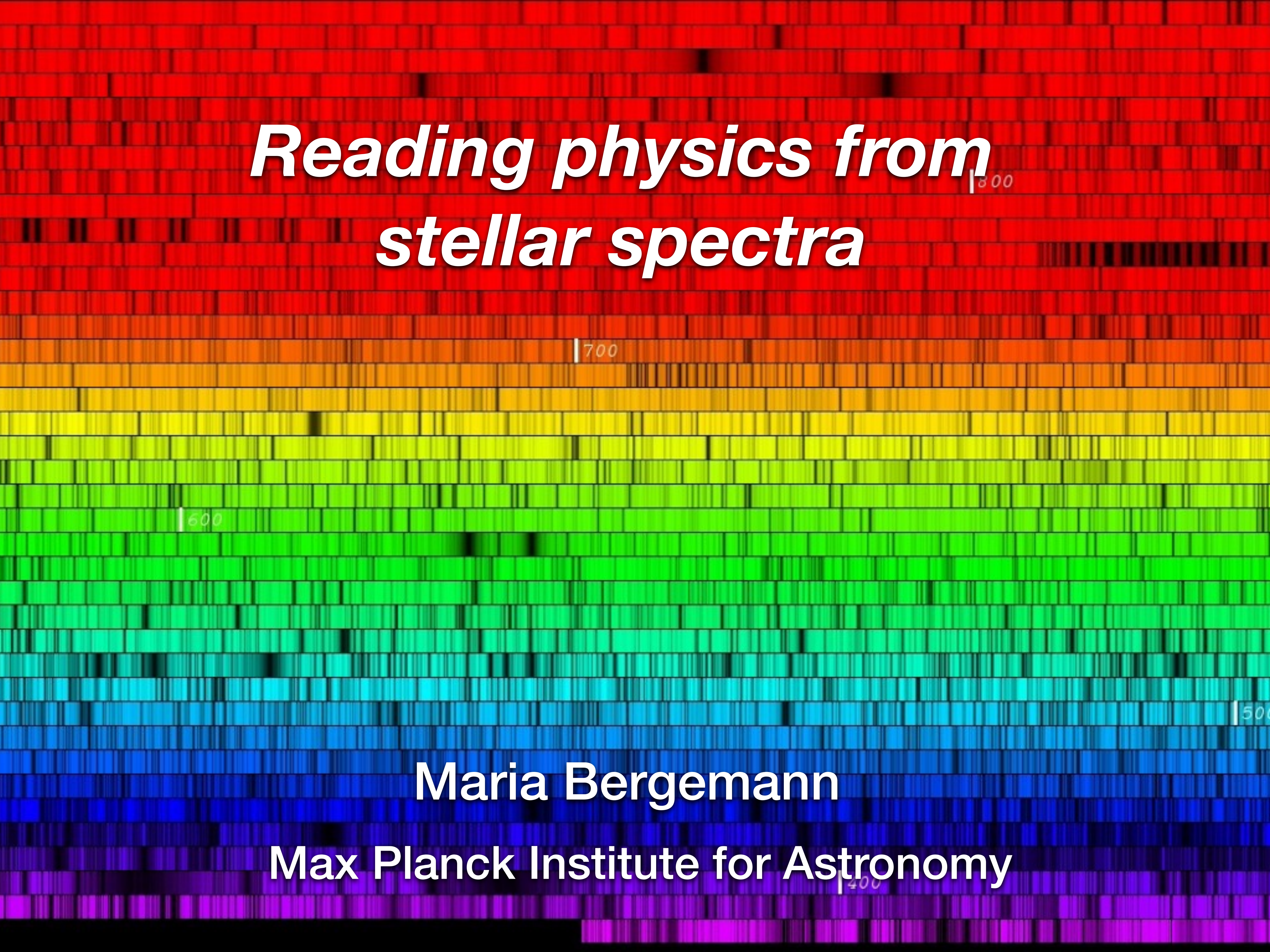
Reading physics from stellar spectra

Maria Bergemann

Max Planck Institute for Astronomy



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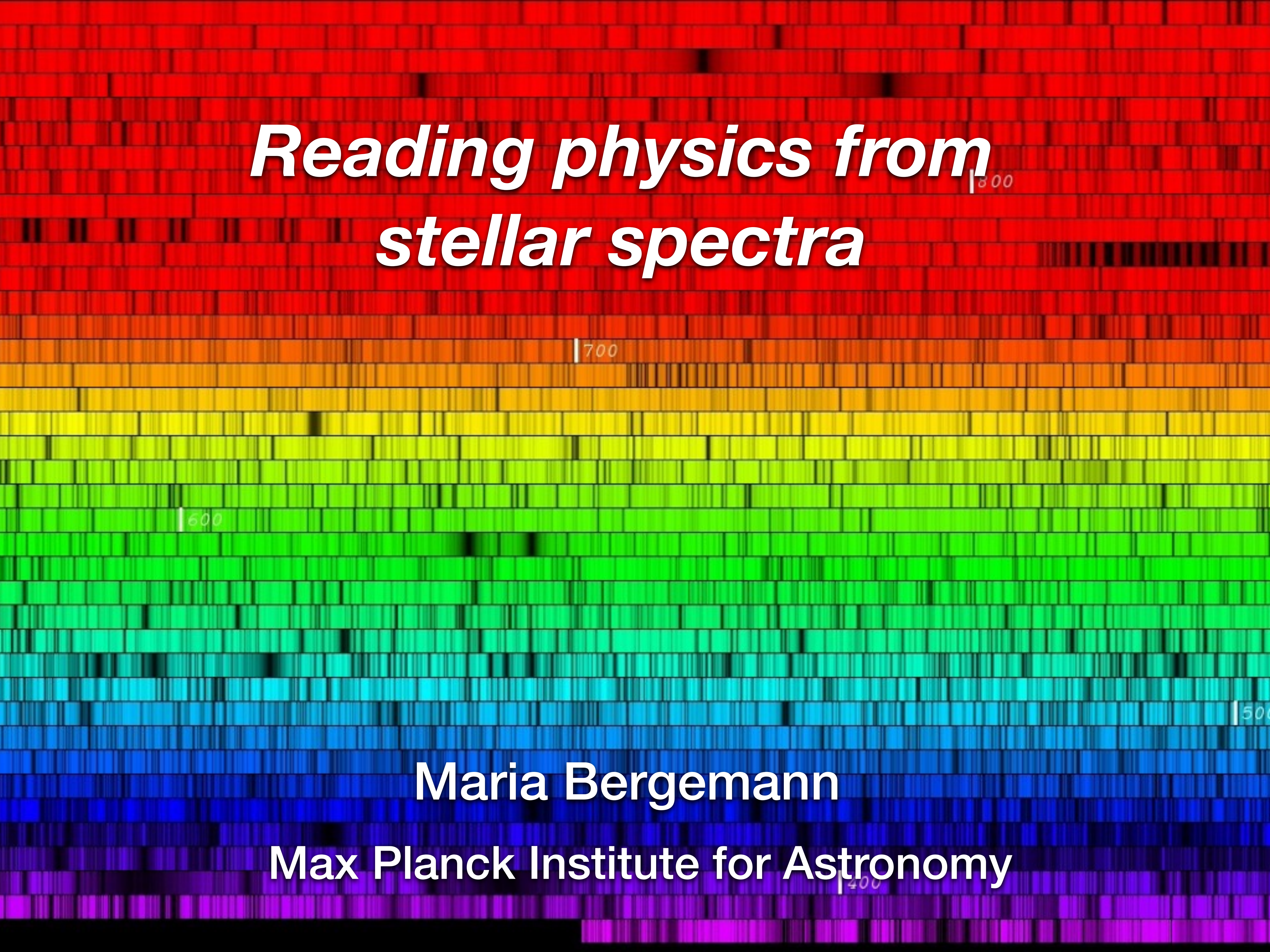
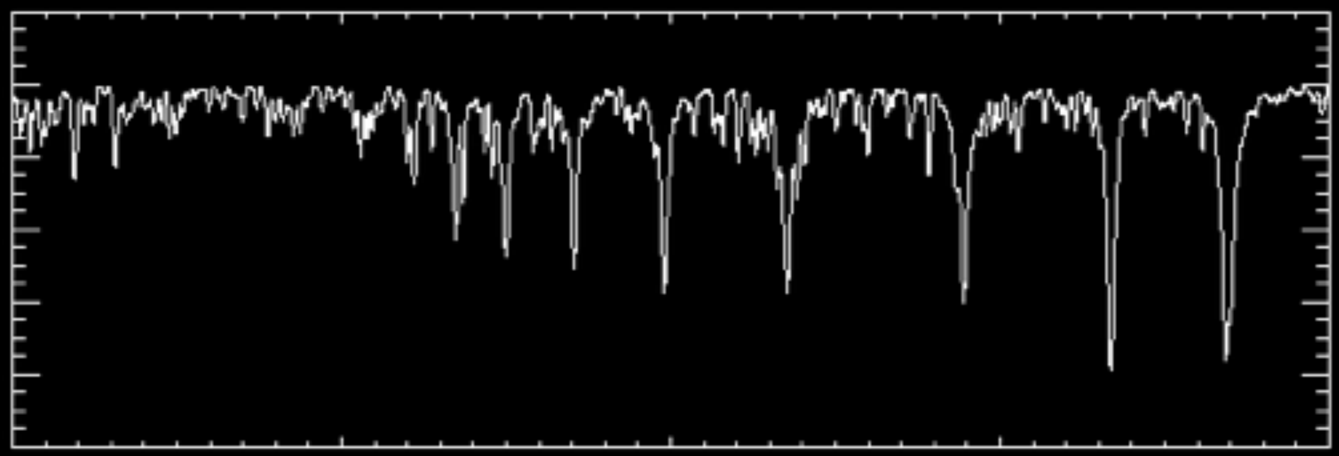


The main goal

develop physical models to interpret stellar spectra

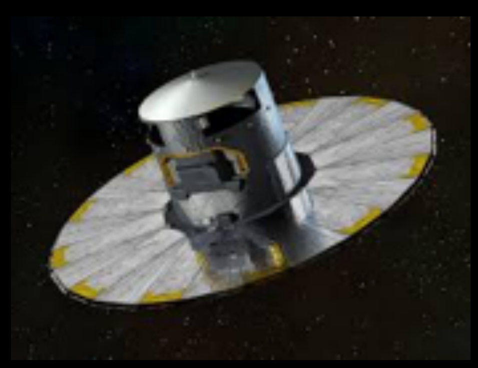
Theory

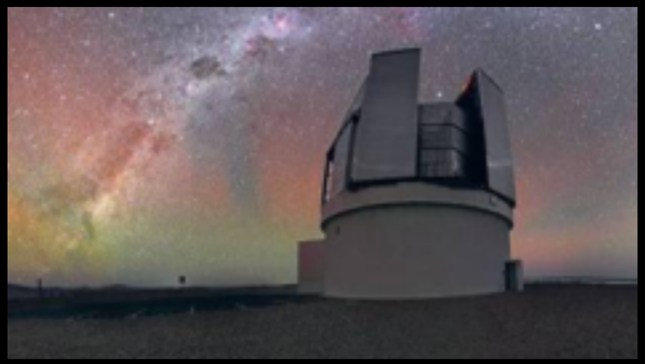


The main goal

Data

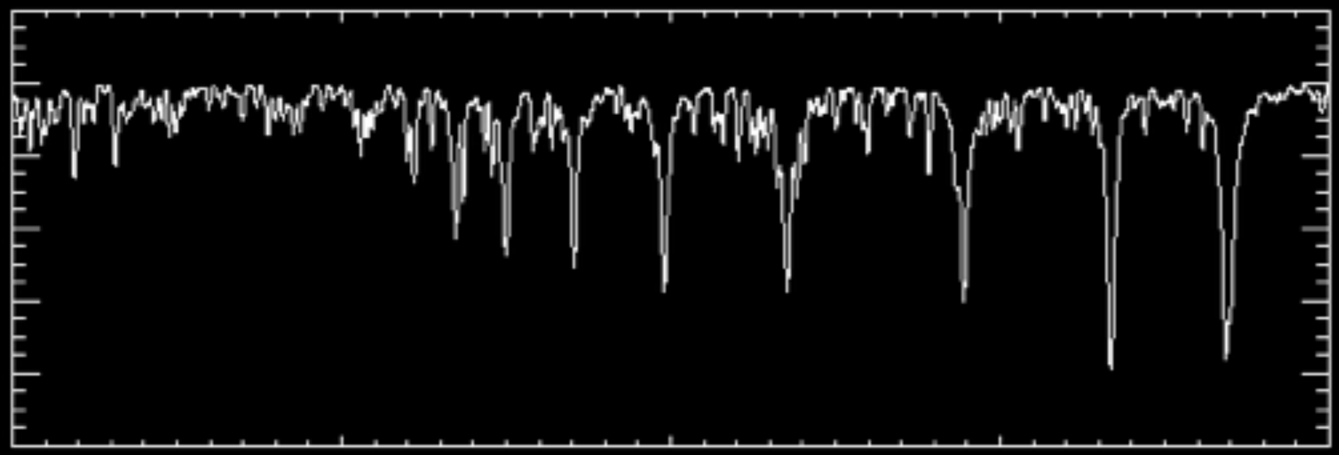
new observational data





Theory

develop physical models to interpret stellar spectra



The main goal

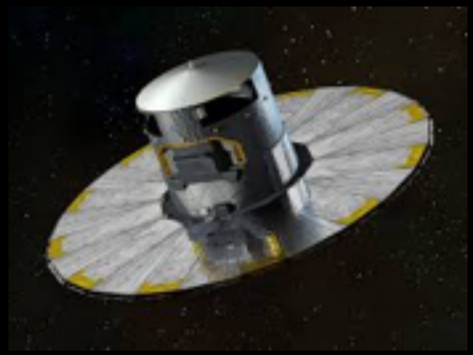
Challenge

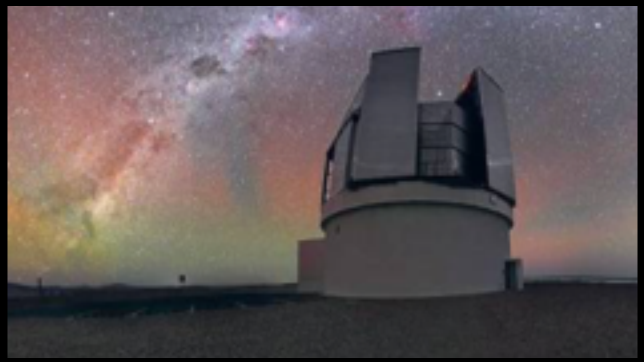
fundamental parameters & chemical composition of stars

- *Galactic stellar populations*
- *Cosmic origins of the periodic table*

Data

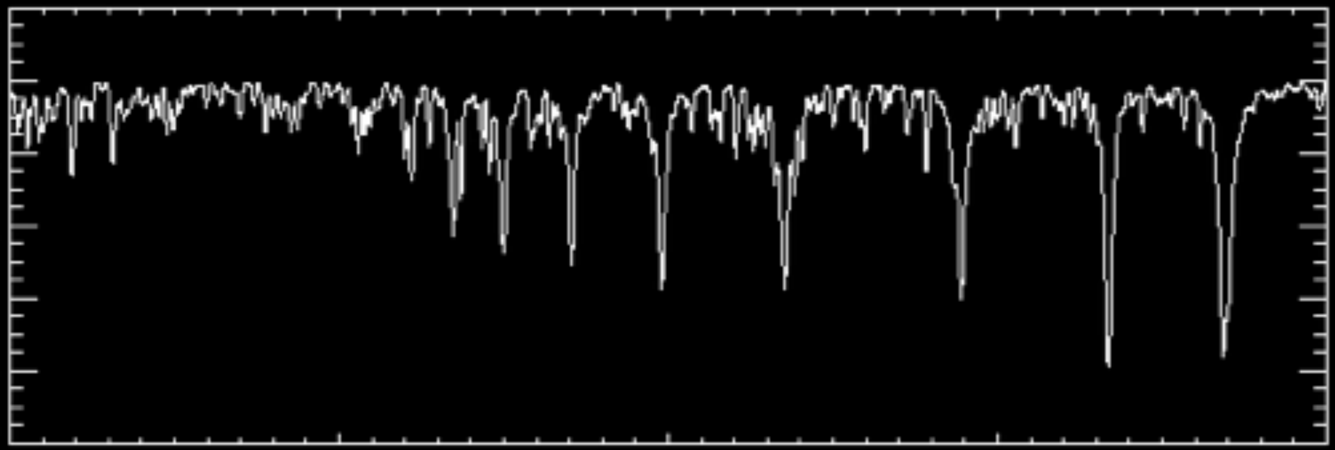
new observational data





Theory

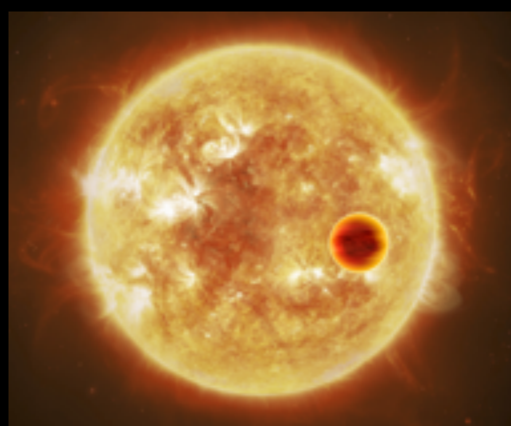
develop physical models to interpret stellar spectra



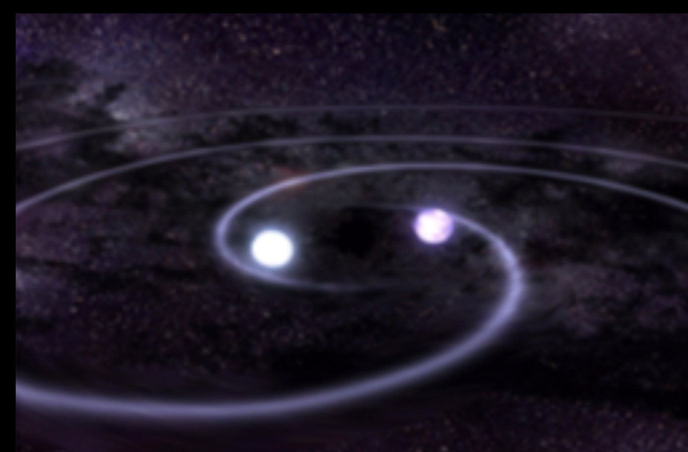
Understanding stellar spectra

fundamental parameters and chemical composition of stars underpin most areas in astrophysics

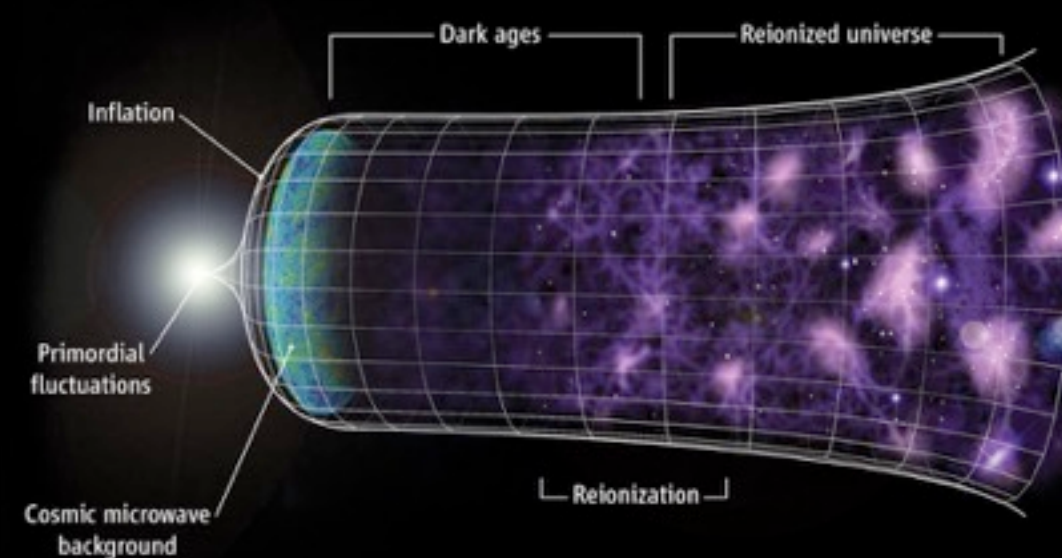
Physics of stars and exoplanets



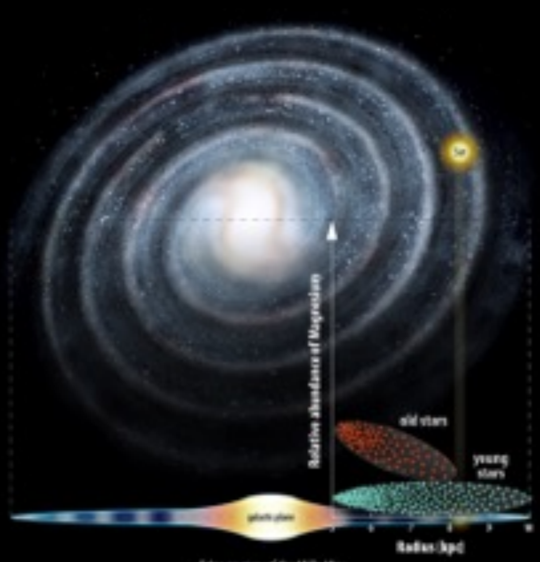
Population statistics remnants, mergers



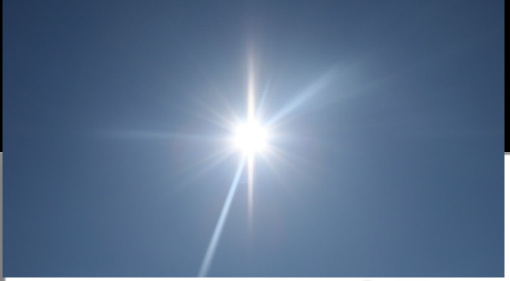
First stars and BBN



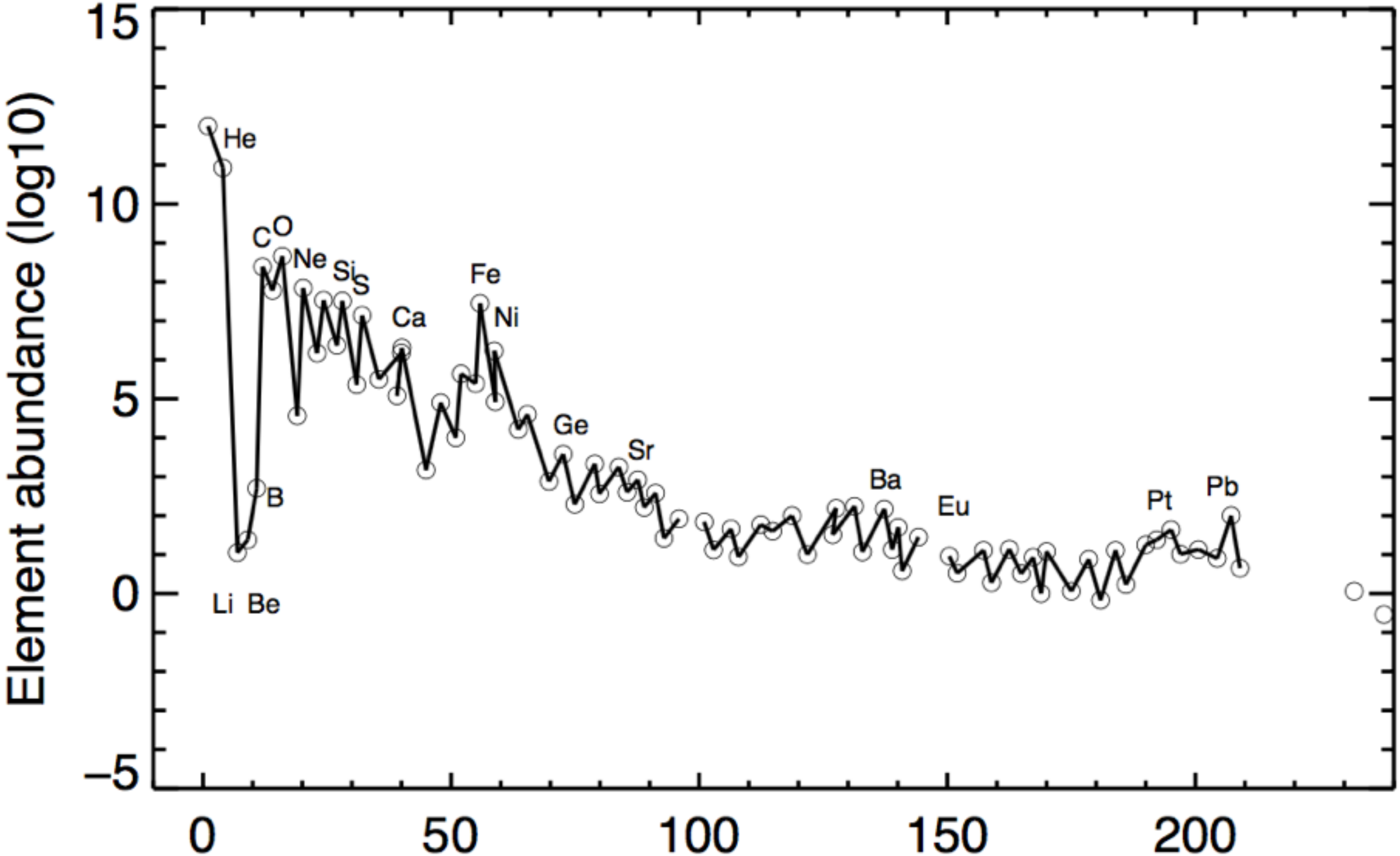
Evolution of the Milky Way and other galaxies



Origins of chemical elements

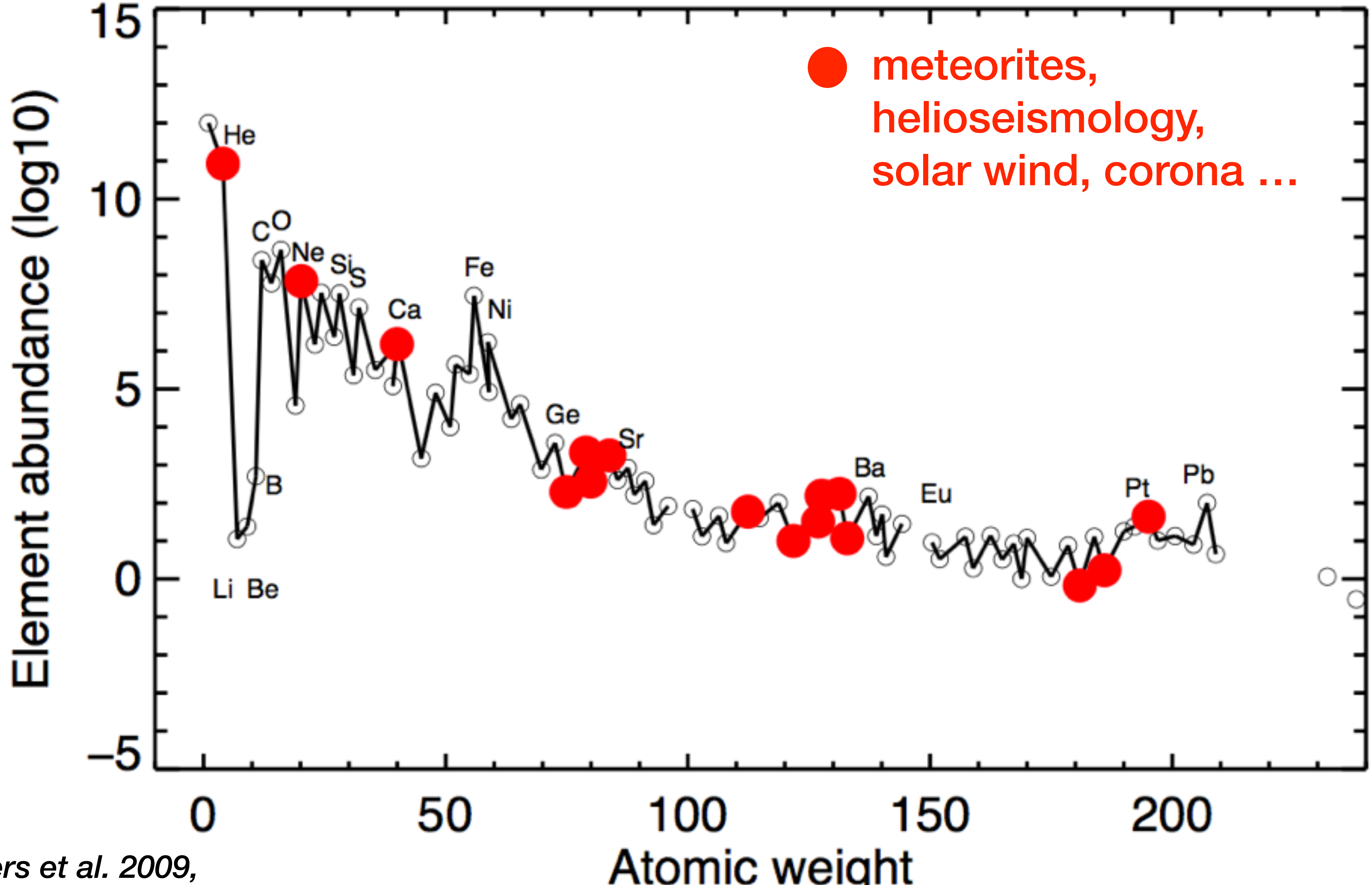


Chemical composition of the Sun



Lodders et al. 2009,
***Bergemann, Hansen**, and Beers (2019, in press)*

Chemical composition of the Sun



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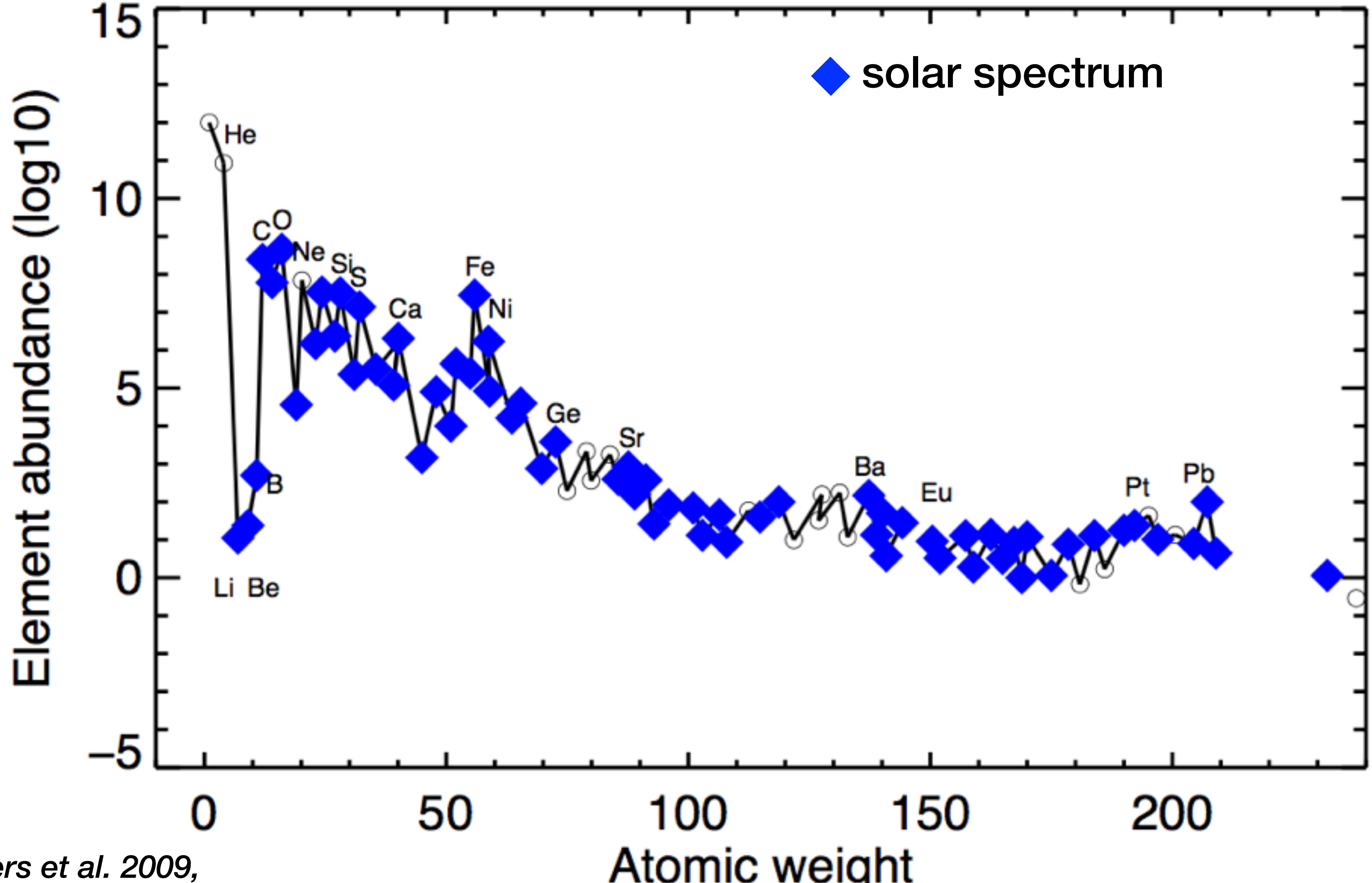
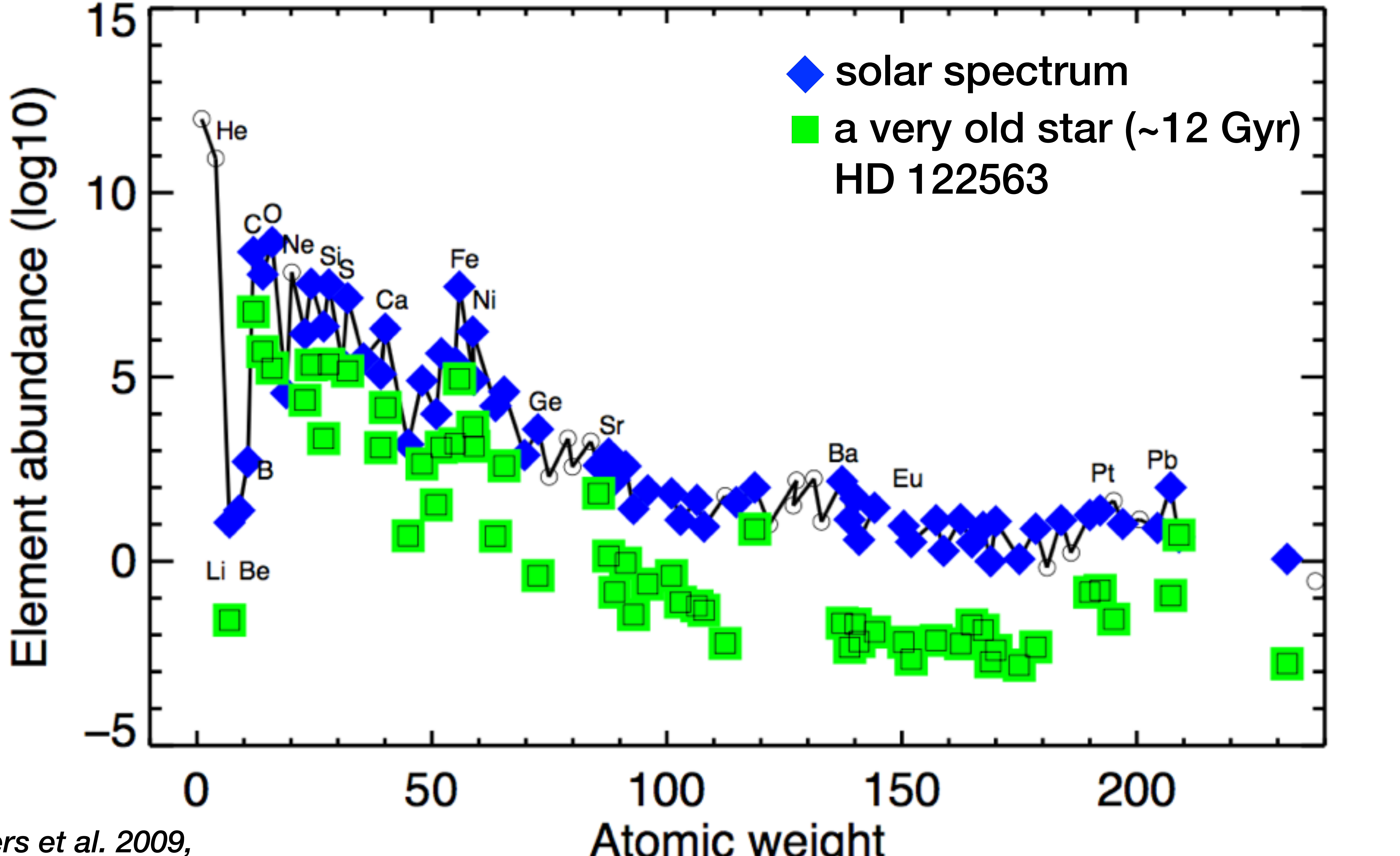
Chemical composition of the Sun



