The Galactic Center

Jason Dexter
MPE Garching

with slides from R. Genzel, S. Gillessen, and the MPE GC group

mpe.mpg.de/ir/GC

ESO/Y. Beletsky

The Galactic Center

1. Evidence for a massive black hole (14.11)

2. A paradox of youth (today)

3. Sgr A* and the faintest black holes (21.11)

4. Compact objects, dark matter, and the high energy GC (23.11)

Seminar: strong gravity around Sgr A* (23.11)

About the lectures

- Selected topics: central parsec, highly biased
- Please ask questions!

- ~1 interactive Q / lecture:
  ~10 mins to think/calculate, discuss, share

- Further reading: Genzel+2010, Morris+2012, Falcke & Markoff 2013

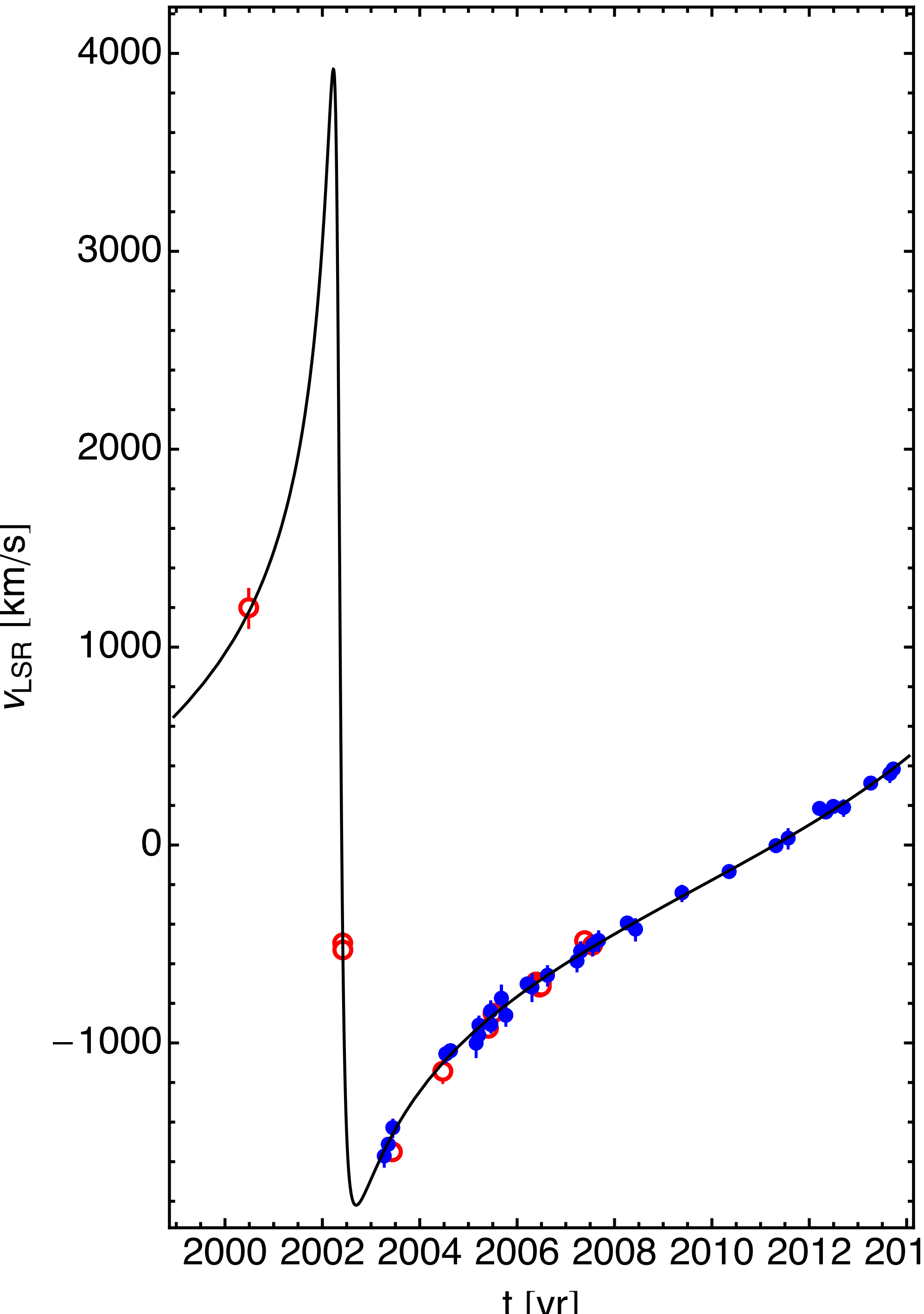
About the lectures

- pdf of slides online: mpe.mpg.de/~jdexter/gcslides.html
- Requests for topics: now or e-mail jdexter@mpe.mpg.de
- Any other Q's: around after, next Mon/Wed

1. The Galactic Center: evidence for a massive black hole

Recap

Young stars in the central parsec



S2: the showcase star

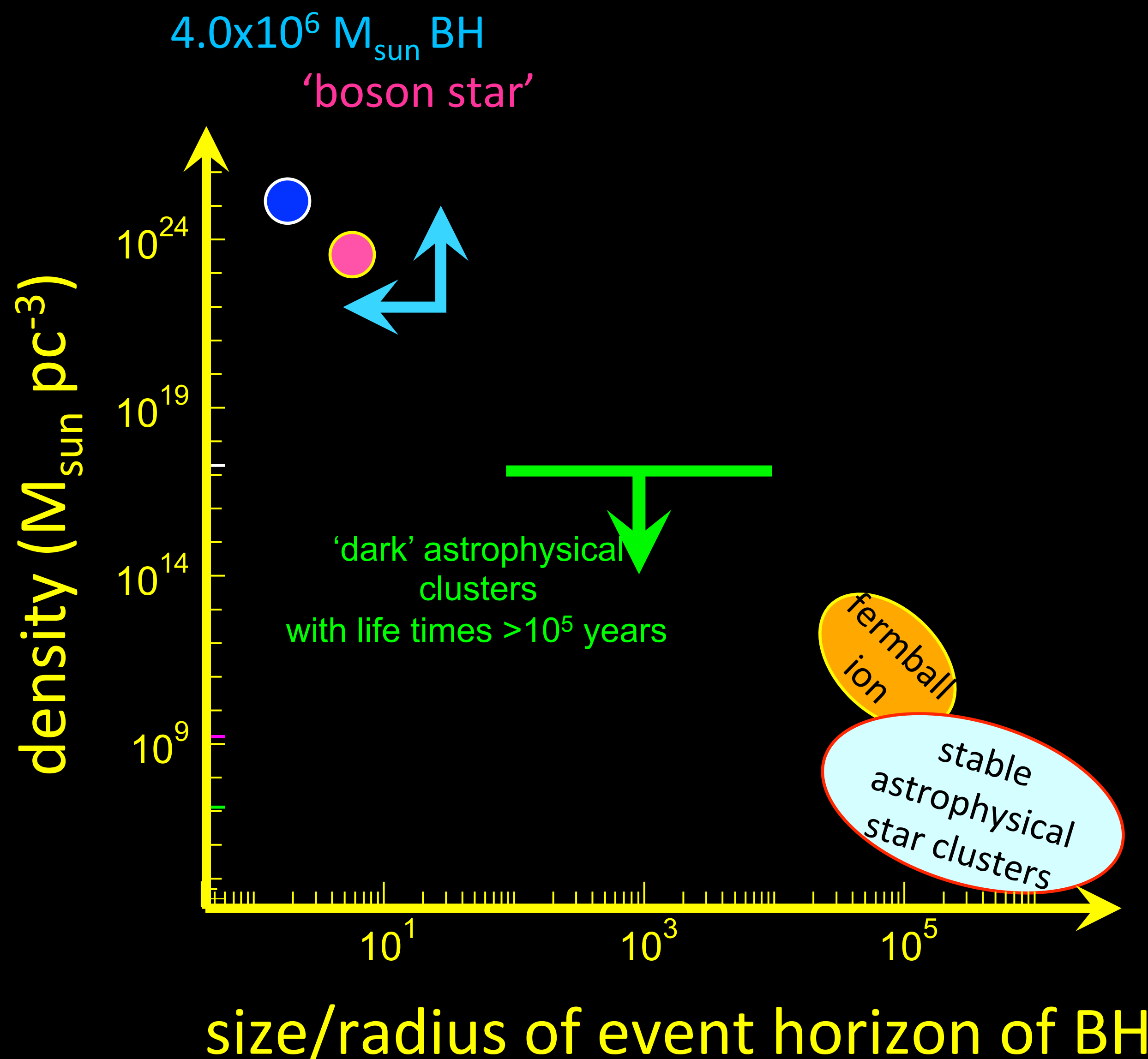
VLT Keck

(Gillessen et al. 2009ab, Ghez et al. 2008, newer data)

- period: 15.9 years
- semi major axis: 125 mas
- eccentricity 0.88

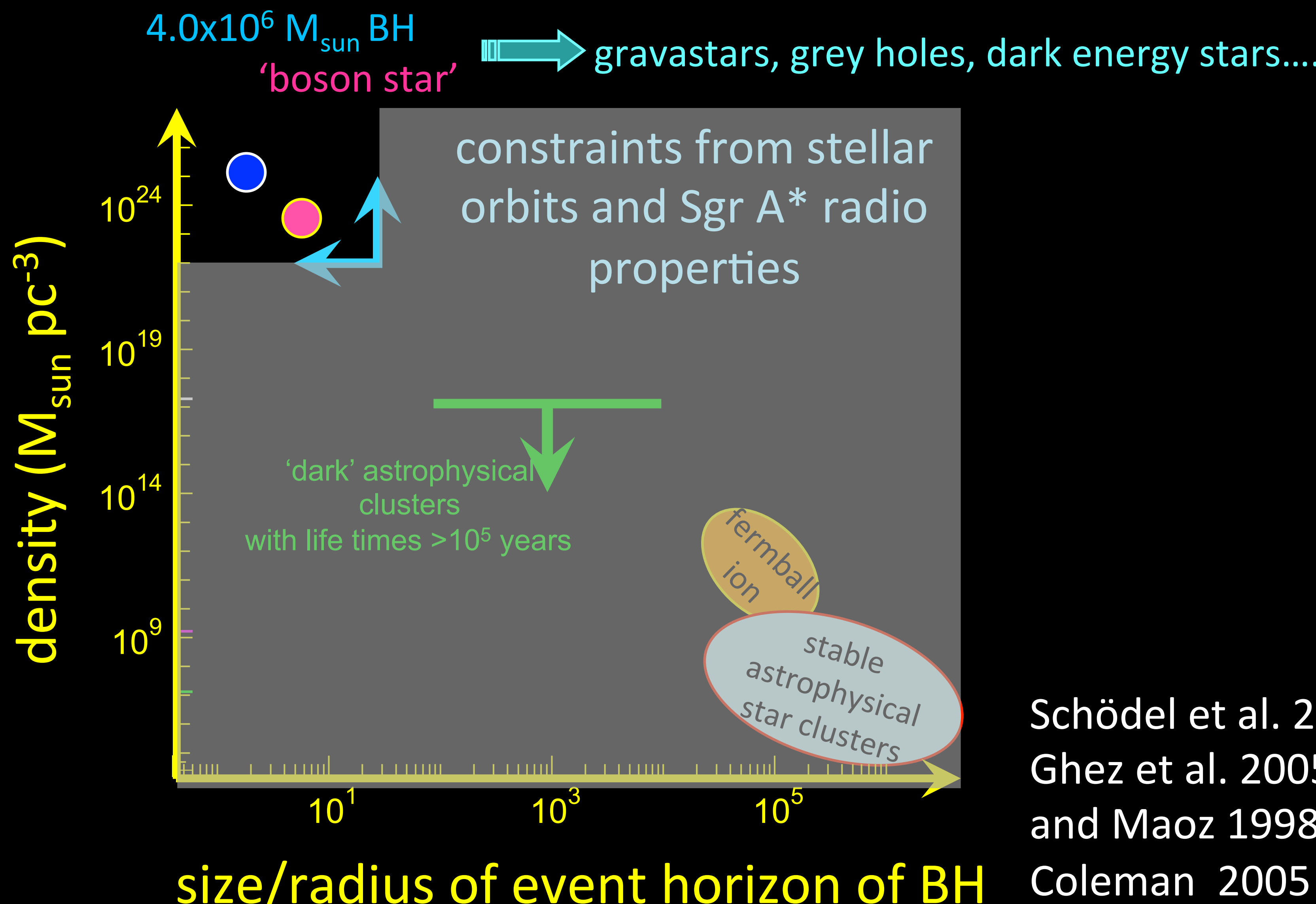
- $M = 4.30 \pm 0.06 \pm 0.35 \times 10^6\ M_\odot$
- $R_0 = 8.28 \pm 0.15 \pm 0.30$ kpc

