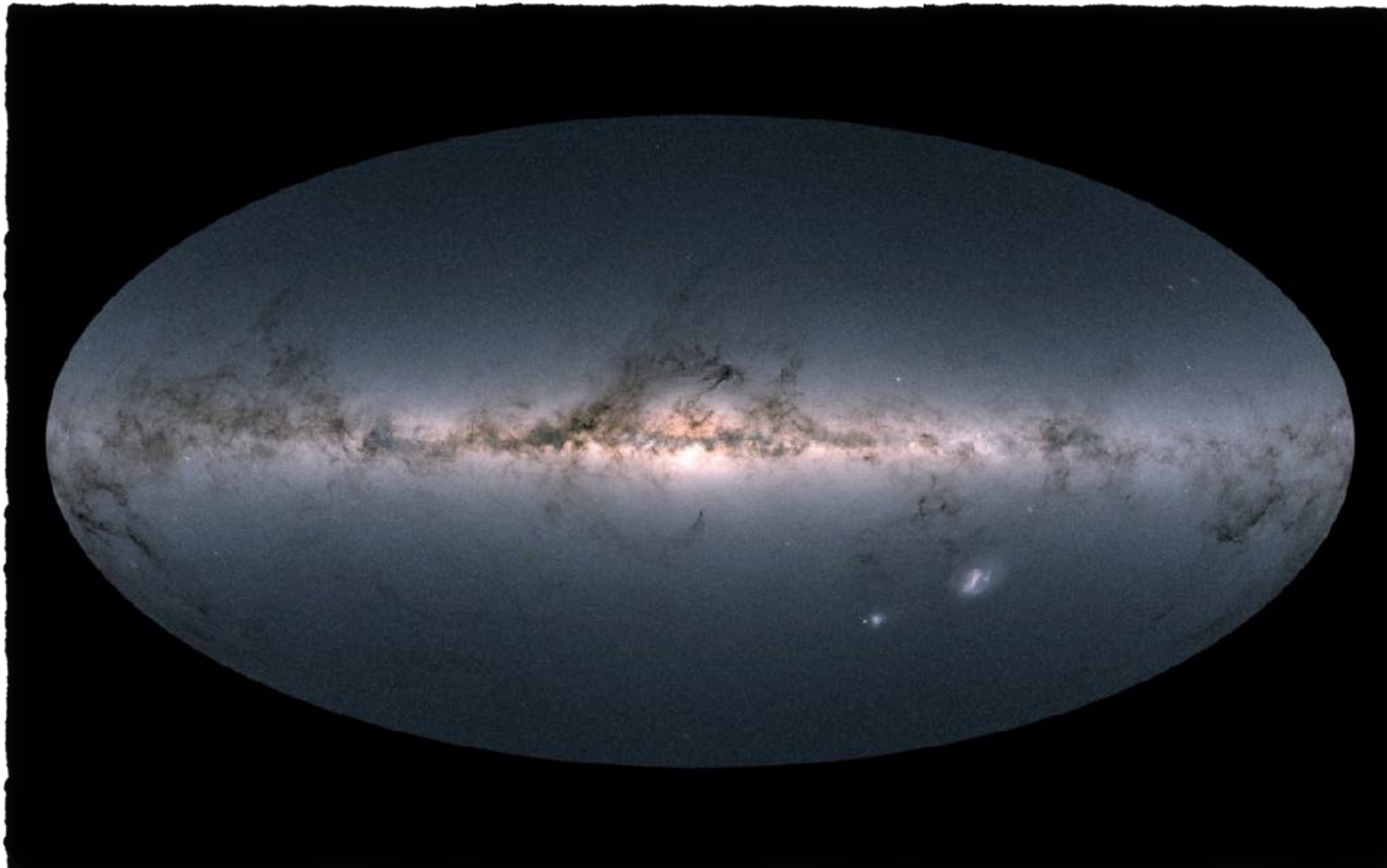
Multi-tracer & multi-messenger tomography of the Milky Way

Elena Maria Rossi

Leiden Observatory, The Netherlands

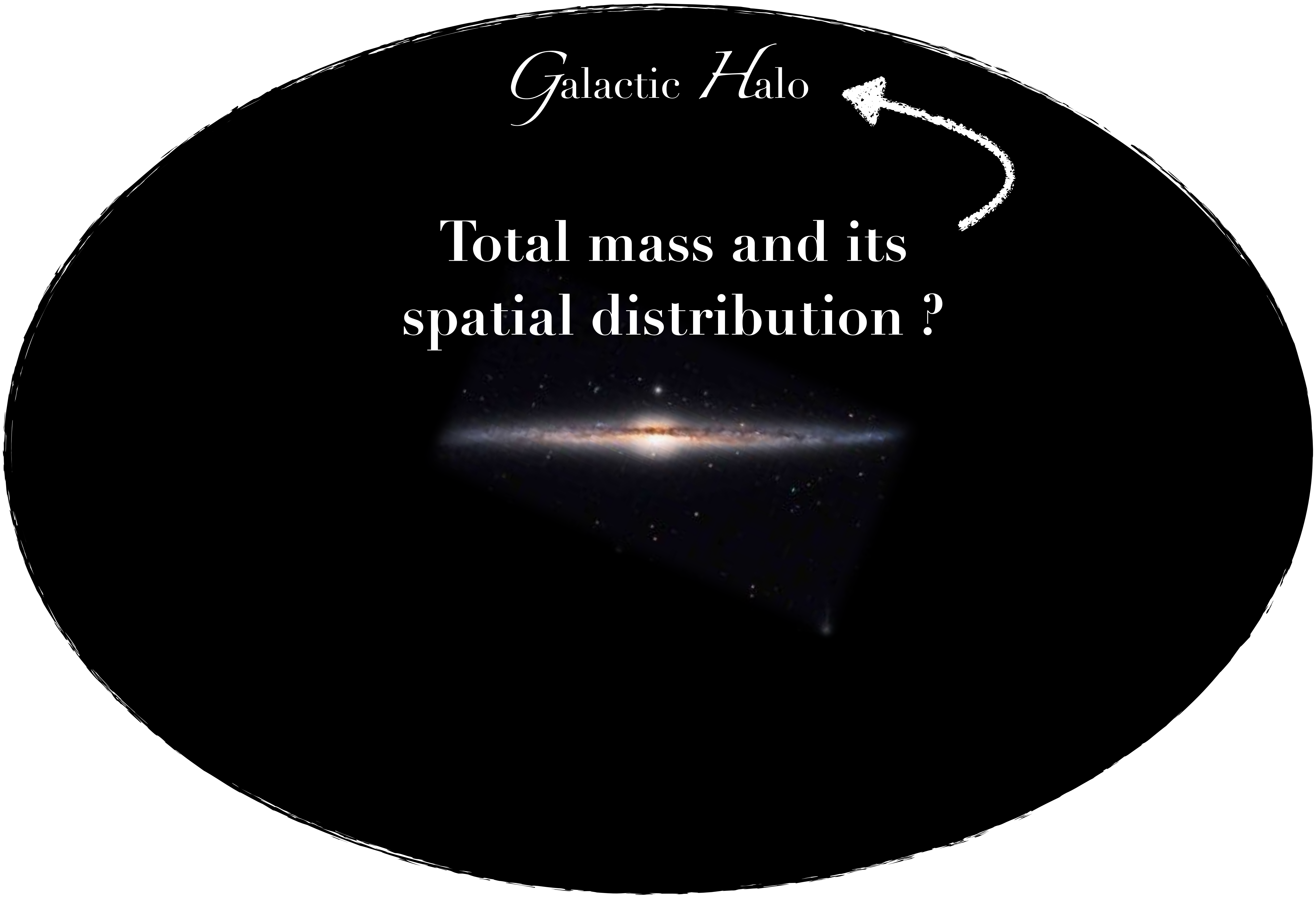
Istitut d'Astrophysique de Paris, Colloquium 17-5-19

Gaia 1.7 billion star map of the Galaxy



Credit: ESA/Gaia/DPAC

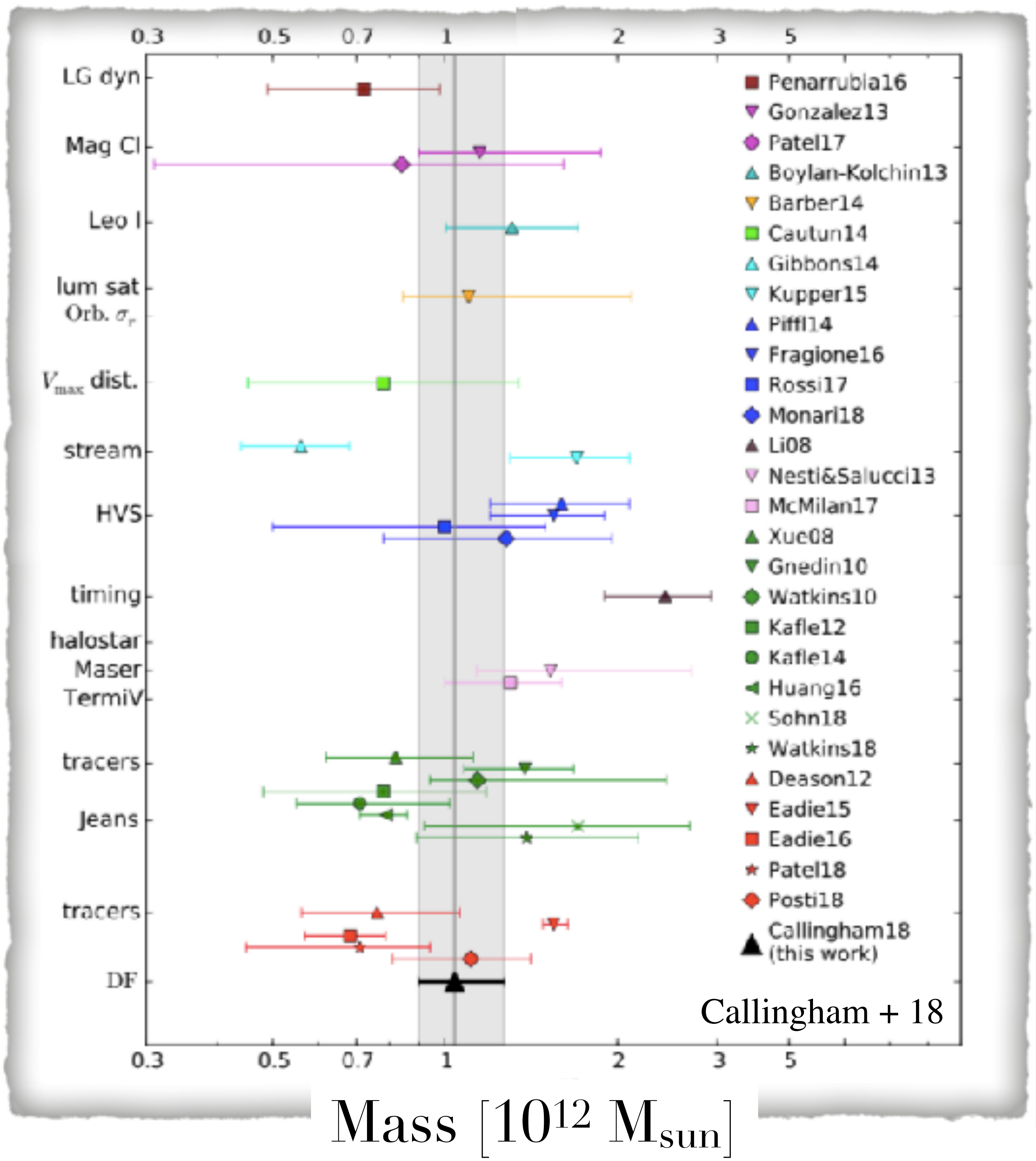
MY RESEARCH QUESTIONS



MILKY WAY MASS MEASUREMENTS

Uncertainties over a factor of 3 and biased differences between probes

Different methods/probes



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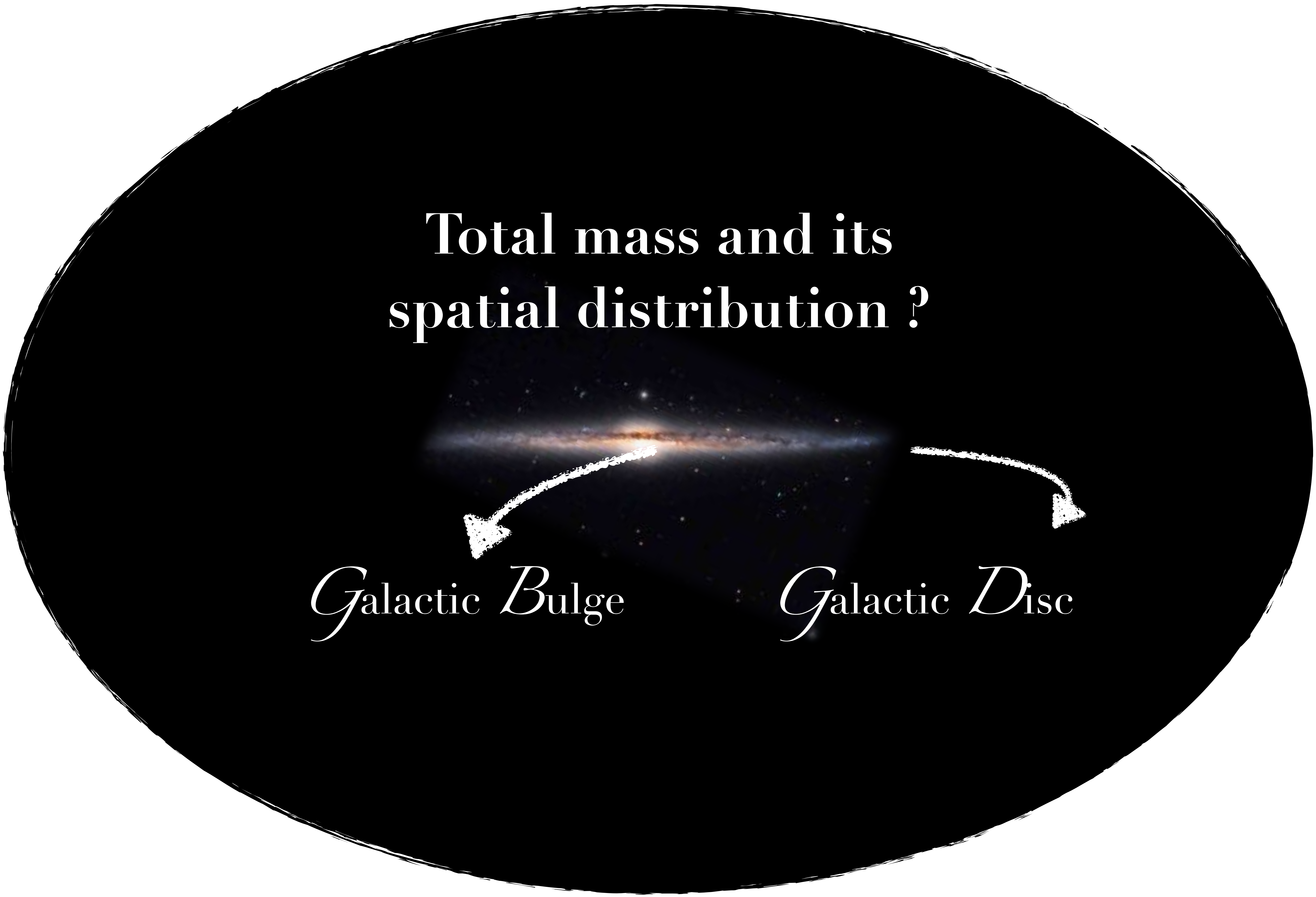


DISC MEASUREMENTS

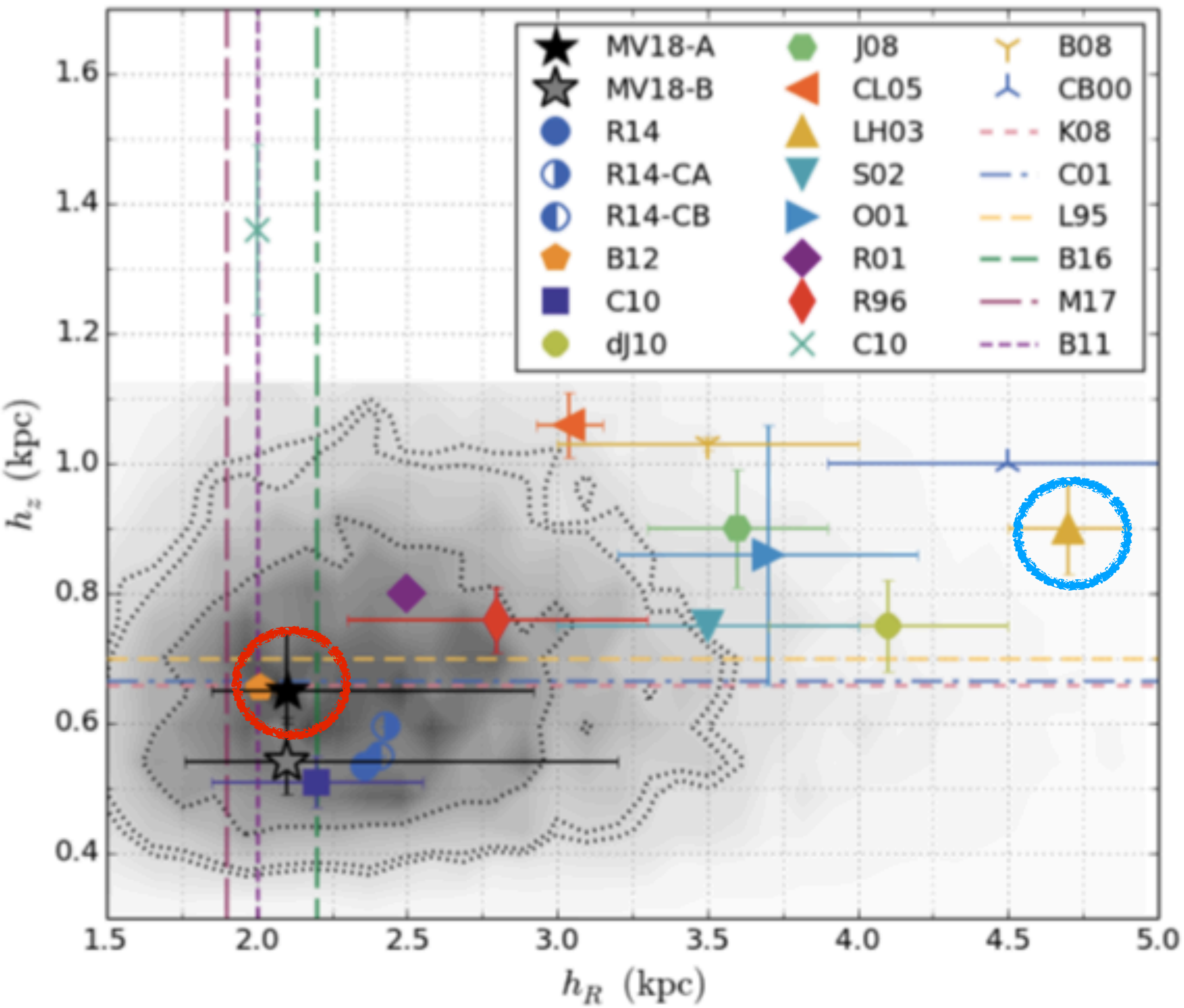


Table 5. Thick Disc scale lengths and heights obtained by different authors.

h_R	h_z	Tracer/Technique	Legend
$\mathbf{2.10^{+0.82}_{-0.25}}$	$\mathbf{0.65^{+0.09}_{-0.05}}$	RRLS	**MV18-A**
$\mathbf{2.10^{+1.10}_{-0.34}}$	$\mathbf{0.54^{+0.07}_{-0.05}}$	RRLS	**MV18-B**
1.9 ± 0.1	...	RGB	M17
2.2 ± 0.2	...	RC	B16
2.36 ± 0.025	0.535 ± 0.0046	CMD fitting	R14
2.43	0.596	CMD fitting	R14-CA
2.41	0.549	CMD fitting	R14-CB
2.01 ± 0.05	0.655 ± 0.013	G-type dwarfs	B12
2.0	...	K-giants	B11
2.2 ± 0.35	0.51 ± 0.04	SEGUE calibration stars	C10
4.1 ± 0.4	0.75 ± 0.07	CMD fitting	dJ10
3.6 ± 0.3	0.9 ± 0.09	MS photometric parallaxes	J08
3.04 ± 0.11	1.06 ± 0.05	2MASS RC counts	CL05
4.7 ± 0.2	0.9 ± 0.07	Photometric parallaxes	LH03
3.5 ± 0.5	0.75	MS photometric parallaxes	S02
...	0.665 ± 0.085	*griz* CMD fitting	C01
3.7 ± 0.5	0.86 ± 0.2	*JHK* CMD fitting	O01
2.5	0.8	CMD fitting	R01
2.8 ± 0.5	0.76 ± 0.05	*UBV* CMD fitting	R96
...	0.66 ± 0.16	RRLS	K06
...	$0.7^{+0.5}_{-0.3}$	RRLS	L95

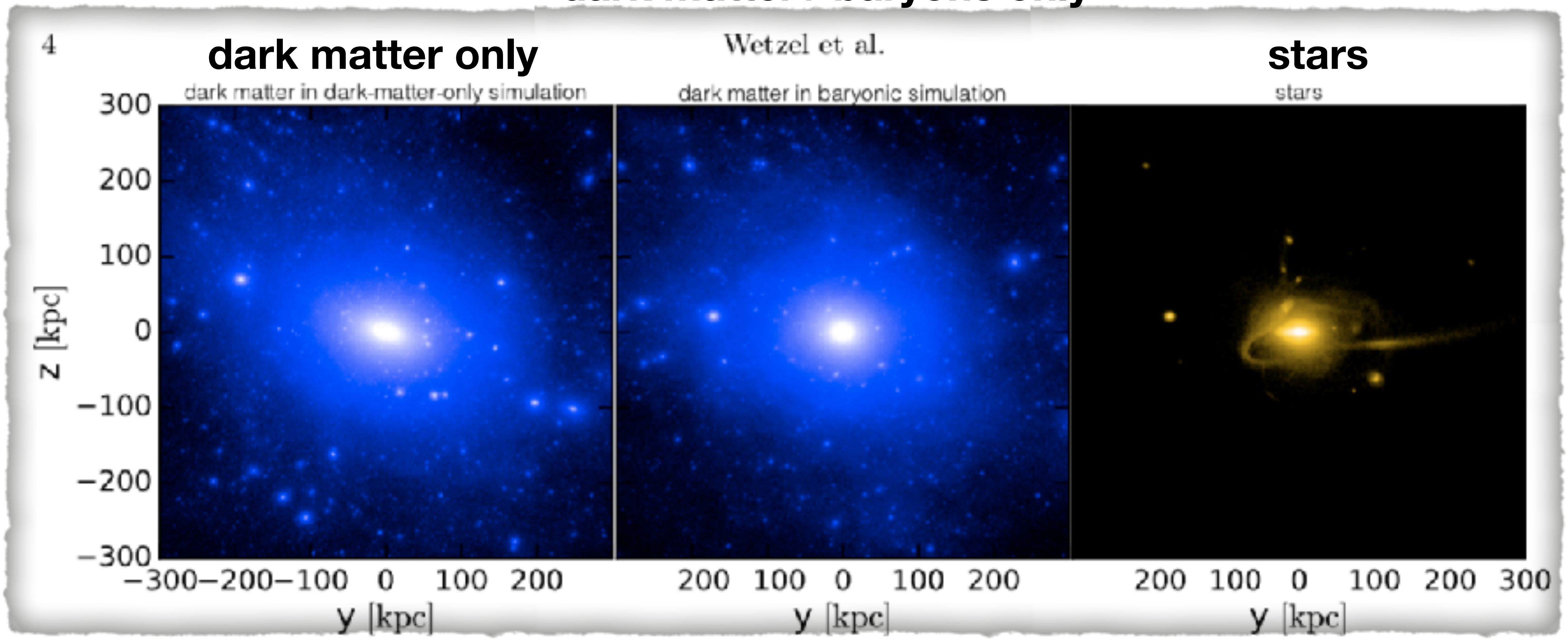
Mateu & Vivas 2018

Why is this important ?

