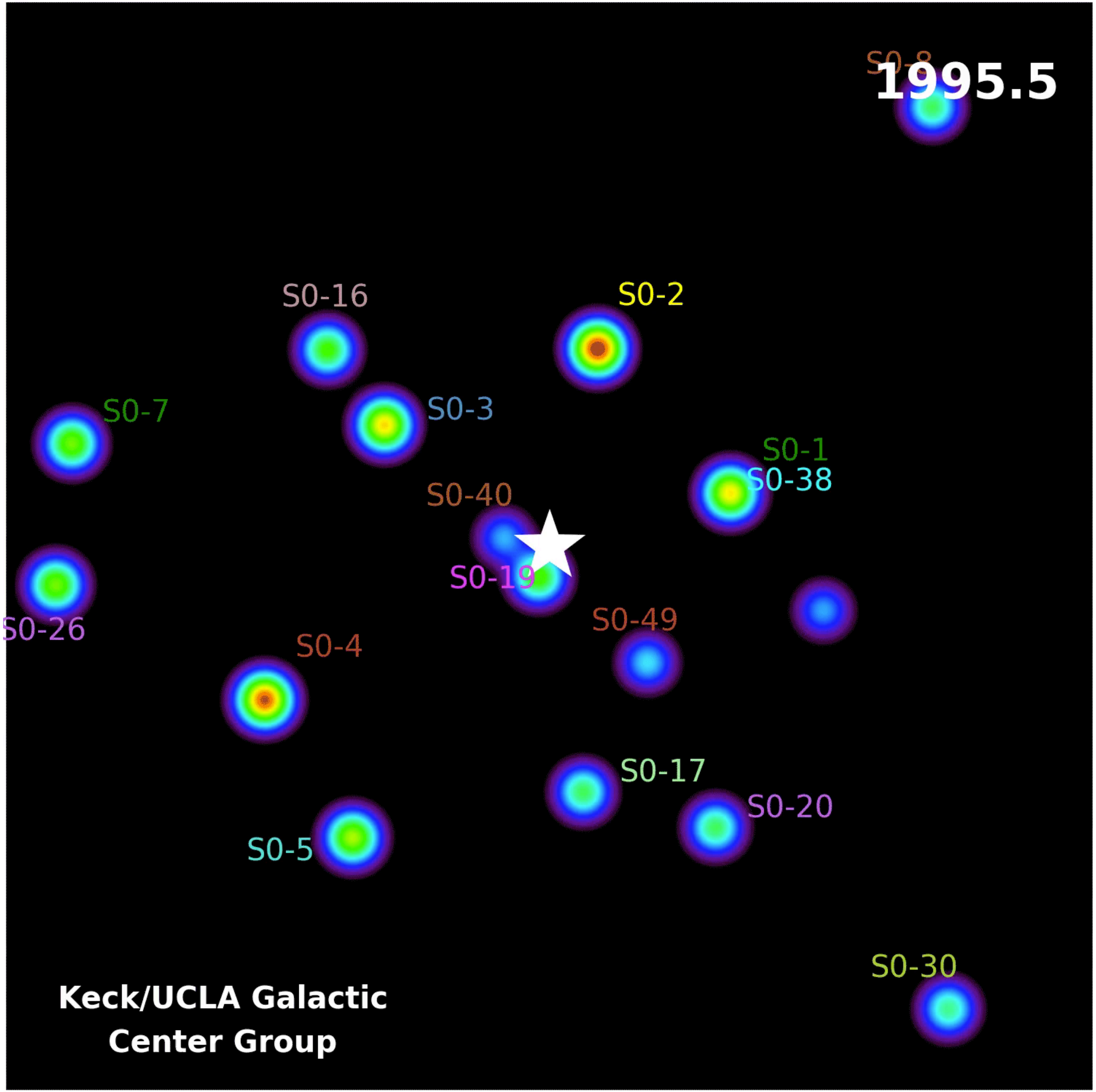
Dynamical Processes in the Galactic Center

Journey to the Galactic Center



>20 years
Stars in our
Galactic Center

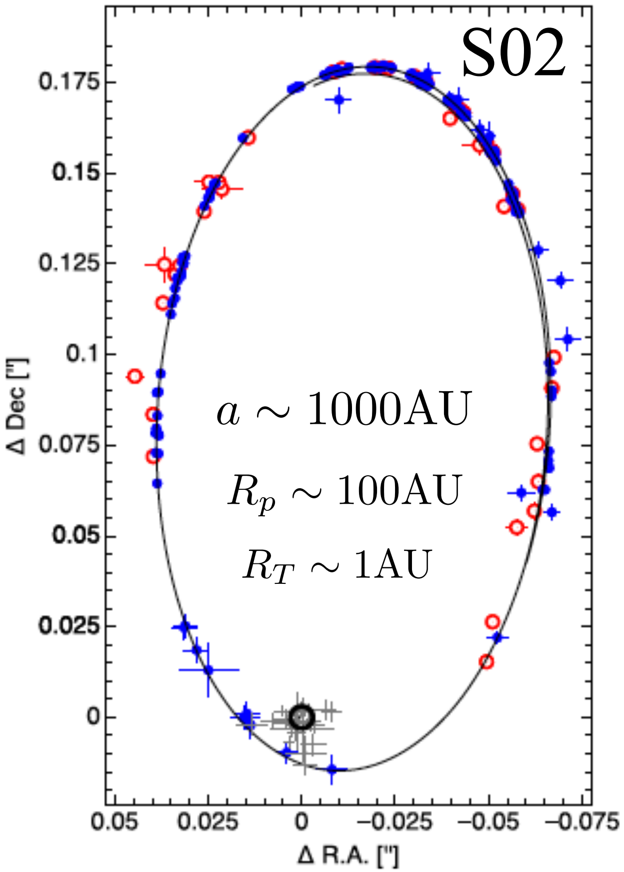
Galactic Center Black Hole - Results

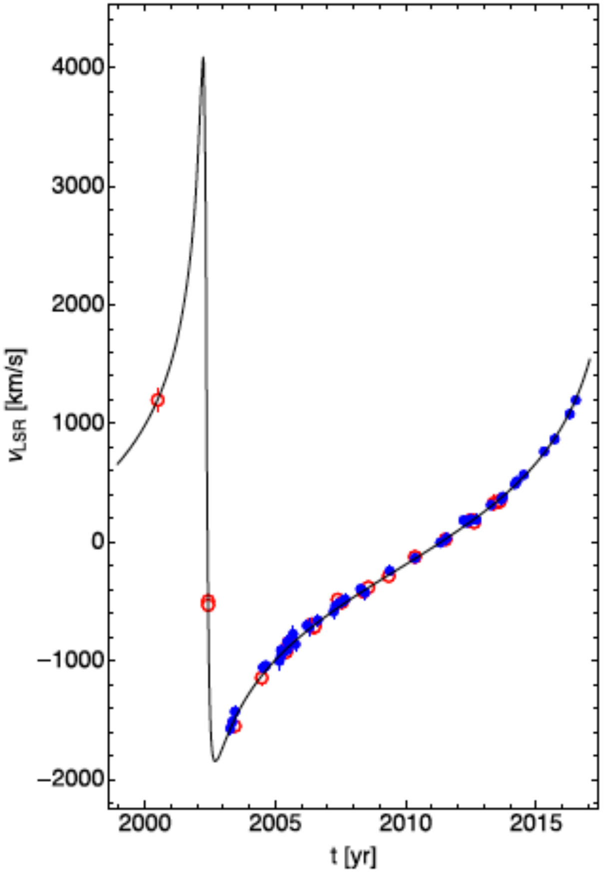
"Proof" for the existence of a black hole

Mass $4.3 \times 10^6 M_\odot$ $R_s \sim 0.1\text{AU}$

distance $27,000$ ly

Future:
precession (~1 years)
BH spin ?



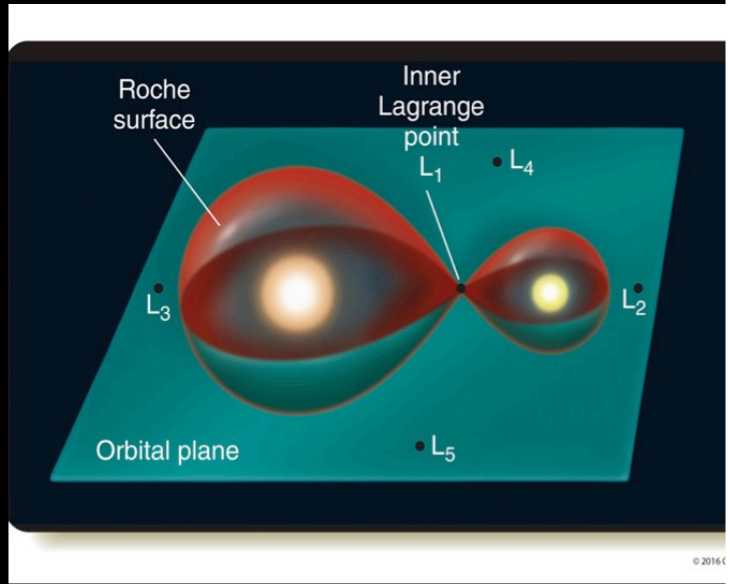


3 phenomena

- Mass transfer to the supermassive black hole.
  - extreme mass ratio inspiral EMRIs
- Tidal Disruption Events.
  - TDEs
- Breakup of binaries produces:
  - Hyper Velocity Stars
  - S- stars

Do they influence each other?

