# Revisiting the *r*-process signatures with 3D (non-)LTE stellar spectroscopy

Mila Racca

Supervisors: Dr. Karin Lind

Nuclear Physics in Astrophysics XII
7-11 September 2026, Cluj-Napoca

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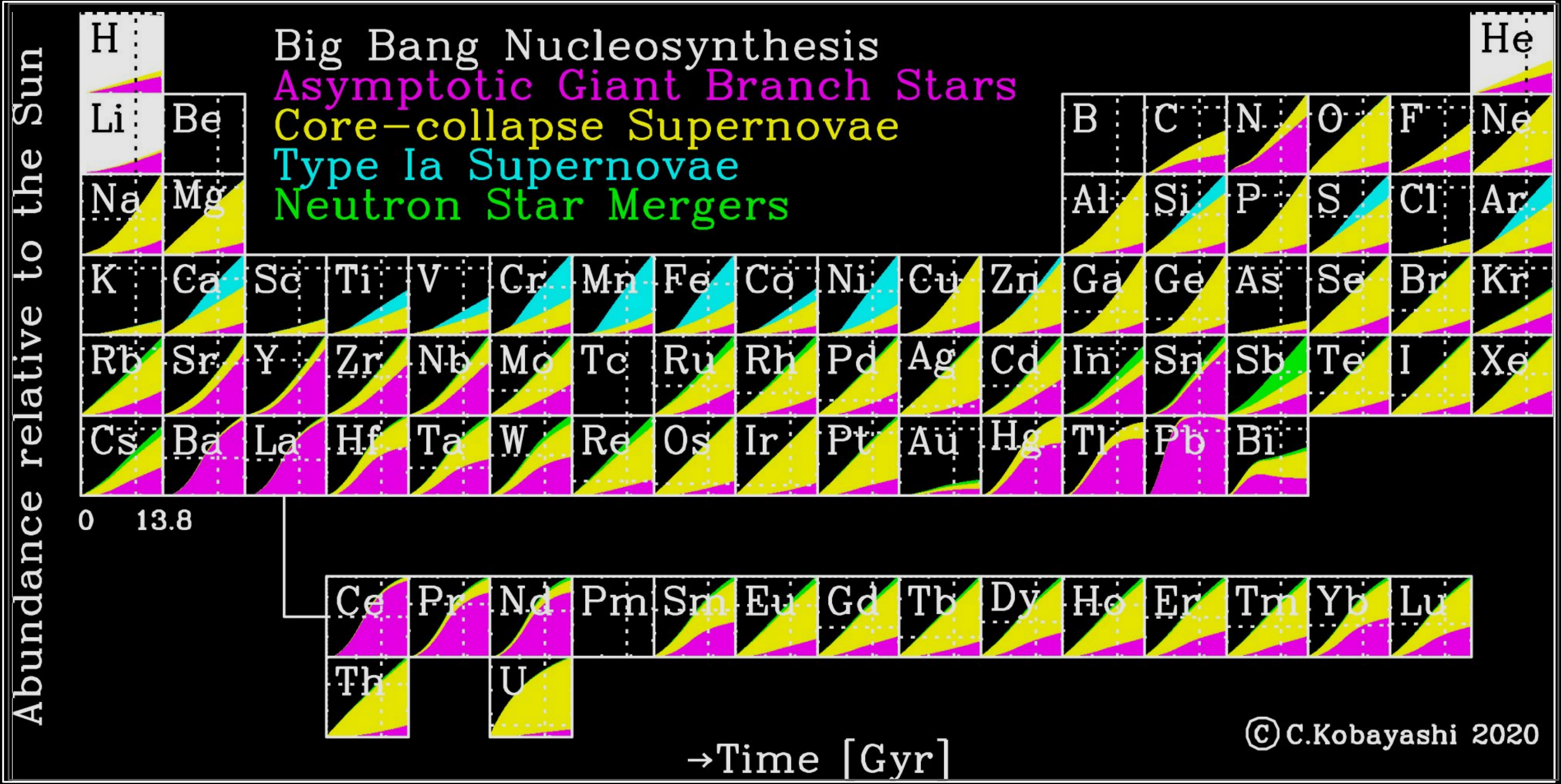
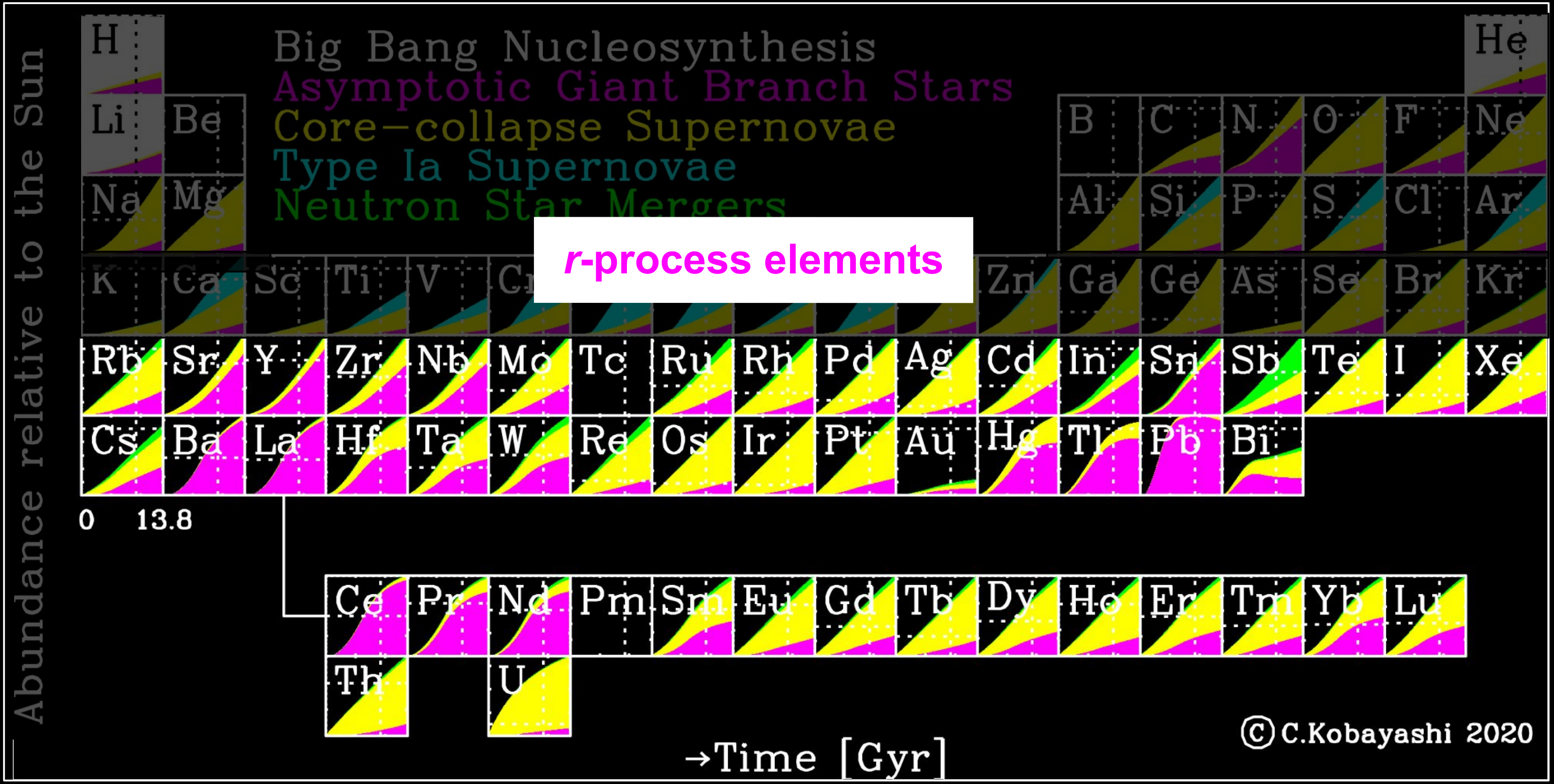
Stockholms universitet

# How are the elements of the Solar System created in the Universe?



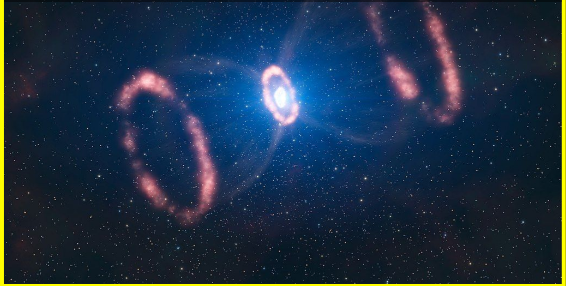
# How are the elements of the Solar System created in the Universe?