Sgr A* is a black hole



Schödel et al. 2003,
Ghez et al. 2005,
and Maoz 1998,
Coleman 2005

Sgr A* is a black hole

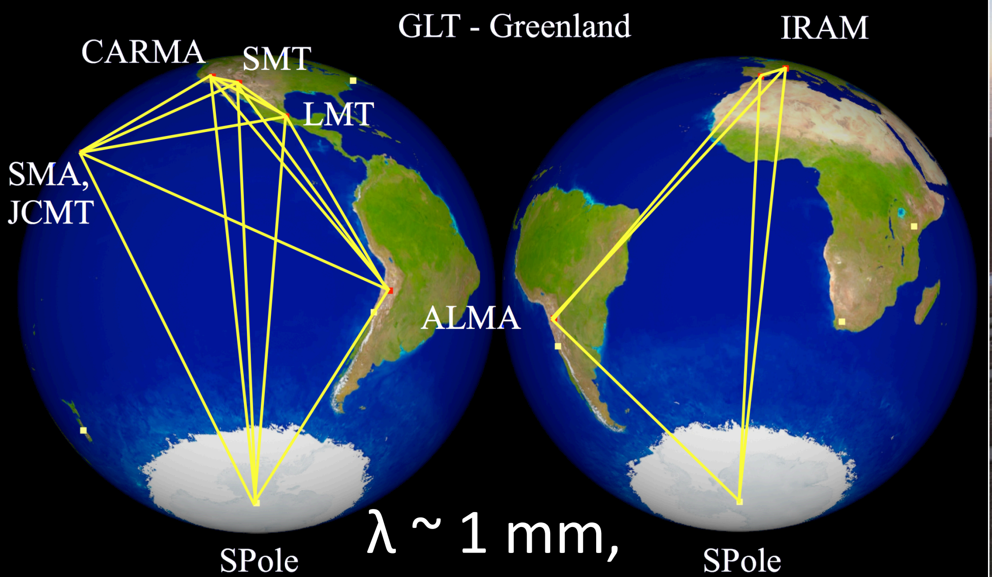


Schödel et al. 2003, Ghez et al. 2005, and Maoz 1998, Coleman 2005

Resolving an event horizon

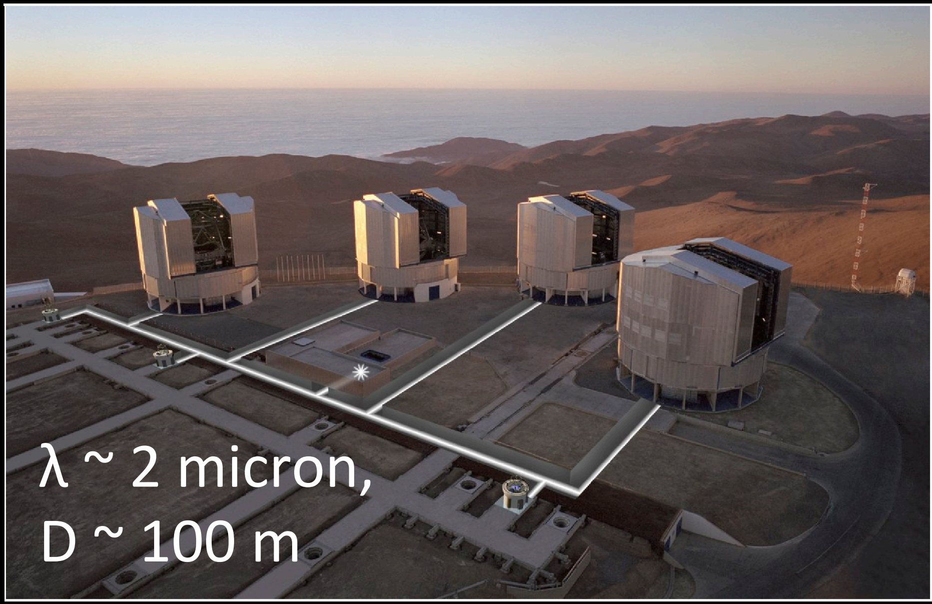
- Two new experiments to resolve gas near Sgr A*
- Resolution: 10-100 μas

Event Horizon Telescope



λ ~ 1 mm,
D ~ 5000 km

VLTI GRAVITY



λ ~ 2 micron,
D ~ 100 m

2. The Galactic Center

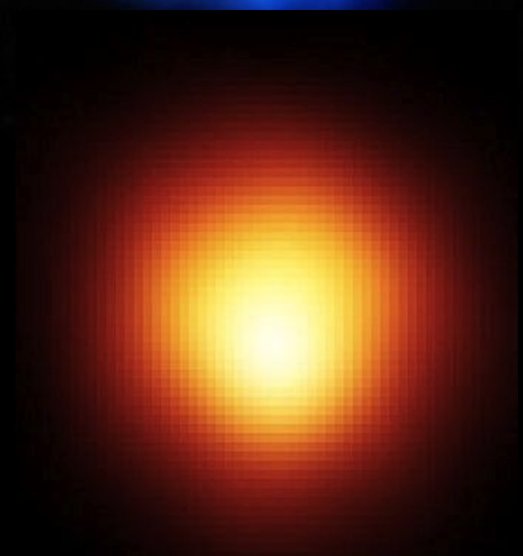
A paradox of youth

Young stars in the central parsec

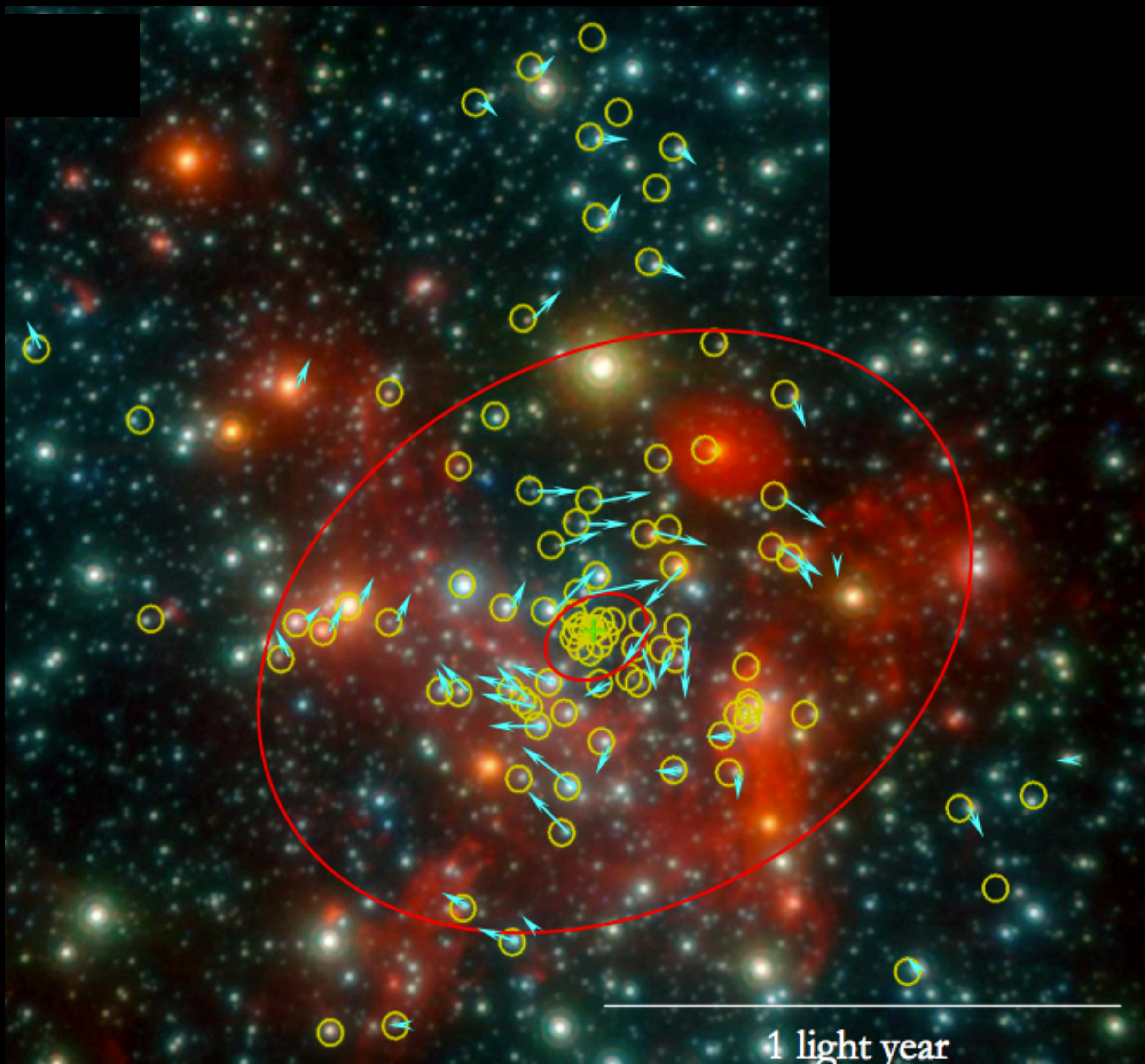
Stars: O/WR, B, late-type/old

- O/WR: ~50 M_{sun}, T ~ 10 Myr
- B: ~10 M_{sun}, T ~ 100 Myr

- ~200 O/WR stars in GC known
- Central parsec supernova and star formation rate ~5-10% of the entire Galaxy



