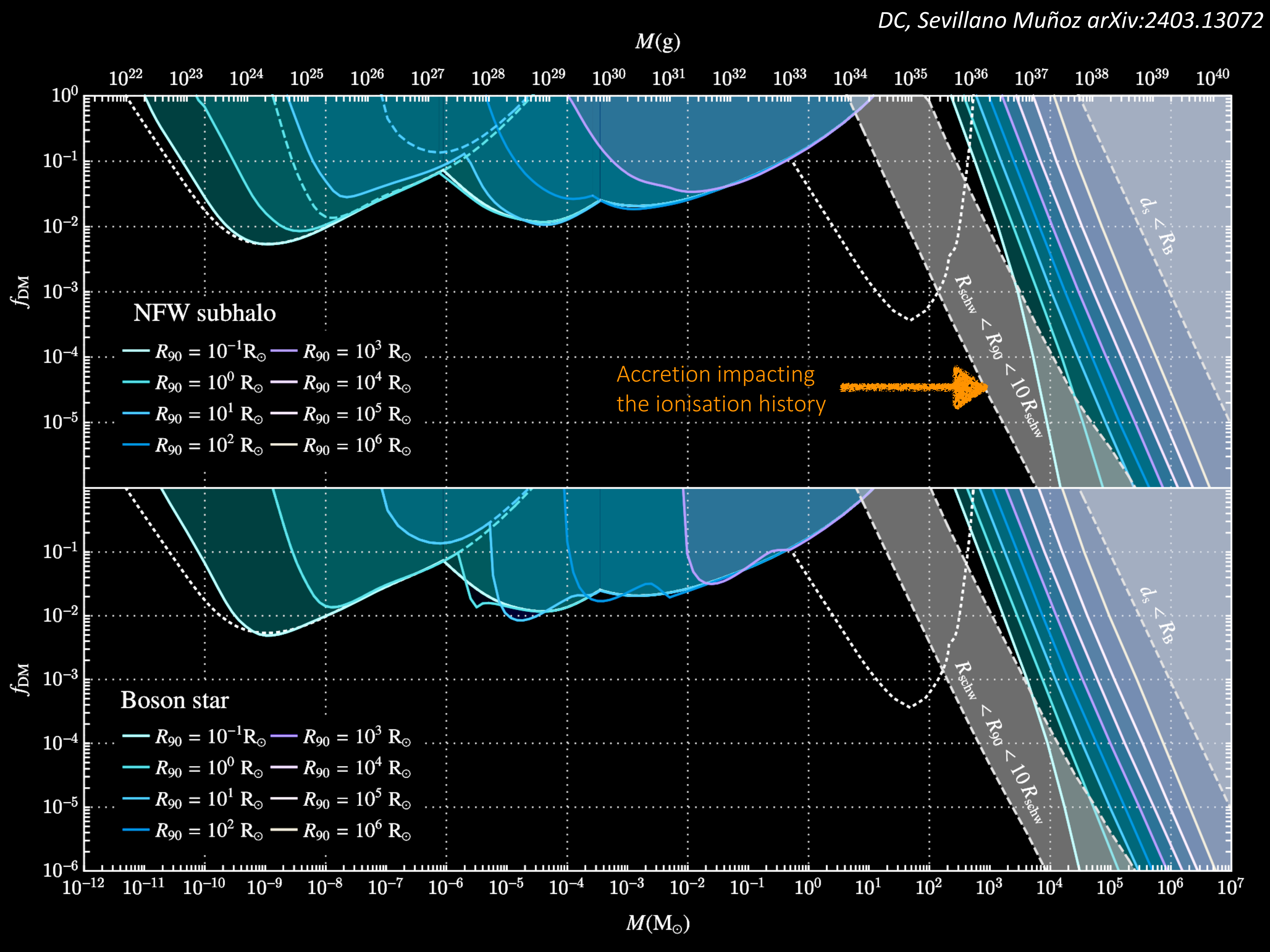


DC, D. McKeen, N. Raj, Z. Wang, PRD, arXiv:2007.12697 [astro-ph.CO]




DC, Sevillano Muñoz arXiv:2403.13072
M(g)
f_DM
NFW subhalo
R_90 = 10^-1 R_⊙
R_90 = 10^0 R_⊙
R_90 = 10^1 R_⊙
R_90 = 10^2 R_⊙
R_90 = 10^3 R_⊙
R_90 = 10^4 R_⊙
R_90 = 10^5 R_⊙
R_90 = 10^6 R_⊙
Accretion impacting
the ionisation history
R_schw < R_90 < 10 R_schw
d_s < R_B
Boson star
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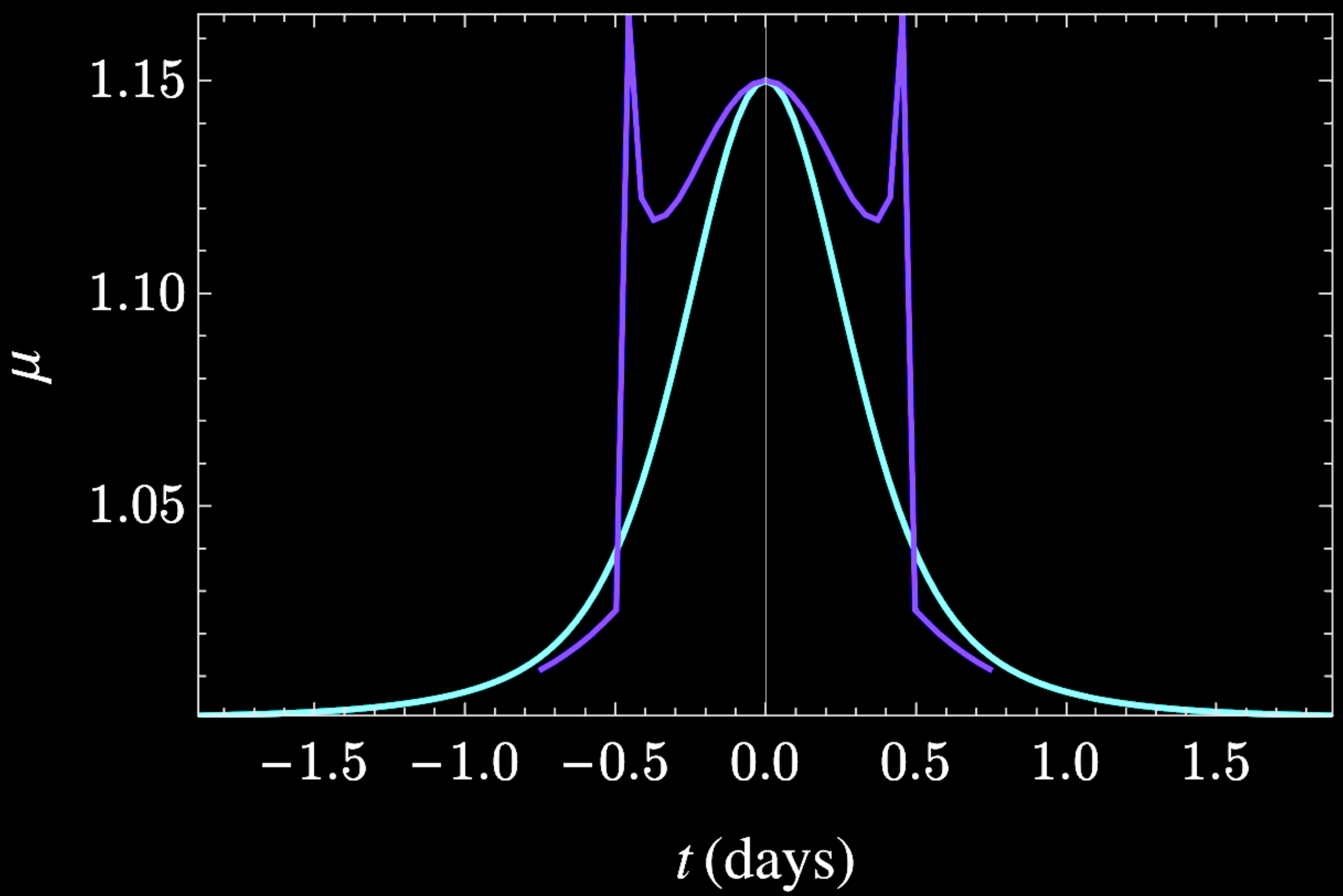
R_schw < R_90 < 10 R_schw
d_s < R_B
M(M_⊙)

BS light curves have different shapes

Miguel Crispim-Romao, DC, arXiv:2402.00107



$\tau = \theta/\theta_E$

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

Boson star with $\tau_m = 1$

PBH (or $\tau_m = 0$)