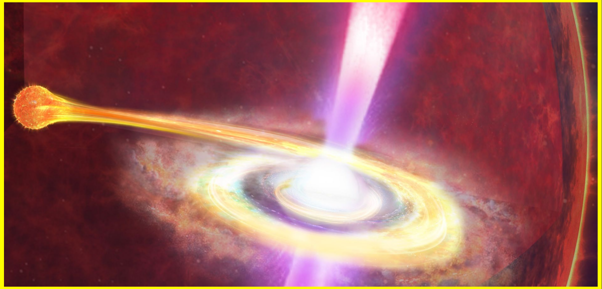
# *r*-process elements sites

Magneto-rotational supernovae (MR-SNe)

CCSN and neutrino-driven winds from proto-neutron stars



Compact binary mergers



Common-envelope jets supernovae (CEJSNe)

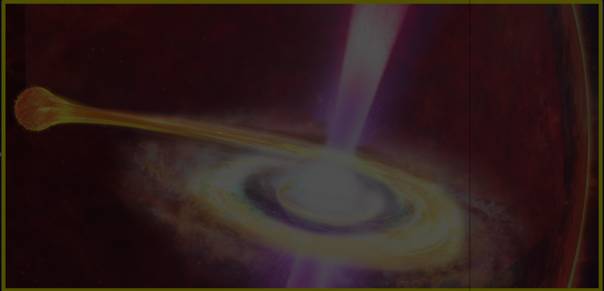
Magnetar flares

# *r*-process elements sites

Magneto-rotational supernovae (MR-SNe)

Compact binary mergers

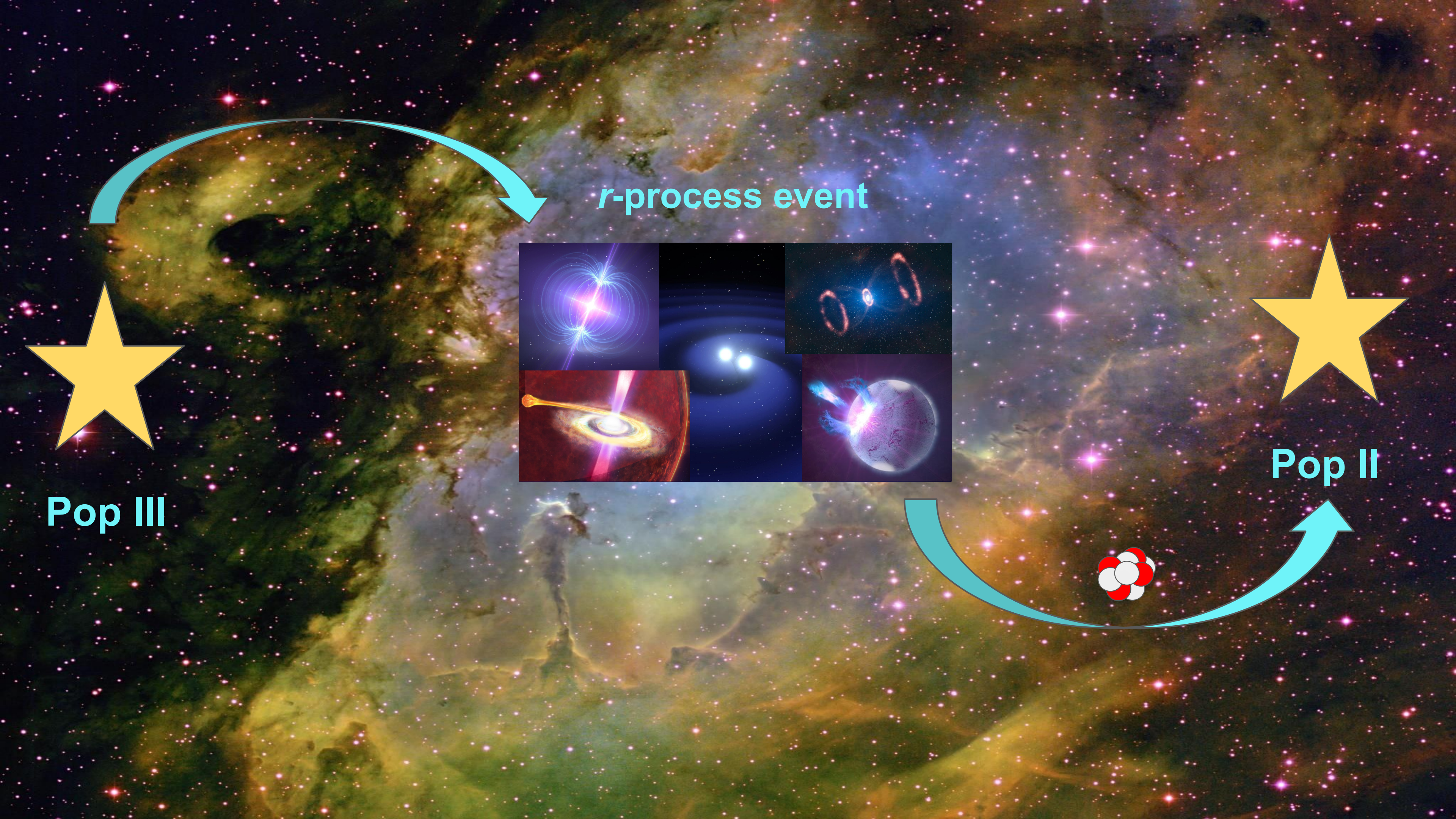
CCSN and neutrino-driven winds from proto-neutron stars

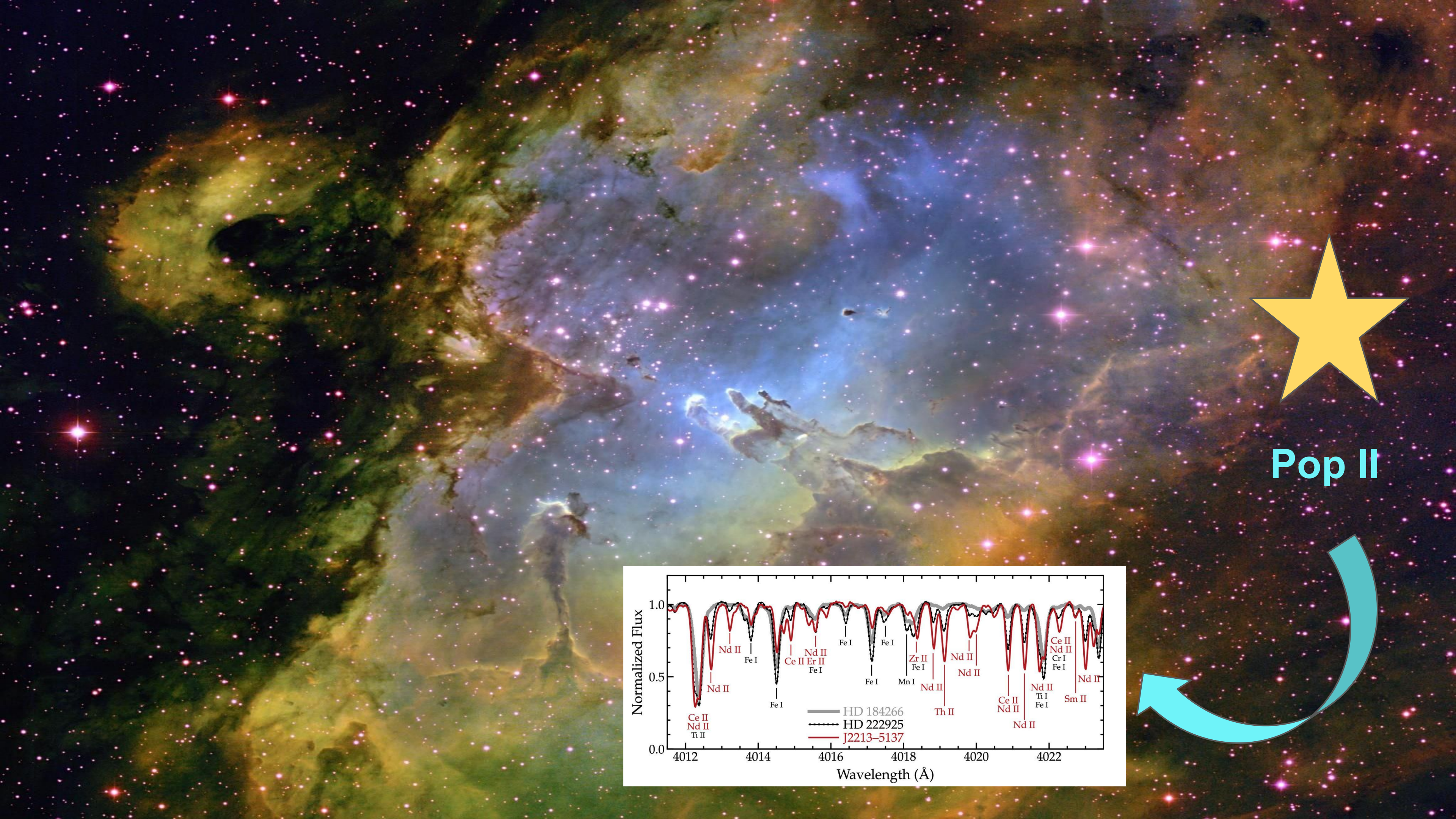


Common-envelope jets supernovae (CEJSNe)

