Probing Intermediate-Mass Black Holes with Tidal Disruption Events

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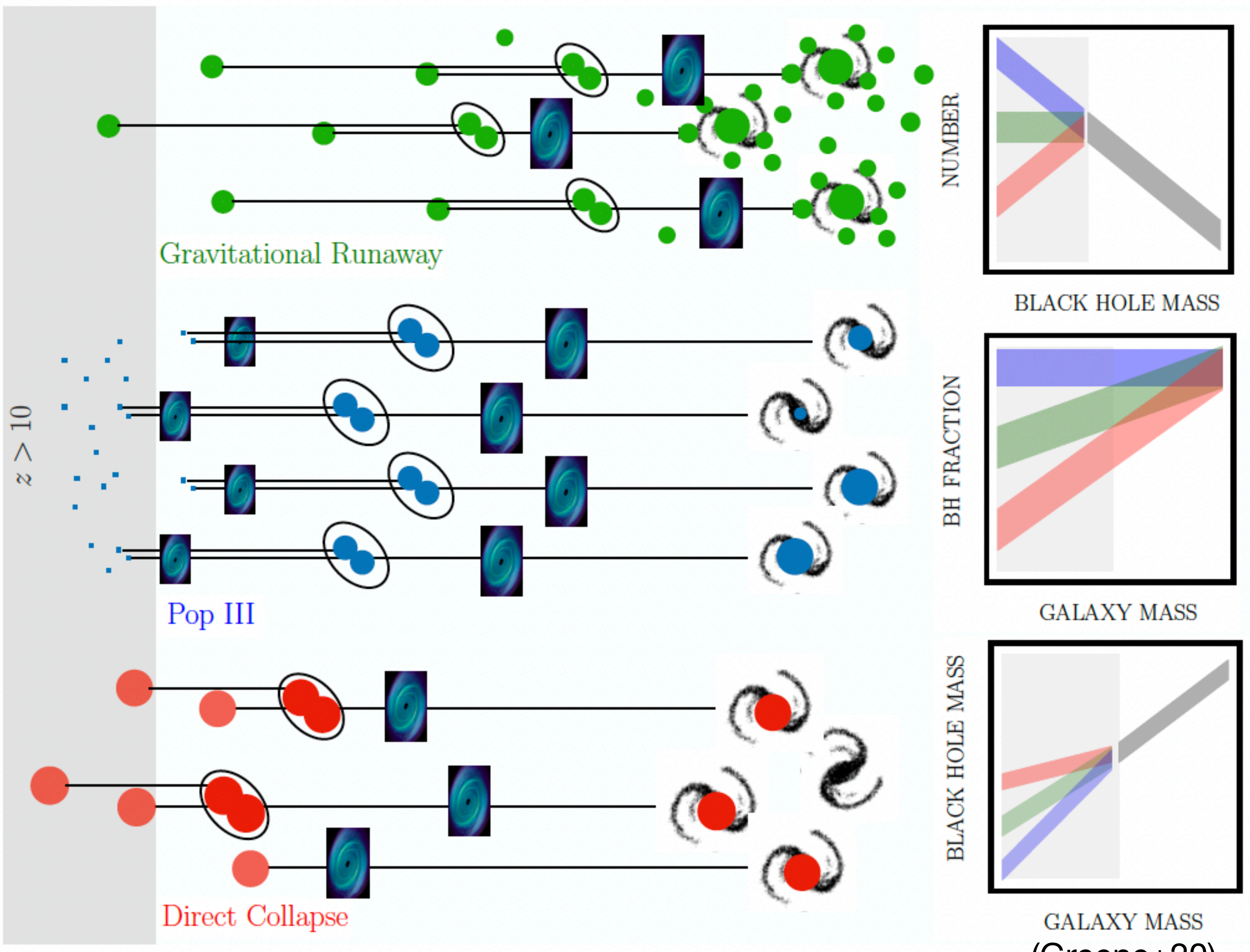
Why IMBHs?

Intermediate-mass black holes ($10^2 - 10^5 M_\odot$)

Formation channel of SMBH seeds:

- Gravitational Runaway
- Death of Pop-III stars
- Direct collapse of cold gas

Different predictions in IMBH regime



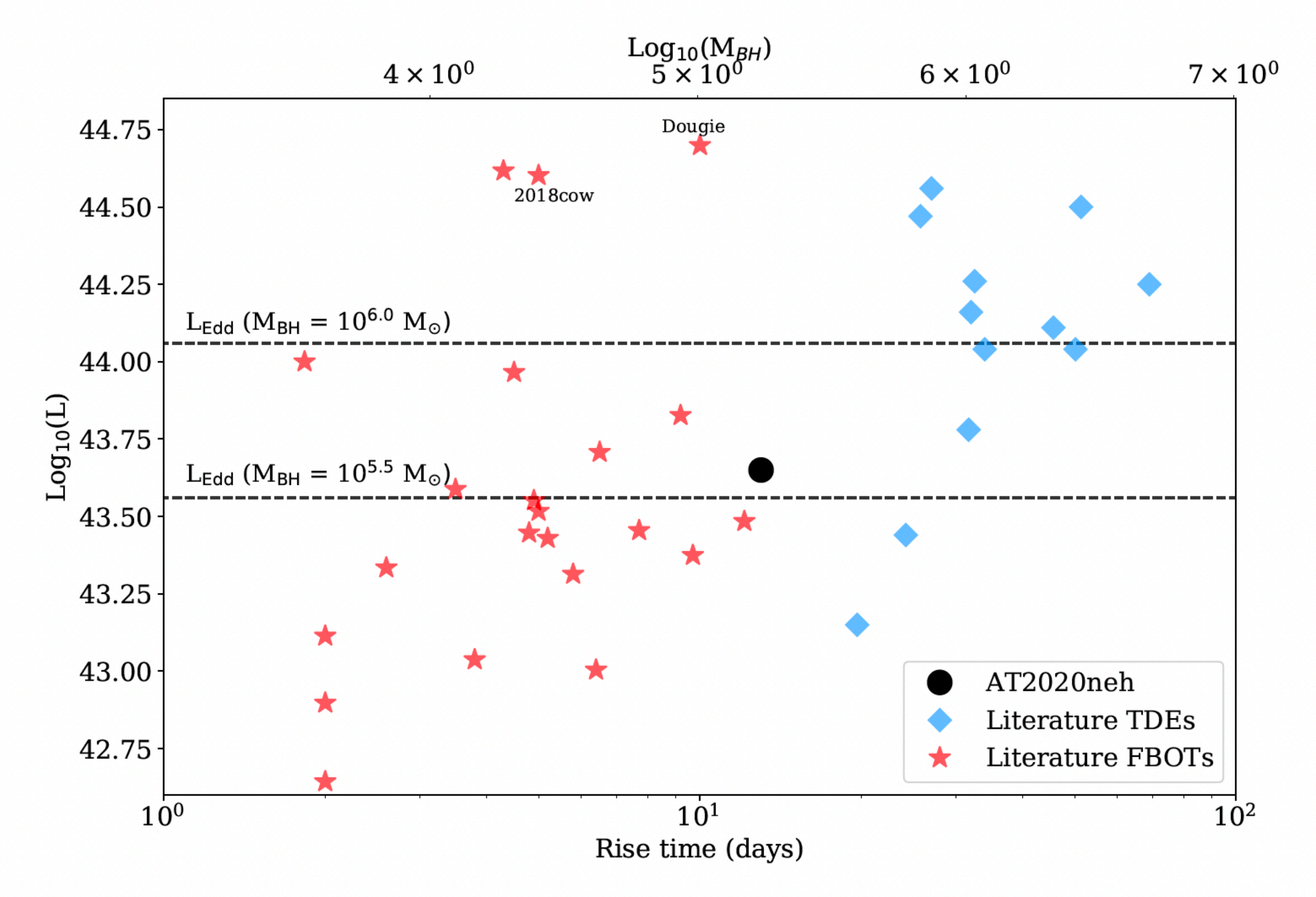
(Greene+20)

Tidal Disruption Event (TDE)

- Fallback timescale $t \propto M_{\rm BH}^{1/2}$
- Connection to fast blue optical transient (FBOT)
- IMBH-TDEs

Obj	$M_{\rm BH}$
iPTF-16fnl	3.2×10^5
ASSASN-14ae	2.6×10^5
PTF-09axc	4.8×10^5
PS1-10jh	7.1×10^5
PTF-09djl	6.6×10^5
WINGS J1348	$5.1\text{-}5.6 \times 10^5$
AT2020neh	$10^{4.7} - 10^{5.9}$
3XMM J2150-0551	10^4

(Lin+18,Angus+20,Greene+20)



(Angus+22)

Method

Galaxies & Clusters

↓ Dynamical measurements

Surface density profile

↓ Deprojection

mass density profile

↓ Eddington formula

stellar distribution function

↓ $$\frac{d^2\Gamma}{dE d\ln\beta} = -8\pi^2 G M_{BH} \frac{r_t}{\beta} \mathscr{G}(q(E), \bar{f}(E), \beta)$$

TDE rate

Name	n	R_{eff} [pc]	$\log_{10}\left(\frac{M_{BH}}{M_\odot}\right)$	$\log_{10}\left(\frac{M_\star}{M_\odot}\right)$
NGC 205	1.60	1.30	4.40	6.26
NGC 5102_1	0.80	1.60	5.94	6.85
NGC 5102_2	3.10	32.00	5.94	7.76
NGC 5206_1	0.80	3.40	5.67	6.23
NGC 5206_2	2.30	10.50	5.67	7.11
NGC 4395	2.25	3.60	5.60	9.30
NGC 300	1.10	2.90	2.00	9.30
NGC 428	1.05	3.36	4.48	9.80
NGC 1042	1.15	1.94	4.40	10.00
NGC 1493	2.36	2.60	5.40	9.60
NGC 2139	1.53	10.30	5.18	10.11
NGC 3423	1.20	4.18	5.18	9.90
NGC 7424	0.91	7.40	5.18	9.60
NGC 7793	1.27	7.70	3.70	9.60
NGC 404_1	0.50	1.60	5.50	6.53
NGC 404_2	1.96	20.10	5.50	7.04
NGC 3621	1.00	4.10	6.48	7.00

IMBH at galaxy nuclei
Exact measurements

IMBH at galaxy nuclei
Upper limit

Name	W_0	R_0	$\log_{10}\left(\frac{M_{BH}}{M_\odot}\right)$	$\log_{10}\left(\frac{M_\star}{M_\odot}\right)$
NGC7078	10.82	0.204	3.38	6.71
NGC6388	11.0	0.41	4.45	6.08
NGC6266	7.59	0.211	3.3	5.85
NGC6624	10.82	0.129	3.88	4.86
NGC6715	7.98	0.813	4.04	6.15
OmegaCen	5.5	4.6	4.67	6.70
NGC104	12.0	0.42	3.36	5.89

