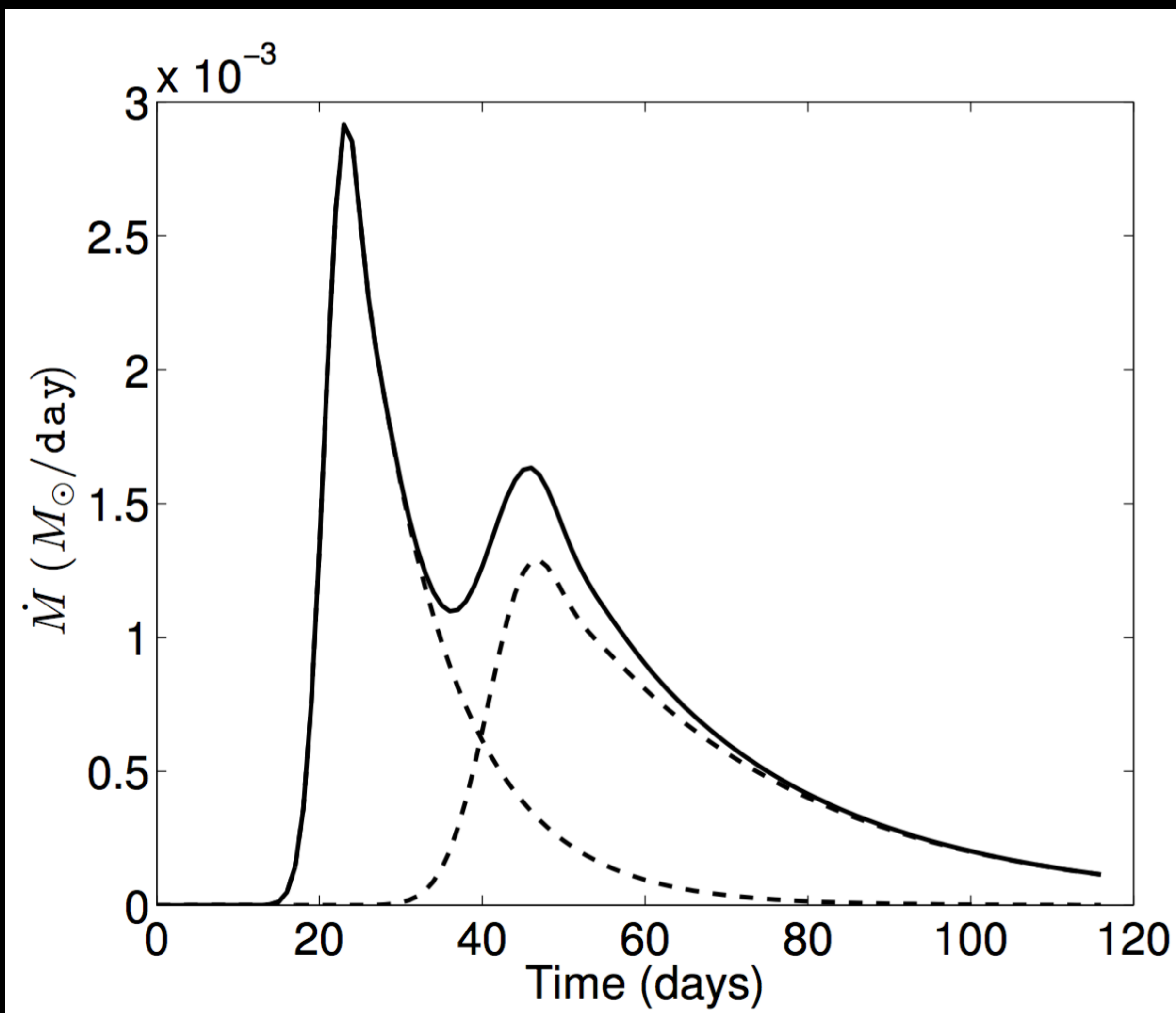
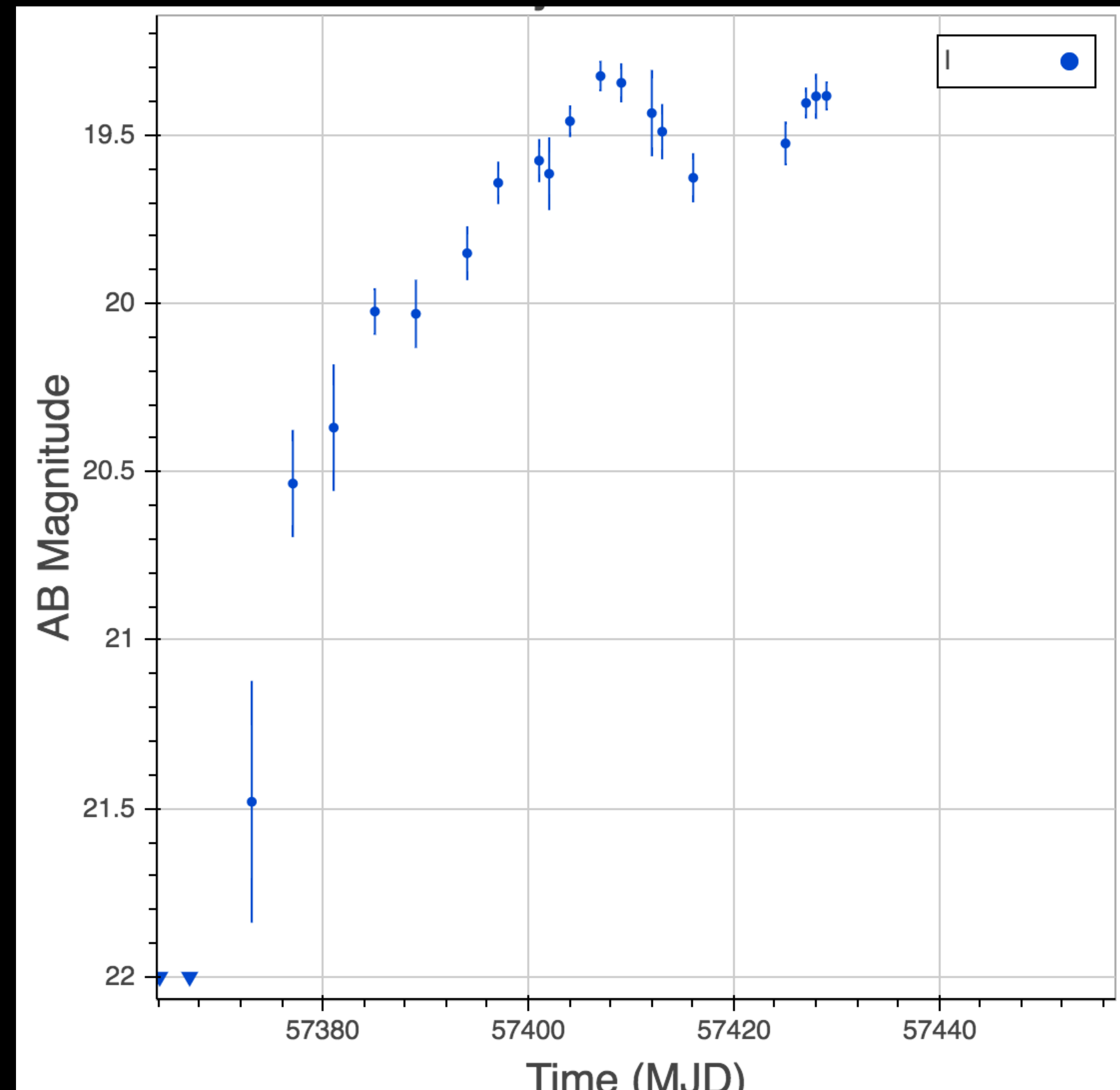


x 10^-3
$\dot{M}$ ($M_\odot$/day)
Time (days)



AB Magnitude
Time (MJD)

Unbound debris streams and remnants from tidal disruptions in the Galactic Center

Speaker: James Guillochon (Harvard)

Collaborators:
Mike McCourt (UCSB), Xian Chen (PUC-Chile),
Michael Johnson (Harvard), Edo Berger (Harvard)

This talk: 1509.08916
Companion paper: 1512.06124 (Gamma rays from UDS)

Blender visualization: 1602.03178

How do tidal disruptions work?

Schwarzschild Radius

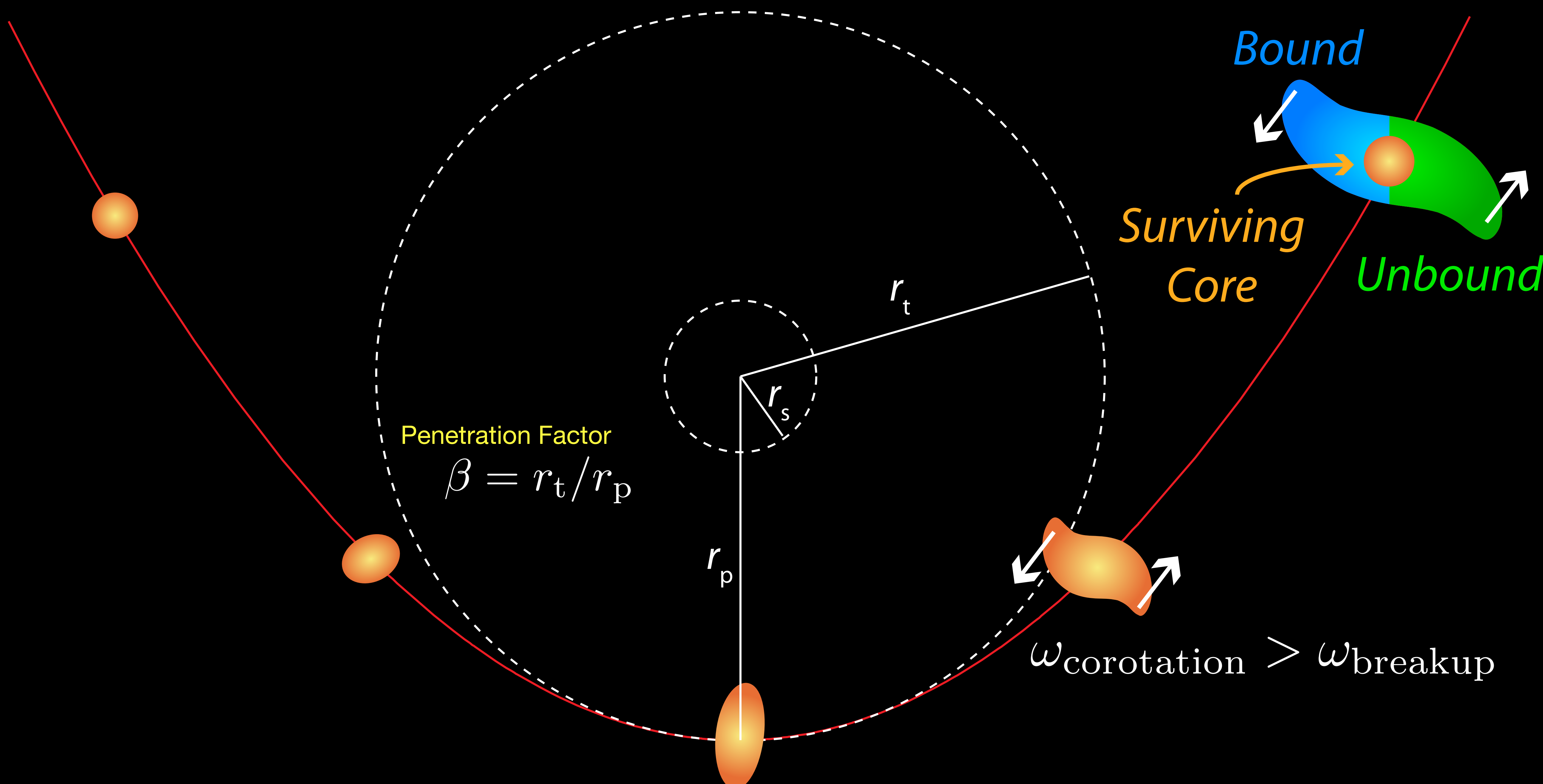
$$r_s = 3 \times 10^{11} M_6 \text{ cm}$$

