CONSTRAINING THE GALACTIC *DARK MATTER HALO* WITH *HYPERVELOCITY* STARS

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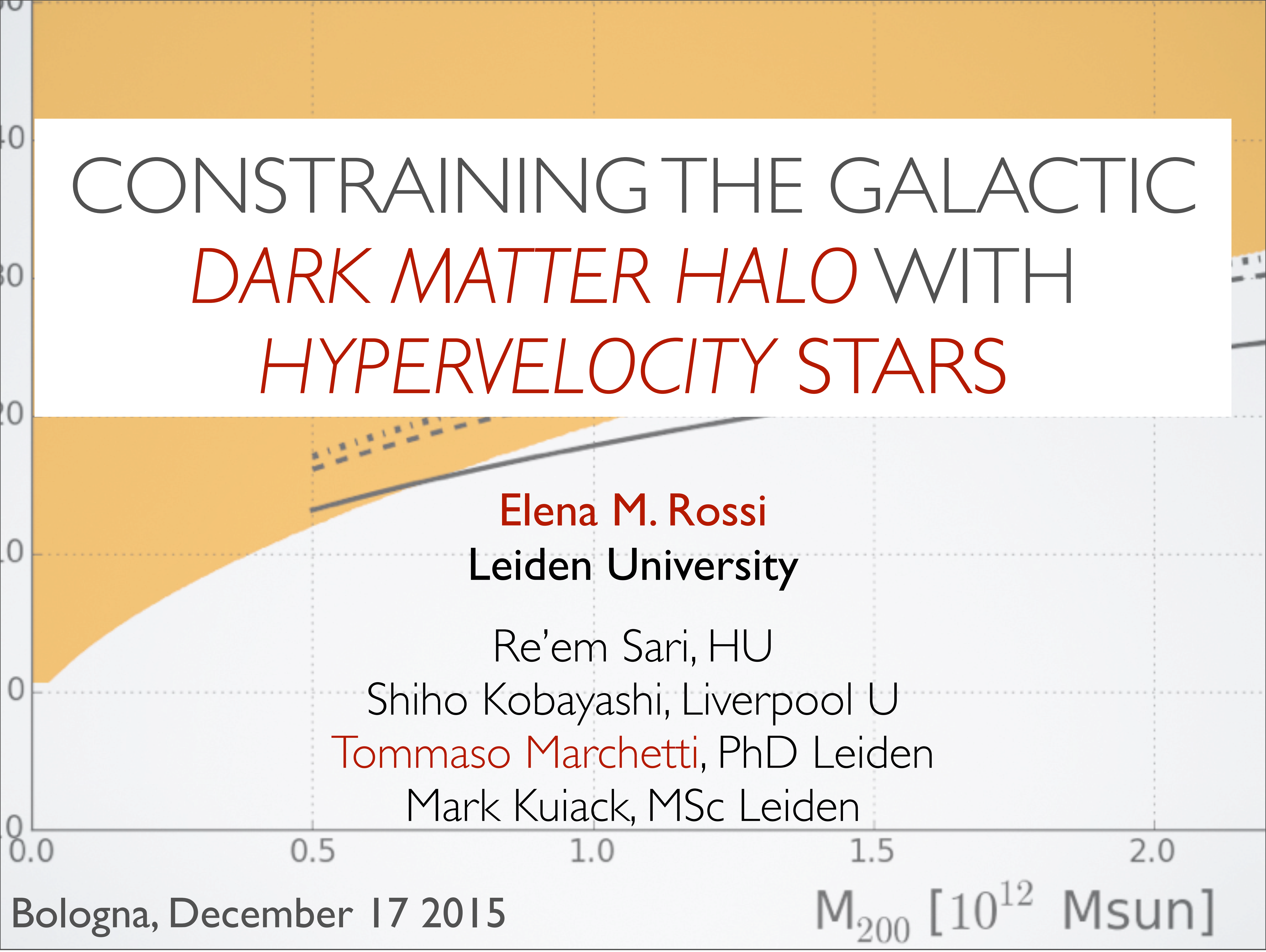
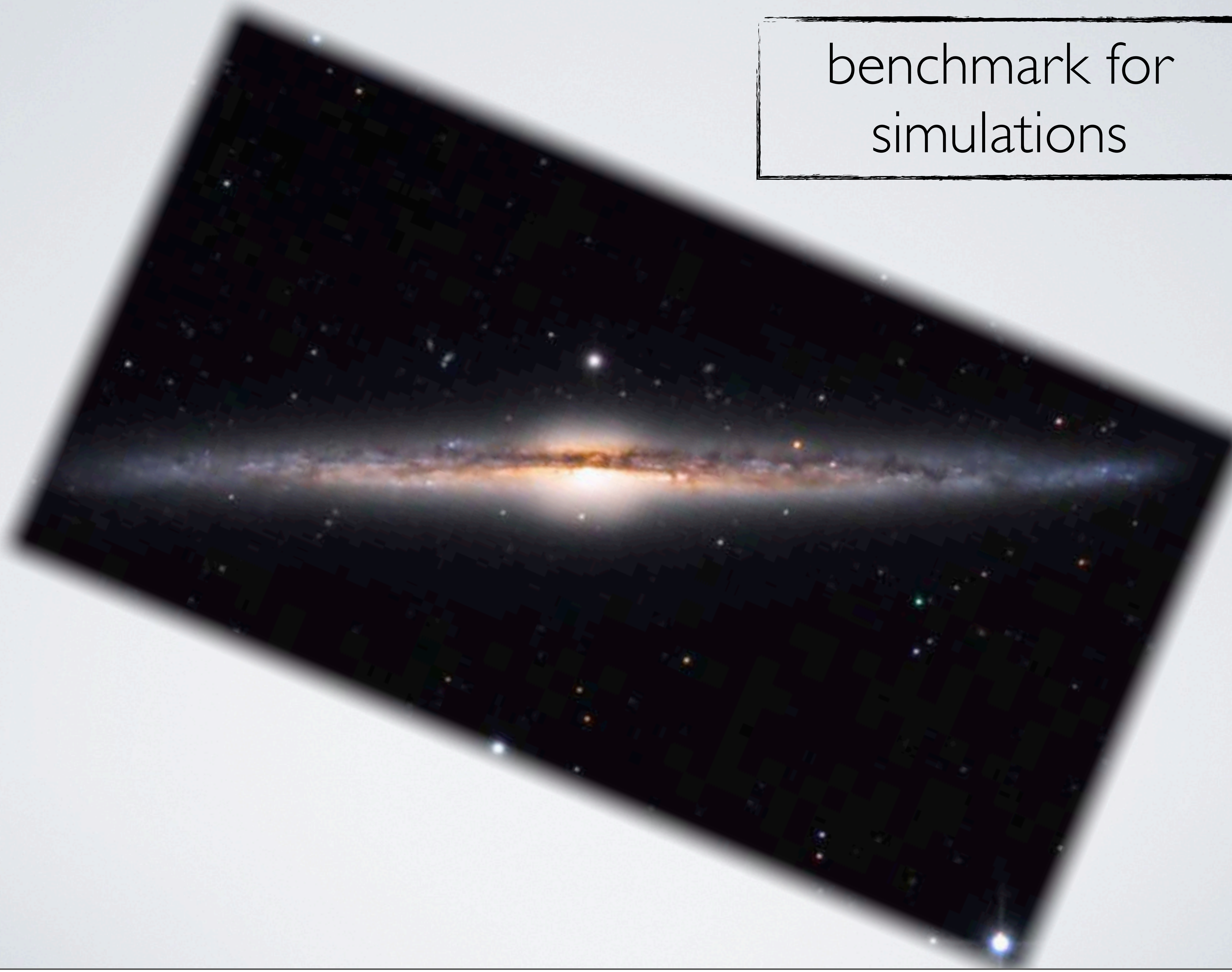


THE ***MILKY WAY*** AS LABORATORY



benchmark for simulations

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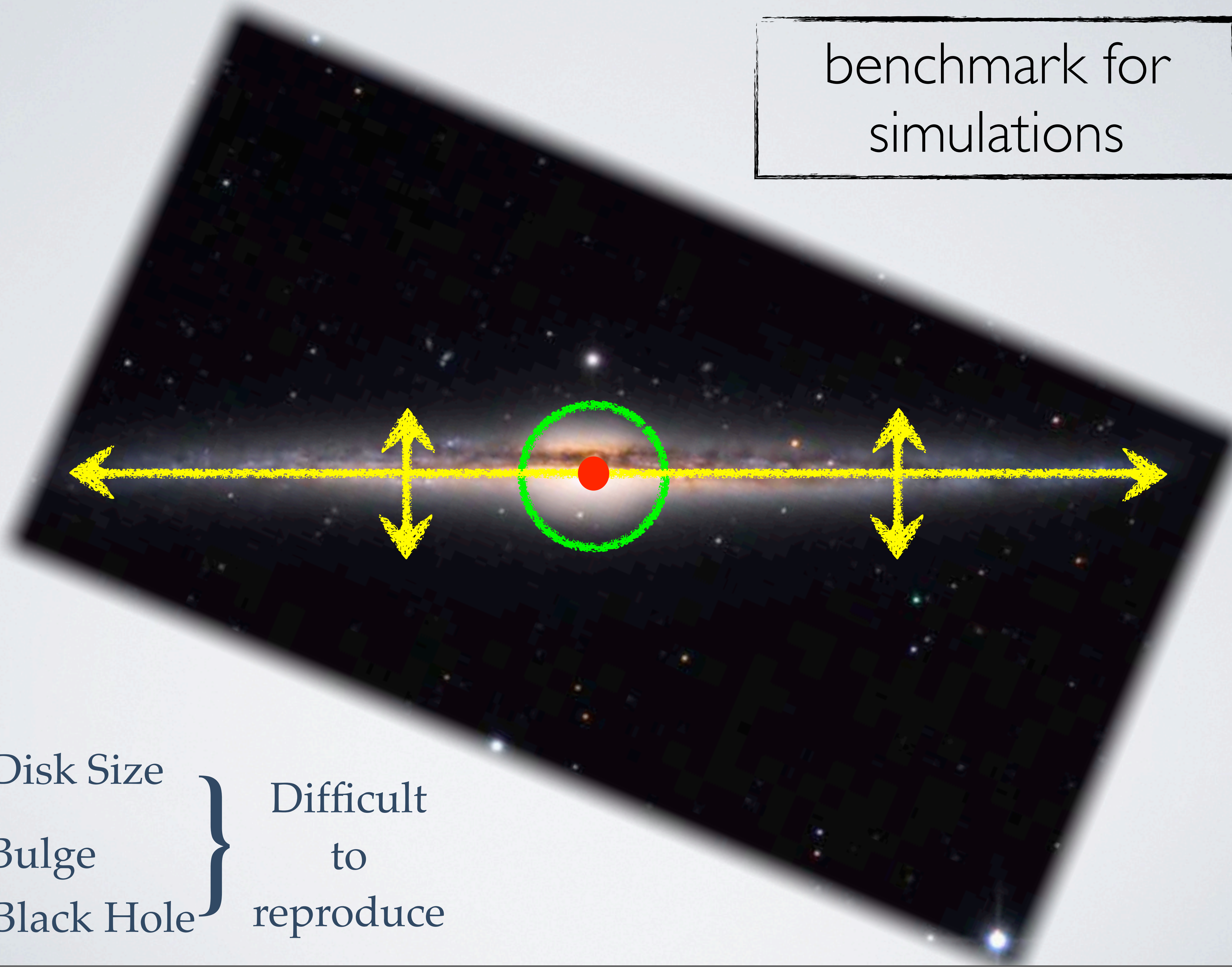
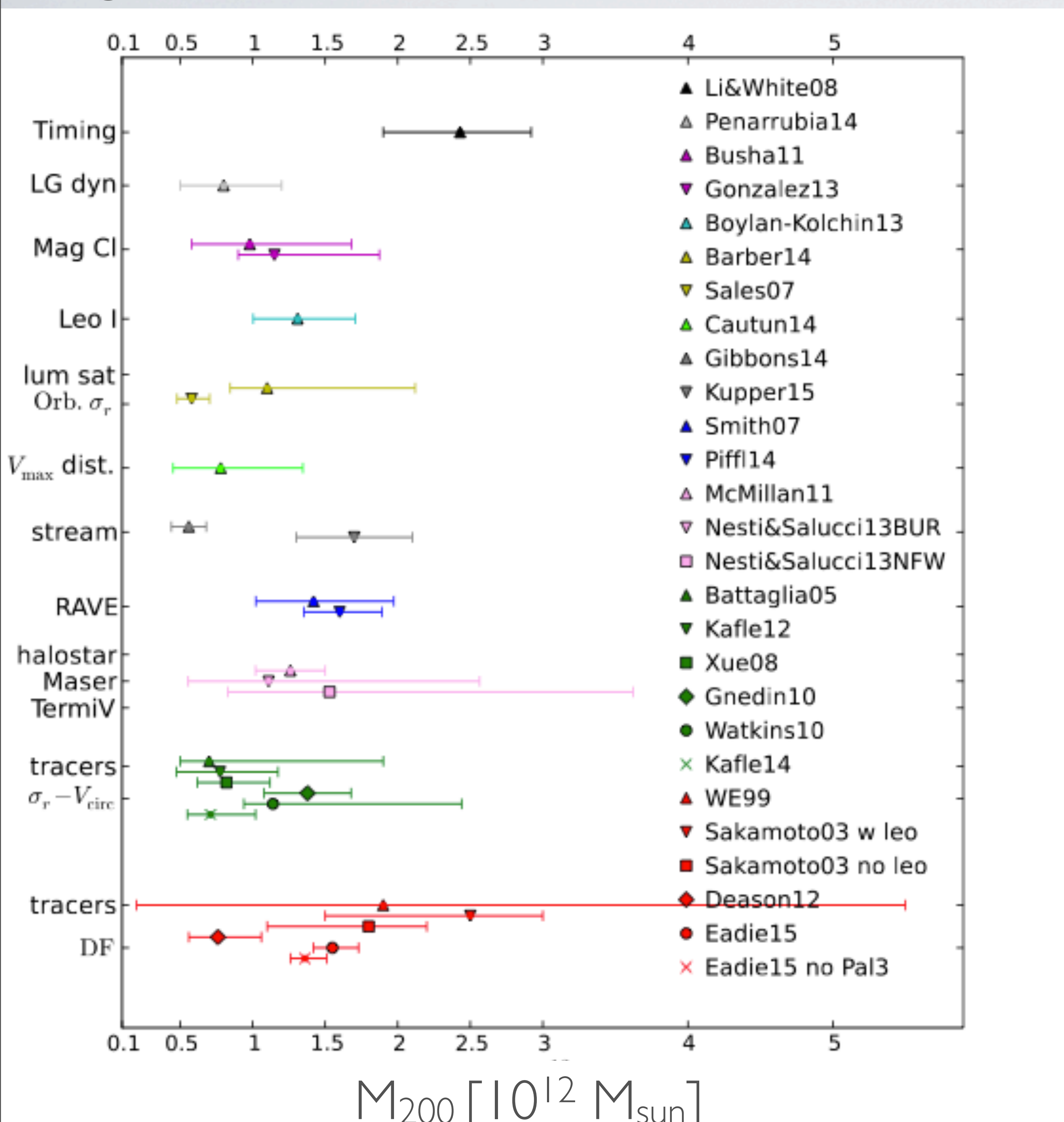


