The Milky Way as a Laboratory for Galaxy Formation

Matthias Steinmetz (AIP)

with contributions by Friedrich Anders, Cristina Chiappini, Guillaume Guiglion, Arman Khalatyan,
Sergey Khoperskov, Lucy Lu, Lea Marques, Ivan Minchev, Samir Nepal, Anna Queiroz,
Bridget Ratcliffe, Katja Weingrill ,Glenn Van de Venn, Paola Di Matteo, Misha Haywood and many others

AIP


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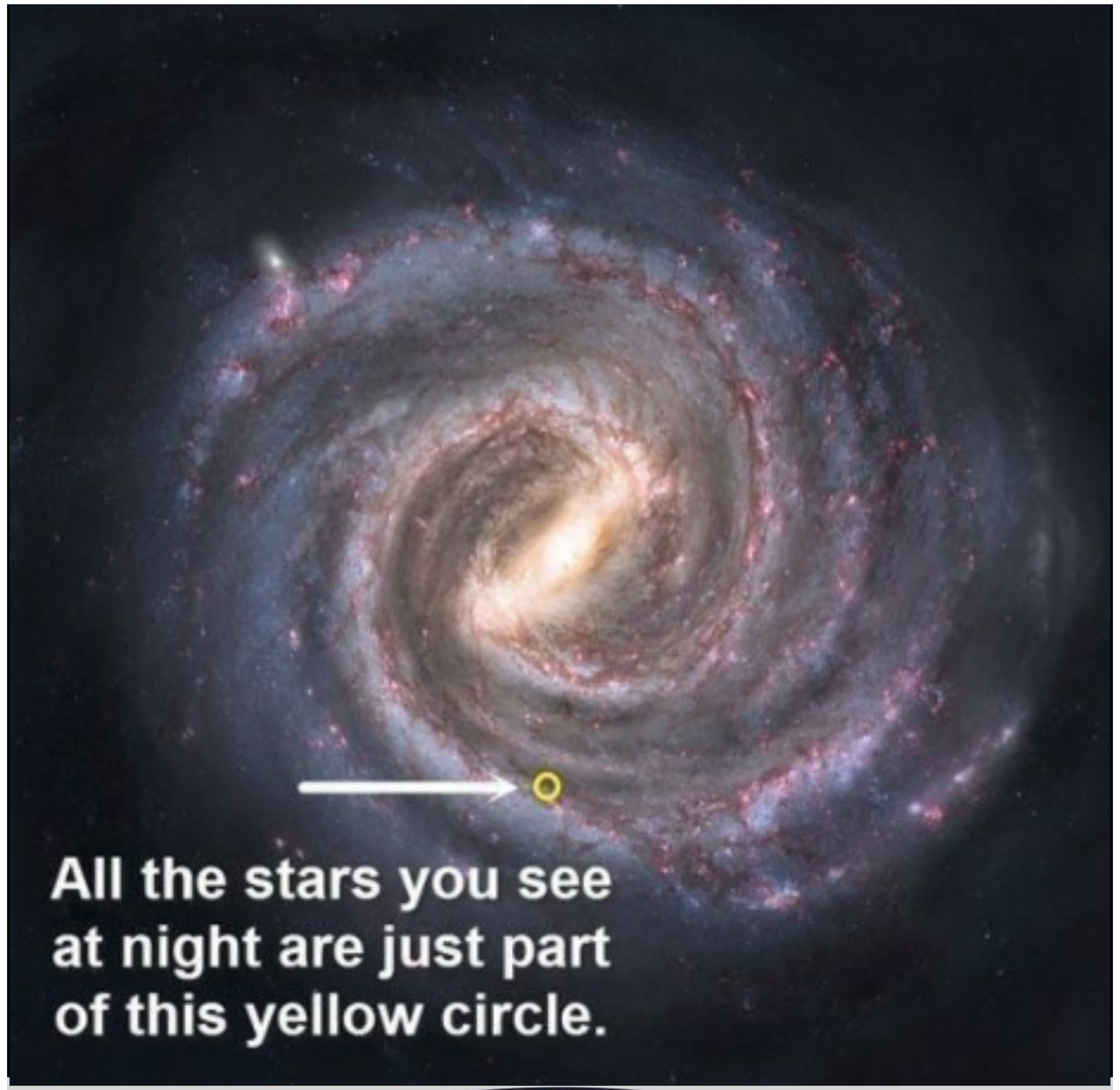
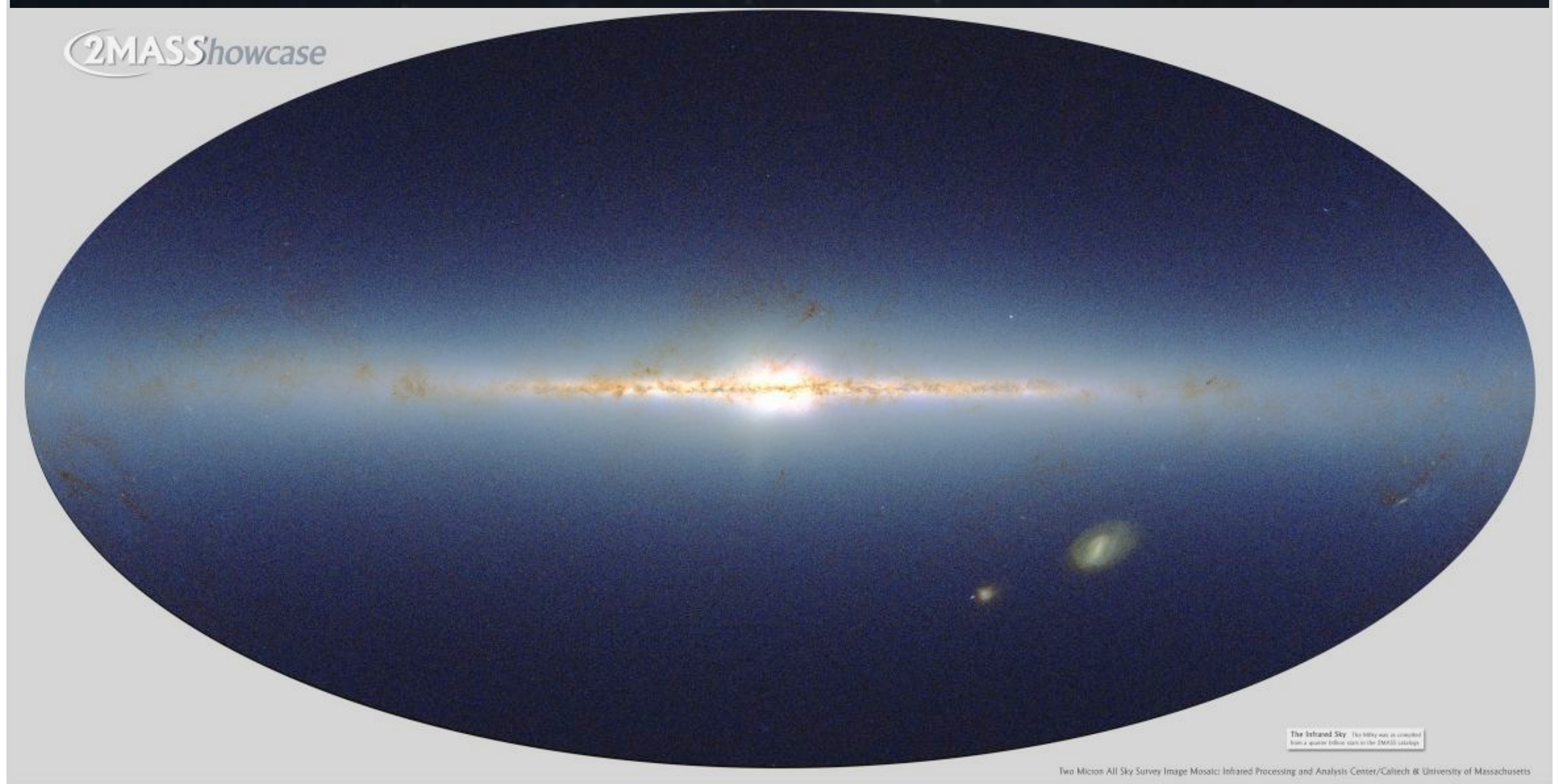
The Milky Way



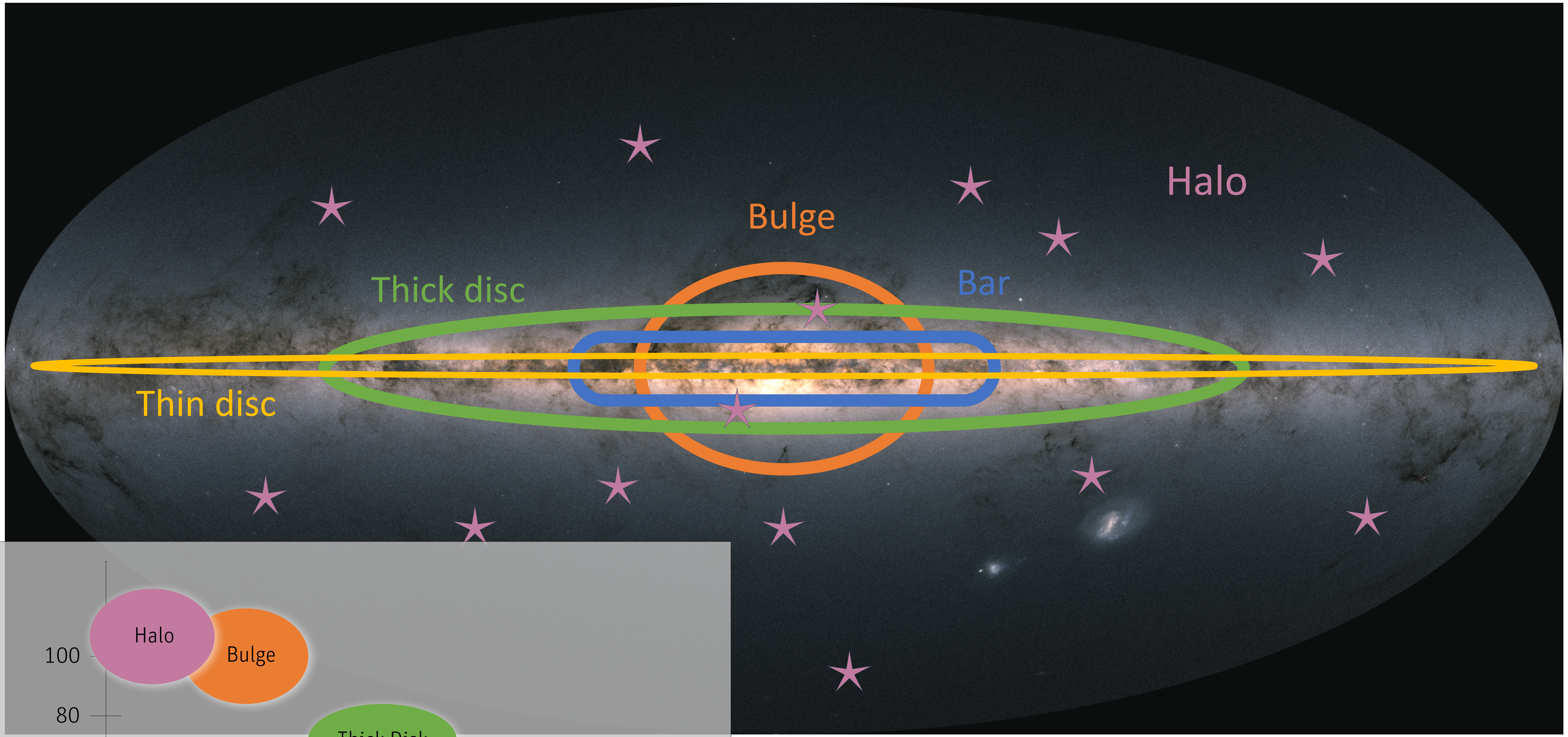


The nice things about stars

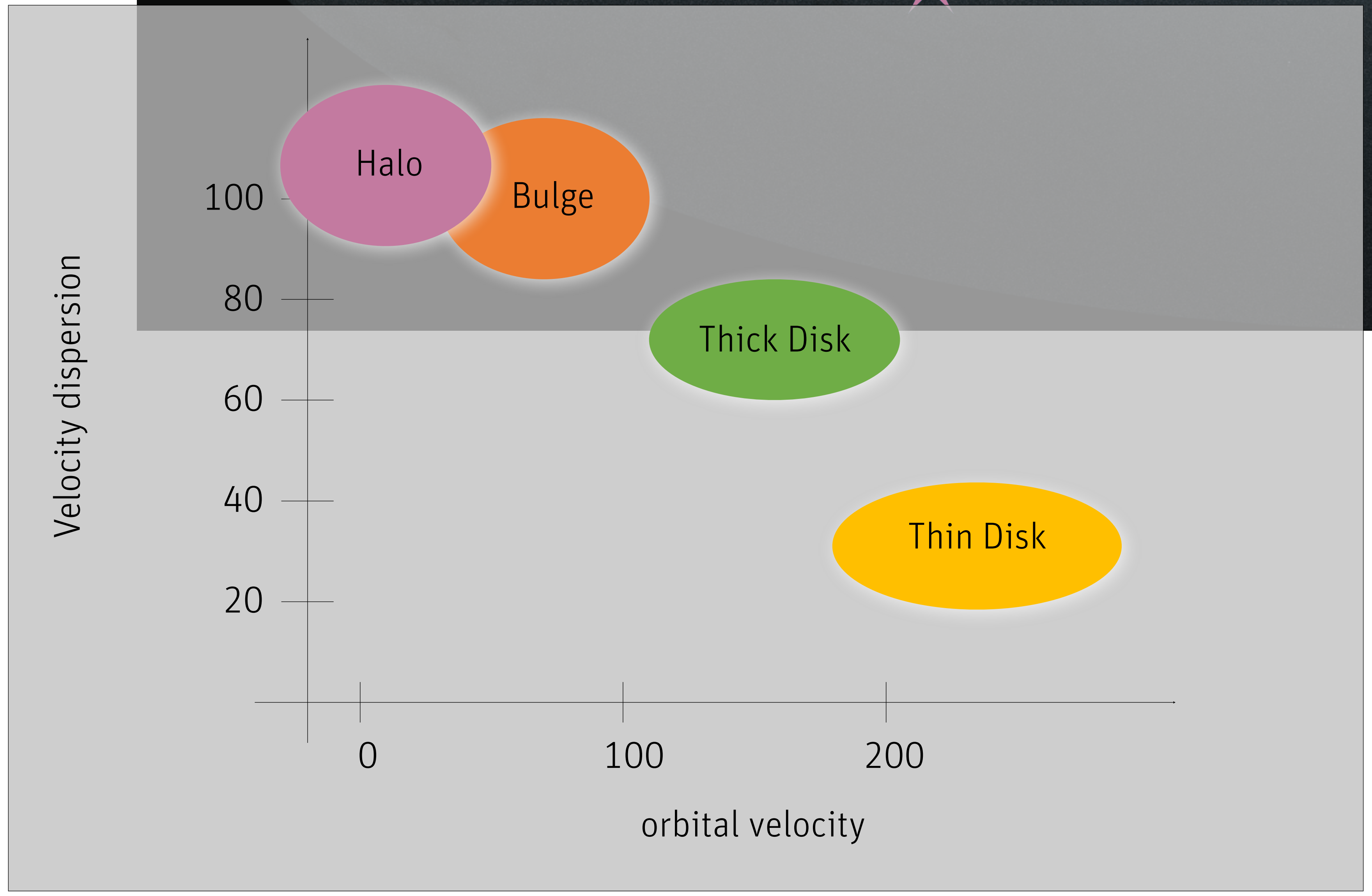
- They come in all ages and compositions
- There are billions of them in the Galaxy
- We understand them (Eddington’s conjecture)
- Russel-Voigt theorem: mass, age and composition of a star uniquely determine its inner structure
  – at least as long as rotation and magnetic fields are ignored…
- So by measuring the properties of stars we can get their ages, abundances, i.e. the conditions in their birth cloud
- using their orbits we can chemically tag co-eval groups
- We can dissect the Milky Way into formation epochs

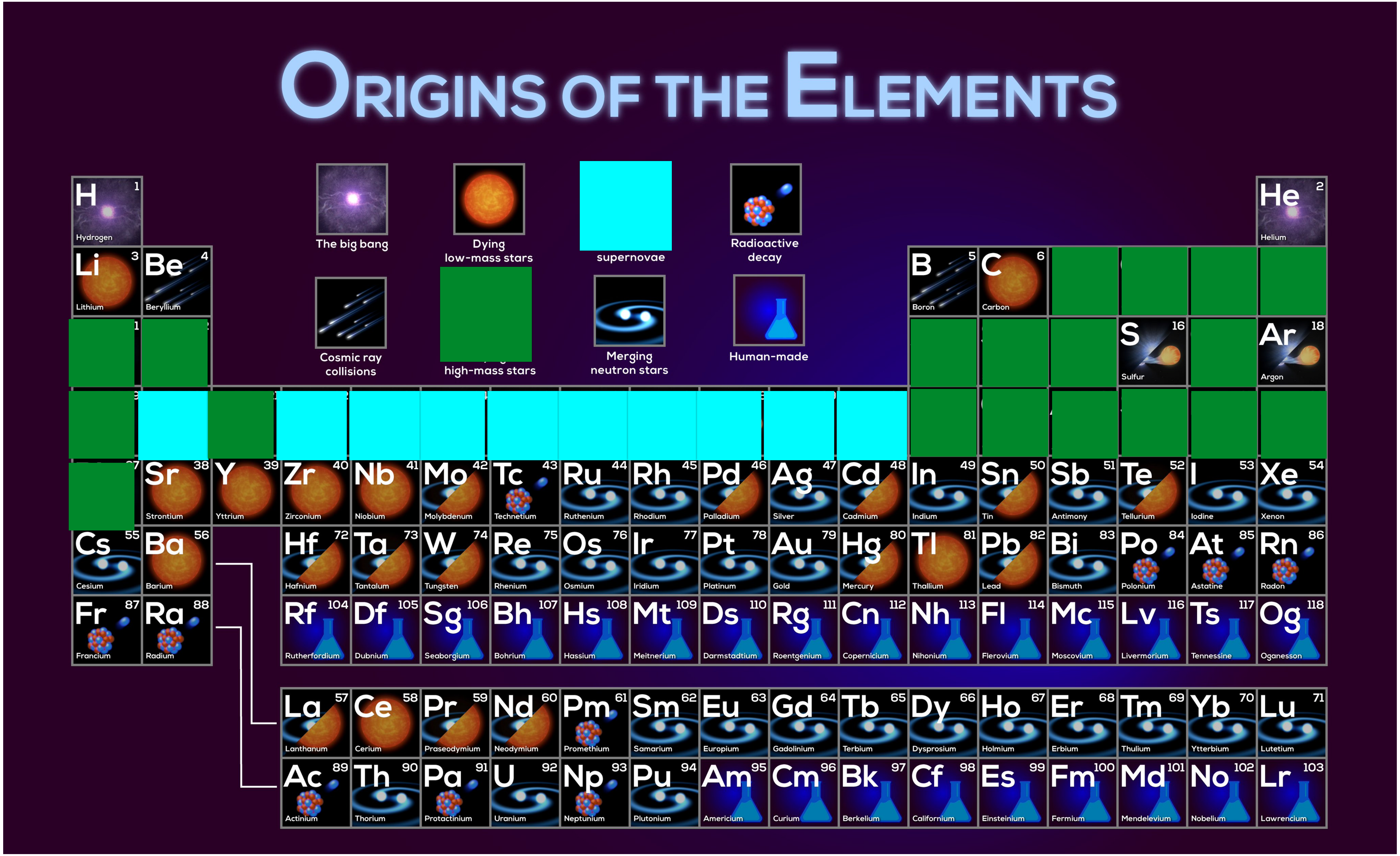
The classical view of the Milky Way:

- A galaxy consists of at least one star (Truran & Hillebrandt, Kiel 1993)
- Chemical abundances preserve the star formation and chemical enrichment history of the birth cloud

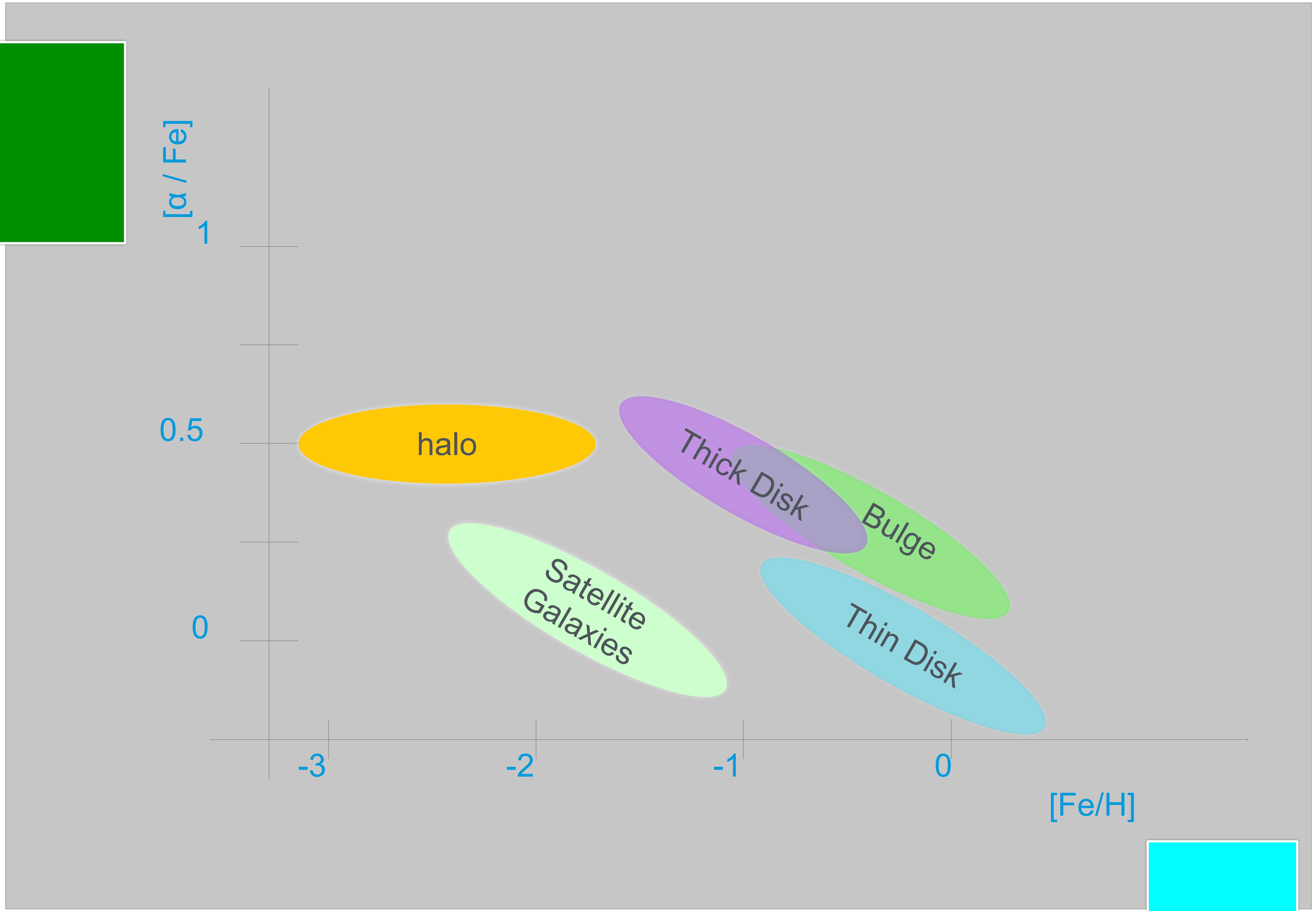


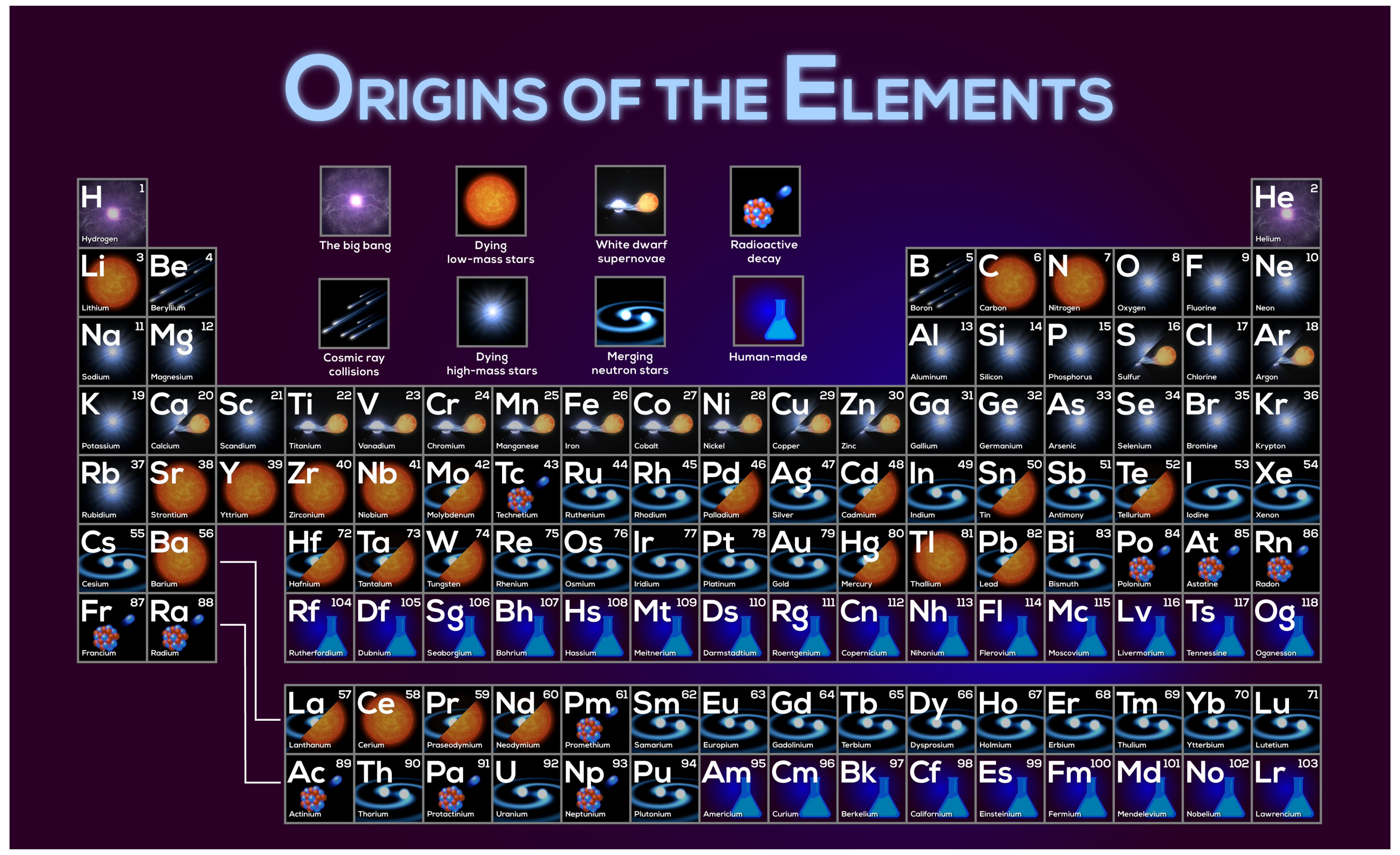
ESA/Gaia/DPAC; CC BY-SA 3.0 IGO. Acknowledgement: A. Moitinho.




ORIGINS OF THE ELEMENTS
The big bang
Dying low-mass stars
supernovae
Radioactive decay
Cosmic ray collisions
high-mass stars
Merging neutron stars
Human-made
H 1 Hydrogen
He 2 Helium
Li 3 Lithium
Be 4 Beryllium
B 5 Boron
C 6 Carbon
S 16 Sulfur
Ar 18 Argon
Sr 38 Strontium
Y 39 Yttrium
Zr 40 Zirconium
Nb 41 Niobium
Mo 42 Molybdenum
Tc 43 Technetium
Ru 44 Ruthenium
Rh 45 Rhodium
Pd 46 Palladium
Ag 47 Silver
Cd 48 Cadmium
In 49 Indium
Sn 50 Tin
Sb 51 Antimony
Te 52 Tellurium
I 53 Iodine
Xe 54 Xenon
Cs 55 Cesium
Ba 56 Barium
Hf 72 Hafnium
Ta 73 Tantalum
W 74 Tungsten
Re 75 Rhenium
Os 76 Osmium
Ir 77 Iridium
Pt 78 Platinum
Au 79 Gold
Hg 80 Mercury
Tl 81 Thallium
Pb 82 Lead
Bi 83 Bismuth
Po 84 Polonium
At 85 Astatine
Rn 86 Radon
Fr 87 Francium
Ra 88 Radium
Rf 104 Rutherfordium
Df 105 Dubnium
Sg 106 Seaborgium
Bh 107 Bohrium
Hs 108 Hassium
Mt 109 Meitnerium
Ds 110 Darmstadtium
Rg 111 Roentgenium
Cn 112 Copernicium
Nh 113 Nihonium
Fl 114 Flerovium
Mc 115 Moscovium
Lv 116 Livermorium
Ts 117 Tennessine
Og 118 Oganesson
La 57 Lanthanum
Ce 58 Cerium
Pr 59 Praseodymium
Nd 60 Neodymium
Pm 61 Promethium
Sm 62 Samarium
Eu 63 Europium
Gd 64 Gadolinium
Tb 65 Terbium
Dy 66 Dysprosium
Ho 67 Holmium
Er 68 Erbium
Tm 69 Thulium
Yb 70 Ytterbium
Lu 71 Lutetium
Ac 89 Actinium
Th 90 Thorium
Pa 91 Protactinium
U 92 Uranium
Np 93 Neptunium
Pu 94 Plutonium
Am 95 Americium
Cm 96 Curium
Bk 97 Berkelium
Cf 98 Californium
Es 99 Einsteinium
Fm 100 Fermium
Md 101 Mendelevium
No 102 Nobelium
Lr 103 Lawrencium

Schematic: Elemental abundances in the Milky Way





Type II supernovae:
exploding massive stars
rapidly recycled (~10 Myr)

Type Ia supernovae:
accreting merging white dwarfs
slowly recycled (~1 Gyr)

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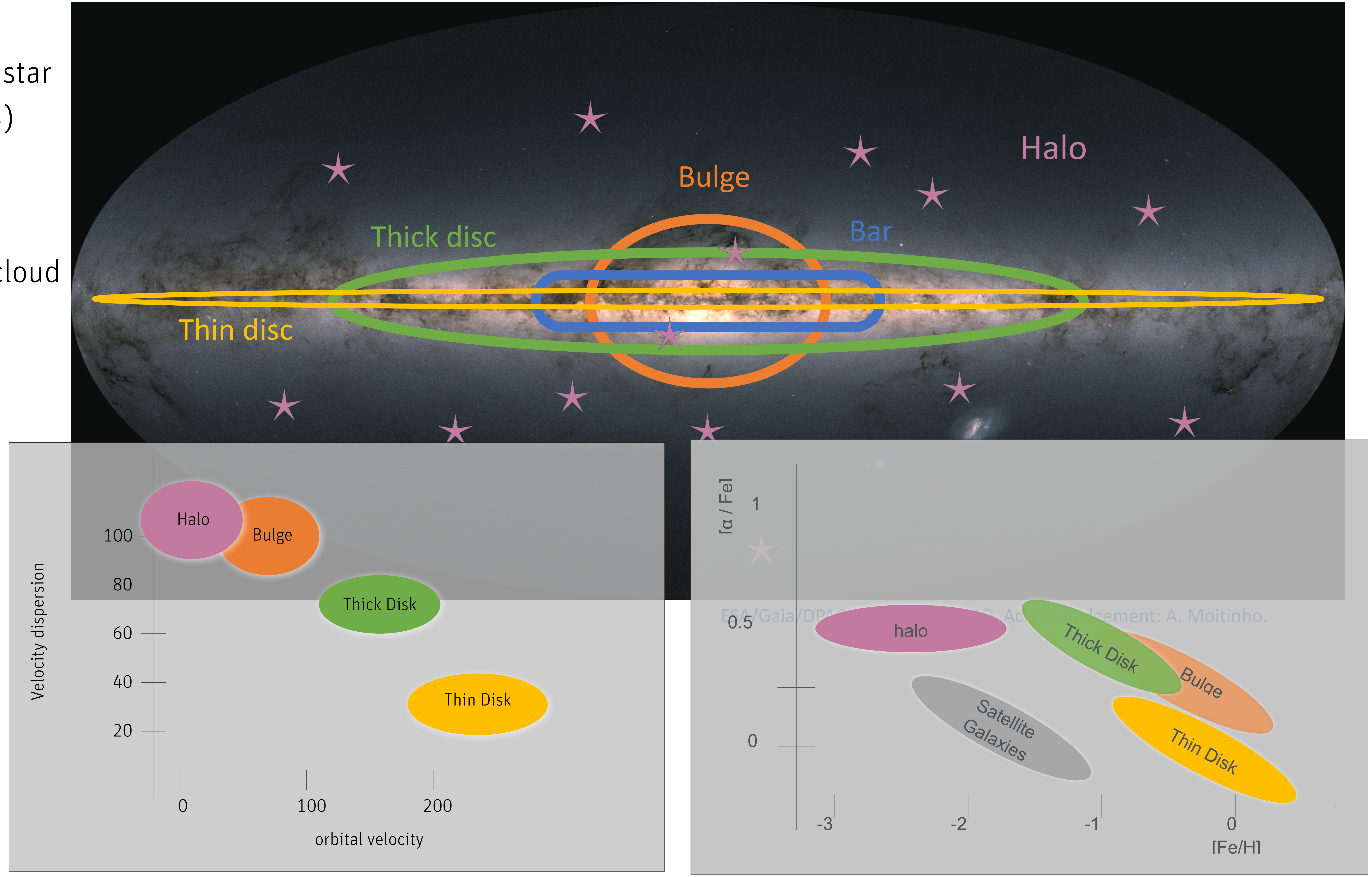
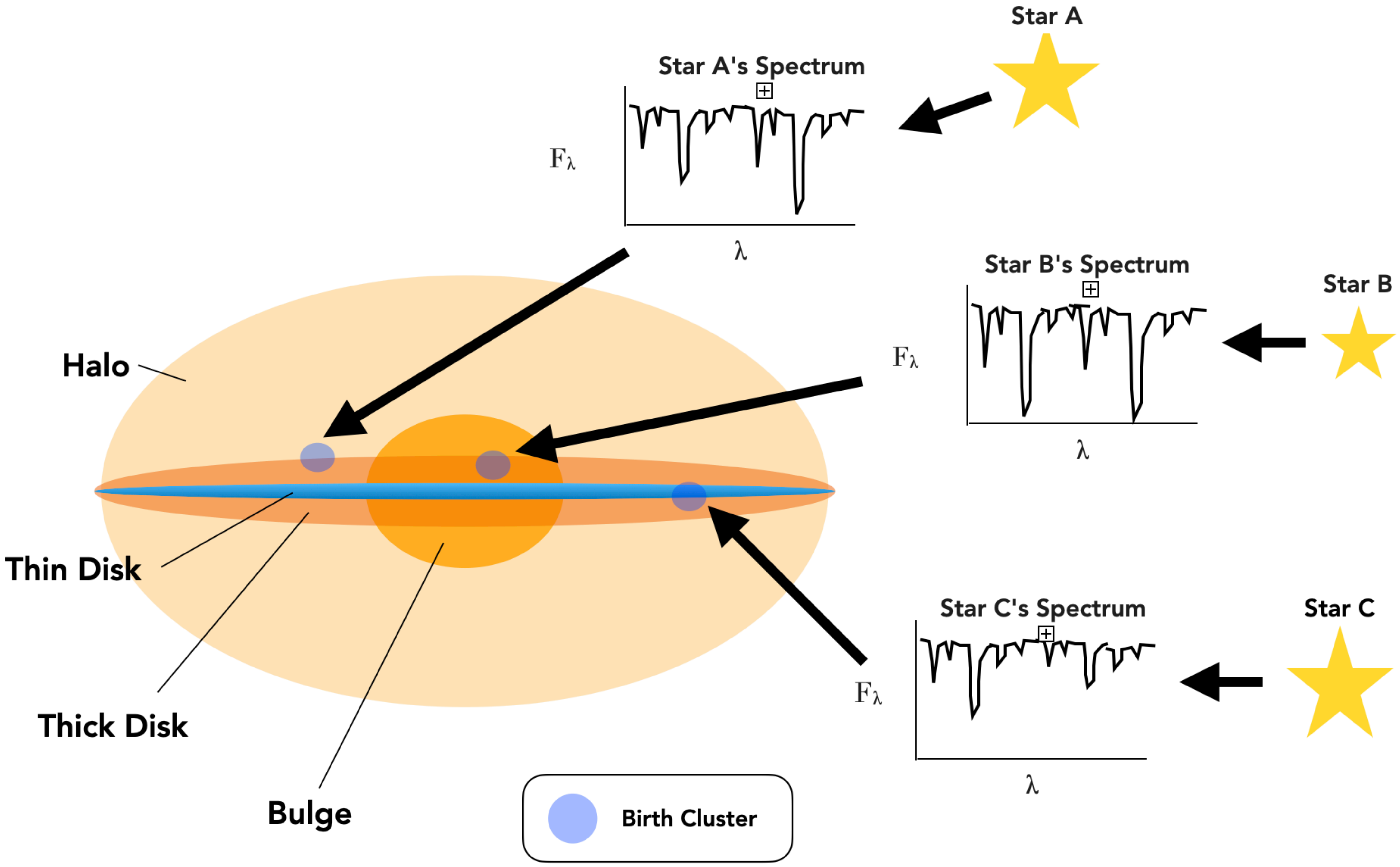


The goal: Chemical tagging



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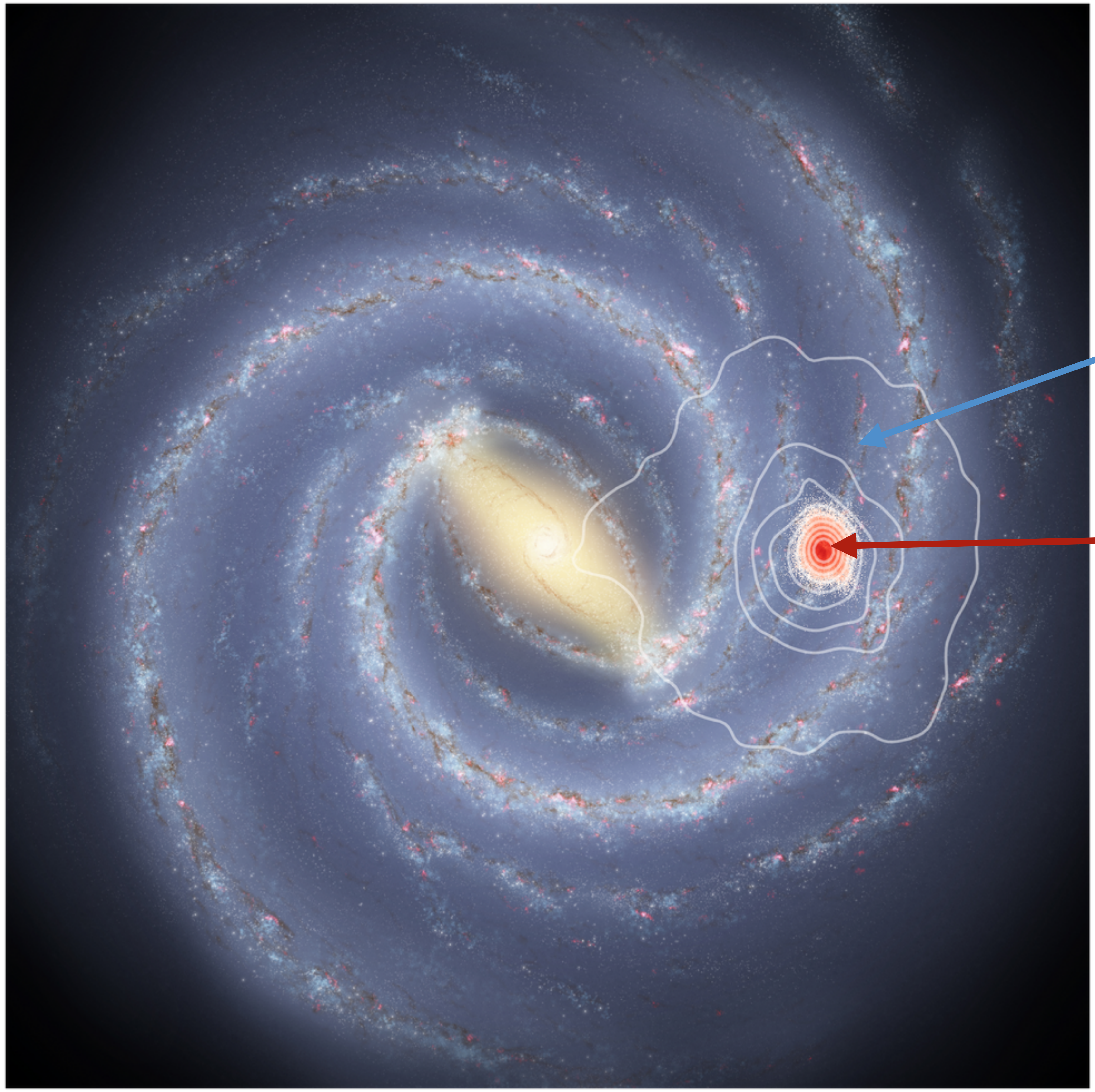
- Chemical tagging: Use the chemical properties of stars to backtrace their birth cluster. As they formed from the same birth cloud, they should have similar, if not identical abundances

- Level to which this is possible, still needs to be proven


⇒ „Galactic Archaeology“ or „Near Field Cosmology“
© Michael Staudt/grafikfoto.de

The Milky Way is not axisymmetric and has substructure - good!