Tidal Radius

$$r_t = 7 \times 10^{12} \left(\frac{r_*}{r_\odot}\right) \left(\frac{M_*}{M_\odot}\right)^{-1/3} M_6^{1/3} \text{ cm}$$

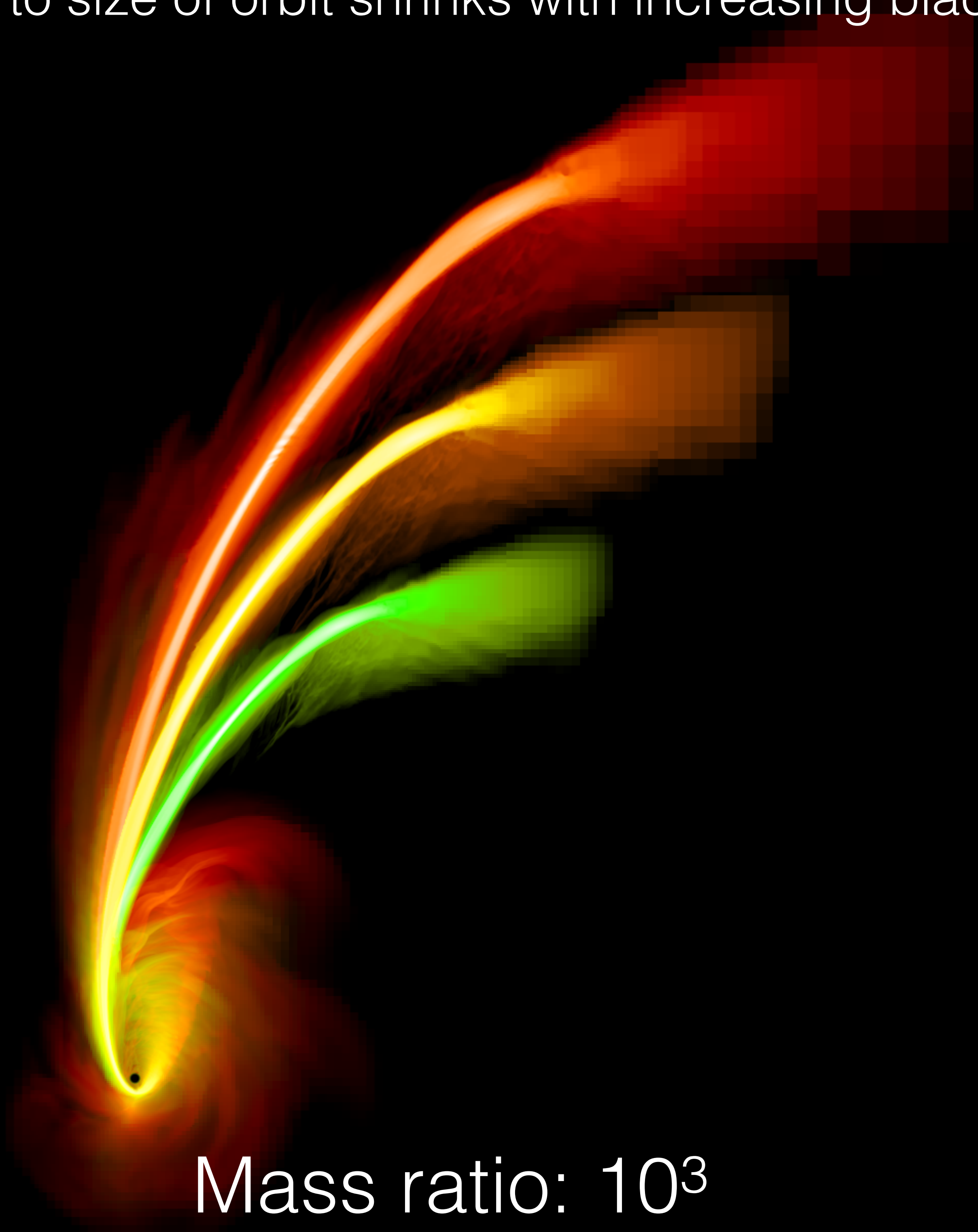
Penetration Factor

$$\beta = r_t / r_p$$

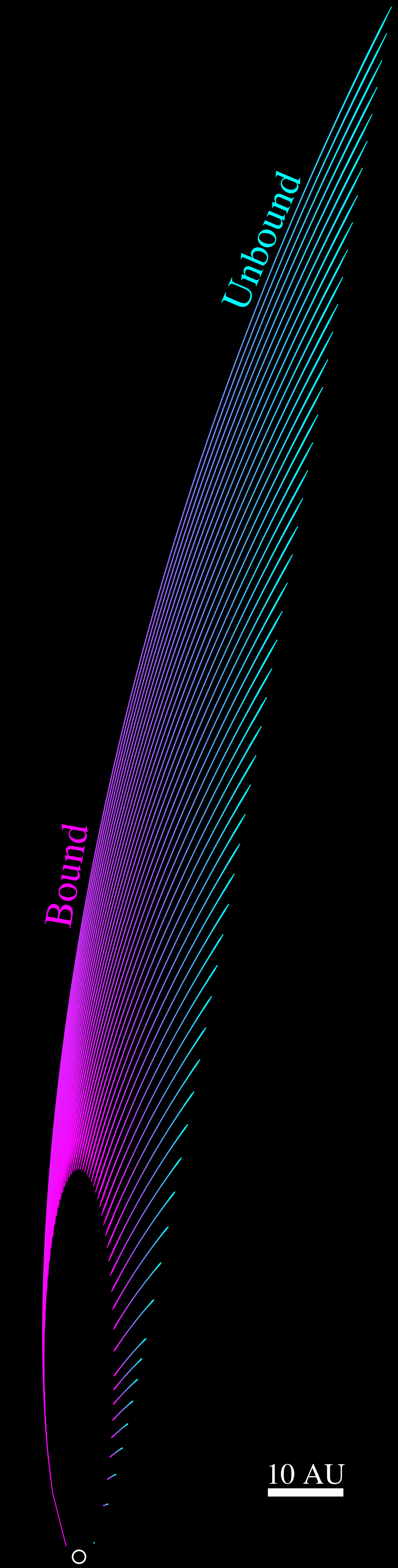


How do tidal disruptions work?

Because tidal radius grows with mass, width of stream compared to size of orbit shrinks with increasing black hole mass.