A clockwise disk of massive O/WR stars



Age: 6 +/- 2 Myr
Mass: ~20 M_{sun}

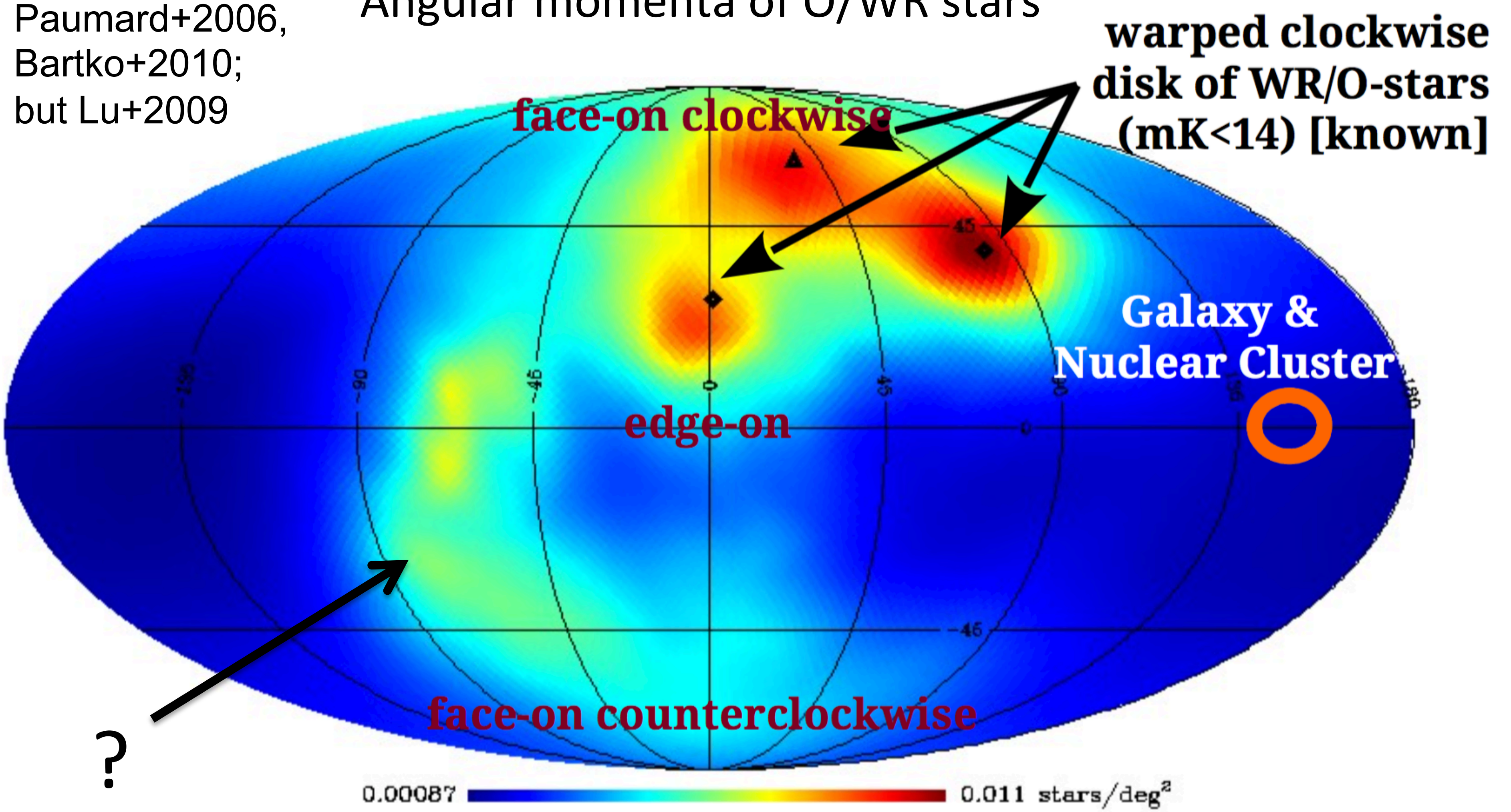
R ~ 0.05-0.5 pc
Thick, warped

Paumard+ 2006
Martins+ 2007
Bartko+ 2009
Bartko+ 2010,
Lu+ 2013

A second, counter-clockwise disk?

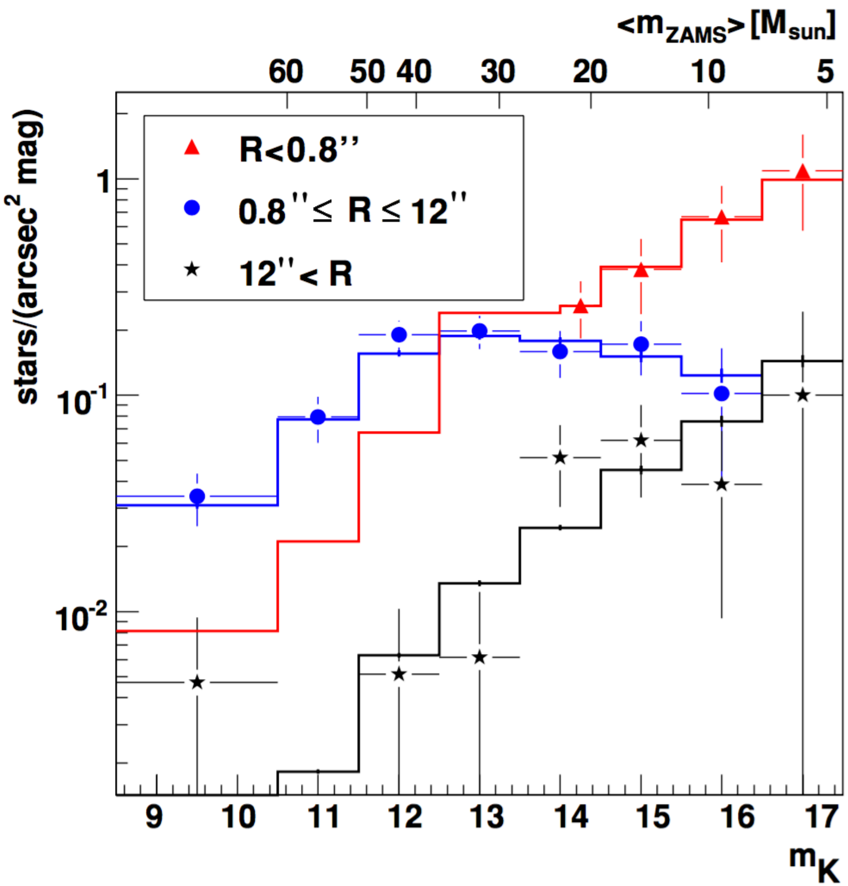
Paumard+2006, Bartko+2010; but Lu+2009

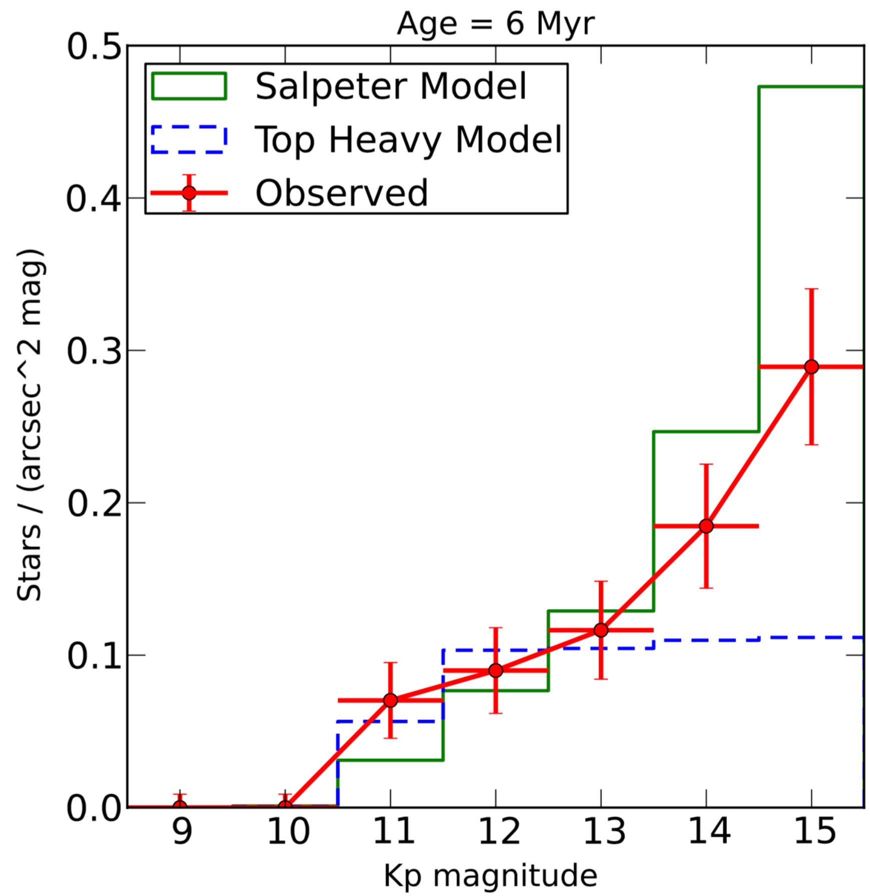
Angular momenta of O/WR stars



Top-heavy initial mass function

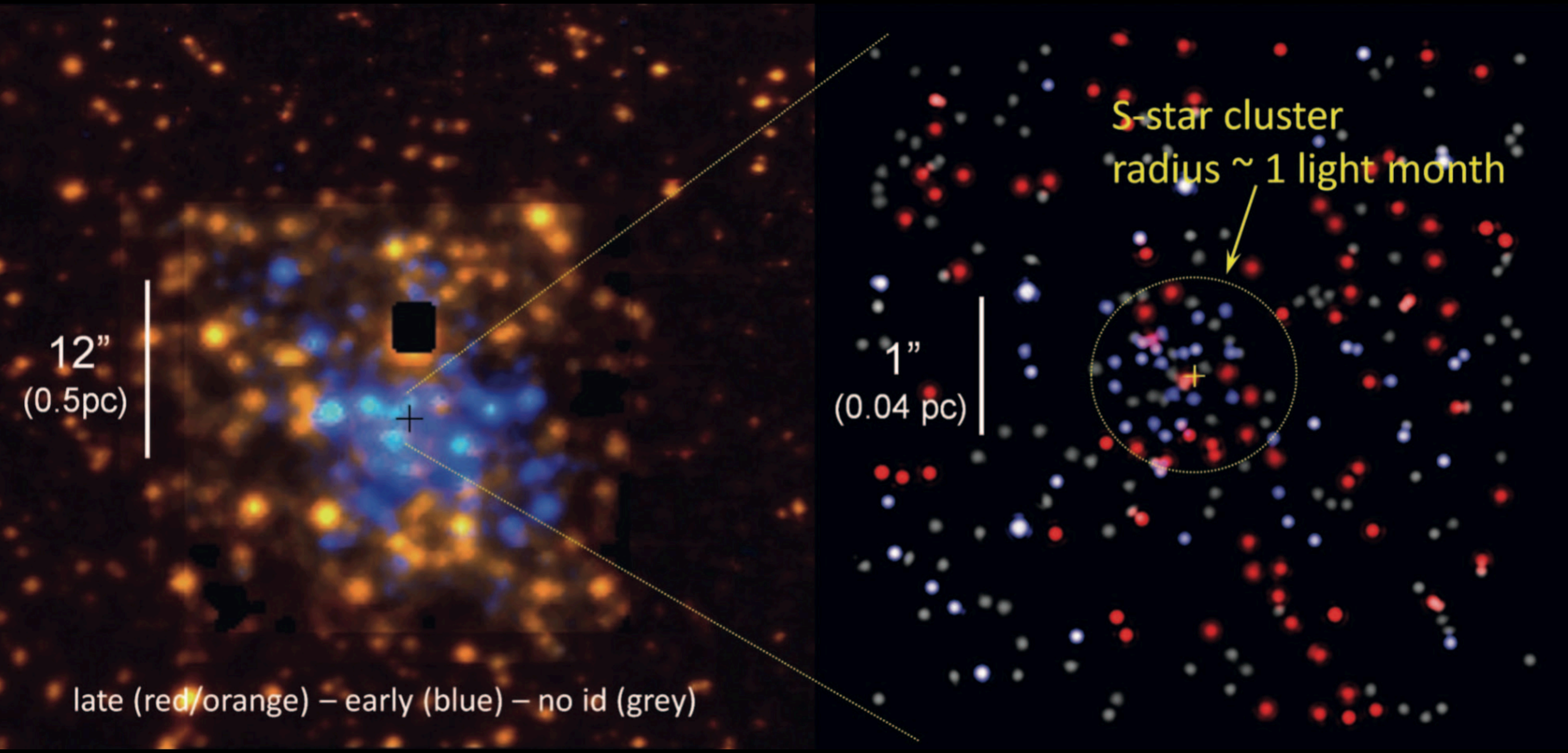
- Salpeter/Kroupa: $dN/dm \sim m^{-\alpha}$, $\alpha = -2.35$
- O/WR disk: $\alpha = -0.45$ (Bartko+2010) or -1.7 (Lu+2013)