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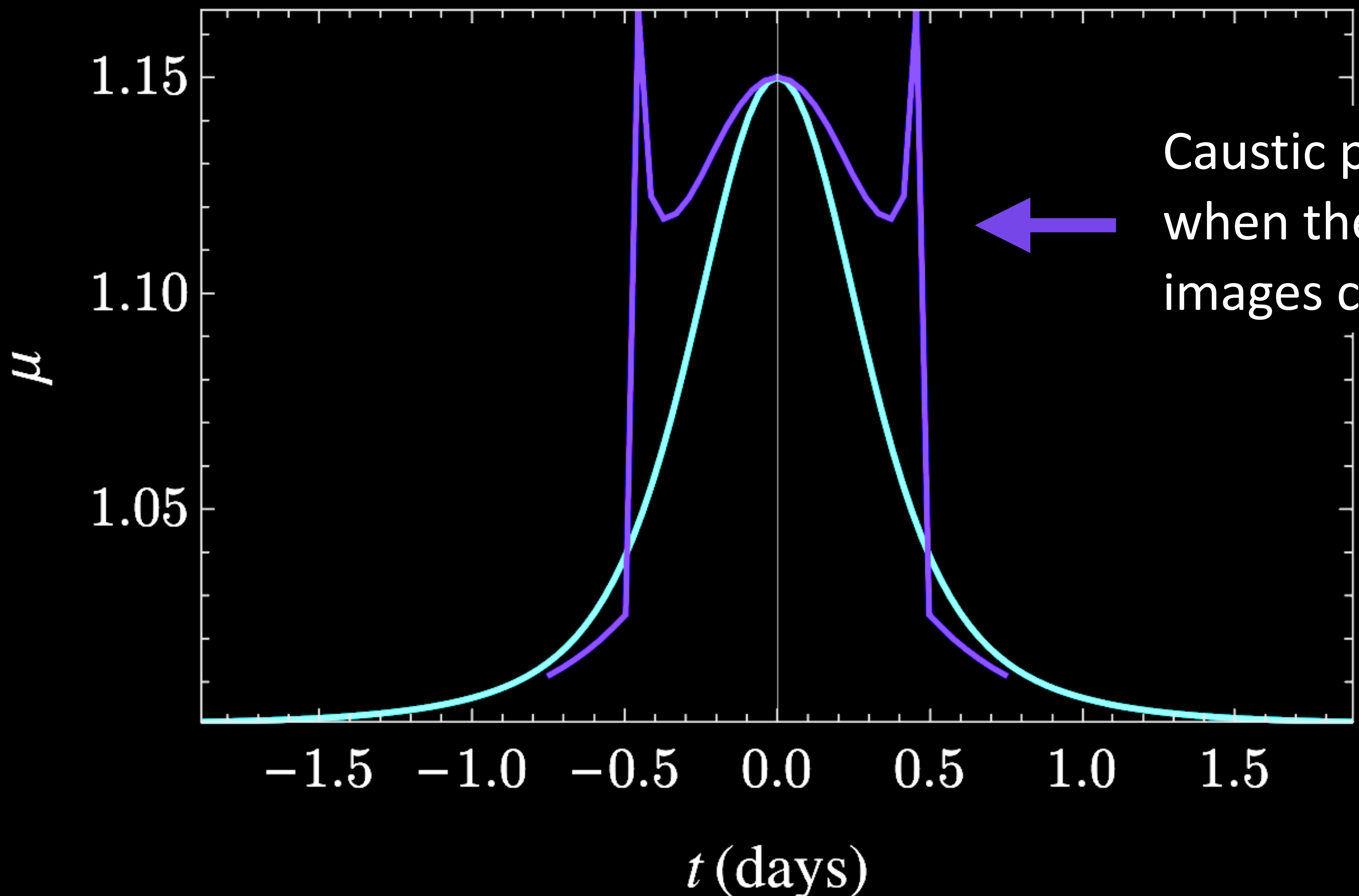
Miguel Crispim-Romao, DC, arXiv:2402.00107



Caustic peaks arise when the number of images changes

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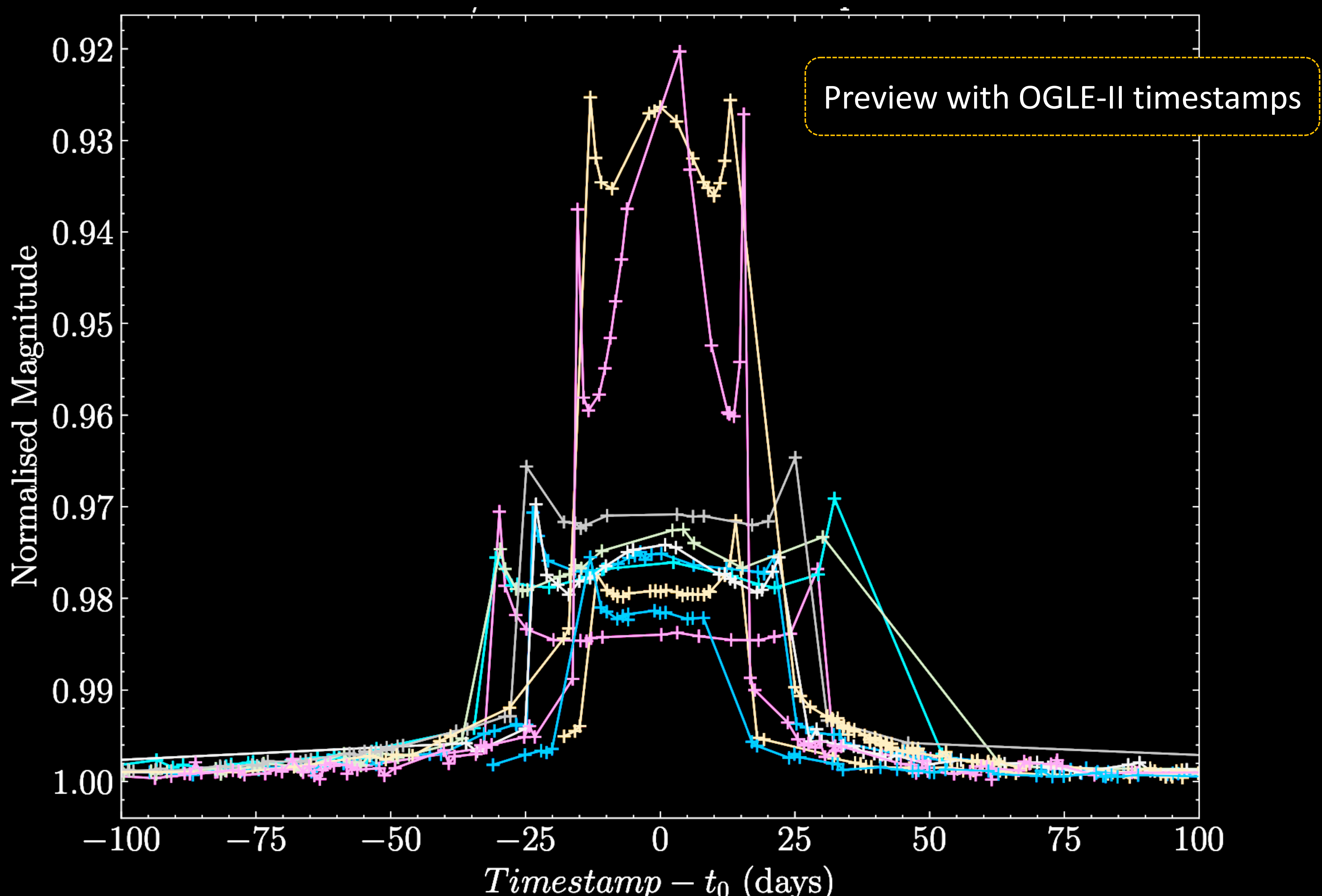
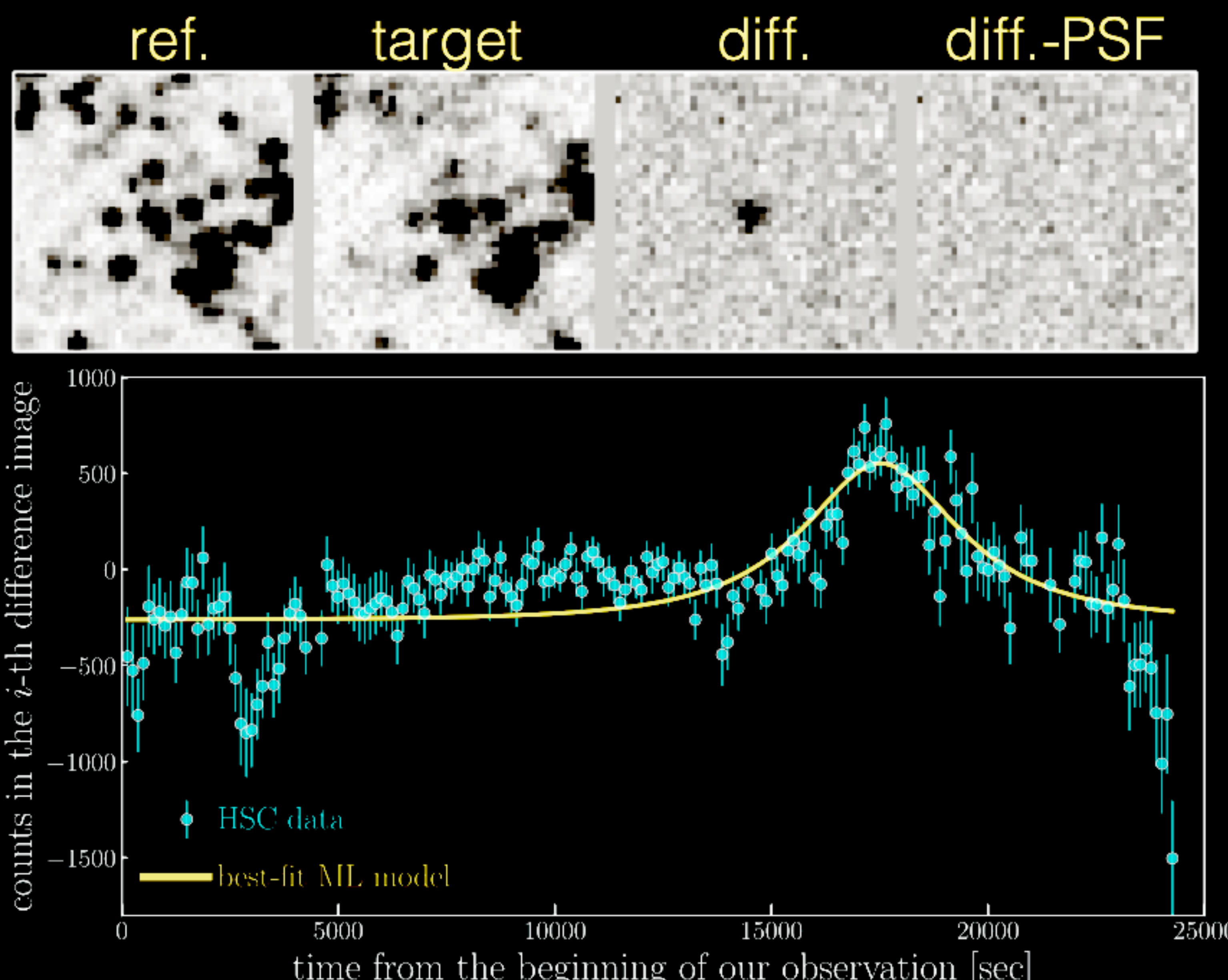