Have data!

Have ages!

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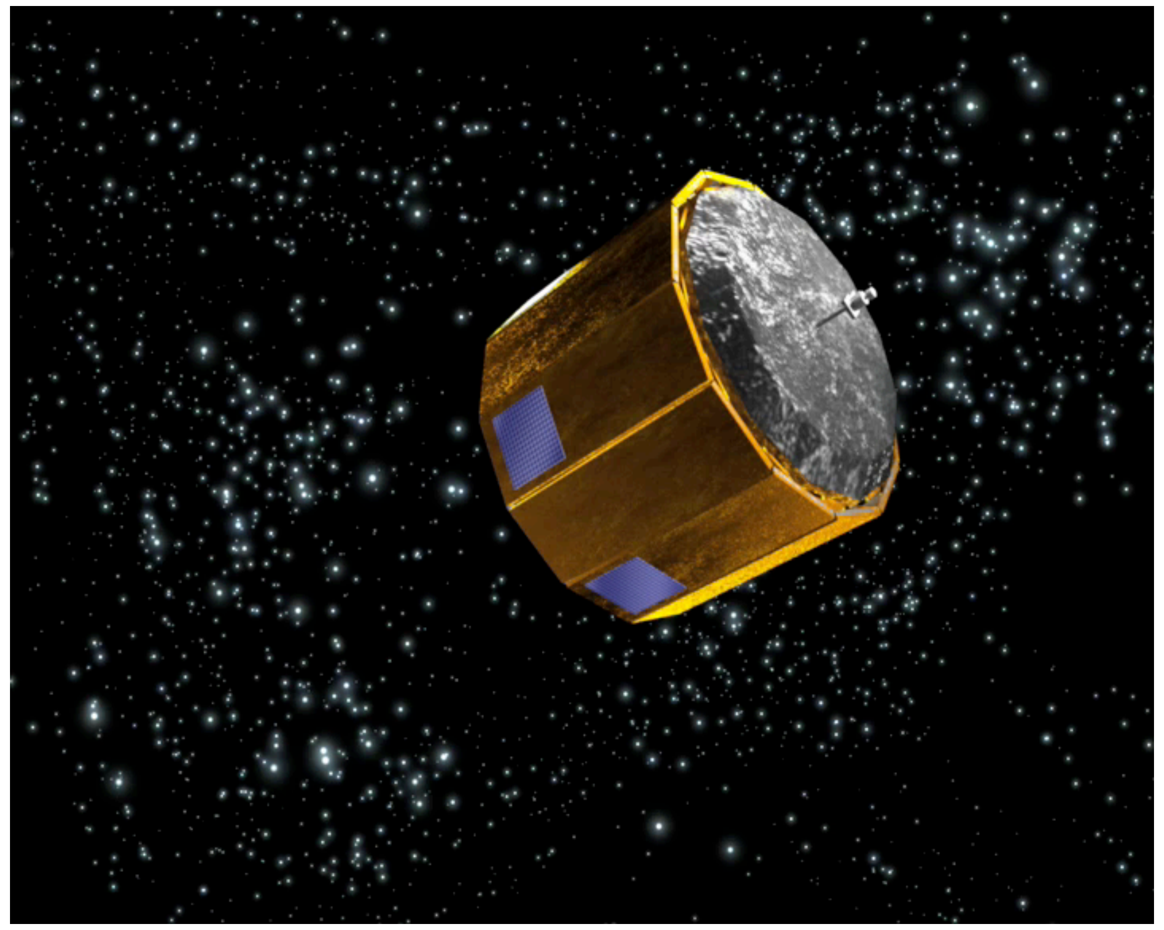
The not so nice things about stars

- Getting the data is hard
- Understanding the data is even harder (completeness and selection effects)
- for almost all stars the available data is highly incomplete
  - data driven and machine learning approaches
- Galaxies are roughly as old as the universe, not really equilibrium or stationary system

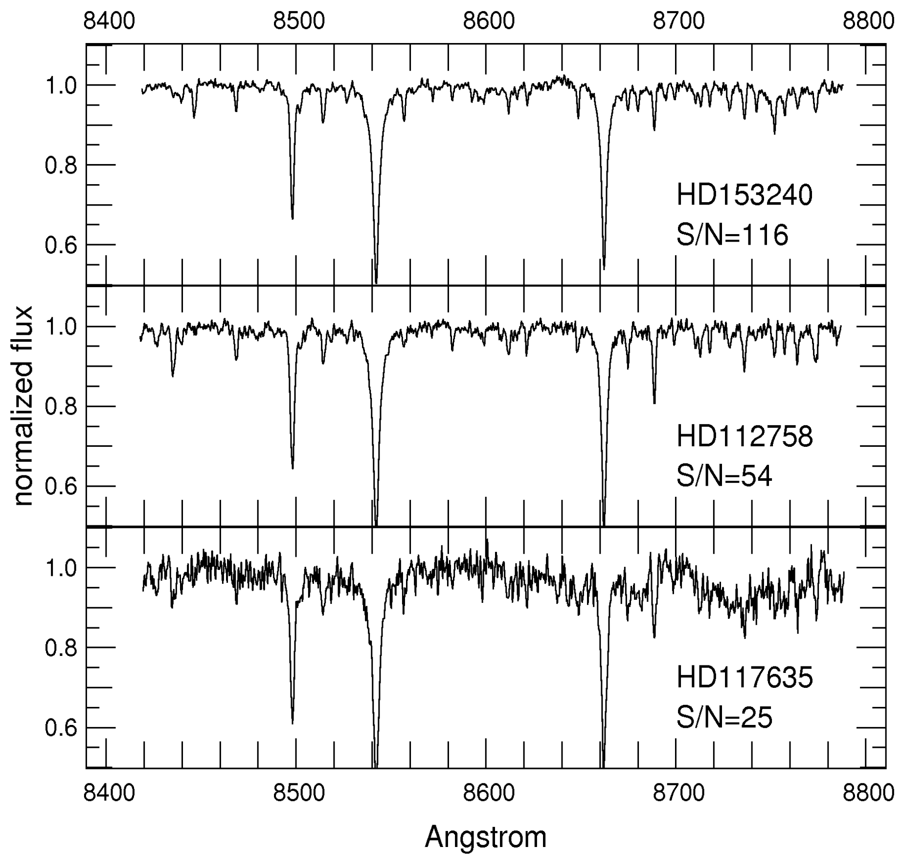
$\Longrightarrow$ modeling is difficult $\Longrightarrow$ simulations

We choose to do these things not because they are easy, but because they are hard

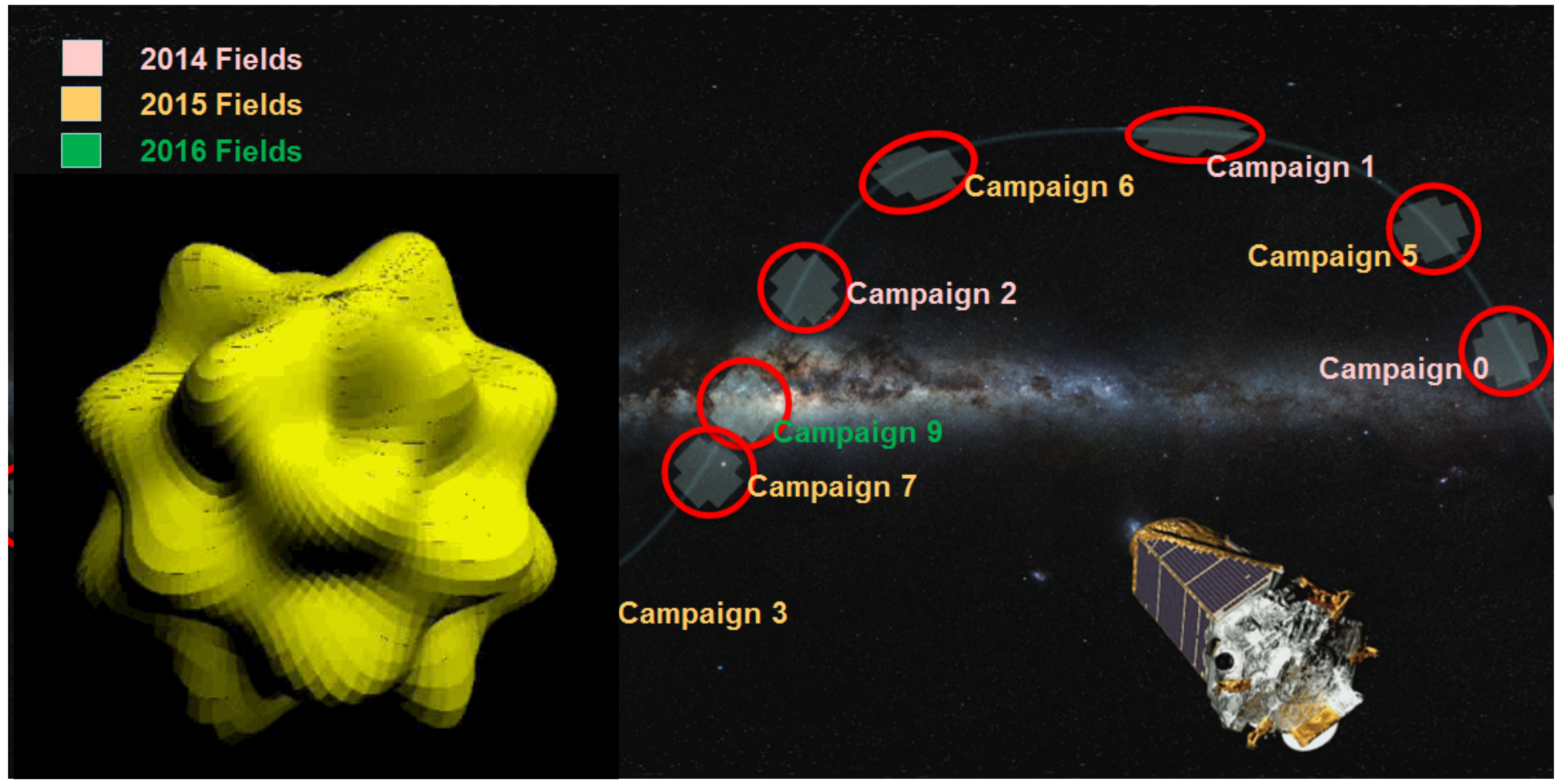
Getting the data



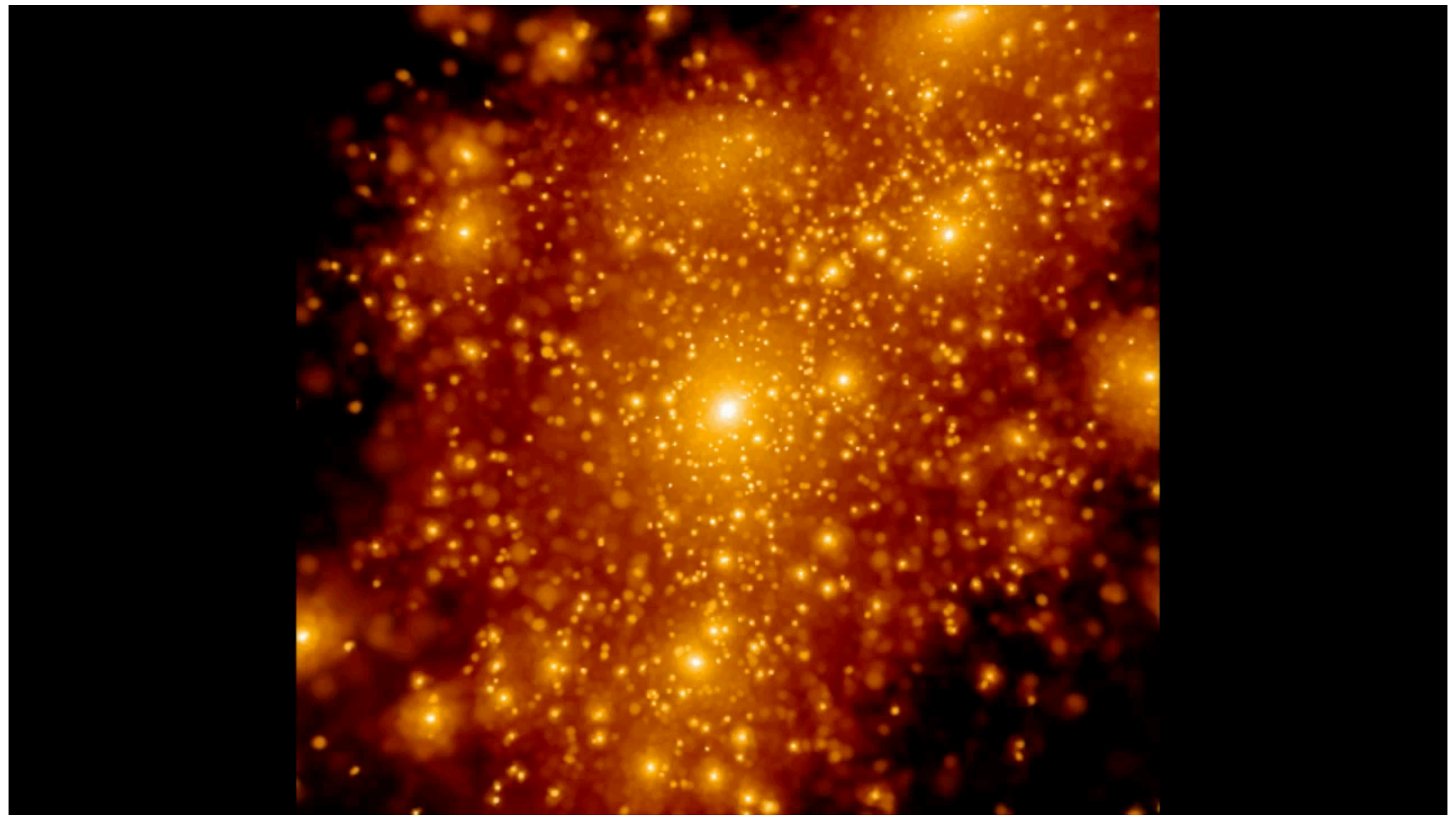
Astrometry: Positions, Distance & Velocities



Spectroscopy: Abundances & Radial Velocities

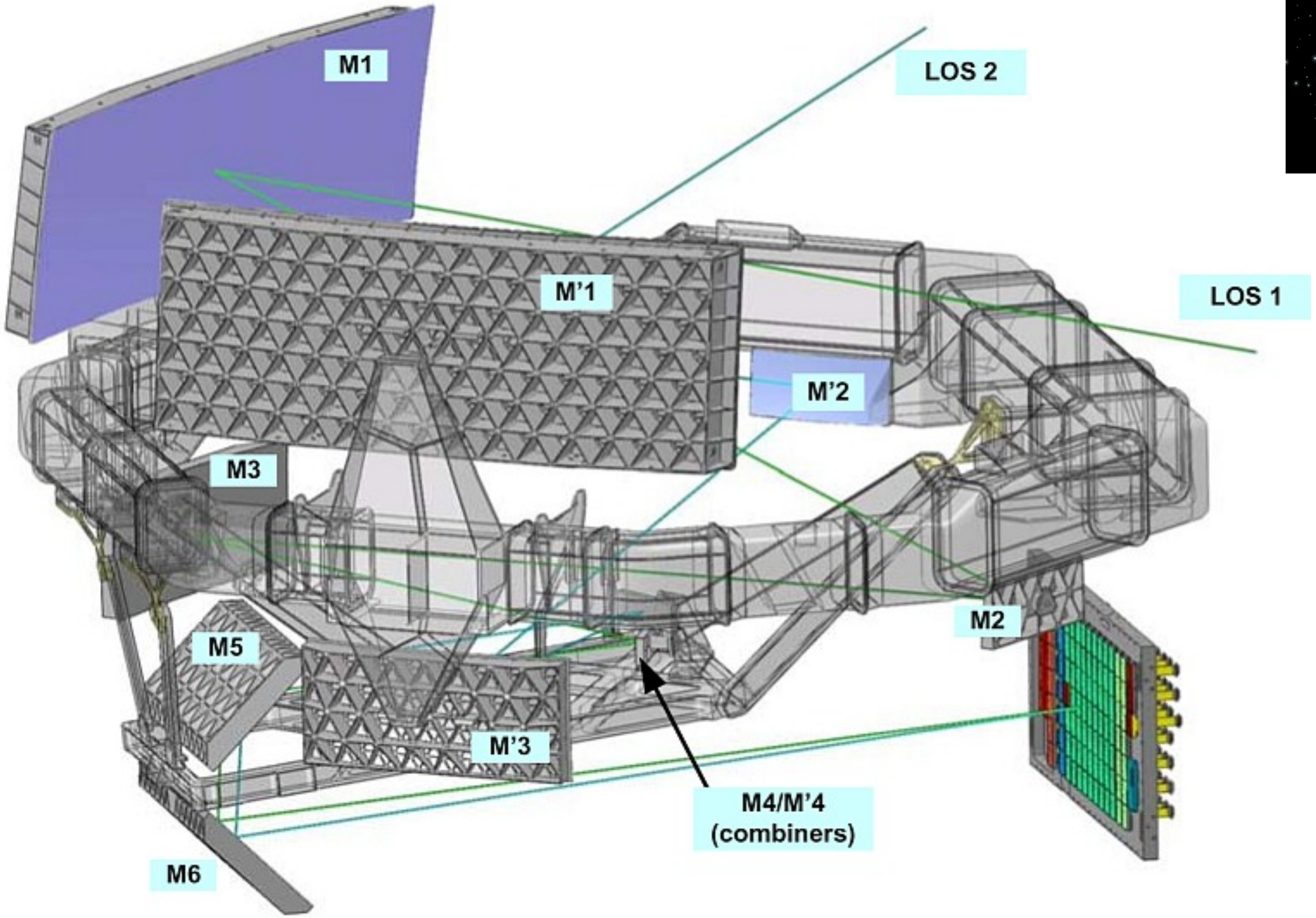


Astroseismology: Ages



Simulations: Theory backbone

The Gaia Telescopes



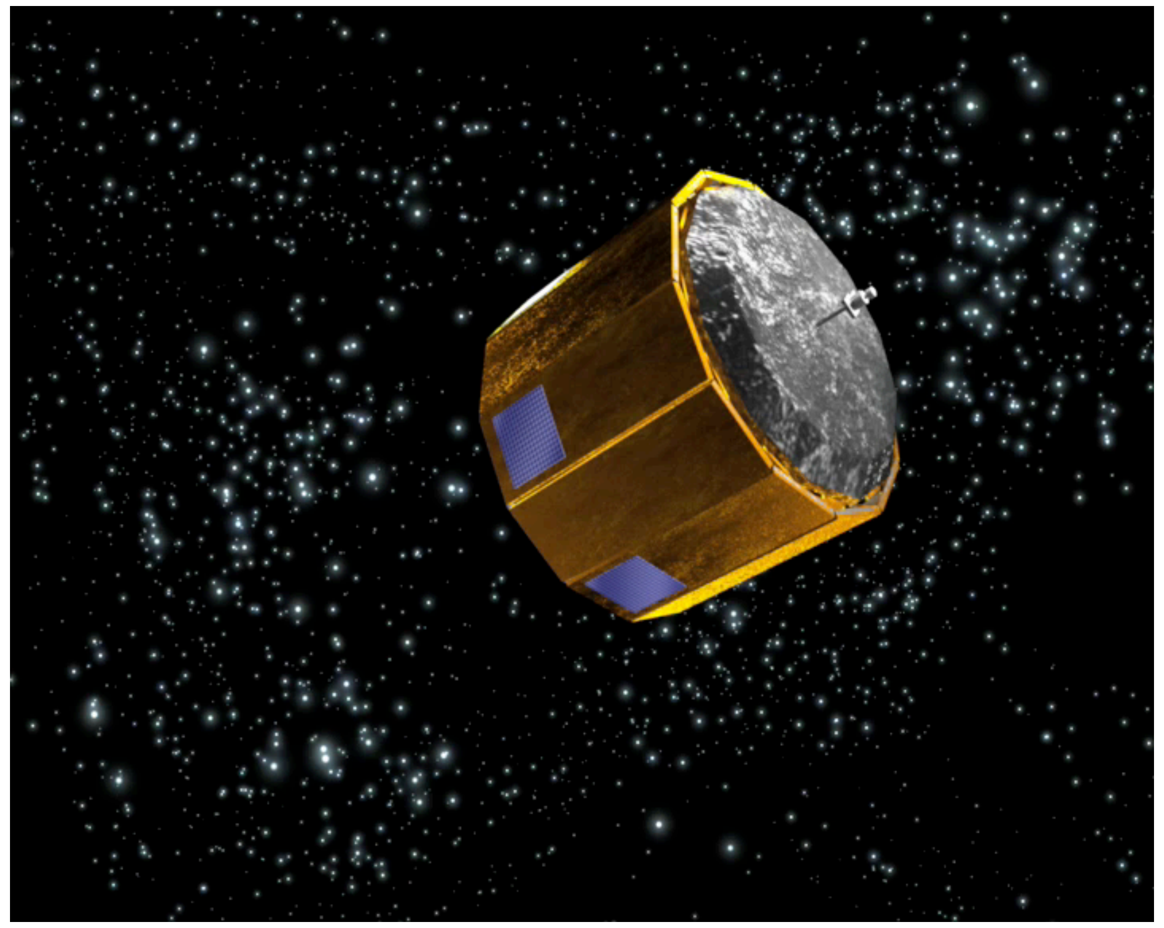


image credit: ESA

The Gaia Optics

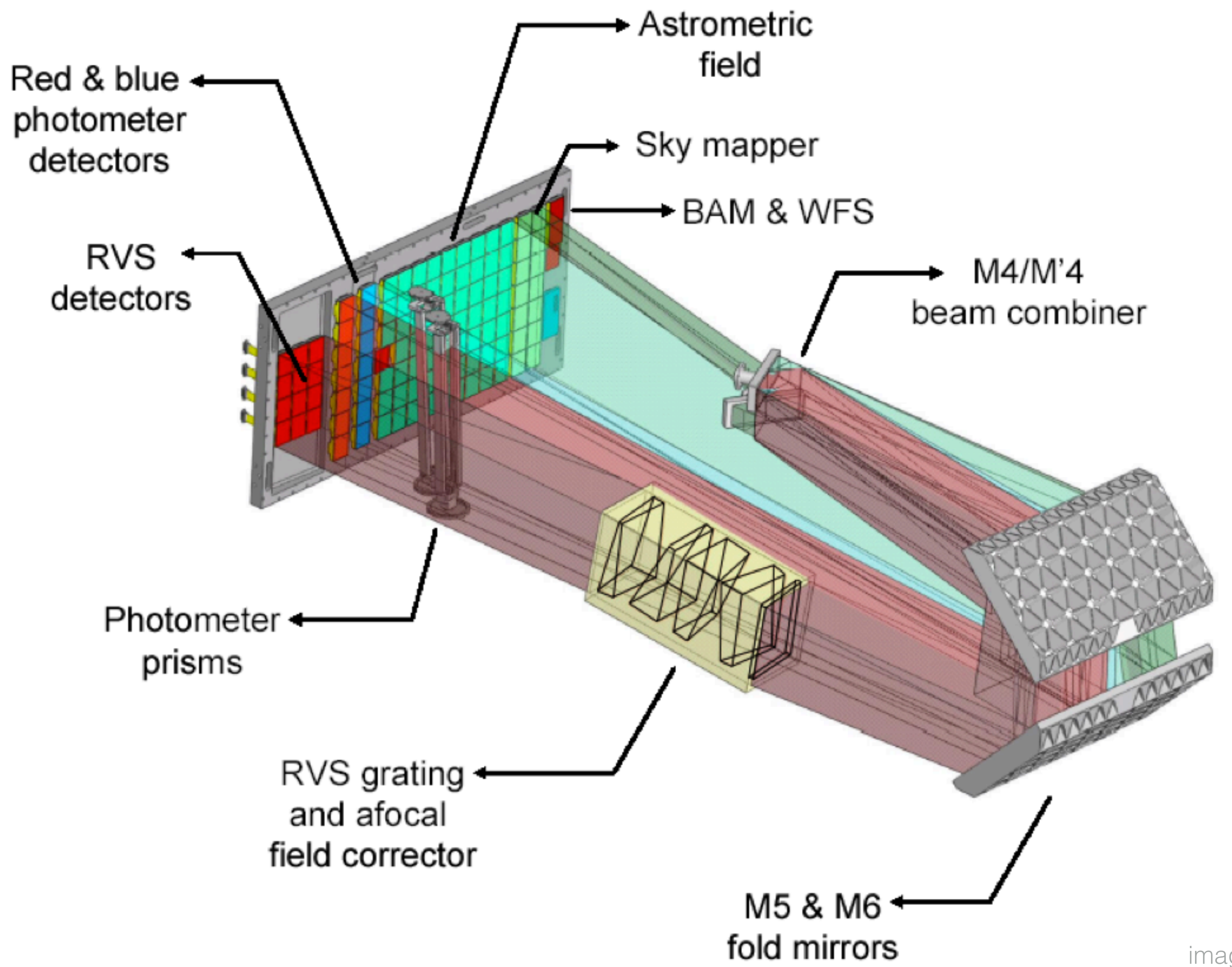
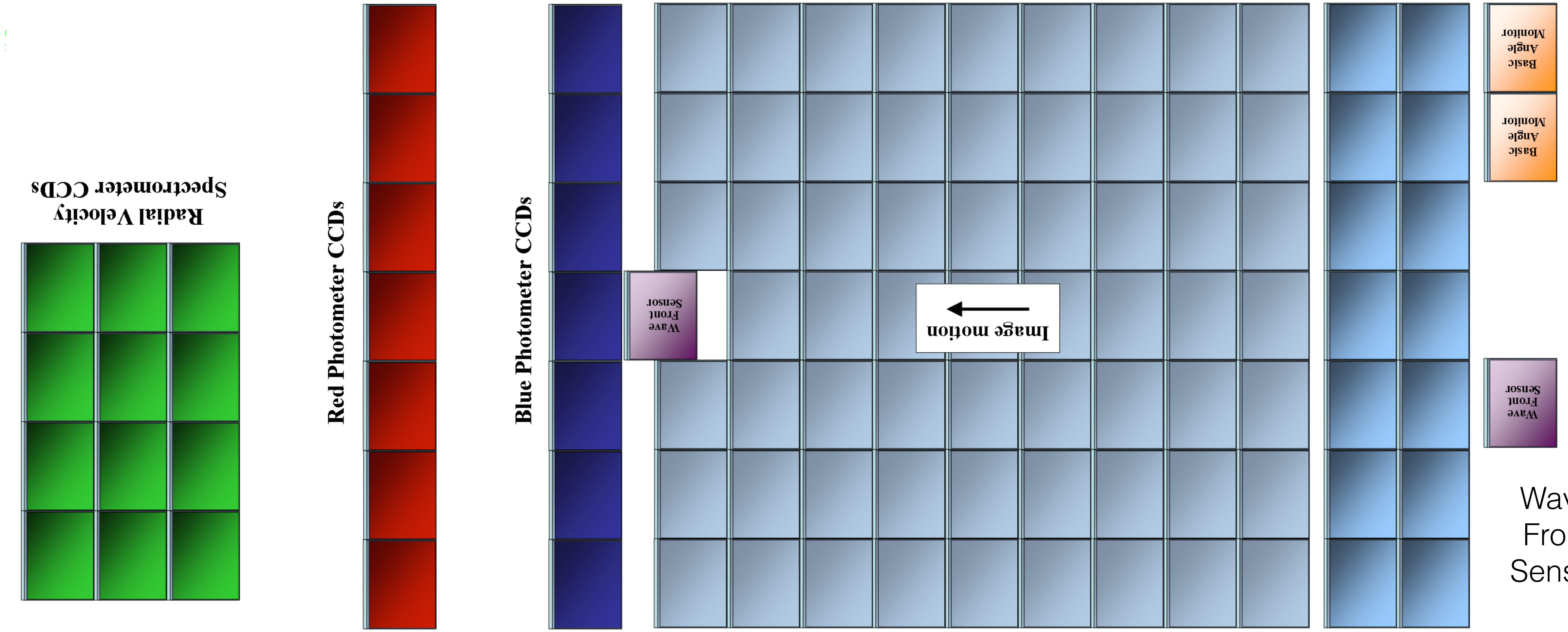