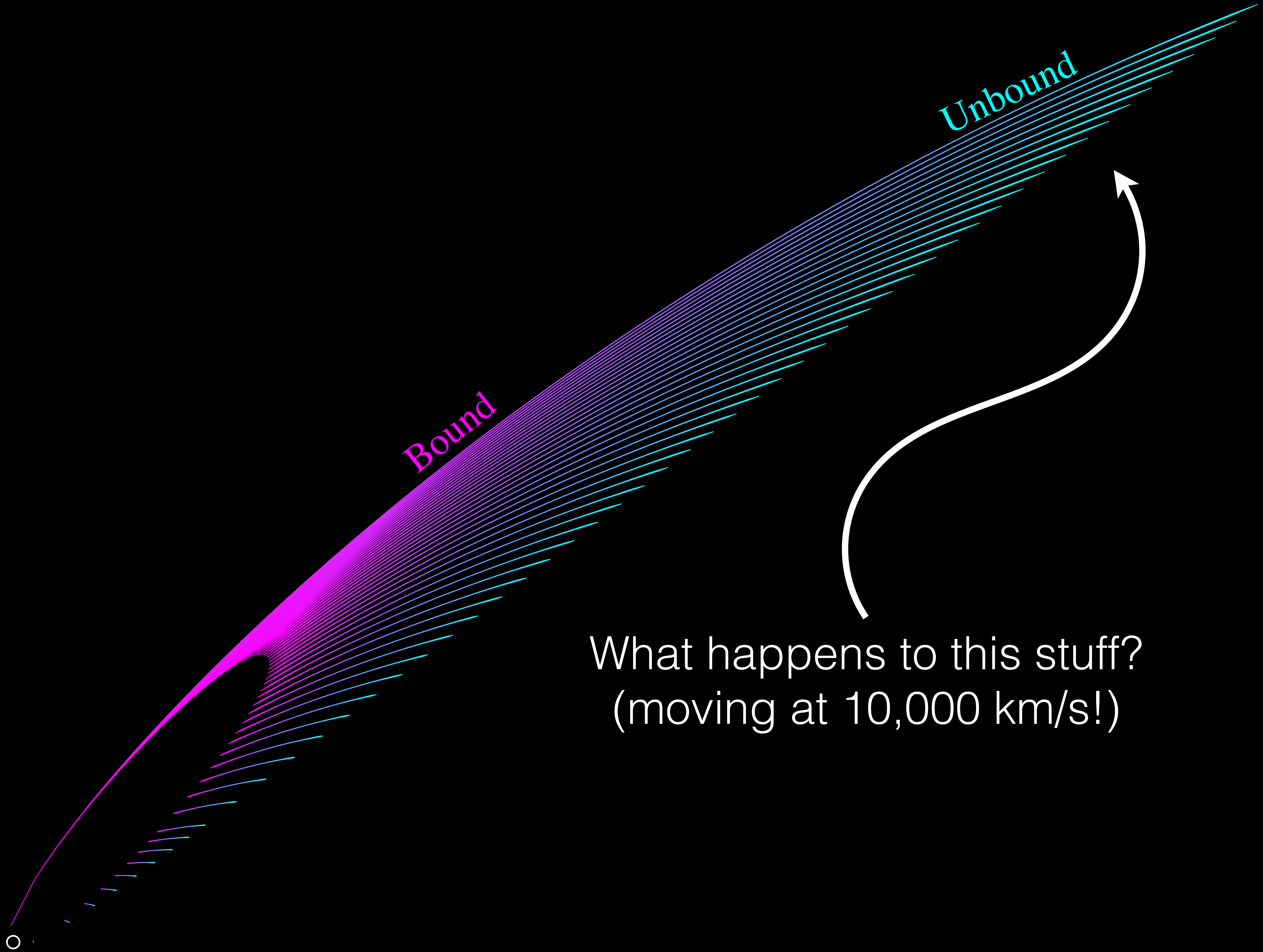


Mass ratio: 10^3

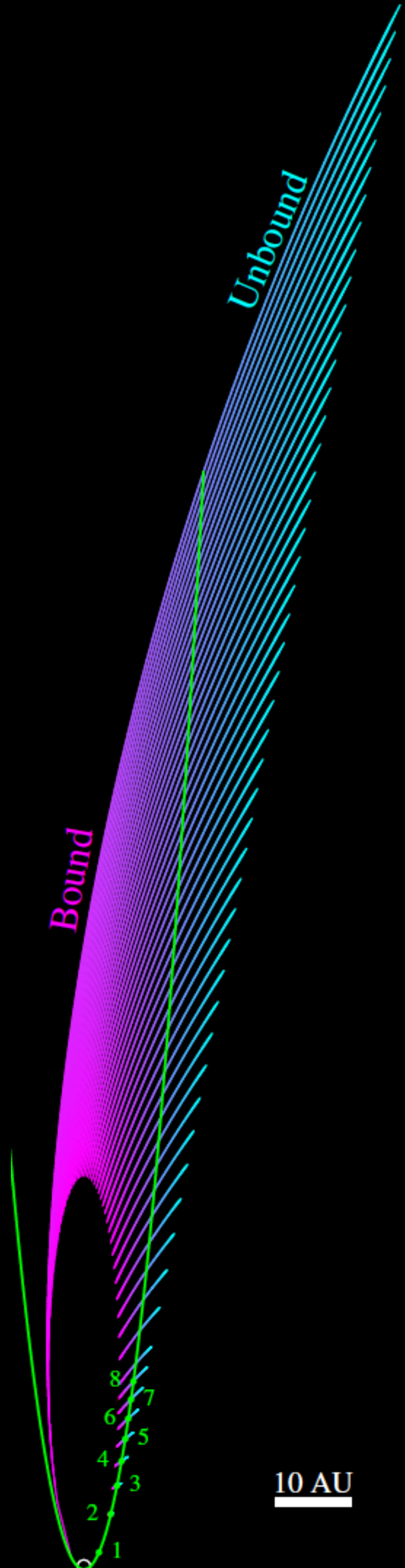


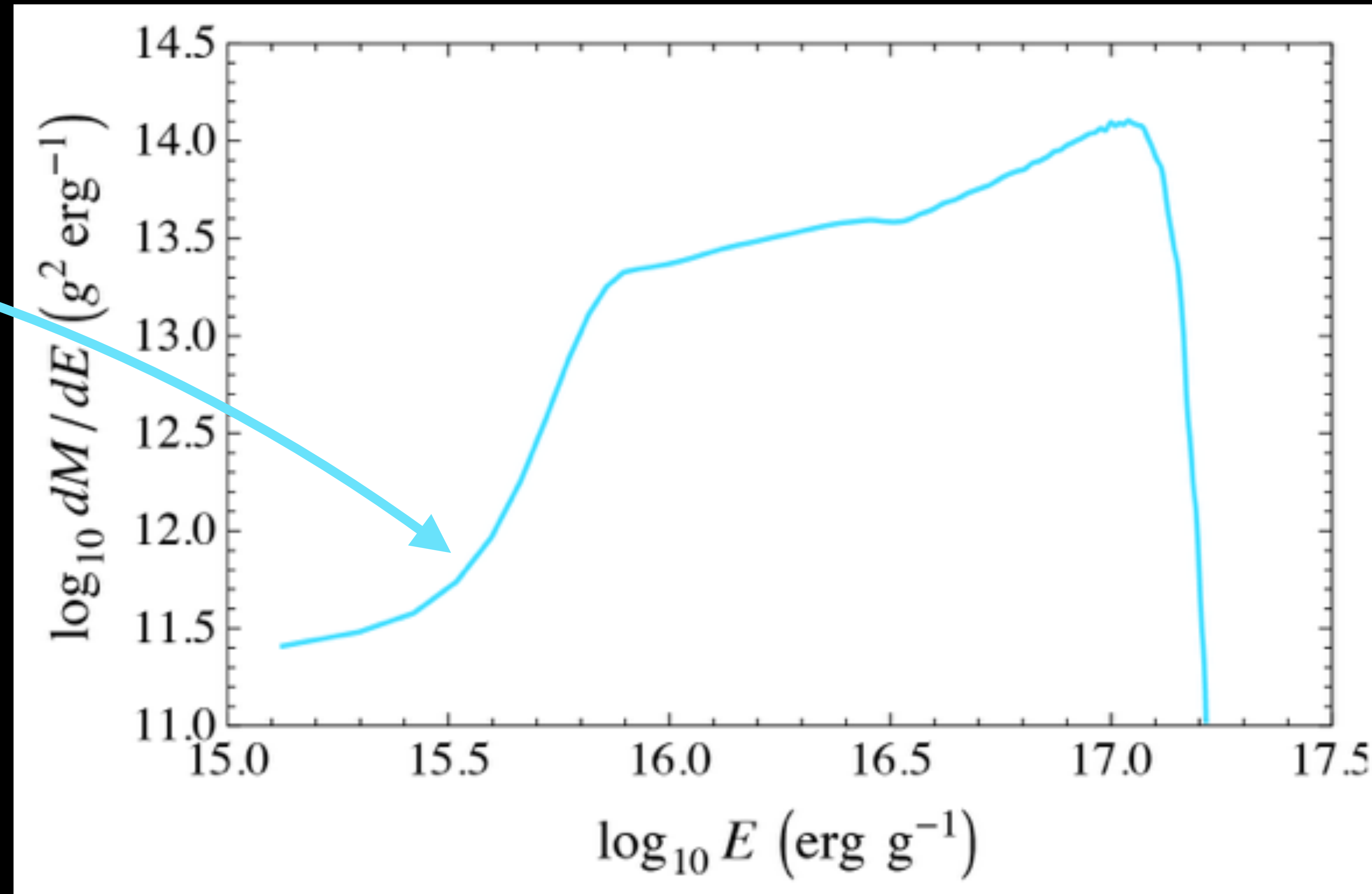
Mass ratio: 10^6

$$r_{\rm t} = 7 \times 10^{12} \left(\frac{r_*}{r_\odot}\right) \left(\frac{M_*}{M_\odot}\right)^{-1/3} M_6^{1/3} \text{ cm} \quad \Rightarrow \quad r_{\rm t}/r_* = 300 M_6^{1/3}$$



What happens to this stuff?
(moving at 10,000 km/s!)

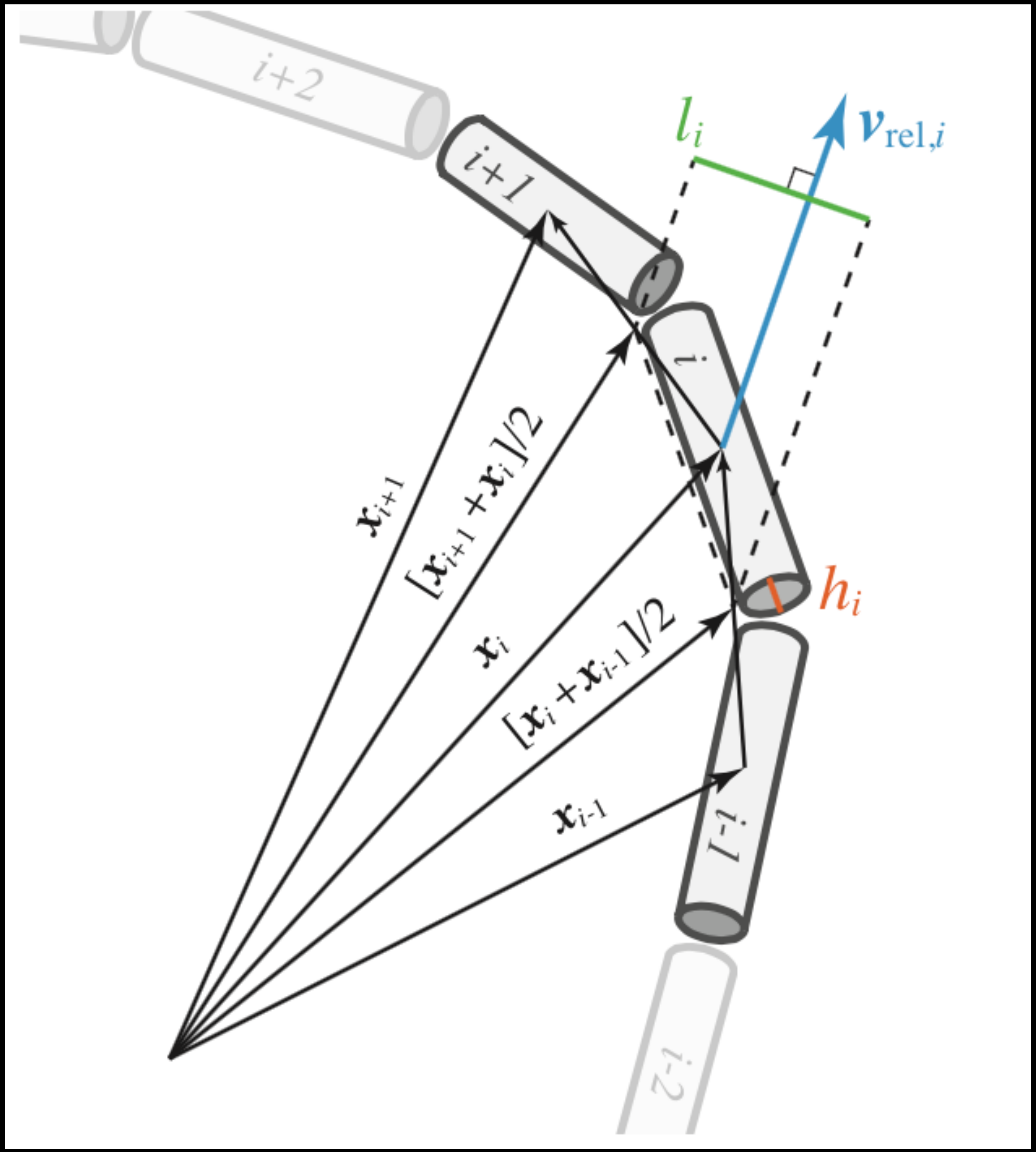


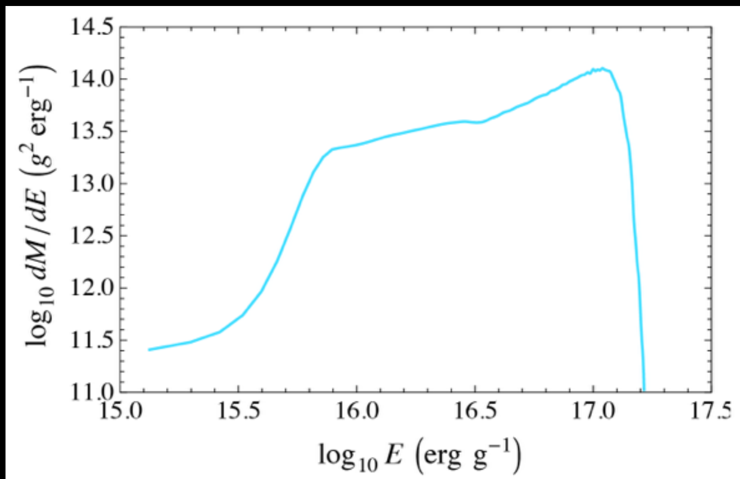


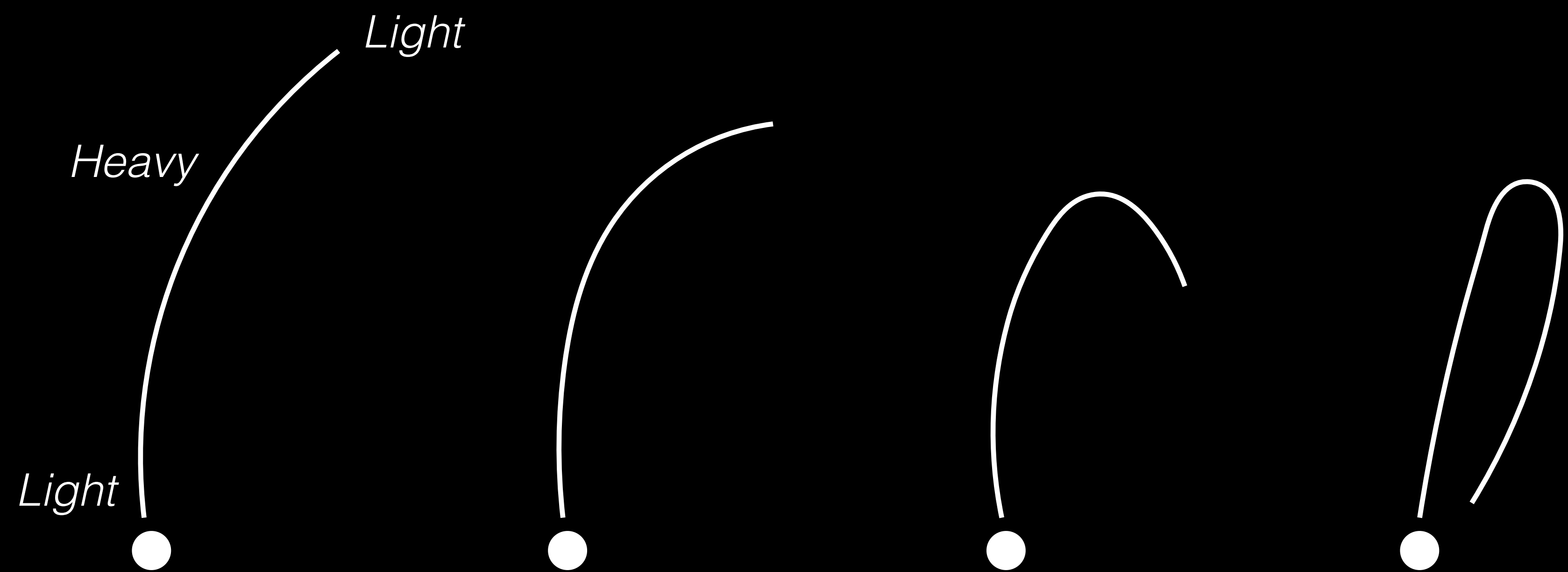
- Unbound debris stream (UDS) has an energy distribution that mirrors the bound matter, is not flat as a function of energy.
- UDS is extremely thin for realistic mass ratios, a few 10^{11} cm at a distance of 10^{15} cm!
- A simple guess as to when the stream would stop suggests as far as 1 kpc from BH, 10^{22} cm. Potentially 11 orders of magnitude in scale, extremely hard to simulate in a hydro code!
- This motivates an analytical approach.