Milky Way as observational benchmark for galaxy formation

related studies

dark matter+ baryons only



Milky-Way-like galaxy simulated within the "LATTE" project with code GIZMO

My speciality is the exploitation of compact-object related phenomena

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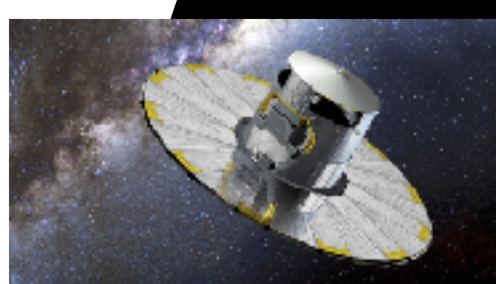
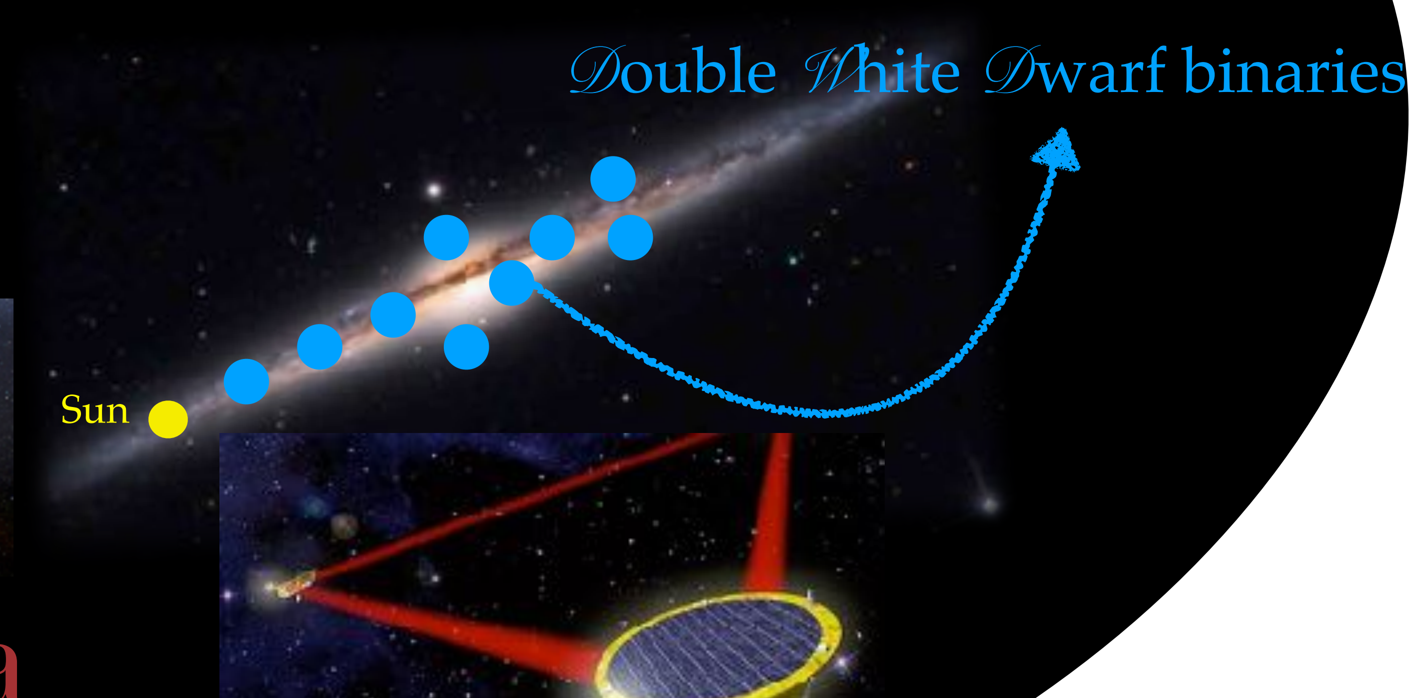
1st part of this talk : Double white dwarfs

LSST Large Synoptic Survey Telescope +



Gaia



LISA

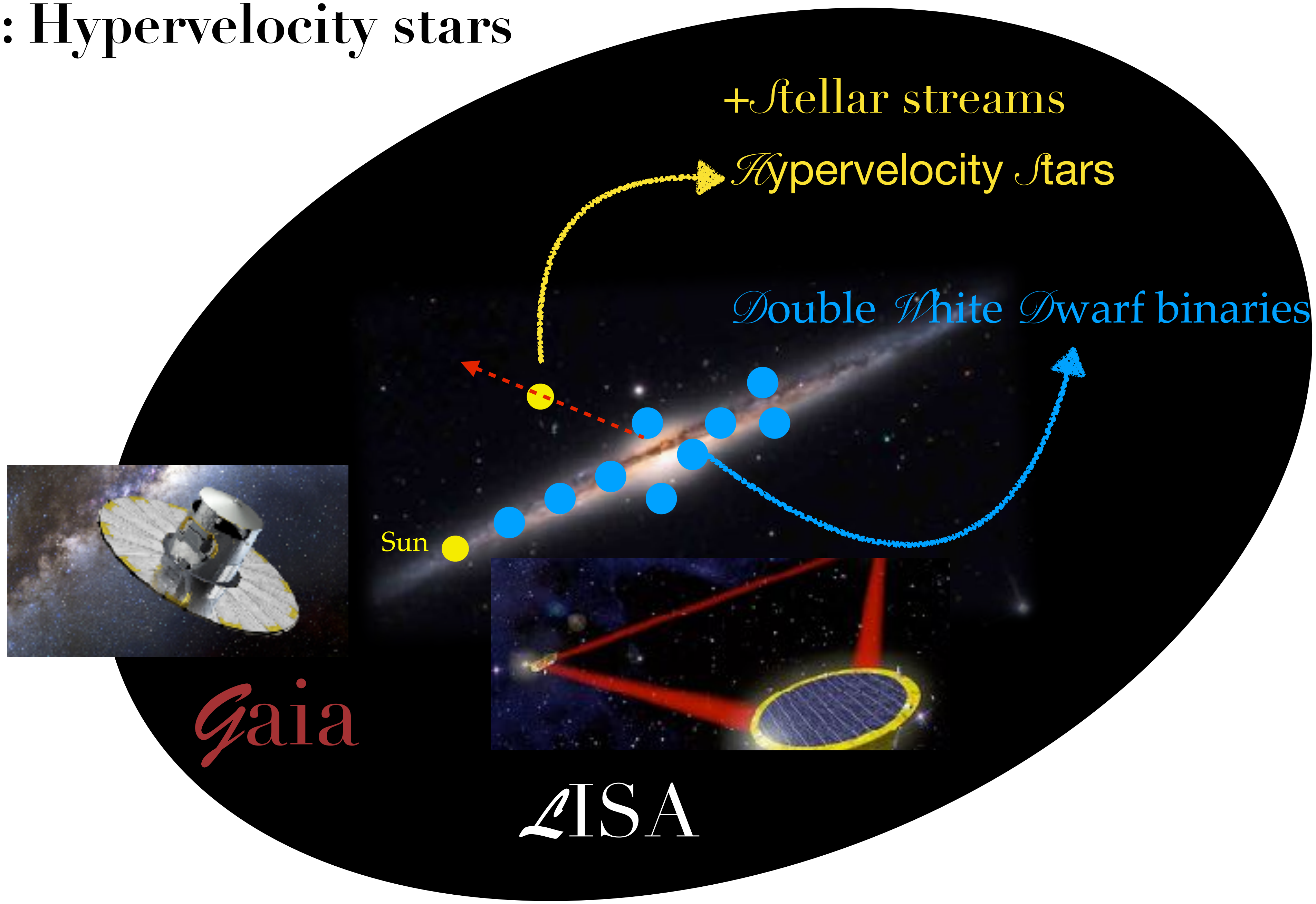
My speciality is the exploitation of compact-object related phenomena

1st part of this talk : Double white dwarfs

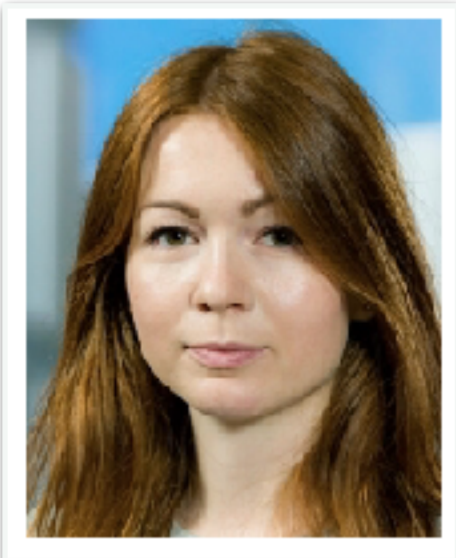
2nd part of this talk : Hypervelocity stars

LSST
Large Synoptic Survey Telescope

+

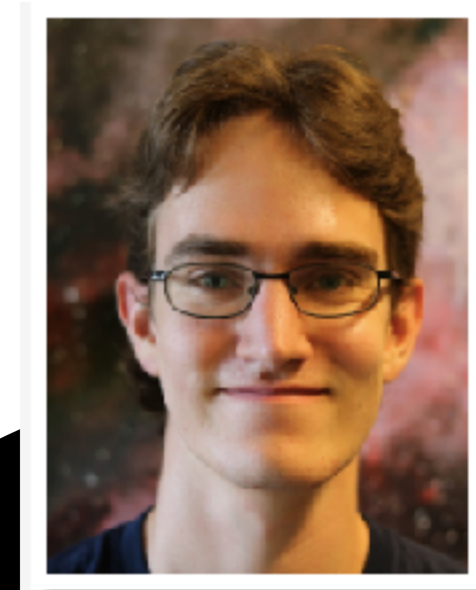


Valeriya Korol, PhD



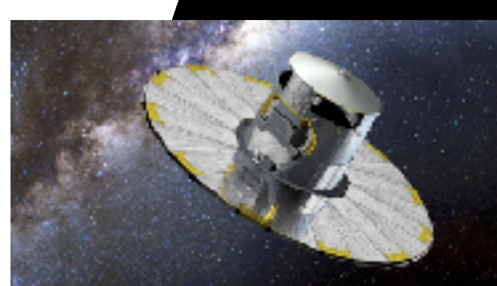
Orlin Koop BSc

Martijn Wilhelm MSc



LSST
Large Synoptic Survey Telescope

+



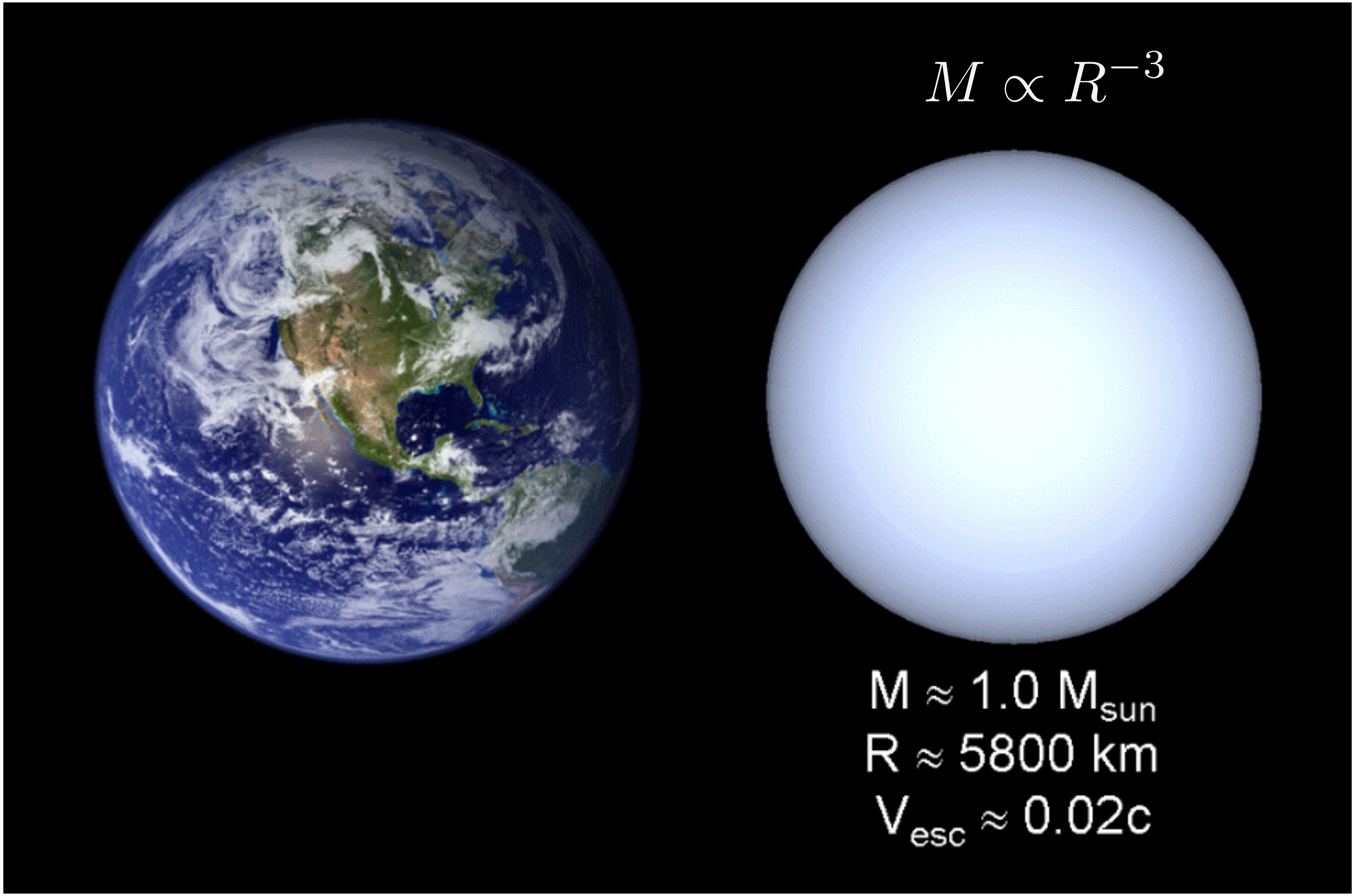
Gaia

LISA

research funded by NWO grant *WARP*

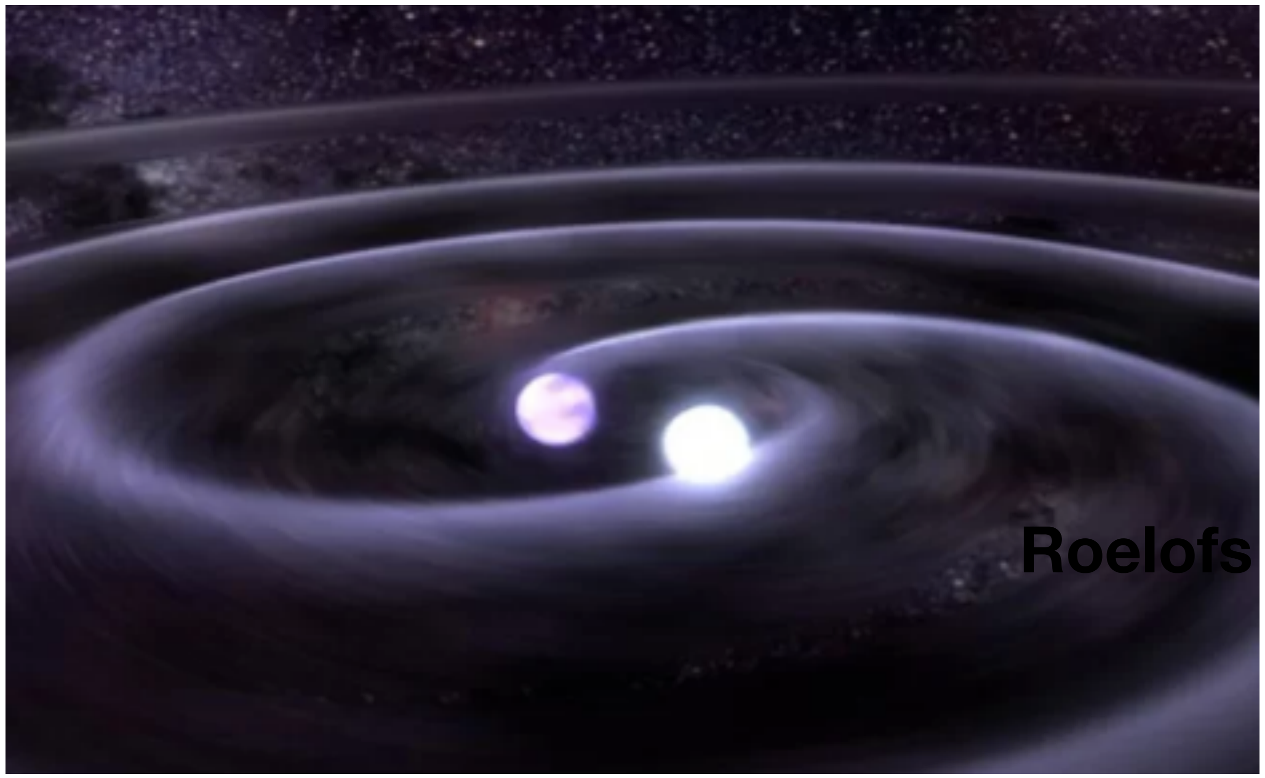
White dwarf

“low mass” star remnant



Double white dwarfs: 5-10% of al WDs

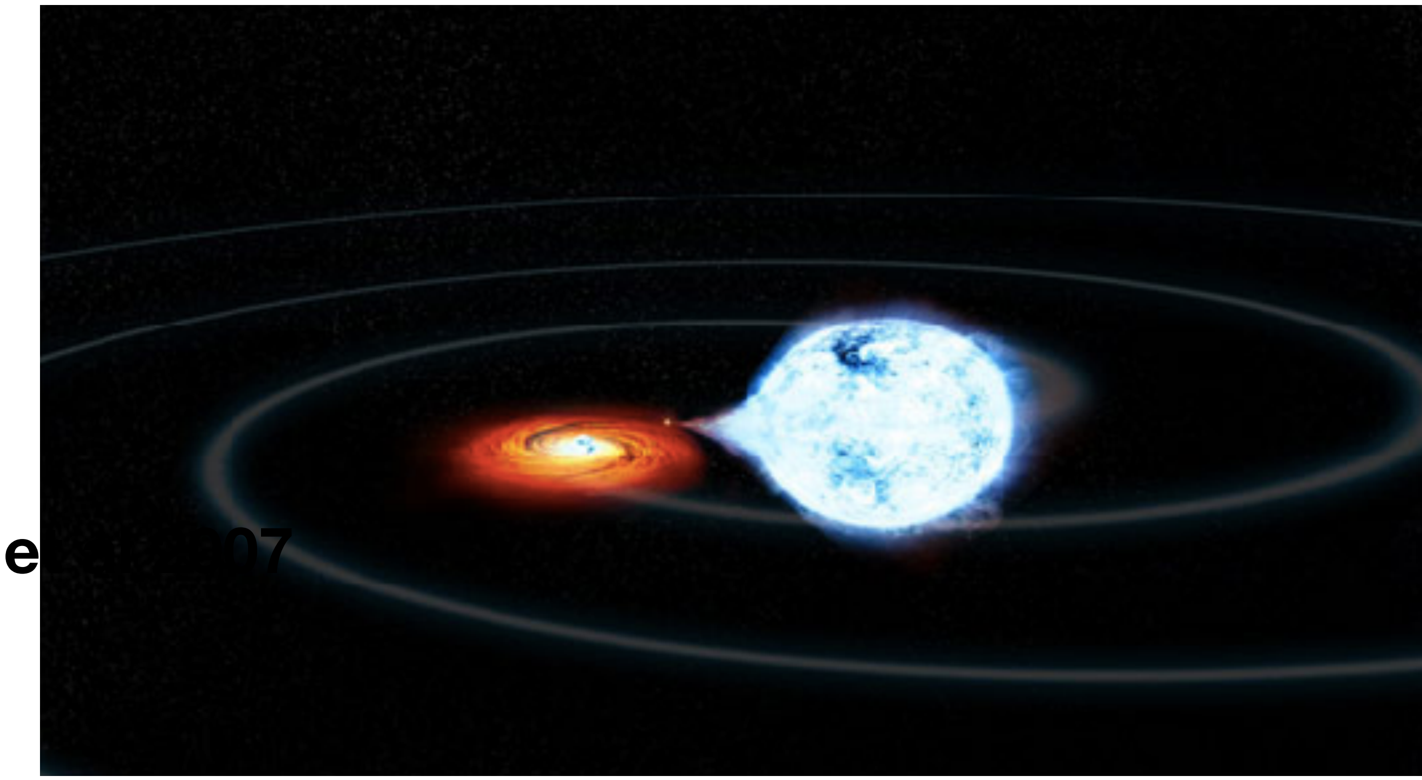
now~10^8 in Milky Way



Credit: NASA/Tod Strohmay

Detached

now ~10^5 in Milky Way



Roelofs e 07

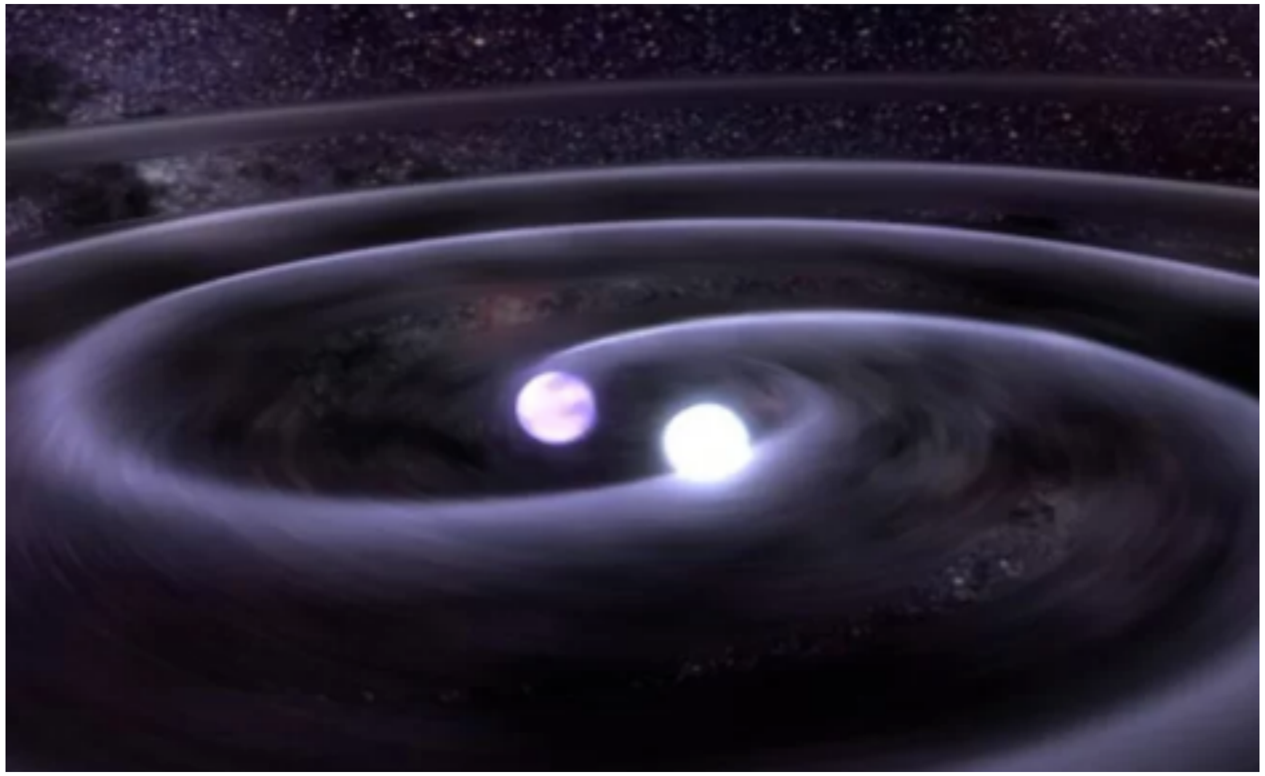
Credit: NASA/CXC/M. Weiss

AM CVn:

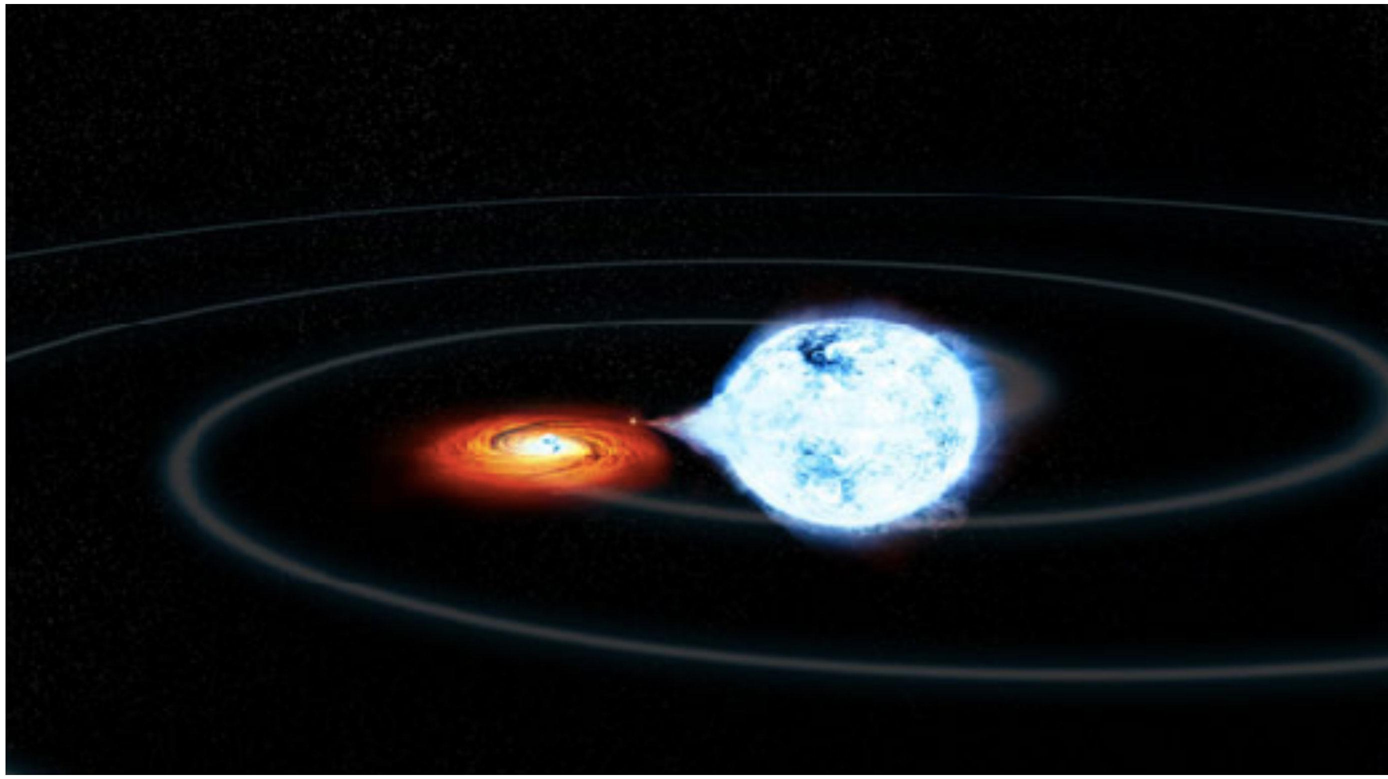
Transferring Mass

Nelemans + 2001, 2004, Toonen + 2012 Breivik +18

Double white dwarfs: EM emitters



Credit: NASA/Tod Strohmay



Credit: NASA/CXC/M. Weiss

Optical emitter

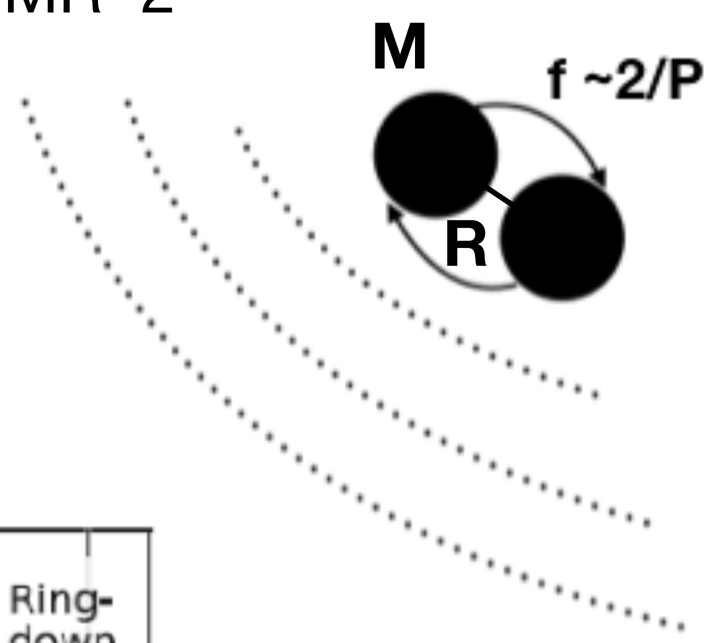
magnitude >> 27 (LSST)