Lodders et al. 2009,
***Bergemann, Hansen**, and Beers (2019, in press)*

Fossils of 12 billion years of Galactic evolution



Lodders et al. 2009,
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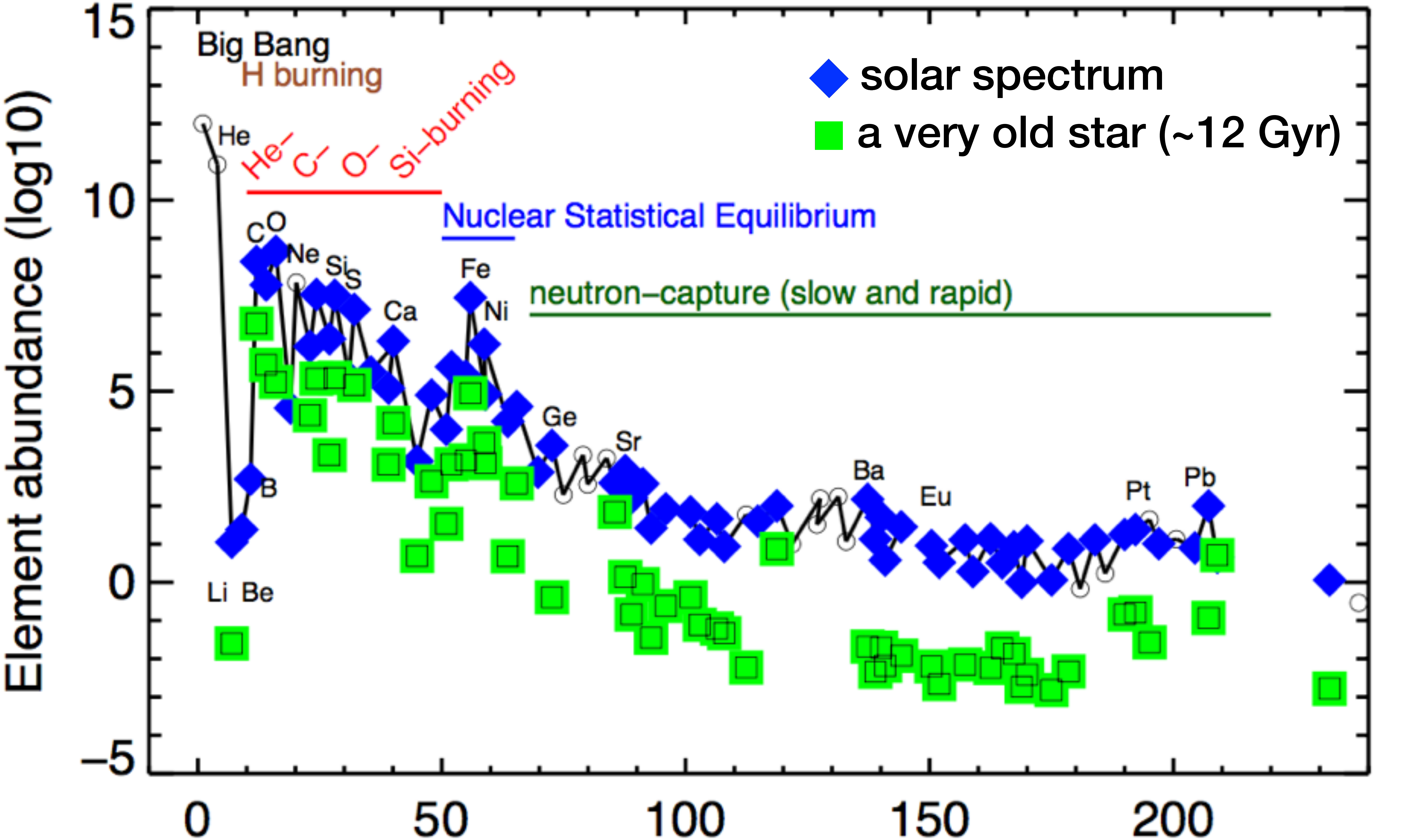
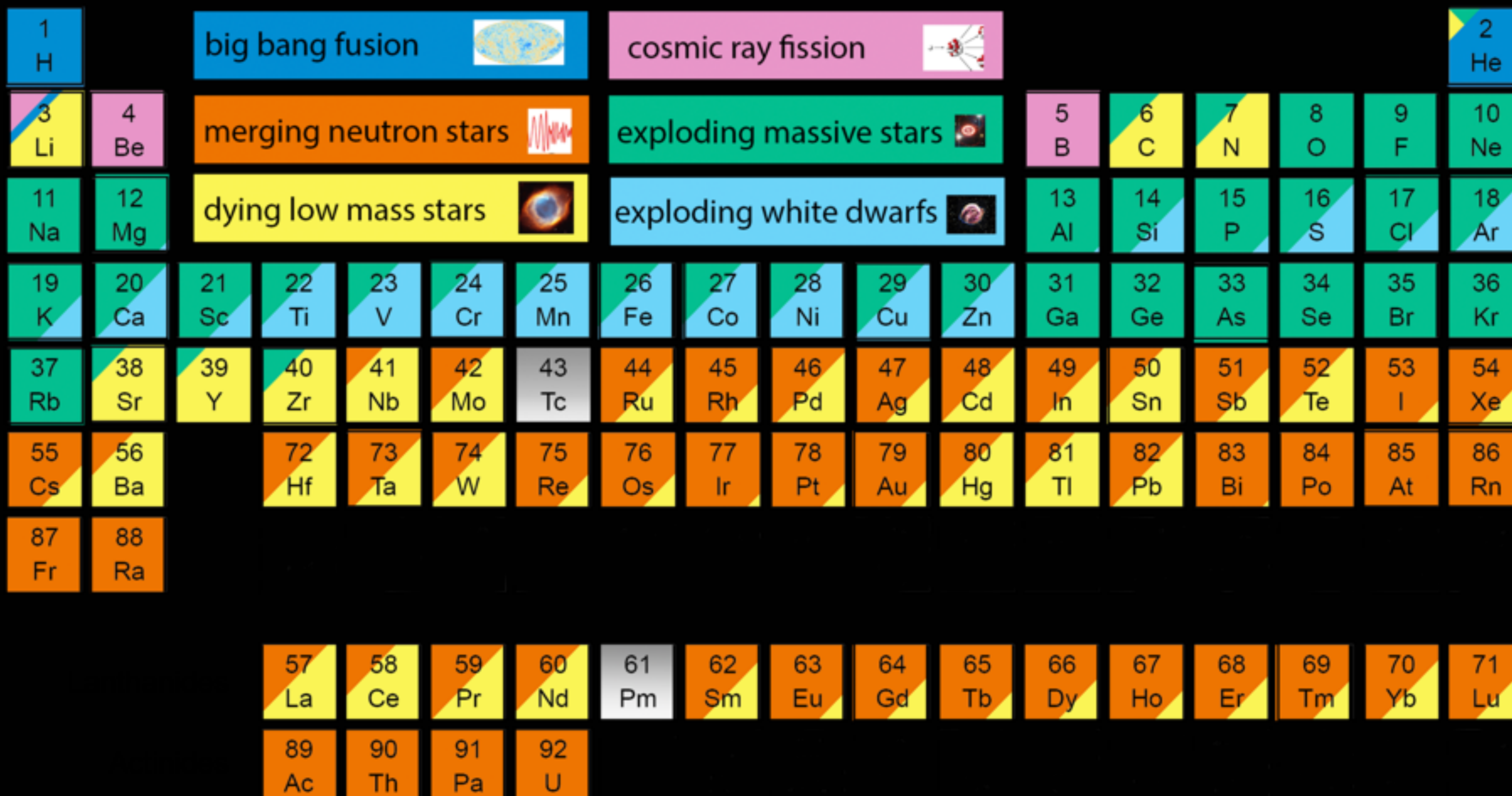
Fossils of 12 billion years of Galactic evolution



Lodders et al. 2009,
***Bergemann, Hansen**, and Beers (2019, in press)*

Key cites, where elements are produced, have been identified but **the details of cosmic nucleosynthesis** are unknown



Graphic created by Jennifer Johnson

Astronomical Image Credits: ESA/NASA/AASNova

Fundamental stellar parameters

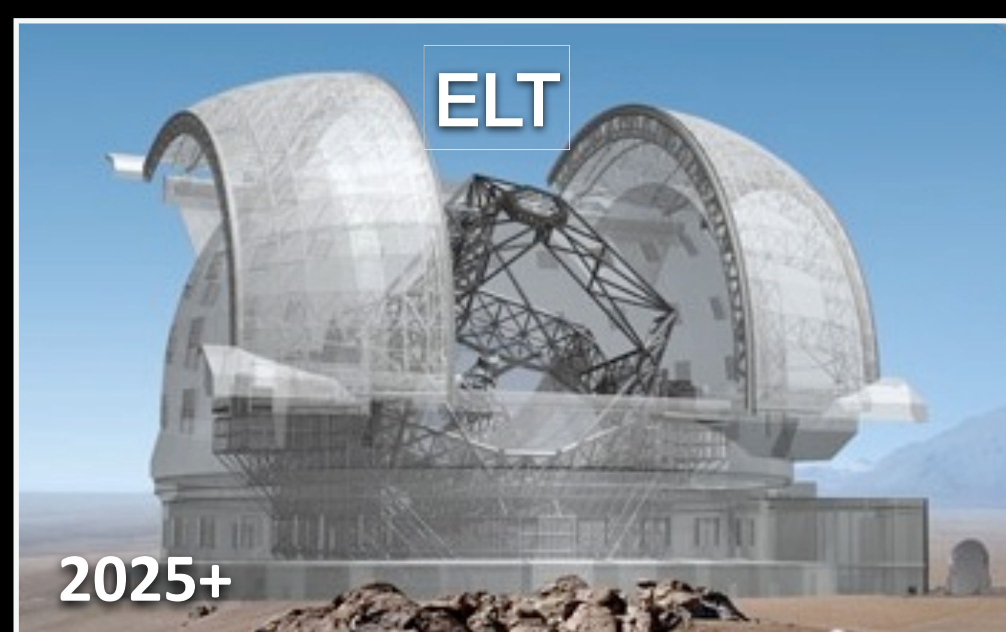
High-quality observations of stars

Powerful spectroscopic facilites

multi-object, large-aperture, wide-field

millions of spectra of stars in galaxies

PI: Bensby & Bergemann
Stellar survey of Galactic disk and bulge



SWG: Bergemann & Huber
Stellar physics & exoplanets

Fundamental stellar parameters

High-quality observations of stars

✓ large facilities,
million-star surveys
APOGEE, Gaia-ESO,
4MOST, WEAVE, SDSS-V …

Robust spectral models and diagnostic tools

?

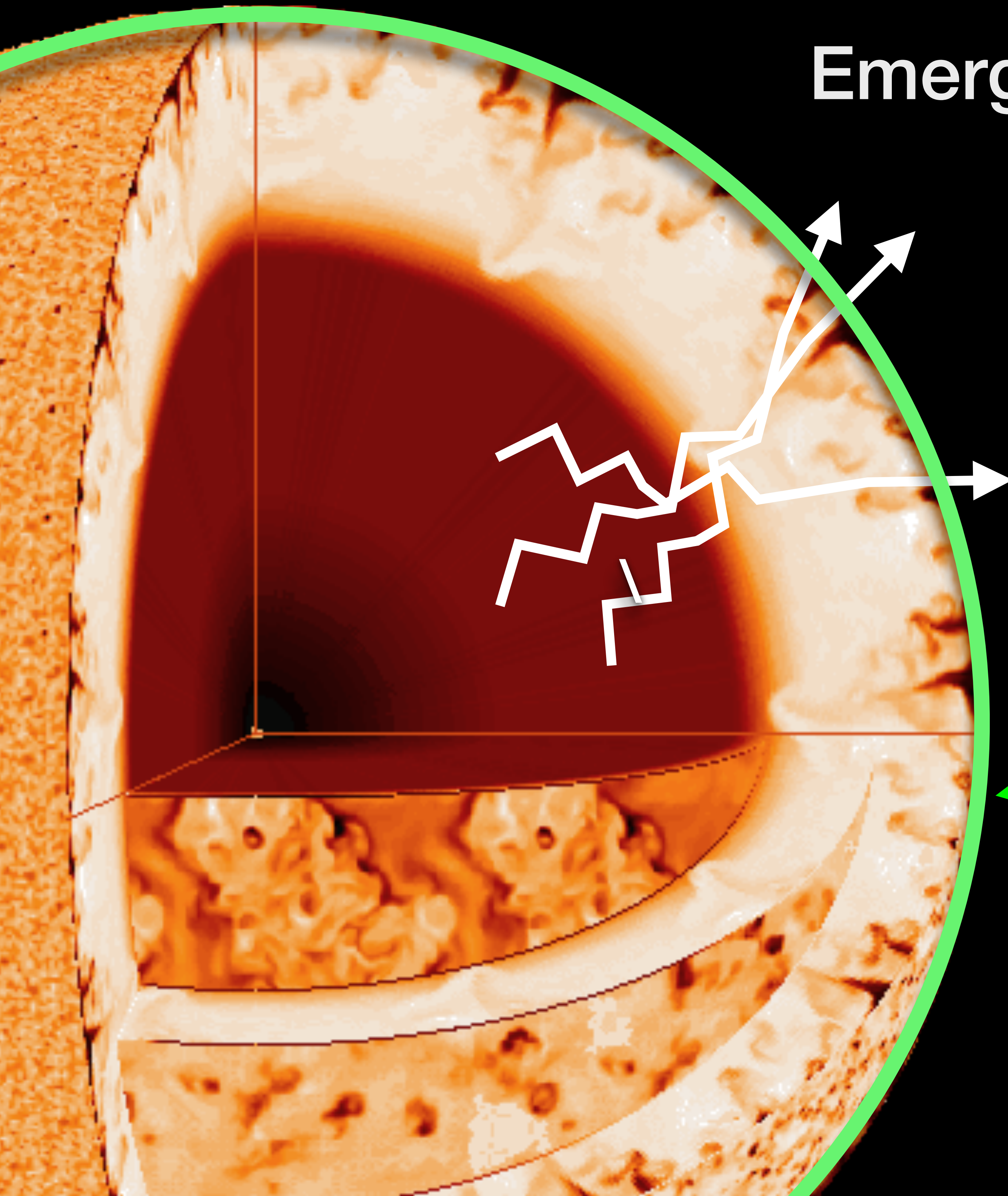
Fundamental stellar parameters

High-quality observations of stars

✓ large facilities, million-star surveys APOGEE, Gaia-ESO, 4MOST, WEAVE, SDSS-V …

Robust spectral models and diagnostic tools

Problem: modelling stellar radiation field



Emergent spectrum depends on:

physical conditions and

chemical composition

of stellar atmospheres

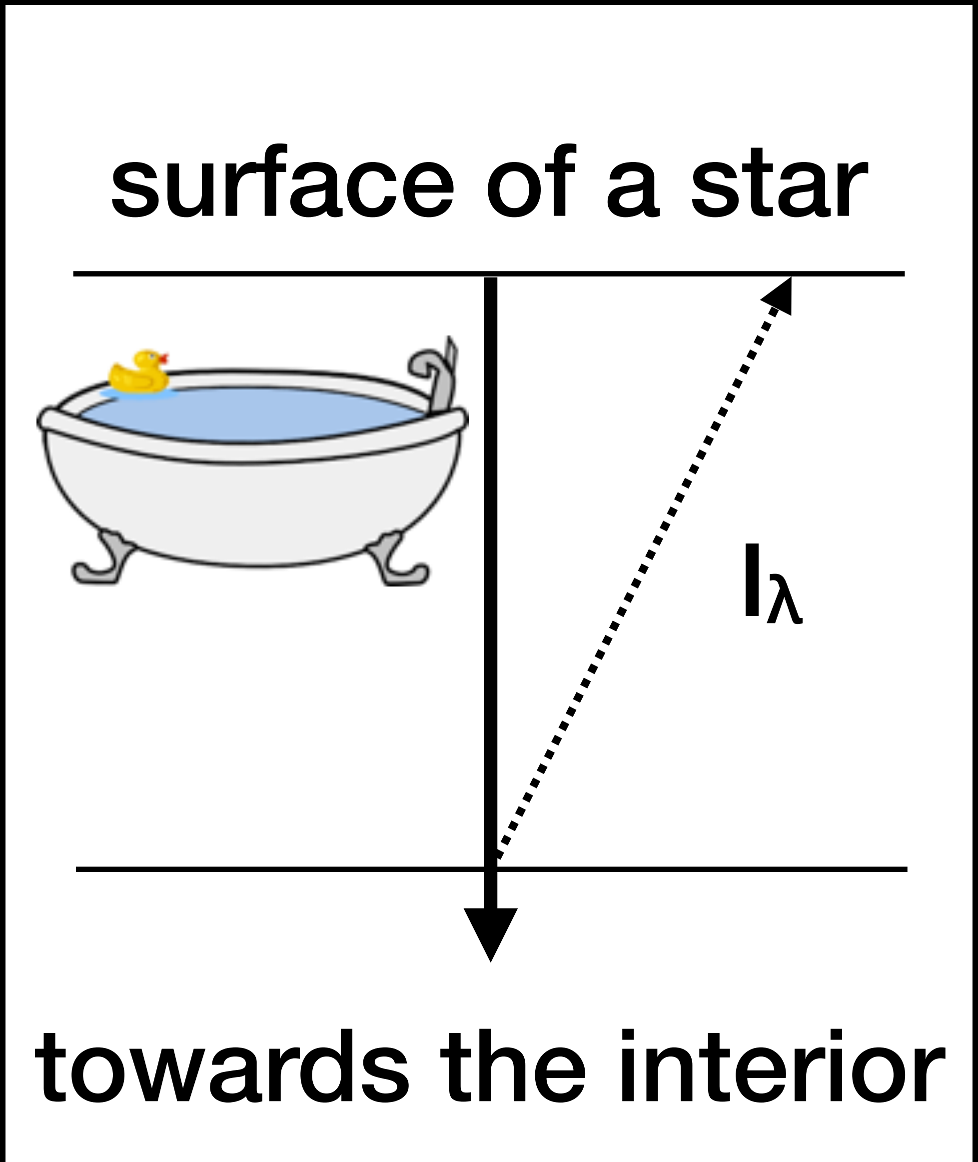
Classical models 1D LTE

1-dimensional

hydrostatic equilibrium

local thermodynamic equilbrium

convection using the Mixing Length Theory



Local Thermodynamic Equilbrium → non-LTE

rate equations for N energy levels + radiation transfer

$$\sum_{n>m} N_n \left(A_{nm} + B_{nm} u_\nu + C_{nm} \right) + \sum_{k<m} N_k \left(B_{km} u_\nu + C_{km} \right) + N_e \left(R_m + Q_m \right)$$
$$- N_m \left\{ \sum_{k<m} \left(A_{mk} + B_{mk} u_\nu + C_{mk} \right) + \sum_{n>m} \left(B_{mn} u_\nu + C_{mn} \right) + \left(P_m + S_m \right) \right\} = 0$$

$$P_m = 4\pi \int \frac{a_\nu J_\nu}{h\nu} d\nu$$

spontaneous radiative emission A_{nm}
photo-ionisation P_m
recombination R_m
collisional excitation C_{mk}
charge transfer …

photons, electrons,
H atoms …

Local Thermodynamic Equilbrium ➡ non-LTE

rate equations for N energy levels + radiation transfer

$$\sum_{n>m} N_n \left(A_{nm} + B_{nm} u_\nu + C_{nm}\right) + \sum_{k<m} N_k \left(B_{km} u_\nu + C_{km}\right) + N_\mathrm{e}\left(R_m + Q_m\right)$$
$$- N_m \left\{ \sum_{k<m} \left(A_{mk} + B_{mk} u_\nu + C_{mk}\right) + \sum_{n>m} \left(B_{mn} u_\nu + C_{mn}\right) + \left(P_m + S_m\right) \right\} = 0$$

$$P_m = 4\pi \int \frac{a_\nu J_\nu}{h\nu} d\nu$$

spontaneous radiative emission A_{nm}
photo-ionisation P_m
recombination R_m
collisional excitation C_{mk}
charge transfer …

photons, electrons,
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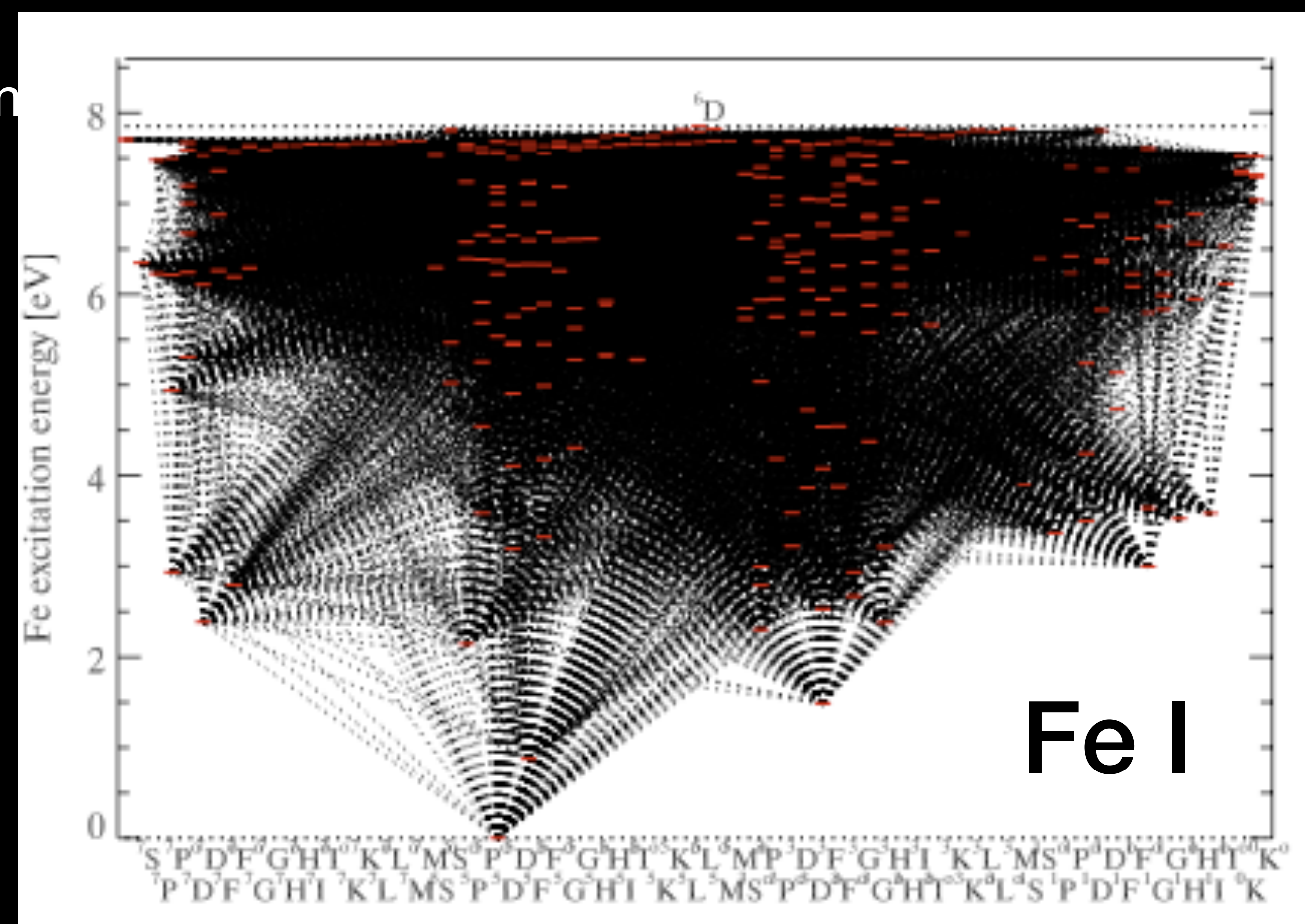
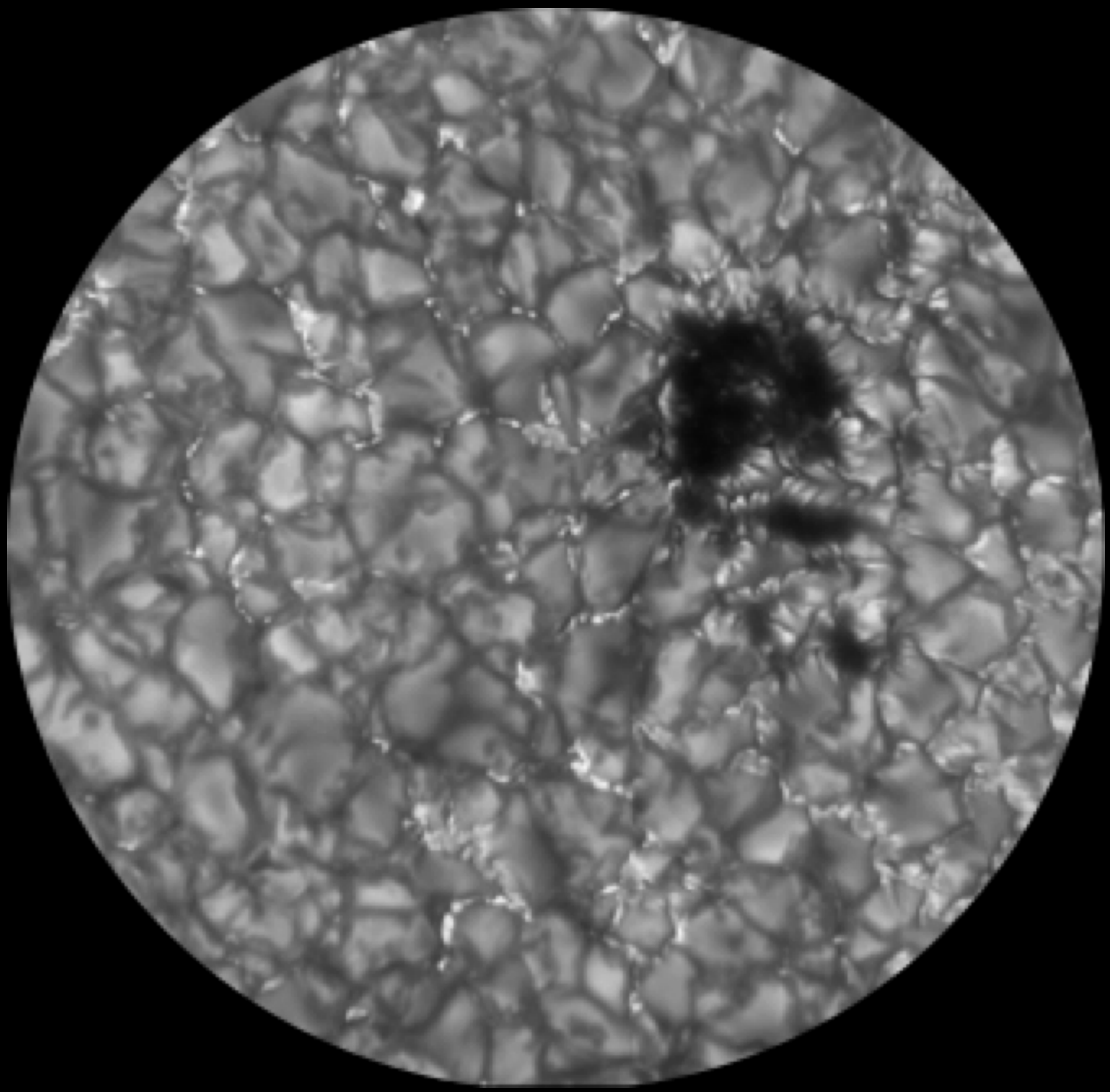


1D hydrostatic structure → 3D convection

1D hydrostatic structure → 3D convection

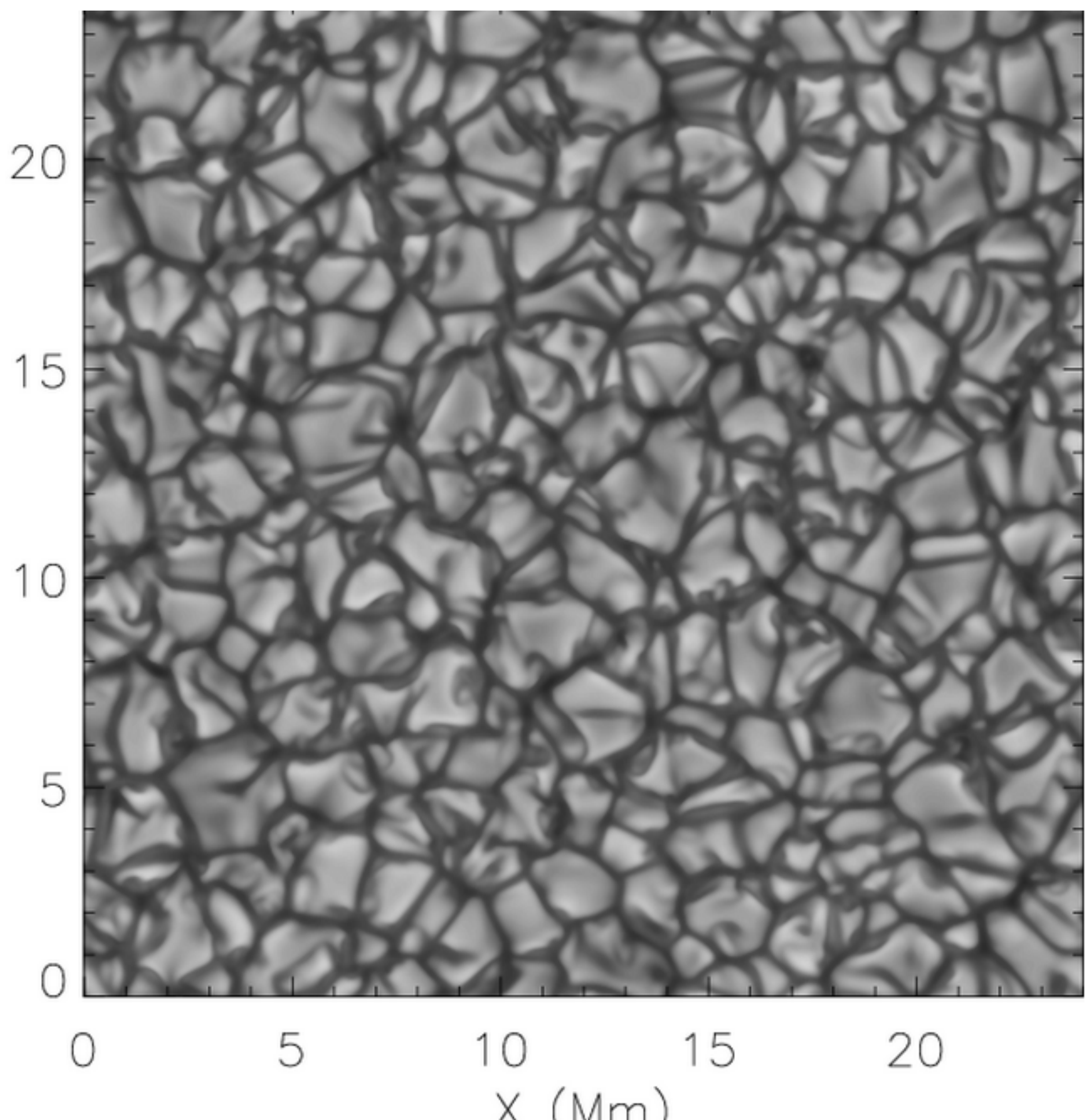
1D hydrostatic structure → **3D convection**