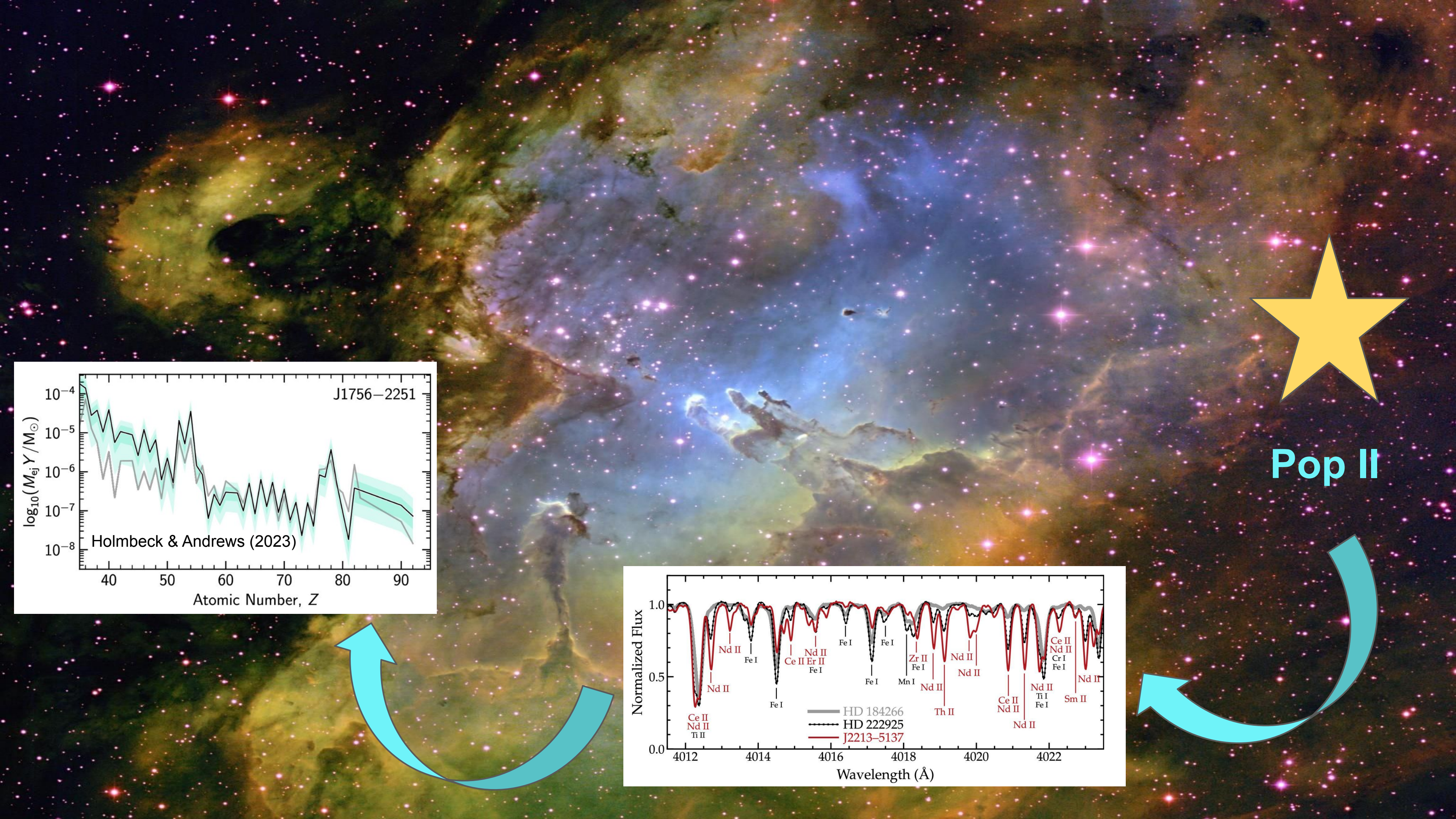
Magnetar flares

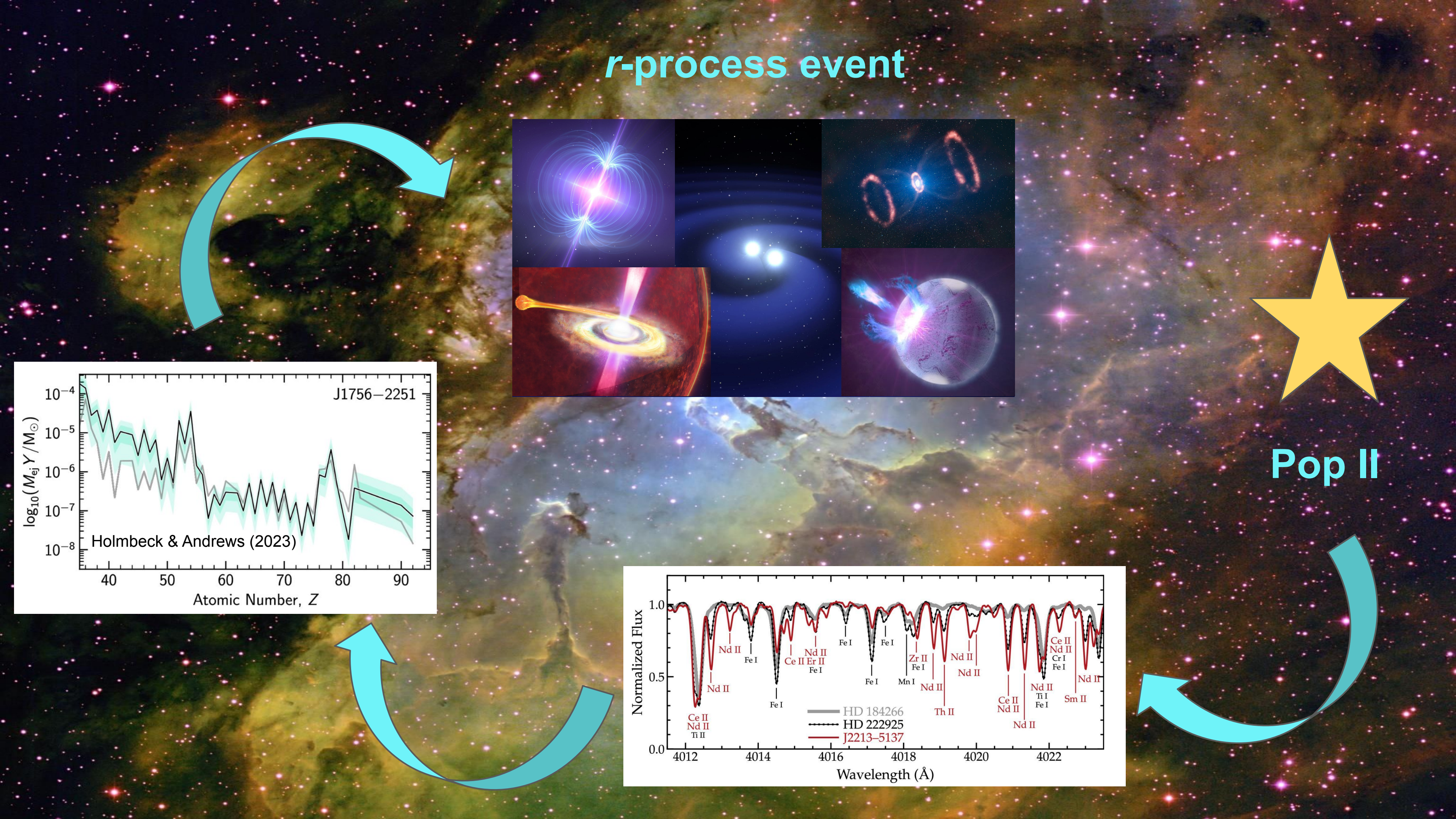
Look at the old metal-poor STARS!

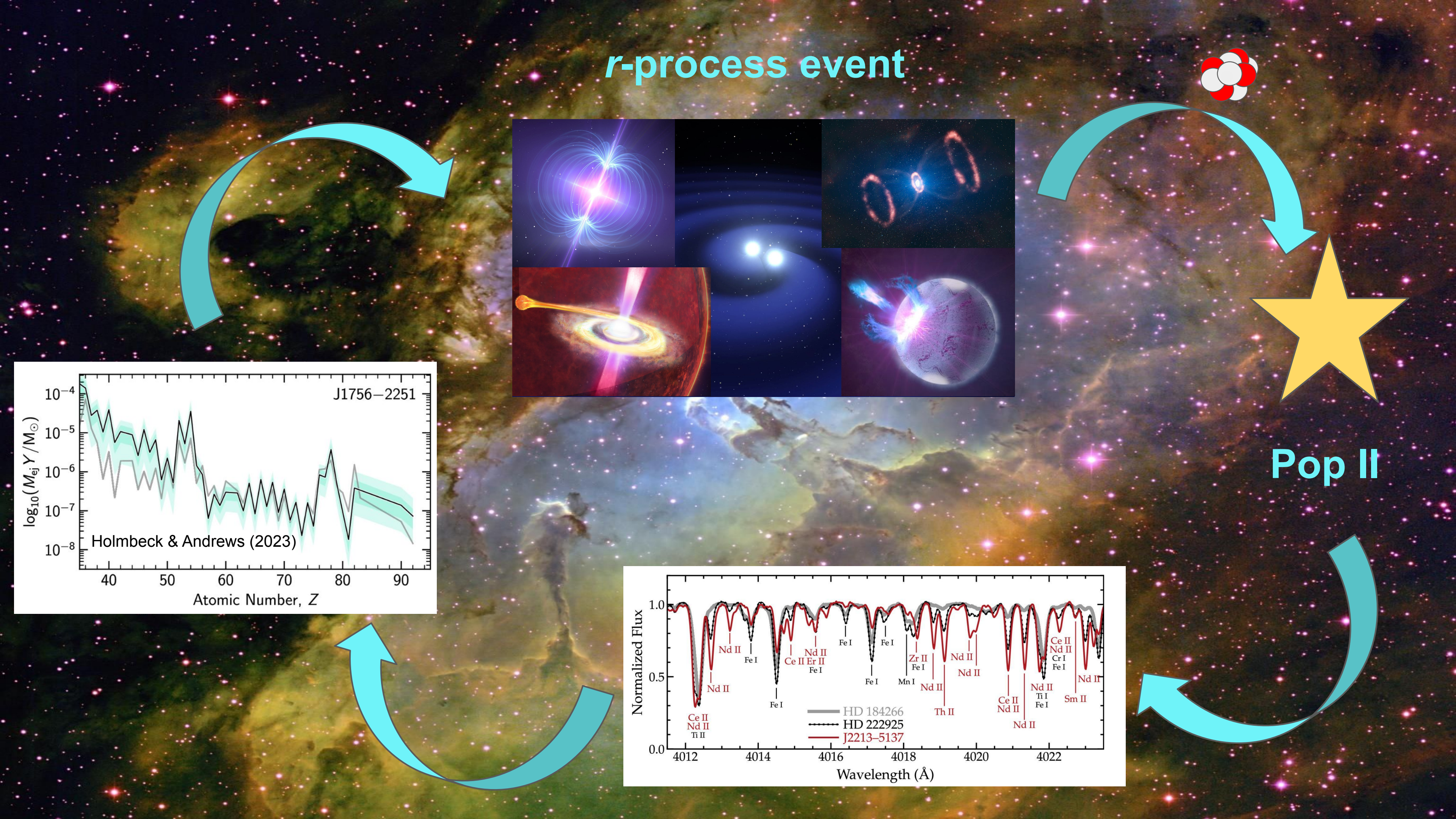

*r*-process event
Pop III
Pop II



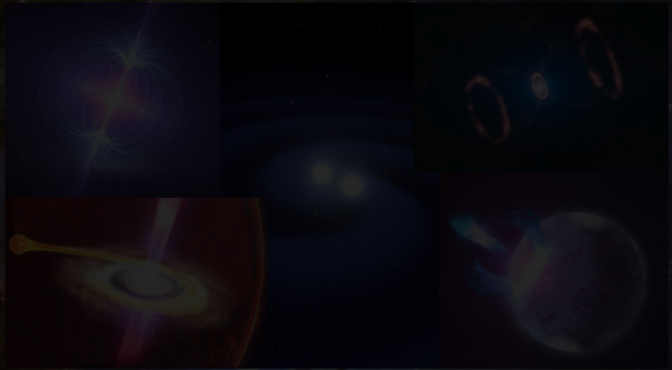
Pop II
Normalized Flux
Wavelength (Å)
1.0
0.5
0.0
4012
4014
4016
4018
4020
4022
HD 184266
HD 222925
J2213–5137
Ce II
Nd II
Ti II
Nd II
Nd II
Fe I
Fe I
Ce II Er II
Nd II
Fe I
Fe I
Fe I
Fe I
Fe I
Mn I
Zr II
Fe I
Nd II
Th II
Nd II
Nd II
Ce II
Nd II
Nd II
Nd II
Ti I
Fe I
Ce II
Nd II
Cr I
Fe I
Sm II
Nd II