IMBH in globular cluster
Upper limit

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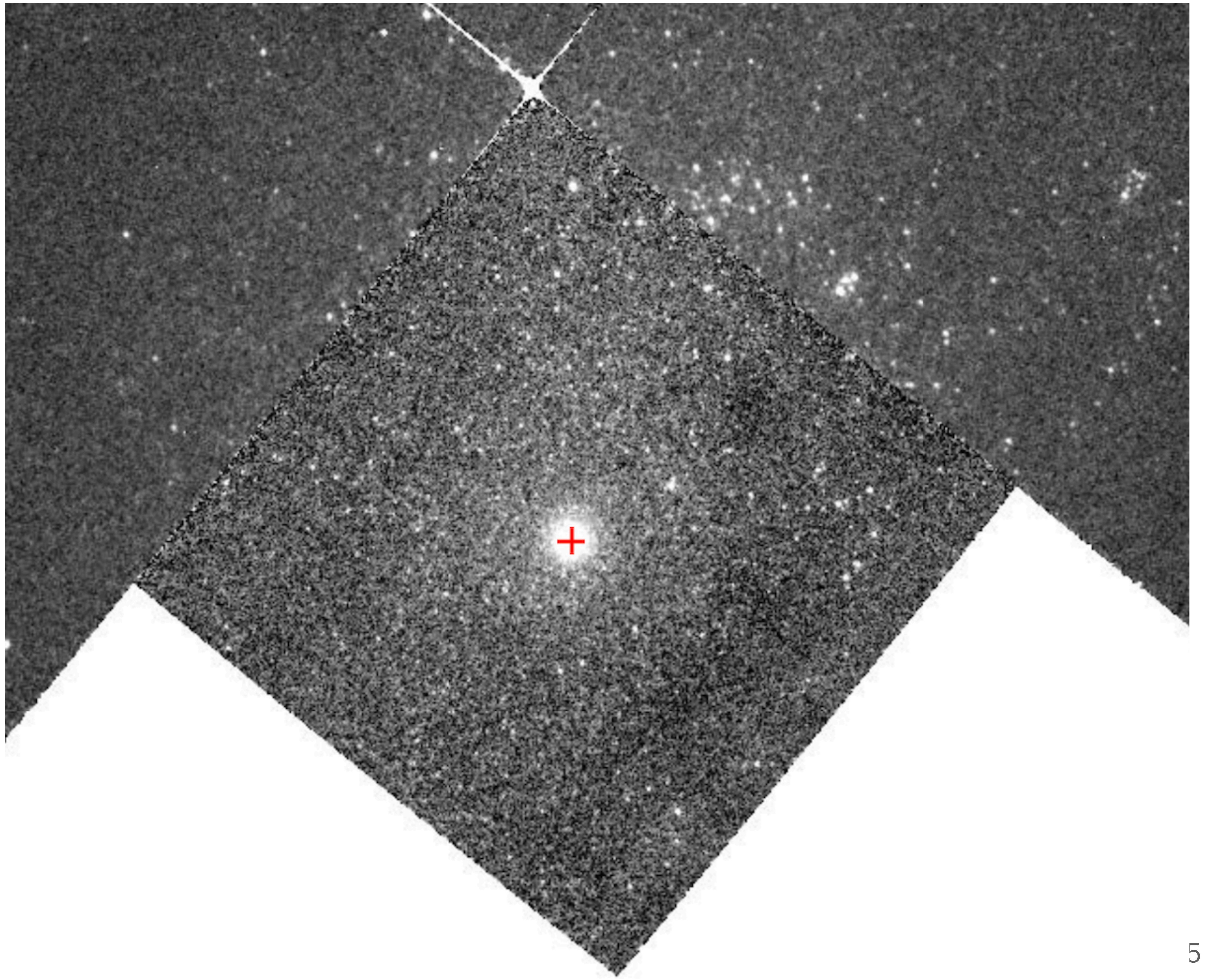
TDE rate



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TDE rate

Sersic profile:

$$\rho(r) = \rho_0 \left(\frac{r}{R_{eff}}\right)^{-p} e^{-b_n (r/R_{eff})^{1/n}}$$

Method

galaxies & clusters

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mass density profile

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Stellar distribution function

↓ $\frac{d^2\Gamma}{dE d\ln\beta} = -8\pi^2 G M_{\rm BH} \frac{r_t}{\beta} \mathscr{G}(q(E), \bar{f}(E), \beta)$

TDE rate

Eddington formula

$$f(E) = \frac{1}{\sqrt{8}\pi^2 m} \frac{d}{dE} \int_0^E \frac{d\rho}{d\psi} \frac{d\psi}{\sqrt{E-\psi}} .$$

Method

galaxies & clusters

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stellar distribution function

↓ $\frac{d^2\Gamma}{dEd\ln\beta} = -8\pi^2 G M_{\rm BH} \frac{r_t}{\beta} \mathscr{G}(q(E), \bar{f}(E), \beta)$

TDE rate

Loss Cone:

Loss cone filling factor

$$q(E) = \frac{P(E)\bar{u}(E)}{R_{\rm lc}(E)}$$

Stellar distribution function

Computed through PHASEFLOW

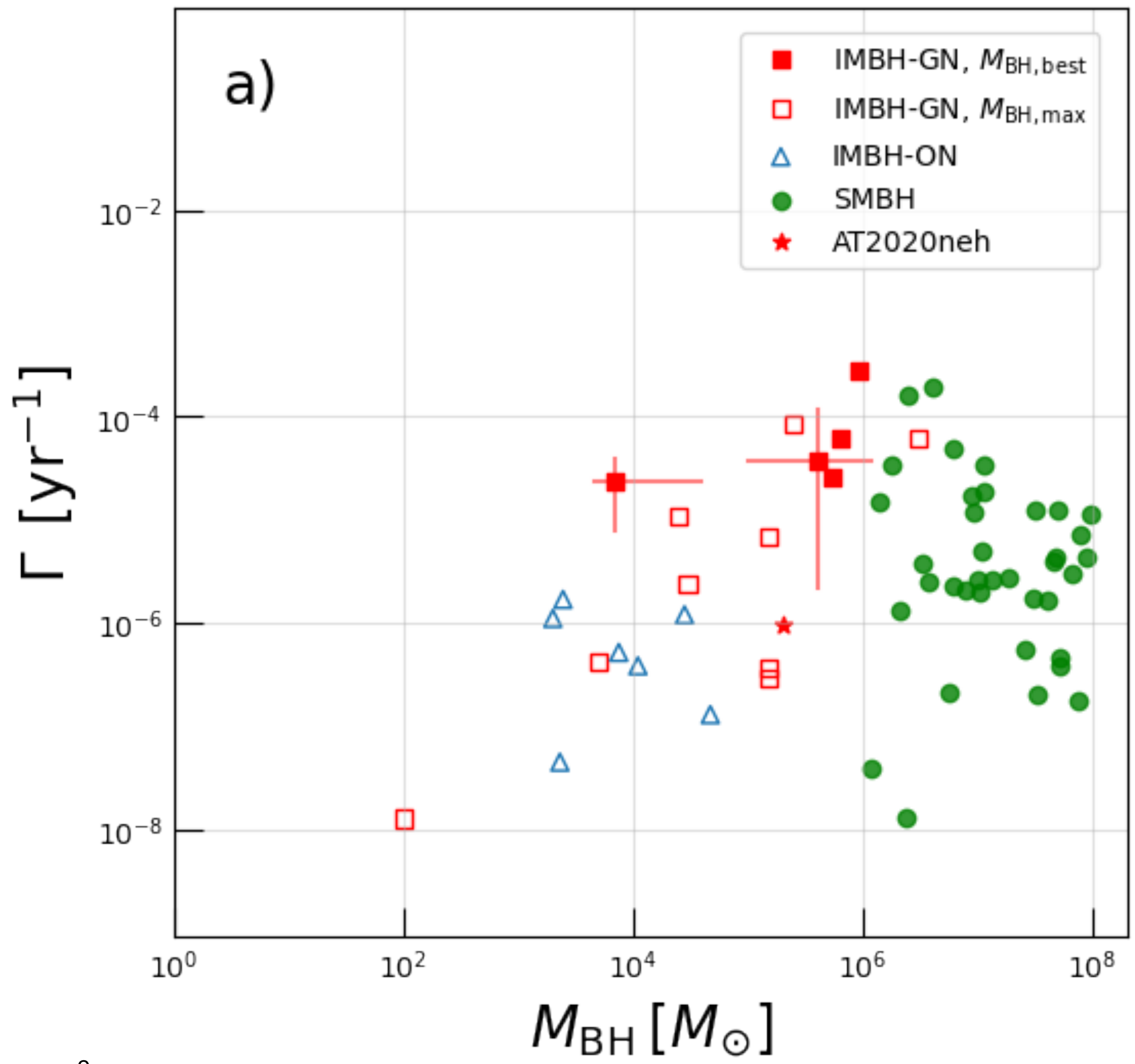
Penetration parameter

$$\beta = \frac{r_t}{r_p}$$

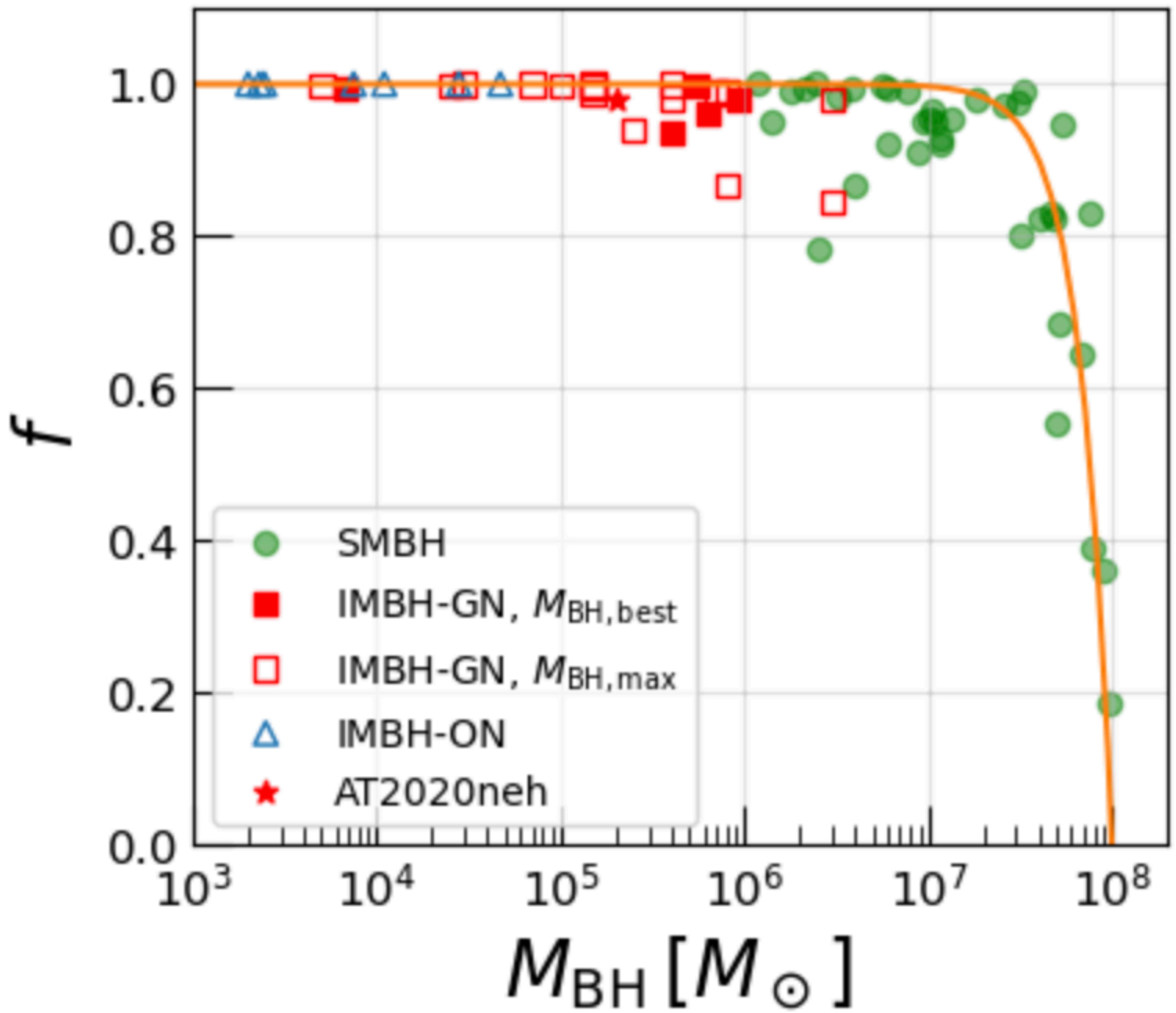
$$\frac{d^2\Gamma}{dEd\ln\beta} = -8\pi^2 G M_{\rm BH} \frac{r_t}{\beta} \mathscr{G}(q(E), \bar{f}(E), \beta)$$