The Sun
model 1D static

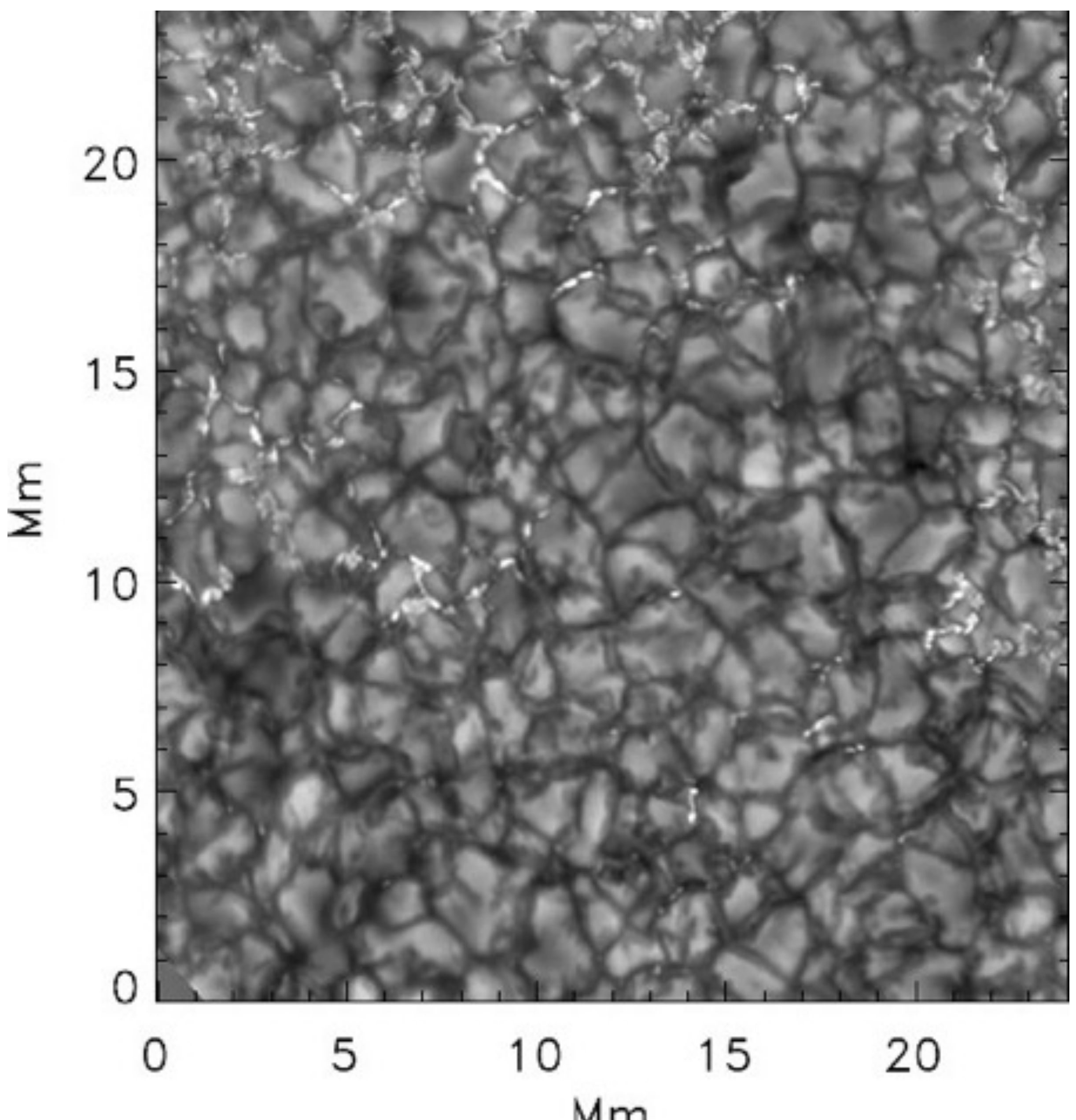


1D hydrostatic structure → 3D convection simulations

the same scales - both images 20x20 Mm



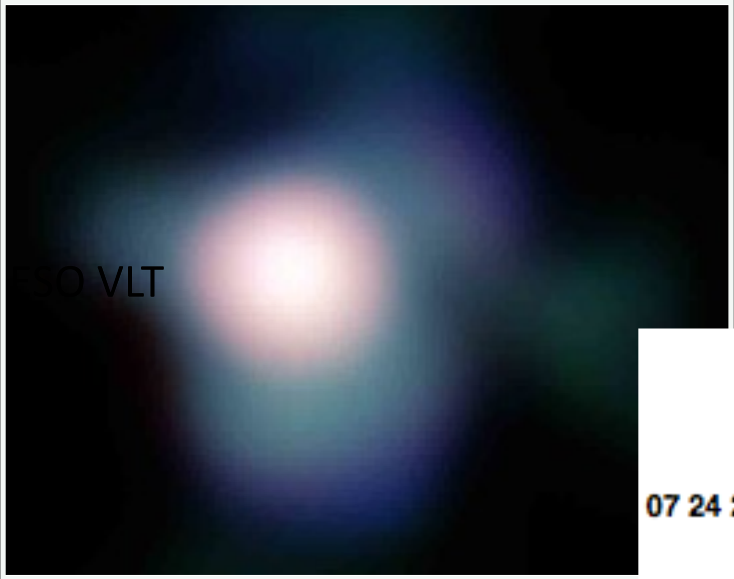
Matloch+ (2010), Collet+(2011), Magic+(2013), Freytag+(2012), Nordlund+(2009)



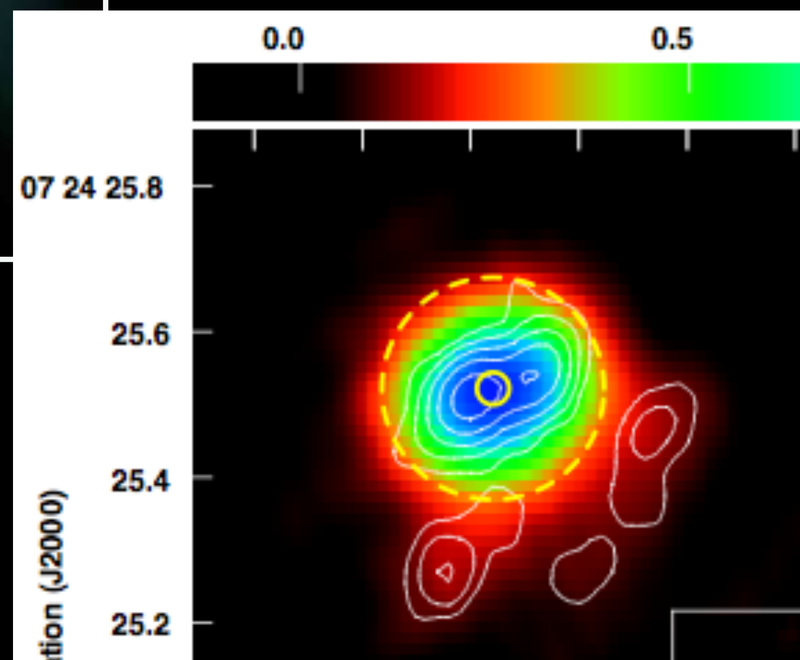
Nordlund+ (2009), observed SST

1D hydrostatic structure

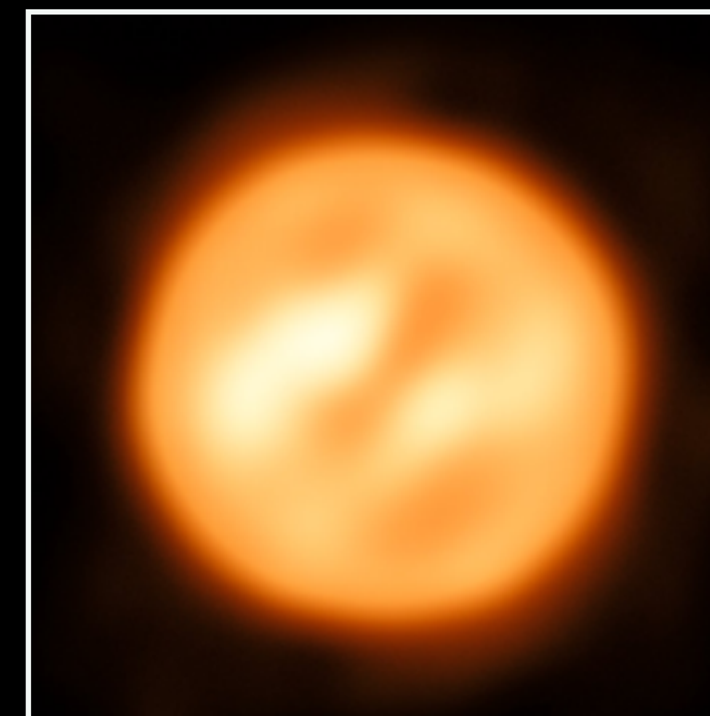
3D convection simulations



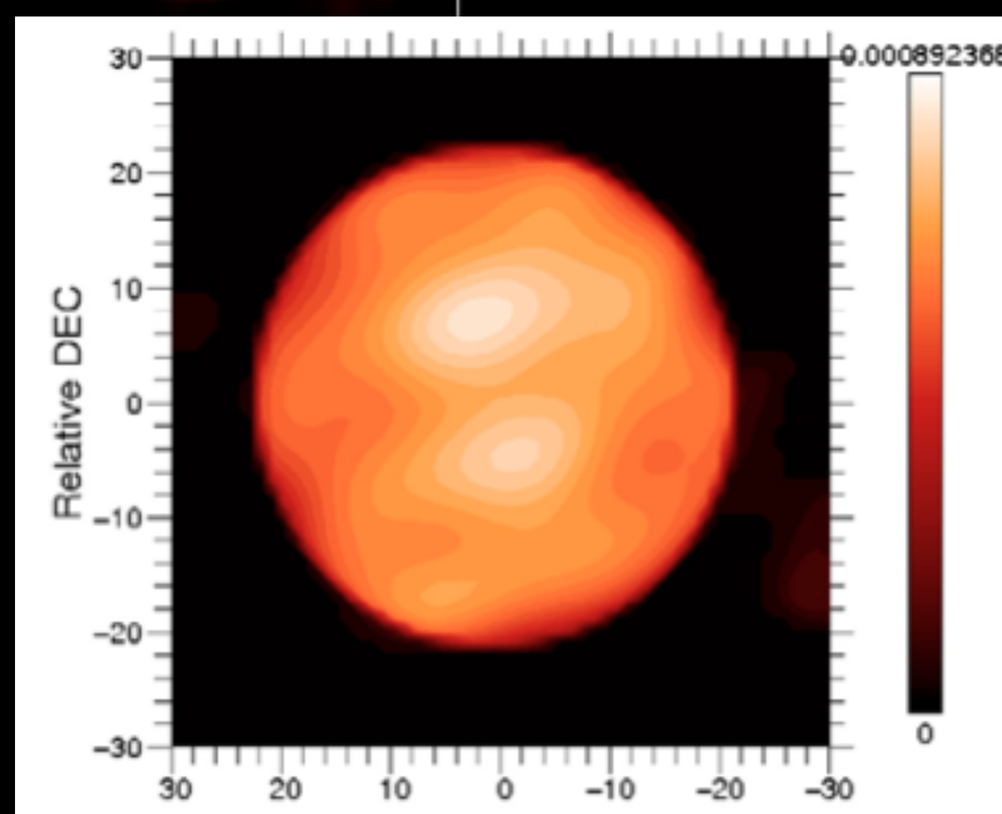
Kervella et al. (2009)



e-MERLIN radio interferometry (5 cm)



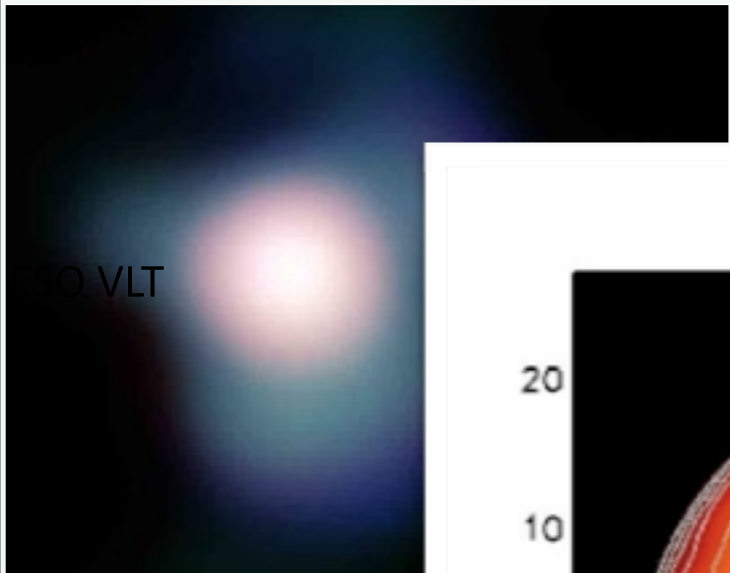
ESO VLTI / AMBER Ohnaka et al. 2017

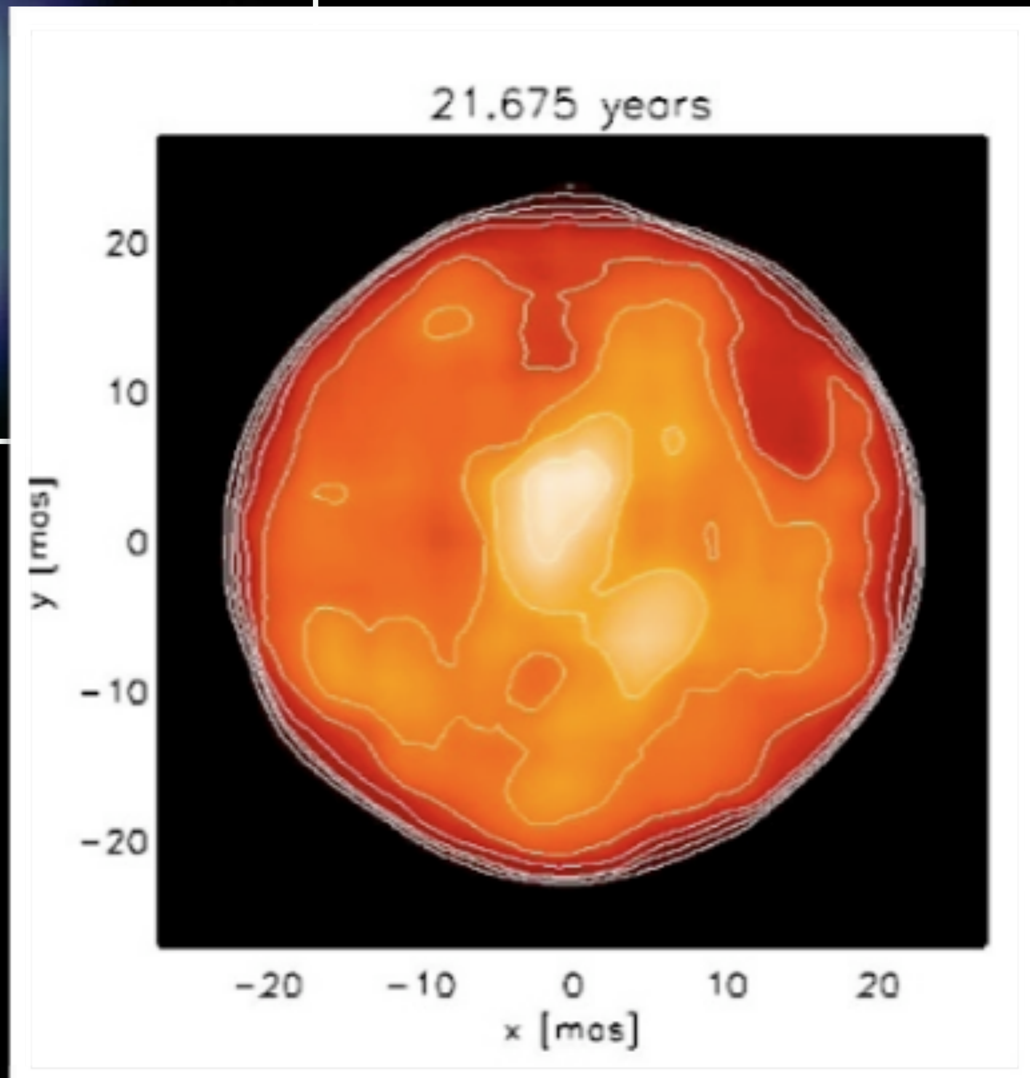


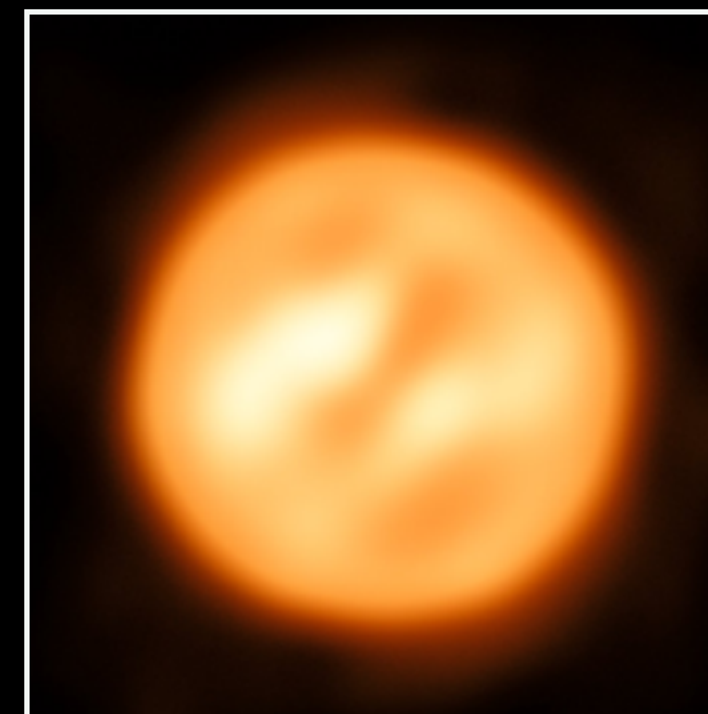
Haubois et al. (2009)

Interferometric observations resolve structure on stars: hot spots, 'plumes' and giant convective cells

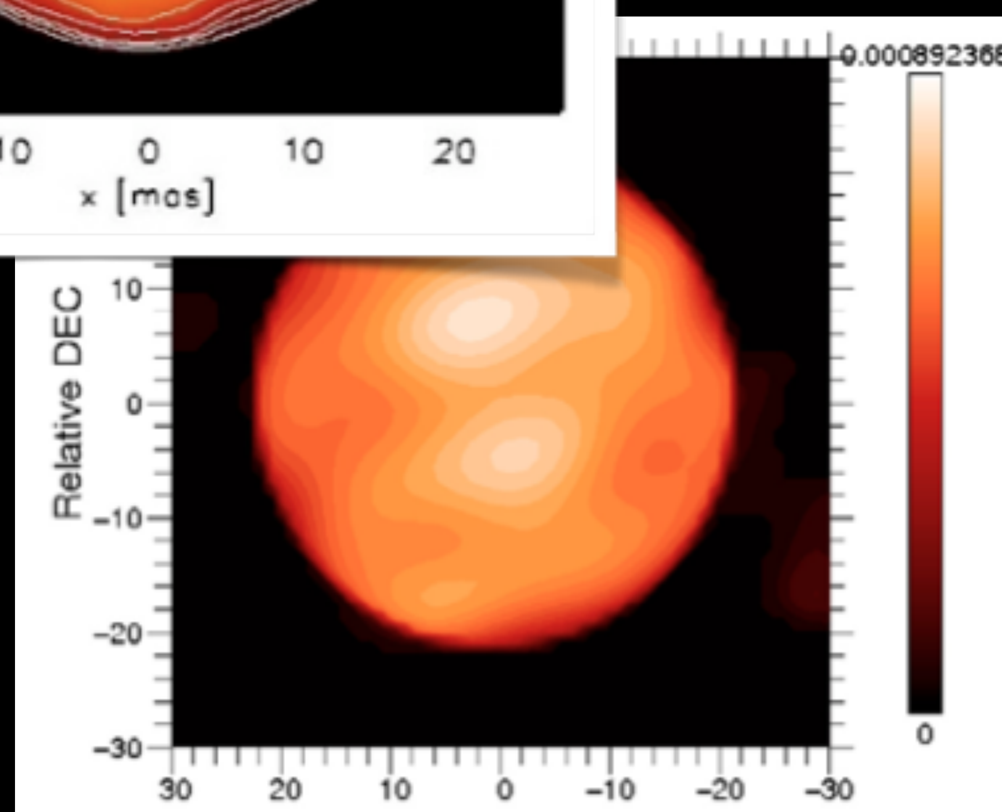
1D hydrostatic structure → 3D convection simulations







ESO VLTI / AMBER
Ohnaka et al. 2017



Haubois et al. (2009)

3D hydrodynamical simulations of convection for red supergiants
Chiavassa et al. 2011a,b, 2014

Fundamental stellar parameters

High-quality observations of stars

✓ large facilities, million-star surveys APOGEE, Gaia-ESO, 4MOST, WEAVE, SDSS-V …

Robust spectral models and diagnostic tools

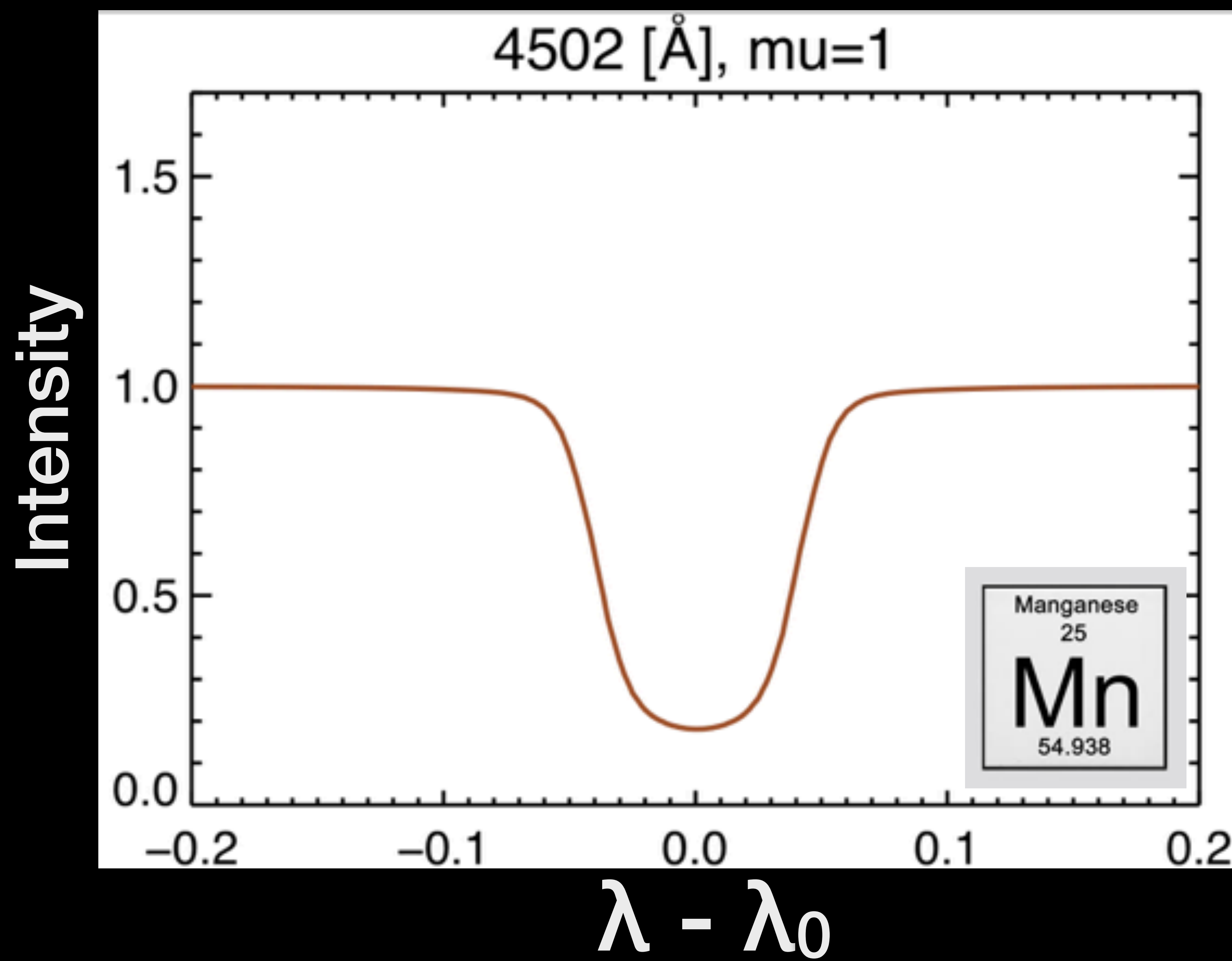
✓ Spectral models: state-of-the-art **modelling** of stellar spectra (**NLTE, 3D**)

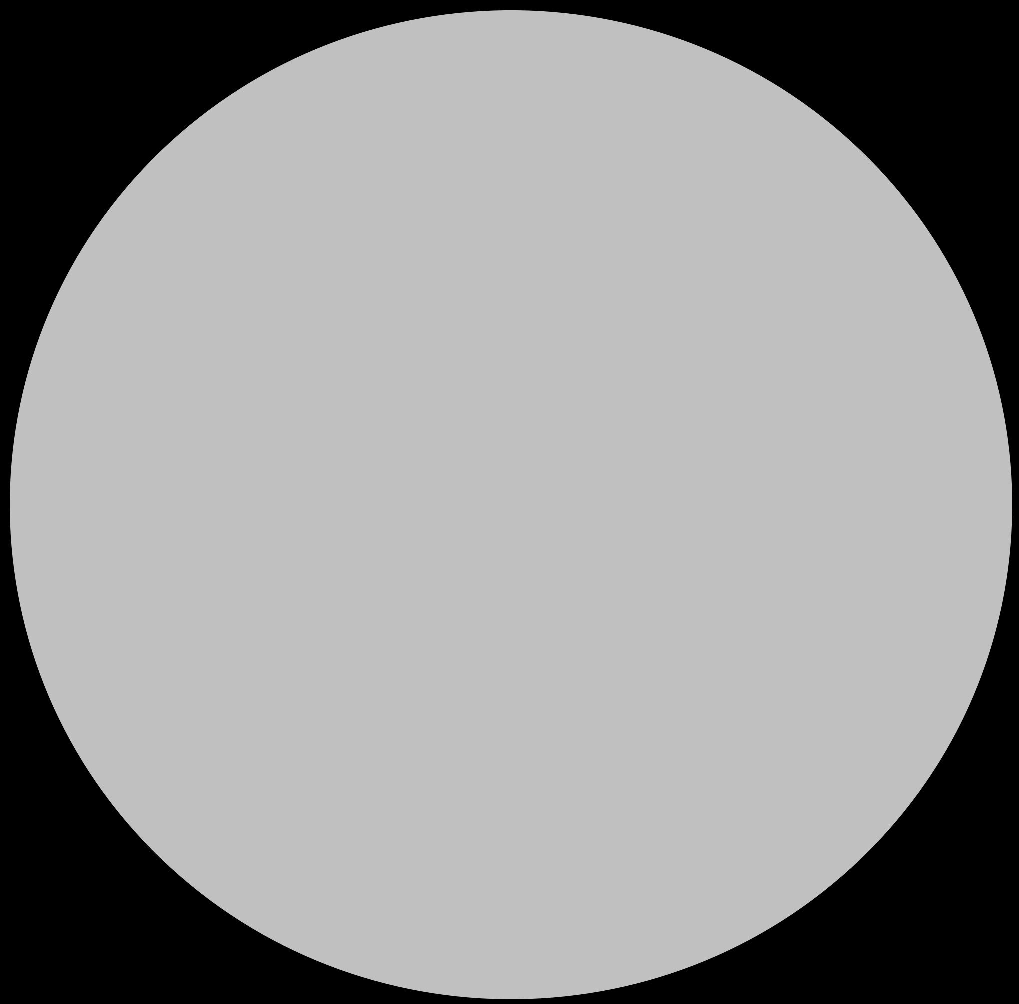
✓ Big data: framework to apply **the models** in the analysis of large datasets

__Bergemann__ et al. 2010, 2011, 2013, 2015, 2017a,b, 2019; __Eitner__ et al. 2019a; Schoenrich & __Bergemann__ (2014), __Gallagher__ et al. in prep, __Kovalev__, __Bergemann__ (2019, subm.)

1D LTE

Mn line in the Sun

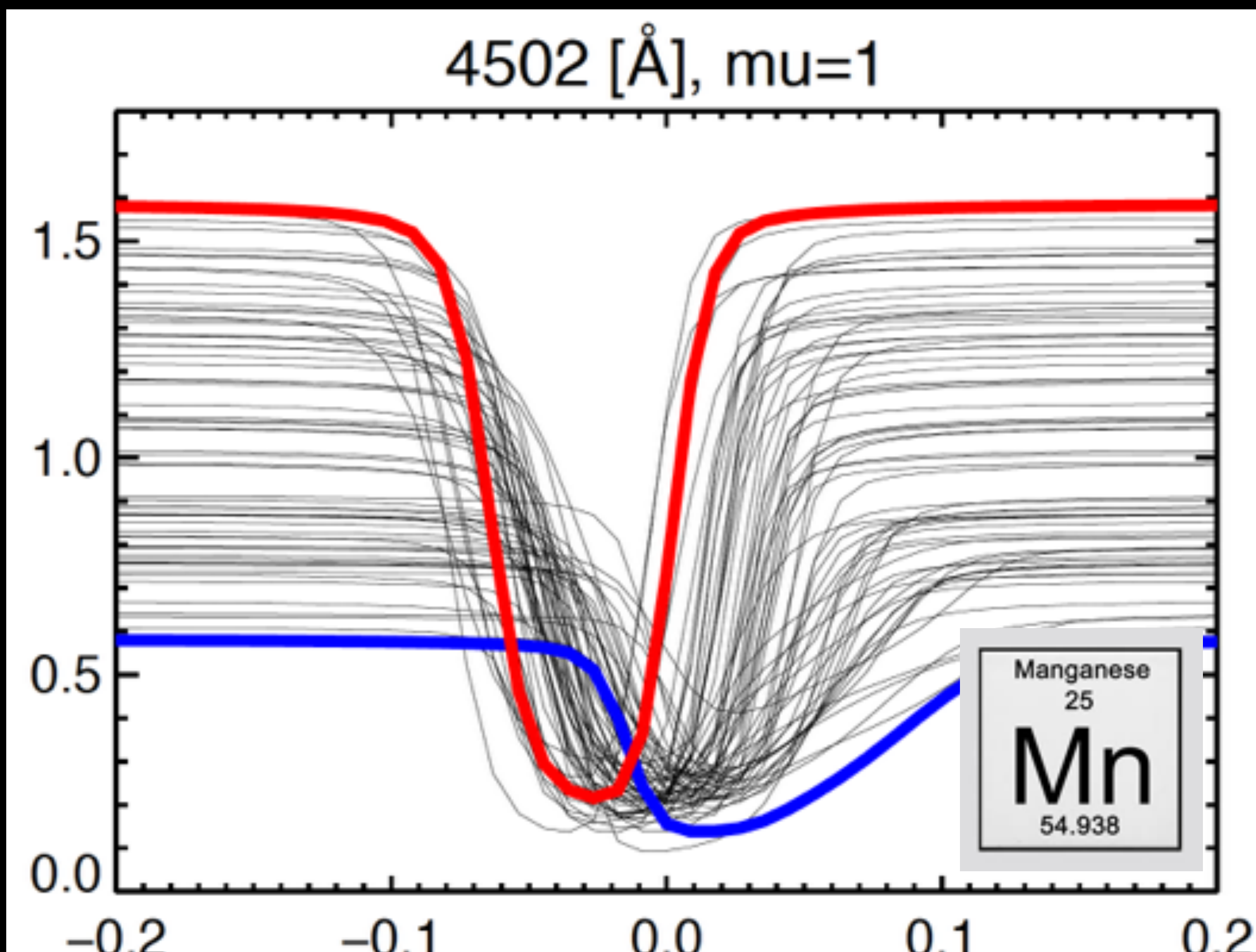




Bergemann et al. (2019, arXiv:1905.01835)
Gallagher et al. in prep.