Disk Size
Bulge
Black Hole
} Difficult to reproduce

THE *MILKY WAY* **DARK MATTER HALO**

Wang et al. 15

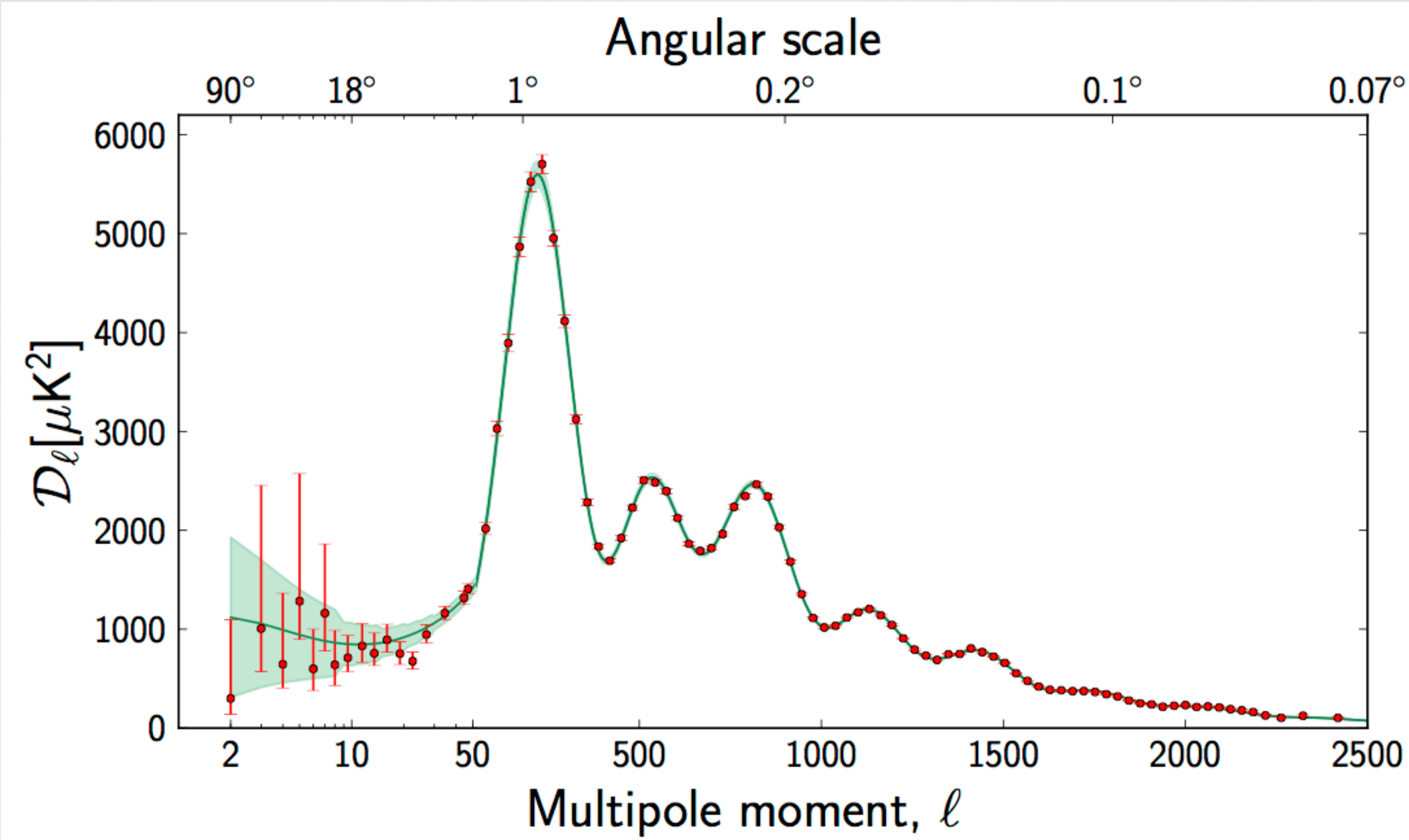


Large uncertainties in shape, orientation, coarseness, ***mass radial profile and total mass***

e.g. Bullock +10; Law & Majewski 10; Vera-Ciro & Helmi 13; Pearson + 15; Gibbons, Belokurov & Evans 15.....+ reference on figure on the left

TESTING ΛCDM

successful concordance cosmological paradigm



Planck collaboration

TESTING ΛCDM

...but comparing cosmological simulations with observations of Milky Way one finds challenges:

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- Mismatch between the number of low-mass sub-halos predicted and faint Milky Way satellites (``the missing satellite problem'' Klyplin +99; Moore + 99)

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- In ΛCDM high mass (~2 10^{12} M_{sun}) halos, the most massive sub-haloes are too dense to correspond to any of the known satellites of the Milky Way. ("too big to fail problem" Boylan-Kolchin, Bullock, & Kaplinghat 11)

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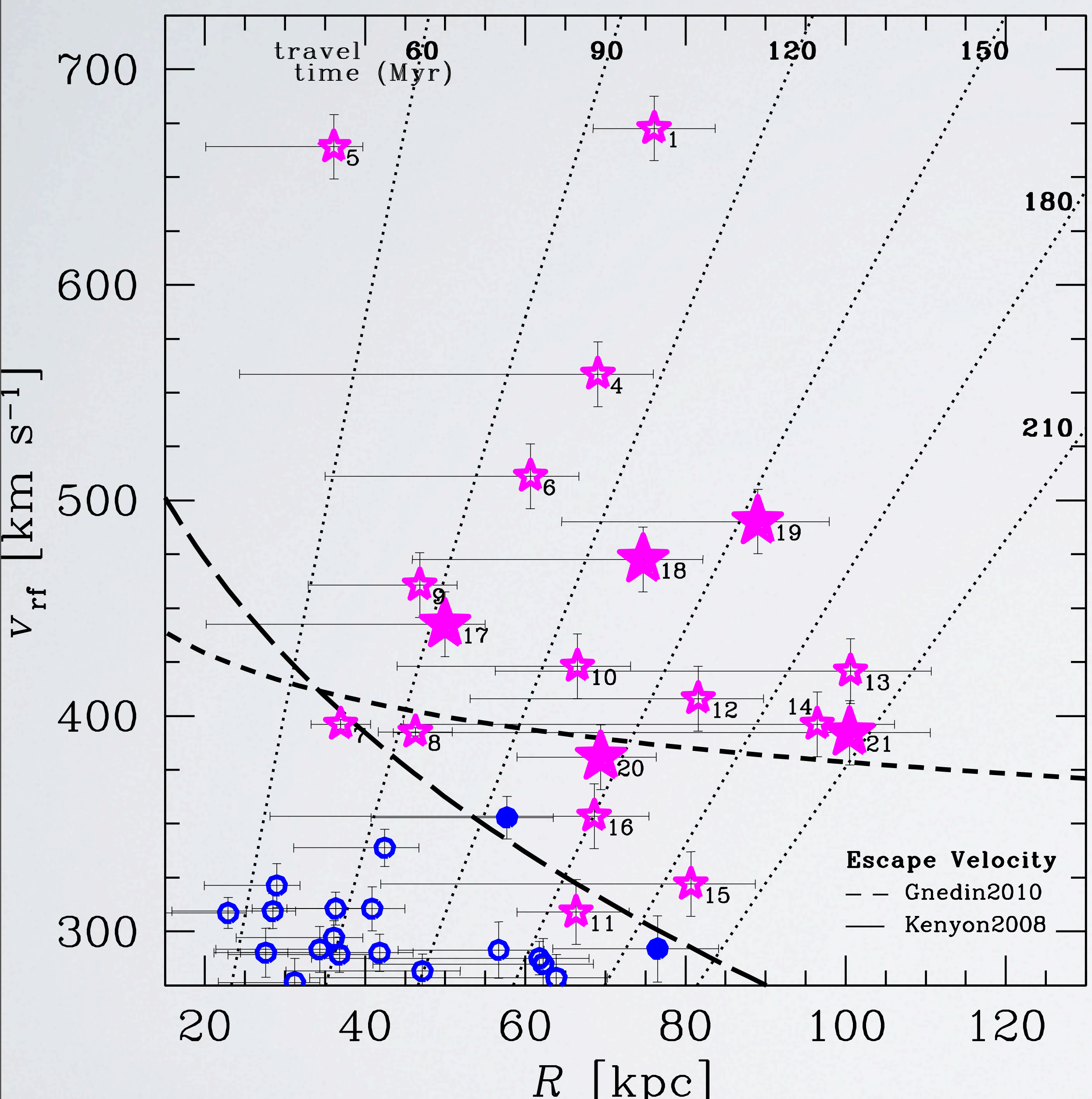
==> halo mass determinations can thus be used to test cosmological models

HYPER-VELOCITY STARS



Brown + 12, 14

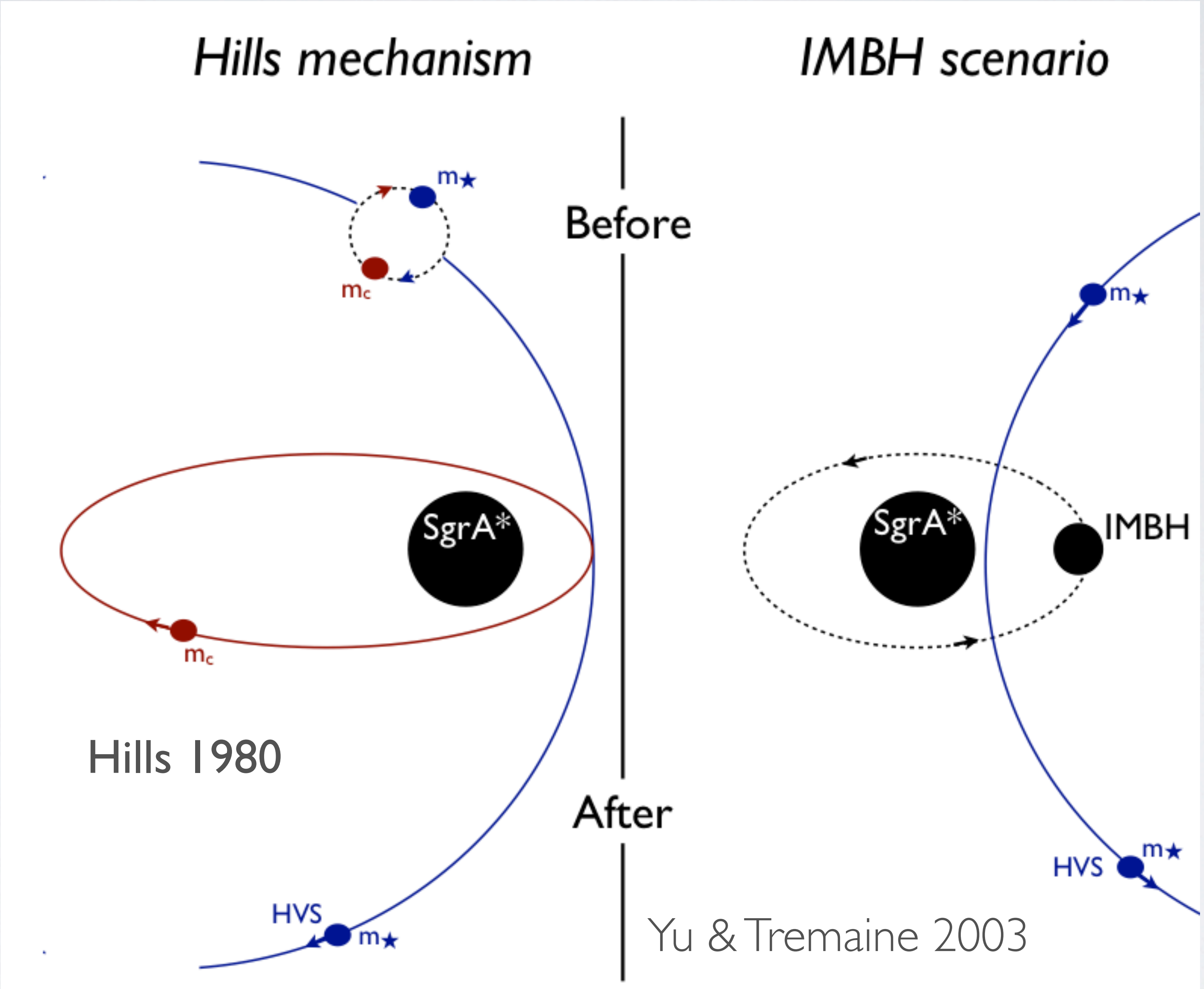
So far, a small fraction detected:

- First detection in 2005 (Brown et al. 05), ~20 detected
- Estimated ~10^4 of all masses out to about 100 kpc (Brown et al. 07)

Current discovery strategy yields biased sample:

- Found spectroscopically (SDSS)
- Targeting the outer halo
- All B-stars (~3 M_{sun})
- Only line-of-sight velocities