image credit: ESA

Detectors and Focal Plane

Basic Angle Monitor



Wave Front Sensor

Radial Velocity Spectrometer

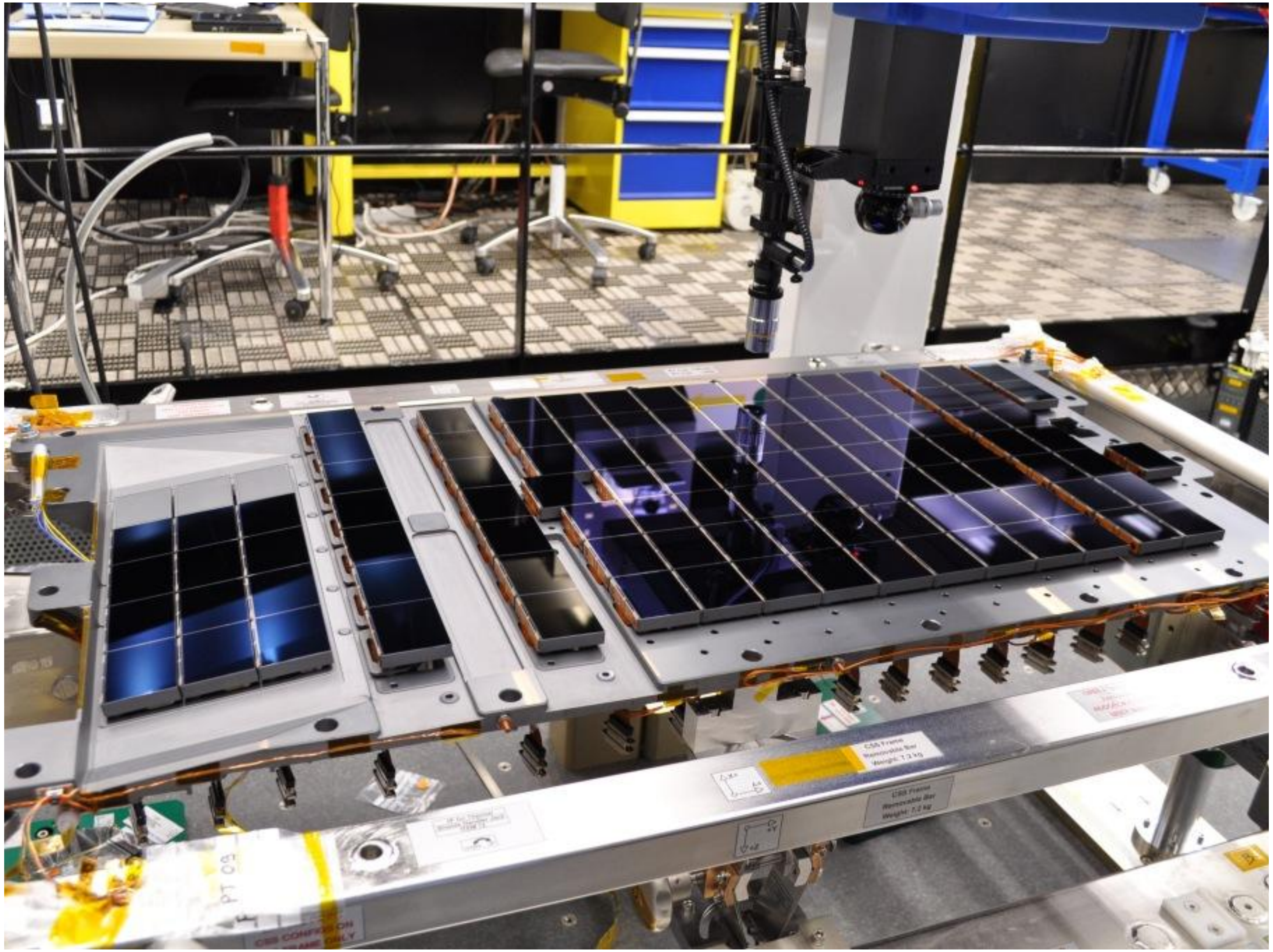
Red & Blue Photometer

Astrometric Field

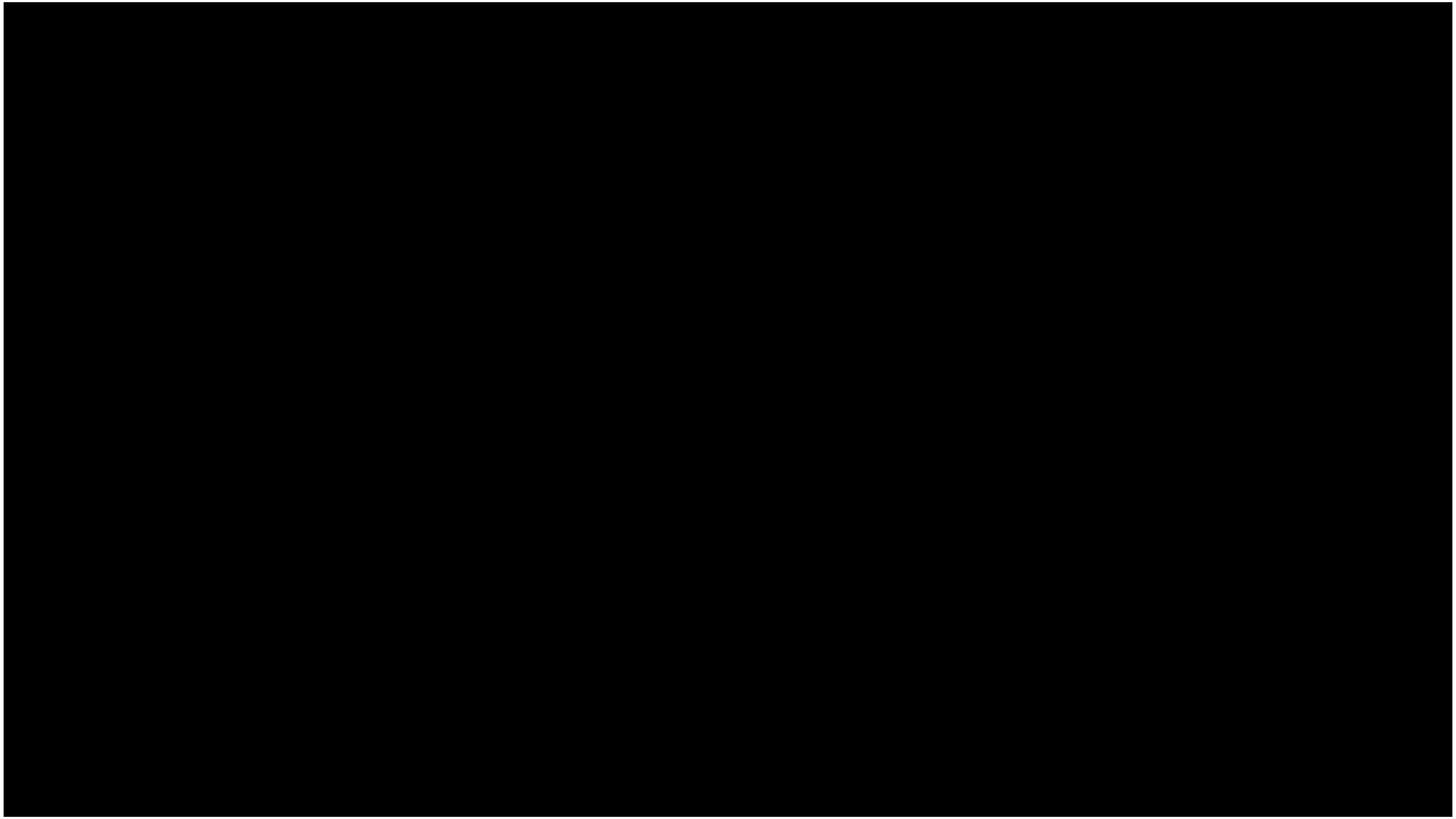
Sky Mapper

image credit: ESA

Gaia recap



Focal Plane

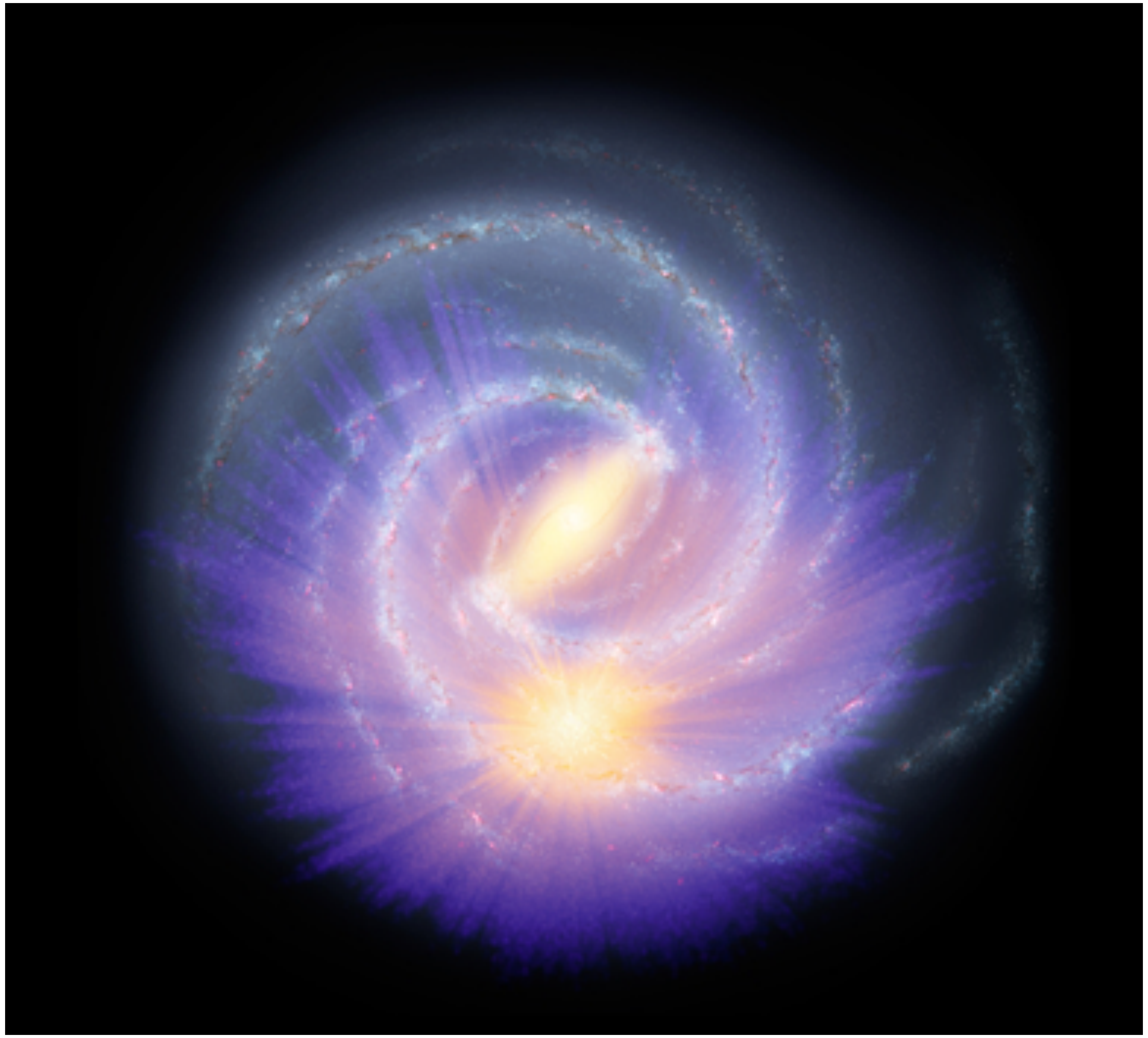


19 December 2013

The Gaia challenge

- Measurement challenge:
  - Milky Way + satellite system:
    - Extend: ~100 kpc ⇒ 10 μas
    - Characteristic velocity: 10km/s at 100 kpc ⇒ 20 μas yr^{-1}
  - 10 μas corresponds to the angular size of a quarter (or a Euro) seen at the distance of the Moon
  - 20 μas yr^{-1} corresponds to the growth rate of the human hair seen at the distance of the Moon
- Data analysis challenge:
  - For comparison: relativistic light bending by the Sun at angle 90° (that's what we call night): 3000 μas
    ⇒ Relativistic light bending of all major planets have to be included, Jupiter even in post Newtonian approximation
  - Tightly coupled equation system involving all data collected (eventually) over the full mission period
  - Systemic biases: distance = parallax^{-1}, and a positively defined properties. Owing to errors, measured parallaxes can be negative. Simple cuts introduce severe biases, in particular when convolved with stellar density distribution
- Spectral data only at medium resolution for a small wavelength range and a limited number of targets, low SNR (but many epochs!)

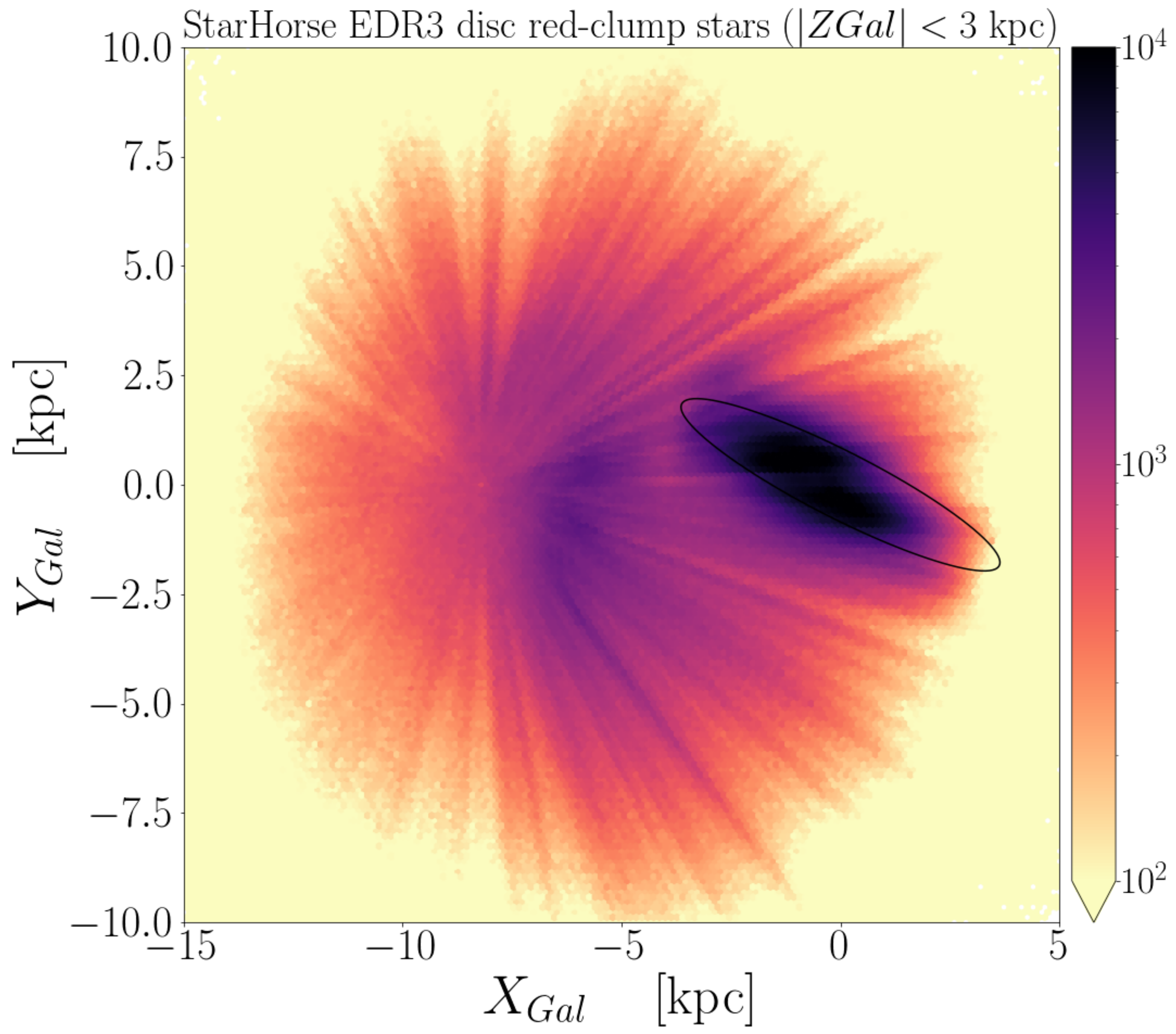
Gaia DR2 + photometric catalogues + Bayesian model



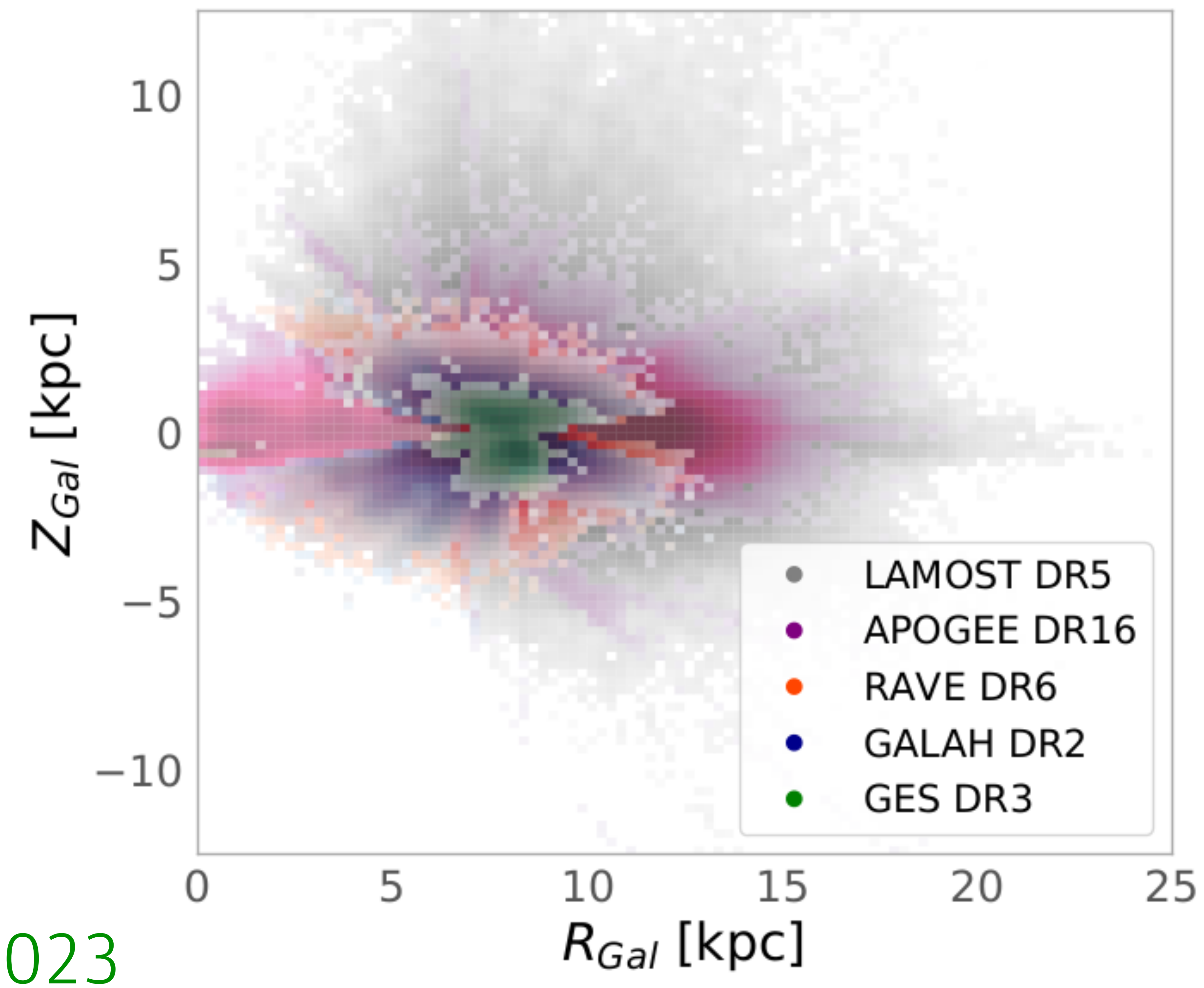
Almost as if we can see our Galaxy from above!

Anders et al 2019 Gaia DR2
(~265 million stars)

Gaia DR3 + photometric catalogues + spectroscopic catalogues+ Bayesian model

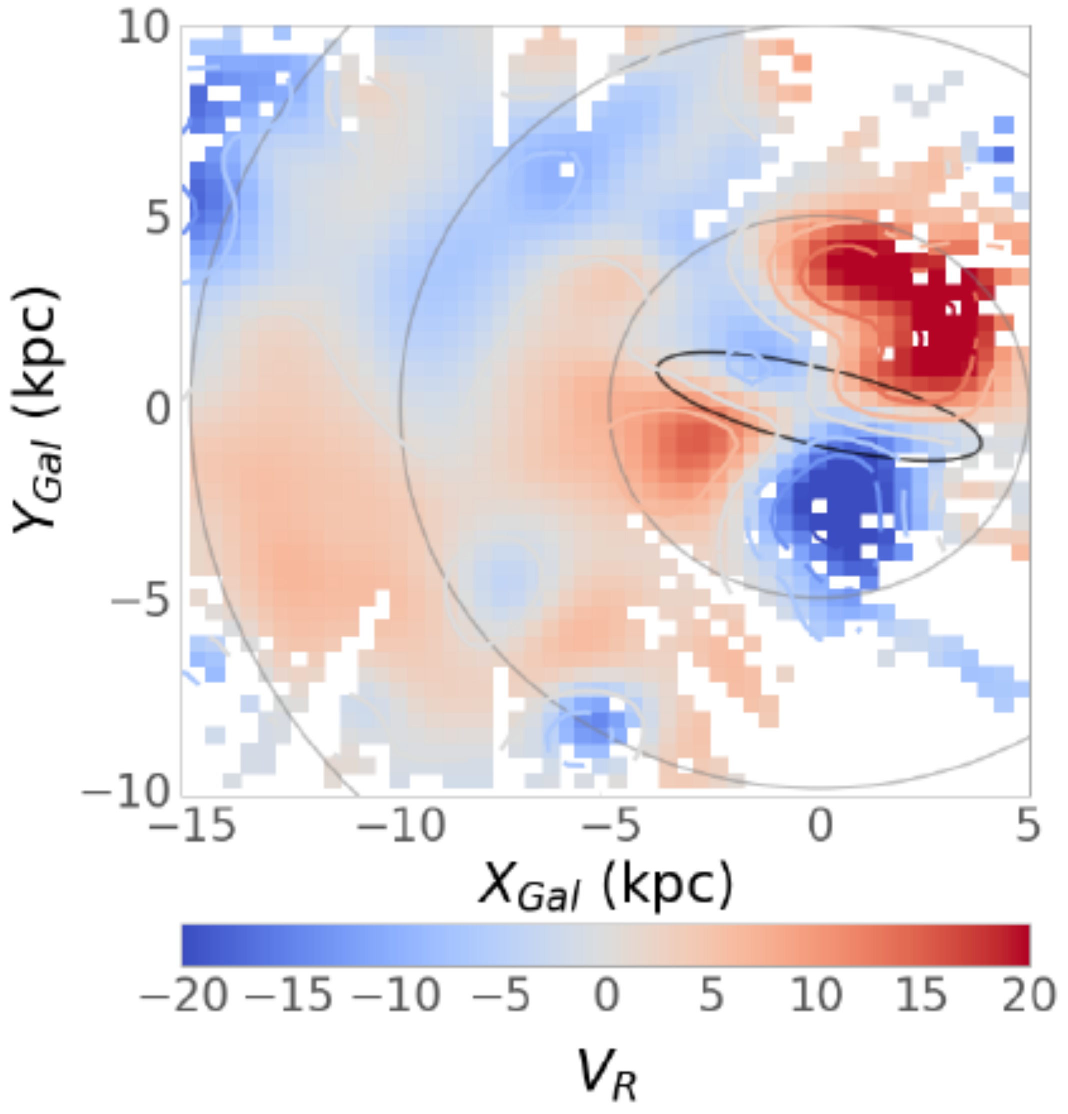


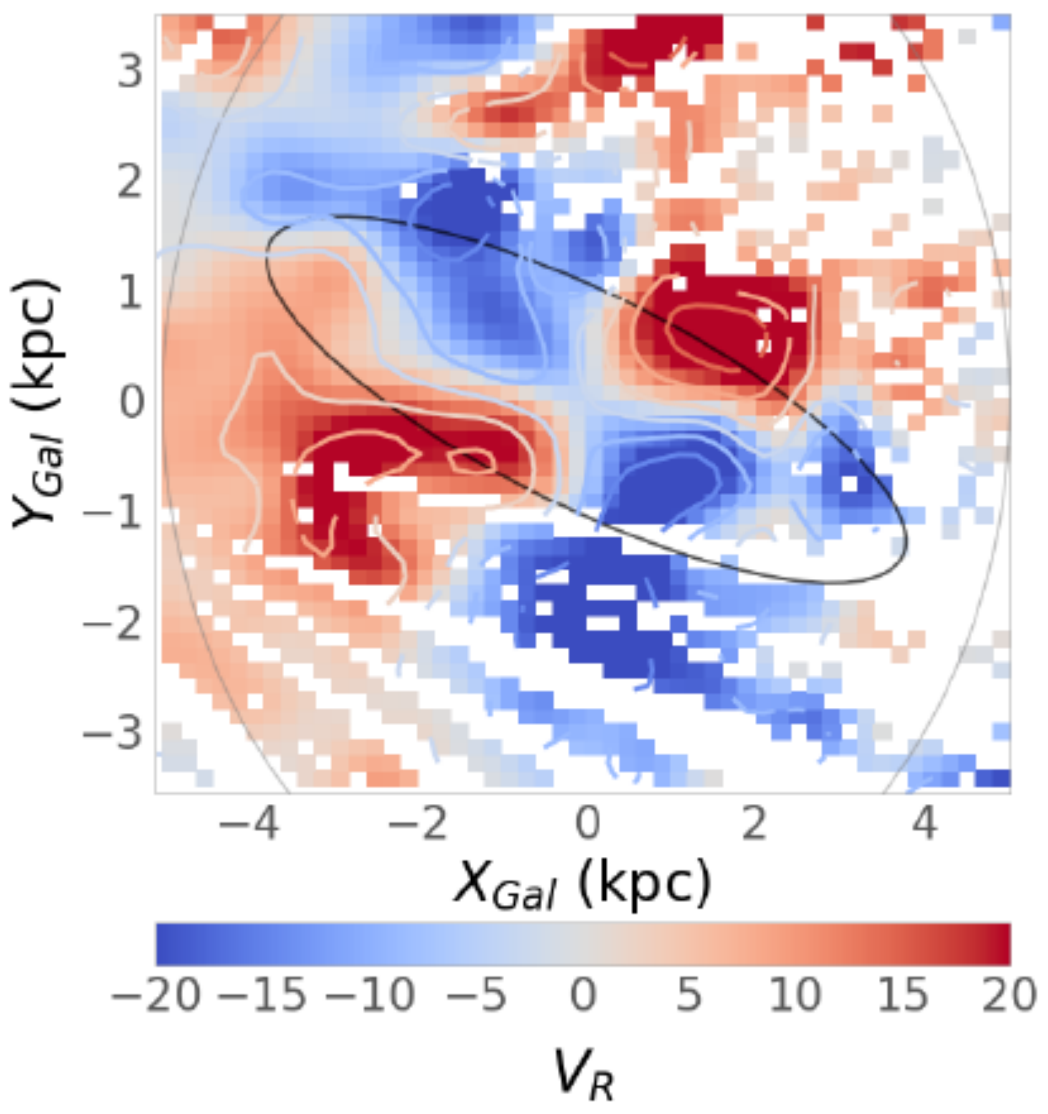
Now with ~360 Million stars



Queiroz et al 2023

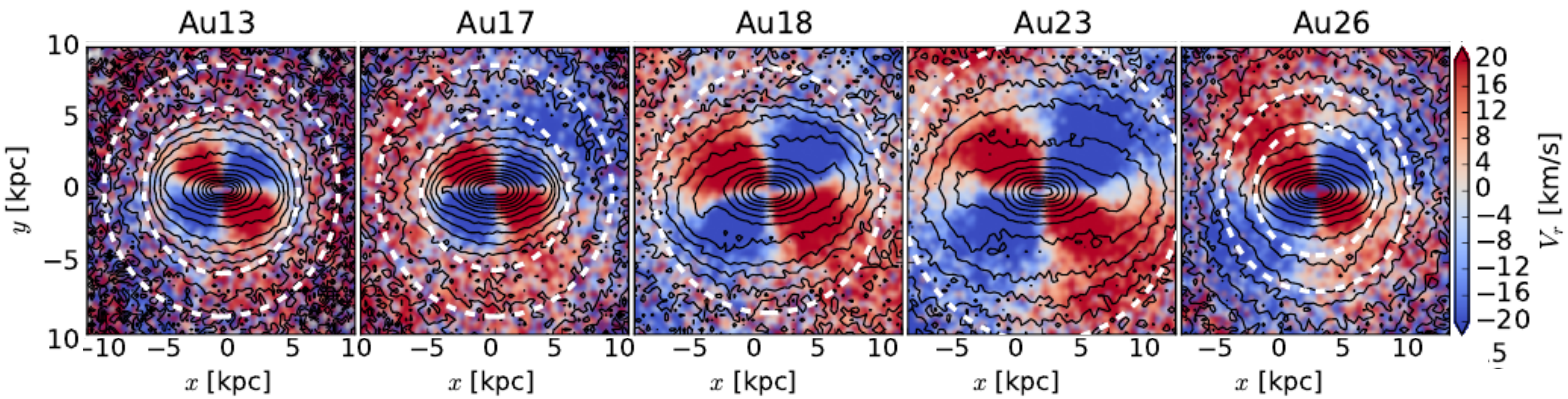
Using APOGEE DR17 + Gaia in the inner Galaxy (Kinematics)





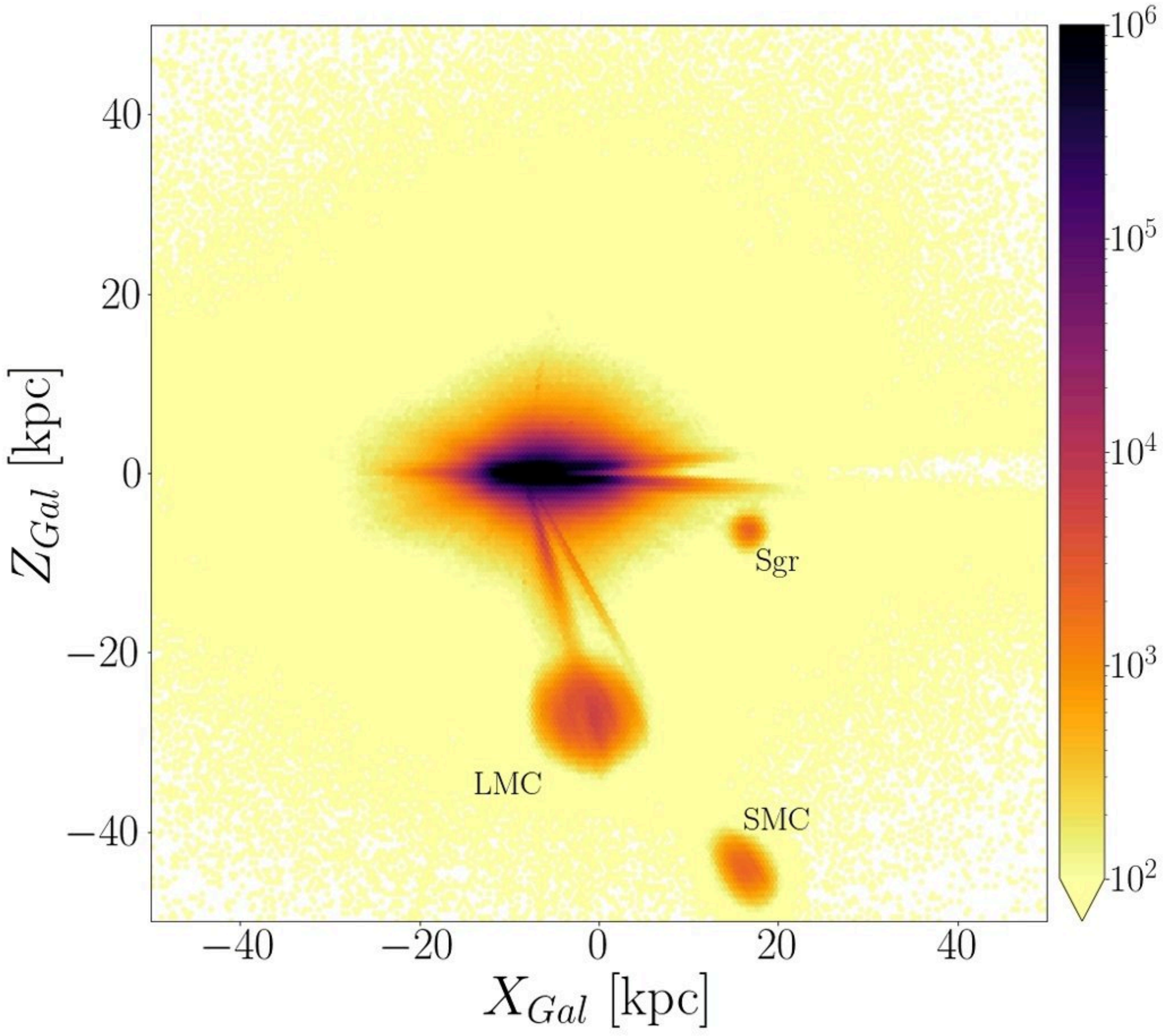
Queiroz et al 2021

The quadrupole of the Galactic bar is confirmed, reassuring distances measurements



Auriga simulations Fragkoudi et al. 2019

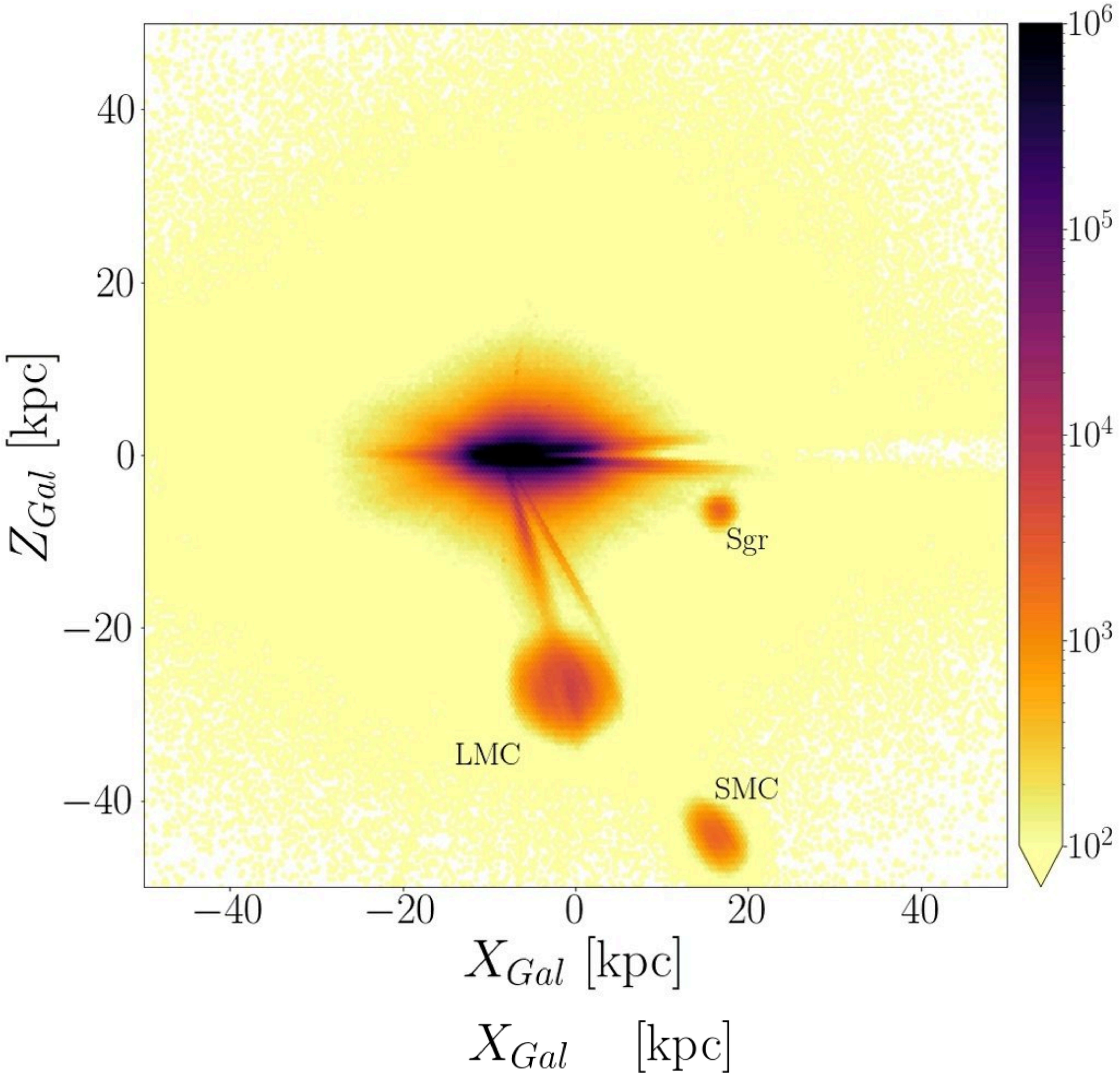
Going deeper …

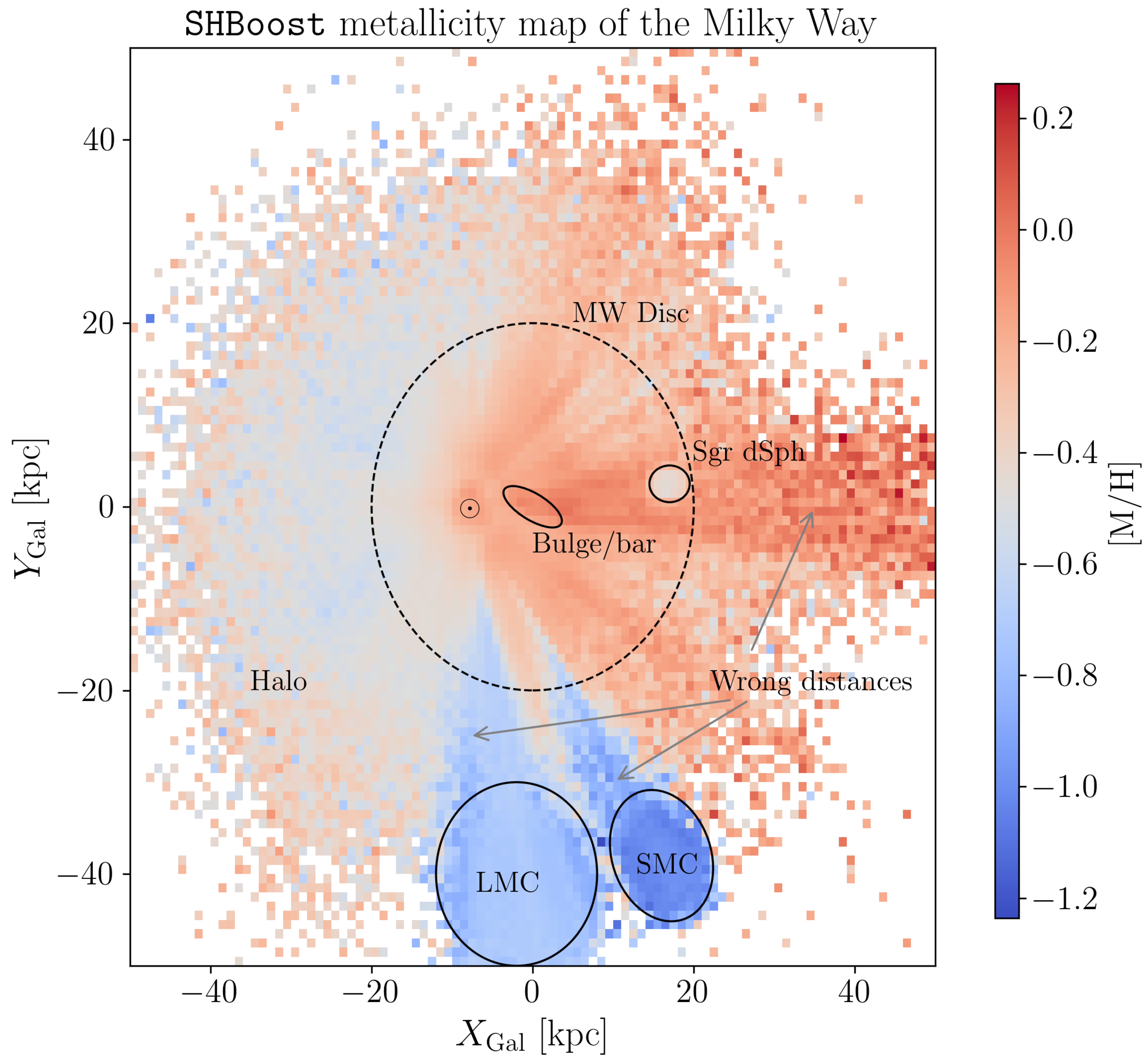


X_{Gal} [kpc]

