# Implications of Stream Self-Crossing

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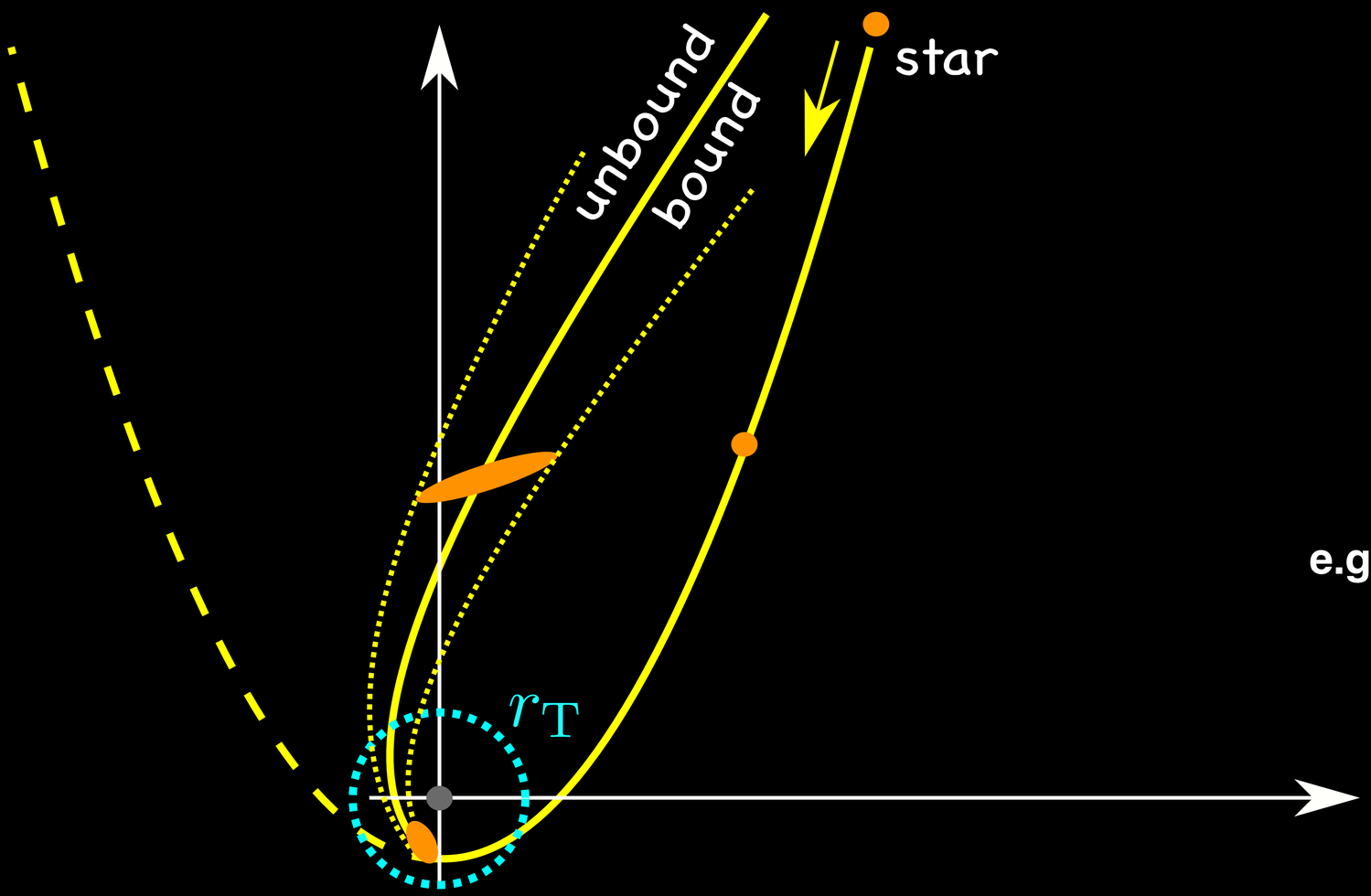
**and Clément Bonnerot**

Jan 20, 2020

## Outline

- ⋆ **Background**
- ⋆ **Our New Approach**
- ⋆ **Predictions**

# Hydrodynamic Disruption



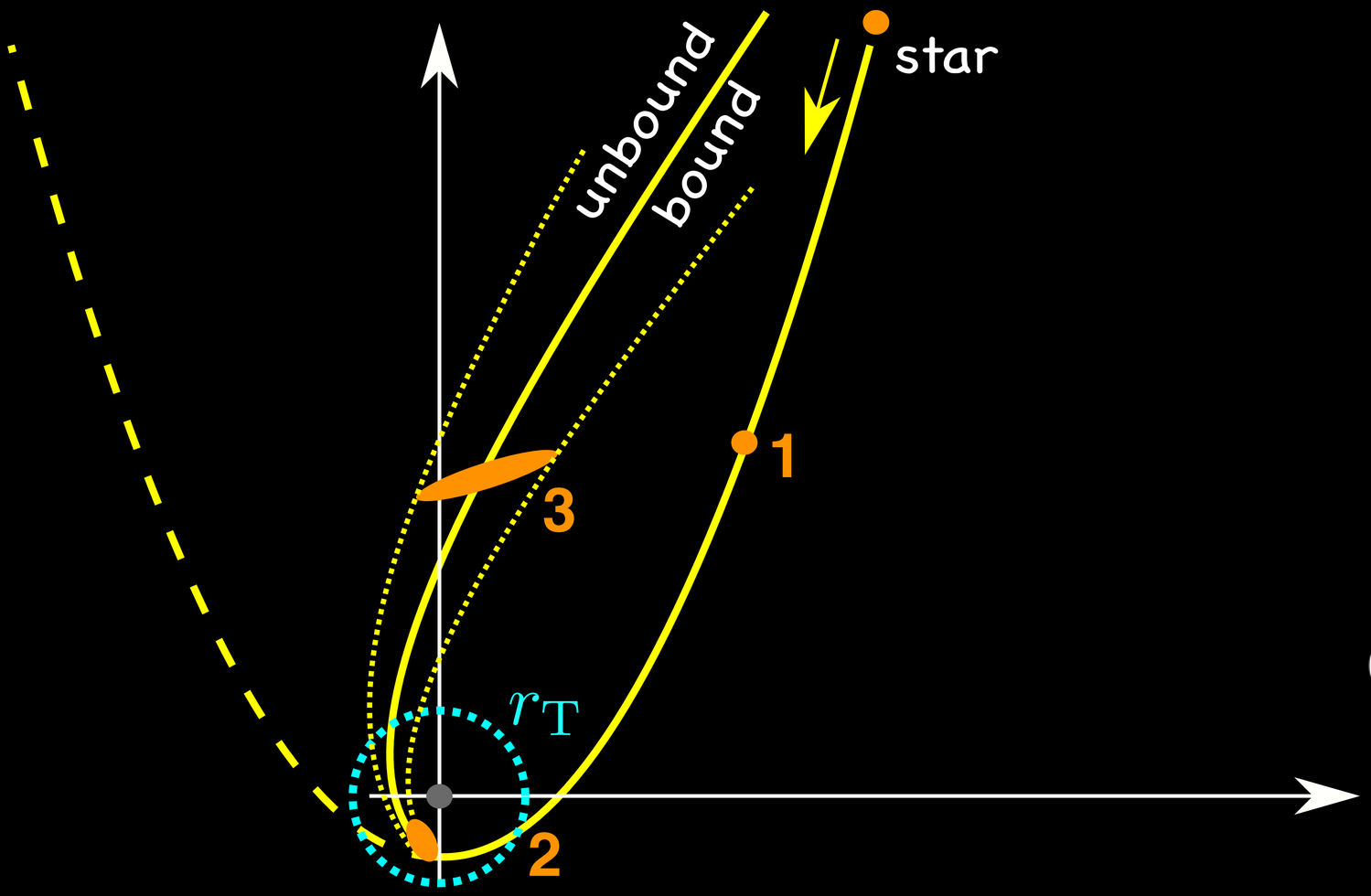

**tidal radius**

$$\frac{r_{\rm T}}{r_{\rm g}} = 47\, q_6^{-2/3} \qquad r_{\rm g} \equiv \frac{GM}{c^2}$$

$$\Phi_{\rm PN1} \sim 20^{\rm o}\, \frac{30 r_{\rm g}}{r_{\rm p}}$$

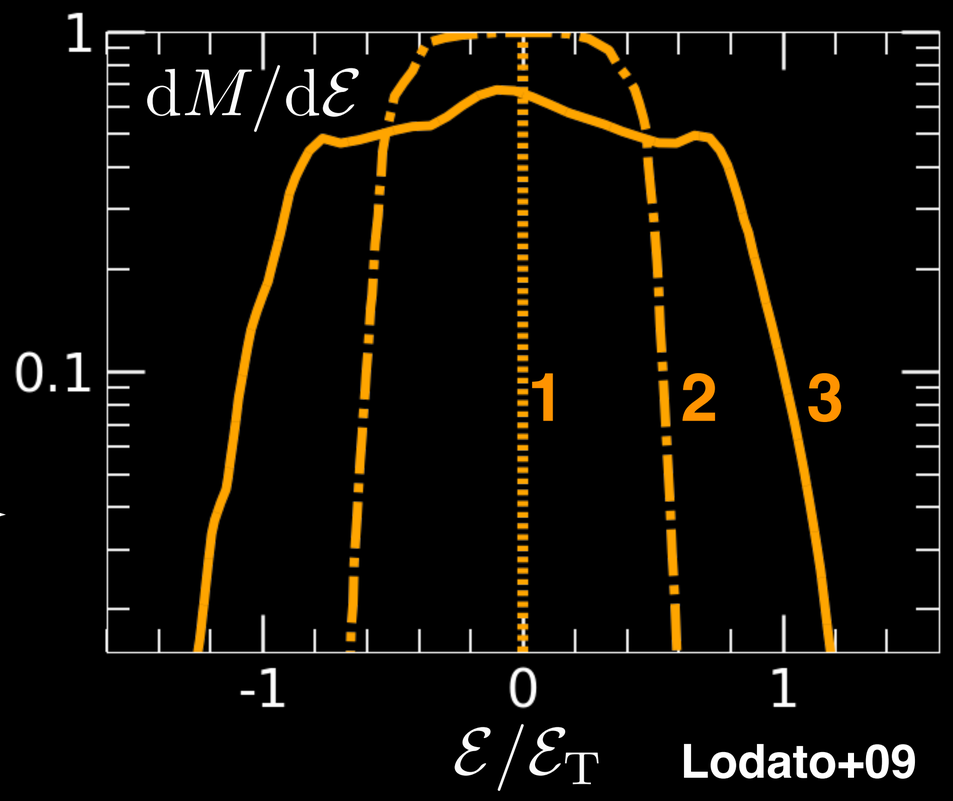
**e.g., Rees 88, Phinney 89, Evans & Kochanek 89, Lodato+09, Kesden 12, Stone+13, Guillochon & Ramirez-Ruiz 13, Cheng & Bogdanovic 14, Bonnerot+17, Coughlin & Nixon 15, Steinberg+19, Gafton & Rosswog+19, Ryu+19**

# Hydrodynamic Disruption




**Energy Spread**

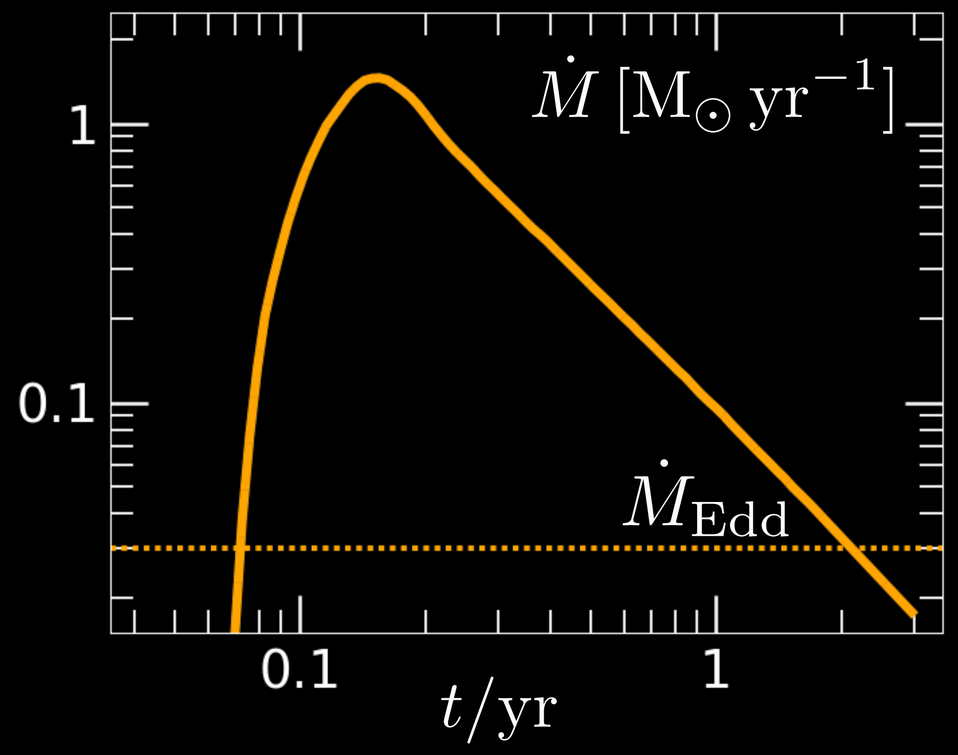
$$\mathcal{E}_{\rm T} = R_* \nabla \Phi = \frac{G M R_*}{r_{\rm T}^2}$$

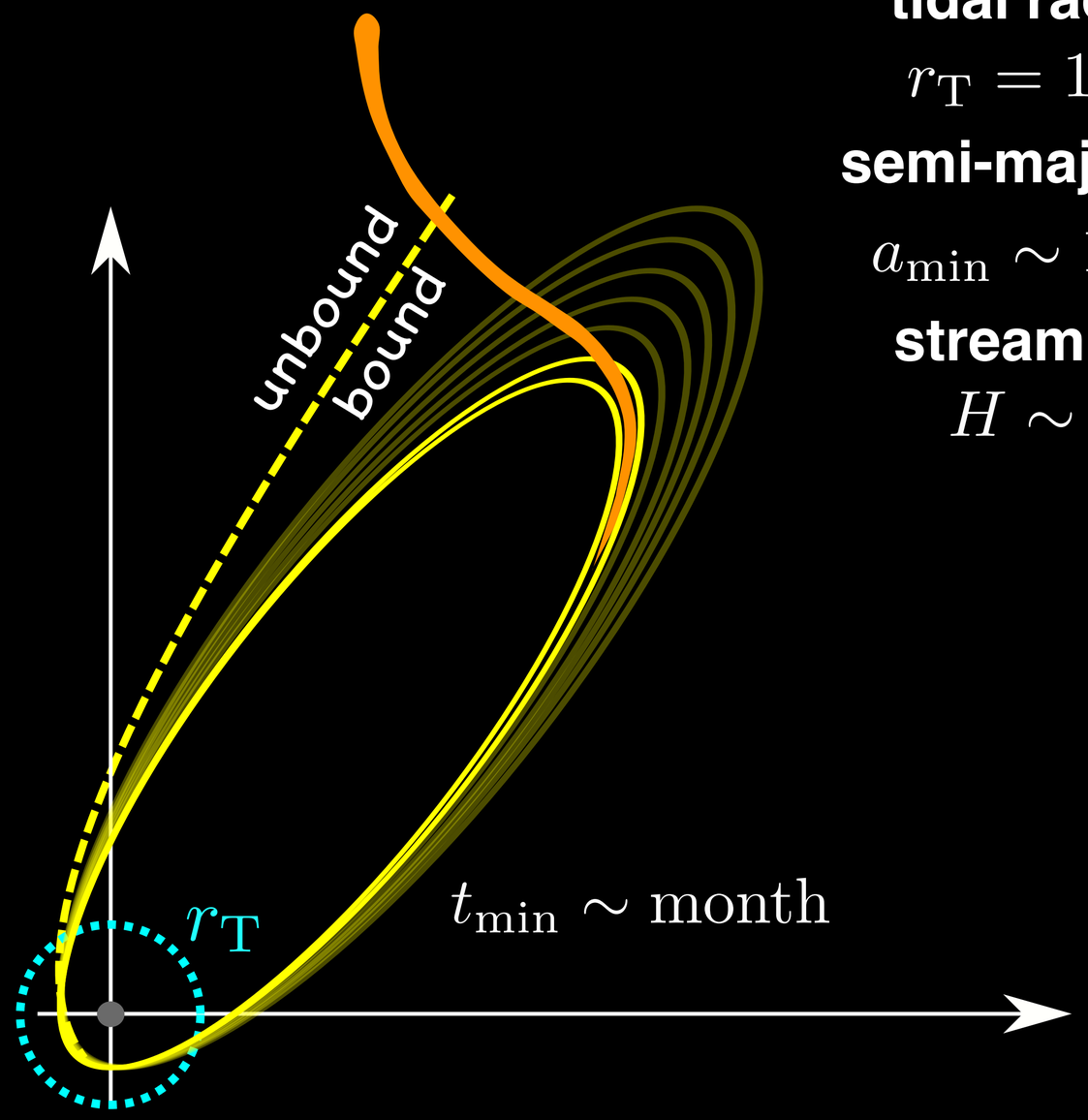



Lodato+09

# Ballistic Fallback

**volume fraction** $f_{\rm V} \sim 10^{-6}$
**range of timescales** $\gtrsim 10^3$

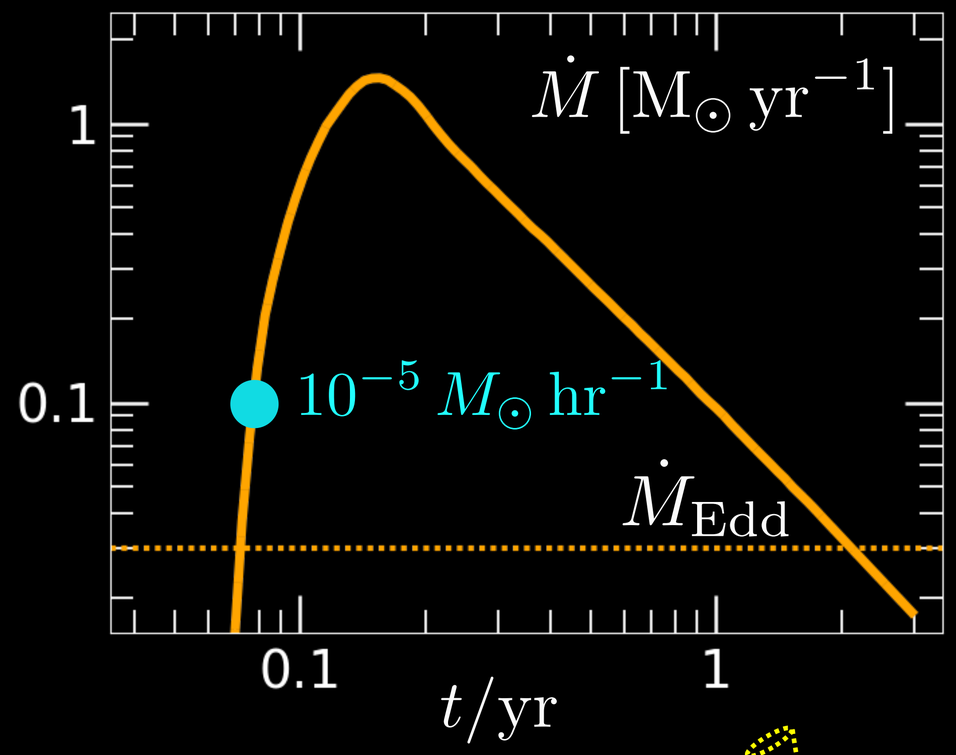


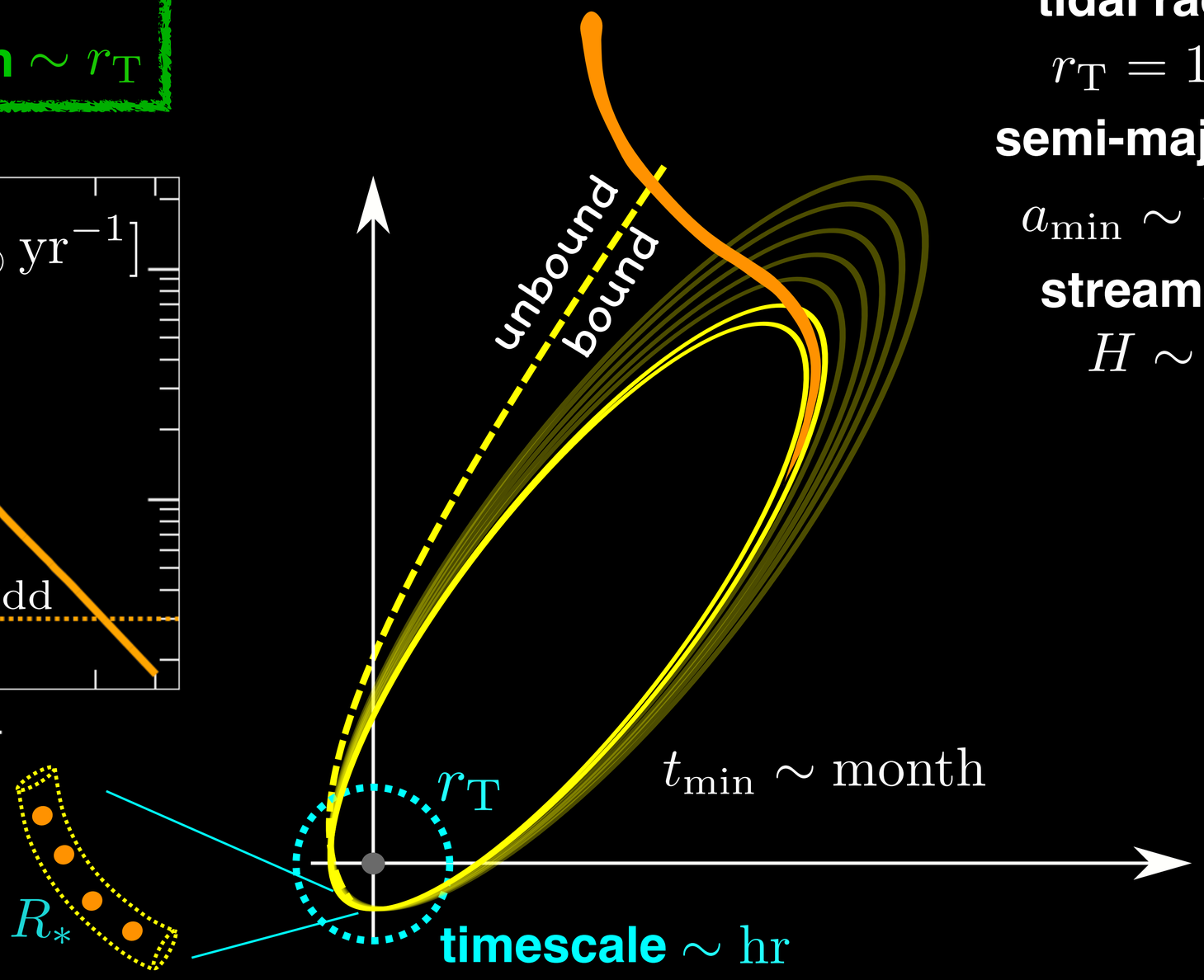




**tidal radius**
$$r_{\rm T} = 100\, q_6^{1/3} R_*$$
**semi-major axis**
$$a_{\rm min} \sim 10^4 q_6^{2/3} R_*$$
**stream width**
$$H \sim 1\text{–}10 R_*$$