HILLS MECHANISM



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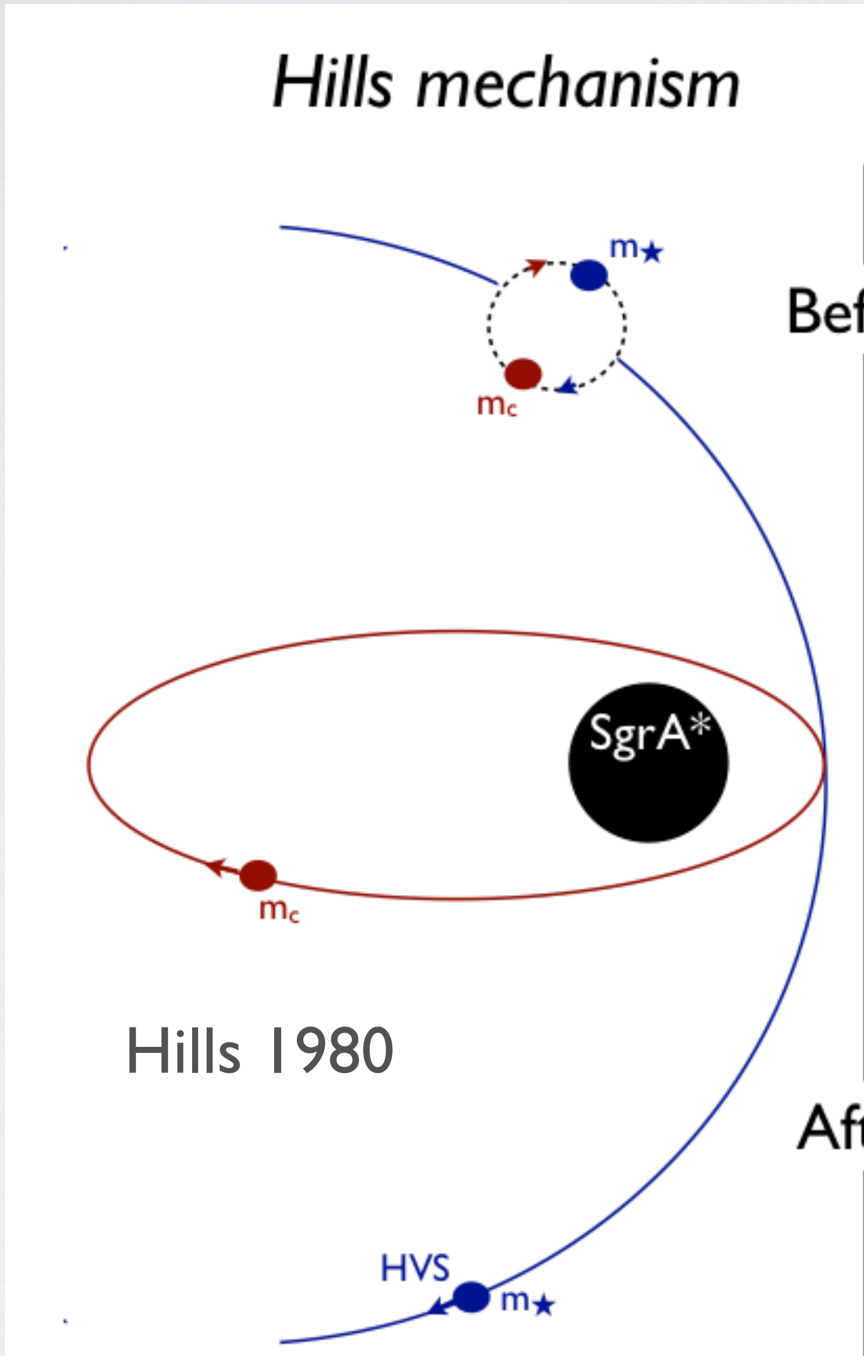
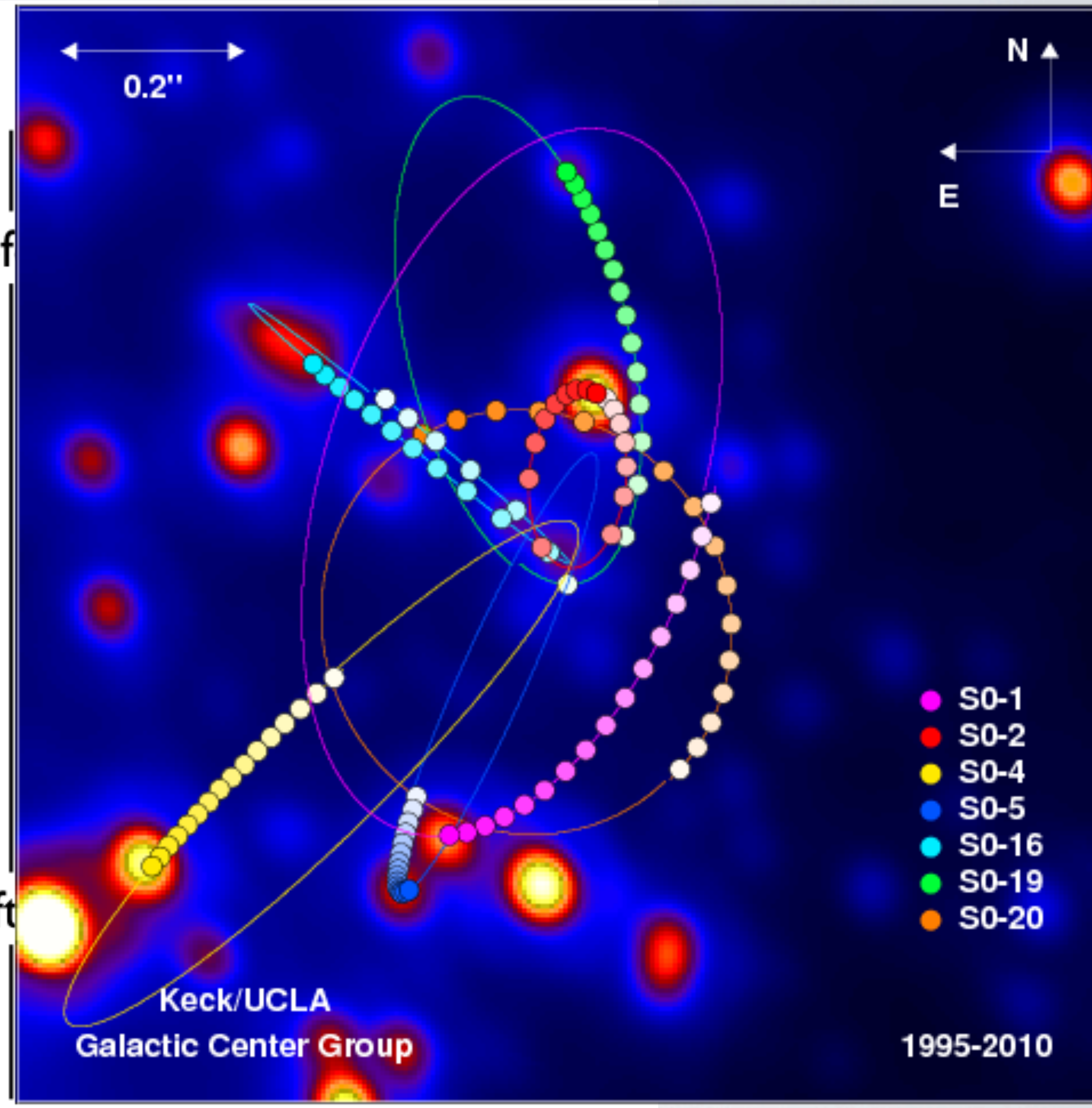
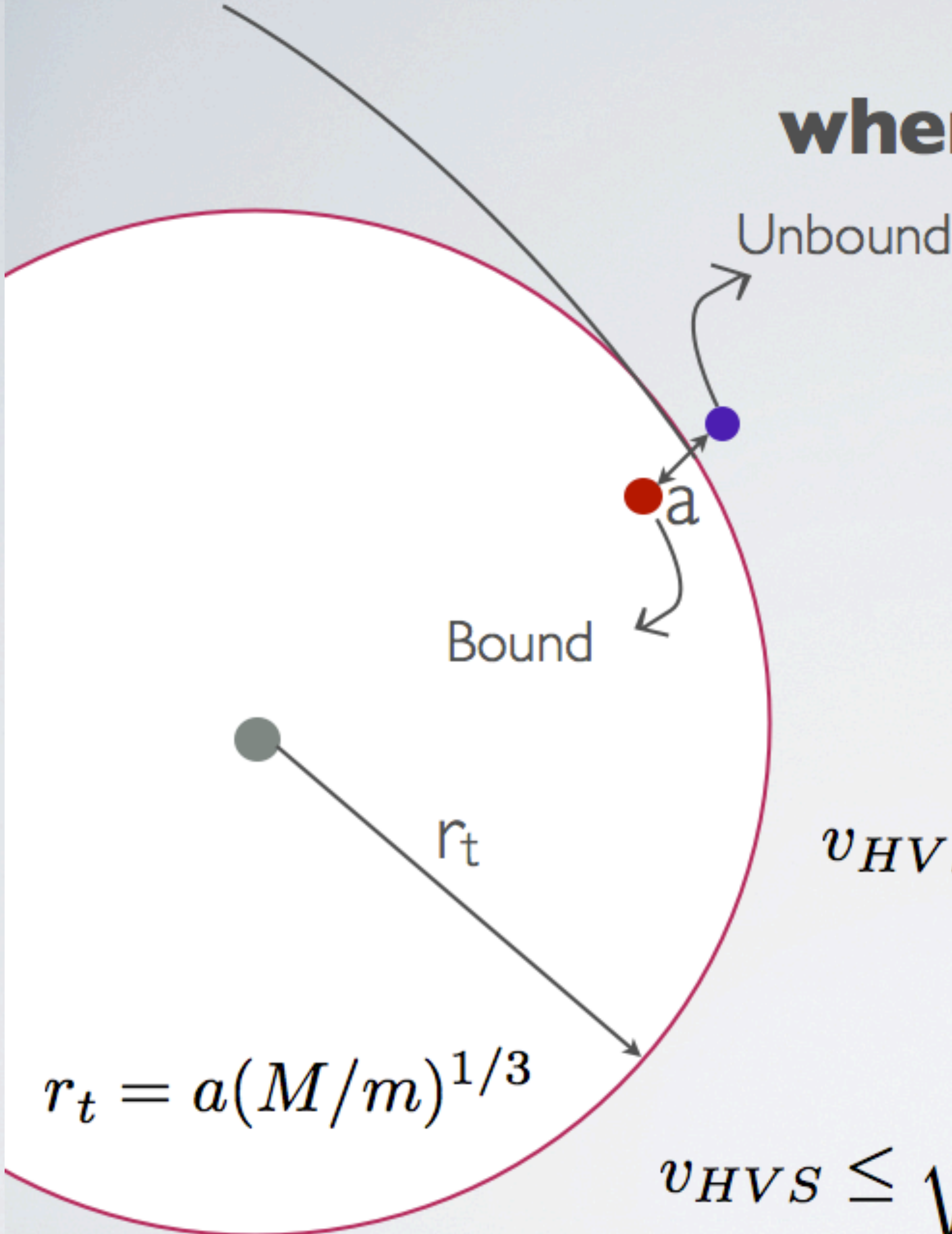




S-star cluster at < 0.04 pc from SgrA*

where does the energy come from?



$$r_t = a(M/m)^{1/3}$$

$$|\Delta E| = \frac{Gm}{a^2} r_t = \frac{GM_{\rm BH}}{r_t}\frac{a}{r_t}$$

The change in the BH potential energy across the binary

$$v_{HVS} = \sqrt{2\Delta E} = \sqrt{\frac{2Gm}{a}(M/m)^{1/6}}$$

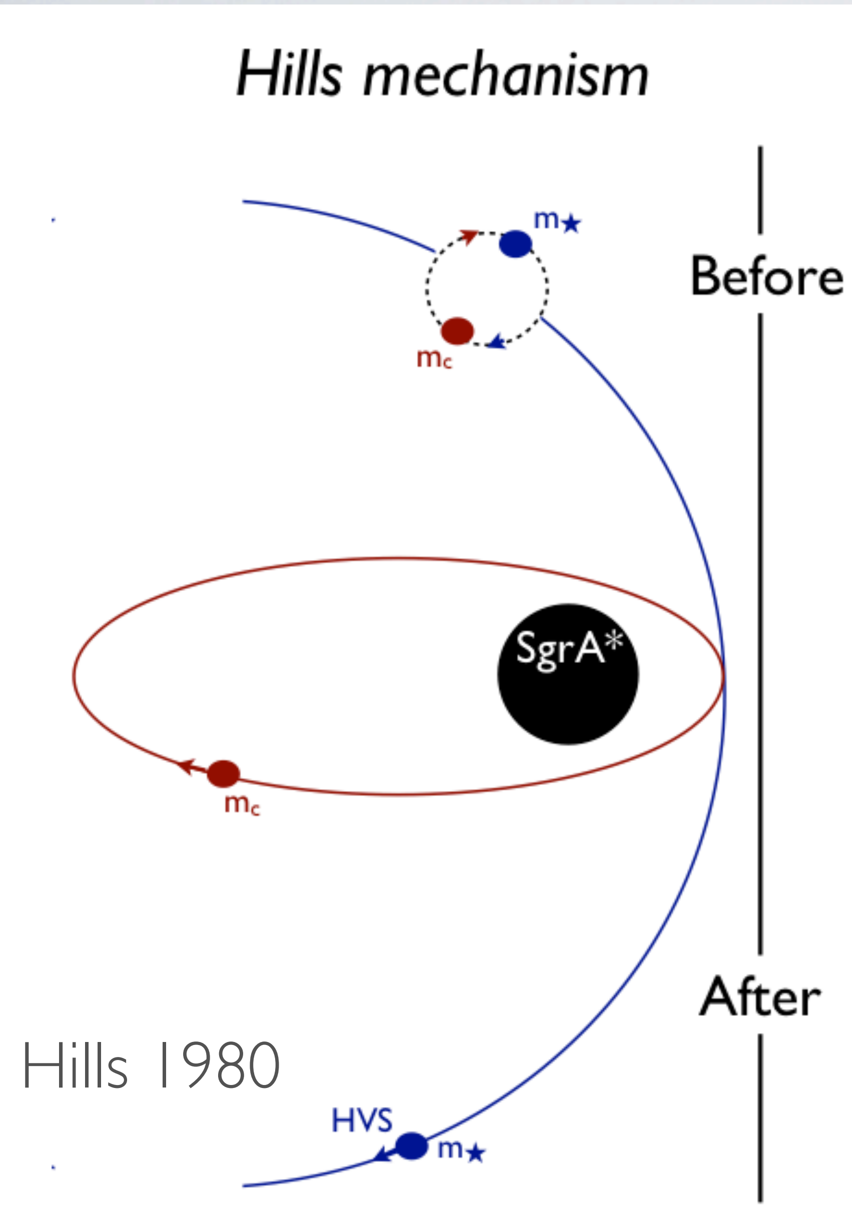
The velocity is maximum for a = R_*

$$v_{HVS} \leq \sqrt{\frac{2Gm}{R_*}(M/m)^{1/6}} \simeq 6000 \text{ km/s}$$

☑ yes, we can account for hyper-velocity

e.g Yu & Tremaine (2002)

OUR COMPUTATIONAL METHOD



- **Others:** Velocities and trajectories are calculated via 3-body or N-body interactions for a given parameter space (e.g. Brown's group; Gualandris +)

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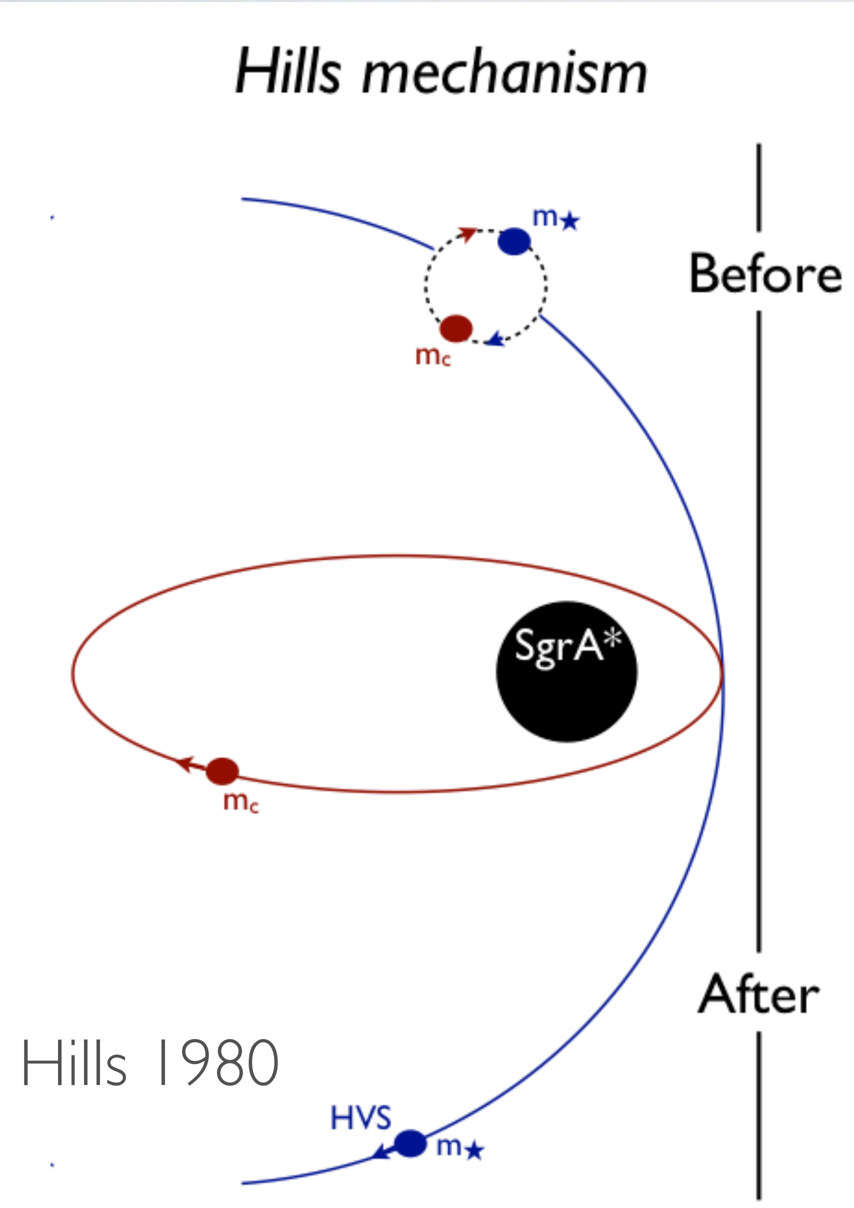

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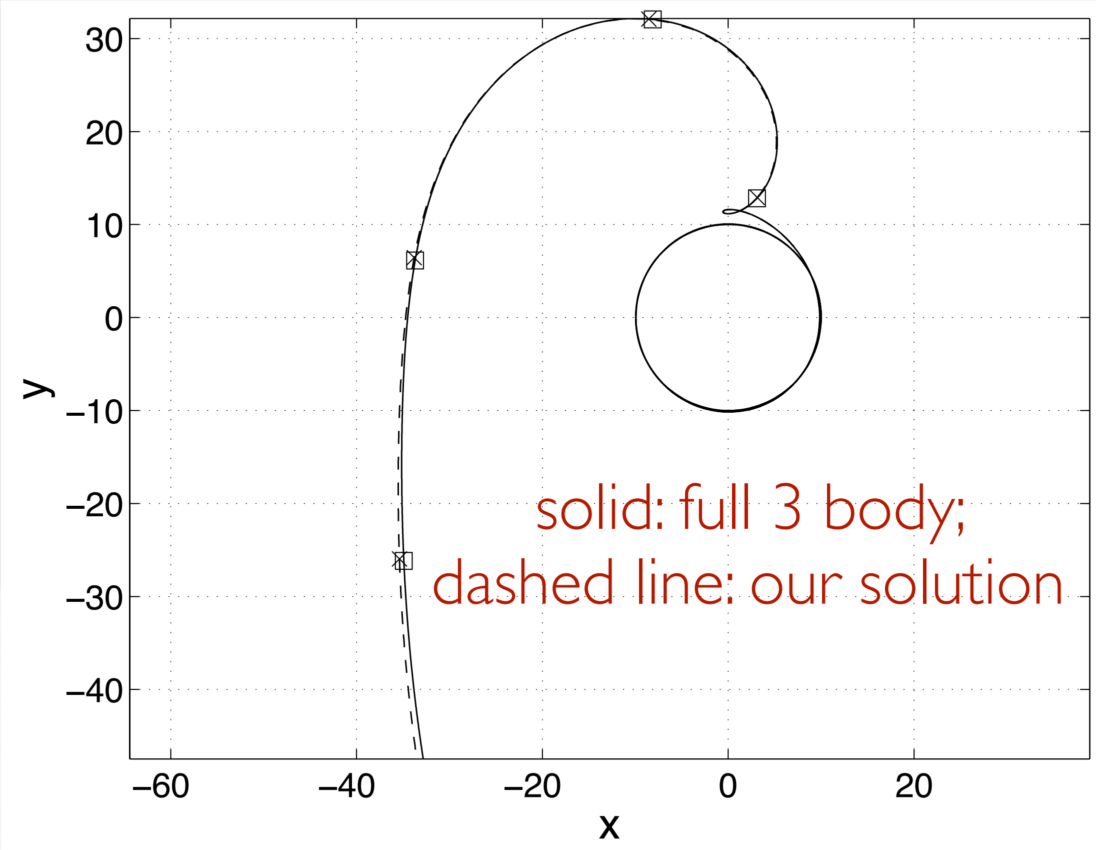
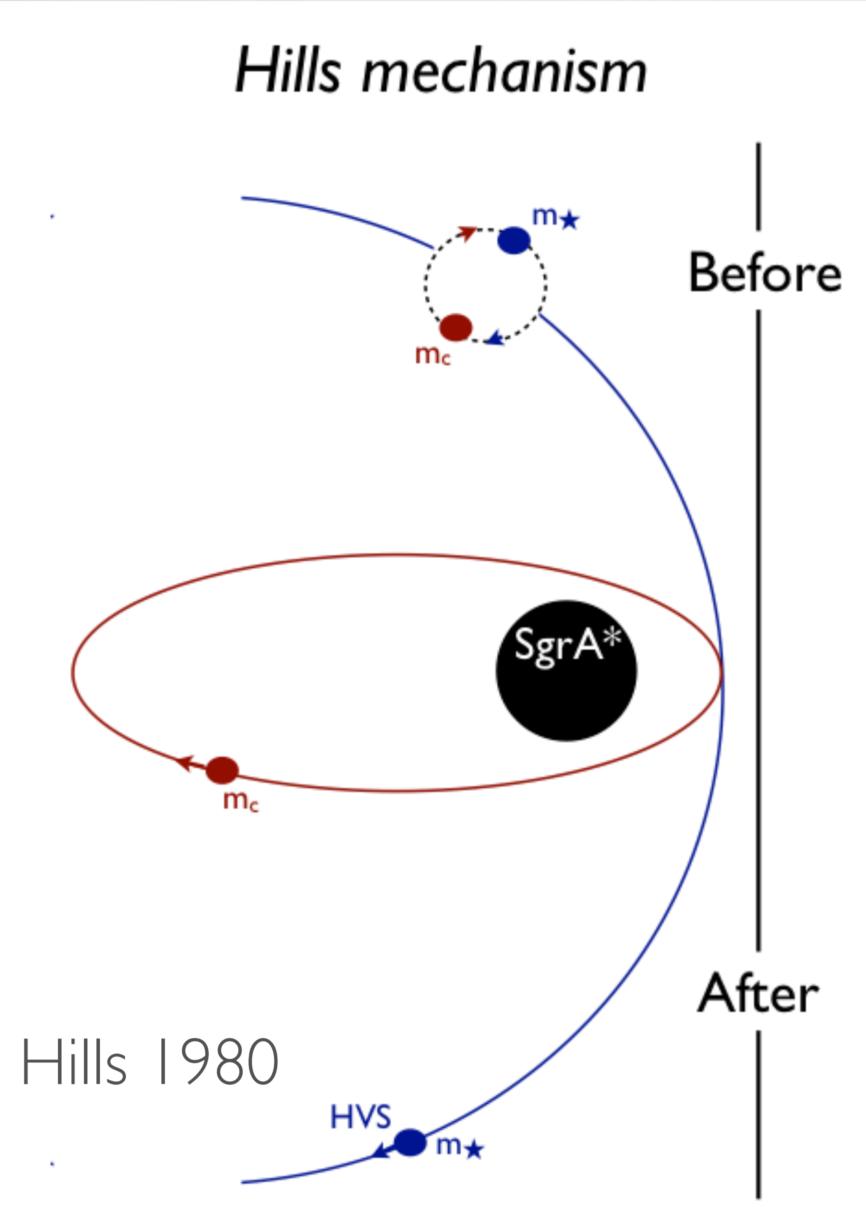
- **We:** restricted 3-body formalism, exploiting m/M <<1 ==> more efficient method
Sari, Kobayashi, EMR10; Kobayashi+12; EMR, Kobayashi & Sari14