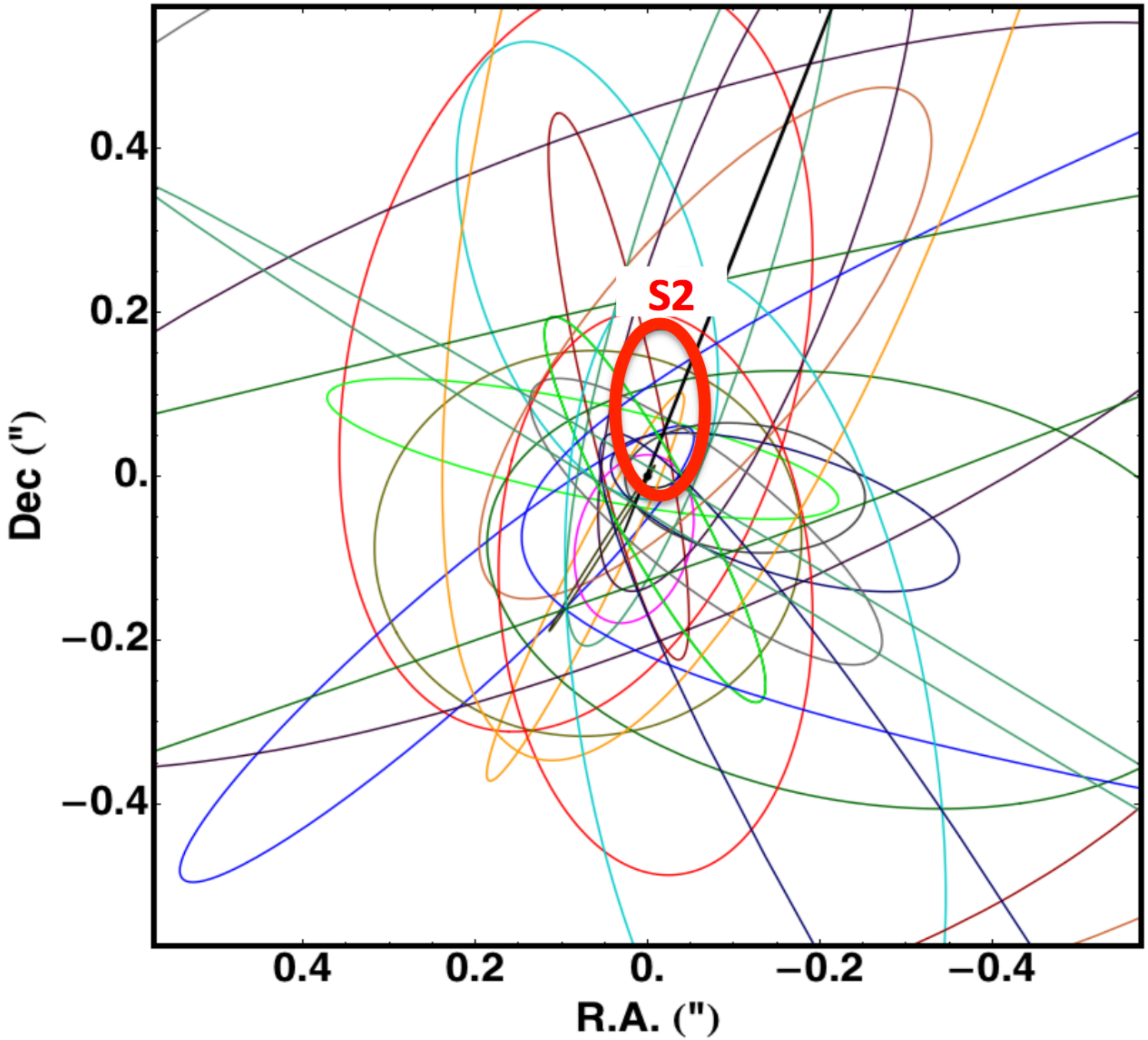


The “S” star cluster is even closer in

O/WR stars B stars



Currently: ≈ 40 orbits known

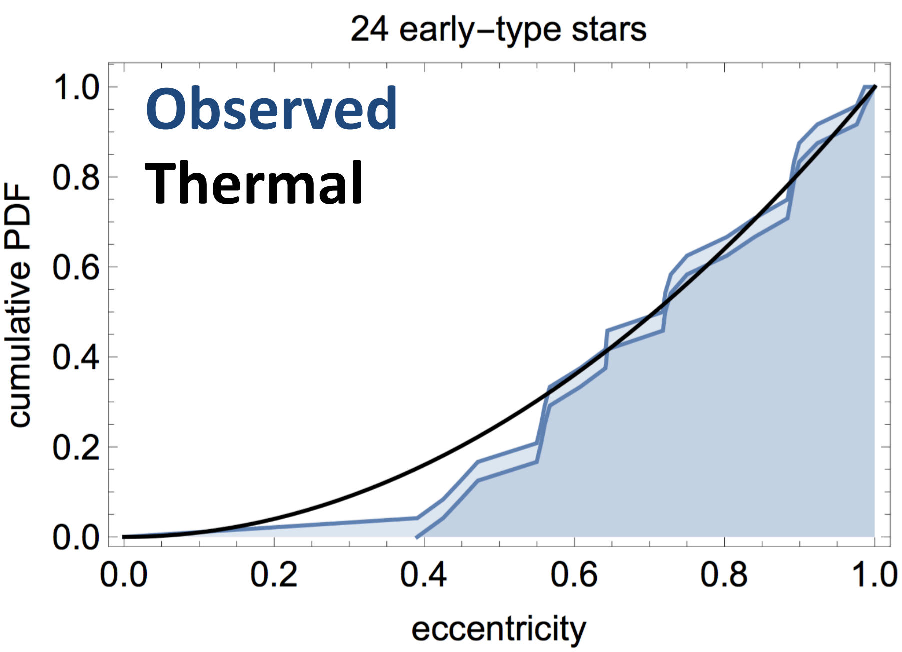


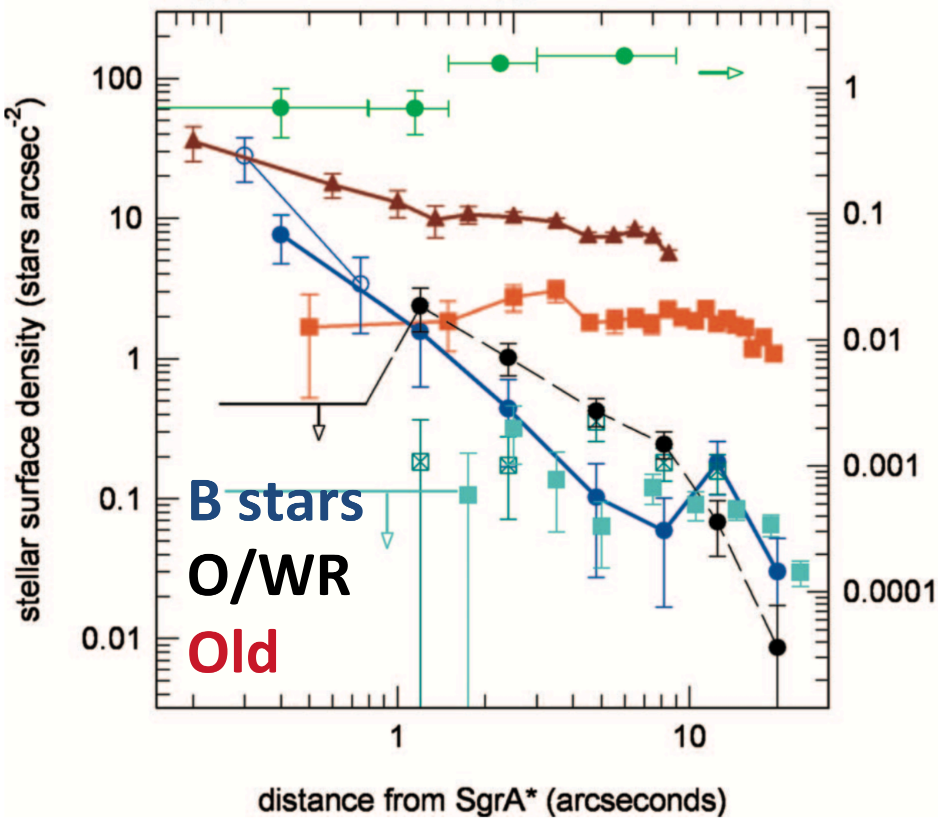
Gillessen et al. 2009

Gillessen+ in prep.

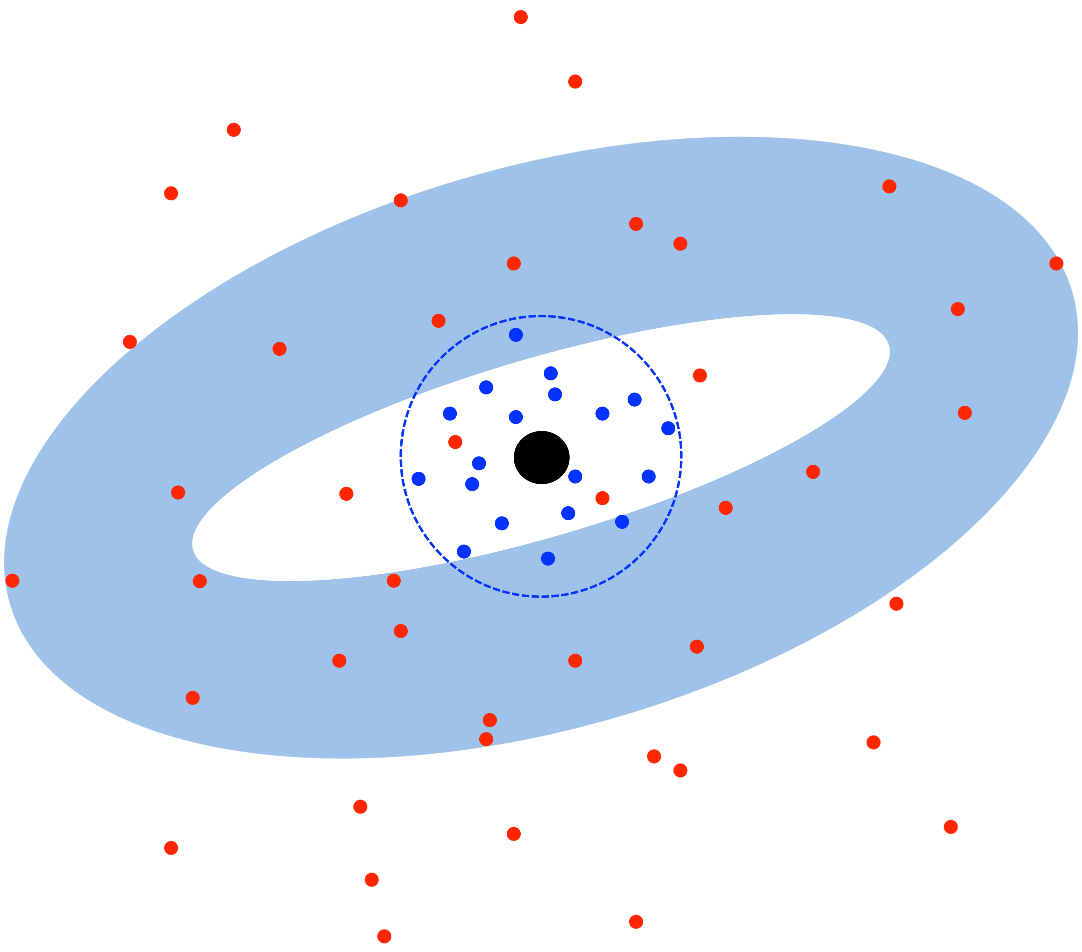
The S stars: random orbits

- S stars: "relaxed" cusp with thermal eccentricity distribution
- Old stars: no cusp