Our Approach

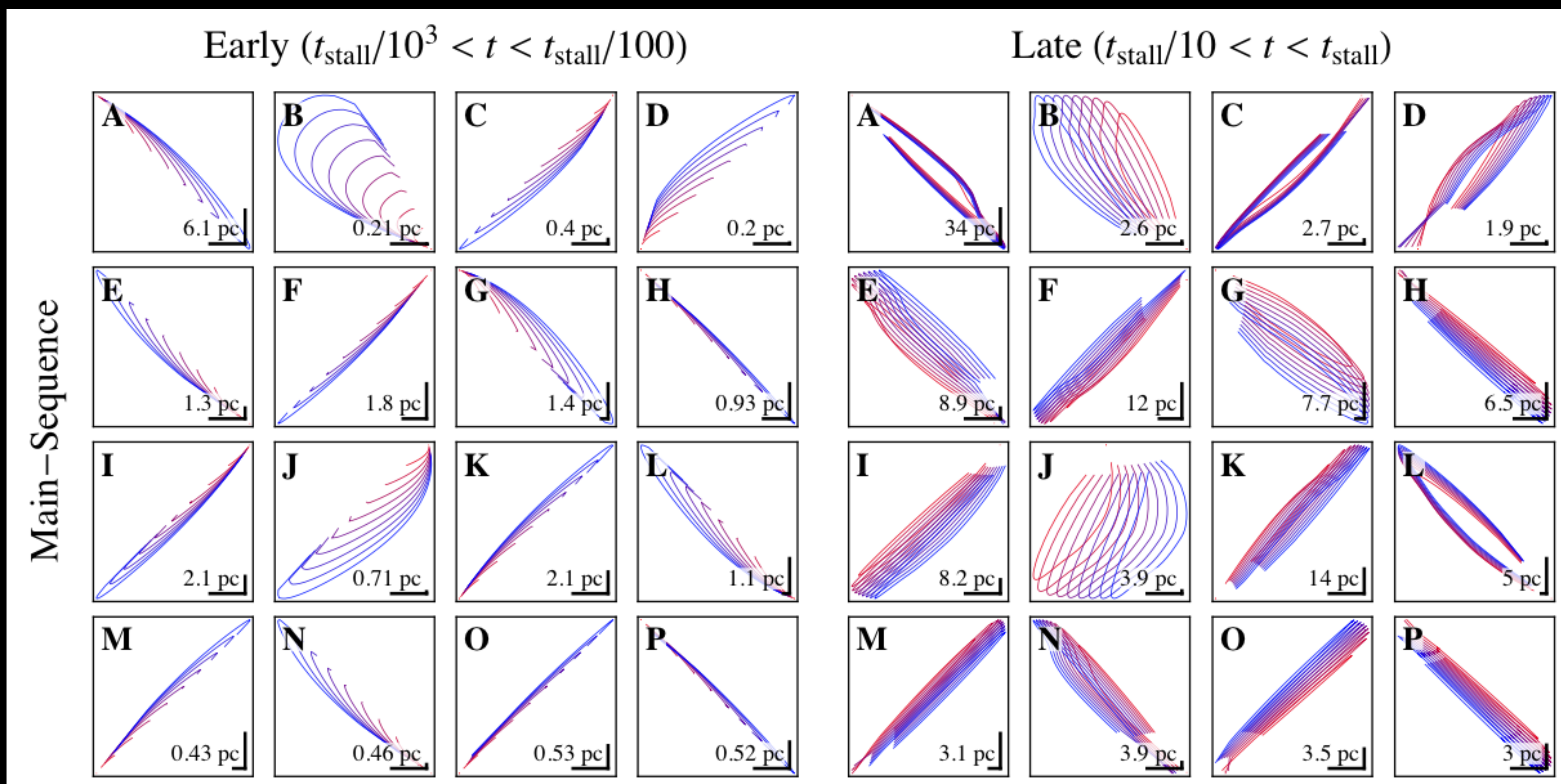
- Treat unbound stream as a connected set of cylinders, each with mass and velocity determined by mass-energy distribution.
- Each cylinder experiences drag as it interacts with ambient gas. Drag is proportional to area of each cylinder projected along the direction of travel. Orientation of cylinders determined by positions of neighboring cylinders.
- Initial conditions for outgoing streams set by outputs from hydro simulations (JFG+ 2013).
- Background profile set according to galactic center observations (Yuan et al., etc.), assumed 50% rotational support.
- Randomly draw disruptions: Stellar mass, impact parameter, orientation.