Optical, UV/X-rays

relatively brighter

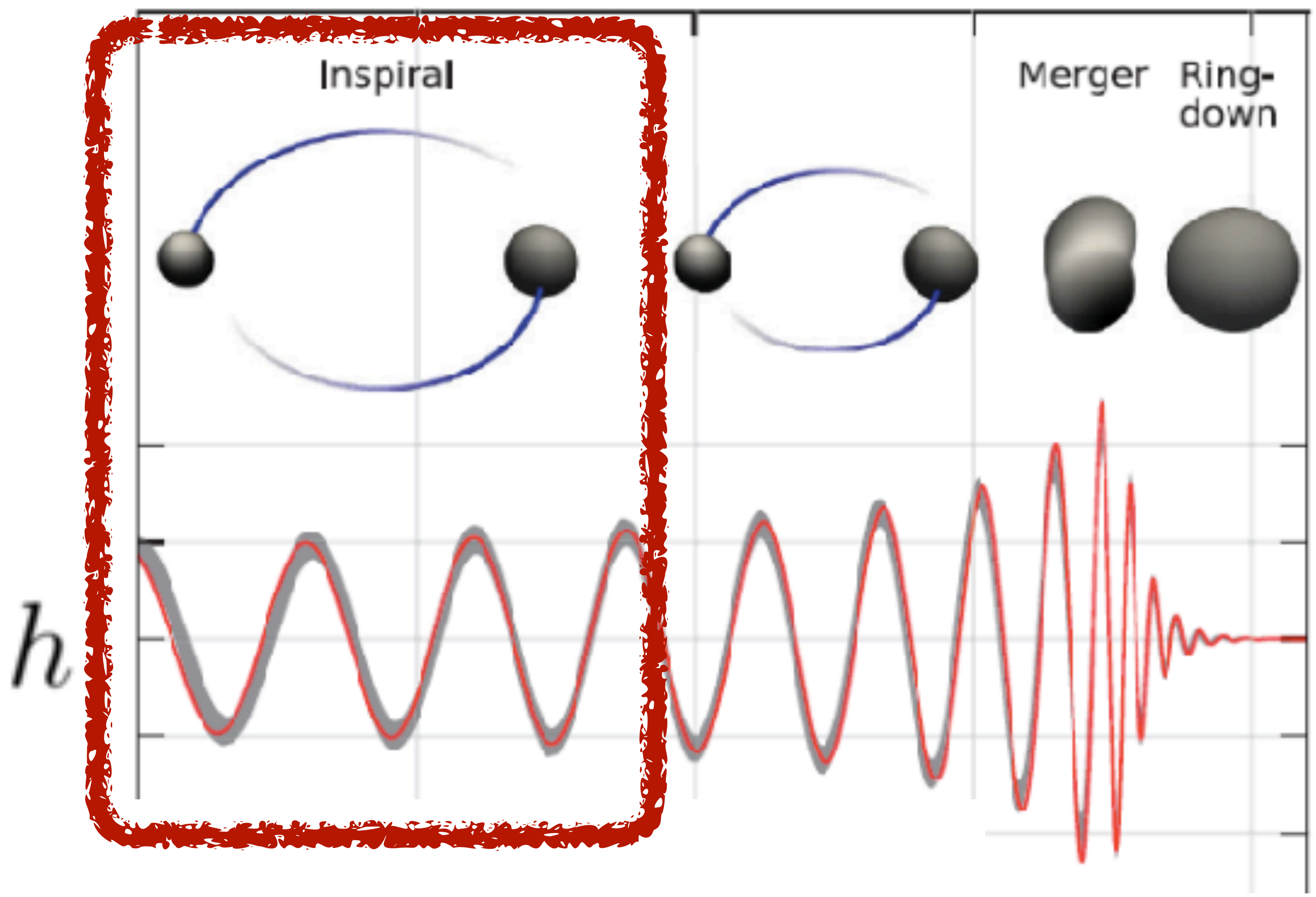
Double white dwarfs: GW emitters

At the lowest order radiation depends on the quadrupole moment ~MR^2



$$h \sim \frac{G}{c^4}\frac{1}{r}\frac{\partial^2(MR^2)}{\partial t^2}$$

$$\partial/\partial t^2 \sim 1/P^2$$



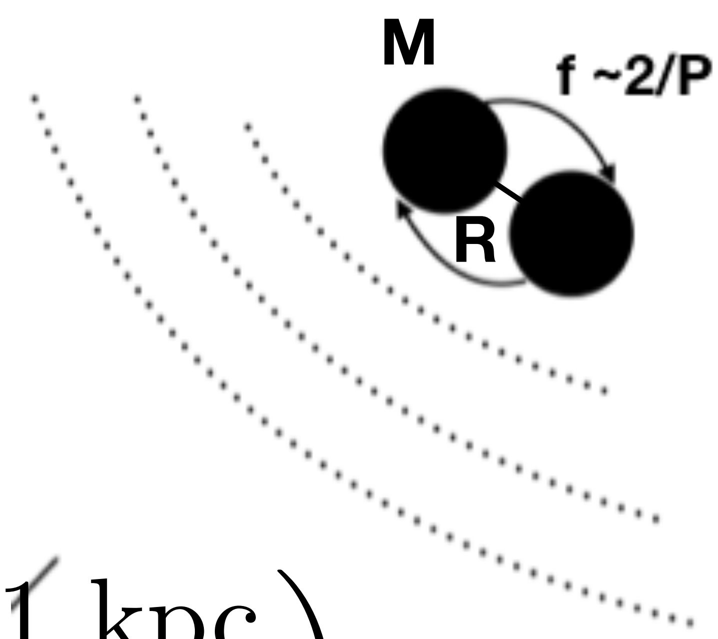
Adapted from Abbott+2016

Double white dwarfs: GW emitters

In ispiral phase changes occur on timescale P:

$$h \sim \frac{G}{c^4}\frac{1}{r}\frac{\partial^2(MR^2)}{\partial t^2}$$

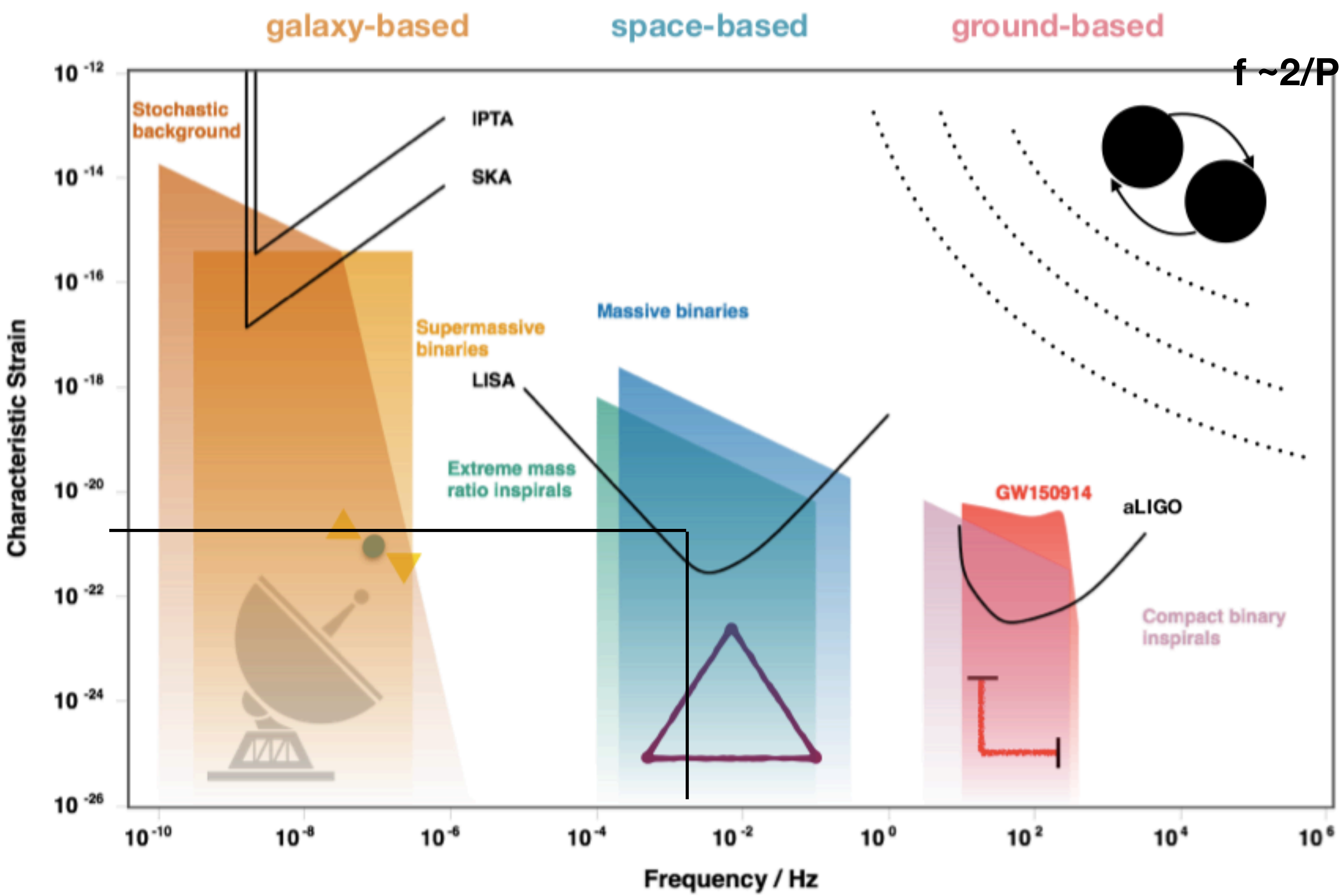
$$\partial/\partial t^2 \sim 1/P^2$$



$$h \approx 10^{-21}\left(\frac{M}{1M_\odot}\right)^{5/3}\left(\frac{12\ \mathrm{min}}{P}\right)^{2/3}\left(\frac{1\ \mathrm{kpc}}{r}\right)$$

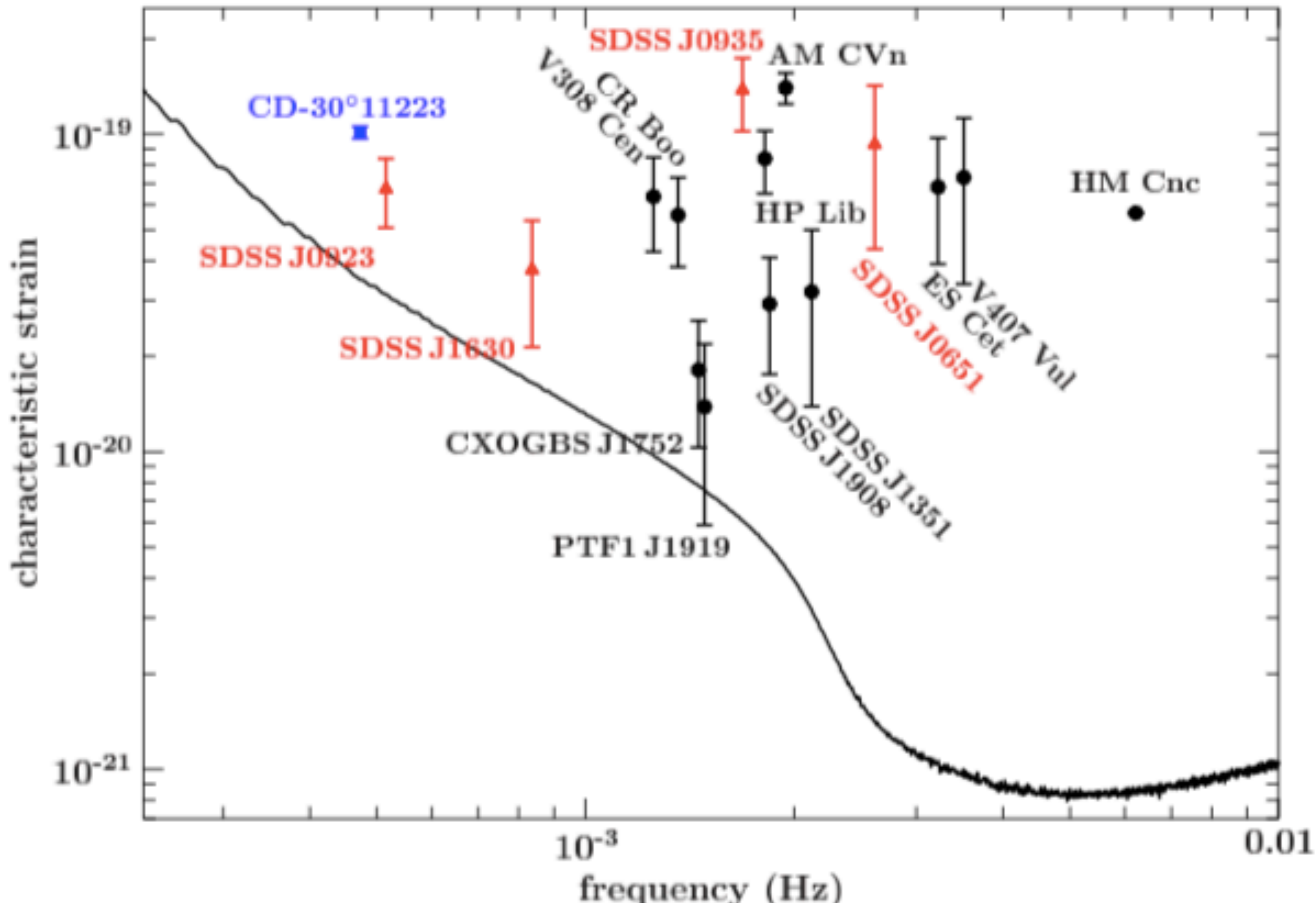
$$f \approx 3\ \mathrm{mHz}\ \left(\frac{12\ \mathrm{min}}{P}\right)$$

Laser Interferometer Space Antenna:



From Roadmap of European COST ACTION: black hole, GW and fundamental physics
Barack et al (including Rossi) 2018

"Current Sample"

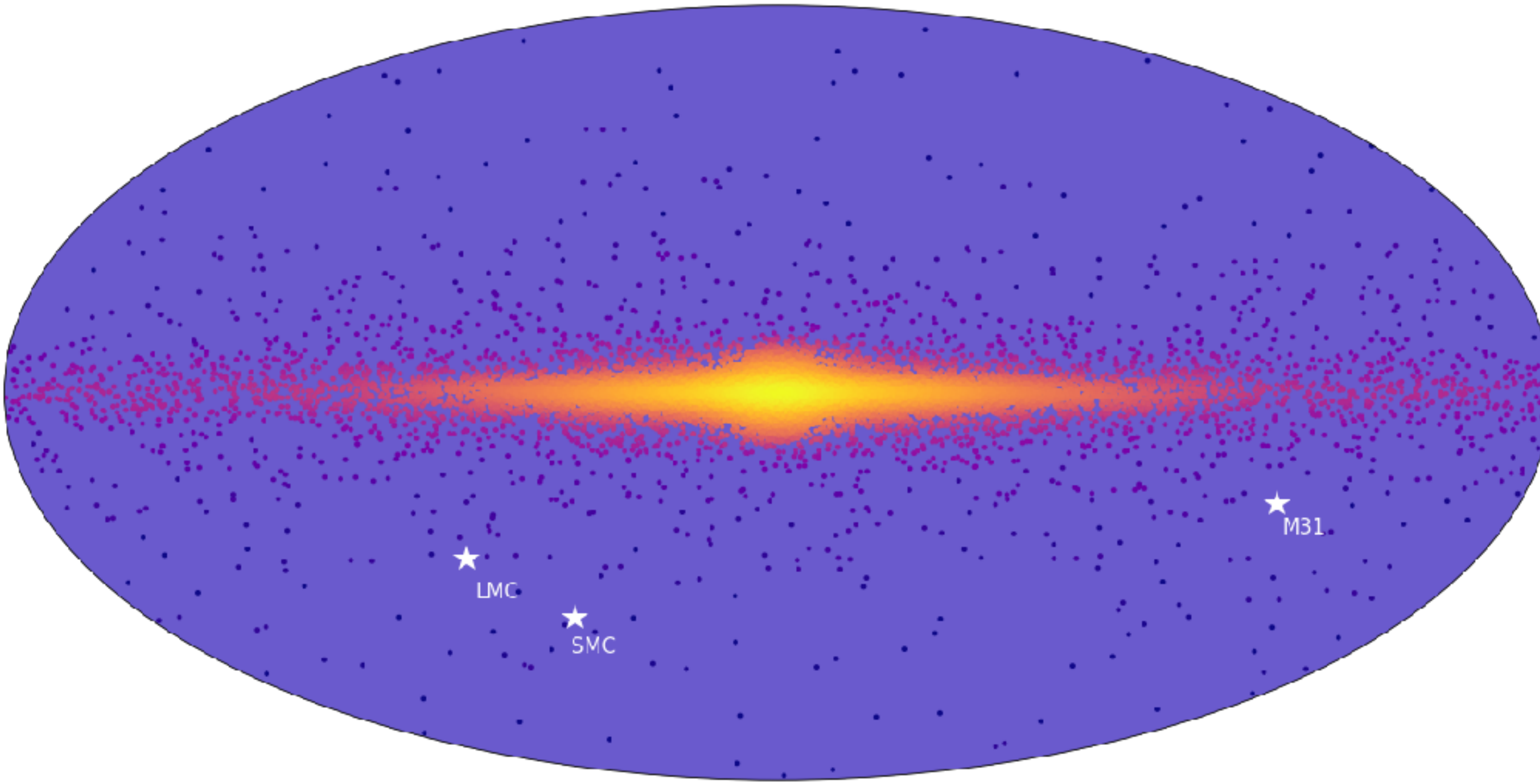


Kupfer, Korol, … EMR 2018

Out of ~10^8, we know of ~ 150 binaries and only ~11 will have SNR > 20 in LISA, all within a few hundred parsec

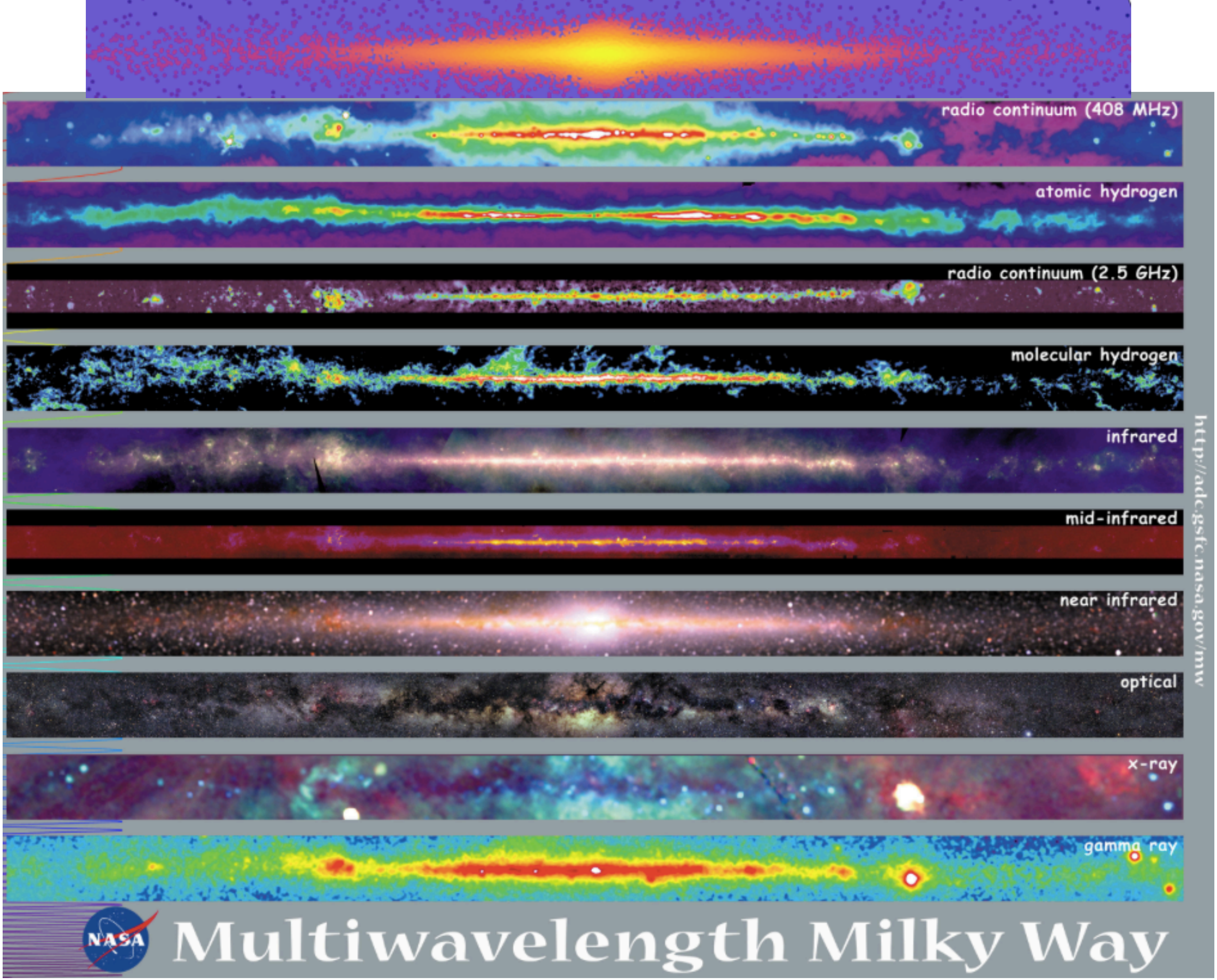
How many LISA will individually resolve?

