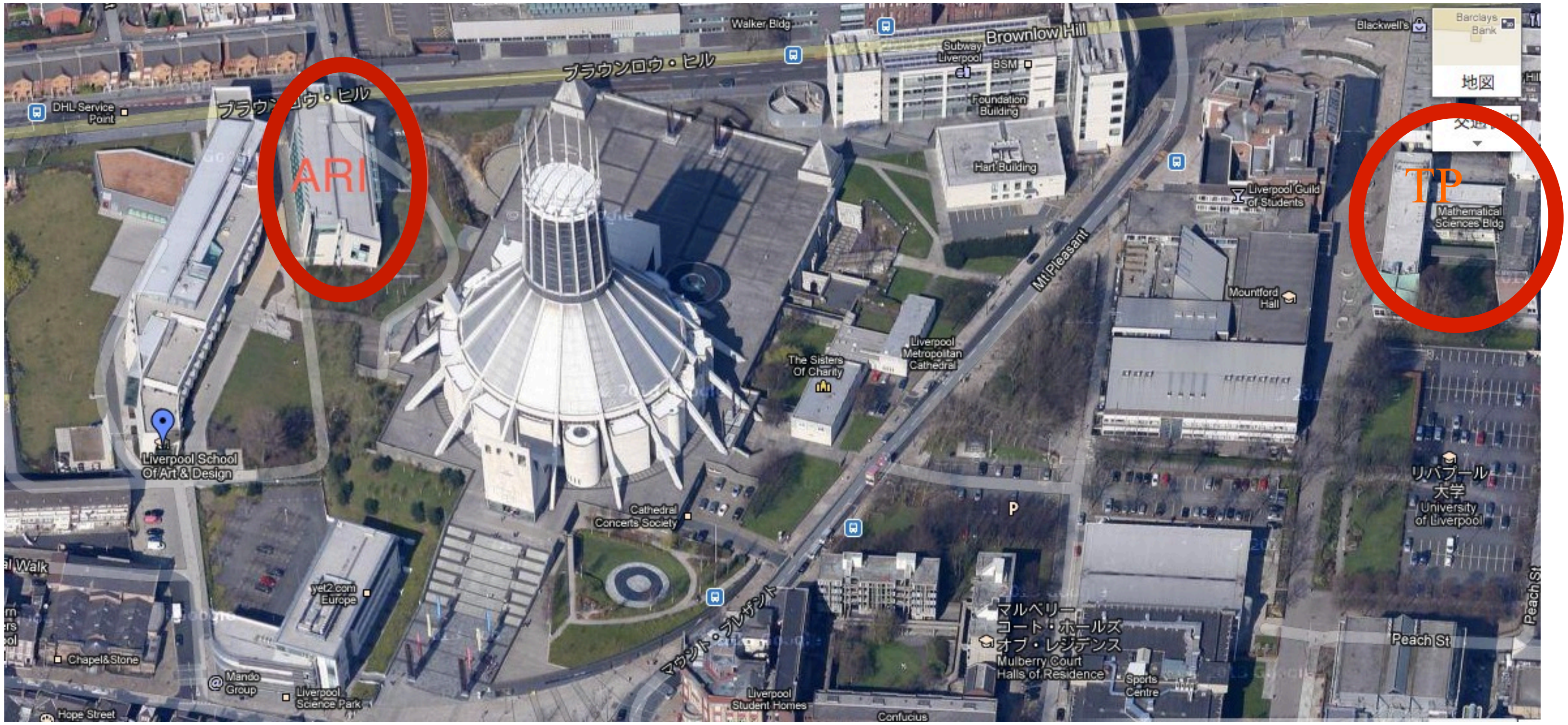
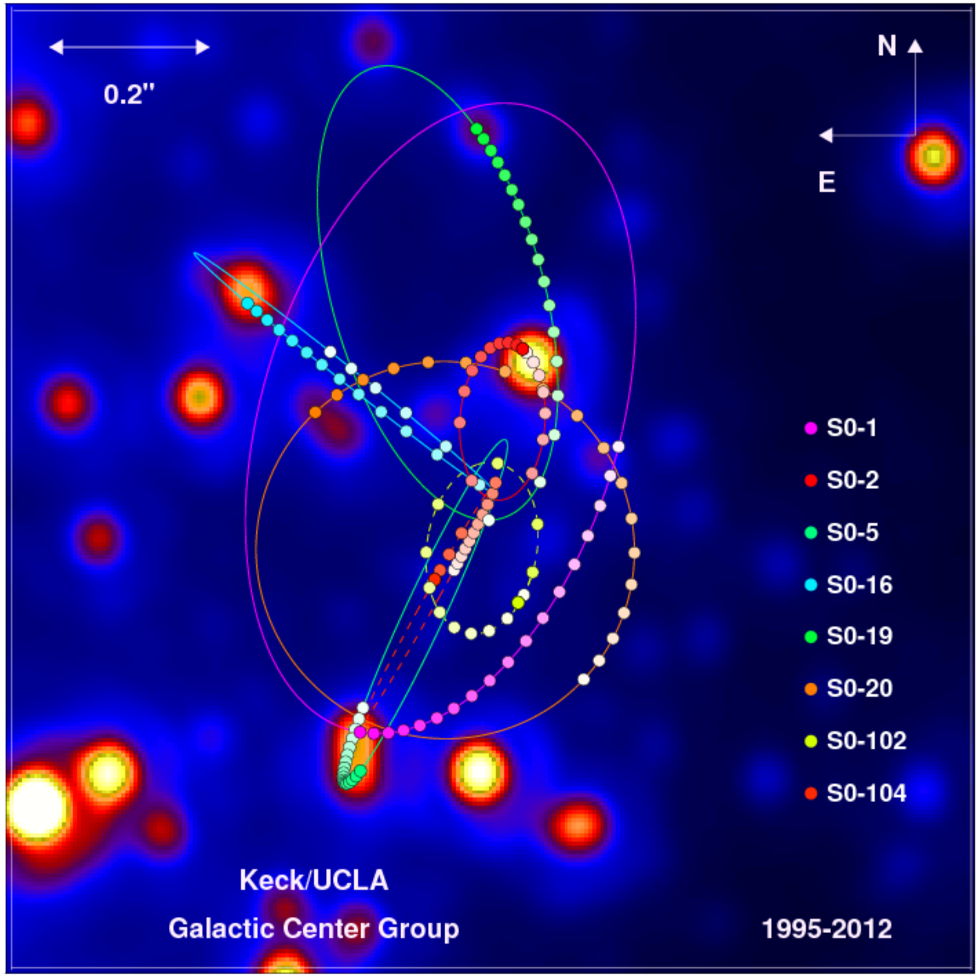
Massive Black Holes, Tidal Disruption Events and Hypervelocity Stars

Shiho Kobayashi (ARI, Liverpool JMU)



Massive BH at the Galactic Centre



S2: orbital period ~15.6yrs,
Pericenter: 17 light hours $\sim 2\times 10^{15}\,cm$