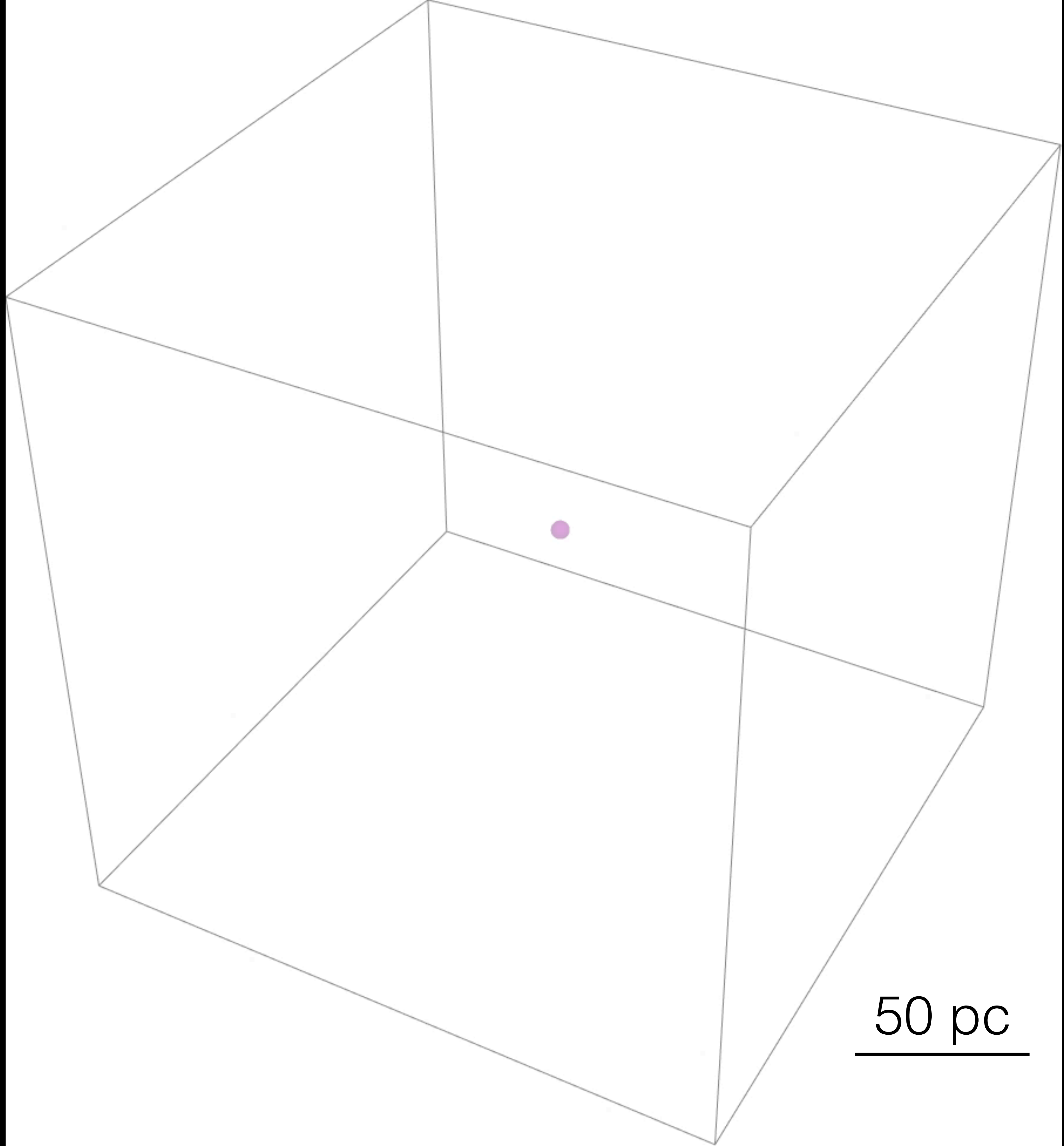


Time →



Guillochon+2015

UDS travel ~10 pc before stalling

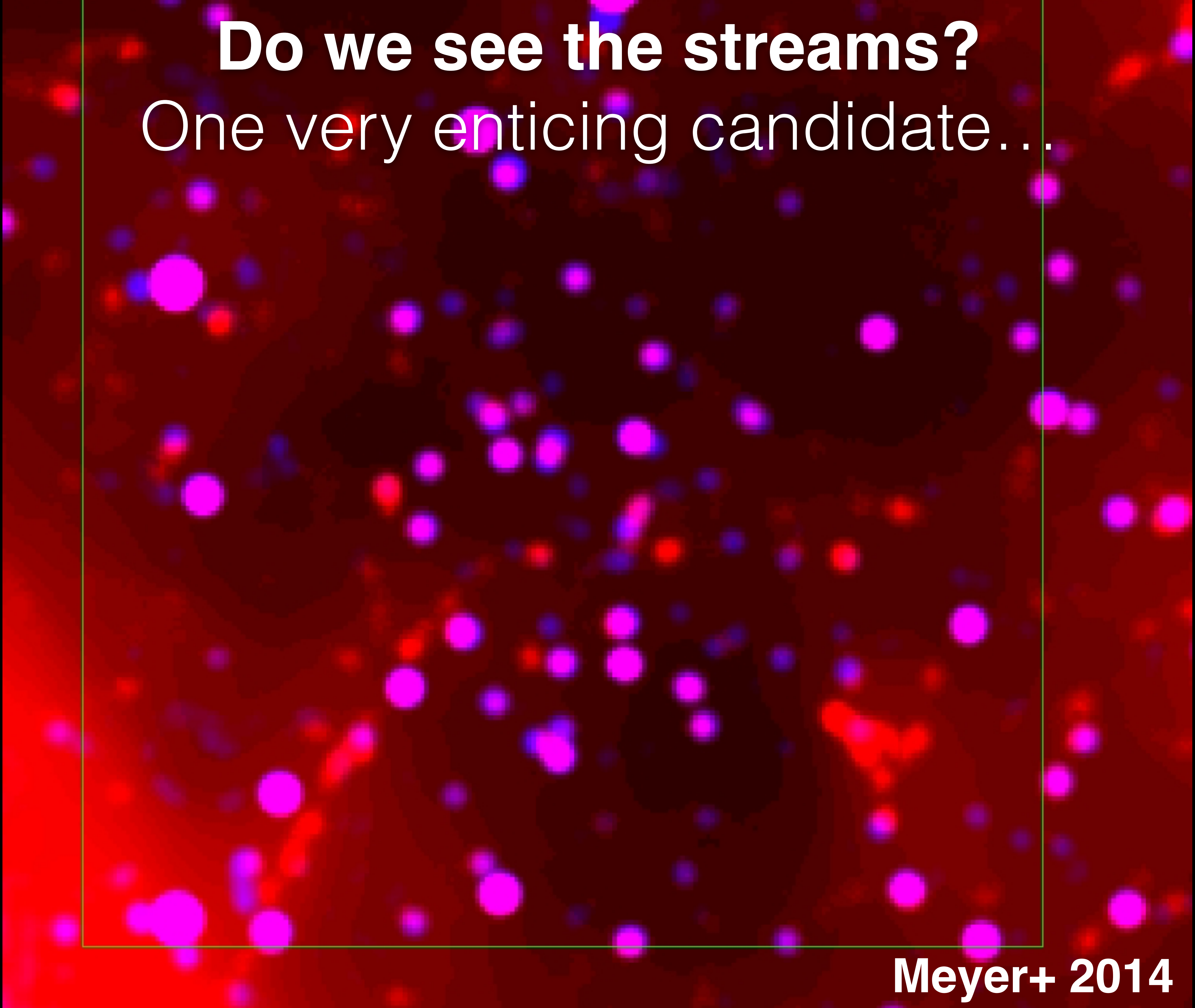

50 pc

Can we see the streams?

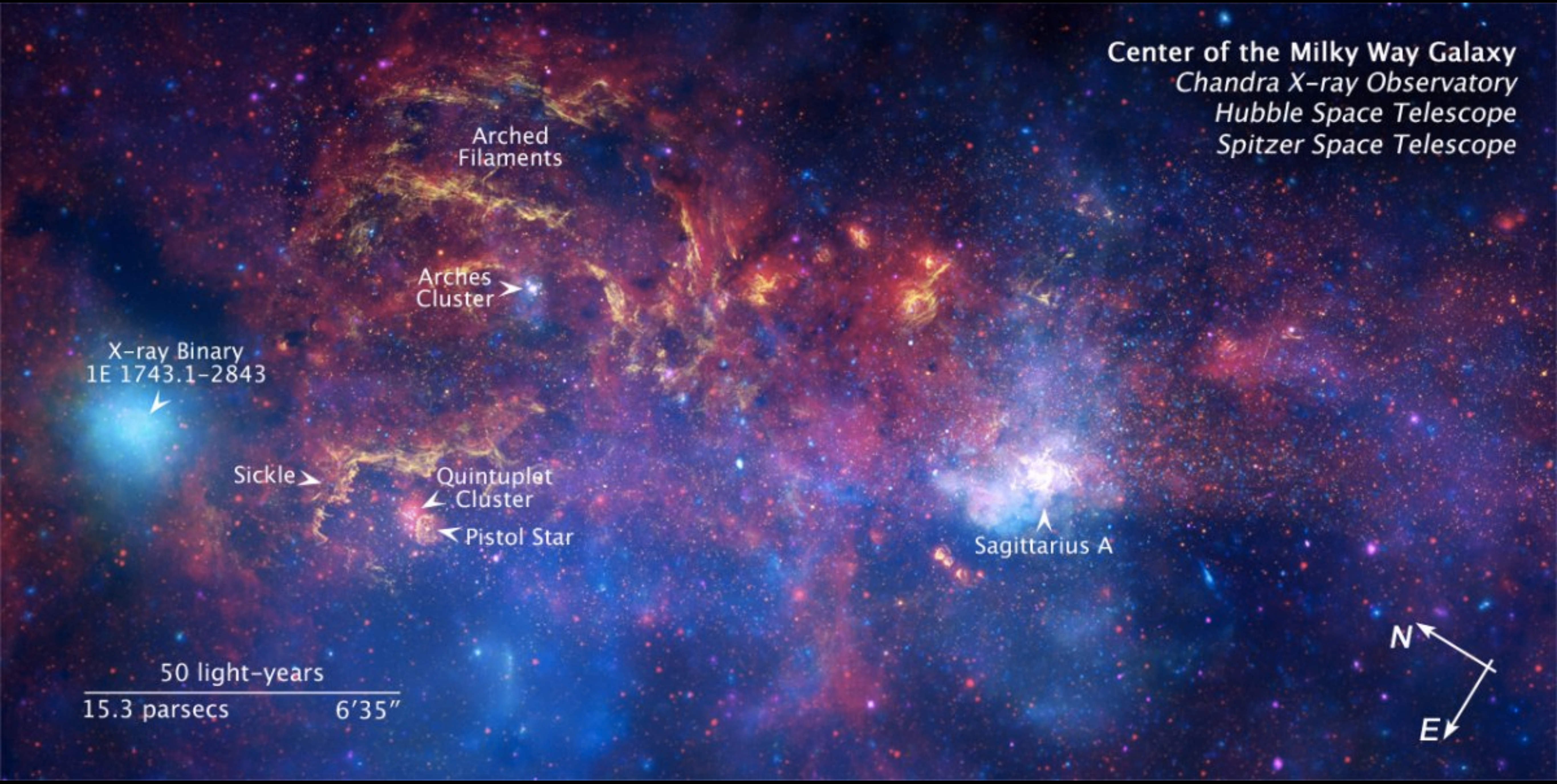
- Each stream contains ~few tenths of a solar mass.
- Temperature of the stream ~100 - 10^4 K.
- The bound portion of the stream would be confined to a small region around the black hole with little cold gas. Due to cooling, the stream can clump before returning to the black hole (especially at late times when the accretion rate is low).
- **This is a scenario we've proposed to explain the G2 cloud and friends** (Guillochon+2014).

Do we see the streams?