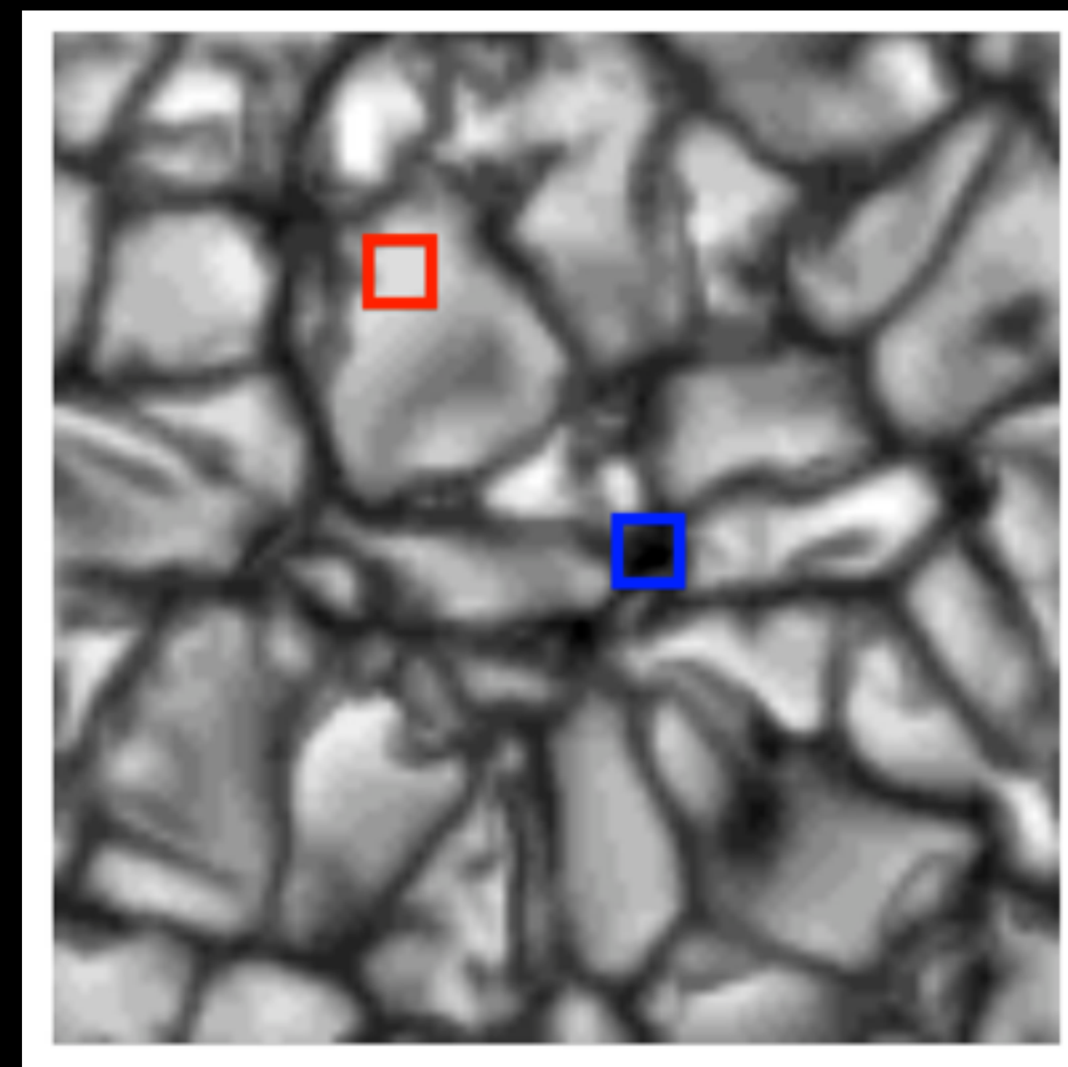
3D NLTE

Mn line in the Sun



Intensity

$\lambda - \lambda_0$



Bergemann et al. (2019, arXiv:1905.01835)
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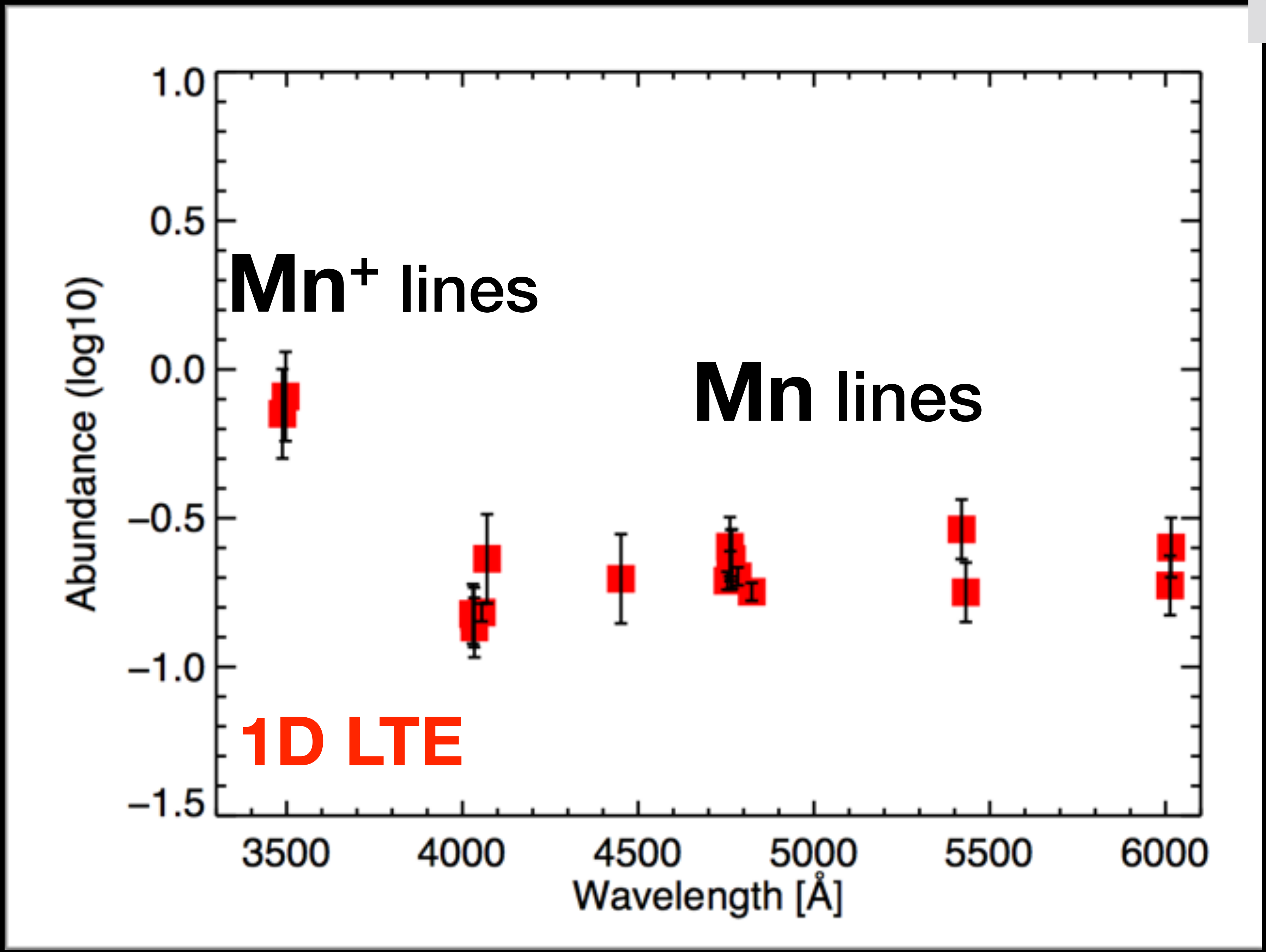
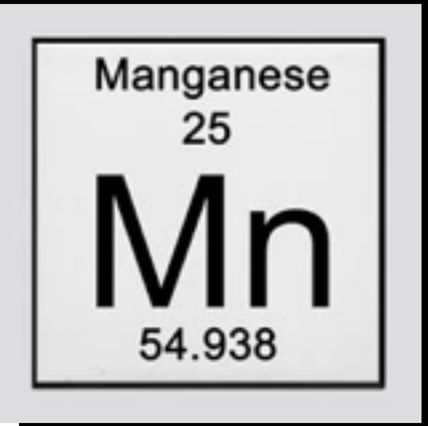
HD 122563





Bergemann et al. (2019, arXiv:1905.01835)
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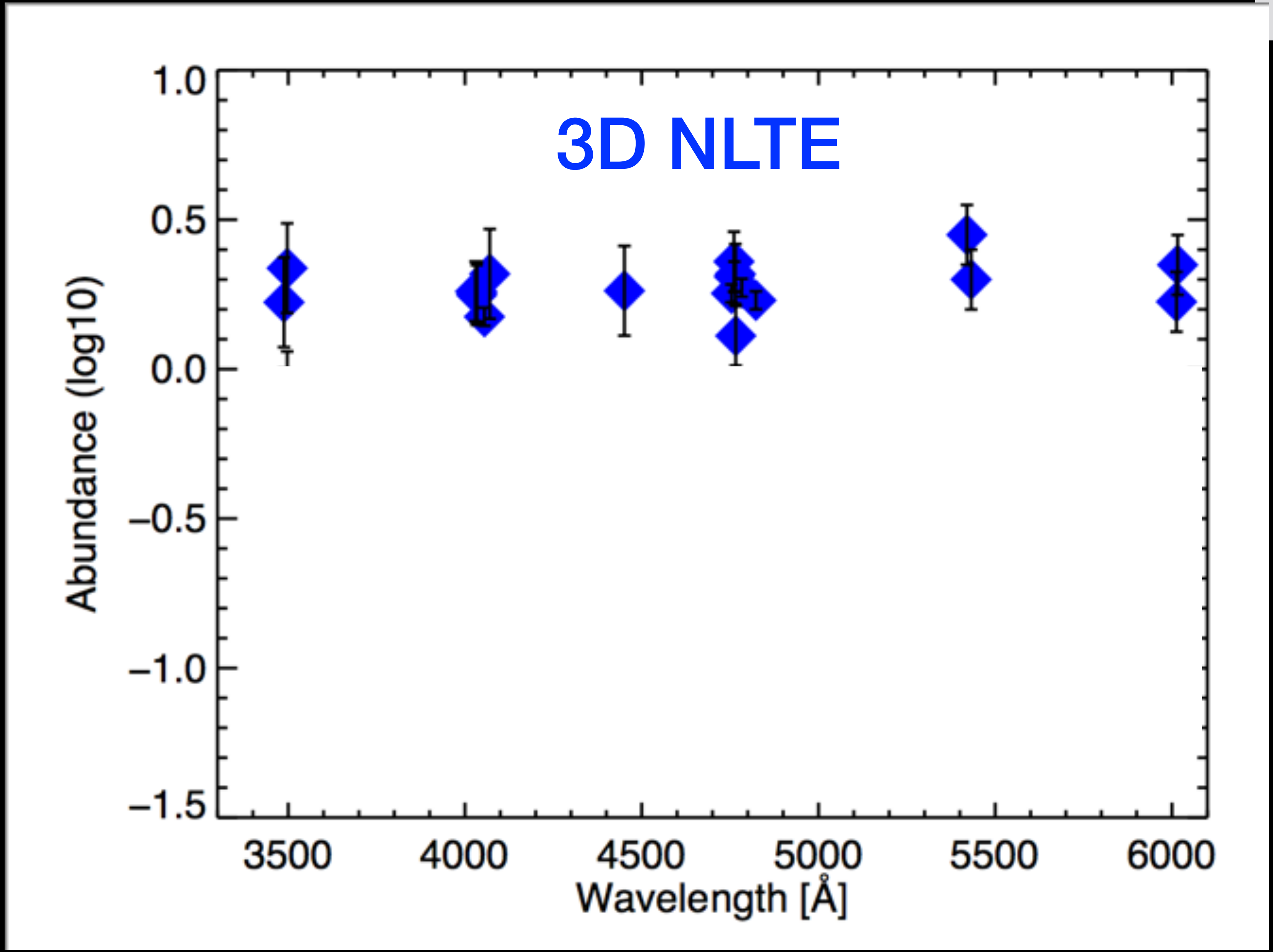
HD 122563



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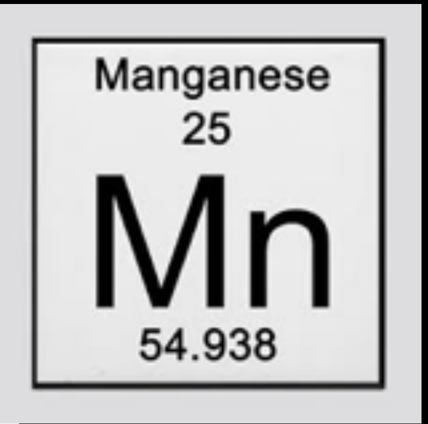
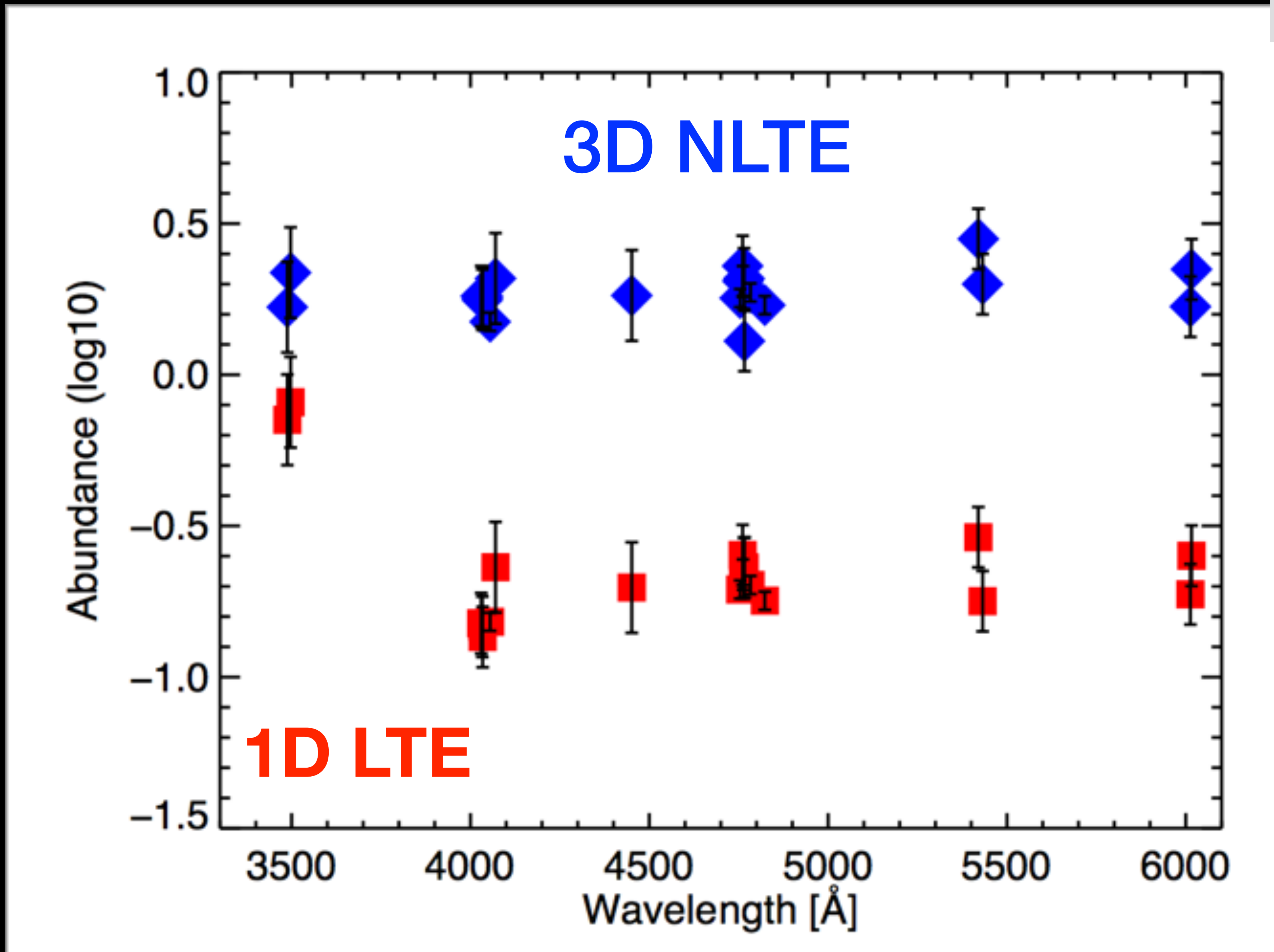


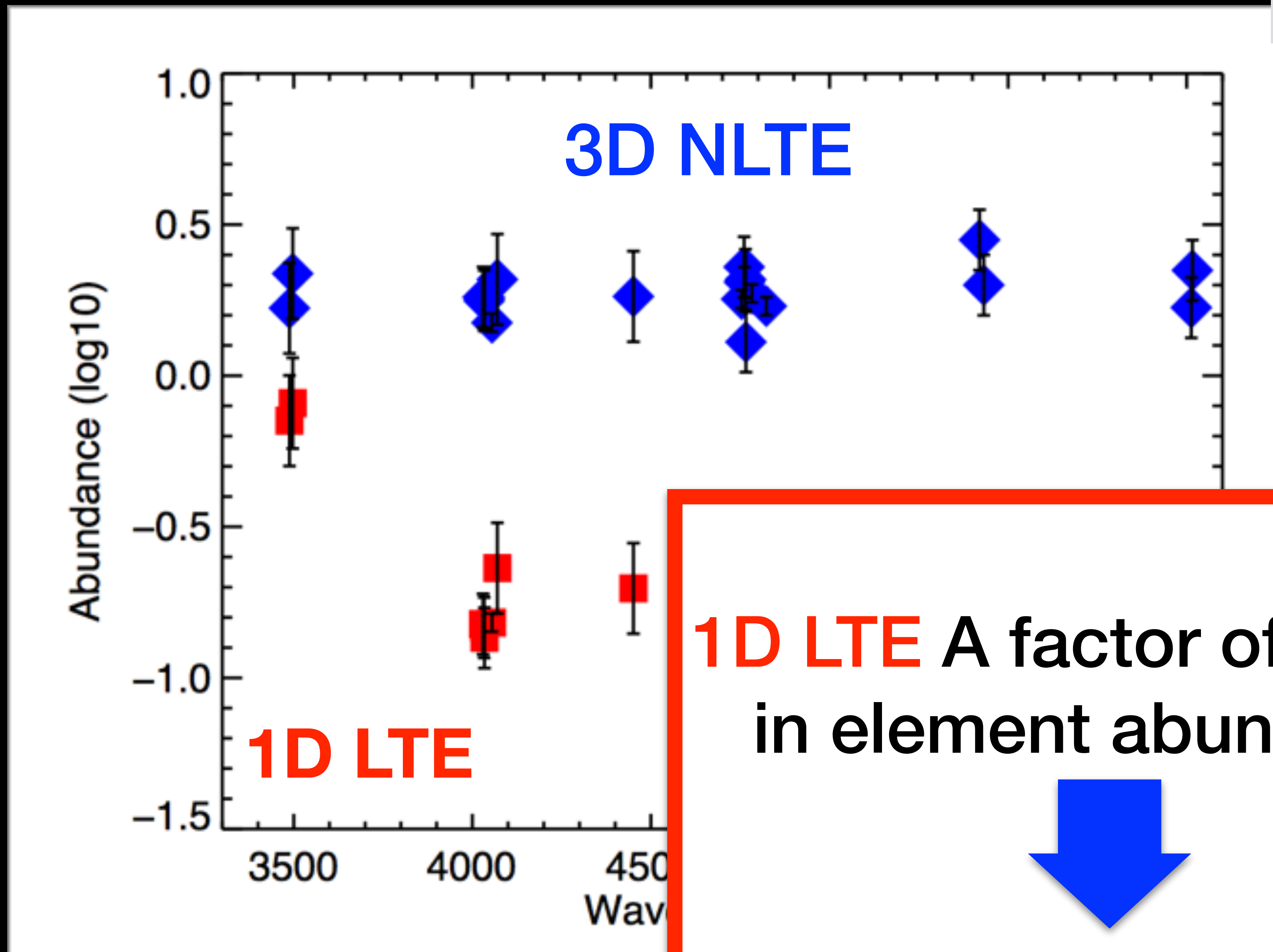
HD 122563



Bergemann et al. (2019, arXiv:1905.01835)
Gallagher et al. in prep.

Manganese
25
Mn
54.938

HD 122563



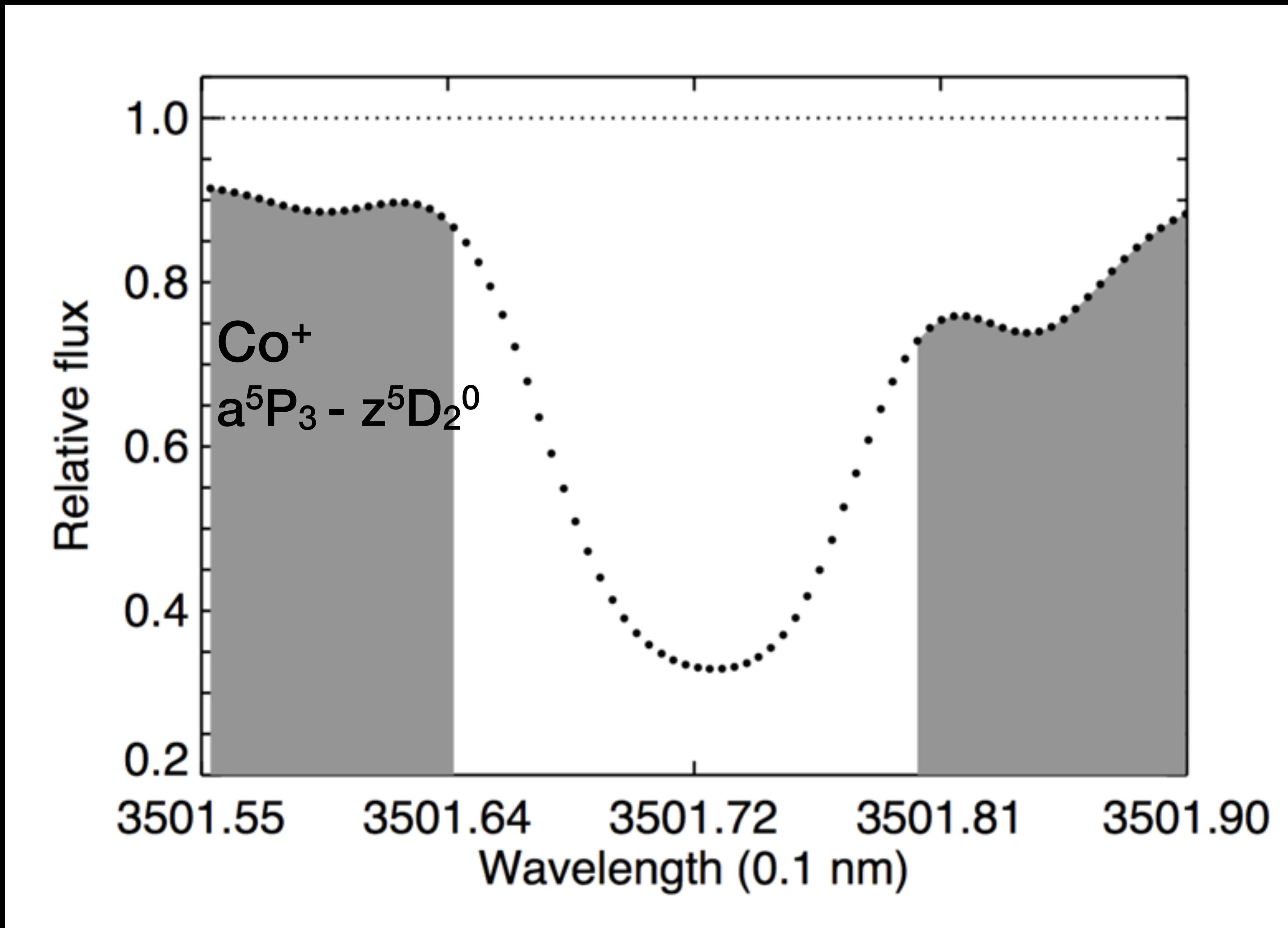
1D LTE A factor of 10 error in element abundance!

↓

3D NLTE

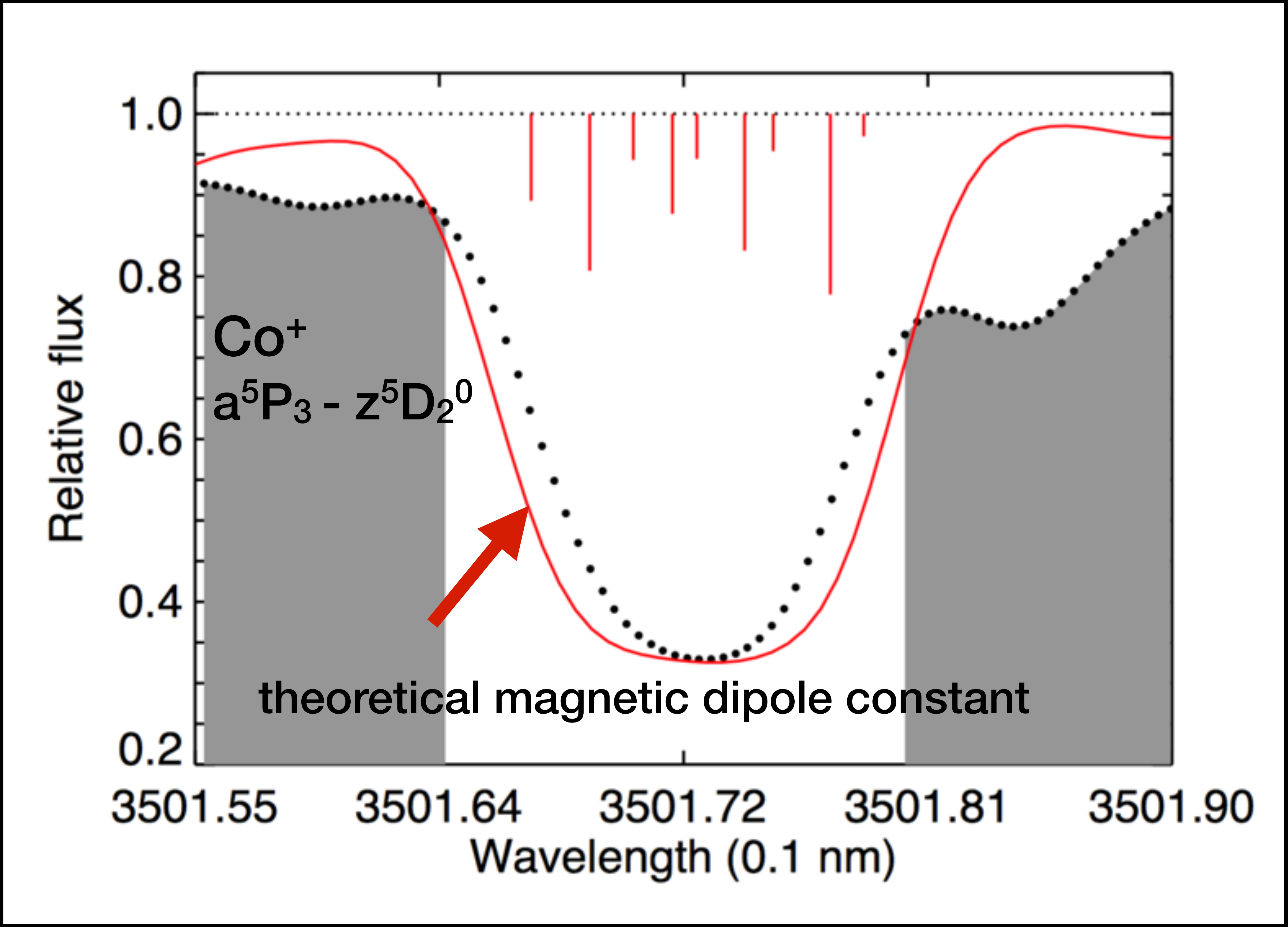
Bergemann et al. (2019, arXiv:1905.0183
Gallagher et al. in prep.

Testing atomic physics



***Bergemann** et al. 2010; Belyaev, Yakovleva, & **Bergemann** in prep.*

Testing atomic physics



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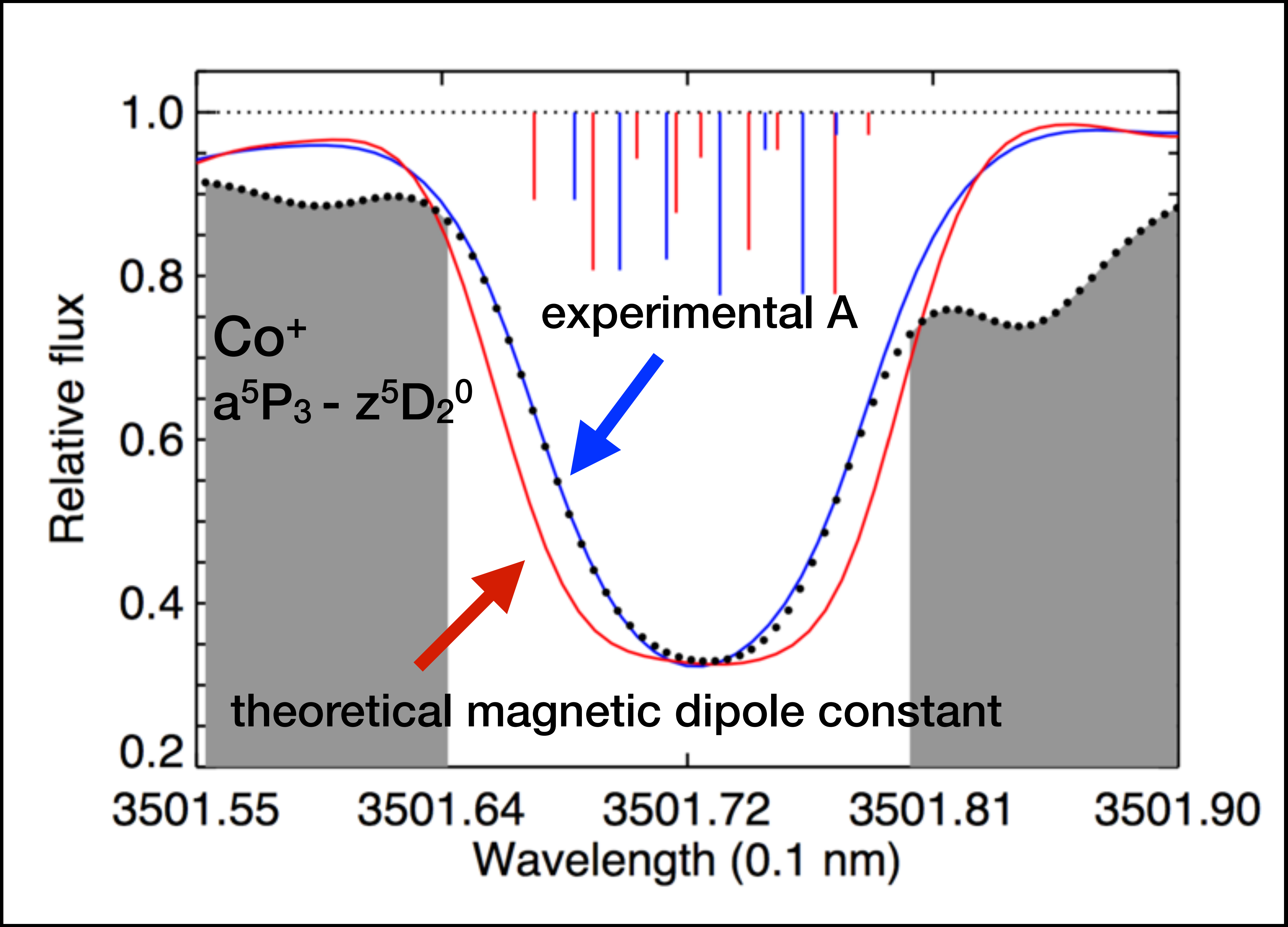
Testing atomic physics