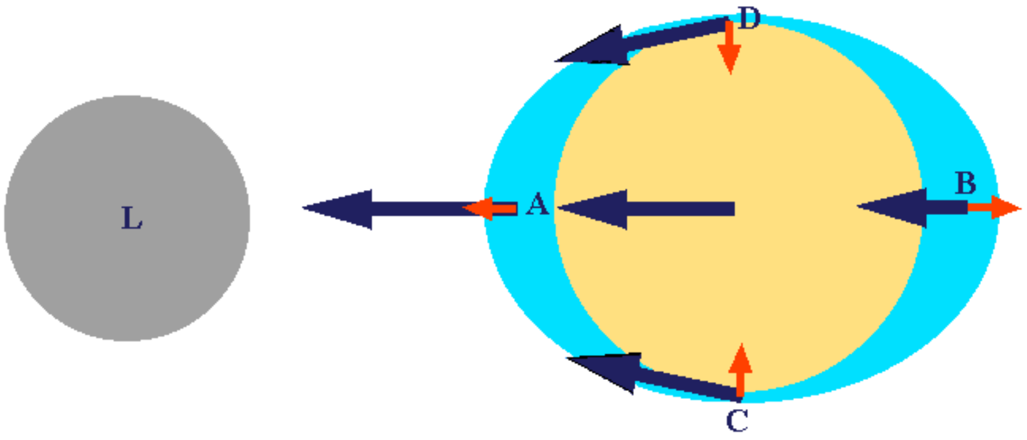
$$M_{BH} \sim 4\times 10^{6}\,M_{sun}$$

Schwarzschild radius $\sim 10^{12}\,cm$

BH at ~26k light years away from us
1”~50 light days

Tidal Force & Tidal Radius

Moon-Earth



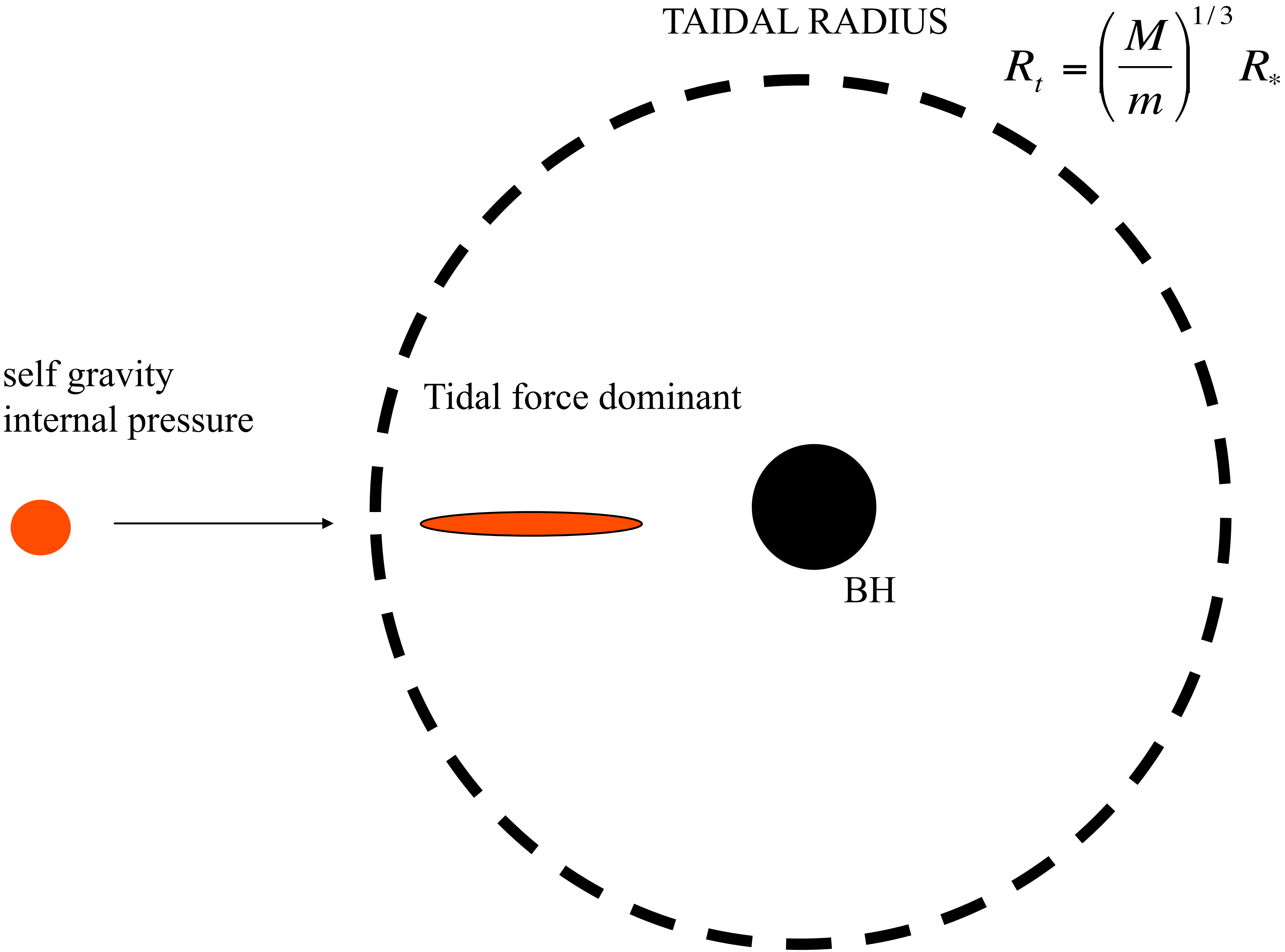
BH: M

star: m
size : R_*

Tidal force

Self gravity

$$\frac{GM}{R^3}R_* \sim \frac{Gm}{R_*^2} \quad \rightarrow \quad R_t = \left(\frac{M}{m}\right)^{1/3} a$$



TAIDAL RADIUS

$$R_t = \left(\frac{M}{m} \right)^{1/3} R_*$$

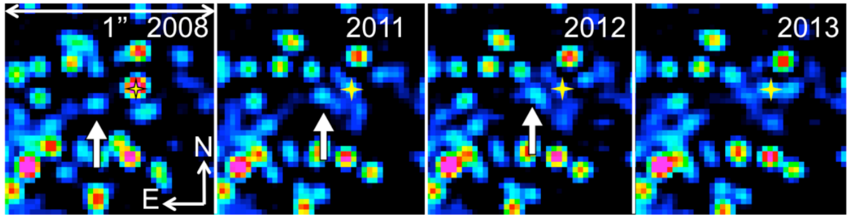
self gravity
internal pressure

Tidal force dominant

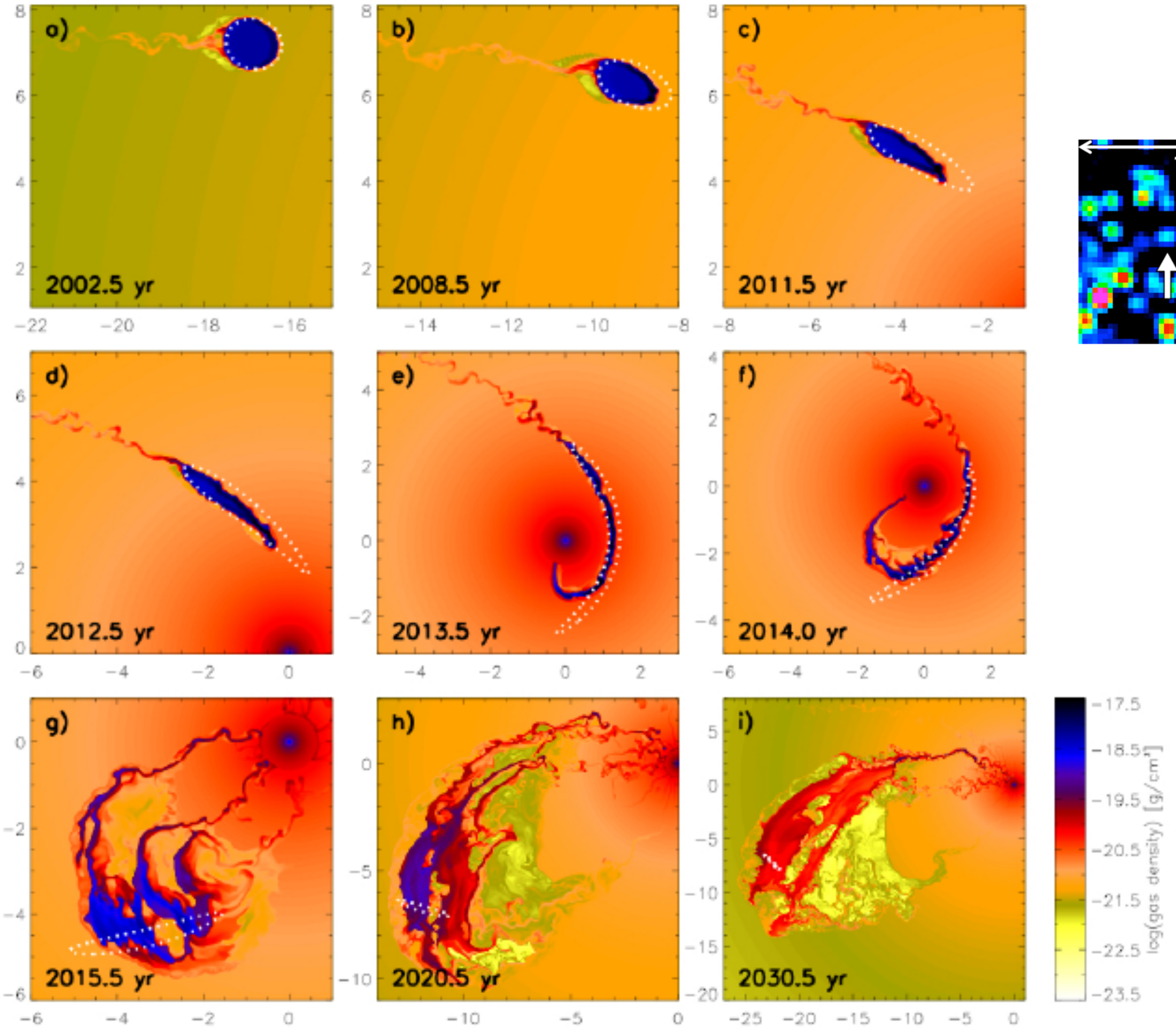
BH

The Galactic Center Cloud G2

~3M_Earth gas cloud currently falling toward the MBH on a near-radial orbit



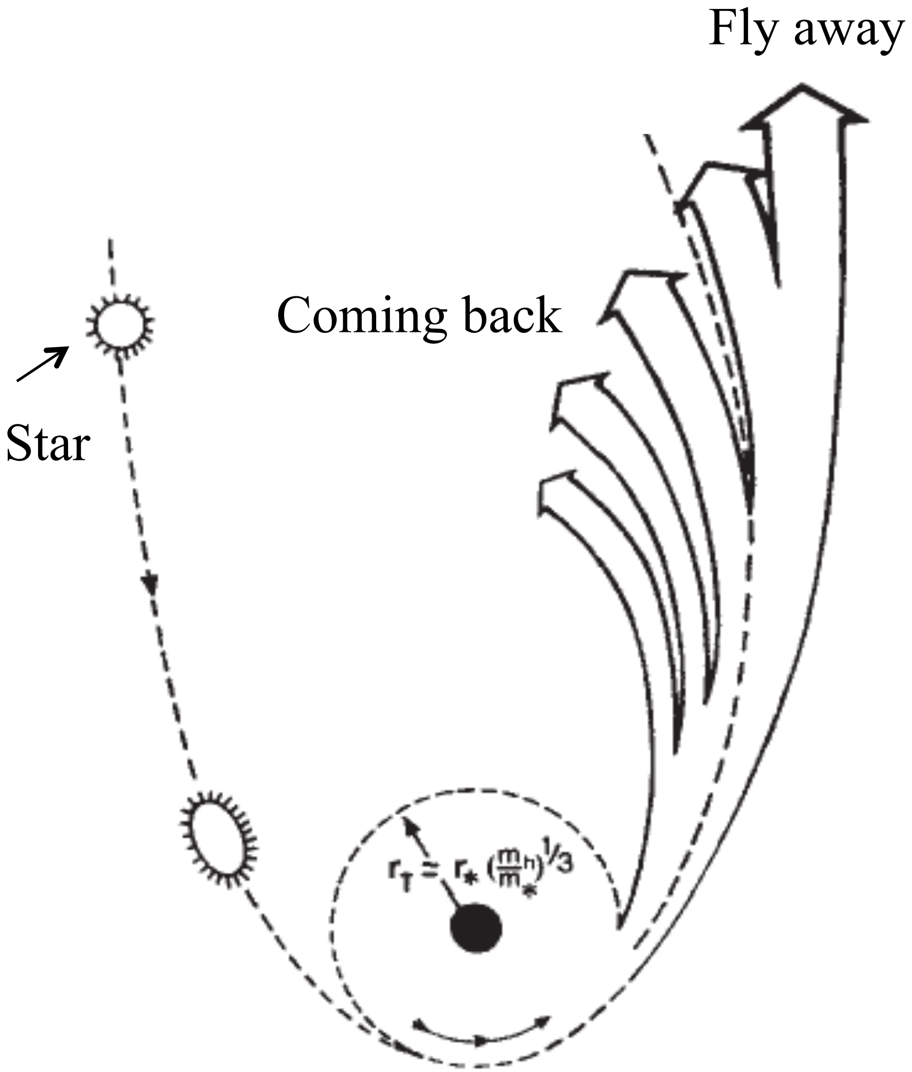
Gillessen et al. 2013



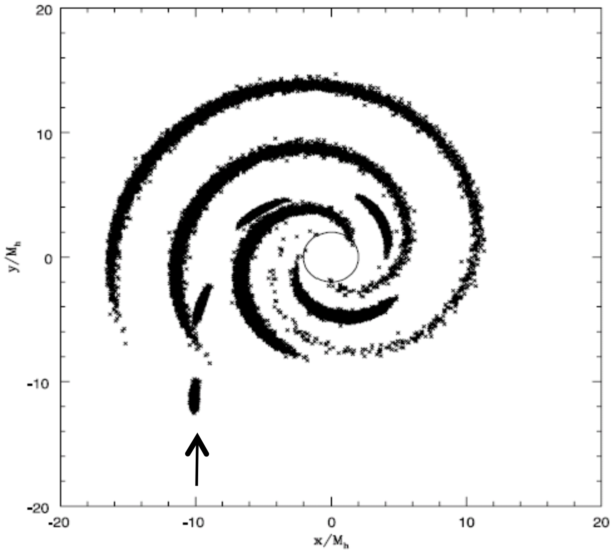
Numerical simulations Schartmann et al. 2012