Miguel Crispim-Romao, DC, arXiv:2402.00107

ML + ML

Microlensing + Machine Learning

- Microlensing data is time series data
- Challenge: low-cadence data, lower signal-to-noise ratios



From the Subaru collaboration, arXiv:1701.02151

Miguel Crispim-Romao, DC, arXiv:2402.00107

ML + ML

Microlensing + Machine Learning

- Microlensing data is time series data
- Challenge: low-cadence data, lower signal-to-noise ratios
- MicroLIA: use a Random Forest (RF) algorithm to find microlensing event (and distinguish from other events)

Godines et al, arXiv:2004.14347

Miguel Crispim-Romao, DC, arXiv:2402.00107

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Microlensing + Machine Learning

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Our adaptations:

- Implement boson star and NFW light curves with $0.5 < \tau_m < 5$
- Instead of an RF, we use a histogram-based gradient boosted classifier (HBGC) to improve speed
- Add criterium $\mu \geq 1.34$

(… and a few fixes)

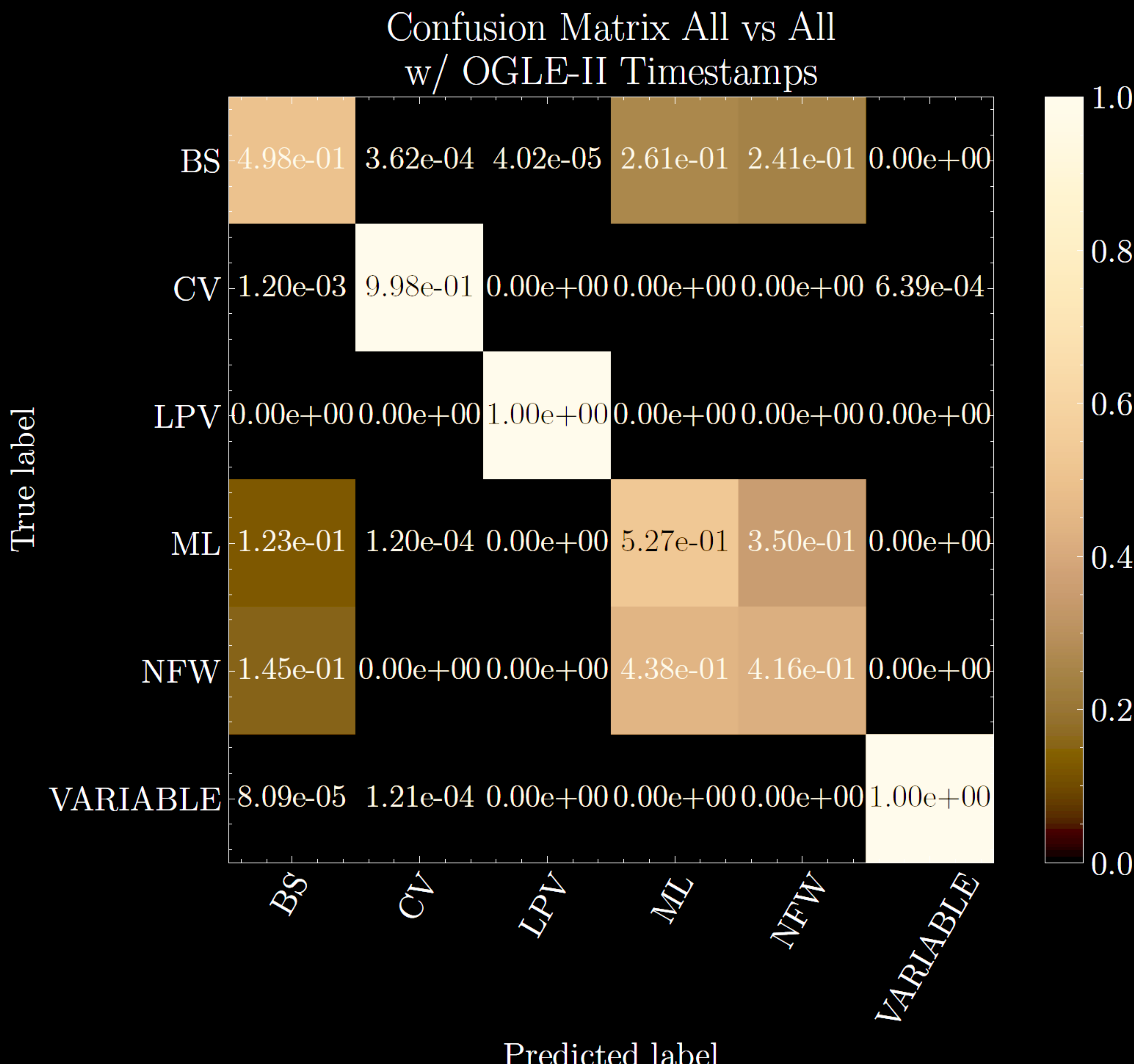
Complete datasets not available

Table 1
Selection Criteria for High-quality Microlensing Events in OGLE GVS Fields

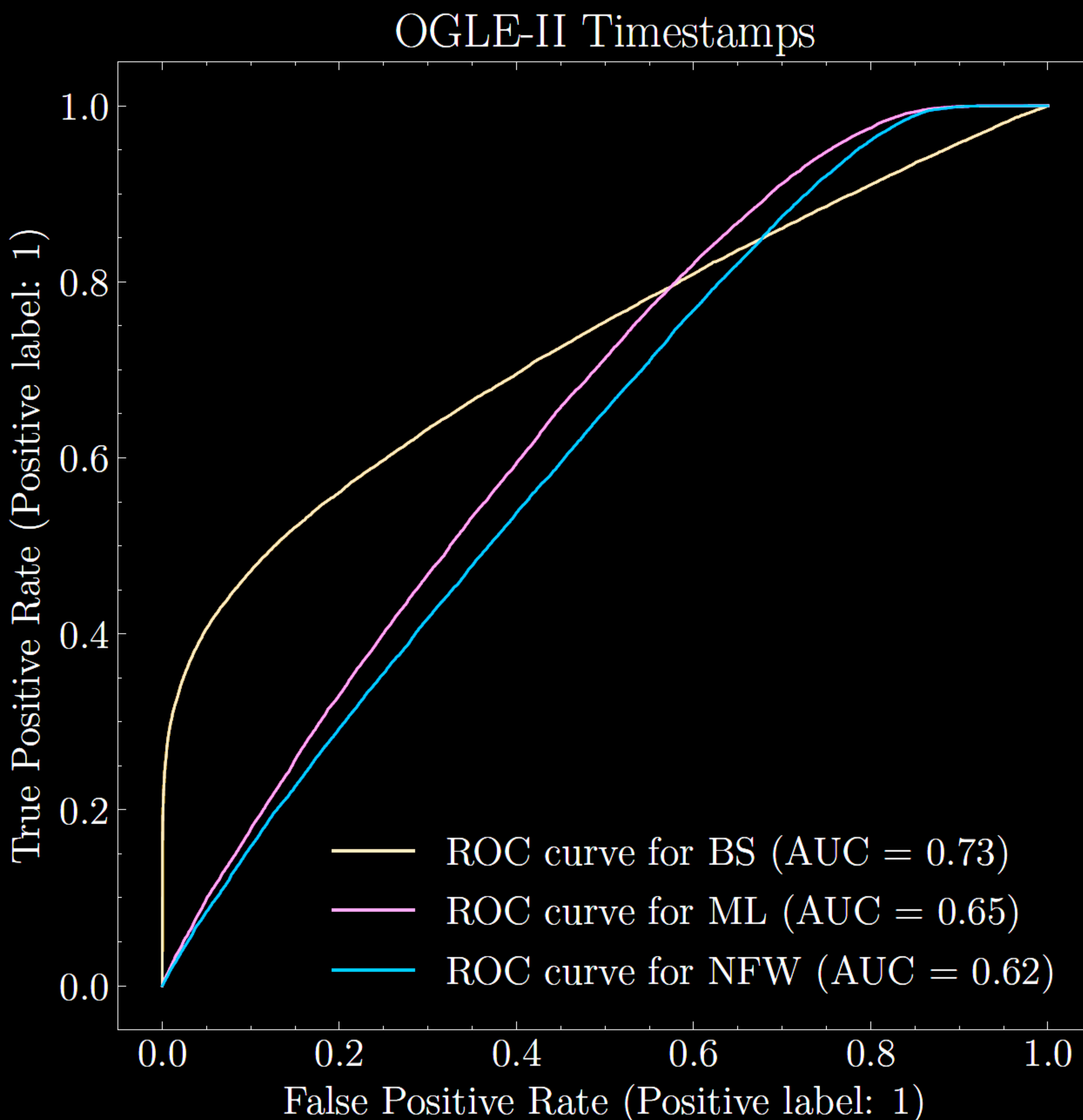
Criteria	Remarks	Number
All stars in databases		1,856,529,265
$\chi^2_{\mathrm{out}}/\mathrm{dof} \leqslant 2.0$	No variability outside a window centered on the event (duration of the window depends on the field)	
$n_{\mathrm{DIA}} \geqslant 3$	Centroid of the additional flux coincides with the source star centroid	
$\chi_{3+} = \sum_i (F_i - F_{\mathrm{base}})/\sigma_i \geqslant 32$	Significance of the bump	23,618
$A \geqslant 0.1$ mag	Rejecting low-amplitude variables	
$n_{\mathrm{bump}} = 1$	Rejecting objects with multiple bumps	18,397
	Fit quality:	
$\chi^2_{\mathrm{fit}}/\mathrm{dof} \leqslant 2.0$	χ^2 for all data	
$\chi^2_{\mathrm{fit,tE}}/\mathrm{dof} \leqslant 2.0$	χ^2 for $\lvert t - t_0 \rvert < t_{\mathrm{E}}$	
$\sigma(t_{\mathrm{E}})/t_{\mathrm{E}} < 0.5$	Einstein timescale is well measured	
$t_{\mathrm{min}} \leqslant t_0 \leqslant t_{\mathrm{max}}$	Event peaked between t_{min} and t_{max}, which are moments of the first and last observation of a given field	
$u_0 \leqslant 1$	Maximum impact parameter	
$t_{\mathrm{E}} \leqslant 500$ d	Maximum timescale	
$A \geqslant 0.4$ mag if $t_{\mathrm{E}} \geqslant 100$ days	Long-timescale events should have high amplitudes	
$I_{\mathrm{s}} \leqslant 21.0$	Maximum I-band source magnitude	
$F_{\mathrm{b}} > -F_{\mathrm{min}}$	Maximum negative blend flux, corresponding to $I = 20.5$ mag star	460