~25 000 detached double white dwarf & few thousands AM CVn in the Galaxy + hundreds in the satellite galaxies out to M31

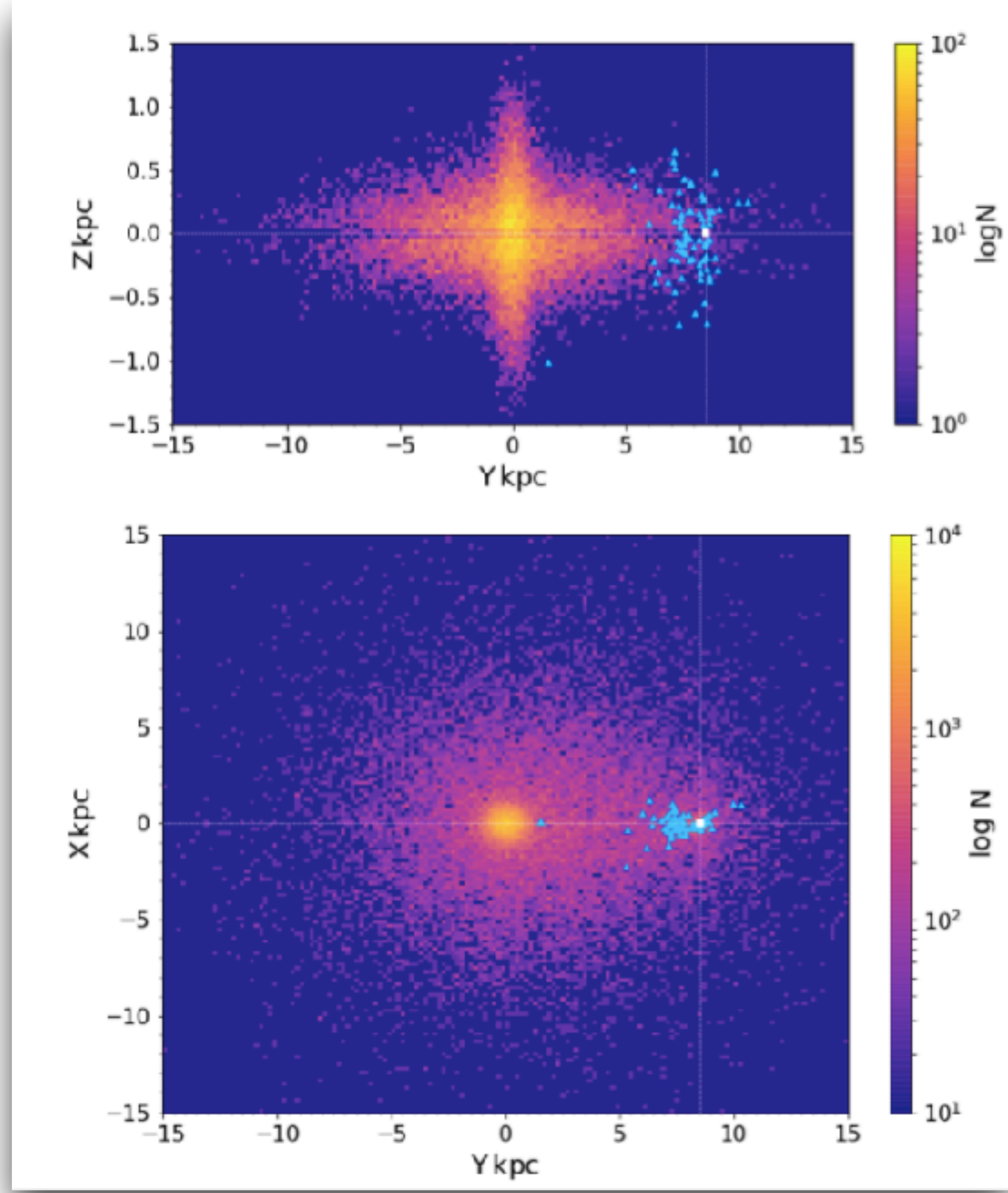


Korol, EMR+17; Korol, Koop & EMR 18

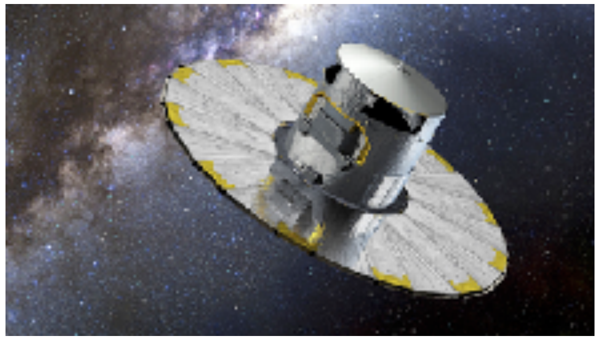
see Breivik +18 for AM Can

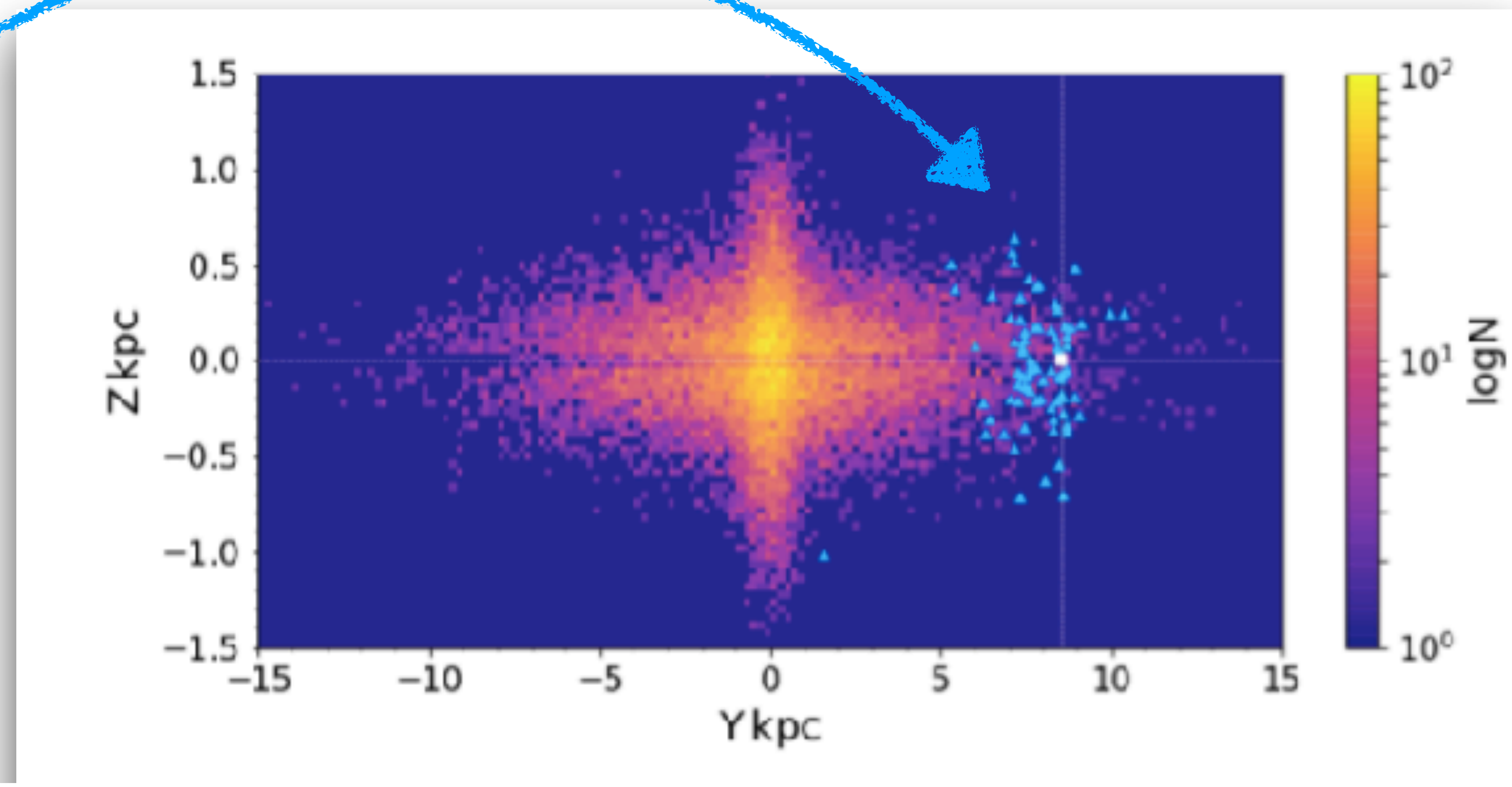

radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

Looking <u>through</u> the Milky Way

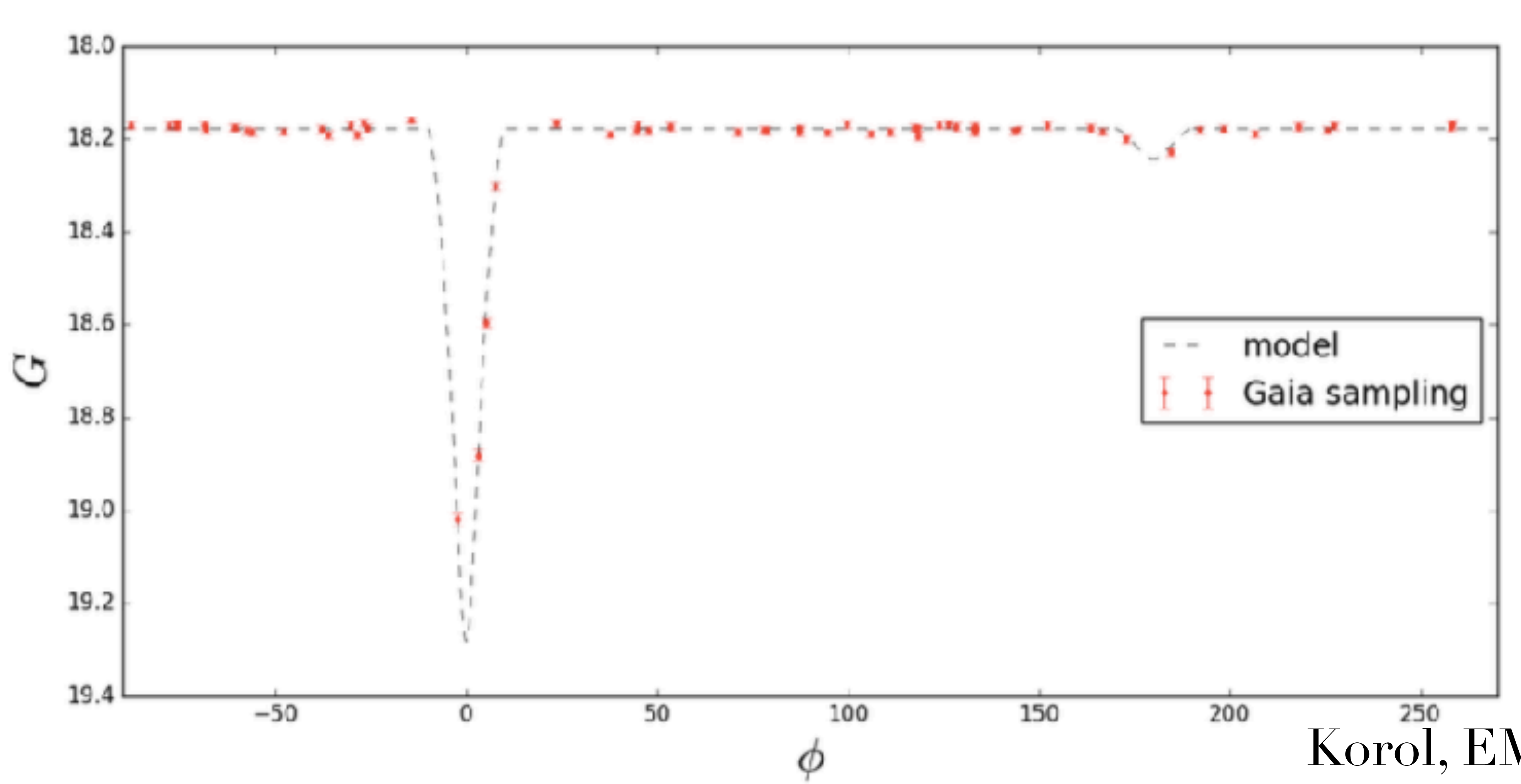


Large Synoptic Survey Telescope

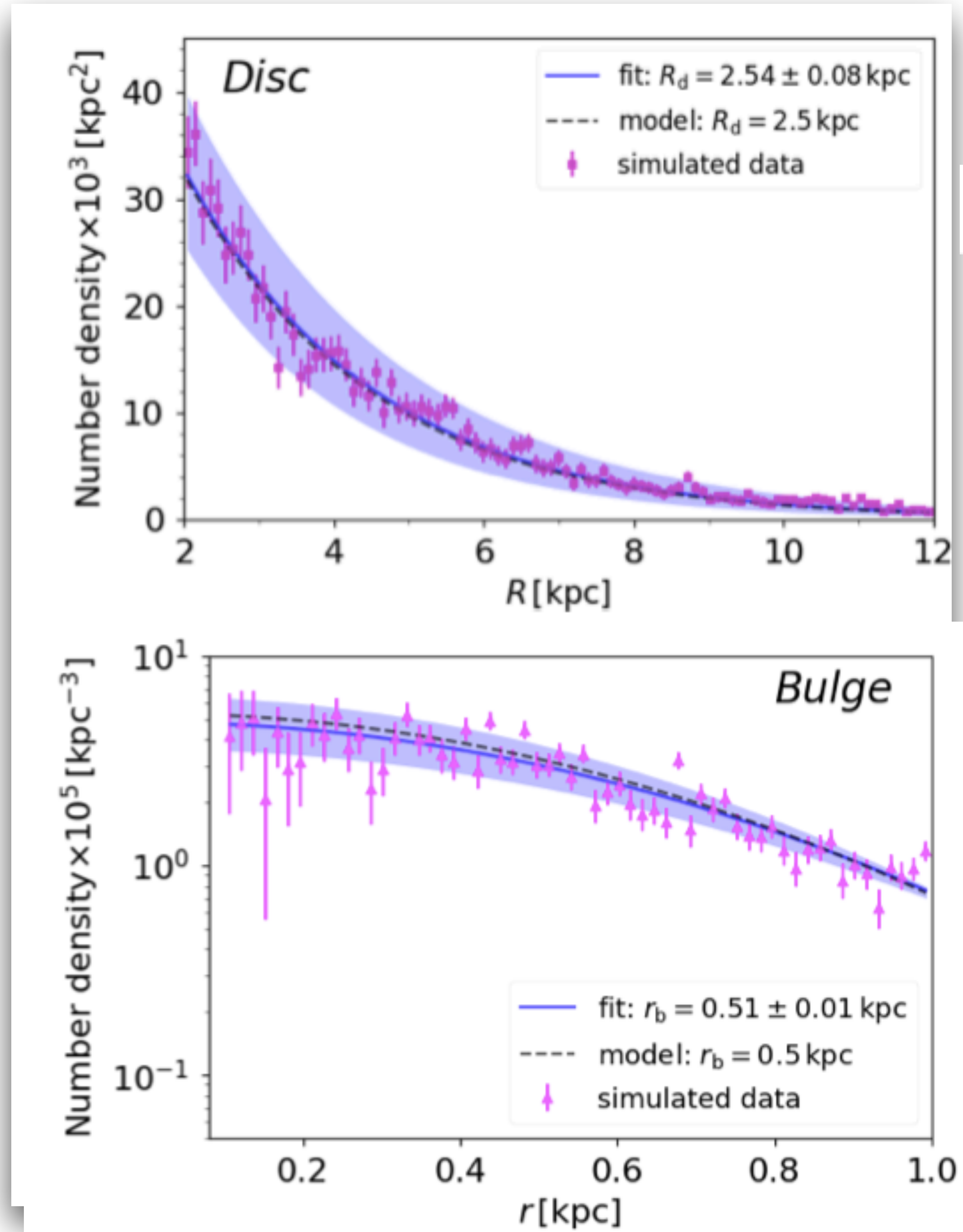




$\sim$100 systems
detected in optical
as eclipsing binaries



Korol, EMR+17



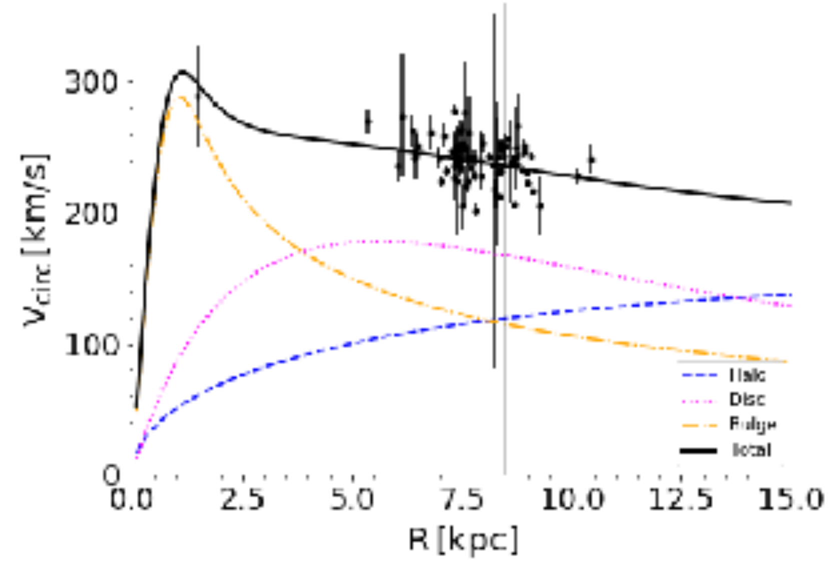
$$\rho_{\rm disc}(t, R, z) = \rho_{\rm BP}(t)\, e^{-R/R_{\rm d}}\, {\rm sech}^2\left(\frac{z}{Z_{\rm d}}\right)\ {\rm M}_\odot\,{\rm kpc}^{-3},$$

scale factors extremely well constrained, with no bias

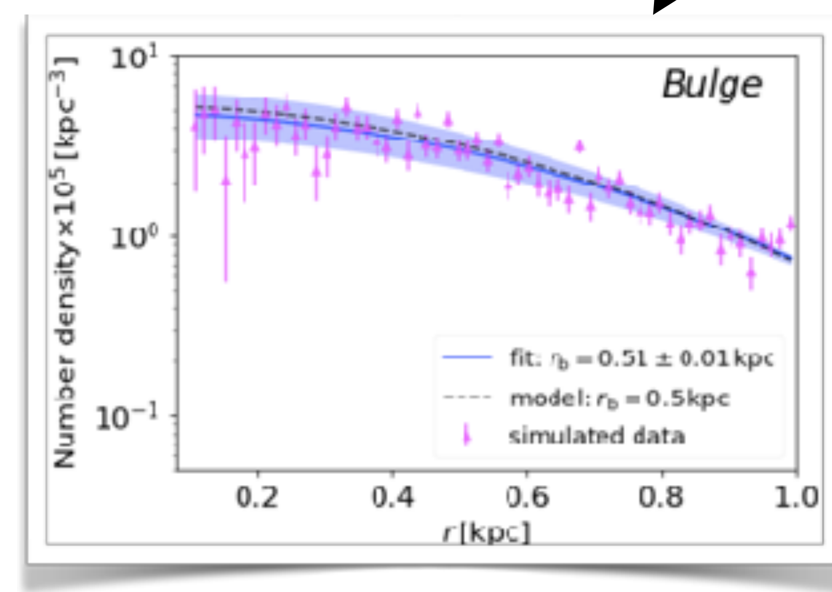
$$\rho_{\rm bulge}(r) = \frac{M_{\rm b}}{(\sqrt{2\pi} r_{\rm b})^3} e^{-r^2/2r_{\rm b}^2}\ {\rm M}_\odot\,{\rm kpc}^{-3},$$