After the tidal disruption

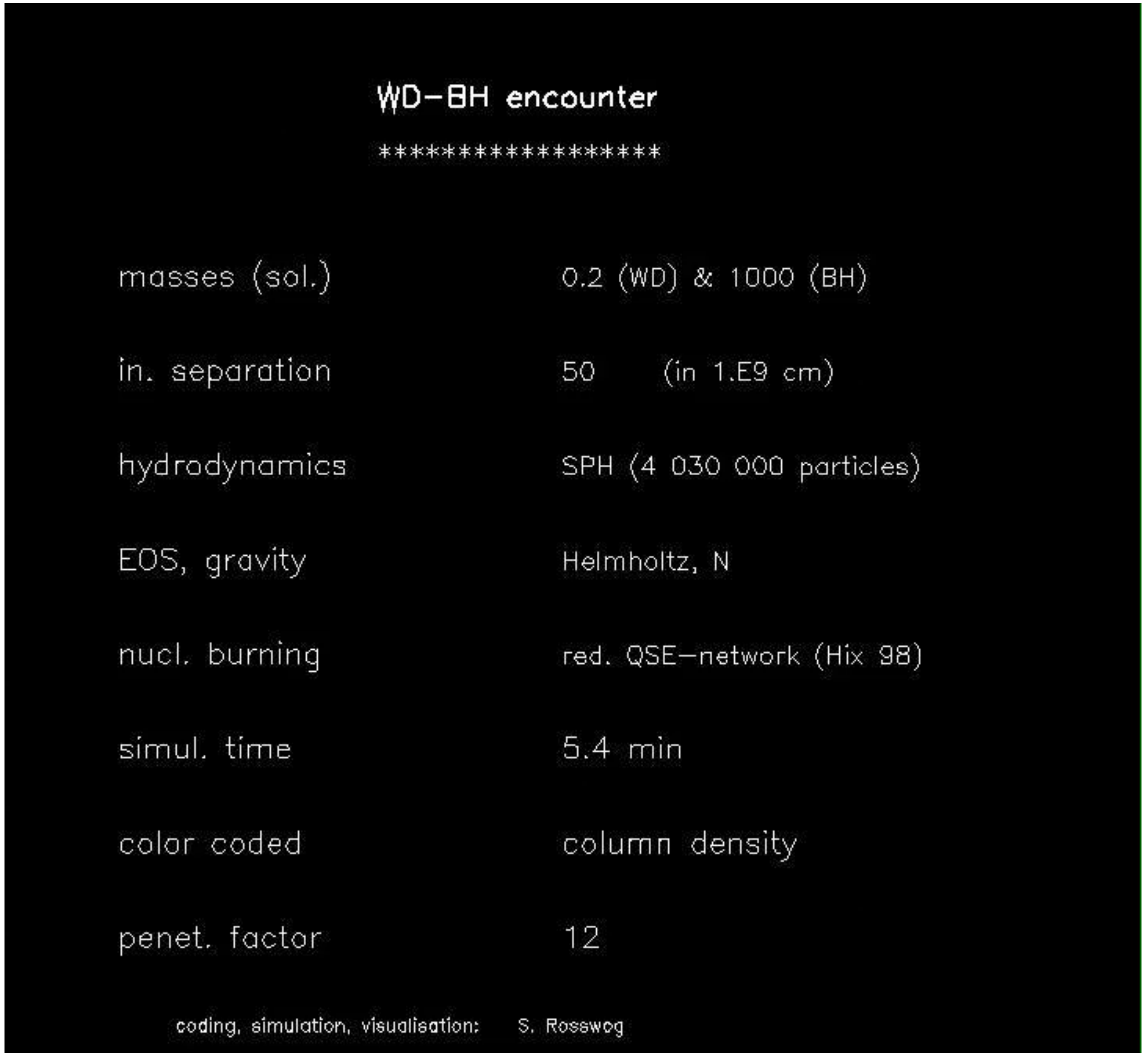
~50% debris: fly away
~50% debris: fallback
to produce a bright flare



Rees 1988



SK, Laguna, Phinney, Meszaros 2004



WD-BH encounter

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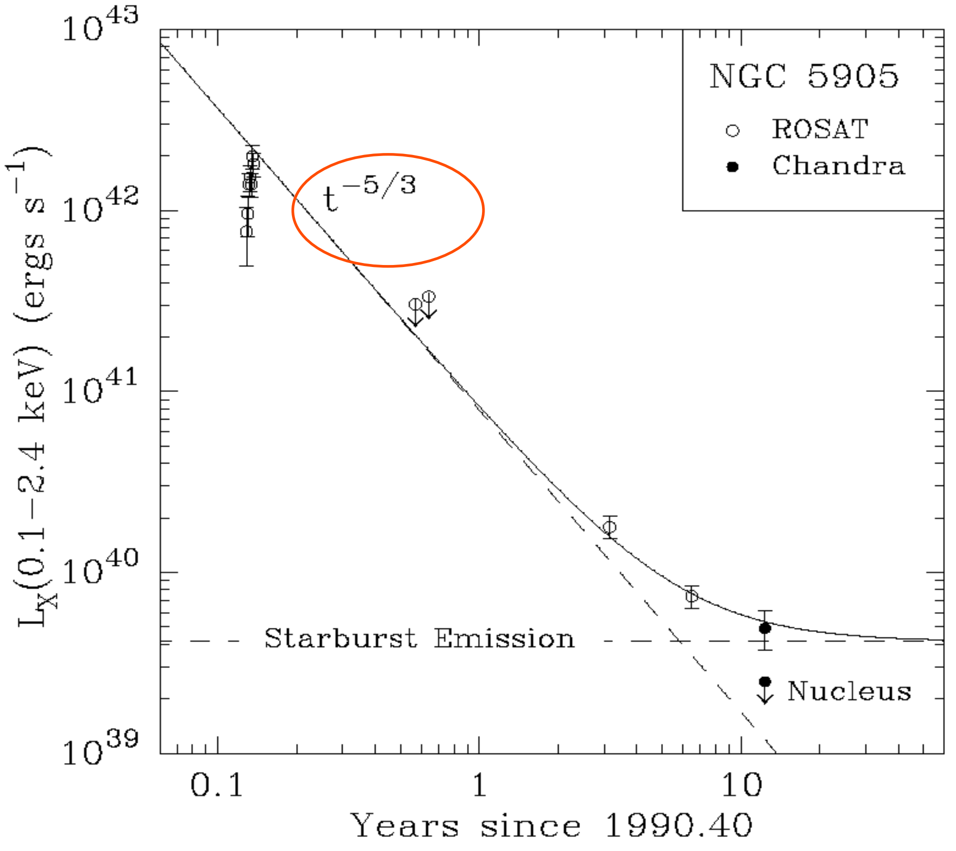
masses (sol.)	0.2 (WD) & 1000 (BH)
in. separation	50 (in 1.E9 cm)
hydrodynamics	SPH (4 030 000 particles)
EOS, gravity	Helmholtz, N
nucl. burning	red. QSE-network (Hix 98)
simul. time	5.4 min
color coded	column density
penet. factor	12

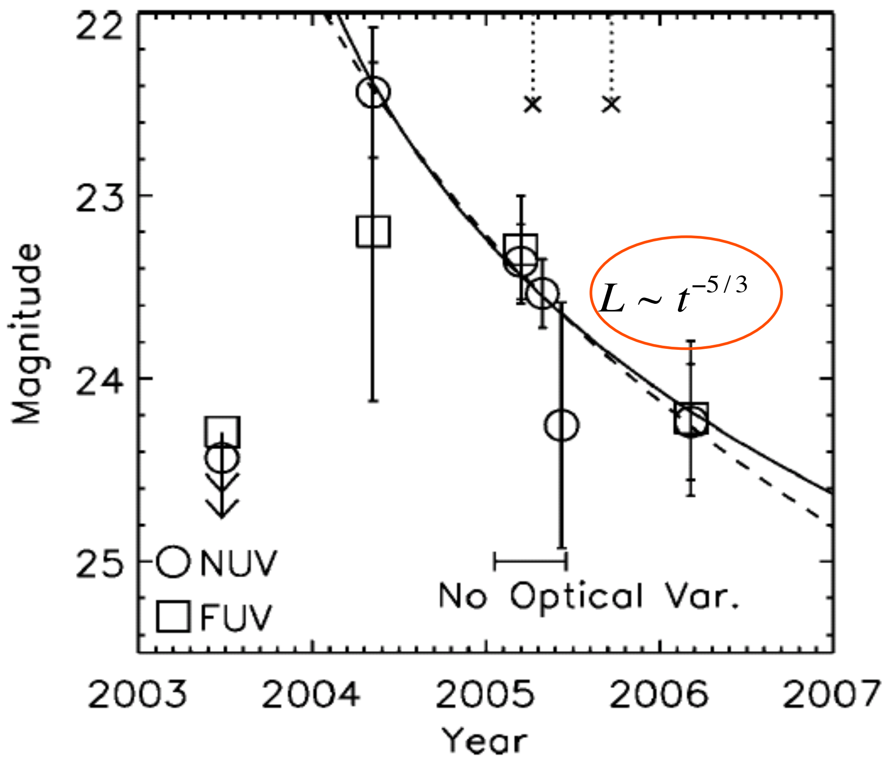
coding, simulation, visualisation: S. Rosswog

WD+1000Msun BH: by Stephan Rosswog

X-ray Flare

UV Flare



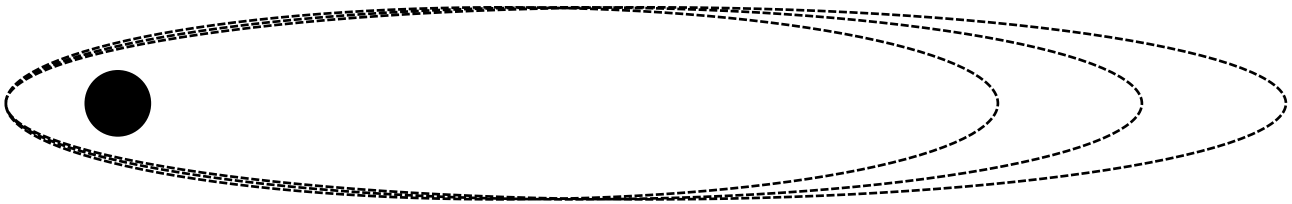


ROSAT: all-sky survey

-- RX J1242.6-1119A

Gezari et al. 2006

GALEX Deep Imaging Survey



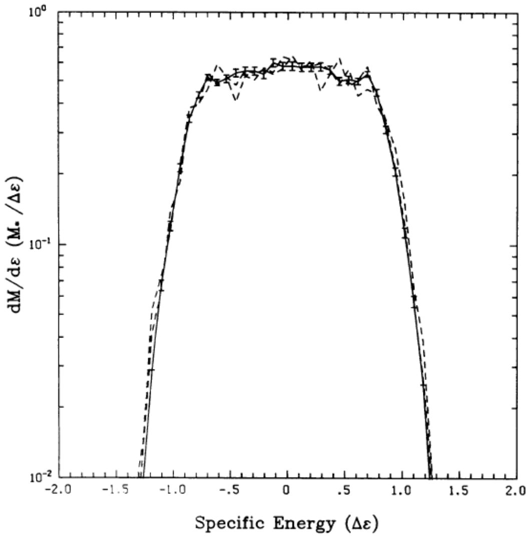
Mass Accretion Rate of Fallback Debris

$$L \propto \frac{dm}{dt} = \frac{dm}{dE}\frac{dE}{da}\frac{da}{dt} \propto \frac{dE}{da}\frac{da}{dt} \propto t^{-5/3}$$