# Ballistic Fallback

**SPH Codes:**
**"fluid" breaks down** $\sim r_{\rm T}$

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**stream width**

$$H \sim 1\text{–}10 R_*$$

$$\delta M = 10^{-7} M_\odot \rightarrow \delta r \sim R_*$$

# “Scaled” Global Simulations

**Lower eccentricity:**

Initially bound star with $e \sim 0.9$

e.g., Rosswog+09, Haas+12, Guillochon+14, Shiokawa+15, Evans+15

**Lower mass ratio** $(q = M/M_*)$

Intermediate-mass black holes (IMBHs) with $q \ll 10^6$

e.g., Hayasaki+13, Bonnerot+16, Hayasaki+16, Sadowski+16

**Difficult to extrapolate to realistic cases**

# Crude Analytic Models

e.g., Rees 88, Phinney 89, Strubbe & Quataert 09, Lodato & Rossi 11

**Assumptions:**

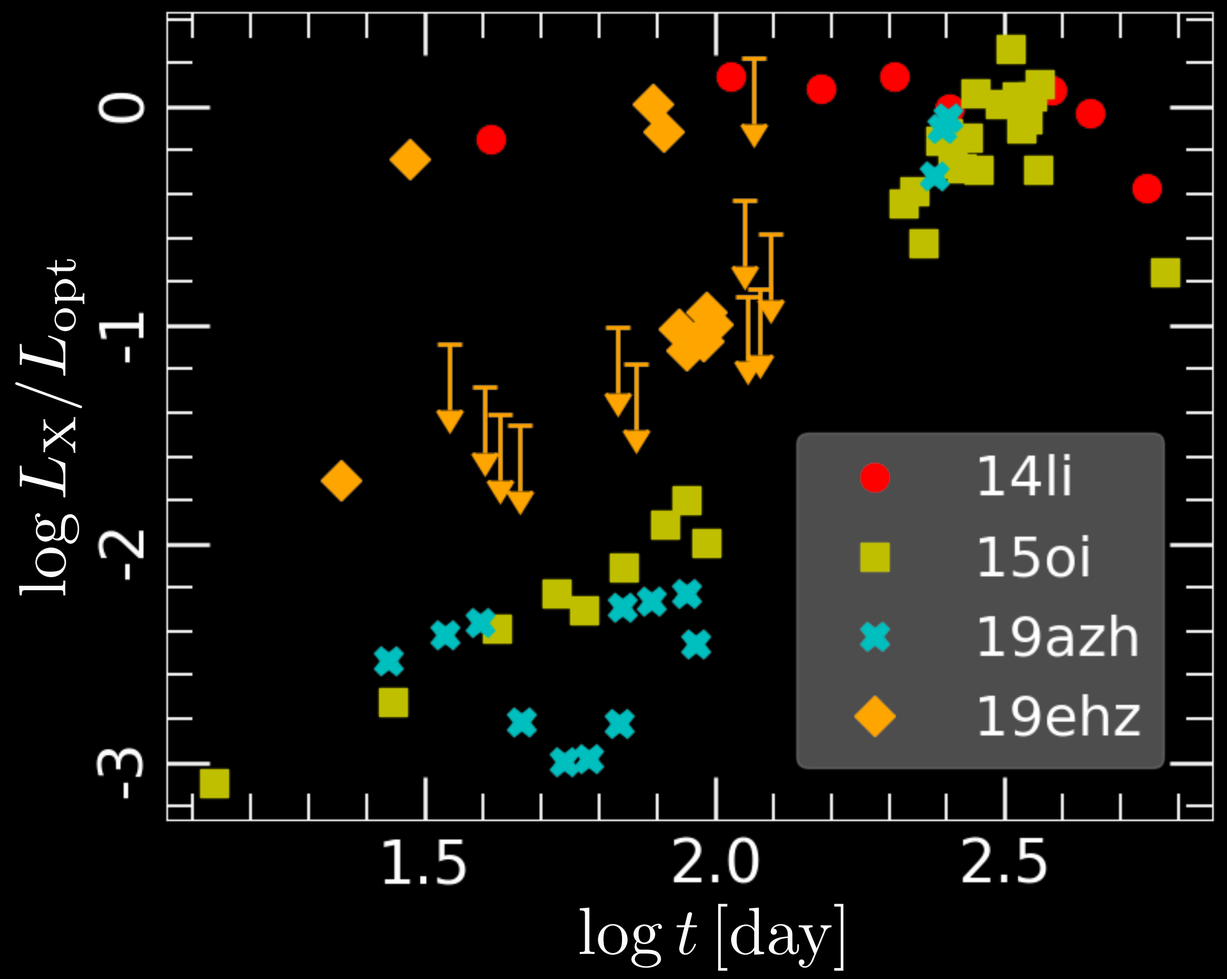
- ⋆ Rapid formation of a compact disk at $\sim 2r_{\rm p}$
- ⋆ Super-Eddington wind

**Predictions:**

- ⋆ $L_{\rm bol} \propto t^{-5/3}$ at late time
- ⋆ $E_{\rm rad} \gtrsim 10^{52}\,{\rm erg}$ even for low-mass stars
- ⋆ color temperature $T \sim 10^5\,{\rm K}$
- ⋆ soft X-ray emission $L_{\rm X} \sim 10^{44}\,{\rm erg\,s^{-1}}$
- ⋆ weak optical emission $\nu L_\nu({\rm g\text{-}band}) \lesssim 10^{42}\,{\rm erg\,s^{-1}}$

# Recent Observations (optical/UV)

**GALEX, SDSS, Pan-STARRS, OGLE, GAIA, (i)PTF, ASASSN, ZTF**




**Gezari+17, Holoien+16, 18, van Velzen+20**

- ⋆ $L_{BB} \sim (10^{43}, 10^{44})\,\mathrm{erg\,s^{-1}}$
- ⋆ $t_{peak} \sim \mathrm{month}$ **(biases!)**
- ⋆ $T_{BB} \sim 3 \times 10^4\,\mathrm{K}\ (\mathrm{R_{BB}} \gg \mathrm{r_T})$
- ⋆ **linewidth** $\sim 10^4\,\mathrm{km\,s^{-1}}$ **(e.g. H, He, C, N, Si)**
- ⋆ $L_X/L_{opt} \sim (< 10^{-3}, 1)$
- ⋆ **green valley hosts over-represented**

# Open Questions

★ **Source of optical emission?**

$R_{\rm BB} \sim 10^3$–$10^4 r_{\rm g} \gg r_{\rm T}$

Strubbe & Quataert 09, Miller 15, Piran+15, Metzger & Stone 16, Jiang+16, Roth+16, 18, Dai+18

★ **X-ray diversity?**

$L_{\rm X}/L_{\rm BB} \sim 10^{-3}$–$1$

Dai+15, 18, Curd & Narayan 18

★ **Rapid/slow disk formation?**

$t_{\rm peak} \sim {\rm month} \sim t_{\rm min}$ **(biases!)**

Hayasaki+13, 16, Guillochon+14, Shiokawa+15, Bonnerot+16, Evans+15, Sadowski+16

★ **Missing energy?**

$E_{\rm rad} \lesssim 10^{51}\,{\rm erg}$

Piran+15, Metzger & Stone 16, WL & Kumar 18

★ **TDE rate and hosts?**

"green valley" favored

Arcavi+14, French+16, Law-Smith+17, Graur+18, Cen+19, van Velzen+20

★ **SMBH demographics?**

dormant BHs with $M \lesssim 10^6$

Ho & Greene's works on AGN

★ **Super-Eddington disk?**

$\dot{M} \gg M_{\rm Edd}$

Narayan & Yi 94, Blandford & Begelman 99, 04 Ohsuga & Mineshige 11 McKinney+14, Jiang+14, Sadowski & Narayan 16

★ **Jet launching?**

$0.3\% \lesssim f_{\rm j} \lesssim 10\%$

Burrows+11, Cenko+12, Brown+15, van Velzen+13, Generozov+17, WL & Kumar 18, de Colle & WL 19

★ **Jet X-ray emission?**

$f_{\rm X} \gtrsim 10\%$

Bloom+11, Kumar+16, Crumley, WL+16, WL+17

⋮

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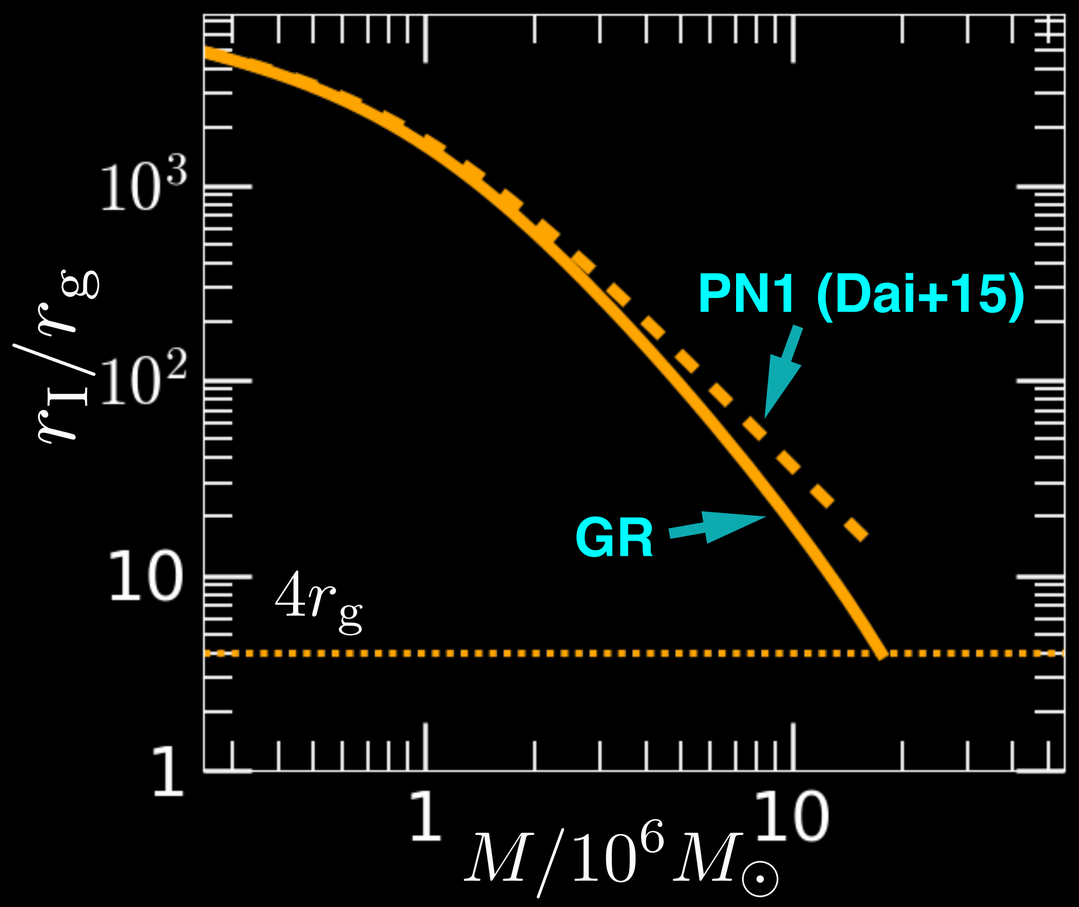
- ⋆ Background
- ⋆ Our New Approach
- ⋆ Predictions

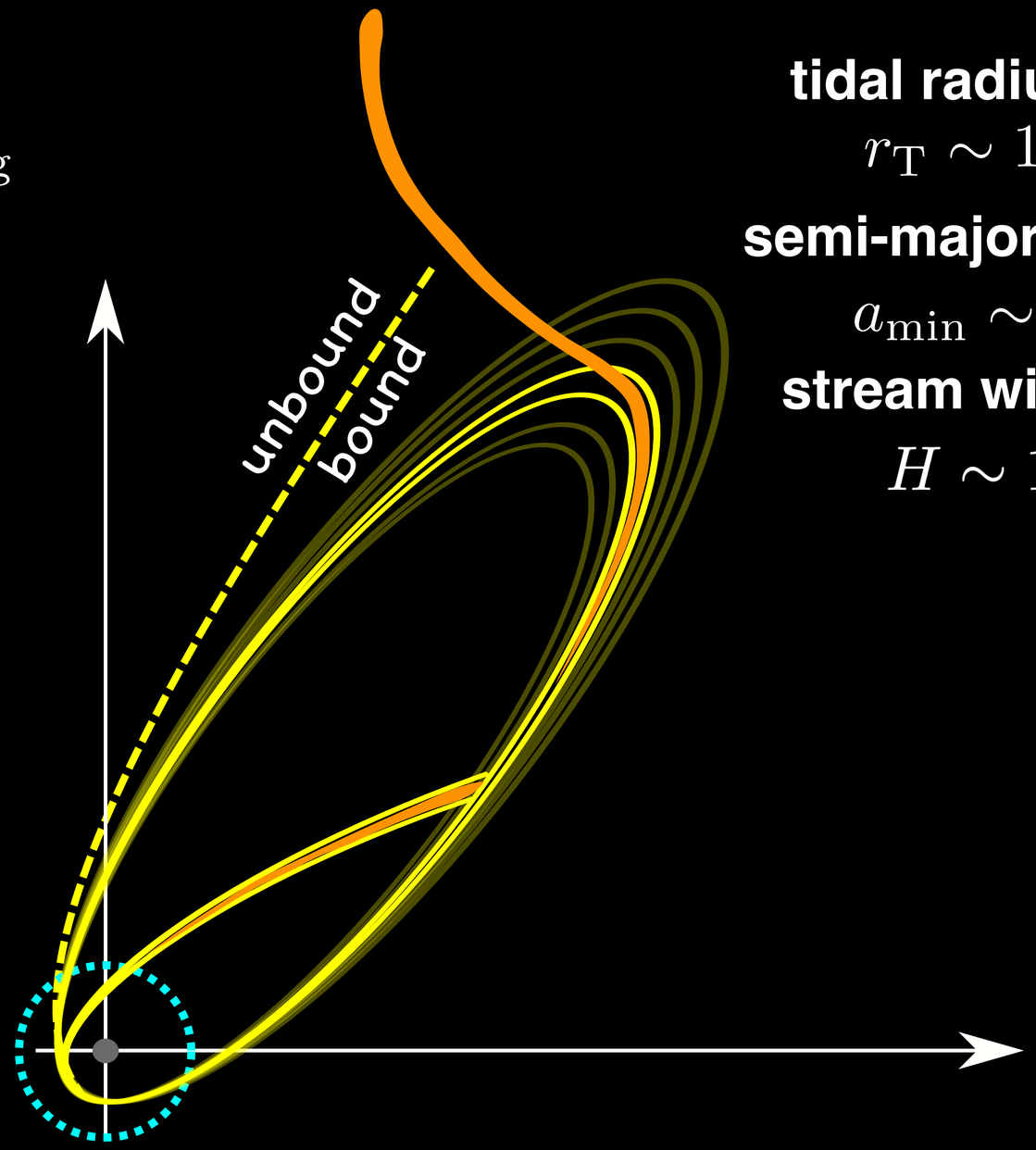
see WL & Bonnerot (2020) MNRAS, 492, 686
Bonnerot & WL, arXiv:1906.05865