One very enticing candidate…



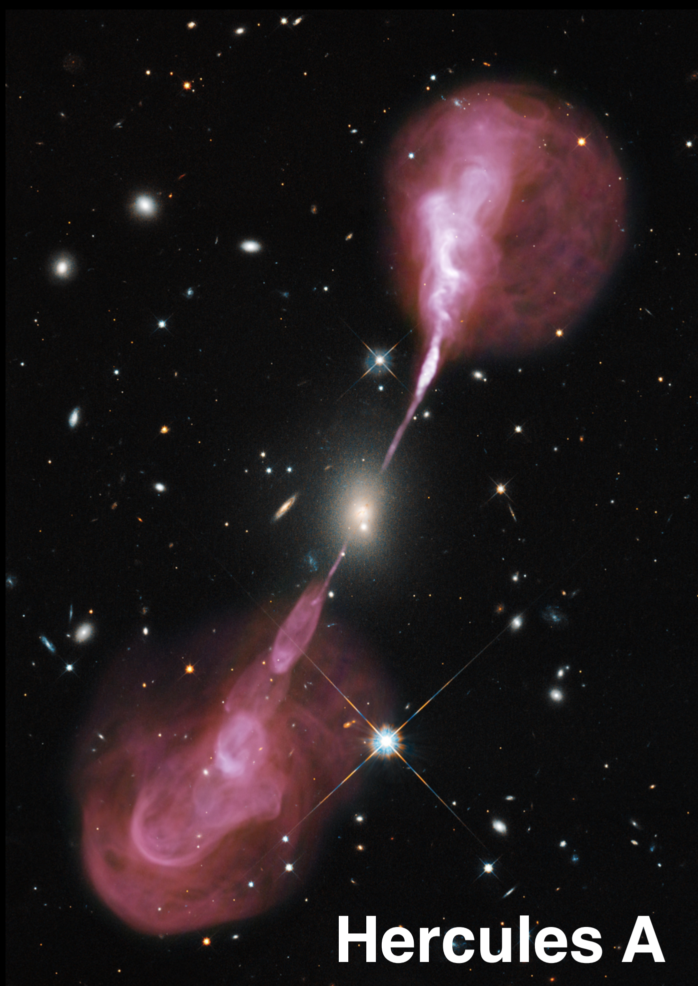
Meyer+ 2014

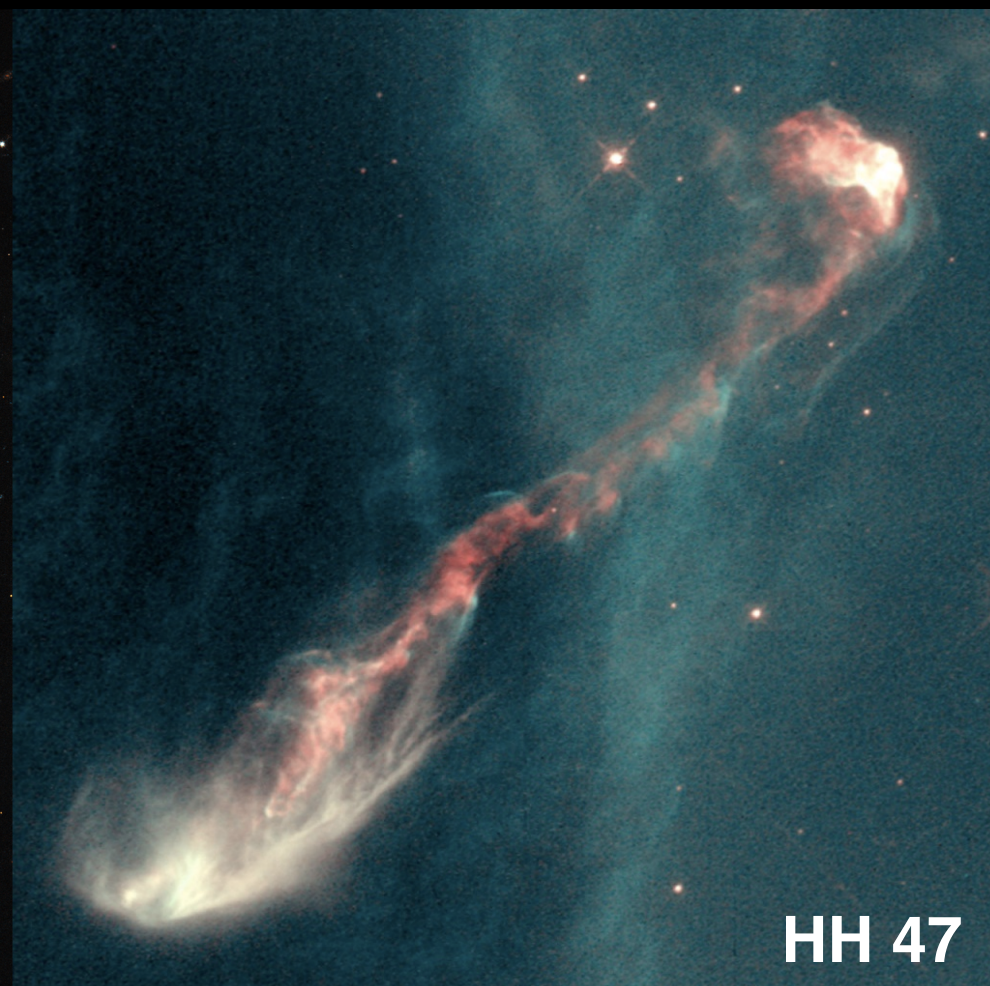


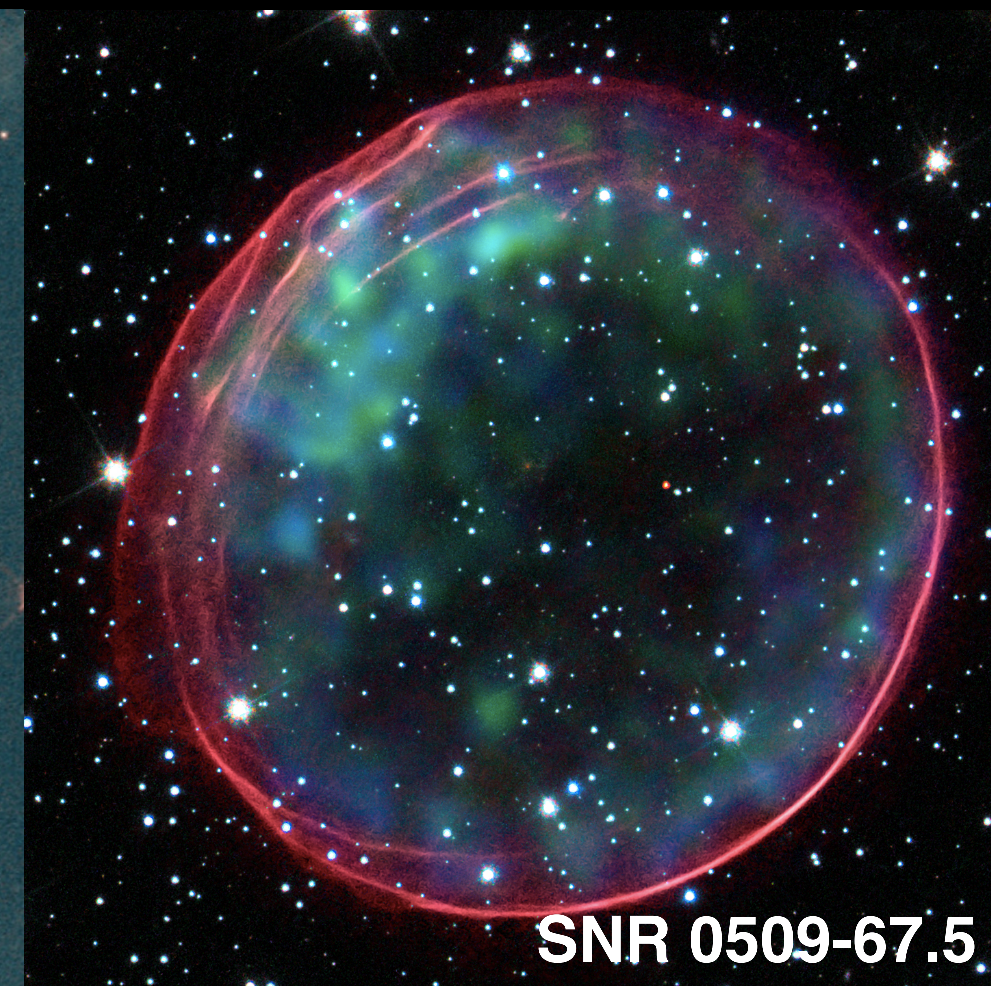
- The CMZ (central molecular zone) has millions of solar masses of cold gas. Not going to be easy to see the unbound streams directly (it's a real mess)!

- Despite the mass difference, each unbound stream contains 0.1% the kinetic energy of the entire CMZ's binding energy (10^{50} vs. 10^{53}).

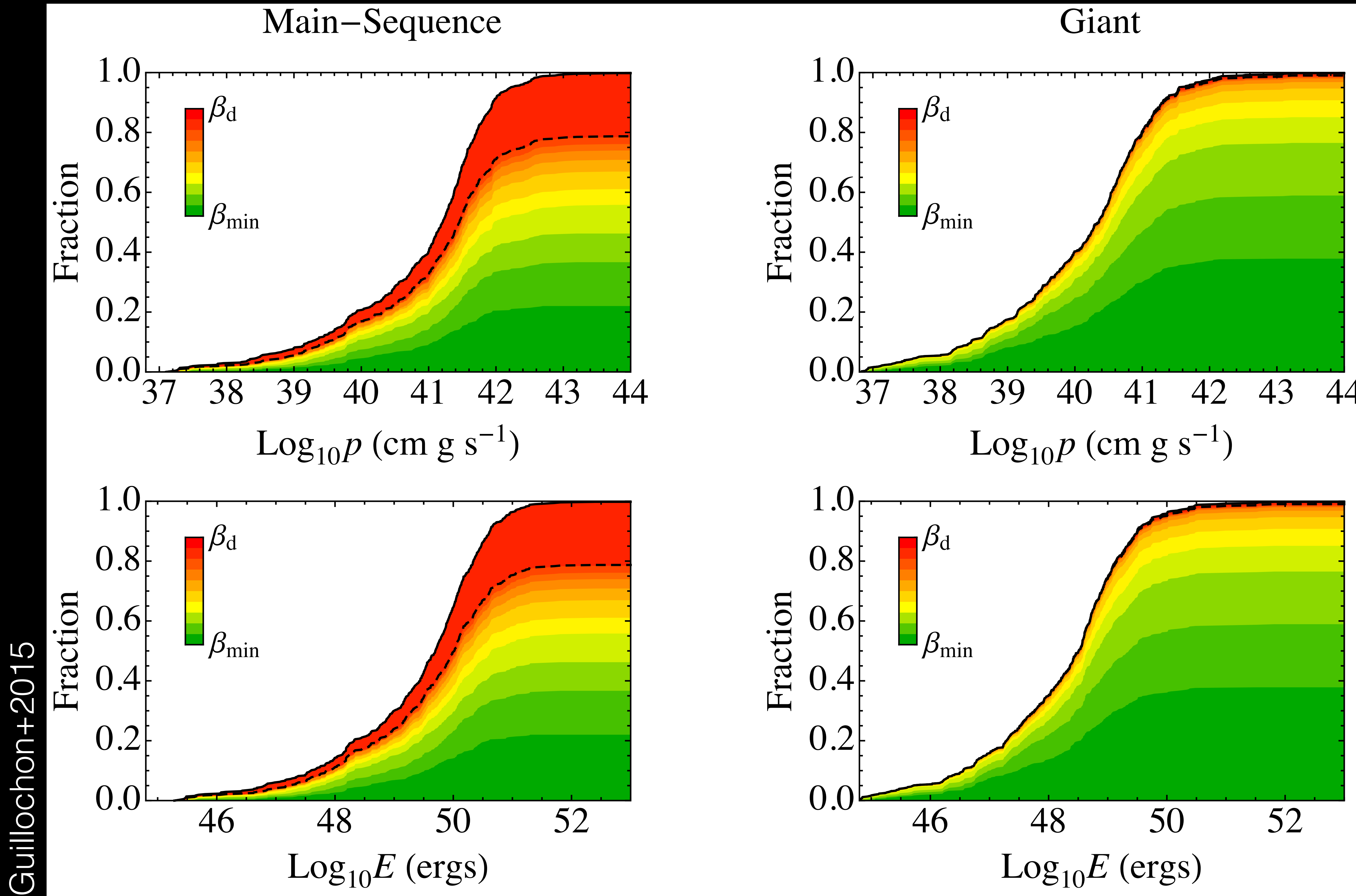
Perhaps we can see the streams when they slam into the background gas?