Each debris with E < 0 forms binary with MBH

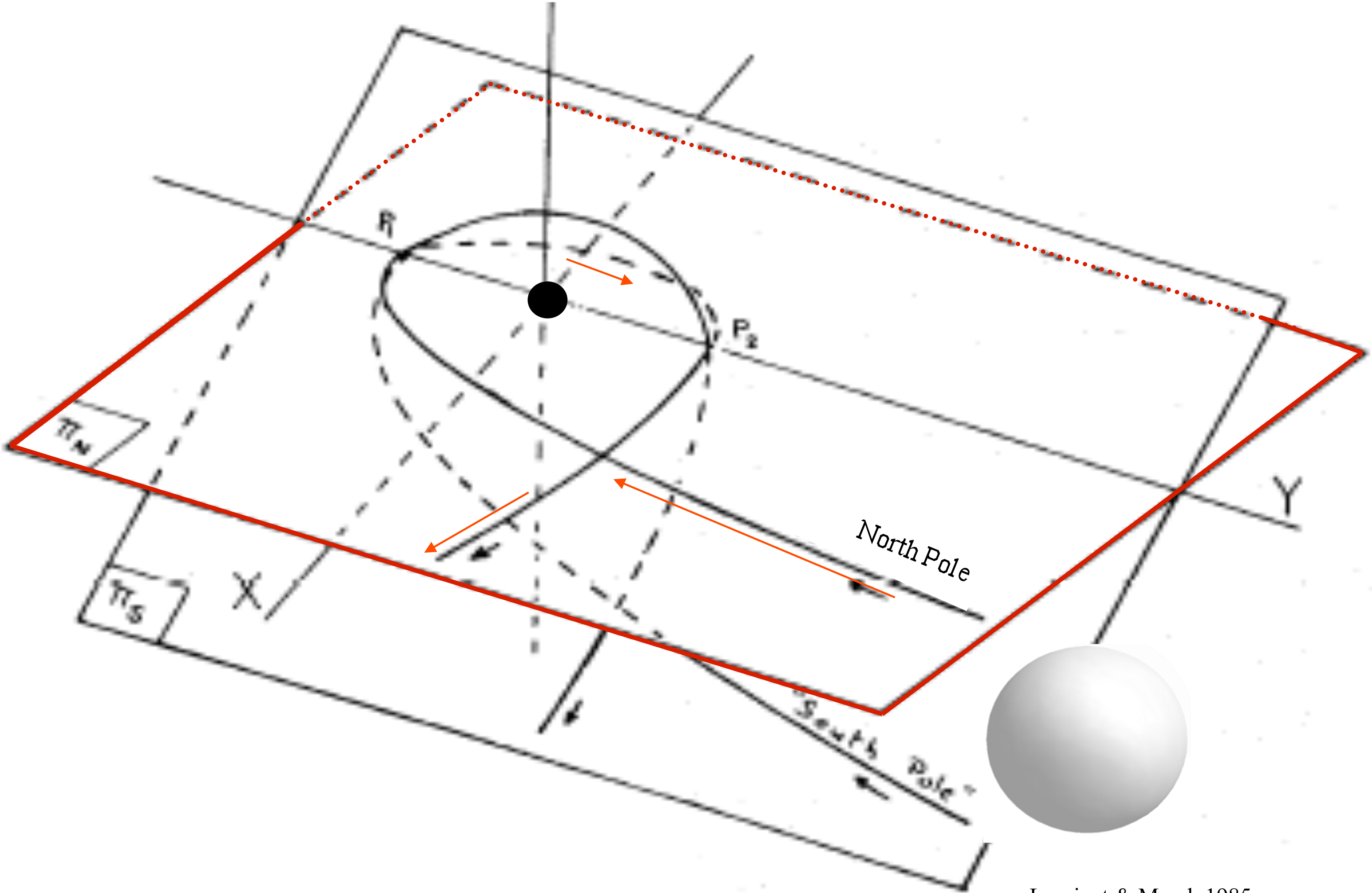
$$\text{Binary}: \quad E = -\frac{GM_{BH}}{2a} \quad , \quad \text{Kepler's law}: \; t \propto a^{3/2}$$

Rees 1988, Phinney 1989

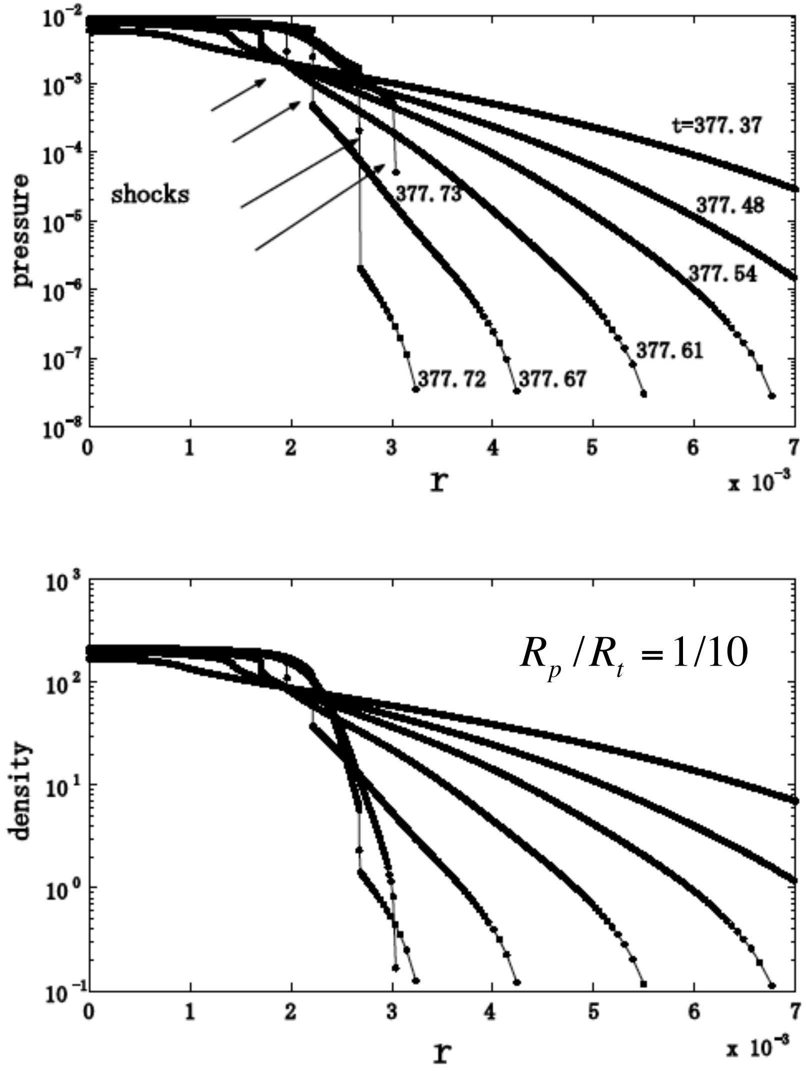


Evans & Kochanek 1989

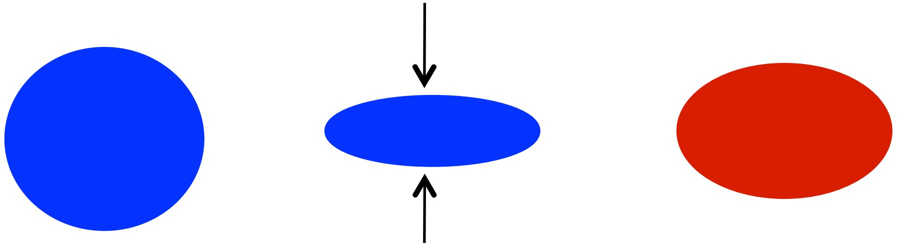
Inside tidal radius: each element independently moves around BH

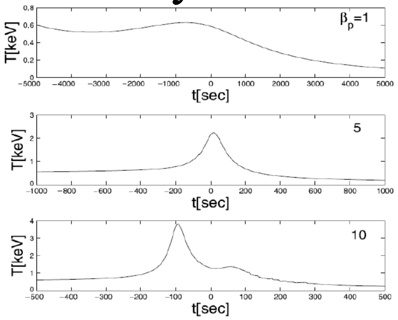


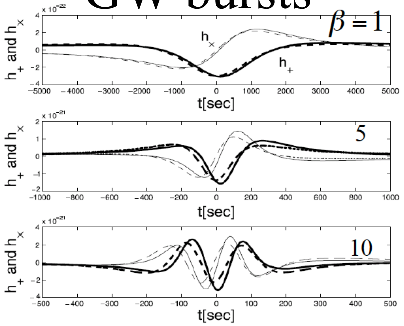
Luminet & Marck 1985



Tidal Compression &
Shock-breakout X-ray Flares



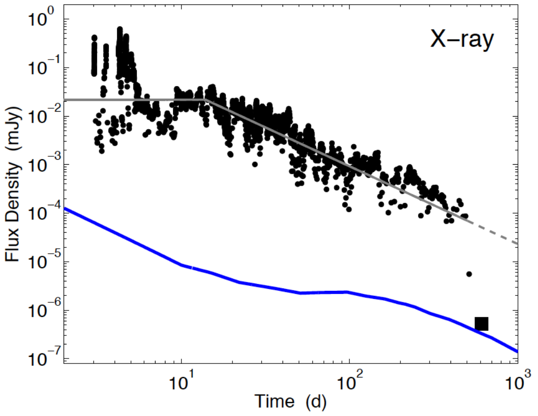

X-ray Flares


GW bursts

Kobayashi et al.; Brassart & Luminet 2008

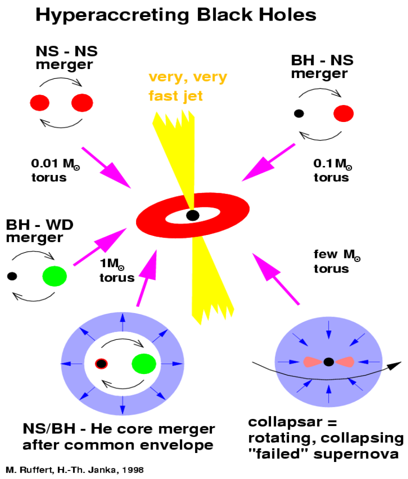
Relativistic Jets from TDEs

Swift 1644+57 (GRB110328A) at z=0.354 ($d = 6\times 10^{27}\,cm$)
X-ray, optical, IR, radio transient with the centroid of the host galaxy
X-ray variability timescale: ~100sec, consistent with those of accreting MBH
X-ray: peak isotropic luminosity > 10^48ergs/s ($L_{Eddington} \sim 10^{44} M_6$ erg/s)
Spectral modeling: non-thermal, Synchrotron-Compton