J1756−2251
Holmbeck & Andrews (2023)
log10(Mej Y/M⊙)
Atomic Number, Z
Pop II
Normalized Flux
Wavelength (Å)
HD 184266
HD 222925
J2213−5137
Ce II
Nd II
Ti II
Fe I
Er II
Mn I
Zr II
Th II
Cr I
Sm II

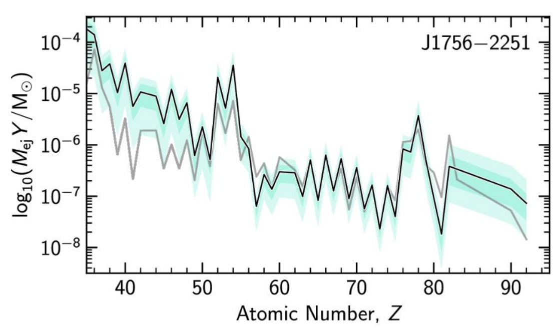

r-process event
Pop II
J1756−2251
Holmbeck & Andrews (2023)
$\log_{10}(M_{ej} Y / M_\odot)$
Atomic Number, $Z$
Normalized Flux
Wavelength (Å)
HD 184266
HD 222925
J2213–5137
Ce II
Nd II
Ti II
Fe I
Er II
Zr II
Mn I
Th II
Cr I
Sm II

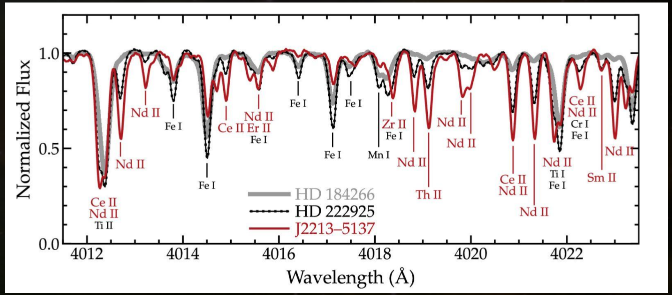

r-process event
Pop II
J1756−2251
Holmbeck & Andrews (2023)
log10(M_ej Y / M_⊙)
10^−4
10^−5
10^−6
10^−7
10^−8
40
50
60
70
80
90
Atomic Number, Z
Normalized Flux
1.0
0.5
0.0
Wavelength (Å)
4012
4014
4016
4018
4020
4022
HD 184266
HD 222925
J2213–5137
Ce II
Nd II
Ti II
Nd II
Nd II
Fe I
Fe I
Ce II
Nd II
Er II
Fe I
Fe I
Fe I
Fe I
Mn I
Zr II
Fe I
Nd II
Th II
Nd II
Nd II
Ce II
Nd II
Nd II
Nd II
Ti I
Fe I
Ce II
Nd II
Cr I
Fe I
Sm II
Nd II

