Galactic Archaeology in the Gaia era

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Lecture I

AIP

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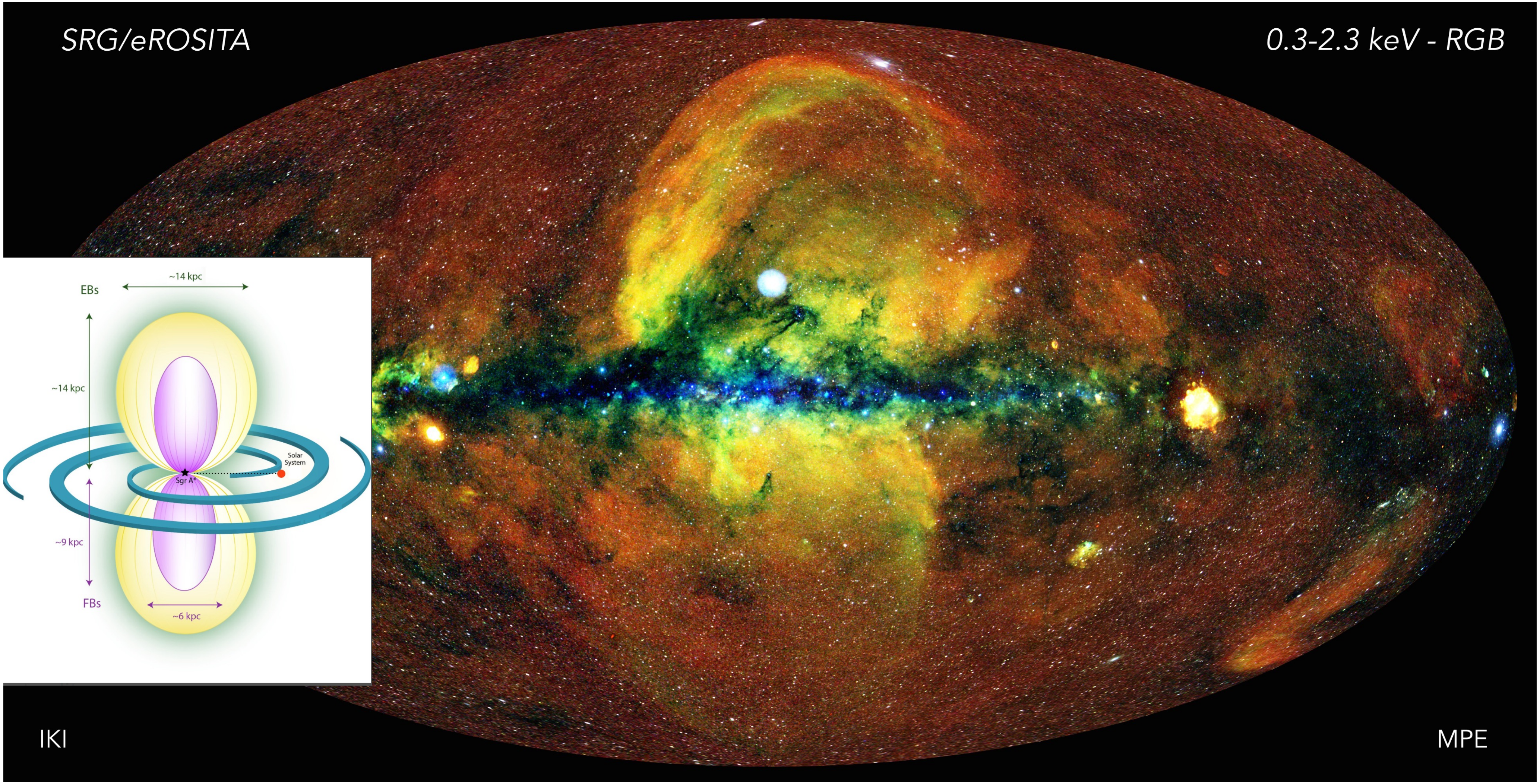
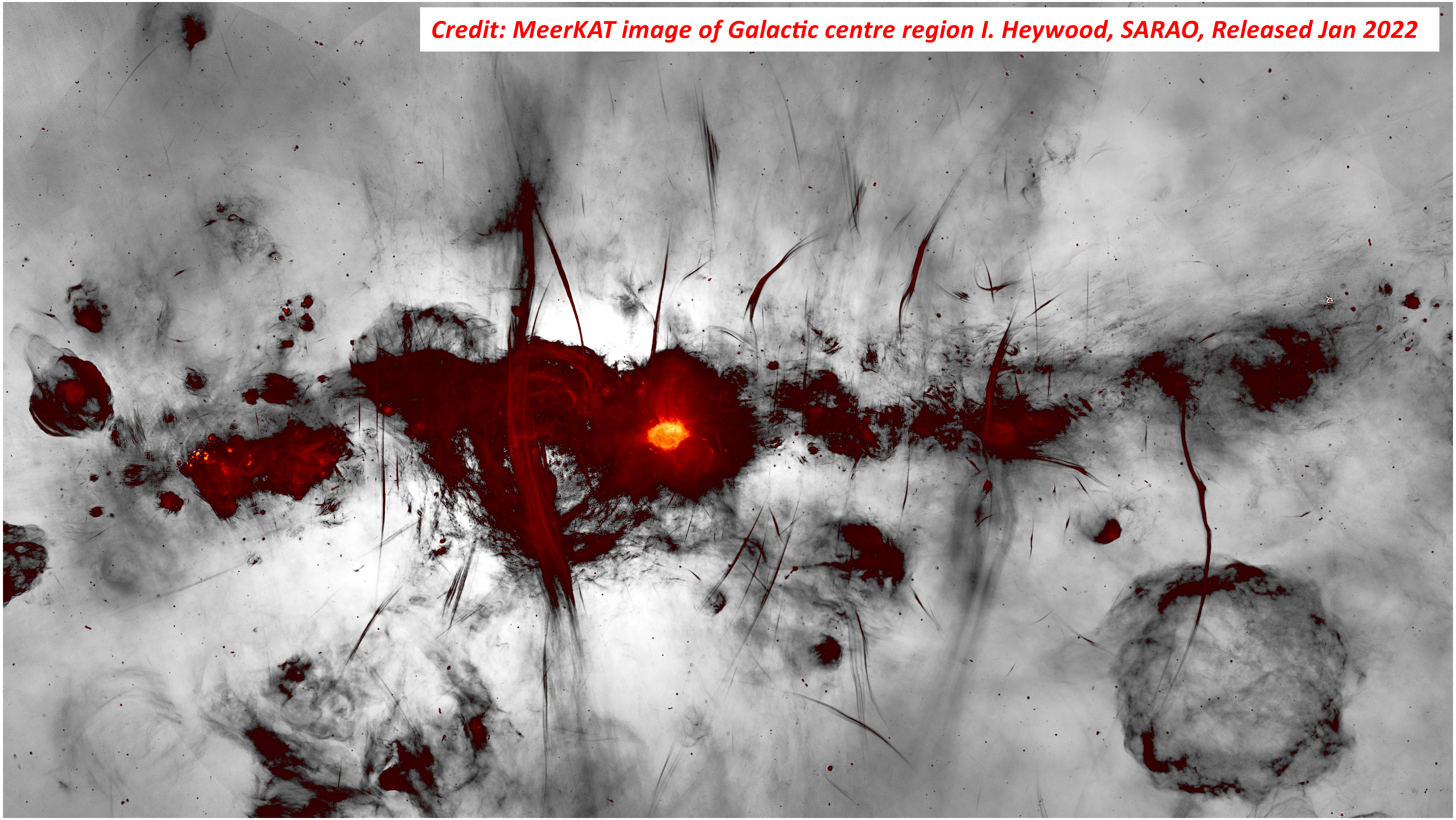
Galactic Archaeology in the Gaia era