Zauder et al. 2012

Gamma-Ray Bursts
Stellar mass BH & Relativistic Jets



- Optical “All-Sky” Surveys
  - PannSTARRs
  - Palomar Transient Factory
  - LSST (2020)

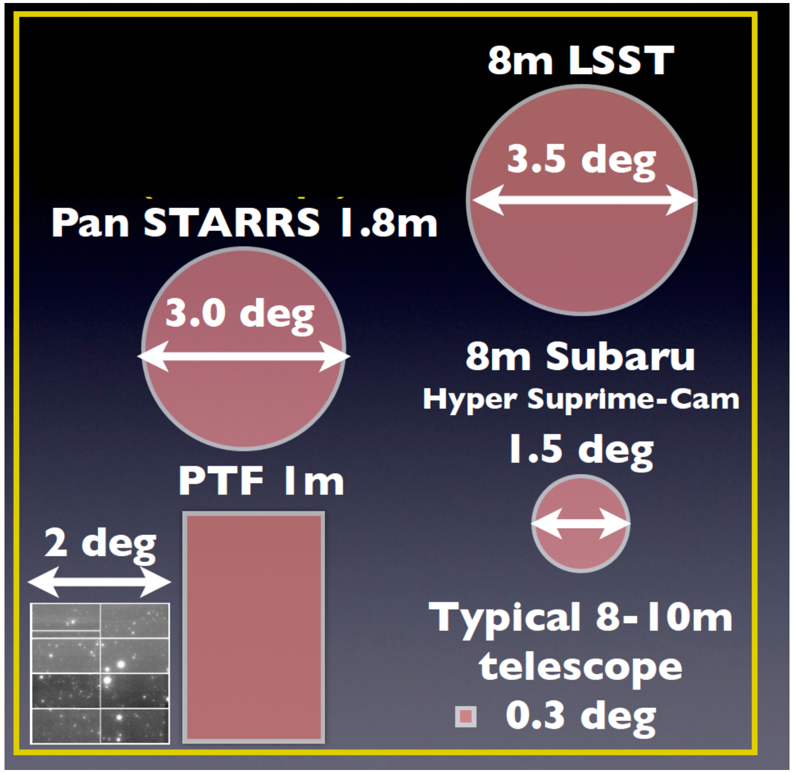
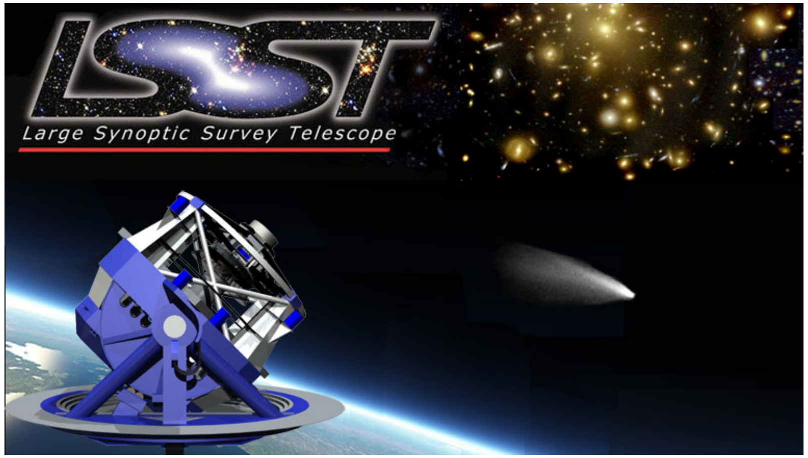


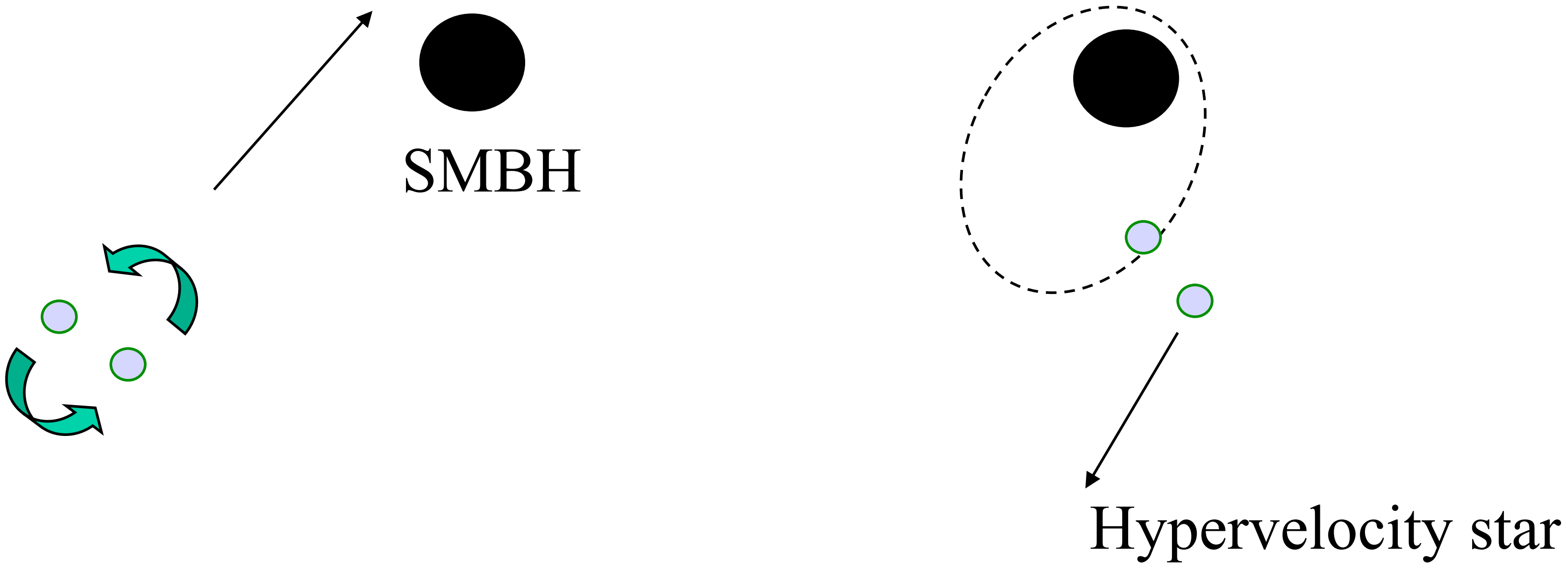
Fig from Tanaka’s multi-messenger talk



Tidal Disruption Event Detection
thousands events/yr

Binary disruption by massive BH

Hills 1988



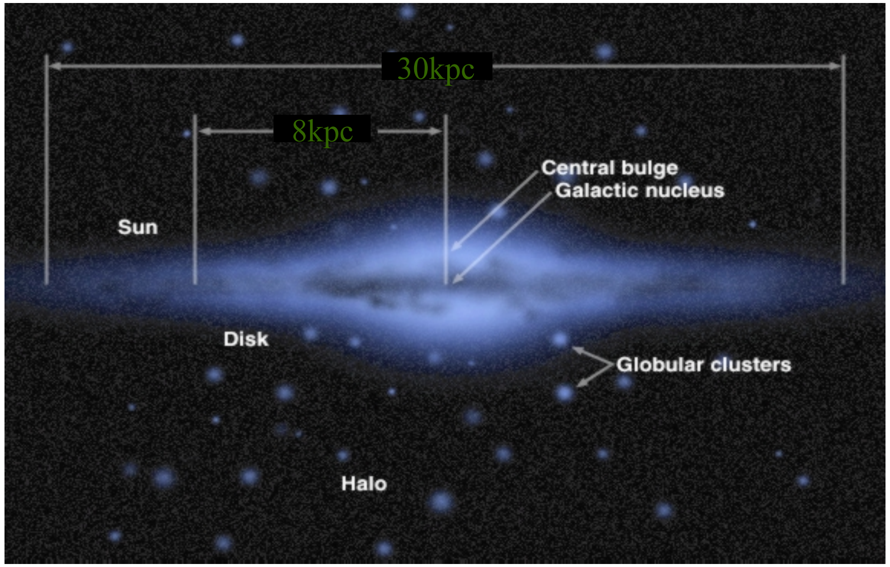
SMBH

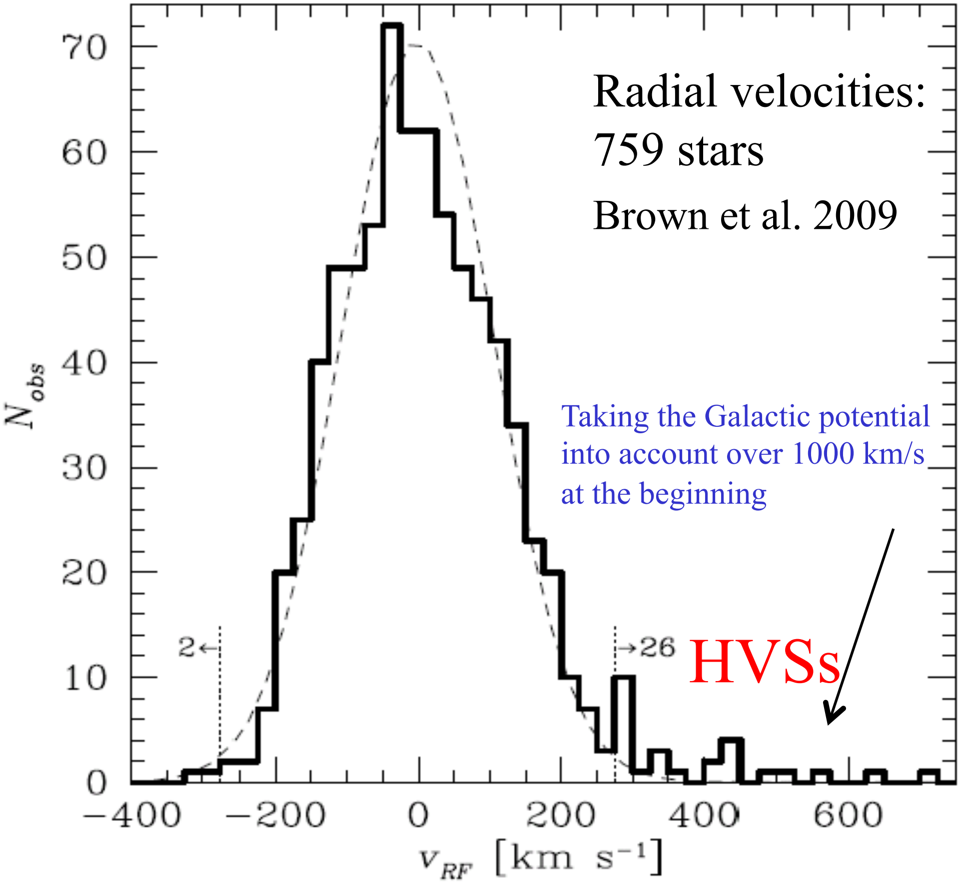
Hypervelocity star

Hypervelocity Stars

Stars with a velocity more than the escape velocity of the Galaxy found in the halo 50-100kpc