Korol, EMR, Barausse 18
Adams+12

Rotation curve from optical

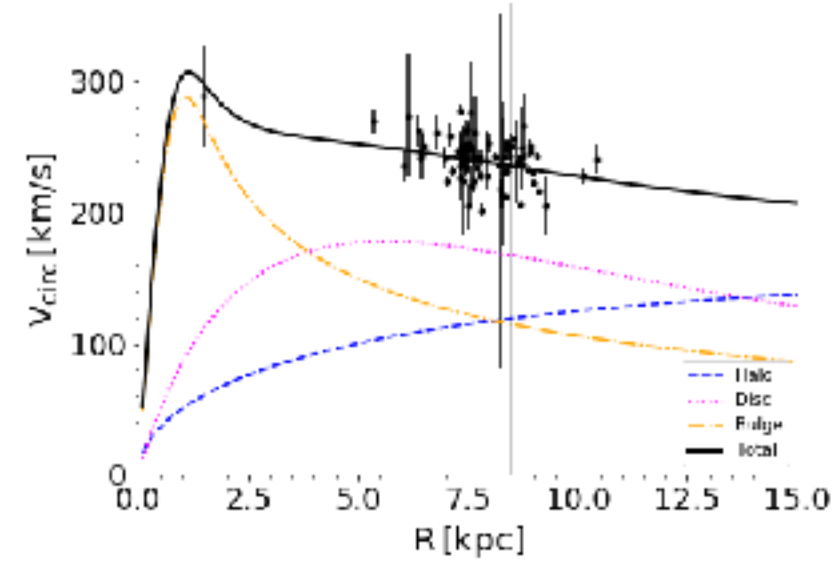


Joint fit

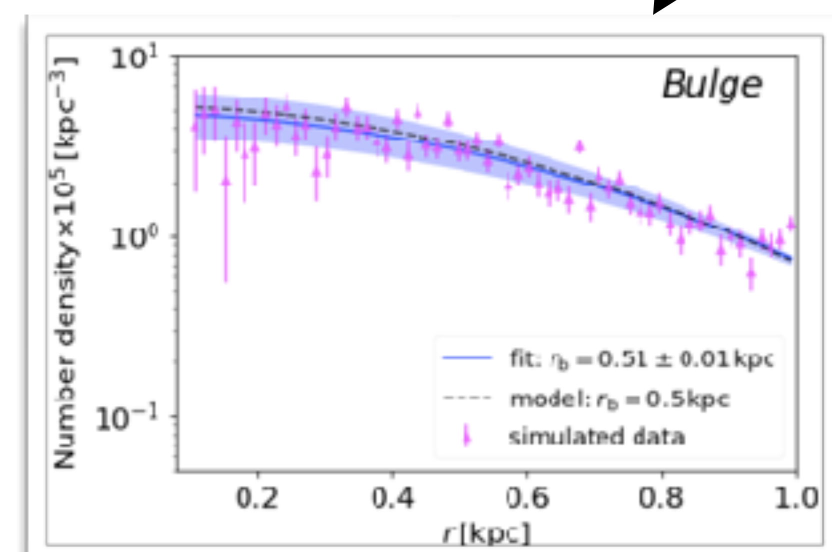


shape from GW

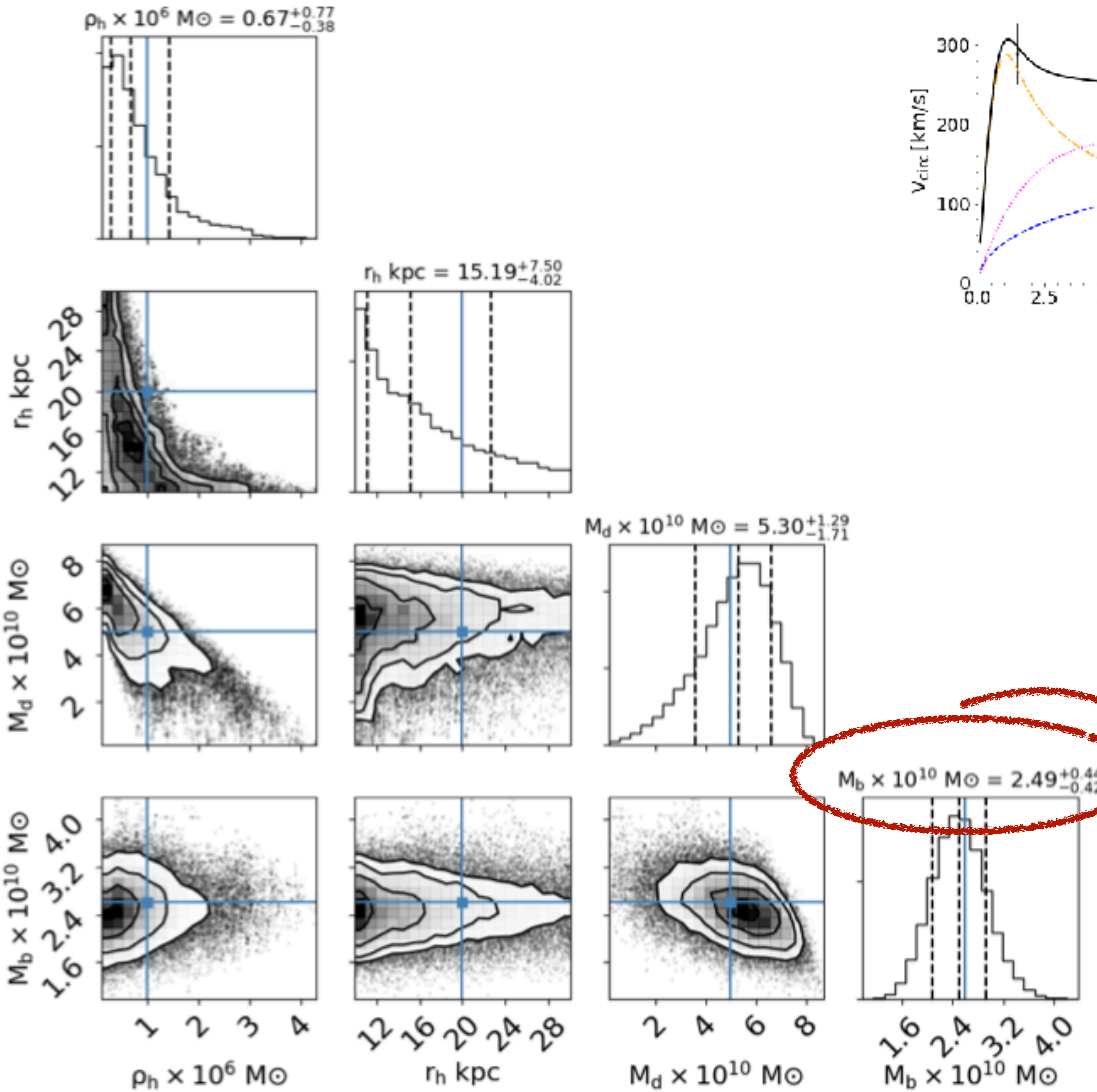
Rotation curve from optical



Joint fit

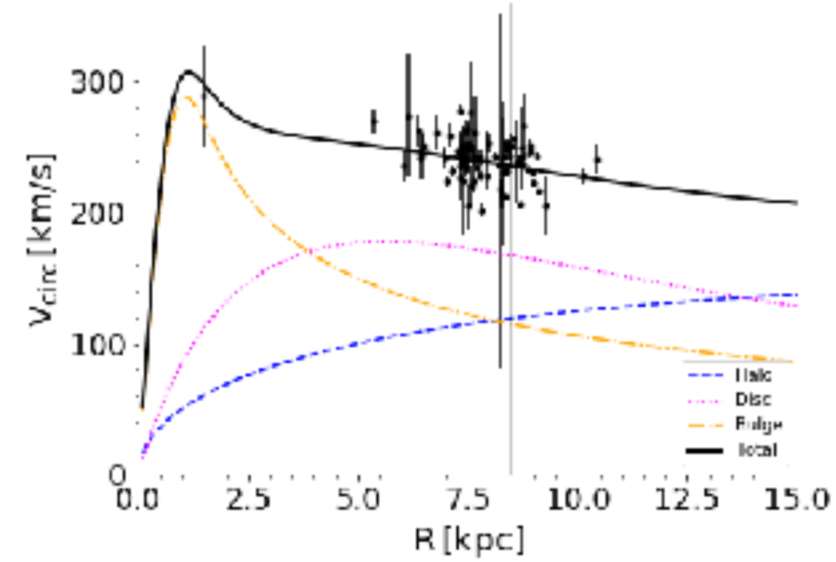


shape from GW

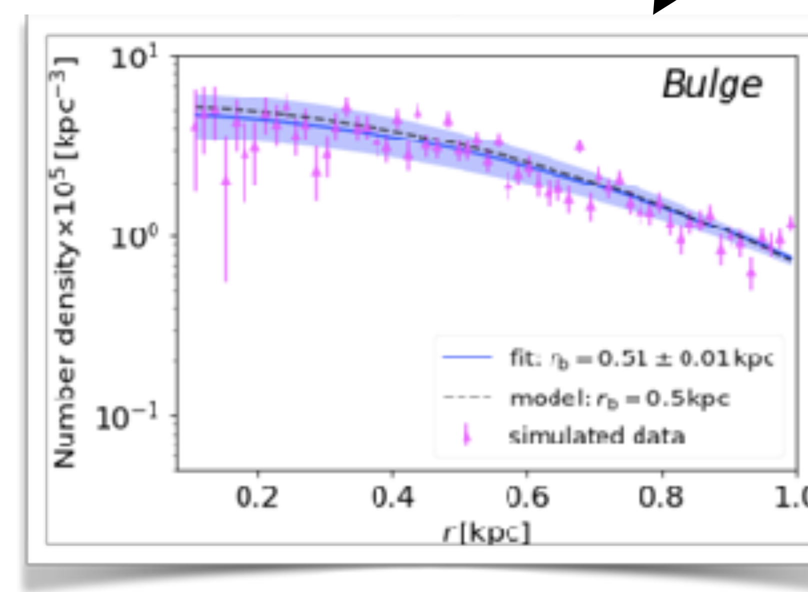


Bulge's mass constrained~17% level w no bias

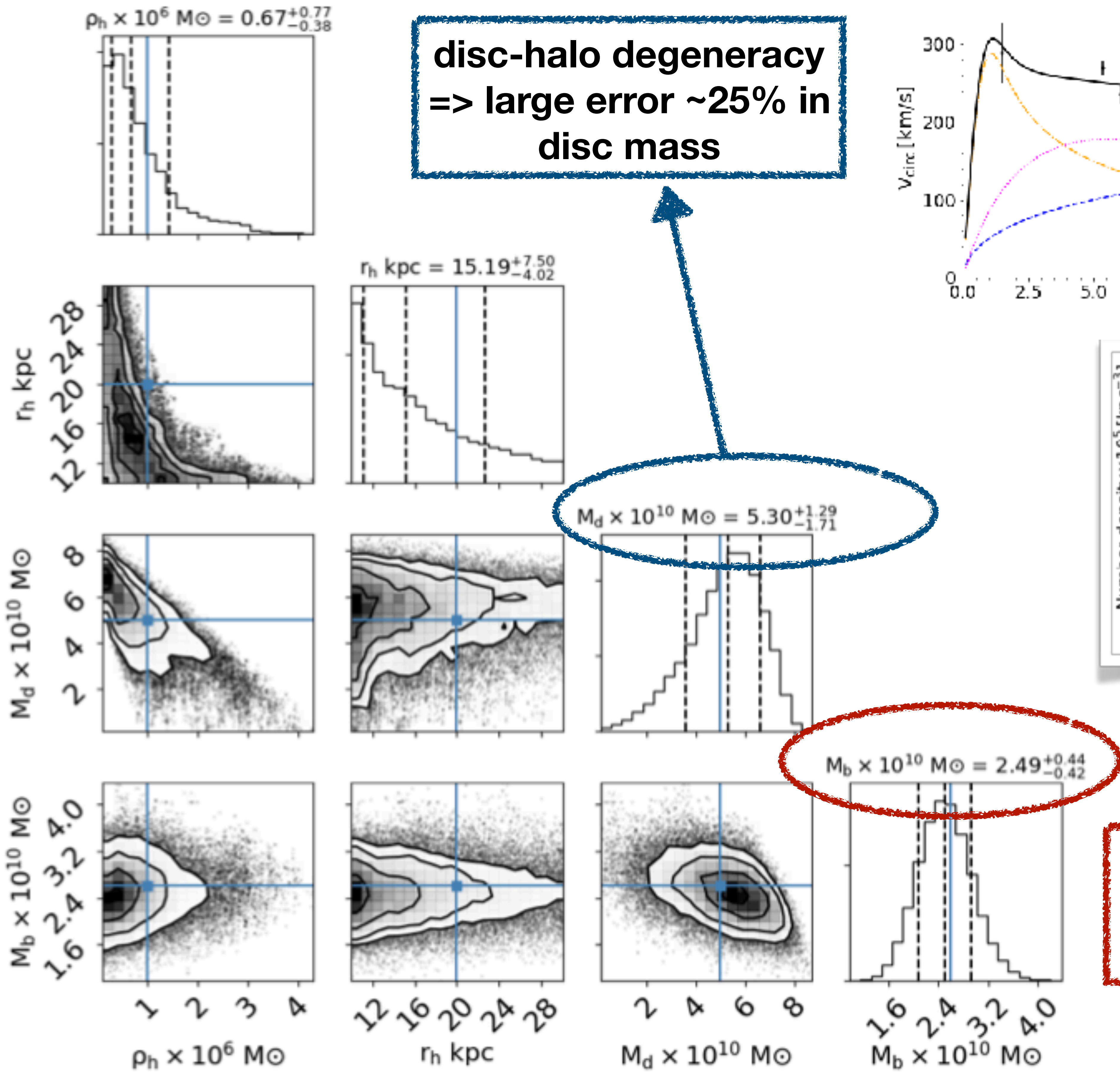
Rotation curve from optical



Joint fit



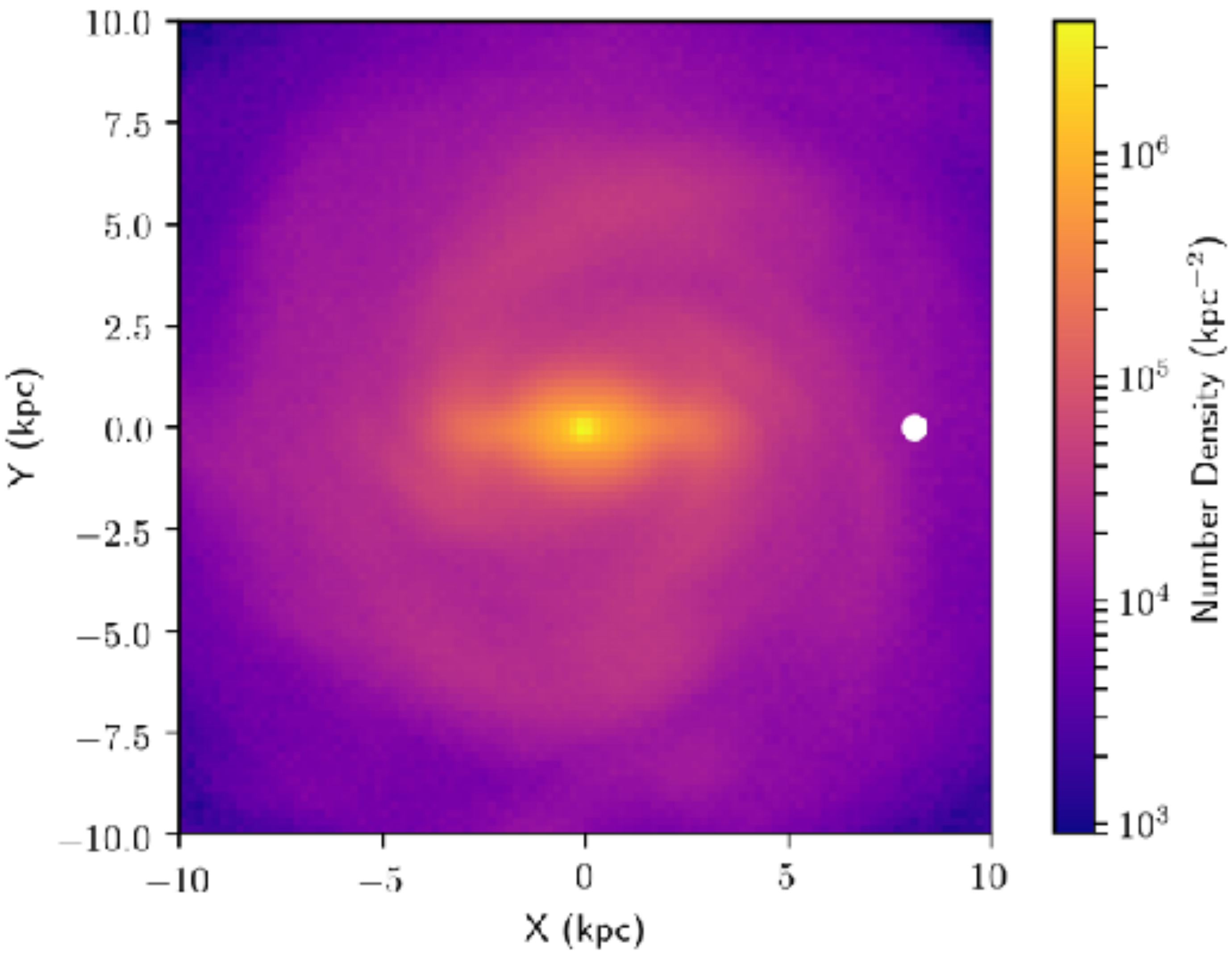
shape from GW



disc-halo degeneracy => large error ~25% in disc mass

Bulge's mass constrained~17% level w no bias

- **Bulge/bar**: what is the smallest structure we can detect in the Galaxy? how well we can detect and characterise the bar

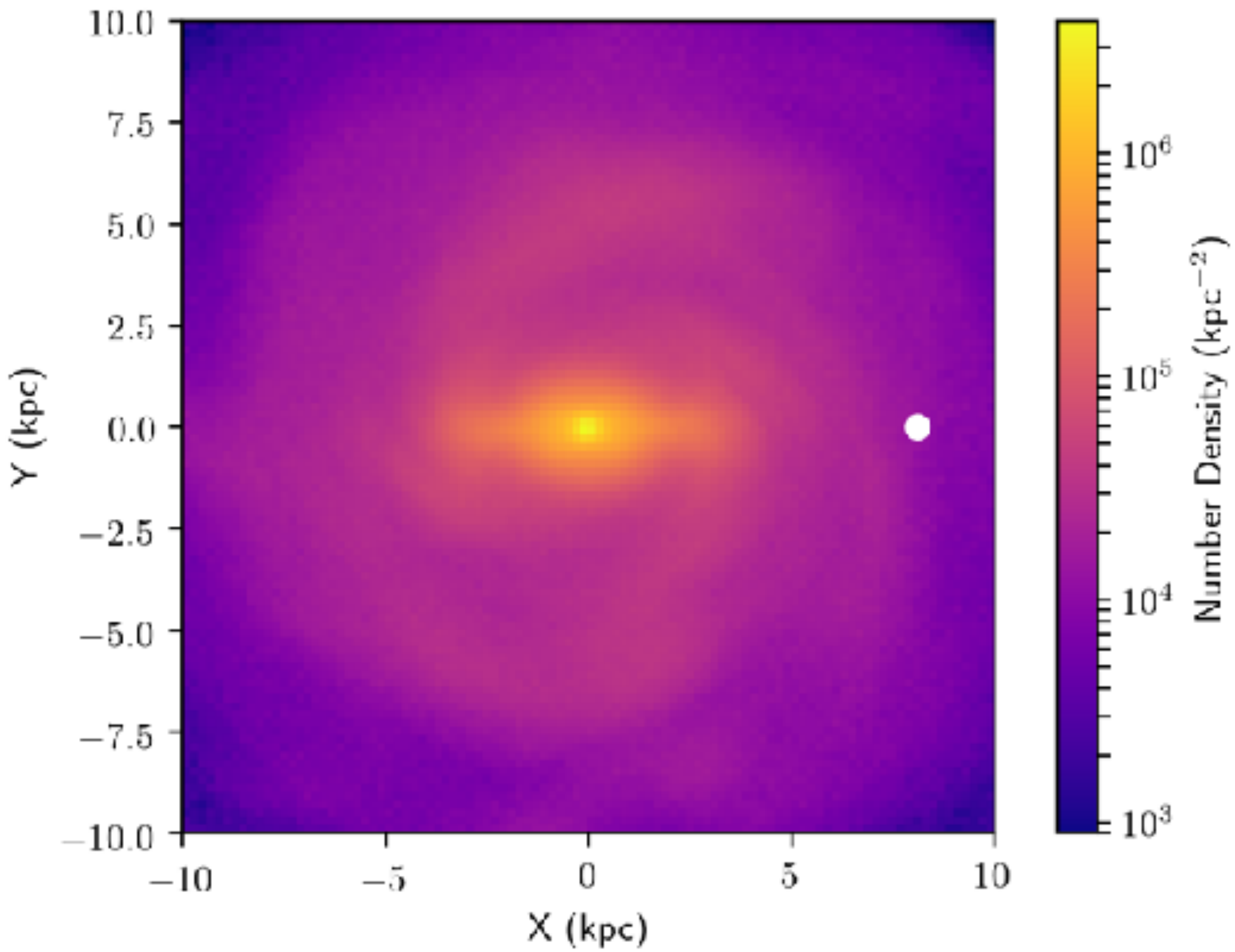


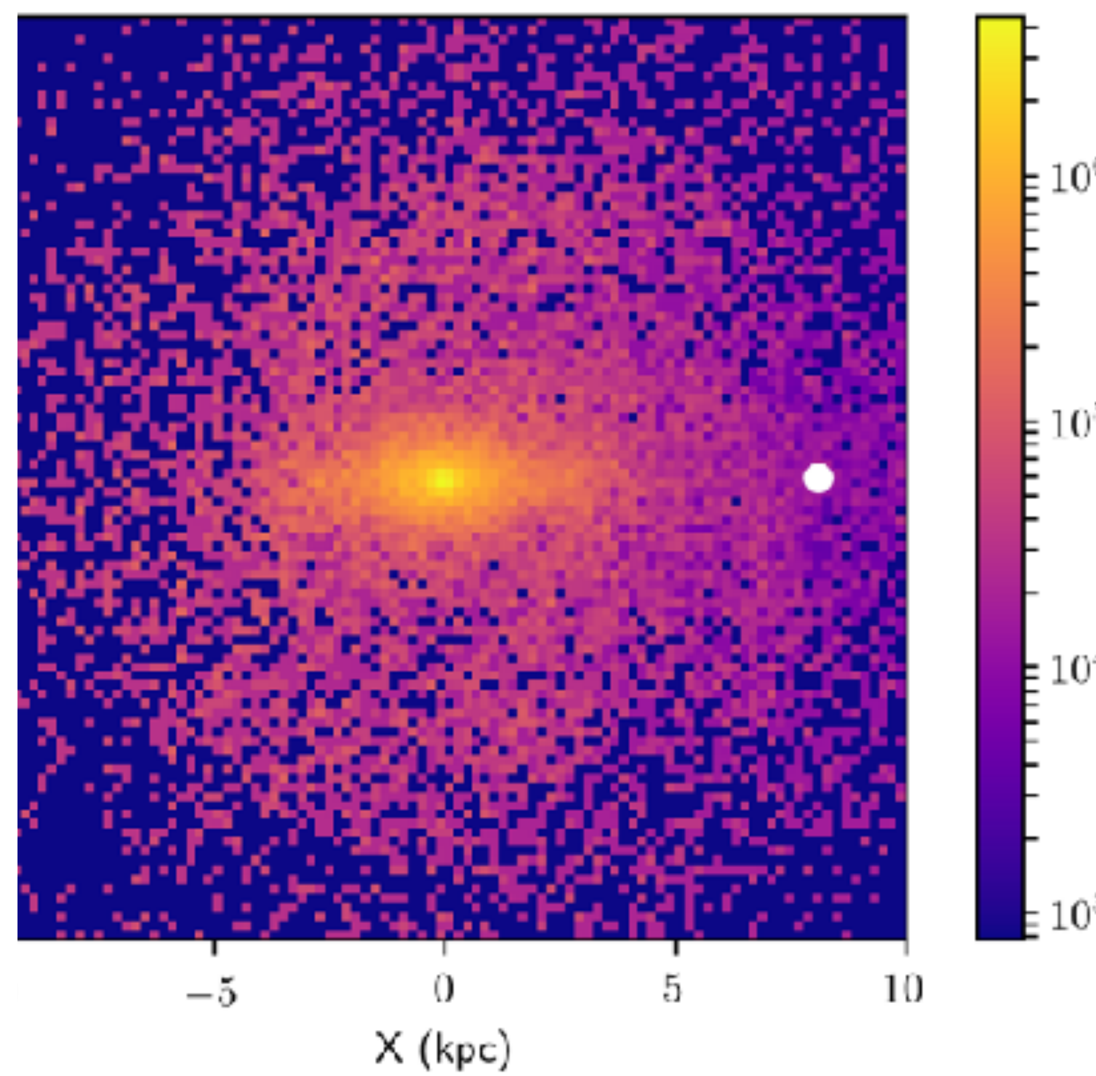
Galakos (Elena D'Onghia)

- **Bulge/bar**: what is the smallest structure we can detect in the Galaxy? how well we can detect and characterise the bar

Stellar distribution

GW map



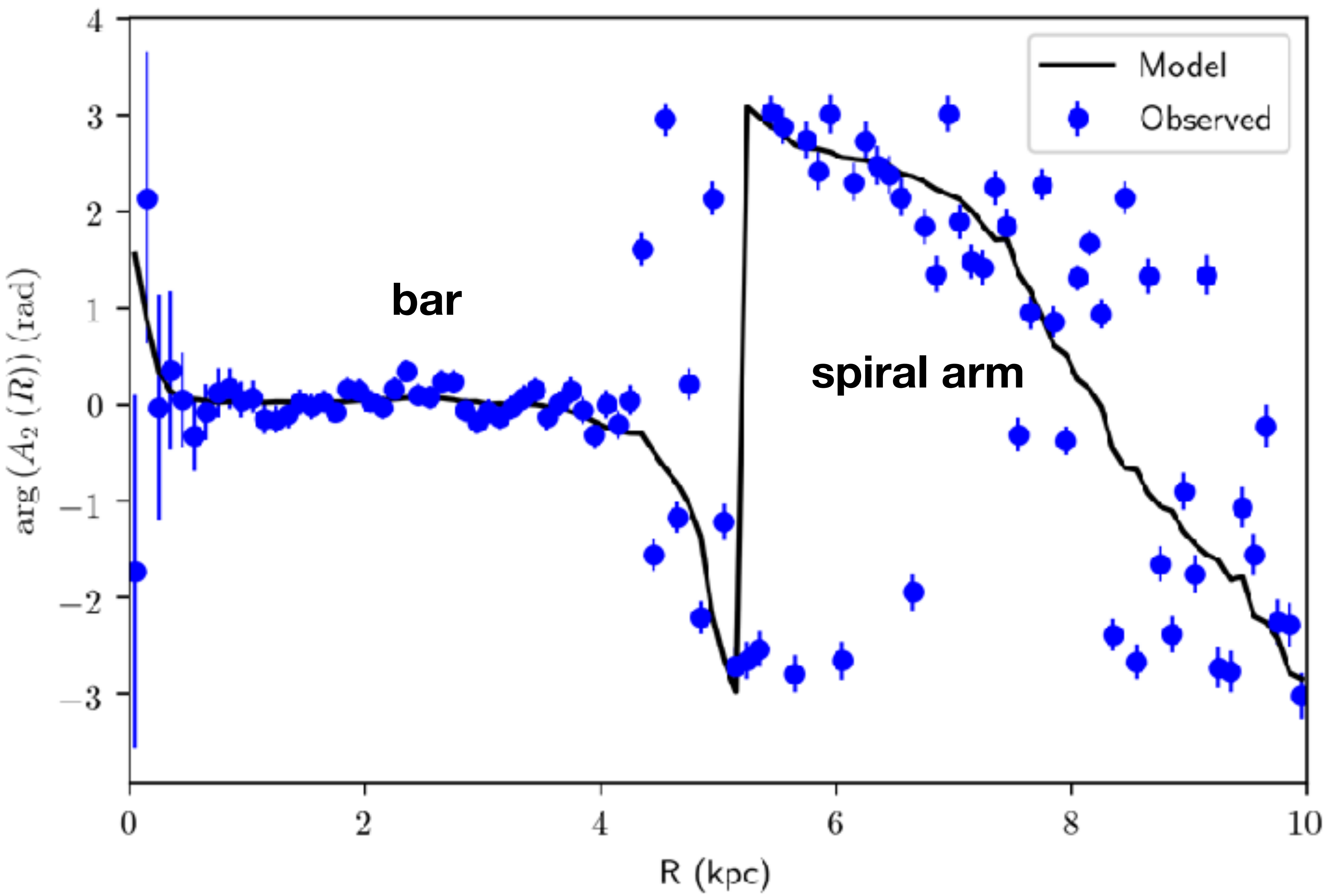


Galakos (Elena D'Onghia)

Wilhelm & Rossi in prep.

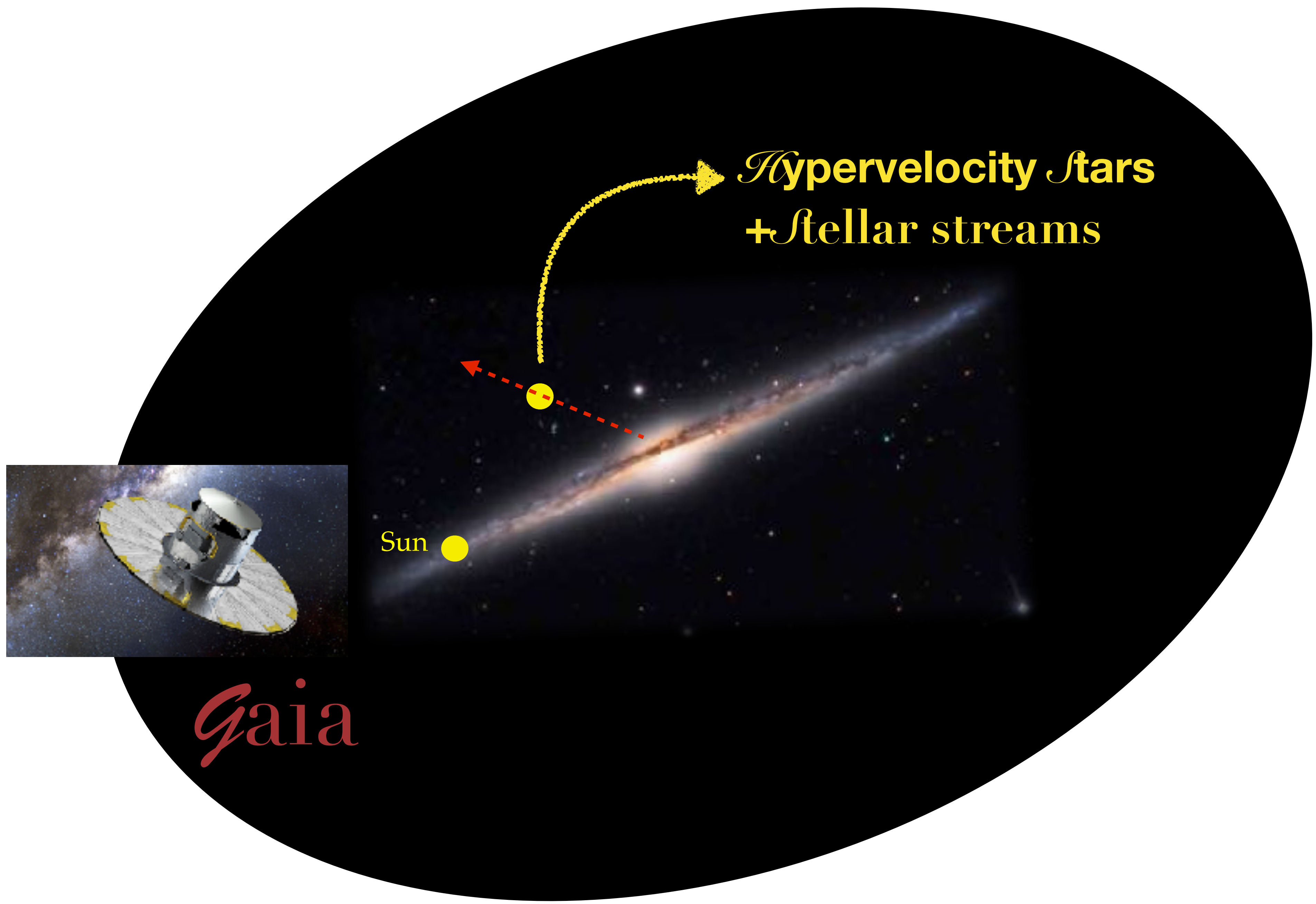
Extracting parameters

preliminary results



Wilhelm & Rossi in prep.