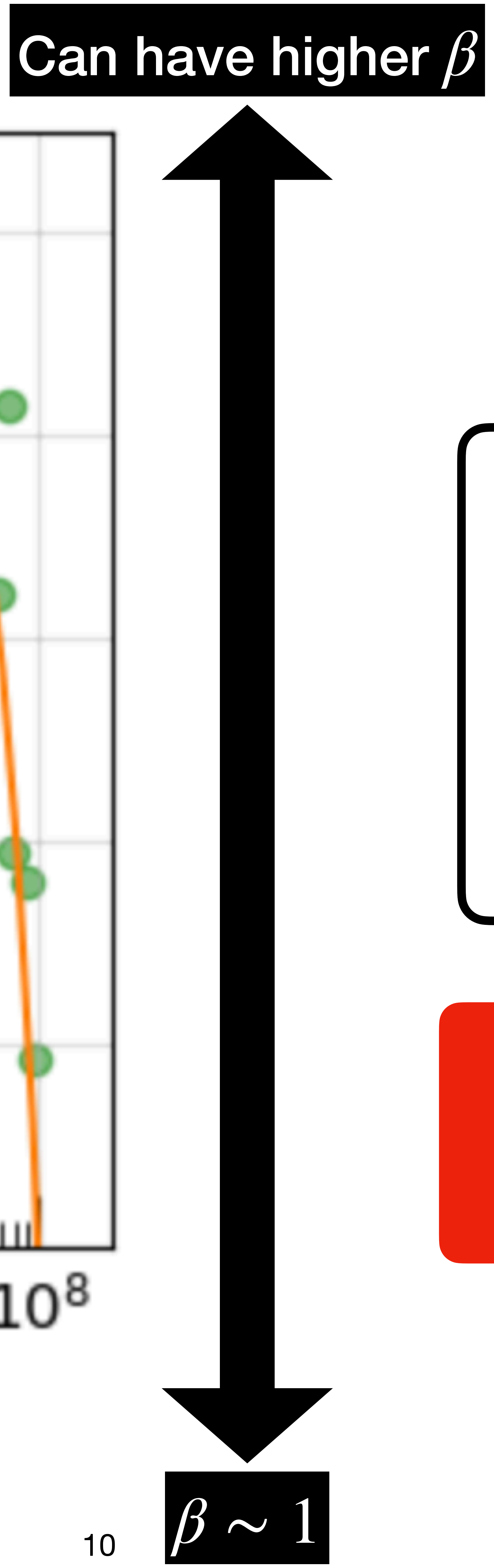
TDE rates of IMBH

- Large uncertainty in BH mass estimate
- TDE rates of IMBH ranges from $10^{-8} - 10^{-4}\,\mathrm{gal}^{-1}\mathrm{yr}^{-1}$
- TDE rate follows different trend compare to SMBH
- Highest rate galaxies: NGC5102, NGC1493, NGC5206



Pinhole fraction f





$$\beta = \frac{r_t}{r_p}$$

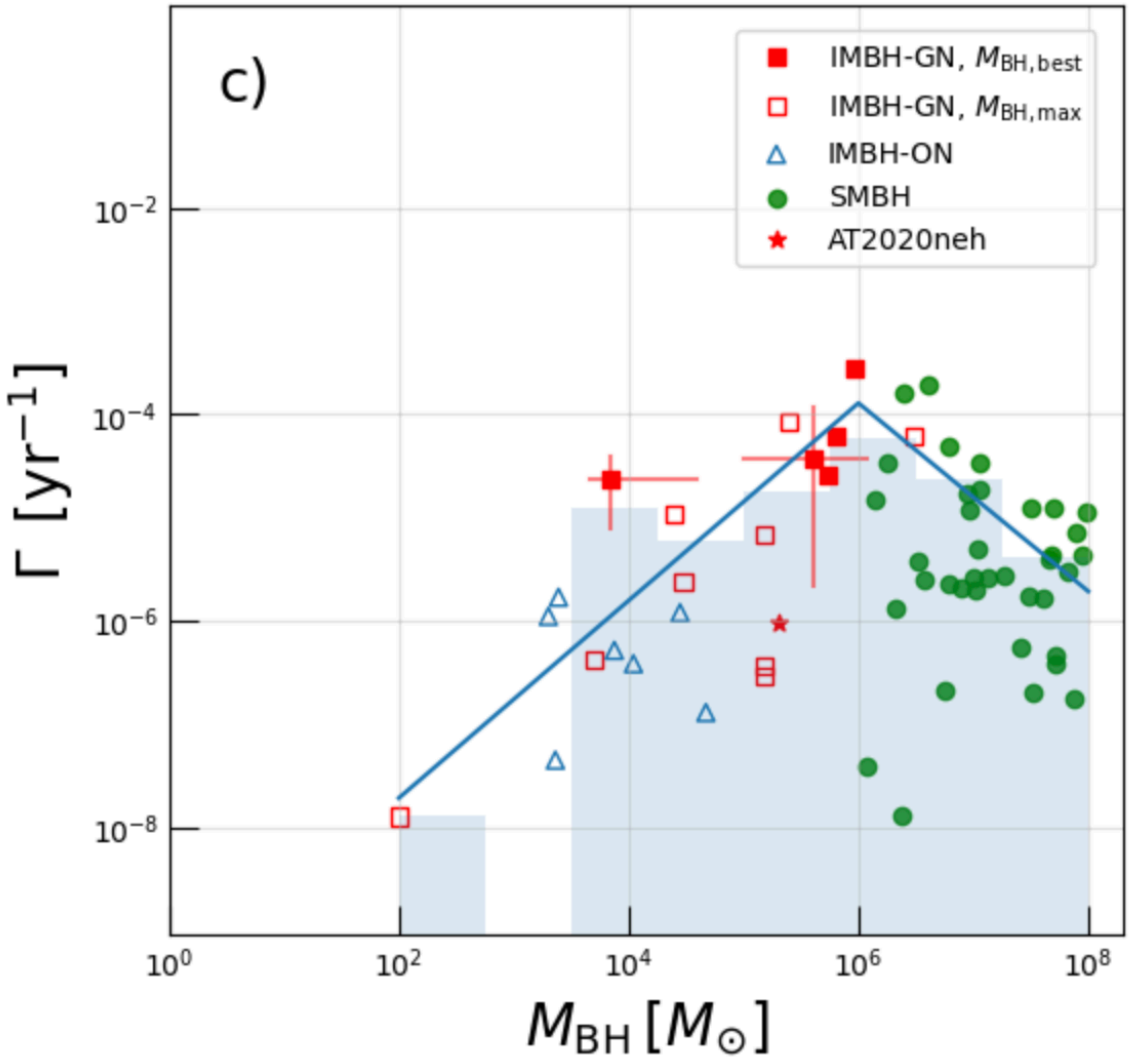
β affects shape of light curve near the peak (Guillochon&Ramirez-Ruiz13)

High β orbits —> less likely to have partial disruptions

Extremely high β (~1000)
High compression —> Explosion?
(Rosswog+21)