Queiroz et al 2023

Going deeper + constraining abundances using machine learning





Khalatyan et al 2024, arxiv:2407.06963

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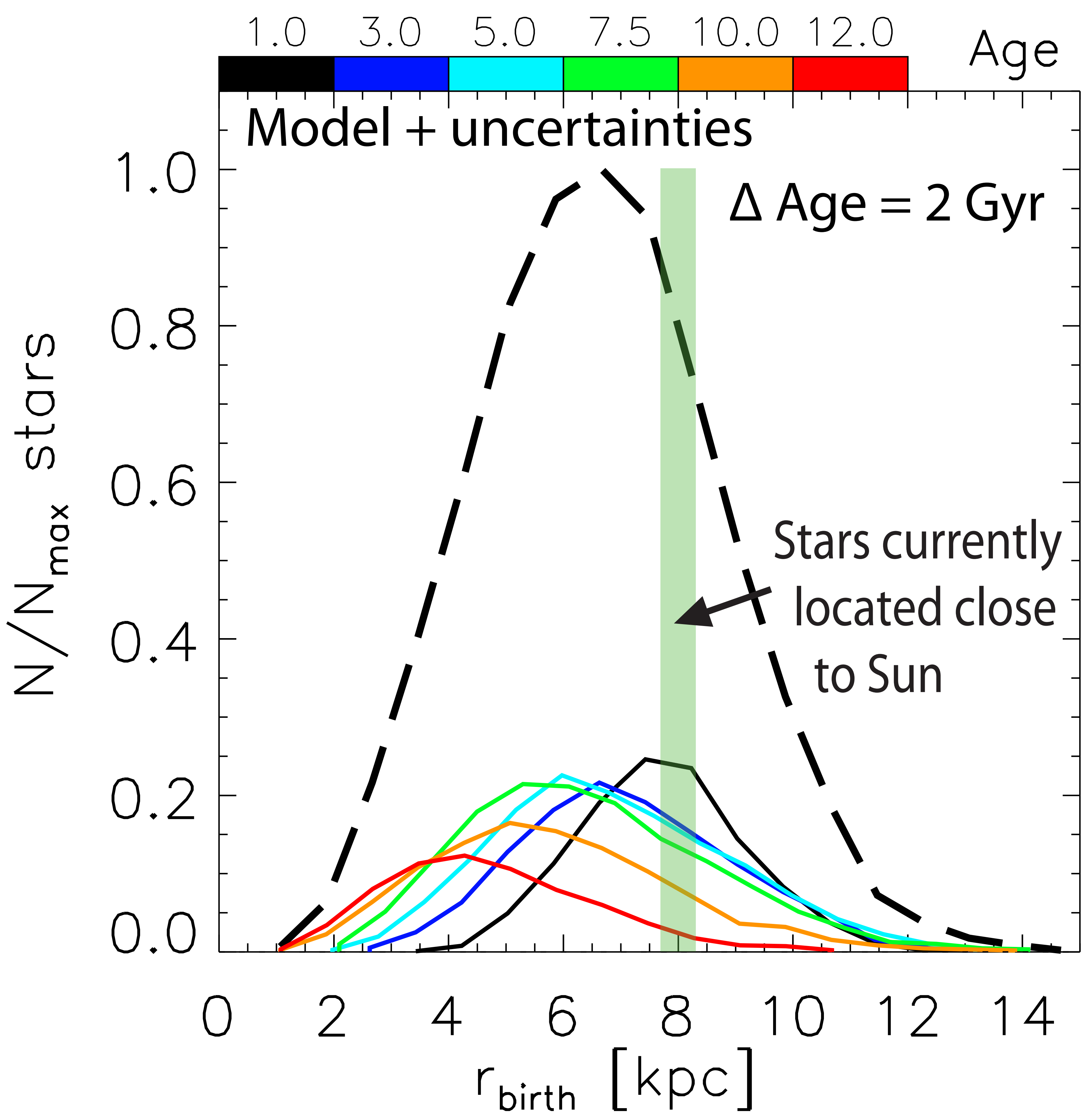
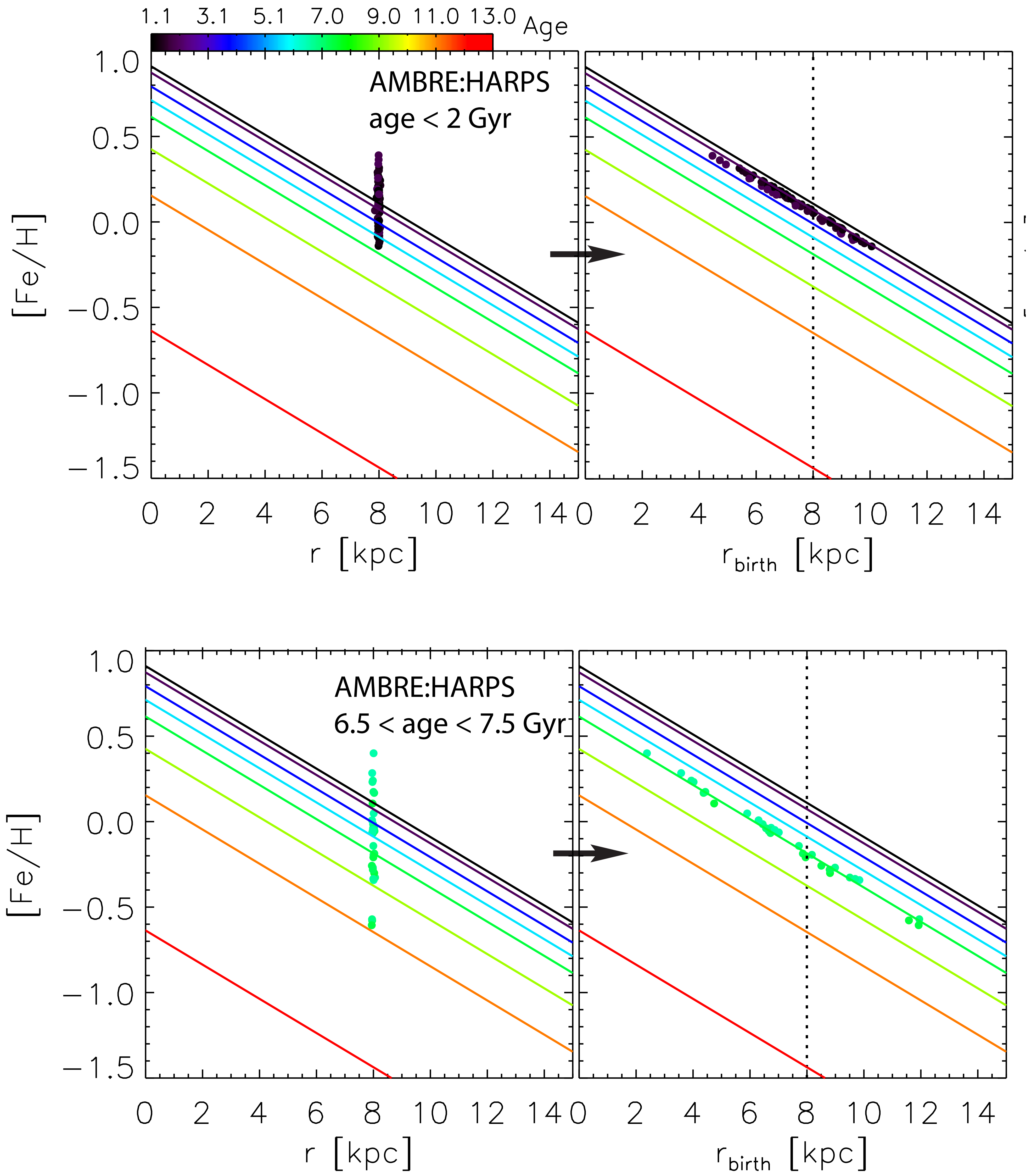
First step: tracing back the birth radius of disk stars (Minchev et al, 2018)

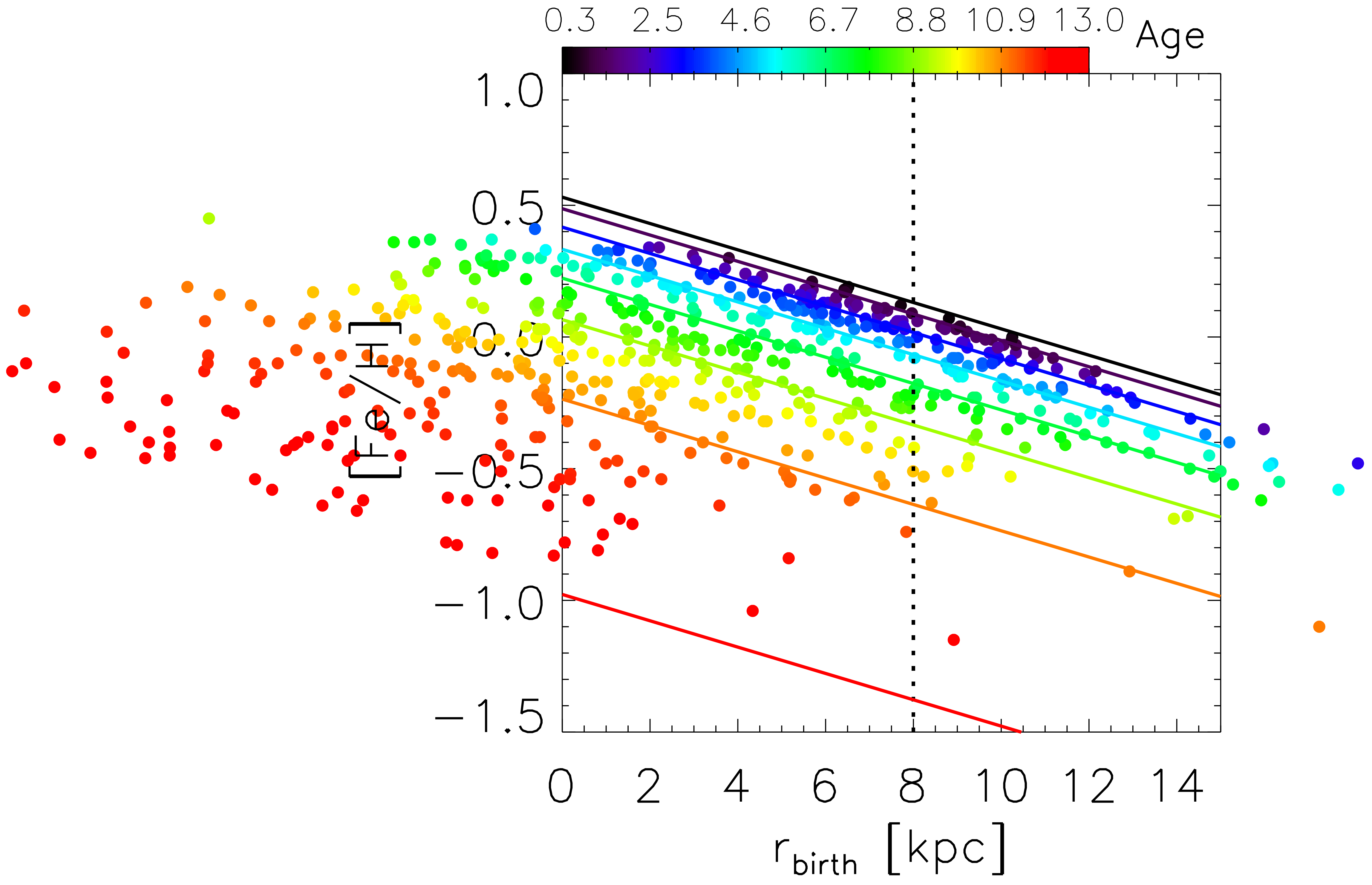


Minchev, Chiappini, Martig 2013 simulations

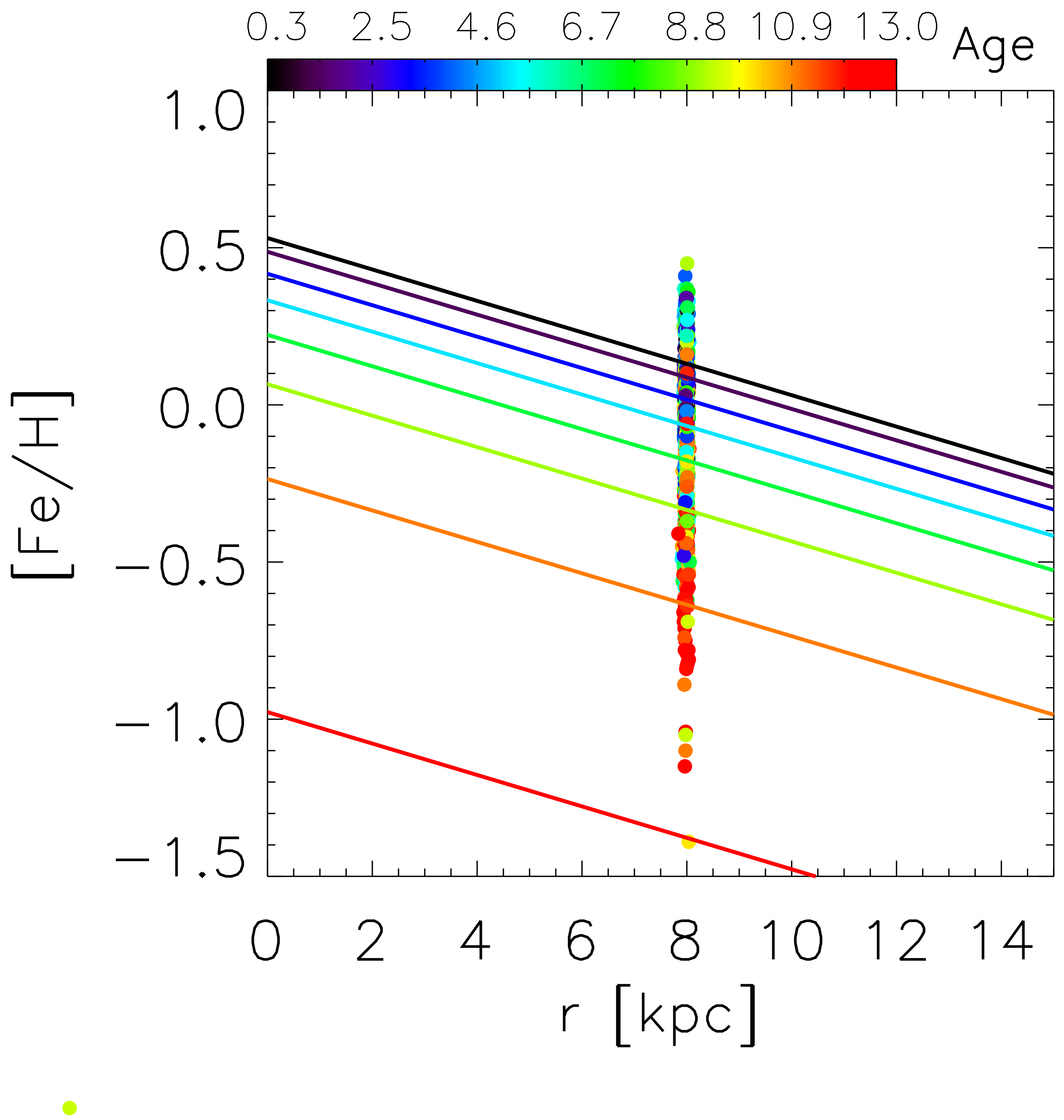


What if gradient was flatter? How flat is too flat?

✓ Only age and metallicity necessary
✓ Assume ISM metallicity gradient evolving with time
✓ Place stars on the slope by shifting in r according to age and [Fe/H](r, t)

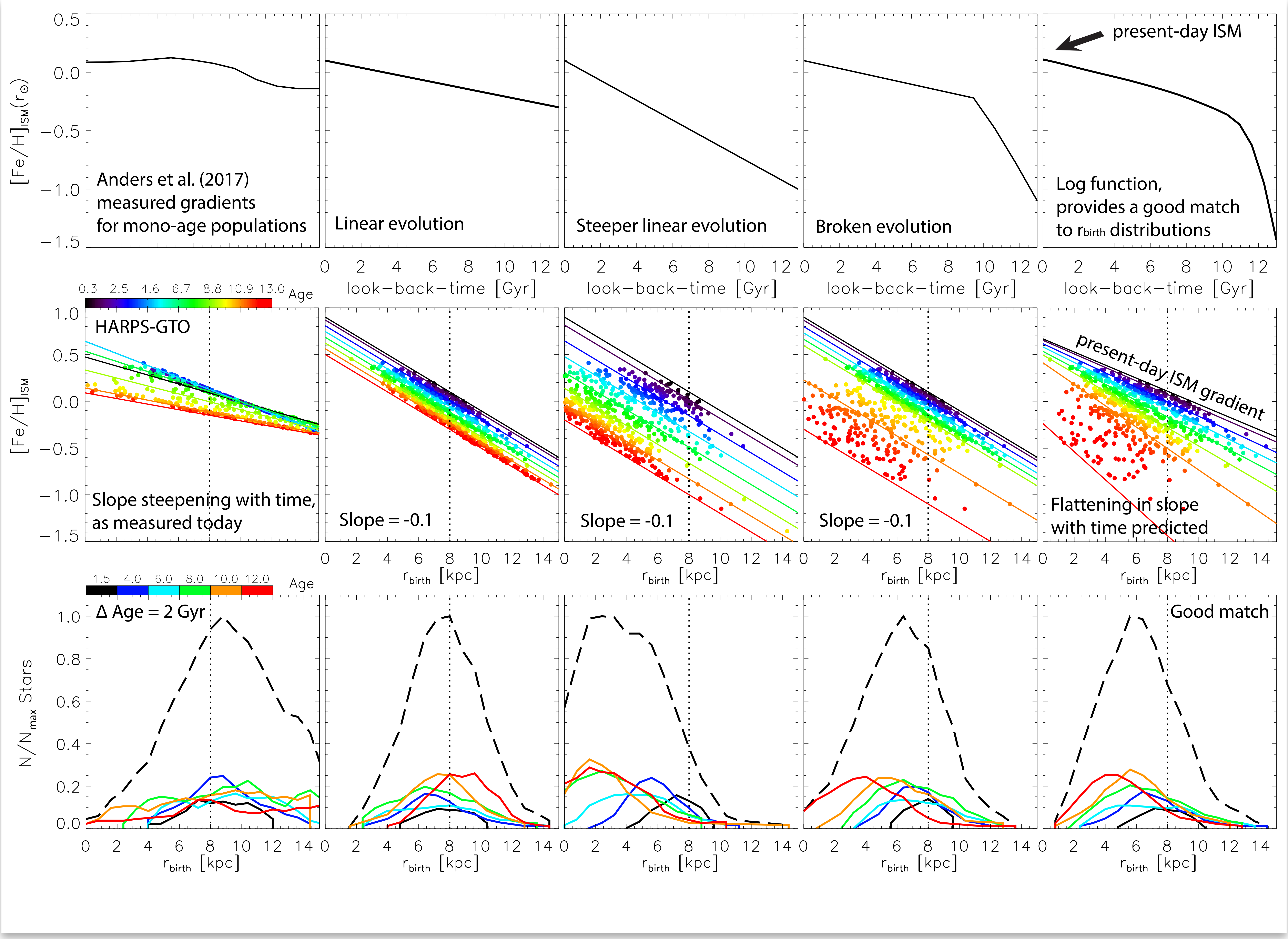


HARPS:AMBRE or HARPS-GTO isochrone ages



- Same scatter in [Fe/H] gives wider birth radius distributions
- When you start getting negative birth radii you know something is wrong

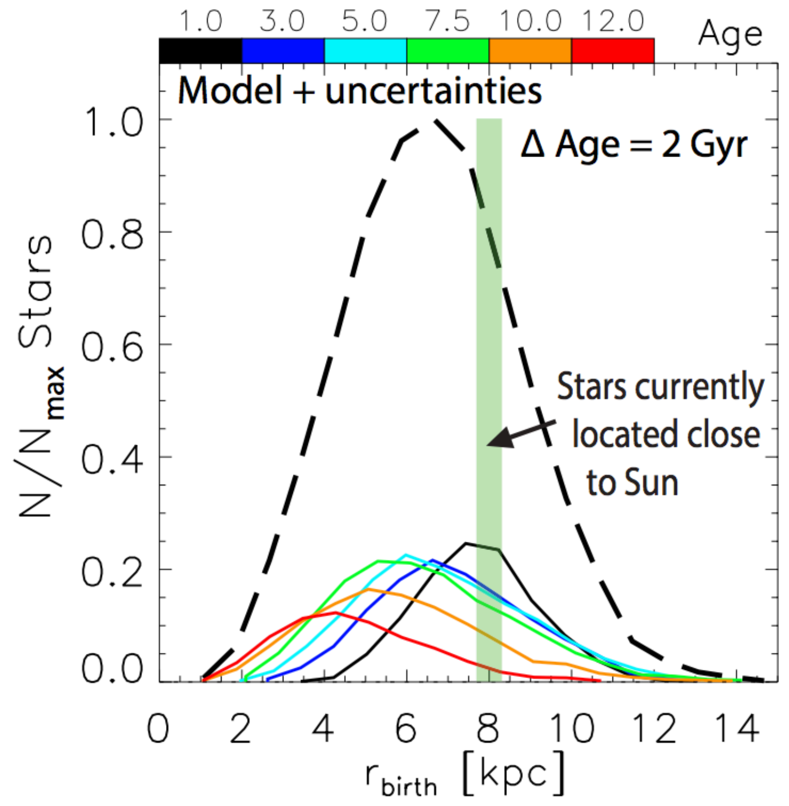
We can try different possibilities for the ISM [Fe/H](r, t)



Time evolution of [Fe/H] at Rsol

Time evolution of [Fe/H] slope

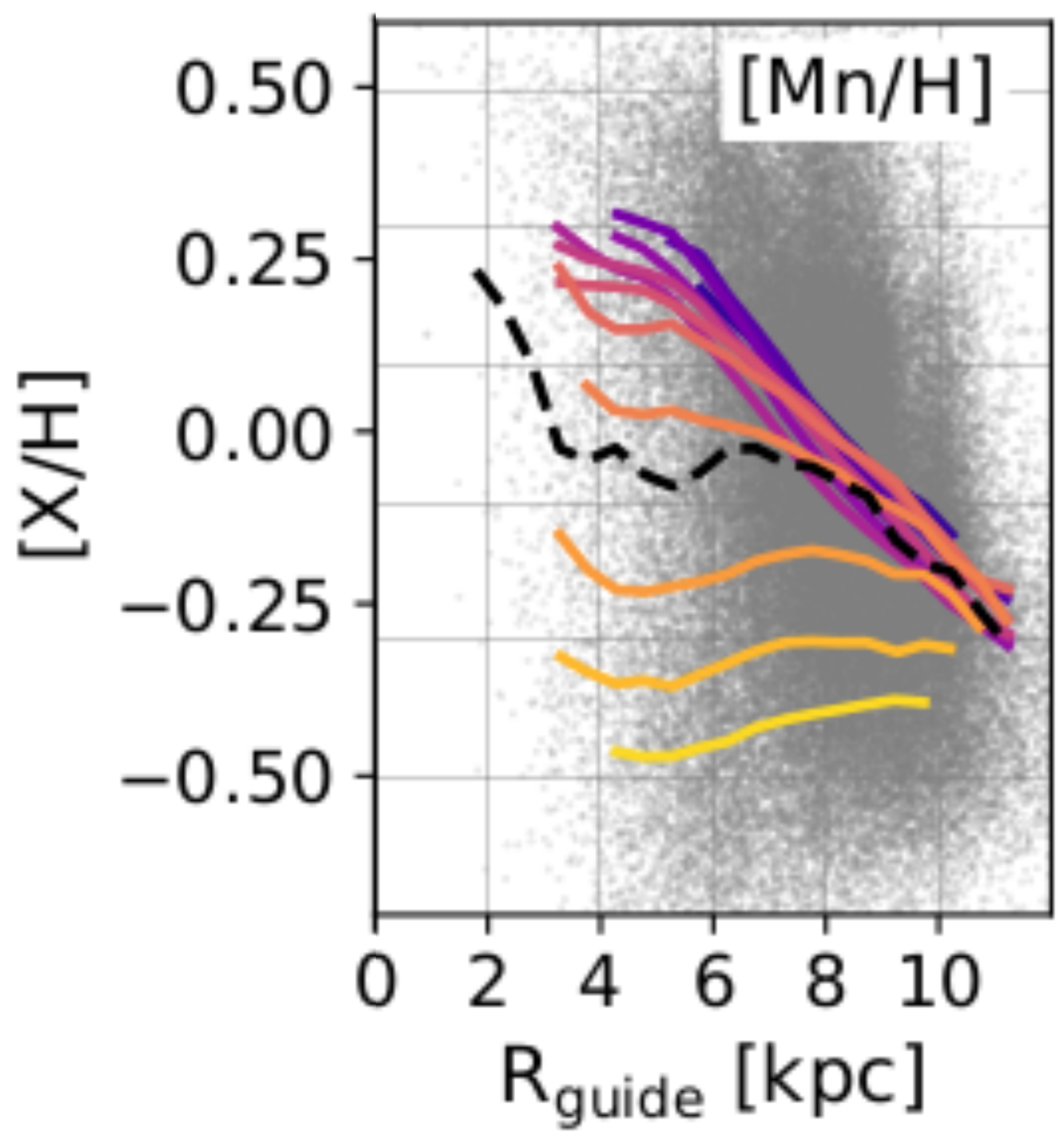
Typical Model



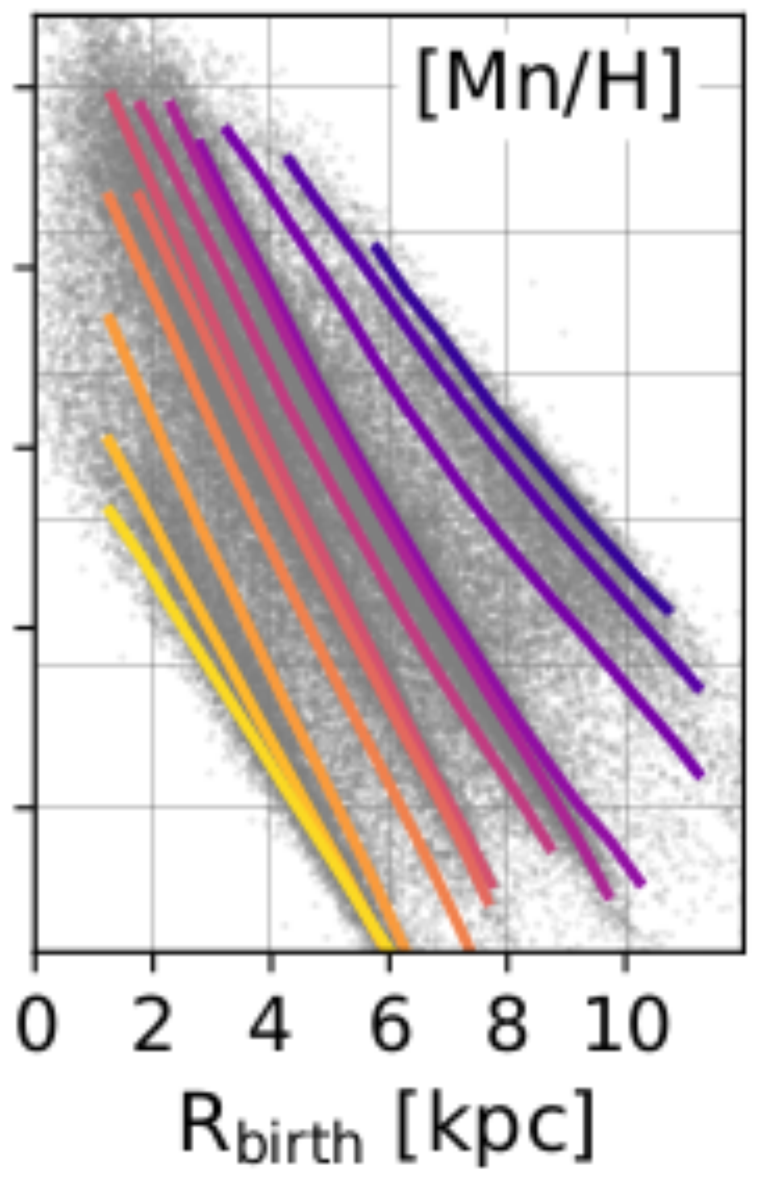
Birth radii of mono-age populations

Evolving Galaxy

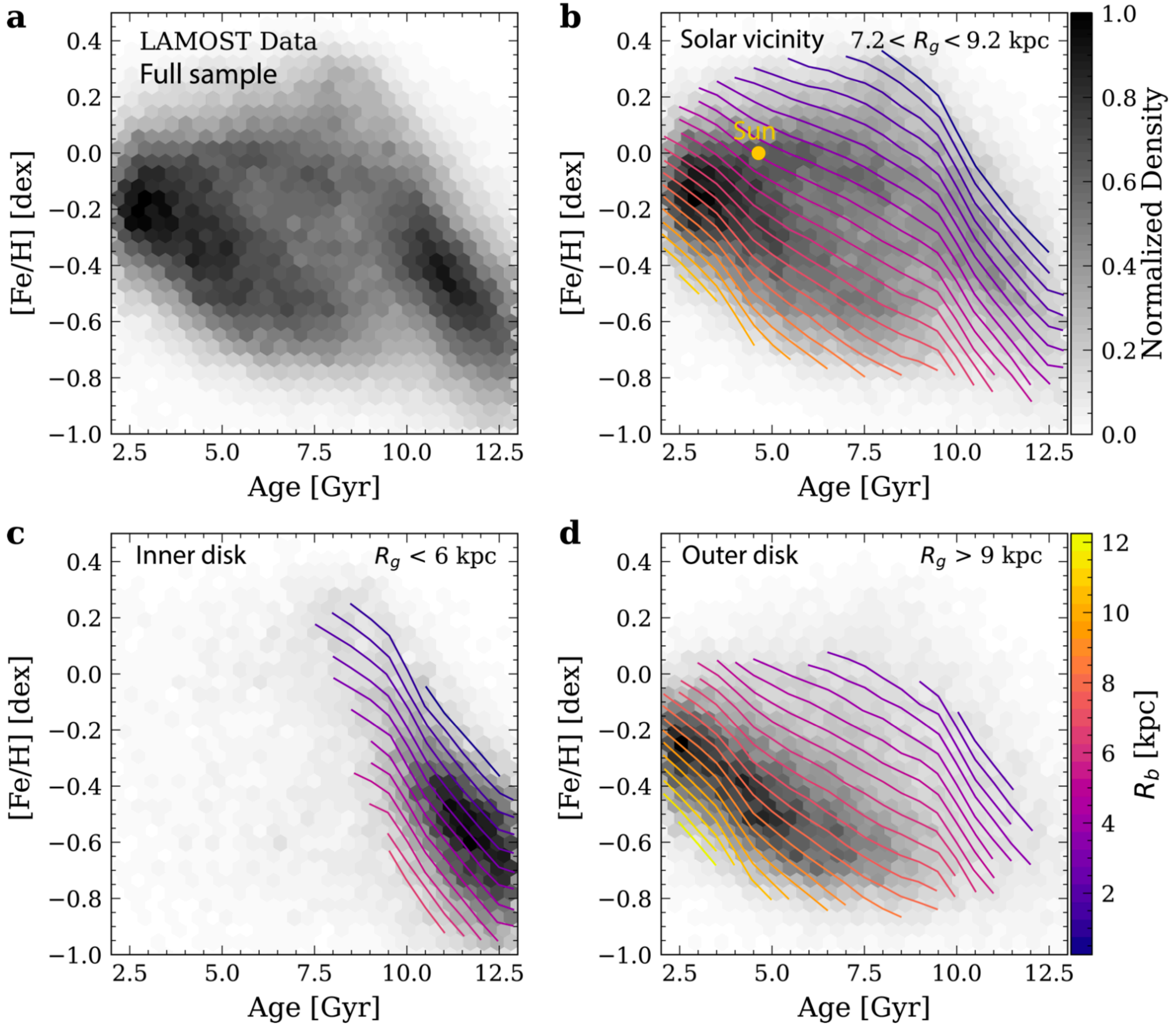
- Stars move and their velocities change, but chemical abundances remain preserved
- tension between observed and modeled/simulated data
  - observational gradients with age (Sales-Silva et al. 2022, Myers et al. 2022)
  - weakening of gradients over time due to migration



+ (age, [Fe/H])
Minchev et al. 2018, Lu et al. 2022,
Ratcliffe at al. 2023



Birth radius tracks in the Age-Metallicity relation
(note change in axis!)

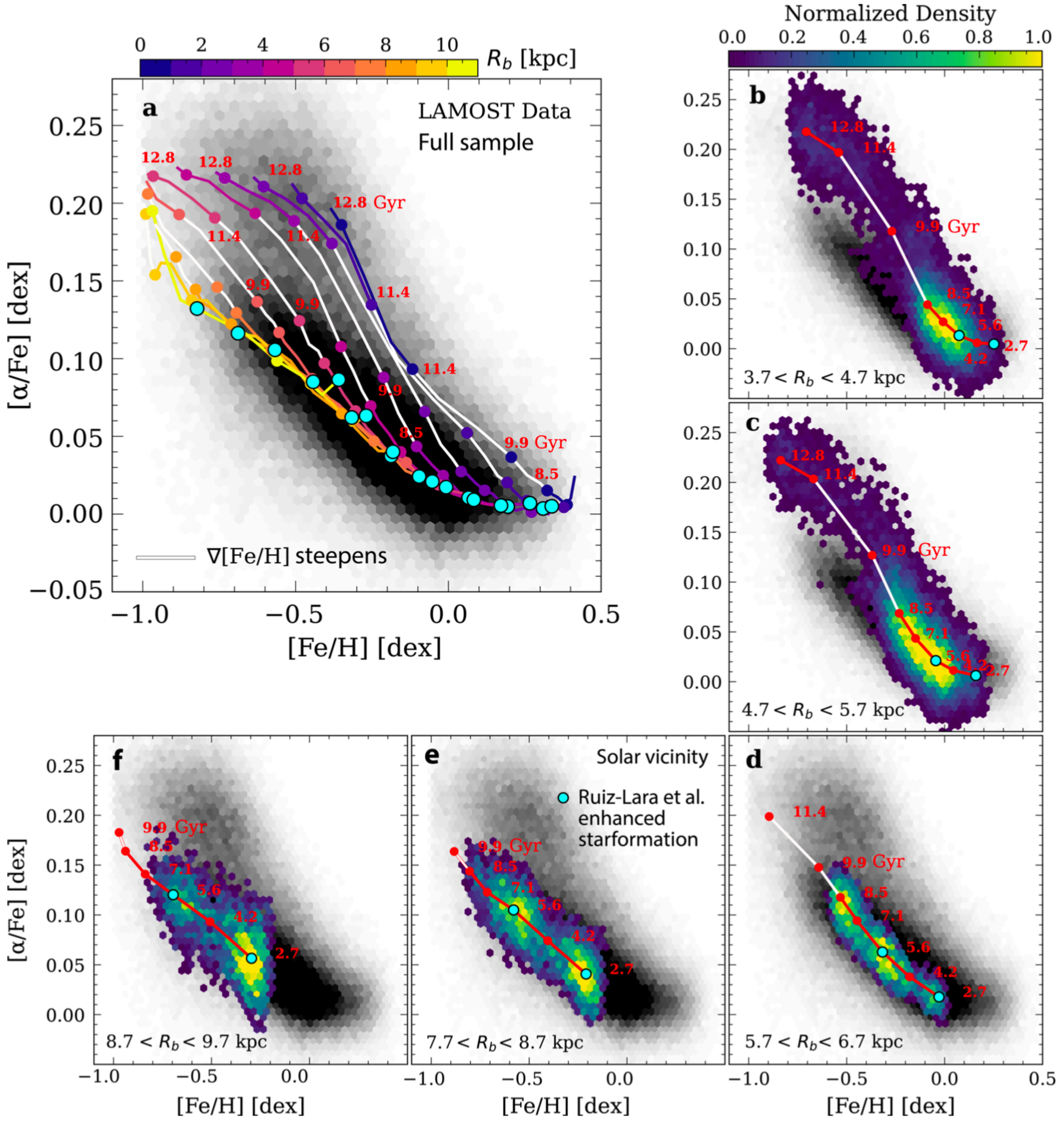


Sun born at R = 4.5 ± 0.5

Old ridge belongs to the inner disk and the young one to the outer disk

Lu et al. (2022)

Lu et al. (2022)



[α/Fe]-[Fe/H] distributions narrow in narrow birth radius bins

Clumps found in outer birth radii. Same mean age, although moving around. Could be associated with SF bursts found by, e.g., Ruiz-Lara et al. (2020)

Abundances from low resolution Gaia RVS spectra - the idea:

APOGEE DR17 labels
T_{eff}, log(g), [M/H], [Alpha/M], [Fe/H]