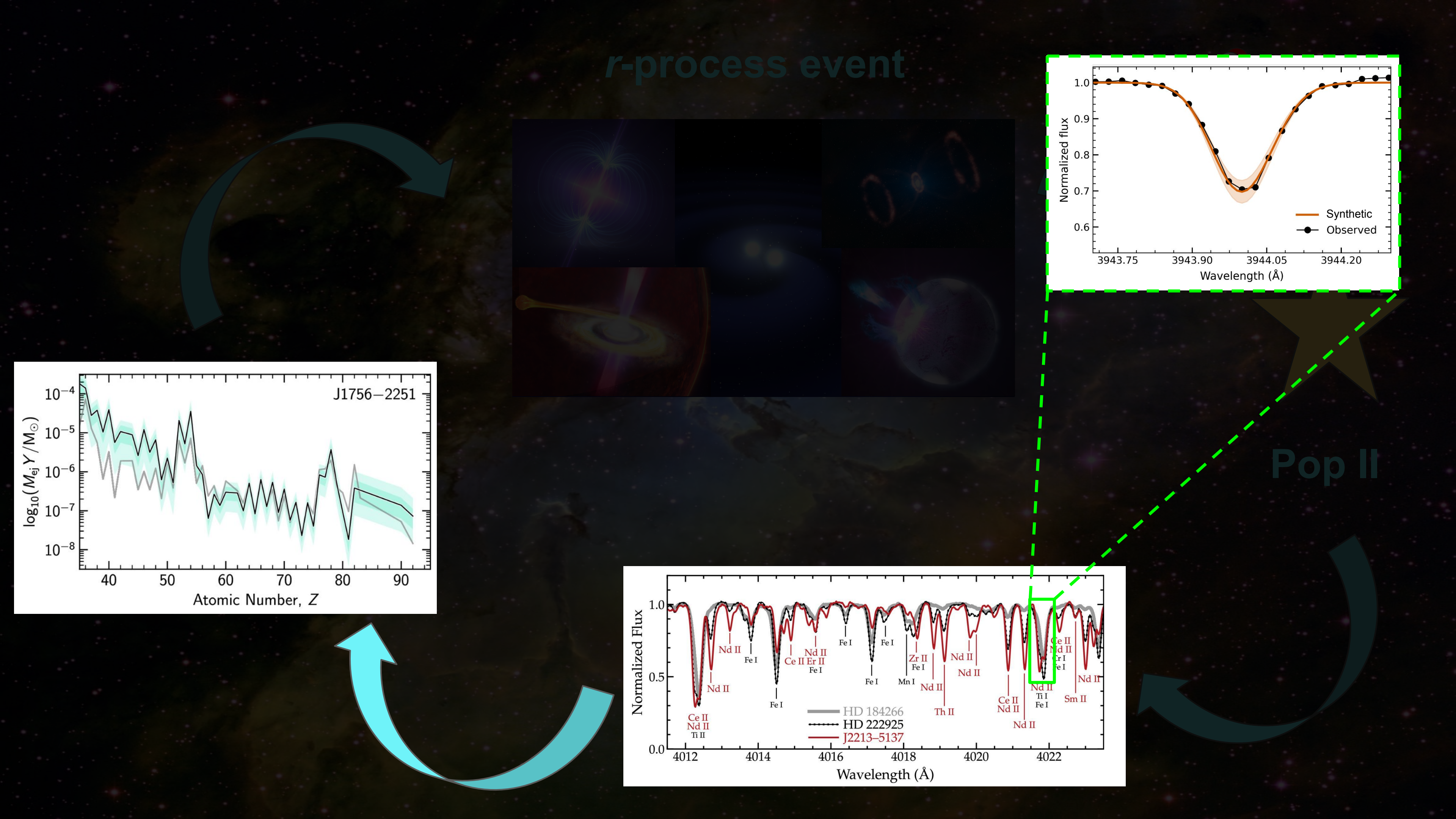
# *r*-process event

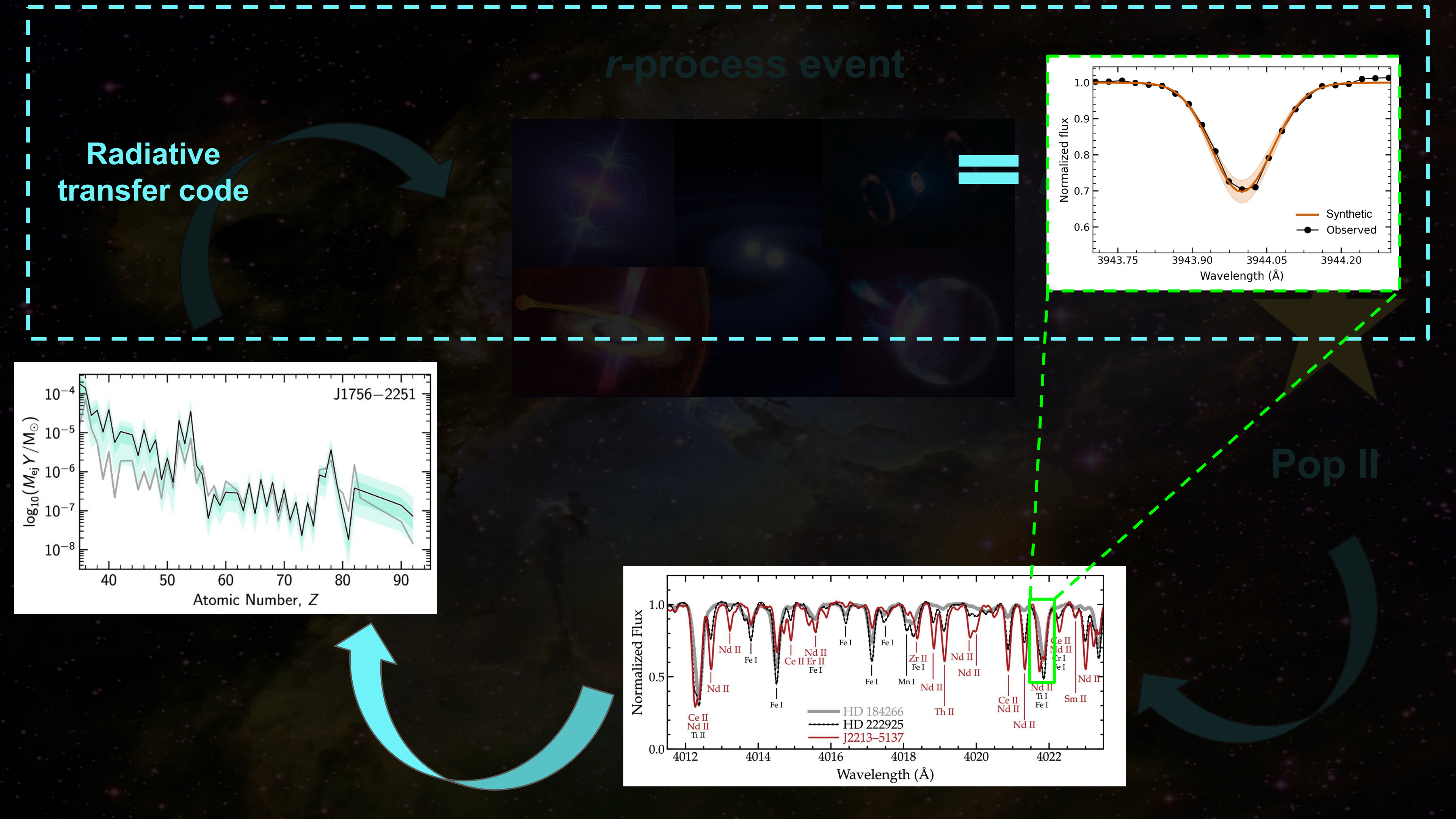


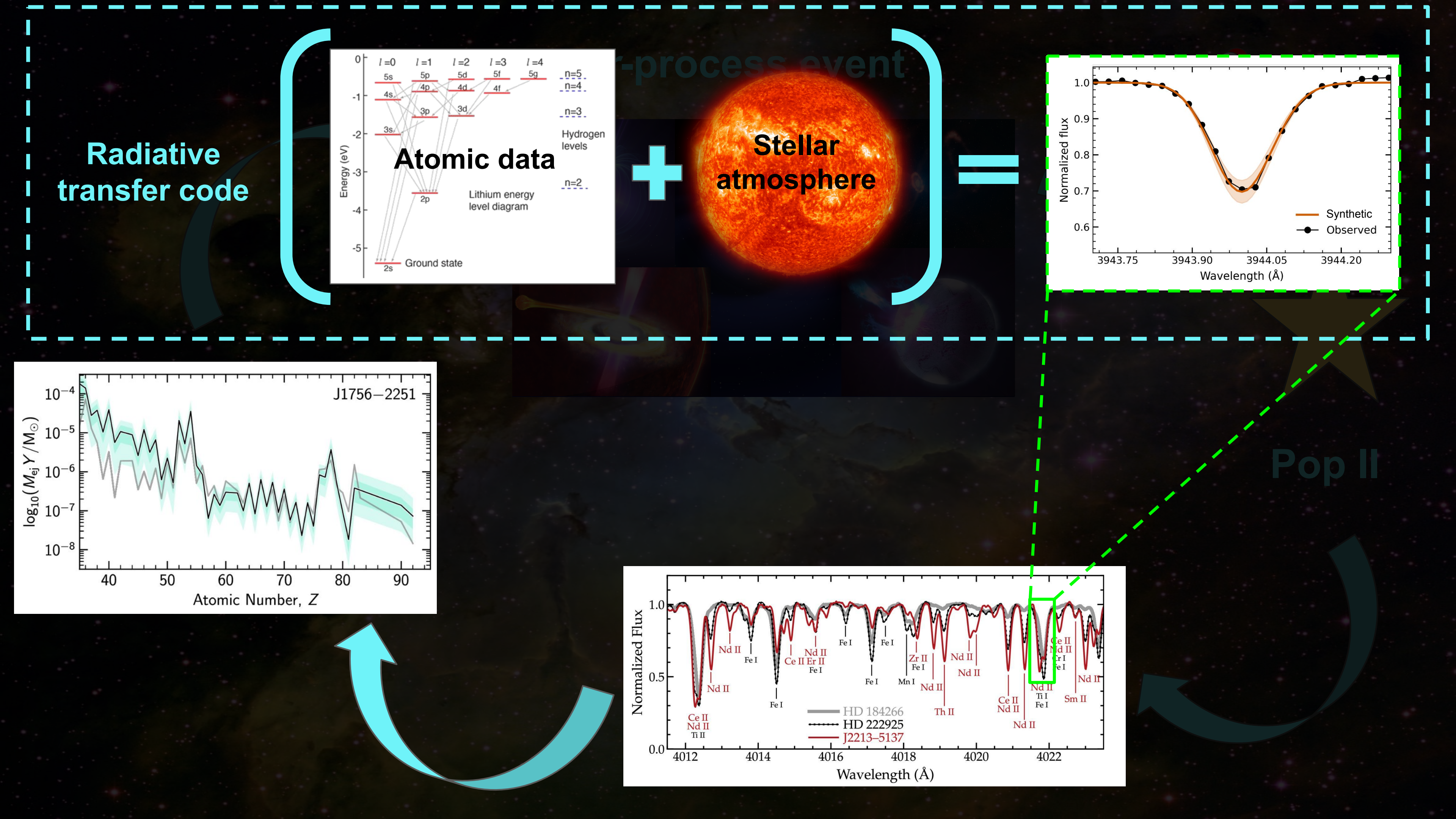
Pop II



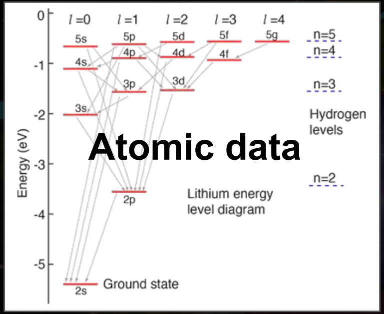




r-process event
Pop II
Normalized flux
Wavelength (Å)
3943.75
3943.90
3944.05
3944.20
Synthetic
Observed
J1756−2251
$\log_{10}(M_{ej} Y / M_\odot)$
Atomic Number, Z
Normalized Flux
HD 184266
HD 222925
J2213–5137
Ce II
Nd II
Ti II
Fe I
Er II
Zr II
Mn I
Th II
Cr I
Ti I
Sm II


r-process event
Radiative transfer code
Pop II
Normalized flux
Synthetic
Observed
Wavelength (Å)
J1756−2251
$\log_{10}(M_{ej} Y / M_\odot)$
Atomic Number, Z
Normalized Flux
HD 184266
HD 222925
J2213–5137
Wavelength (Å)

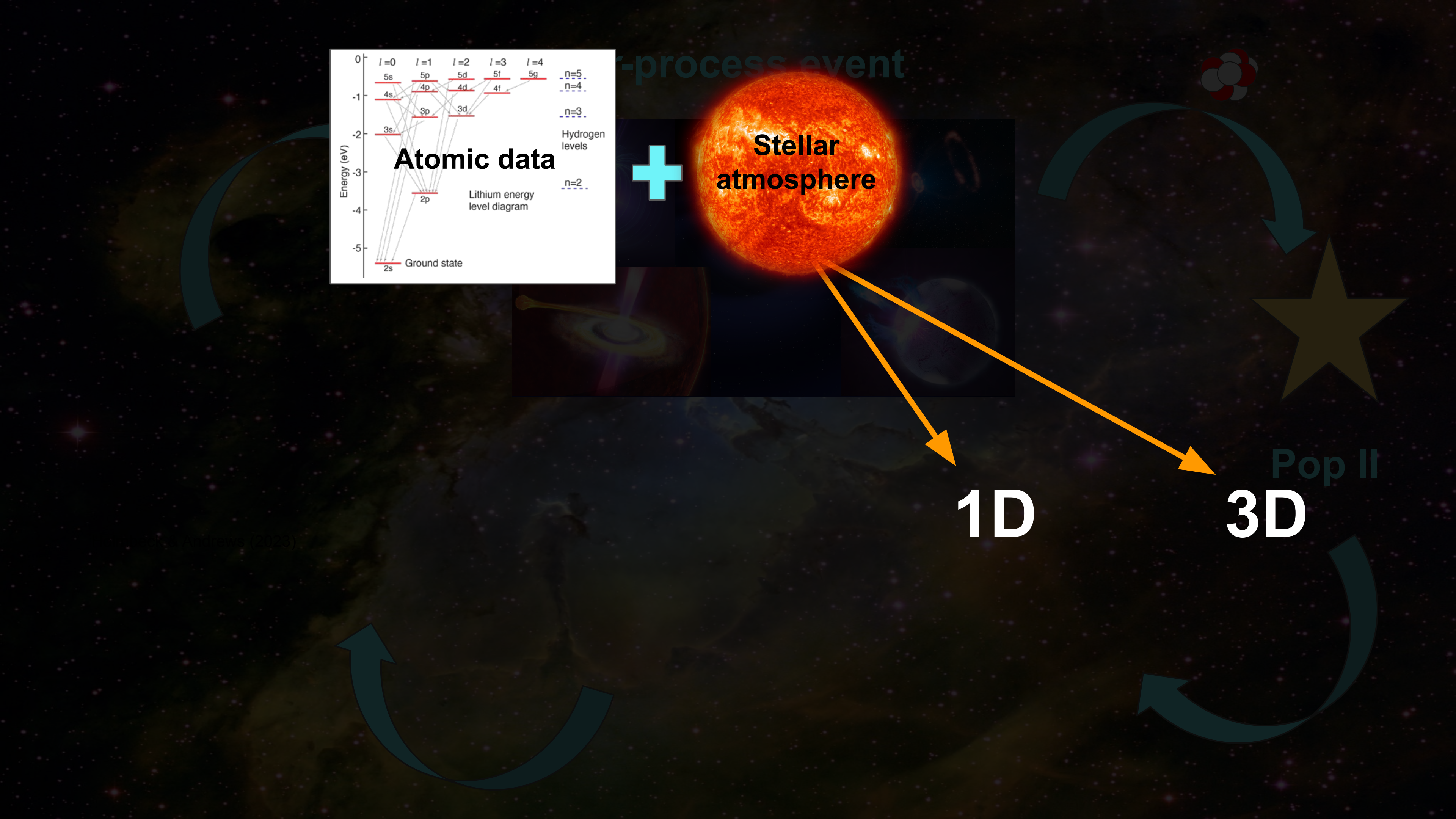

Radiative transfer code
Atomic data
Lithium energy level diagram
Energy (eV)
Hydrogen levels
Ground state
n=5
n=4
n=3
n=2
5s 4s 3s 2s
5p 4p 3p 2p
5d 4d 3d
5f 4f
5g
Stellar atmosphere
Normalized flux
Wavelength (Å)
Synthetic
Observed
J1756−2251
Atomic Number, Z
HD 184266
HD 222925
J2213−5137
Normalized Flux
Wavelength (Å)
Pop II