EJECTION VELOCITY



One major results:

The HVS ejection velocity depends *analytically* on binary mass and separation

$$v_{HVS} \cong \sqrt{\frac{2Gm_c}{a}} \left(\frac{M}{m}\right)^{1/6}$$

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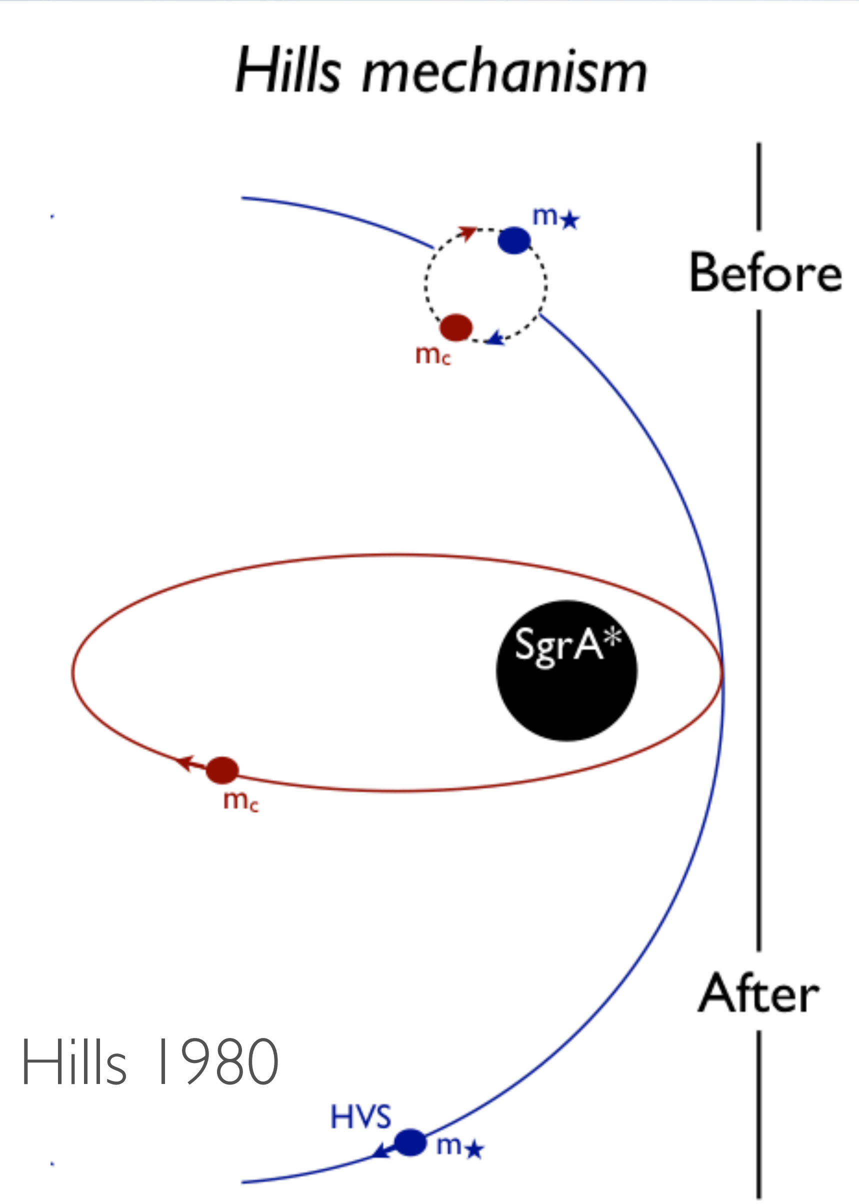

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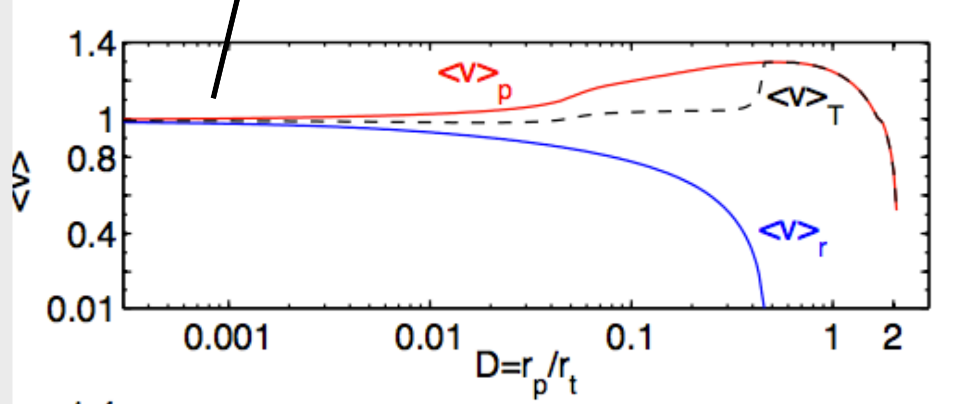

numerical factor here of order of unity

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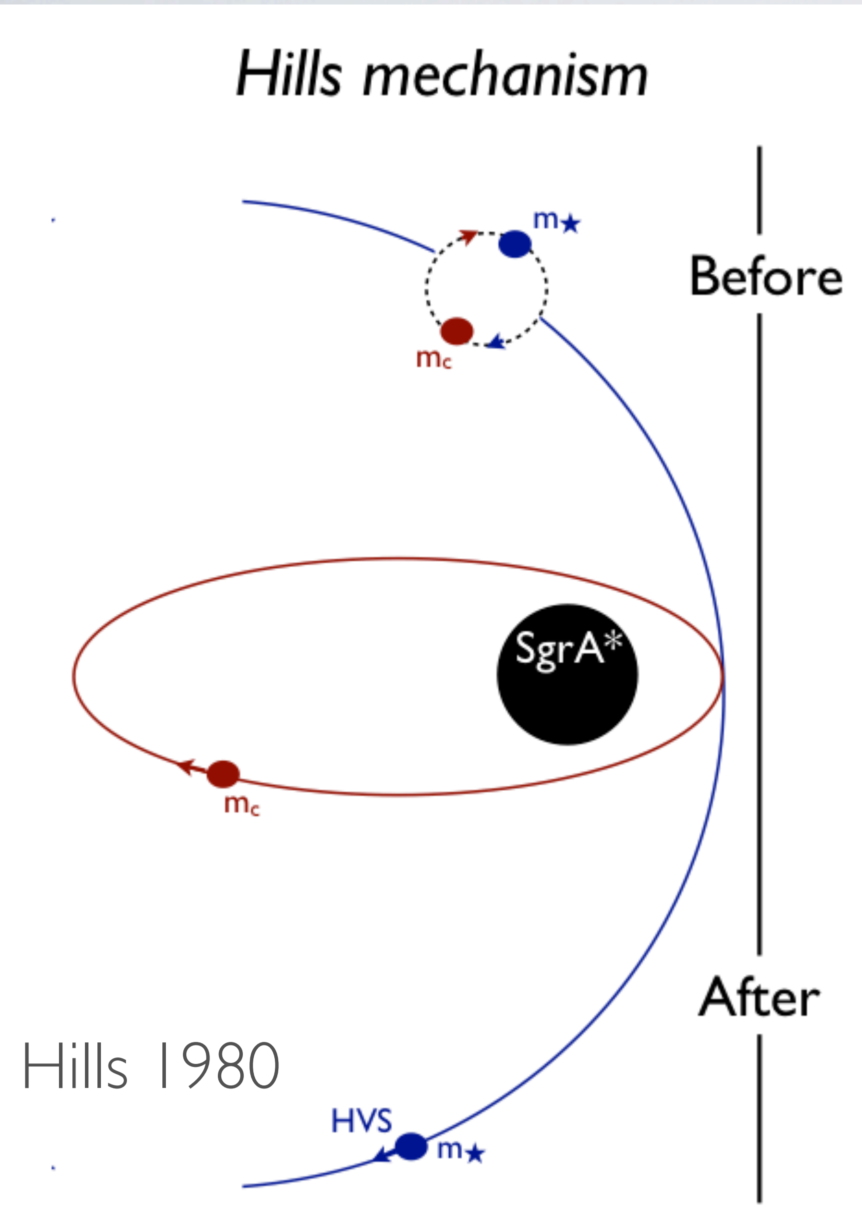

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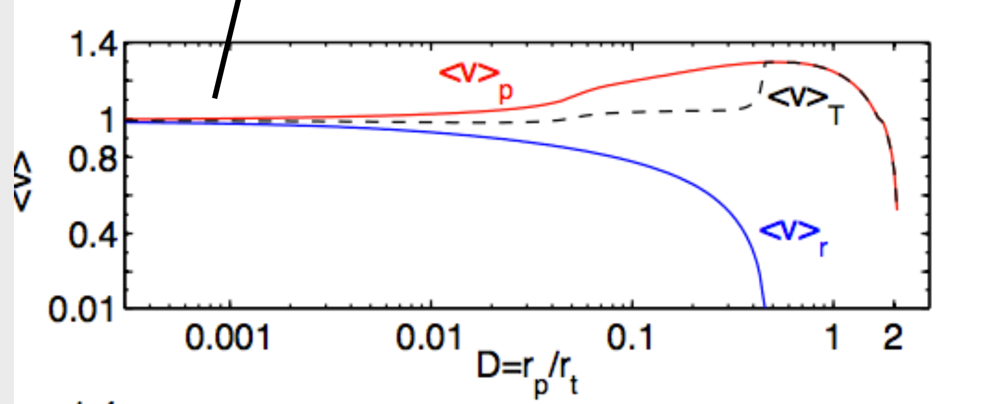


numerical factor here of order of unity

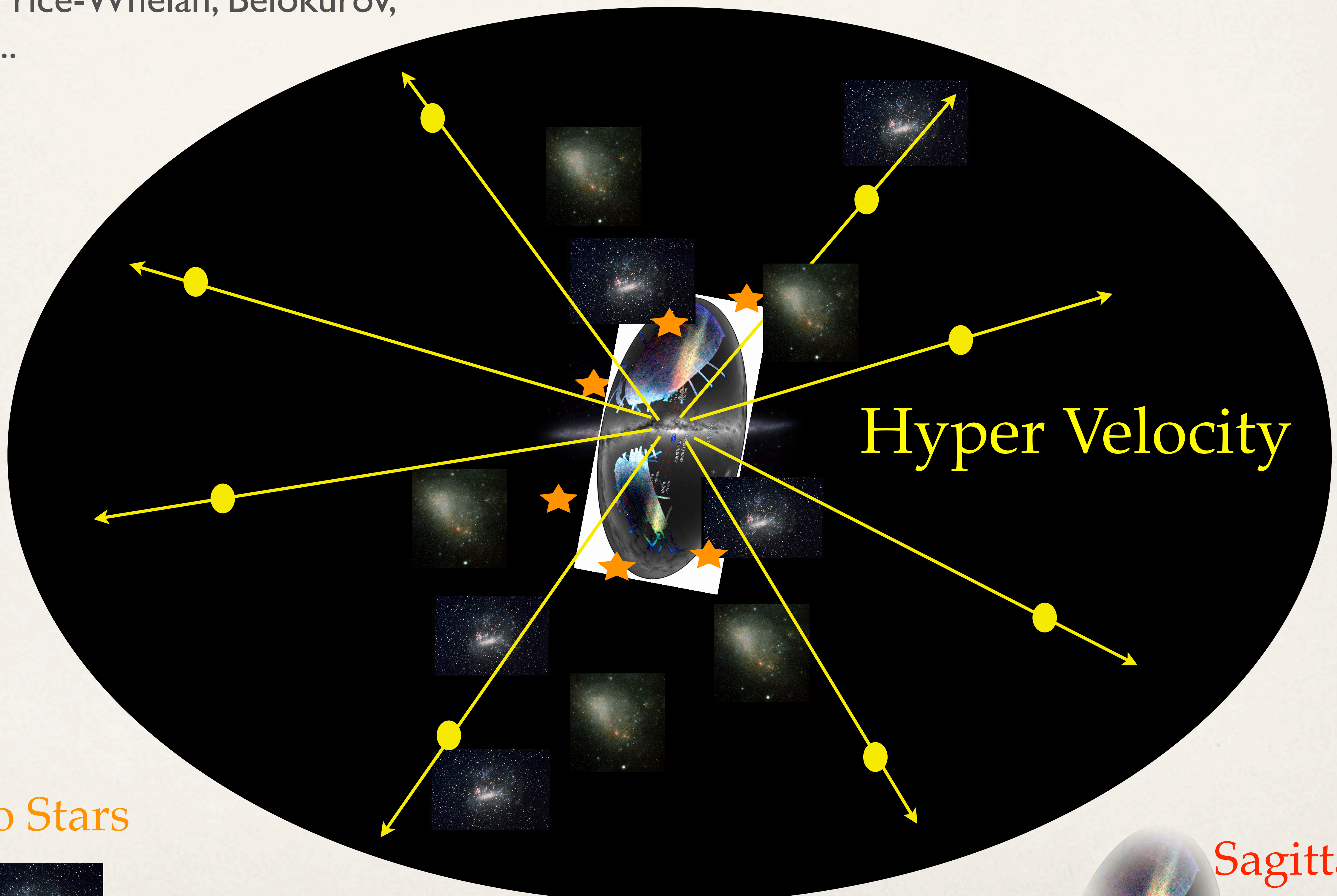
Given a separation and mass distribution => HVS velocity distribution

Complementary dynamical tracers

e.g. Johnson, Gibbons, Law & Majewski, Helmi, Wang, Bullock, Ibata, Price-Whelan, Belokurov, Hogg...