Volumetric Rate

TDE rate per galaxy per year



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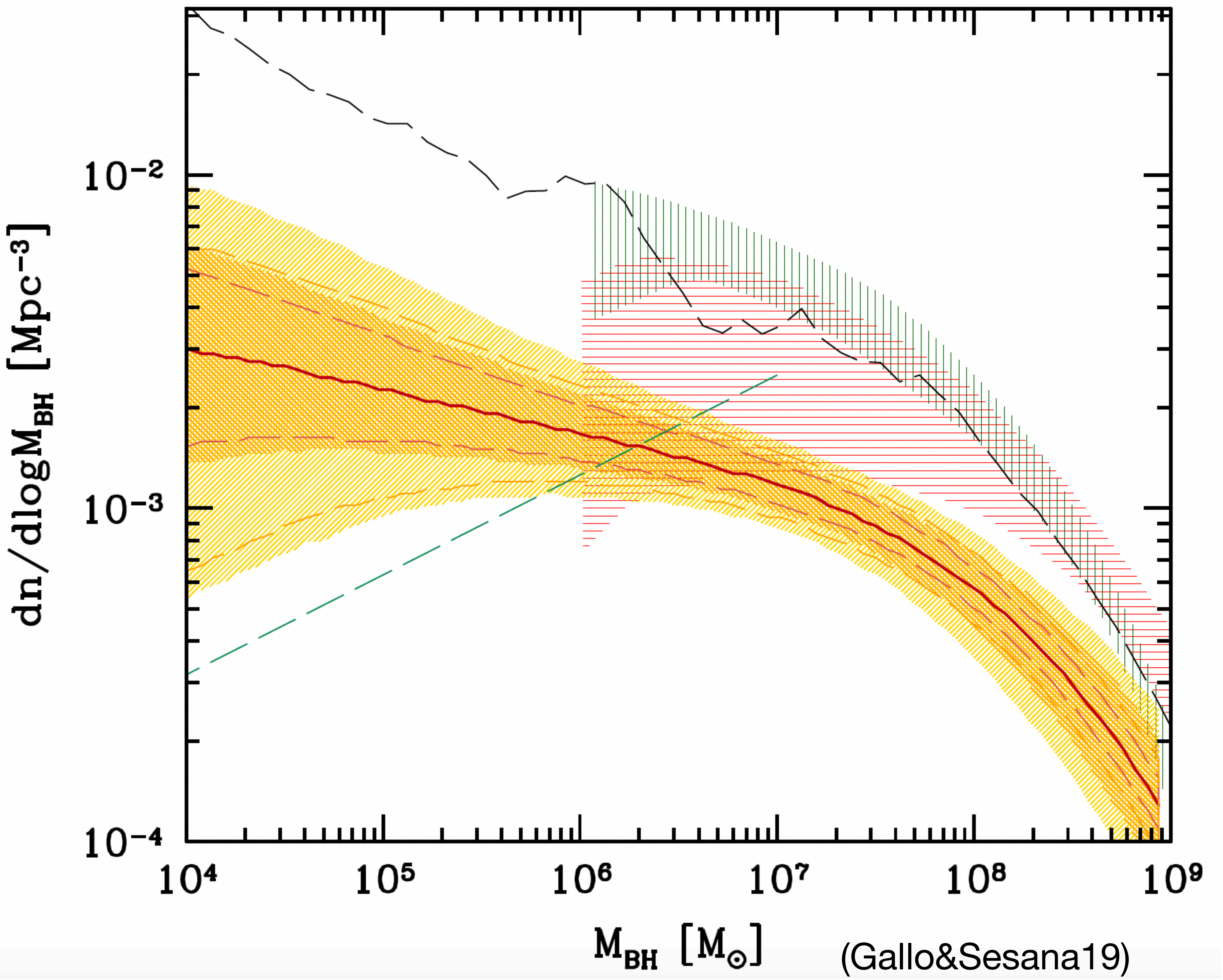
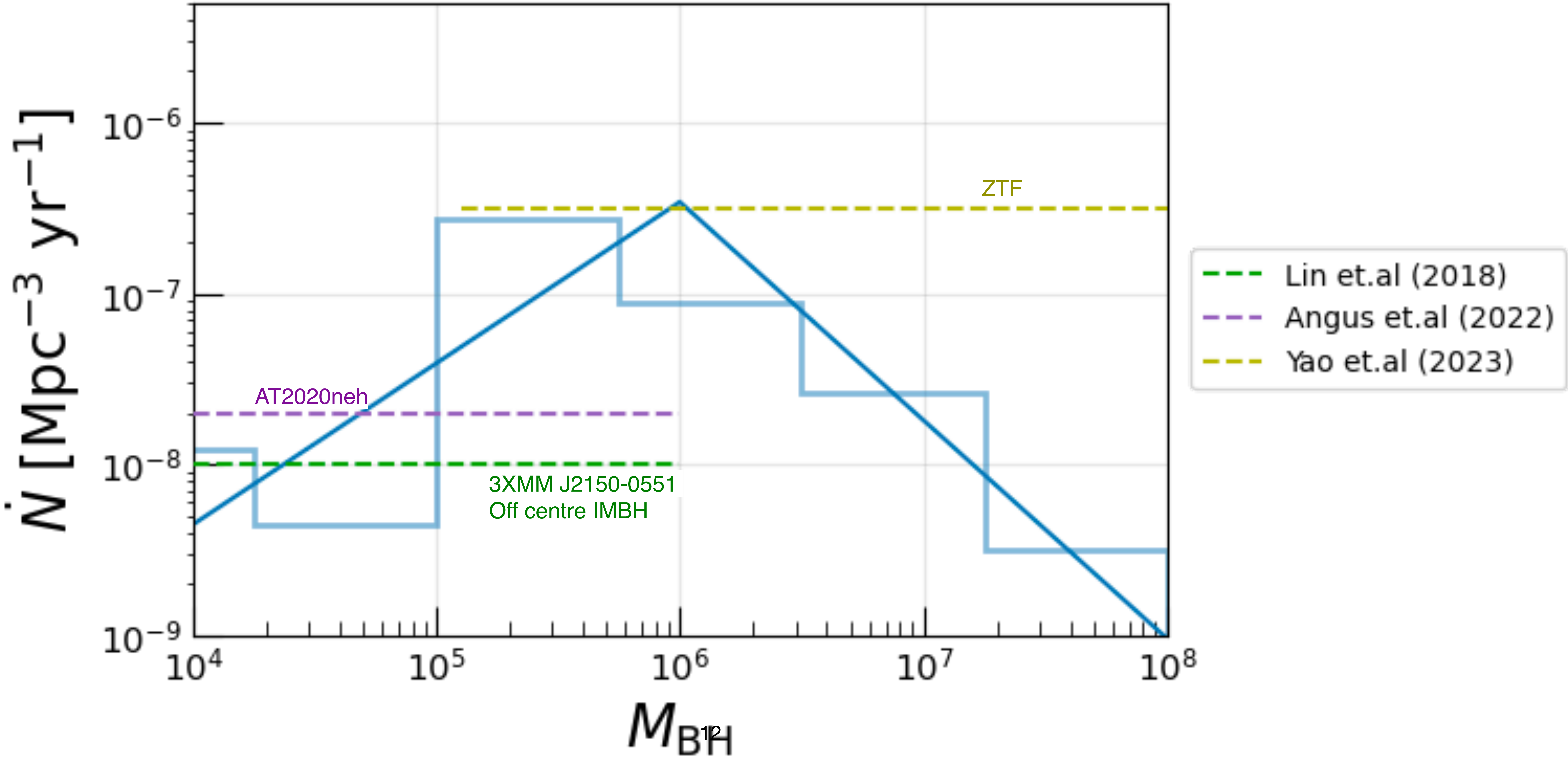
Black Hole Mass Function

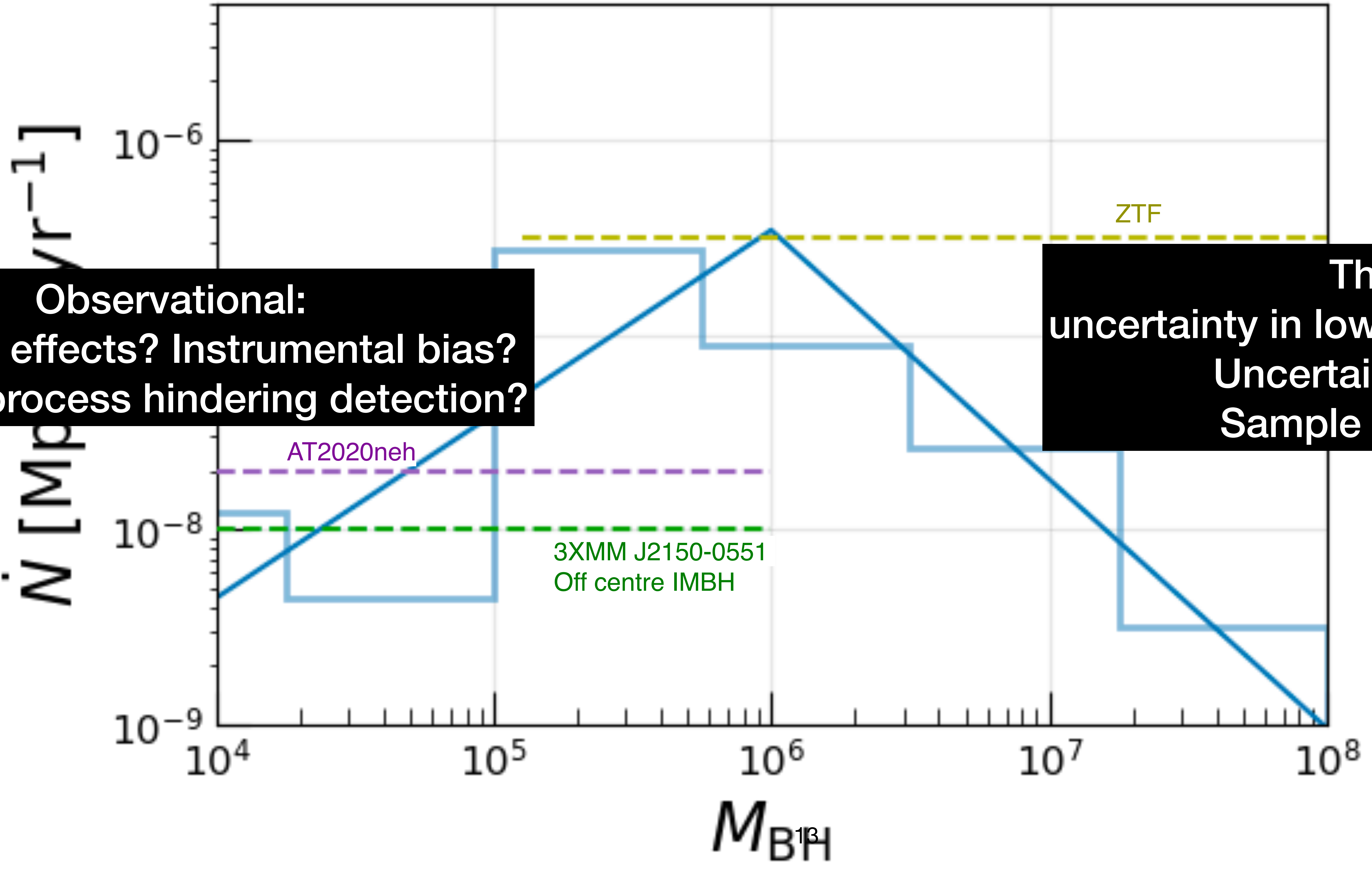


(Gallo&Sesana19)

Volumetric Rate



Volumetric Rate

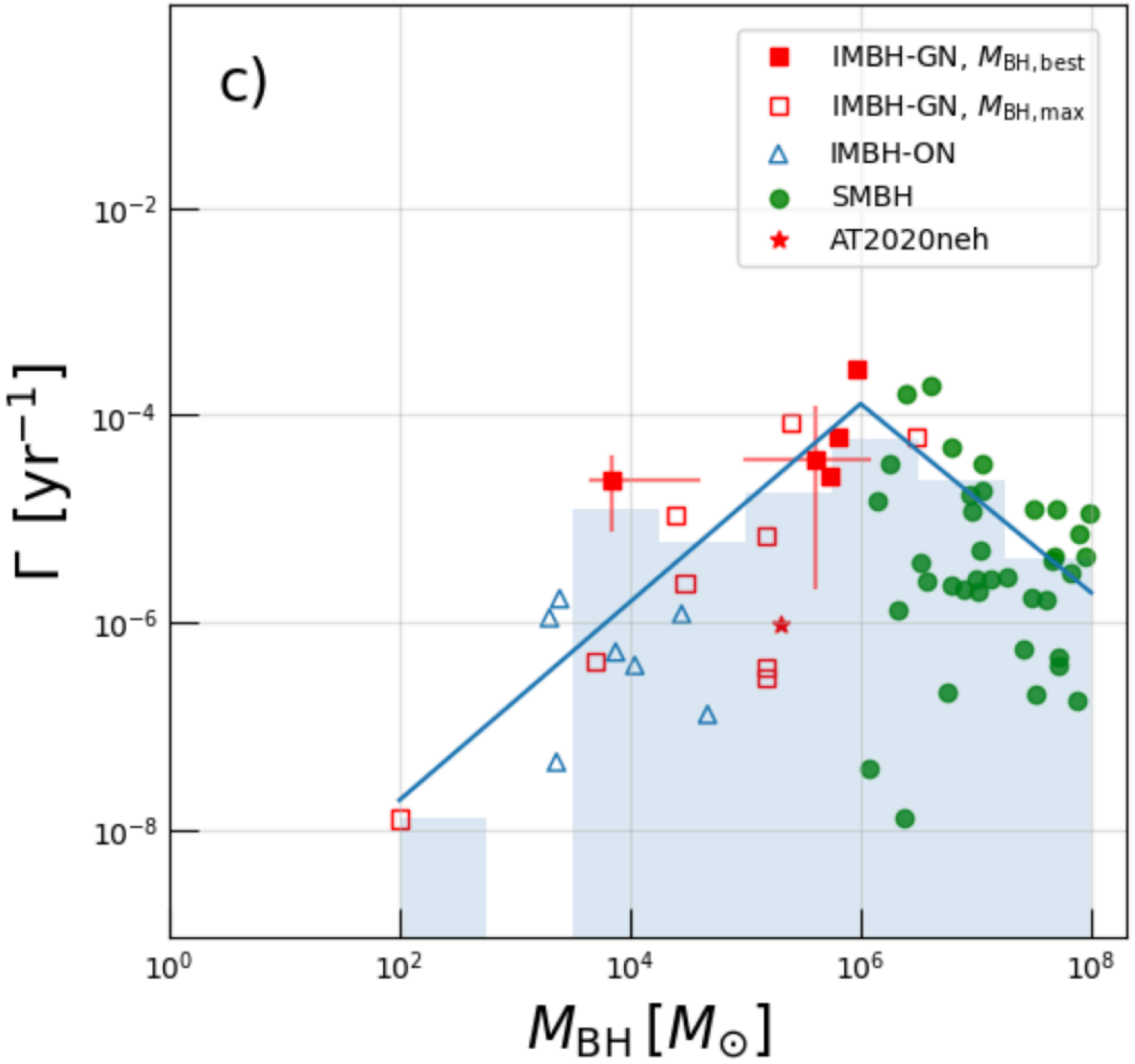


Observational:
Selection effects? Instrumental bias?
Physical process hindering detection?