Brown et al. 2005, 2009, Hirsch et al. 2005



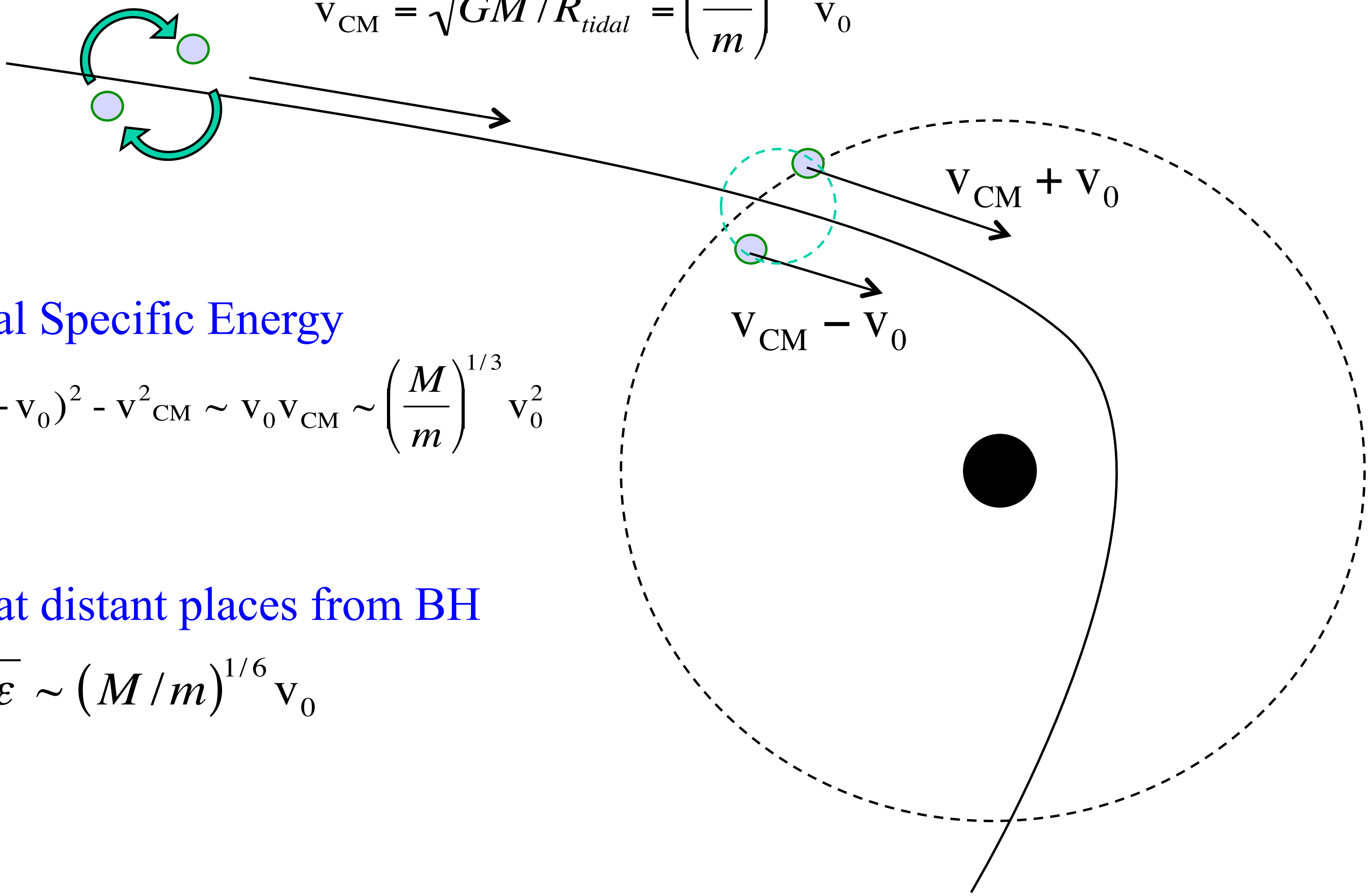


Radial velocities:
759 stars
Brown et al. 2009

Taking the Galactic potential into account over 1000 km/s at the beginning

HVSs

$$\mathrm{v}_0 \sim \sqrt{Gm/a}$$



$$\mathrm{v}_{\mathrm{CM}} = \sqrt{GM/R_{tidal}} = \left(\frac{M}{m}\right)^{1/3} \mathrm{v}_0$$

Additional Specific Energy

$$\delta\varepsilon \sim (\mathrm{v}_{\mathrm{CM}} + \mathrm{v}_0)^2 - \mathrm{v}^2{}_{\mathrm{CM}} \sim \mathrm{v}_0 \mathrm{v}_{\mathrm{CM}} \sim \left(\frac{M}{m}\right)^{1/3} \mathrm{v}_0^2$$

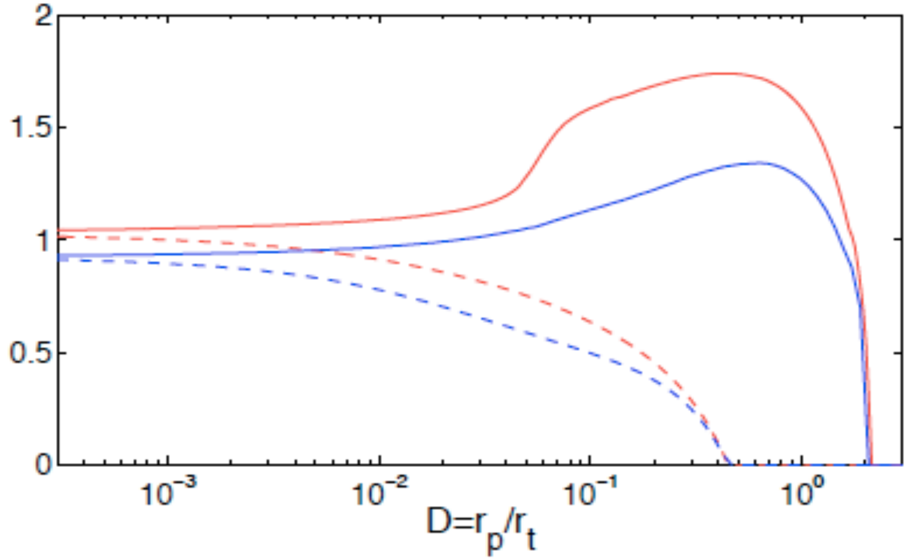
Velocity at distant places from BH

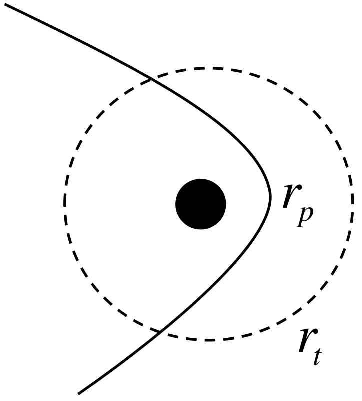
$$\mathrm{v}_{\mathrm{eje}} \sim \sqrt{\delta\varepsilon} \sim (M/m)^{1/6} \mathrm{v}_0$$