Supermassive Black Holes



Stable Mass Transfer

- Orbit Evolves:
    - Gravitational waves
    - (Tides)
- Mass transfer (L1)
- Radius of object changes

Orbit shrinks

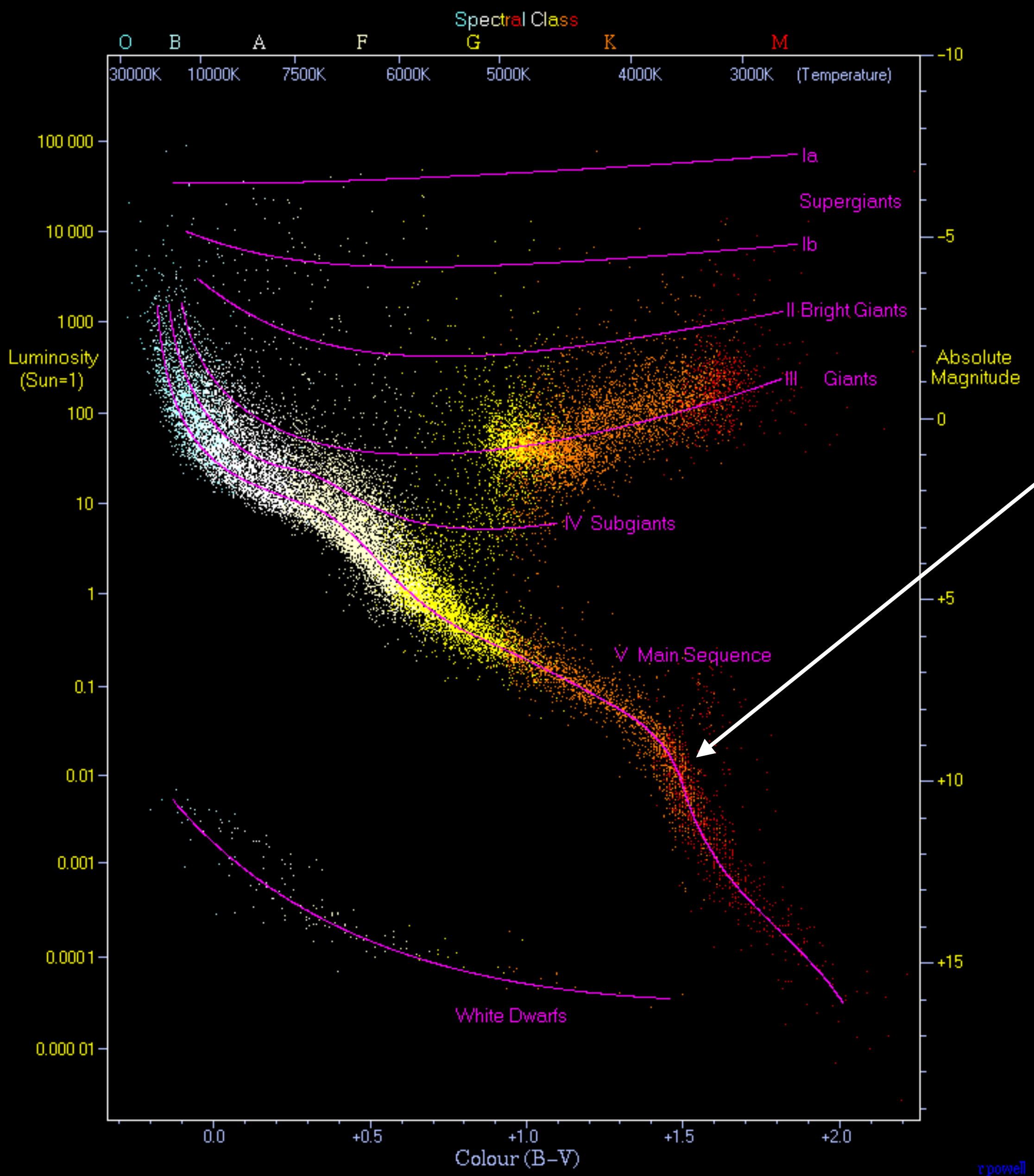
Orbit expands

Orbit evolves to keep Roche lobe just full

$R \propto m^{\epsilon}$

$$\epsilon > -5/3$$

Mass-Radius for Stars



Main Sequence

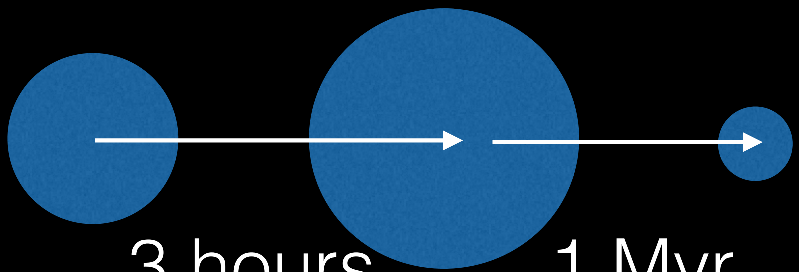
$$R \propto M^{0.8}$$

- Hydrogen Burning
- Constant T~10^7K
- $\frac{GM\mu}{R} \sim kT \quad \rightarrow \quad R \propto M$

Adiabatic Changes

$$\frac{GM^2}{R^4} \sim P \propto \left(M/R^3\right)^{5/3}$$

$$R \propto M^{-1/3}$$



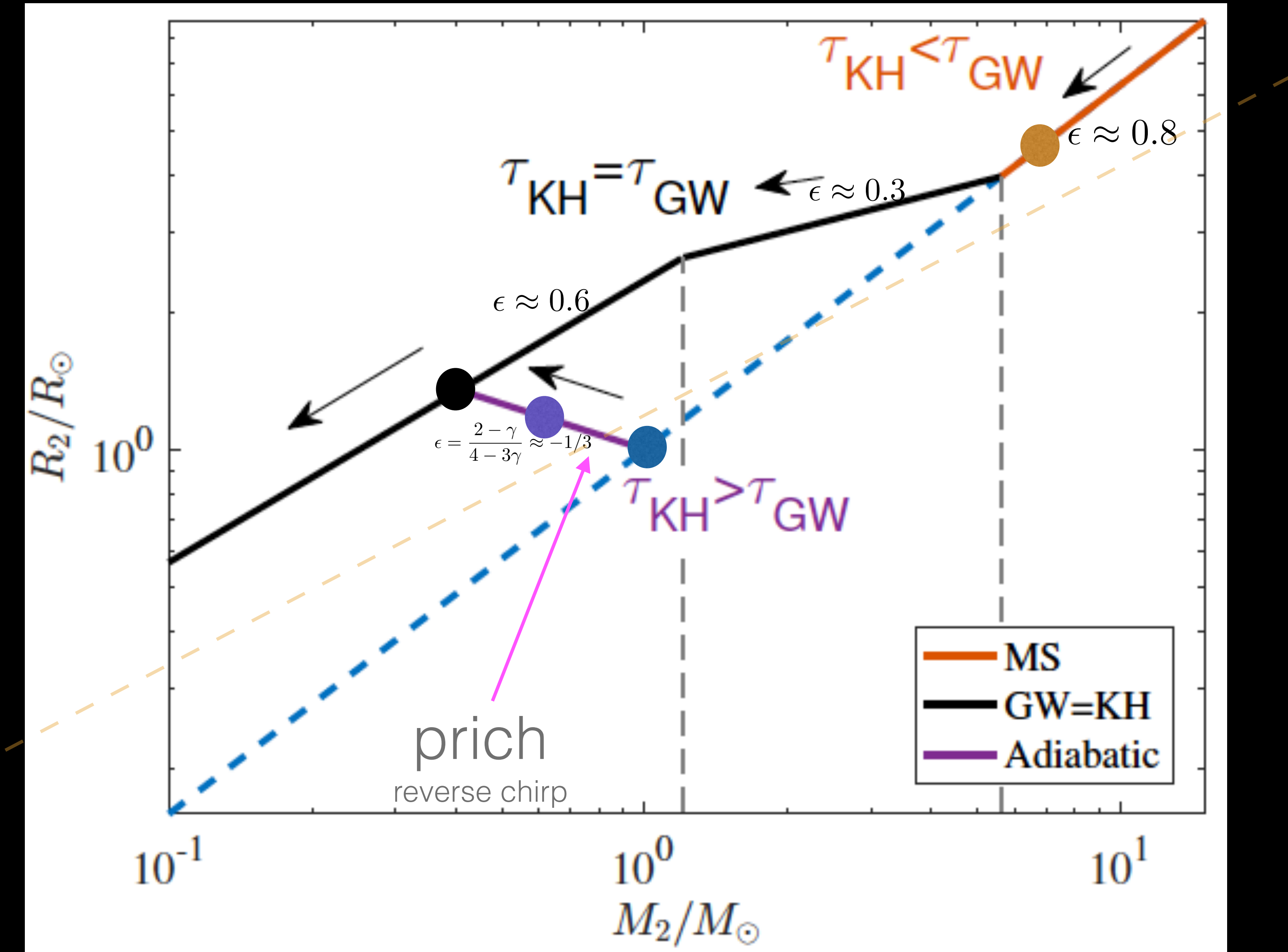
3 hours $\epsilon = -1/3$

1 Myr $\epsilon = +0.8$

Evolution

BH = Sgr A*

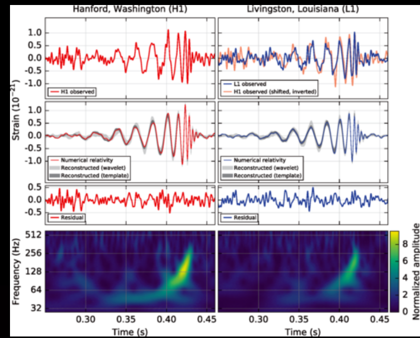
Tgw=0.5Myr

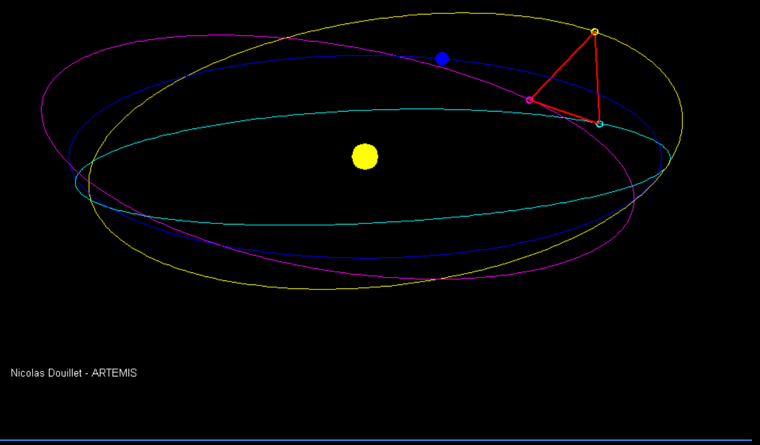


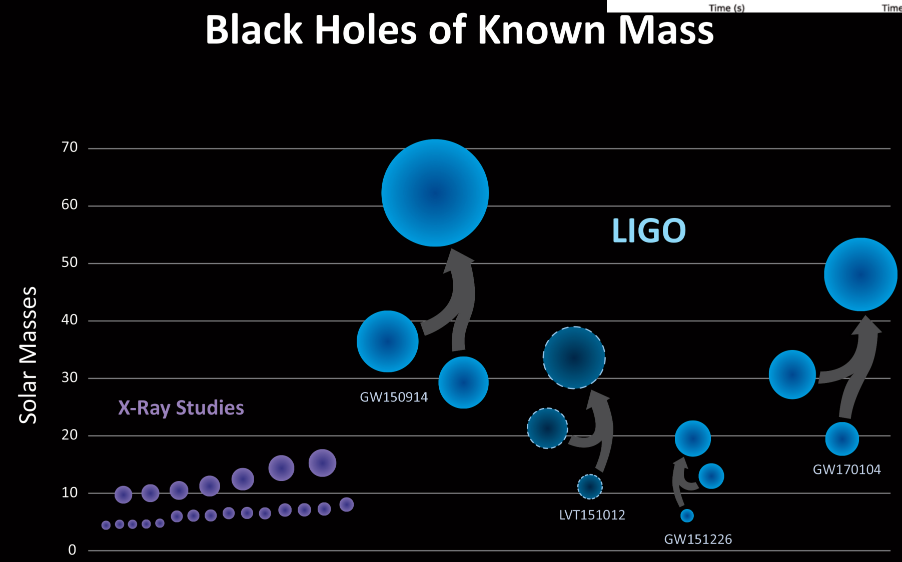
also Dai & Blandford 2013

Gravitational Waves

- Detectable with LISA (but >2030).