Gnedin et al. 2005

Yu, Q. & Madau, P. 2007



★ Halo Stars

Satellite Galaxies

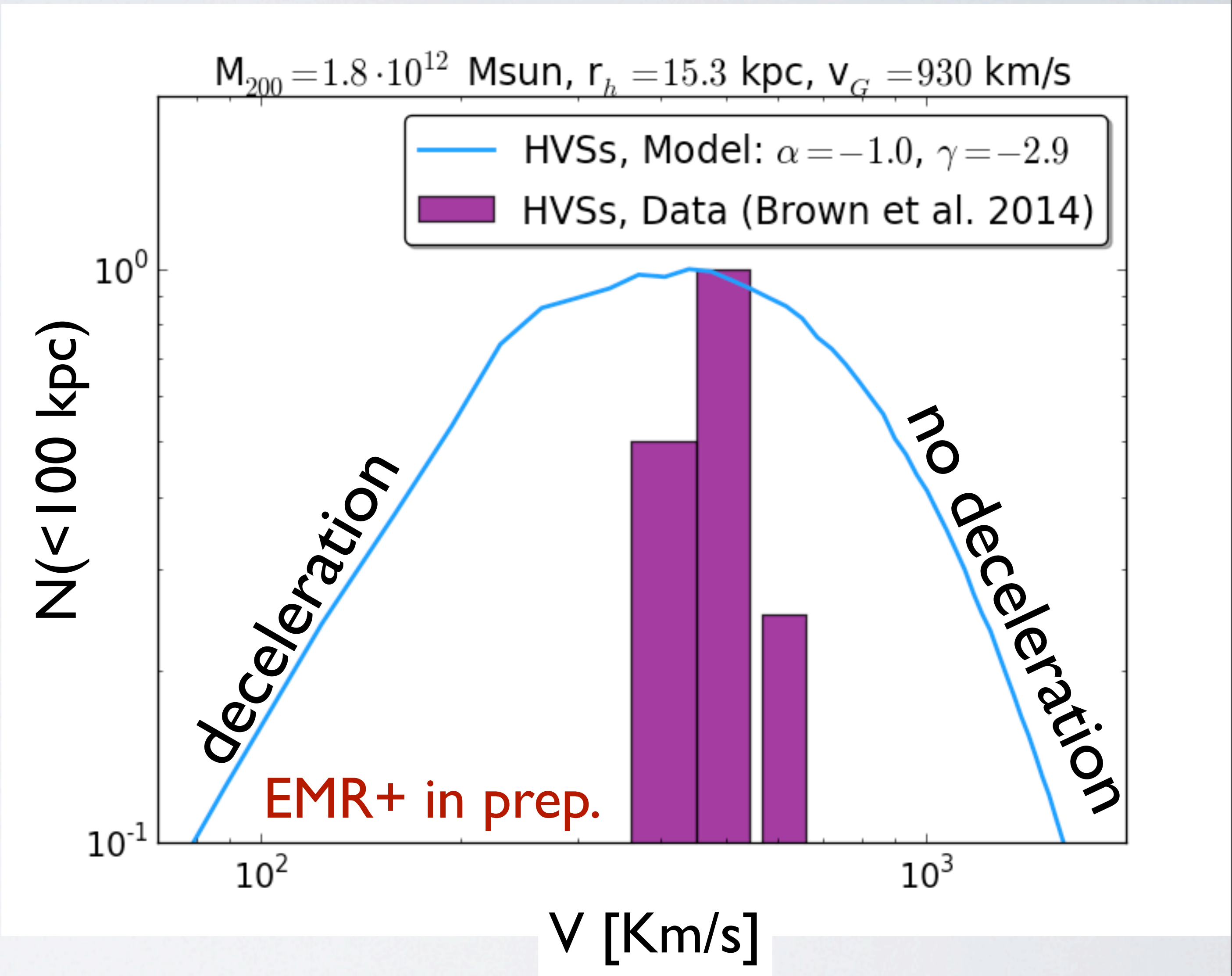
Sagittarius Stream

VELOCITY DISTRIBUTION IN THE HALO

- **Binary distributions:** $f(q) \sim q^{\gamma}$ $f(a) \sim a^{\alpha}$

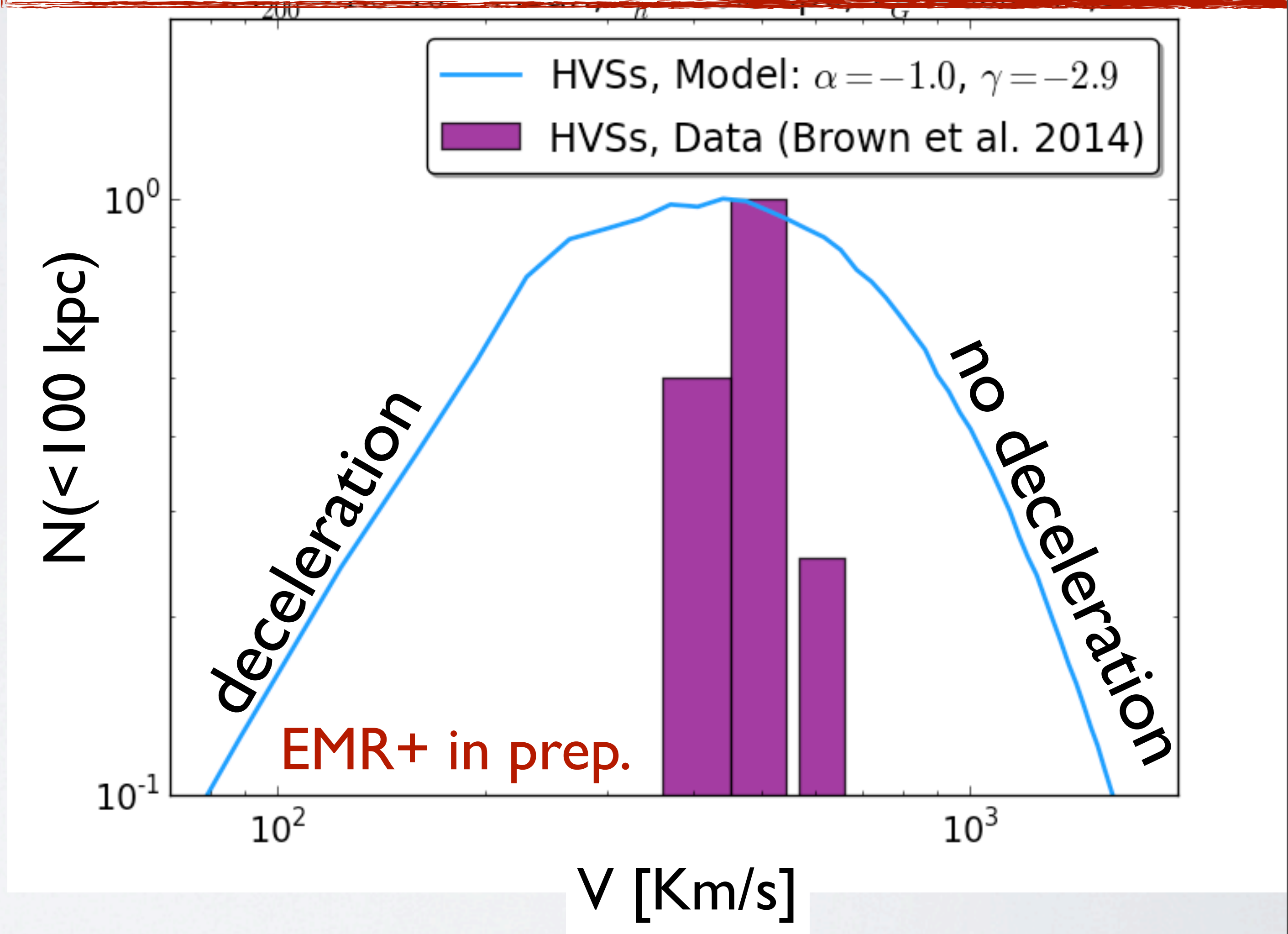
Left: B-type binaries, in star burst region in Tarantula Nebula in LMC (Dunstall+ 15)

- **Galactic Potential:**
  - Bulge: Hernquist spheroidal (Hernquist 1990)
  - Halo: NFW potential
  - DISC: (Miyamoto & Nagai 1975)



VELOCITY DISTRIBUTION IN THE HALO

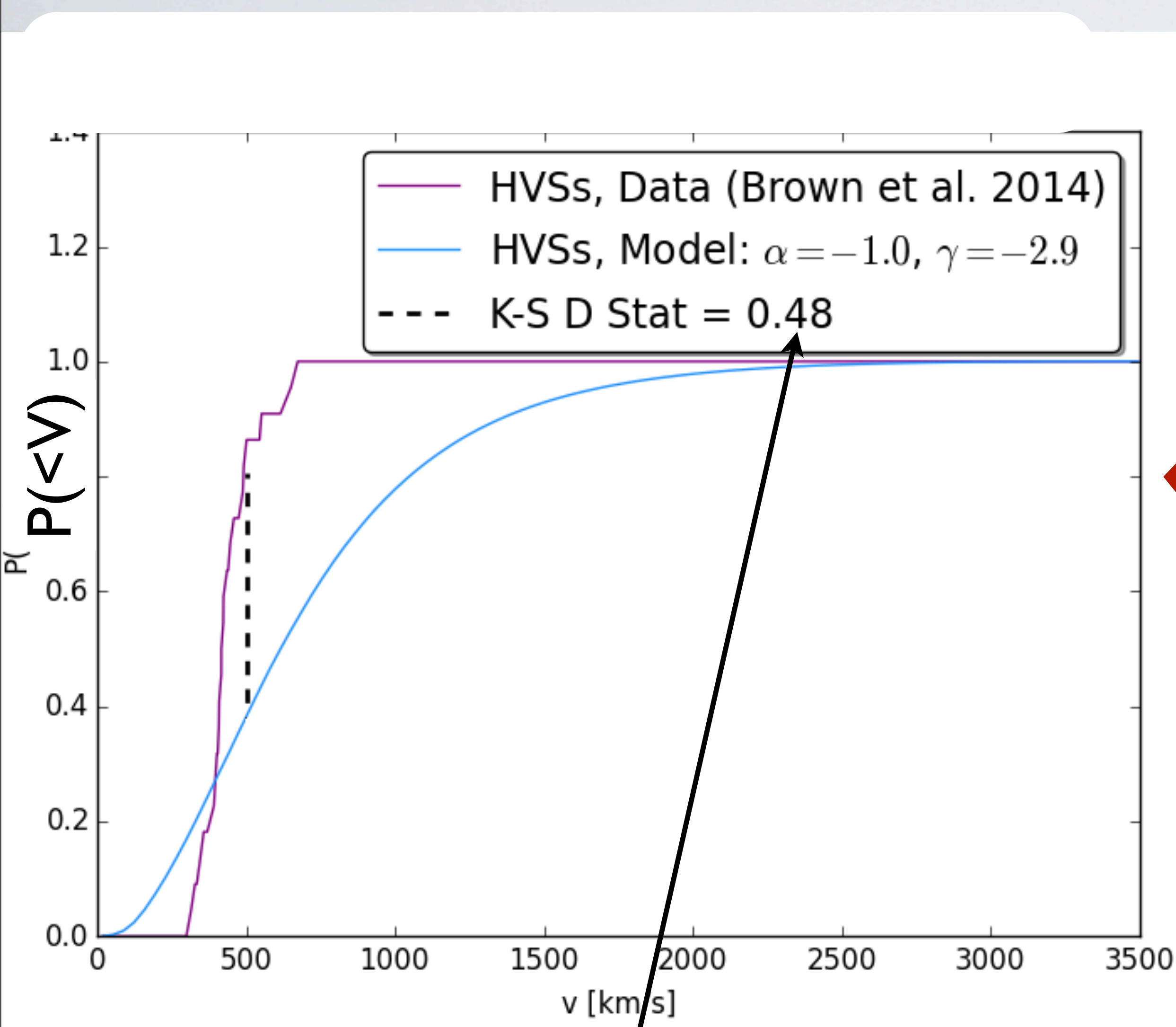
M_{200} = 1.8 10^{12} ; r_s = 15 kpc ; V_G =930 km/s

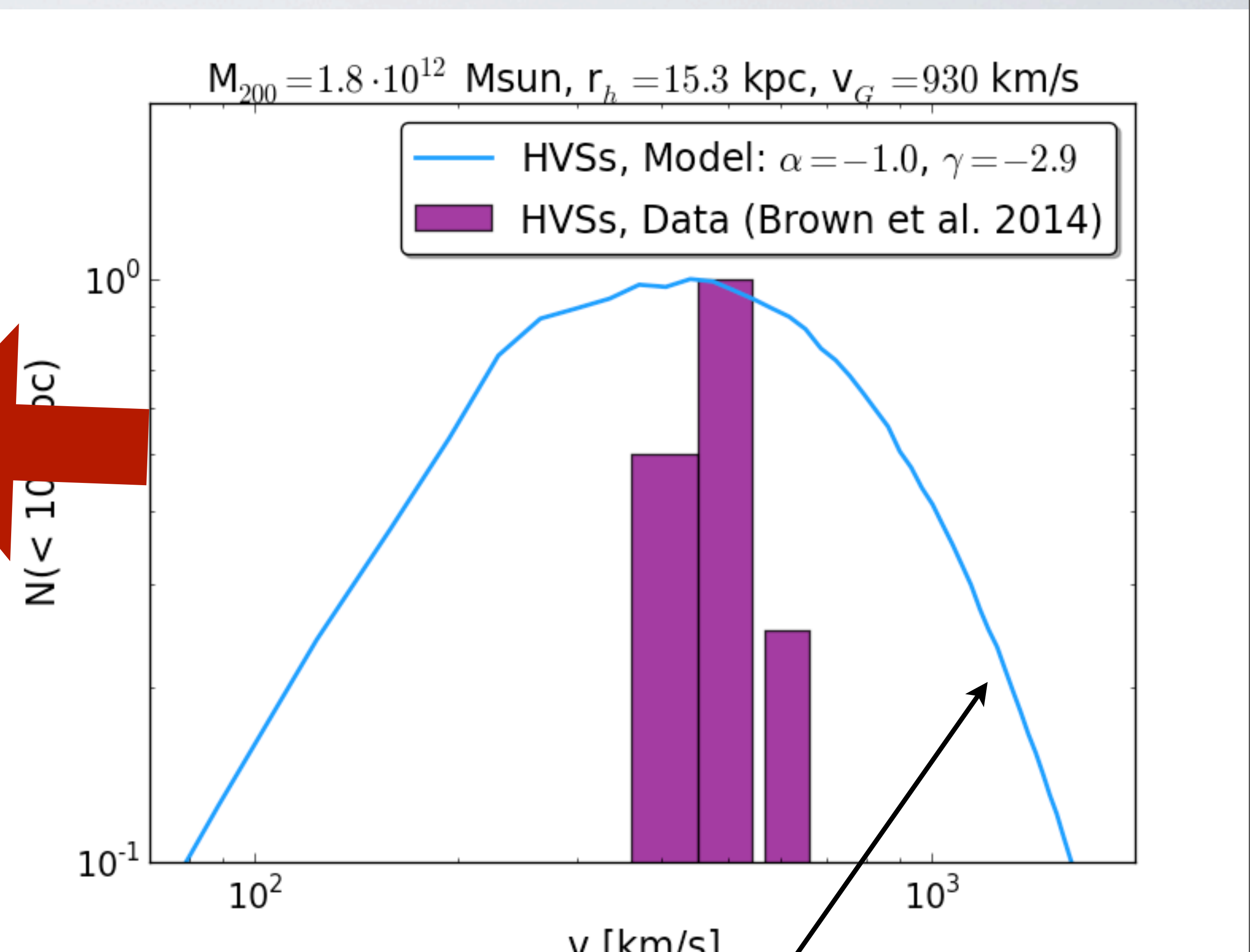


V_G is minimum ejection velocity at GC to get to 20 kpc with V>0.