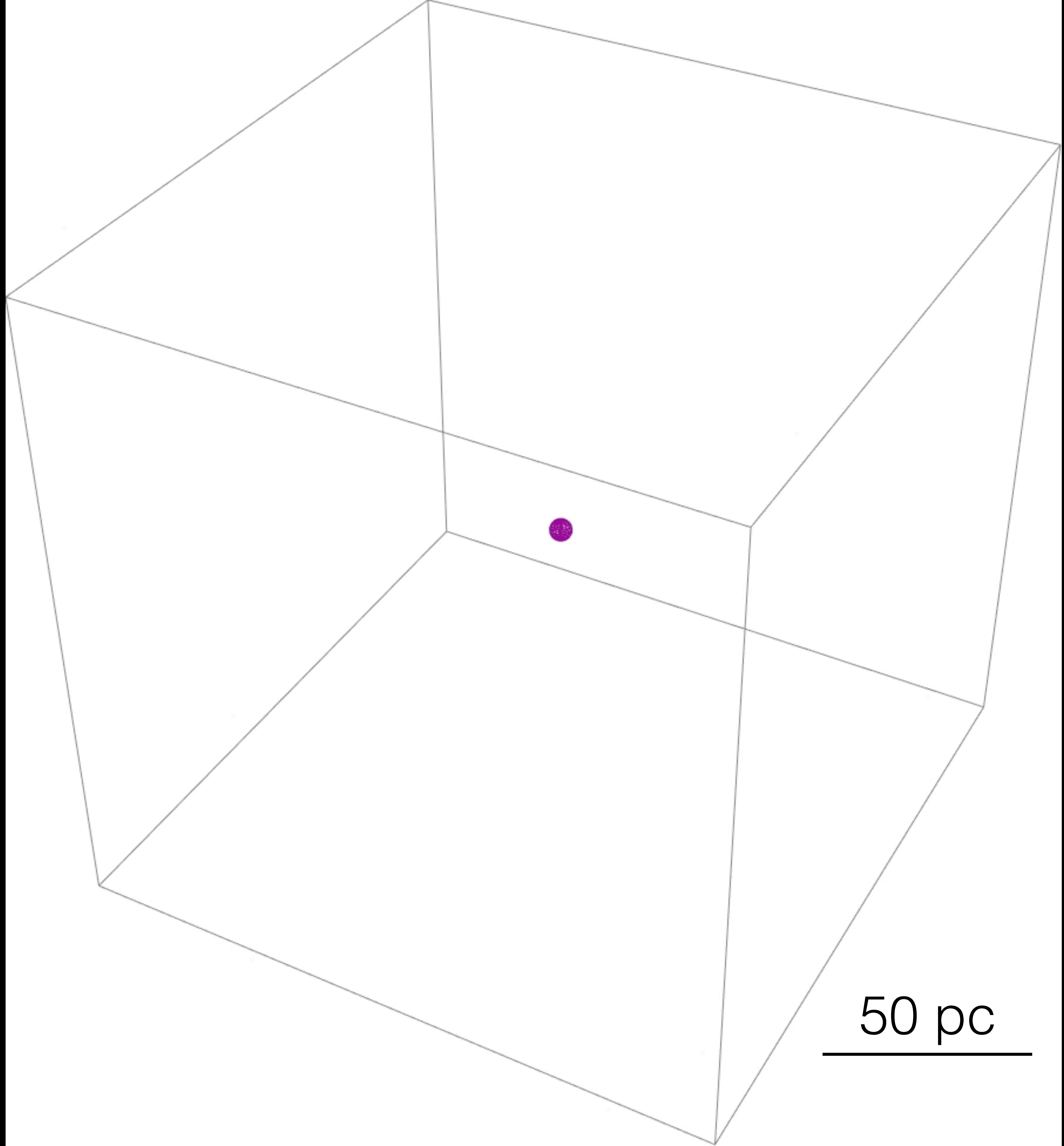




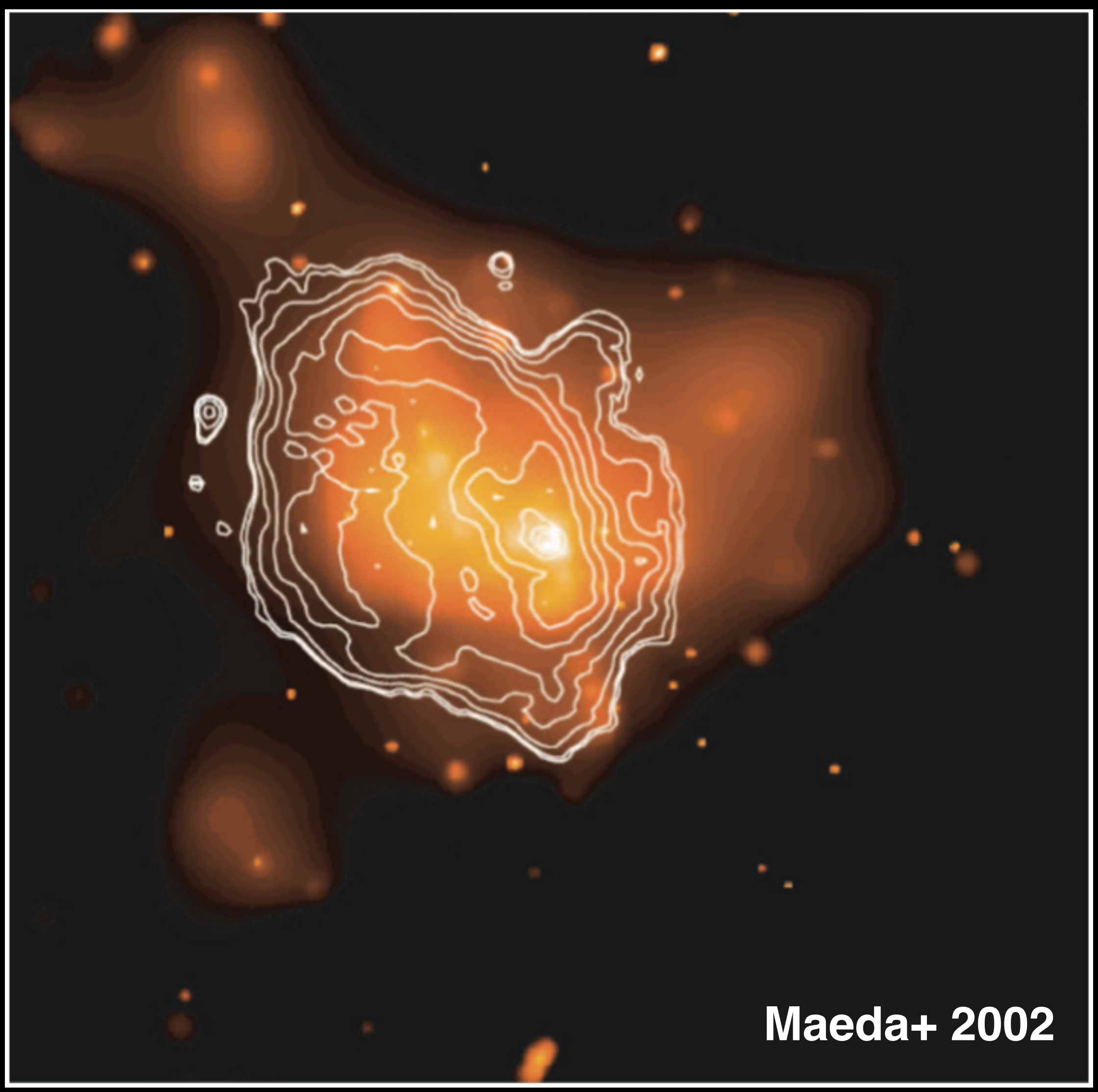
Above: All sorts of examples of astrophysical mayhem that's visible for hundreds of thousands to millions of years



Typical SNe: 1 Foe (Ten to the **f**ifty **o**ne **e**rgs)
Typical UDS: 0.1 Foe
UDS range: 0.00001 — 100 Foe


50 pc

Sgr A East: UDR candidate?



- Idea for Sgr A East as a "unbound debris remnant" (UDR) was first considered by Khokhlov and Melia in 1996.
- At the time, Sgr A East was thought to have *much* more energy than what is presently believed: ~10^{53} ergs!
- Khokhlov and Melia estimated the amount of energy deposited by a single UDS as

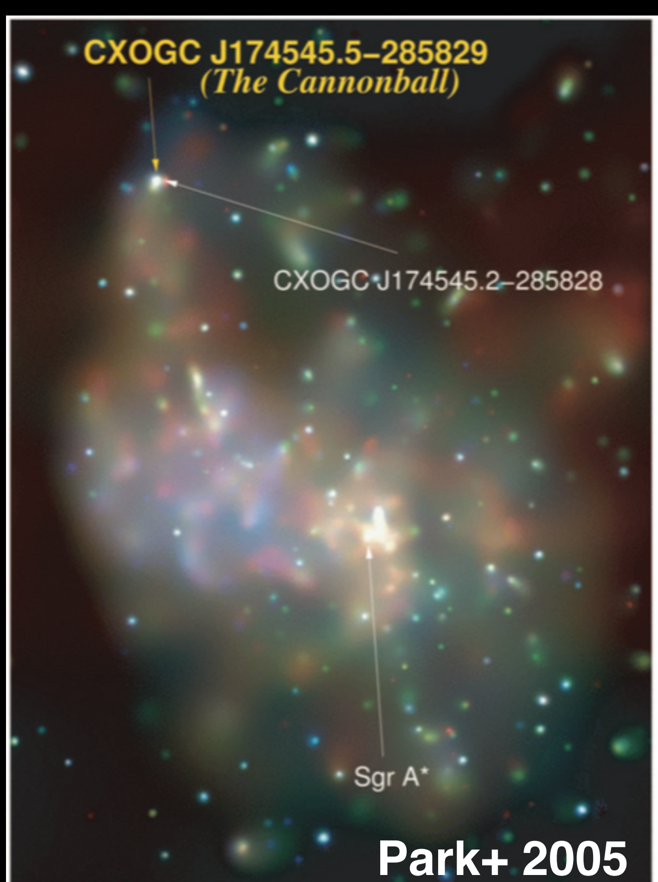
$$E_{\rm dep} \approx \frac{1}{4} M_* v_\infty^2 \approx 3.8 \times 10^{52} \text{ ergs}$$

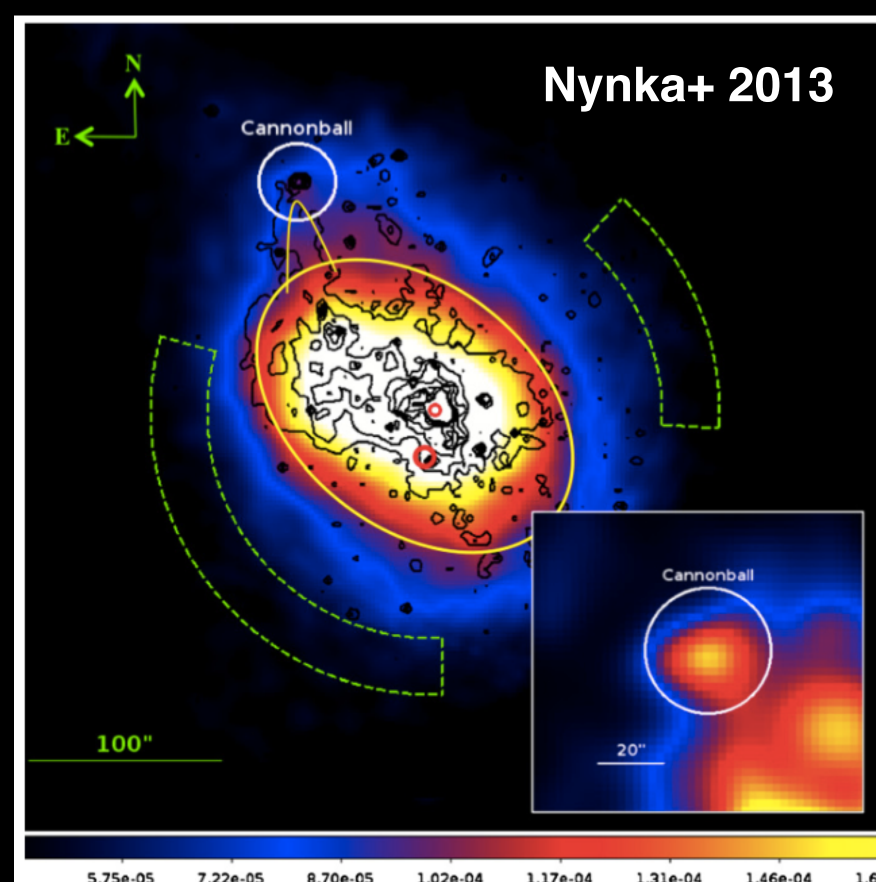
$$\times \left(\frac{M_*}{M_\odot}\right)^2 \left(\frac{R_\odot}{R_*}\right) \left(\frac{M_h}{10^6 M_\odot}\right) \left(\frac{10 R_*}{R_p}\right)^2$$

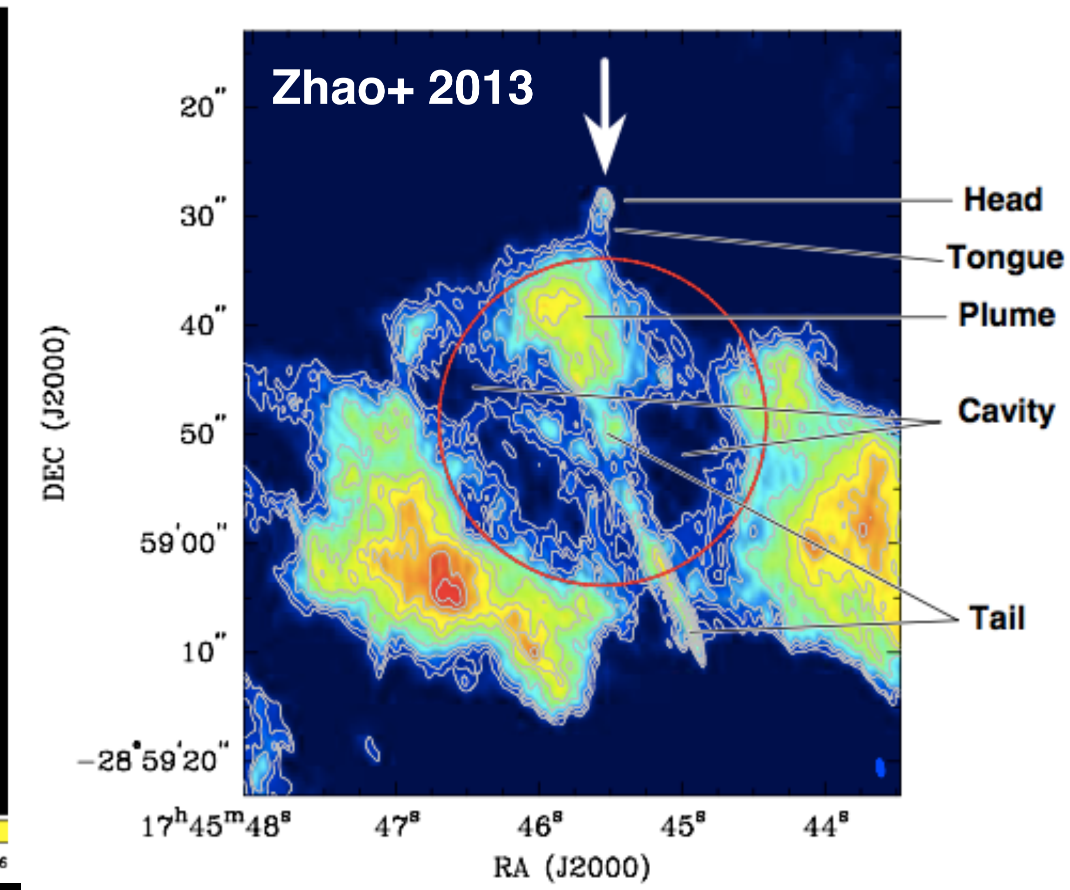
- As our results show, these sorts of energies are very rare, more typical is 10^{50} ergs.