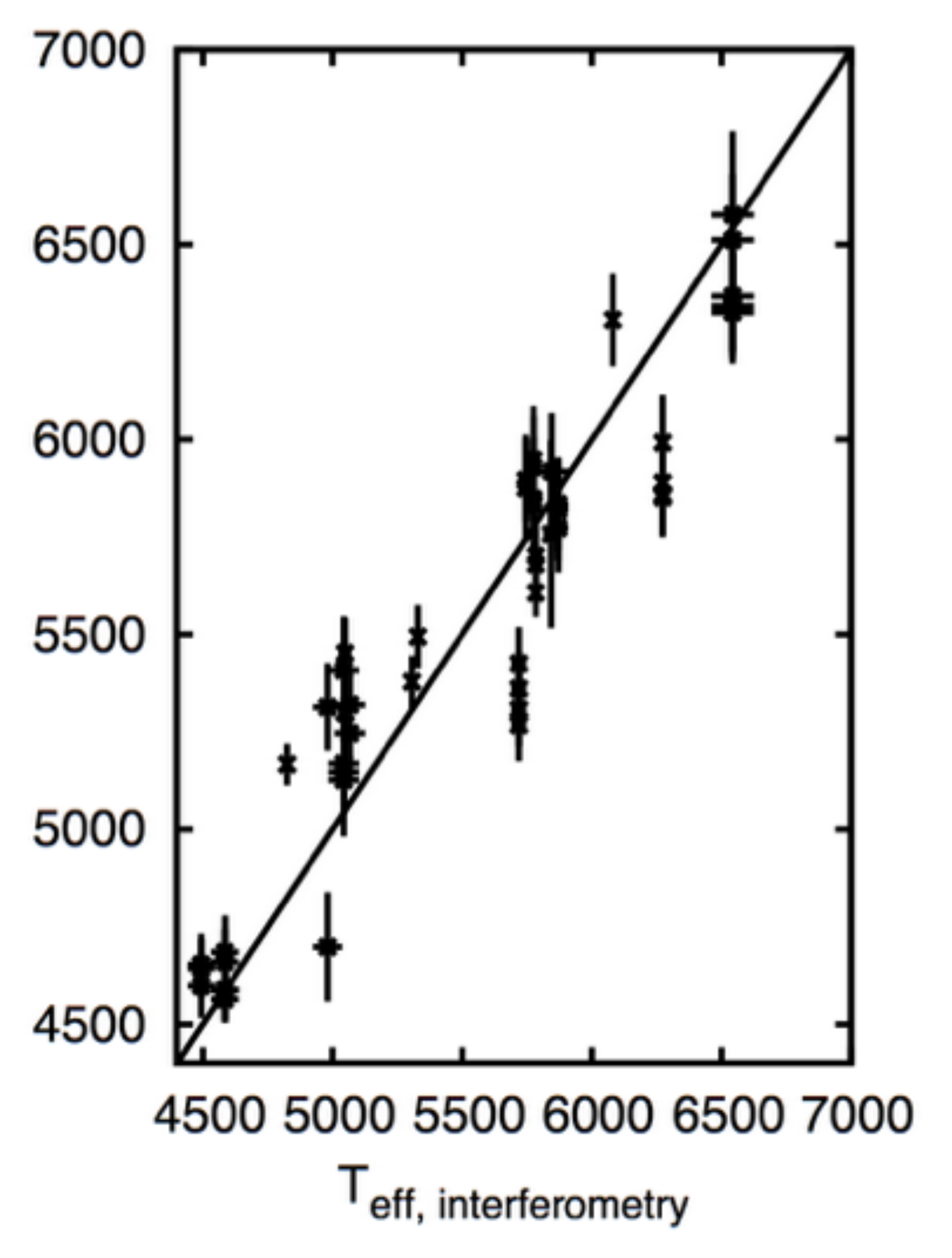


Bergemann *et al. 2010; Belyaev, Yakovleva, &* ***Bergemann*** *in prep.*

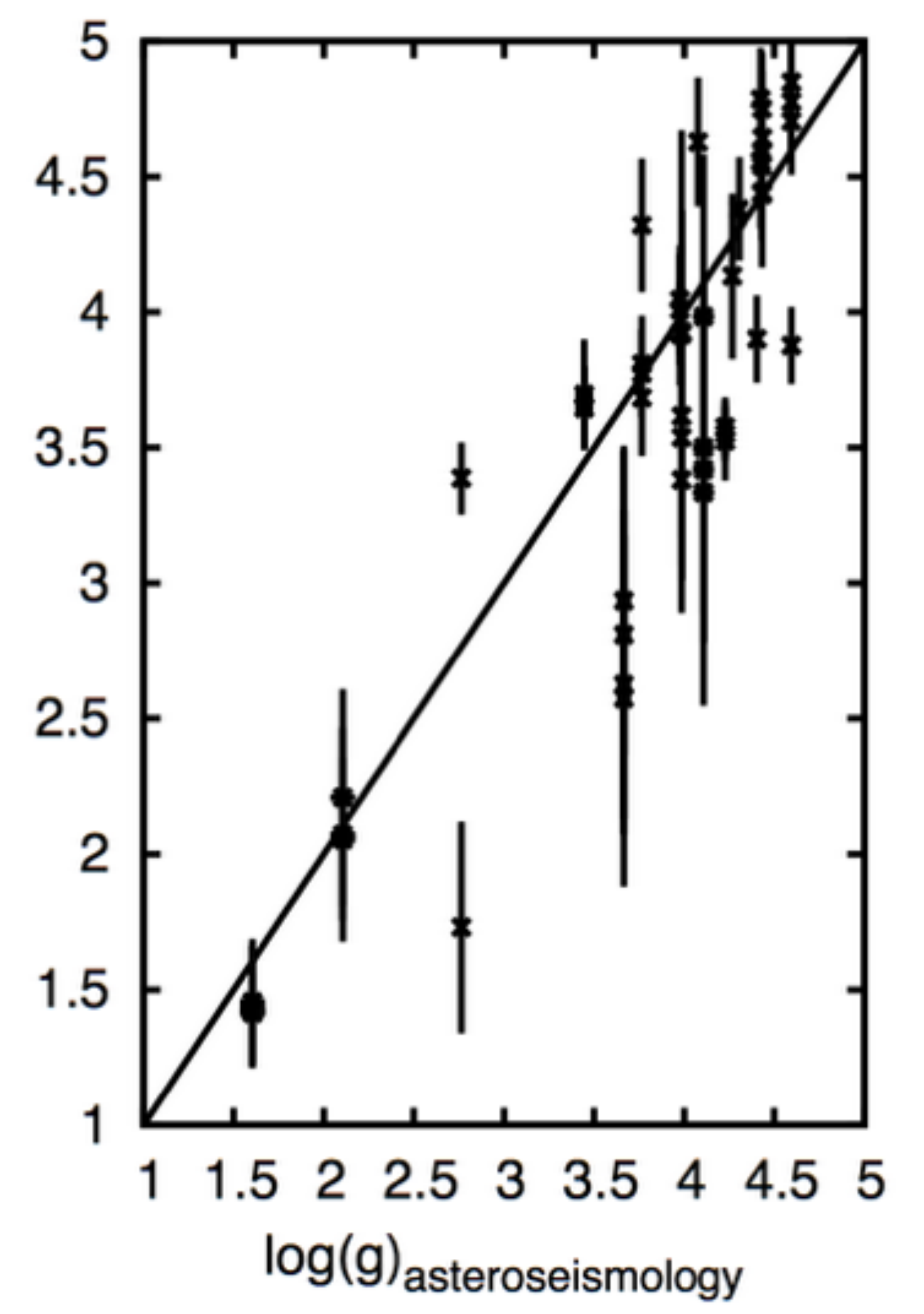
comparing with interferometry & asteroseismology

LTE: large uncertainties

LTE T_{eff}



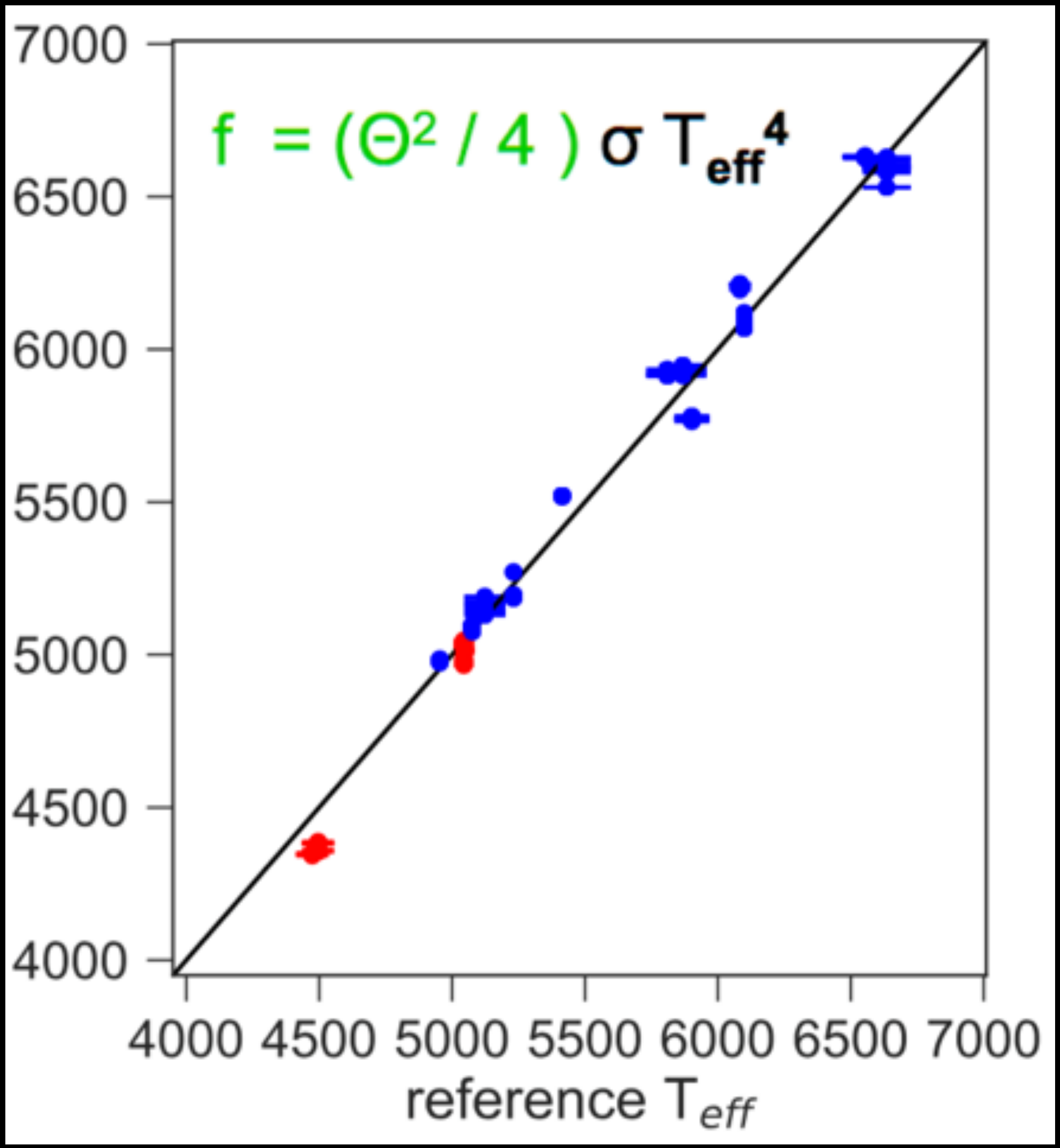
LTE log(g)



Schoenrich & Bergemann (2014)

comparing with interferometry & asteroseismology
NLTE

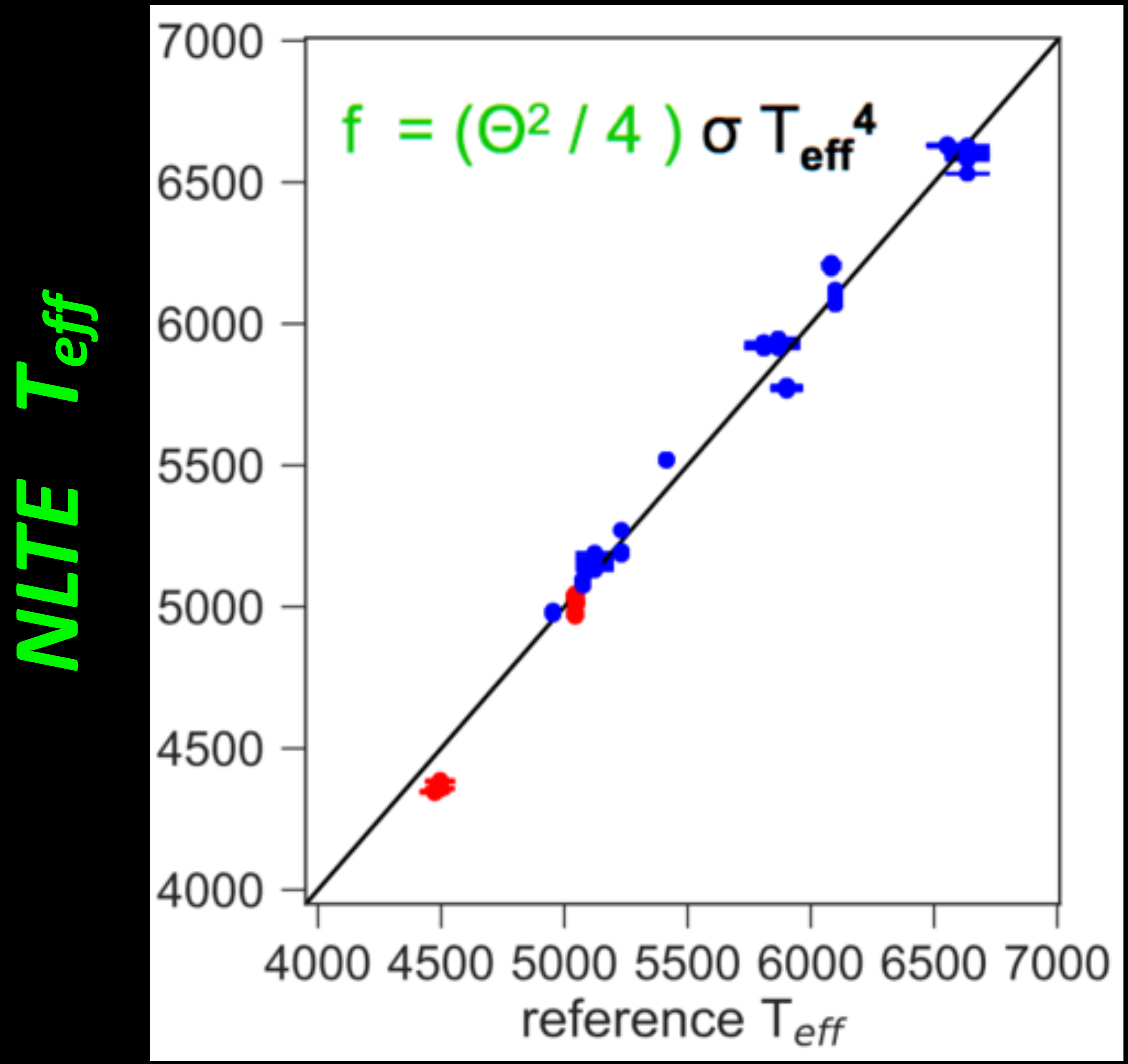
NLTE T_{eff}



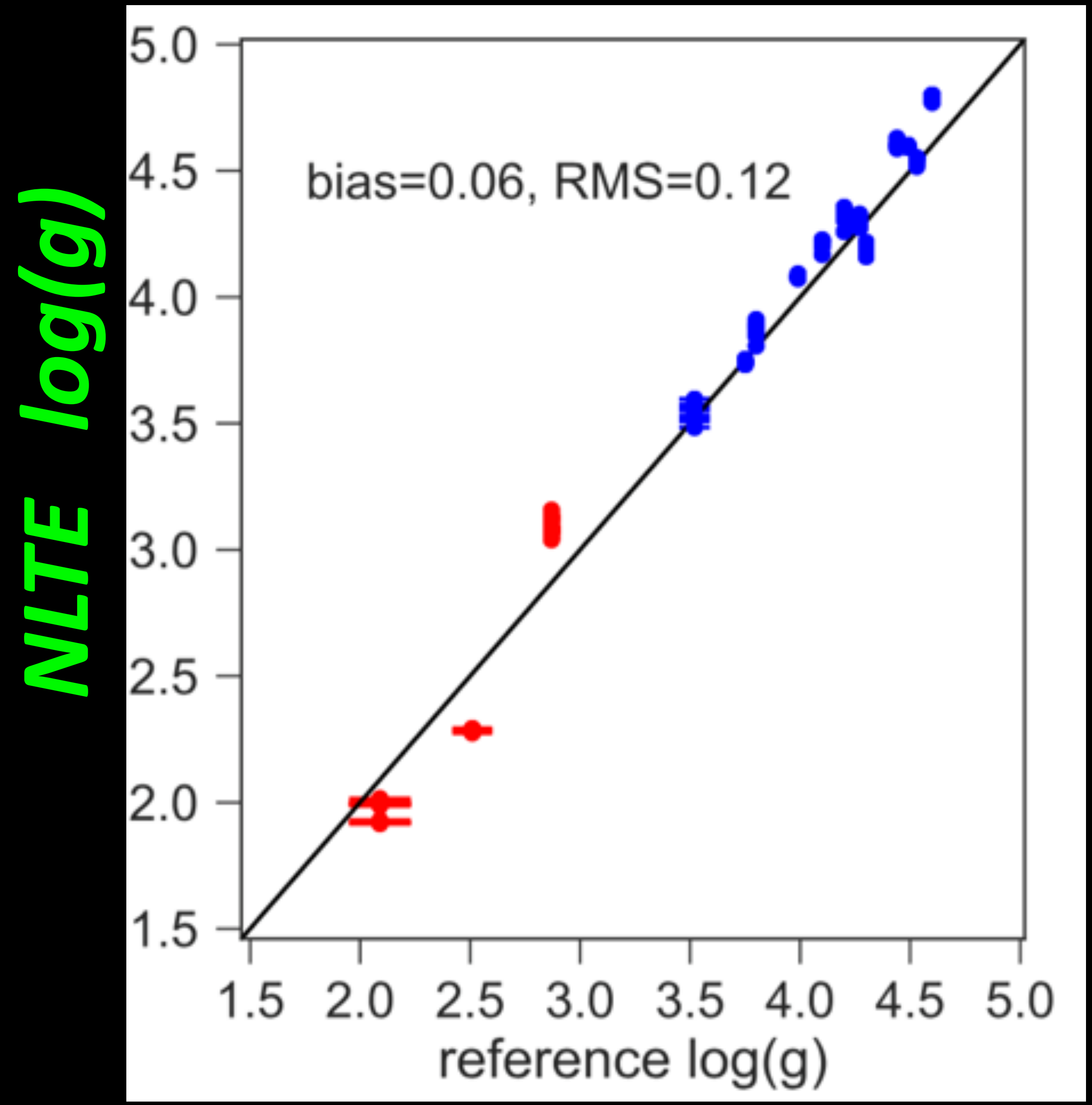
interferometry

Kovalev et al. subm.

comparing with interferometry & asteroseismology
NLTE



interferometry



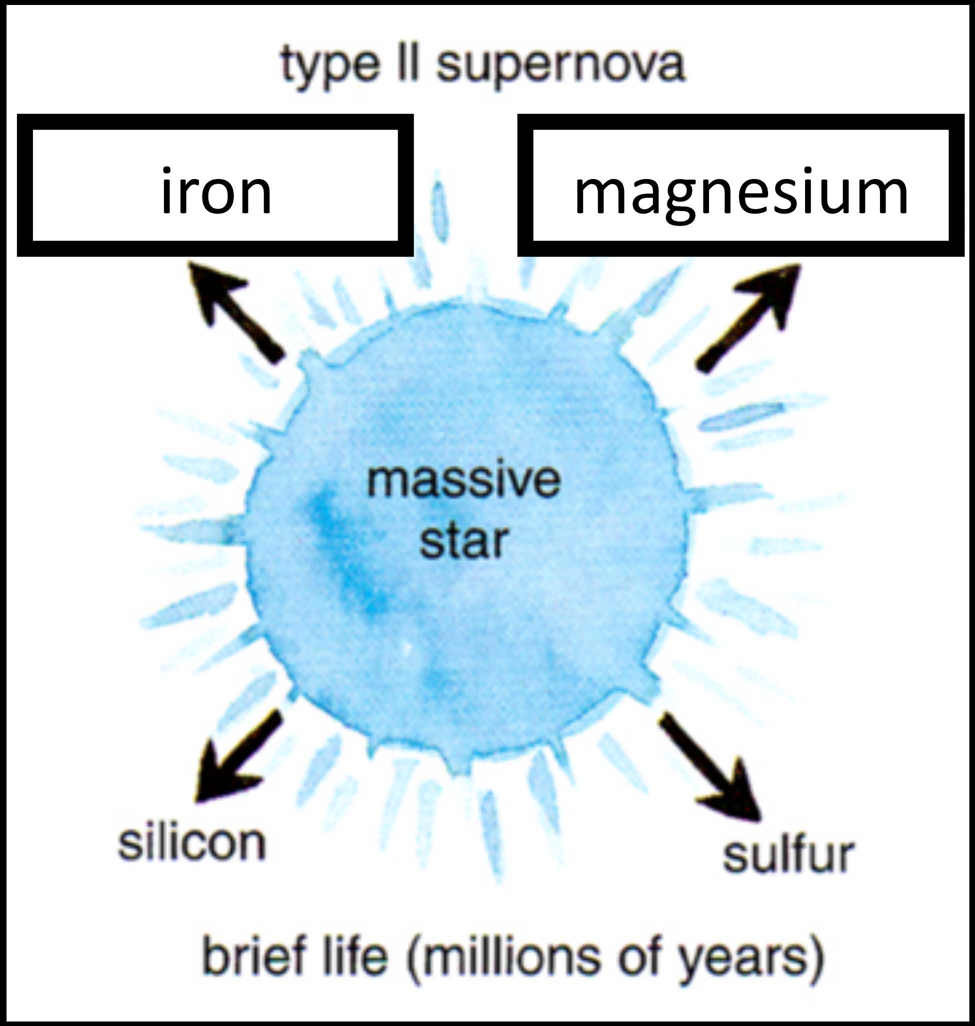
asteroseismology

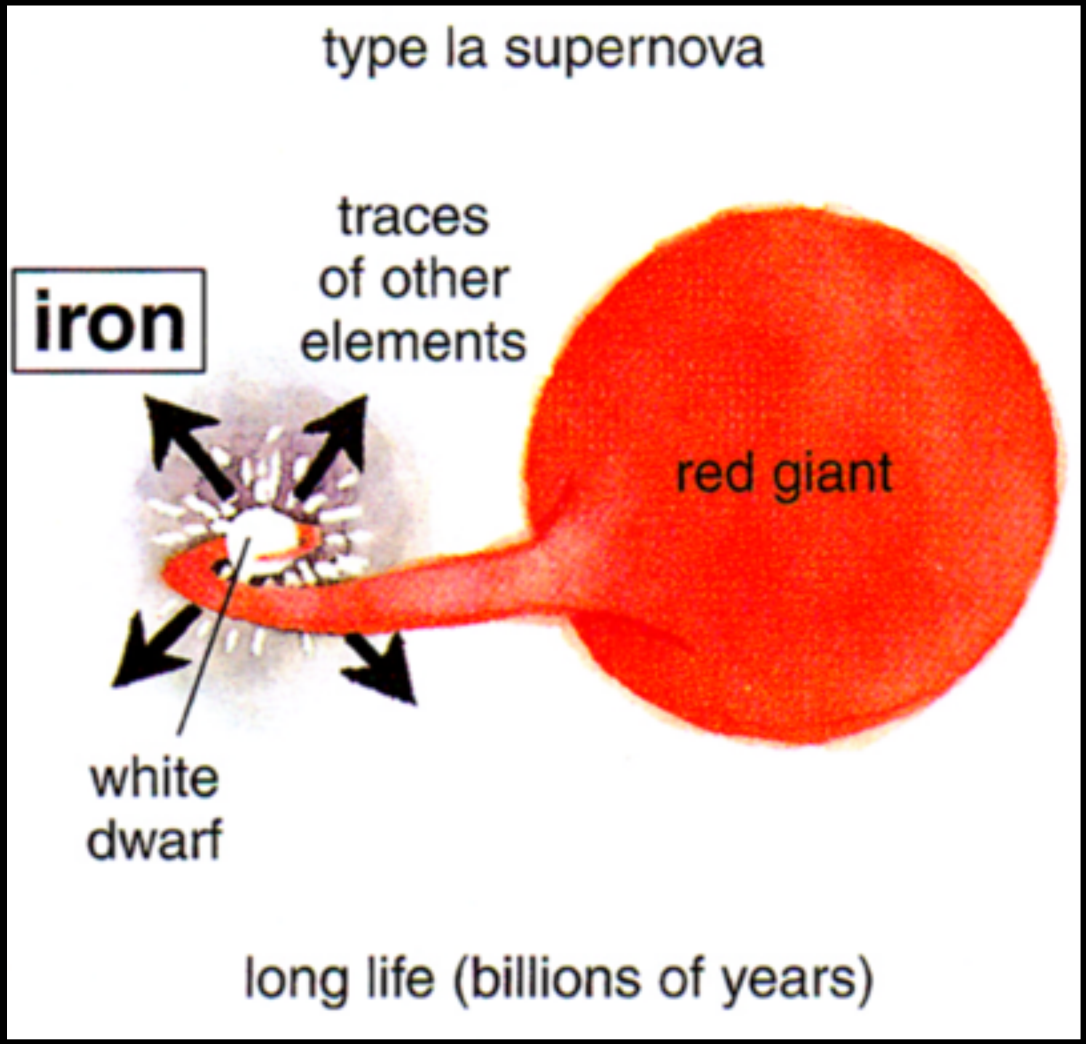
Kovalev et al. subm.

Does 3D NLTE spectral modelling matter?

Testing astrophysical scenarios. I

Evolution of the Milky Way



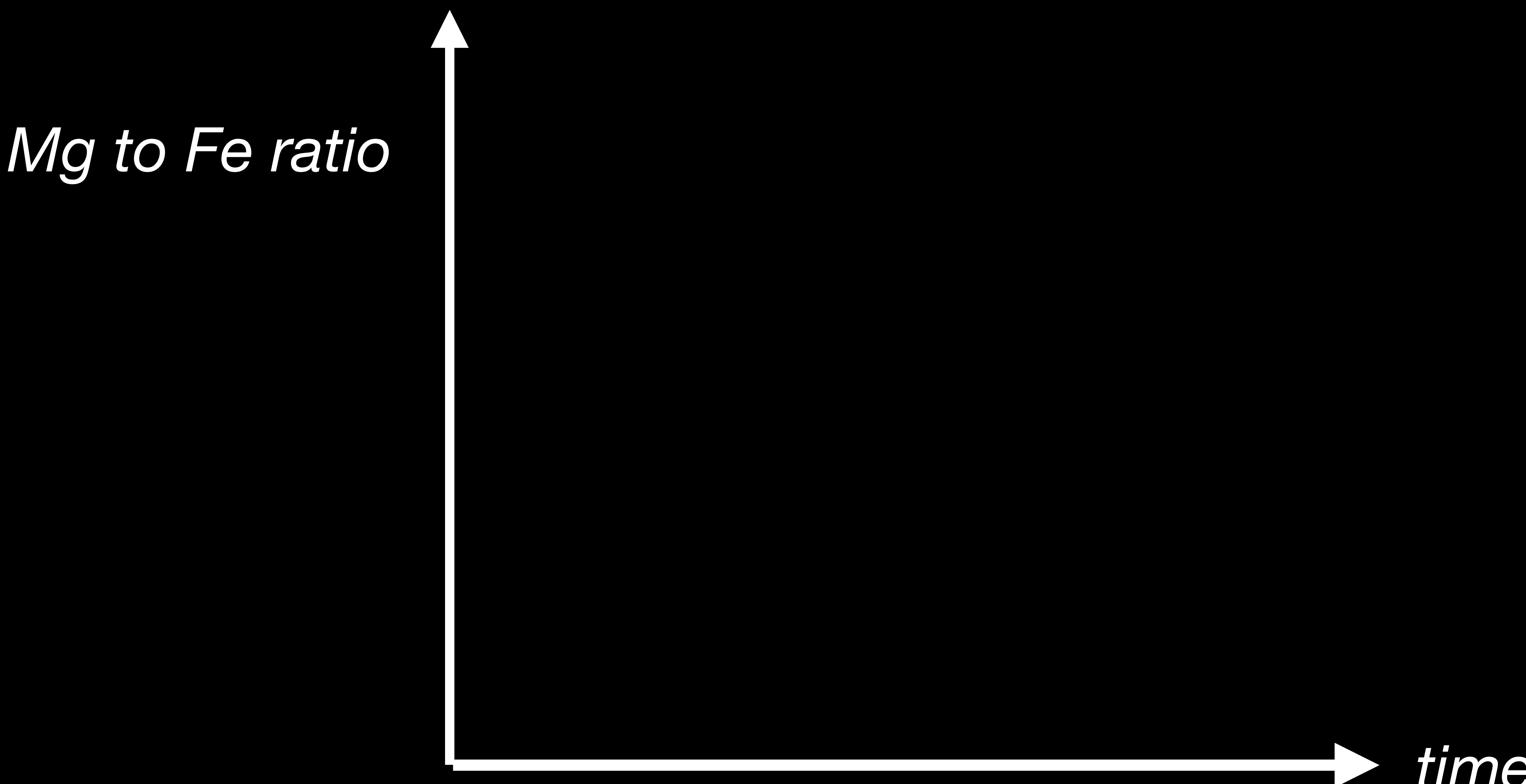


Chiappini 2000

**in astronomy, metals are all elements heavier than H and He*
[Fe/H] - metallicity

Testing astrophysical scenarios. I

Evolution of the Milky Way

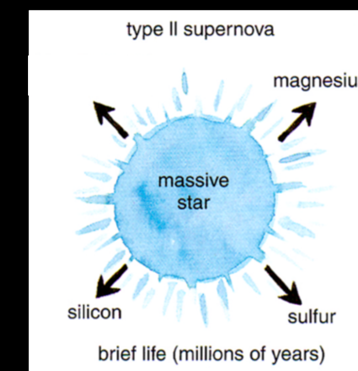


*in astronomy, metals are all elements heavier than H and He

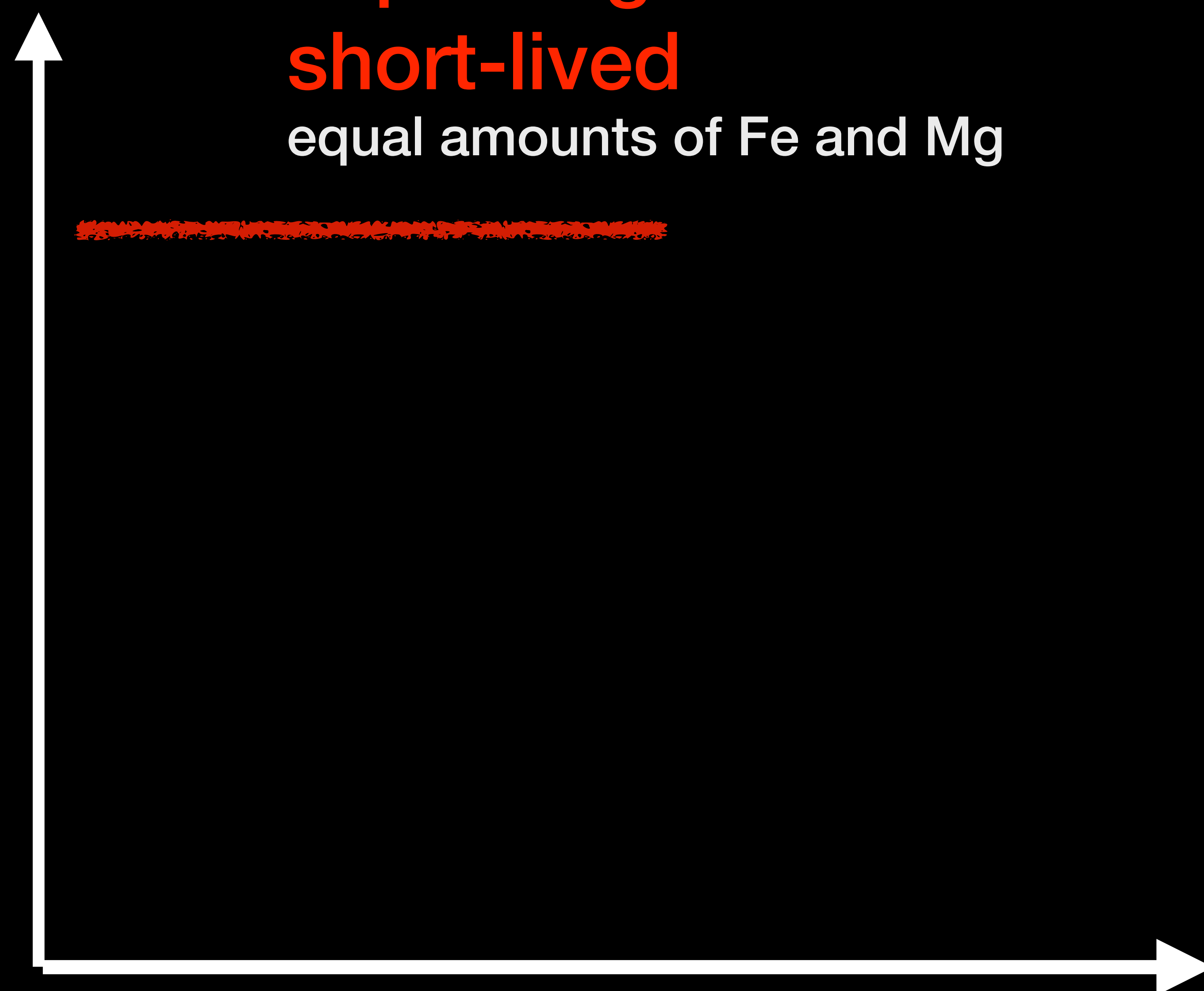
Testing astrophysical scenarios. I

Evolution of the Milky Way

exploding massive stars
short-lived
equal amounts of Fe and Mg



Mg to Fe ratio



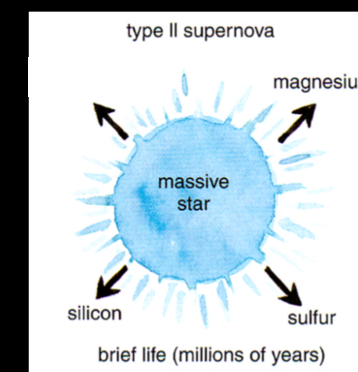
time

in astronomy, metals are all elements heavier than H and He

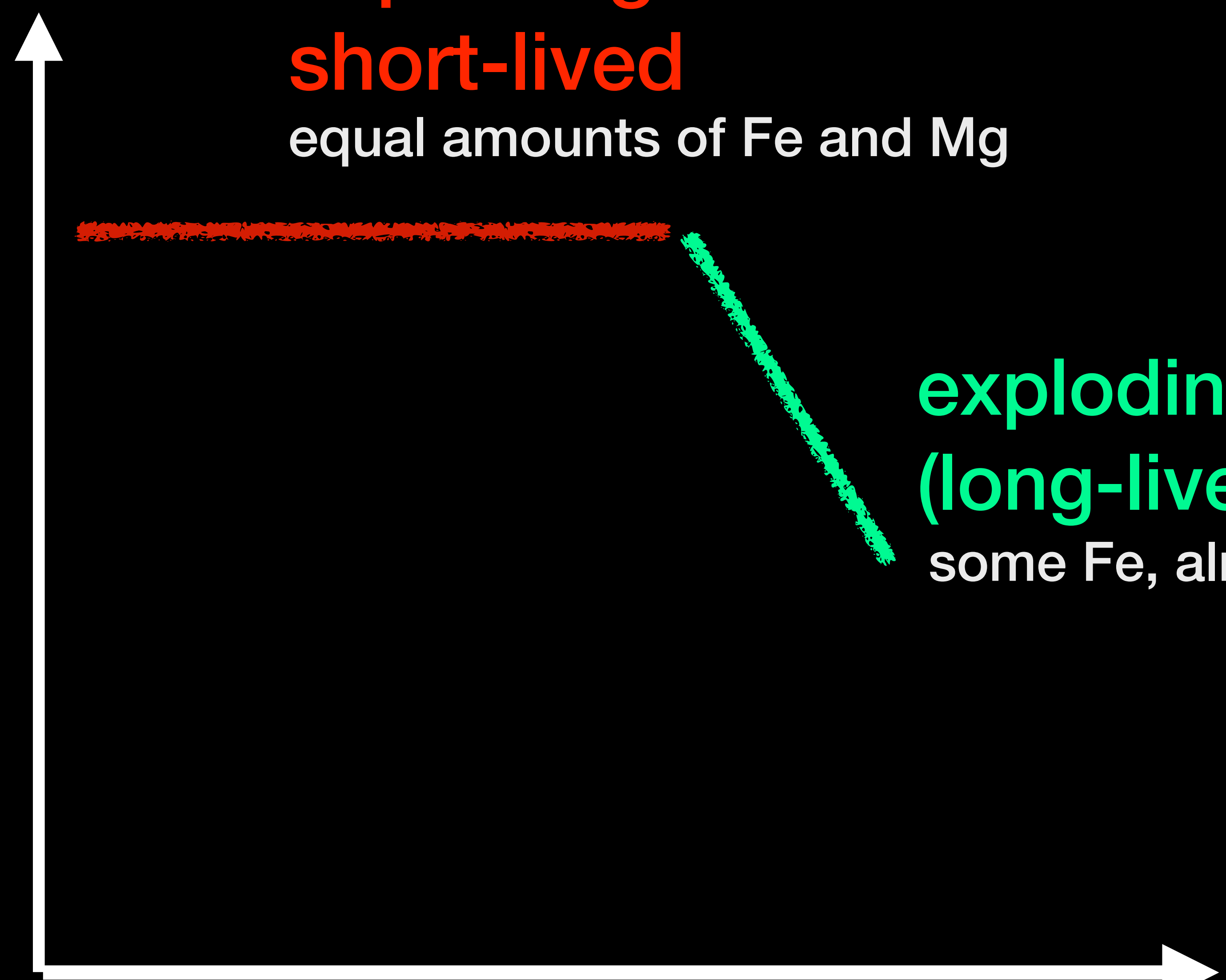
Testing astrophysical scenarios. I

Evolution of the Milky Way

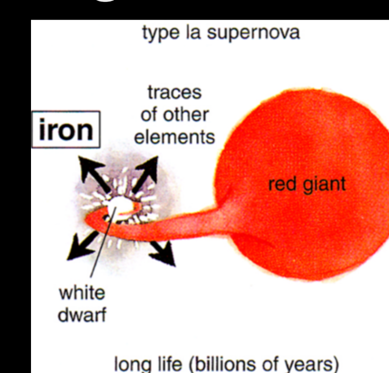
exploding massive stars
short-lived
equal amounts of Fe and Mg