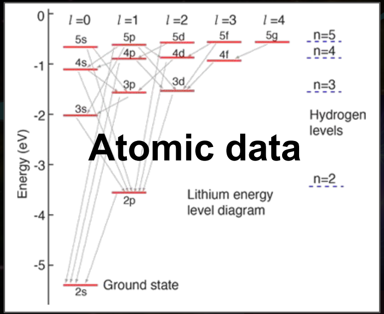
r-process event




+


Pop II


Atomic data
Energy (eV)
0
-1
-2
-3
-4
-5
l =0
l =1
l =2
l =3
l =4
5s
4s
3s
2s
5p
4p
3p
2p
5d
4d
3d
5f
4f
5g
n=5
n=4
n=3
n=2
Hydrogen levels
Lithium energy level diagram
Ground state
Stellar atmosphere
Pop II
1D
3D

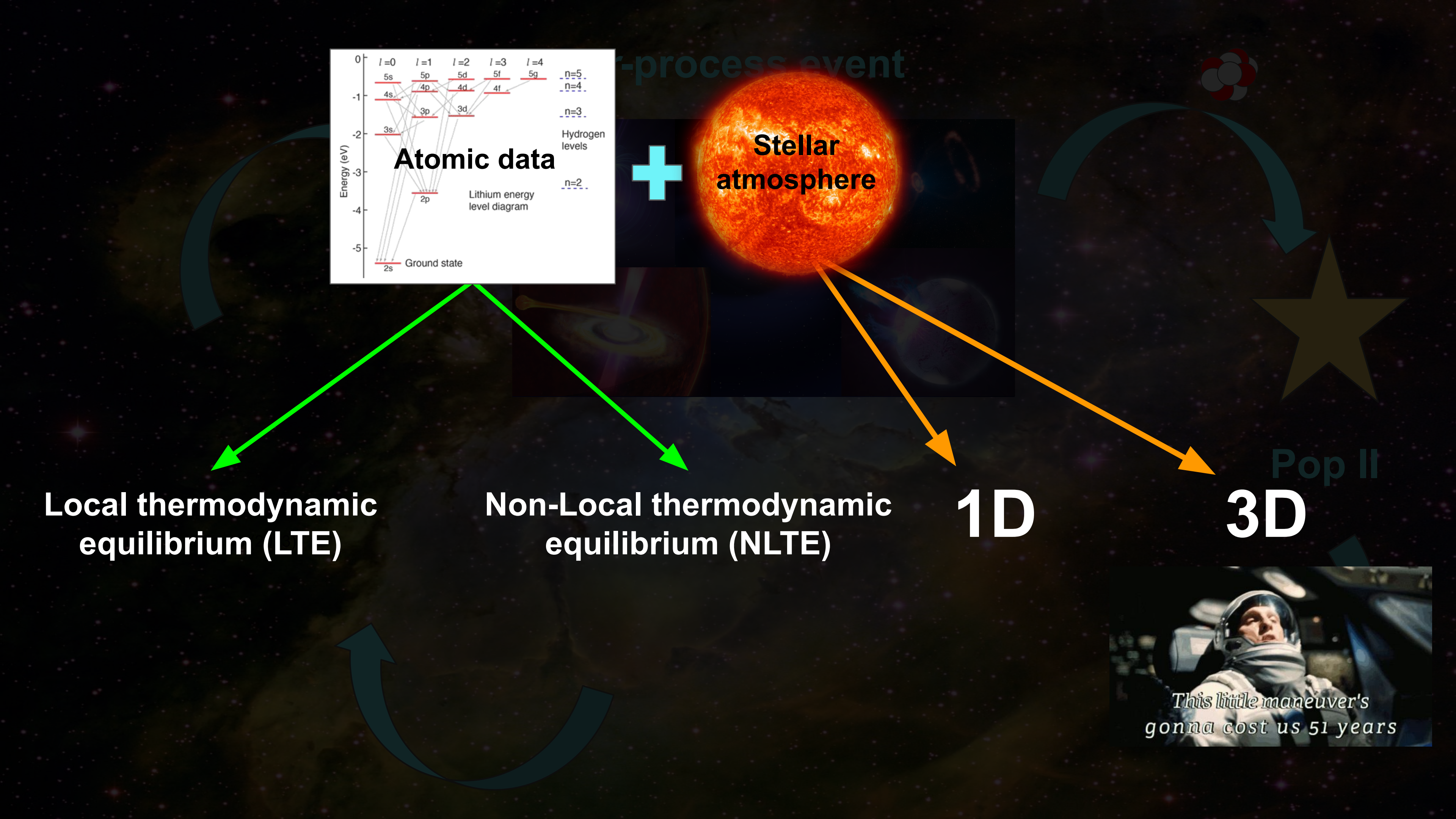

Atomic data
Energy (eV)
l =0
l =1
l =2
l =3
l =4
5s
5p
5d
5f
5g
4s
4p
4d
4f
3s
3p
3d
2p
2s
Ground state
n=5
n=4
n=3
n=2
Hydrogen levels
Lithium energy level diagram


Stellar atmosphere

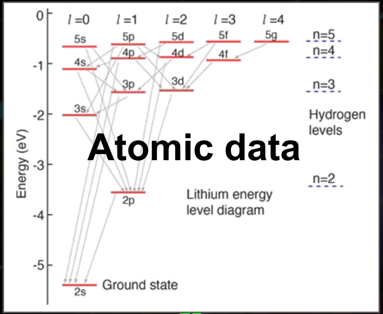
1D

3D


This little maneuver's gonna cost us 51 years



Atomic data
Energy (eV)
0
-1
-2
-3
-4
-5
l =0
l =1
l =2
l =3
l =4
5s
5p
5d
5f
5g
4s
4p
4d
4f
3s
3p
3d
2p
2s
n=5
n=4
n=3
n=2
Hydrogen levels
Lithium energy level diagram
Ground state
Stellar atmosphere
r-process event
Pop II
Local thermodynamic equilibrium (LTE)
Non-Local thermodynamic equilibrium (NLTE)
1D
3D
This little maneuver's
gonna cost us 51 years





**Local thermodynamic equilibrium (LTE)**

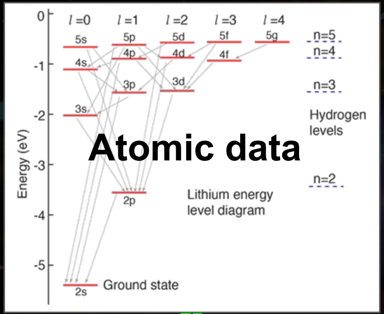
Valid only in stellar interiors

**Non-Local thermodynamic equilibrium (NLTE)**

Valid in the outer layers of the photosphere

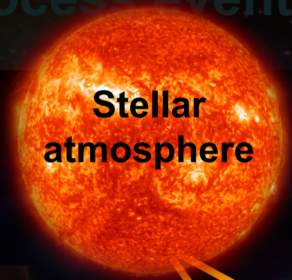
**1D**

**3D**




Atomic data

\+



Stellar atmosphere

## Local thermodynamic equilibrium (LTE)

- ✖ Valid only in stellar interiors
- ☺ Requires few atomic data

## Non-Local thermodynamic equilibrium (NLTE)

- ☺ Valid in the outer layers of the photosphere
- ✖ Requires atomic models

## 1D

## 3D

## The *R*-Process Alliance: Exploring the cosmic scatter among ten *r*-process sites with stellar abundances★

M. Racca[1,★★], T. T. Hansen[1], I. U. Roederer[2,3], V. M. Placco[4], ...
R. Ezzeddine[7,3], E. M. Holmbeck[8,3], C. M. Sakari[9], S. ...
C. Sneden[12], and I. B. Th...

## The *R*-Process Alliance: Hunting for gold in the nea... spectrum of 2MASS J05383296−5904280★

Terese T. Hansen[1,★★], Ian U. Roederer[2,3], Shivani P. Shah[4], Rana Ezzeddine[4,3], Timothy ...
Anna Frebel[6,3], Erika M. Holmbeck[7,3], Vinicius M. Placco[8], Charli M. Sakari[9], Alexander Ji[10], ...
Jennifer L. Marshall[11], Mohammad K. Mardini[12,13,6,3], and Anirudh Chiti[10,14]

## Chemical Evolution of *R*-process Elements in Stars (CERES)
### I. Stellar parameters and chemical abundances from Na to Zr★,★★

...ardo[1], Piercarlo Bonifacio[1], Patrick François[1], Camilla J. Hansen[2], Elisabetta Caffau[1], Michael Hanke[3],
...[4,5], Almudena Arcones[6,7], Marius Eichler[6], Moritz Reichert[6,8], Athanasios Psaltis[6],
...ndreas J. Koch Hansen[3], and Luca Sbordone[9]

## Chemical Evolution of R-process Elements in Stars (CERES)
### IV. An observational run-up of the third r-process peak with Hf, Os, Ir, and Pt

Arthur Alencastro Puls[1], Jan Kuske[2], Camilla Juul Hansen[1], Linda Lombardo[1], Giorgio Visentin[3,4], Almudena Arcones[2,4,5], Raphaela Fernandes de Melo[1], Moritz Reichert[6], Piercarlo Bonifacio[7], Elisabetta Caffau[7] and Stephan Fritzsche[3,4,8]

**Local thermodynamic equilibrium (LTE)**

- ✗ Valid only in stellar interiors
- ☺ Requires few atomic data

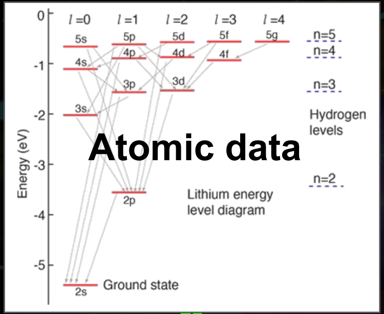
**Non-Local thermodynamic equilibrium (NLTE)**