2nd part of this talk : Hypervelocity stars + Stellar tidal streams



research funded by NWO grant *TOP*

VEGA project @ Leiden

Velocity-Extreme Galactic Astrometry project

Data acquisition

Tommaso Marchetti
(PhD, Leiden)
Anthony Brown
(chair of the Gaia DPAC)
Else Starkenburg
(Potzdam)
Yuri Levin
(Columbia, U)

Data exploitation

Omar Contigiani
(PhD, Leiden)

Re'em Sari
(HUJI),
Shiho Kobayashi
(Liverpool),
Alberto Sesana
(Birmingham)

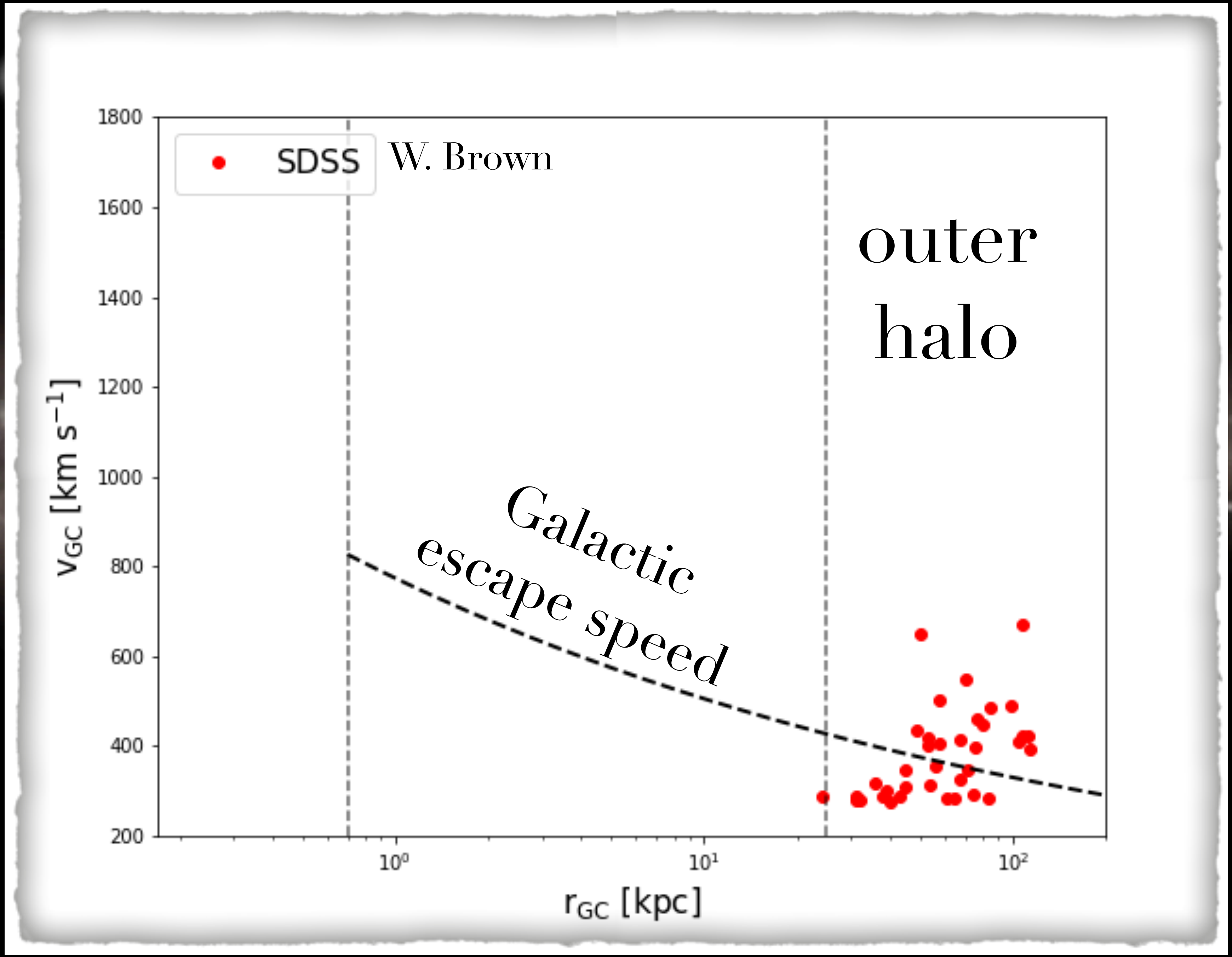
Combining probes

Stella Reino
(PhD, Leiden)
Amina Helmi
(Groningen U.)
Tim de Zeeuw
(Leiden U.)
Robyn Sanderson
(U Penn, flatirons)

Hypervelocity stars:
very fast stars coming from the Galactic Centre

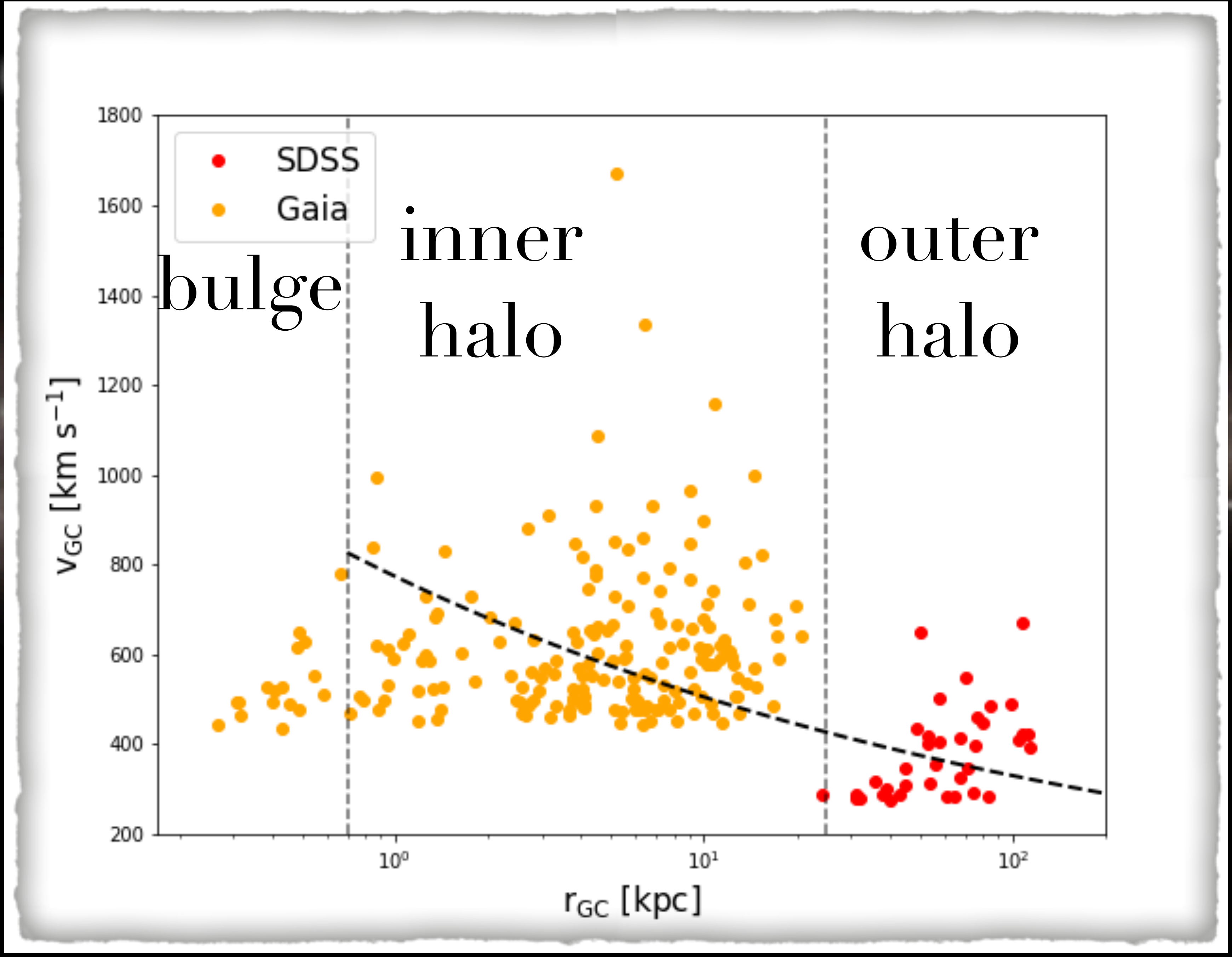
Credit: ESA press release of Marchetti, Rossi+17

Hypervelocity stars: current sample



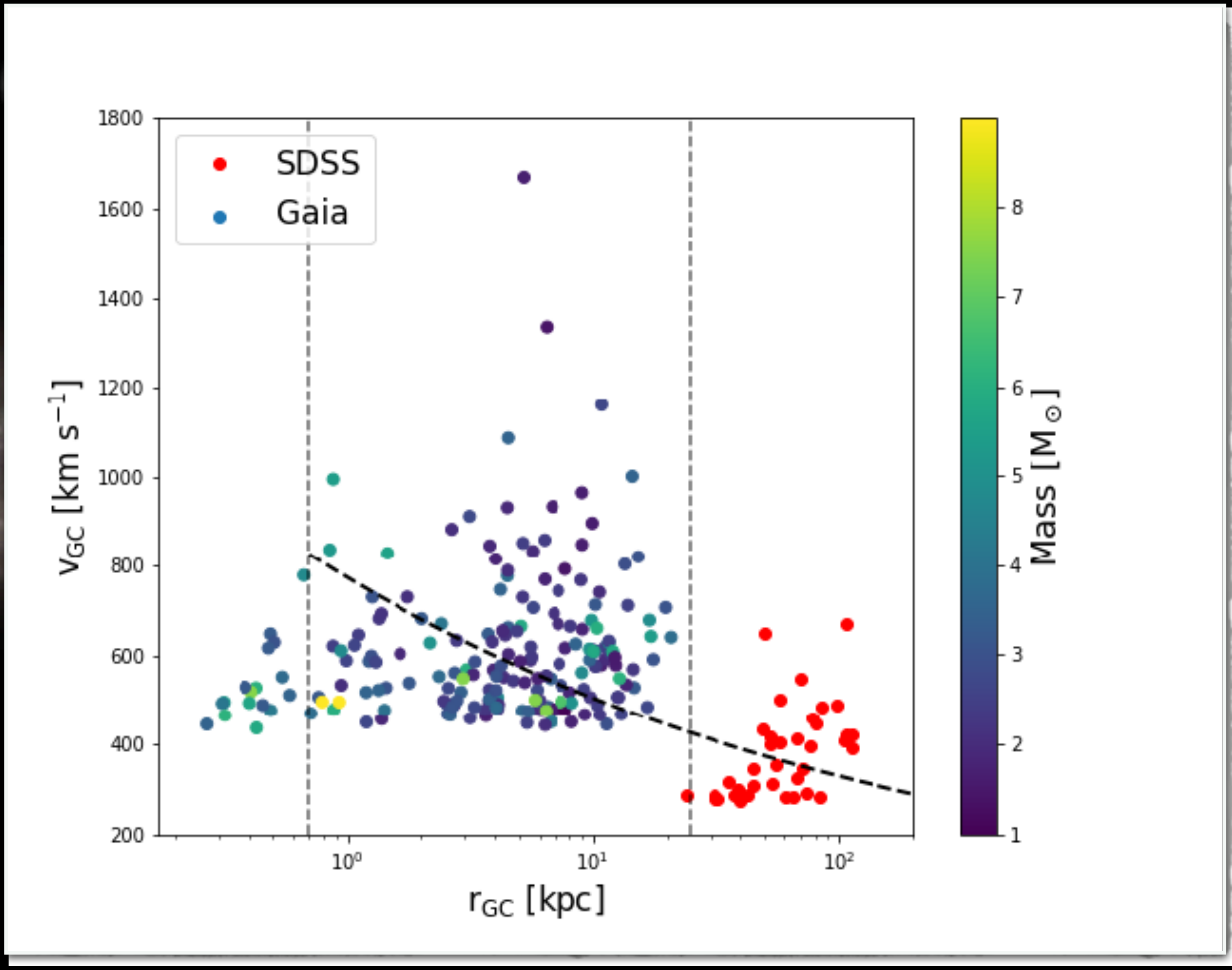
Brown+14,18

Hypervelocity stars: Gaia sample



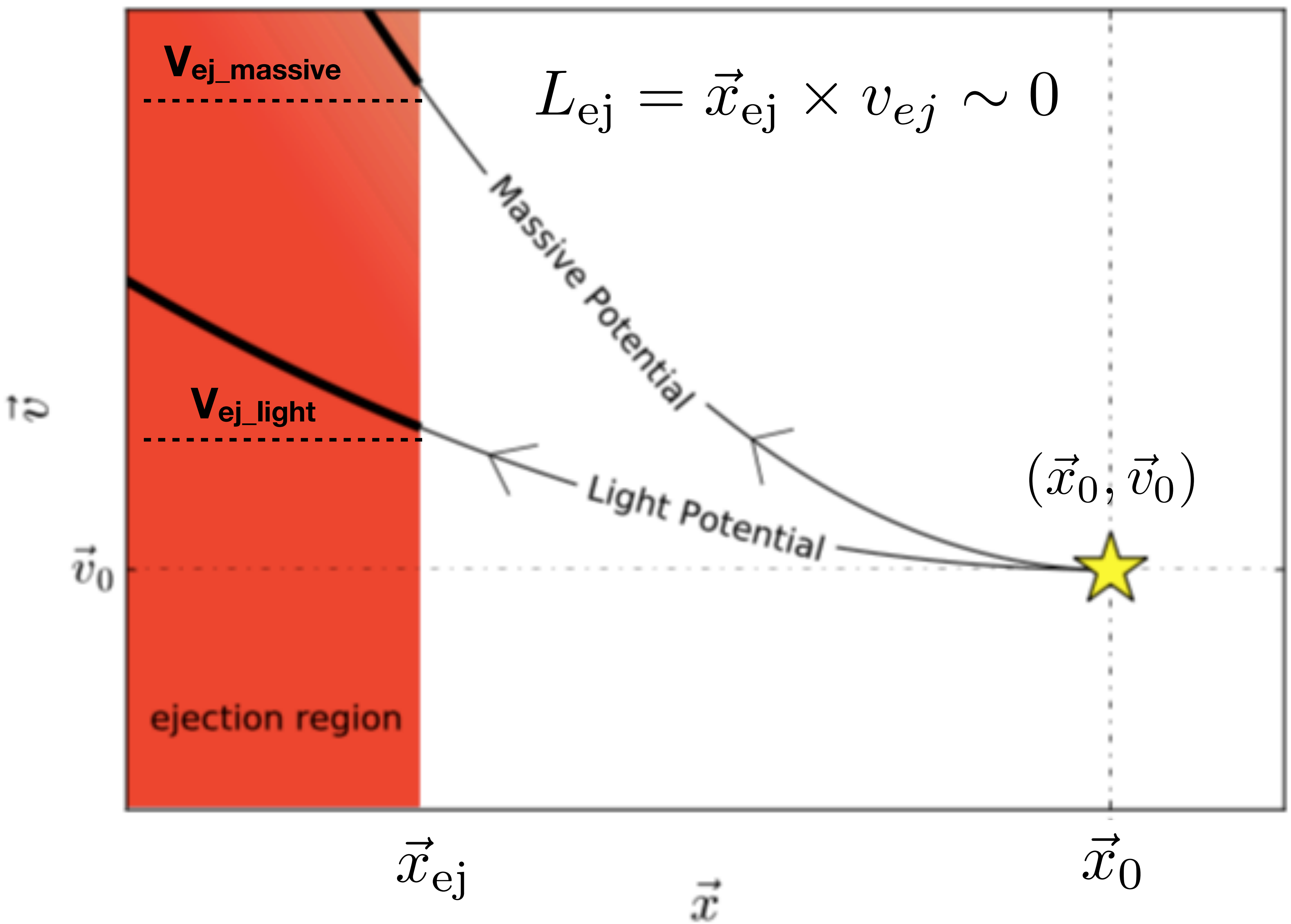
Marchetti, Contigiani, Rossi+2017

Hypervelocity stars: Gaia sample



Marchetti, Contigiani, Rossi+2017

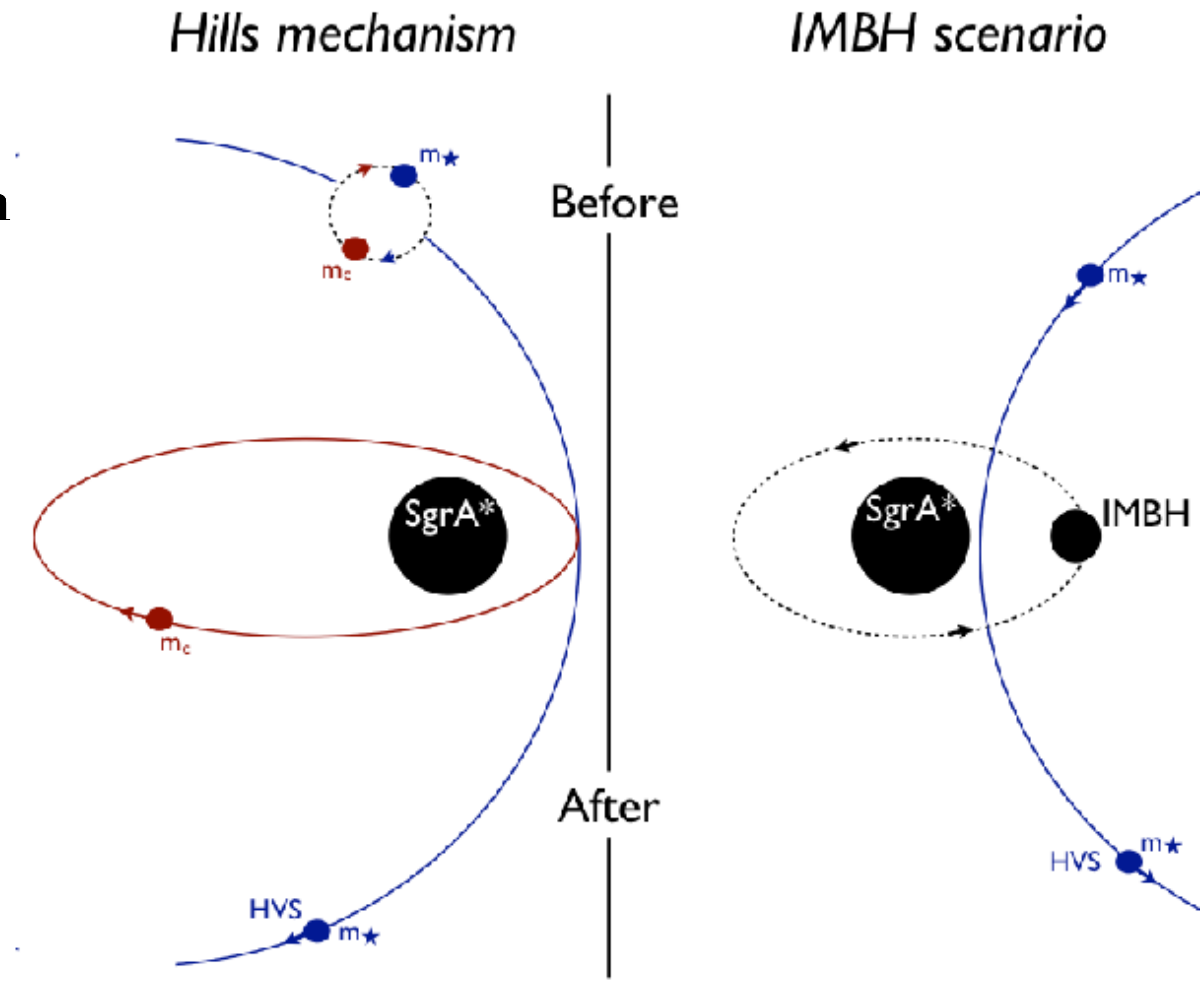
HVSs as dynamical tracers



strength: we know where they came from and their angular momentum at ejection

Data exploitation

restricted 3-body formalism



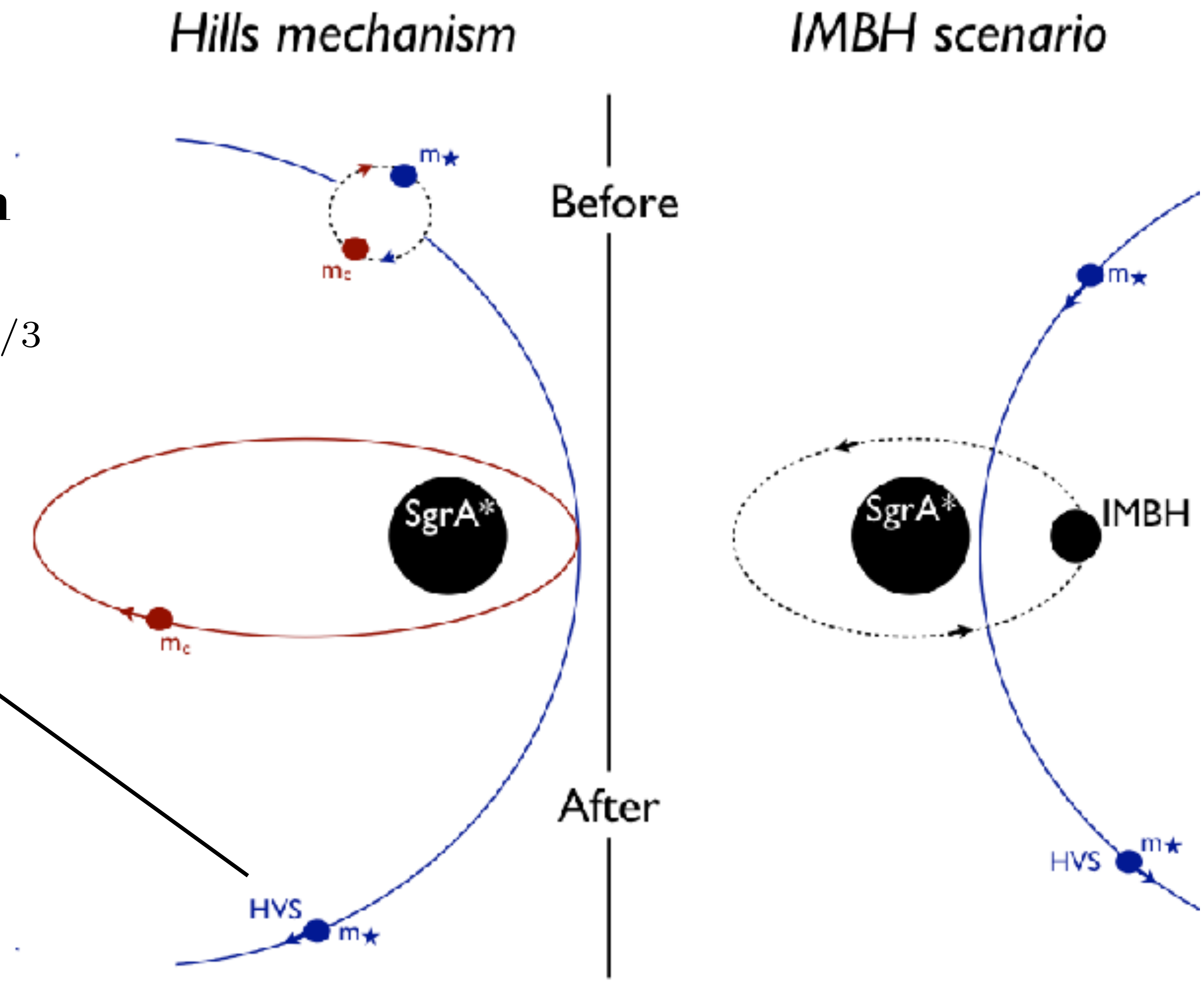
Hills 88 Yu & Tremaine 03

Sari +10, Kobayashi+12, Rossi +14,17,
Marchetti, Contigiani, Rossi+17, Rasskazov +18

Data exploitation

restricted 3-body formalism

$$v_{\rm ej} = K\sqrt{\frac{2Gm_{\rm c}}{a}}\left(\frac{M_{\rm bh}}{m_* + m_{\rm c}}\right)^{1/3}$$



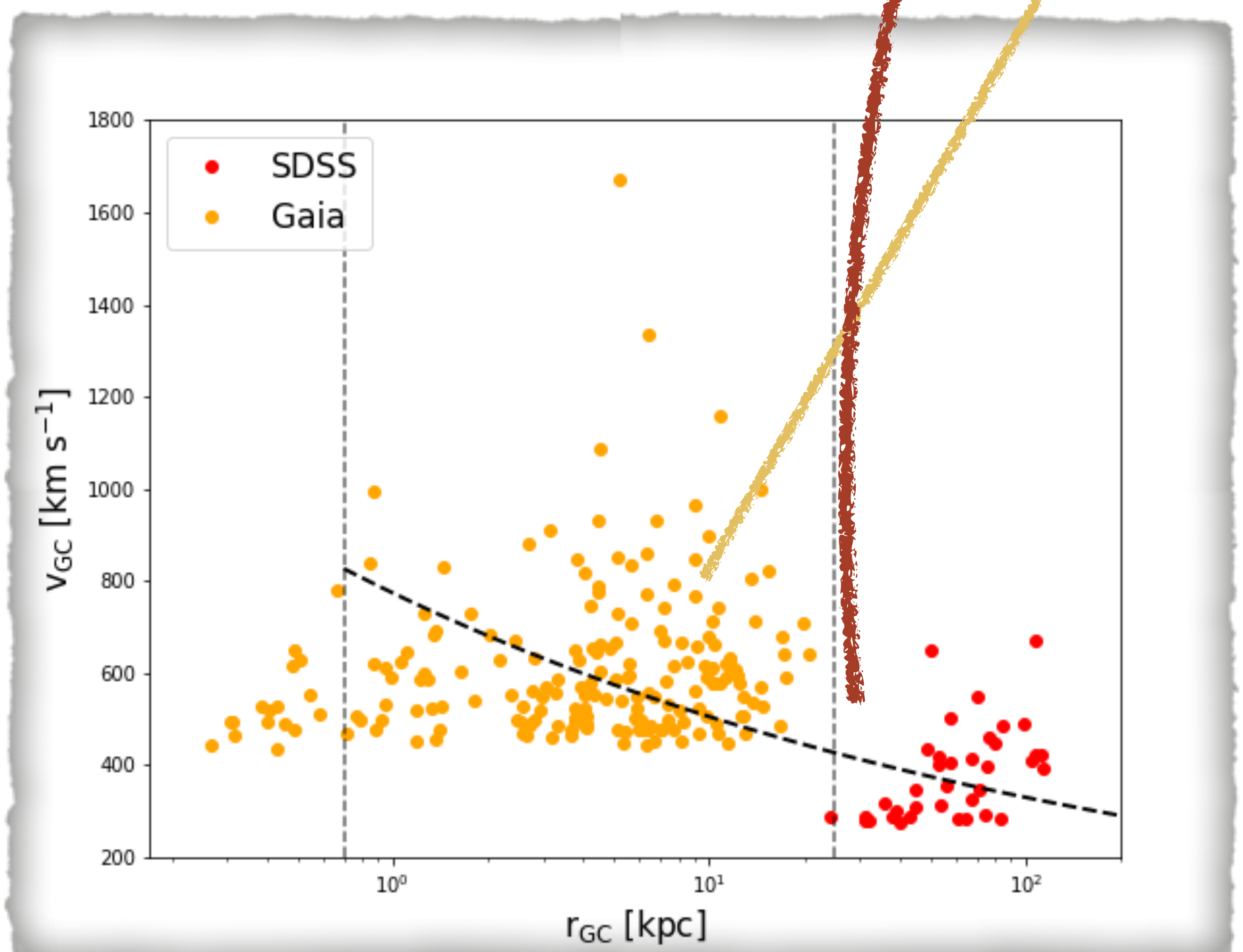
Hills 88 Yu & Tremaine 03

Sari +10, Kobayashi+12, Rossi +14,17,
Marchetti, Contigiani, Rossi+17, Rasskazov +18