Theoretical:
uncertainty in low mass regime of BHMF?
Uncertainty in BH mass?
Sample completeness?

Summary

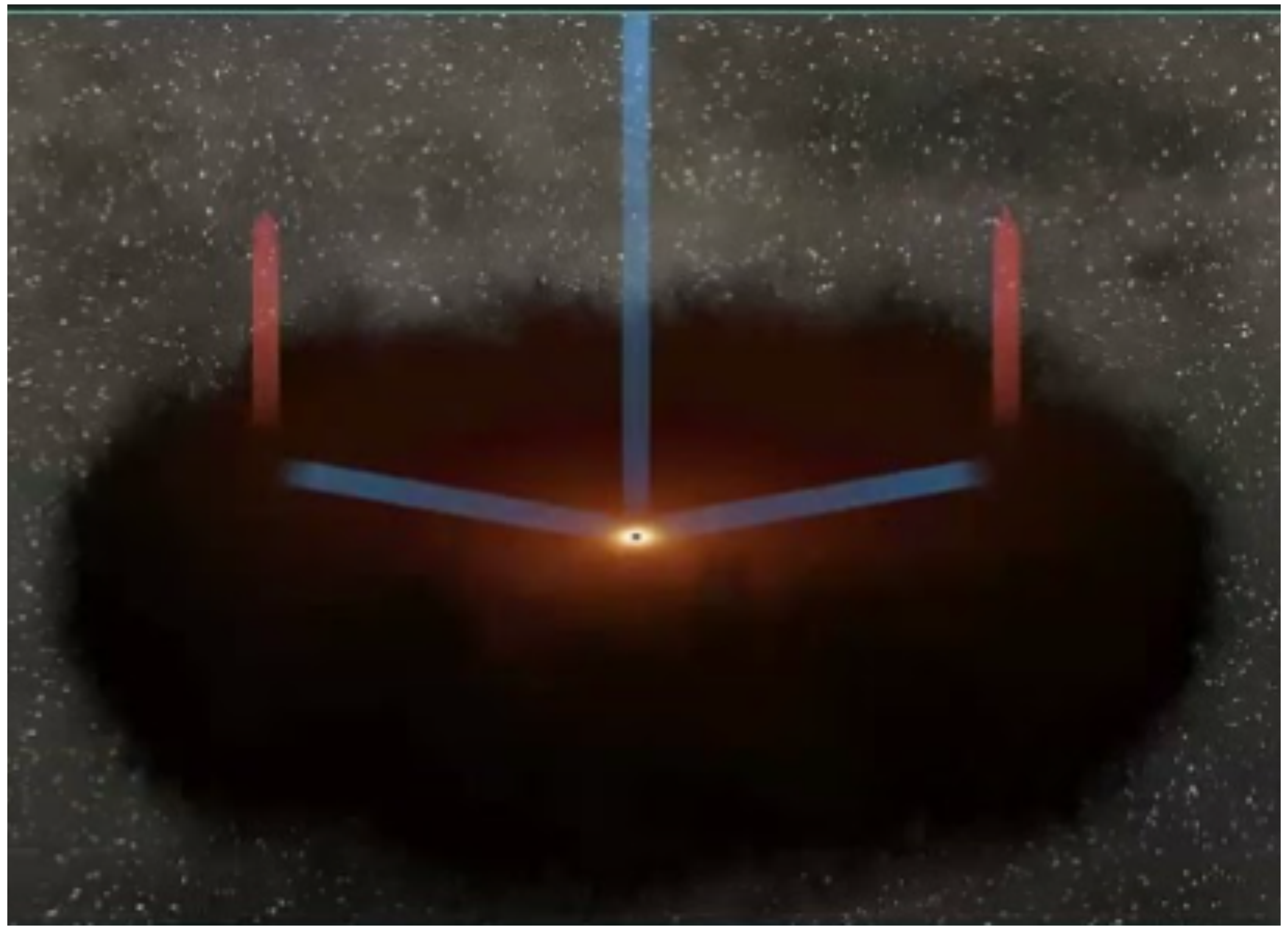
- TDE rates around IMBHs is $10^{-8} - 10^{-4}\,\mathrm{gal}^{-1}\mathrm{yr}^{-1}$, similar to the TDE rates of SMBHs. Making TDE a great way to probe IMBHs
- The volumetric rate of IMBH TDE is between $10^{-9} - 10^{-7}\,\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$, in agreement with observations
- TDEs around IMBHs can be deeply plunging, hence less likely to be partially disrupted. These IMBH-TDE can have β as high as 1000
- IMBH-TDE rate observed in future can be used to constrain the IMBH BHMF and occupation fraction