# Geodesic Motion

**Stream Intersection** $r_{\rm I} \sim 10\text{–}10^3 r_{\rm g}$

for $M_* = 0.5 M_\odot$ $\beta = r_{\rm T}/r_{\rm p} = 1$




**tidal radius**
$r_{\rm T} \sim 10\text{–}100 r_{\rm g}$

**semi-major axis**
$a_{\rm min} \sim 10^3\text{–}10^4 r_{\rm g}$

**stream width**
$H \sim 1\text{–}10 r_{\rm g}$

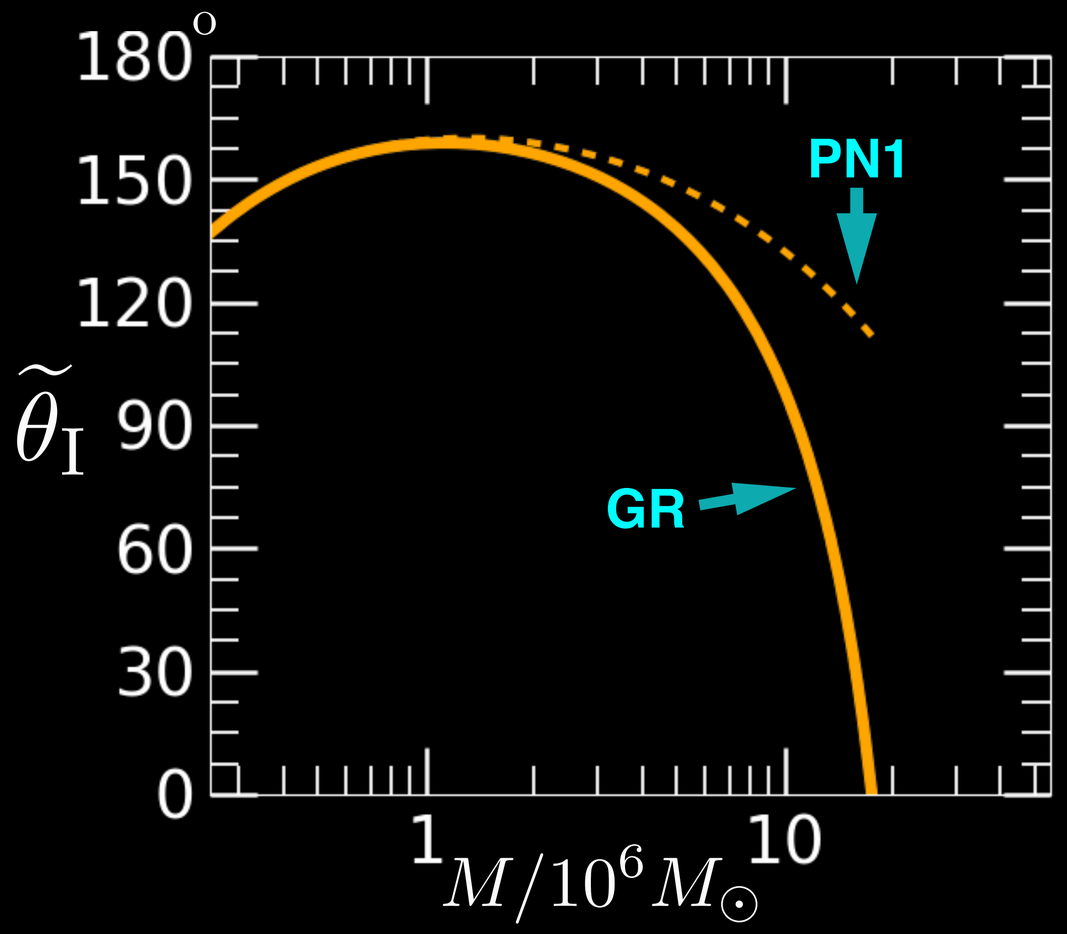
# Geodesic Motion

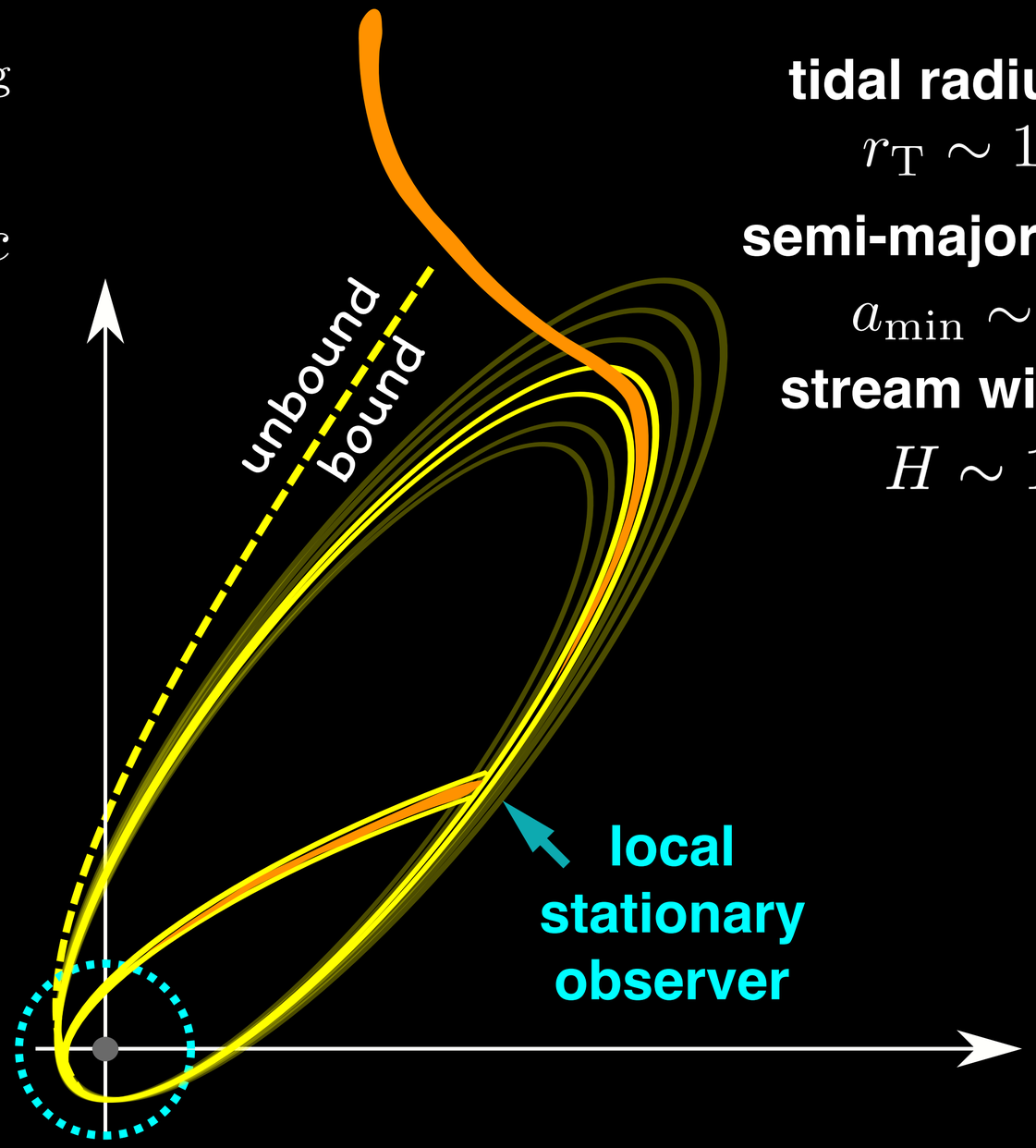
**Stream Intersection**

$r_{\rm I} \sim 10\text{–}10^3 r_{\rm g}$

$\widetilde{\theta}_{\rm I} \sim 90\text{–}160^{\rm o}$

$\widetilde{v}_{\rm I} \sim 0.01\text{–}0.1c$

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# Black Hole Spin

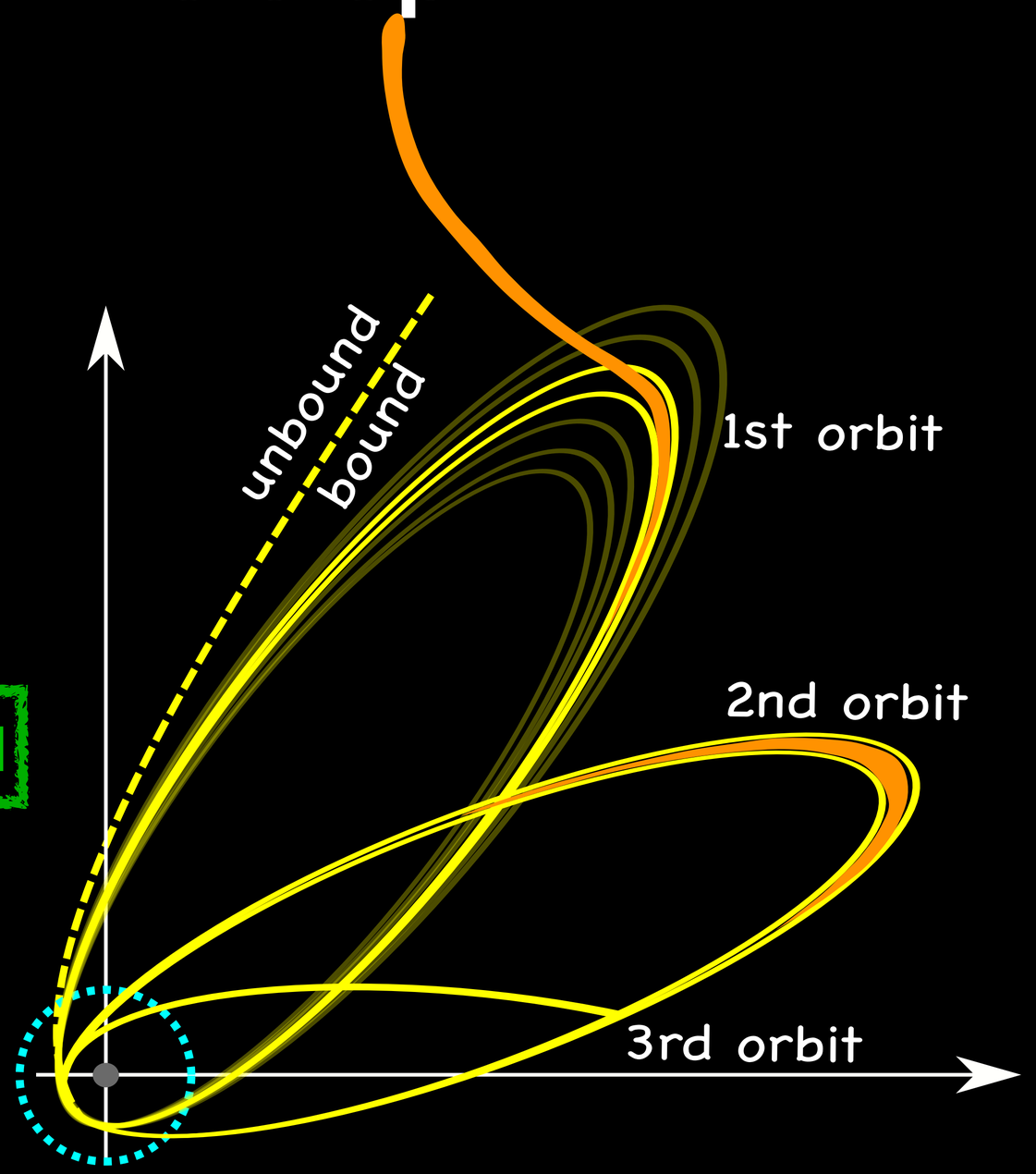
**apsidal precession**

$$\Phi_{\rm PN1} \sim 20^{\rm o}\,\frac{30 r_{\rm g}}{r_{\rm p}}$$

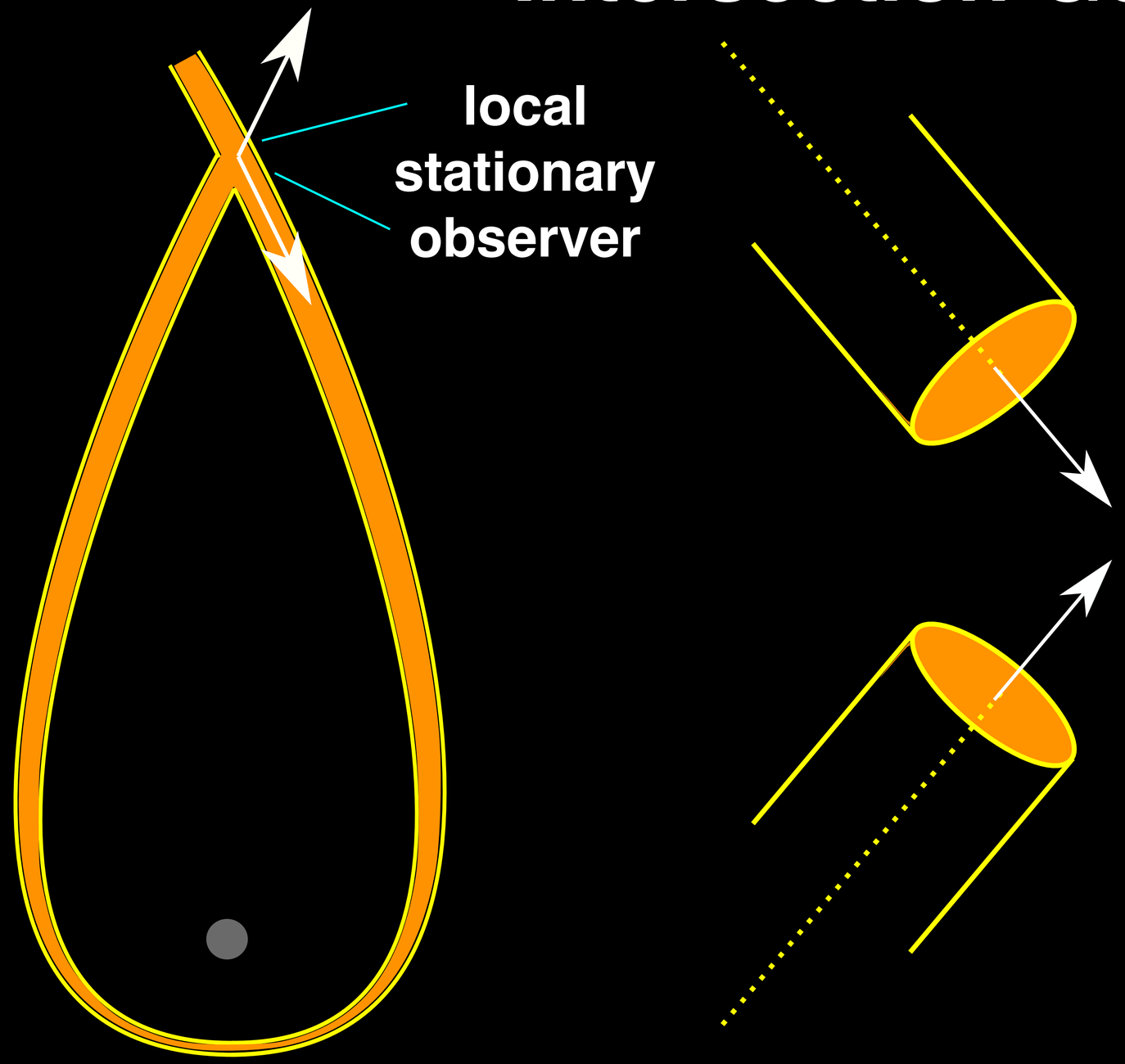
**Lense-Thirring precession** $(\chi \neq 0)$

$$\Phi_{\rm LT} \sim 1^{\rm o}\left(\frac{30 r_{\rm g}}{r_{\rm p}}\right)^{3/2}\chi$$

$r_{\rm I},\ \widetilde{\theta}_{\rm I},\ \widetilde{v}_{\rm I}$ **are only weakly affected**



# Intersection Geometry



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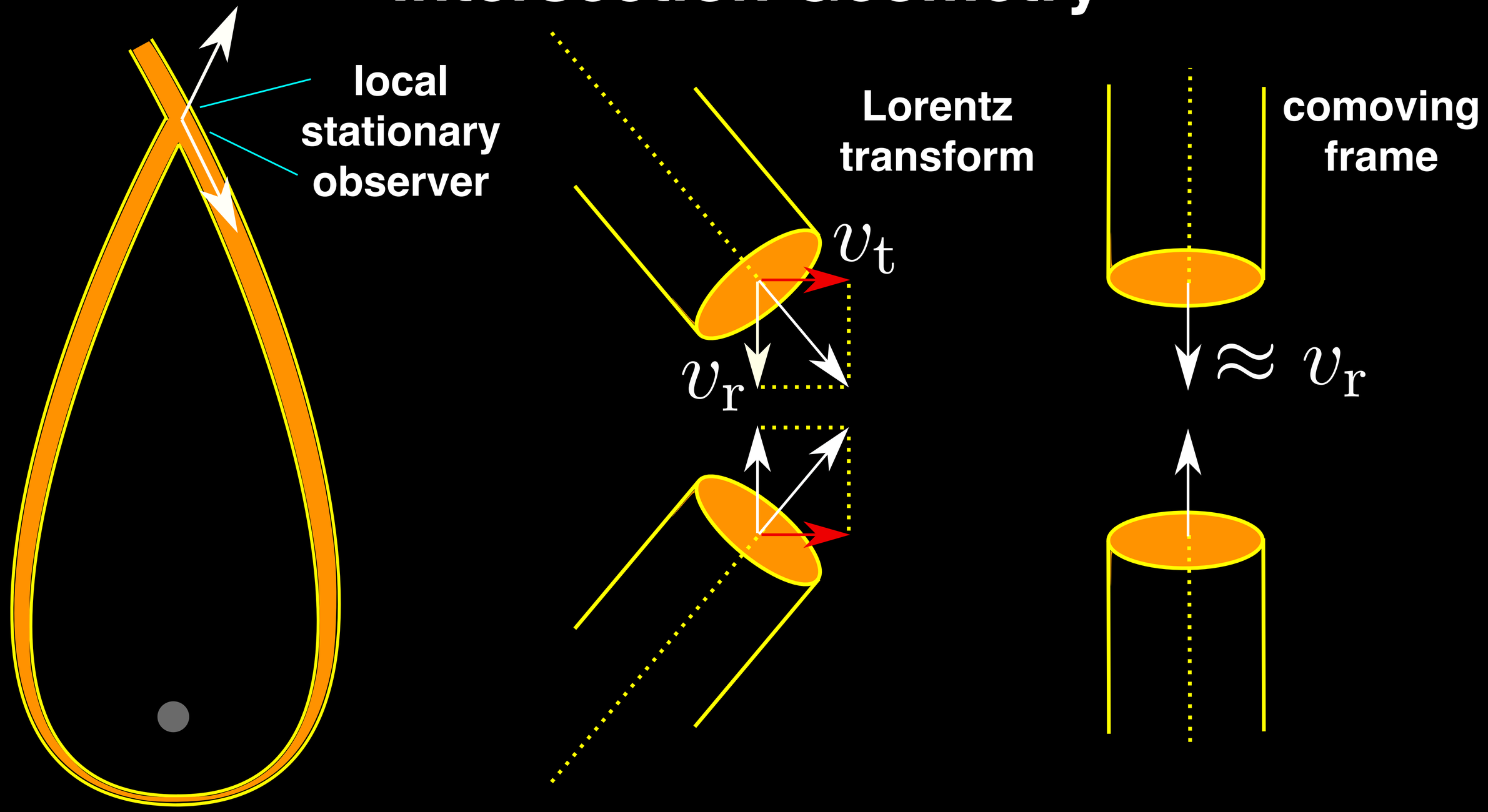
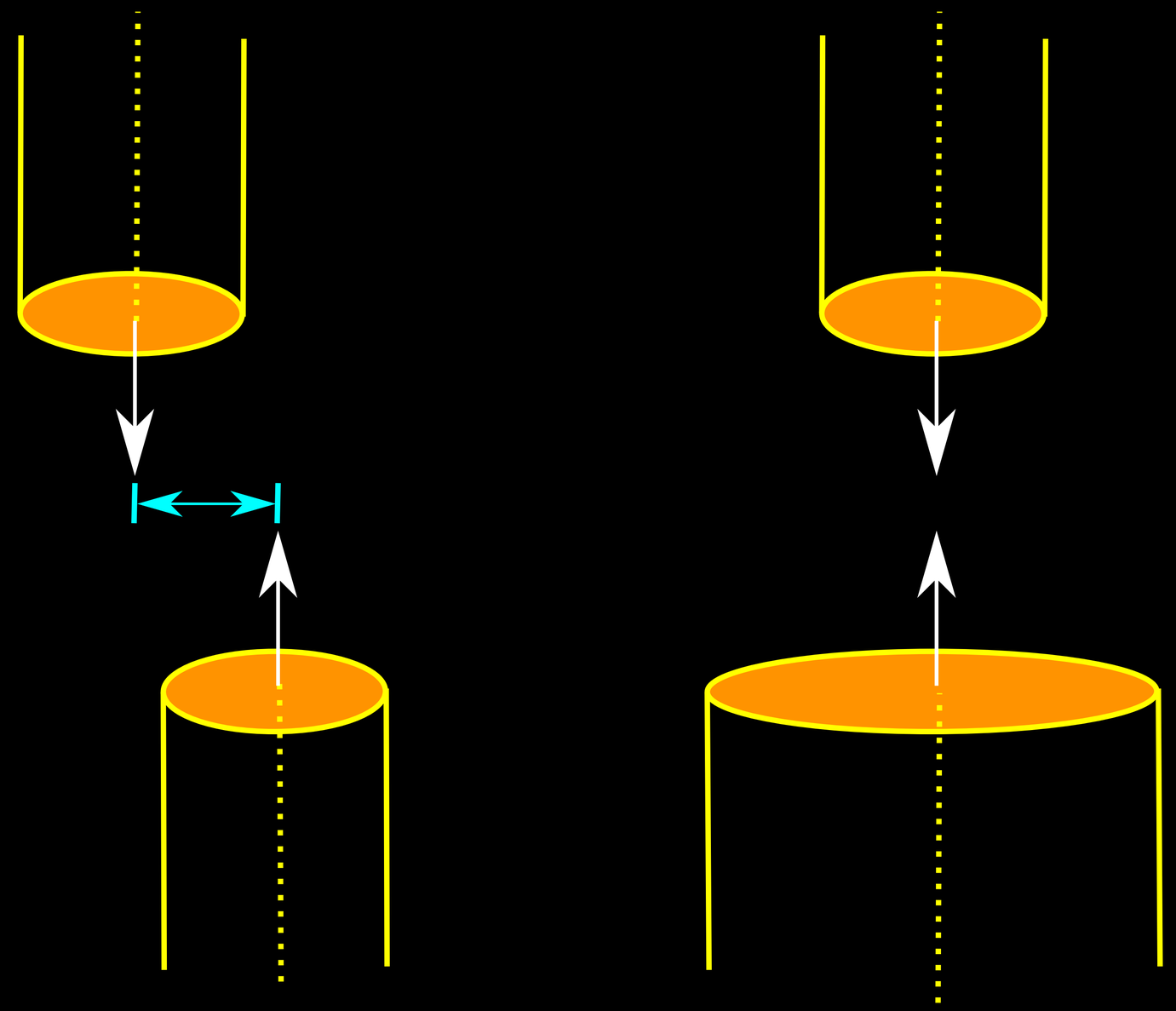
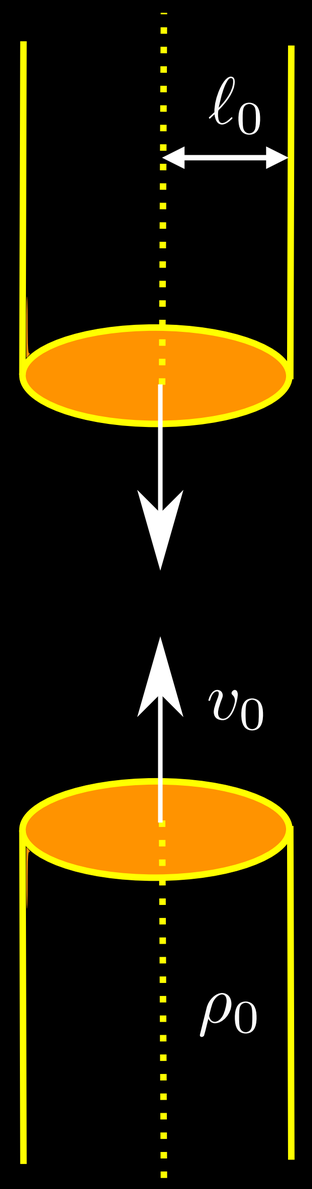


# Complications



comoving frame

# Hydrodynamic Simulations



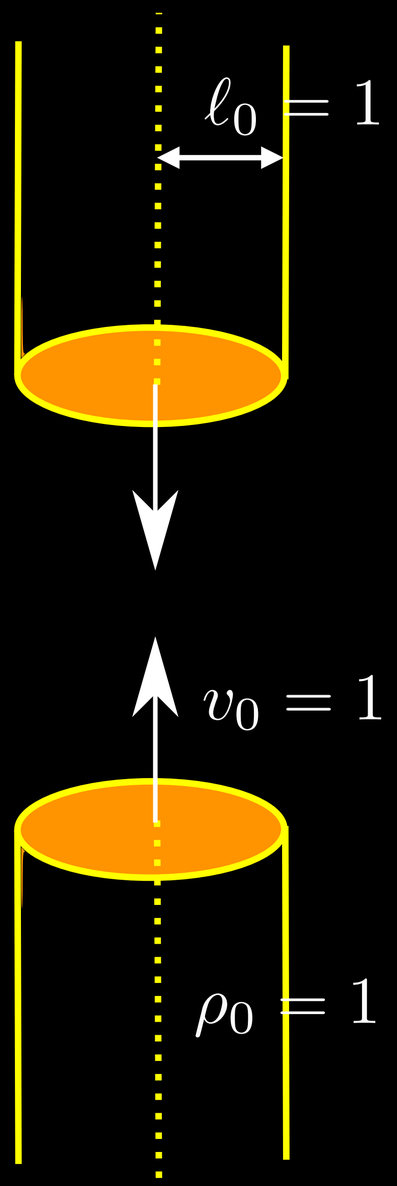

simplest case

**Adiabatic EoS** $\gamma = 4/3$ **(Jiang+16, rad-HD)**

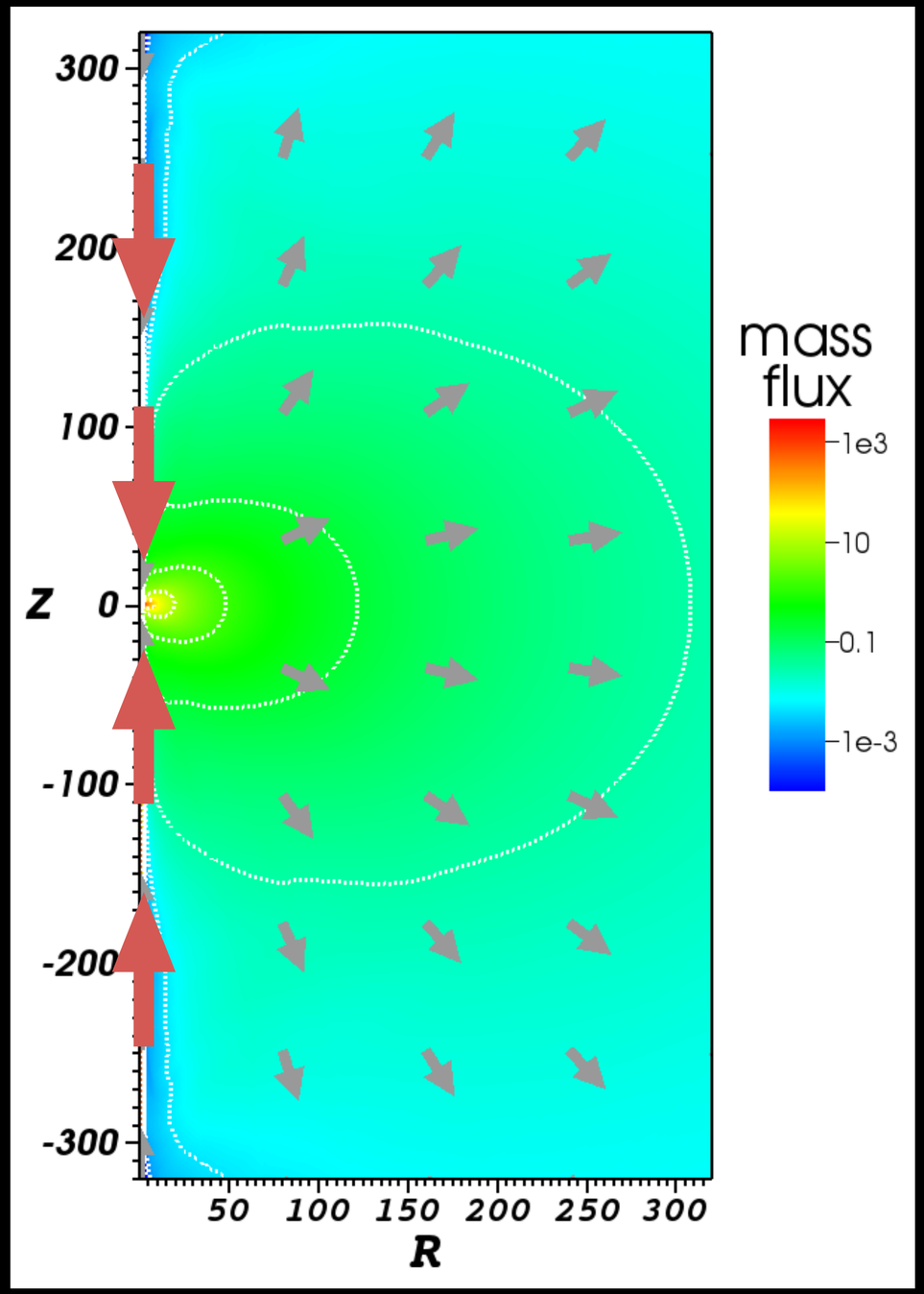
**Initial Conditions:** **cold streams**

**Steady-State Solution:** **self-similar**

- **length** $\ell_0 = 1$
- **time** $\ell_0/v_0 = 1$
- **mass** $\rho_0 \ell_0^3 = 1$