Data exploitation

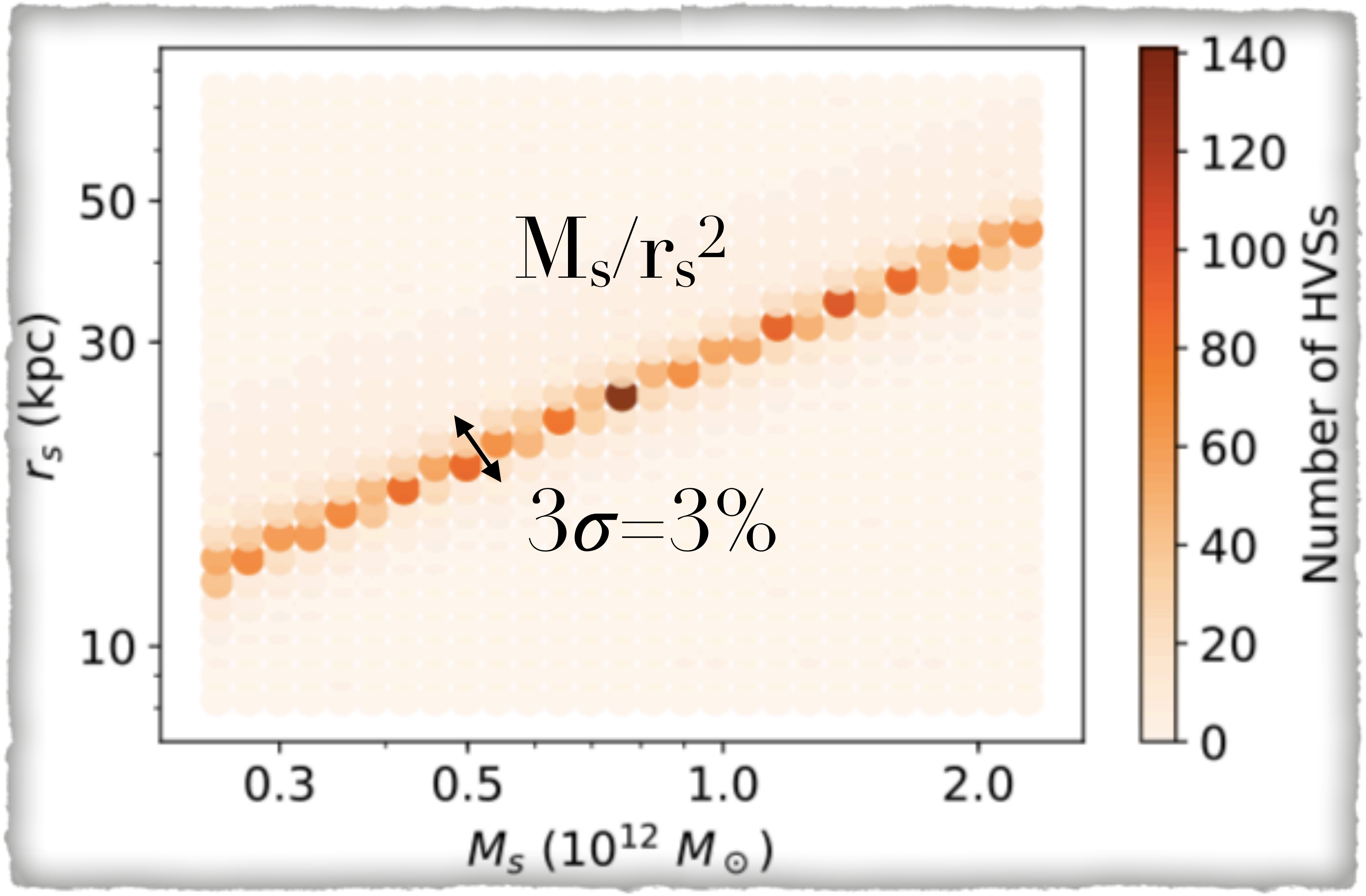
- Modelling velocity distribution of SDSS data (Rossi+14,17)
- Modelling 6D distribution of Gaia data

Contigiani, Rossi & Marchetti 18

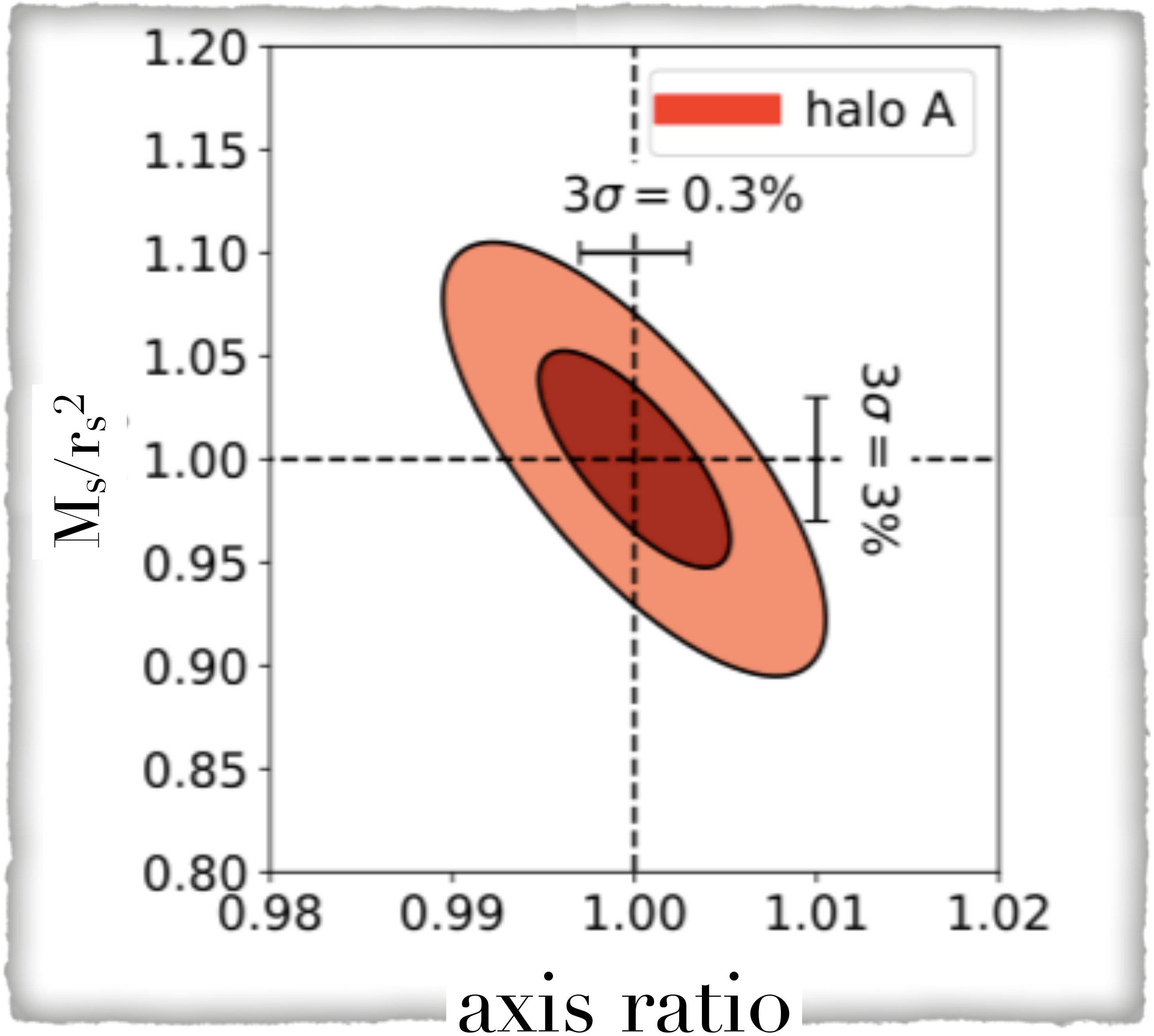


Degeneracy between mass and radius

With 120 HVSs

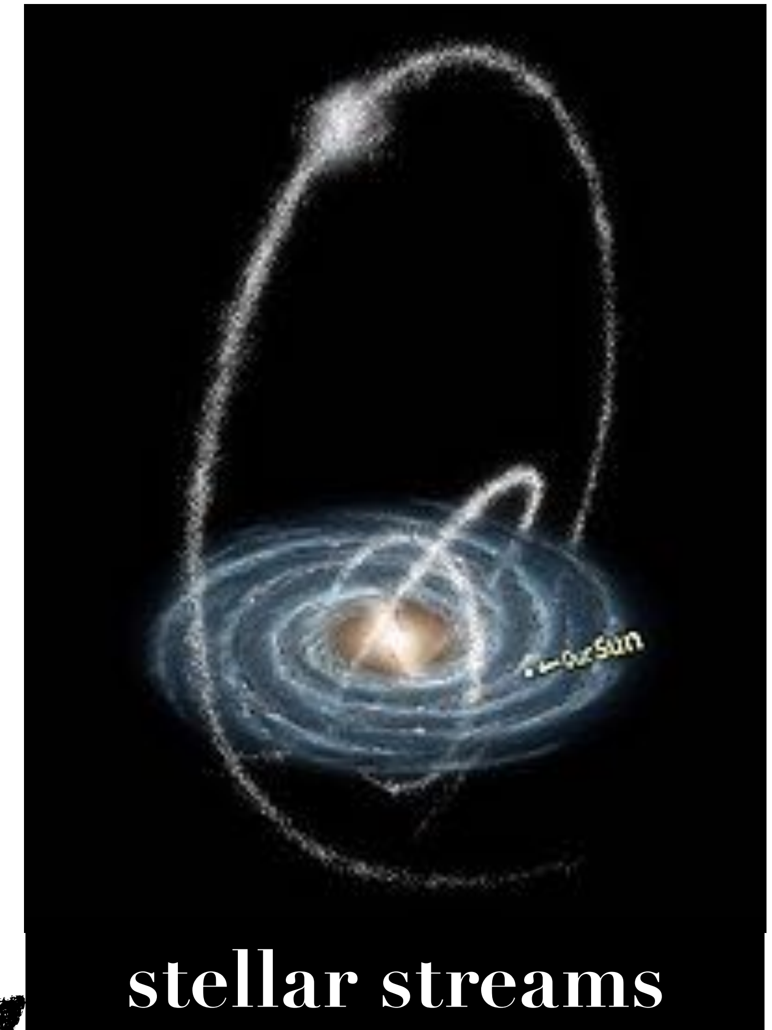


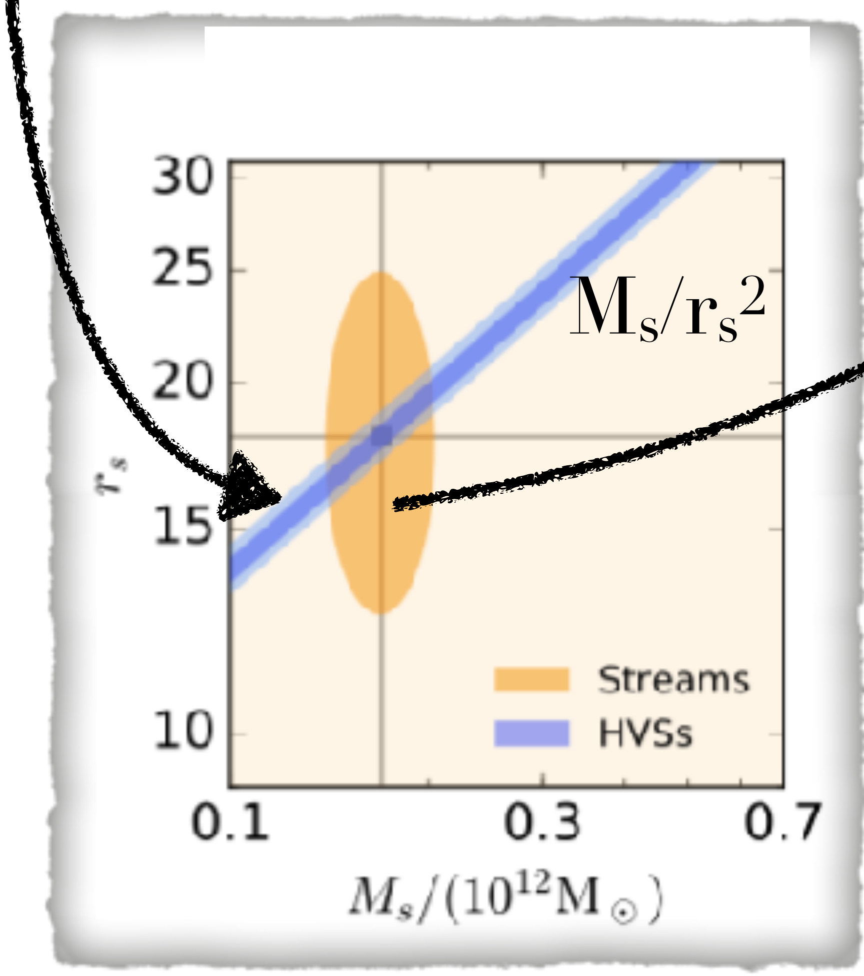
HVSs are exquisite shape tracers



breaking degeneracies

+

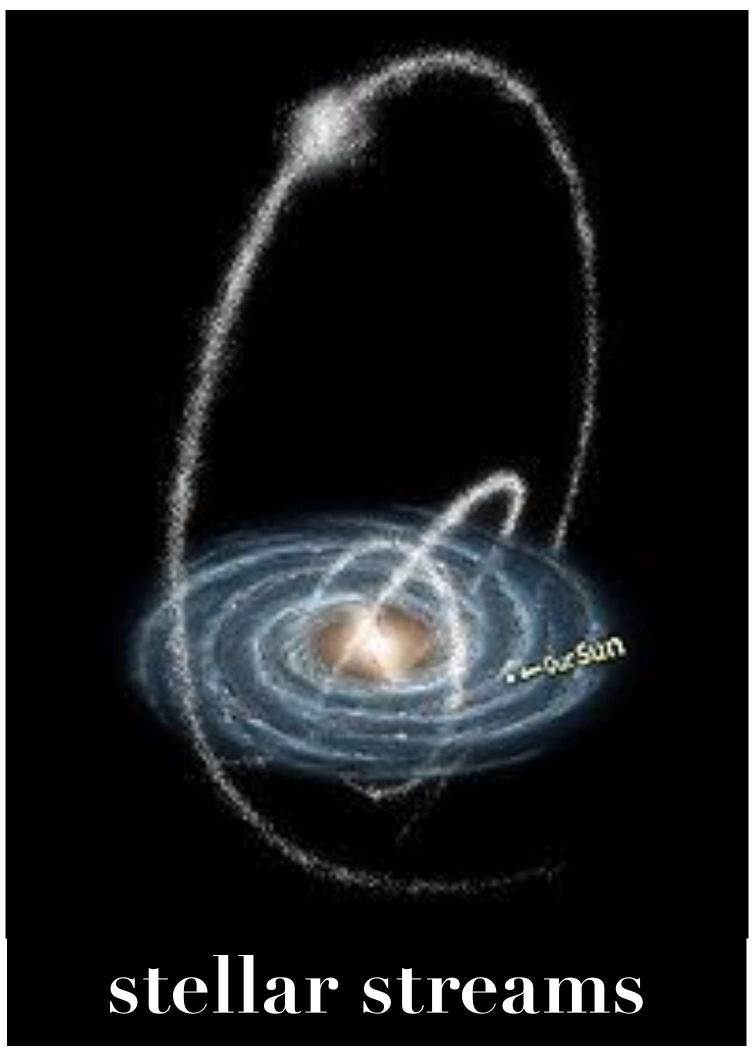


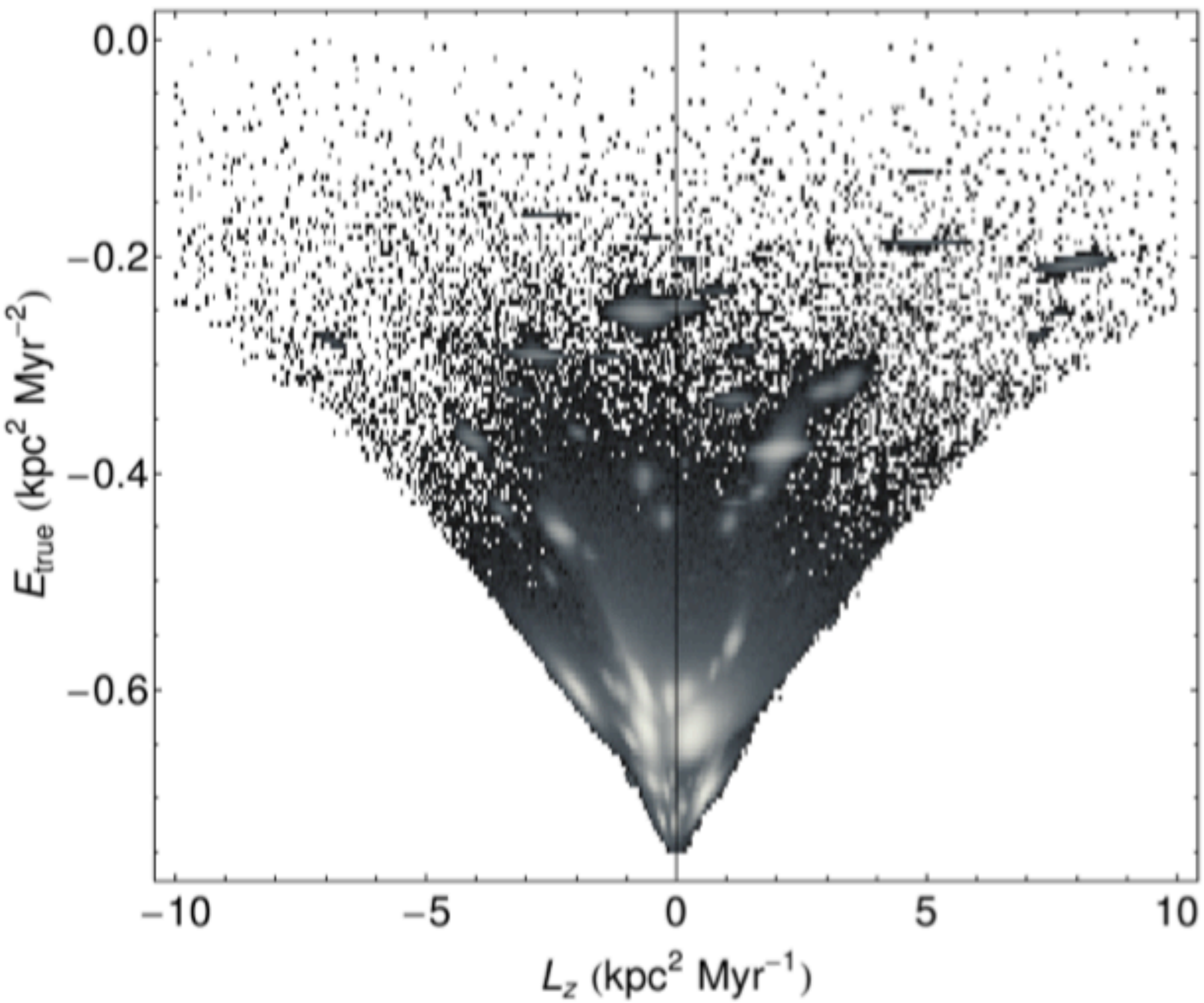


Adapted from my group's work (Contigiani, EMR + 2018)

Modelling in action space

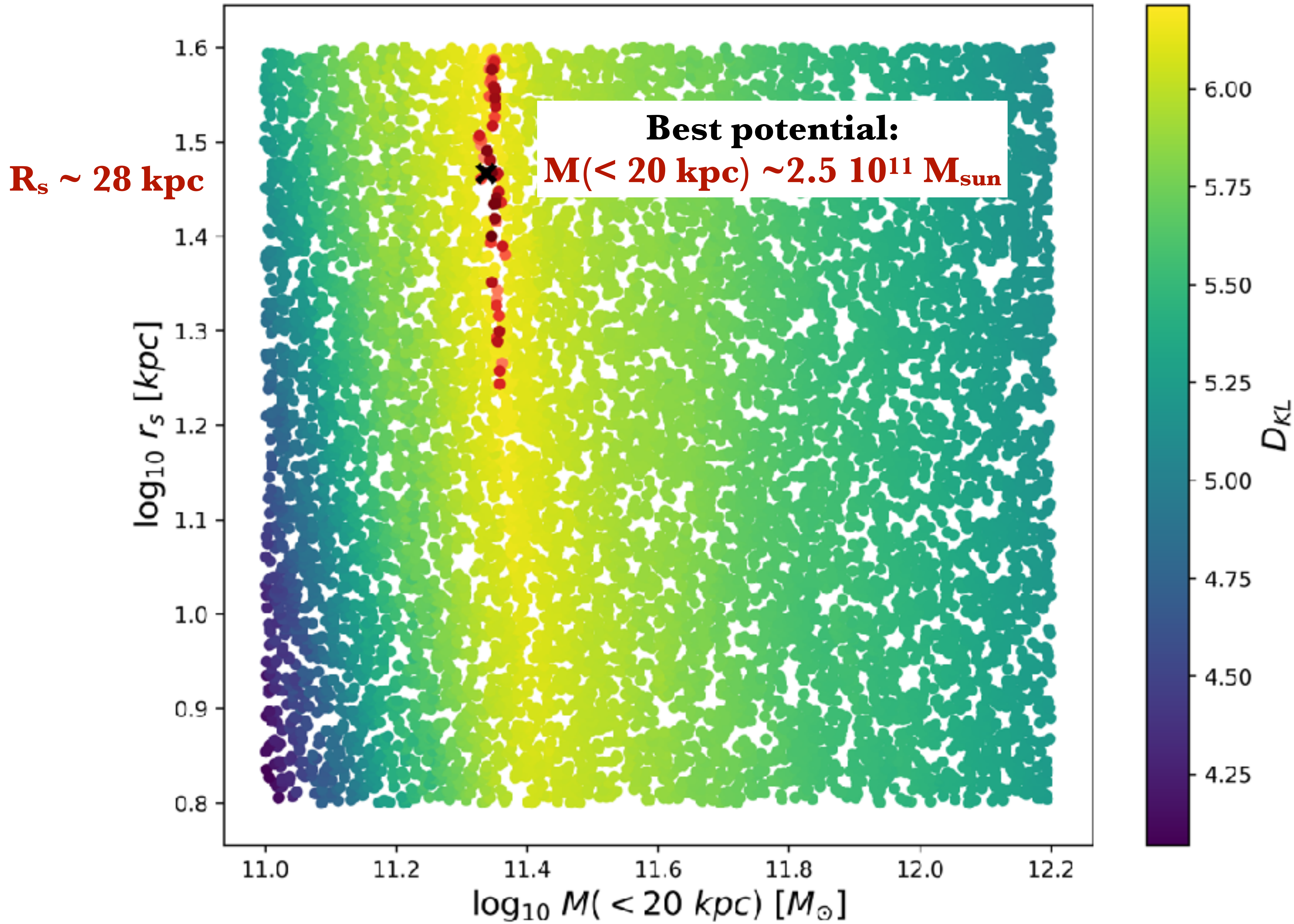
stars in stellar streams have memory of the energy and angular momentum of they progenitor





Sanderson, + 2015

Streams in (angle-) action



Reino, EMR, Sanderson & Helmi in prep.