- Valid in the outer layers of the photosphere
- ✗ Requires atomic models

**1D**

**3D**

Pop II





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- ☺ Valid in the outer layers of the photosphere
- ✗ Requires atomic models

## 1D

## 3D

Article

# r-Process elements from magnetorotational hypernovae

https://doi.org/10.1038/s41586-021-03611-2

Received: 5 November 2020

D. Yong[1,2]✉, C. Kobayashi[2,3], G. S. Da Costa[1,2], M. S. Bessell[1], A. Chiti[4], A. Frebel[4], K. Lind[5], A. D. Mackey[1,2], T. Nordlander[1,2], M. Asplund[6], A. R. Casey[2,7], A. F. Marino[8], S. J. Murphy[1,9] & B. P. Schmidt[1]

**Article**

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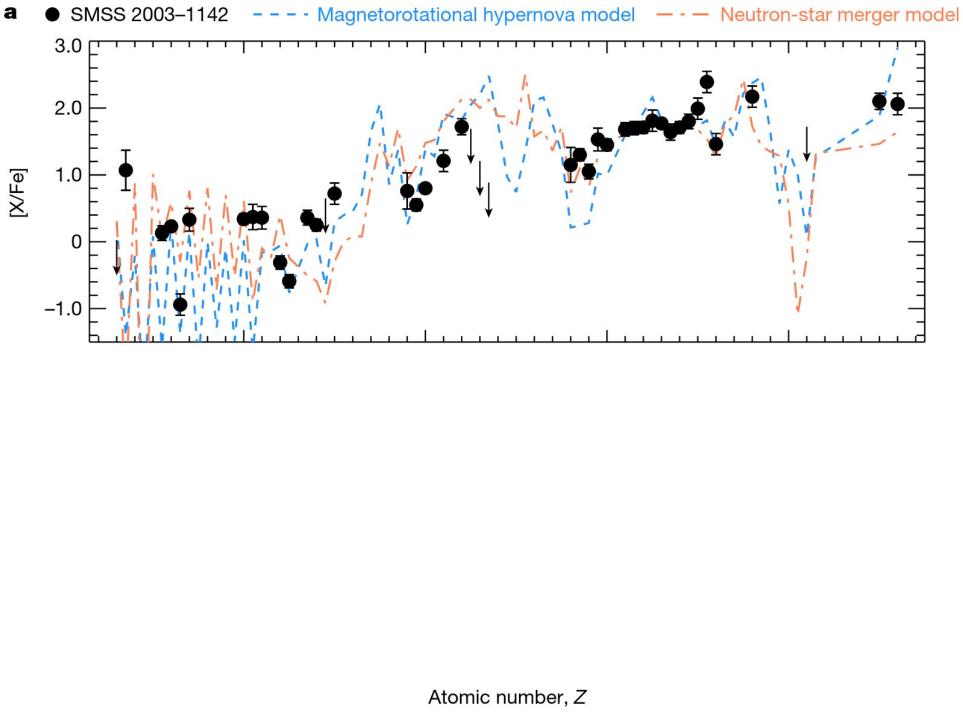
1D LTE




$T_{eff}$ = 5175 K,   log $g$ = 2.4,   [Fe/H] = -3.5 dex,   [Eu/Fe] = 1.7 dex

1D LTE

Article

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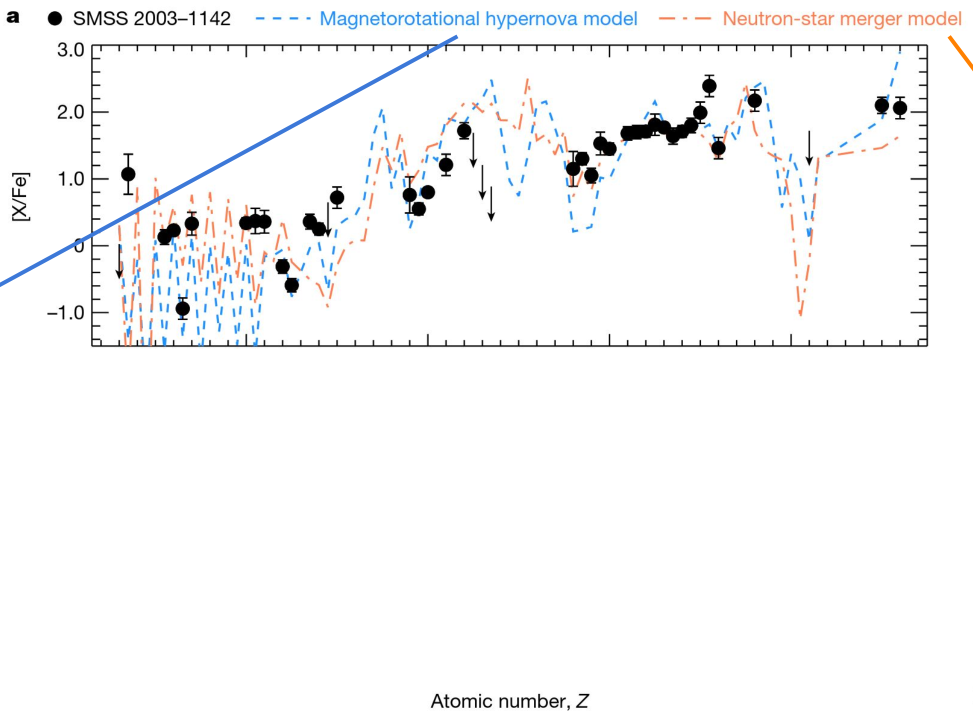


25-40 M☉ star with Z=0

NSM of two 1.3 M☉

$T_{eff}$ = 5175 K, log $g$ = 2.4, [Fe/H] = -3.5 dex, [Eu/Fe] = 1.7 dex

**Article**

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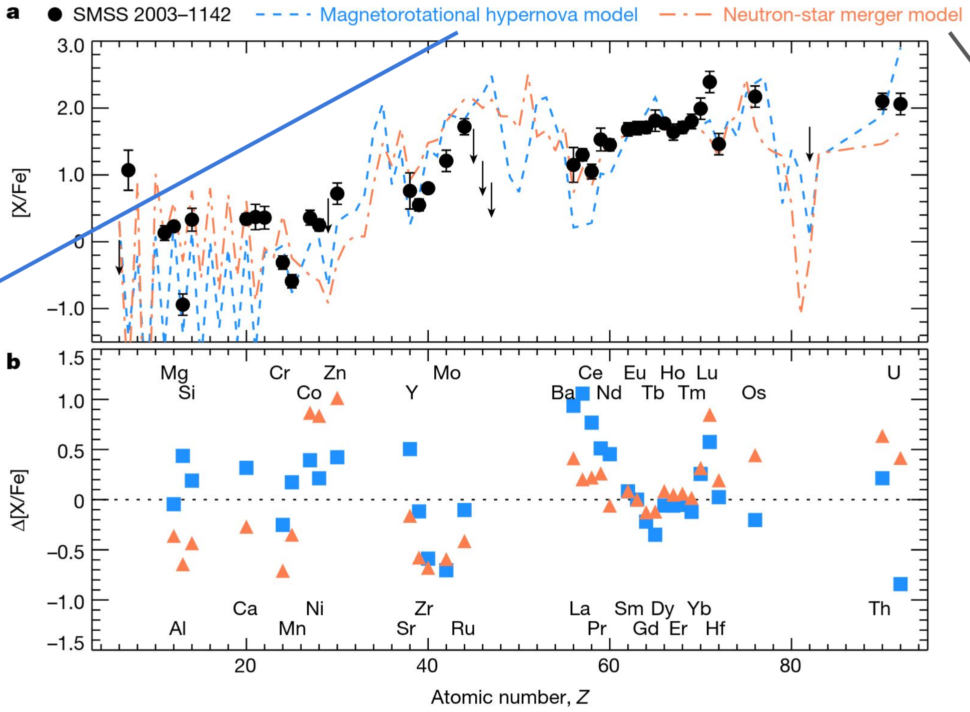
1D LTE




25-40 M⊙ star with Z=0

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# Revisiting r-process element origins through 3D NLTE stellar abundance analysis

Mila Racca[1], Gloria Canocchi[2], Karin Lind[1], Marco Palla[3], Thomas Nordlander[4], Sema Caliskan[4], and Cis Lagae[5]