**simplest case**



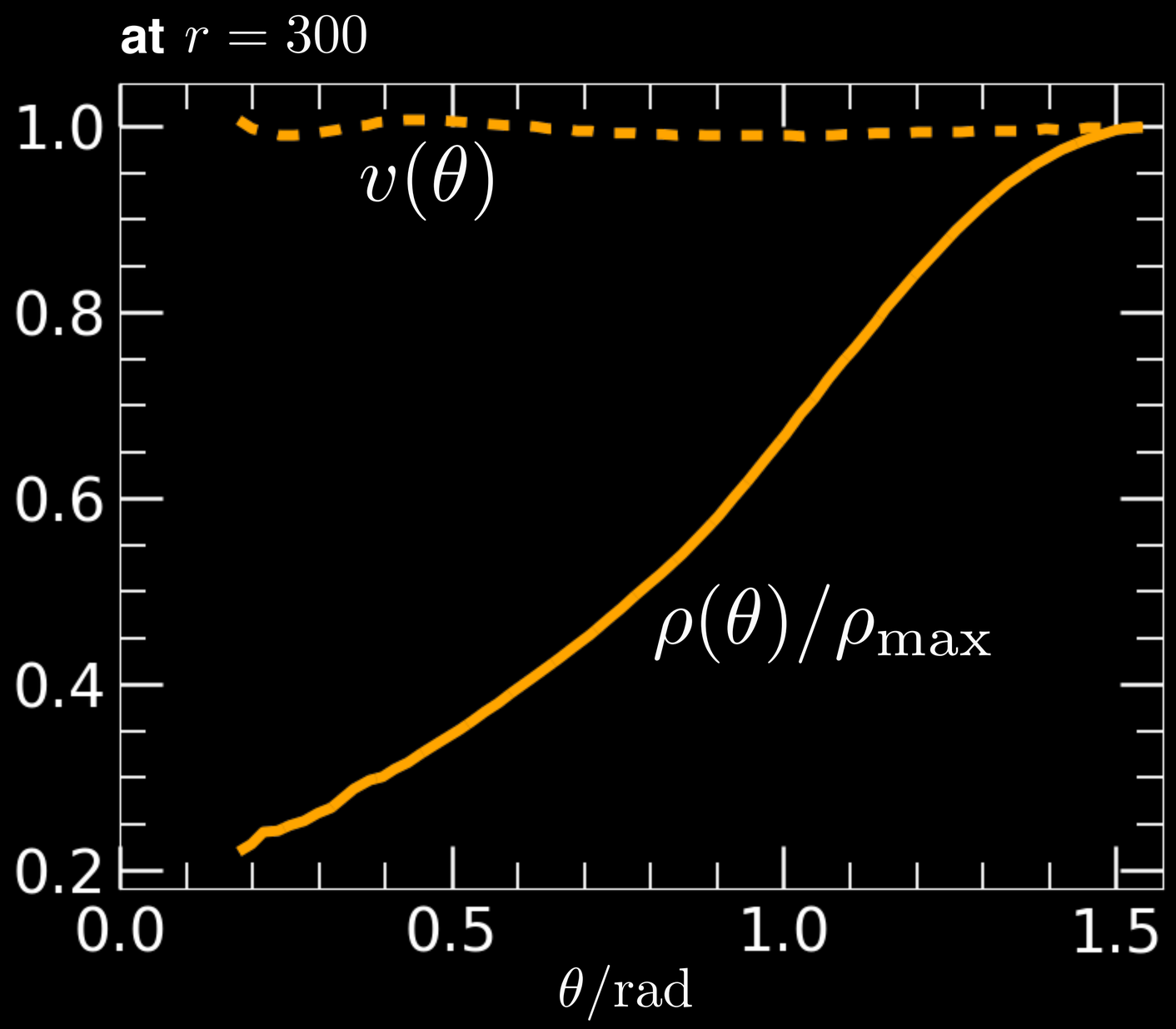

- ⋆ **Quasi-spherical wind**

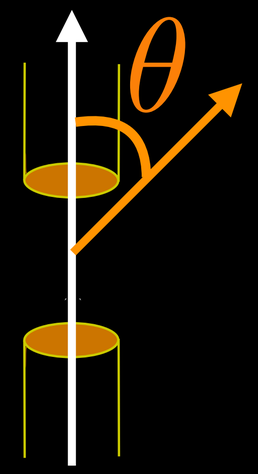
$$\rho \propto r^{-2}$$

- ⋆ **Angular profile** $\rho(\theta), v(\theta)$ **(equatorial concentration)**

**PLUTO (Mignone+07)**

# Angular Profile



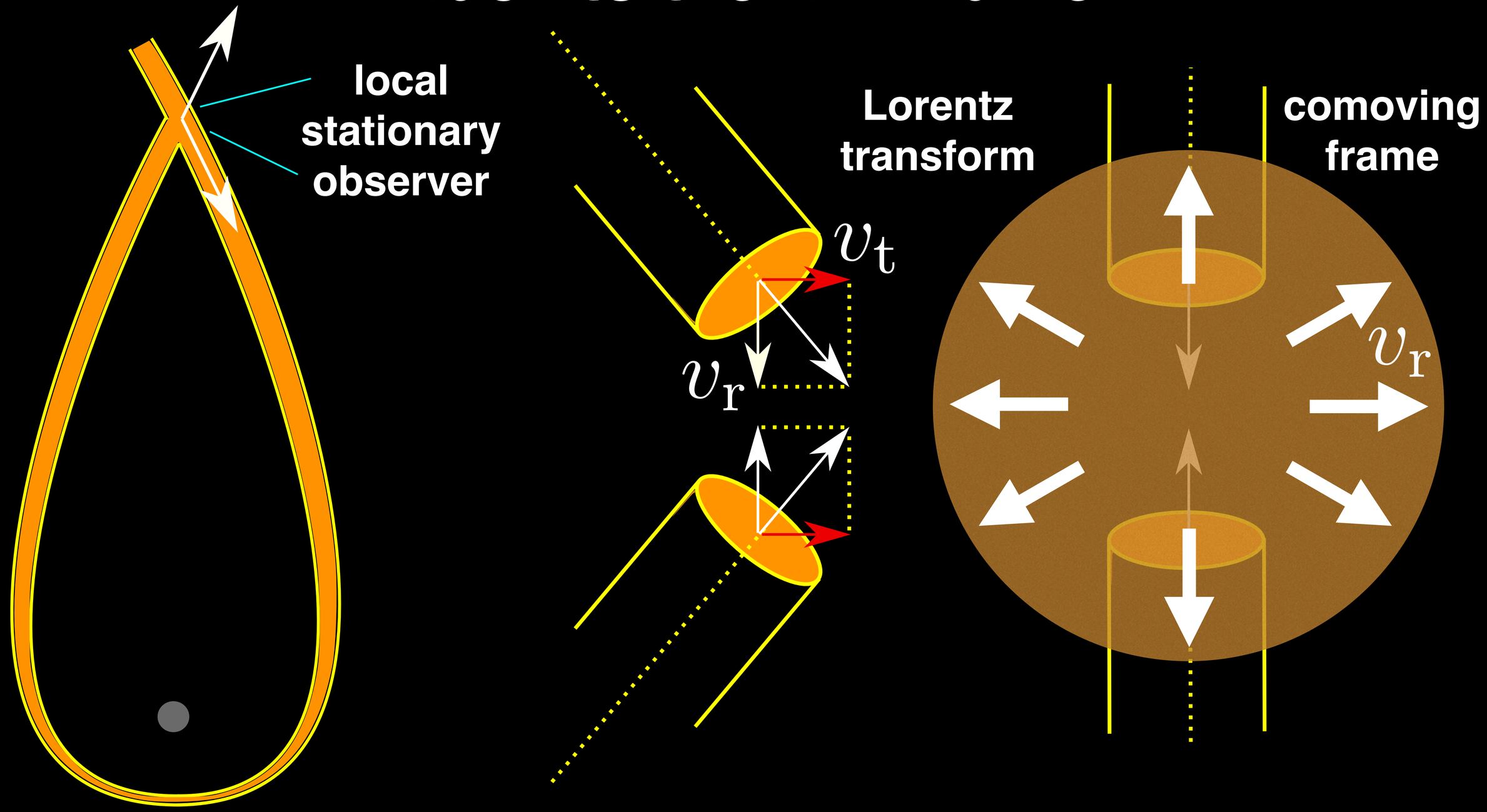

**simplified:**

$$v(\theta) = 1$$

$$\rho(\theta)/\rho_{\max} = \sum_{i=0}^{4} q_i \theta^i$$

**(mass conservation → $\rho_{\max}$)**

# Back to the BH Frame



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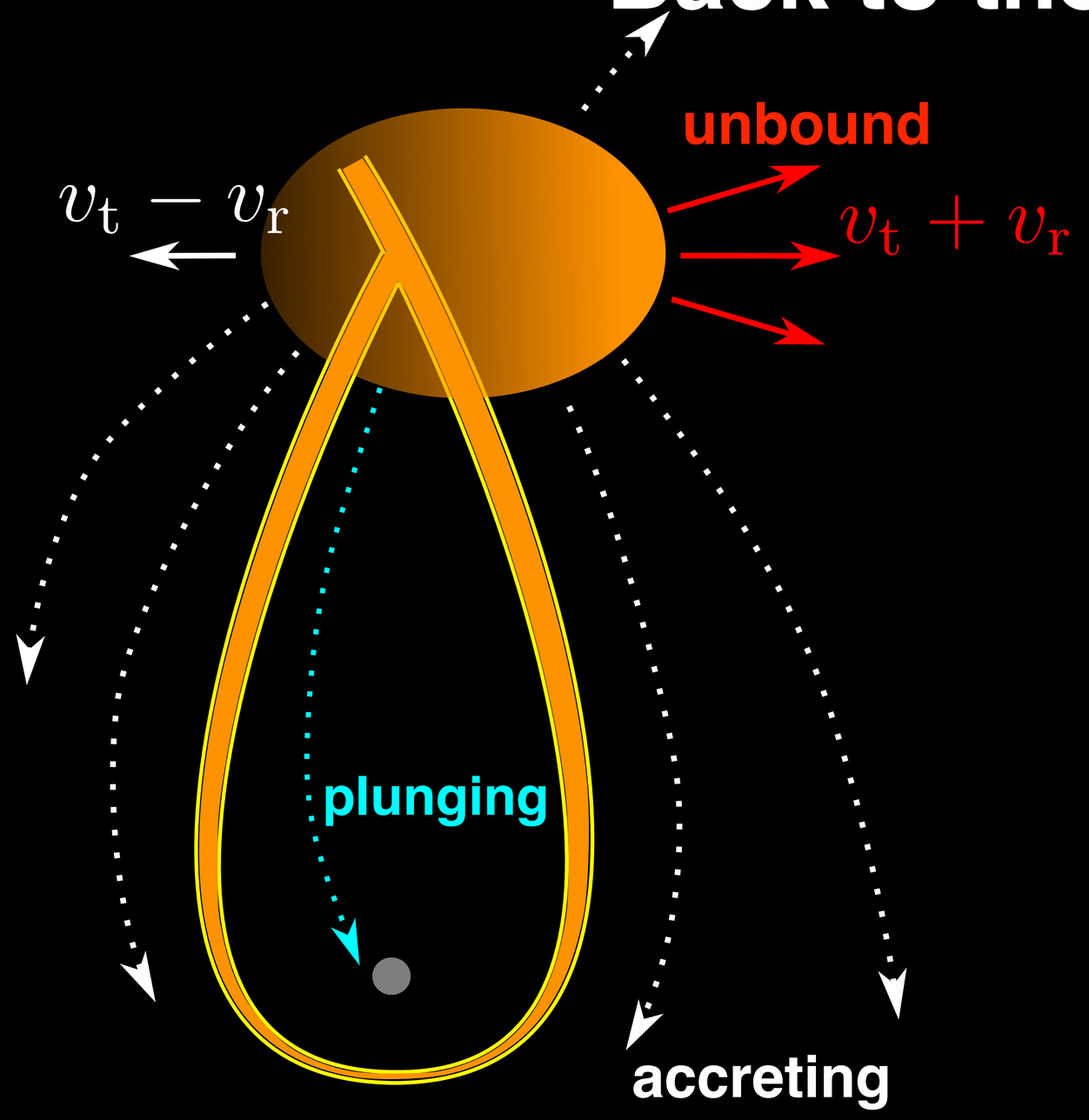



**3 Classes of Trajectories:**

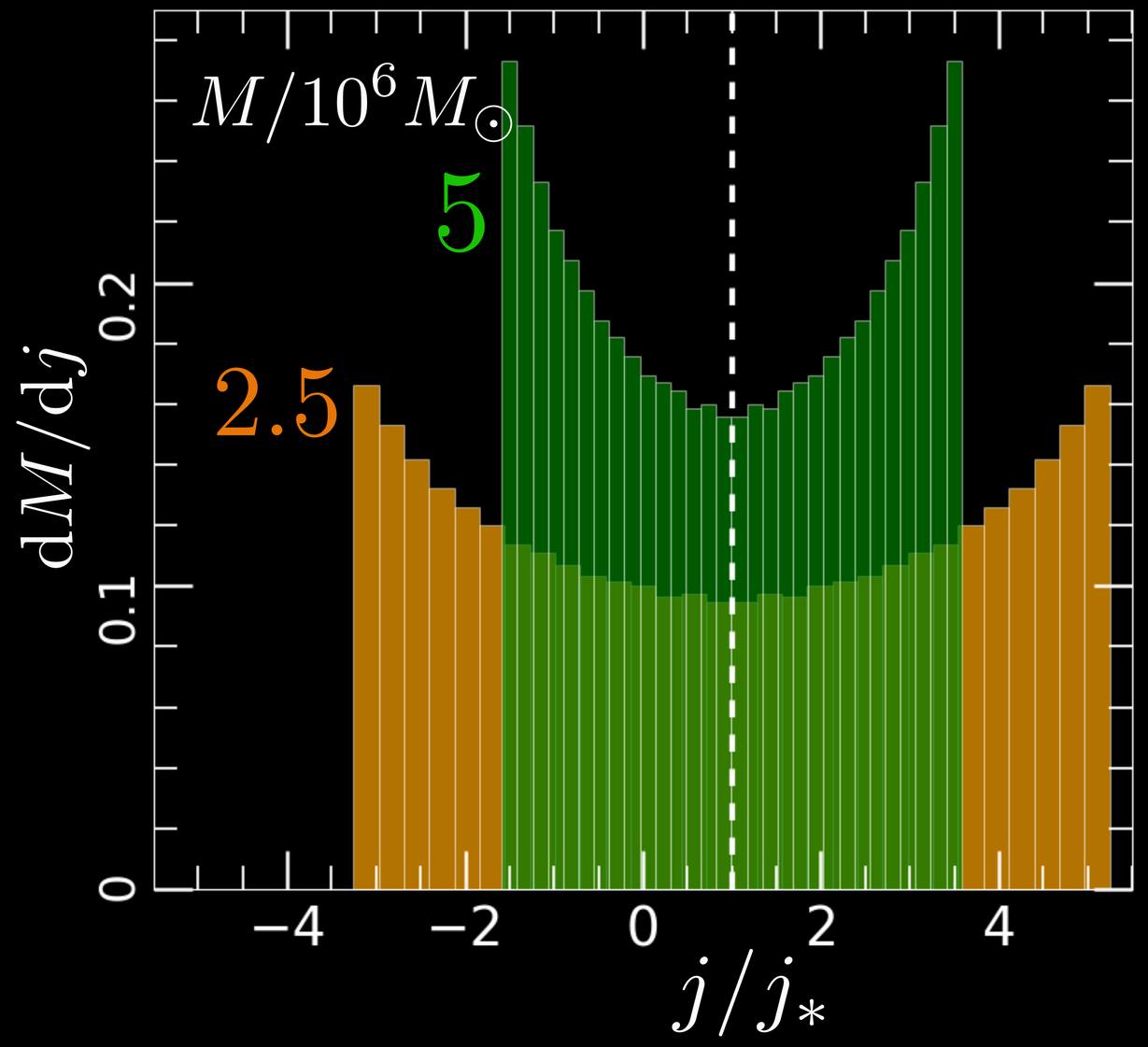
- ⋆ **unbound (forward direction)**

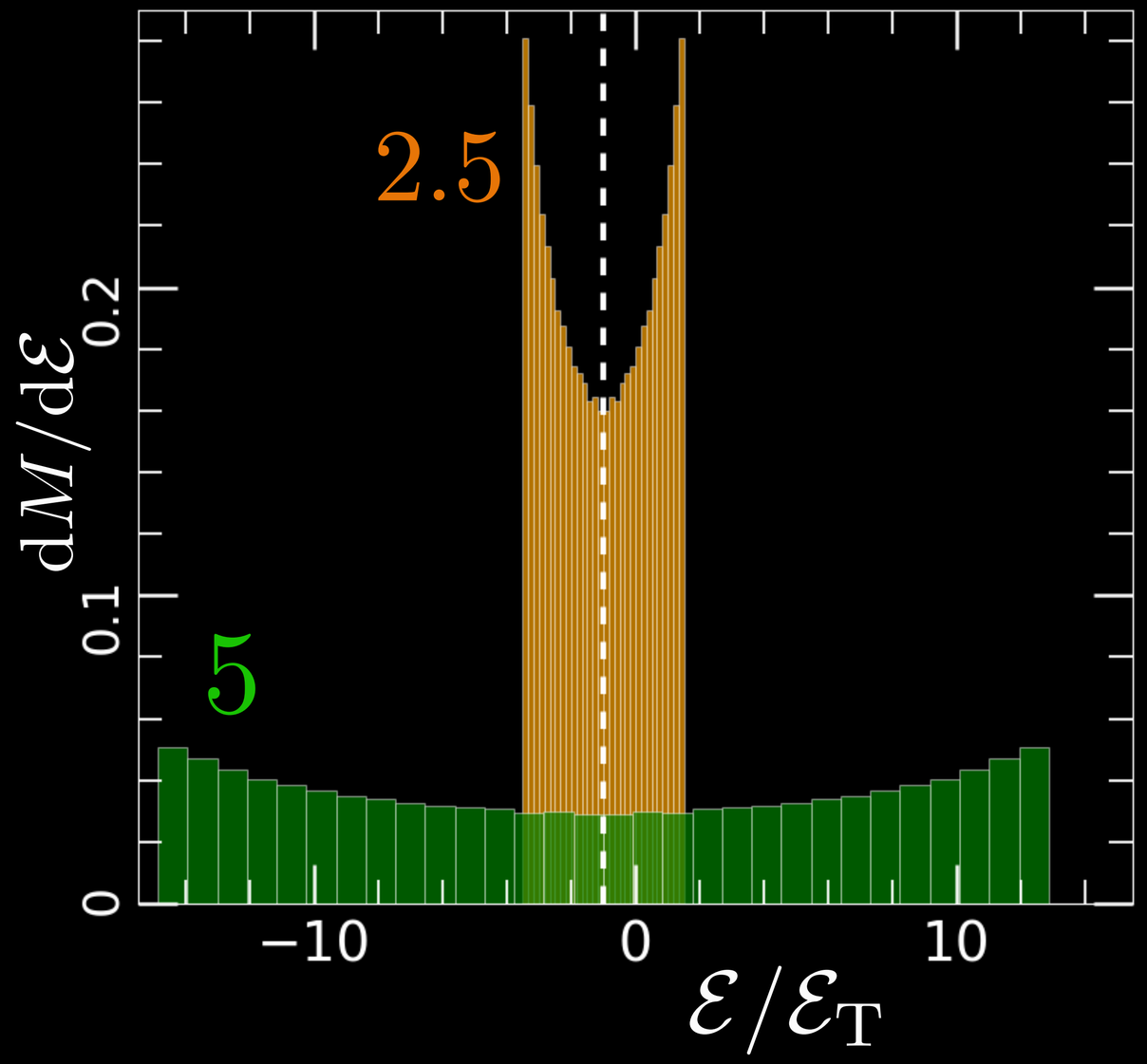
$$v_\mathrm{r} + v_\mathrm{t} > \sqrt{v_\mathrm{r}^2 + v_\mathrm{t}^2} \simeq v_\mathrm{esc}$$

- ⋆ **plunging** $(j \approx 0)$
- ⋆ **accreting (most of the mass)**

# Energy and A.M. Re-Distribution

for $M_* = 0.5 M_\odot$ $\beta = r_{\rm T}/r_{\rm p} = 1$



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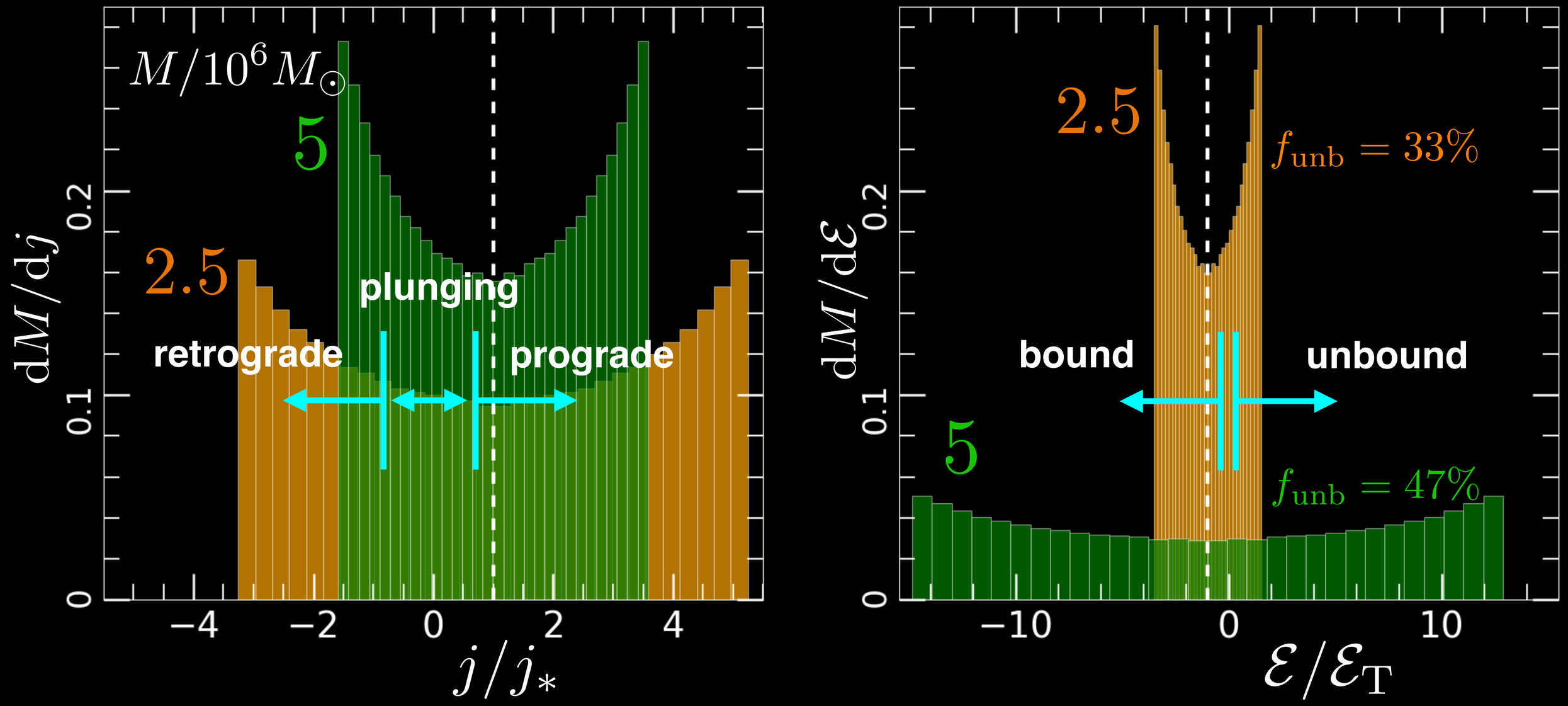
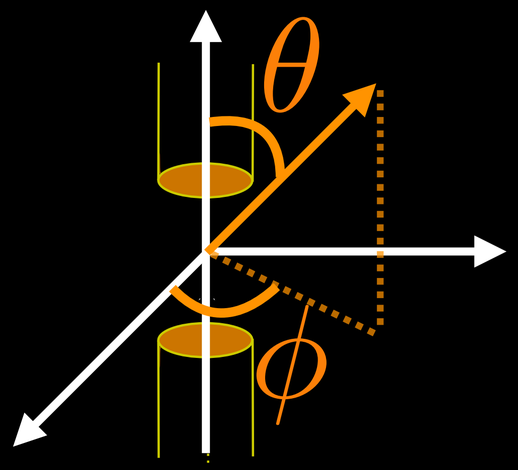


# Fate of the Shocked Gas

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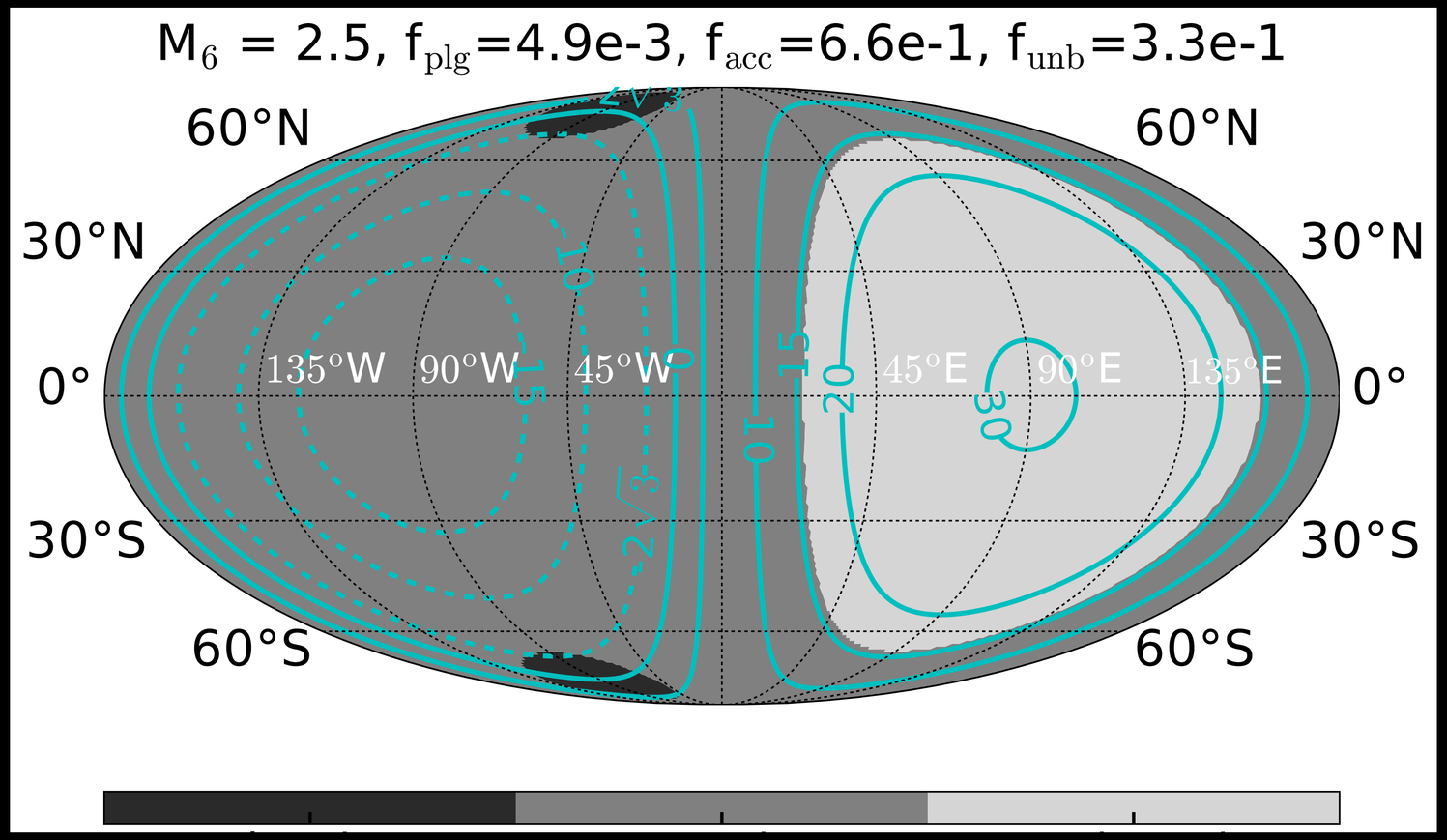
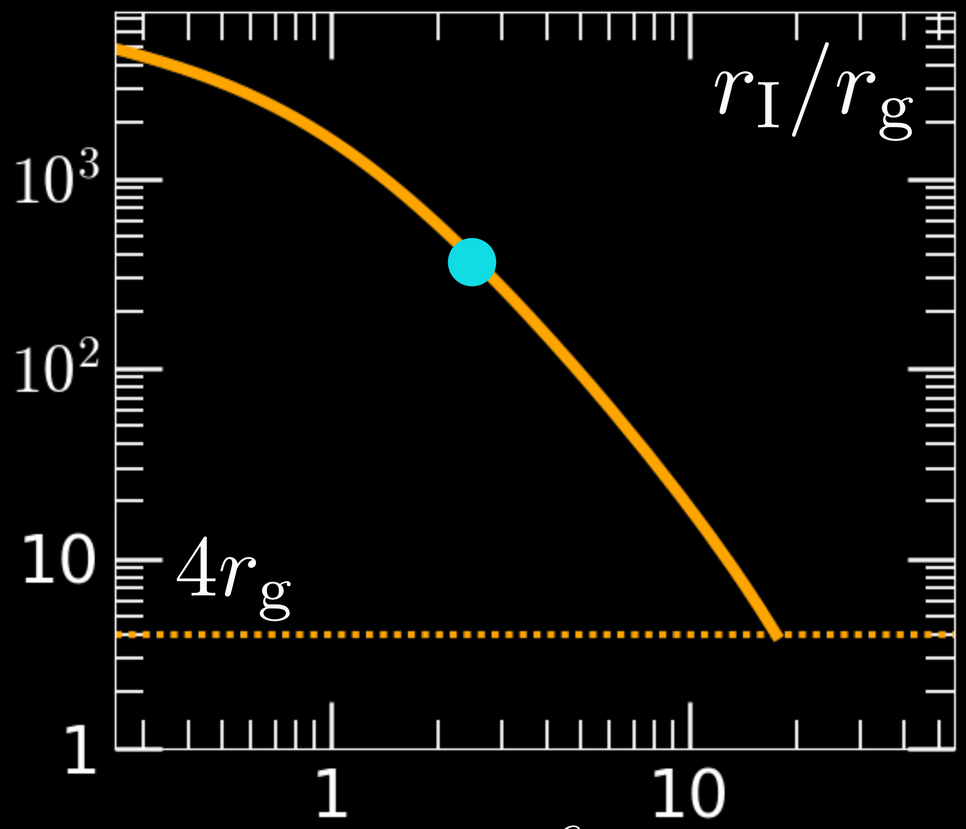