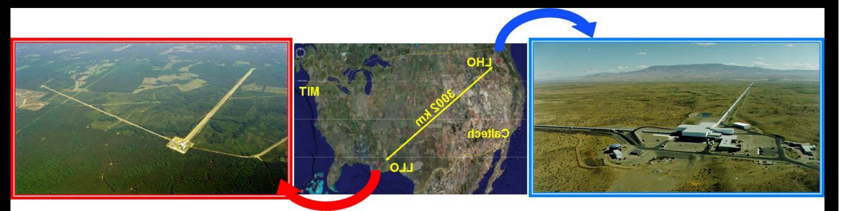


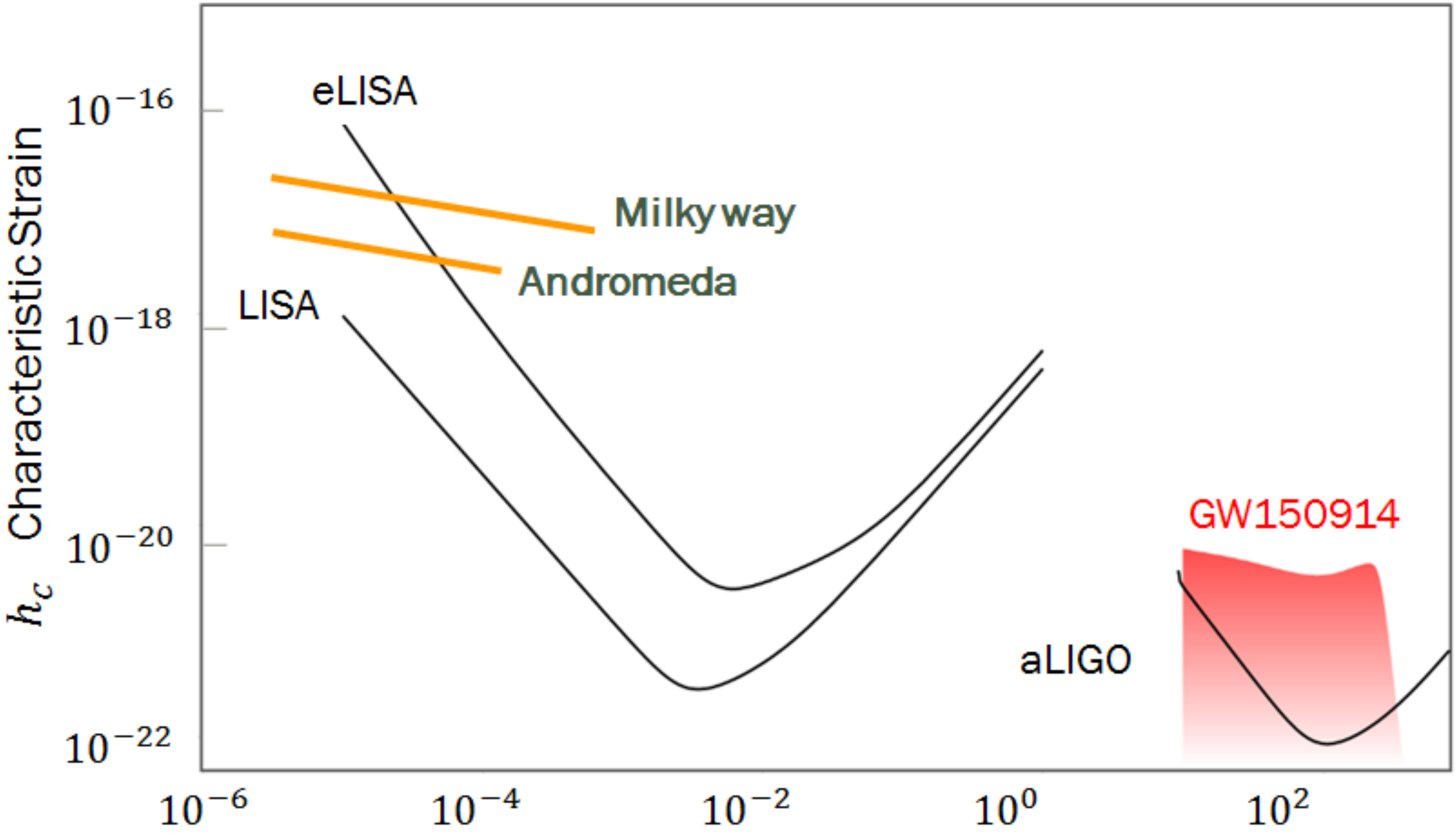




LISA

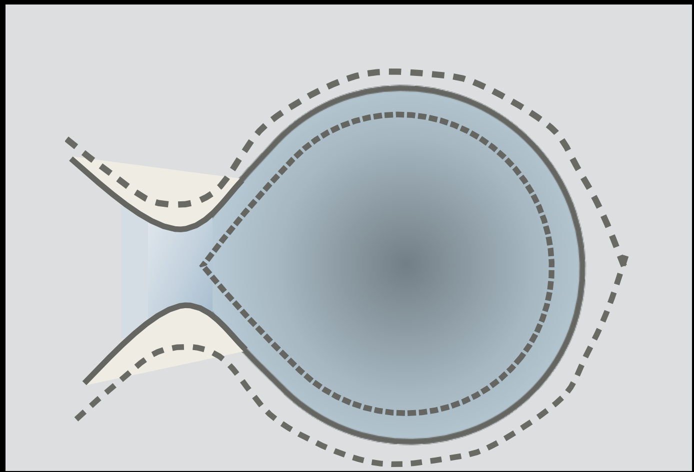
LIGO

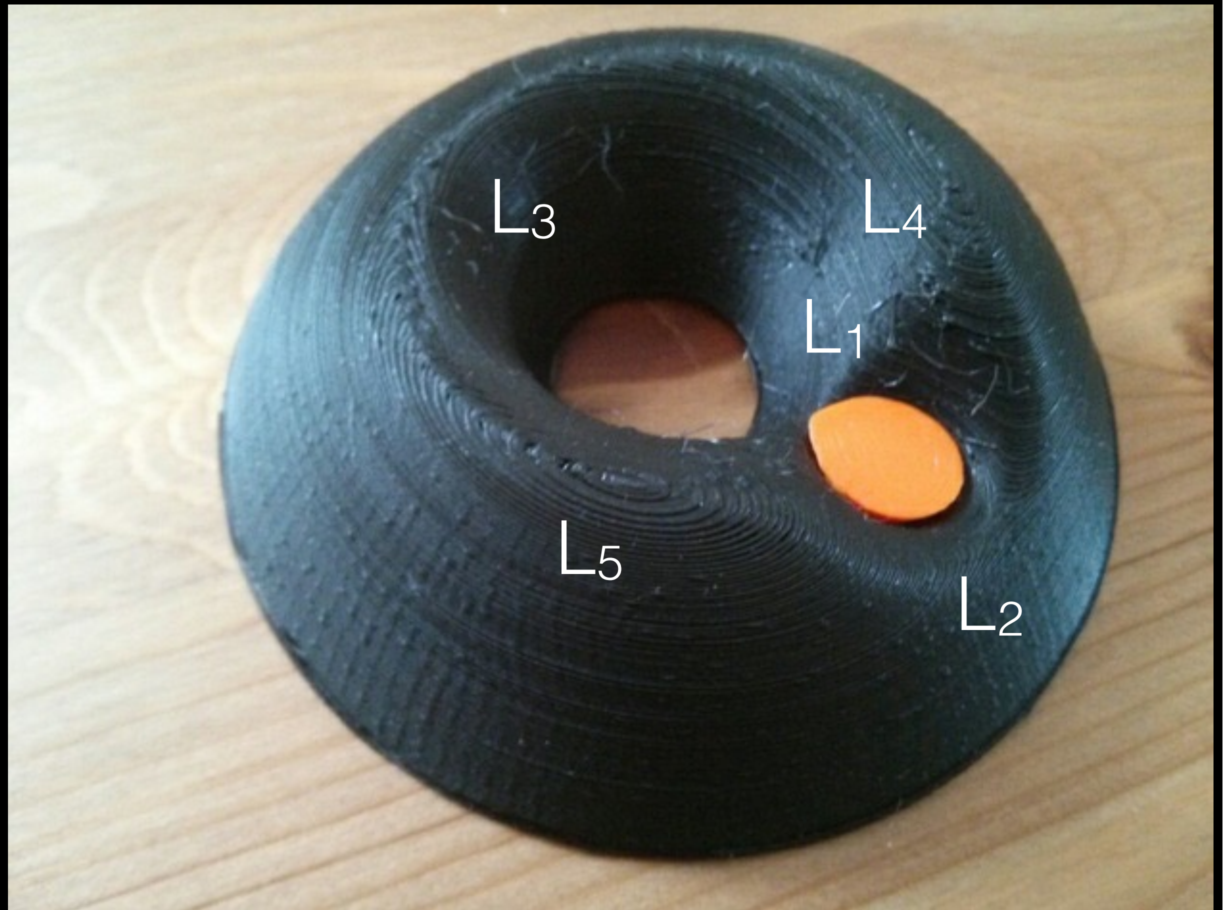




Created with GW plotter http://rhcole.com/apps/GWplotter/

L1 Leakage

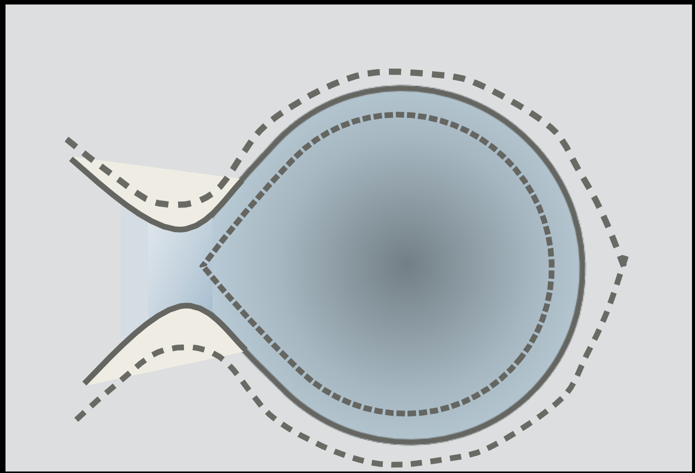


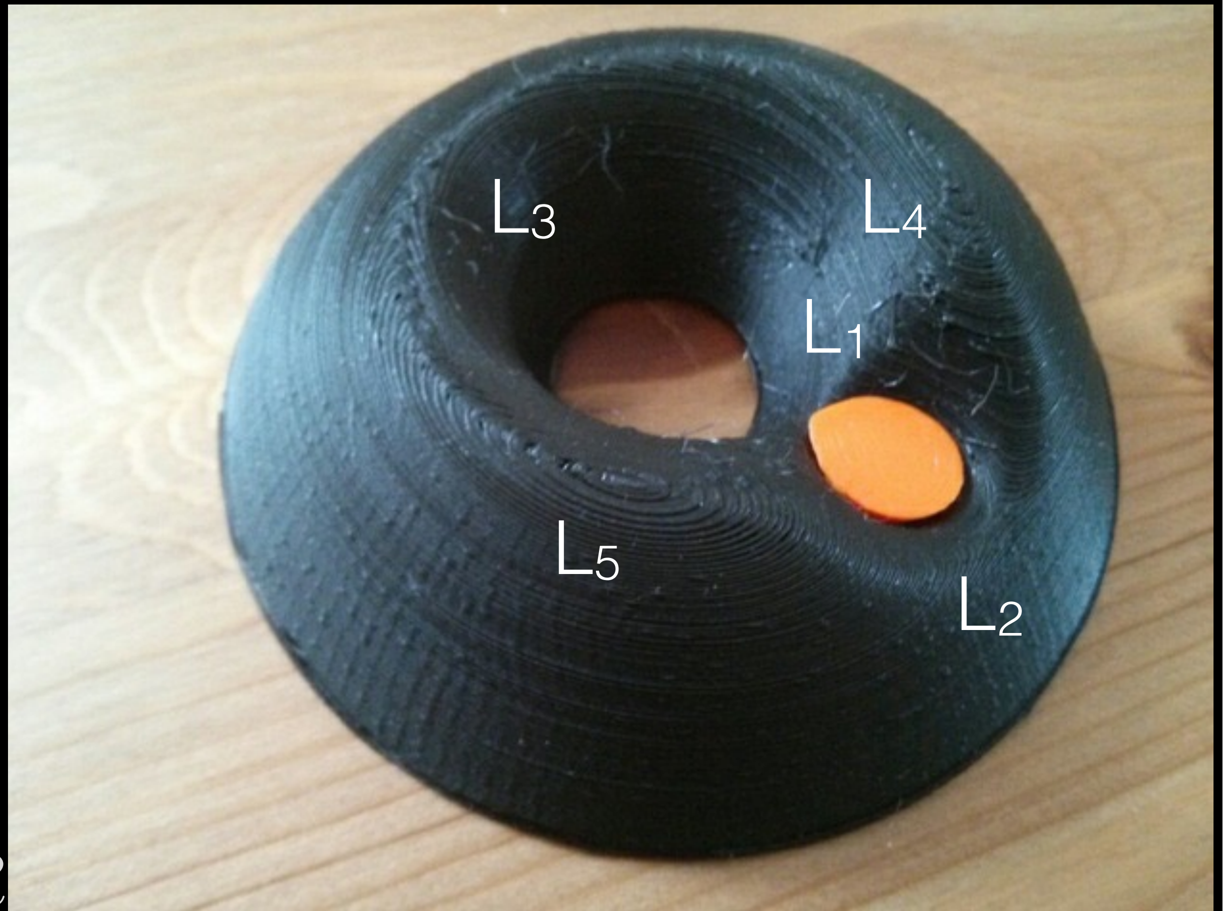


- Nozzle area $R\delta$
- density $\rho \propto \delta^n$
- velocity $v \sim \sqrt{kT/\mu} \propto \delta^{1/2}$