Gaia parallax + magnitudes

Gaia XP spectra

CONVOLUTION NEURAL NETWORK

Parameter for ~1 million RVS

Ages, dist, etc with StarHorse
+
possible new Metal Poor stars

Improving Performance of Spectroscopic Surveys with Machine Learning

Astronomy & Astrophysics manuscript no. output ©ESO 2023
October 26, 2023

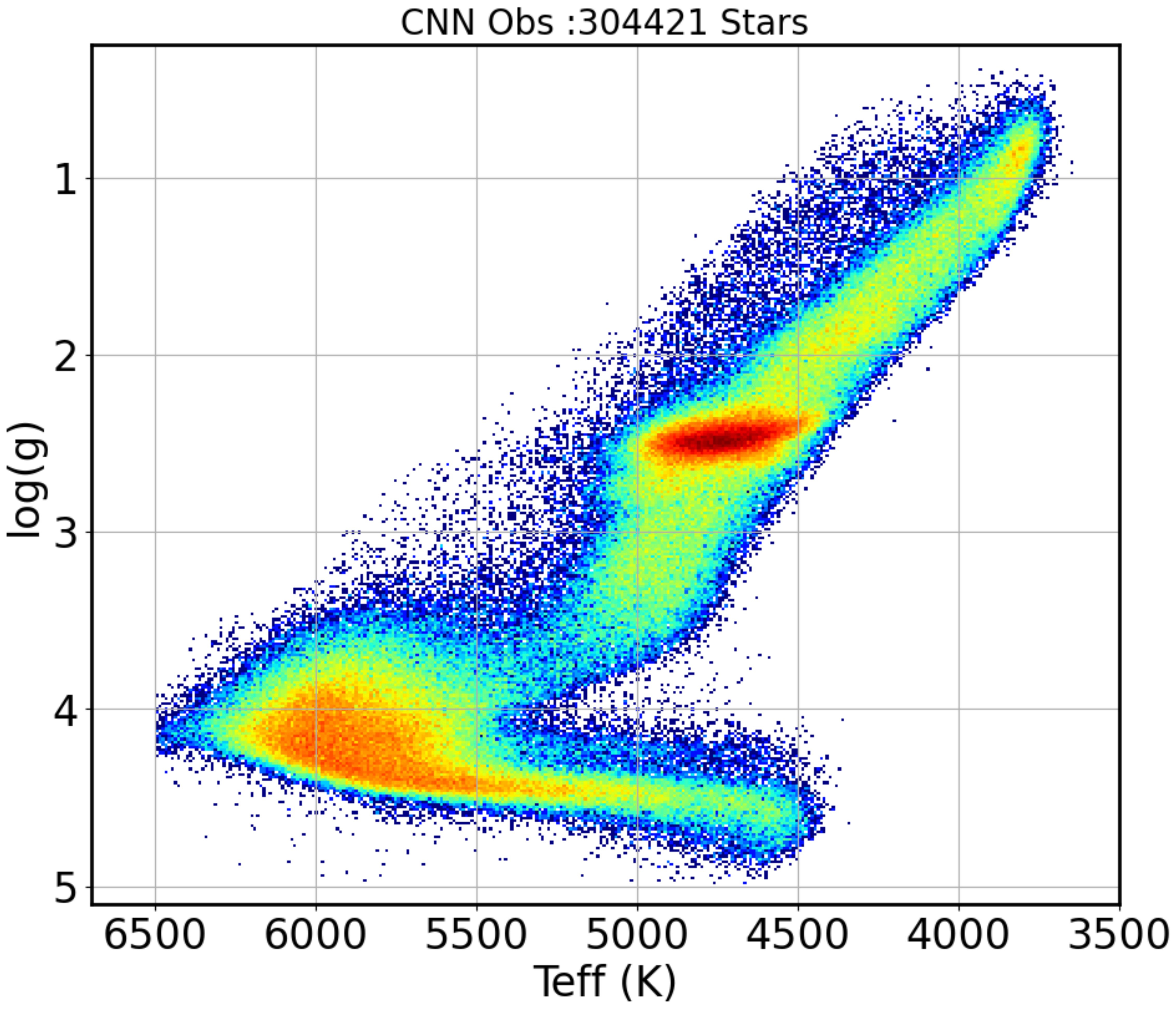
Beyond *Gaia* DR3:
tracing the [α/M] – [M/H] bimodality
from the Inner to the outer Milky Way disc
with *Gaia* RVS and Convolutional Neural-Networks

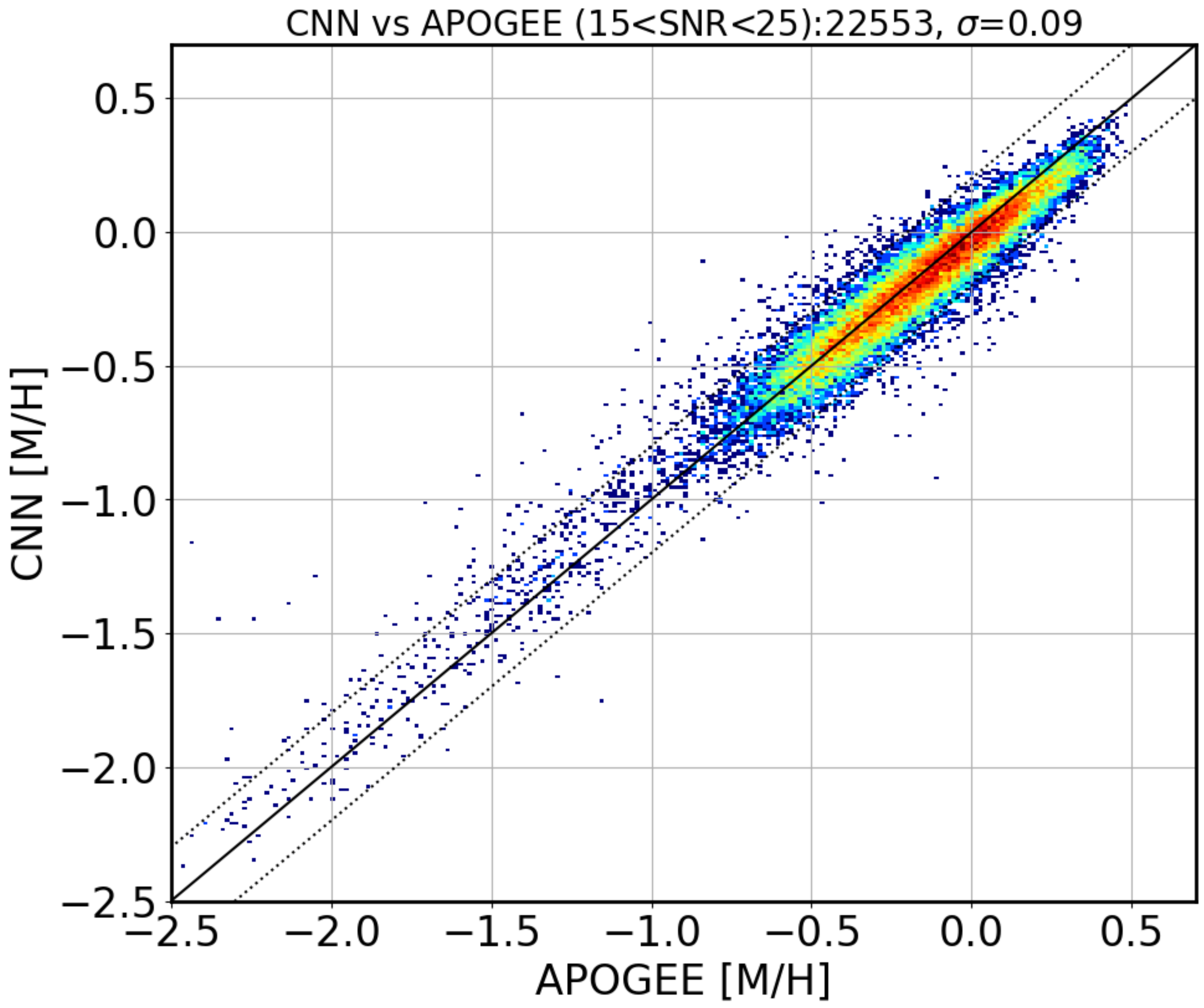
G. Guiglion[1,2], S. Nepal[3,4], C. Chiappini[3], S. Khoperskov[3], G. Traven[5], A. B. A. Queiroz[3], M. Steinmetz[3], M. Valentini[3], Y. Fournier[3], A. Vallenari[6], K. Youakim[7], M. Bergemann[2], S. Mészáros[8,9], S. Lucatello[10,11], R. Sordo[6], S. Fabbro[12], I. Minchev[3], G. Tautvaišienė[13], Š. Mikolaitis[13], J. Montalbán[14]

The RVS-CNN Catalog (Guiglion, Nepal et al. 2024 A&A):

- T_{eff}, log(g), [M/H], [α/M] and [Fe/H] for >840,000 stars. (Catalog is public, use it!)
- >12,000 metal-poor ([Fe/H]<-1.0) stars with reliable parameters (GSP-spec flags: <100)
- ~19,000 super-metal-rich ([Fe/H]>0.2) stars with reliable parameters (GSP-spec: ~6,500)
- ~4500 bulge candidates with Gaia-RVS (GSP-spec: 8)

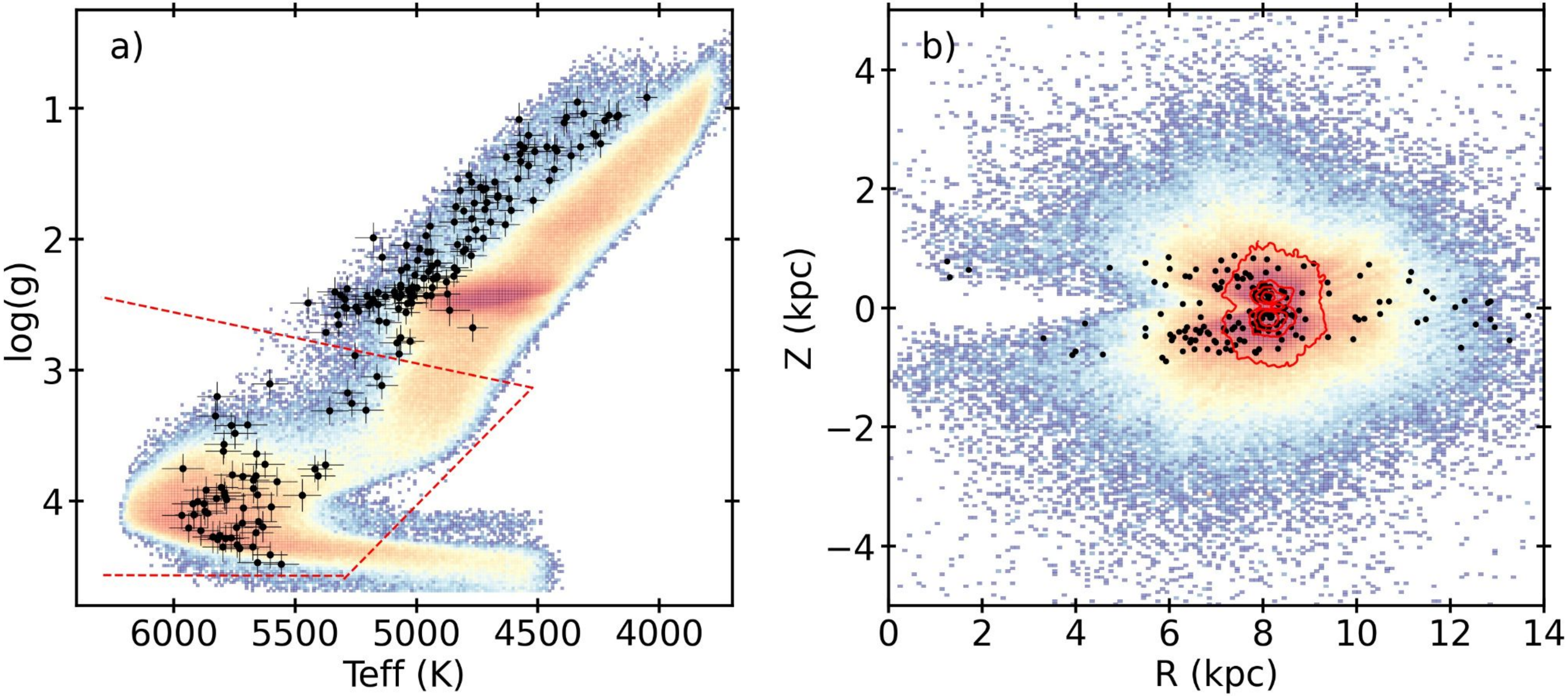
Fetching abundances from Gaia RVS spectra trained on APOGEE



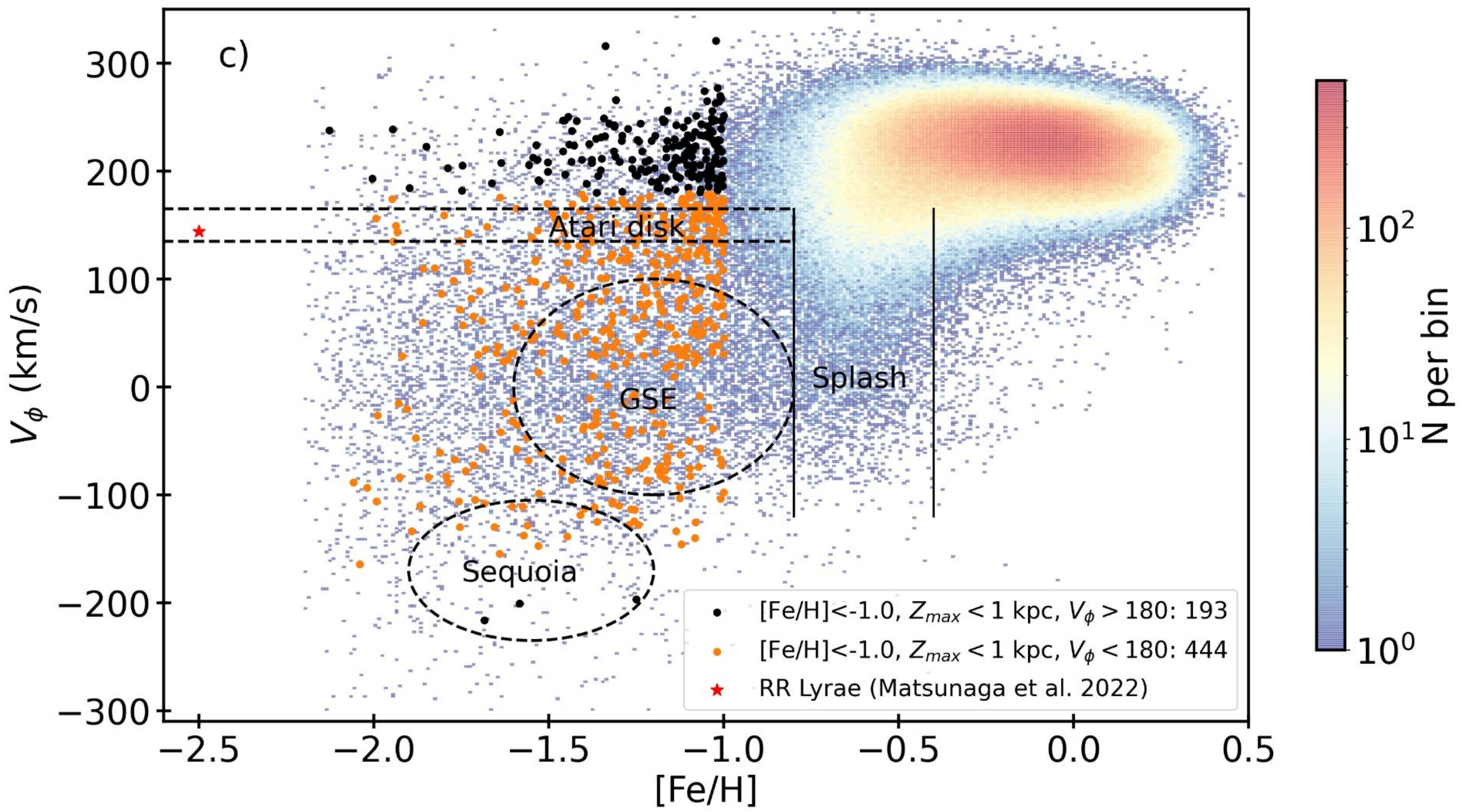


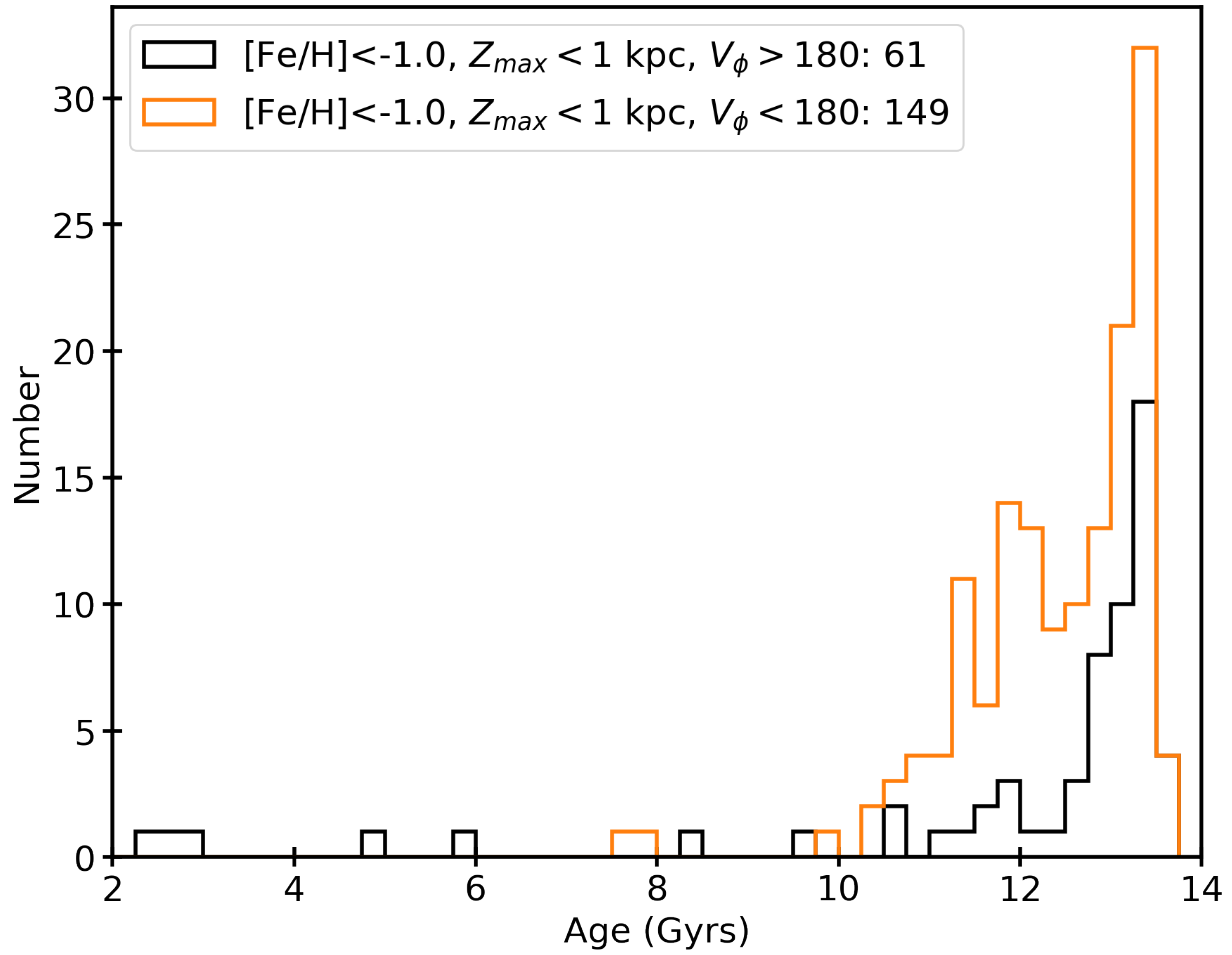
- Left: High-quality result for selected Obs sample. (Total obs sample = 841300)
- 1-to-1 comparison of CNN prediction vs APOGEE [M/H] for low S/N (15-25) RVS spectra.

The data:


a)
1
2
3
4
log(g)
6000
5500
5000
4500
4000
Teff (K)
b)
4
2
0
−2
−4
Z (kpc)
0
2
4
6
8
10
12
14
R (kpc)

The metal-poor thin disc:



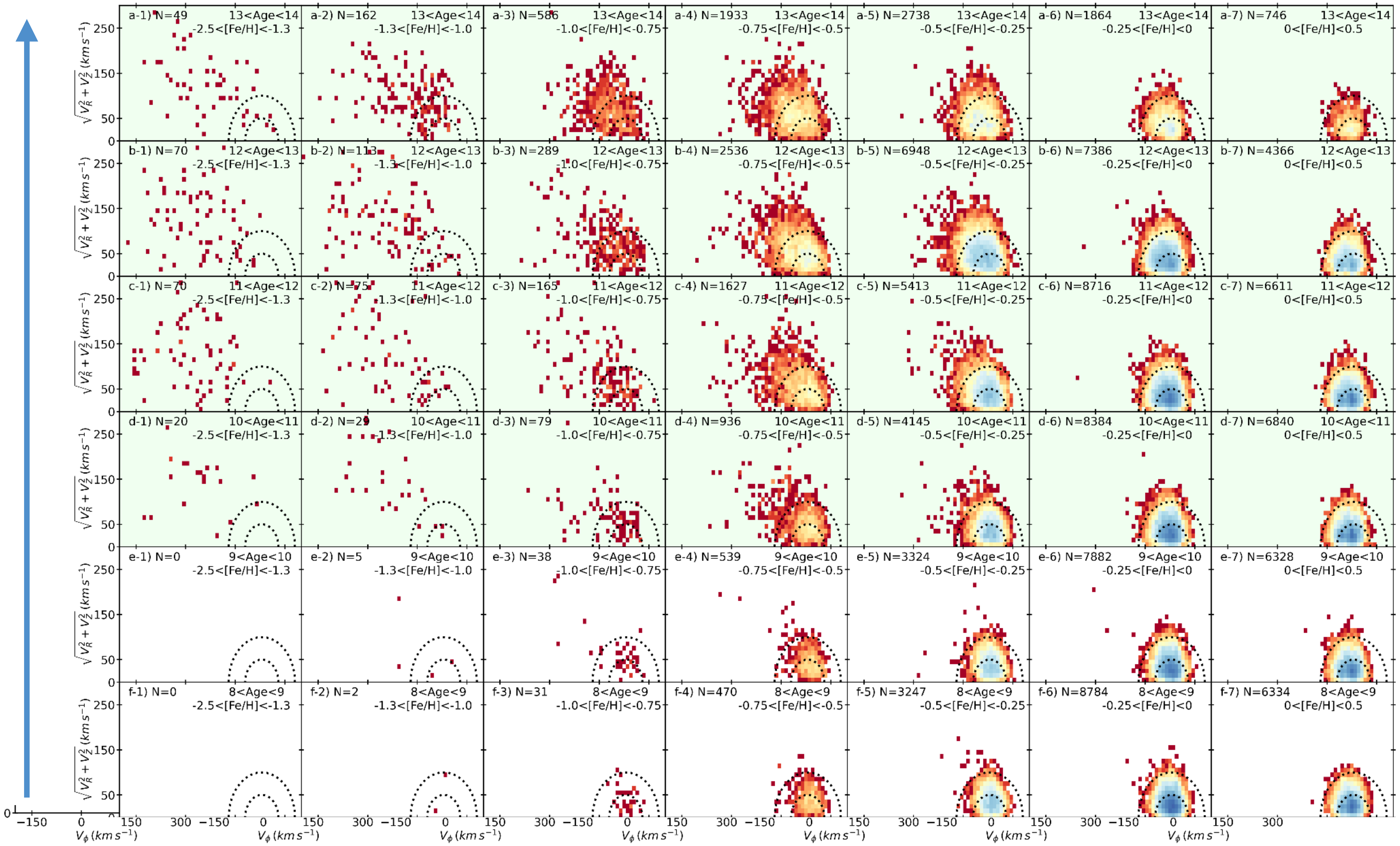


> 50% of MP thin disc star >13 Gyr

significant % of kinematically hotter MP stars < 13 Gyr

The oldest thin disc of MW:

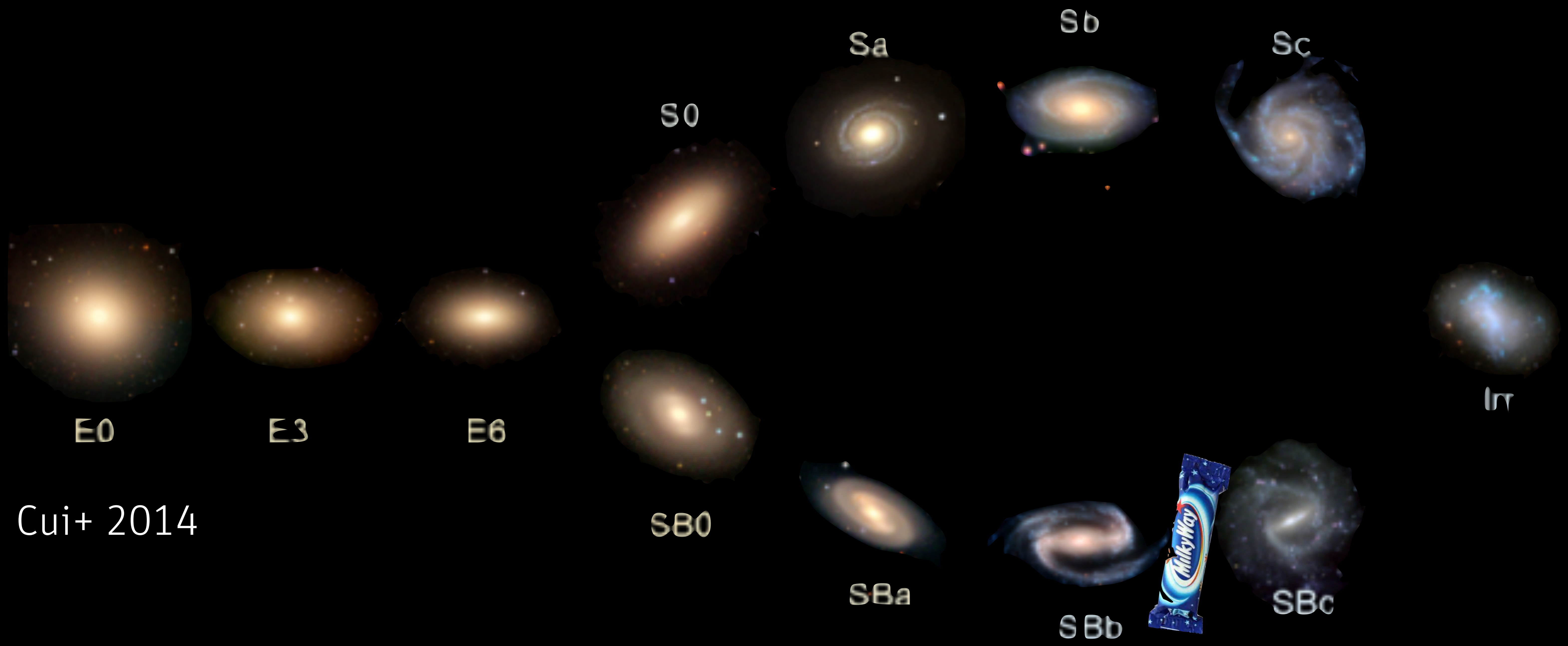
Old
to
Young



Metal-poor to Metal-rich

Significant fraction of old stars with wide [Fe/H] range already in thin/thick disc orbits at the oldest ages.

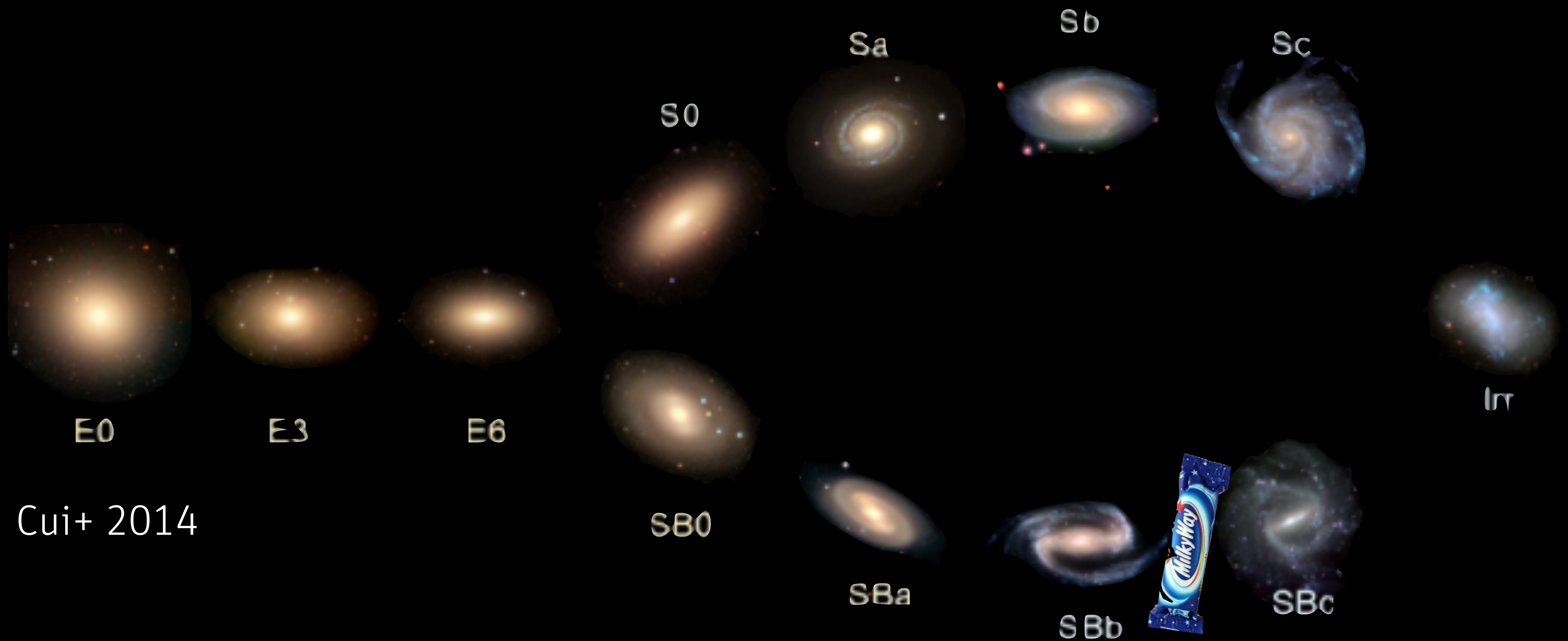

NGC 2336



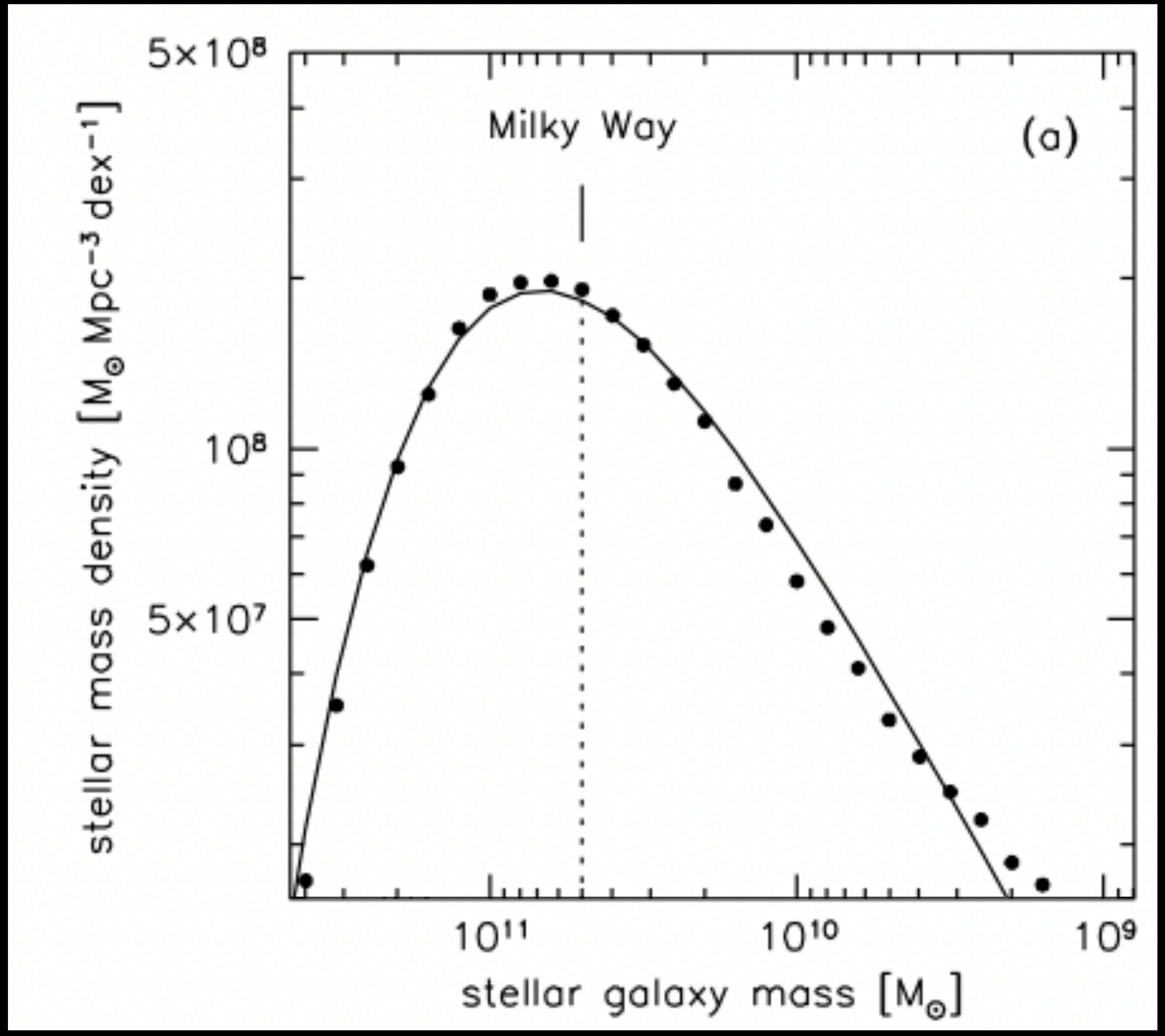
Cui+ 2014

stellar disk	$5 \times 10^{10} M_\odot$
bulge	$2 \times 10^{10} M_\odot$
gaseous disk	$2 \times 10^{9} M_\odot$
halo	
stellar	$8 \times 10^{8} M_\odot$
gaseous	$2 \times 10^{10} M_\odot$
dark matter	$1 \times 10^{12} M_\odot$

Bland-Hawthorn & Gerhard 2016



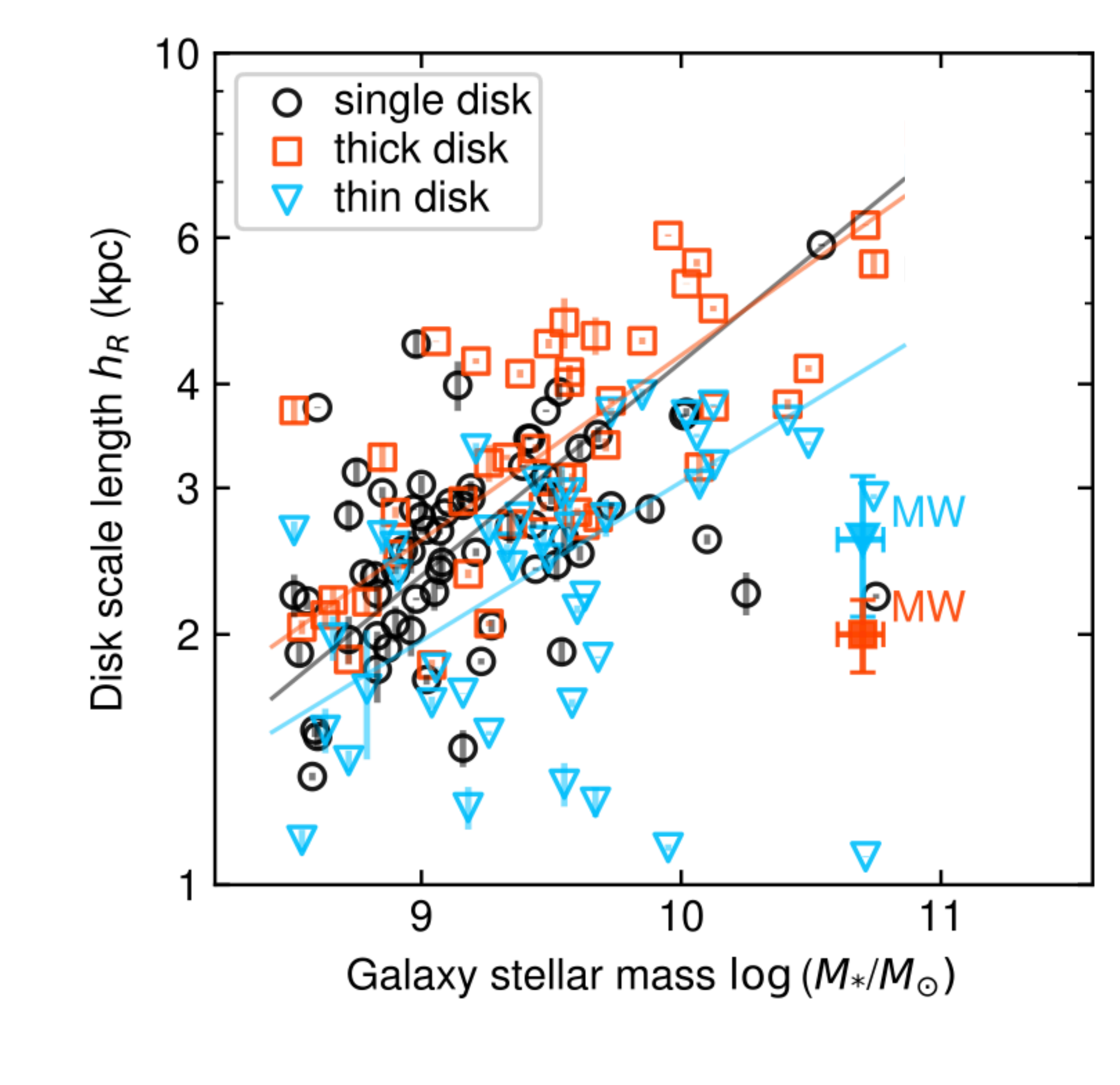
Cui+ 2014



van Dokkum+ 2013

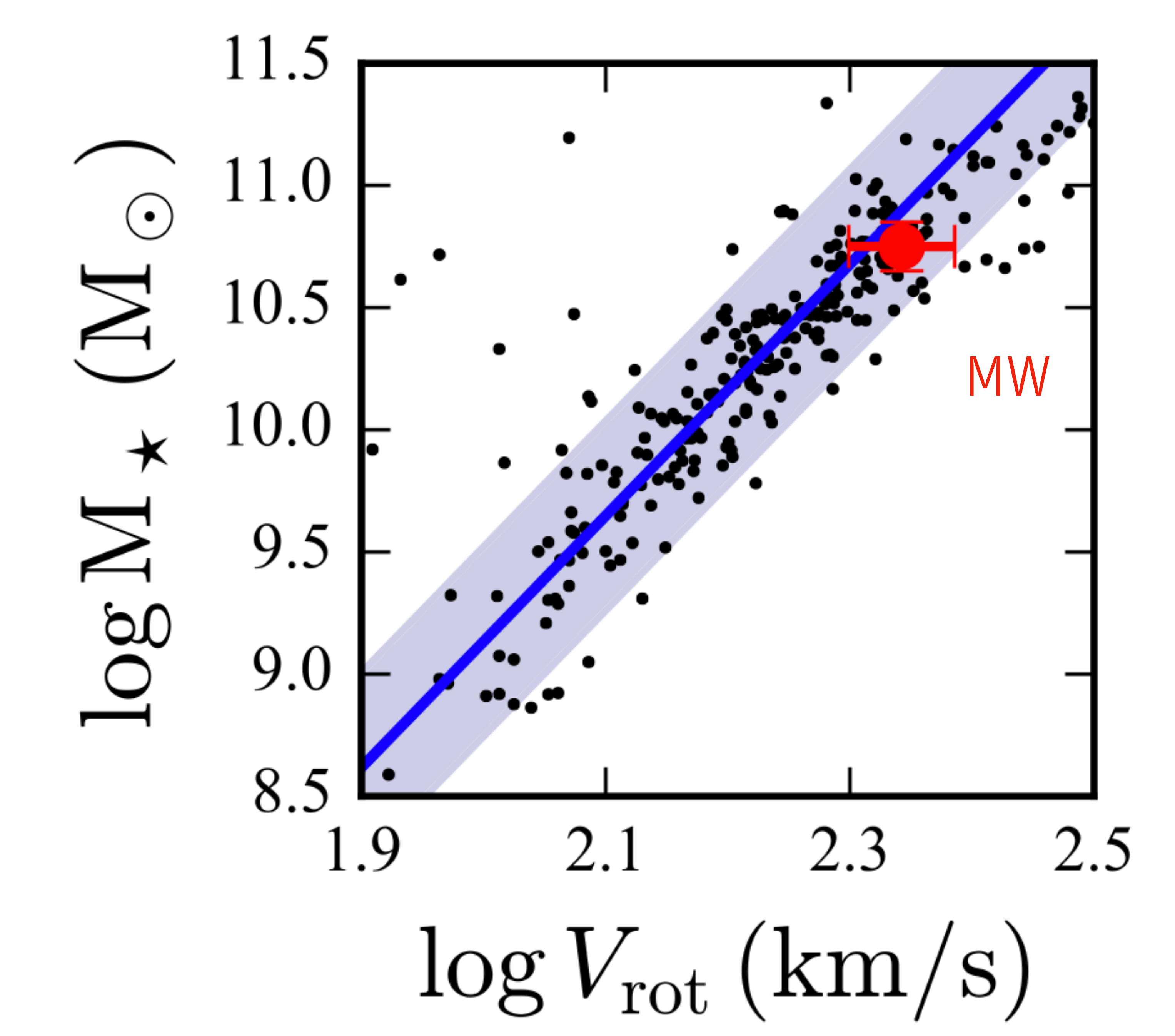
Milky Way galaxy: normal or weird?