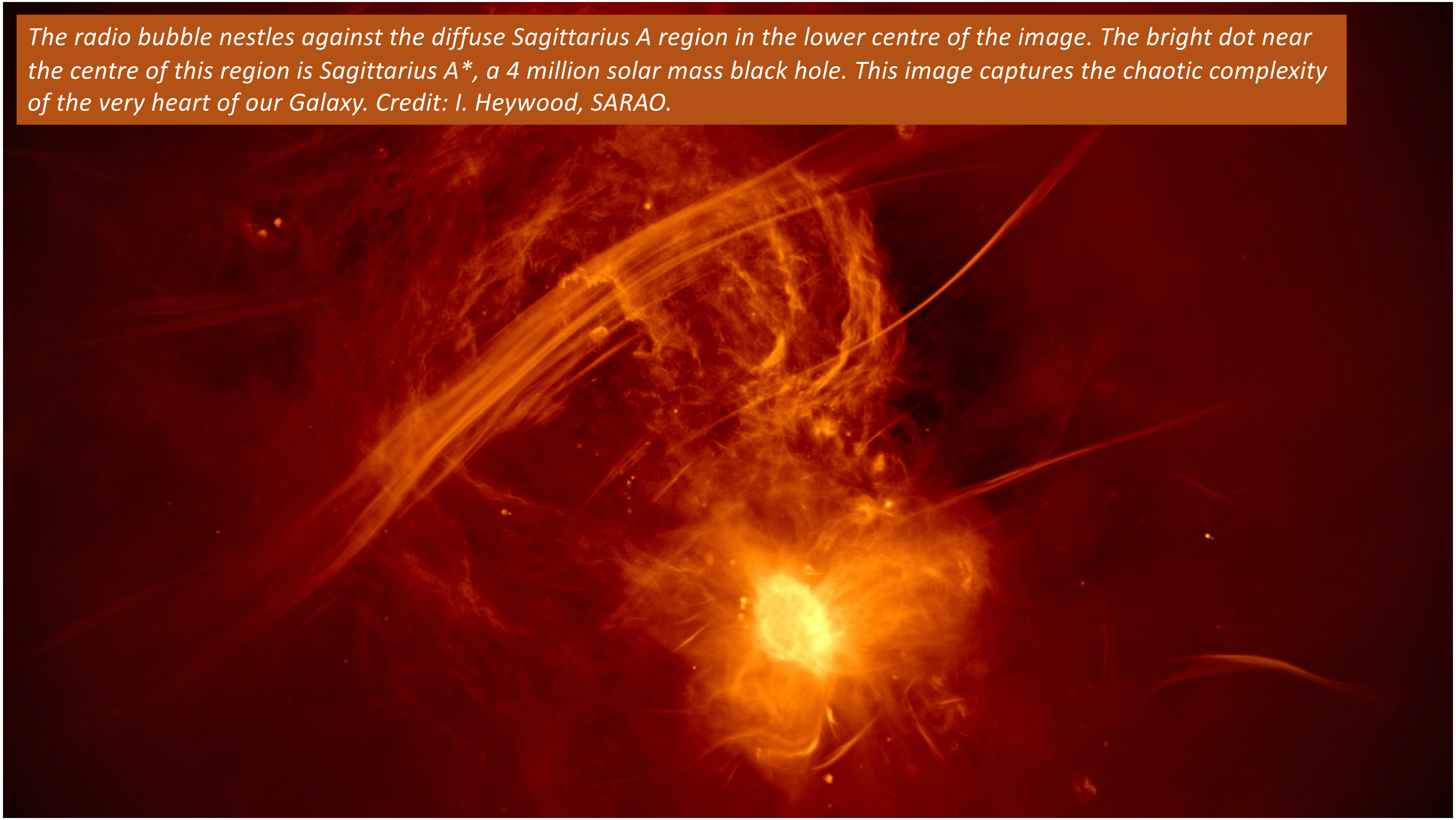
1. Mapping the Milky Way: Gaia, Spectroscopic Surveys and asteroseismology
2. The Galaxy is complex: finding debris and culprits of radial migration by combining ages, chemistry and kinematics
3. The galactic bulge I
4. The galactic bulge II and future outlook

Gigantic hot-gas structures above and below the galactic disc
Shock waves generated by past energetic activity in the center of our Galaxy (Dec 2020)



Credit: J. Sanders, H. Brunner (MPE), E. Churazov, M. Gilfanov (IKI), and eSASS team


Credit: MeerKAT image of Galactic centre region I. Heywood, SARAO, Released Jan 2022