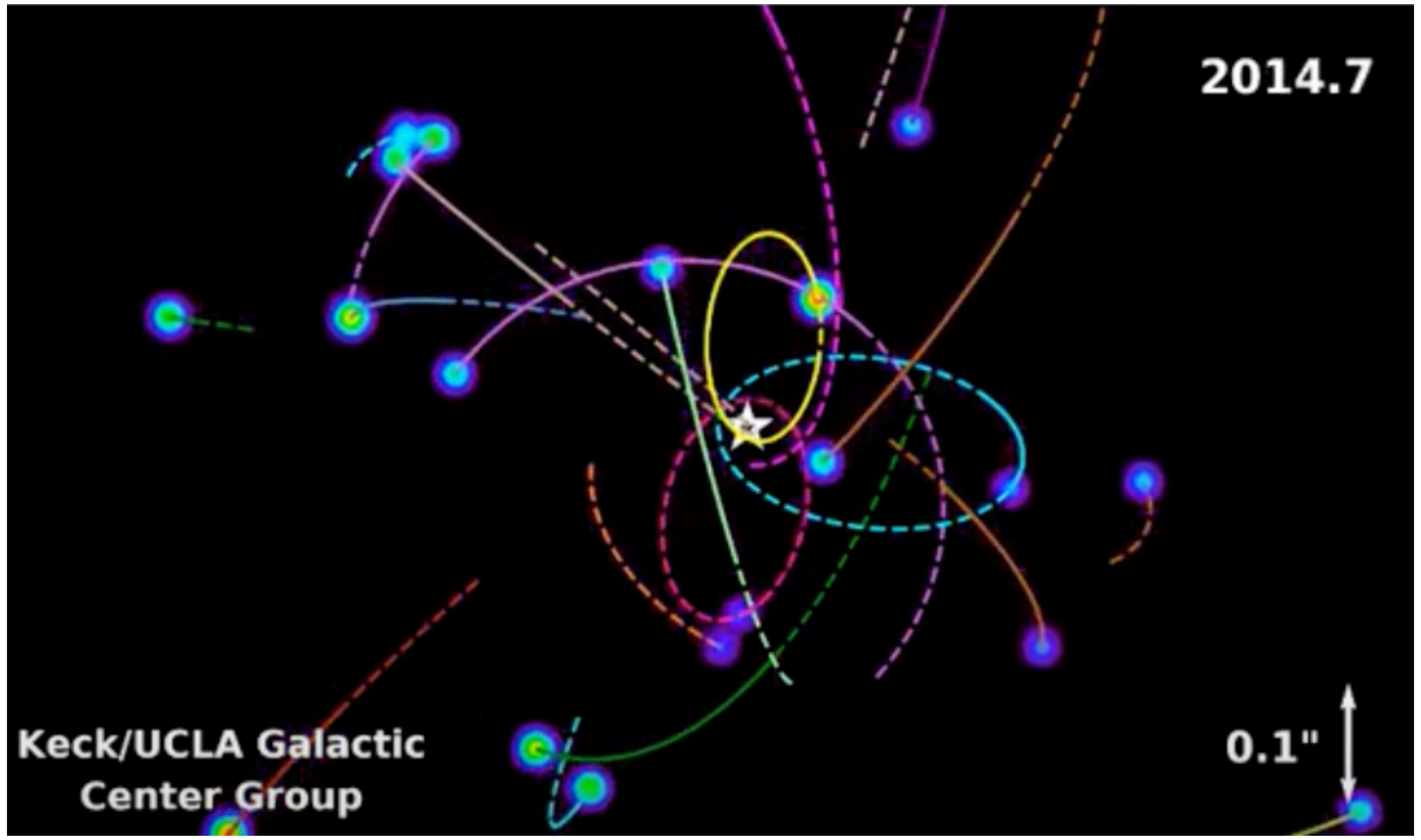
Additional

Probing IMBHs

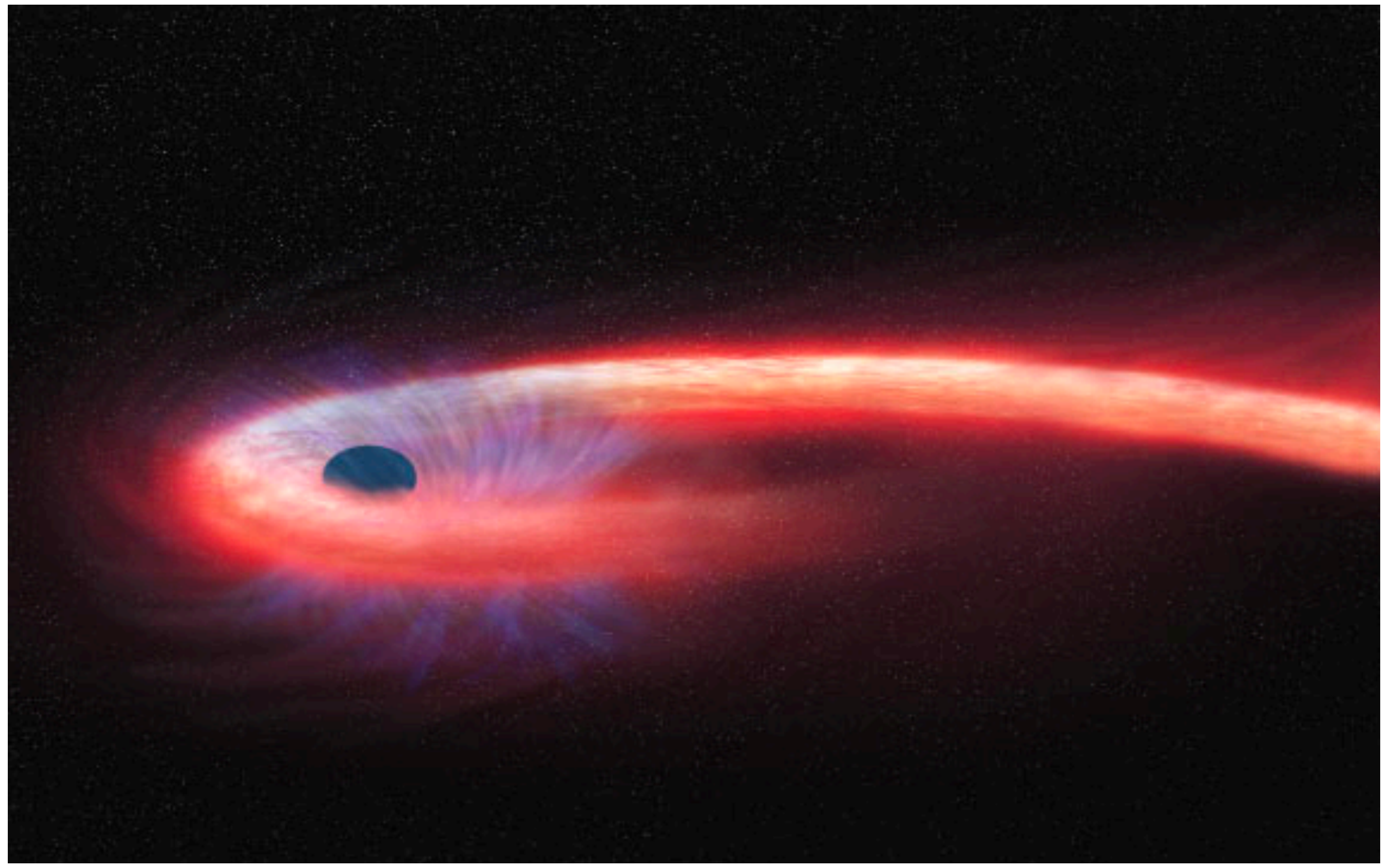
AGN



Dynamical measurements



TDE



The Loss Cone

- Tidal disruption radius

$$R_t = R_\star \left(\frac{M_\bullet}{M_\star}\right)^{1/3}$$

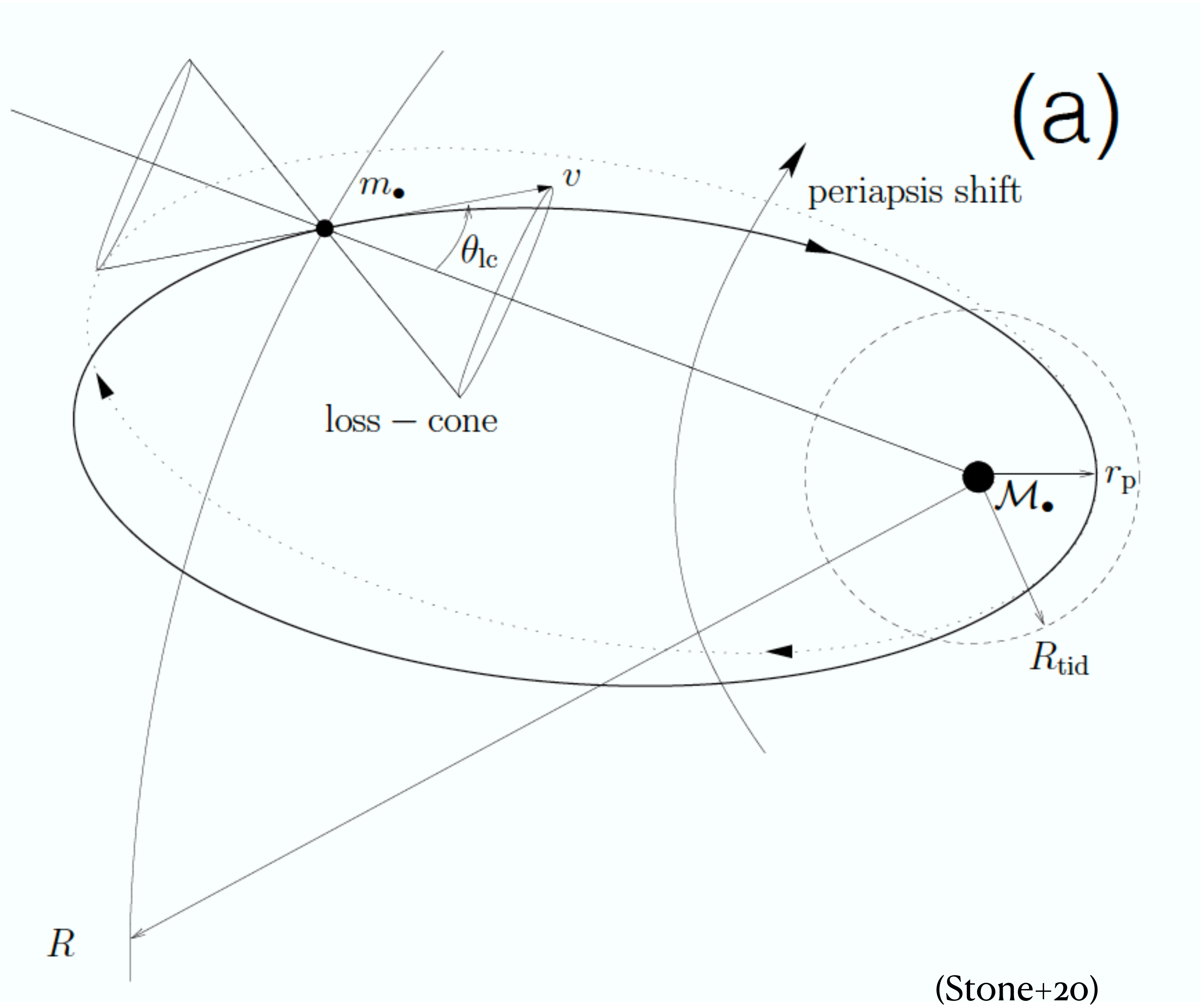
- Critical angular momentum

$$L_t = \sqrt{2GM_\bullet R_t},$$

- Stars with $L < L_t$ falls into the loss cone, and will be disrupted within an orbit

- TDE rate = rate stars enter the loss cone

- With a distribution of stars, they scatter among themself, some will loss momentum end up in the loss cone



(Stone+20)

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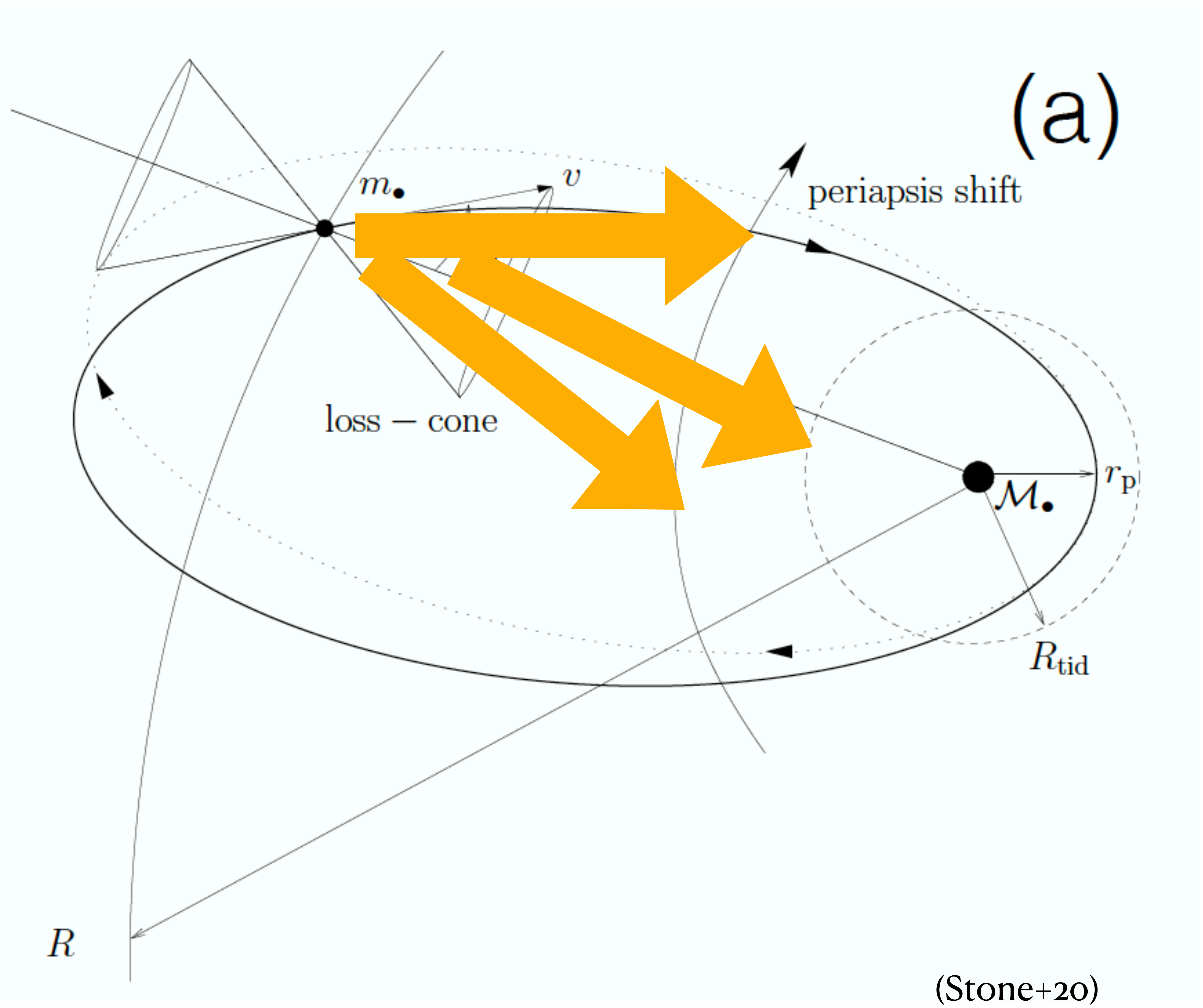

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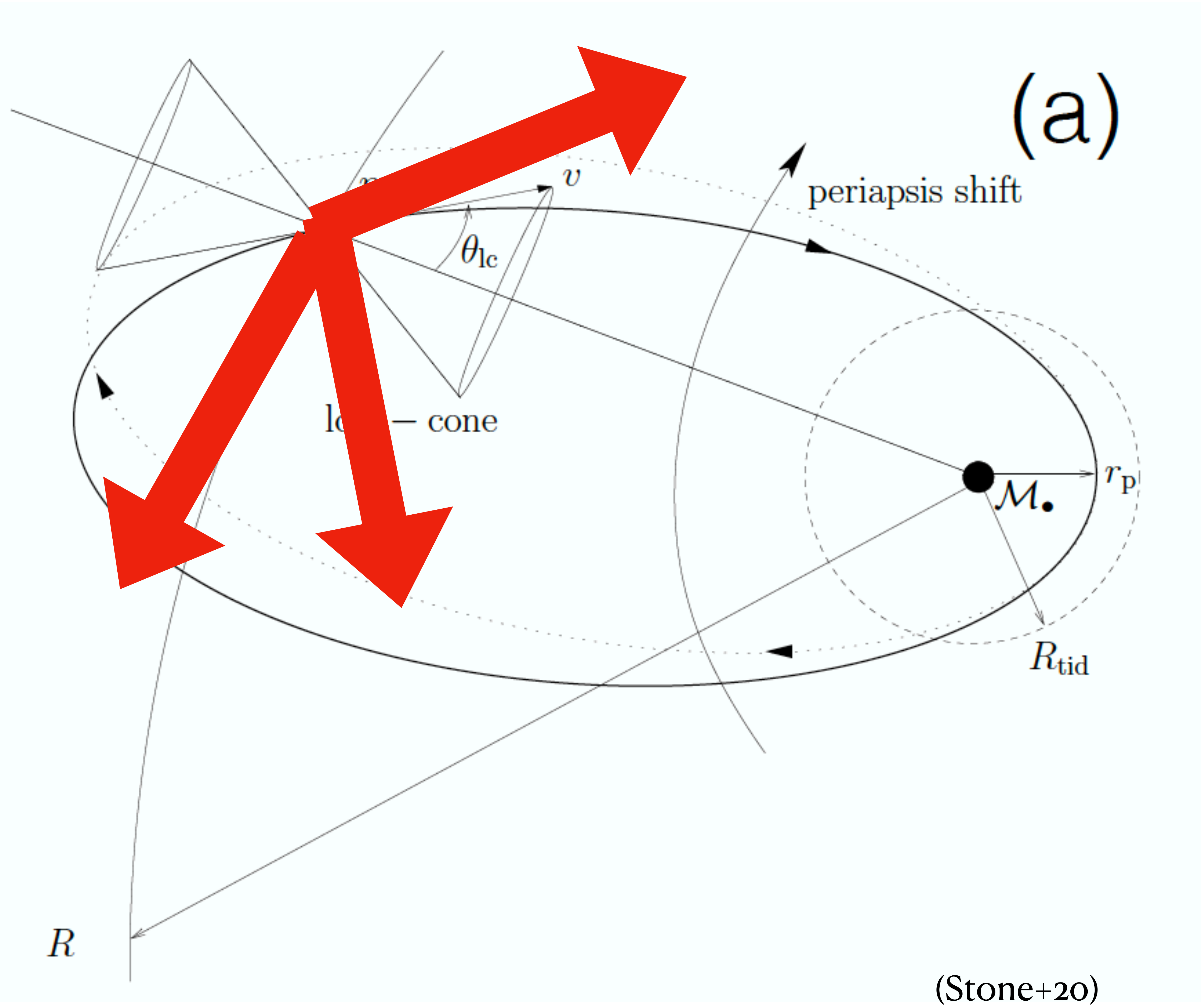