Reject events with multiple bumps

So for now… generating and injecting events



Miguel Crispim-Romao, DC, arXiv:2402.00107



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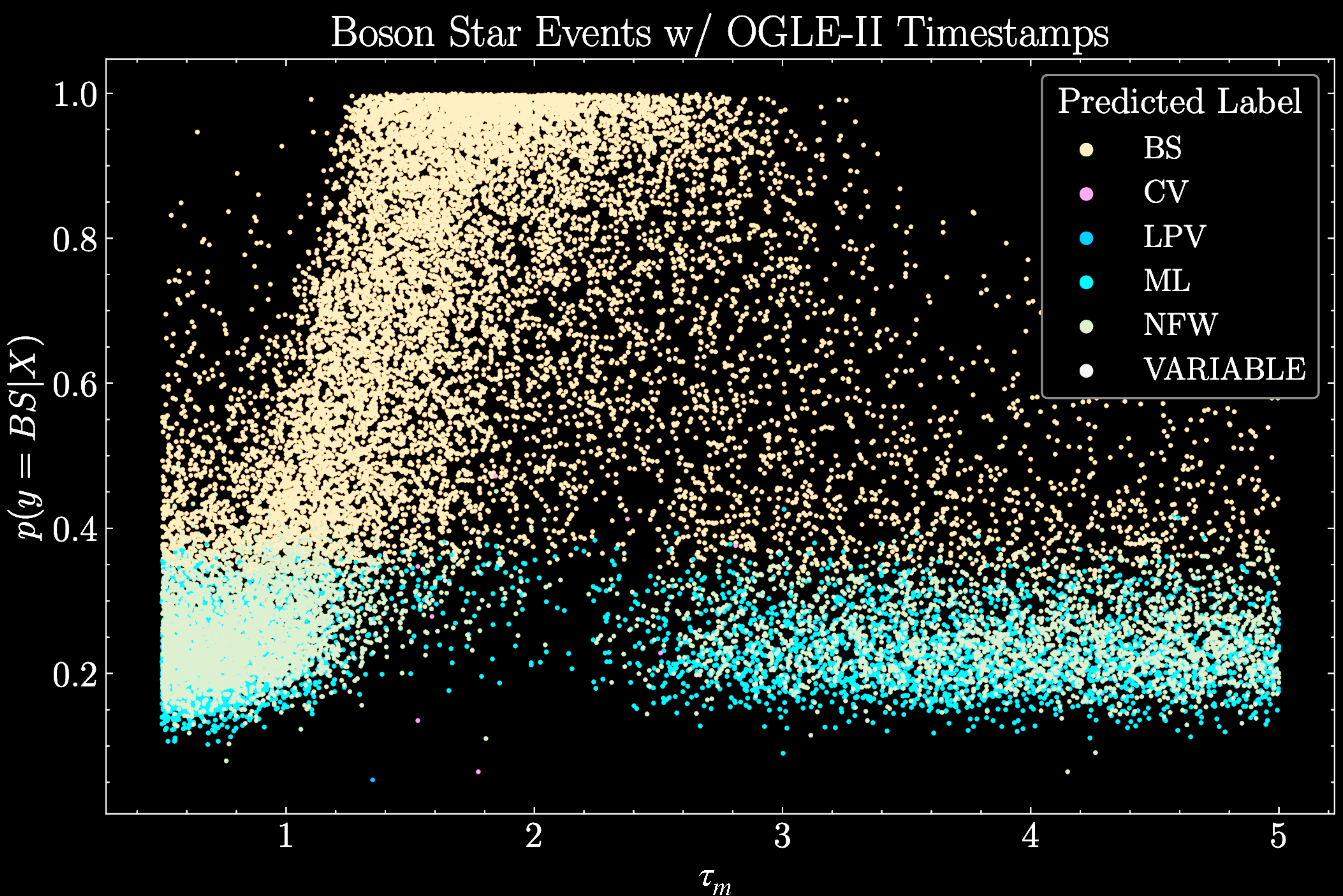

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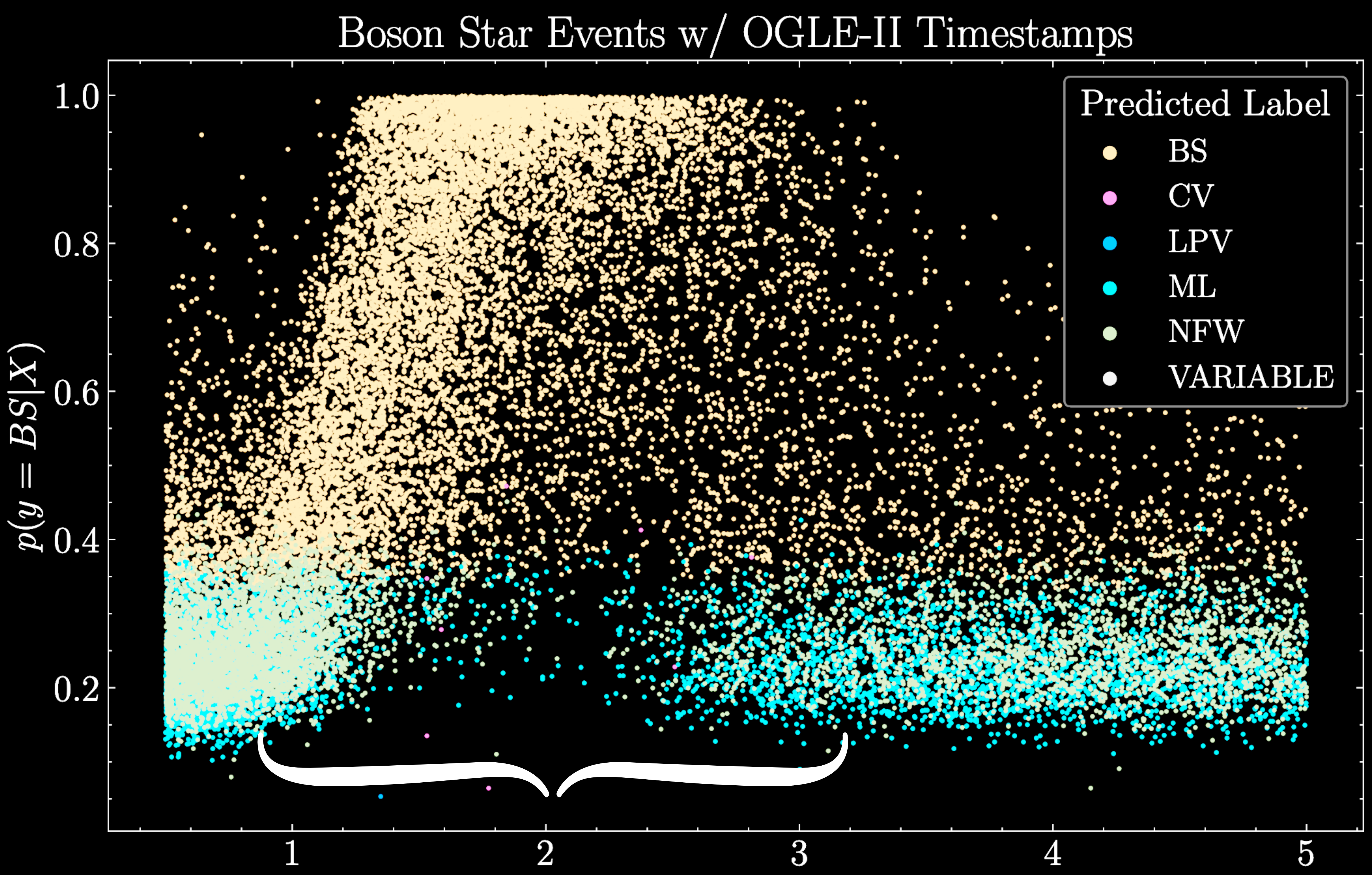