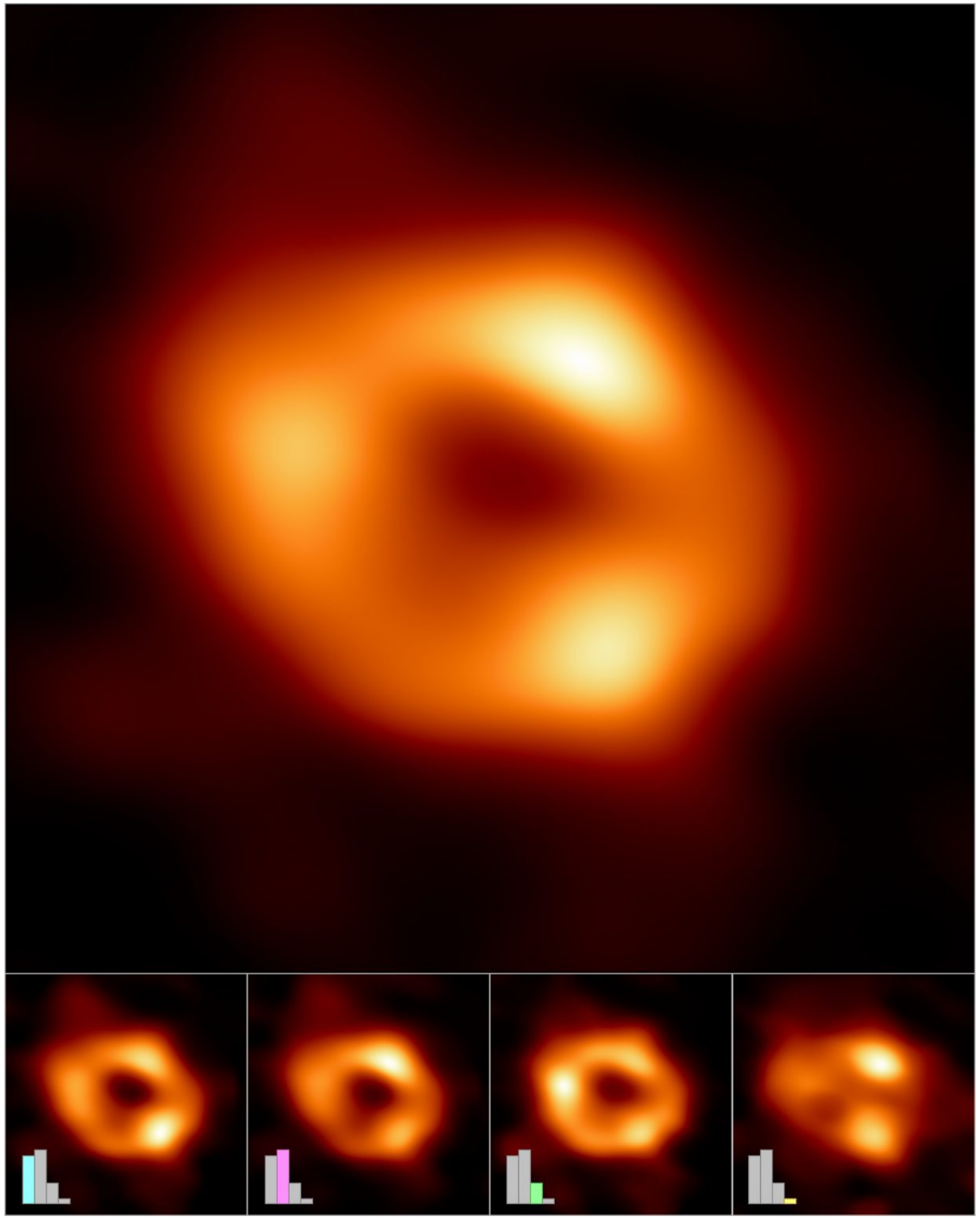


The radio bubble nestles against the diffuse Sagittarius A region in the lower centre of the image. The bright dot near the centre of this region is Sagittarius A, a 4 million solar mass black hole. This image captures the chaotic complexity of the very heart of our Galaxy. Credit: I. Heywood, SARAO.*

Event Horizon Telescope

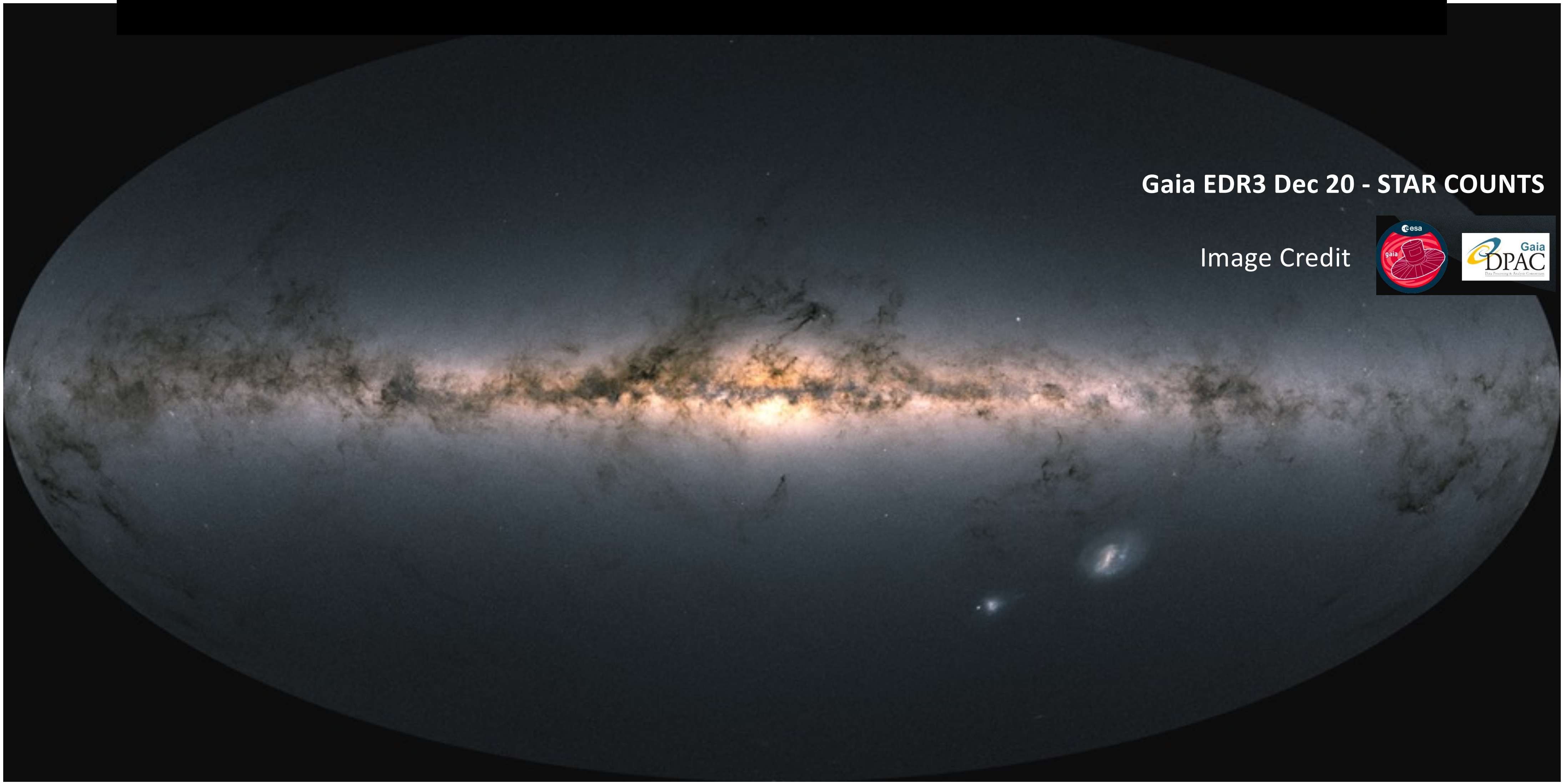
MW BH

Just two years after Nobel Prize in 2020
To Penrose, Ghez and Genzel



May 2022

Mapping the Milky Way & Galactic Archaeology



Chemical evolution aims at describing the evolution of chemical elements in the gas of galaxies, and can thus explain the stellar properties of stars of different ages whose present composition reflects that of the gas at the time of their formation.