Mg to Fe ratio



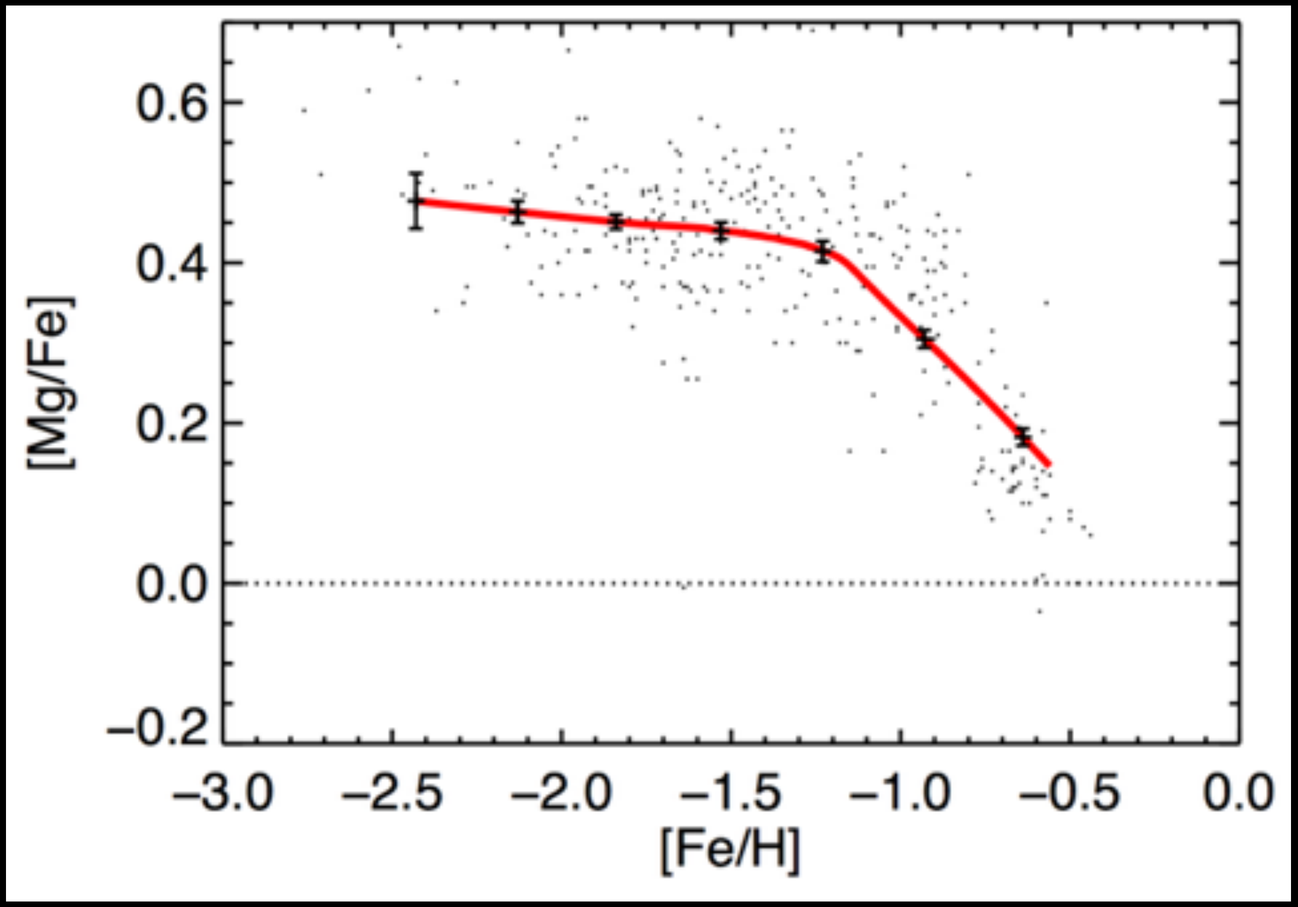
exploding white dwarfs
(long-lived)
some Fe, almost no Mg



time

**in astronomy, metals are all elements heavier than H and He*

1D LTE

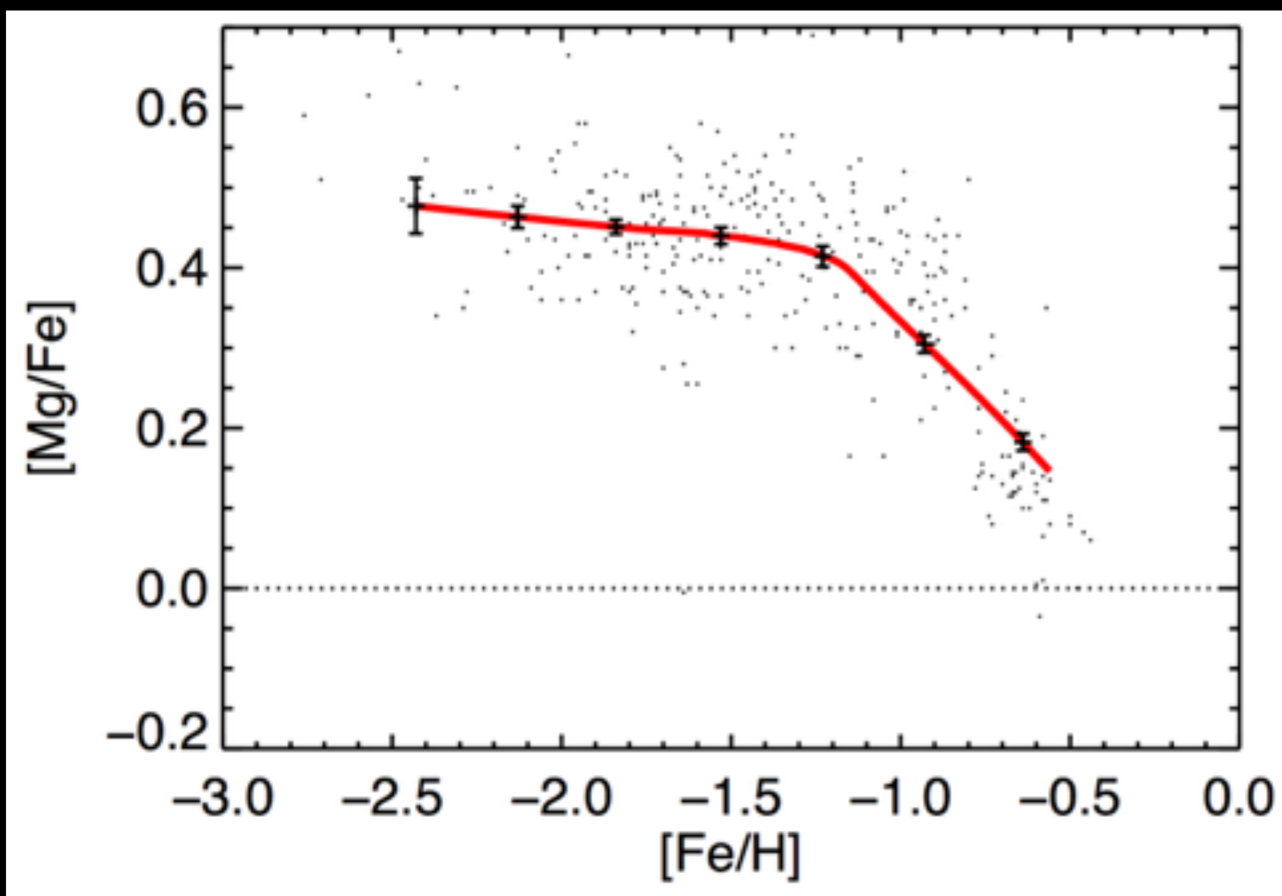


time

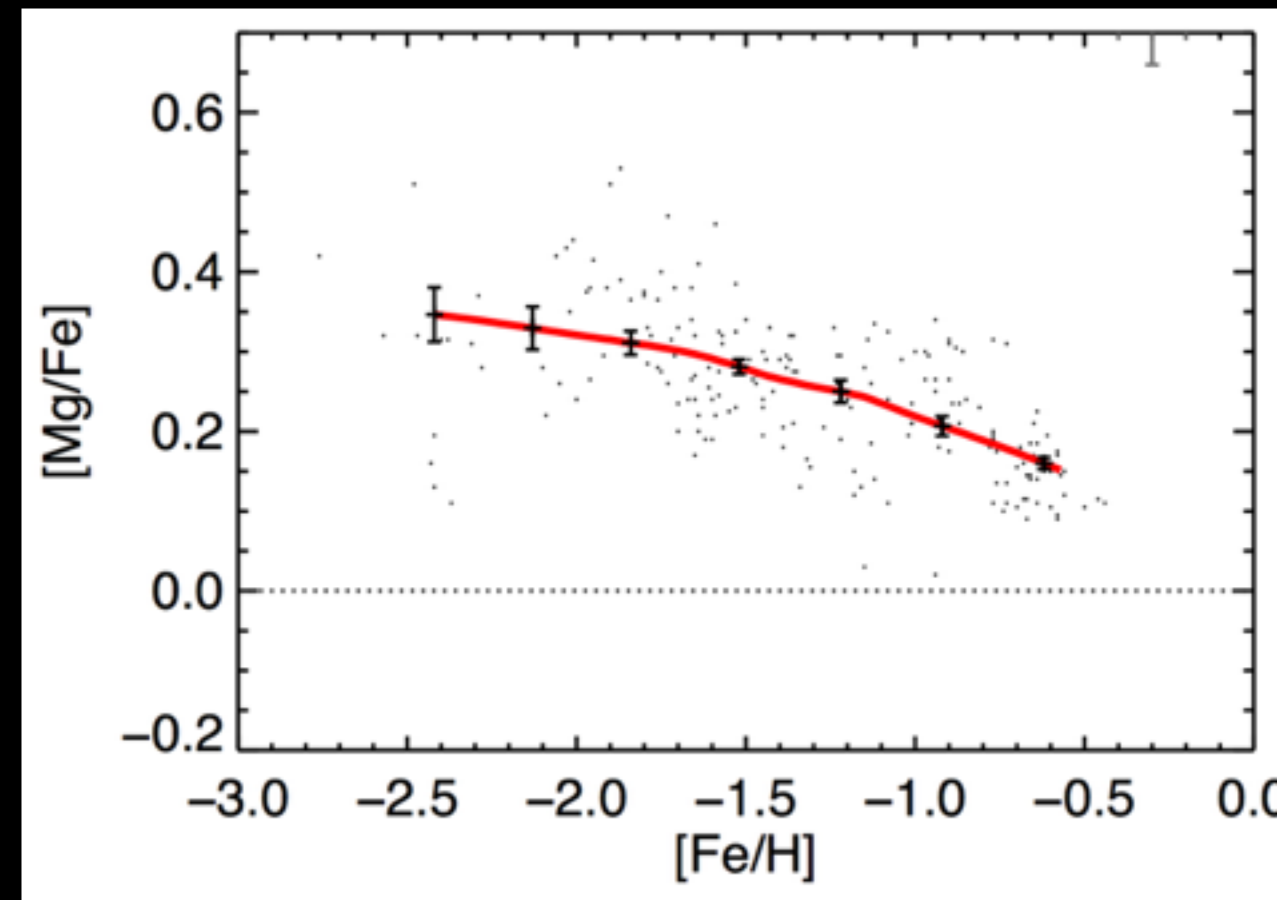
Bergemann et al. (2017b)

<u>same</u> stars, just <u>different</u> models

1D LTE



<3D> NLTE



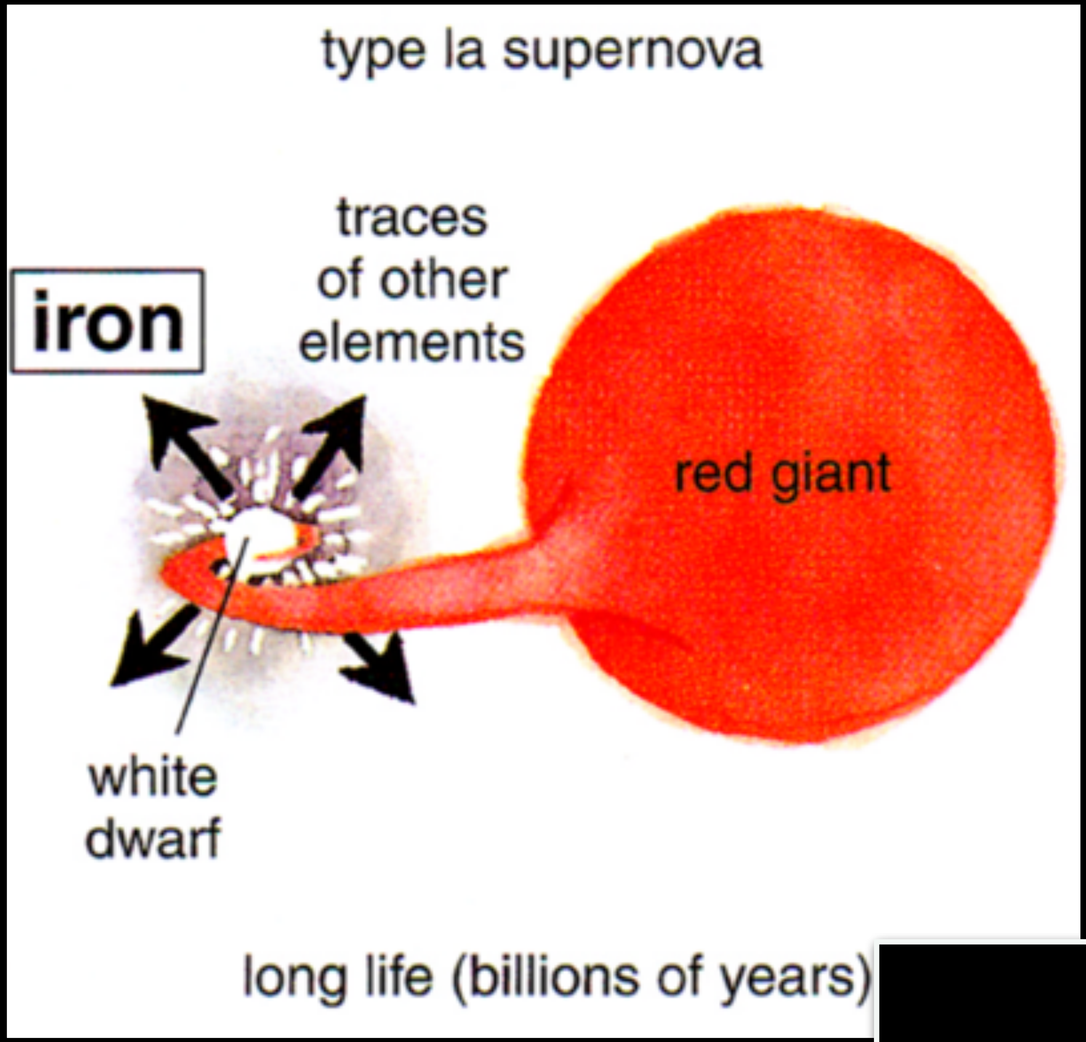
time

we do not understand which explosions produce which elements

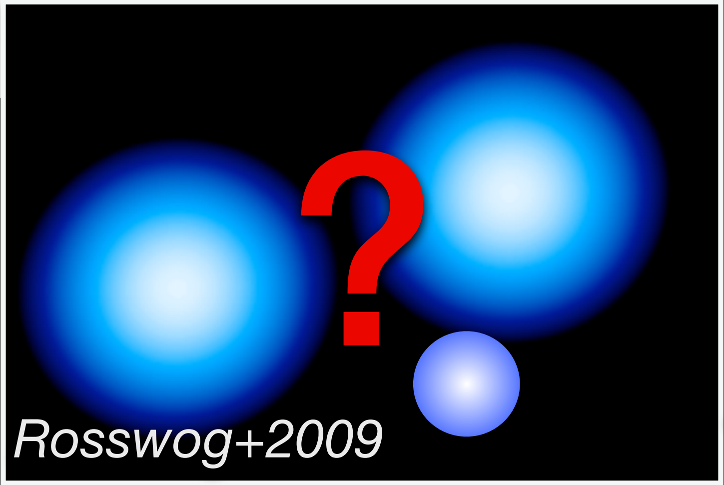
Bergemann *et al. (2017b),* ***Kovalev*** *et al. subm*

Testing astrophysical scenarios. II

Progenitors of Type Ia supernova (SN)

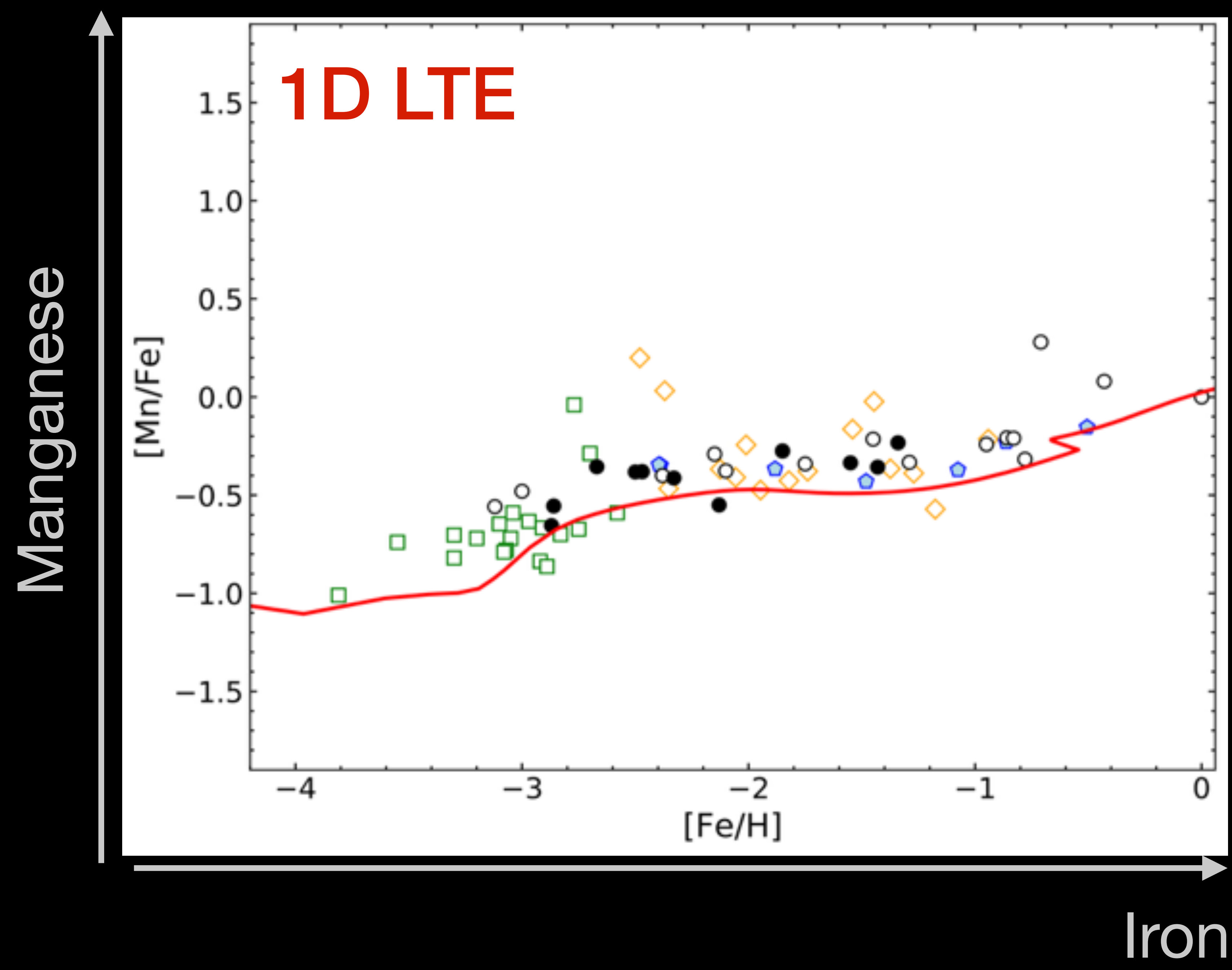


Explosion channels unknown - source of a systematic uncertainty in cosmological measurements



Tod Strohmayer (GSFC), CXC, NASA, Illustration: Dana Berry (CXC)

Progenitors of Type Ia supernova (SN)

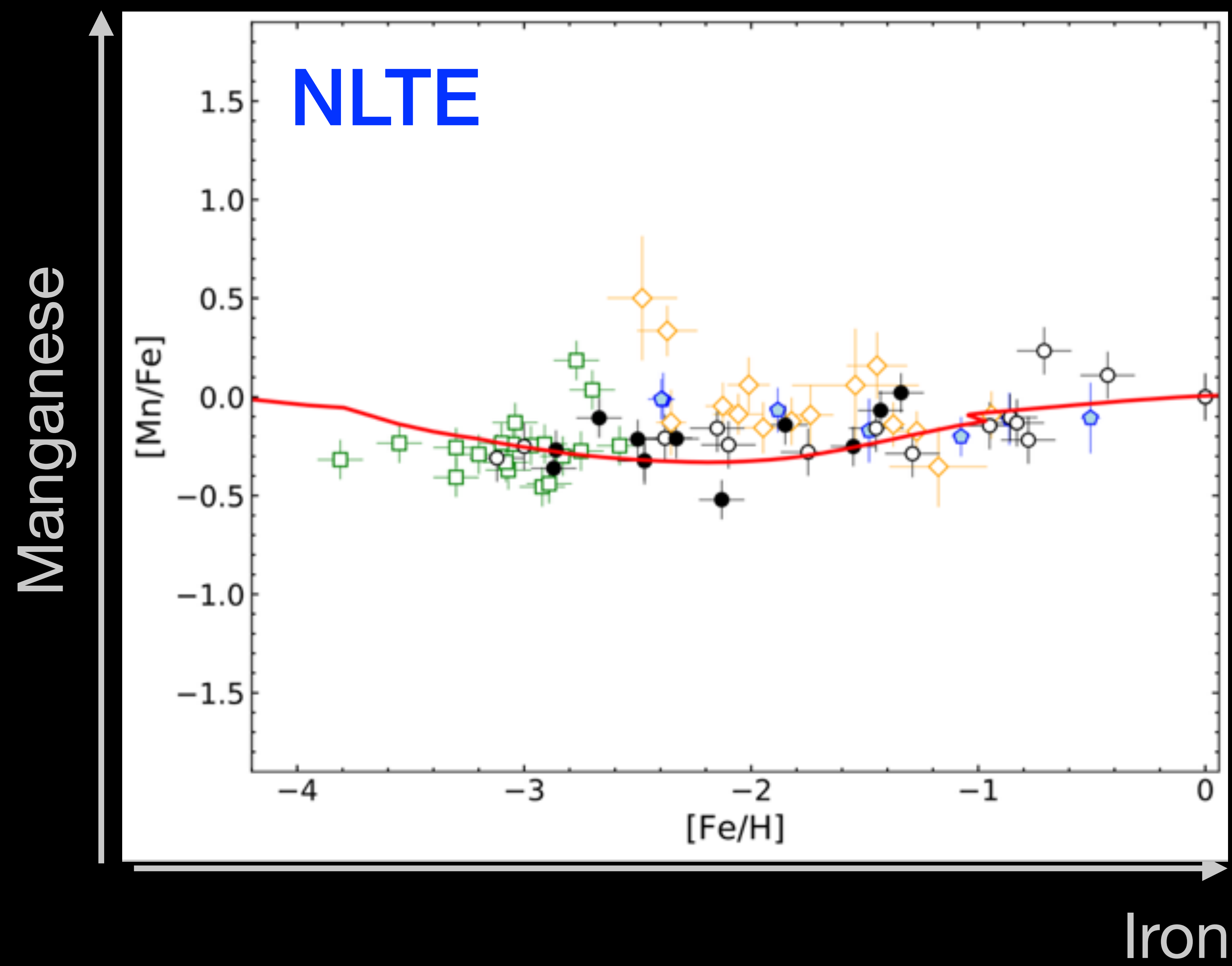


Type Ia SNe <u>are standard candles</u>

Standard explosions
- *near-Chandrasekhar mass channel*

Bergemann *& Gehren 2008*
*Kirby…**Bergemann, Kovalev** 2019*
***Eitner, Bergemann, Hansen** et al. (in prep.)*
*Kirby…**Bergemann, Kovalev** et al. (subm.)*

Progenitors of Type Ia supernova (SN)



Type Ia SNe are **not** standard candles

dominant contribution from sub -/ super-Chandrasekhar mass channel dominates

Bergemann & Gehren 2008
Kirby…Bergemann, Kovalev 2019
Eitner, Bergemann, Hansen et al. (in prep.)
Kirby…Bergemann, Kovalev et al. (subm.)

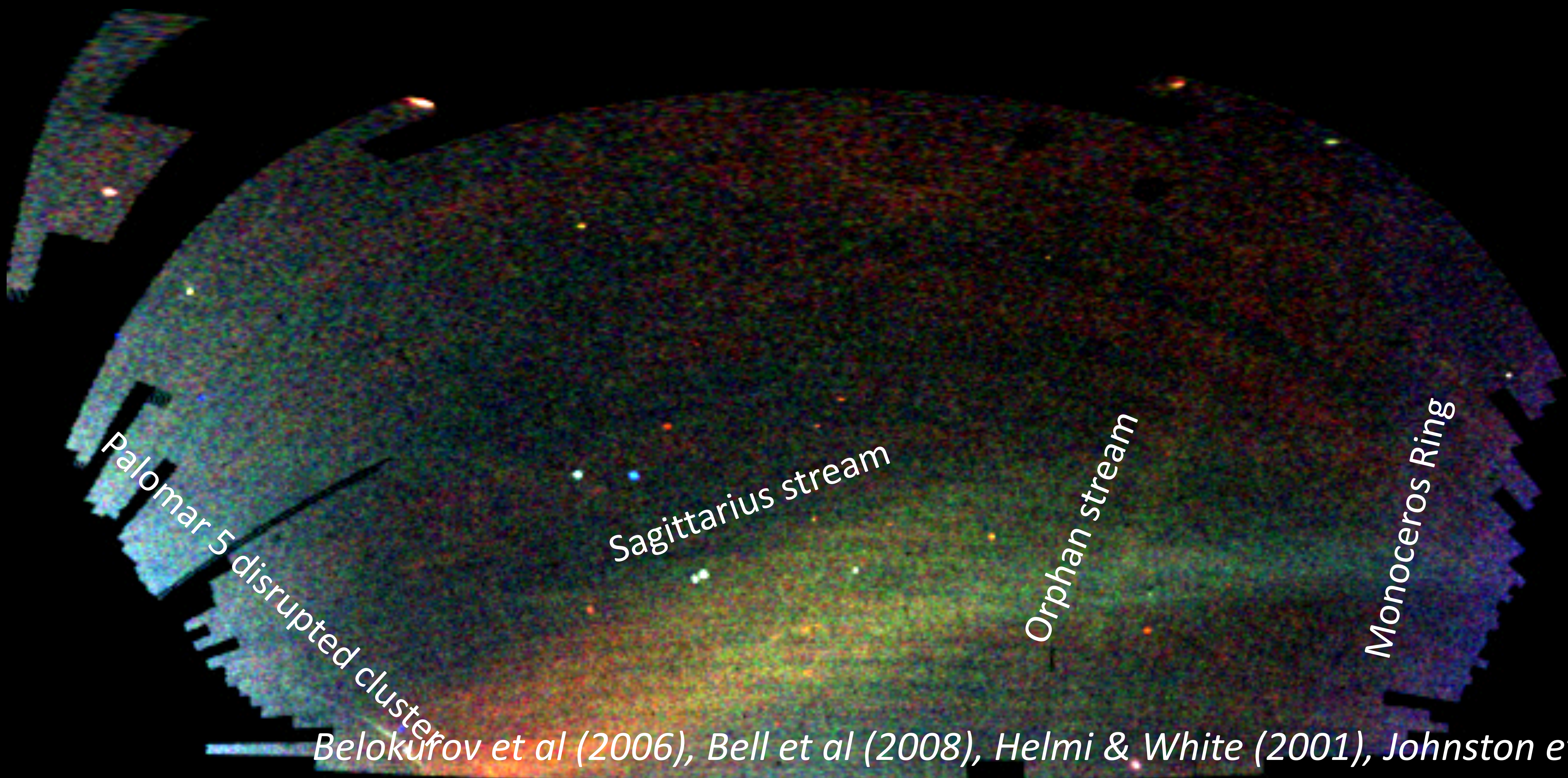
Testing astrophysical scenarios. III

Dynamical history of the Galaxy

Testing astrophysical scenarios. III

Dynamical history of the Galaxy

Milky Way: rich in substructure: streams and overdensities
constraints on the Galactic potential, accretion history



Belokurov et al (2006), Bell et al (2008), Helmi & White (2001), Johnston et al (2005), Martin et al. (2007), Penarrubia et al. (2010), Law & Majewski (2010)

Testing astrophysical scenarios. III

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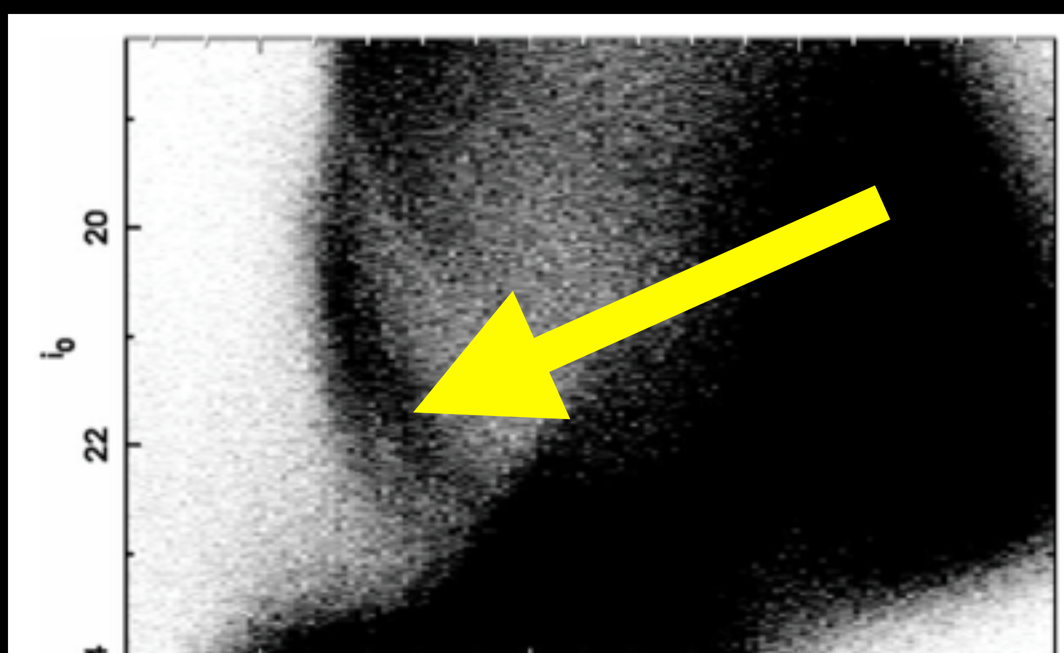
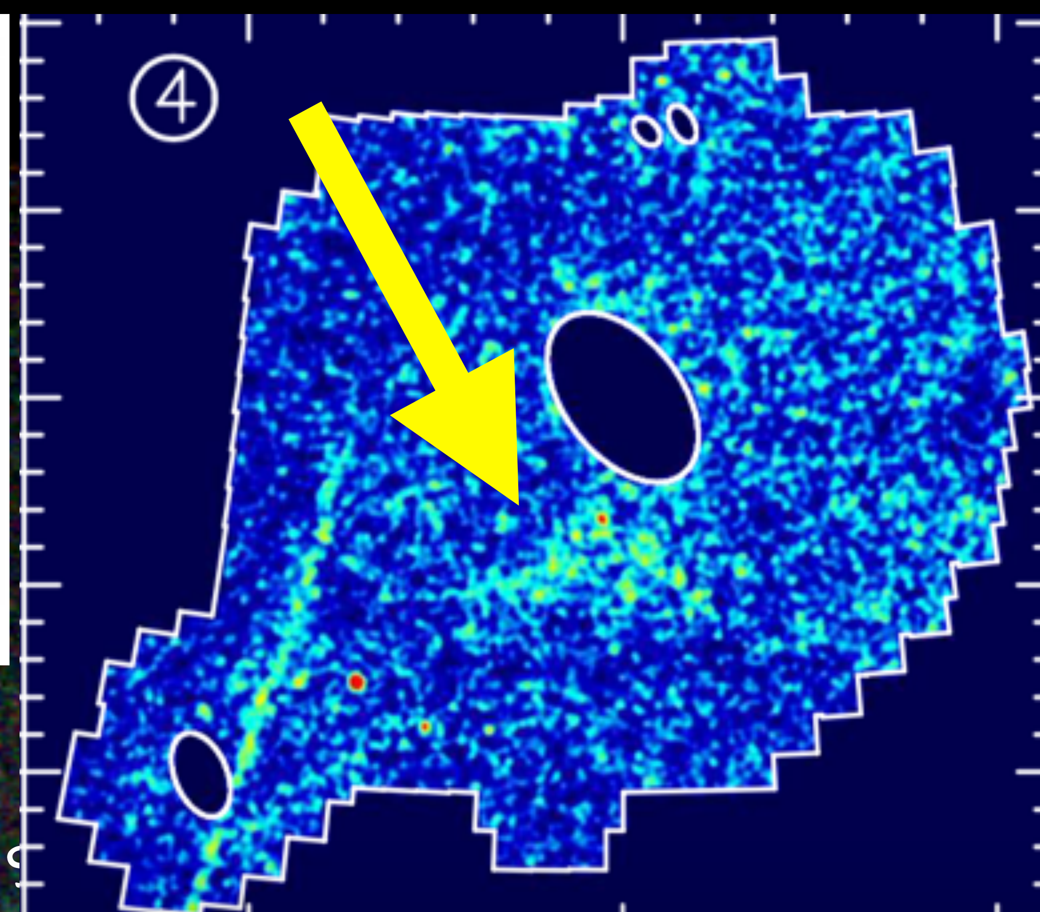


Martin et al. (2007)



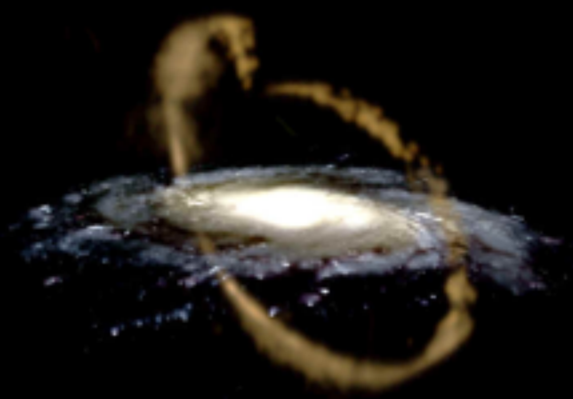
Origin of stellar overdensities in the halo?