- Mass flow $\dot{M} \propto \delta^{n+3/2}$

$$\frac{\delta}{R} = \left(\frac{\tau_{dyn}}{\tau_{orbit}}\right)^{\frac{1}{n+3/2}}$$

L_2 Leakage ?





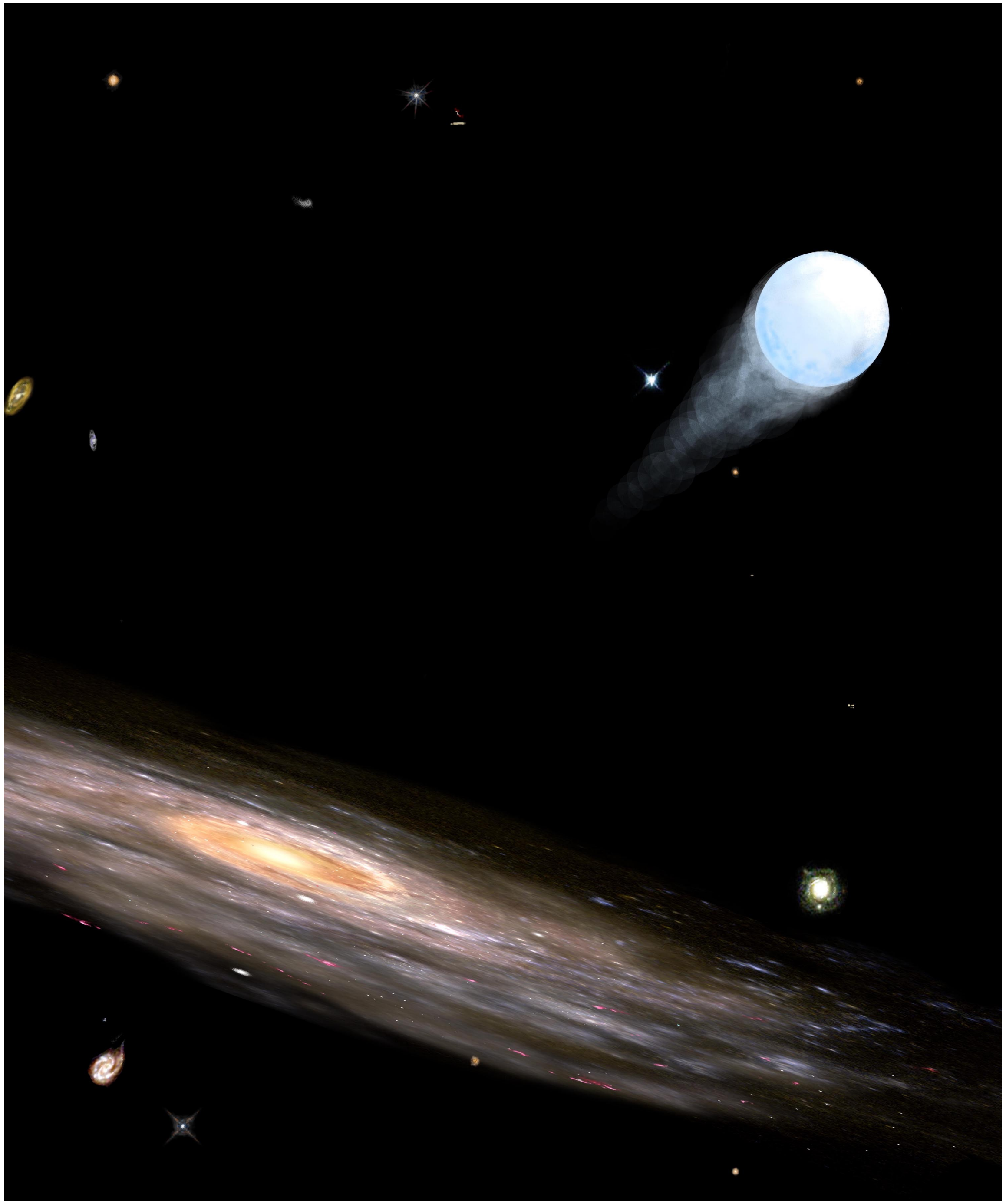
- Mostly L_1 $\dot{M} \propto \delta^{n+3/2}$
- L_1 and L_2 "distance" $q^{1/3}R$
- L_2 leakage if

$$q < \left(\frac{\tau_{dyn}}{\tau_{orbit}}\right)^{\frac{3}{n+3/2}}$$

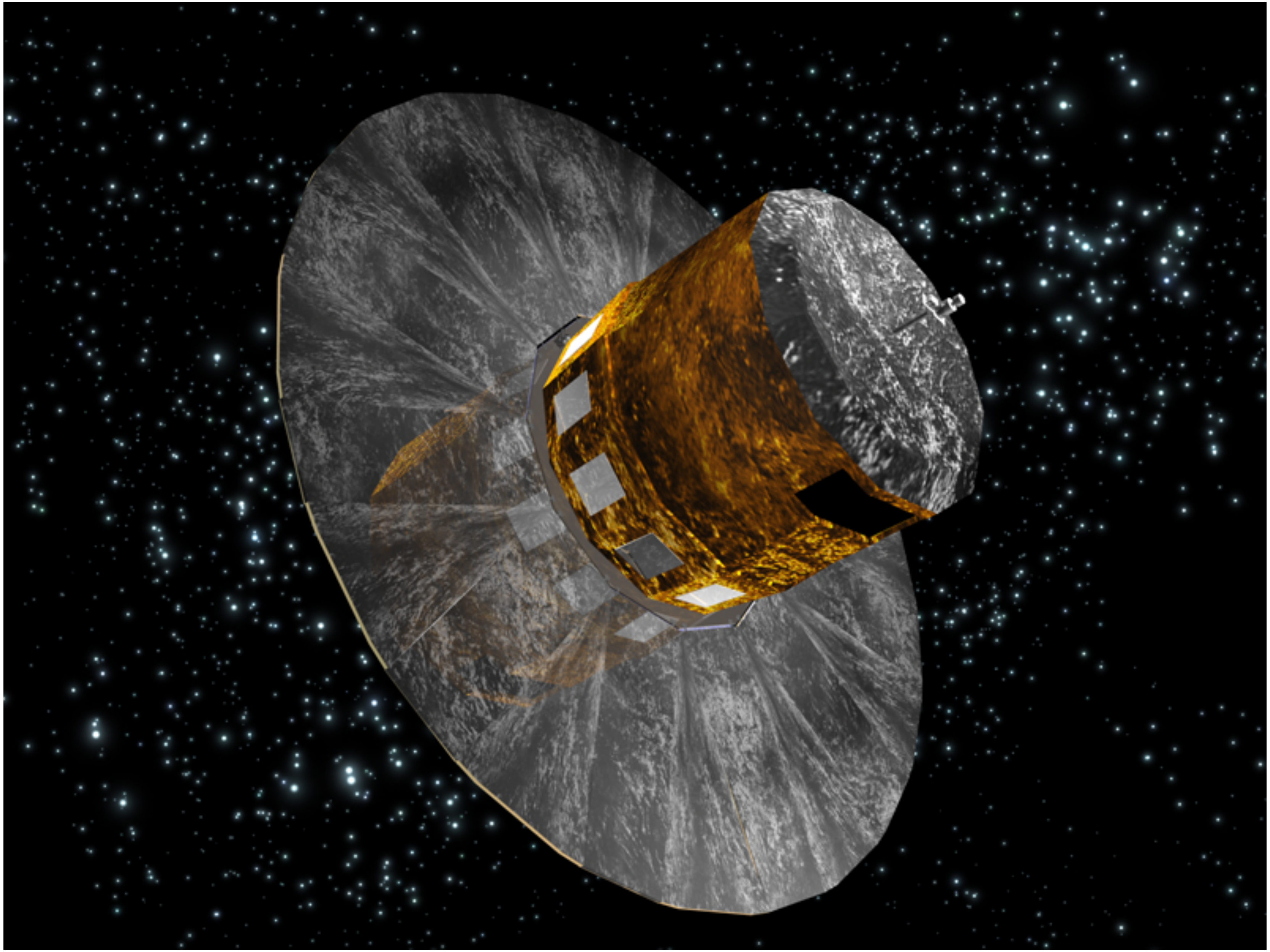
$$\beta^3 < q < \beta^{\frac{15}{n+7/2}} \qquad \beta = \frac{v_{esc}}{c}$$