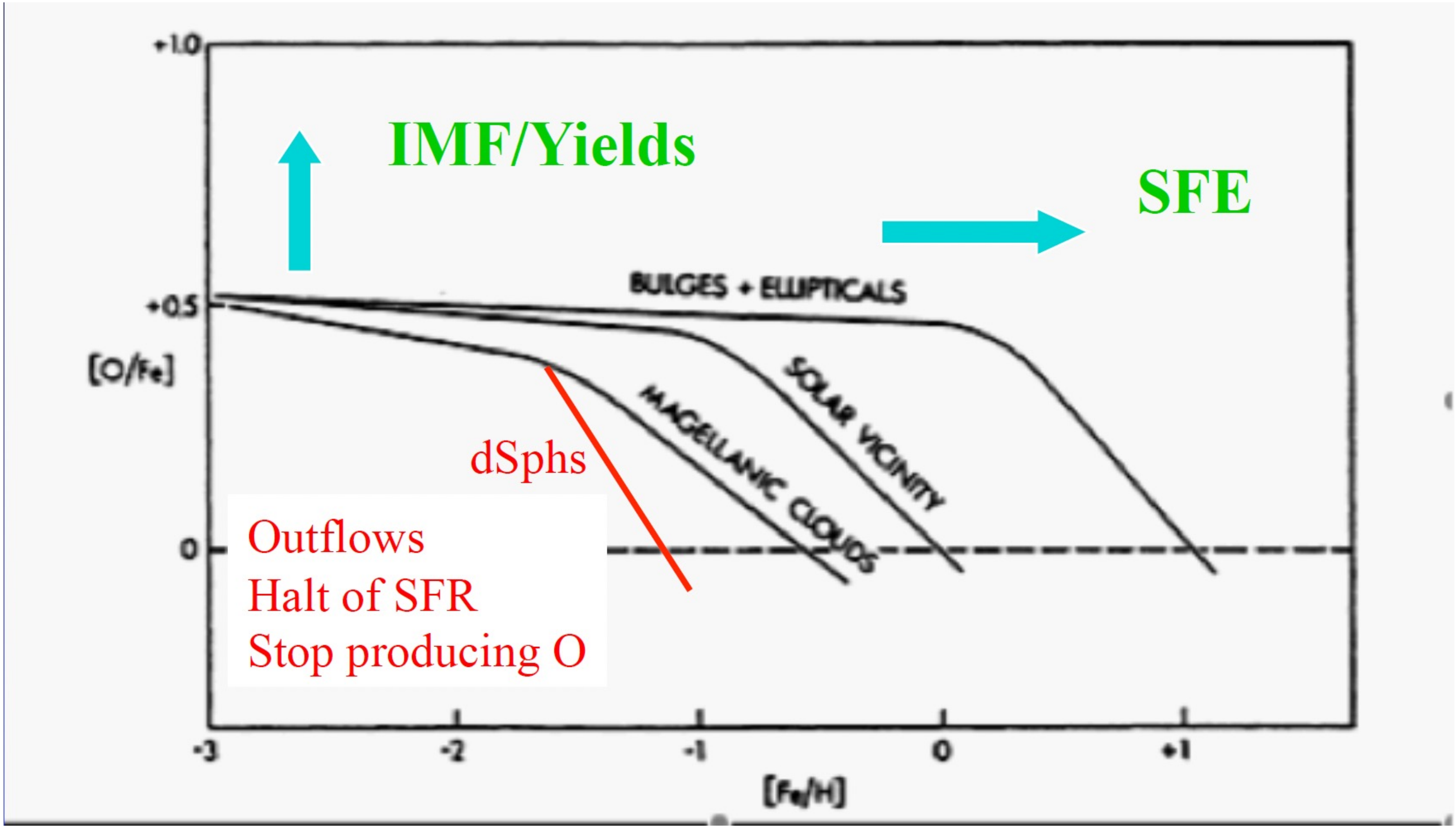
- Star formation rate -> gas flows
- Initial mass function
- Stellar nucleosynthesis (yields & lifetimes)

Different elements are made in different nucleosynthetic sites and therefore released to the interstellar medium, on different timescales.

BUT

Models and conclusions can be erroneous due to mix of stellar populations, dynamical processes affecting the distribution of stars (secular processes, mergers), lack of sufficient information (dimensions) leading to non univoque answers.

Foundations: Eggen et al. 1962, Schmidt 1963, Pagel & Patchett 1975, Searle & Zinn 1978, Tinsley 1980



Matteucci & Brocato 1990

Challenges

Galaxies

- Spatial Resolution
- Age Resolution
- Luminosity weighted quantities

Milky Way

- Volume coverage
- Age precision at larger distances
- Large extinction through disk towards Bulge

Advantages

- Volume coverage
- Diversity of Galaxies
- Multiwavelenght – gas / stars

- Chemical properties for individual stars
- Ages for individual stars
- Kinematics for individual stars
- Multi-D tracers of MW history (chemistry)

Chemical evolution

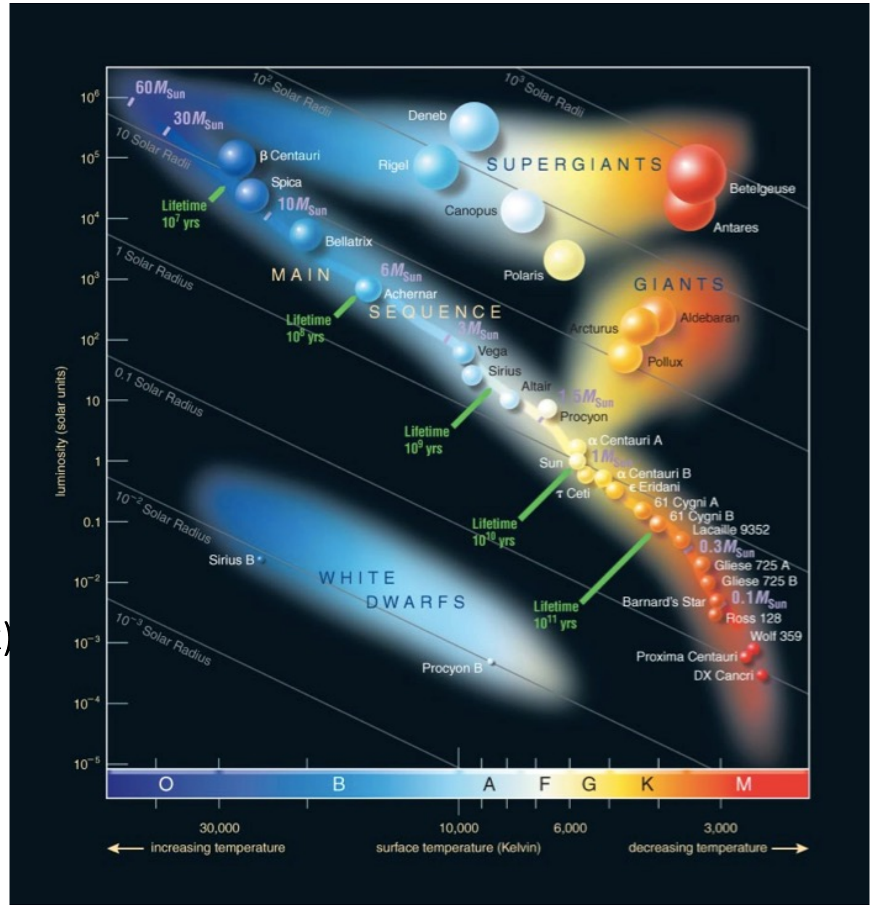
Reviews Matteucci 2021, Maiolino & Mannucci 2019, Barbuy, Chiappini, Gehrard. 2018,
Helmi 2020, N. Forster Schreiber & S. Wuyts 2020, Freeman & Bland-Hawthorn 2002, Romano 2022

- Simple analytical descriptions, instantaneous recycling aproximation assumed (ok for modelling Oxygen for instance)
- Numerical models, without instantaneous recycling approximation but instantaneous mixing (most of the current Chemical Evolution Models)
- Same as above, but relaxing instantaneous mixing, and taking into account stochastic star formation – learn from scatter in abundances
- Chemodynamical models (here again a broad family of methods)
- Cosmological simulations with chemistry (a lot is happening here!) connects high-z to local redshift

References in the above-mentioned reviews

We will focus on long-lived stars (specially those that can be seen far away as Red Giants)

- With lifetimes spaning the whole Galaxy history
- Most of them with chemical abundances from the gas from which they were born
- We can translate the sky view into real positions and velocities (6D phase space – compute Energy, angular momentum, ecc, zmax, rapo, rperi
- We can trace past merger events (phase space + chemistry)
- We can trace the Galactic populations back in time (chem clocks/ ages)
- Trace inside-out disc formation
- Can ”observe” secular processes such as radial migration
- We can see disk flaring and warp
- We can compare the old MW to what we see at high-redshifts (Bulges?)
- We can compare the present day MW with local volume galaxies (Thick disk)
- We can constrain nucleosynthetic sites
- We can add constraints to the nature of the first stellar stars / VMP stars
- ...



What is Galactic Archaeology?

Galactic Archaeology strives to reconstruct the past history of the Milky Way from the present day kinematical and chemical information.

Why is it Challenging in the MW?