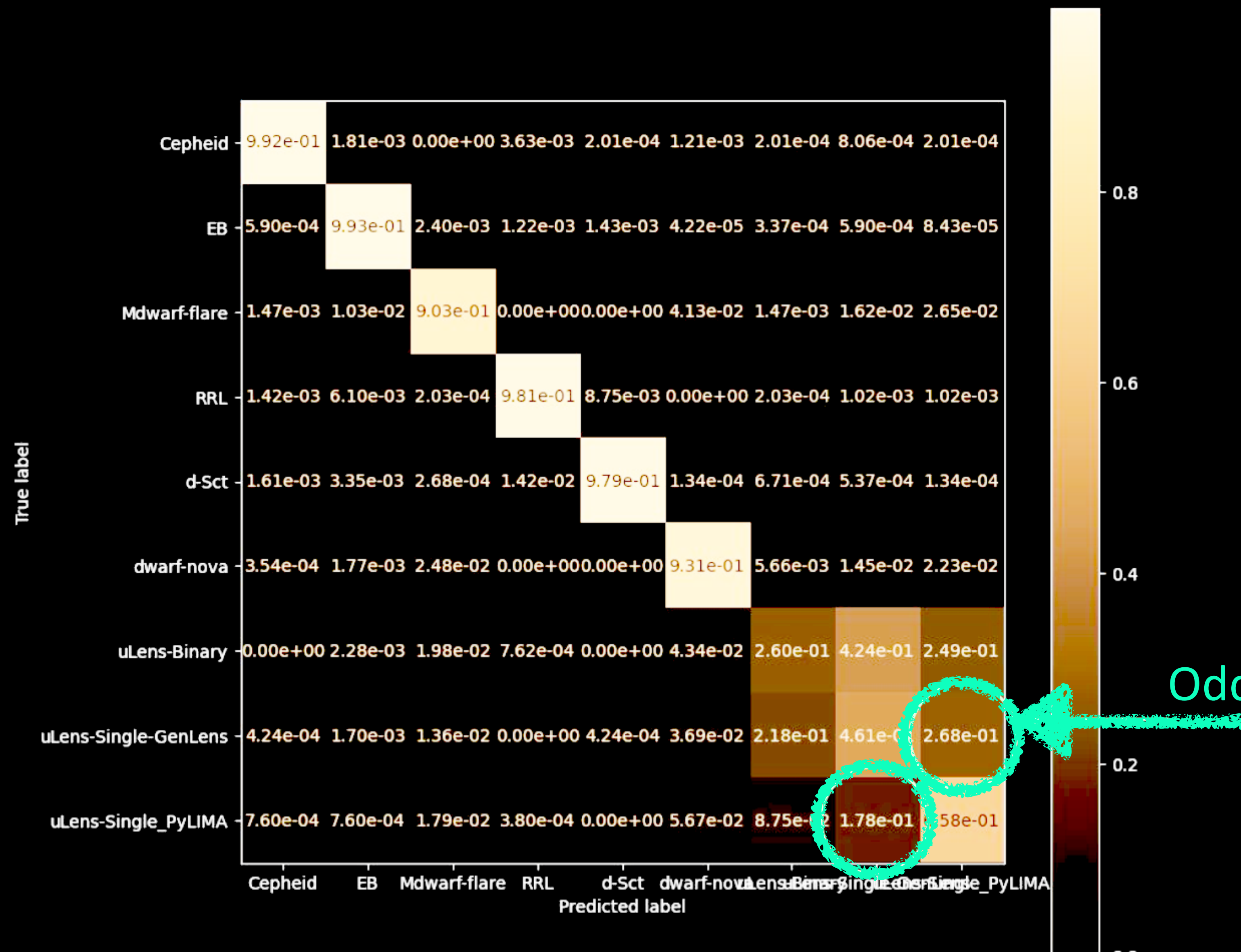
Indeed, the most probable detections are for $0.8 < \tau_m < 3$

Current work

Teamed up with MicroLIA's main author Daniel Godines (and Miguel)

- ELAsTiCC dataset (Extended LSST Astronomical Time Series Classification Challenge)
  - Multiple sources, galactic and extragalactic
  - Science purposed

ELAsTiCC presents the first simulation of LSST alerts, with millions of synthetic transient light curves and host galaxies. The data is being used to test broker alert systems and classifiers, and develop the infrastructure for LSST's Dark Energy Science Collaboration Time-Domain needs.



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

- Microlensing signatures of extended objects can be distinguished using machine learning

- Future work: comparing to all events in ELaSTiCC, deep learning on the light curves, …

Thank you!

…ask me anything you like!

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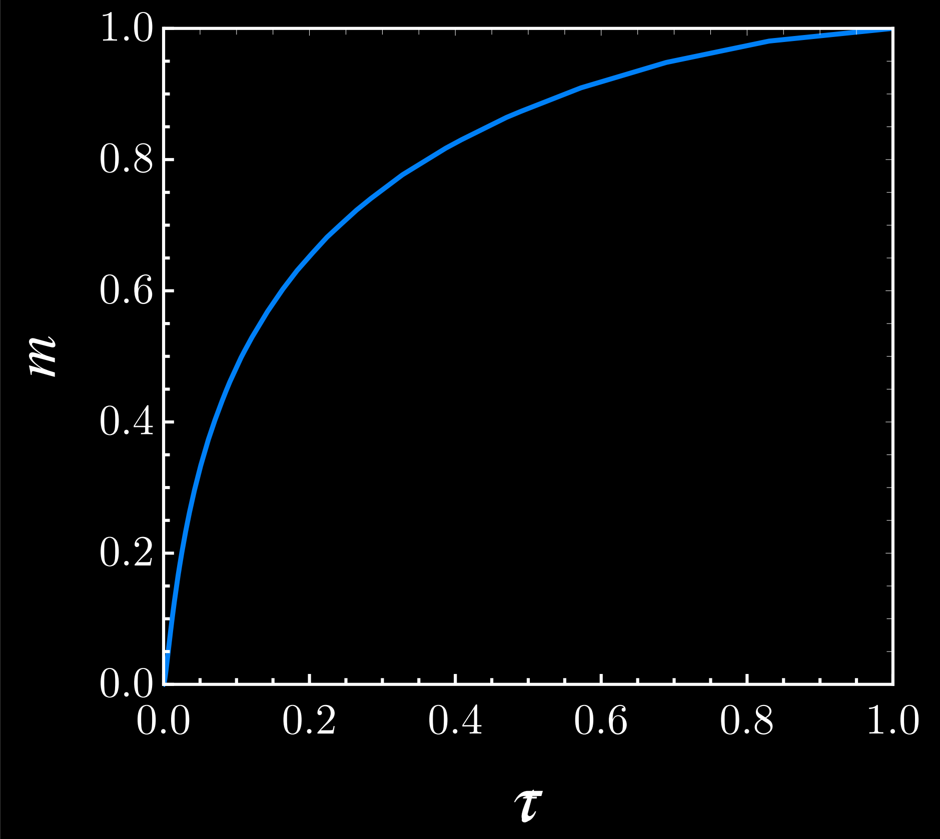
Back up slides

Case study 1: NFW-halo mass profile

- Well-known halo profile: $\rho(r) = \dfrac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$

- As the mass inclosed formally diverges, we cut it off at $R_{\text{cut}} = 100\, R_{\text{sc}}$
- Enclosed mass $\propto \log(\kappa + 1) - (\kappa/(\kappa + 1))$ where $\kappa = R_{\text{cut}}/R_{\text{sc}}$
- Computing $m(\tau)$ is then a trivial exercise:



Case study 2: Boson star mass profile

- The Schrodinger-Poisson equation,

$$\mu\Psi = -\frac{1}{2m_\phi}\left(\Psi'' + \frac{2}{r}\Psi'\right) + m_\phi \Phi \Psi$$

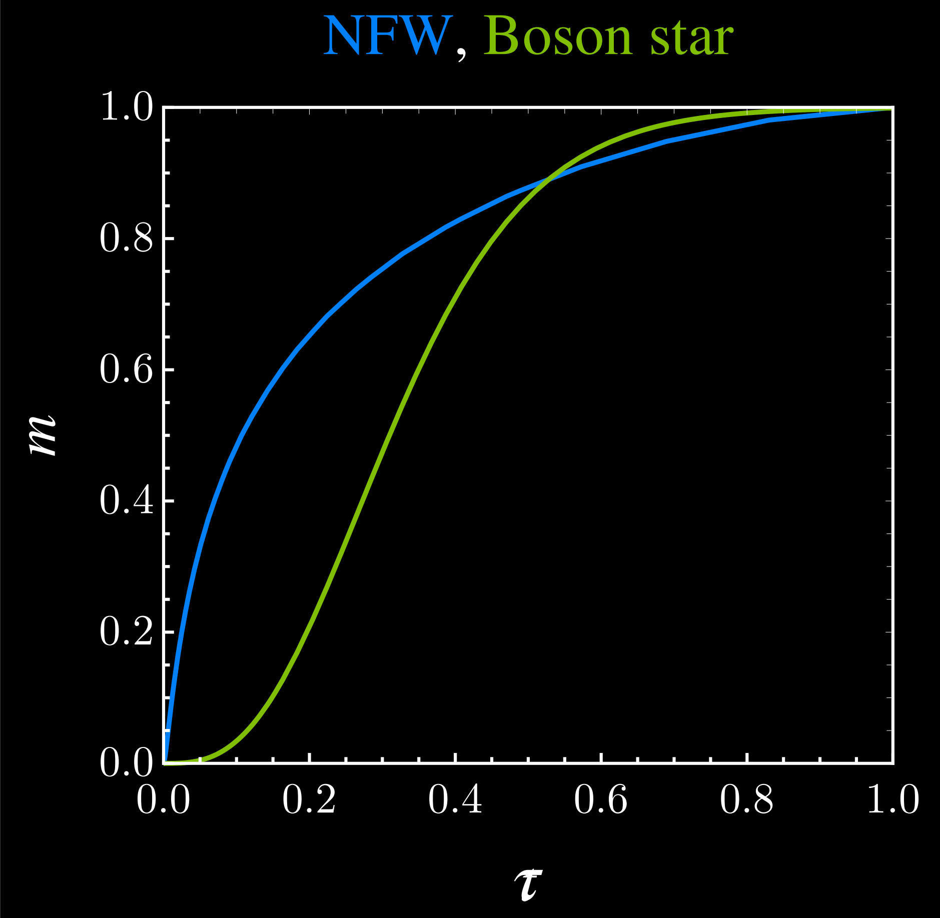
Describes the radial distribution

describes a *spherically symmetric ground state of a free scalar field in the non-relativistic limit*