- It is a measure of the effect of the Galactic potential.
- **The peak of the distribution is proportional to V_G** (EMR+ 14)

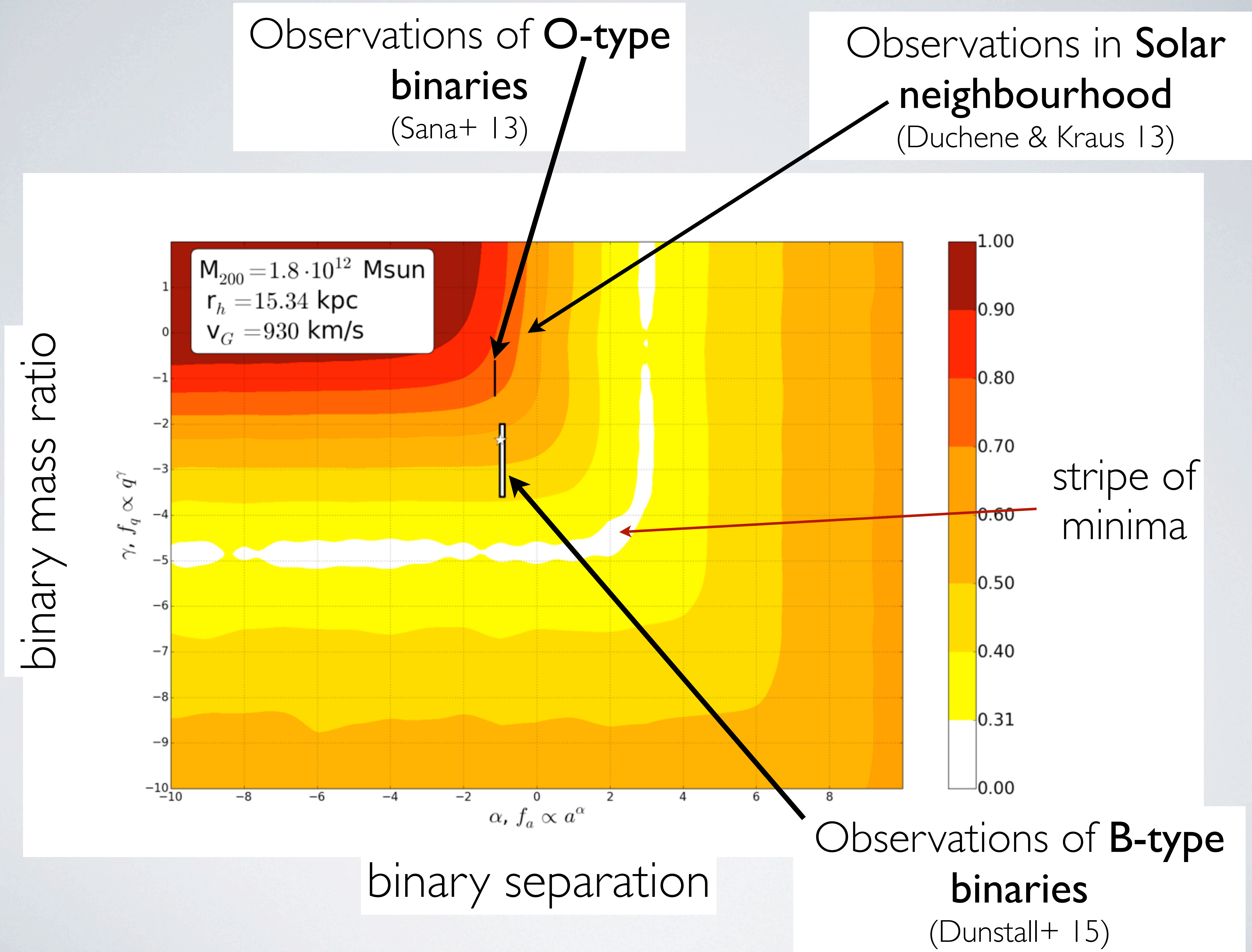
VELOCITY DISTRIBUTION IN THE HALO





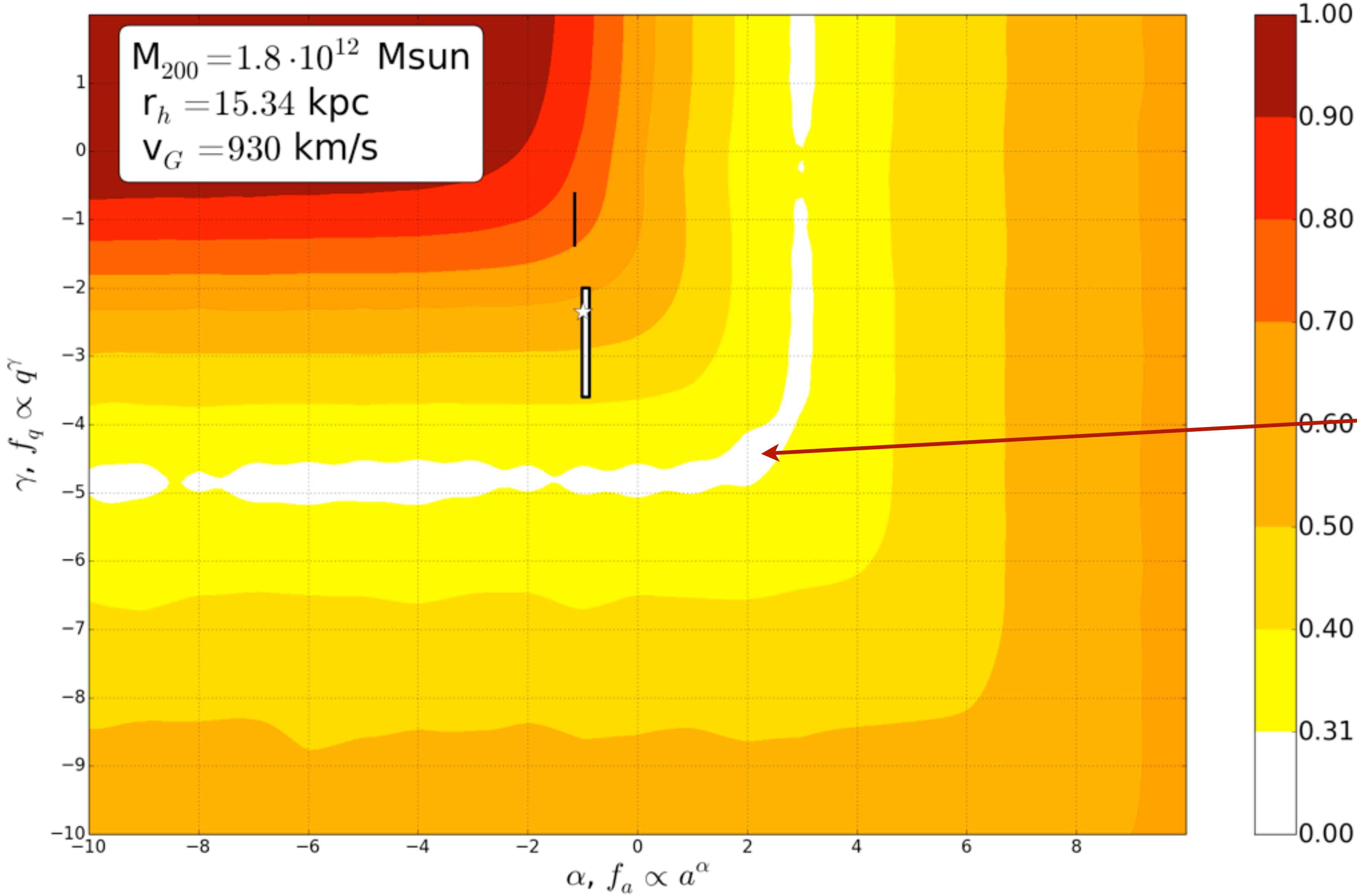
- not a good match, too prominent high velocity tail...

D Stat = 0.48 ==> 99% data do NOT come from model


Observations of **O-type binaries**
(Sana+ 13)
Observations in **Solar neighbourhood**
(Duchene & Kraus 13)
$M_{200} = 1.8 \cdot 10^{12}$ Msun
$r_h = 15.34$ kpc
$v_G = 930$ km/s
stripe of minima
Observations of **B-type binaries**
(Dunstall+ 15)
binary mass ratio
$\gamma,\ f_q \propto q^{\gamma}$
binary separation
$\alpha,\ f_a \propto a^{\alpha}$
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.31
0.00

It would imply a binary population in the Galactic Centre *very different* from that observed

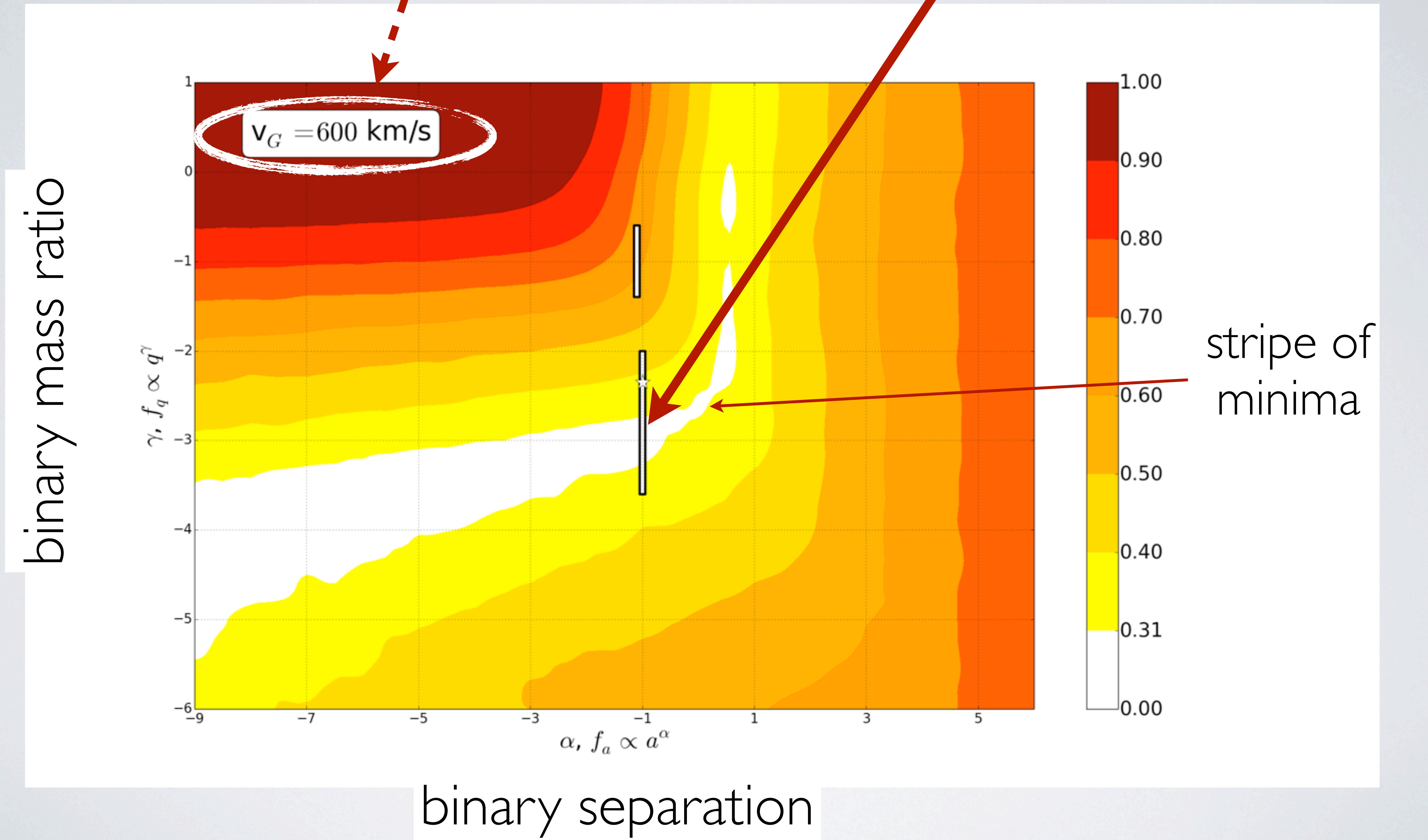
binary mass ratio

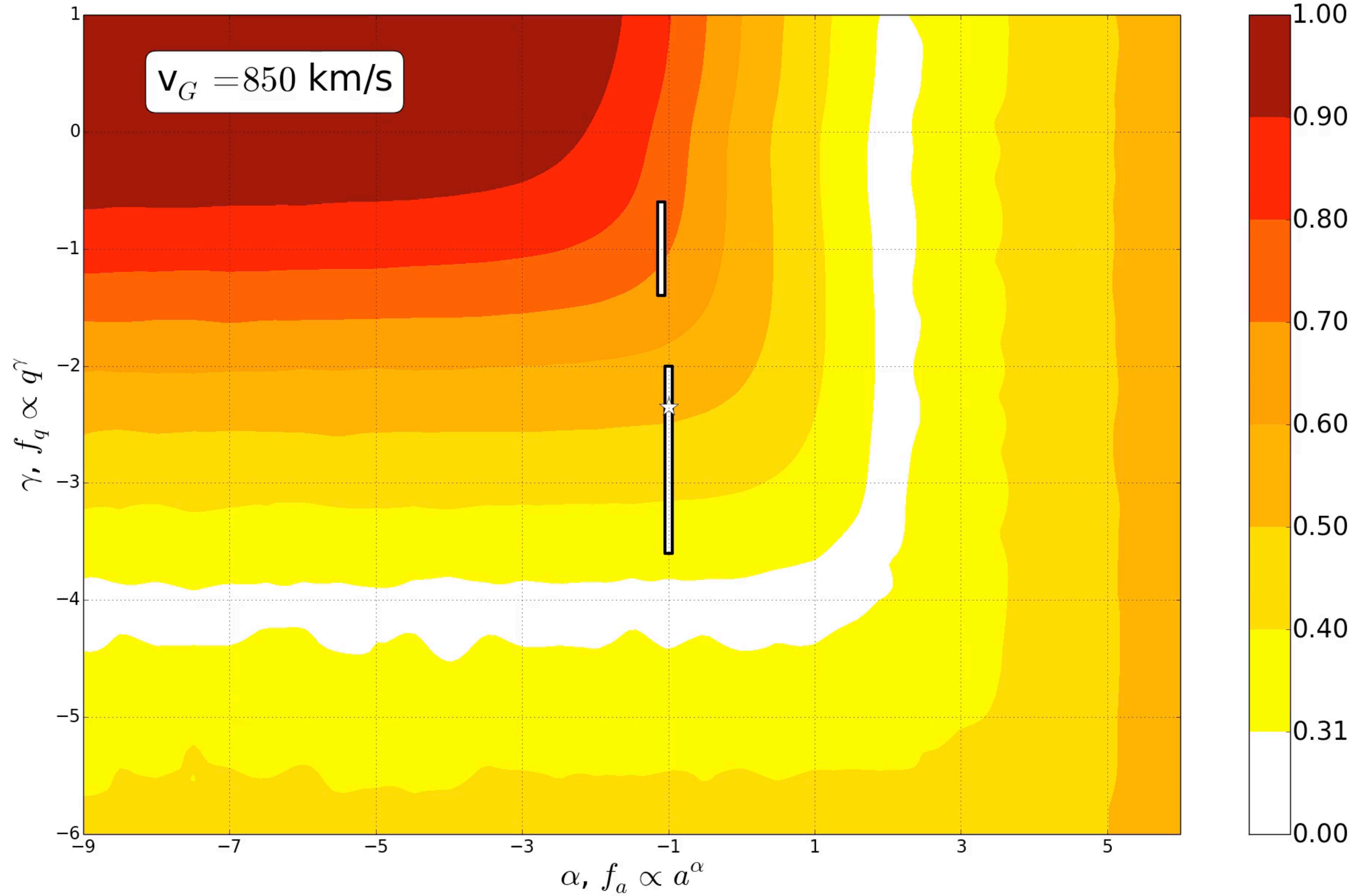


stripe of minima

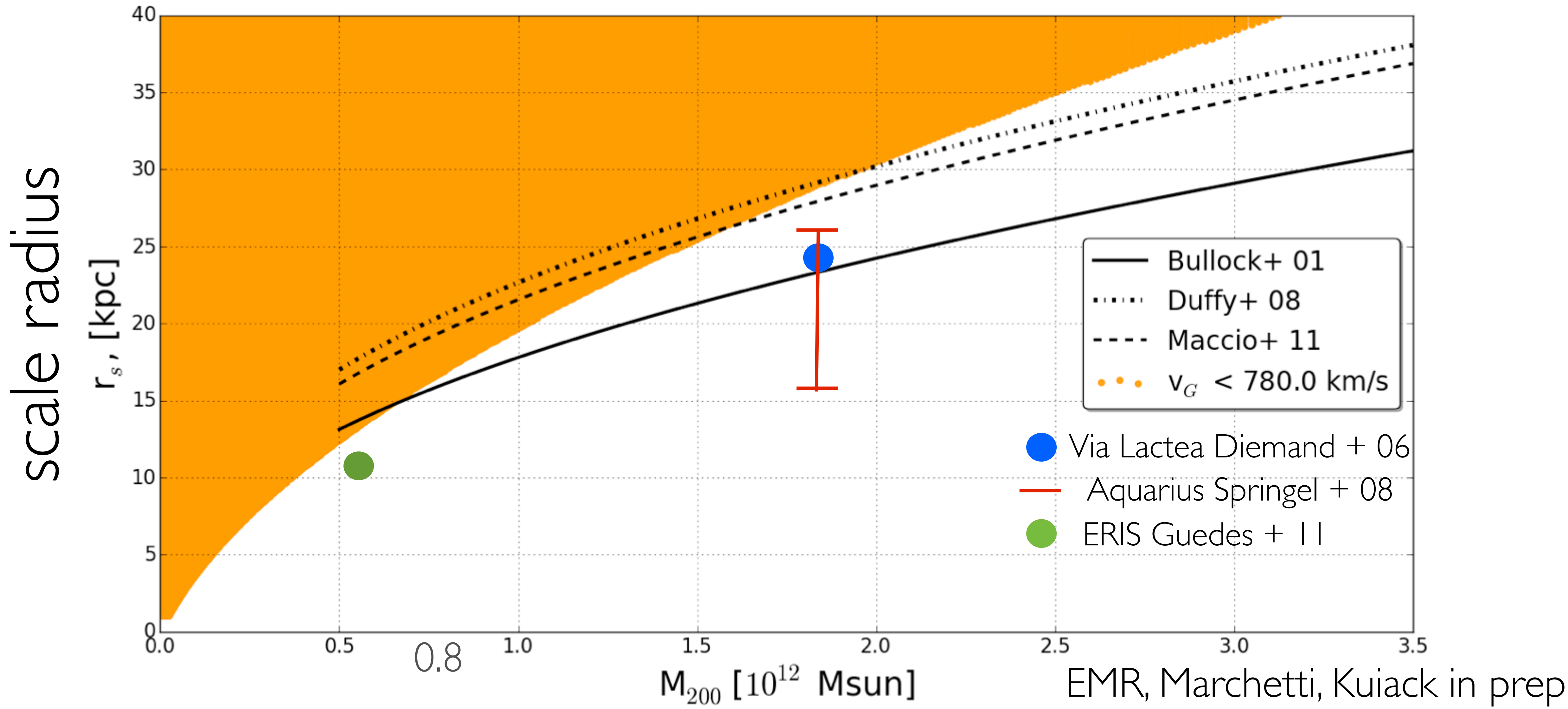
binary separation

With lower V_G, the minimum goes through the observed parameter space for B-type stars