$$n > 3/2$$

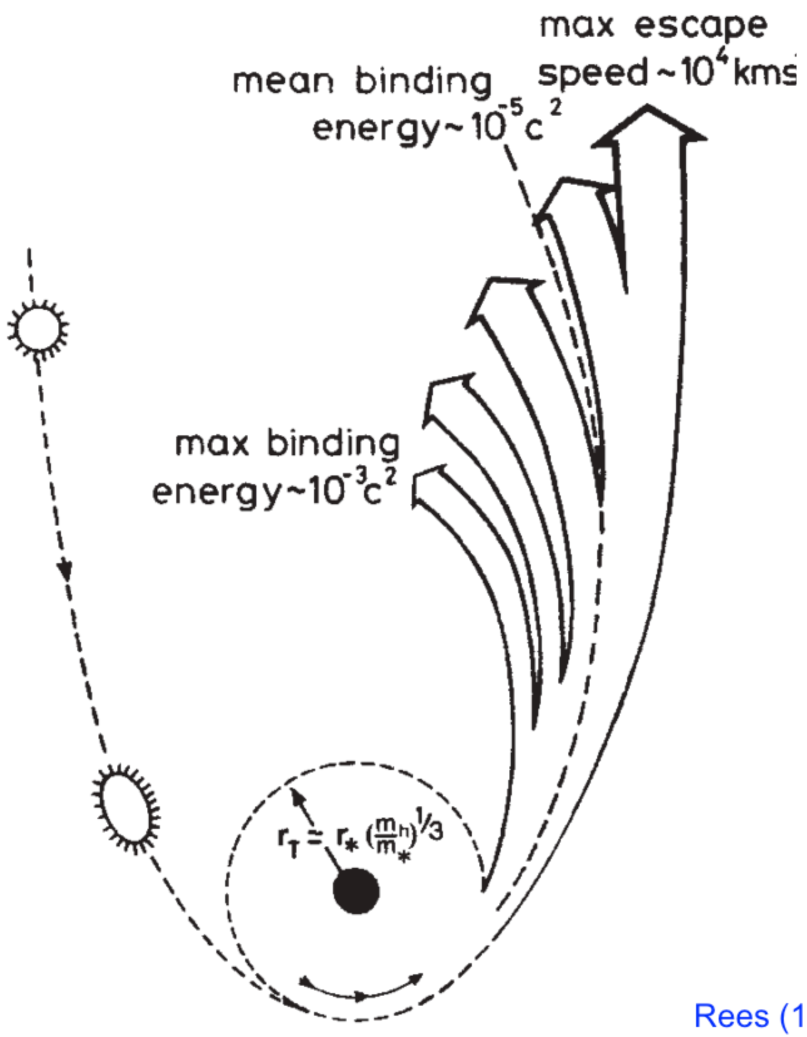
Hyper Velocity Stars



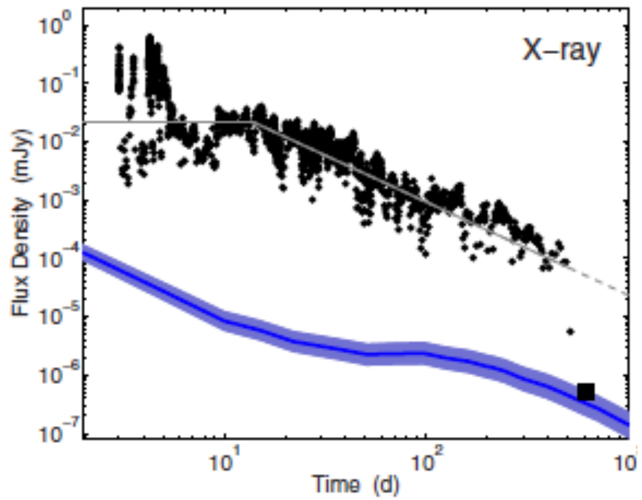
GAIA and HyperVelocityStars



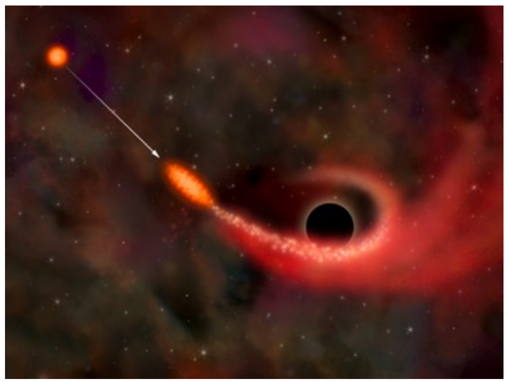
Tidal Disruption of Stars - TDE

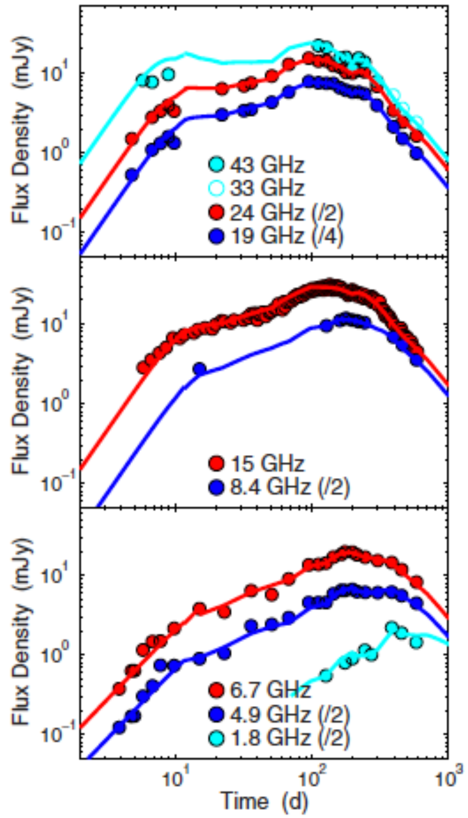


Rees (1988)



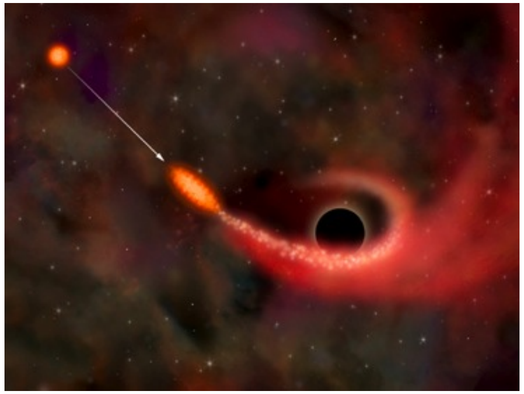
SWIFT J164449.3+573451.





Galactic Tidal Streams vs. TDEs

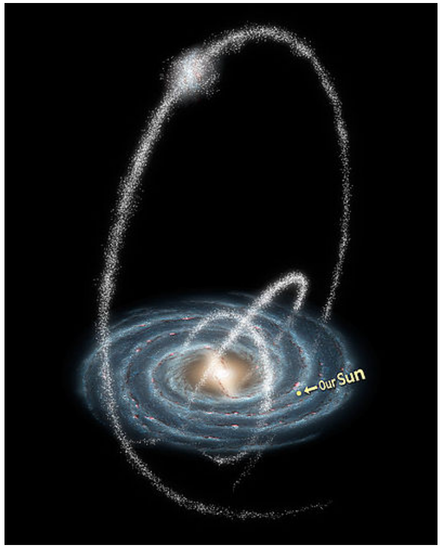
- Tidal streams dE/E <<1



- Tidal Destruction Events dE>>E

$$dE \sim v_{esc} v_{orb,t} \sim \left(\frac{M}{m}\right)^{1/3} v_{esc}^2$$

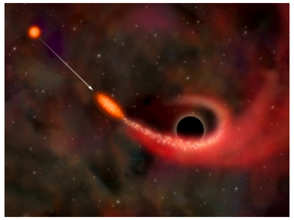
$$E \sim v_{orb,t}^2 \left(a/r_t\right)^{-1} \sim \left(\frac{M}{m}\right)^{2/3} \left(a/r_t\right)^{-1} v_{esc}^2$$



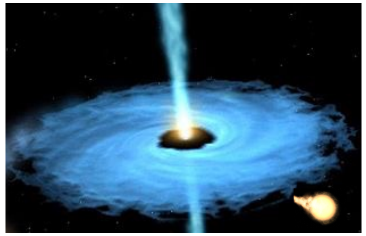
$$\frac{dE}{E} \sim \left(\frac{a}{r_t}\right) \left(\frac{M}{m}\right)^{-1/3}$$

Dynamics of Stars @ Galactic Centers

- What sets the slope of the stellar cusp?
- What is the rate of Tidal Disruption Events?
  - how many deep penetrators?
  - what is the history before disruption?



- What is the rate of Extreme Mass Ratio Inspirals?