- The mass enclosed is given by

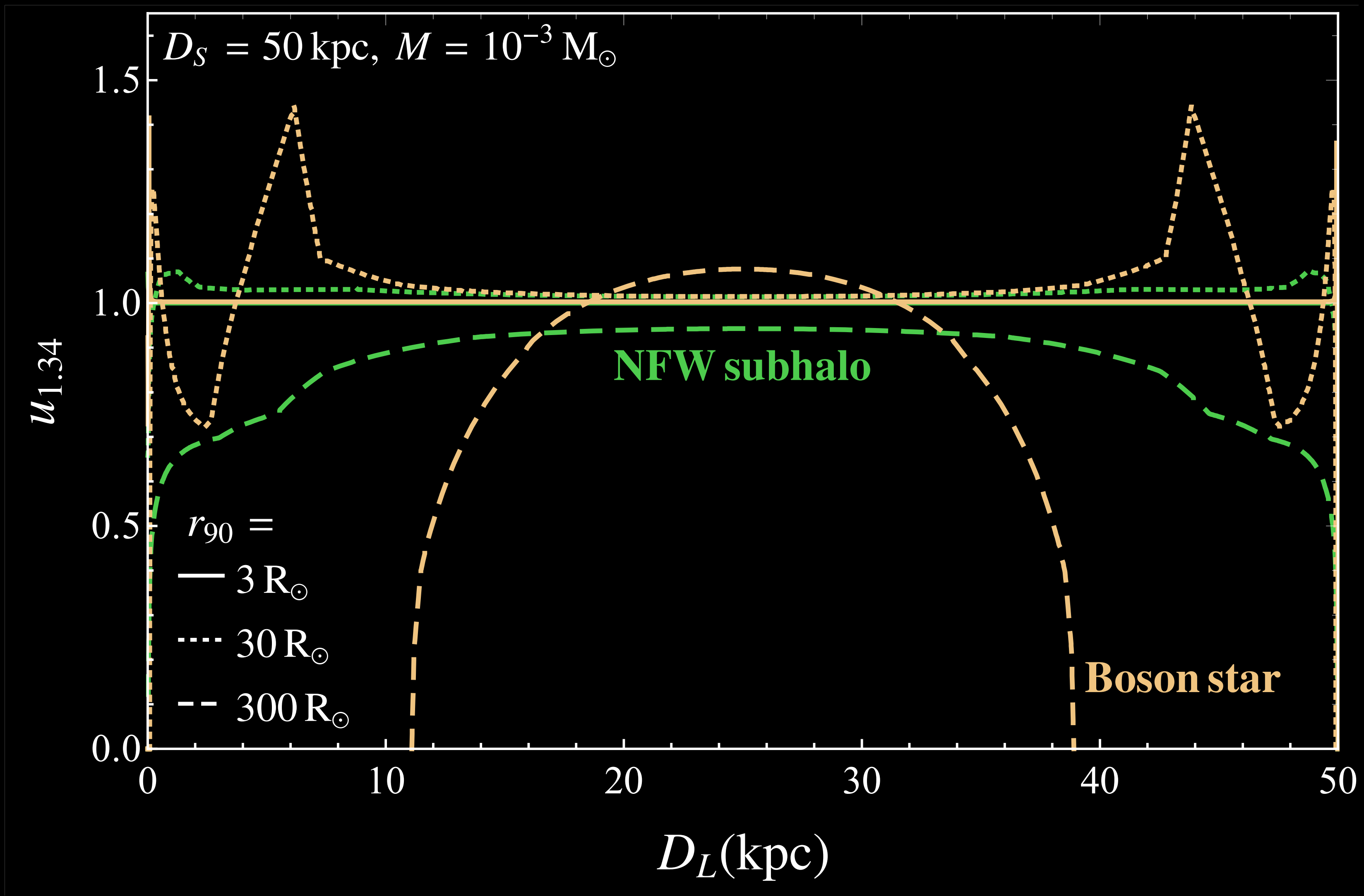
$$M_{\rm BS}(r) = \frac{1}{m_\phi G}\int_0^{m_\phi r} dy\; y^2\; \Psi^2(y)$$

from which $m(\tau)$ may be computed



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

$$x = \frac{D_{\mathrm{L}}}{D_{\mathrm{S}}}$$

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

Constraining extended objects

The differential event rate contains all the essential physics

Fraction of Ω_{DM}

$x = \frac{D_{\mathrm{L}}}{D_{\mathrm{S}}}$

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

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

$220\ \mathrm{km/s}$

Efficiency of the experiment

Halo profile: isothermal

Constraining extended objects

The total number of expected events depends on the experiment

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

Constraining extended objects

The total number of expected events depends on the experiment

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

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

Constraining extended objects

The total number of expected events depends on the experiment

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

Maximum and minimum transit time

Number of observed stars

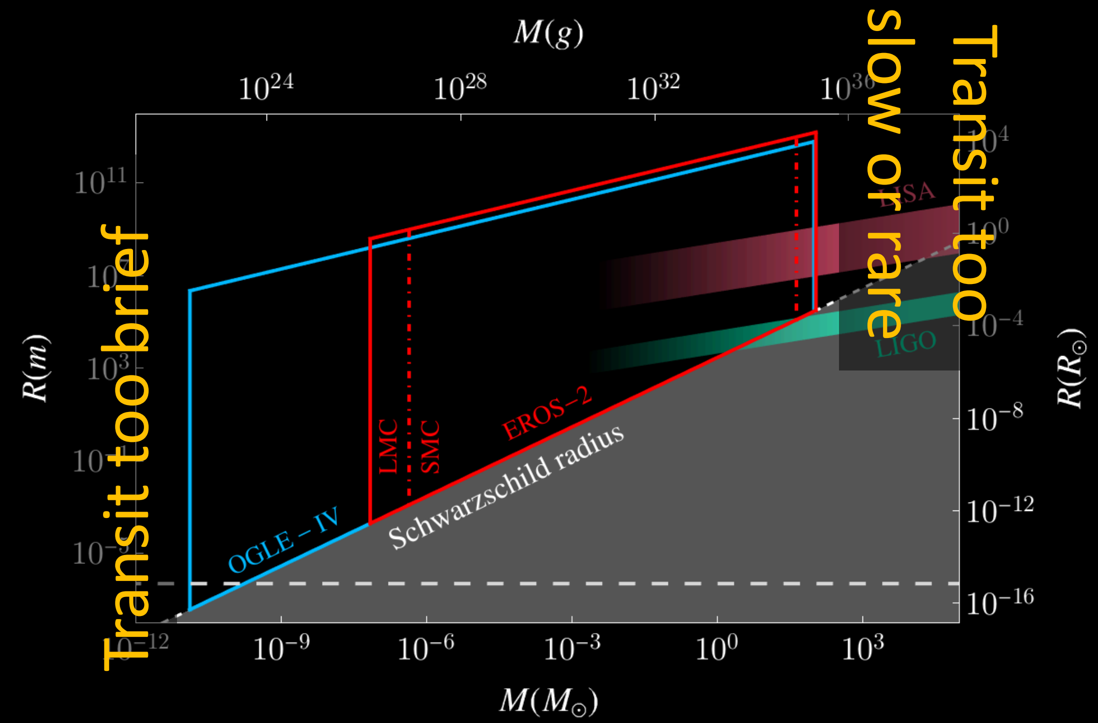
EROS-2 LMC: 5.49×10^6

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: $\mathcal{O}(1000)$ astrophysical events, Poissonian 90% CL: $\kappa = 4.61$

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

Bin events in $\rm t_E$

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

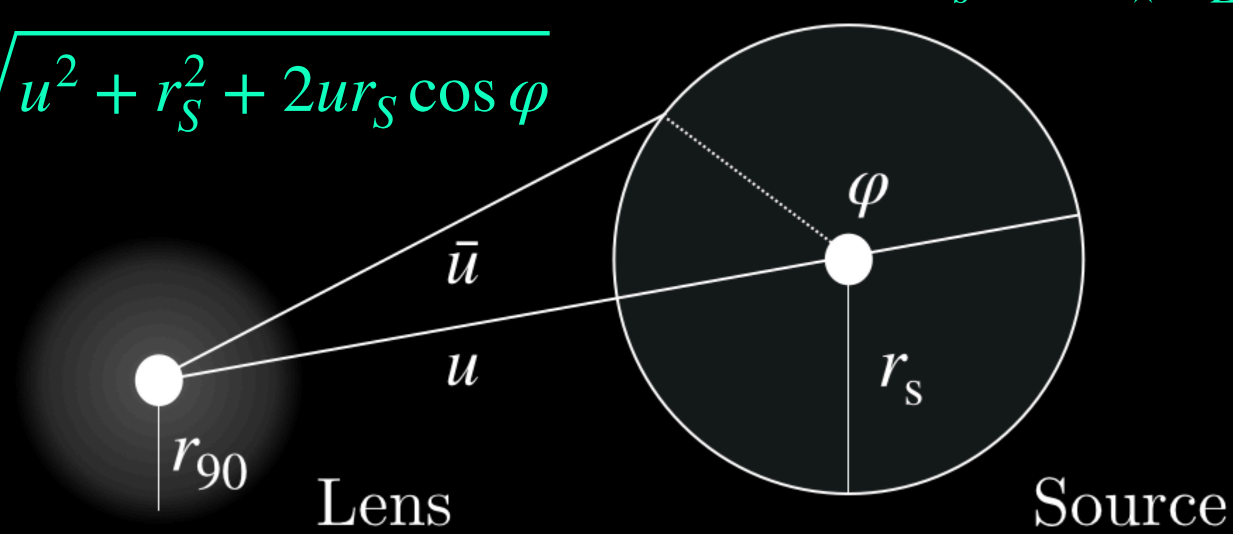
Lensing geometry

- Up to this point, we have assumed that the sources are point-like light sources (a good approximation for EROS/OGLE)
- This approximation breaks down when $r_E = \theta_E D_L \sim r_S$

- Geometry in the lens plane:

$$r_s \equiv x R_\star / r_E$$

$$\bar{u}(\varphi) = \sqrt{u^2 + r_S^2 + 2 u r_S \cos\varphi}$$



Lensing equation:

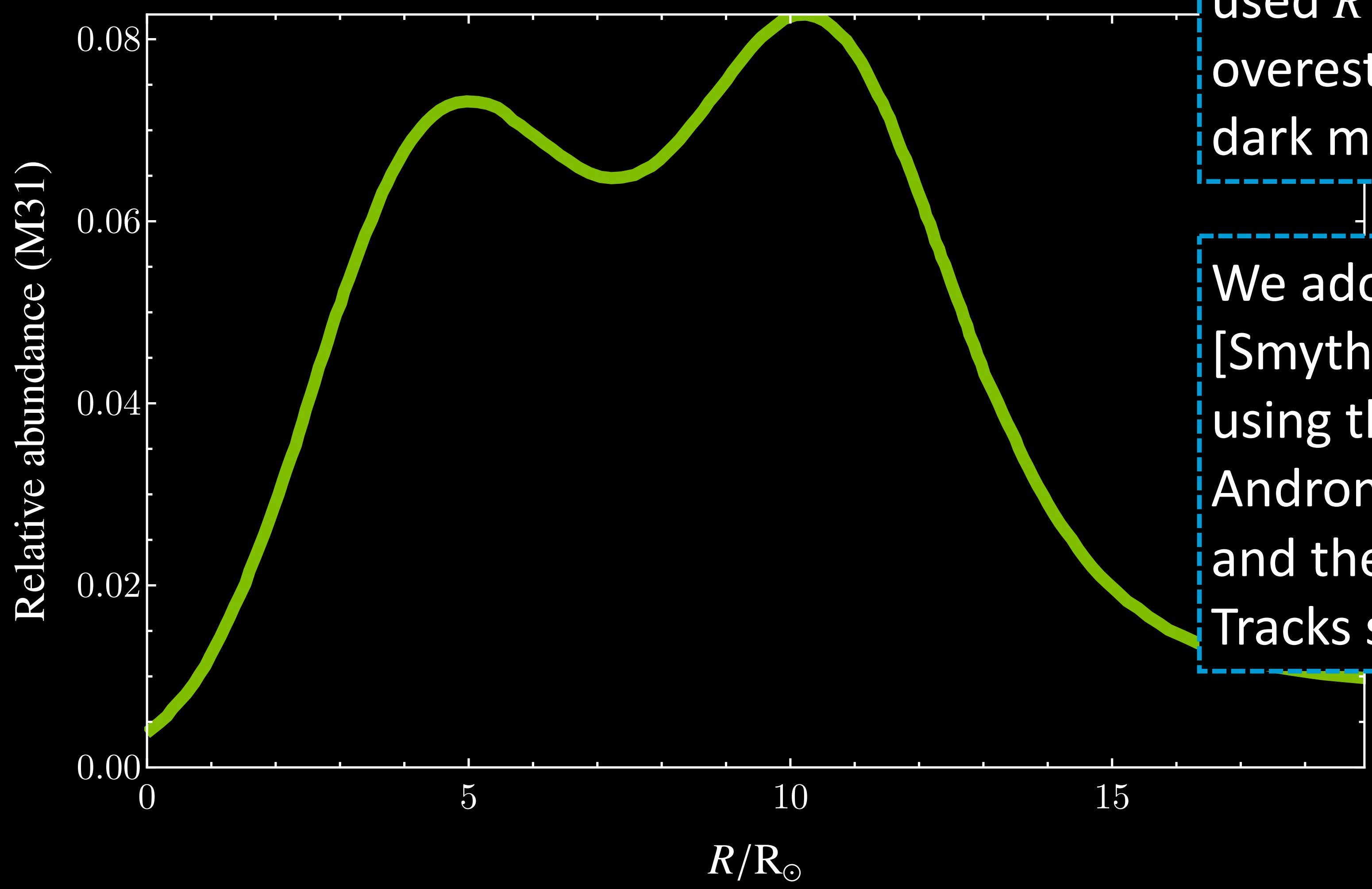
$$\bar{u}(\varphi) = \tau(\varphi) - \frac{m(\tau(\varphi))}{\tau(\varphi)}$$

Image

Image

$$\mu_i = \eta \frac{1}{\pi r_S^2} \int_0^{2\pi} d\varphi \, \frac{1}{2} \tau_i^2(\varphi)$$

Star sizes in M31

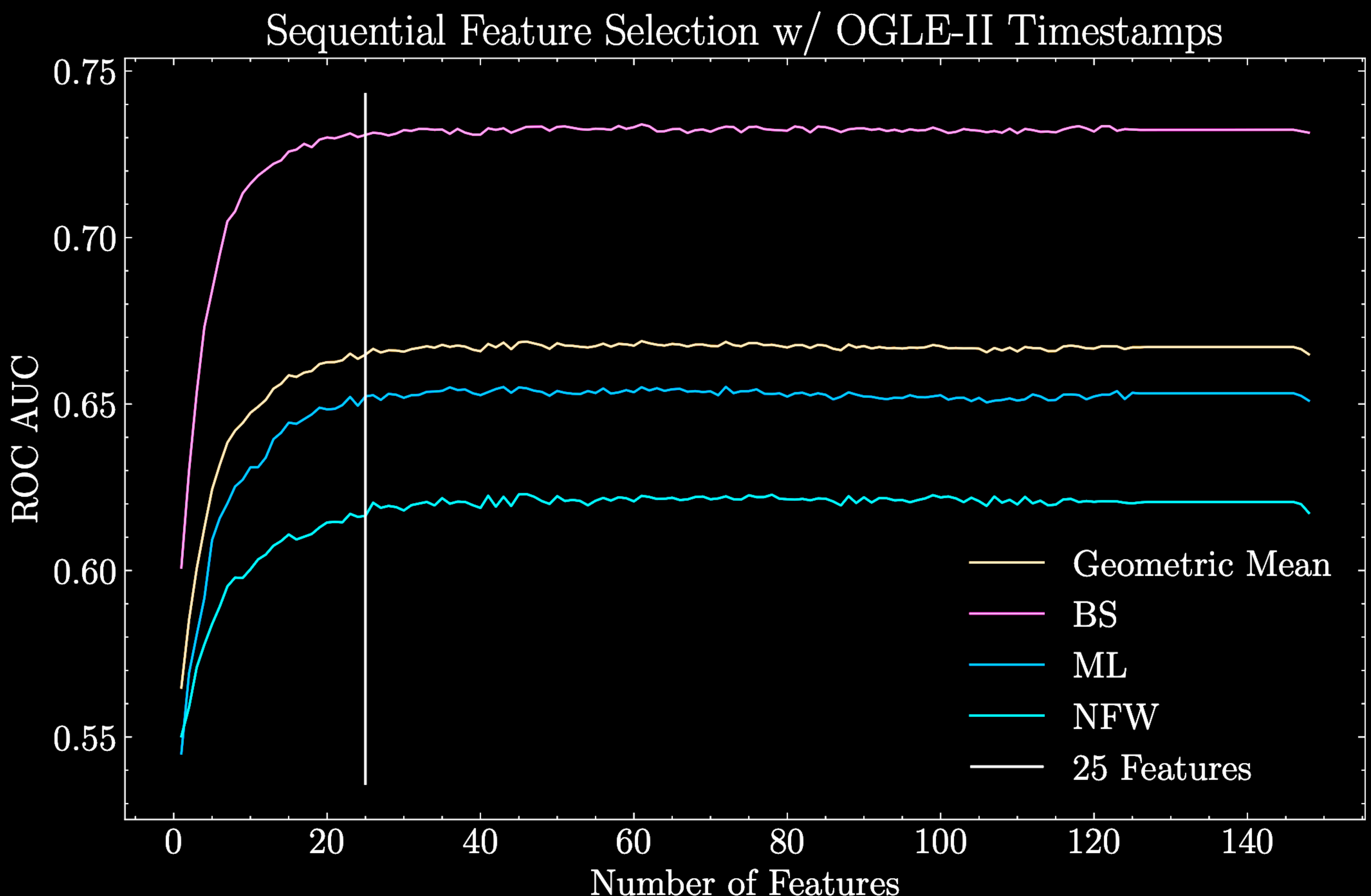


Initially, the Subaru-HSC collaboration used $R = \mathrm{R}_\odot$ for all stars, but this overestimates the constraints on the dark matter fraction

We adopt the distribution derived in [Smyth et al., PRD, arXiv:1910.01285] using the Panchromatic Hubble Andromeda Treasury star catalogue and the `MESA` Isochrones and Stellar Tracks stellar evolution package

$$N_{\text{events}} = N_\star T_{\text{obs}} \int dt_{\mathrm{E}} \int dR_\star \int_0^1 dx \, \frac{d^2\Gamma}{dx\,dt_{\mathrm{E}}} \, \frac{dn}{dR_\star}$$