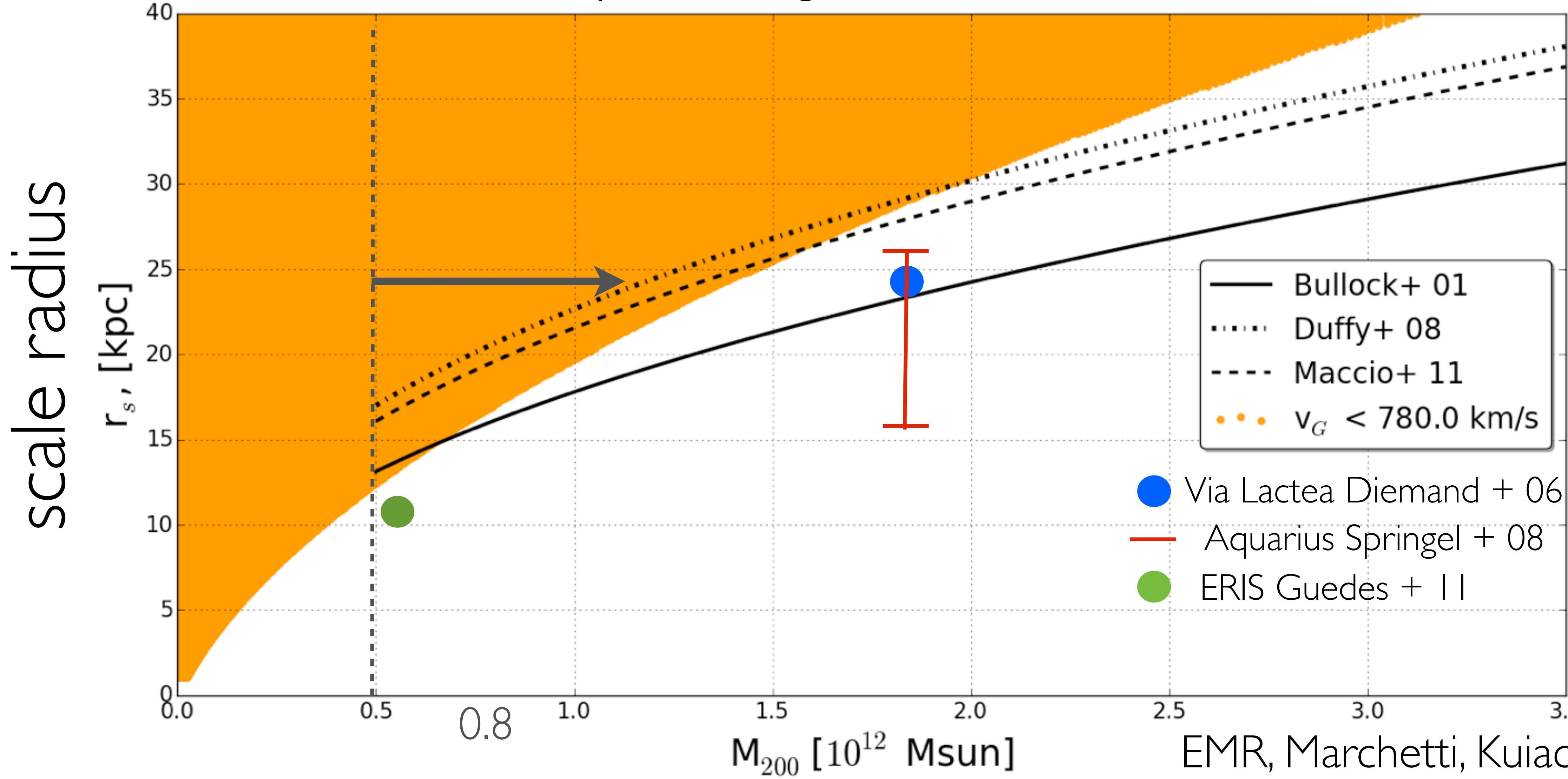


For V_G < 800 km/s the stripe of minima minima goes through B-type binary parameter space



scale radius
r_s, [kpc]
40
35
30
25
20
15
10
5
0
0.0
0.5
0.8
1.0
1.5
2.0
2.5
3.0
3.5
M_{200} [10^{12} Msun]
Bullock+ 01
Duffy+ 08
Maccio+ 11
v_G < 780.0 km/s
Via Lactea Diemand + 06
Aquarius Springel + 08
ERIS Guedes + 11
EMR, Marchetti, Kuiack in prep.

all other probes gives $M_{200} > 0.5$



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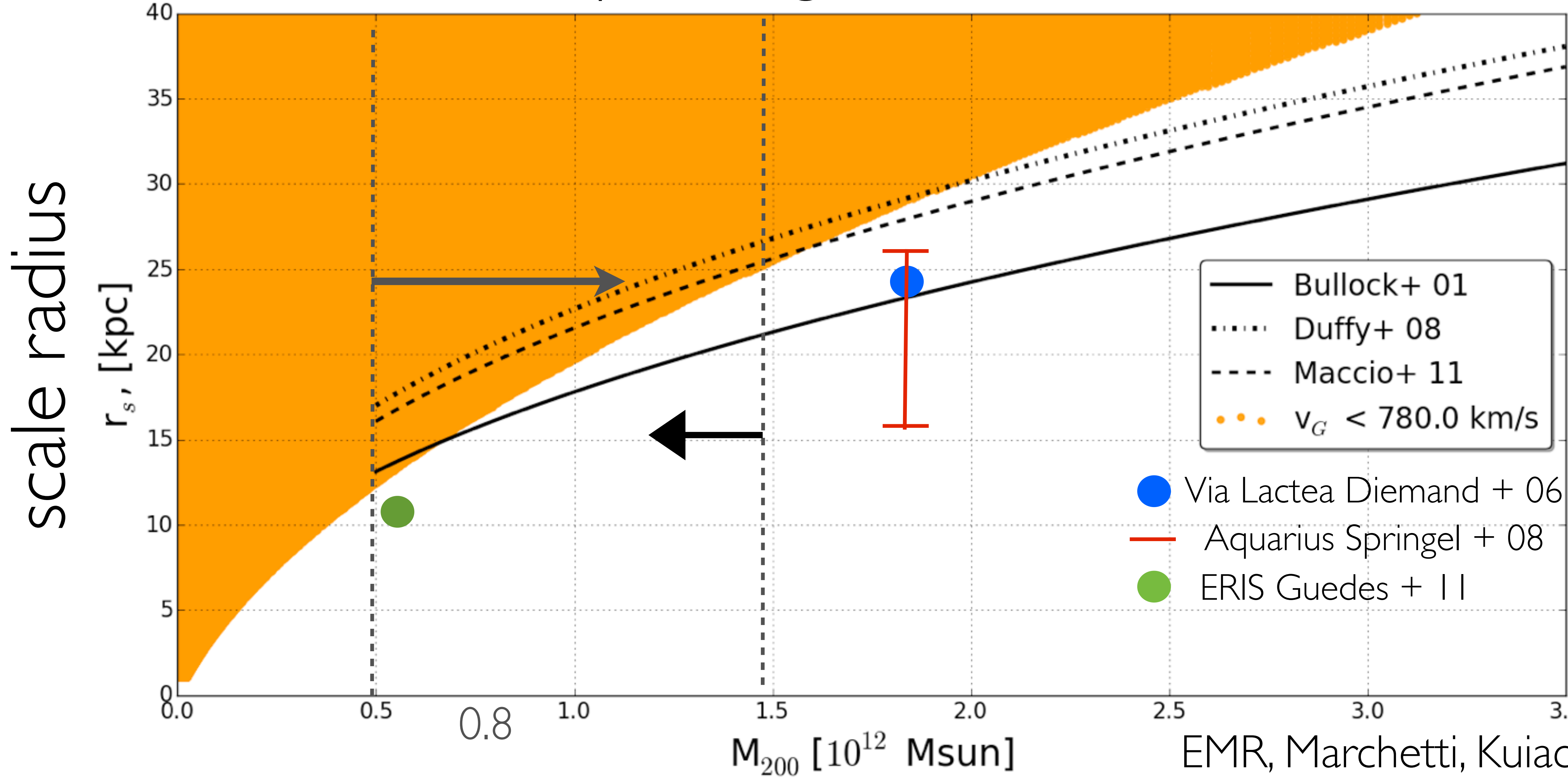

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- Our data may suggest $M_{200} < 1.5\ 10^{12}\ M_{sun}$

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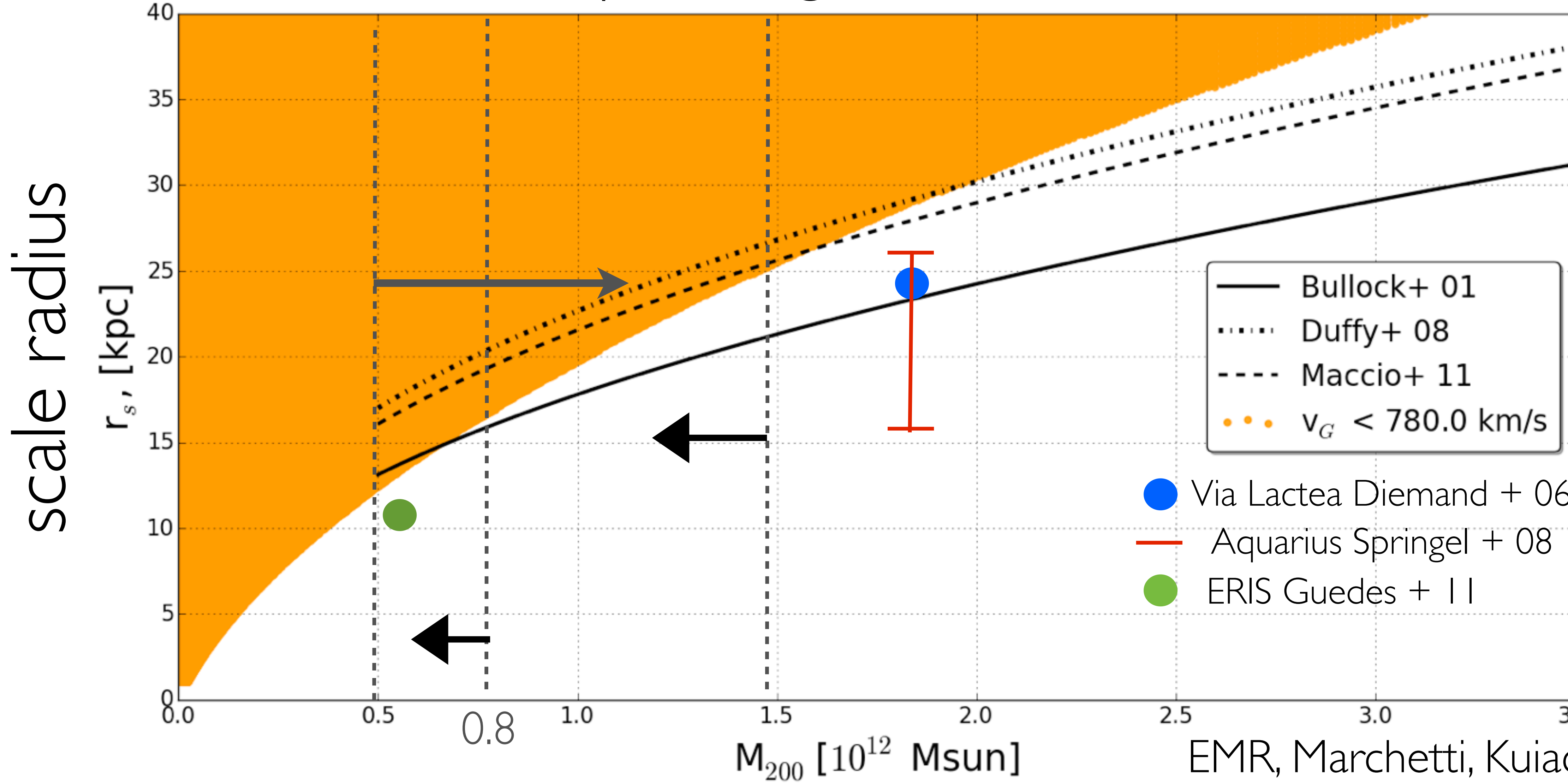

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- If Bullock+ is ``right'', the halo is ``*light*'' M_{200} < 0.8 10^{12} M_{sun}

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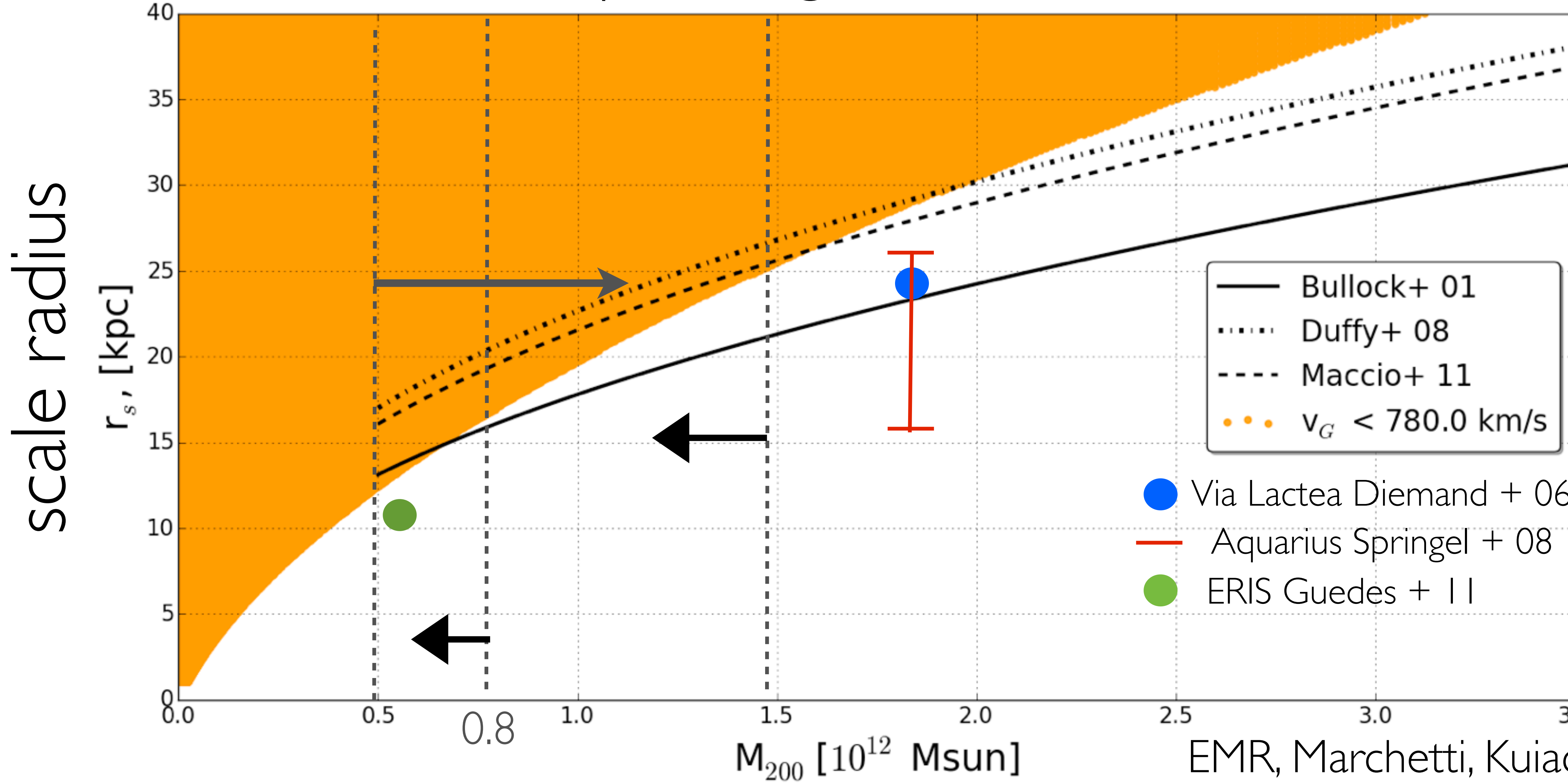