- Which events are more common?

$$\frac{\mathcal{R}_{\mathrm{EMRIS}}}{\mathcal{R}_{\mathrm{TDEs}}} = ?$$

Setup

- BH embedded in a thermal bath of stars
- Some given velocity dispersion.
- Radius of influence of black hole: R_h
  - orbital velocity equals velocity dispersion
  - mass of stars equals mass of black hole.
  - we focus on $r<R_h$
- Simplifications:
  - All stars have the same mass
  - Ignore resonant relaxation
  - Spherical symmetry
  - Ignore finite stellar sizes: no collisions, no binary formation.

Slopes

- Peebles: constant stellar flux

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

$$partical\ flux \sim \rho(r) r^3 \times \rho \times \left(\frac{Gm}{v^2}\right)^2 \times v \propto \frac{\rho^2 r^3}{v^3} \propto \rho^2 r^{9/2}$$

- Bahcall-Wolf: constant energy flux

$$Energy\ flux \sim E(r)\rho(r) r^3 \times \rho \times \left(\frac{Gm}{v^2}\right)^2 \times v \propto \rho^2 r^{7/2}$$

$$\rho \propto r^{-7/4}$$

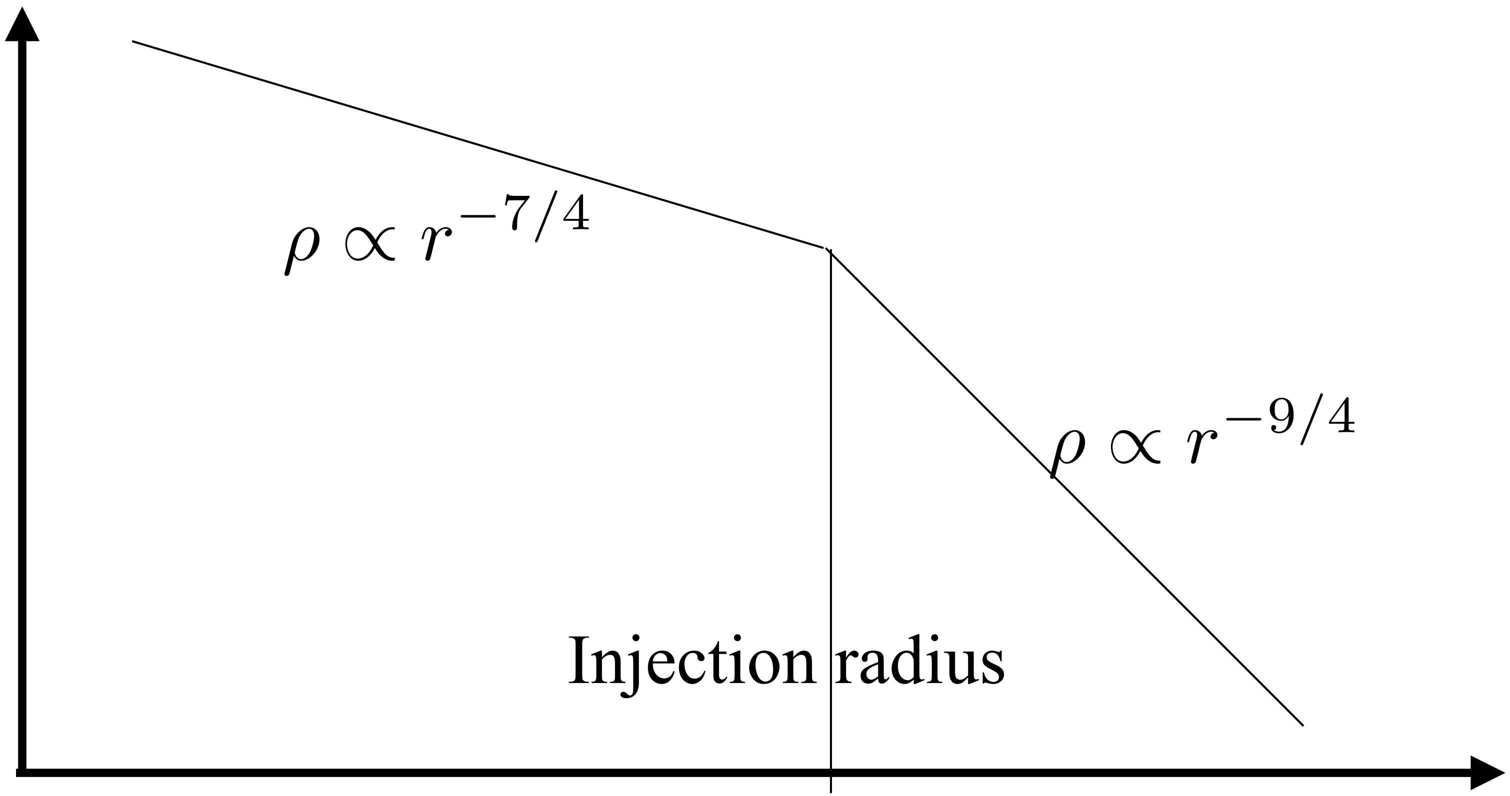
Slopes - Injection @ $r_i < R_h$

- Peebles: constant stellar flux

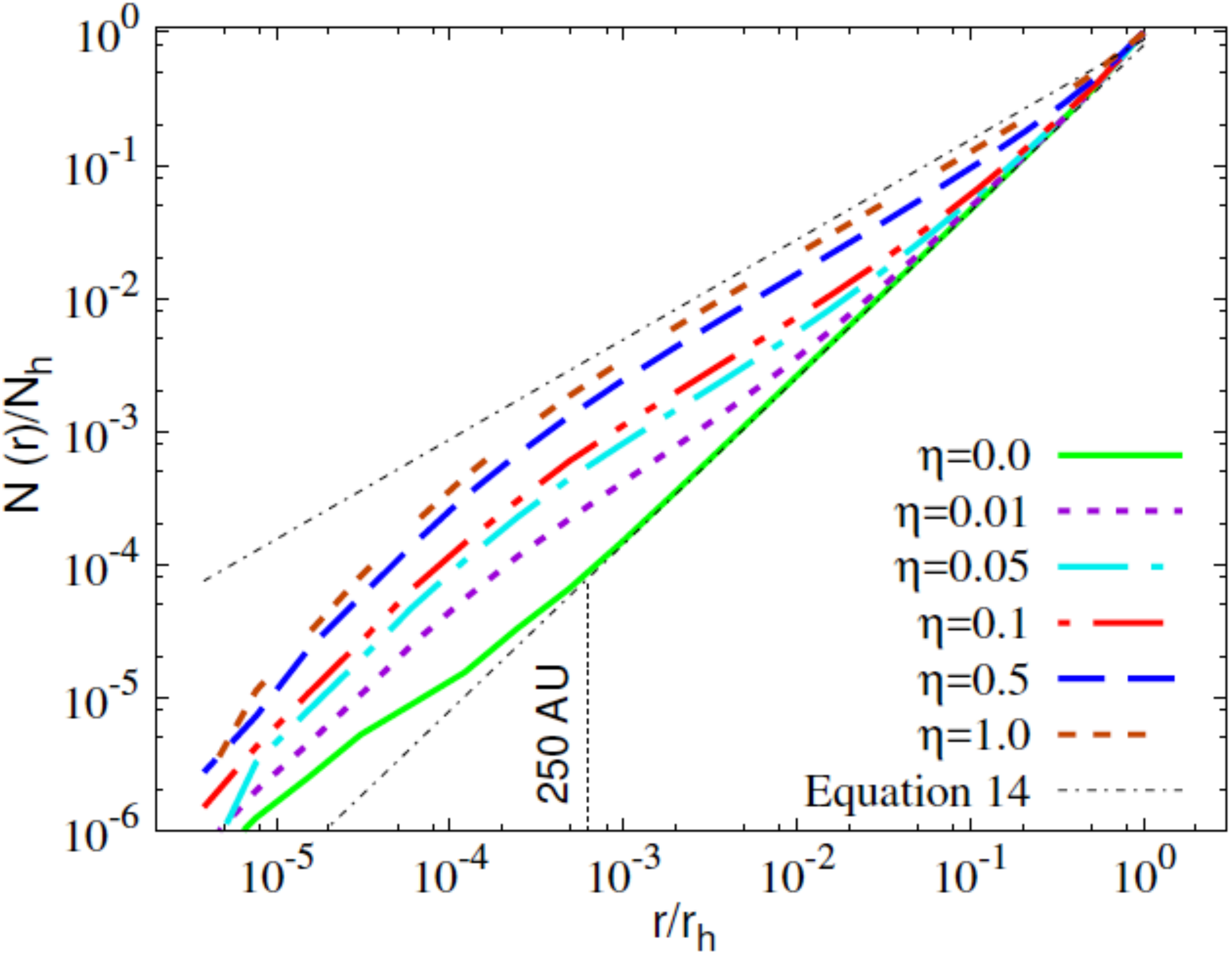
  $$\rho \propto r^{-9/4}$$

- Bahcall-Wolf: constant energy flux

  $$\rho \propto r^{-7/4}$$



Slopes - Injection @ $r_i<R_h$



Giacomo Fragione

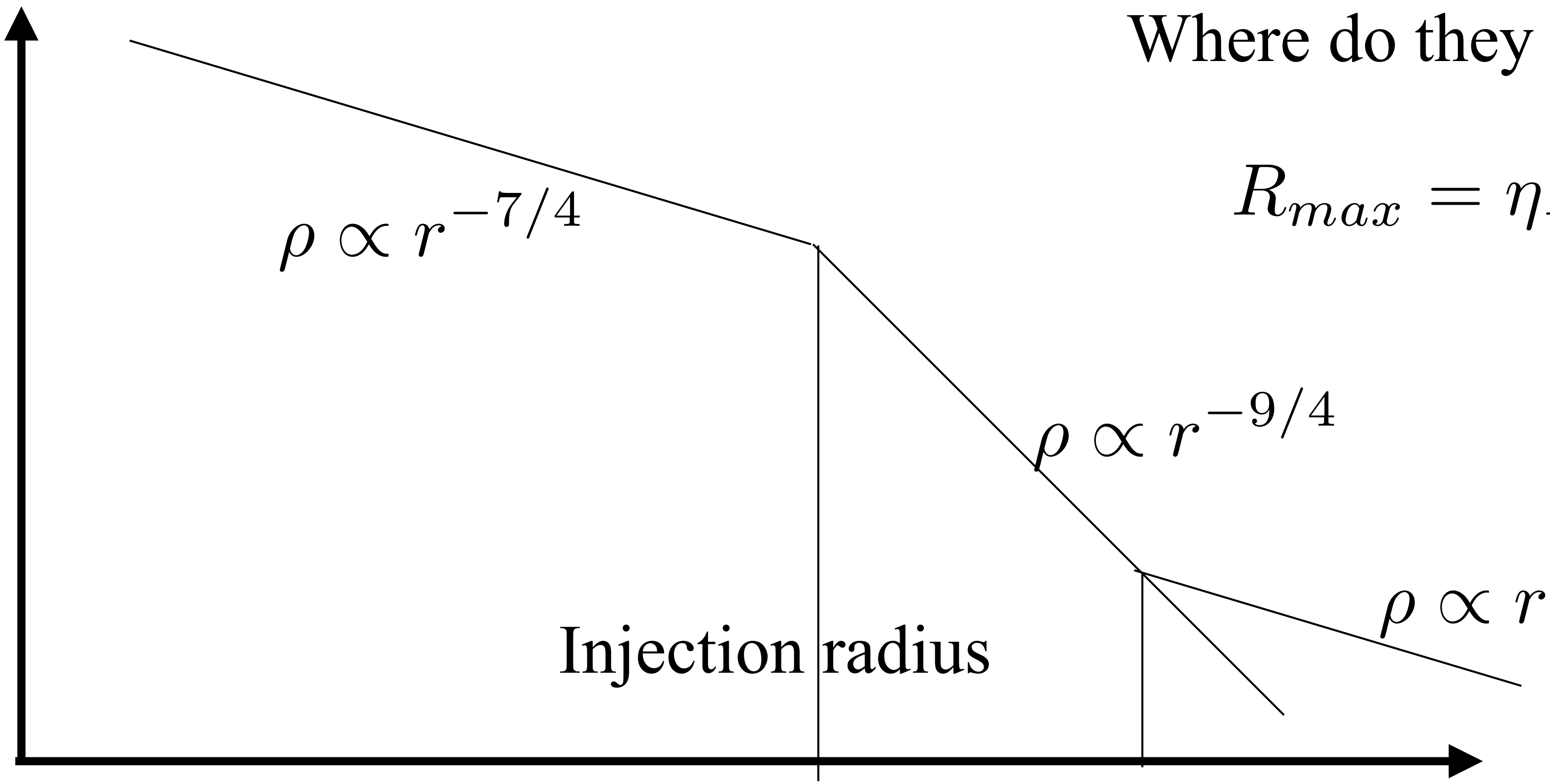