Energy change in units of $(Gm_1m_2/a)(M/m)^{1/3}$

$\langle|\Delta E|\rangle$

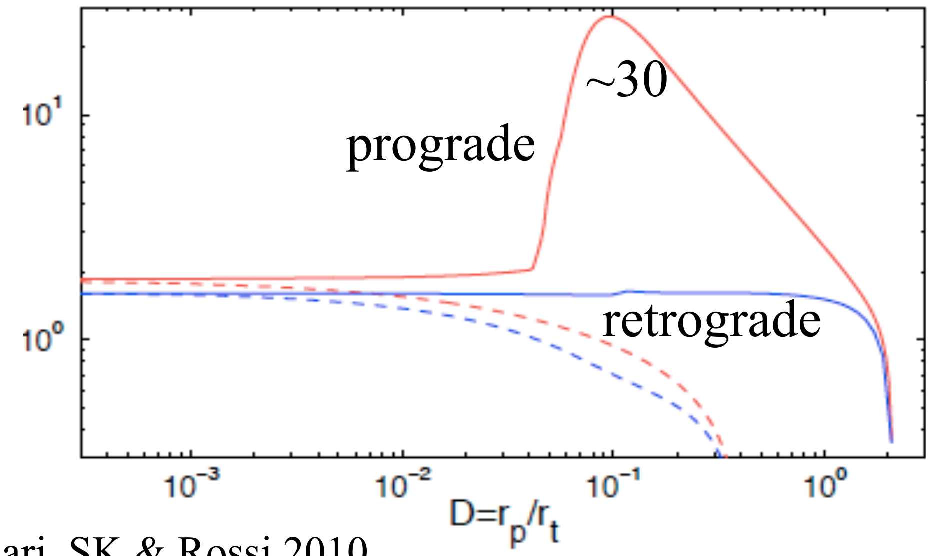
Averaged energy over binary phase

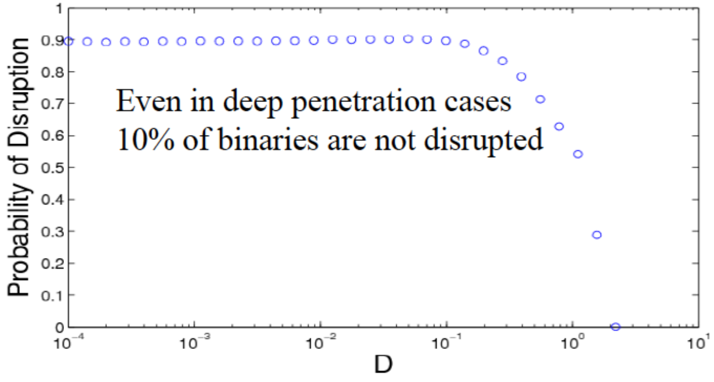




$\Delta E_{\max}$

max energy for different binary phases

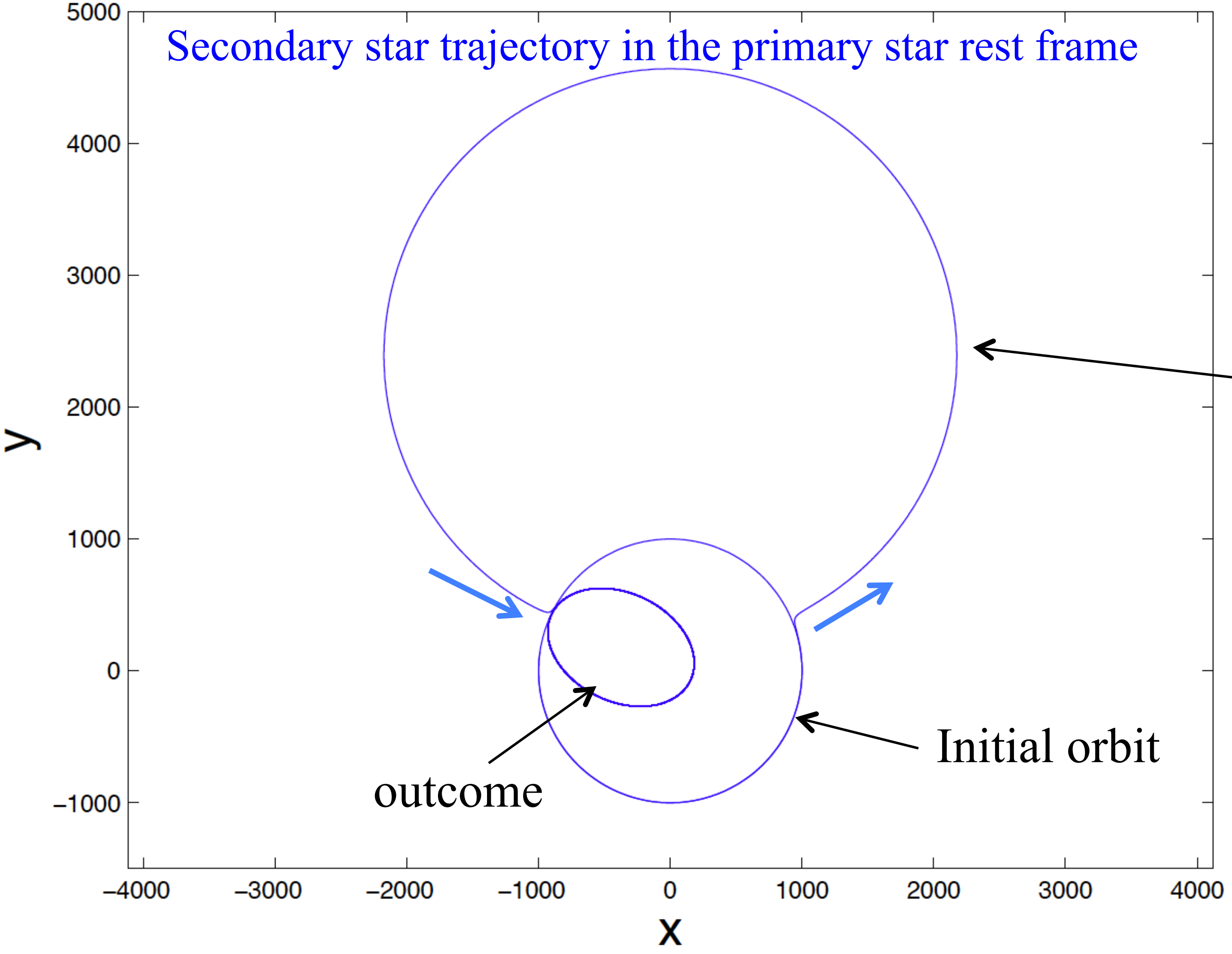




Even in deep penetration cases
10% of binaries are not disrupted

Sari, SK & Rossi 2010

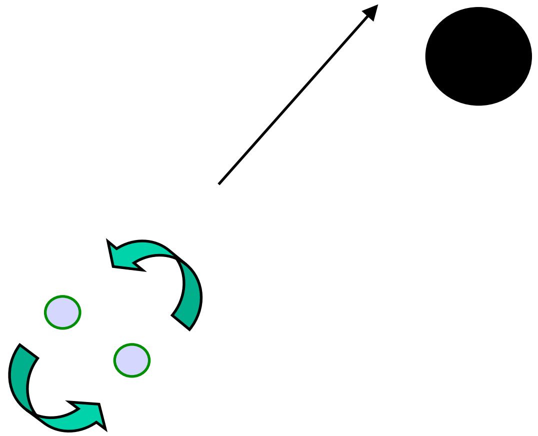
In deep encounters, one of the free solutions dominates around the periapsis passage. Binary dissolves, but after the periapsis passage, they come close to each other.

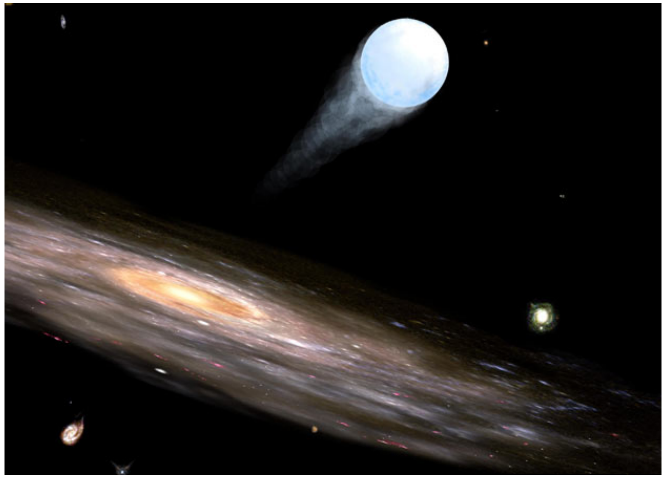


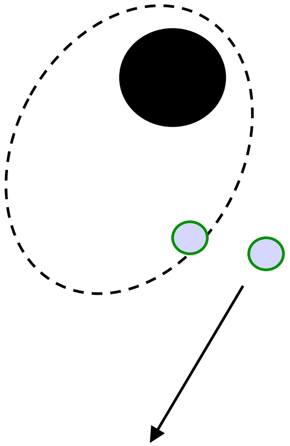
Analytic solution for a deep encounter: the binary members are in the same trajectory in the BH frame but slightly separated in time.

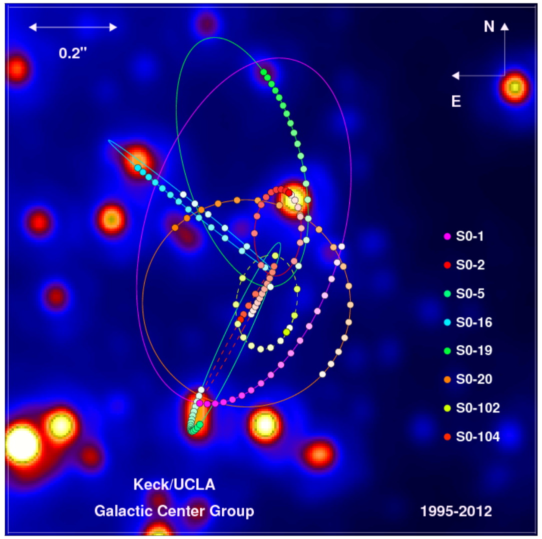
$$\frac{d^2\vec{r}}{dt^2} = \frac{GM}{r_m^3}\left(-\vec{r} + \frac{3(\vec{r}_m\vec{r})}{r_m^2}\vec{r}_m\right) + \cancel{\frac{Gm}{r^3}\vec{r}}$$

Hypervelcity Stars and S-stars



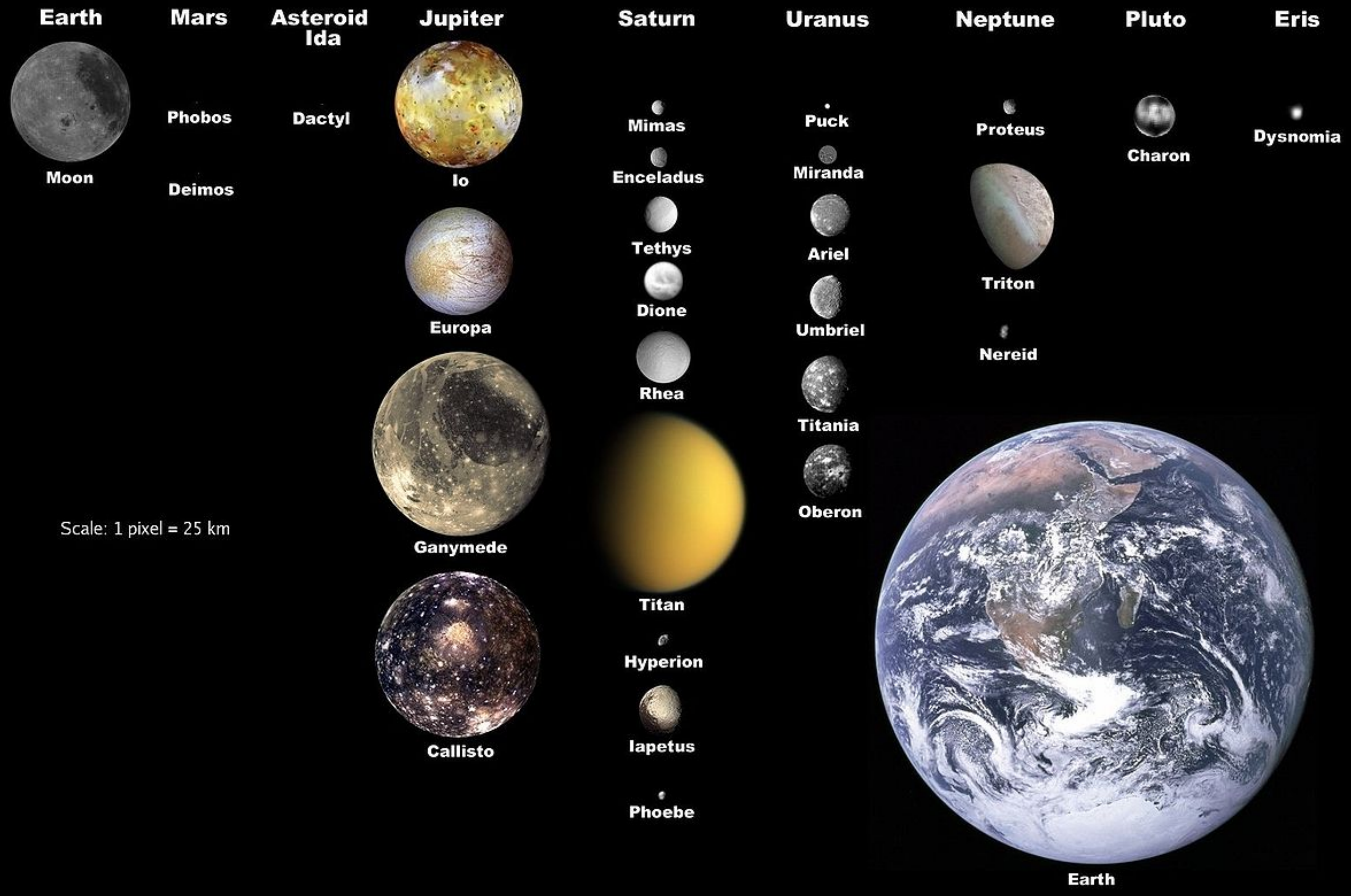






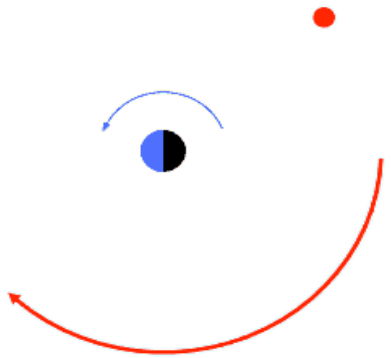
Over 100 satellites are orbiting the giant planets in the Solar system.