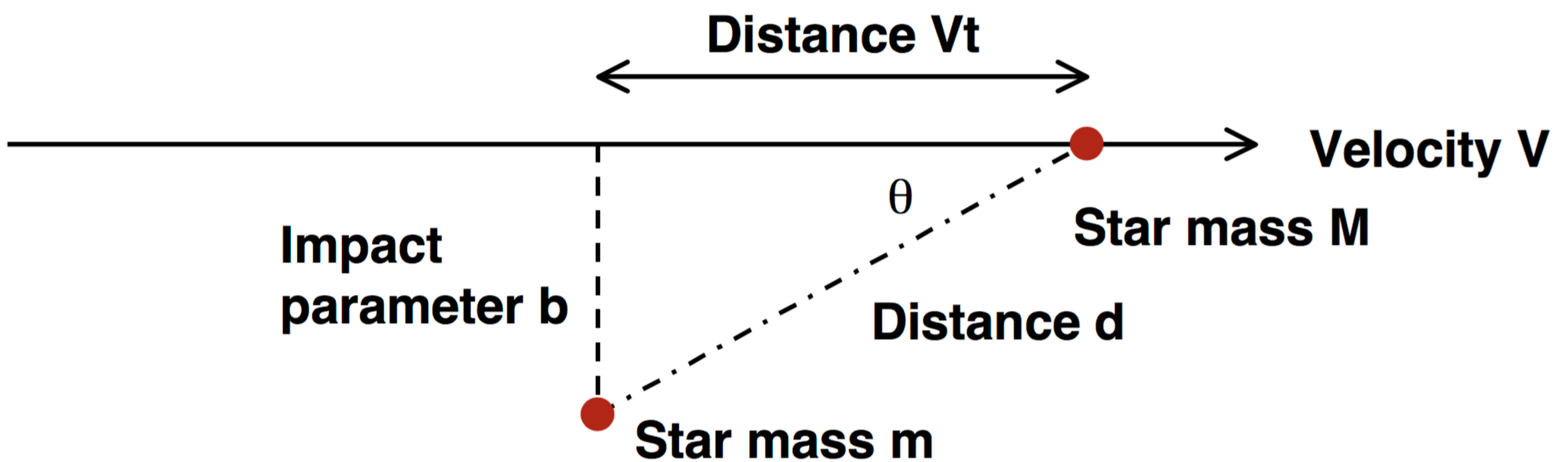
Cartoon version of the stellar system



- S-stars
  - young, 10^8 yr
  - r < 0.05 pc
  - orbits
- Stellar disk
  - younger, 10^7 yr
  - 0.05 pc < r < 0.5 pc
- Old stars
  - everywhere
- and more:
  - stellar black holes
  - neutron stars
  - white dwarfs
  - fainter MS stars

Two-body relaxation

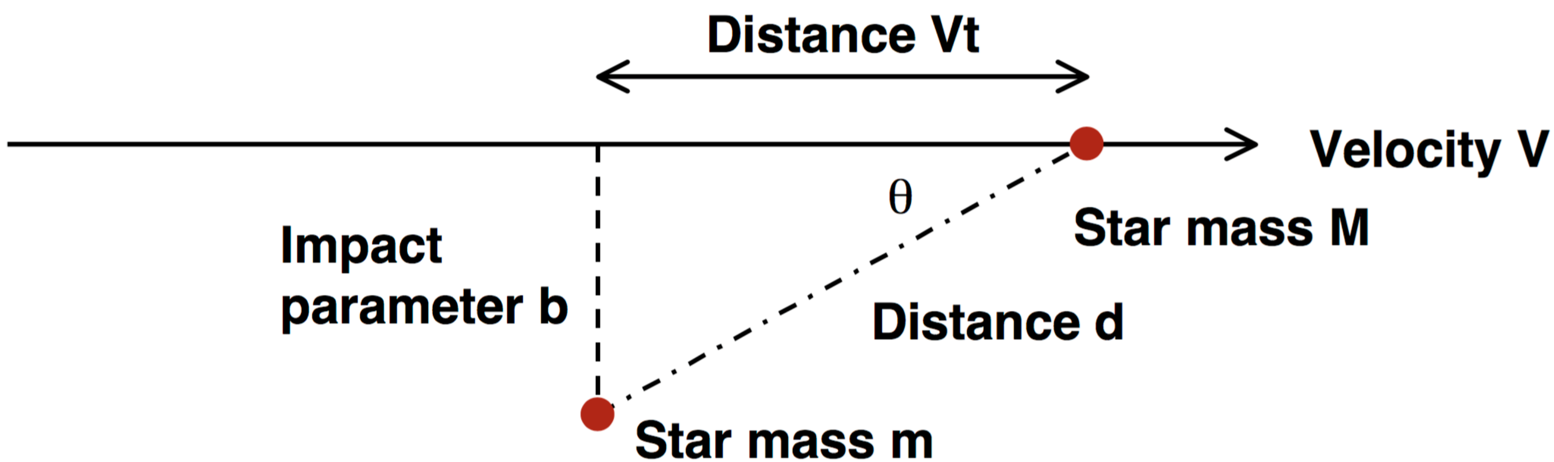
- How long does it take for stellar orbits to change from random scattering with stars?



- Assume: $\delta v \perp v$, $\delta v << v$

Two-body relaxation

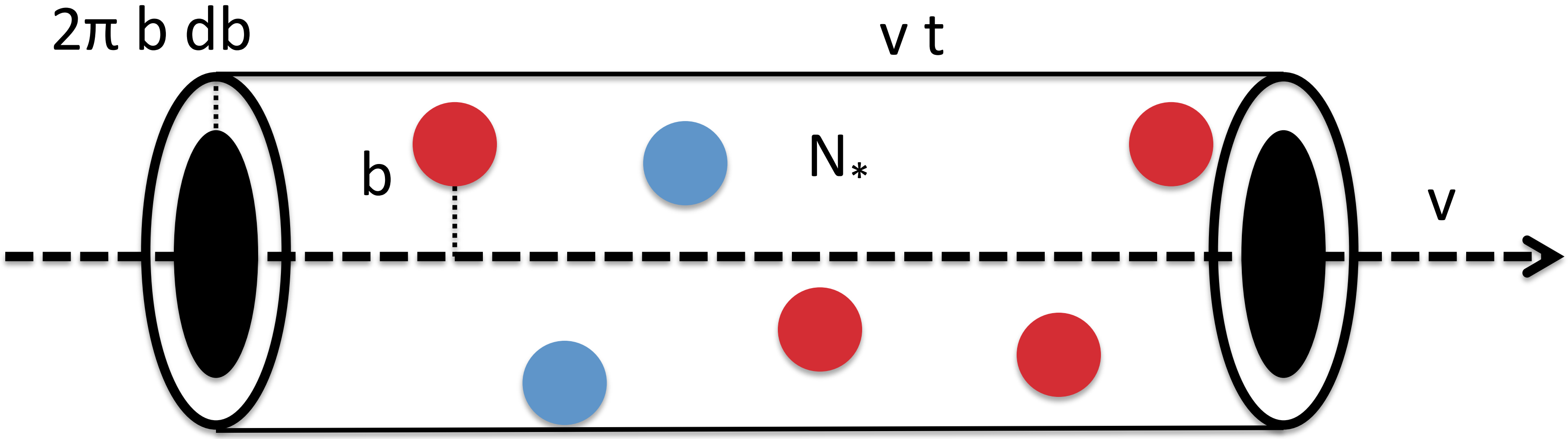
- How long does it take for stellar orbits to change from random scattering with stars?



- Assume: $\delta v \perp v$, $\delta v << v$
- Impulse:
  $\delta v \sim F/M\ dt \sim Gm_*/b^2 * b/v \sim Gm_*/bv$

Two-body relaxation

- Add up deflections over time t = R / v



Two-body relaxation

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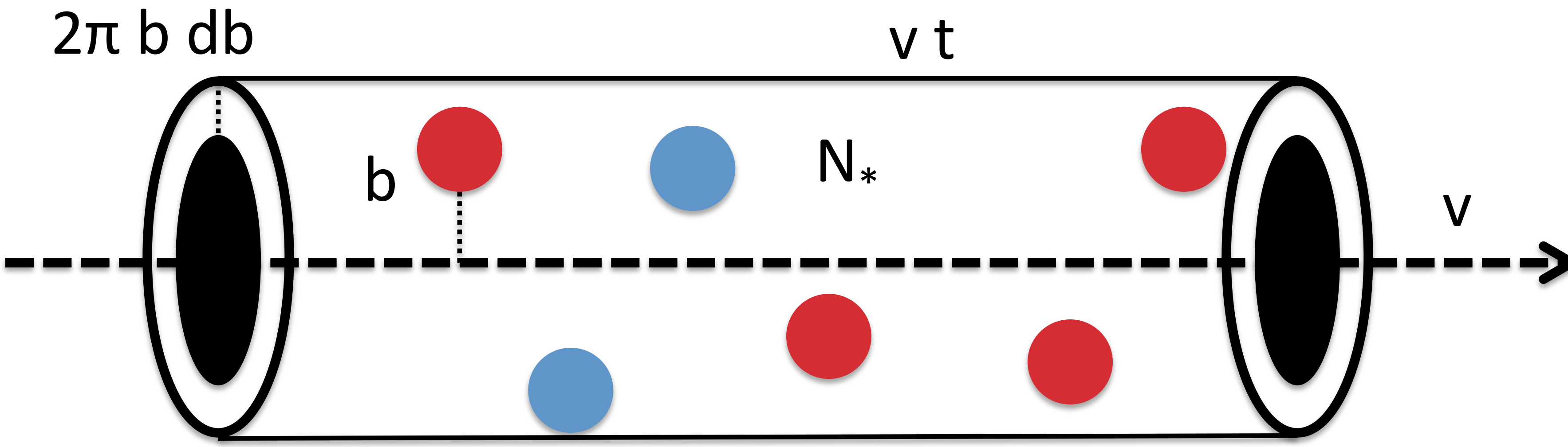
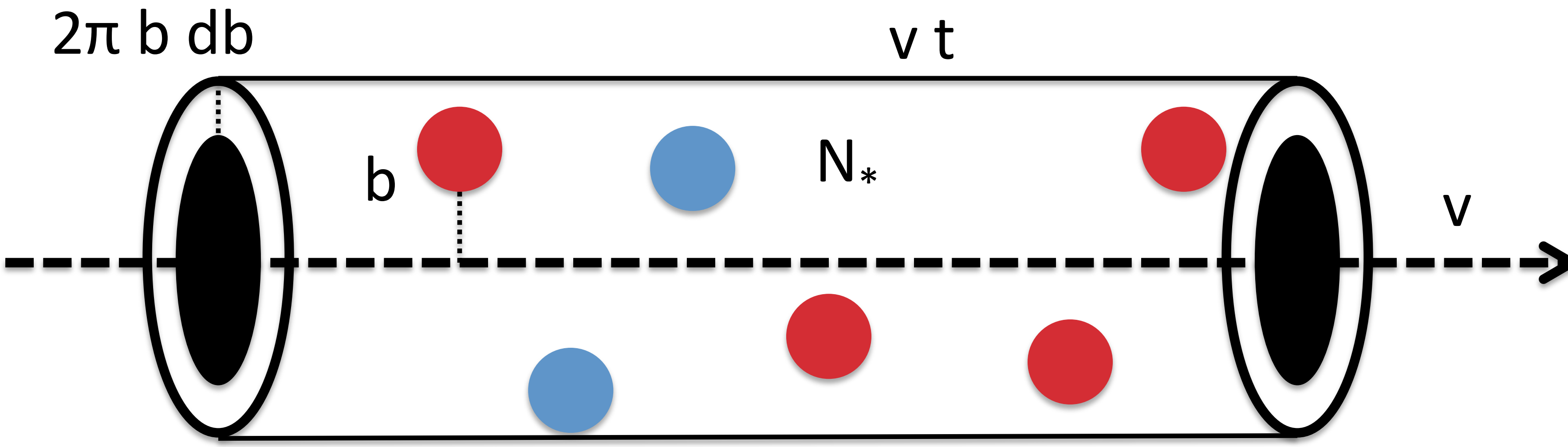