$M = 2.5 \times 10^6 M_\odot$



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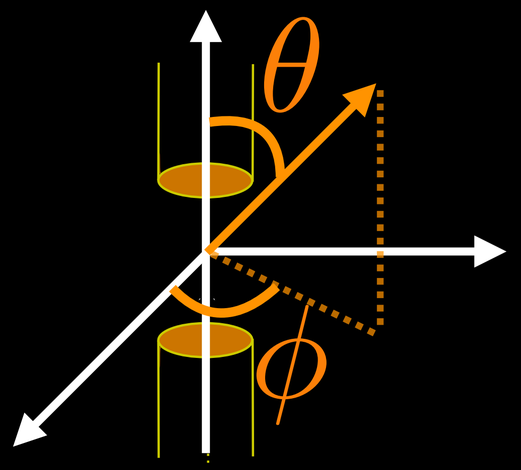
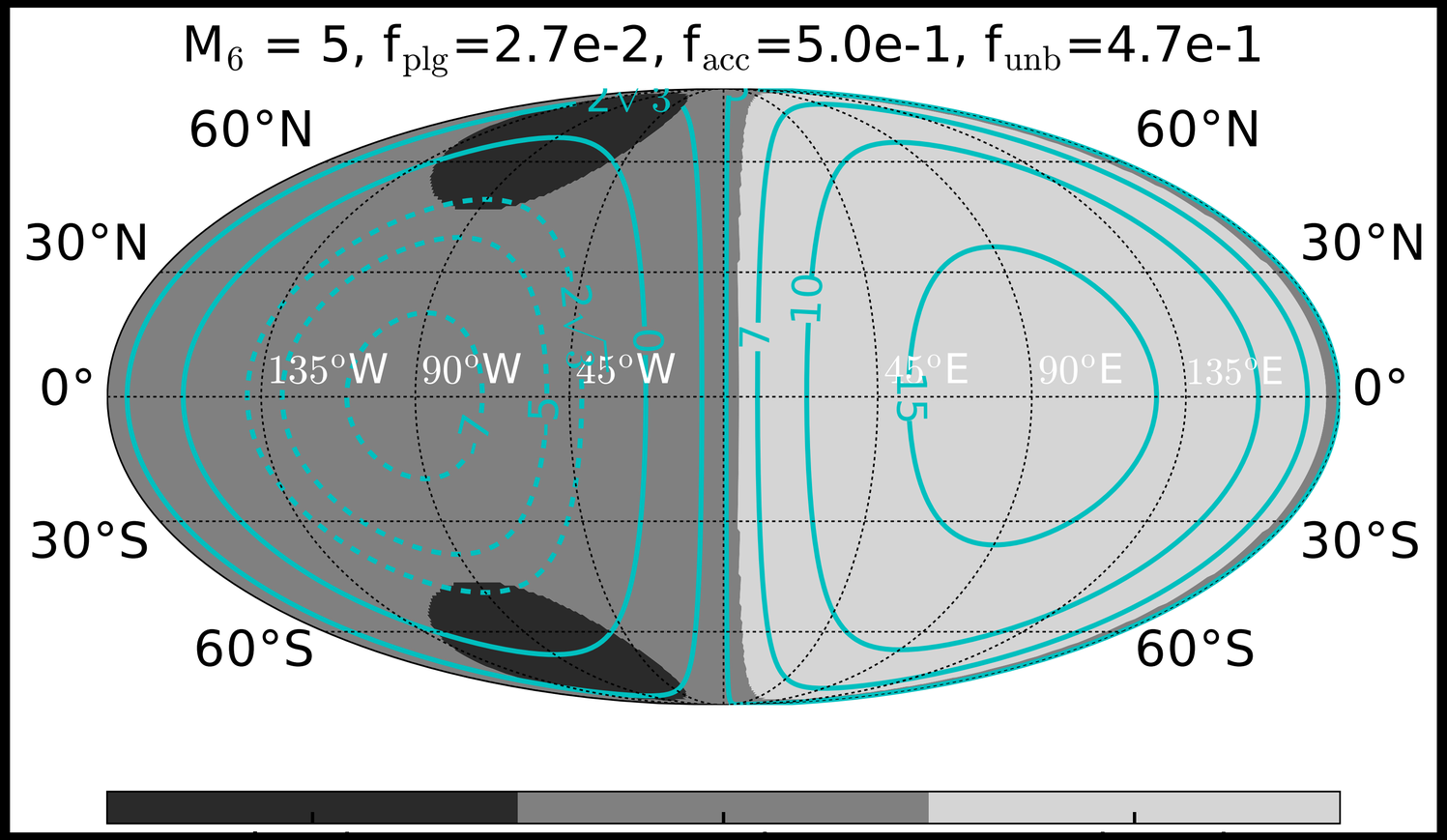
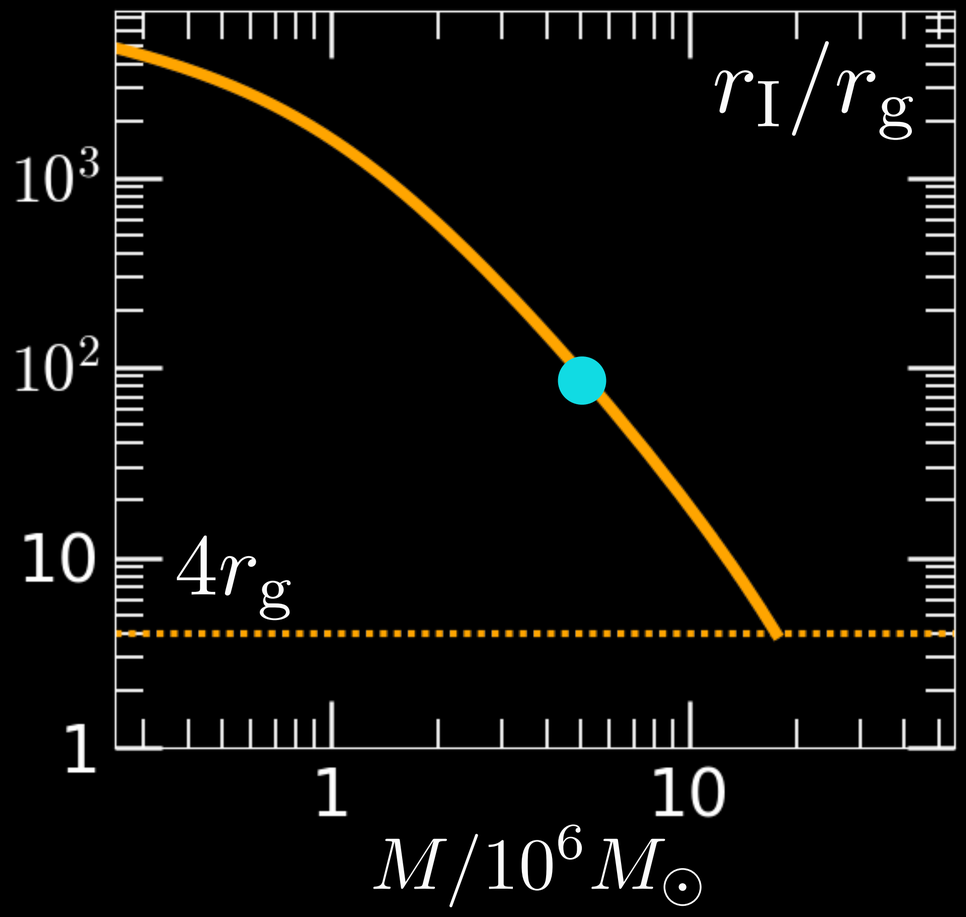



for $M_* = 0.5 M_\odot \quad \beta = r_{\rm T}/r_{\rm p} = 1$




**plunging** **accreting** **unbound**

$M = 5 \times 10^6 M_\odot$



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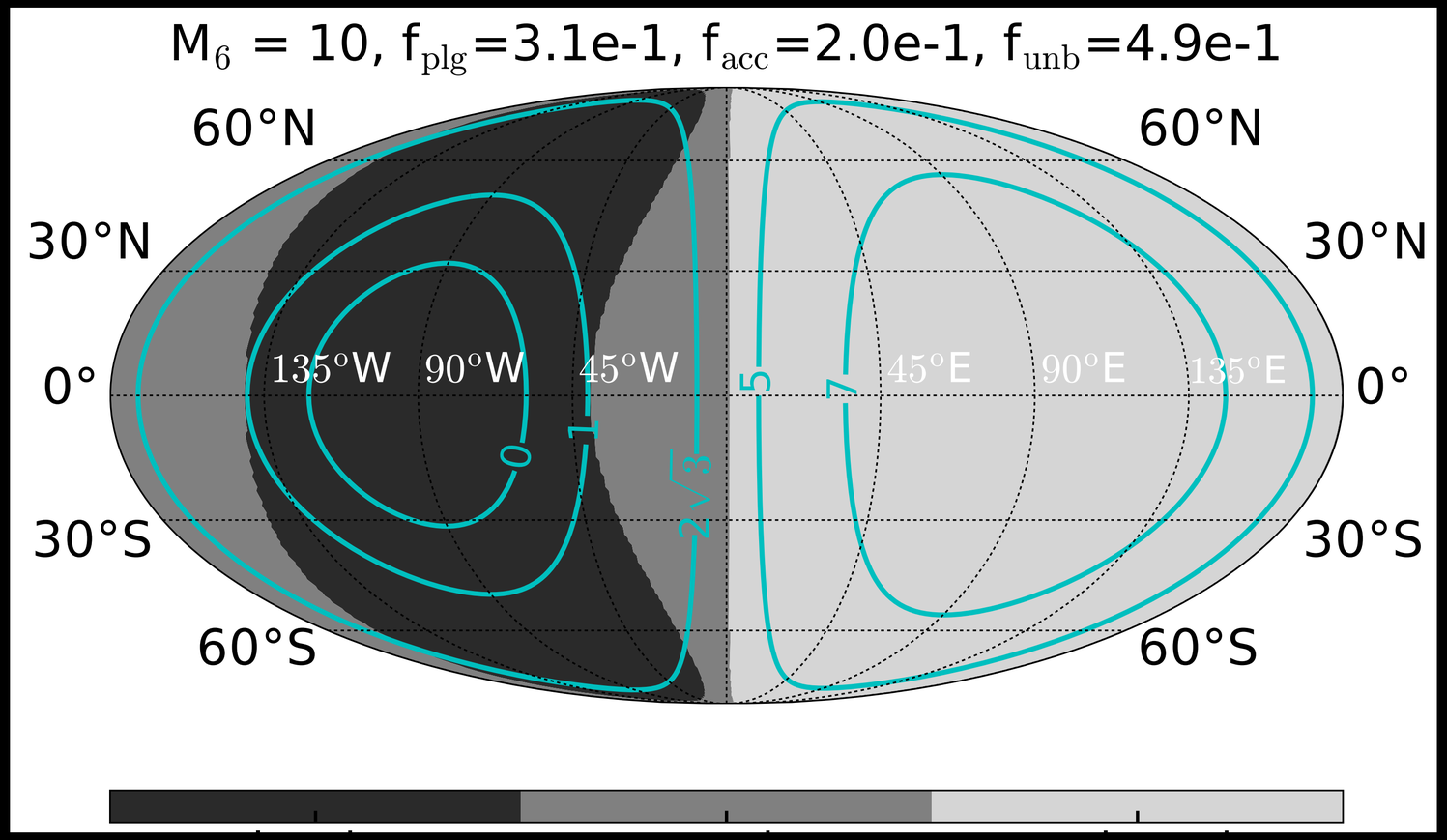
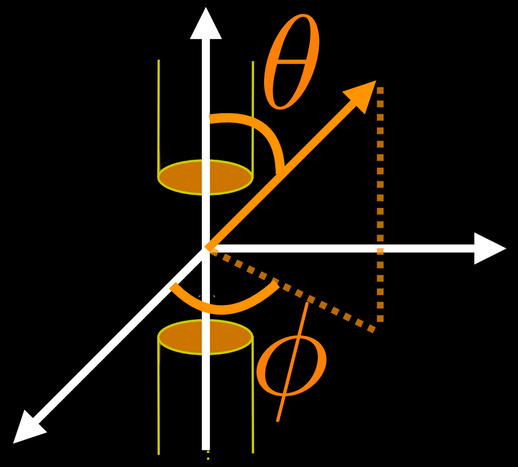
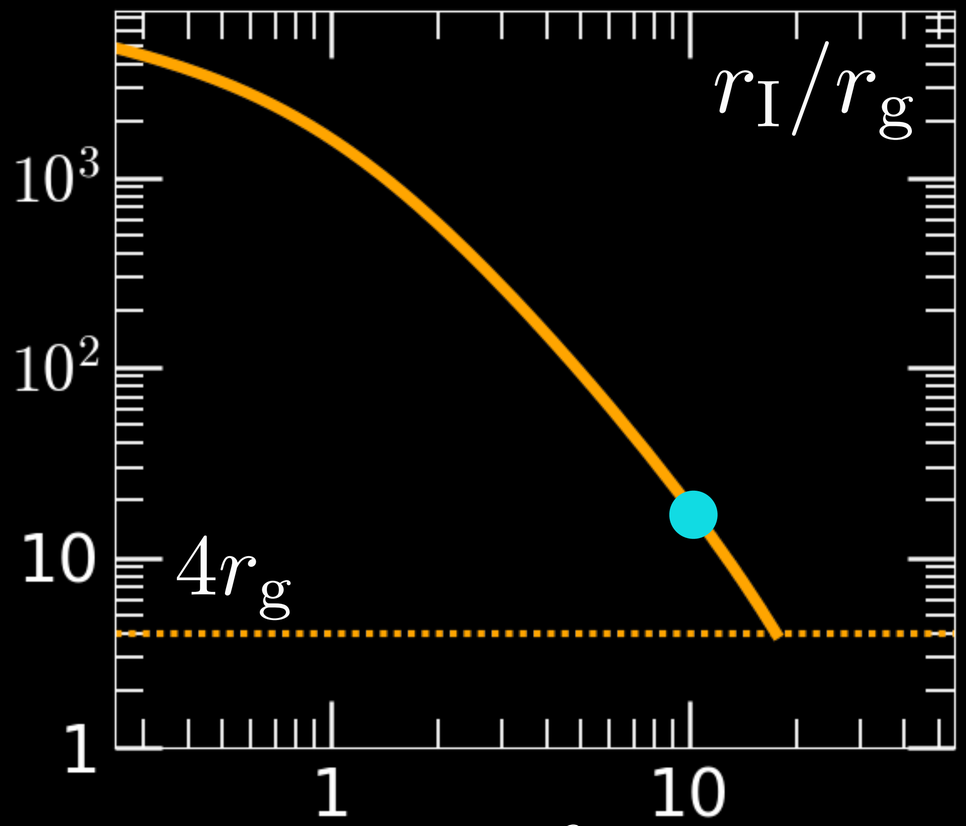
for $M_* = 0.5 M_\odot \quad \beta = r_{\rm T}/r_{\rm p} = 1$




**plunging** **accreting** **unbound**

$M = 10^7 M_\odot$



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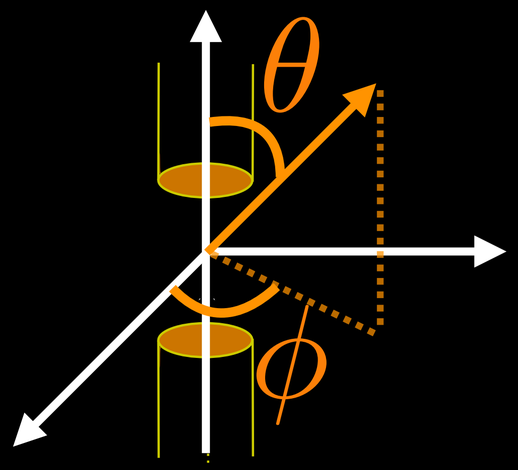


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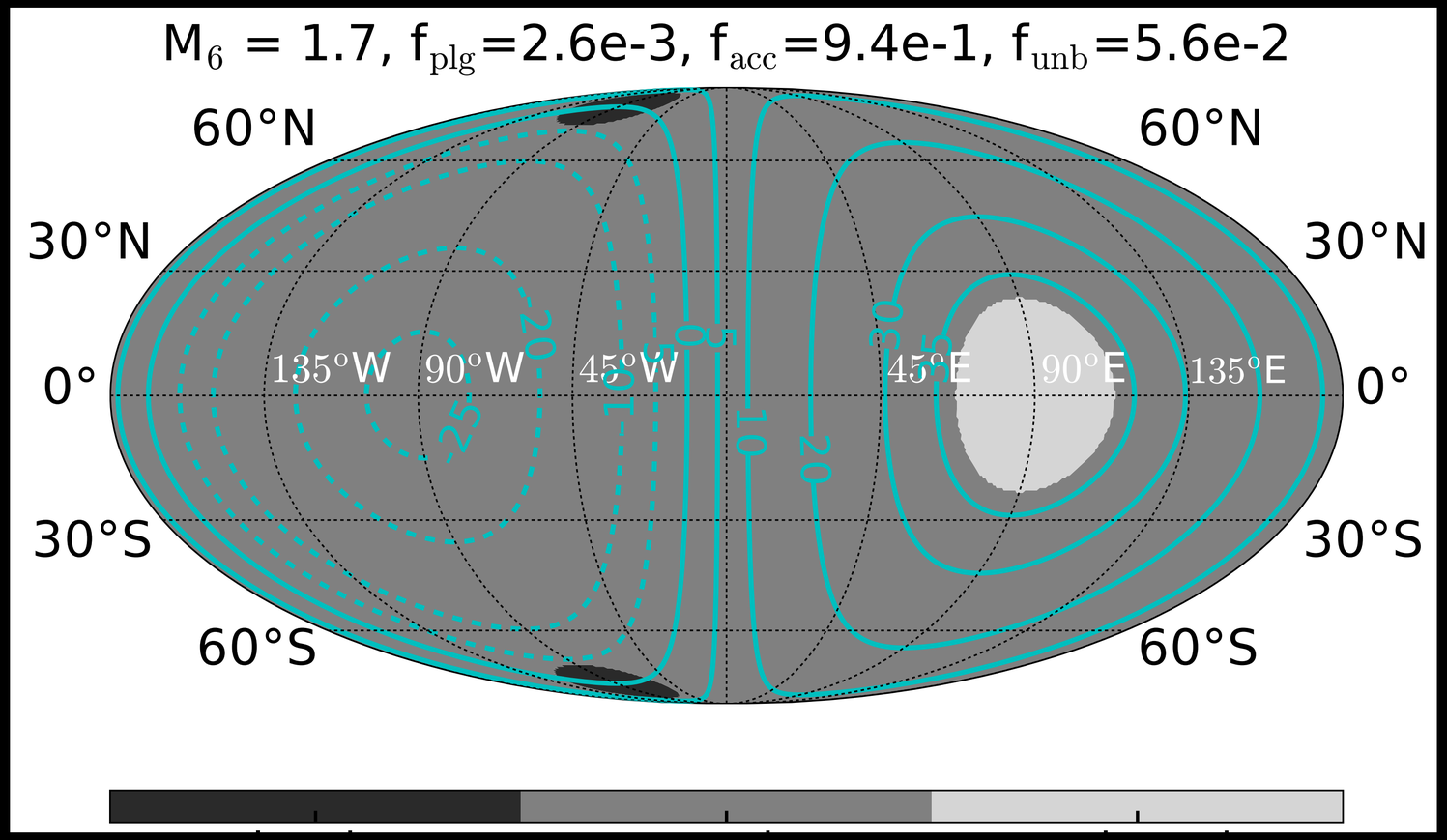
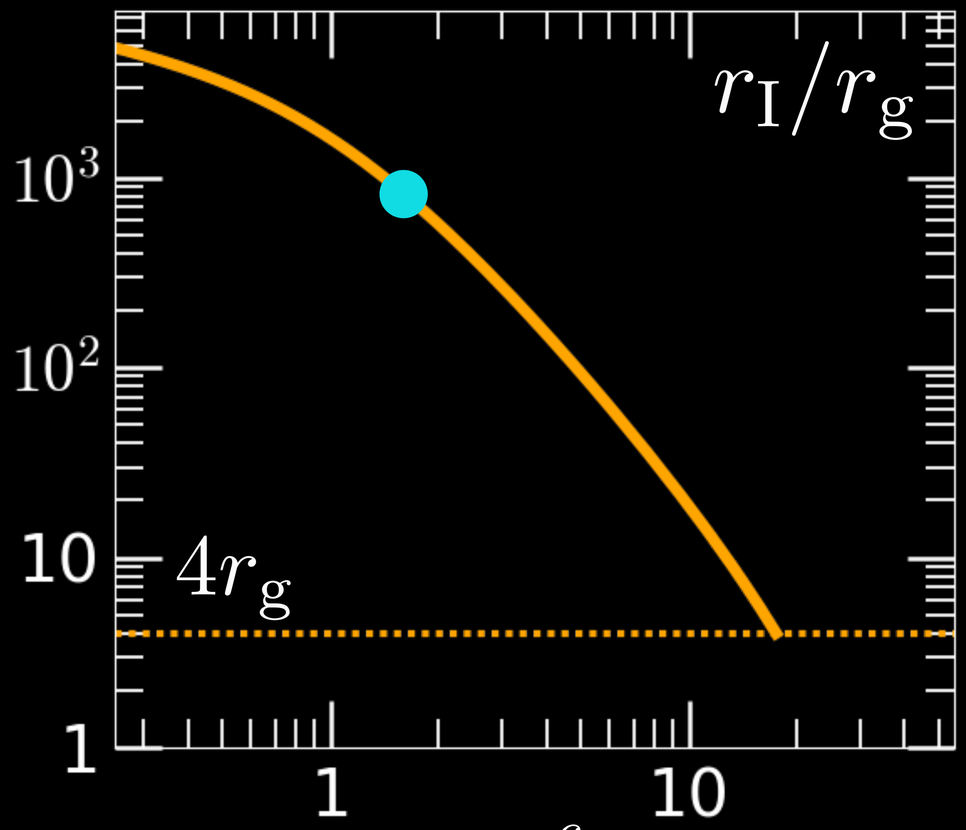