Selected Moons of the Solar System, with Earth for Scale



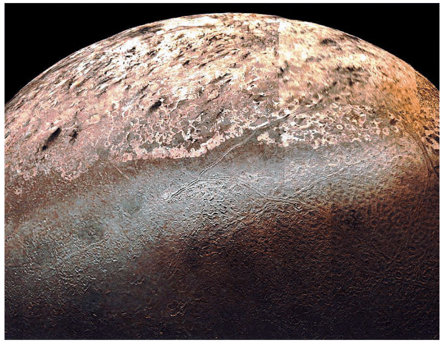
1/3 of the known satellites are classified as regular, with circular and planar orbits.

The majority is irregular ones which have larger eccentricity and/or inclination. A large fraction of them orbit their planet in the retrograde direction. It is very unlikely that they were formed by accretion in a circum-planetary disk.

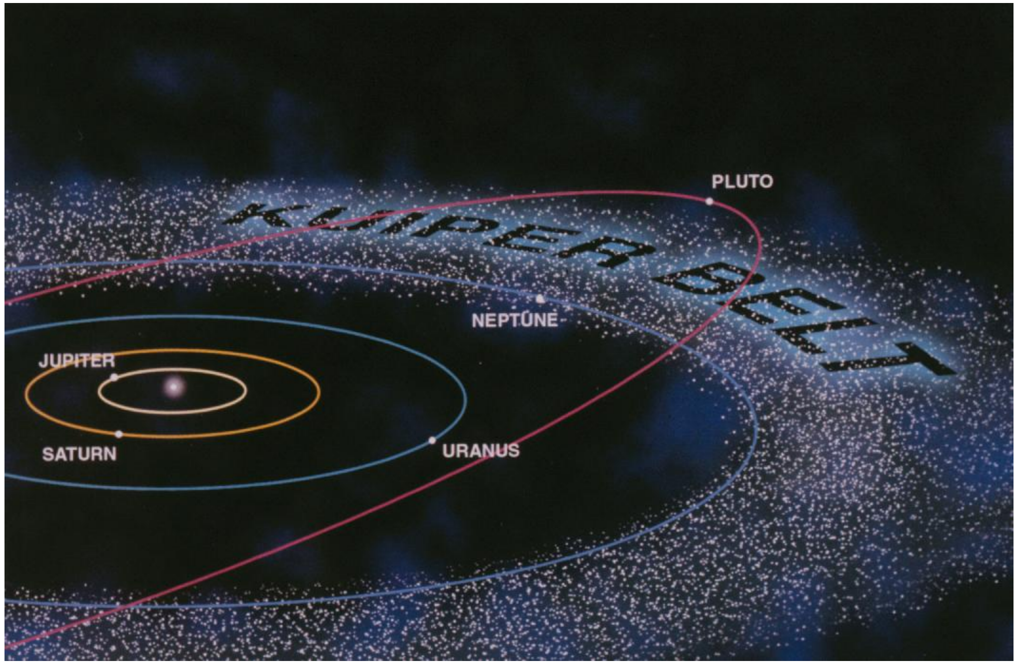


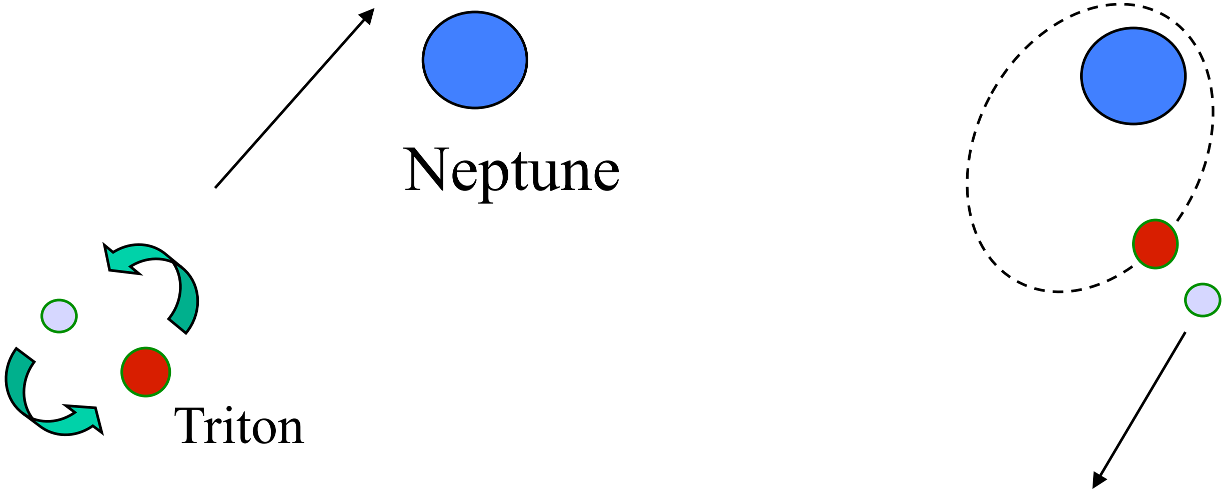
Retrograde orbits

Saturn's Phoebe



Neptune's Triton



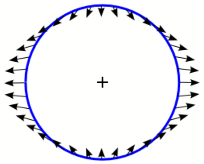


Neptune

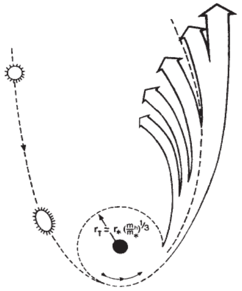
Triton

Agnor & Hamilton 2006; Kobayashi et al. 2012

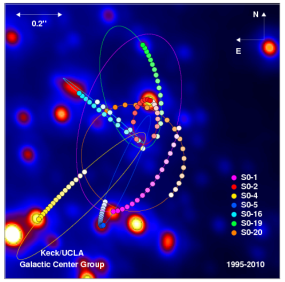
Summary



- Tidal Force
  - Spaghettification, Cloud G2



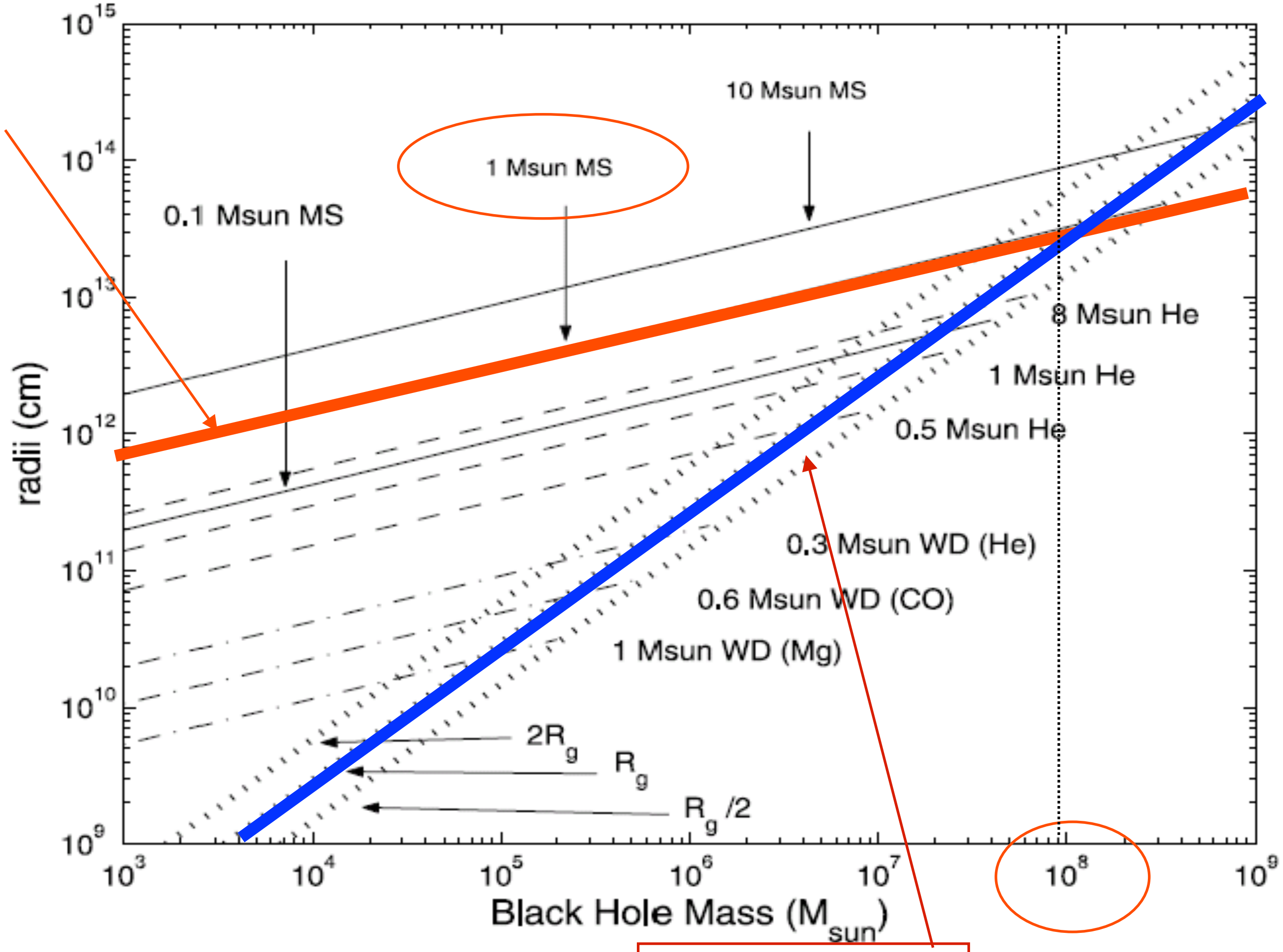
- Tidal disruption of a star by massive BH
  - Tidal compression flares, relativistic jets, t^{-5/3}
  - All-sky surveys



- Tidal disruption of a binary by massive object (BH, planet)
  - Hypervelocity stars in the halo
  - S-stars in the Galactic centre
  - Irregular satellites around giant planets

$R_t \propto M^{1/3}$

Tidal Radius



$R_g \propto M$

Schwarzschild radius