- # of scatters between b, b+db:

$= n_* \sigma R = 2\pi\, b\, db\, n_*\, v\, t$

Two-body relaxation

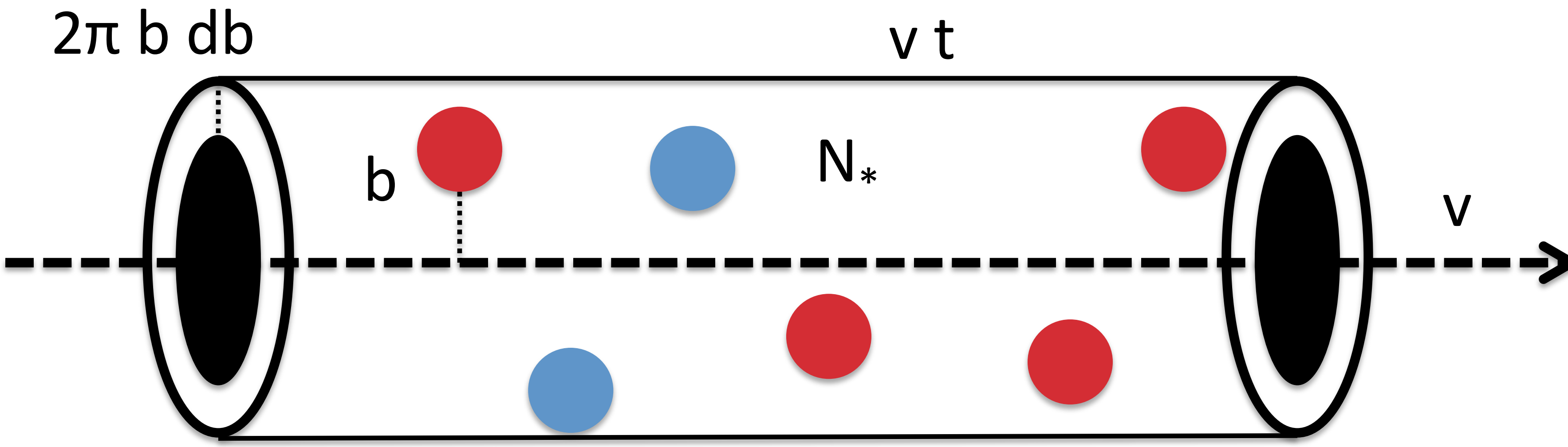
- Random changes to velocity → random walk



- dv^2 ~ # of scatters * δv^2:

Two-body relaxation

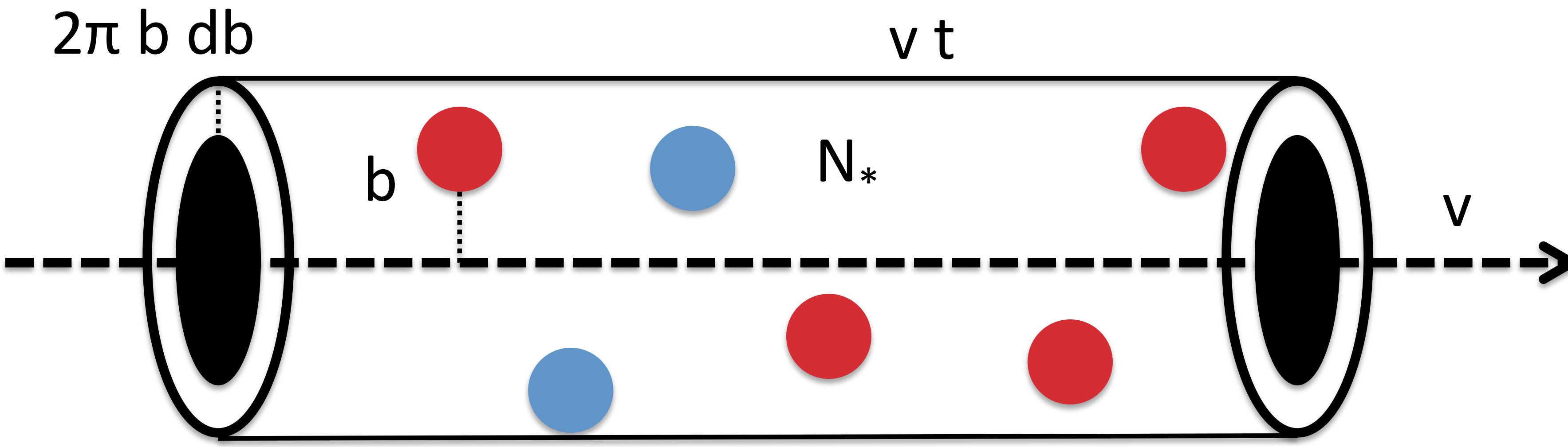
- Random changes to velocity → random walk



- $dv^2 \sim$ # of scatters * δv^2:
$dv^2 \sim (2\pi\ b db\ n_* vt) * (Gm_*/bv)^2$
$= 2\pi\ G^2 m_*^2\ n_*\ t\ /\ v\ db/b$

Two-body relaxation

- Random changes to velocity → random walk



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  $= 2\pi\, G^2 m_*^2\, n_*\, t\, /\, v\, db/b$
- Integrate: $\Delta v^2 = 2\pi\, G^2 m_*^2\, n_*\, t\, /\, v \ln(b_{max}/b_{min})$

Two-body relaxation

- Star forgets its original motion when $\Delta v \sim v$:

$$v^3 = 2\pi\, G^2 m_* \, n_* \, t_{2BR} \ln(b_{max}/b_{min})$$

$$t_{2BR} = v^3 / 2\pi\, G^2 m_*^2 \, n_* \ln(b_{max}/b_{min})$$

Two-body relaxation

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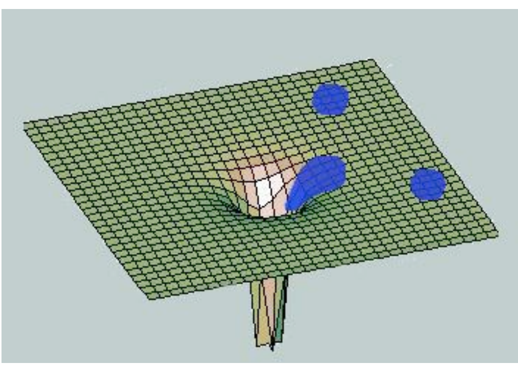
- GC: $v \sim 100$ km/s, $n_* \sim 10^6 / pc^{-3}$, $b_{max} \sim 1$ pc, $b_{min} \sim 1$ AU

$t_{2BR} \sim 3\, (v / 100\ \mathrm{km/s})^3 \, (m_*/m_{sun})^2$ Gyr

The S stars as a "paradox of youth"

Ghez+ 2003: S2 is young
Eisenhauer+ 2005: All S-stars are young
Martins+ 2008: S2 is an ordinary star



$$t_{2\mathrm{BR}} \approx 3\,\mathrm{Gyr}$$

$$\gg$$

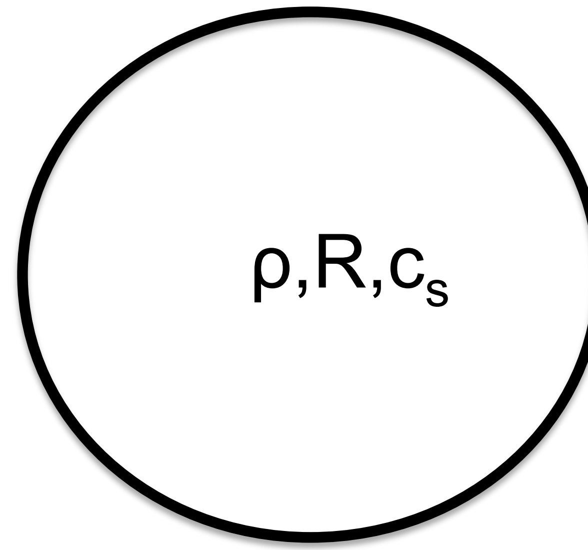
$$t_{\mathrm{MS}} \approx 0.1\,\mathrm{Gyr}$$

Star formation so close to the MBH is impossible

Stars too young to have migrated from further out

Star formation

- Self-gravity must overcome pressure support ("Jeans instability")
- $U_{grav} + U_{int} < 0$:
  $-3/5\ G\ M^2/R + ½\ M\ c_s^2 < 0$



$c_s^2 = \gamma p/\rho$

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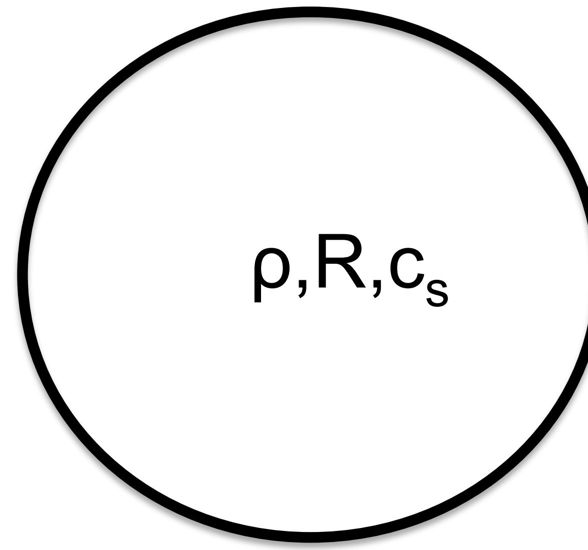
  $8/5\ \pi\ \rho\ G\ R_J^2 = c_s^2$
  $R_J \sim c_s\ /\ \rho^{1/2}$



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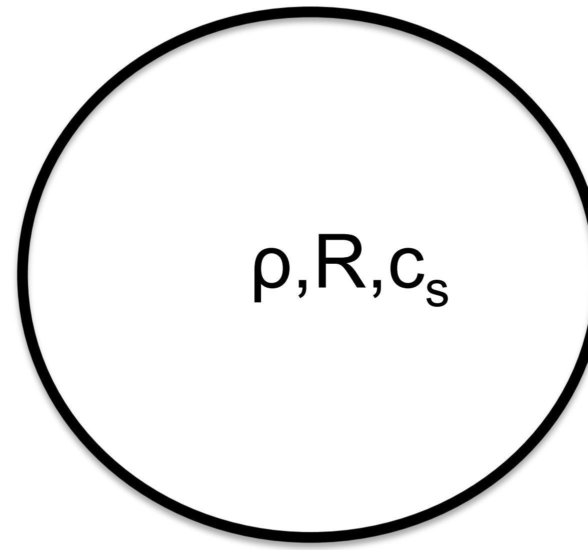
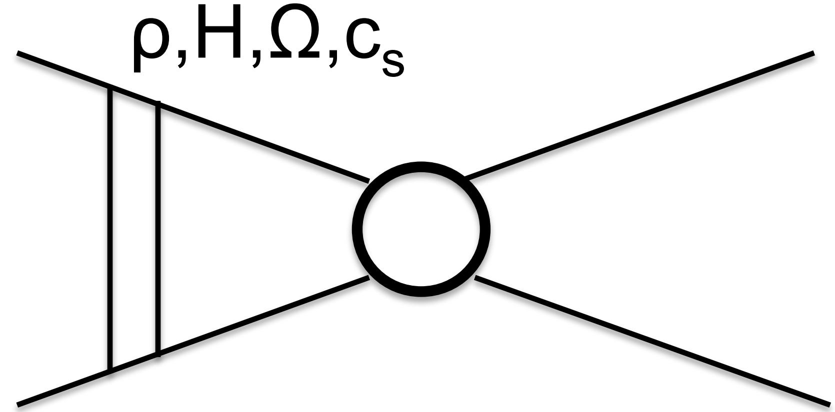
  $8/5\ \pi\ \rho\ G\ R_J^2 = c_s^2$
  $R_J \sim c_s / \rho^{1/2}$
- corresponding mass for collapse:
  $M_J = 4/3\pi\ \rho R_J^3 \sim 100\ (T^3 / n)^{1/2}\ M_{sun}$
- Stars form in cold, dense gas!