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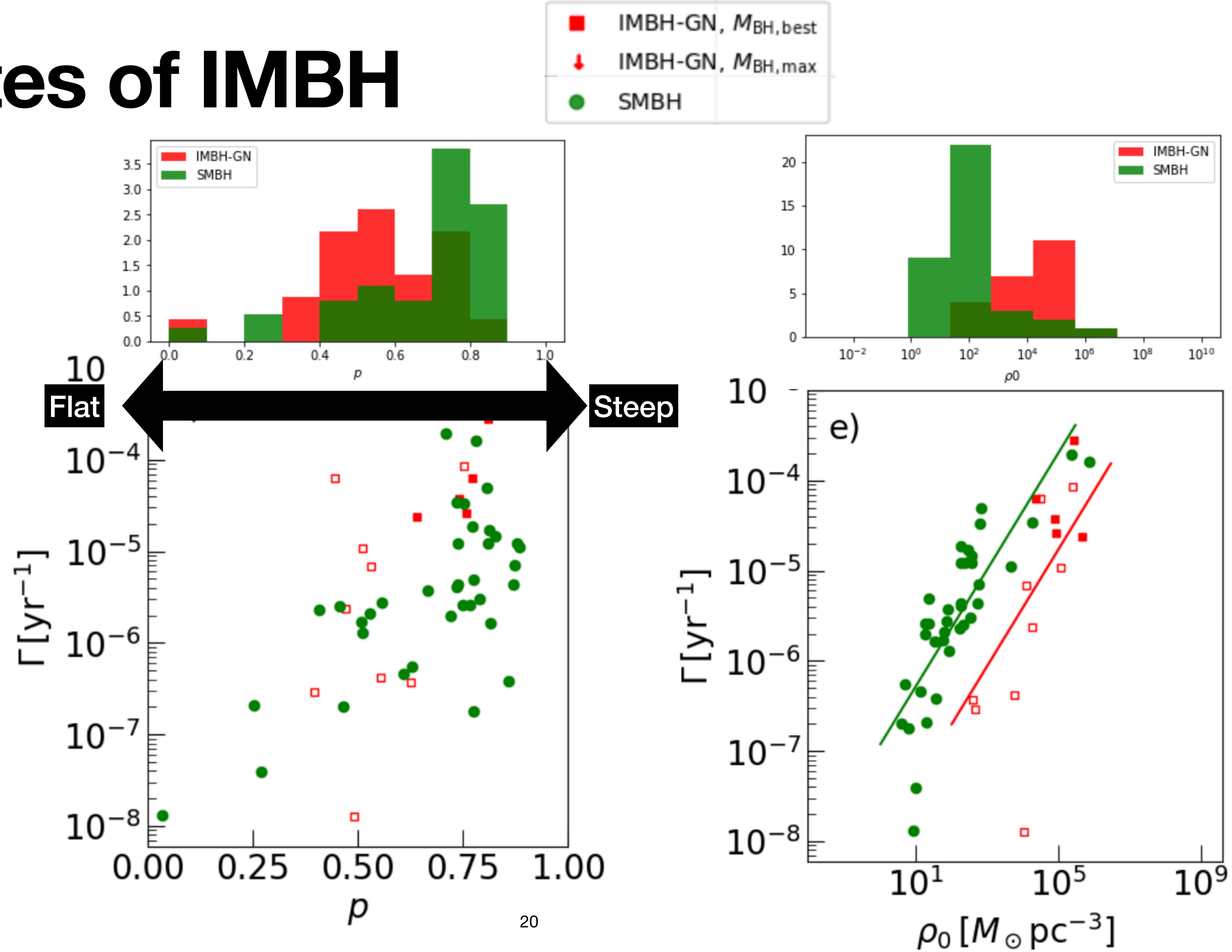
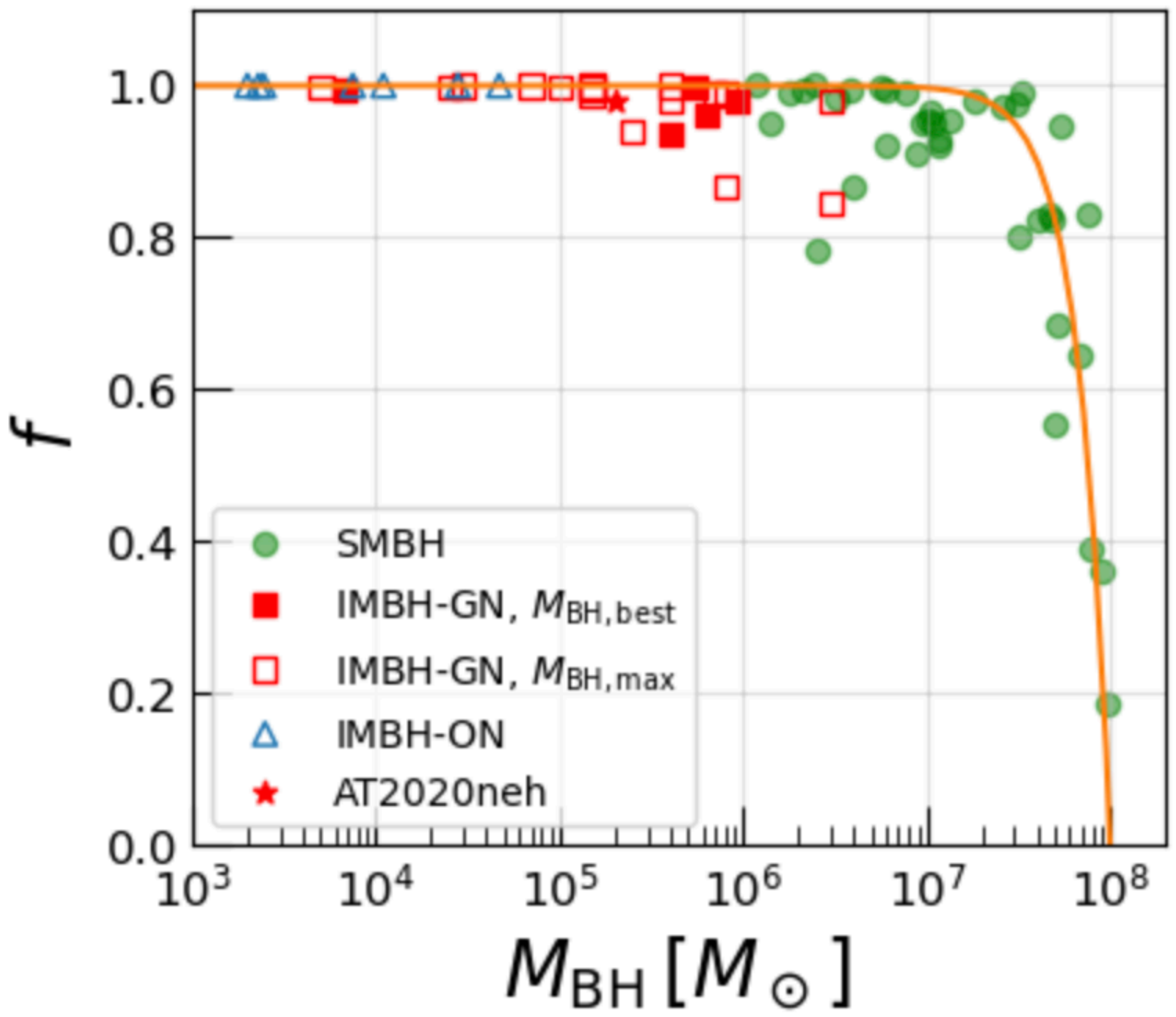
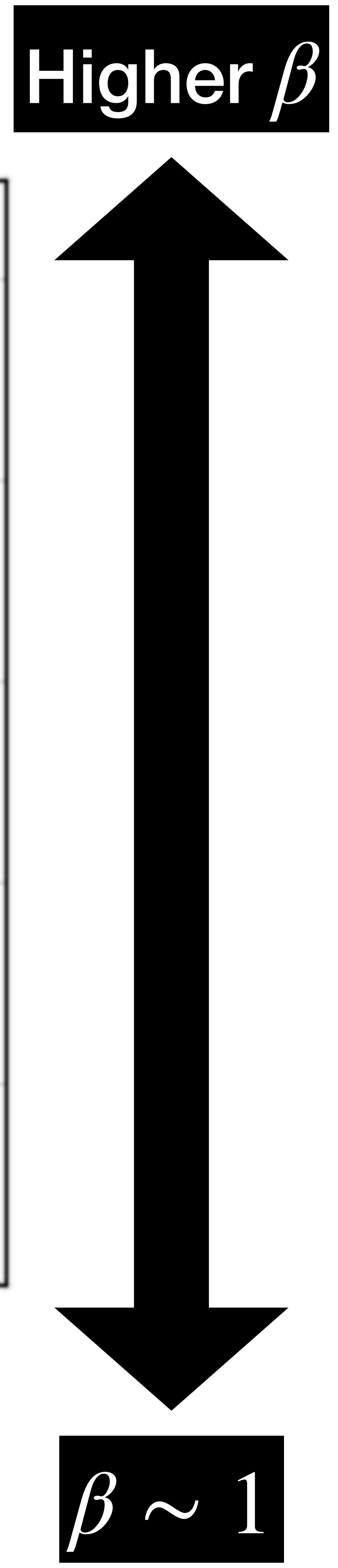