Slopes - Injection @ $r_i < R_h$

- Peebles: constant stellar flux

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

- Bahcall-Wolf: constant energy flux

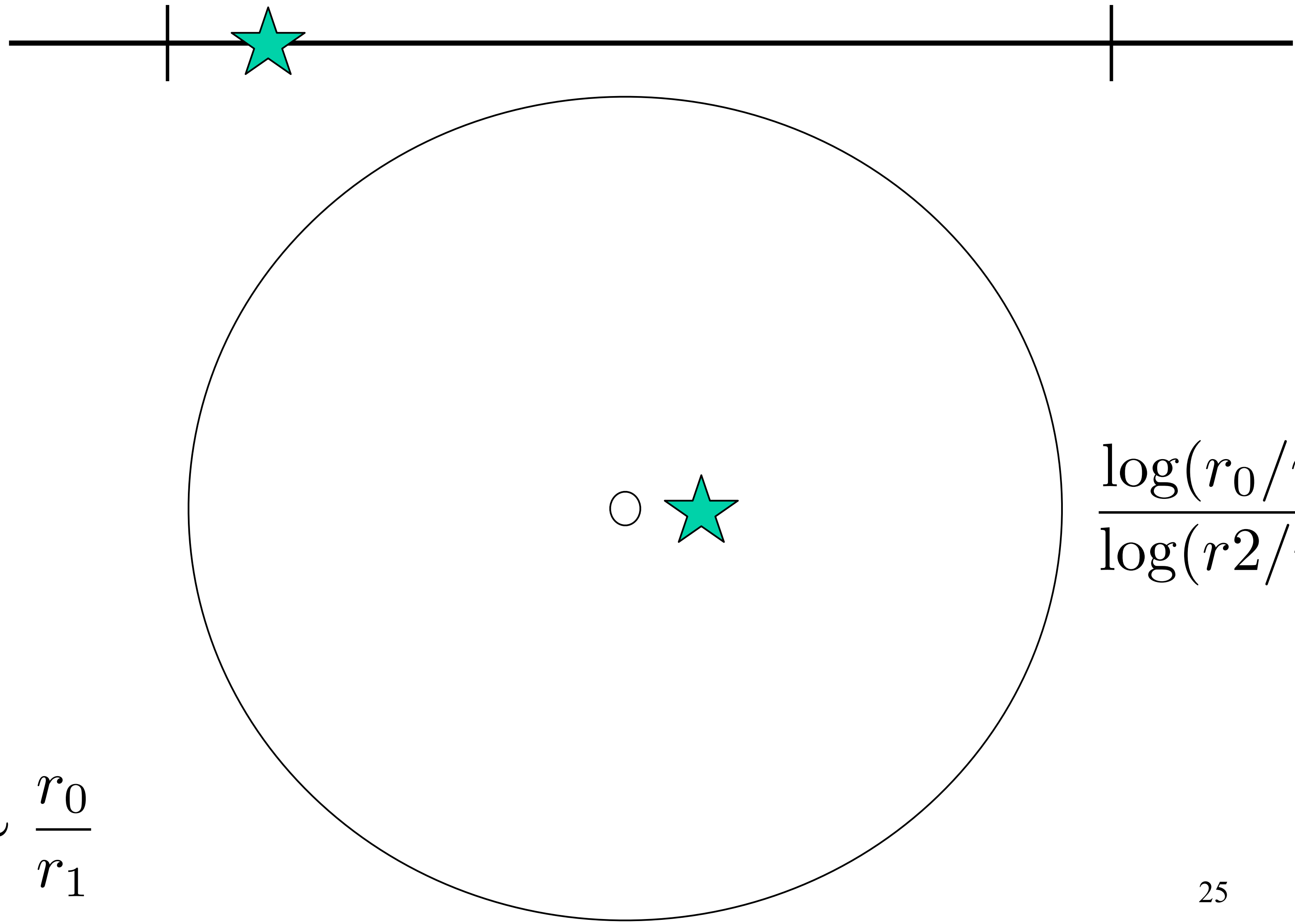
  $\rho \propto r^{-7/4}$



Where do they go?

$$R_{max} = \eta R_h$$

1,2&3D diffusion



1D $\frac{x_1}{x_2}$

2D $\frac{\log(r_0/r_1)}{\log(r2/r_0)} \sim 1$

3D $\sim \frac{r_0}{r_1}$

2 Body Relaxation & The Cusp

- The typical time for significant scattering.

$$T_{rel} = \left[\frac{N(r)}{r^3} \left(\frac{Gm}{v^2} \right)^2 v \right]^{-1} = P(r) \left(\frac{M}{m} \right)^2 N(r)^{-1}$$

- Constant partical flux:

Peebles

$$\frac{N(r)}{T_{rel}} = const. \rightarrow N \propto P(r)^{1/2} \propto r^{3/4} \qquad \rho \propto r^{-9/4}$$

- Constant energy flux:

Bahcall Wolf

$$\frac{E(r)N(r)}{T_{rel}} = const. \rightarrow N \propto r^{1/2} P(r)^{1/2} \propto r^{5/4} \quad \rho \propto r^{-7/4}$$

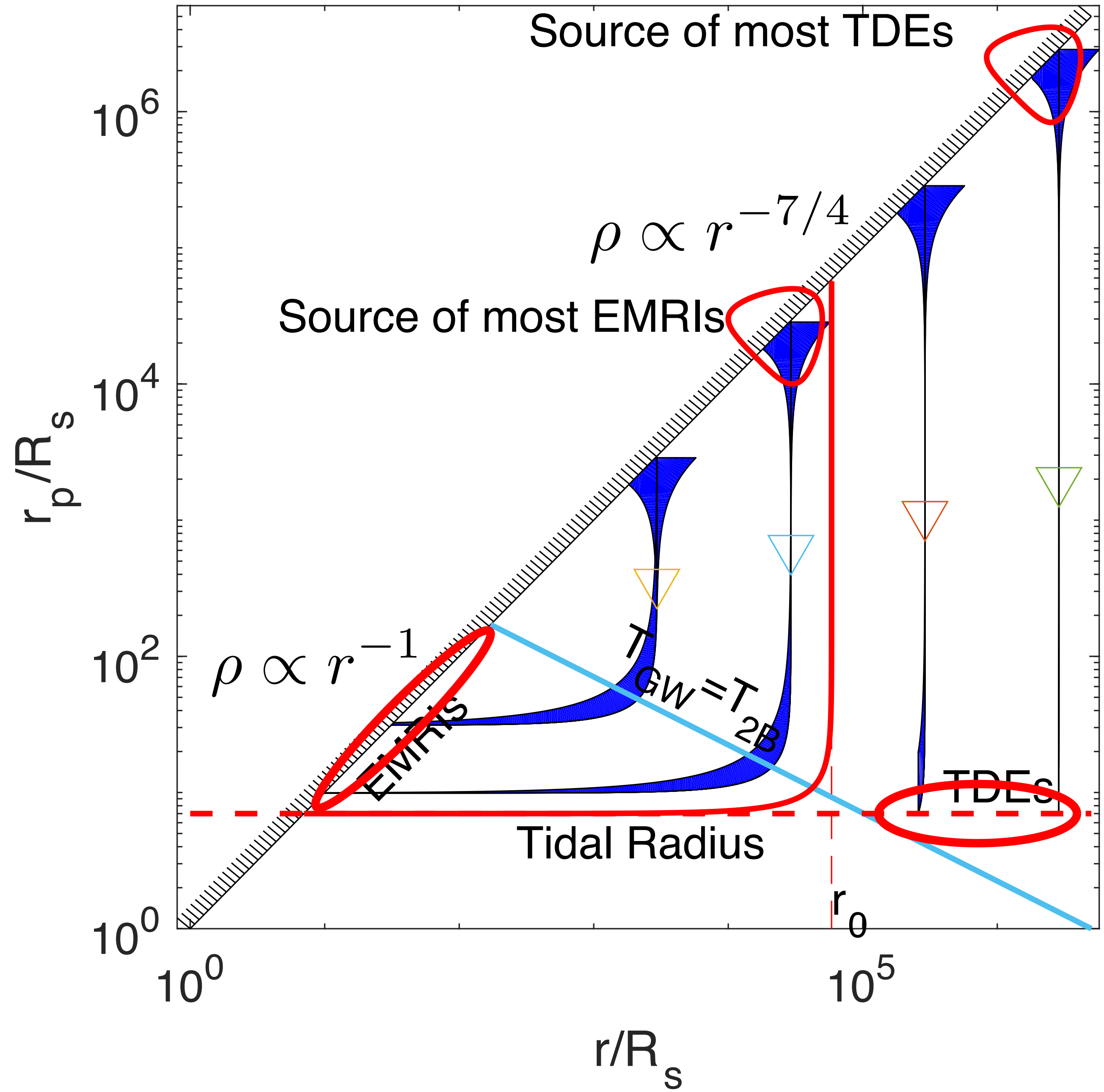
Gravitational Waves & Eccentric Orbits

$$T_{GW} = \frac{R_s}{c}\frac{M}{m}\left(\frac{r_p}{R_s}\right)^4\left(\frac{r}{r_p}\right)^{1/2}$$

$$T_{2B} = \frac{R_s}{c}\left(\frac{M}{m}\right)^2 N(r)^{-1}\left(\frac{r}{R_s}\right)^{3/2}\frac{r_p}{r}$$

$$T_{GW} = T_{2B} \quad \rightarrow \quad r_p = R_s\left(\frac{r}{R_h}\right)^{-1/2}$$