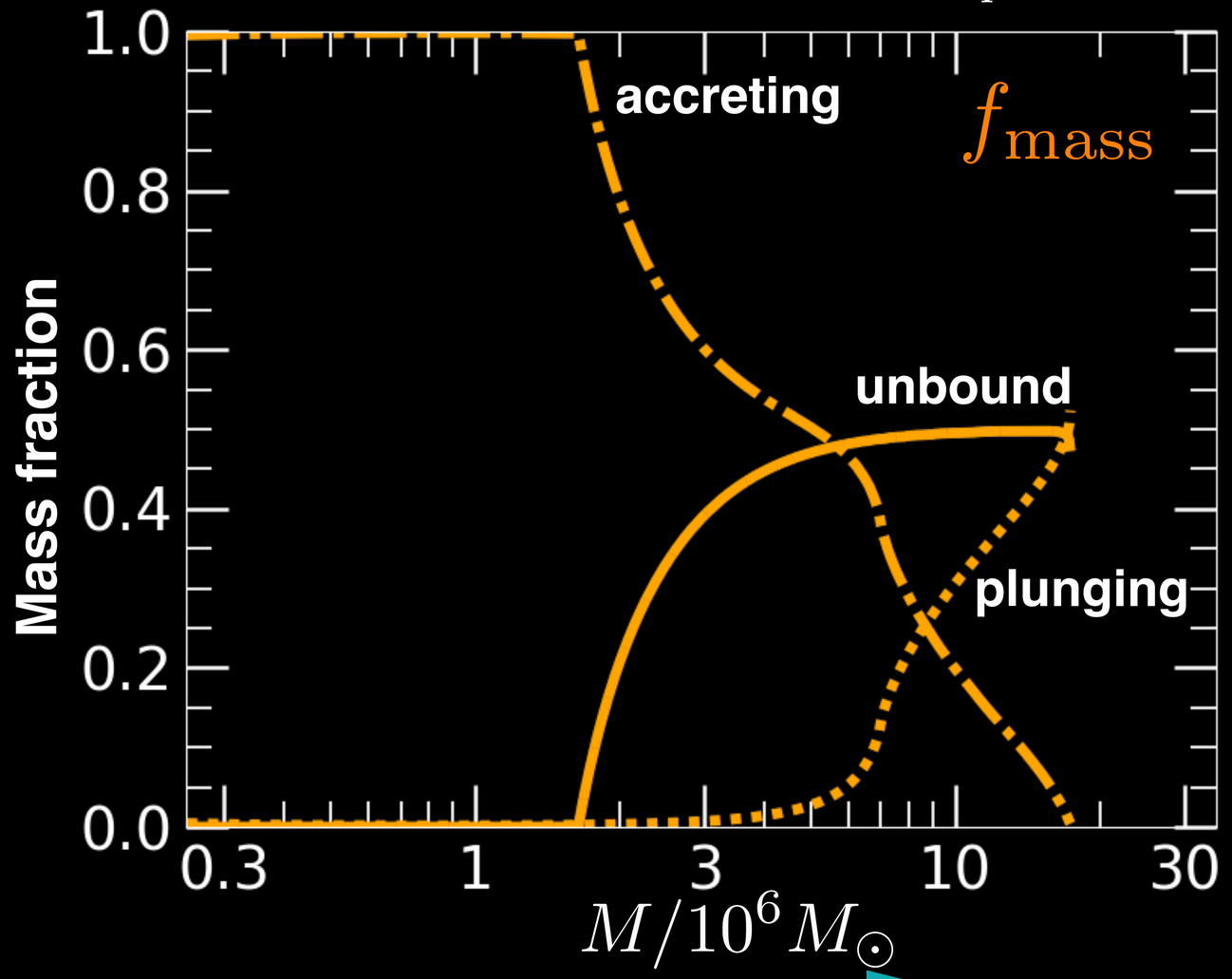

**plunging** **accreting** **unbound**

$M = 1.7 \times 10^6 M_\odot$



# Fate of the Shocked Gas

for $M_* = 0.5 M_\odot$ $\beta = r_\mathrm{T}/r_\mathrm{p} = 1$




smaller $r_\mathrm{p}$, self-crossing closer to the BH

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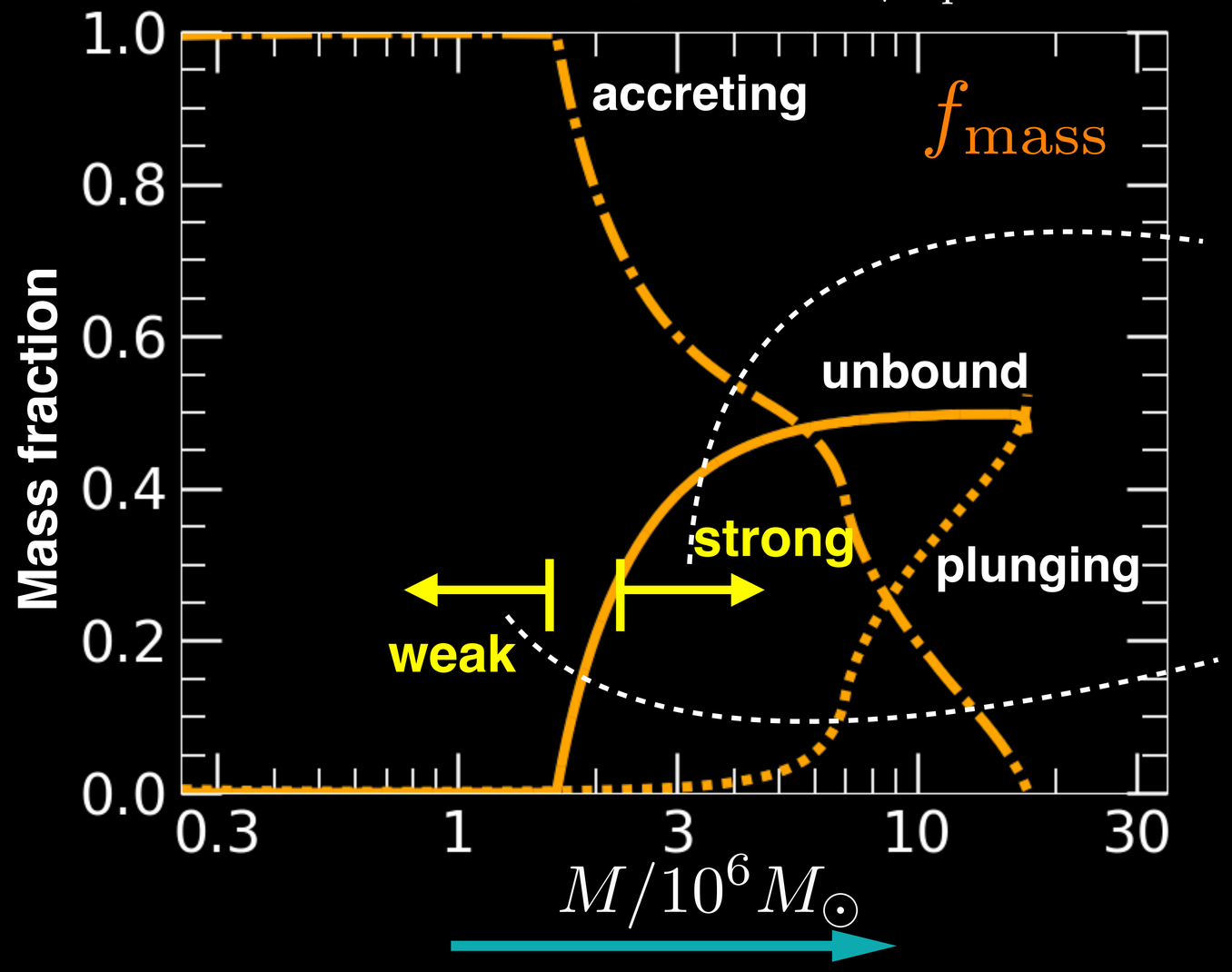



smaller $r_{\rm p}$, self-crossing closer to the BH

**Strong intersection** $(r_{\rm p} \lesssim 15 r_{\rm g})$

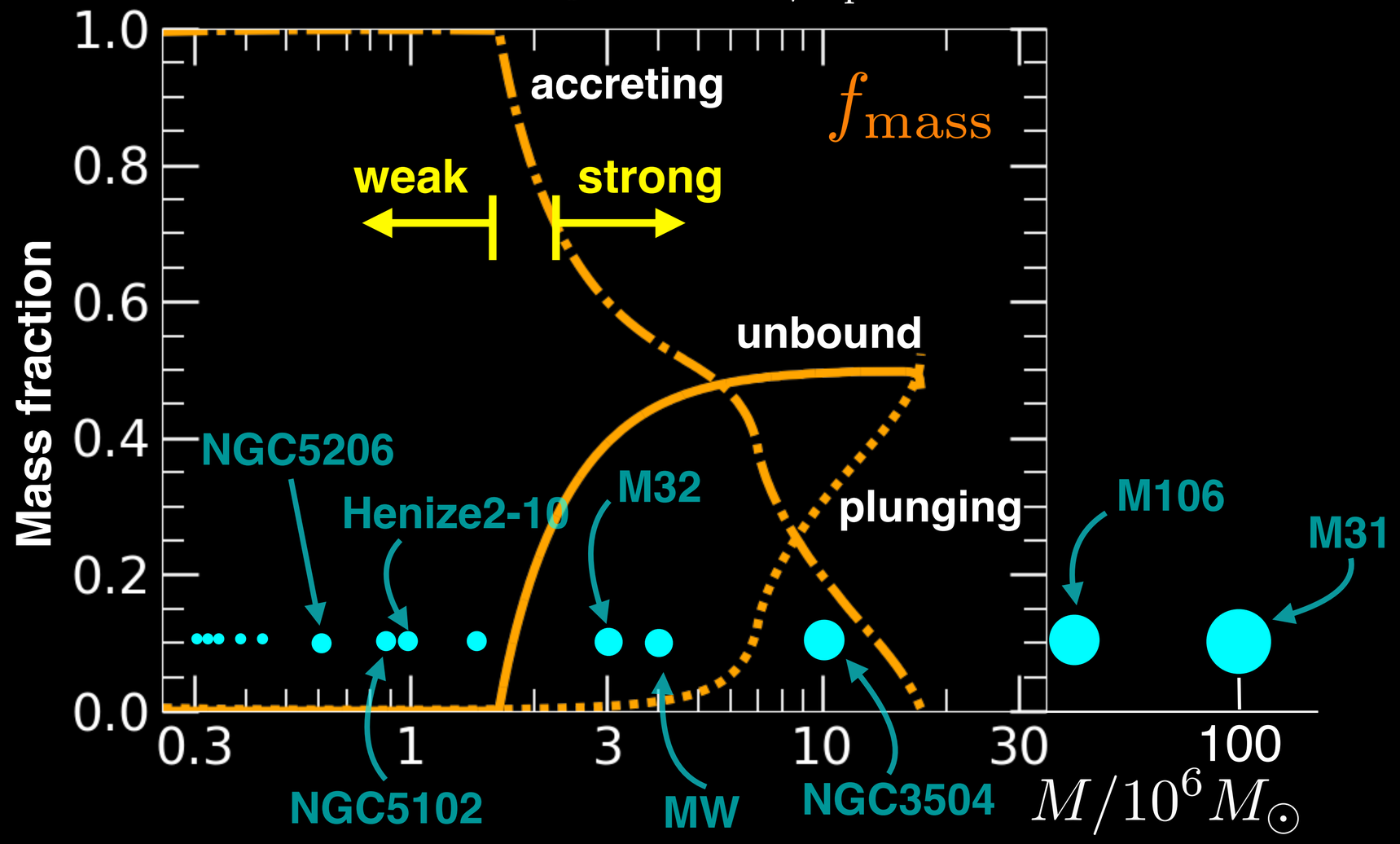
- ⋆ Collision-Induced Outflow (CIO)
- ⋆ Rapid disk formation $\sim t_{\rm min}$

**Weak intersection** $(r_{\rm p} \gg 15 r_{\rm g})$

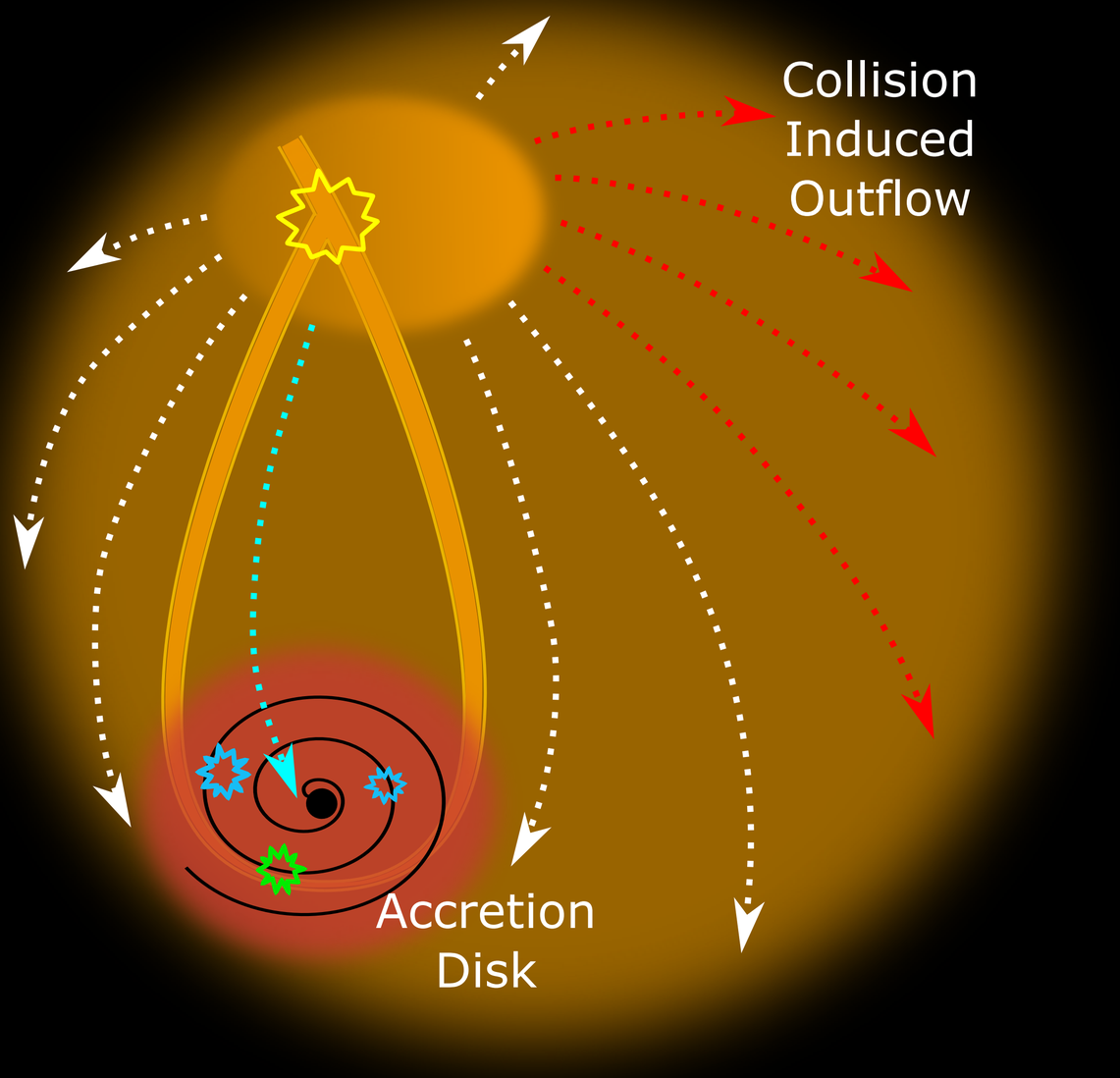
- ⋆ Slow disk formation $\gg t_{\rm min}$ (?)