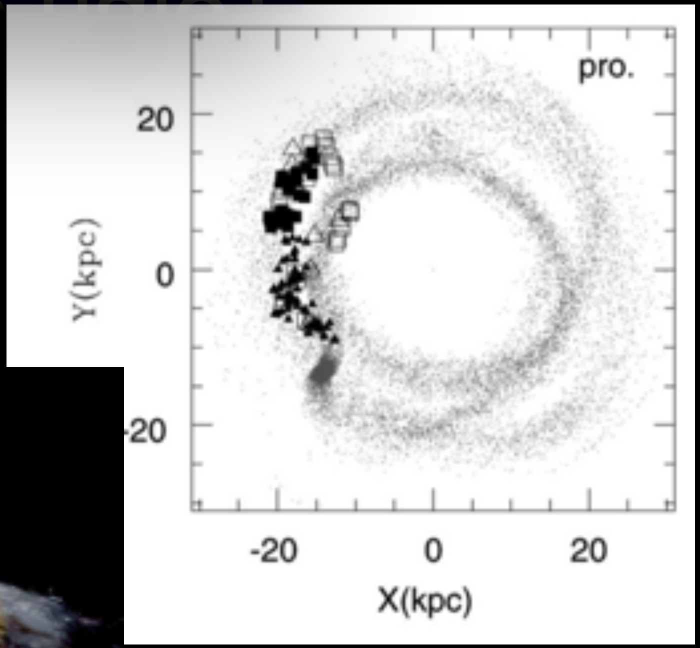
Belokurov et al (2006), Bell et al (2008), Helmi & White (2001), Johnston et al (2005), Martin et al. (2007), Penarrubia et al. (2010), Law & Majewski (2010)

Testing astrophysical scenarios. III

Origin of stellar overdensities in the halo?

- debris from disrupted satellite galaxies?
  Yanni et al 2003, Penarrubia et al 2005, Sheffied et al 2014





Testing astrophysical scenarios. III

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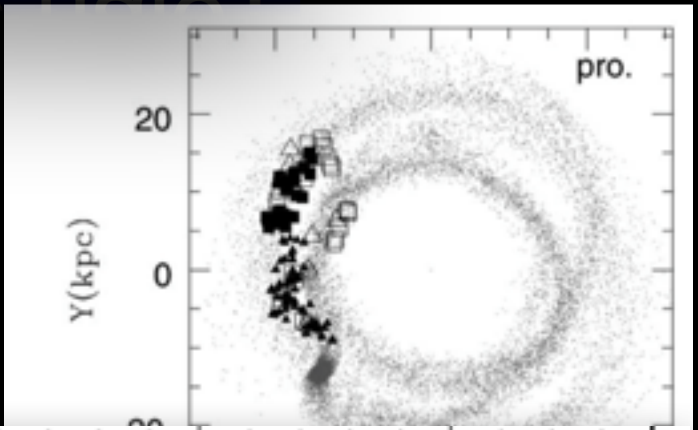

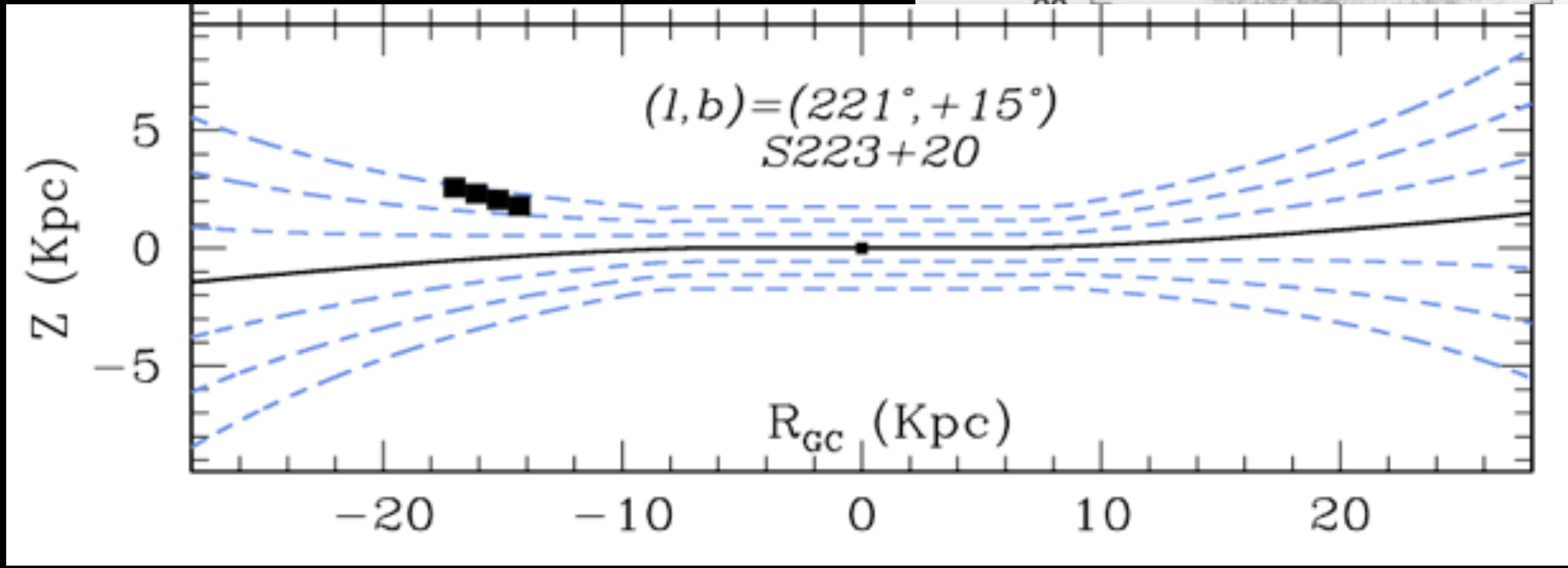

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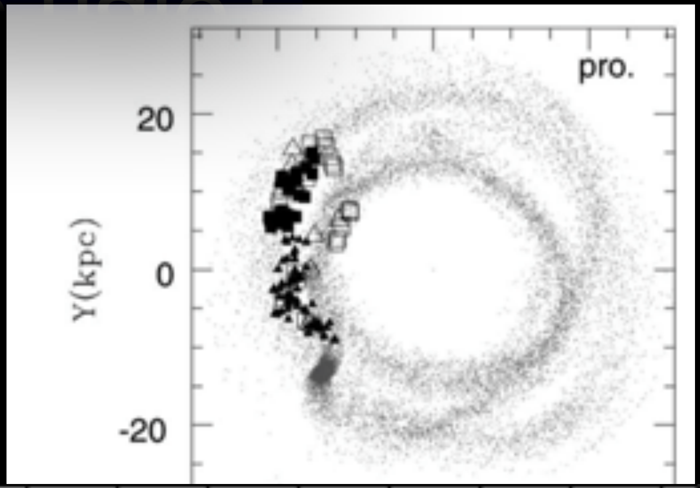

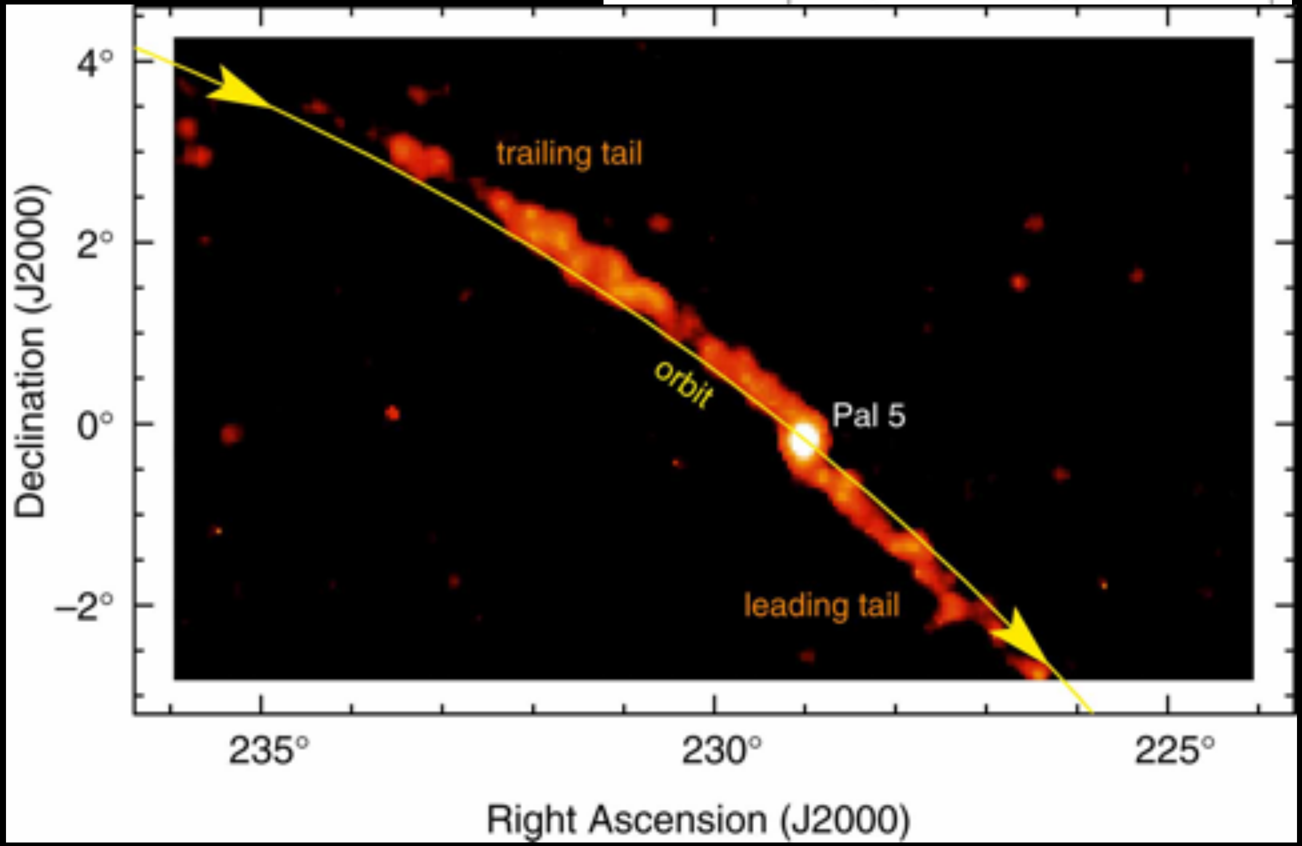

Testing astrophysical scenarios. III

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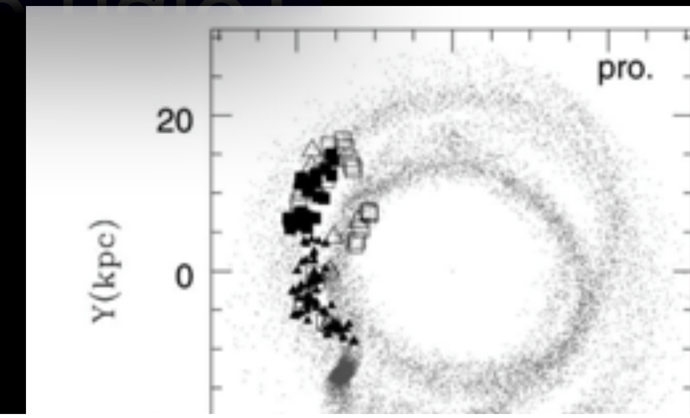
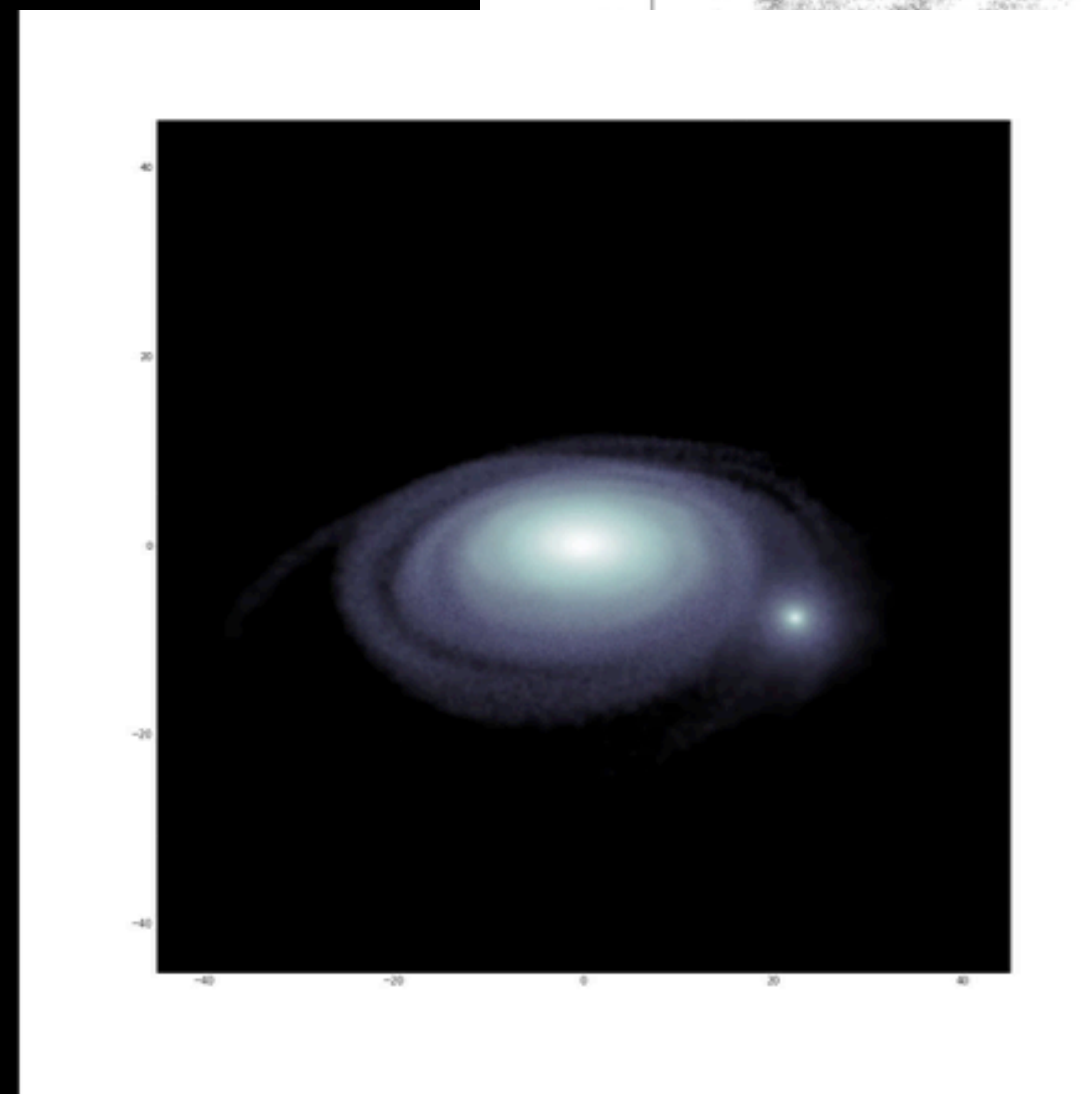
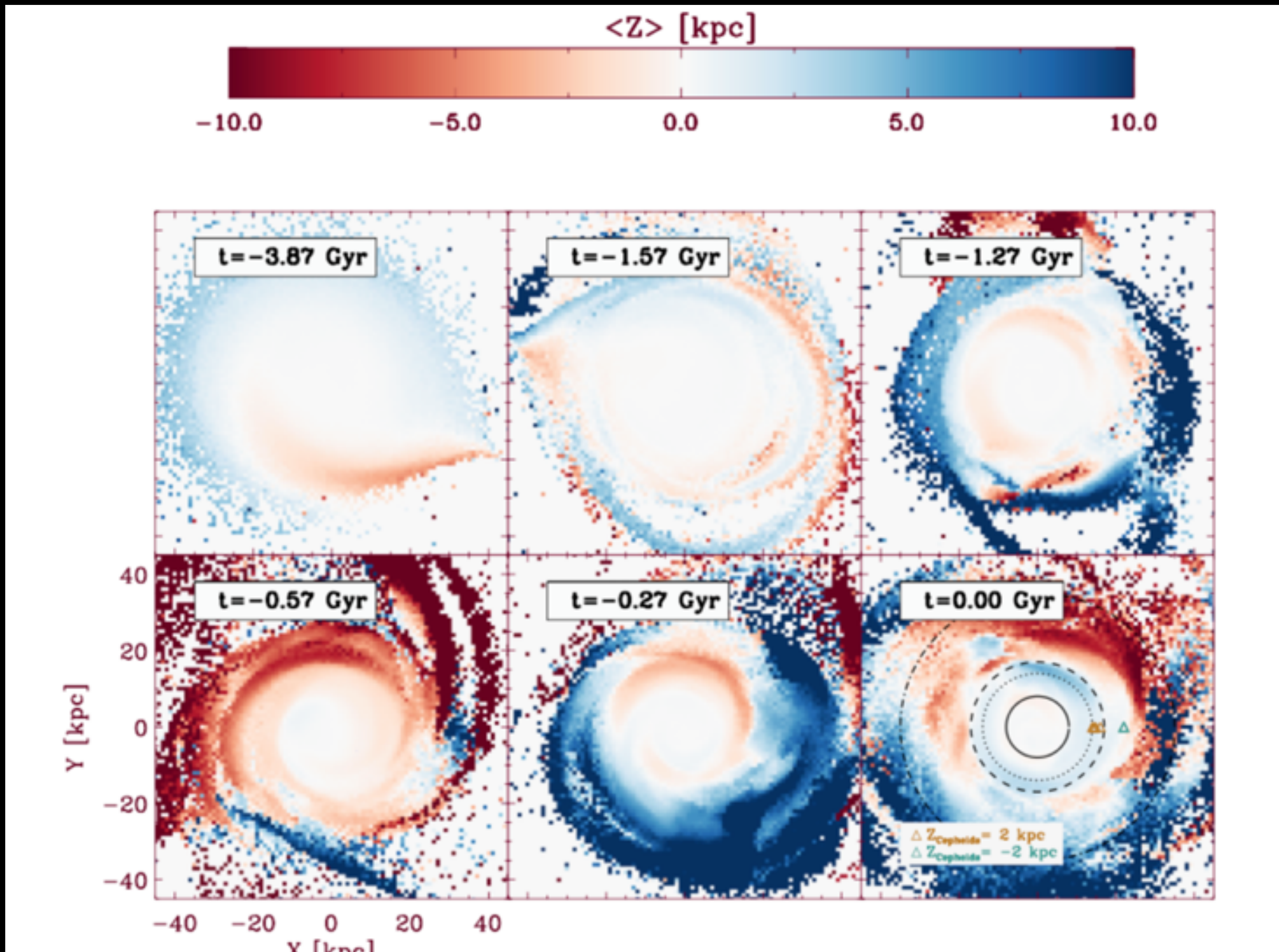


- debris from disrupted satellite galaxies?
  Yanni et al 2003, Penarrubia et al 2005, Sheffied et al 2014
- a giant flare / warp in the outer disc?
  Momany et al 2006
- disrupted globular clusters, or halo stars?
- remnants of the disc oscillation induced by the interaction with a **satellite galaxy**?
  Weinberg 1989, 1998, Gomez et al 2016, Laporte et al 2017, 2018



Weinberg 1989, Purcell et al 2011, Gomez et al 2013, 2016, Laporte et al 2017, 2018

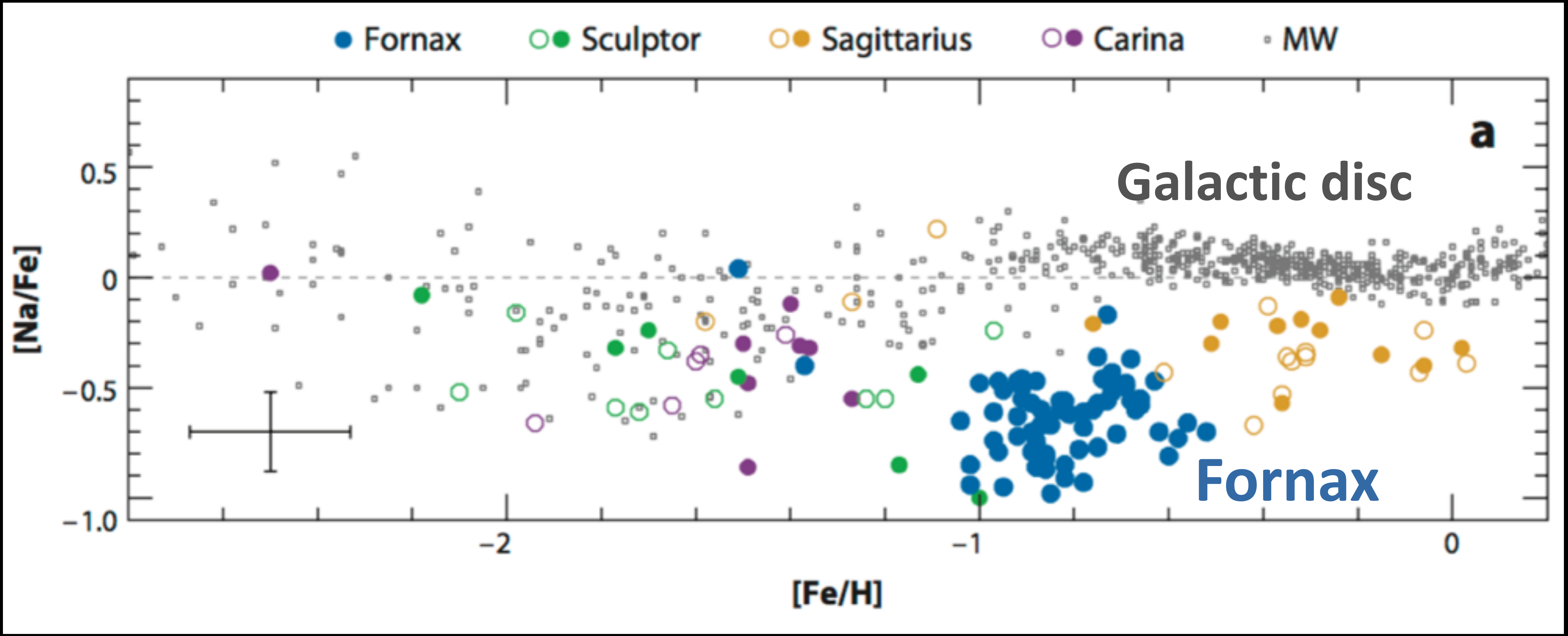
Sagittarius + Milky Way interaction



Laporte et al 2017, 2018

Chemical tagging?

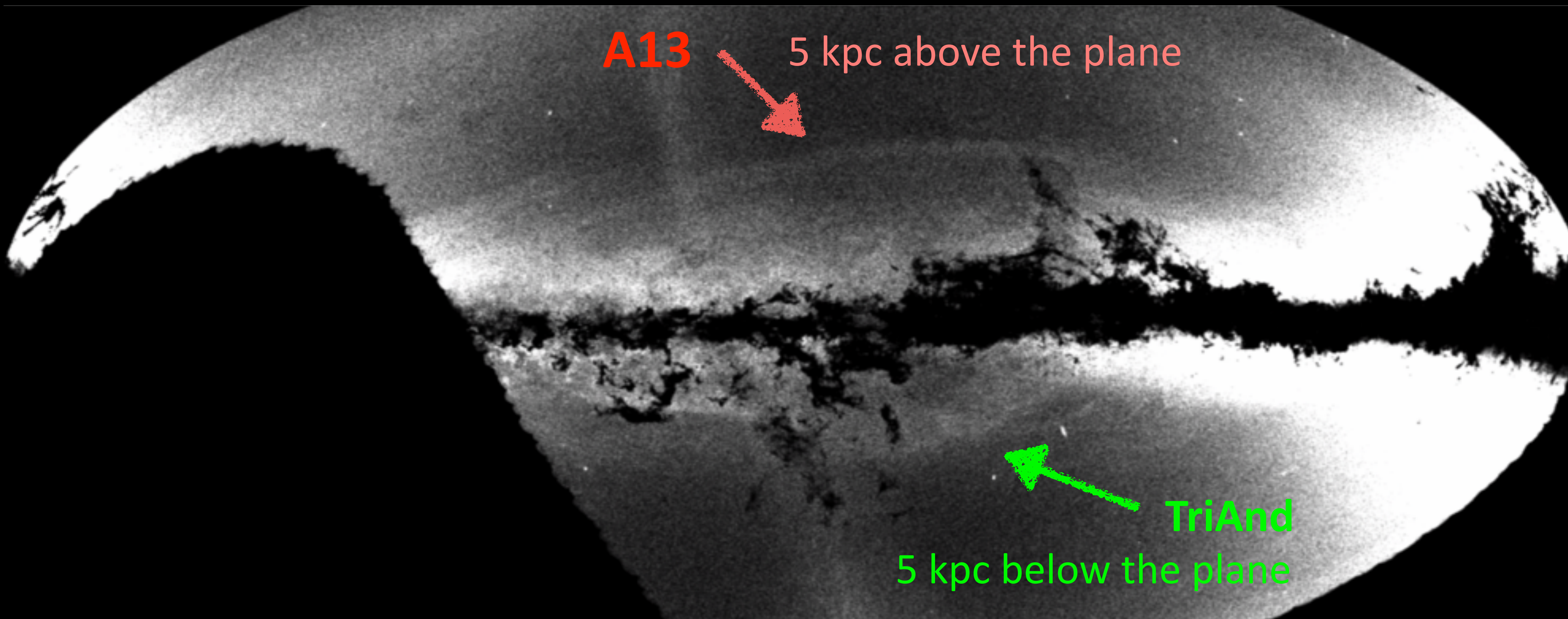
dwarf galaxies stand out in the chemical abundance space



Tolstoy, Hill, & Tosi (2009)

Testing astrophysical scenarios. III

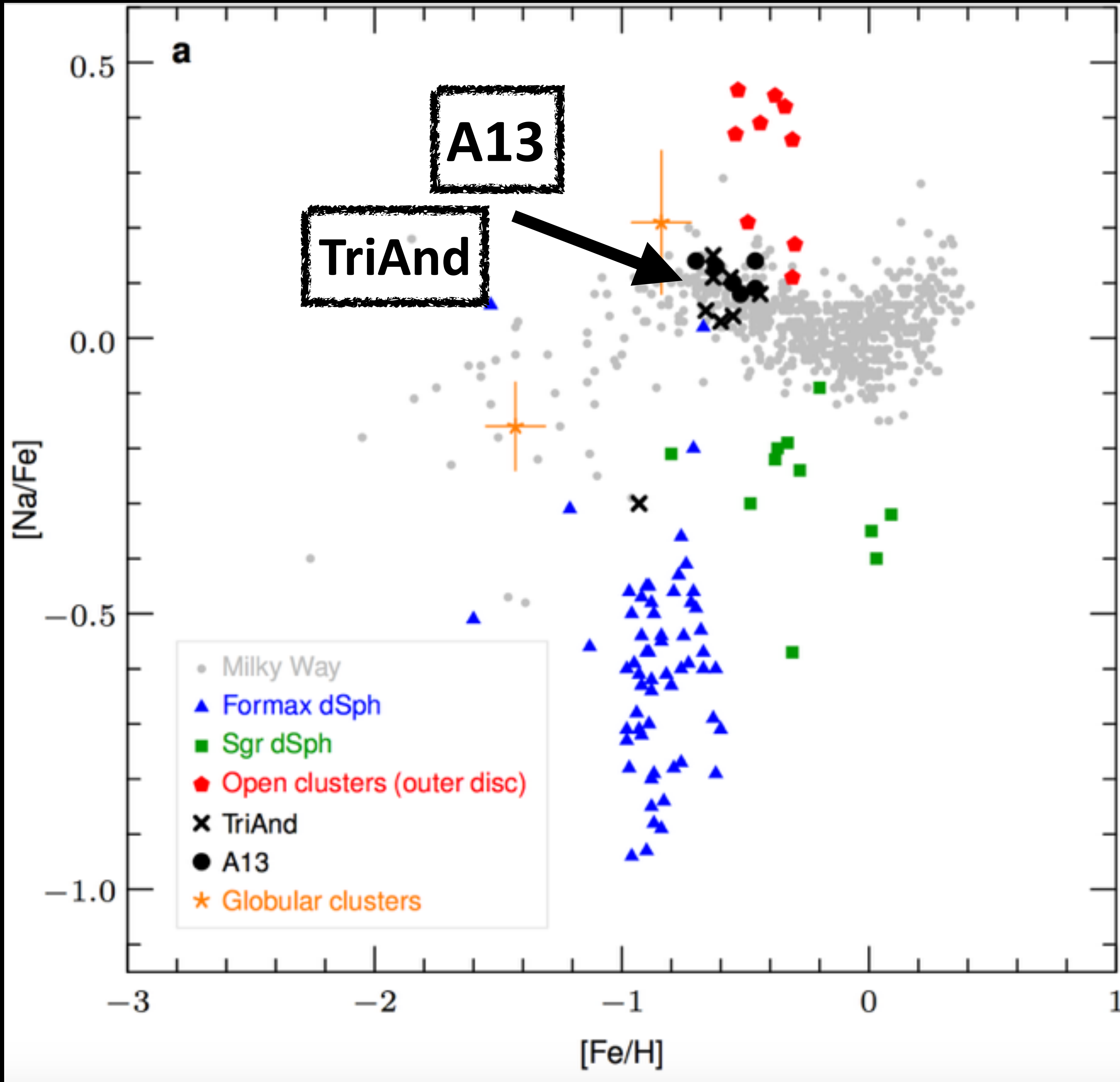
two prominent overdensities in the halo

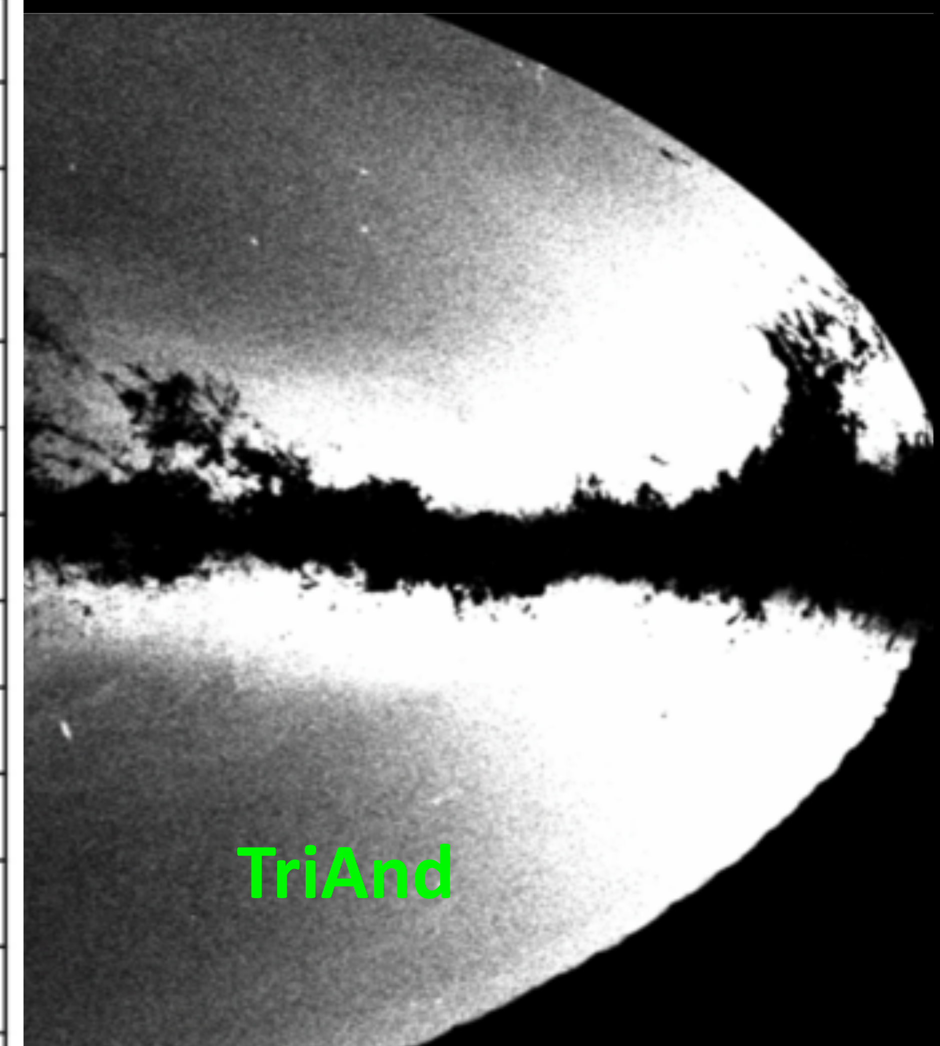


Sheffield et al., Slater et al. (2014)