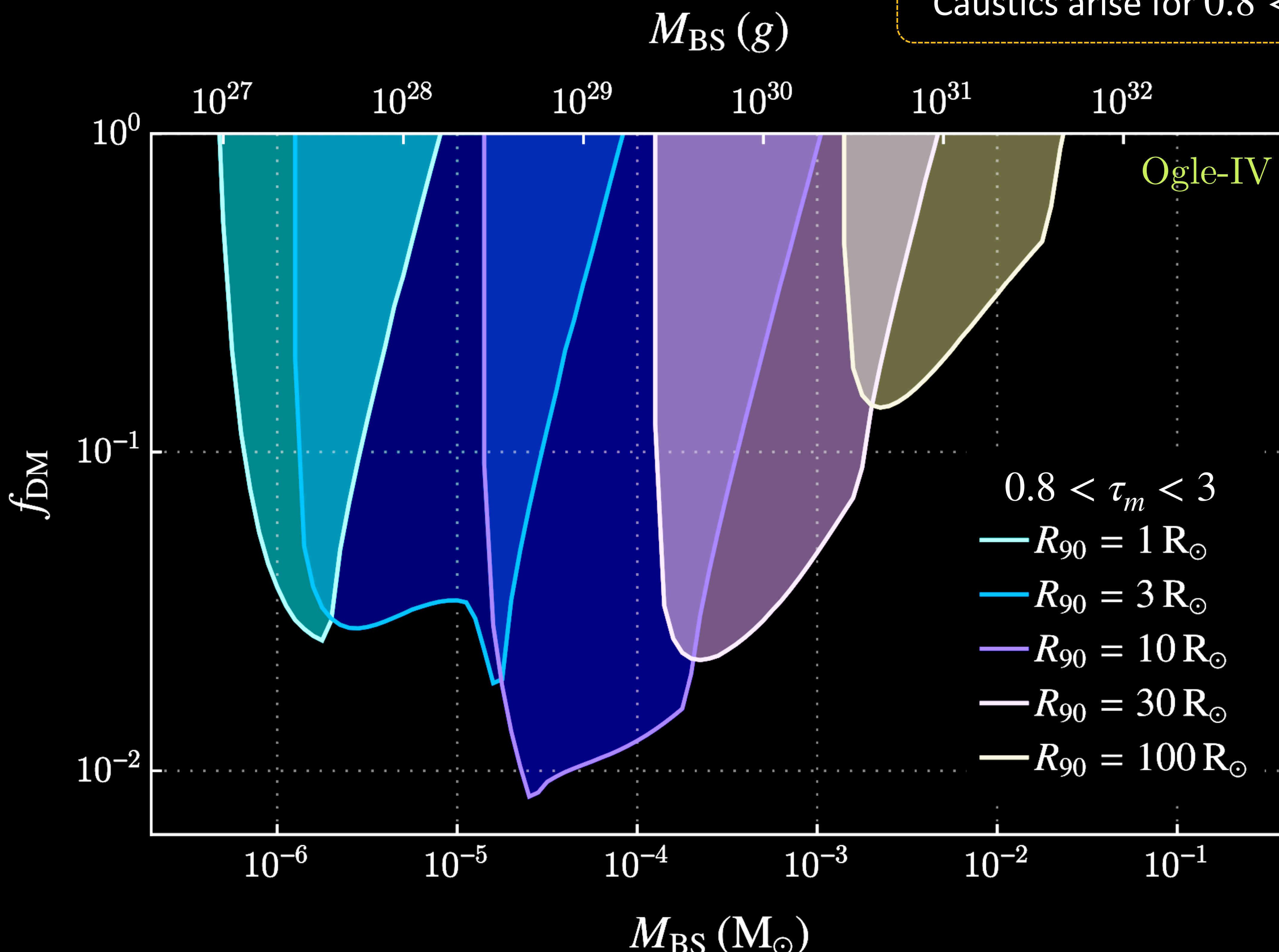
Feature importance



Opportunities for positive detection

Miguel Crispim-Romao, DC, arXiv:2402.00107

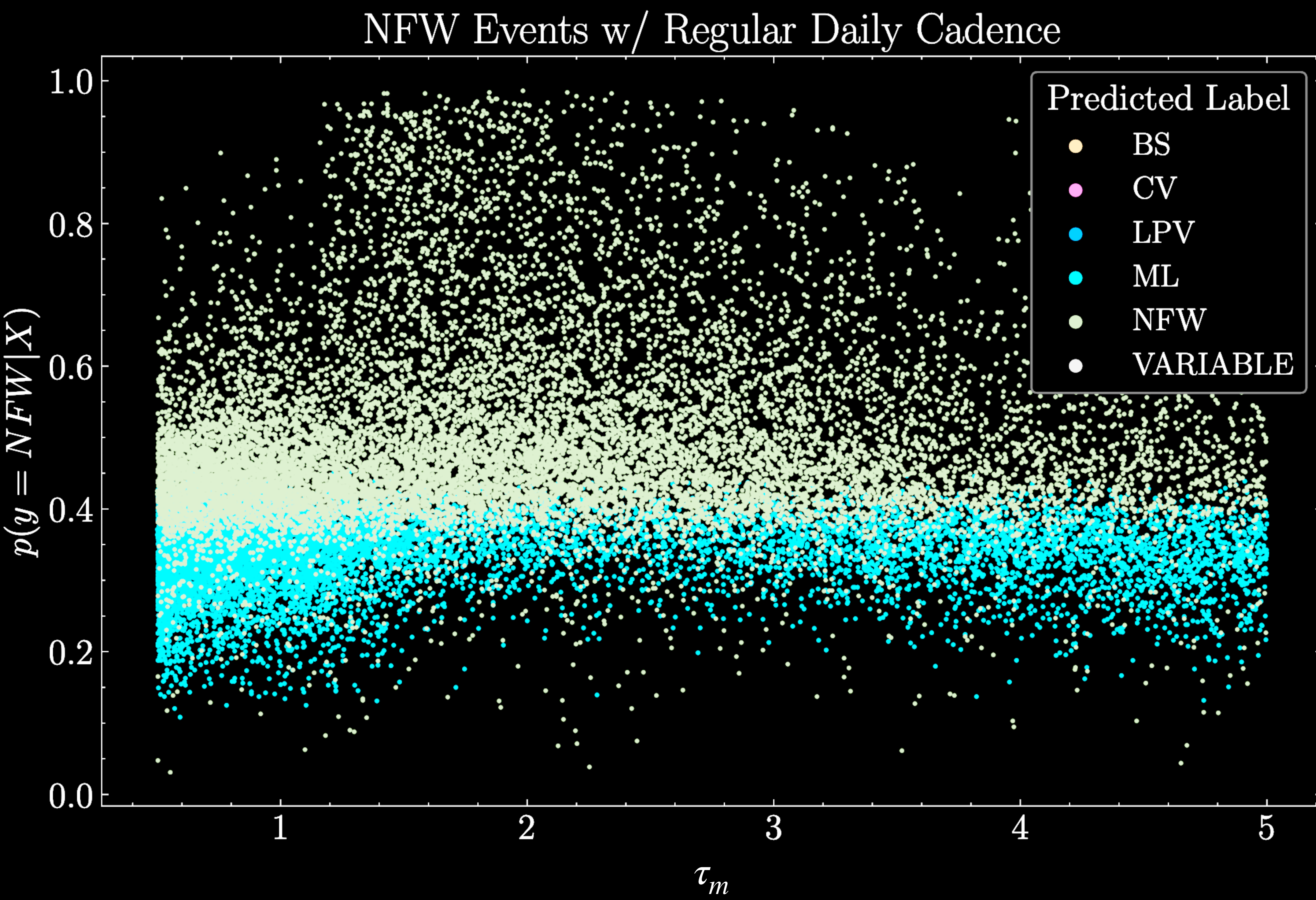
Caustics arise for $0.8 < \tau_m < 3$



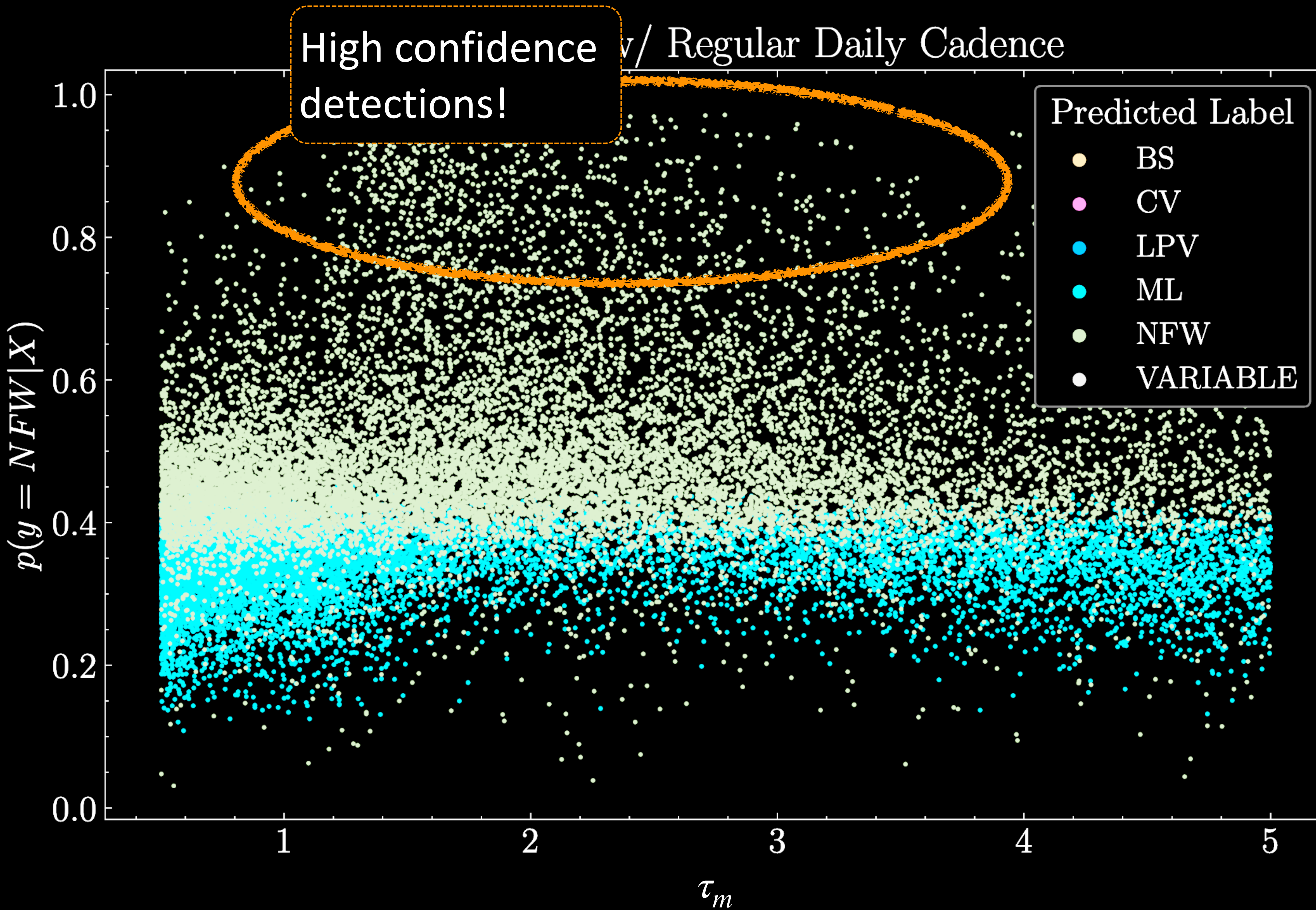
Let's dream…

- The OGLE time steps are quite irregular
- Many different factors play a role…
  - Observational Constraints (weather, moon phase, …)
  - Resource Allocation
  - Target Prioritization
  - Technical Maintenance and Downtime

- But it is interesting what the effect of cadence (ir)regularity is on the observational prospects
- So, let us imagine for a moment that we could achieve perfect daily cadence



Miguel Crispim-Romao, DC, arXiv:2402.00107



… only observed if regular cadence is achieved

Miguel Crispim-Romao, DC, arXiv:2402.00107