# Fate of the Shocked Gas

for $M_* = 0.5 M_\odot \;\; \beta = r_{\rm T}/r_{\rm p} = 1$

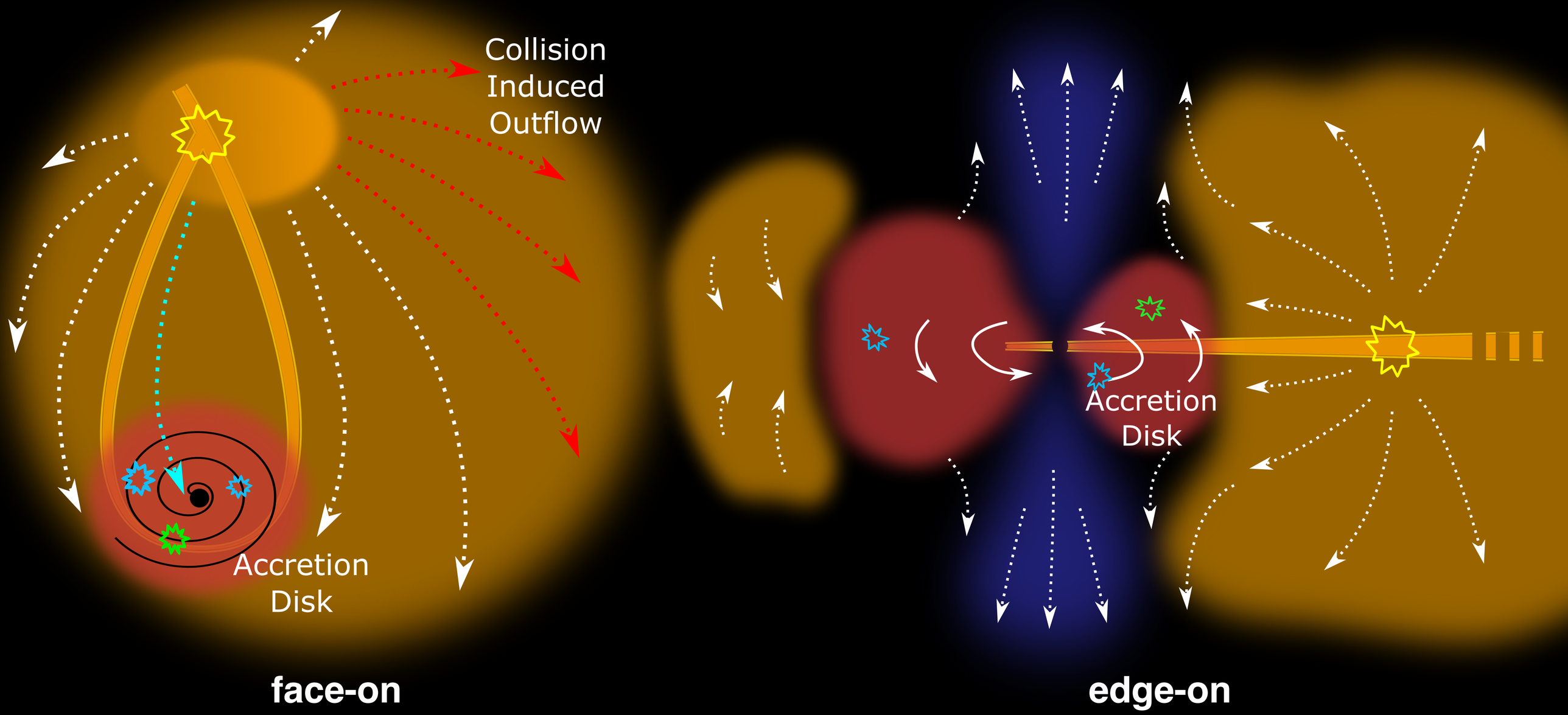


# Global Picture

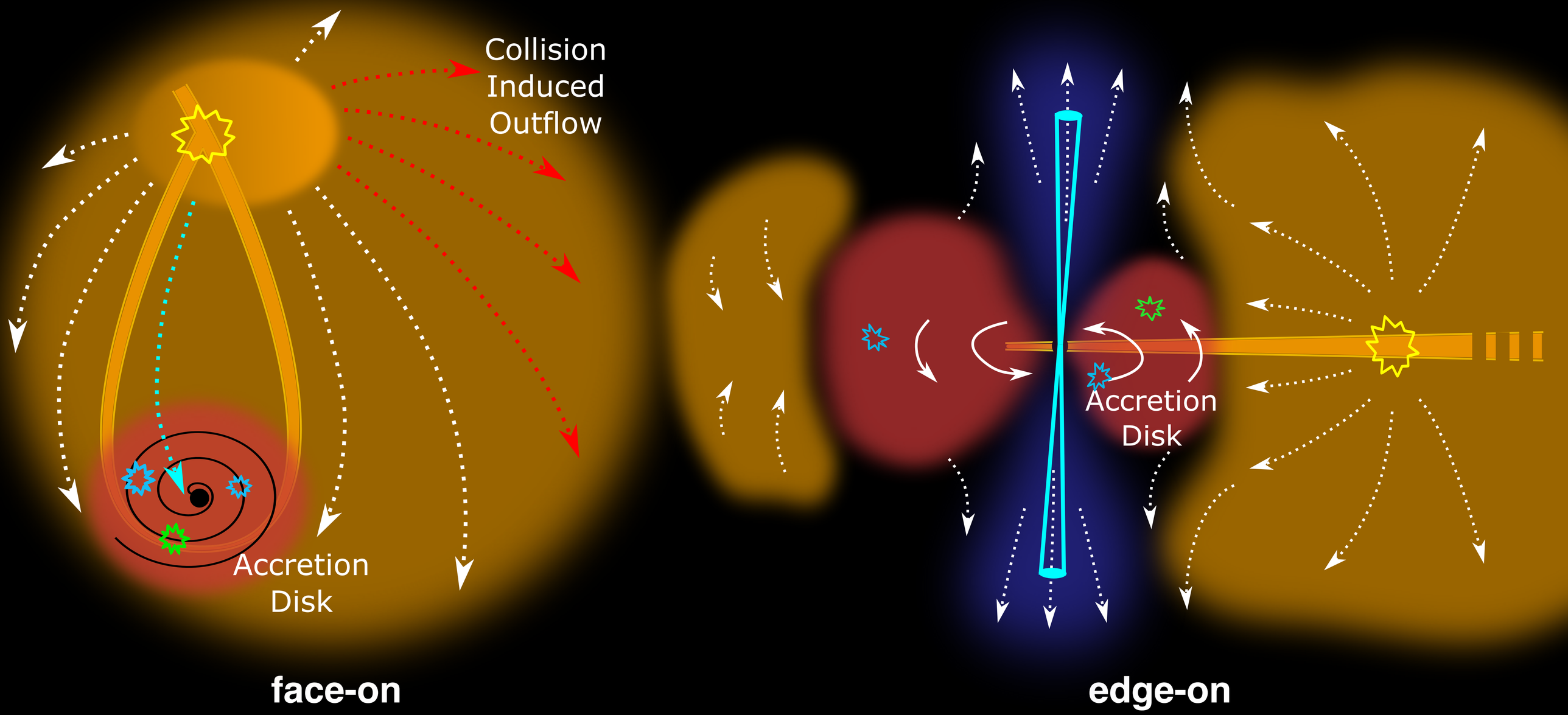



**face-on**

# Global Picture



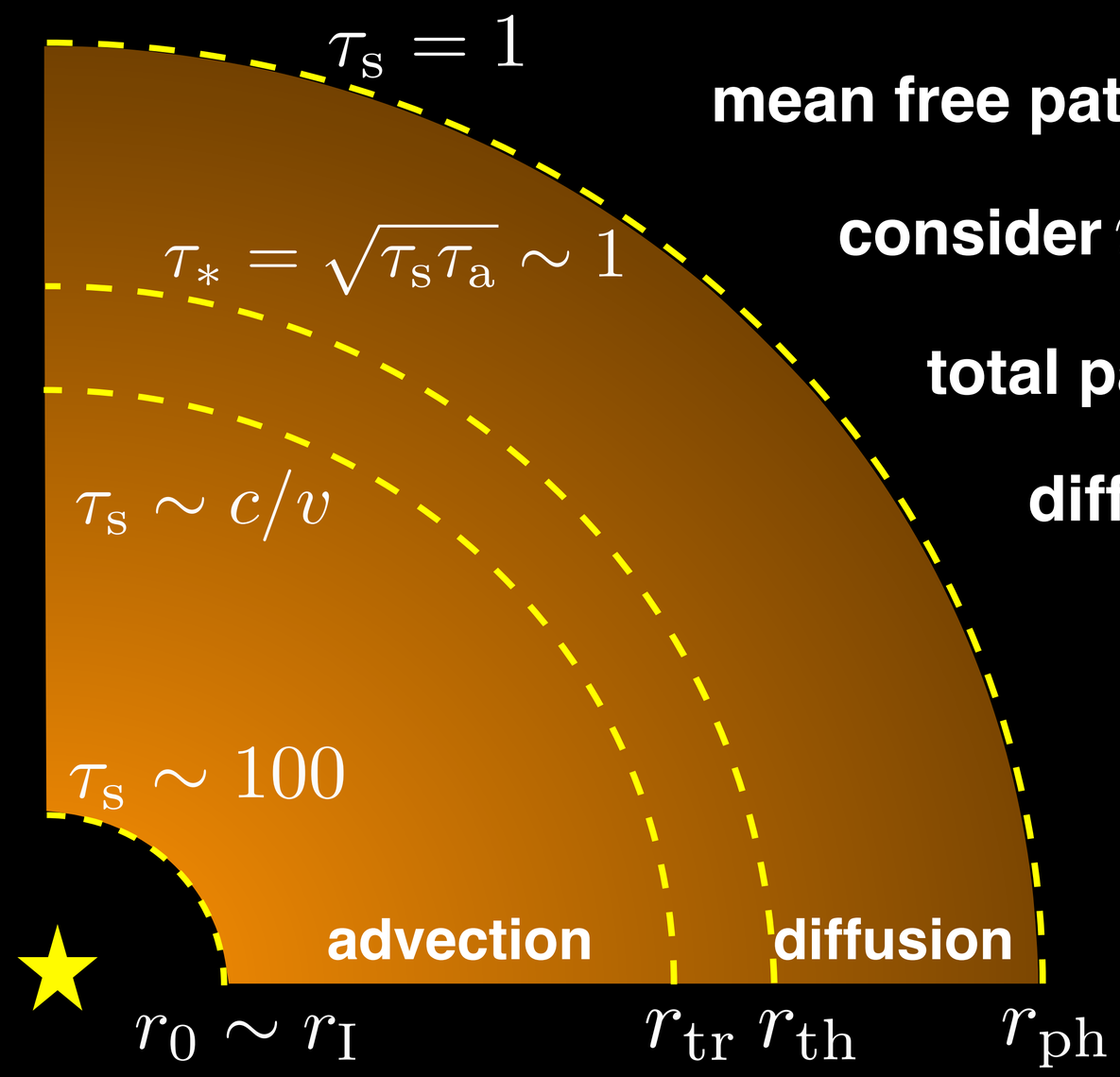
# Global Picture



# Outline

- ⋆ Background
- ⋆ Our New Approach
- ⋆ Predictions

# Optical Emission from CIO




see Metzger & Stone 16, Roth+16

**mean free paths:** $\lambda_s \ll \lambda_a$

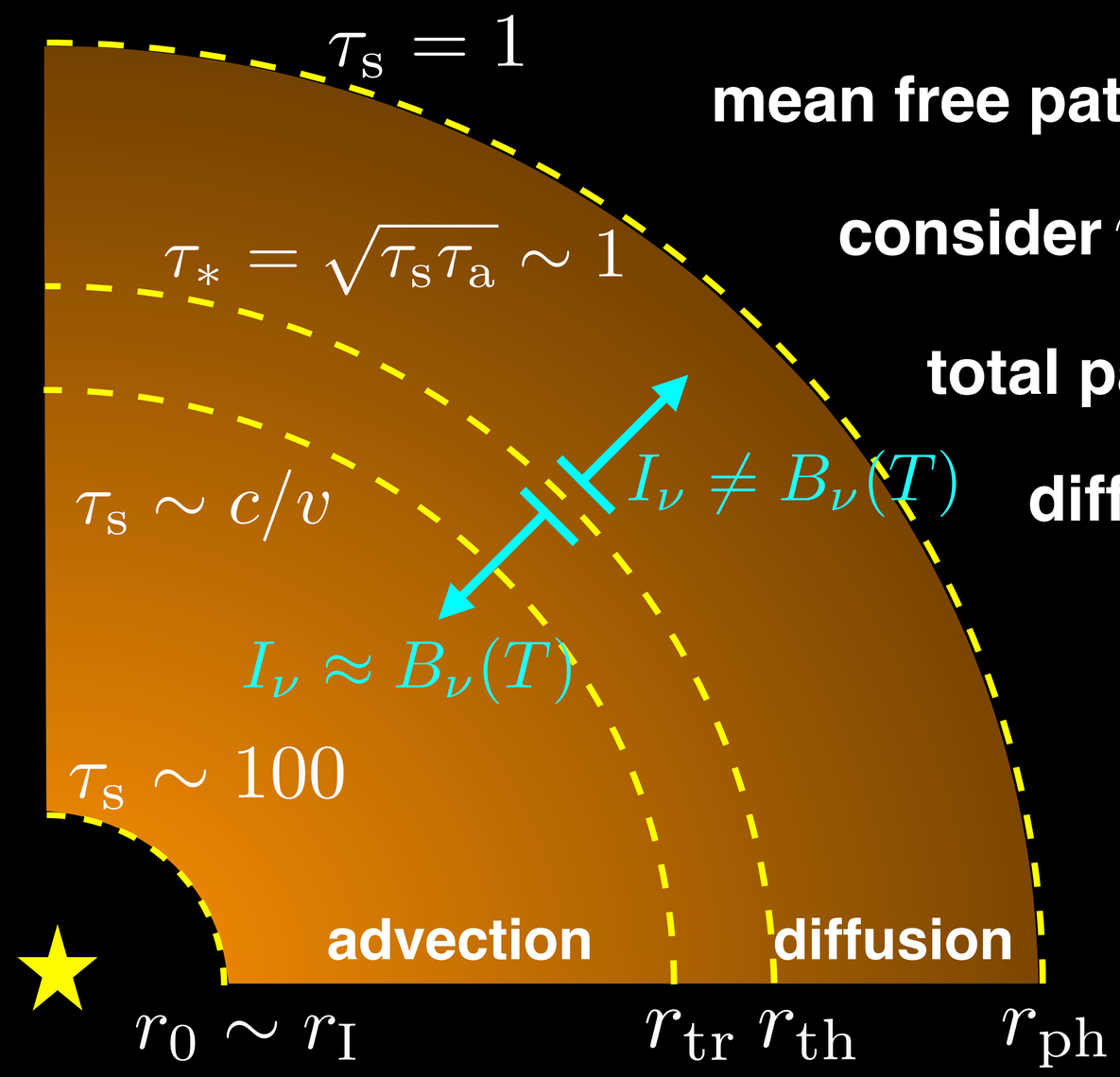
**consider** $r \to 2r$, $N_{sca} \sim \tau_s^2$

**total path length** $\sim \tau_s^2 \lambda_s \sim \tau_s r$

**diffusion time** $t_{diff} \simeq \tau_s r / c$

**absorption probability** $\tau_s r / \lambda_a \sim \tau_s \tau_a$

# Optical Emission from CIO

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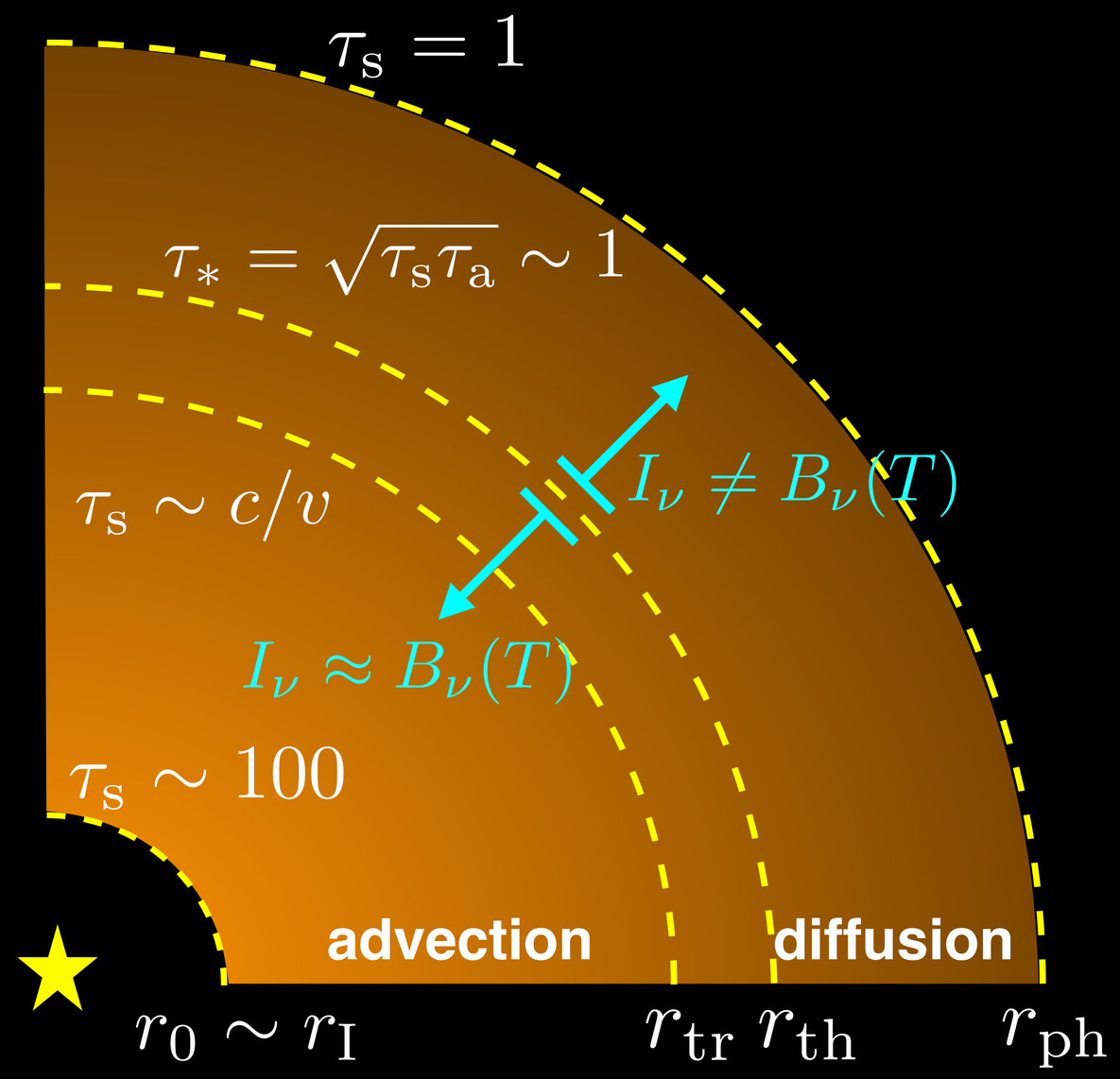



see Metzger & Stone 16, Roth+16

**Example:**

$$r_0 = 10^{14}\,\mathrm{cm}$$

$$L(r_0) = 10^{44}\,\mathrm{erg\,s^{-1}}$$

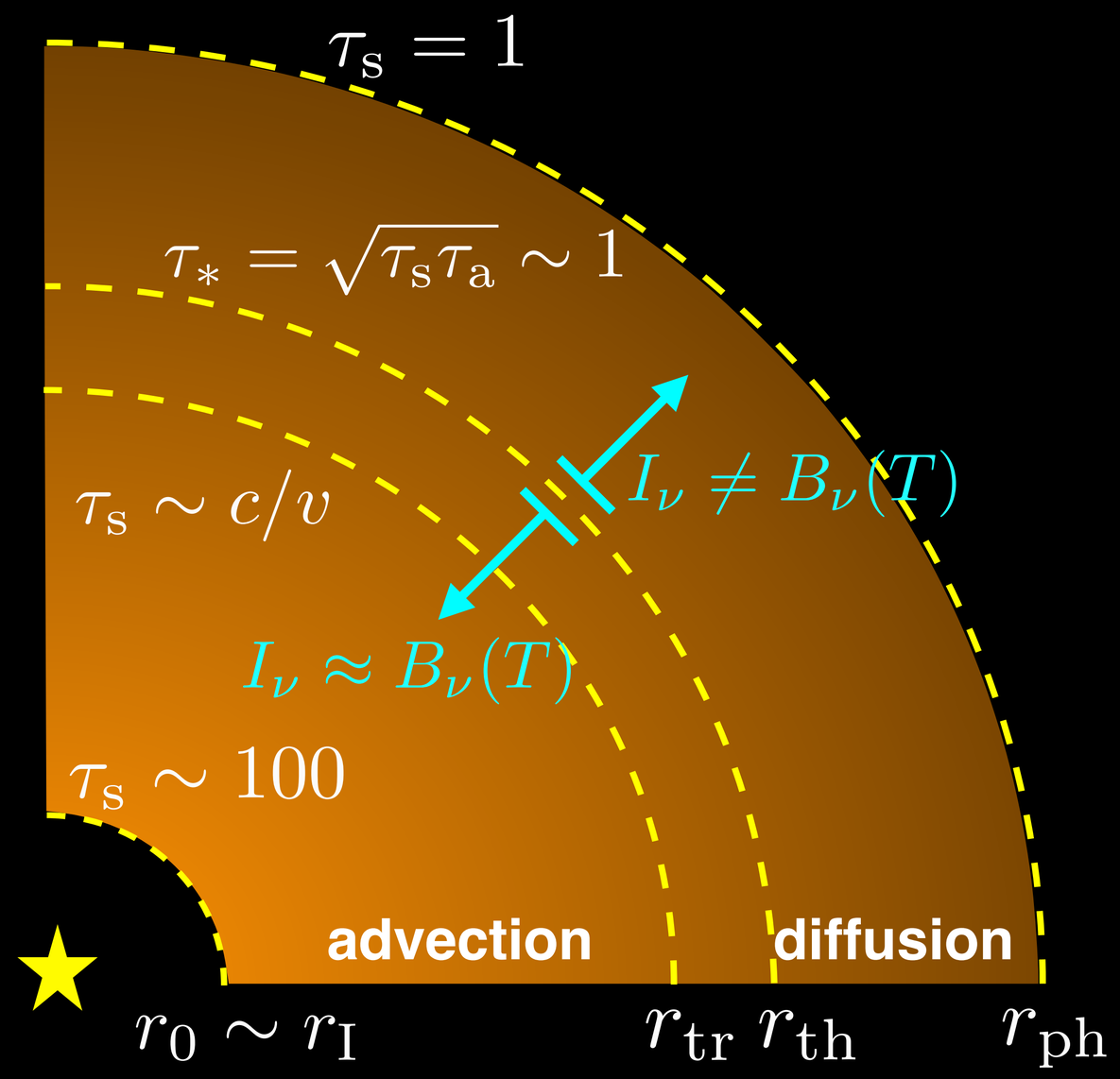
$$v = 10^{9}\,\mathrm{cm\,s^{-1}}$$

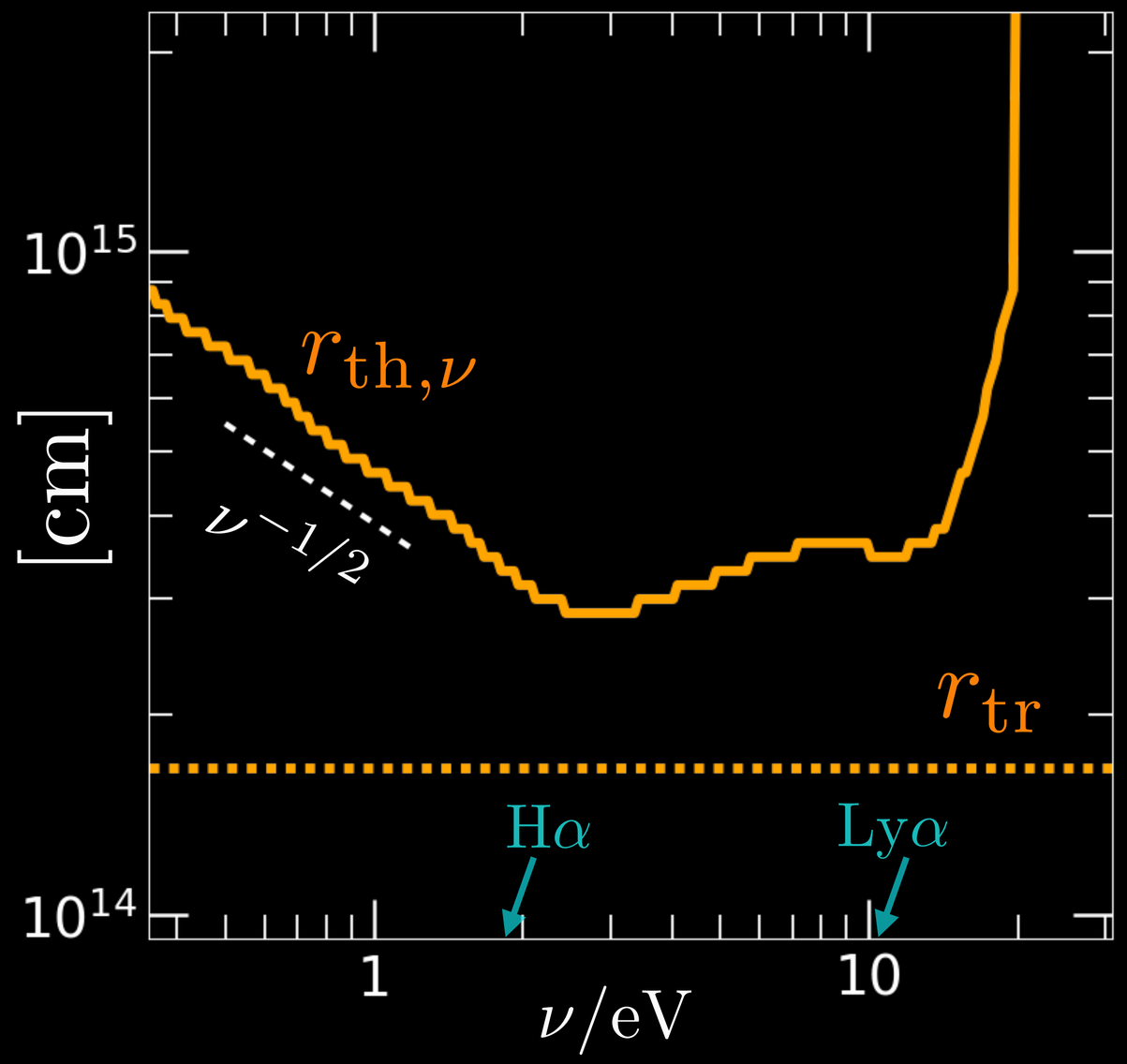
$$\dot{M} = 3\,\mathrm{M_\odot\,yr^{-1}}$$