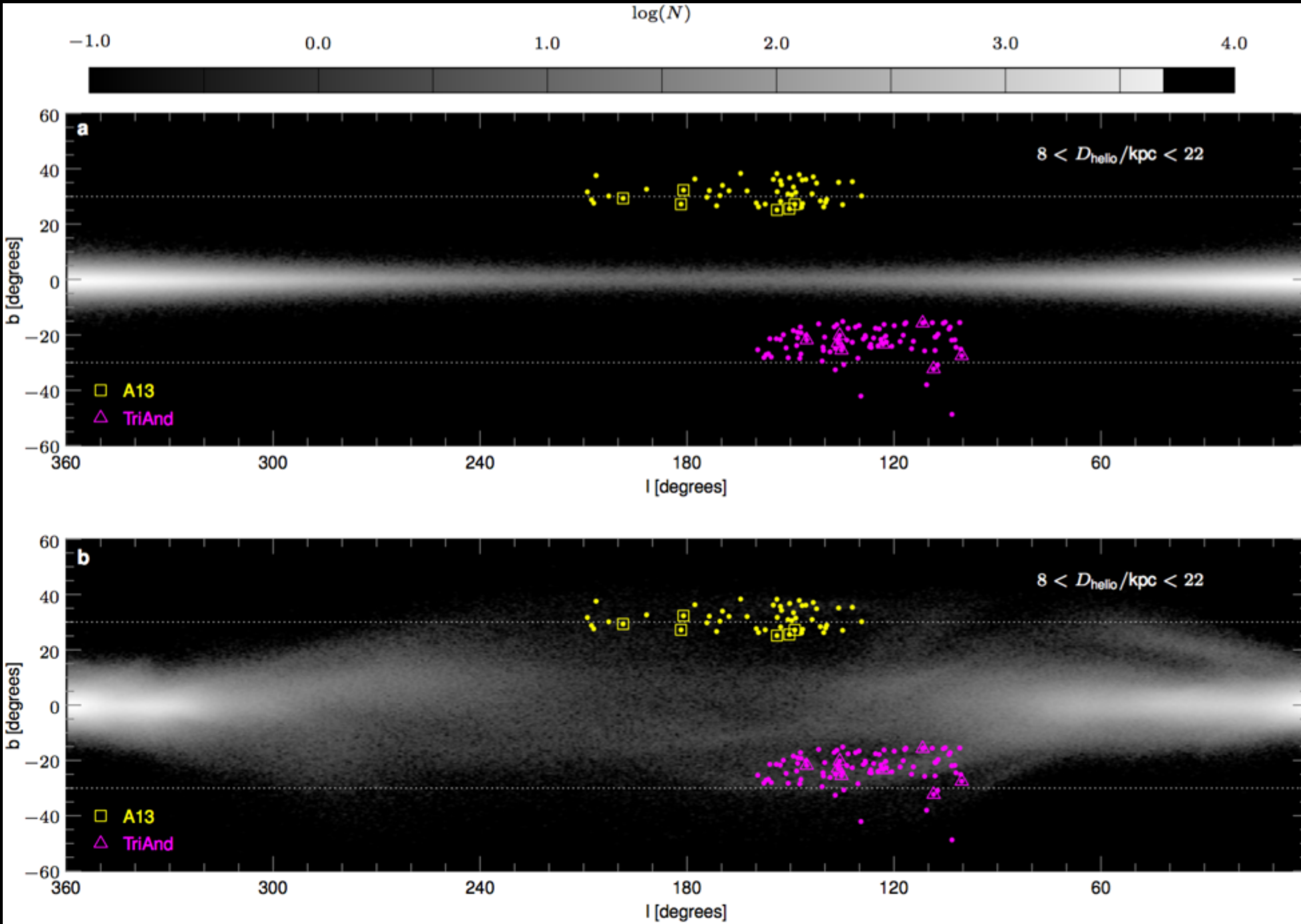
Testing astrophysical scenarios. III

two prominent overdensities in the halo





***Bergemann** et al. (2018, Nature)*



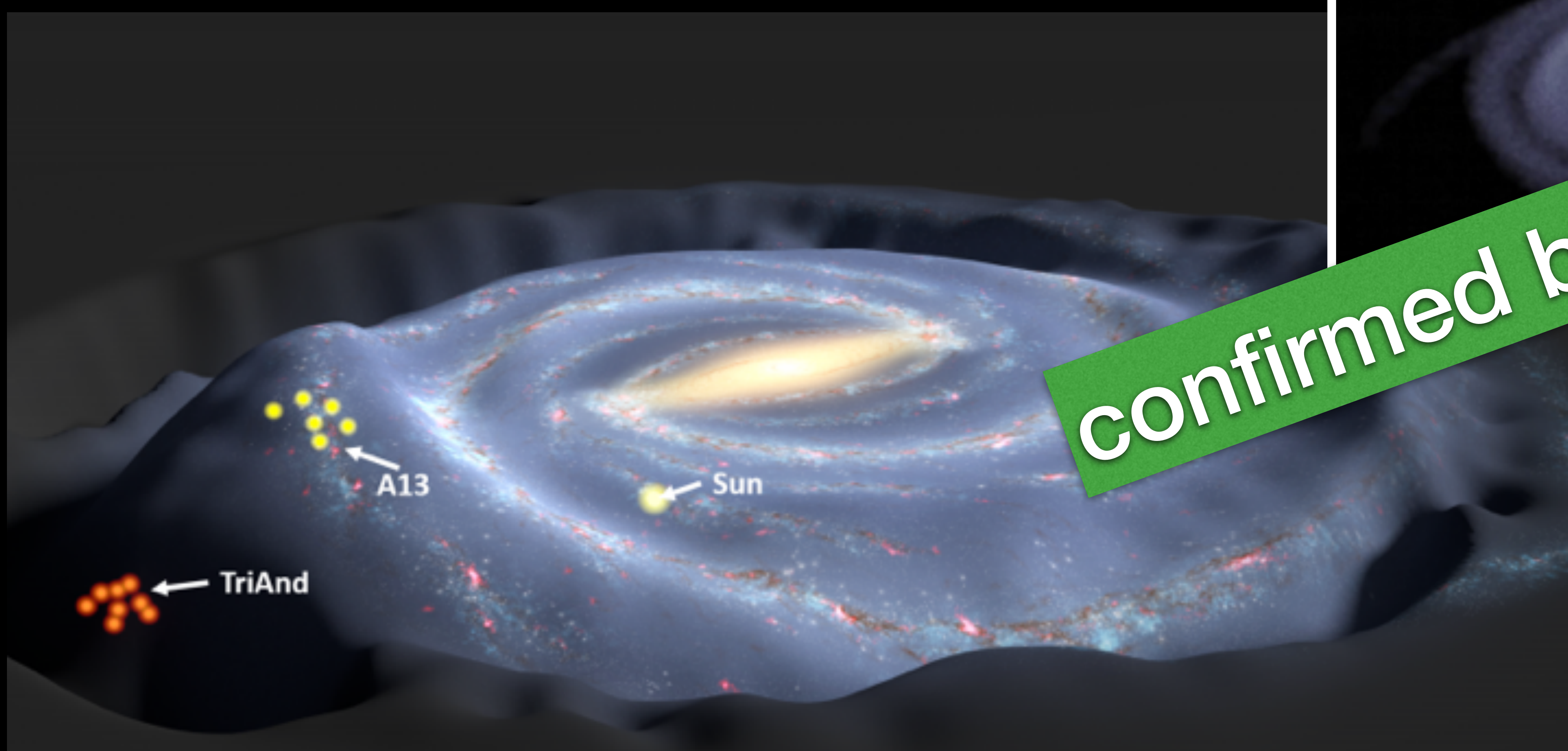
Bergemann et al. (2018, Nature)

Testing astrophysical scenarios. III

Dynamical history of the Galactic disk

- **Stellar abundances diagnose birth origin of stars**
- **The Milky Way disc is oscillating vertically**

Bergemann *et al. (2018, Nature)*



confirmed by Gaia!

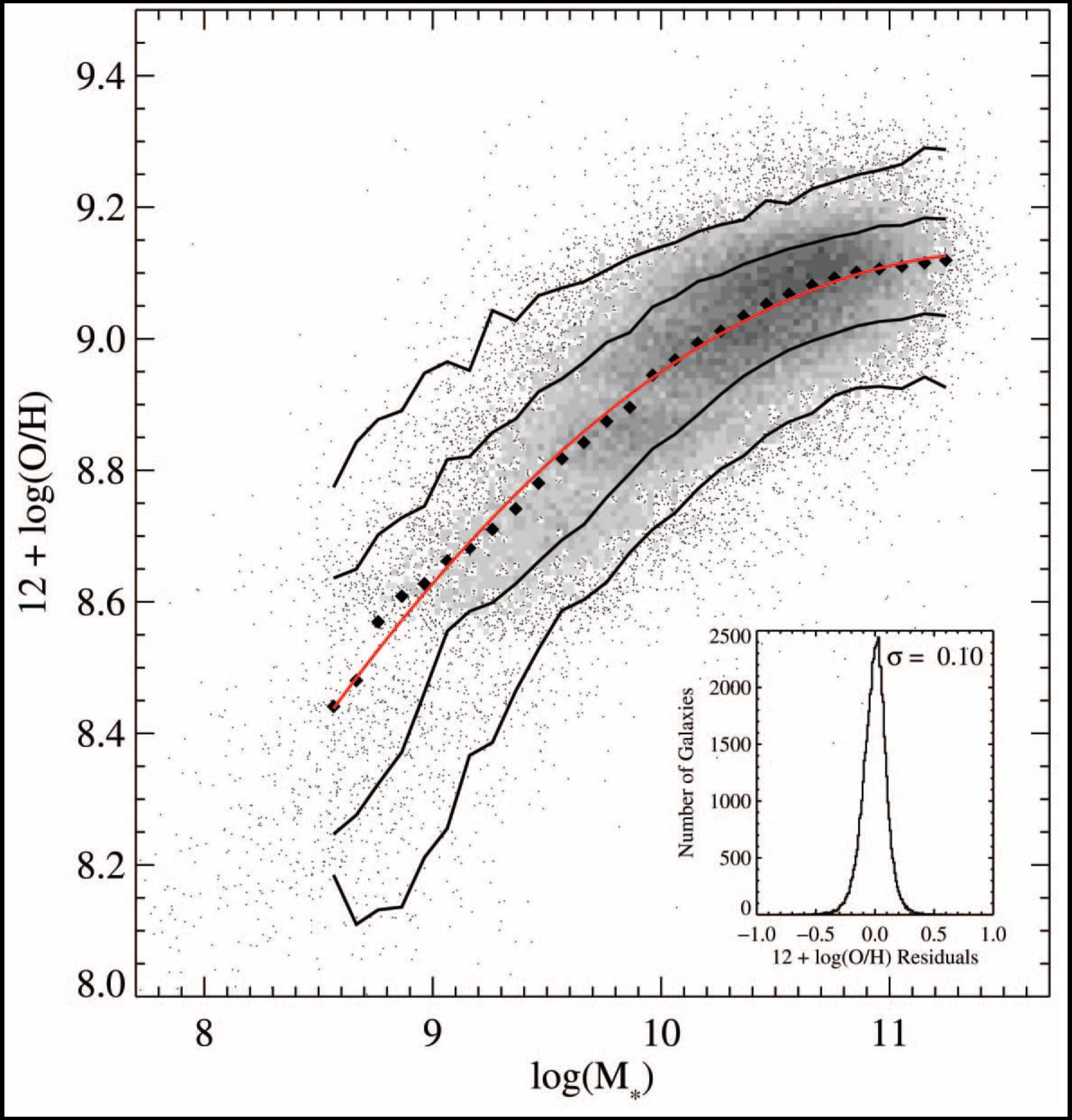
Antoja et al. (2018), Bland-Hawthorn et al. (2019), Fernandez-Alvar et al. (2019), …

Testing astrophysical scenarios. VI

Mass-metallicity relationship of galaxies

50,000
SDSS galaxies

O abundance from nebular emission lines (empoying calibrations)



Tremonti et al. 2004

Testing astrophysical scenarios. VI

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50,000
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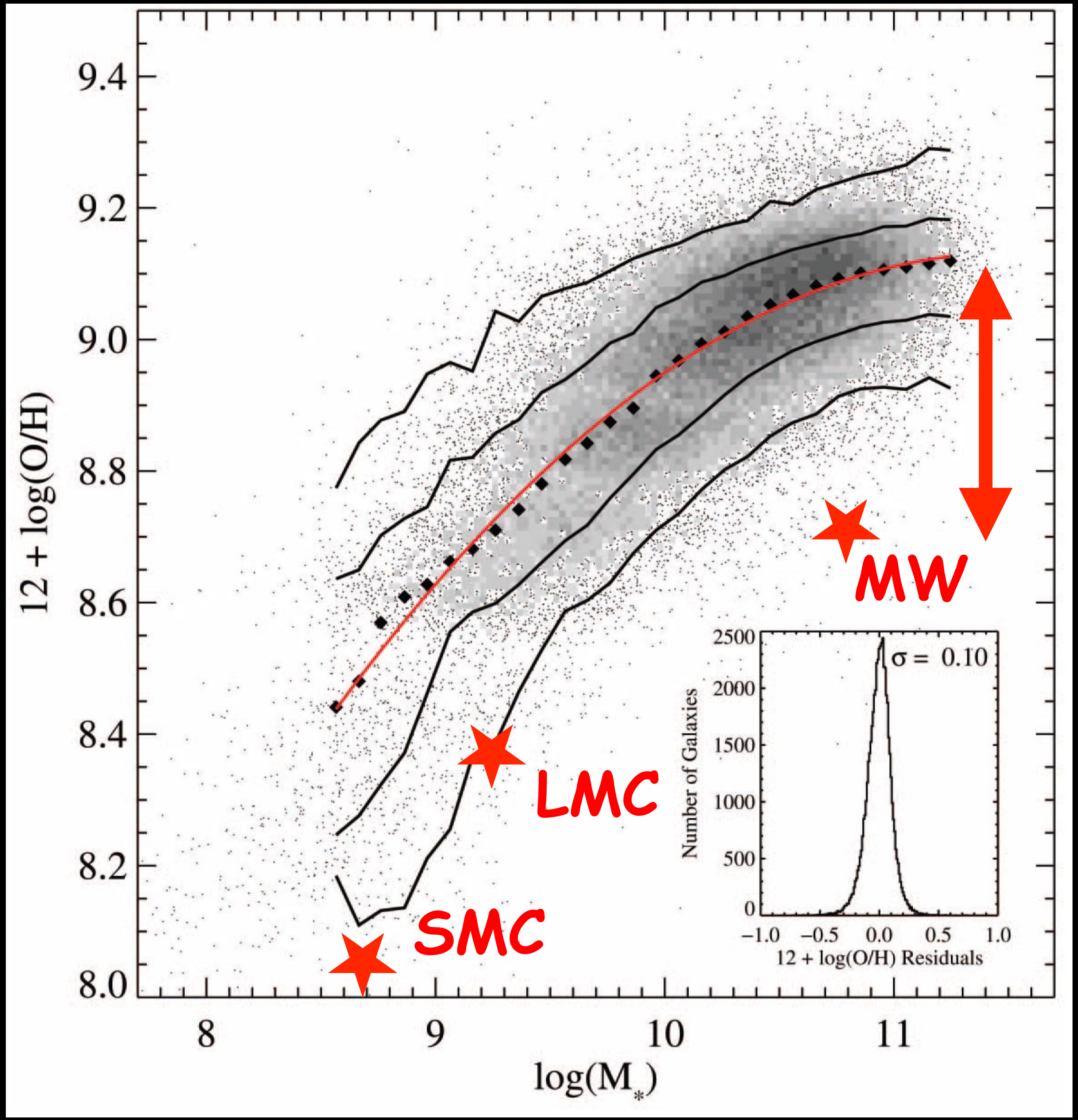
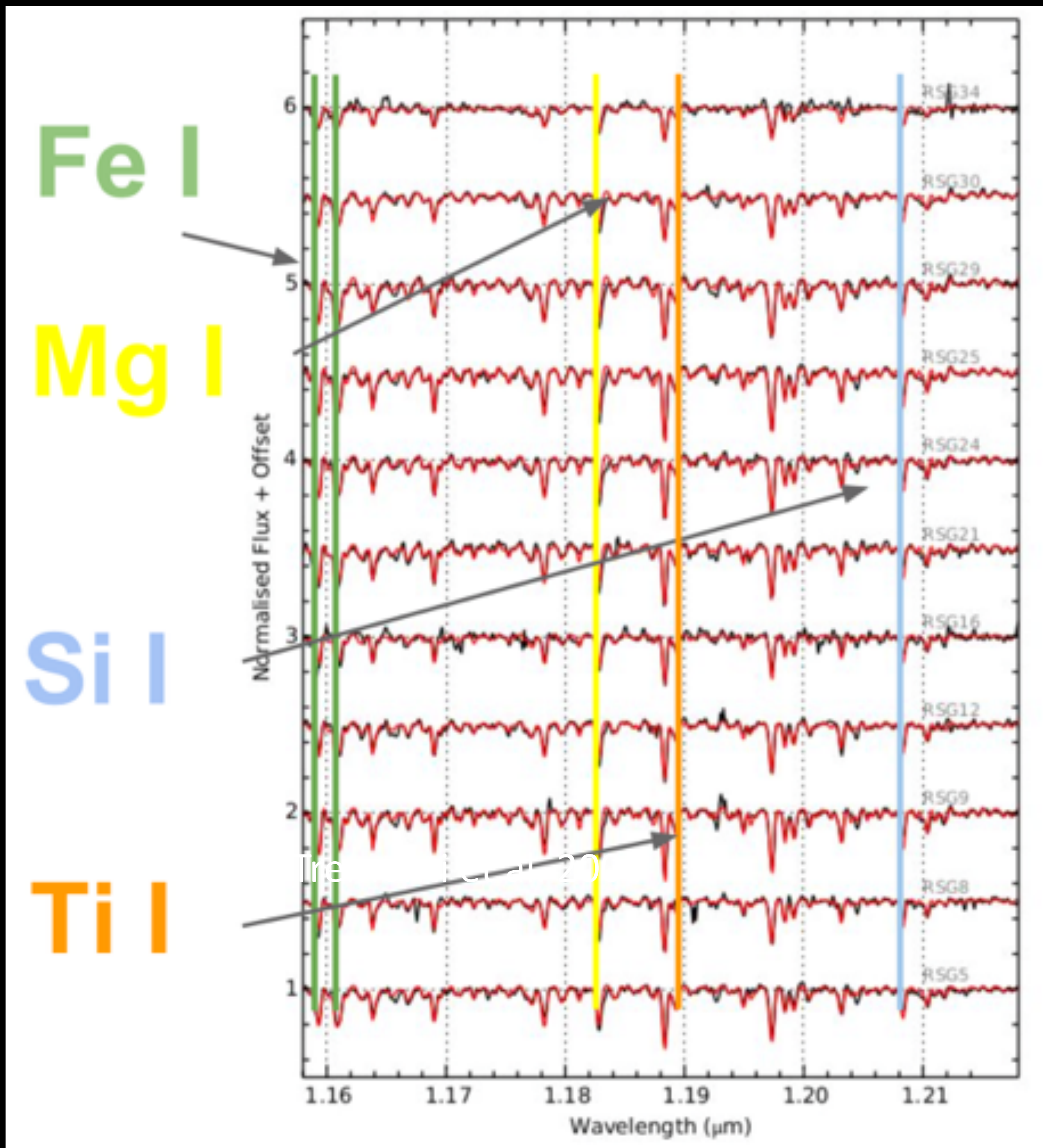


Milky Way data:
<u>direct</u>
abundances from stars

Tremonti et al. 2004

Stellar spectroscopy beyond the Milky Way

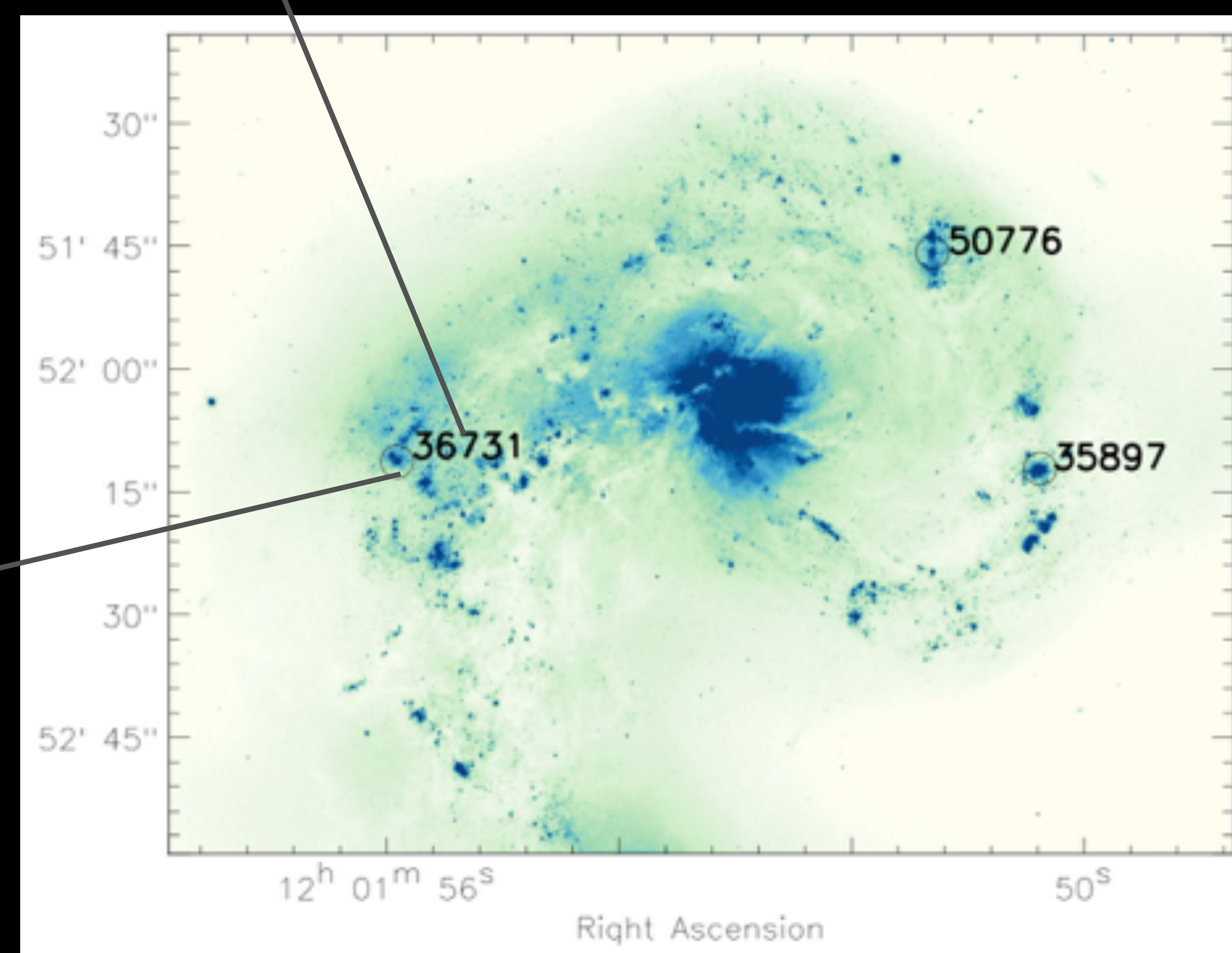


New models to allow quantitative stellar spectroscopy and abundances in galaxies

Bergemann et al. (2012,2013,2015)

Eitner, Bergemann, & Larsen (2019)

NGC 4038



Davies et al. (2011, 2015, 2017)

Lardo et al. (2015), Patrick et al. (2017)

IC 1613 proposal submitted

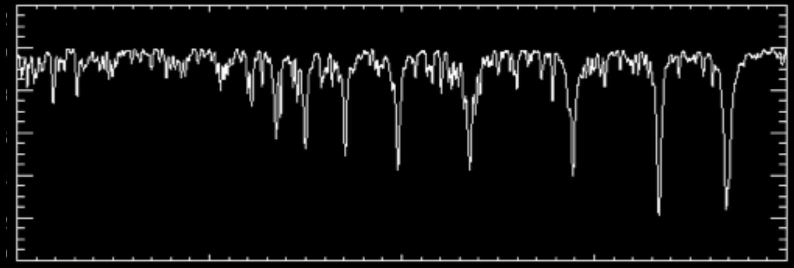
Summary

- **Discovery**

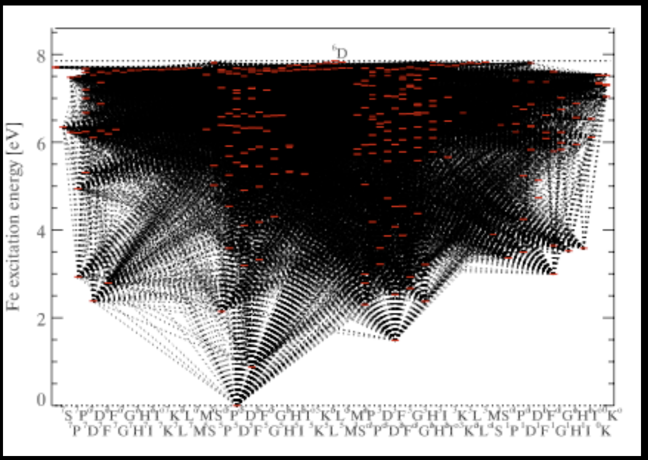
  - large telescopes and million star surveys
  - over next 20 years (Gaia, 4MOST, …ELT)

- **Characterisation**

  - rigorous machinery in place (**NLTE, 3D**)
  - physical diagnostics: elemental abundances, masses, ages

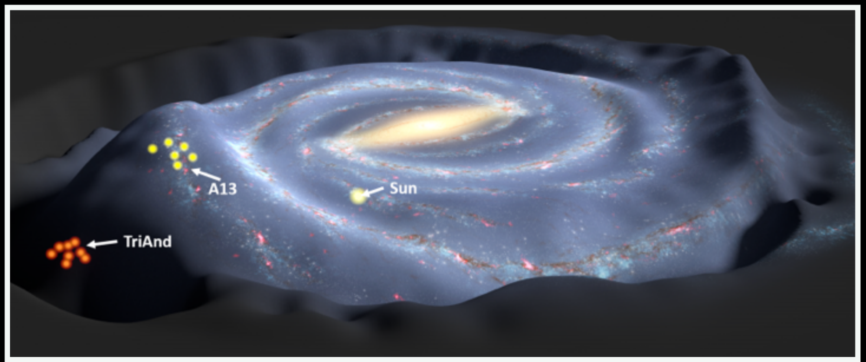


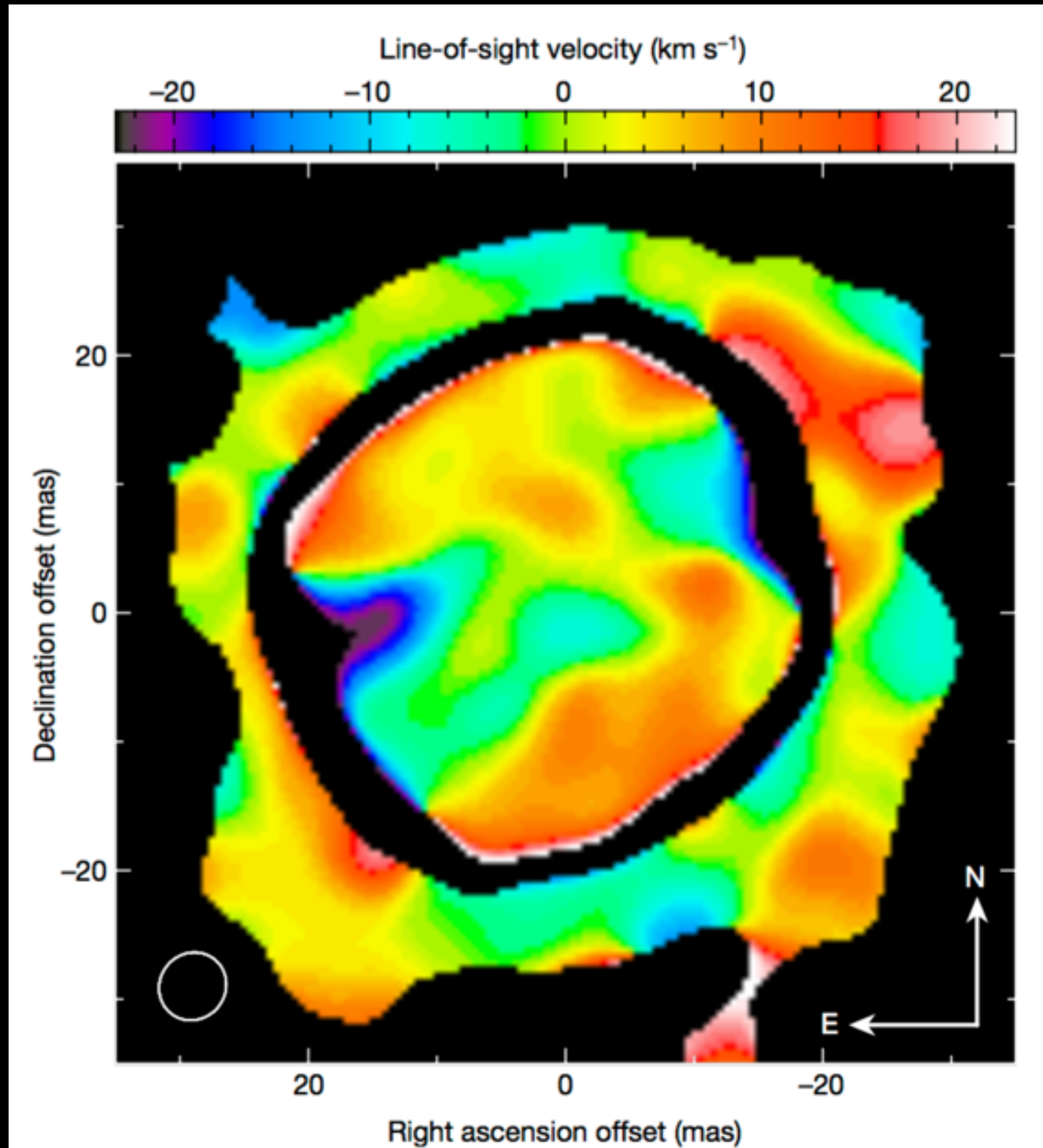
nlte.mpia.de



- **Beyond**

  - cosmic nucleosynthesis
  - stellar populations, Milky Way formation history
  - metallicity distributions of galaxies based on stars: **pathfinder** to first large extra-galactic surveys for resolved stars: JWST, E-ELT





Line-of-sight velocity (km s^{-1})
−20
−10
0
10
20
Declination offset (mas)
20
0
−20
Right ascension offset (mas)
20
0
−20
N
E

UV to infra-red spectra of stars, model