Complex mix of populations with large overlaps in parameter space (such as Velocities, Metallicities, and Ages) & small volume sampled by current data

Why is it even more challenging in the Bulge?

Large distance from us, large extinction, maximum mix of populations

Reviews…

- **Helmi 2020**, Streams, Substructures, and the Early History of the Milky Way , **ARAA**, vol. 58, p.205-256
- **Brown 2021**, Microarcsecond Astrometry: Science Highlights from Gaia, **ARAA**, vol. 59, 59-115
- **Barbuy, Chiappini, Gehrard** 2018, Chemodynamical History of the Galactic Bulge, **ARAA**, vol. 56, 223-276
- **Matteucci 2021**, Modelling the chemical evolution of the Milky Way, The **A&A Review**, vol.29, Issue 1, article id.5
- **Chiappini, Minchev, Starkenburg, Valentini 2018**, **IAU Symposium 234**, Rediscovering the MW
- **Chaplin & Miglio 2013**, Asteroseismology of Solar-Type and Red-Giant Stars, **ARAA** vol 51, 353-392

3 important observational breakthroughs (2010-now)

Volume coverage & 6D phase space information & precision for ages & distances - extinction

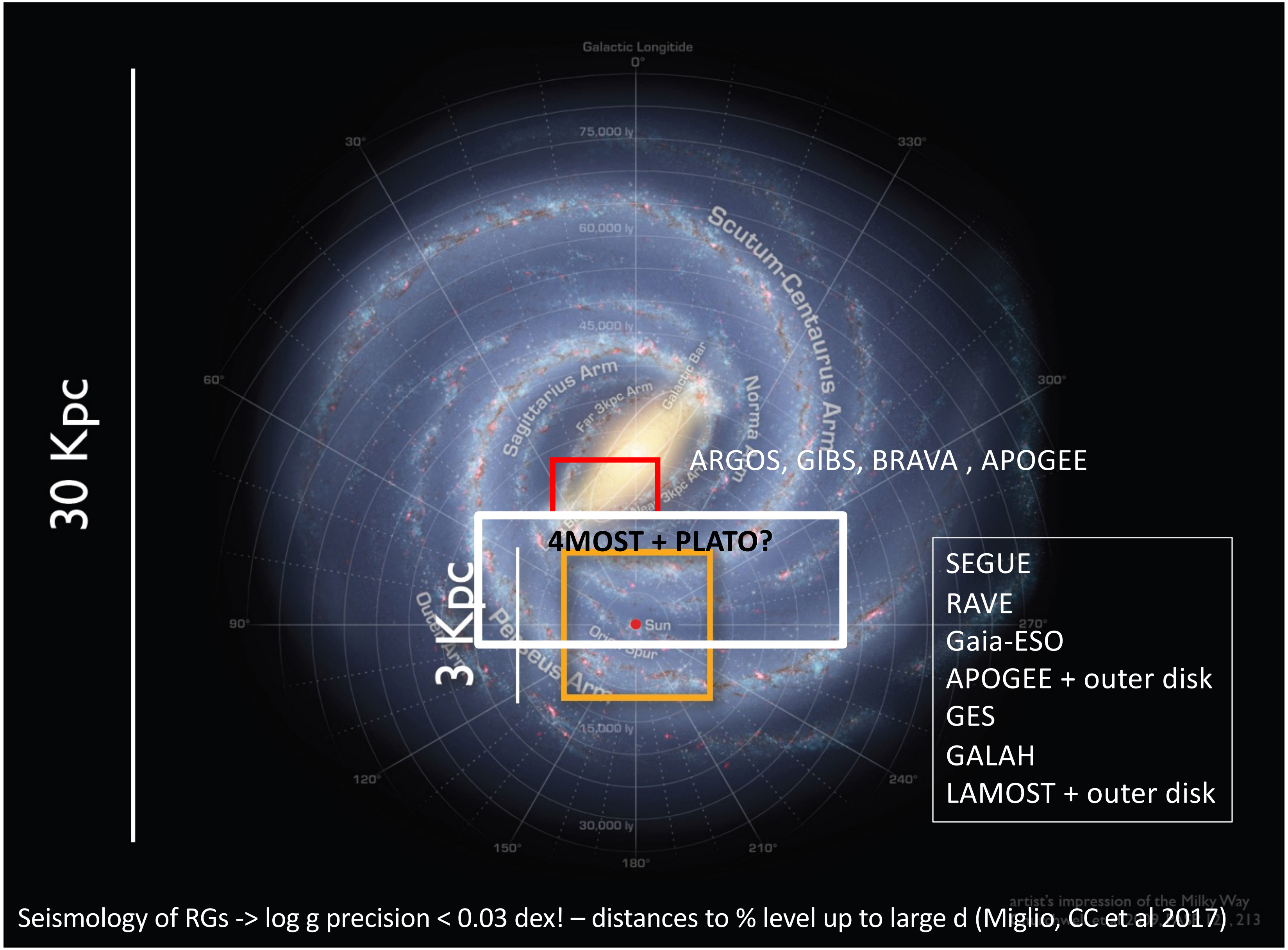
1. **Asteroseismology for Red Giants** discovered in 2009 -> Masses and Radius for stars as far as 15 kpc! CoRoT, Kepler, K2, TESS and in the future PLATO

Precise distance and age for stars far away!
But pencil beam observations in few fields, low density

2. **Astrometry with high precision** -> Gaia - more precise than Hipparcos and large volume coverage – down to G ~ 20 , 1.7 billion targets!

Precise position and velocities -> **but need to work with complementary data (photometry and spectroscopy - Radial velocities and chemistry) in order to increase the studied volume.**

3. **APOGEE** **DR16-DR17 revealing the innermost MW region and more!**


30 Kpc
3 Kpc
Galactic Longitude
0°
75,000 ly
60,000 ly
45,000 ly
15,000 ly
30,000 ly
30°
330°
60°
300°
90°
270°
120°
240°
150°
210°
180°
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Perseus Arm
Sun
Orion Spur
ARGOS, GIBS, BRAVA , APOGEE
4MOST + PLATO?
SEGUE
RAVE
Gaia-ESO
APOGEE + outer disk
GES
GALAH
LAMOST + outer disk
artist's impression of the Milky Way
Seismology of RGs -> log g precision < 0.03 dex! – distances to % level up to large d (Miglio, CC et al 2017)

1st Revolution in Galactic Archaeology

Asteroseismology of Red Giants

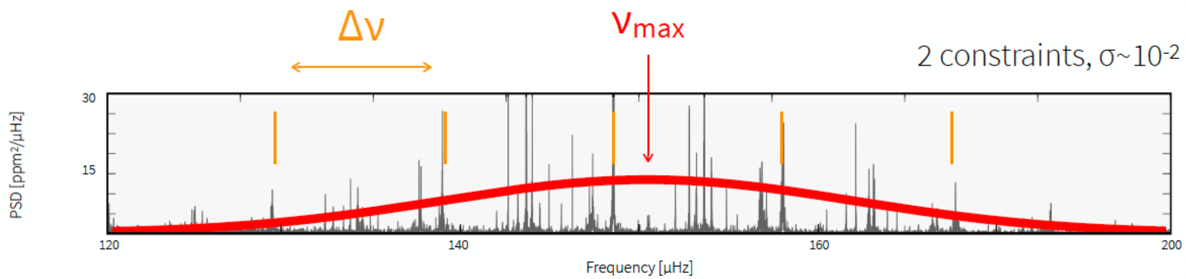
AGES FROM ASTEROSEISMOLOGY

Slide from Miglio SDSS 2021 colab.