**+**

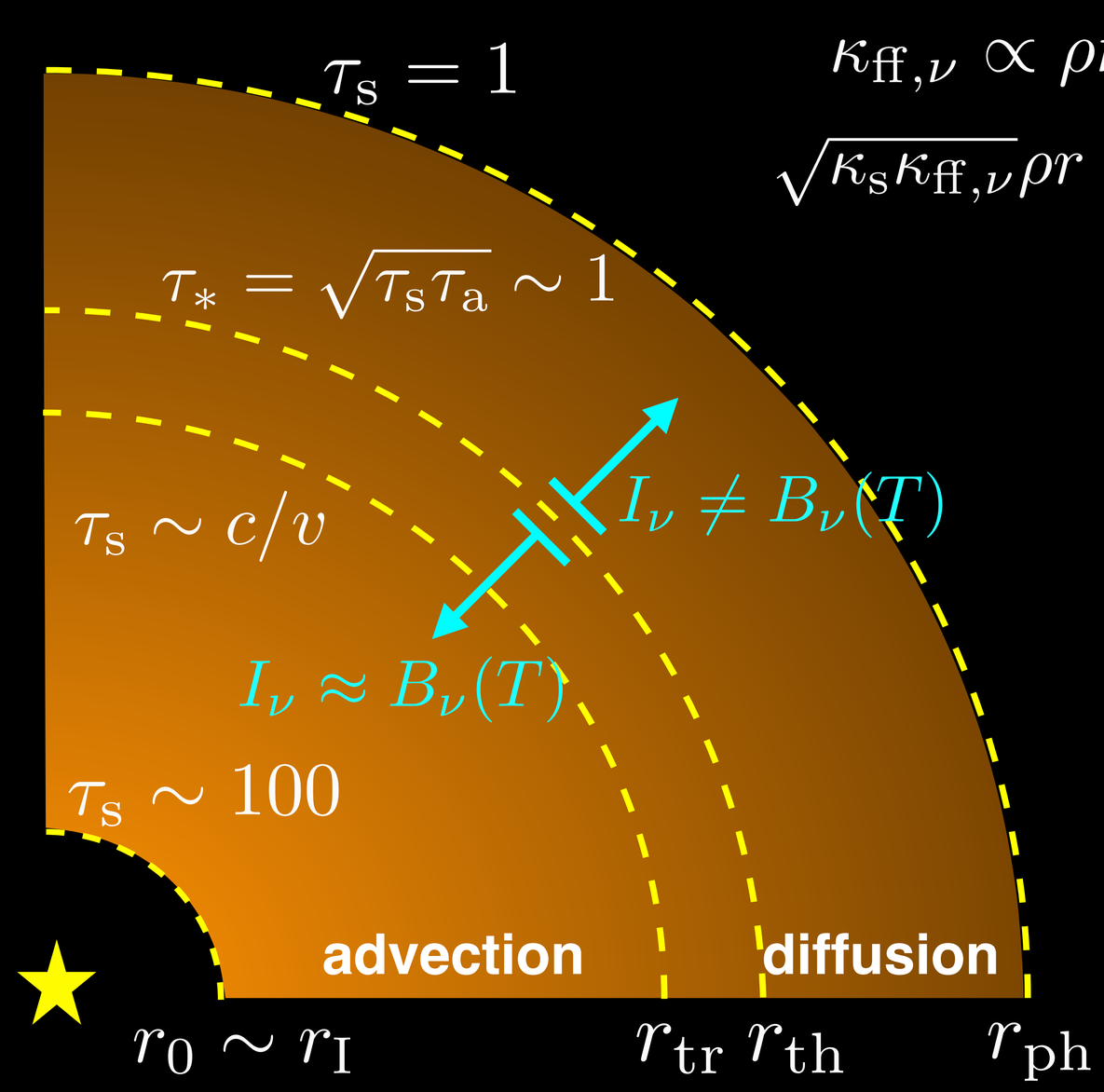
**Cloudy opacity**

# Optical Emission from CIO



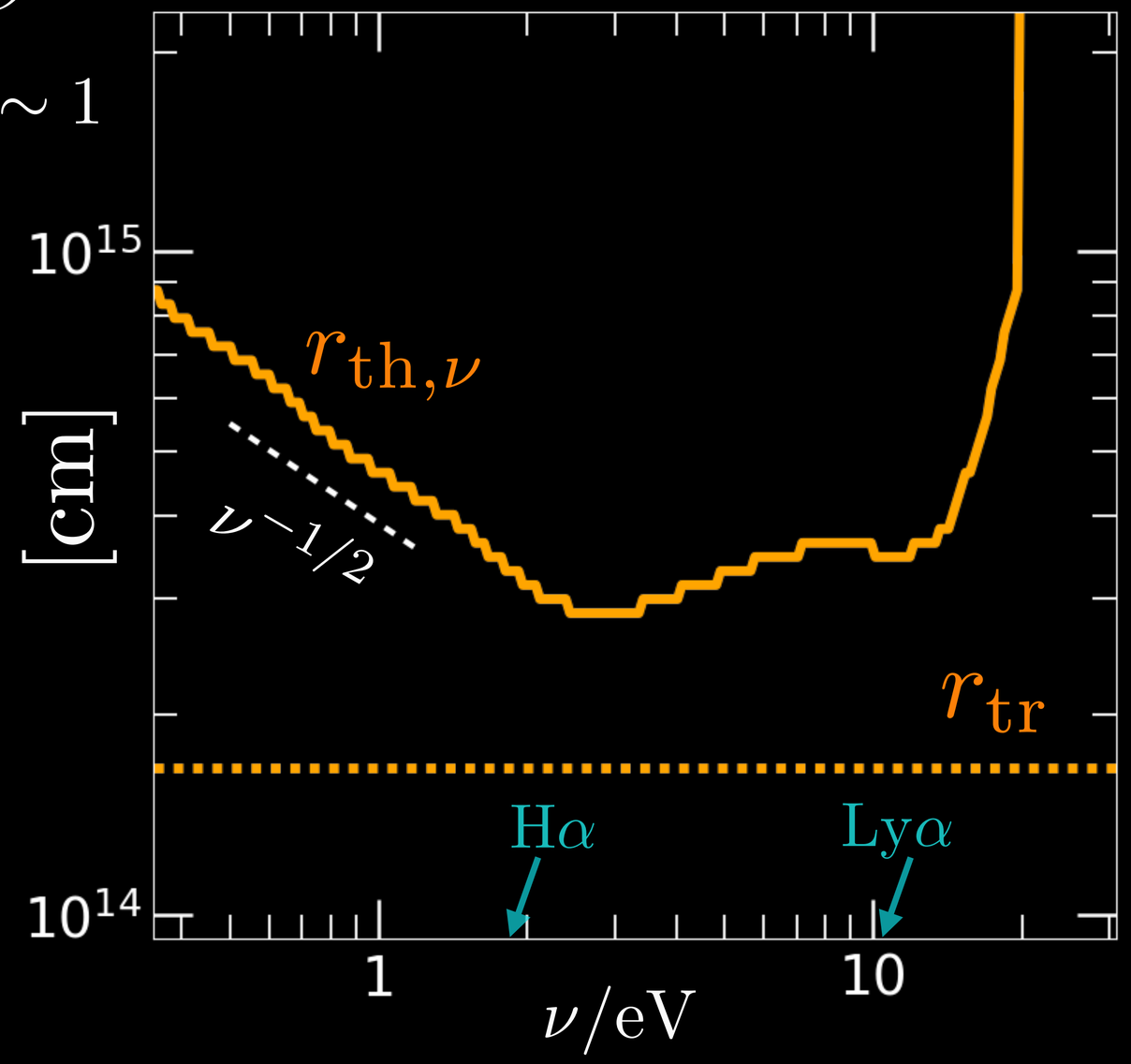



# Optical Emission from CIO

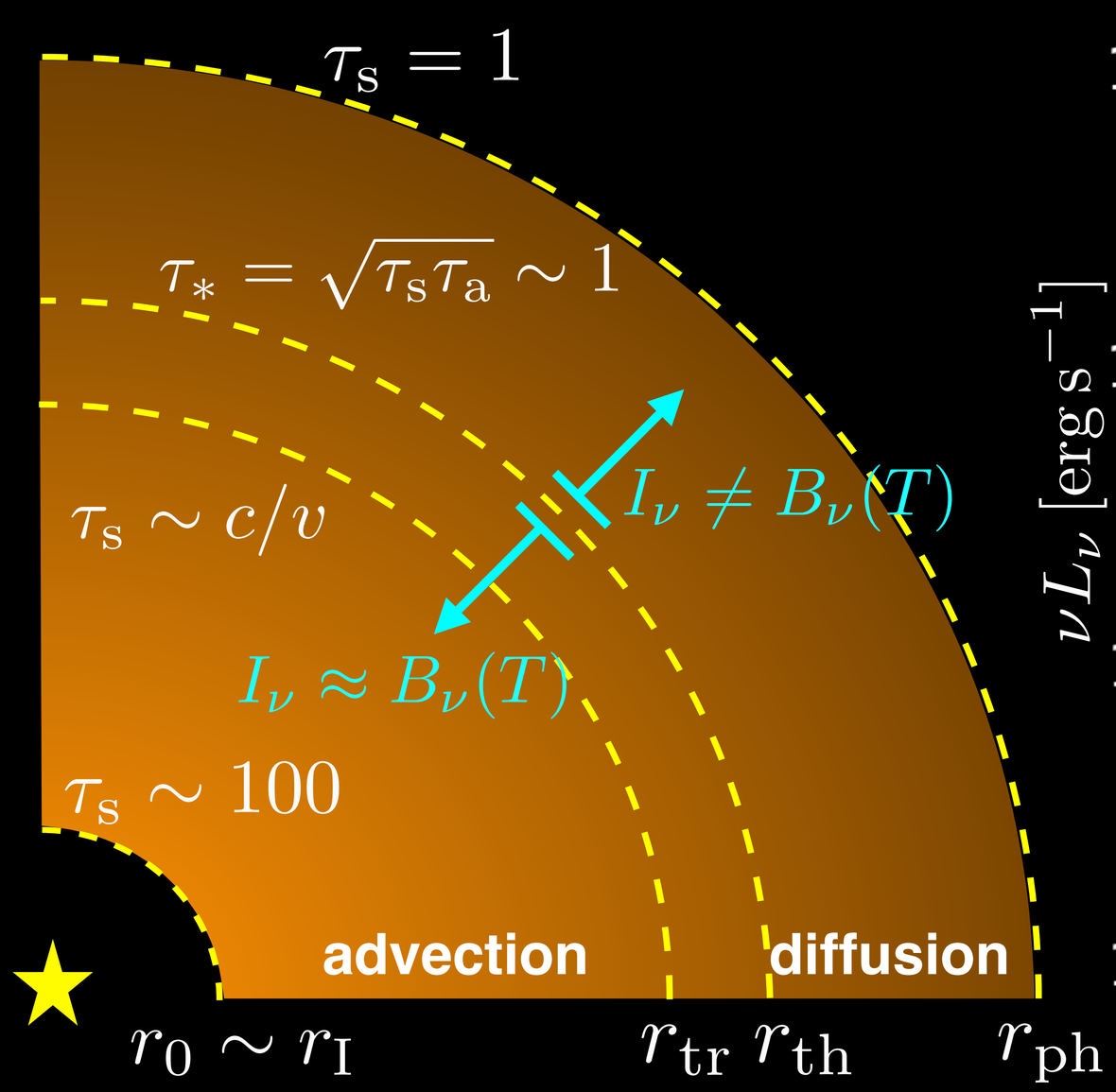


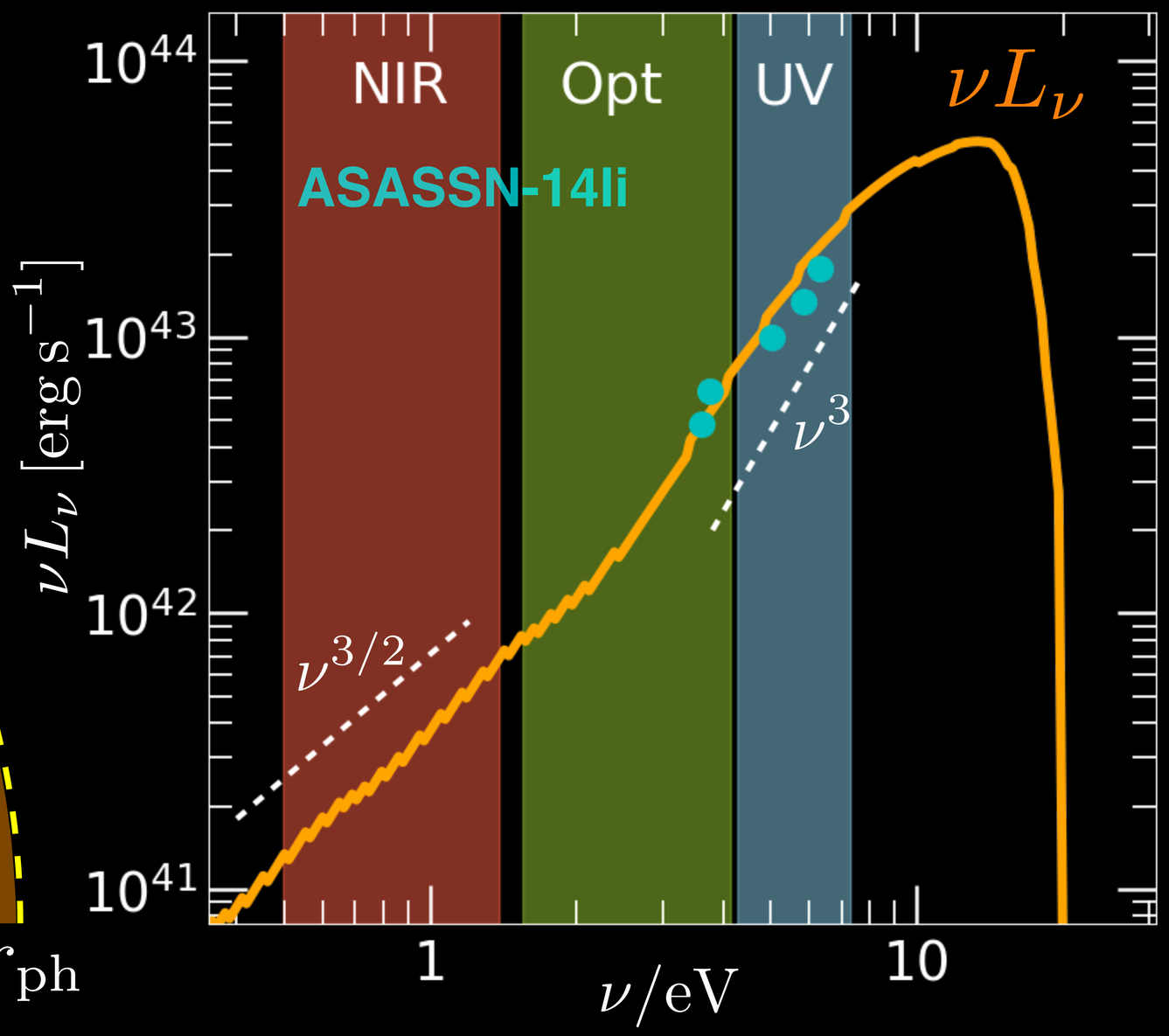

$$\kappa_{ff,\nu} \propto \rho \nu^{-2}$$

$$\sqrt{\kappa_s \kappa_{ff,\nu}} \rho r \sim 1$$



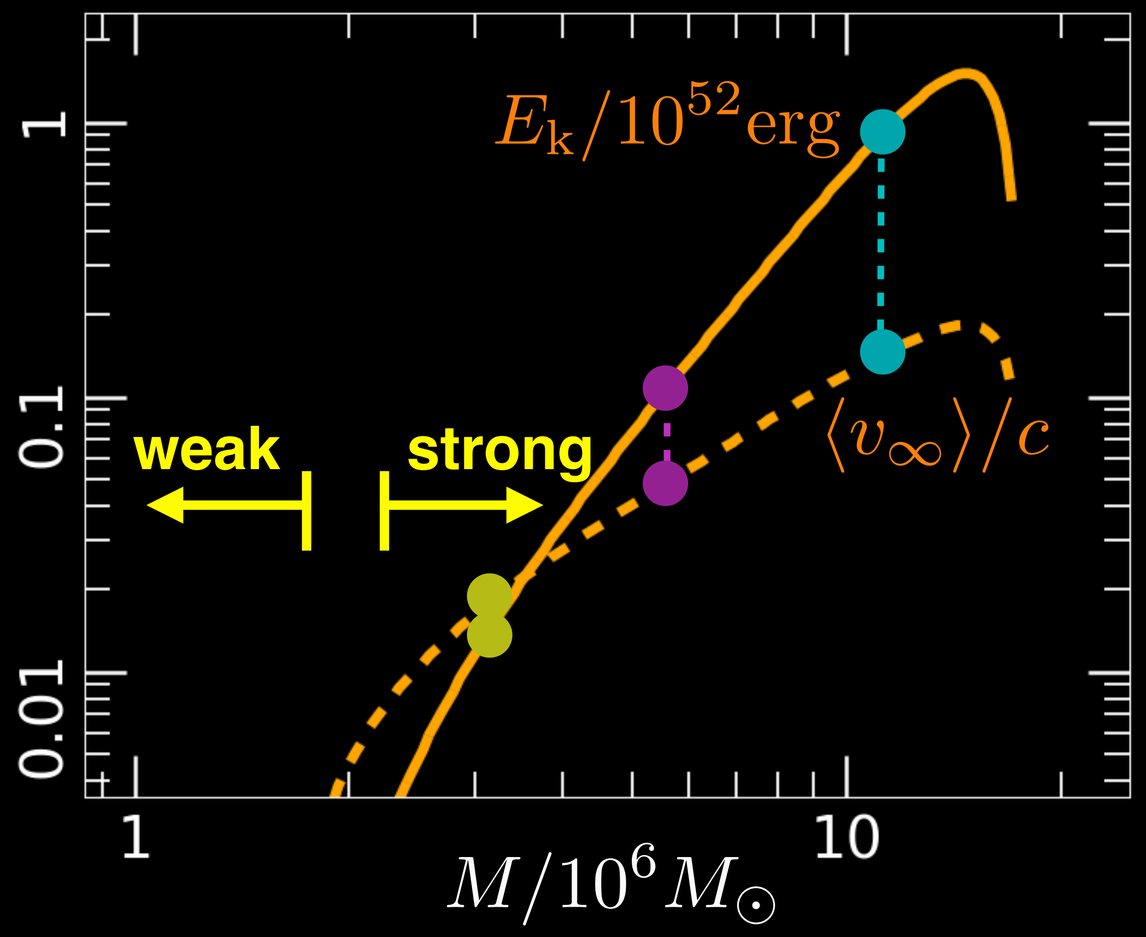
# Optical Emission from CIO



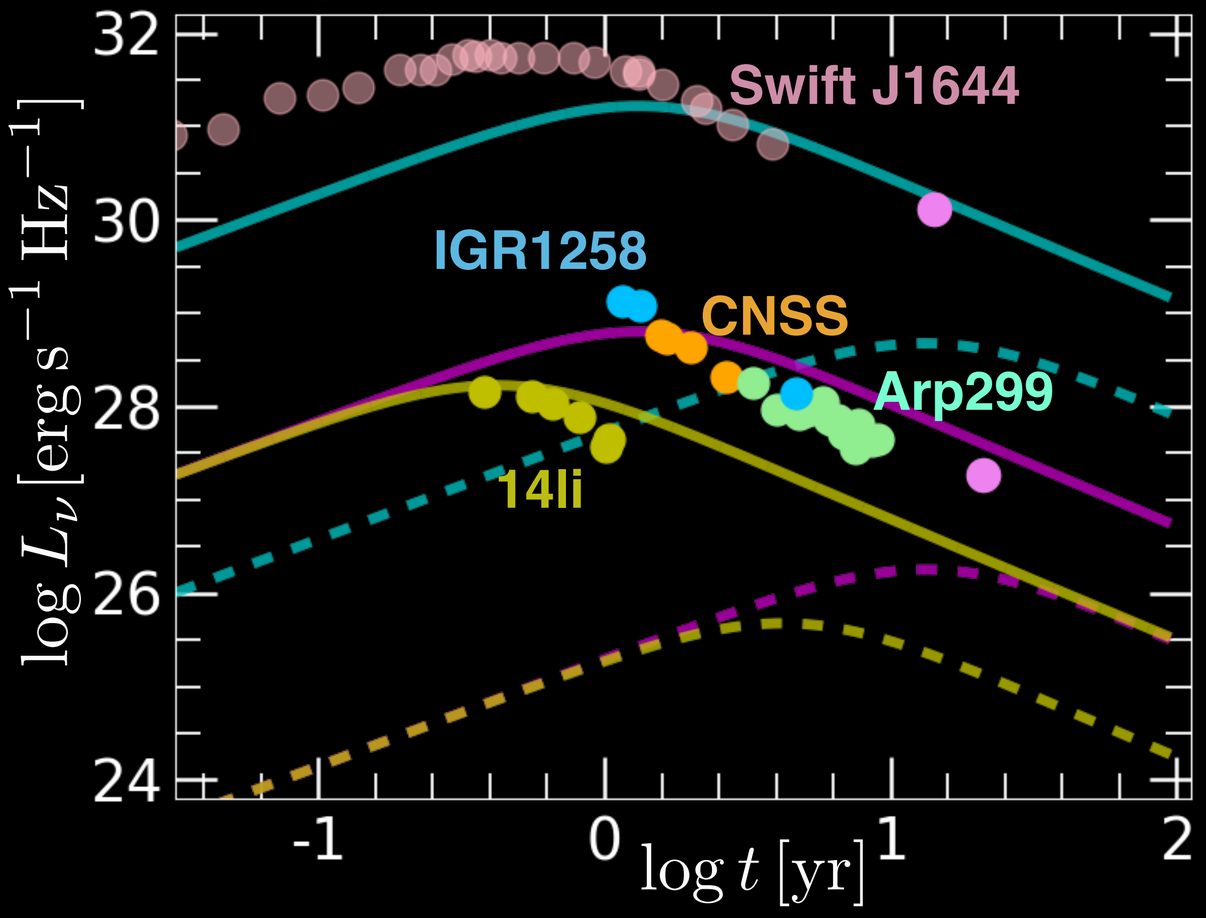
# Radio Emission from CIO

for $M_* = 0.5 M_\odot$ $\beta = r_{\rm T}/r_{\rm p} = 1$




for $n \propto r^{-1}$ $n_{\rm pc} = 10^3$ or $10\,{\rm cm}^{-3}$

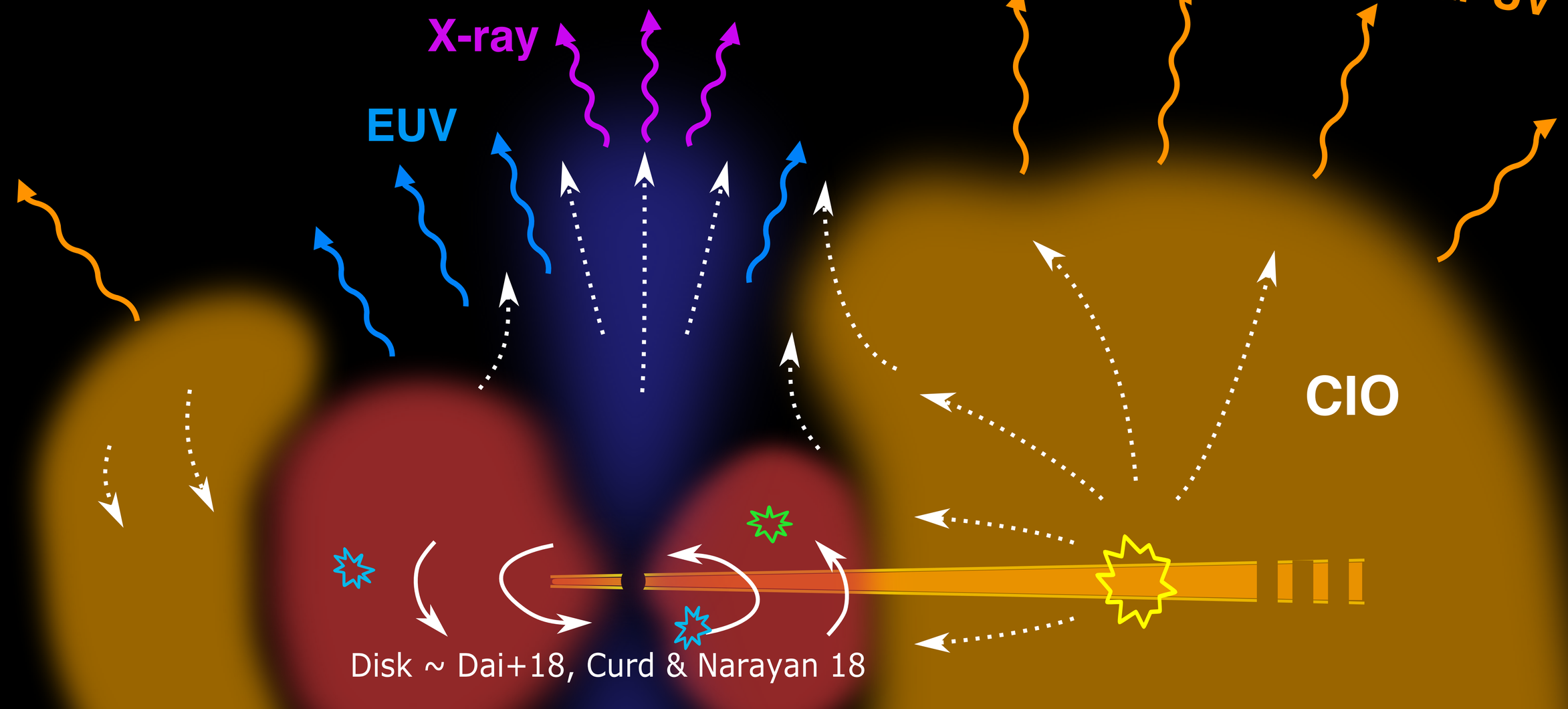
$p = 2.4$ $\epsilon_{\rm e} = 0.1$ $\epsilon_{\rm B} = 0.01$




Bower+13, Irwin+15, Alexander+16, Perlman+17, Eftekhari+18, Mattila+18, Anderson+19

# Viewing Angle Effects

- **Early-time:** $L_{\rm X}/L_{\rm opt} \in (0, \sim 1)$
- **Late-time:** thin disk $L_{\rm X} \sim 0.1\dot{M}c^2$ at all angles



# Demographics (see also Kochanek 16)

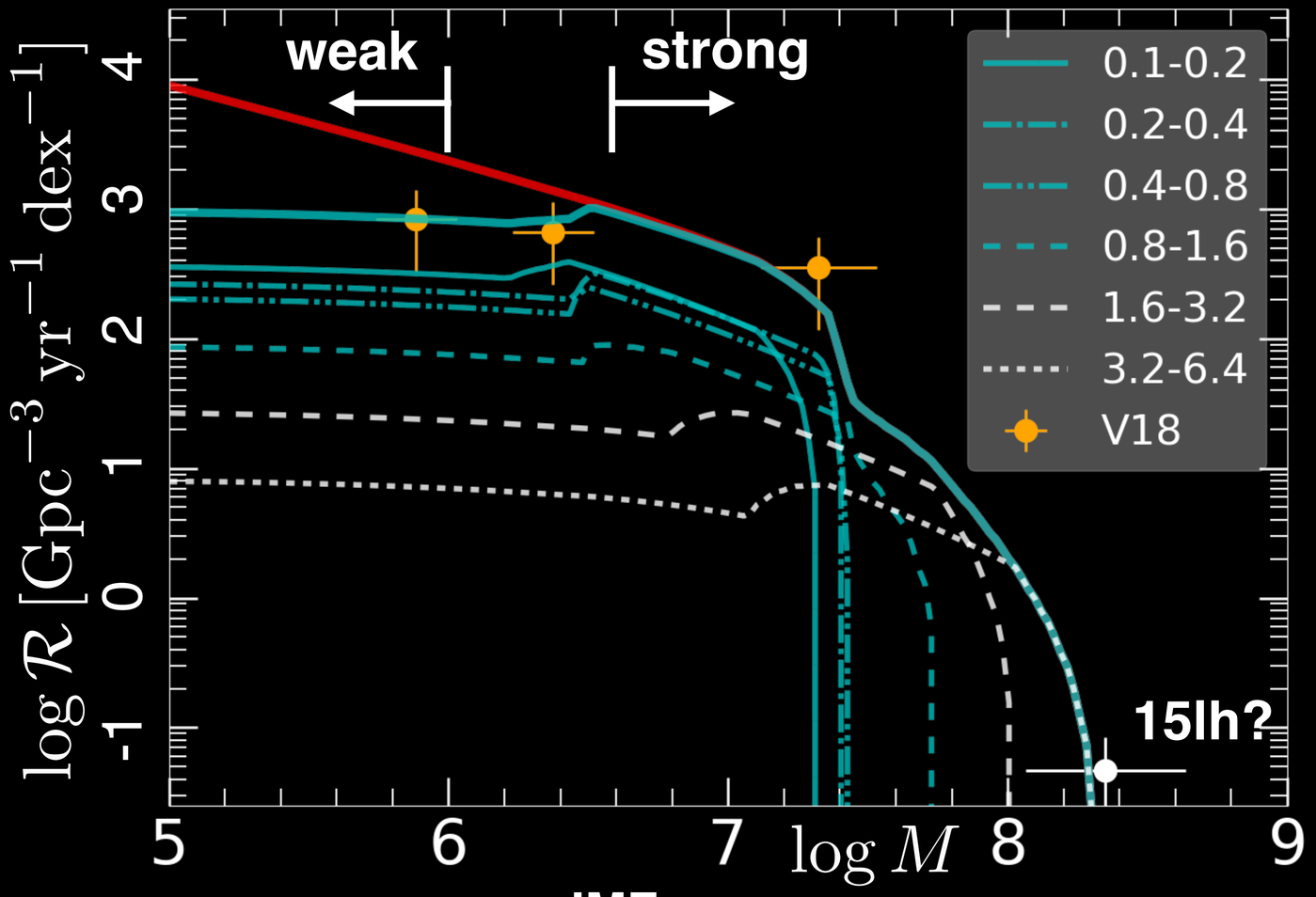
**For $M \lesssim 10^6 M_\odot$**

- ★ Most do not have CIO
- ★ Eddington-limited, soft X-rays

**For $M \sim (10^{6.5}, 10^8) M_\odot$**

- ★ Most optically bright

Note: eROSITA also probes late-time disk accretion



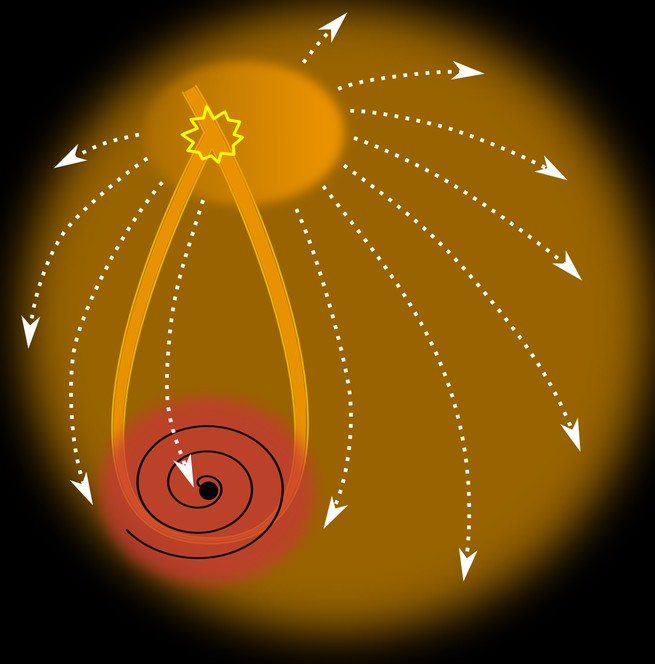

$$\frac{\mathrm{d}\mathcal{R}}{\mathrm{d}M_*\,\mathrm{d}\beta\,\mathrm{dlg}M} \propto M^\alpha \frac{\mathrm{d}N_*}{\mathrm{d}M_*}\frac{\mathrm{d}P}{\mathrm{d}\beta}\frac{\mathrm{d}n_{\mathrm{BH}}}{\mathrm{dlg}M}$$

IMF

Loss-cone dynamics

BH mass function (Merloni+08)

# Summary



## Open Qs addressed:

- **Source of optical emission?**
  - reprocessing by the CIO
  - optically bright for $r_{\rm p} \lesssim 15 r_{\rm g}$
- **X-ray diversity?**
  - viewing-angle effects give $\frac{L_{\rm X}}{L_{\rm opt}} \in (0, \sim 1)$
  - optically faint for $r_{\rm p} \gg 15 r_{\rm g}$
- **Disk formation time?**
  - rapid ← strong intersection
  - slow (?) ← weak intersection

## Future predictions:

- **For $M \lesssim 10^6 M_\odot$**
  - Mostly X-ray bright (eROSITA)
- **For $M \sim (10^{6.5}, 10^8) M_\odot$**
  - Optically bright (ZTF)
  - NIR spectrum $L_\nu \propto \nu^{\sim 0.5}$
  - (Faint) radio emission (~ASSASN-14li)

**Thank you!!**