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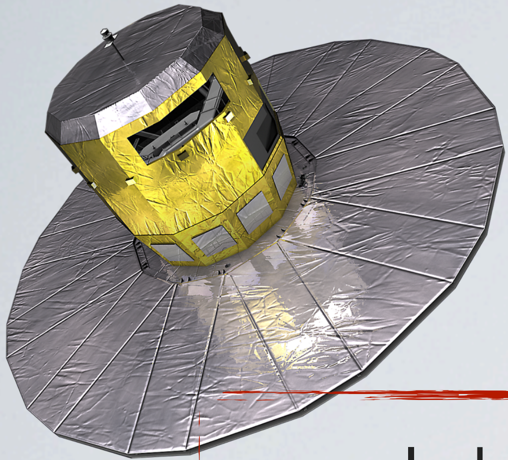
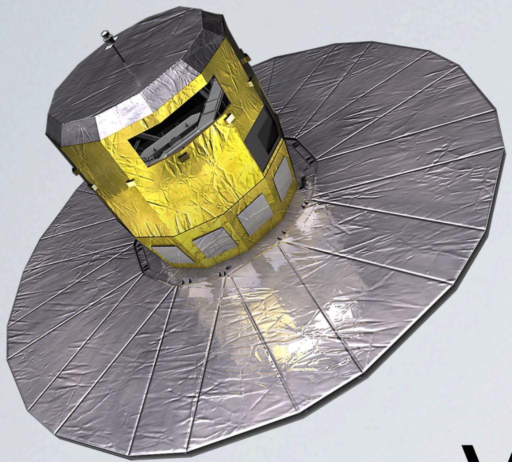
Note: $M_{200} < 1$ in agreement with that obtained with other tracers (streams: Gibbons+14; halo stars: Deason + 12 Rashkov+ 13; satellites: Watkins+ 10....



THE NEAR FUTURE IS *GAIA*

~1 billion star astrometric mission at **μ**as precision down to G~20

Radial Velocities down to G~16



THE NEAR FUTURE IS *GAIA*

We construct a mock population of HVSs

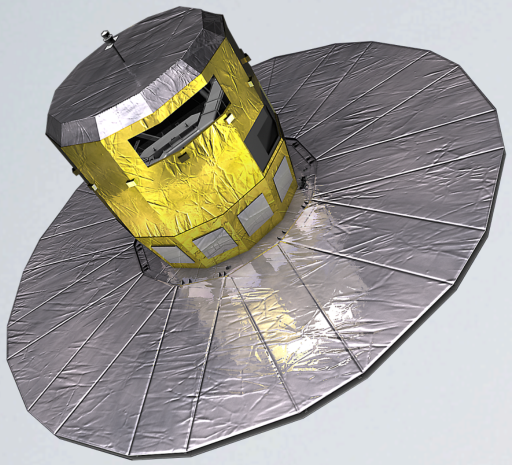
Marchetti, EMR, Brown in prep.

- We eject HVSs with a from GC in radial orbit

- Give a random age and evolve with stellar evolution code SeBa (Portegies Zwart +09)

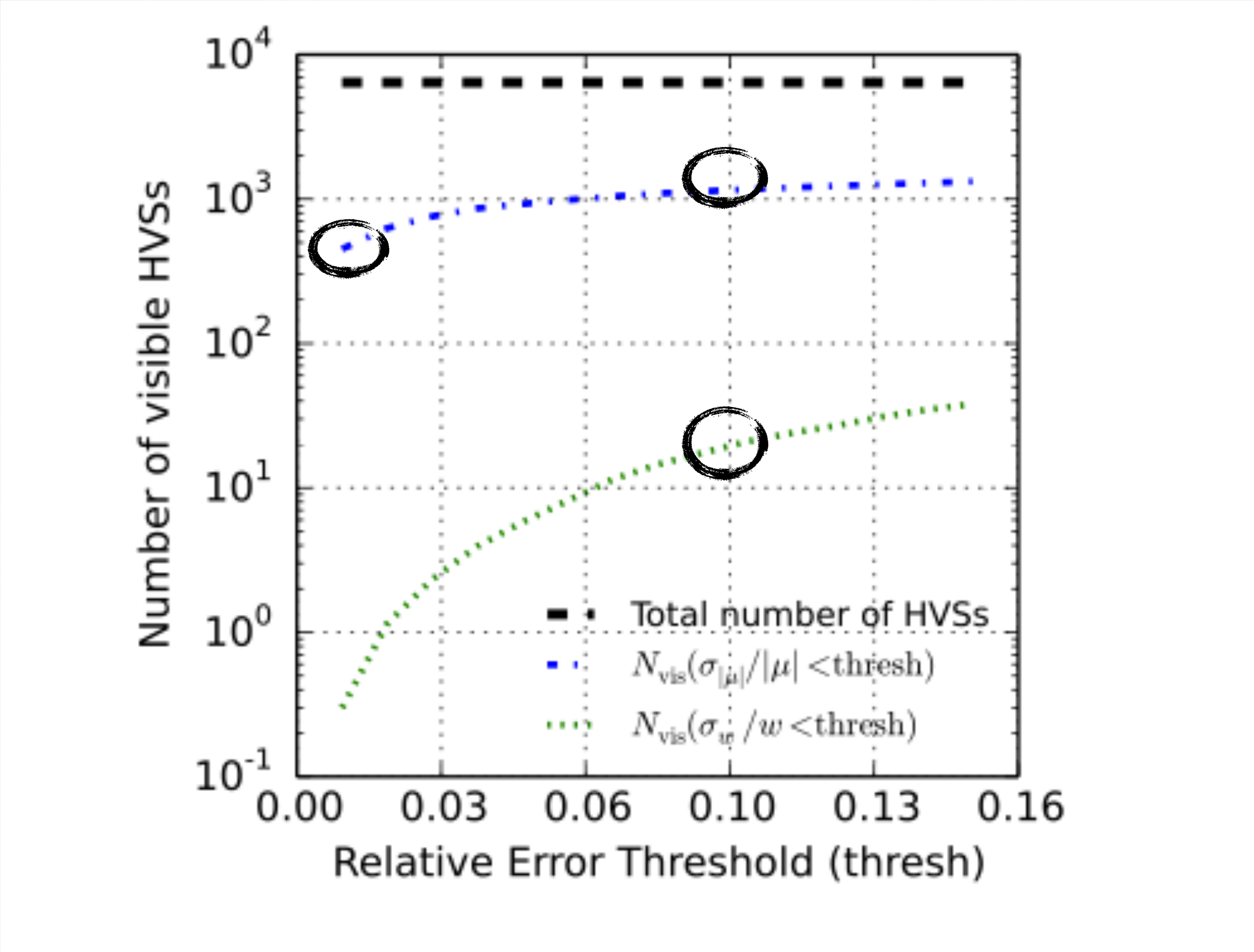
-Associate a spectrum using BaSel SED libriary (Westera & Buser 03)

-Calculate Gaia errors with Pi-Gaia (A. Brown)from G and colour

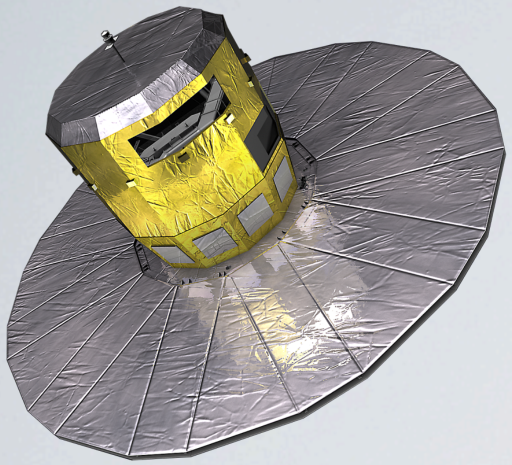


THE NEAR FUTURE IS *GAIA*

Proper motion and parallaxes

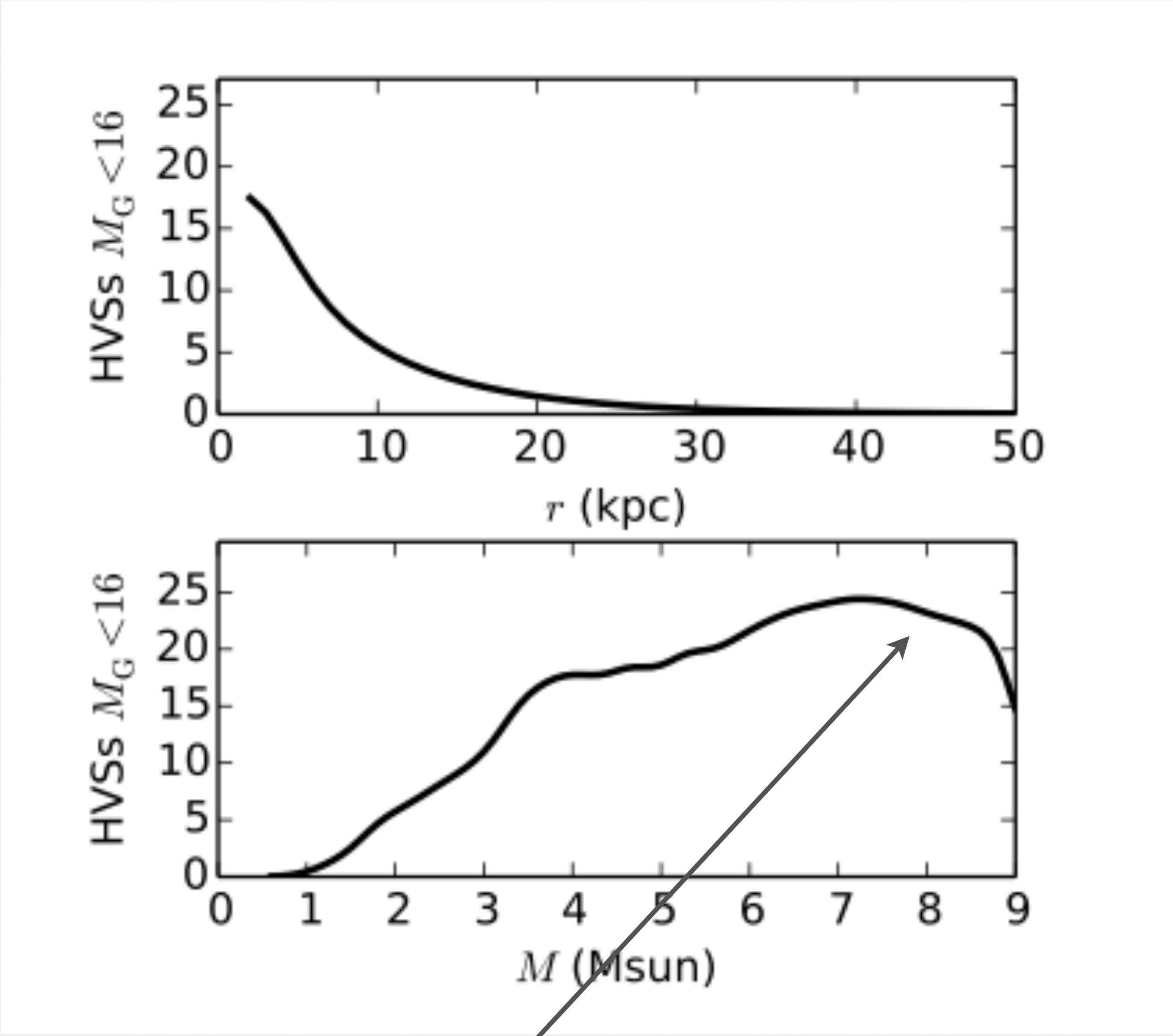


100s-1000s HVS with precise proper motion
most stars will have 1-3 M_{sun}

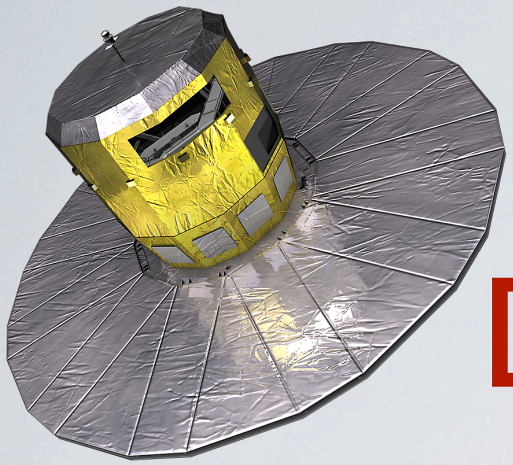


THE NEAR FUTURE IS *GAIA*

Radial velocities



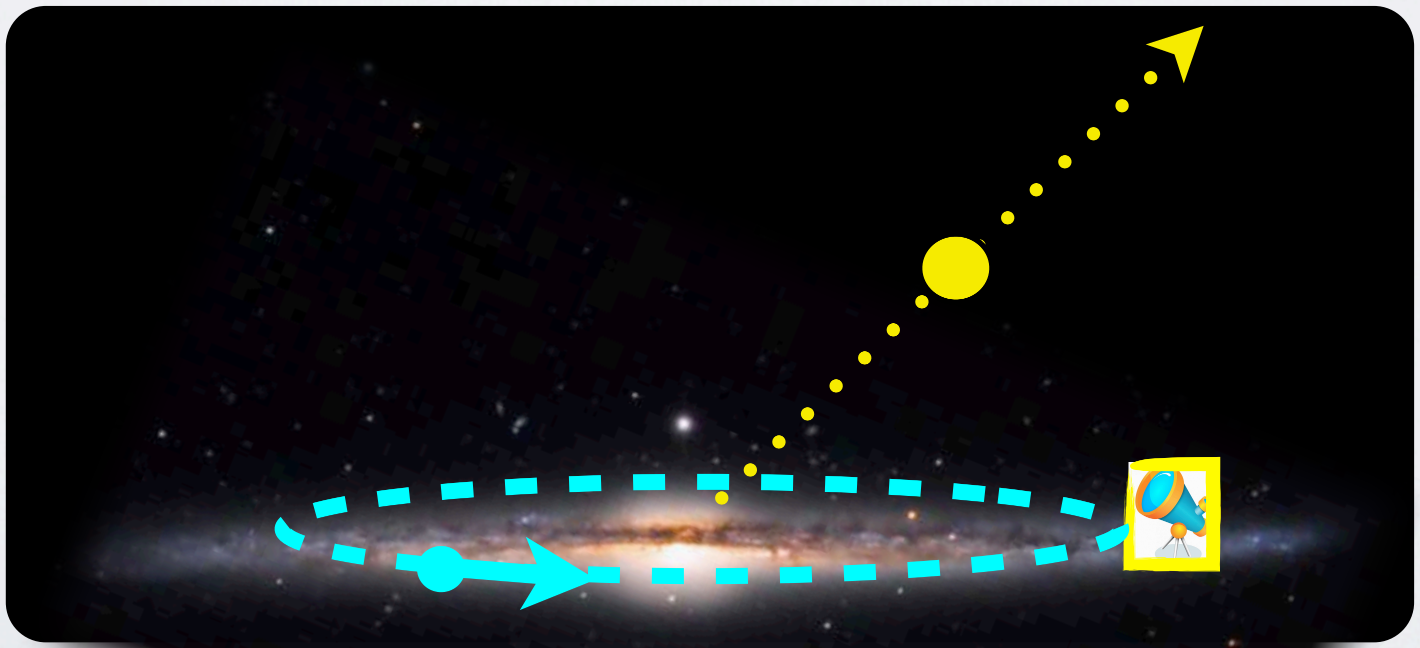
Several tens of HVSs, but massive stars will be more easily selected



DATA MINING+FOLLOW UP

- Collect that sample requires efficient way to extract HVSs candidate from catalogue of 10^9 stars..

- Have an effective follow-up programme for radial velocity stars



In collaboration with
A. Brown,
A. Helmi,
E. Starkenburg,