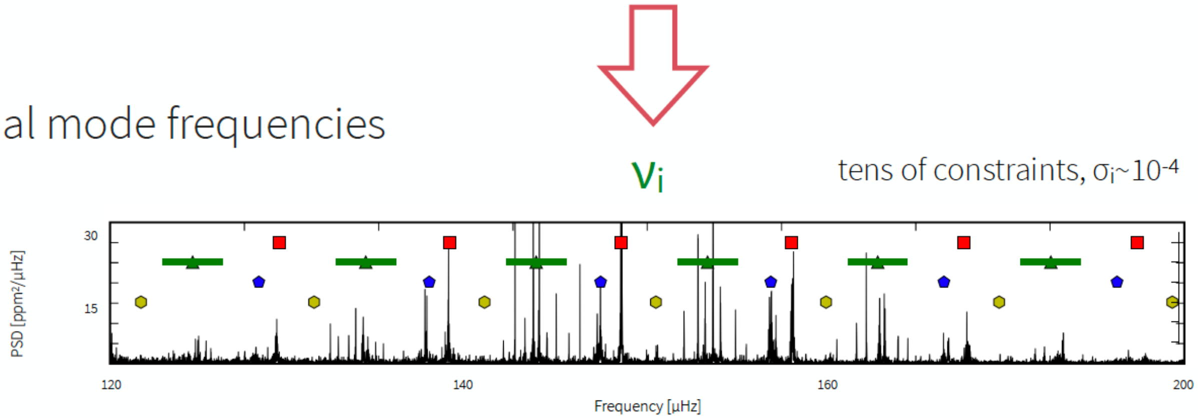
different approaches, different datasets, empirical tests

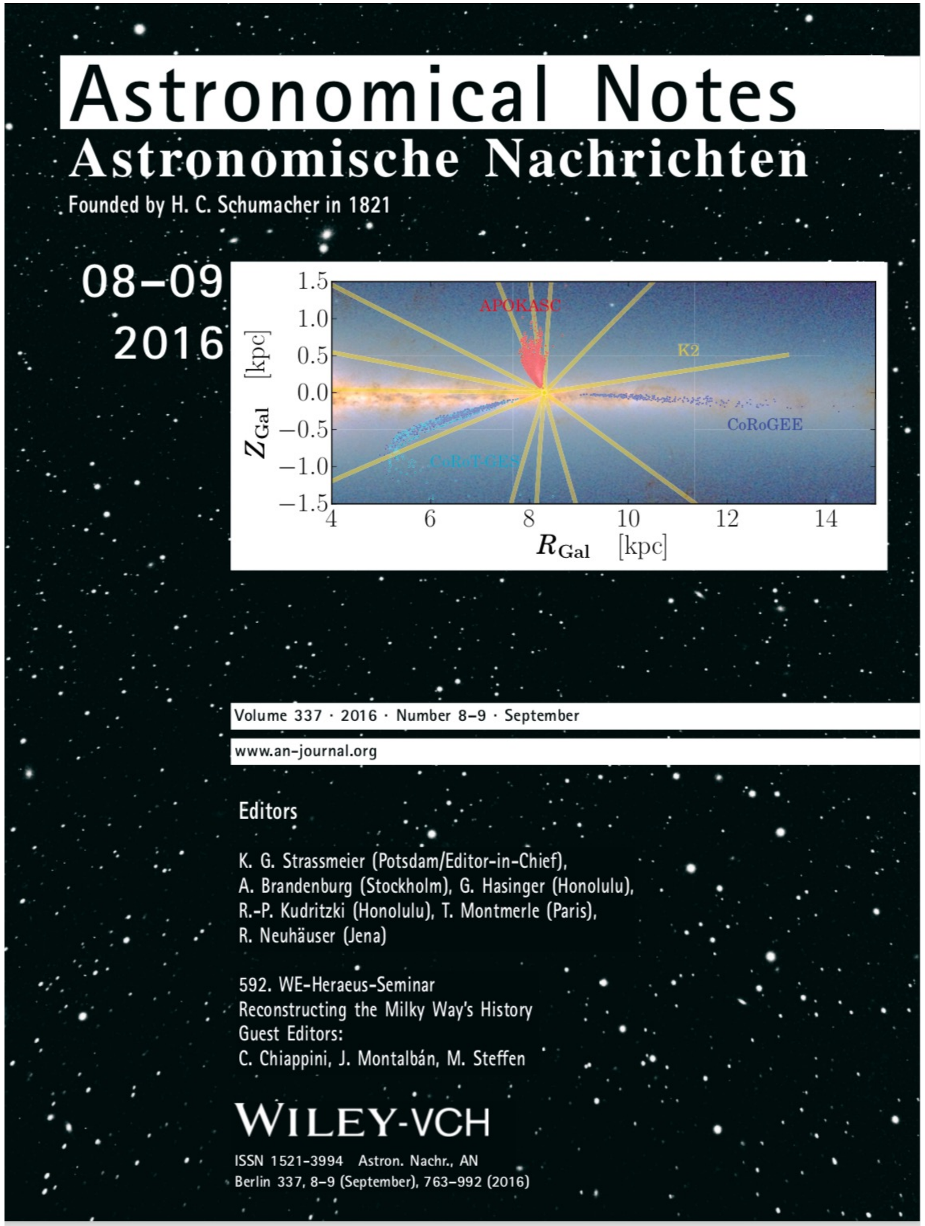
(e.g. papers by Anders et al., Joergensen et al., Miglio et al., Montalban et al, Pinsonneault et al., Rendle et al., Sharma et al., Silva Aguirre et al., Stello et al., Valentini et al., …)

- average seismic parameters



- individual mode frequencies





Asteroseismology: time series measuring stellar variability of very-high quality have become widely available. Analysis of these time series can deliver precise estimates of stellar ages (Davies & Miglio 2016), in Chiappini et al. 2016 dedicated AN Issue.

See also:

Chaplin & Miglio 2013 ARAA
Miglio, Chiappini et al. 2013 MNRAS
Noel, Montalban, Chiappini 2016 AN
Miglio, Chiappini et al. 2017 AN

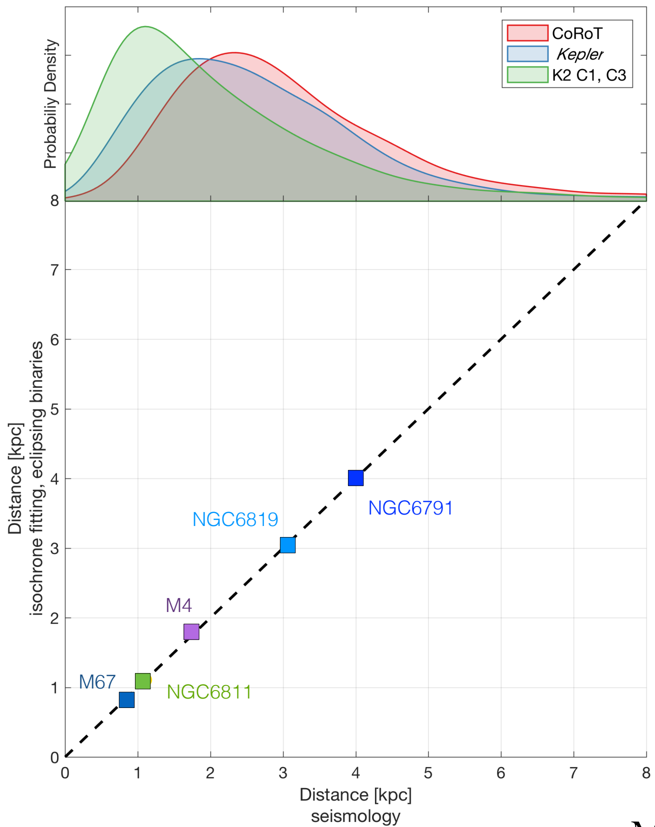
And more recently:

Miglio, Chiappini et al. 2021
Montalban et al. 2021

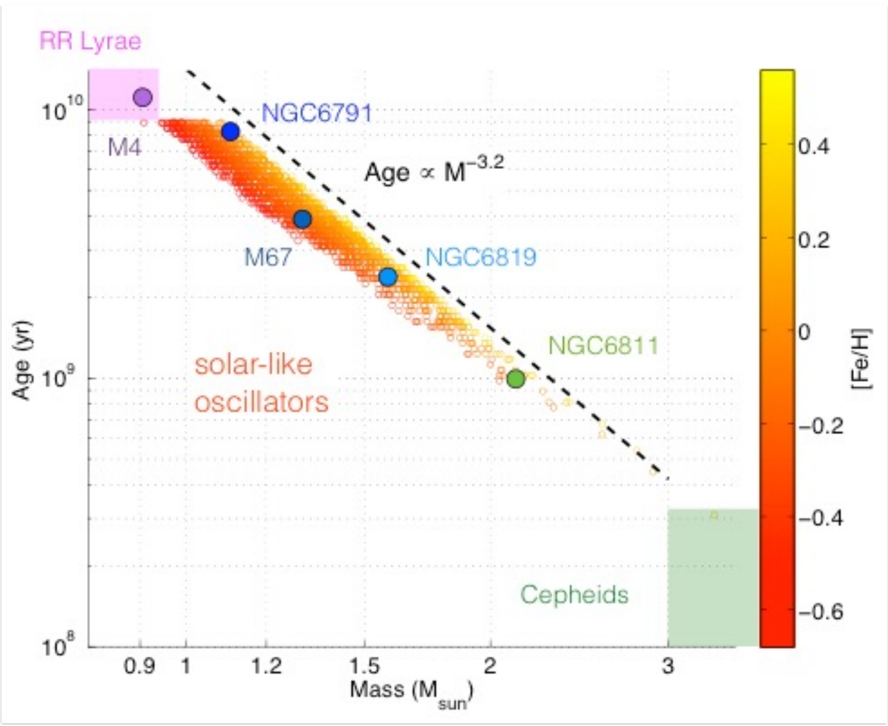
Impact of Asteroseismology of red giants

- Uncertainty on M ∼ 10%
- Uncertainty on R ∼ 3%

Distances to a few % uncertainty!



Masses to Ages ~ 20-35 % uncertainties

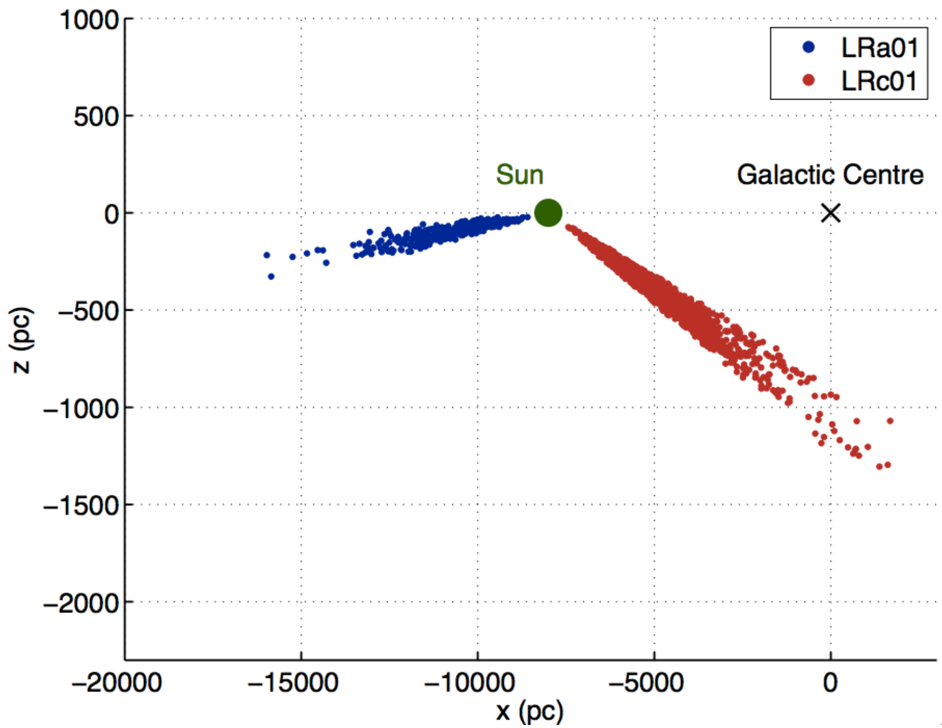


Miglio, Chiappini et al. 2017

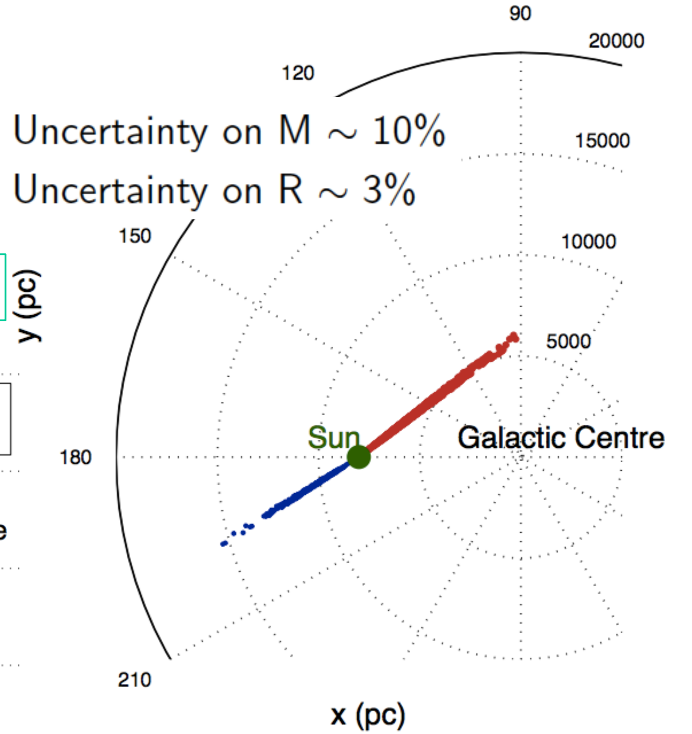
CoRoT

First use of asteroseismology to determine precise distances for a large (~2000) sample of field stars (giants) spread across nearly 15 kpc of the Galactic disc.