$c_s^2 = \gamma p/\rho$

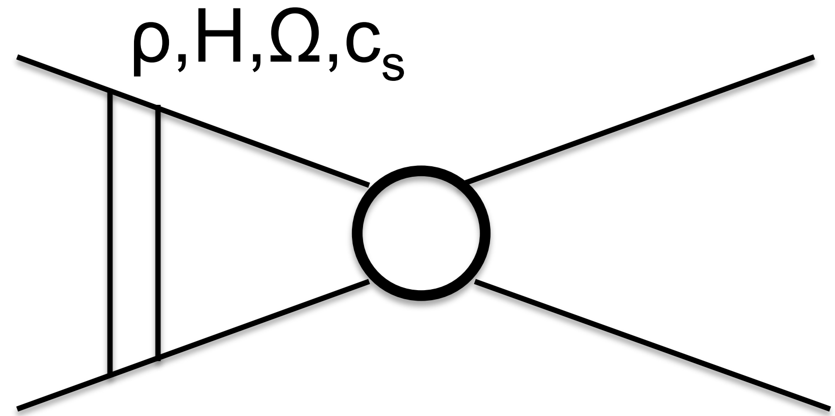
Star formation near a massive black hole

- Self-gravity must overcome pressure and rotational support
- $U_{grav} + U_{int} + U_{rot} < 0$



Star formation near a massive black hole

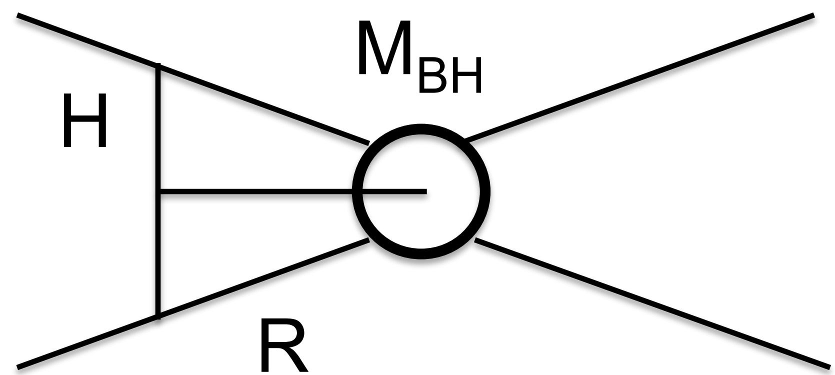
- Self-gravity must overcome pressure and rotational support
- $U_{grav} + U_{int} + U_{rot} < 0$
- Unstable when:
  $Q = c_s\Omega / \pi G\rho H < 1$



- "Toomre Q parameter" < 1 for collapse

Star formation near a massive black hole

- $H = c_s / \Omega$, $\Omega^2 = G M_{BH} / R^3$, $M_d = \pi R^2 H \rho$
- Re-write Q in a nicer way:
  $c_s \Omega / \pi G \rho H < 1$



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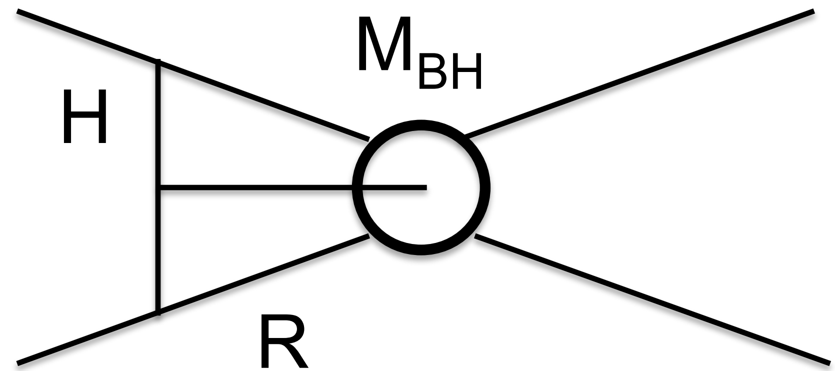
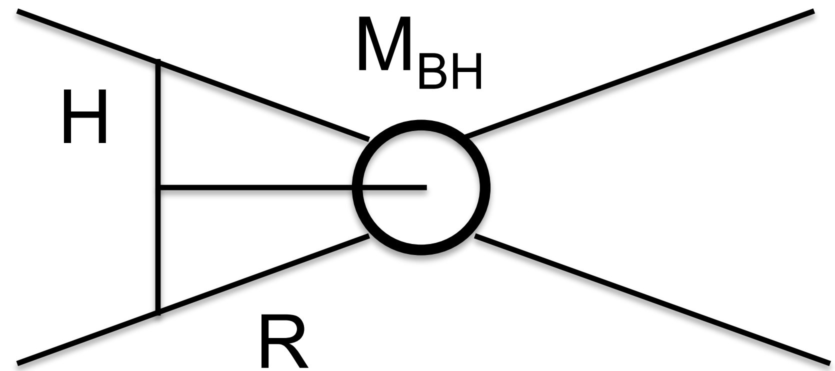


- $H/R < M_d/M_{BH}$ or
- $\rho > M_{BH}/\pi R^3$

- Disk must be thin (cold) and massive (dense) to collapse (Paczynski 1978)

Star formation near a massive black hole

- $\rho > M_{BH}/\pi R^3$
- GC: $n > 10^{10}\,(R/0.1\ \mathrm{pc})^{-3}\ \mathrm{cm}^{-3}$
- $M_d \sim 10^4\ M_{sun}$:
  $H/R \sim 0.003$



- Compare:
  giant molecular clouds
  $n \sim 10^4\ \mathrm{cm}^{-3}$

Star formation in the central parsec from a self-gravitating gas disk

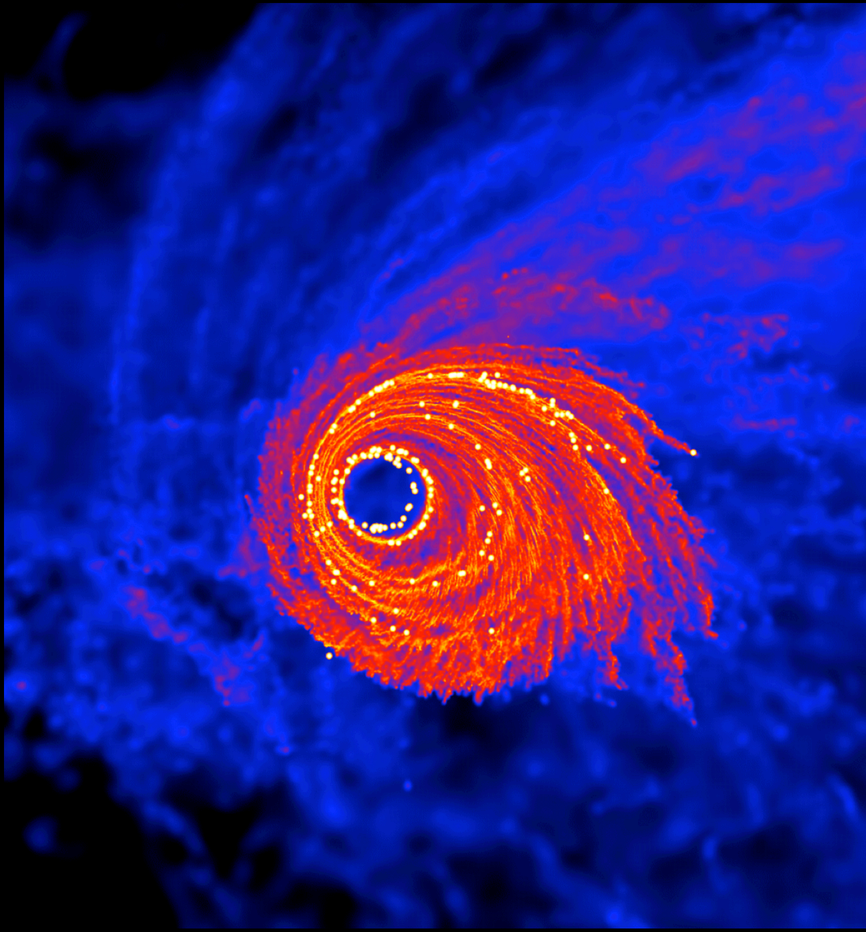
(Levin & Beloborodov 2003)

- Dense, cold:
  $M_J \sim 100\ (T^3 / n)^{1/2}\ M_{sun}$
  $\sim 1\ M_{sun}$ for $T = 10$ K, $n = 10^{10}\ cm^{-3}$
- Stars grow until they open gaps in the disk
- Expect massive stars → top-heavy IMF
- Issues: formation of disk? eccentric, inclined orbits?

An eccentric stellar disk from disrupting a giant molecular cloud

- Gas is tidally heated by interaction with black hole, but stars can form in dense clumps (Bonnell & Rice 2008, Hobbs & Nayakshin 2009)