Z ~ 0.1 -3 (JWST)



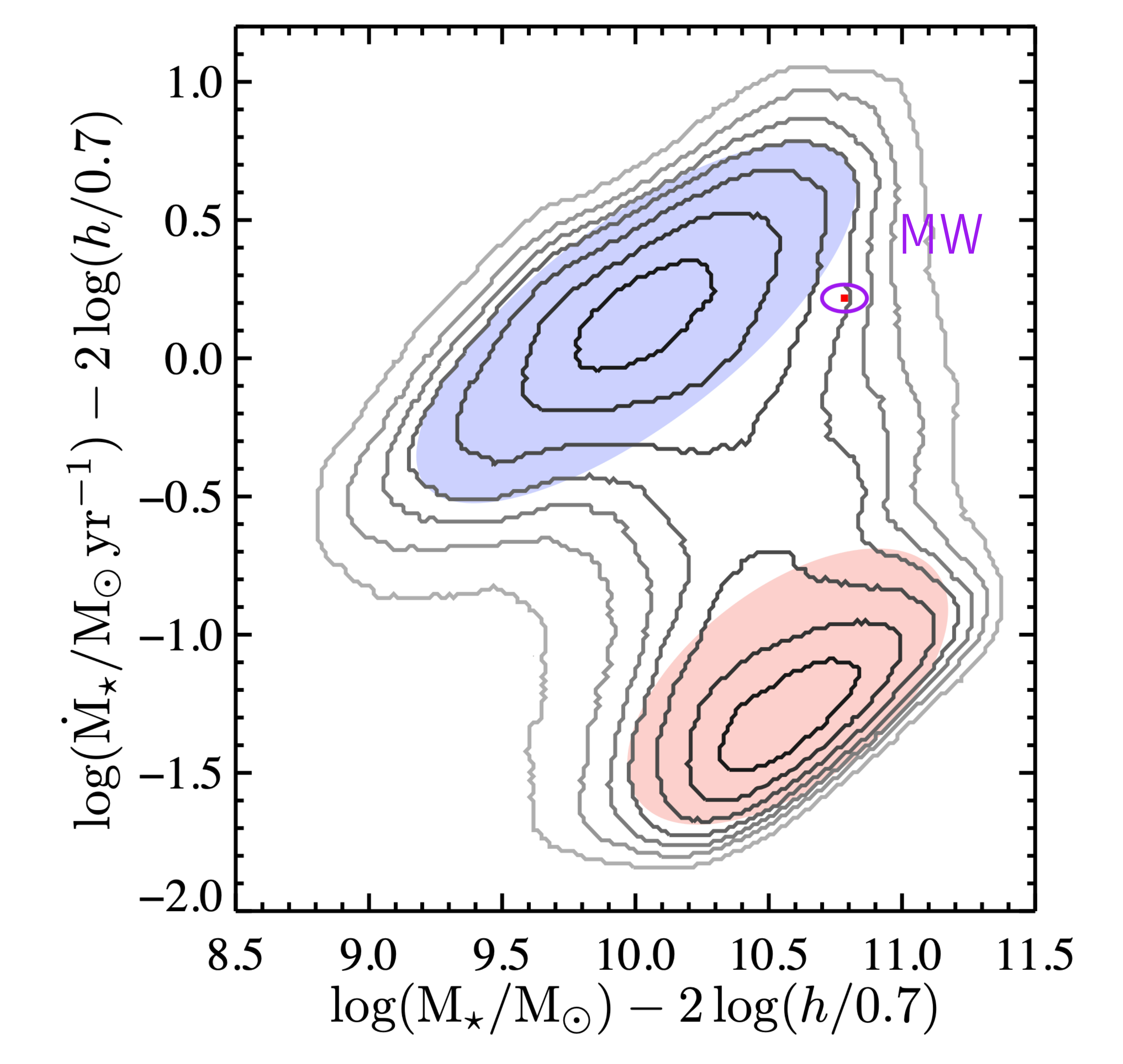
Tsukui+ 2024

258 SDSS spiral galaxies



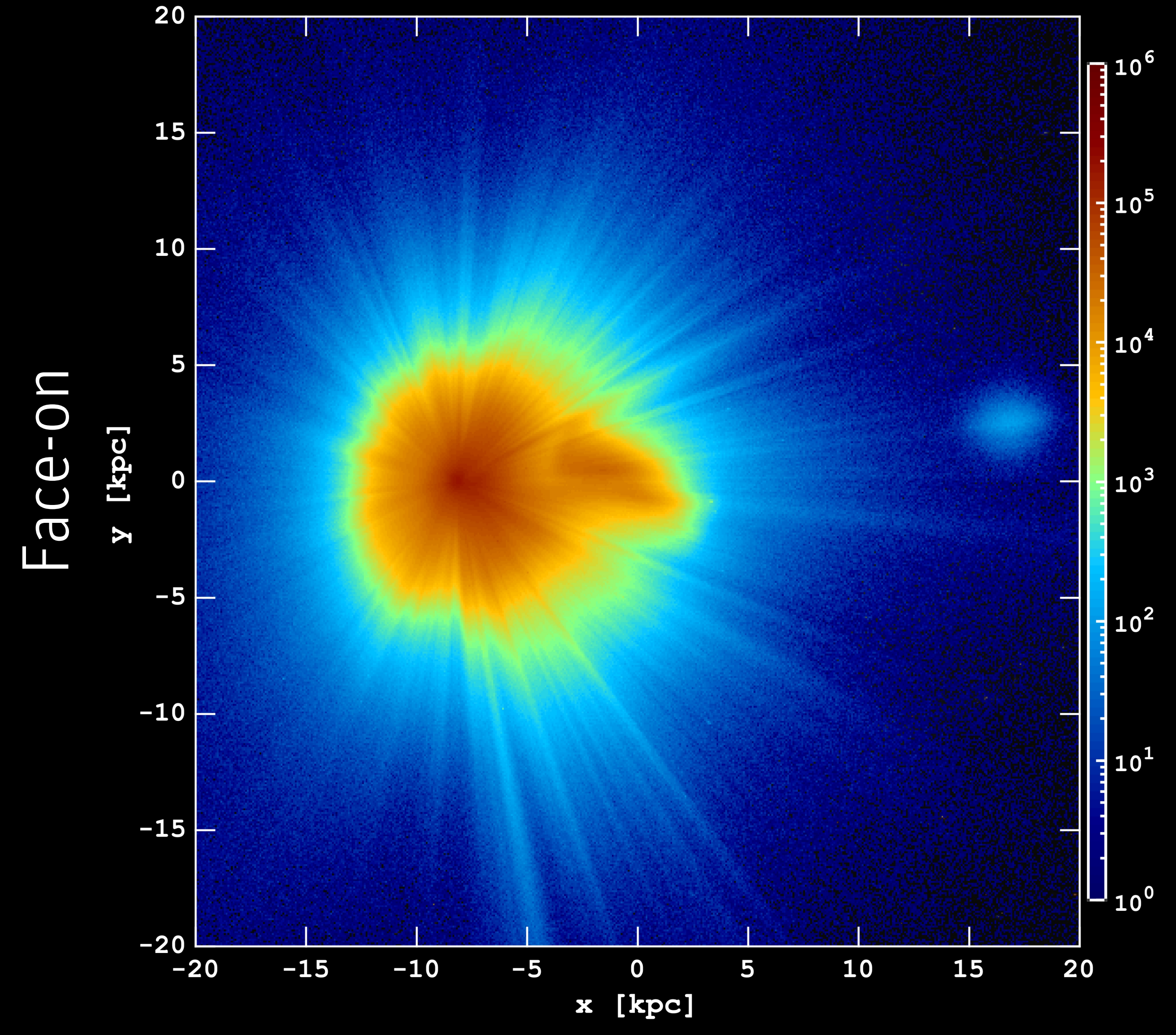
Licquia+ 2016

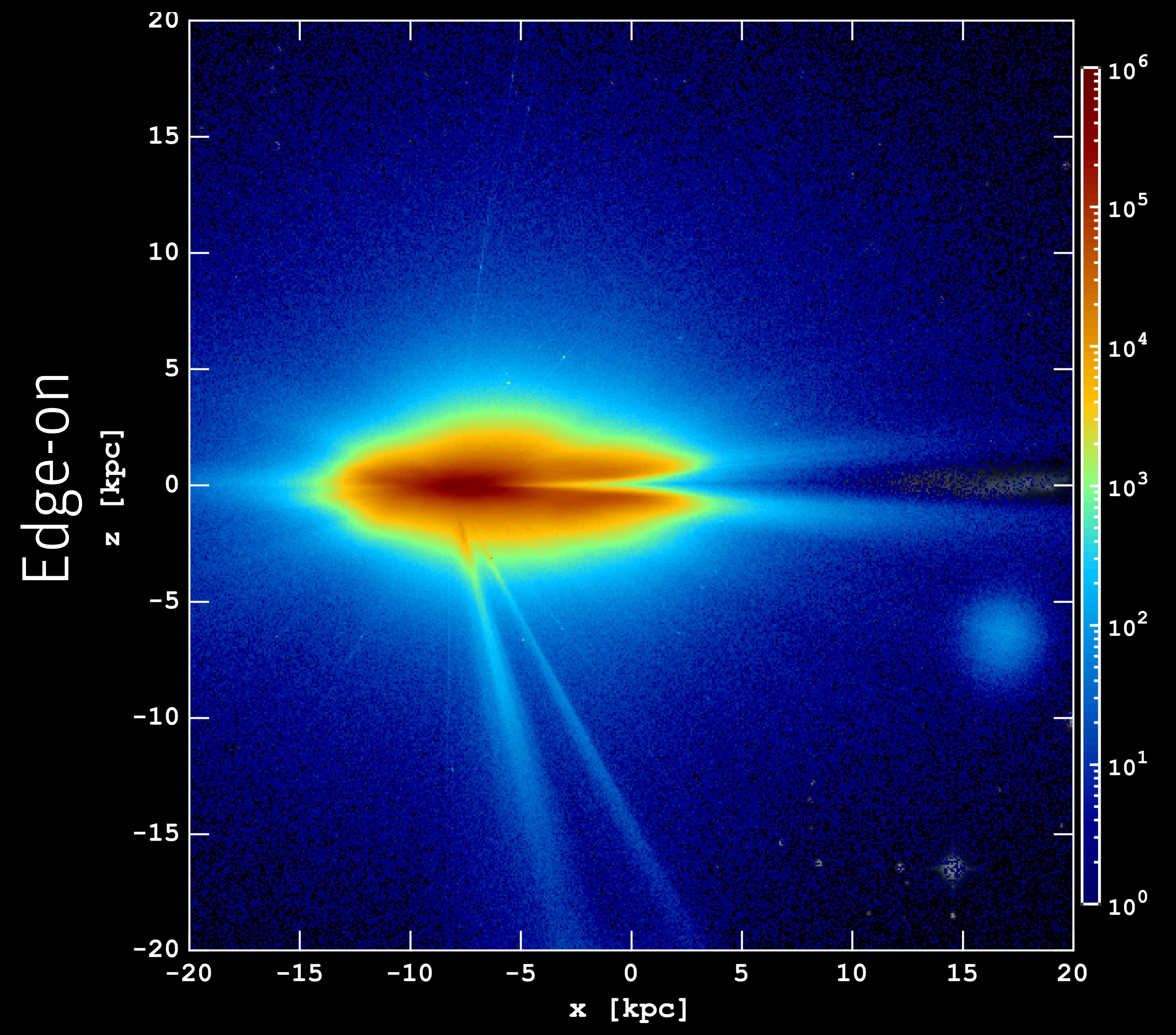
SDSS galaxies



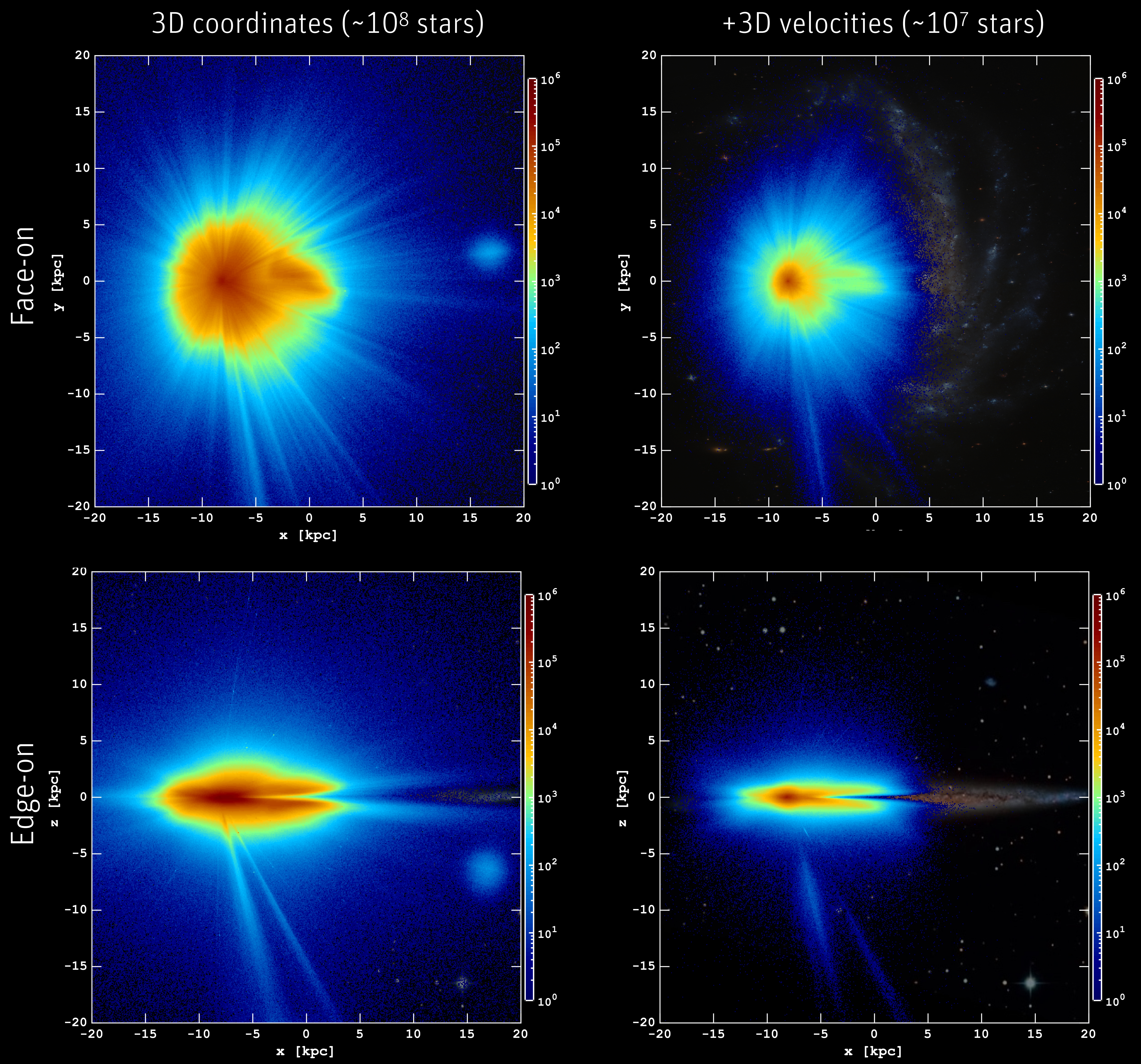
Milky Way disc coverage

3D coordinates (~10^8 stars)