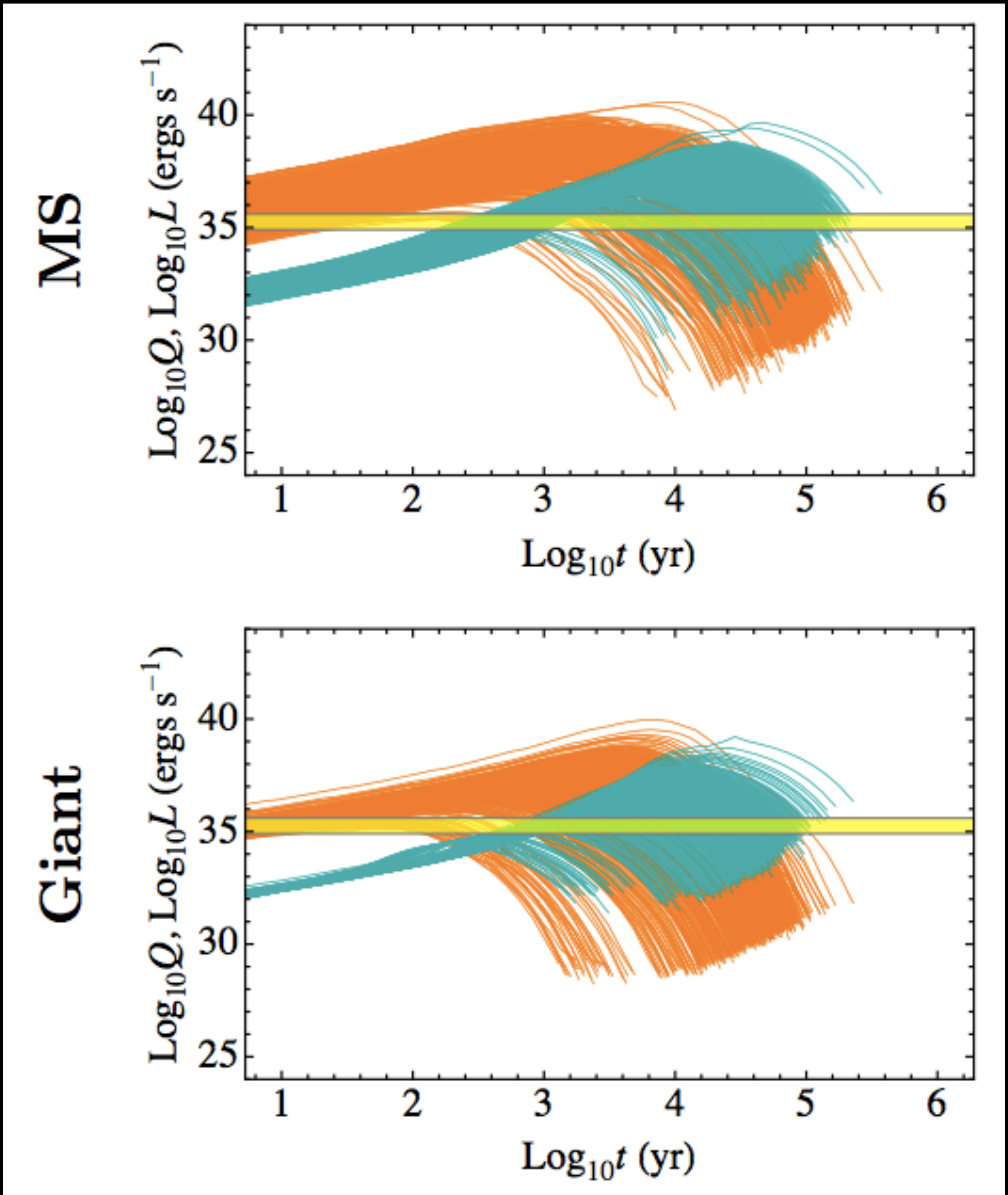
Current observations of Sgr A East compared to UDR model

- Energy much less, 10^{49} - 10^{50} (Park 2005). **We're back in business!**
- Age very uncertain, 10^{3} - 10^{5} yr? **Consistent, but anything is consistent!**
- Few solar masses total, much of which is swept up ISM. **Also consistent.**
- Super-solar metallicity (2 - 5 times solar). **Hints SNR, but many stars metal-rich in GC.**
- Feature known as "cannonball" discovered (hard X-ray & radio source), posited as runaway neutron star. Proper motion of 500 km/s (Zhao+ 2013). **Could be tip of UDS loop?**

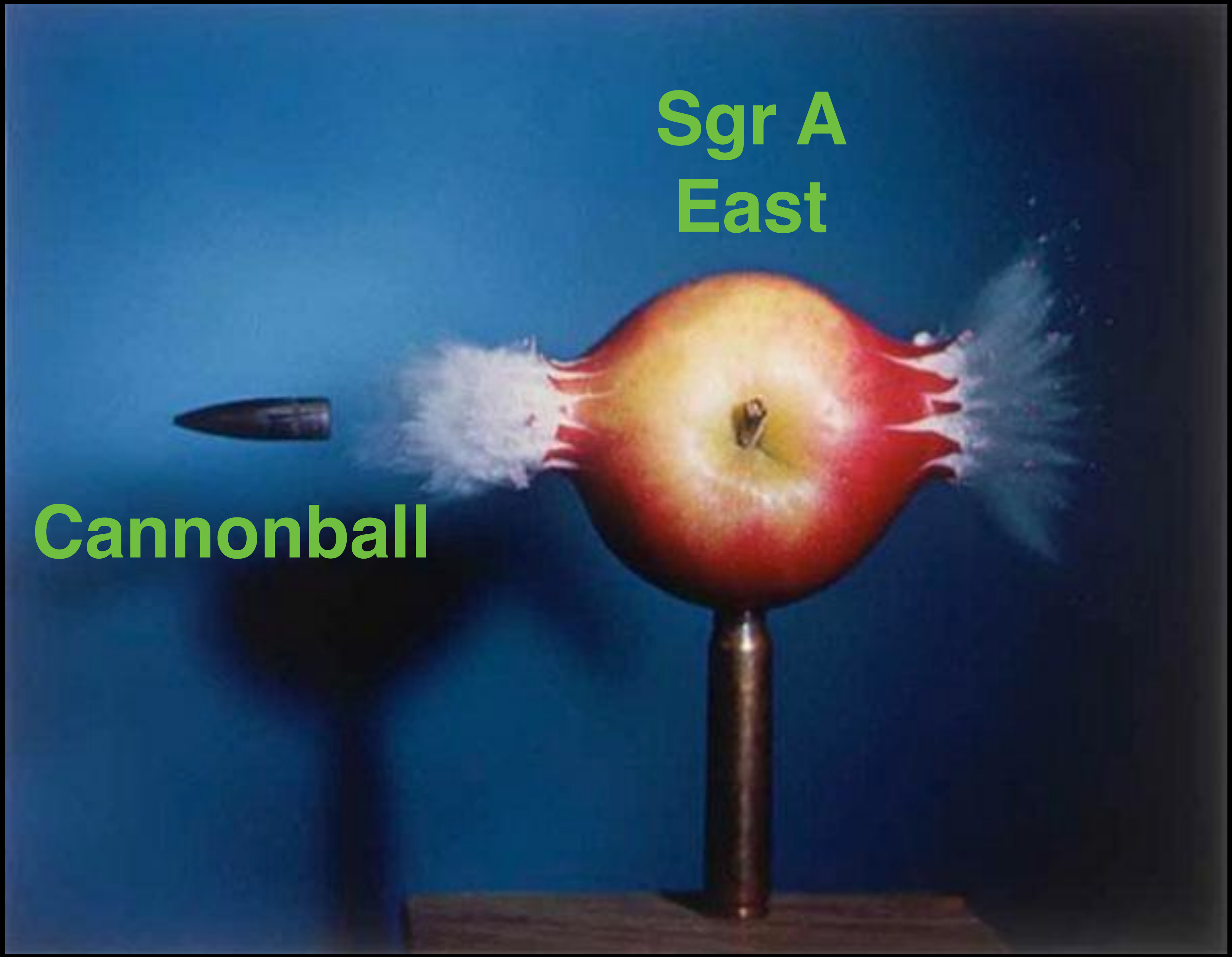




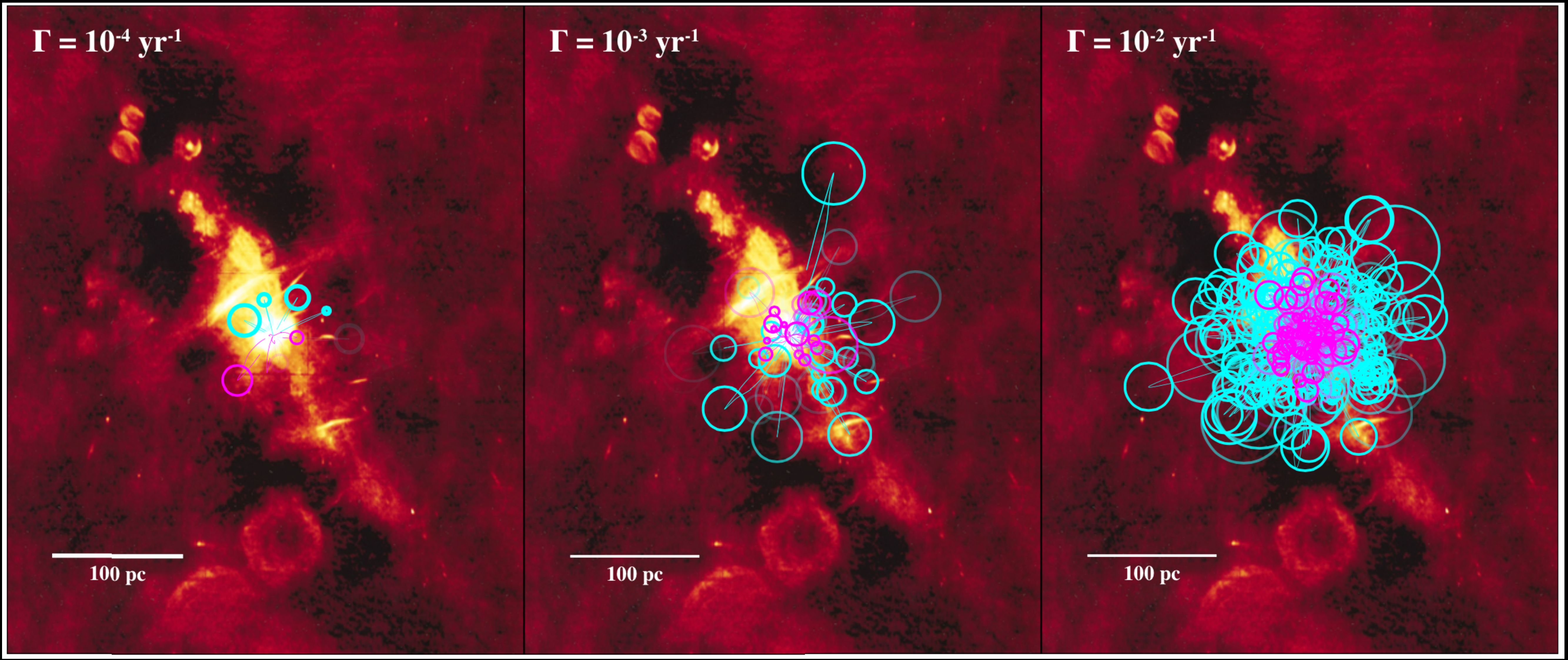




- Plots to left: Heating (orange) and cooling (aqua) for an ensemble of UDS/UDR.
- Energy injected into ISM much more quickly than remnant can cool, region at head of UDS is adiabatic.
- Thus the bubble that formed at the head of the UDS is well-described by Sedov solution.
- Age very poorly constrained (same as SN hypothesis).
- Yellow band: Sgr A East.


Sgr A
East
Cannonball

Constraints on TDE rate in our own galaxy



I've mostly focused on Sgr A East for historical reasons, but as you can see, there are others…

Tell me your favorite! Thanks!