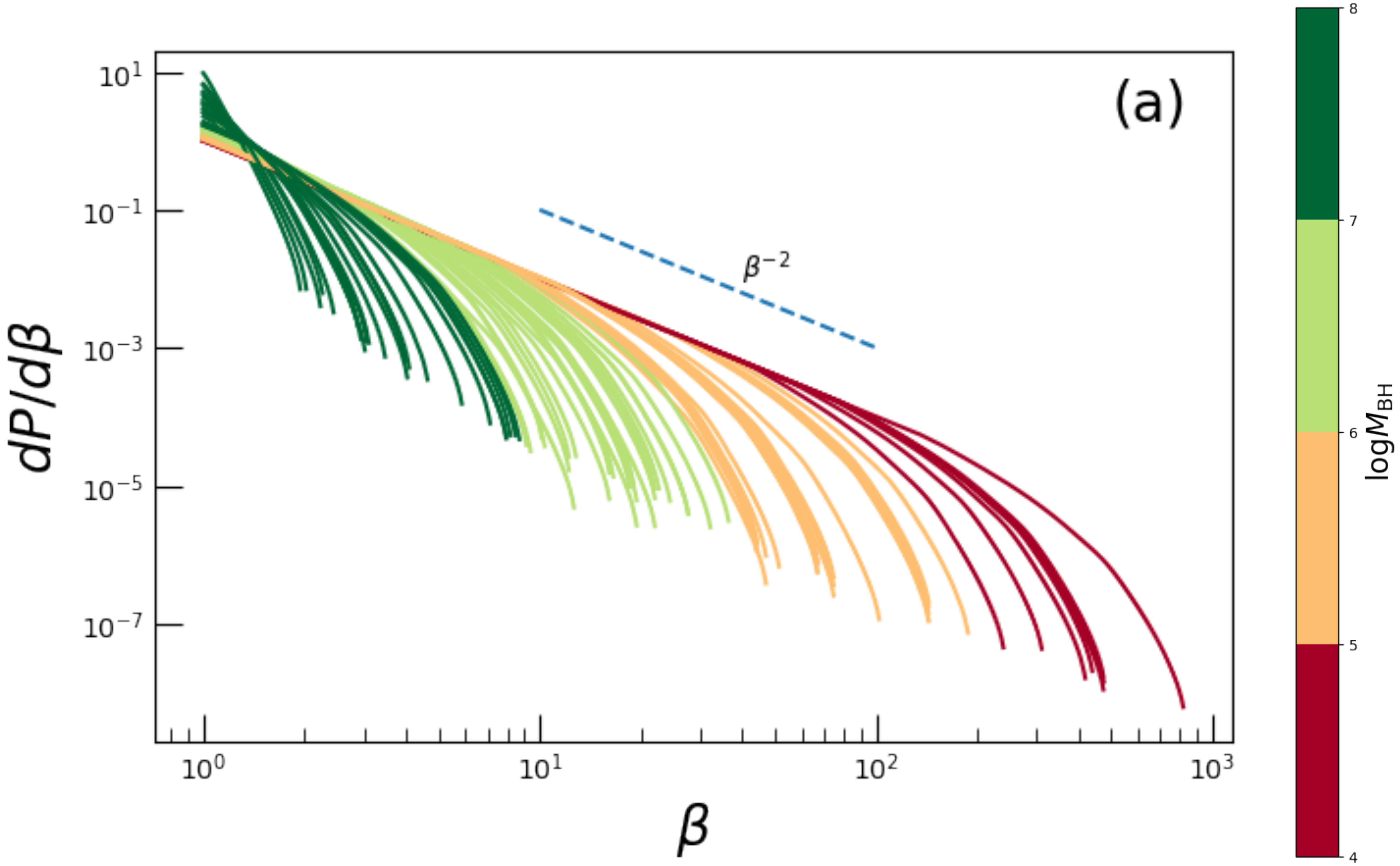
Pinhole fraction

β affects shape of light curve near the peak (Guillochon&Ramirez-Ruiz13)

High β orbits —> less likely to have partial disruptions







Explosion? (Rosswog+21)

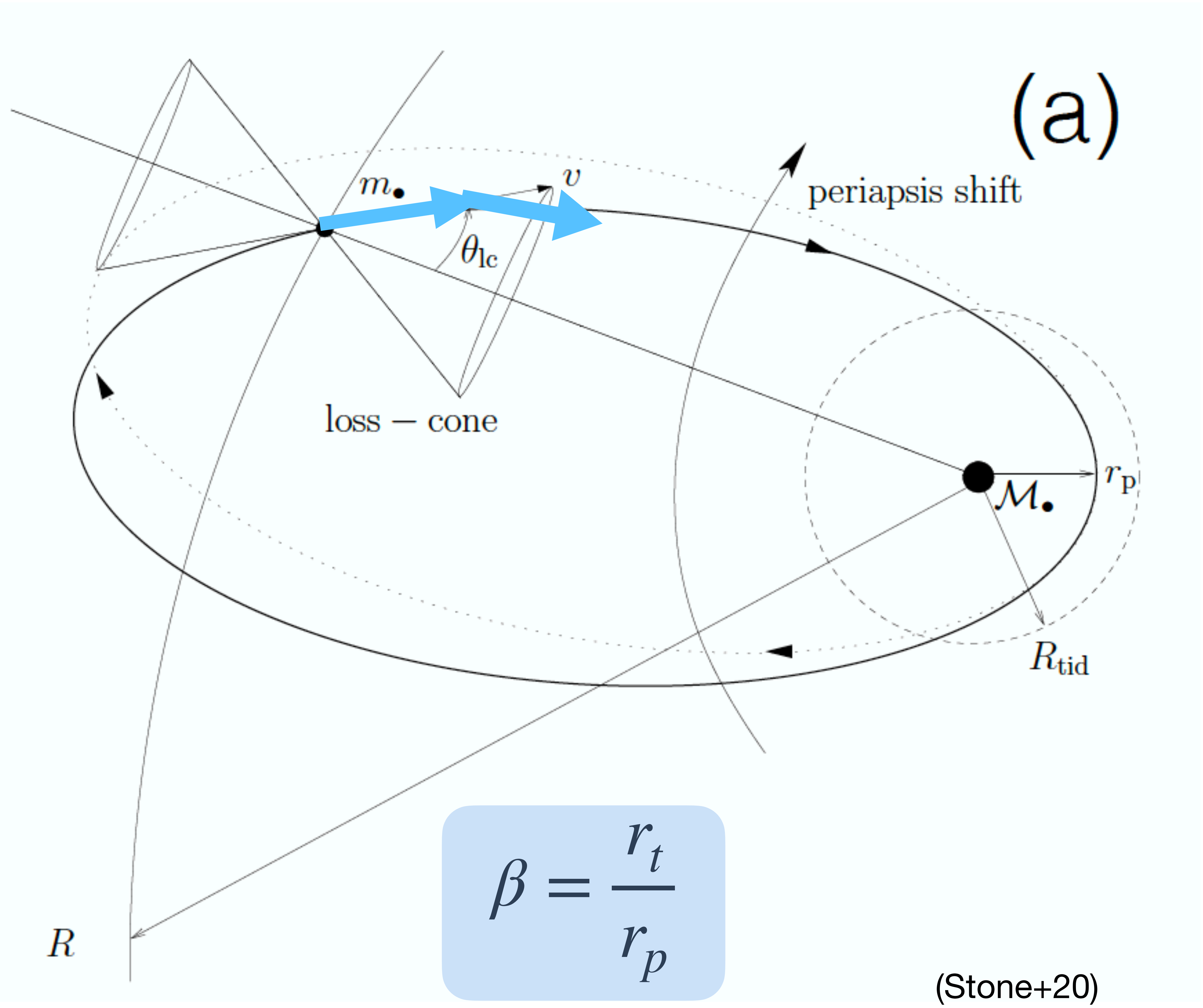
Pinhole fraction

Diffusive (empty loss cone) regime:

- $t_{\rm orbit} \ll t_{\rm relaxation}$
- Stars diffuse into disruption zone slowly
- Associated with $\beta \sim 1$

Pinhole (full loss cone) regime:

- $t_{\rm orbit} \gg t_{\rm relaxation}$
- Star can repeatedly enter and exit the loss cone
- Can have higher β



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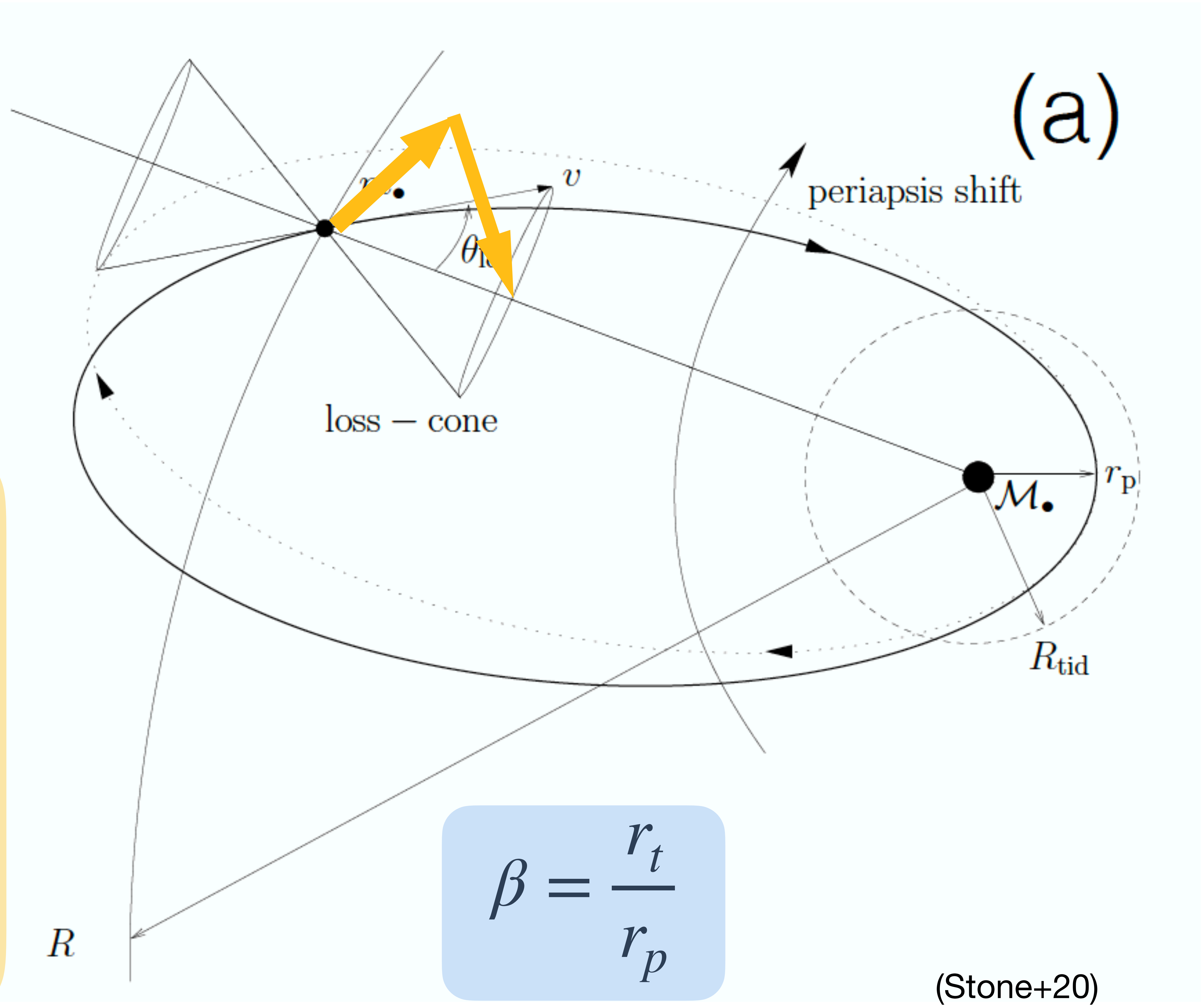

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