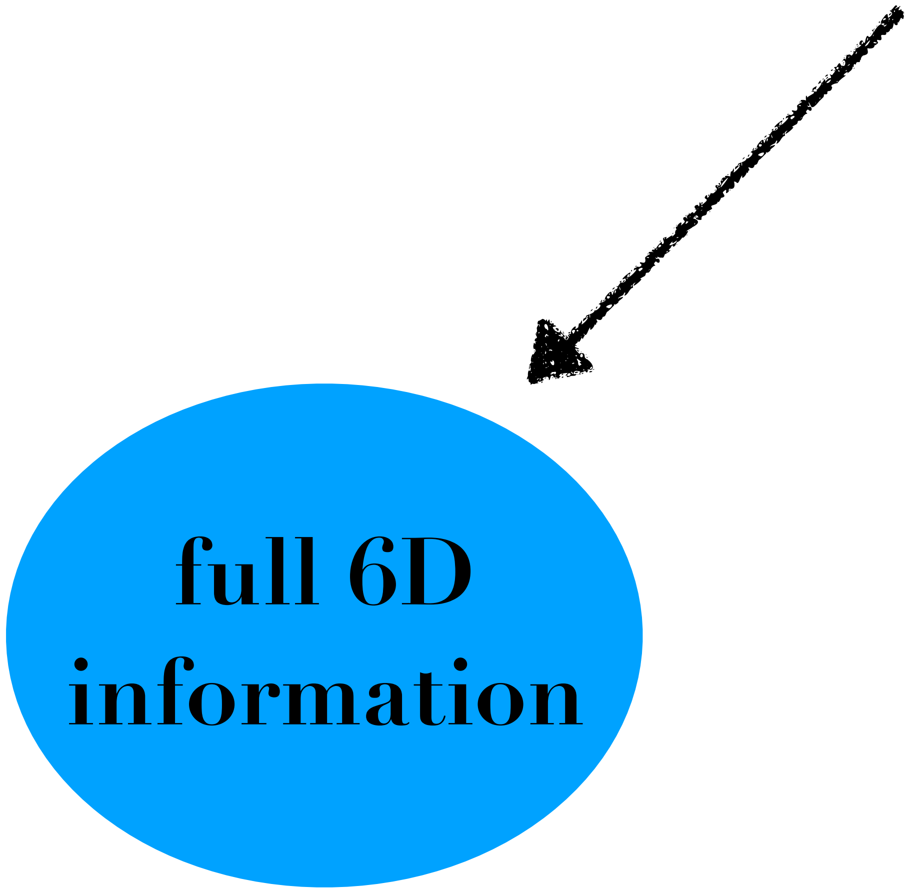
Take away messages

- Galactic/Local group tomography with gravitational waves is in its infancy but very promising
- We are working towards “combining probes” to minimise systematics and get more robust constraints on the Milky Way potential

Elena Maria Rossi, Leiden Observatory, The Netherlands

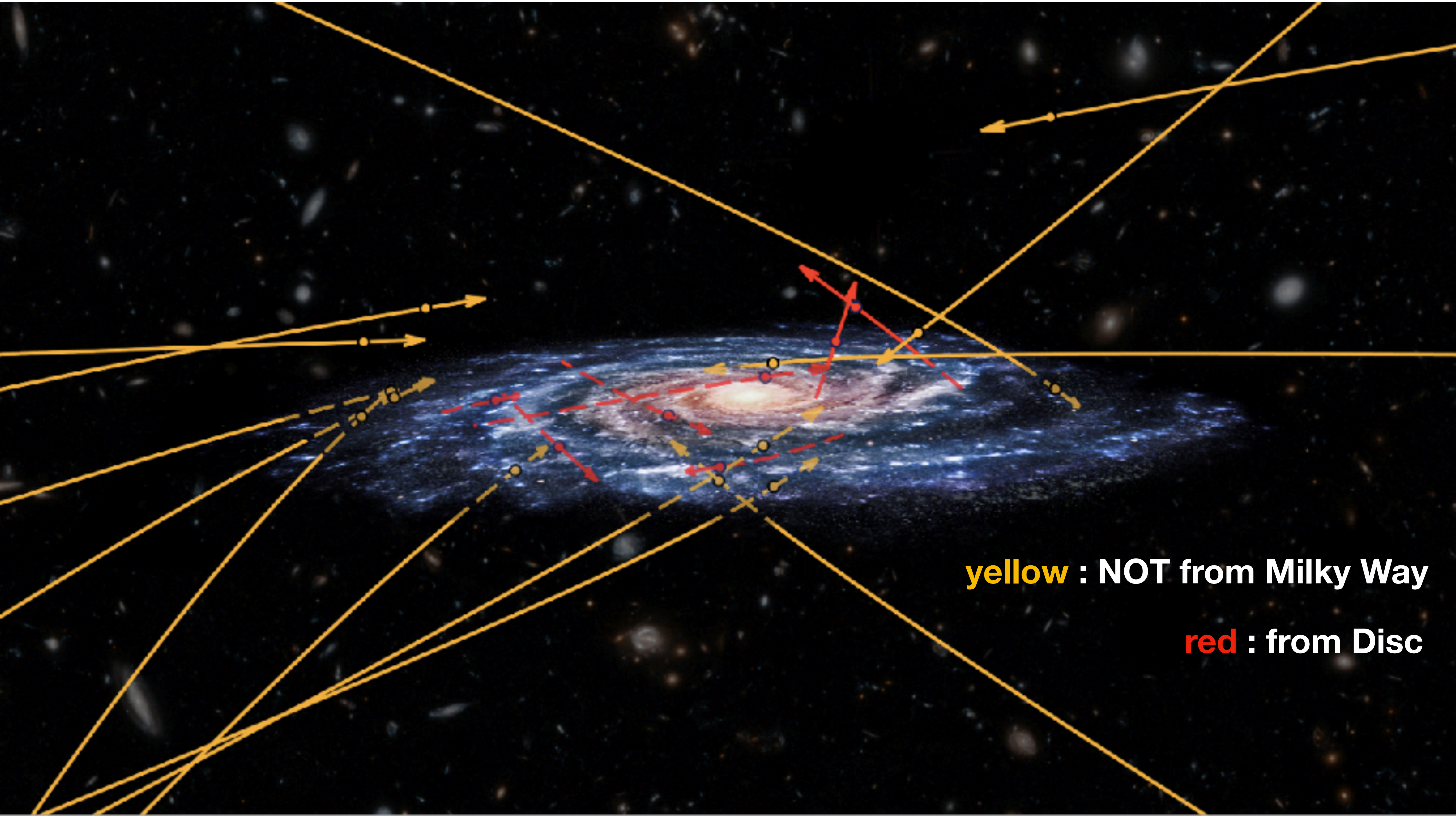
Data acquisition

Two sets of data in Gaia DR2



7 million stars in DR2

~20 unbound stars in DR2



Credit: ESA press release of Marchetti, Rossi, Brown 18

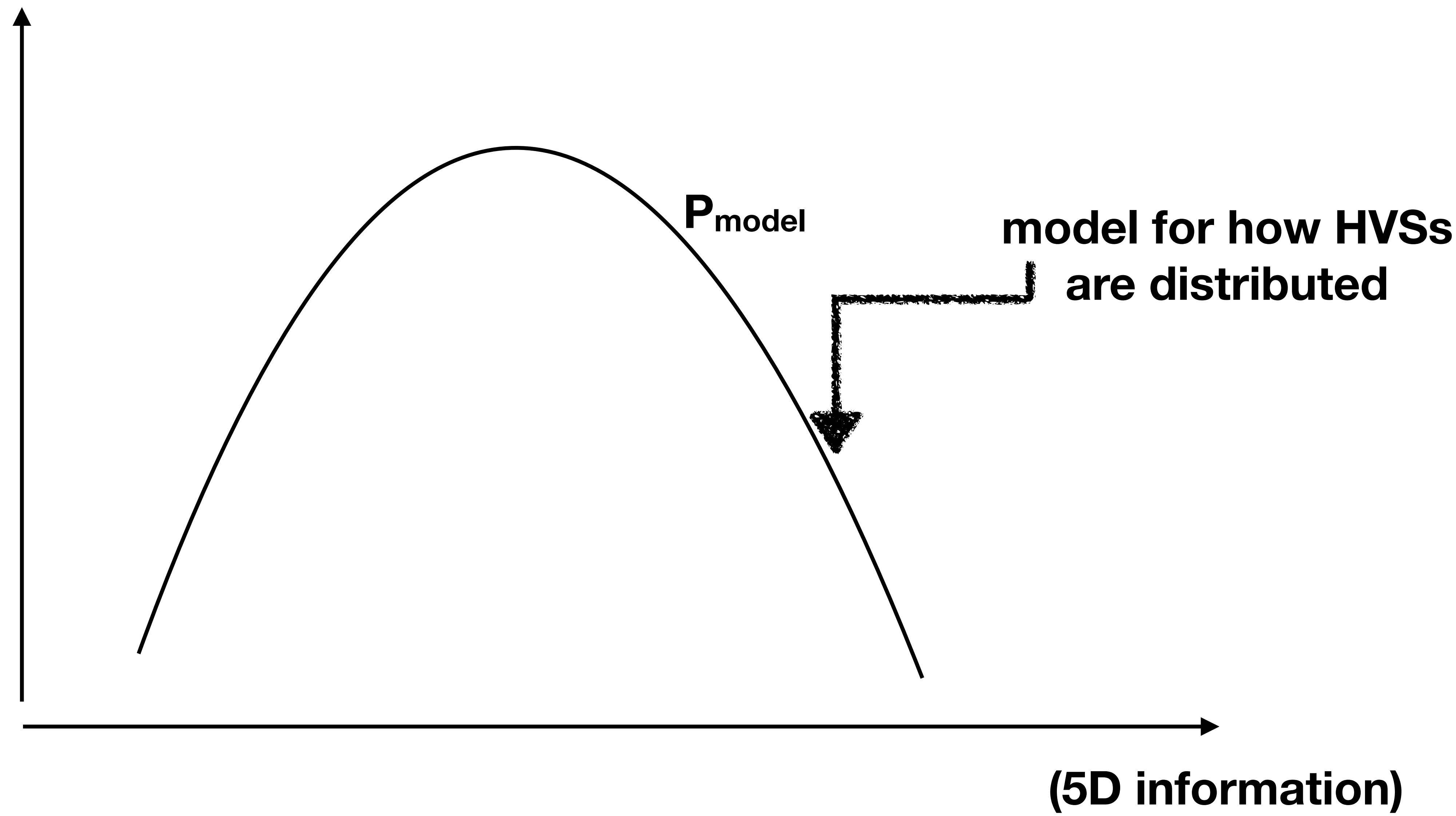
Data acquisition

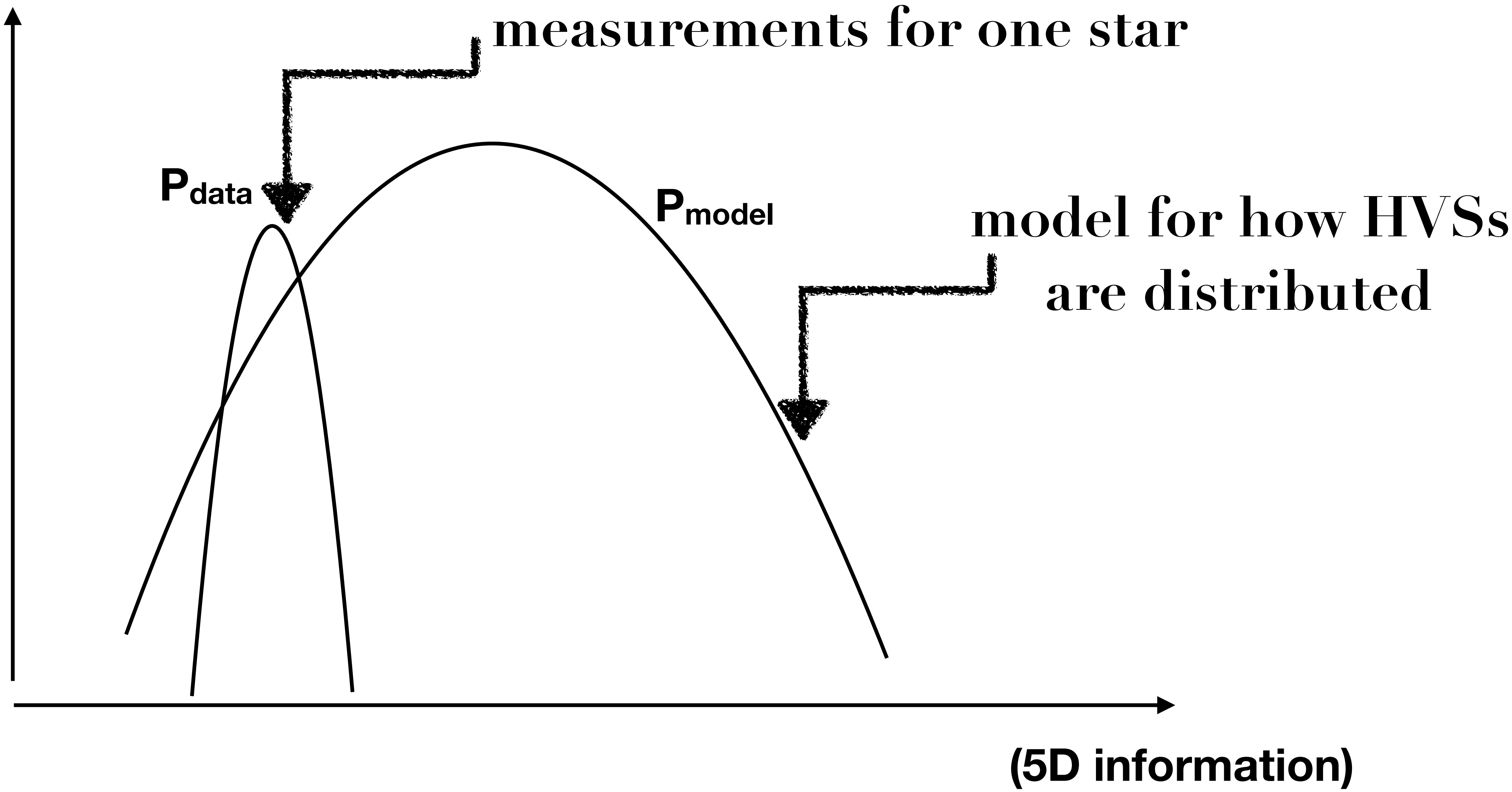
Two sets of data in Gaia DR

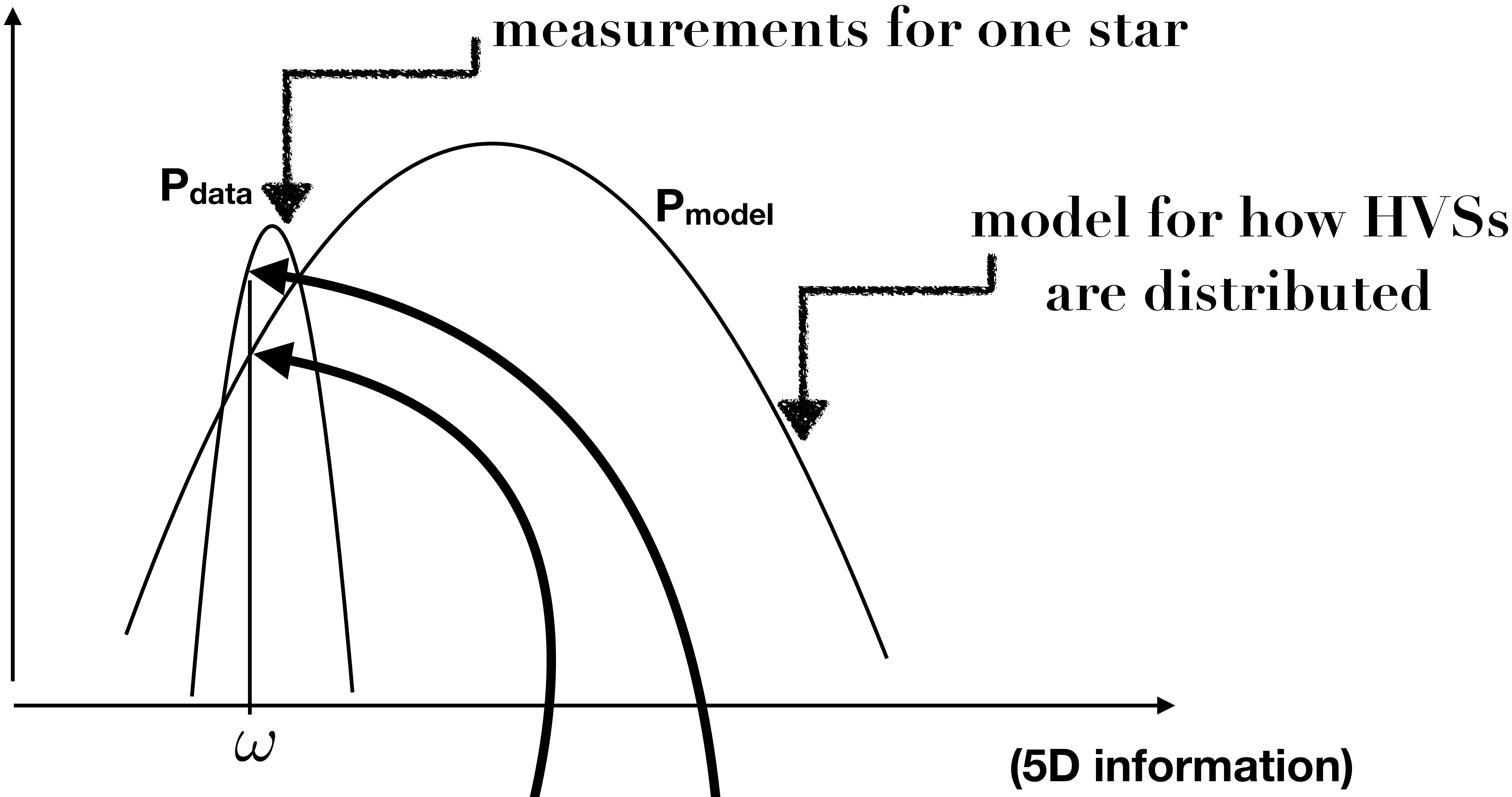
full 6D information

7 million stars in DR2

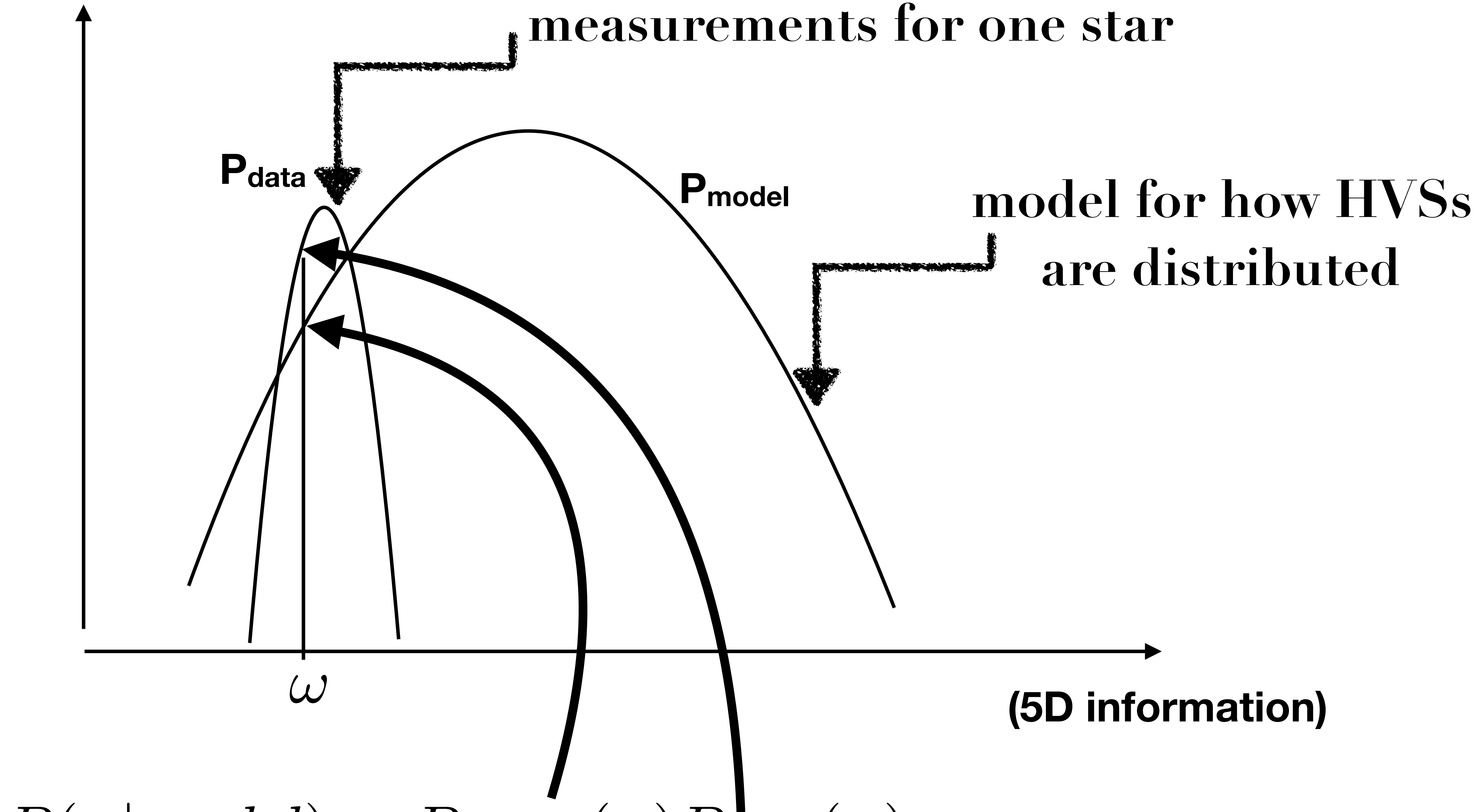
5D information
(no radial velocity)
~1 billion stars


P_{model}
model for how HVSs are distributed
(5D information)


measurements for one star
P data
P model
model for how HVSs are distributed
(5D information)



$$P(\omega|model) \propto P_{\rm model}(\omega) P_{\rm data}(\omega)$$



$$P(\omega|model) \propto P_{\mathrm{model}}(\omega)P_{\mathrm{data}}(\omega)$$

data mining routine exploiting artificial neural network

DR1 results

=> 2 million —> 47 stars —> 5 HVSs

(**Marchetti, EMR+2017**)

...not confirmed by DR2 data :-(((

DR2 results are coming…

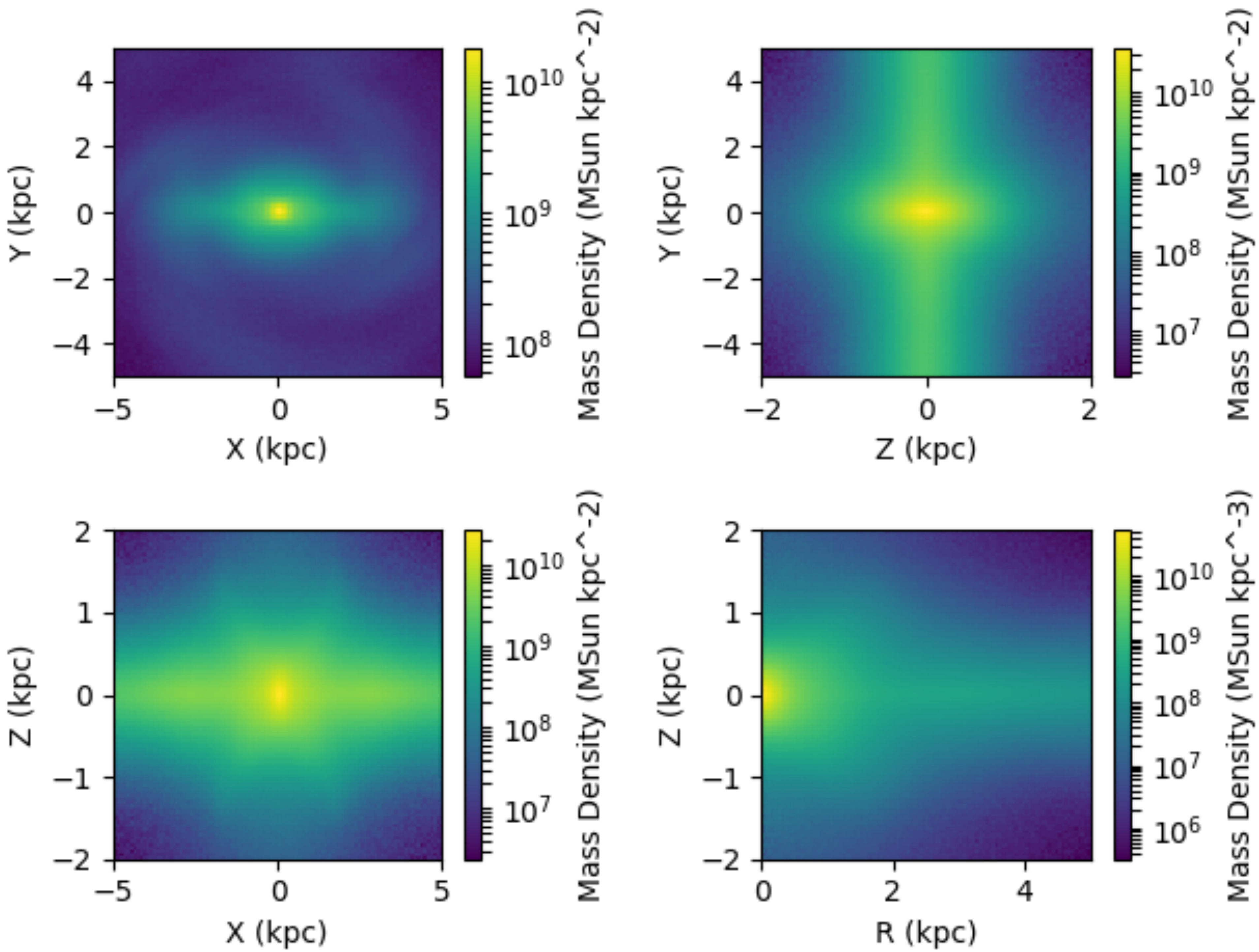
=> **Data mining of Gaia DR2:**

1 billion —> ~100 candidates —> ?? HVSs

waiting for INT, WHT and X-shooter observations

back-up slides

Next: how fine a structure can we trace with GW ?



Elena D'Onghia's simulations