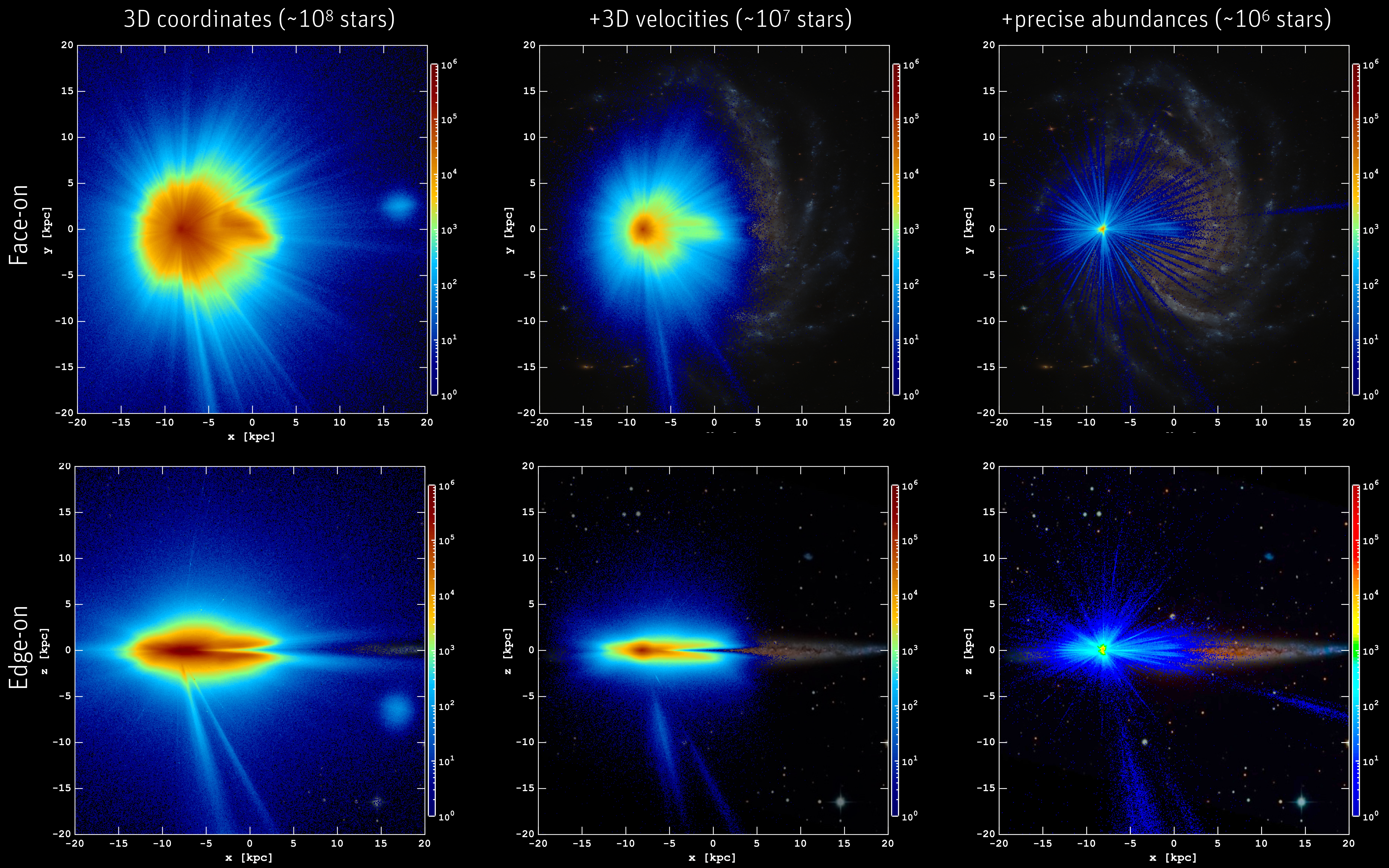




Milky Way disc coverage

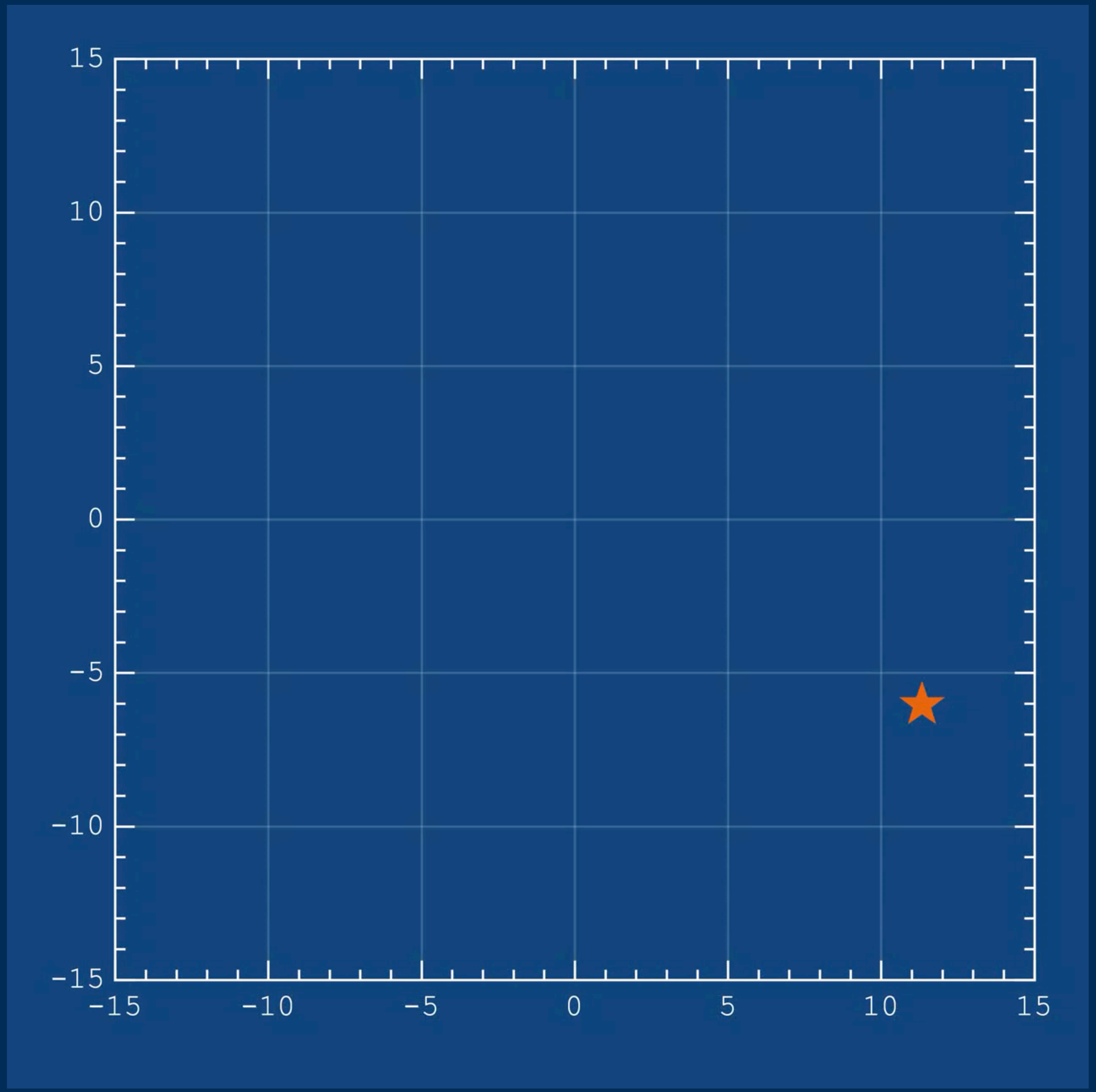


Milky Way disc coverage

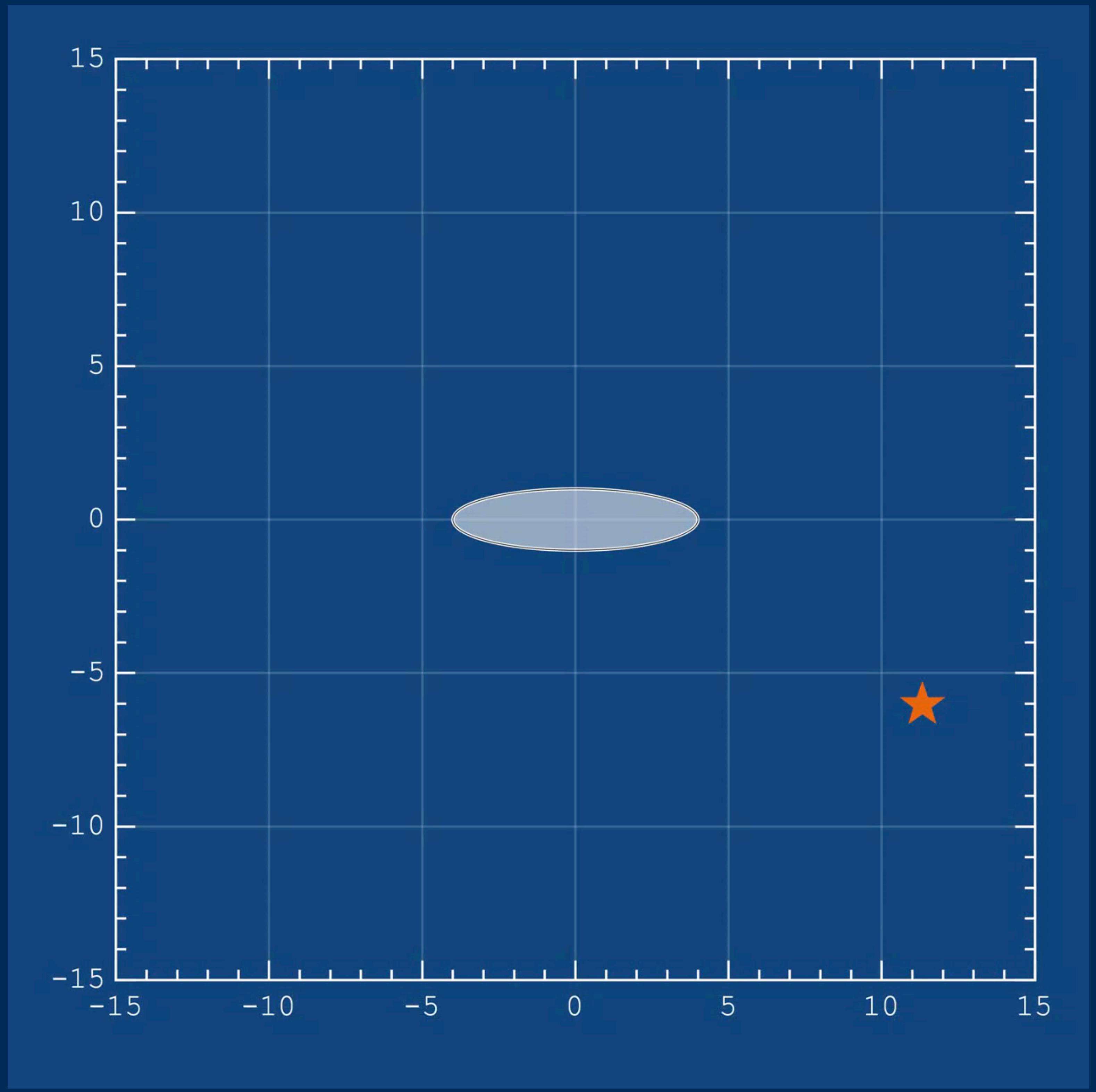


Orbits of disc stars

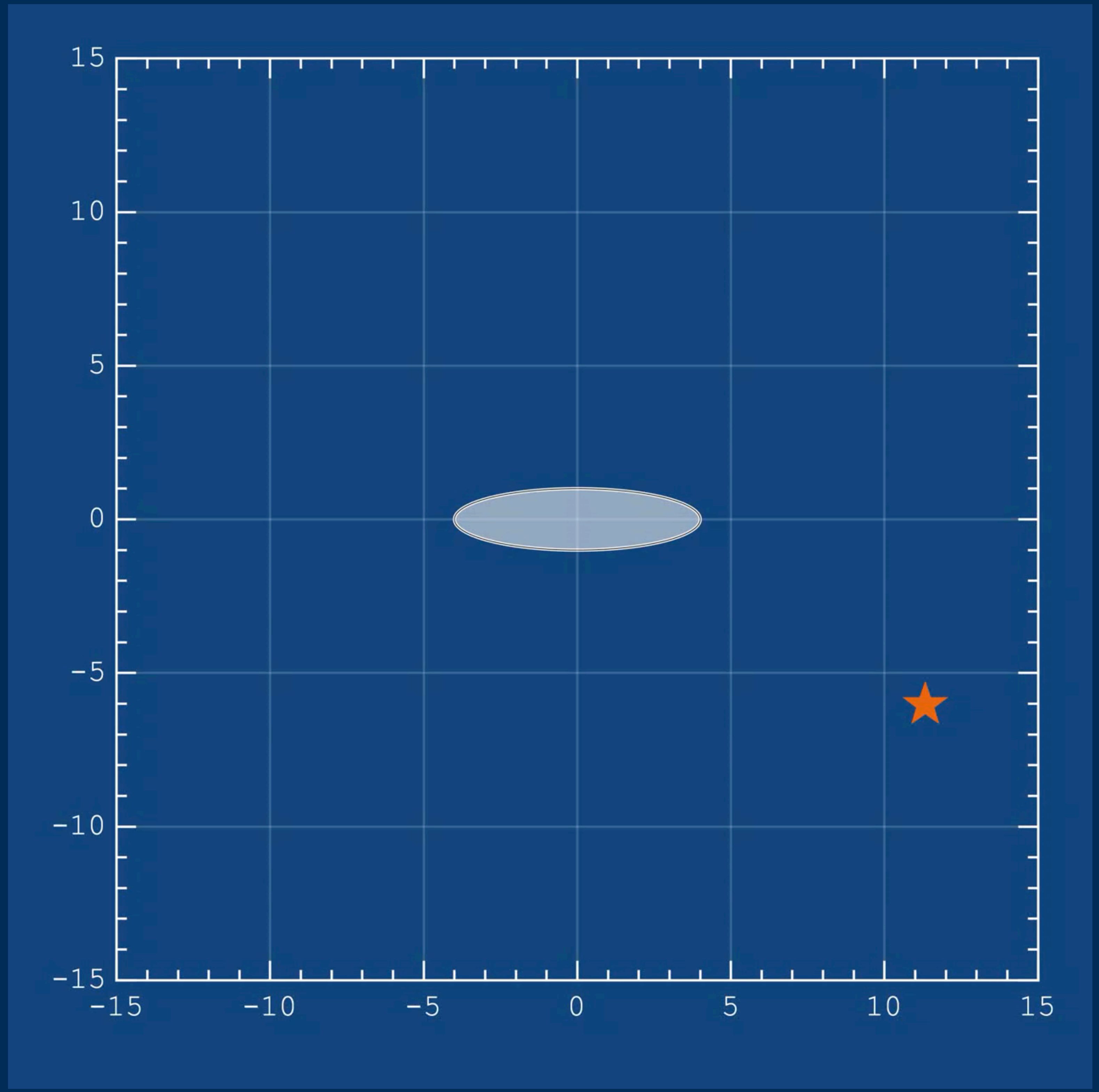
Axisymmetric potential



Barred potential
inertial rest frame

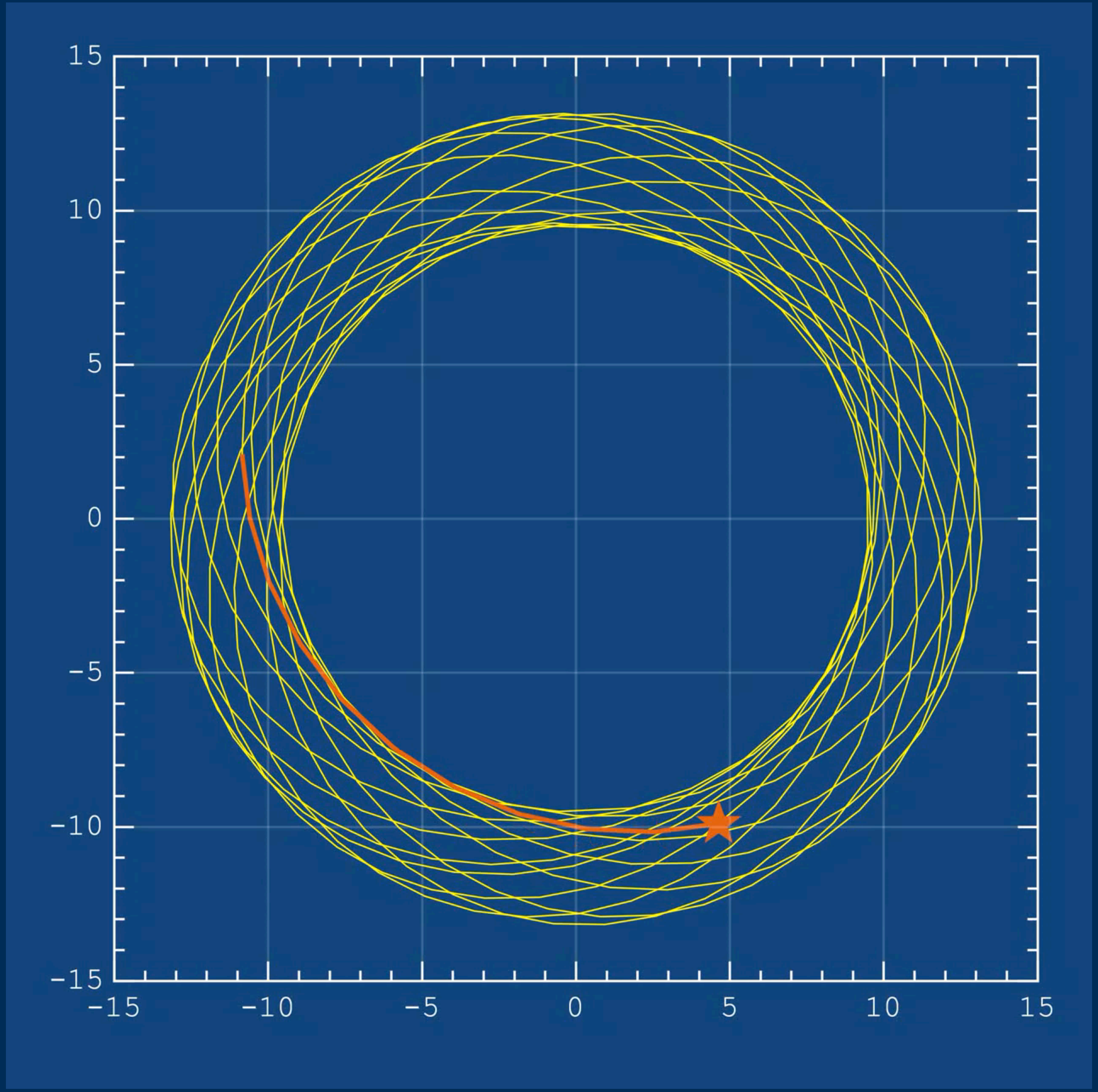


Barred potential
rotating rest frame

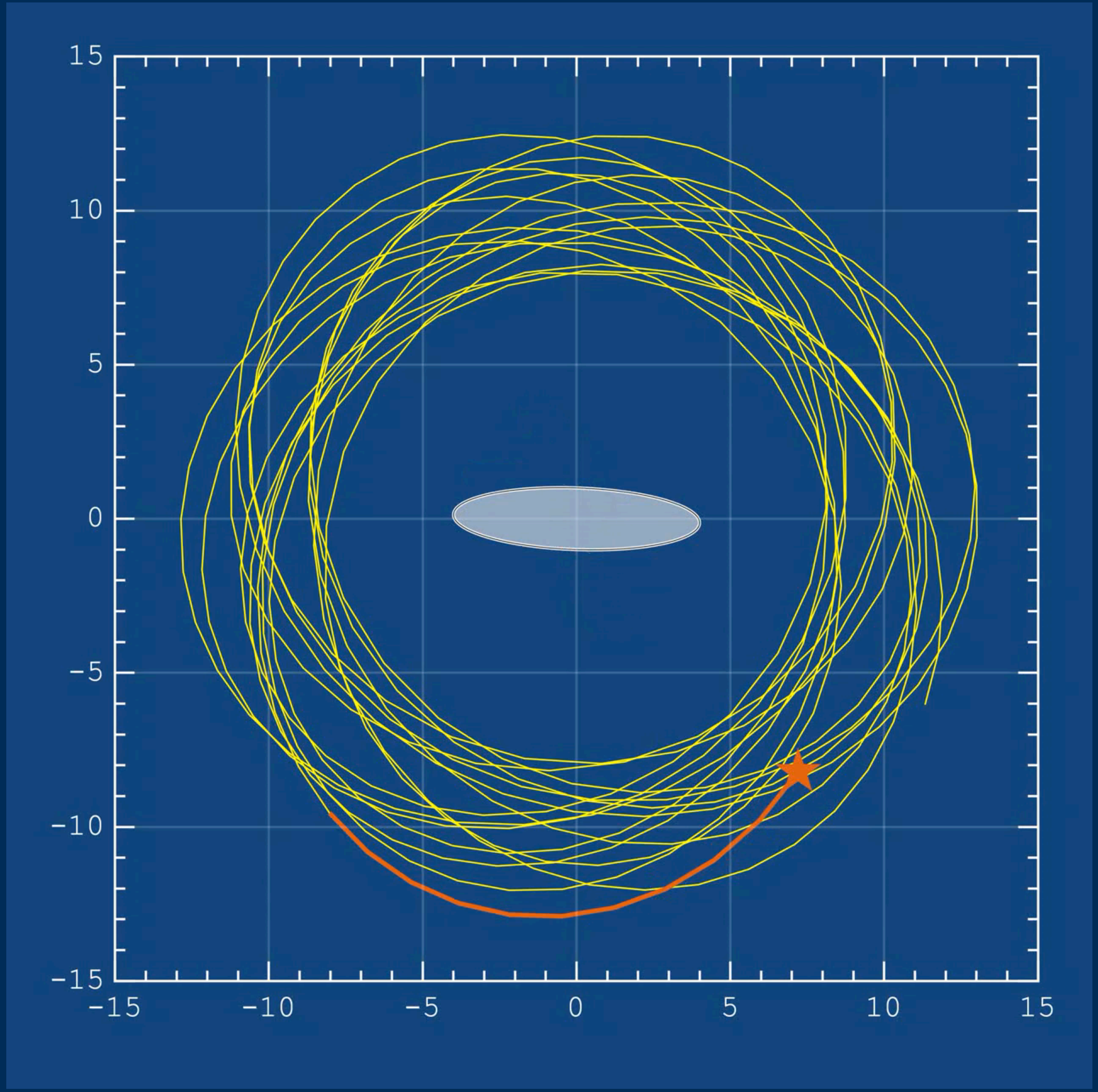


Orbits of disc stars

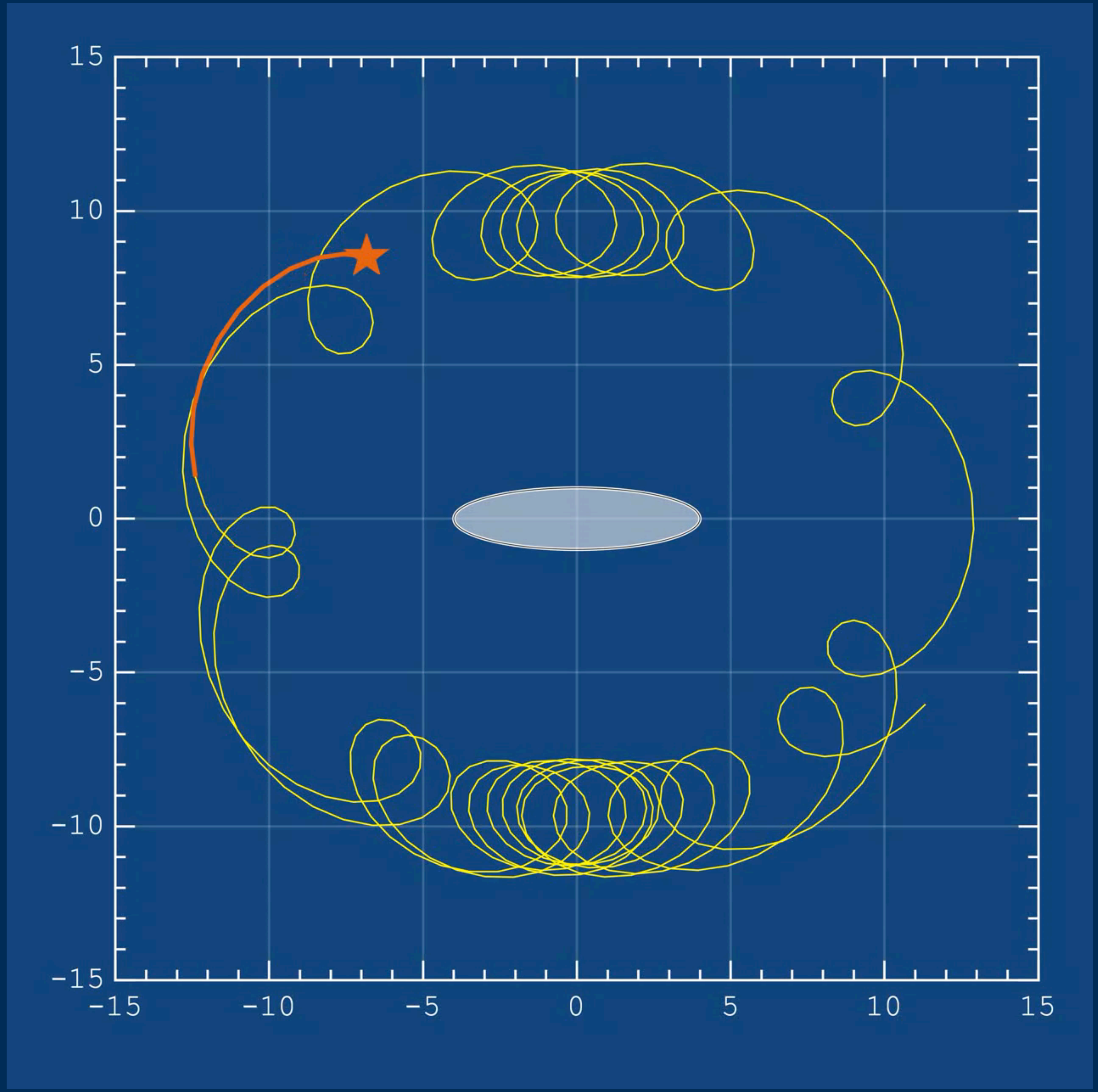
Axisymmetric potential



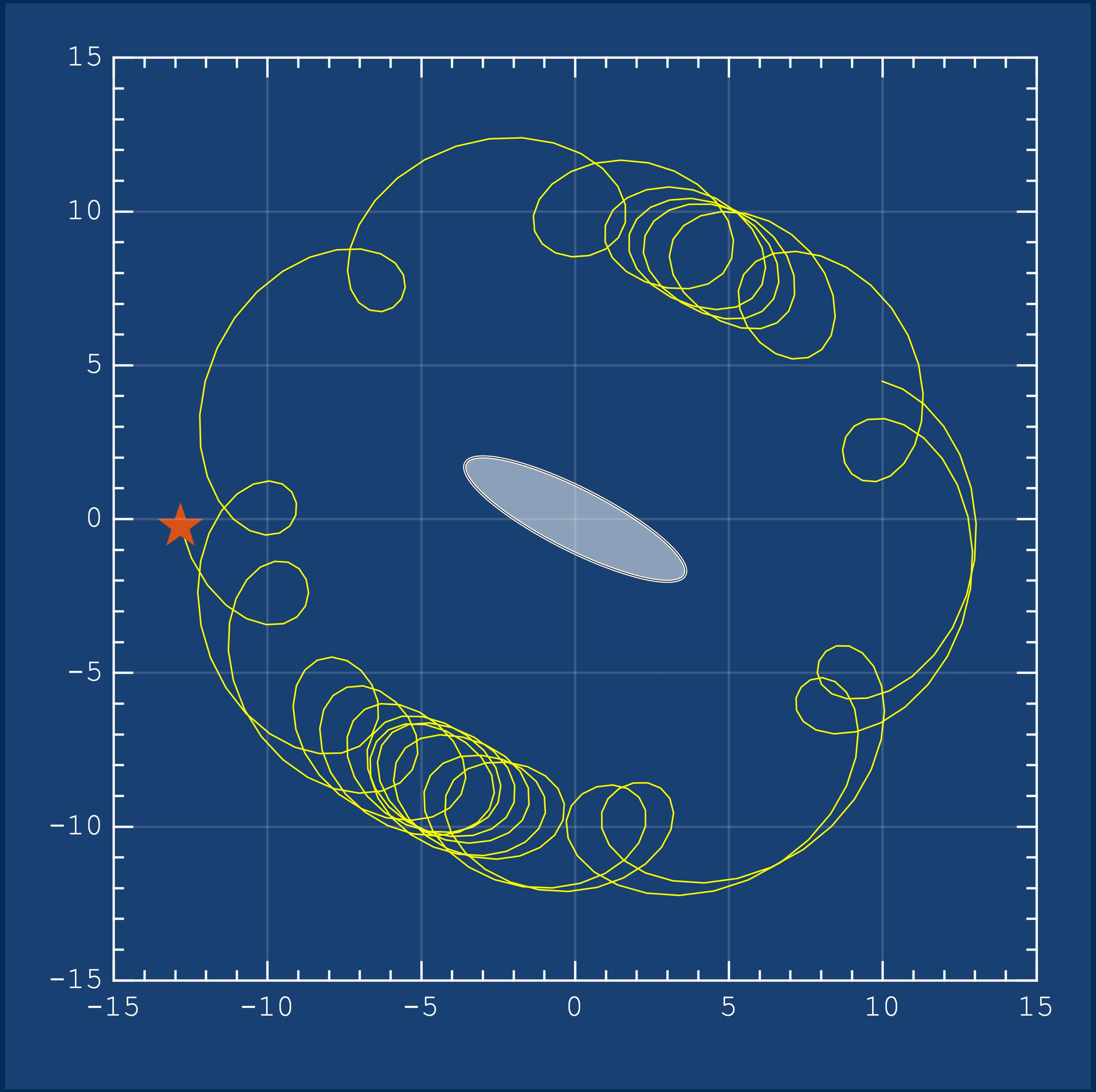
Barred potential
inertial rest frame



Barred potential
rotating rest frame



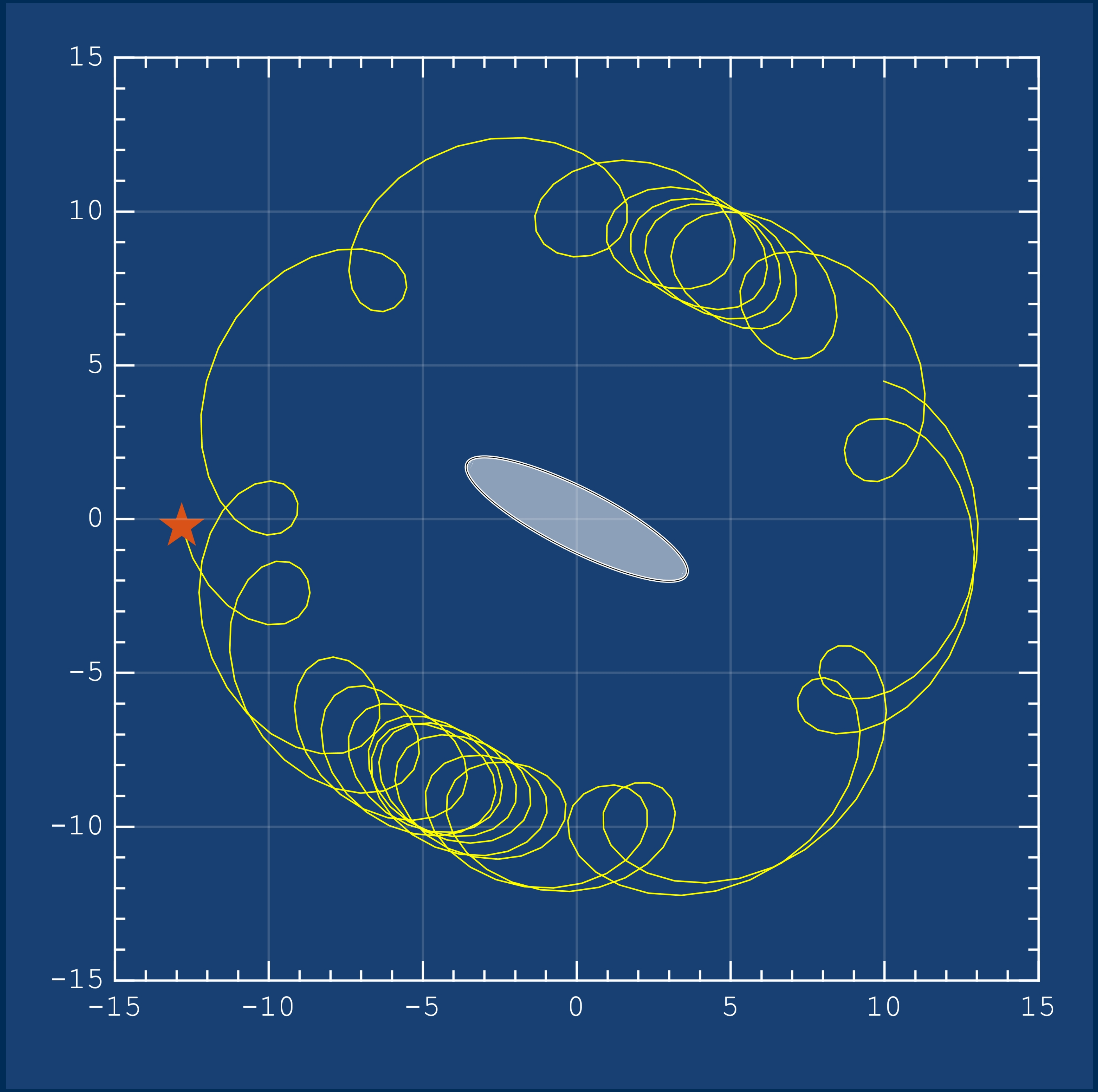
Orbits of disc stars

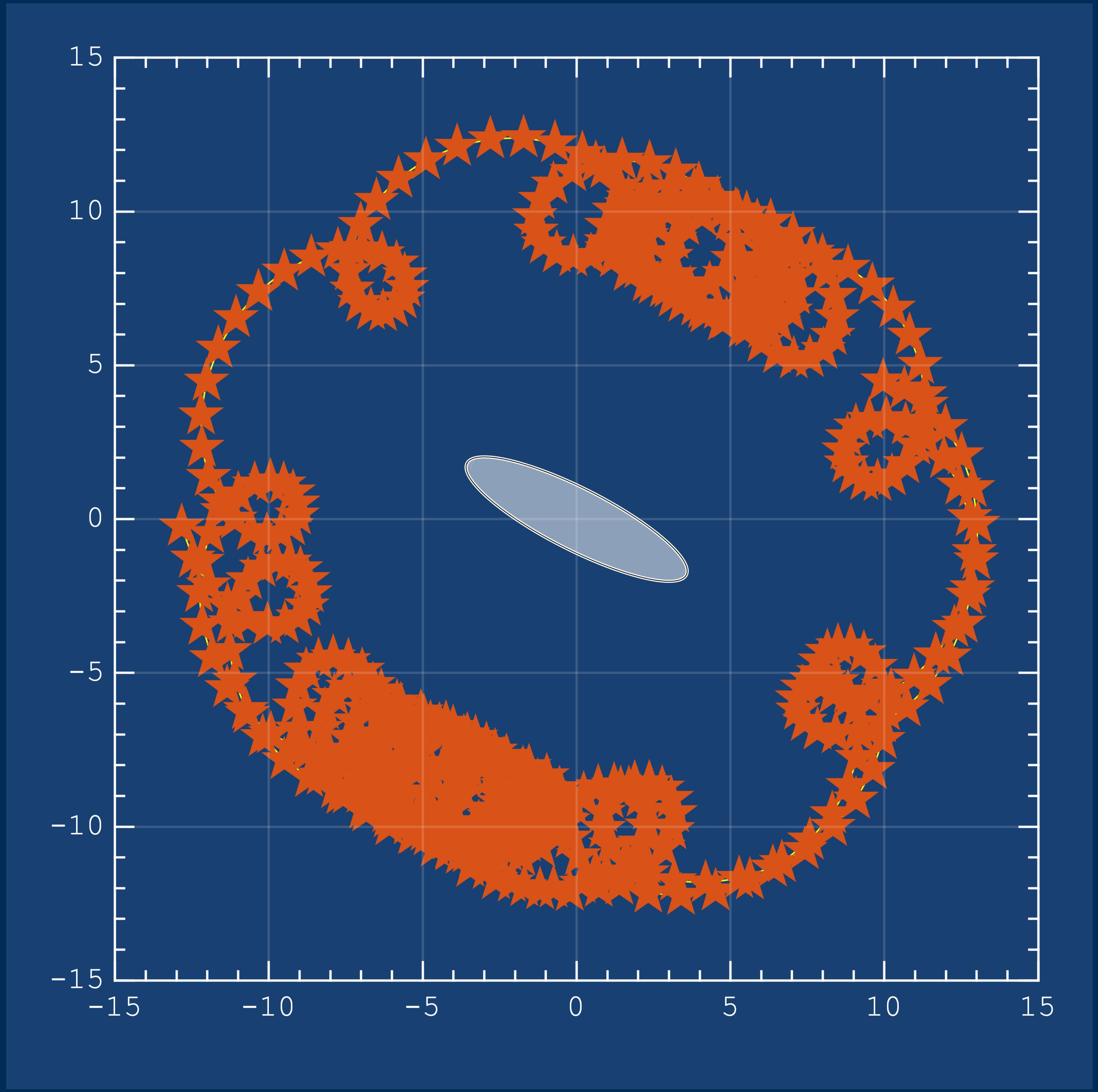


Observed star with 6D phase-space information

Orbit of the star — positions of the star in the past

Orbits of disc stars

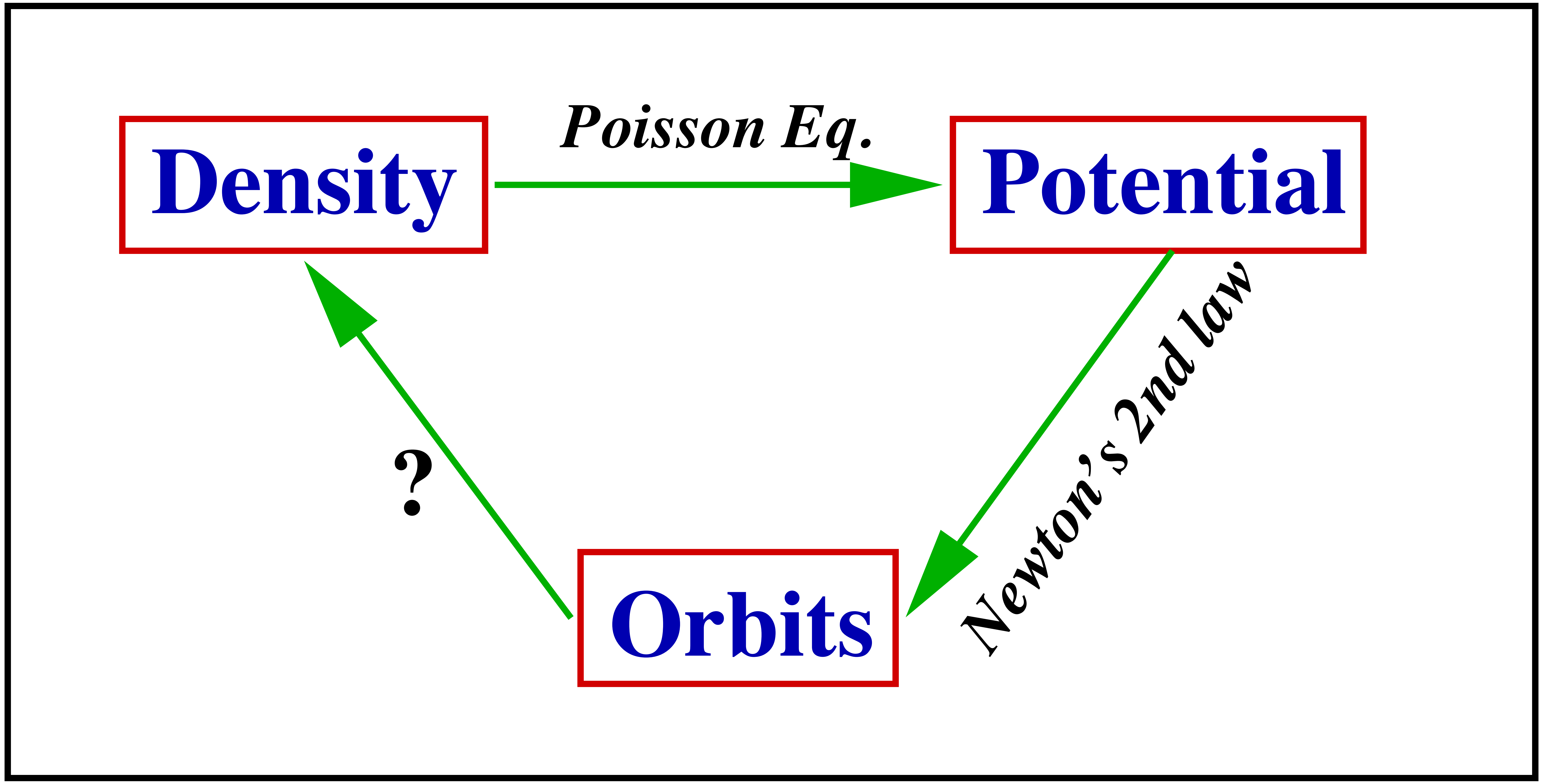




★ Observed star with 6D phase-space information

Orbit of the star – positions of the star in the past

"Invisible" population of stars following the orbit of a single observed star


Density
Poisson Eq.
Potential
Newton's 2nd law
Orbits
?

Reconstruction of the MW with orbit superposition

$$\Psi_{total}(x,y,z) = \Psi_{stars}(x,y,z) + \Psi_{DM}(x,y,z) + \Psi_{gas}(x,y,z) + \ldots$$

$$\Delta\Psi_{stars}(x,y,z) = 4\pi G\rho_{stars}(x,y,z)$$

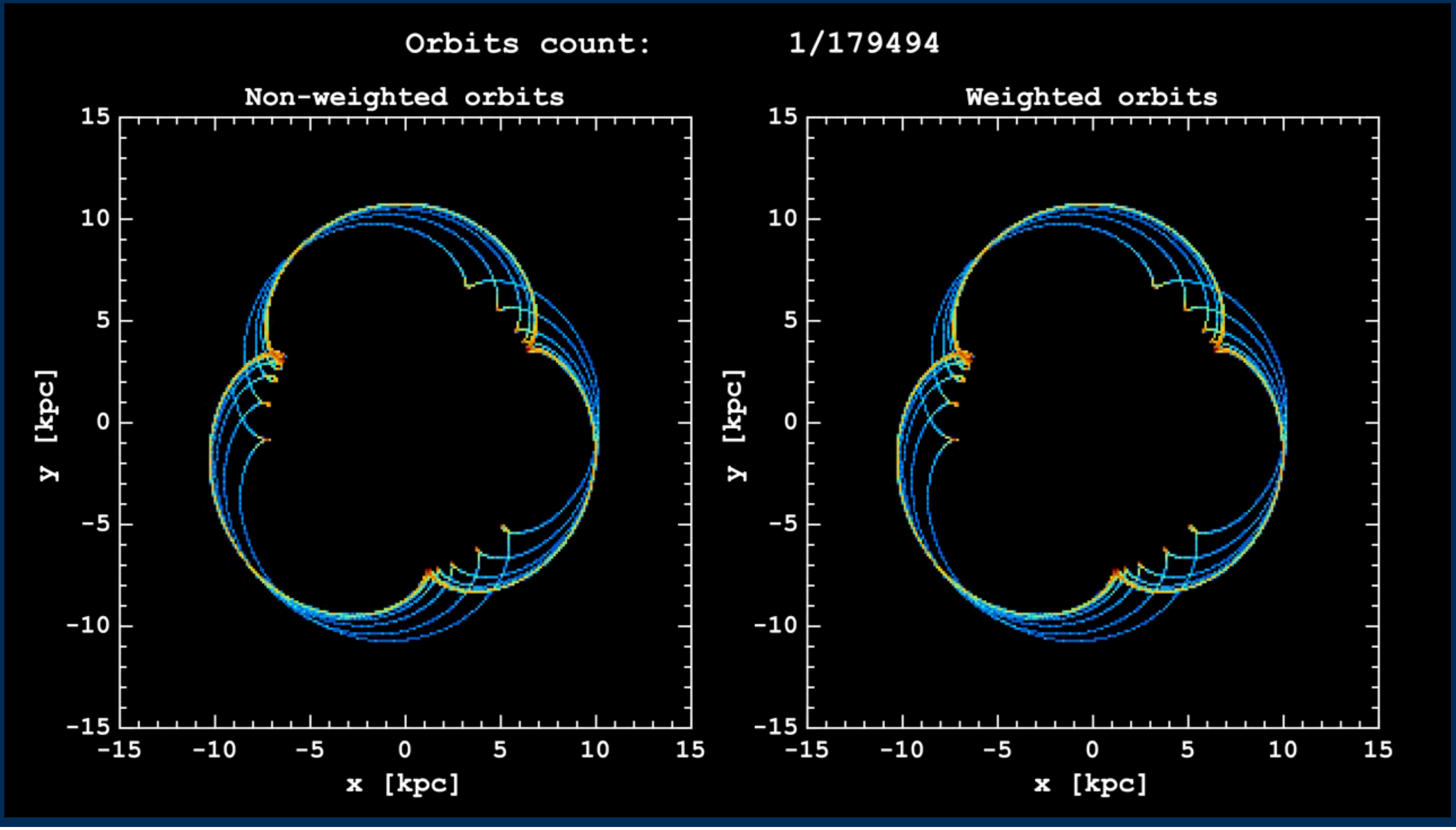
Schwarzschild 1979

$$\rho_{stars}(x,y,z) = \sum_{i=1}^{n} w_i \rho_i^{orbit}(x,y,z)$$

$$\Psi_{total}(x,y,z)$$

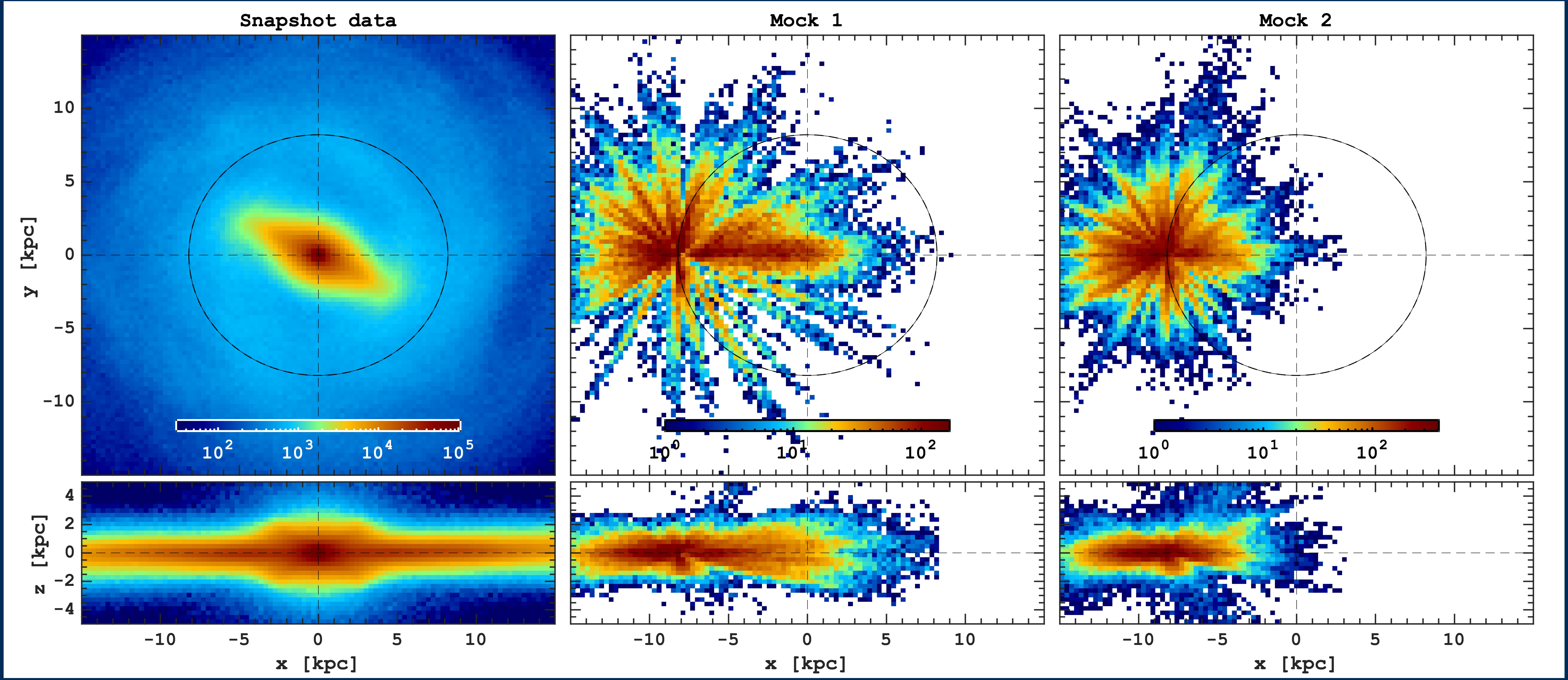
+ 6D phase-space MW data

APOGEE data + 3D MW potential from Portail+2017 & Sormani+2022

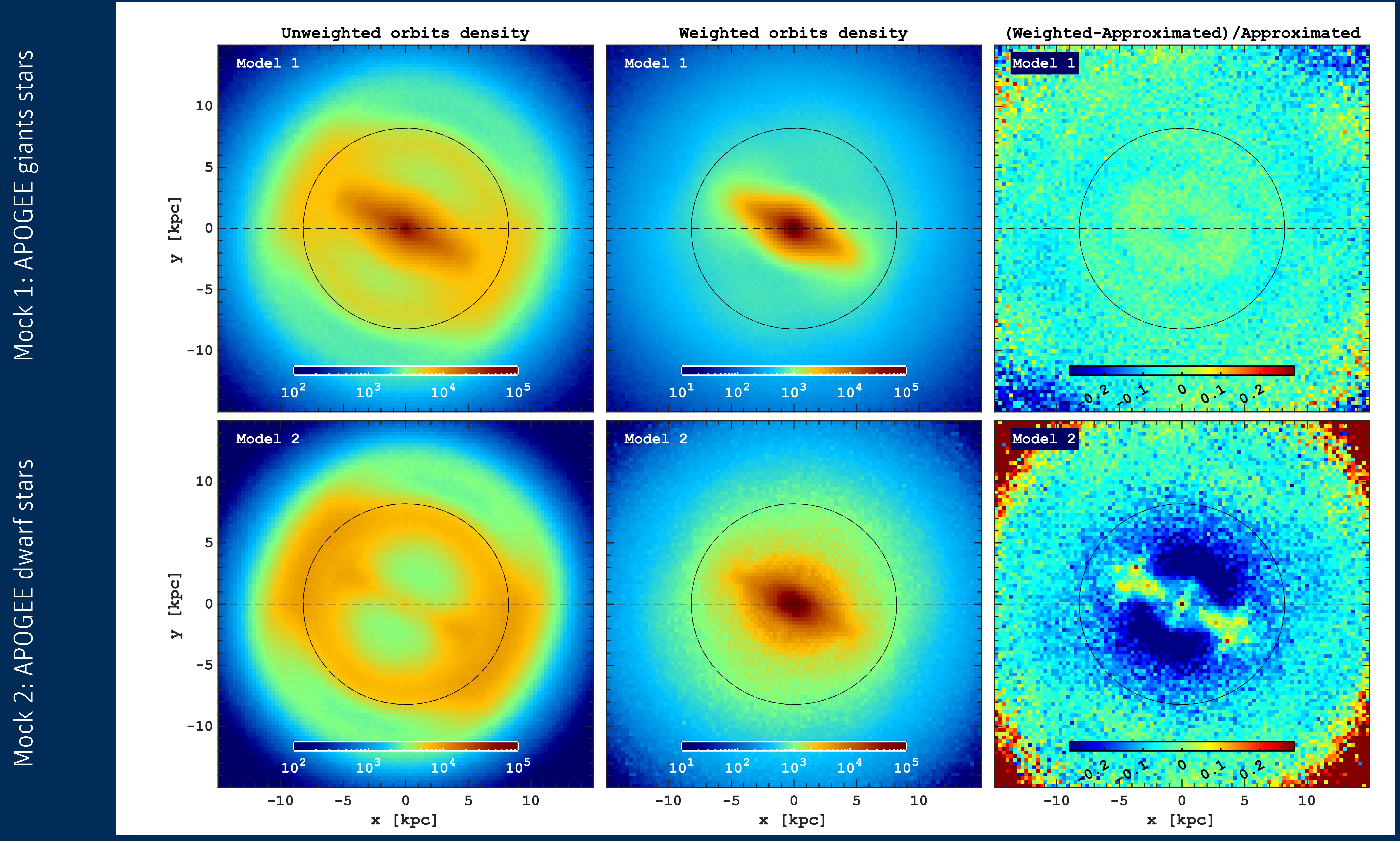


Testing orbit superposition on mock galaxy

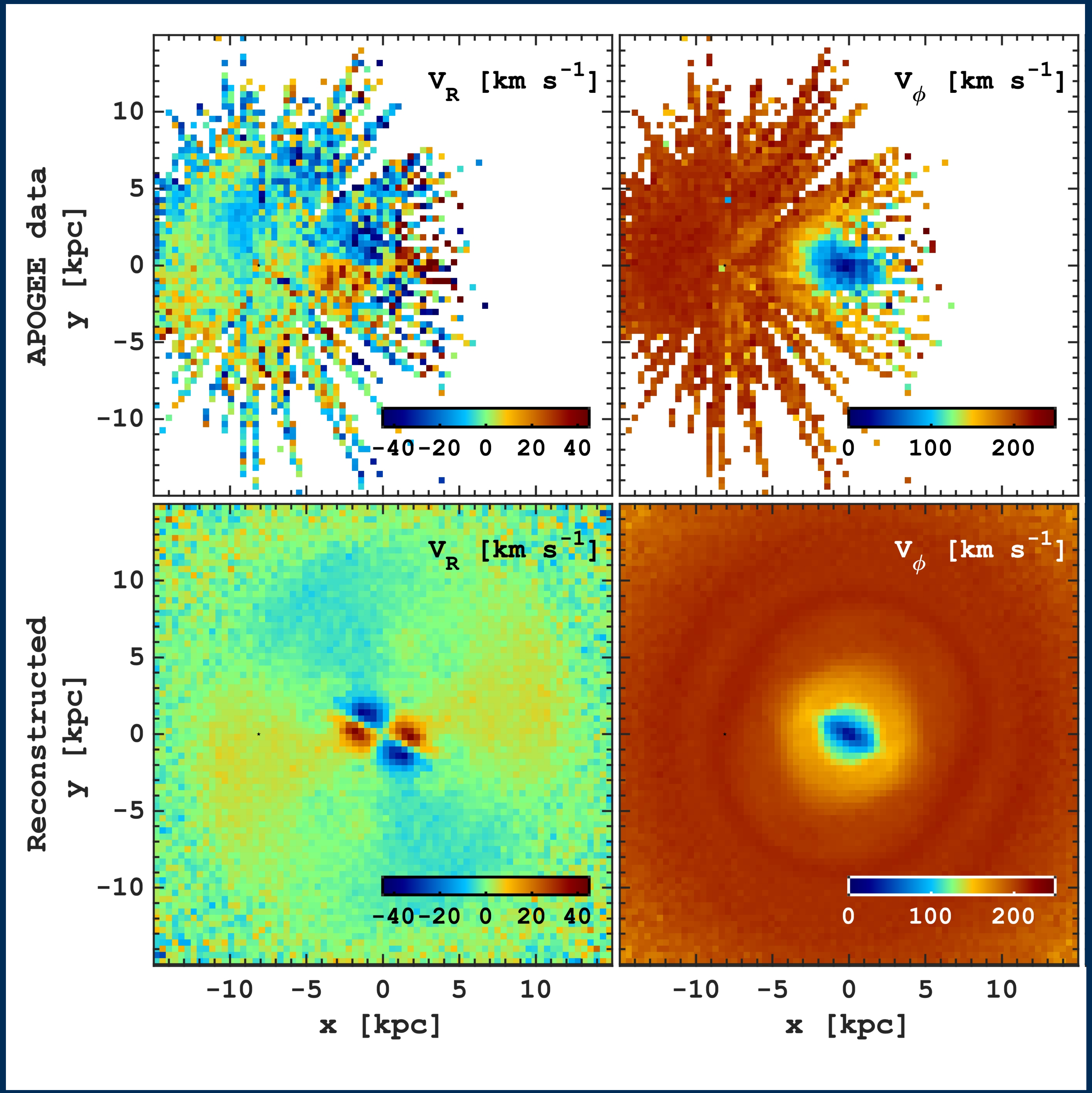
Complete simulation data | Mock 1: APOGEE giants stars | Mock 2: APOGEE dwarf stars