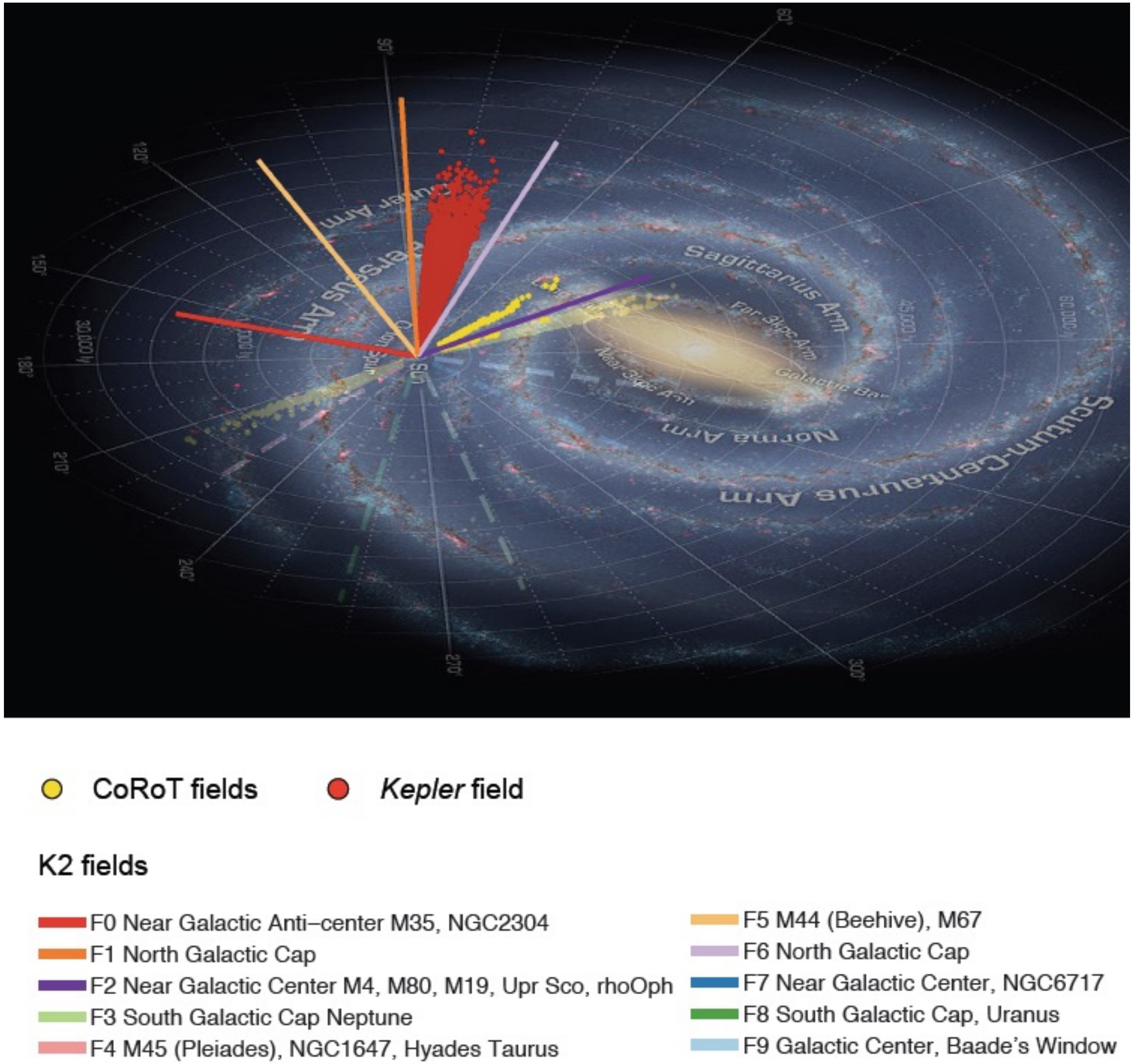
Different Mass Distributions -> Age vertical gradient



- Uncertainty on M $\sim 10\%$
- Uncertainty on R $\sim 3\%$



Miglio, Chiappini, Morel, Barbieri, Chaplin, Girardi, Montalban, Noels, Valentini, Mosser, Baudin, Casagrande, Fossati, Silva Aguirre & Baglin 2013, MNRAS 429, 423
[LRa01+Lrc01 analysis]



90°
60°
120°
150°
180°
210°
240°
270°
300°
Sagittarius Arm
Norma Arm
Scutum-Centaurus Arm
Outer Arm
Far 3kpc Arm
Near 3kpc Arm
Galactic Bar
Sun
CoRoT fields
Kepler field
K2 fields
F0 Near Galactic Anti–center M35, NGC2304
F1 North Galactic Cap
F2 Near Galactic Center M4, M80, M19, Upr Sco, rhoOph
F3 South Galactic Cap Neptune
F4 M45 (Pleiades), NGC1647, Hyades Taurus
F5 M44 (Beehive), M67
F6 North Galactic Cap
F7 Near Galactic Center, NGC6717
F8 South Galactic Cap, Uranus
F9 Galactic Center, Baade's Window

Seismology of RGs: Major impact on GA

- Precise distances out to 15 kpc
- Spectroscopic follow up with main surveys
- Precise log g enabling high precision chemical analysis thanks to more robust determination of T_{eff}, and bringing different surveys on a same scale (e.g. Valentini et al. 2017)
- Ages for far away giants lowering the uncertainties from ~100% to 30% (hopes to improve to ~10% set up timeline of events in early MW history & ages for metal poor)
- **Opens possibility of studying very old field stars and look for chemical contribution of first stars (Valentini et al. 2019)**

2020 -> 11% precision!

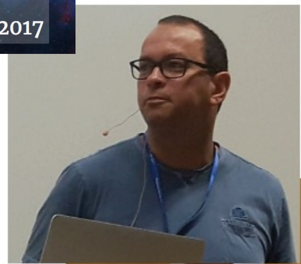
Montalban et al. 2021 Nature Astronomy

What have we achieved with the era of large spectroscopic surveys before Gaia DR2 ?
IMPORTANT ROLE OF ASTEROSEISMOLOGY

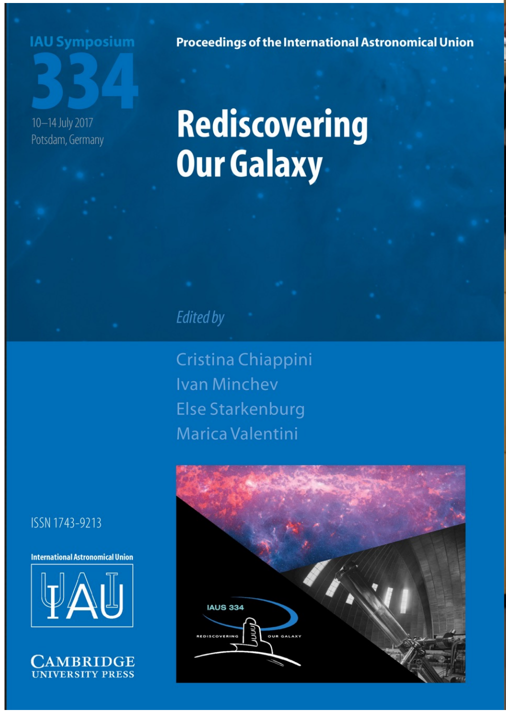
How to compare data and models?

How to extract the information we need from the data?

How to tackle the challenge of the data avalanche?



Chiappini, Minchev, Starkenburt, Valentini 2018



ANNUAL REVIEWS

Annual Review of Astronomy and Astrophysics

Chemodynamical History of the Galactic Bulge

Beatriz Barbuy,[1] Cristina Chiappini,[2] and Ortwin Gerhard[3]

Summary what we knew about Bulge just before the APOGEE DR16 + Gaia DR2 revolution

Galactic Archaeology in the Bulge : in the era of Gaia & Large Spectroscopic Surveys

Show affiliations

Chiappini, Cristina

Publication: The Galactic Bulge at the Crossroads (GBX2018), held 10-14 December, 2018 in Pucón, Chile. Online at http://www.eso.org/sci/meetings/2018/gbx2018.html, galacticbulge2018, id.5

Pub Date: December 2018

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