- T is higher, M_J higher, form massive stars

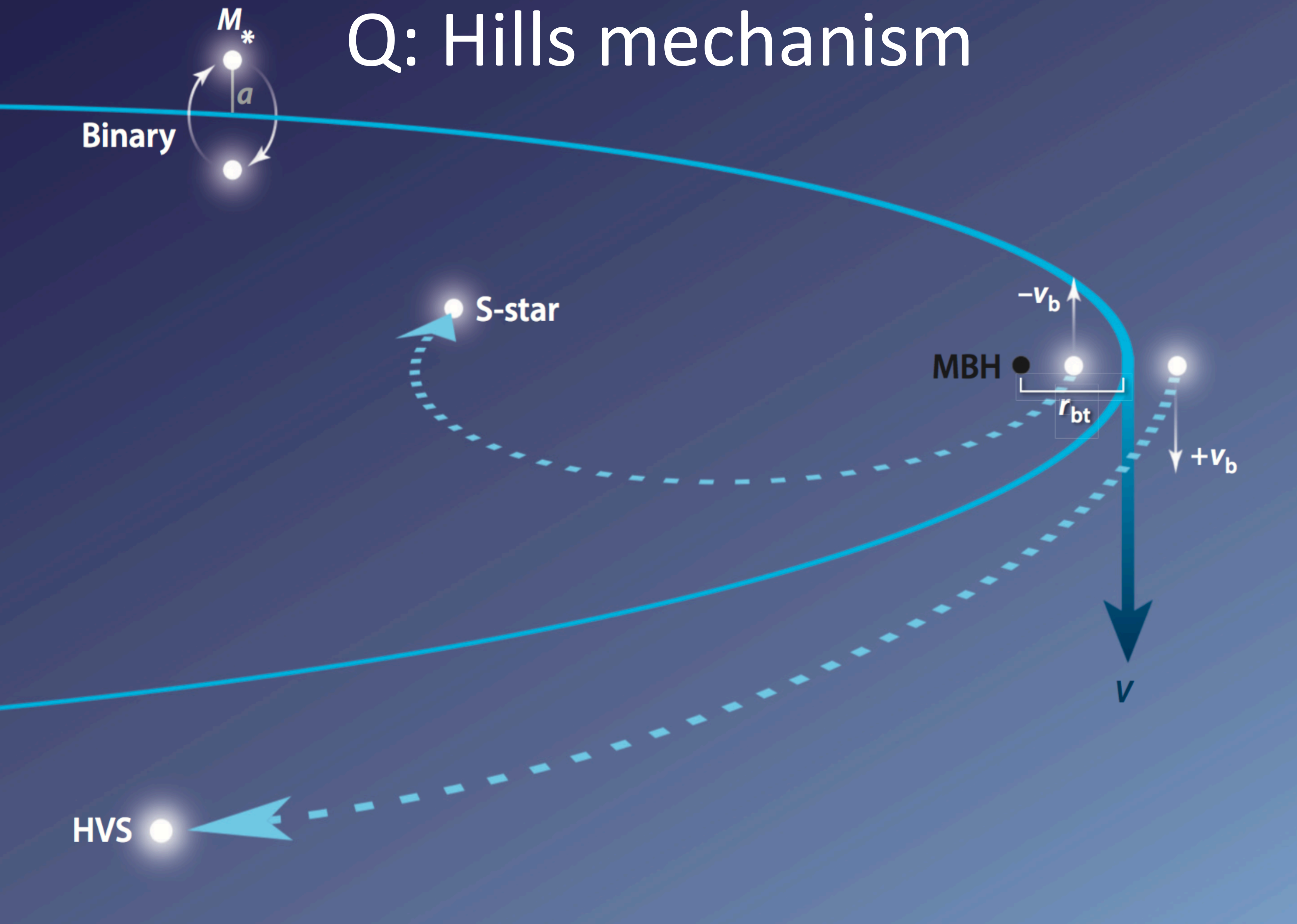


Forming the S stars

- Cannot form at current locations!

- Why such small radii, steep radial distribution, eccentric orbits?

Q: Hills mechanism



Q: Hills mechanism and hyper-velocity stars

1. At what radius can a black hole of mass M_{BH} tidally disrupt the binary (M_b, a)?

2. Assume one star is ejected: what is its kinetic+potential energy pre-ejection? From energy conservation, what final speed can it reach?

Hyper-velocity stars

- Binary disrupted if tidal force stronger than its own gravity:

  $GM_{BH}\, M_b\, a / r^3 > G\, M_b^2 / a^2$

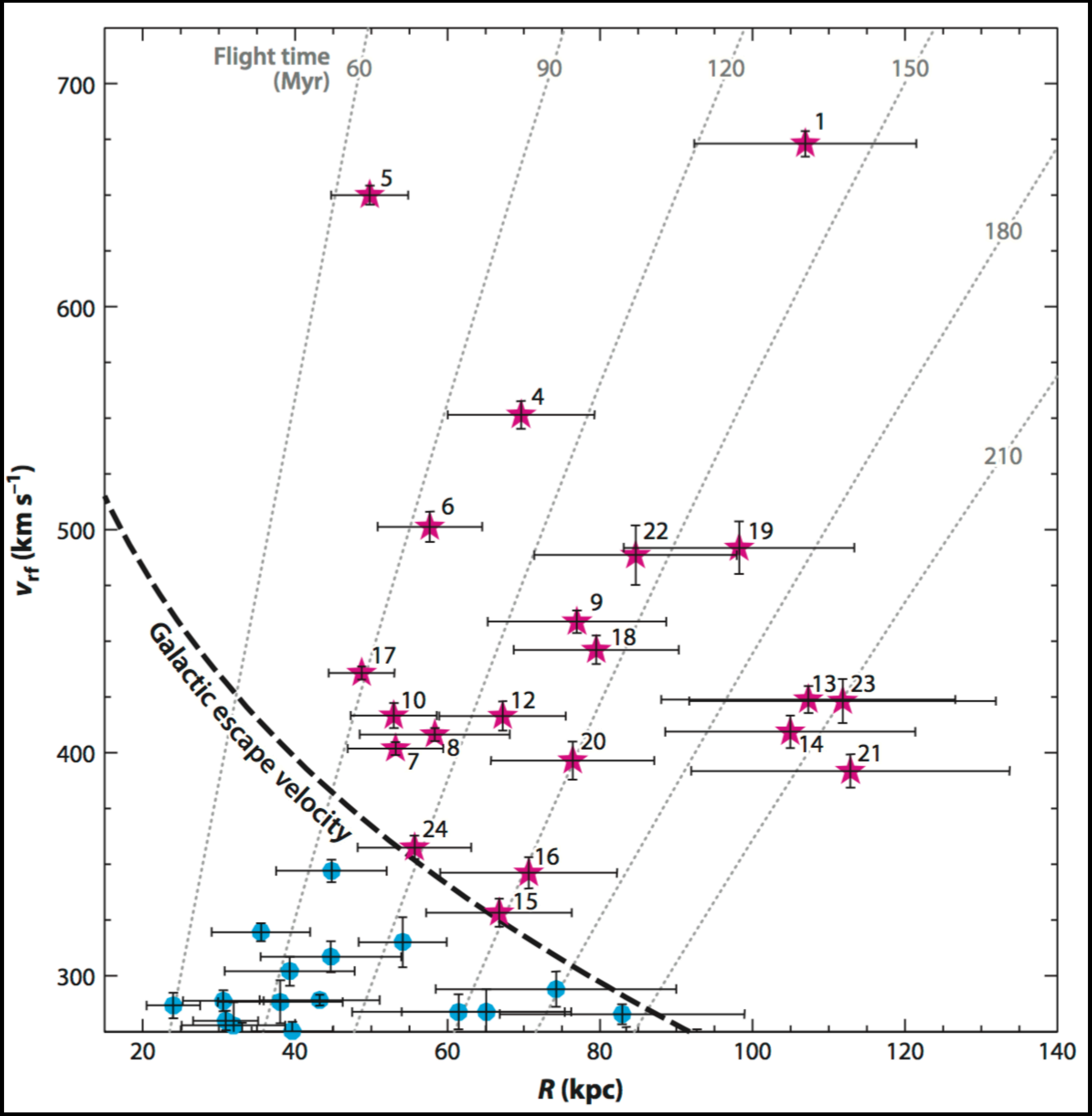
  $r < a\, (M_{BH} / M_b)^{1/3}$

Hyper-velocity stars

- Energetics of ejected star:
  - $E_0 = ½\, m\, (v+v_b)^2 - G\, M_{BH}\, m\, /\, r$
  - $E_f = ½\, m\, v_{inf}^2$

- $E_0 = E_f$, $G\, M_{BH}\, /\, r \sim v^2$:
  - $v_{inf}^2 = (v+v_b)^2 - G\, M_{BH}\, /\, r \sim (v+v_b)2 – v^2 \sim 2\, v\, v_b$
  - $v_{inf} \sim 500\, (v_b/50\ \mathrm{km\ s^{-1}})^{1/2}\, (1\ \mathrm{mpc}/r)^{1/4}\ \mathrm{km/s}$

Hypervelocity stars are observed!



Brown 2016

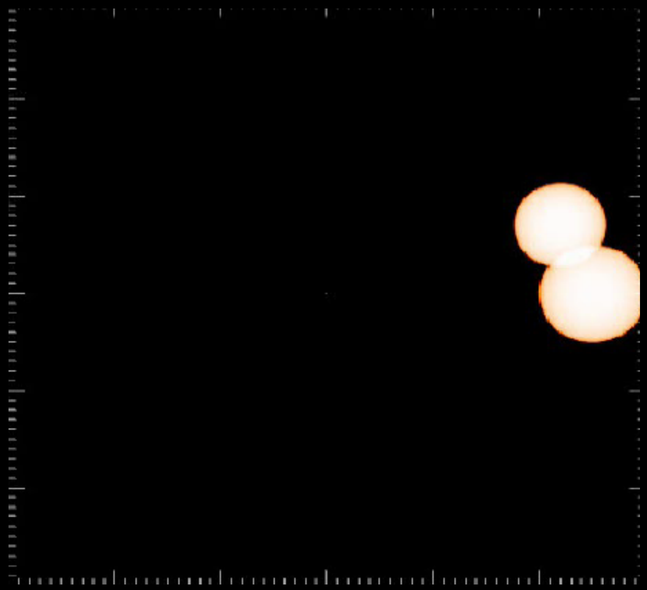
Where do the eccentric binaries come from?

- Field/nuclear cluster
- O/WR disk
  - Young B stars still part of the disk? (Madigan+2014)
  - Explains anisotropy of hypervelocity stars? (Subr & Haas 2016)

Two paradoxes of youth

O/WR stars

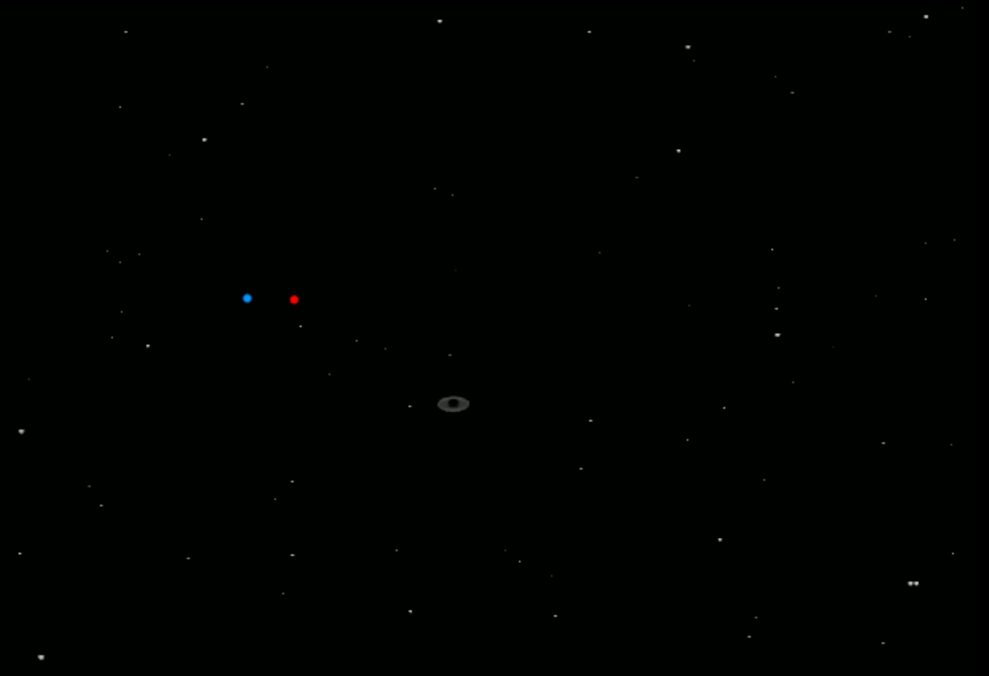
- 6 Myr young
- mean eccentricity 0.35
- disk configuration
- top-heavy IMF



Bonnell+ 2008, Hobbs+ 2009

B stars

- typical age 100 Myr
- eccentricities > 0.8
- randomly oriented
- normal IMF



Hills 1998, Perets+ 2007, Genzel+ 2010

Open questions

- O/WR stars
  - One disk or two? Separate B star disk?
  - How extreme is the IMF?
  - What about the non-disk stars?
- S stars
  - Relaxation mechanism?
  - Originate in the disks? Or further out?
- Missing red giants?

Next time:
Sgr A* and the faintest black holes

How can a 4 million solar mass black hole be so faint?