Testing orbit superposition on mock galaxy



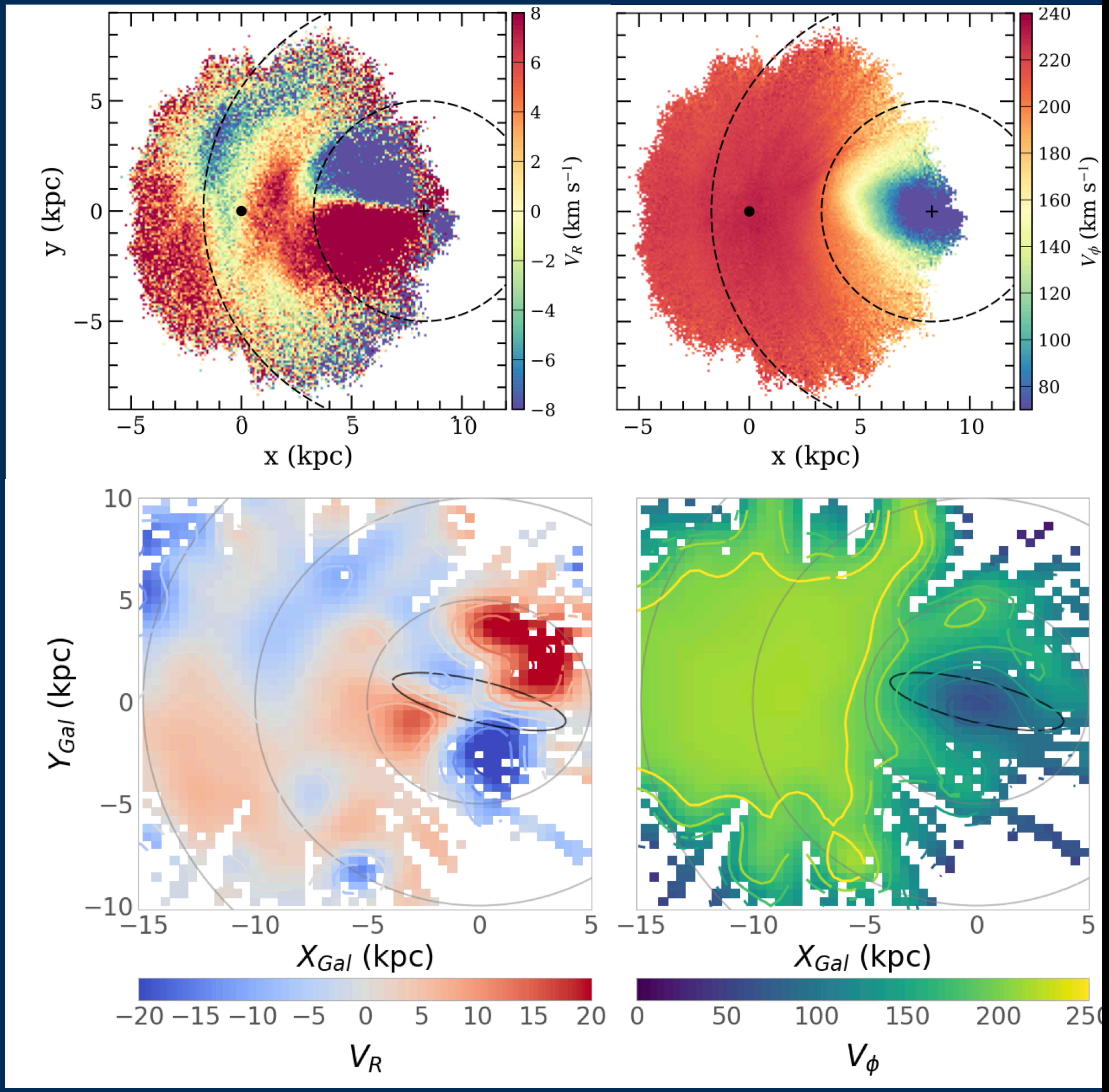
MW disc reconstructed kinematics vs Gaia/StarHorse



Khoperskov+ 2024b

Gaia RVS

Drimmel+ 2023 (Gaia DR3)

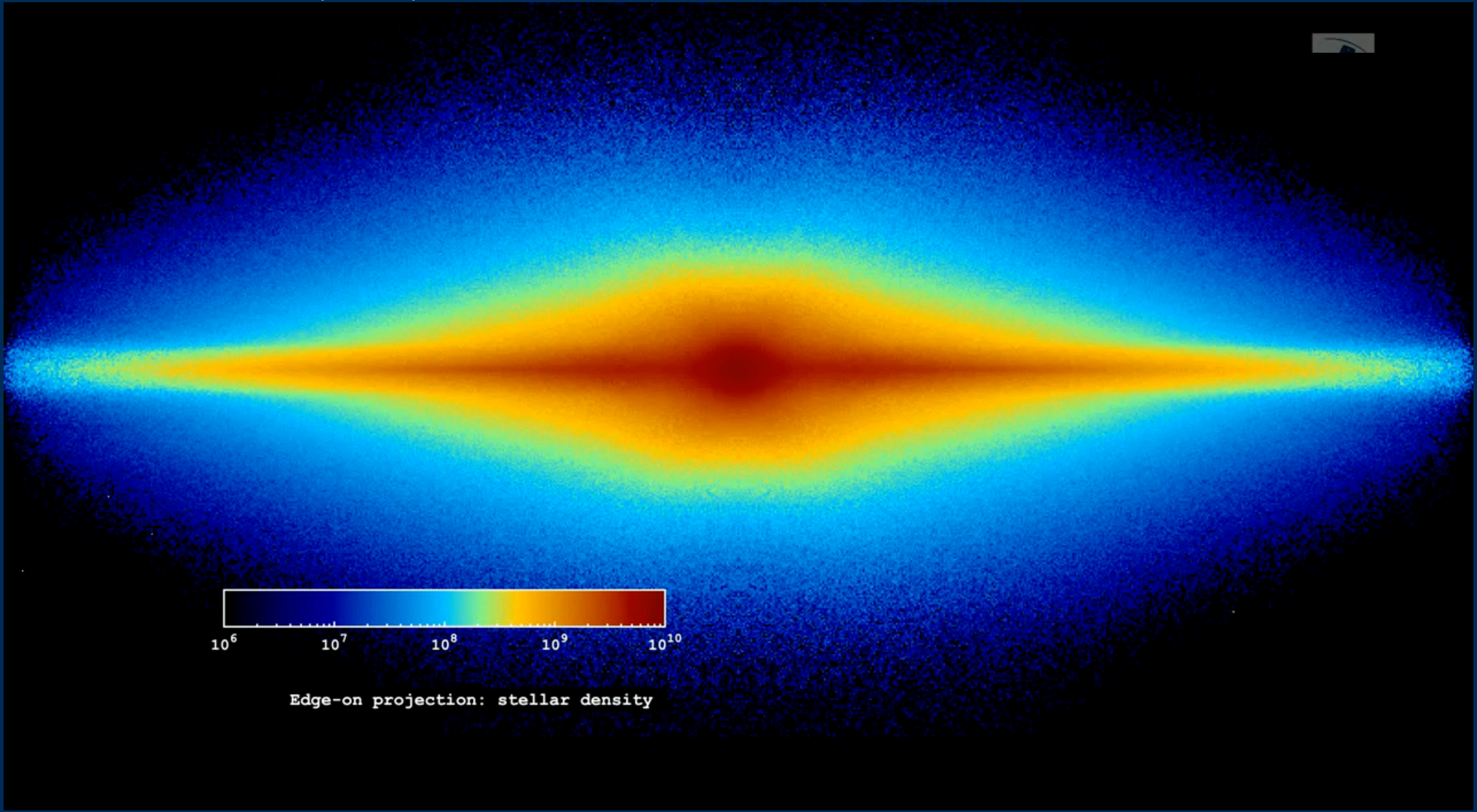


Quieroz+ 2022 (APOGEE/StarHorse)

Age structure of the MW disc

Khoperskov, MS+ 2024b

The extragalactic Milky Way



Milky Way: mock IFU observations

Each phase-space coordinate along the orbit — SSP

[Mg/Fe]-variable MILES SSP

Masses of SSP - orbit weights
metallicities and ages from APOGEE

Khoperskov + (in prep)

Extragalactic Milky Way from IFU: kinematics

Inclination = 70 deg

Khoperskov+ (in prep)

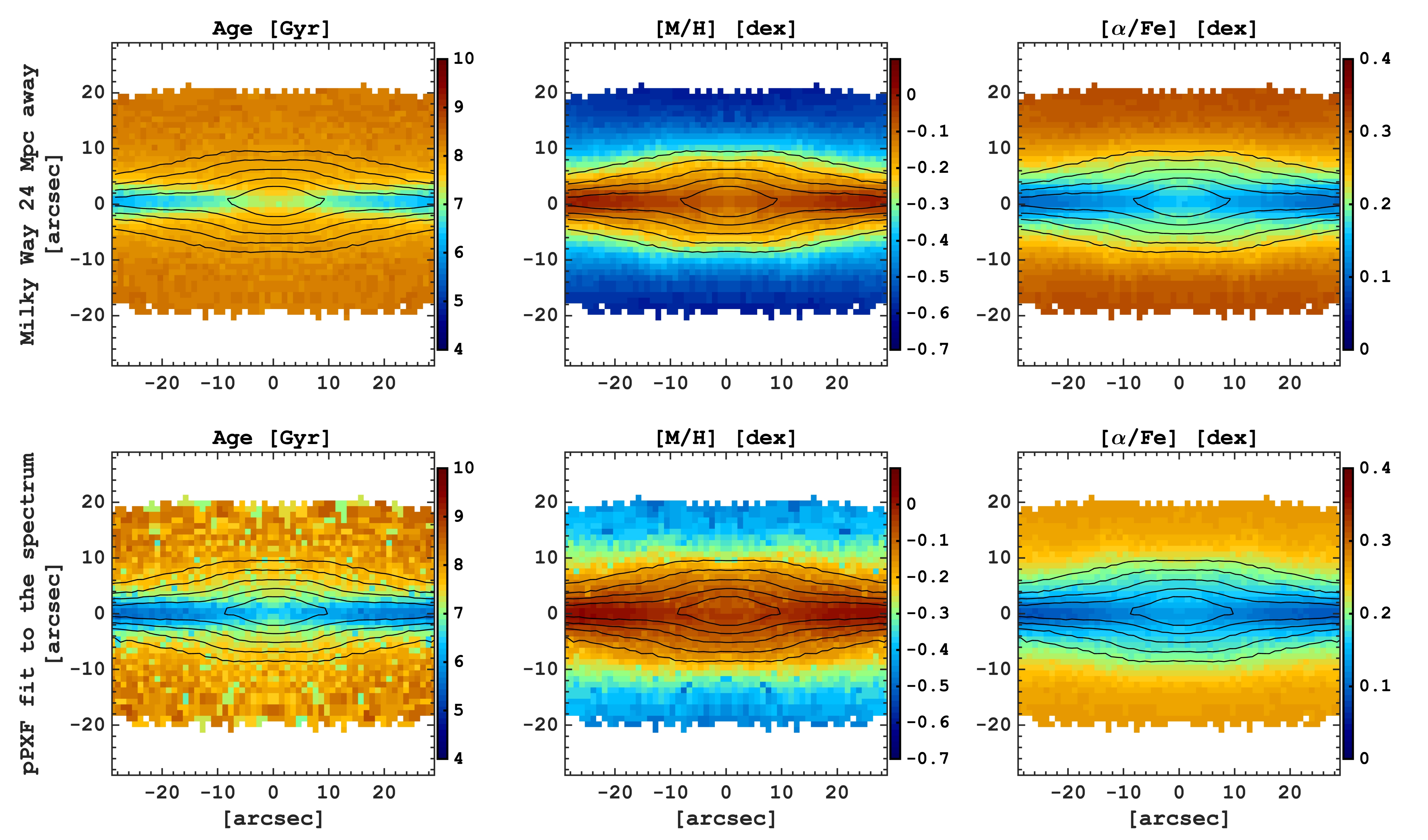
Extragalactic Milky Way from IFU: kinematics

Edge-on projection

Khoperskov+ (in prep)

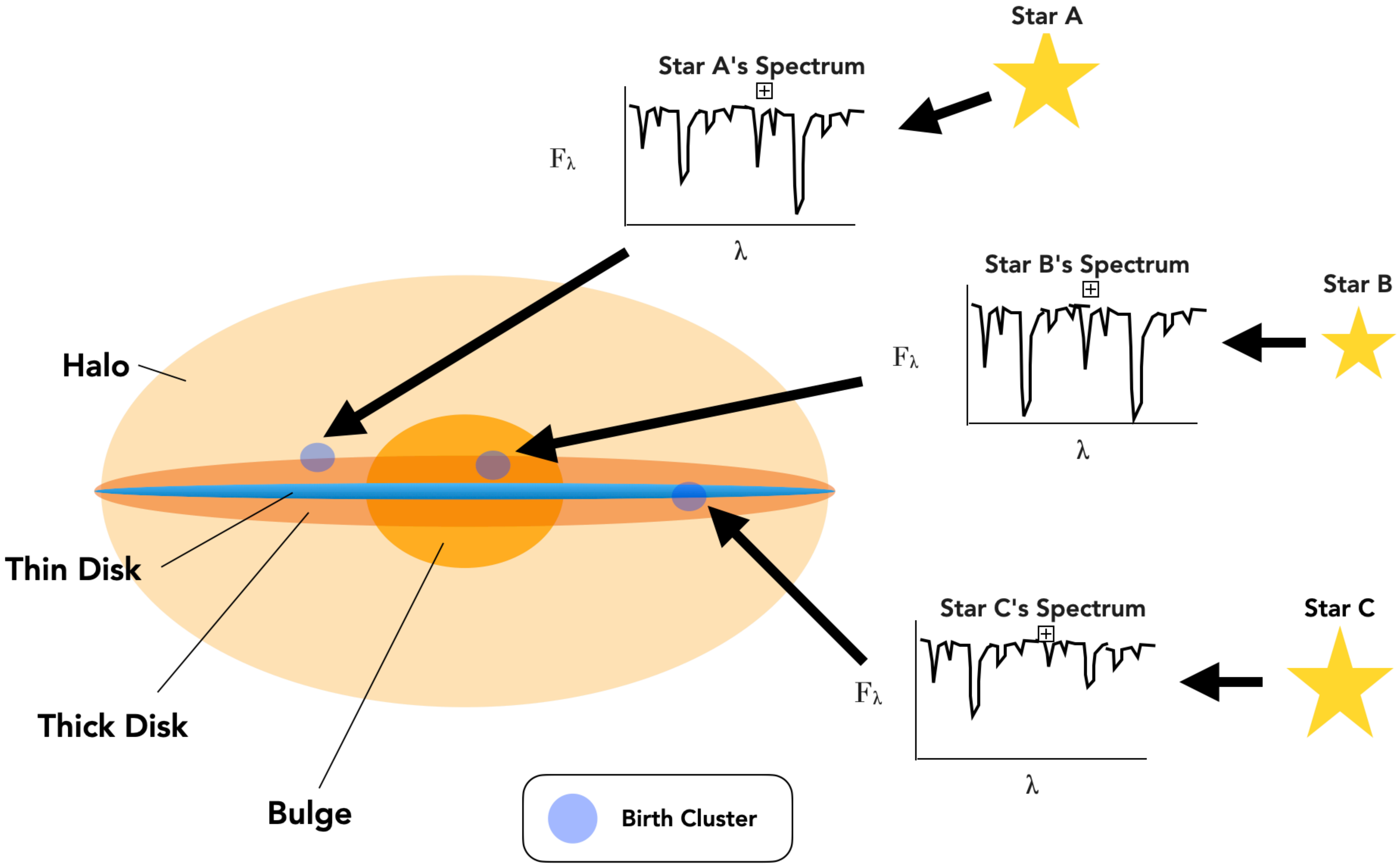
Extragalactic Milky Way: chemical composition

Edge-on projection



Khoperskov+ (in prep)

The goal: Chemical tagging

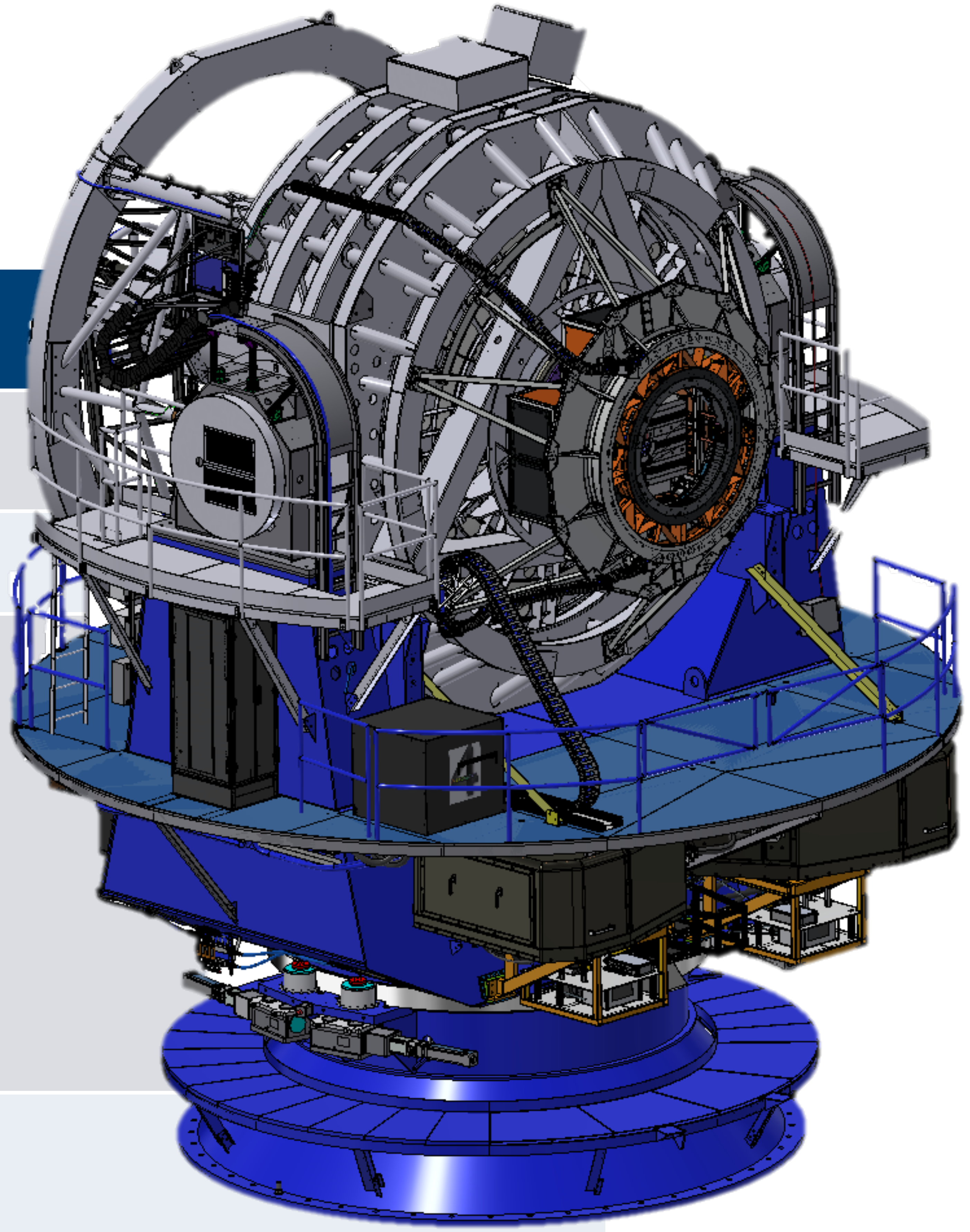


- Chemical tagging: Use the chemical properties of stars to backtrace their birth cluster. As they formed from the same birth cloud, they should have similar, if not identical abundances
- Level to which this is possible, still needs to be proven

© Catherine Manea (U Texas)

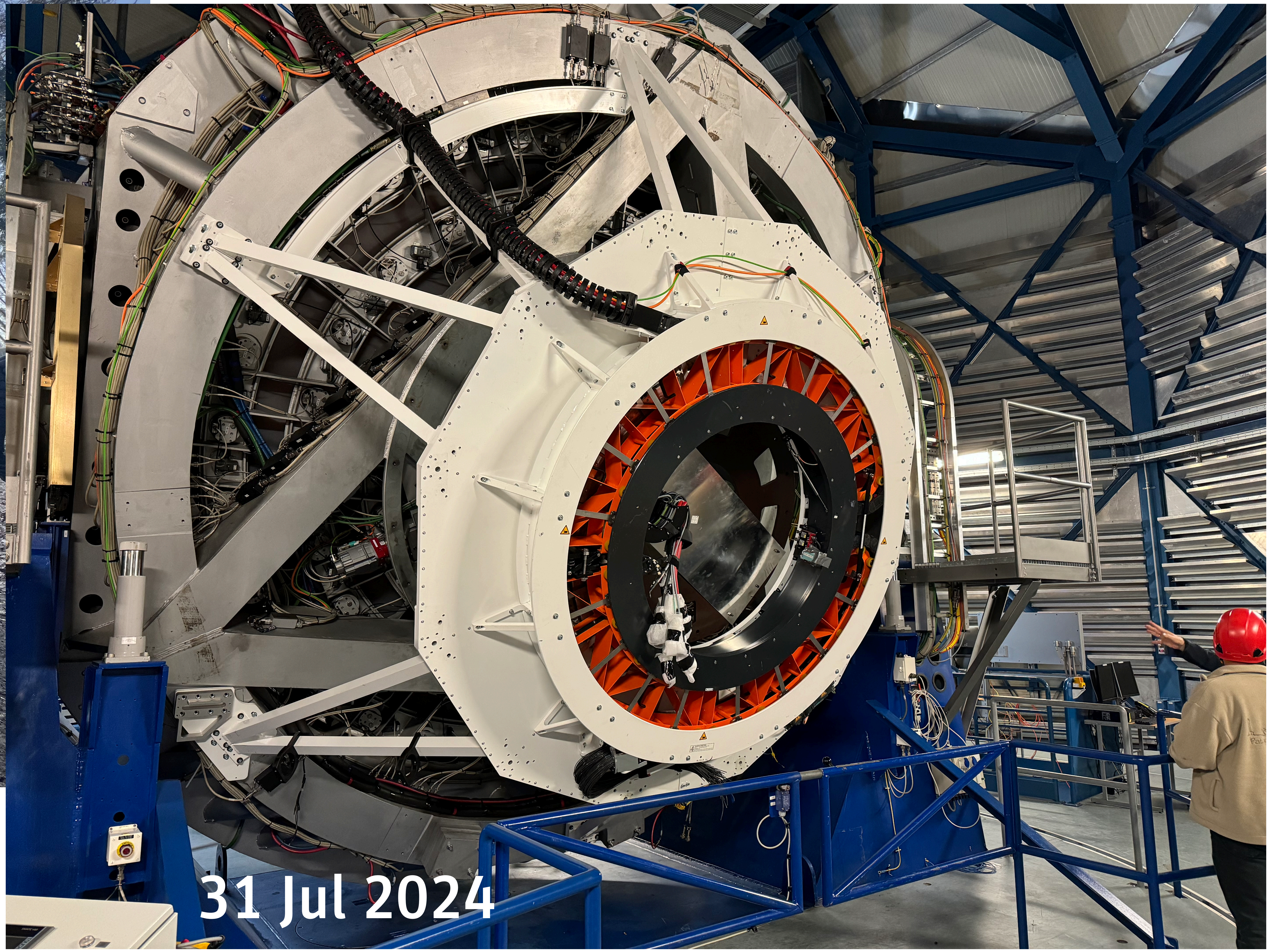
4MOST – 4m Multi-Object Spectroscopic Telescope

Instrument Characteristics

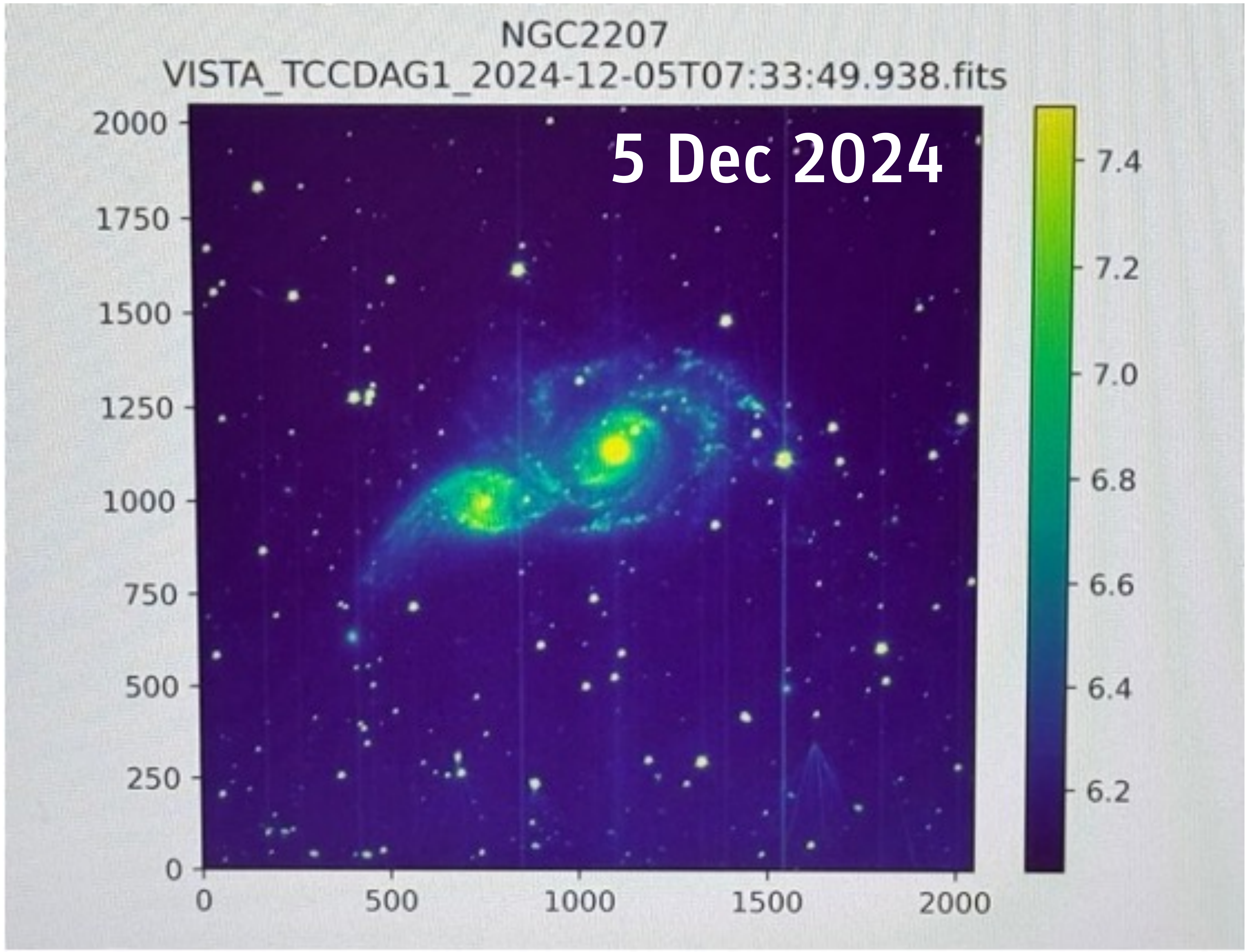


Specification	Design value
Field-of-View (hexagon)	~4.2 degree^2 (∅ > 2.6°)
Multiplex fiber positioner	2436
Medium Resolution Spectrographs (2x) # Fibres Passband Velocity accuracy Spectral sampling (pixels/FWHM)	R~4000–7500 812 fibres (2x) 370–950 nm < 1 km/s > 2.8 pixels
High Resolution Spectrograph (1x) # Fibres Passband Velocity accuracy Spectral sampling (pixels/FWHM)	R~20,000 812 fibres 392.6–435.5 nm, 516–573 nm, 610–679 nm < 1 km/s > 2.56 pixels
# of fibers in ∅=2' circle	>3
Fibre diameter	∅=1.42 arcsec

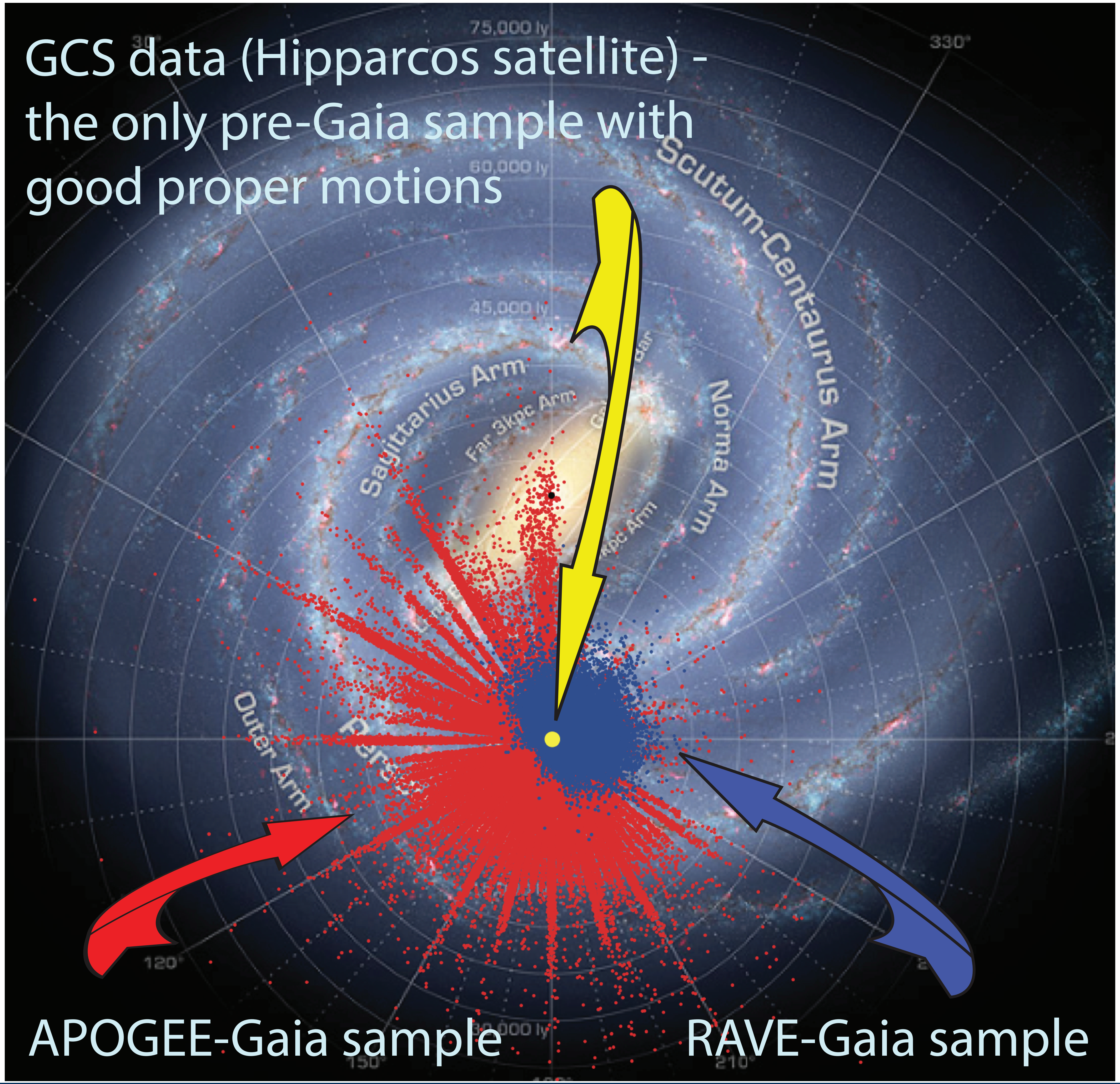
Leistikow
SCANIA
Feuerwehrfläche freihalten
29 Feb 2024



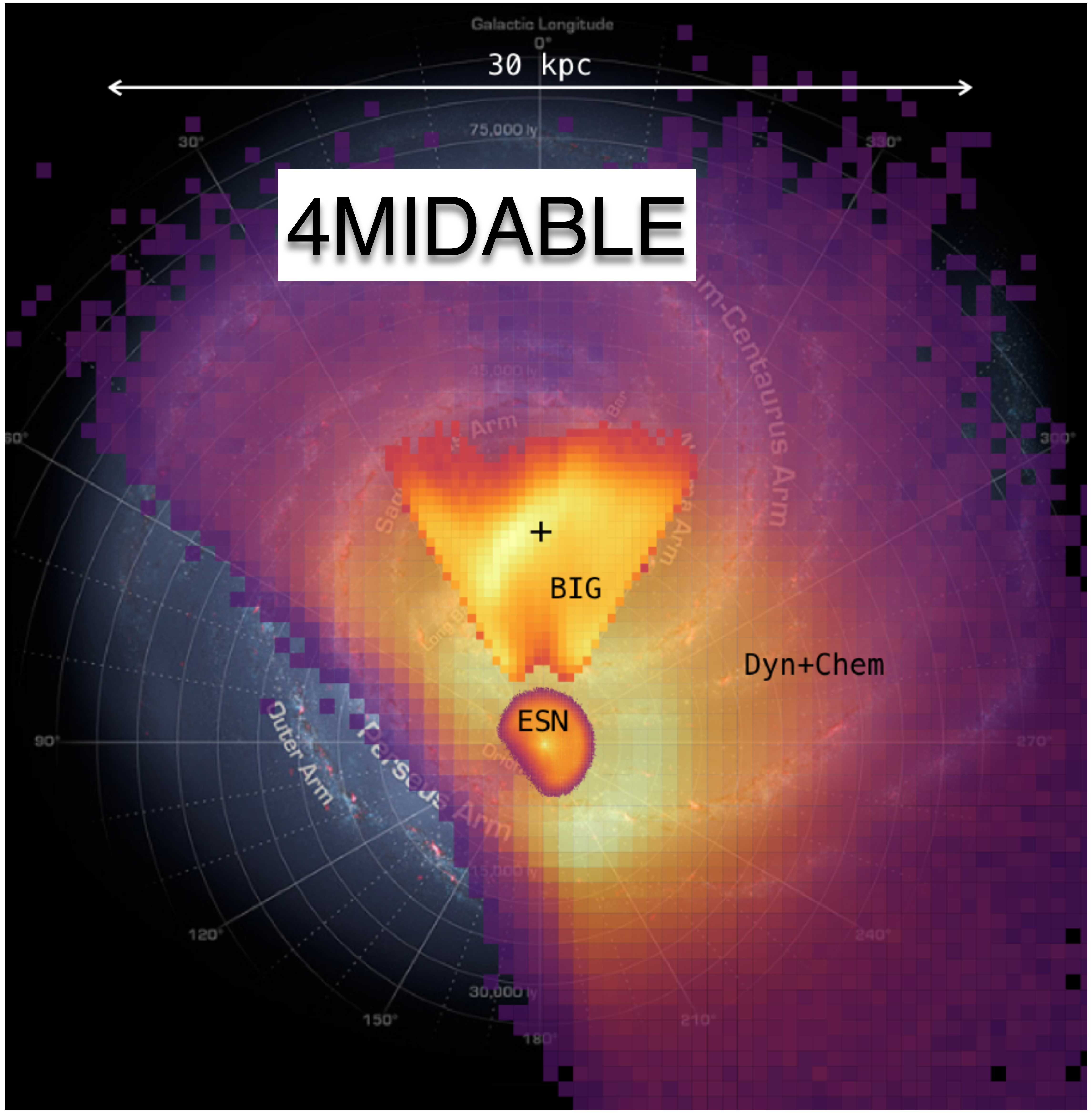
31 Jul 2024


NGC2207
VISTA_TCCDAG1_2024-12-05T07:33:49.938.fits
5 Dec 2024
2000
1750
1500
1250
1000
750
500
250
0
0
500
1000
1500
2000
7.4
7.2
7.0
6.8
6.6
6.4
6.2

2025: Gaia + RAVE + APOGEE + ...



Starting 2026: Gaia and 4MOST



Summary and Conclusion

- Ongoing revolution in stellar science driven by Gaia ⇒ „precision stellar science"
- We can chemically map fair fractions of the MW and reach out to its satellite system
- We can use Scharzschild's method to
  - map into Galaxia incognita
  - analyze the Milky Way as it would be an external galaxy
- Critical feature: base data needs to adequately sample relevant orbital families
- Soon to come: Massive systematic spectroscopic campaigns

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