Scatterings & Gravitational Waves



$$r_0 = R_h \left(\frac{R_s}{R_t} \right)^2$$

$$\frac{\mathcal{R}_{\rm EMRIS}}{\mathcal{R}_{\rm TDEs}} = \left(\frac{R_s}{R_T} \right)^2$$

$\sim 1\%$

Galaxy mass
Stellar mass
Compact objects

Resonant Relaxation

- Related to **secular theory** in planetary dynamics.
- Not important close to Rh (fast precession by other stars)
- Not important close to Rs (fast precession due to GR)
- May farther decrease

$$\frac{\mathcal{R}_{EMRIS}}{\mathcal{R}_{TDEs}}$$

Two times 4 million in The Milky Way

- Stars compared to black hole

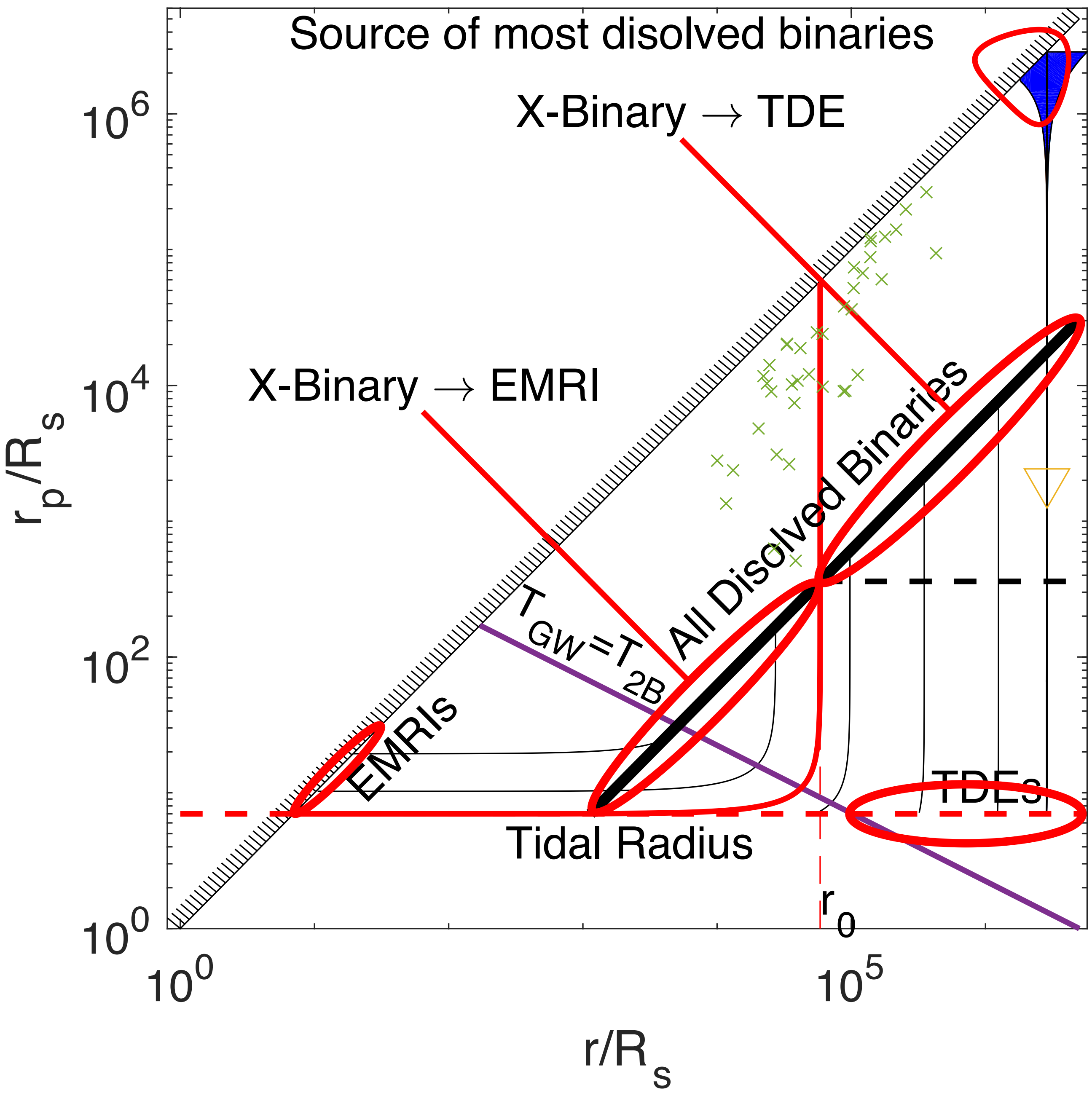
$$\frac{M}{m} \sim 4 \times 10^6$$

- Radius of influence compared to Schwarzschild.

$$\frac{R_h}{R_s} \sim 4 \times 10^6$$

$$\frac{R_p}{a_b} \sim \left(\frac{M}{m}\right)^{1/3} \sim 100 \qquad \frac{a_{survive}}{r_t} \sim \left(\frac{M}{m}\right)^{1/3} \sim 100$$

Scatterings + GW + BINARIES



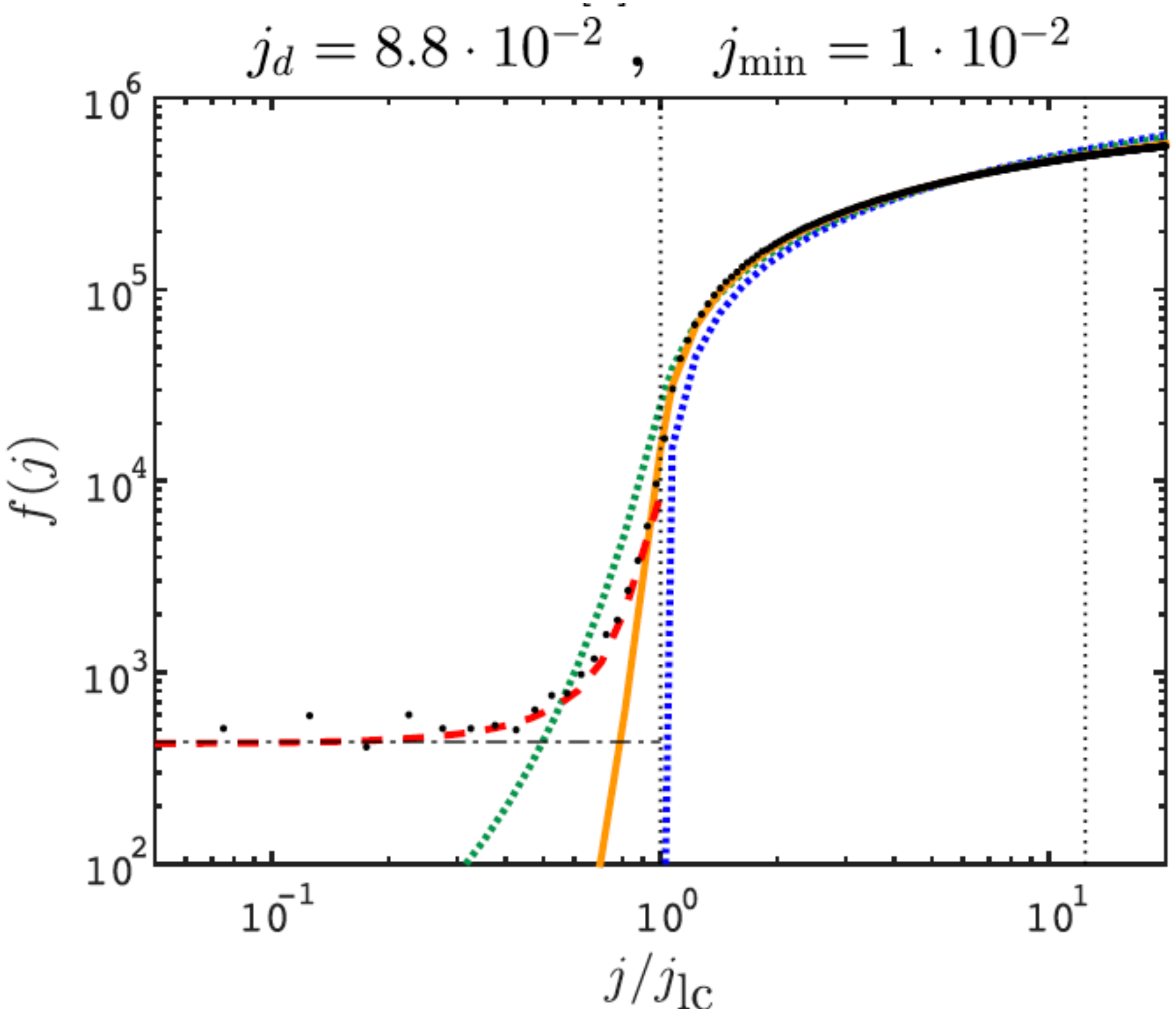
$$r_0 = R_h \left(\frac{R_s}{R_t}\right)^2$$

$$\frac{\mathcal{R}_{\rm EMRIS}}{\mathcal{R}_{\rm TDEs}} = \eta_b$$

~10%

Empty Loss Cones

- Deep penetrators
  - common in full loss cone
  - extreme compression inside tidal radius
  - shock breakout/nuclear reactions.
- How common in empty loss cone?
- Rare large kicks.



Amir Weisbein

Summary

- Stellar density slopes
  - particle flux $\rho \propto r^{-9/4}$
  - energy flux $\rho \propto r^{-7/4}$
- Breakup of Binaries:
  - Creates hyper velocity stars
  - Injects stars deep in the BH potential
- Bound broken binary stars:
  - source of most EMRIs.
  - Creates outward stellar flux.
  - Steeper cusp slope.
- Emris Gravitational Wave signal:
  - Both chirp and prich
  - Reflects stellar properties.
  - More than prev. thought.