3D NLTE

1D NLTE

3D LTE

1D LTE

## Model atmosphere

**STAGGER (3D)** (Rodriguez Diaz+24)

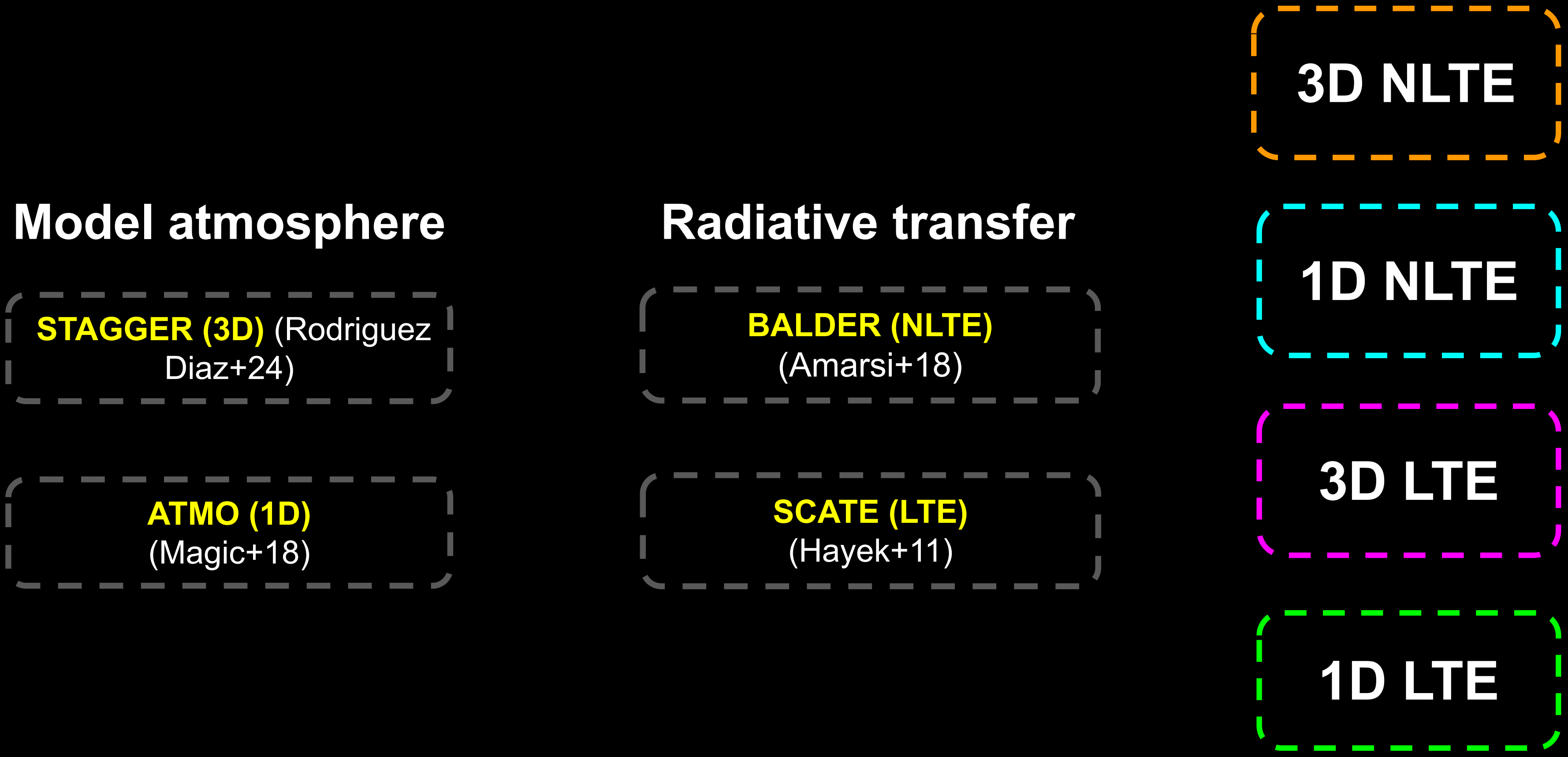
**ATMO (1D)** (Magic+18)

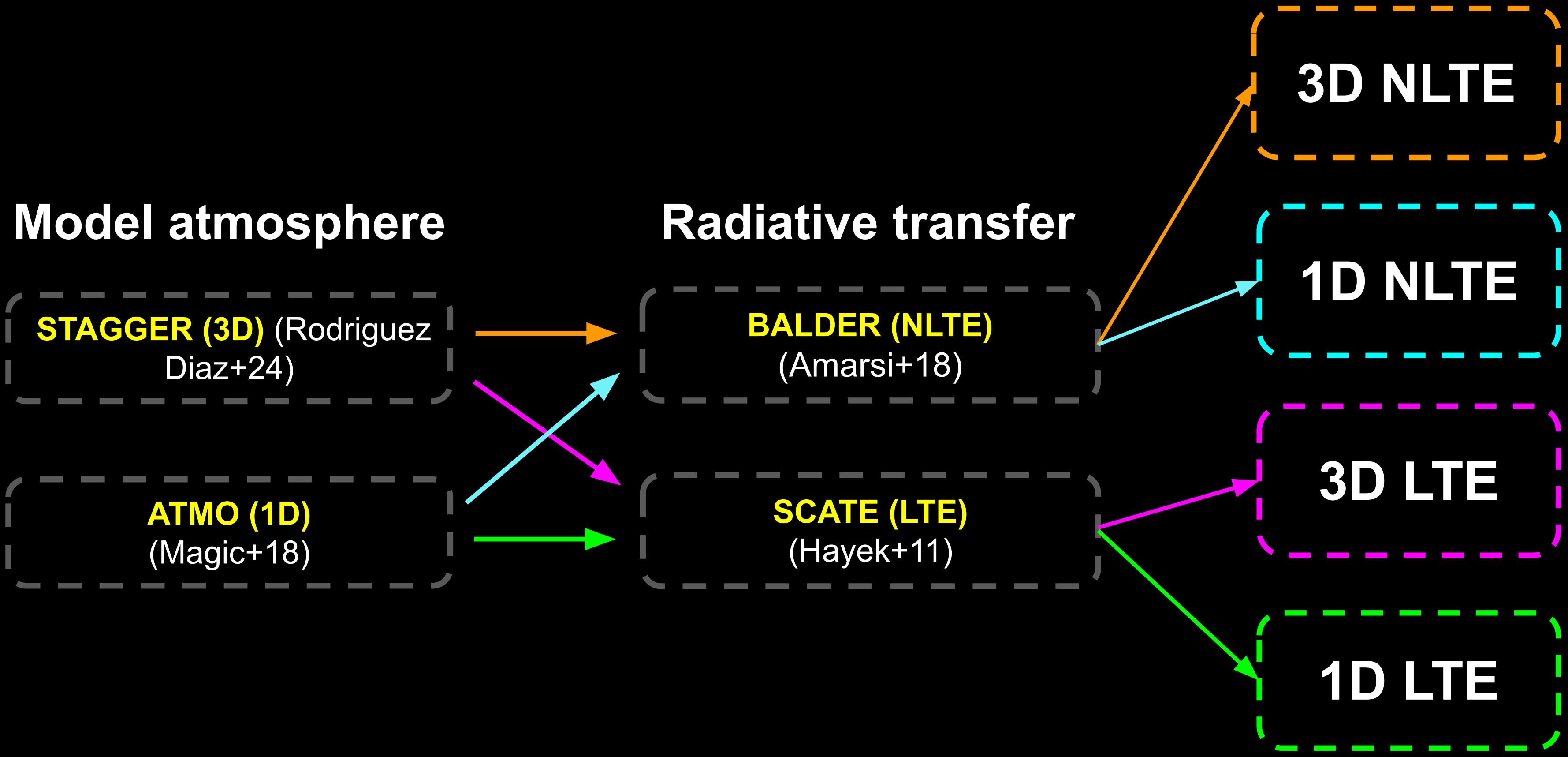
**3D NLTE**

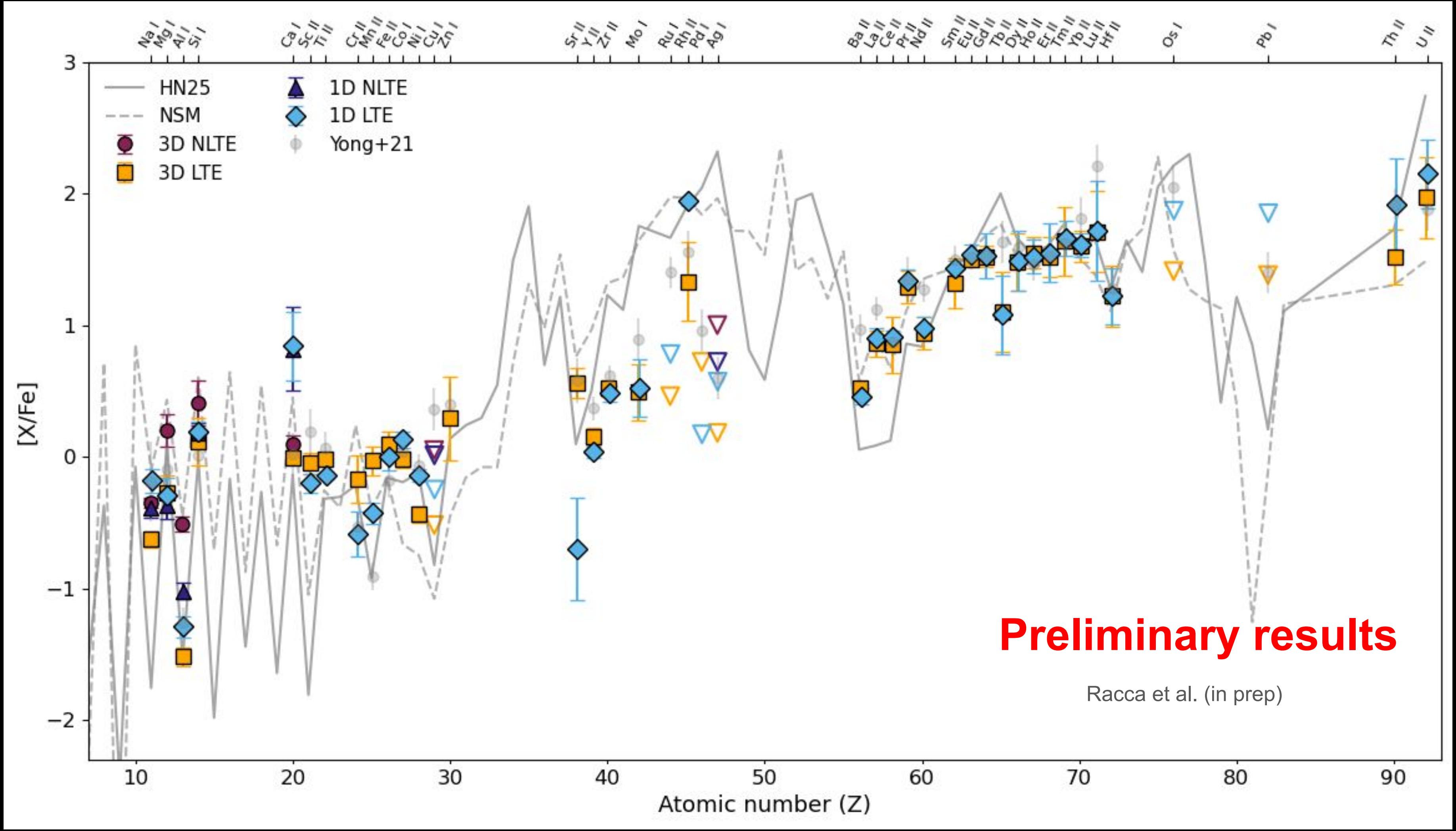
**1D NLTE**

**3D LTE**

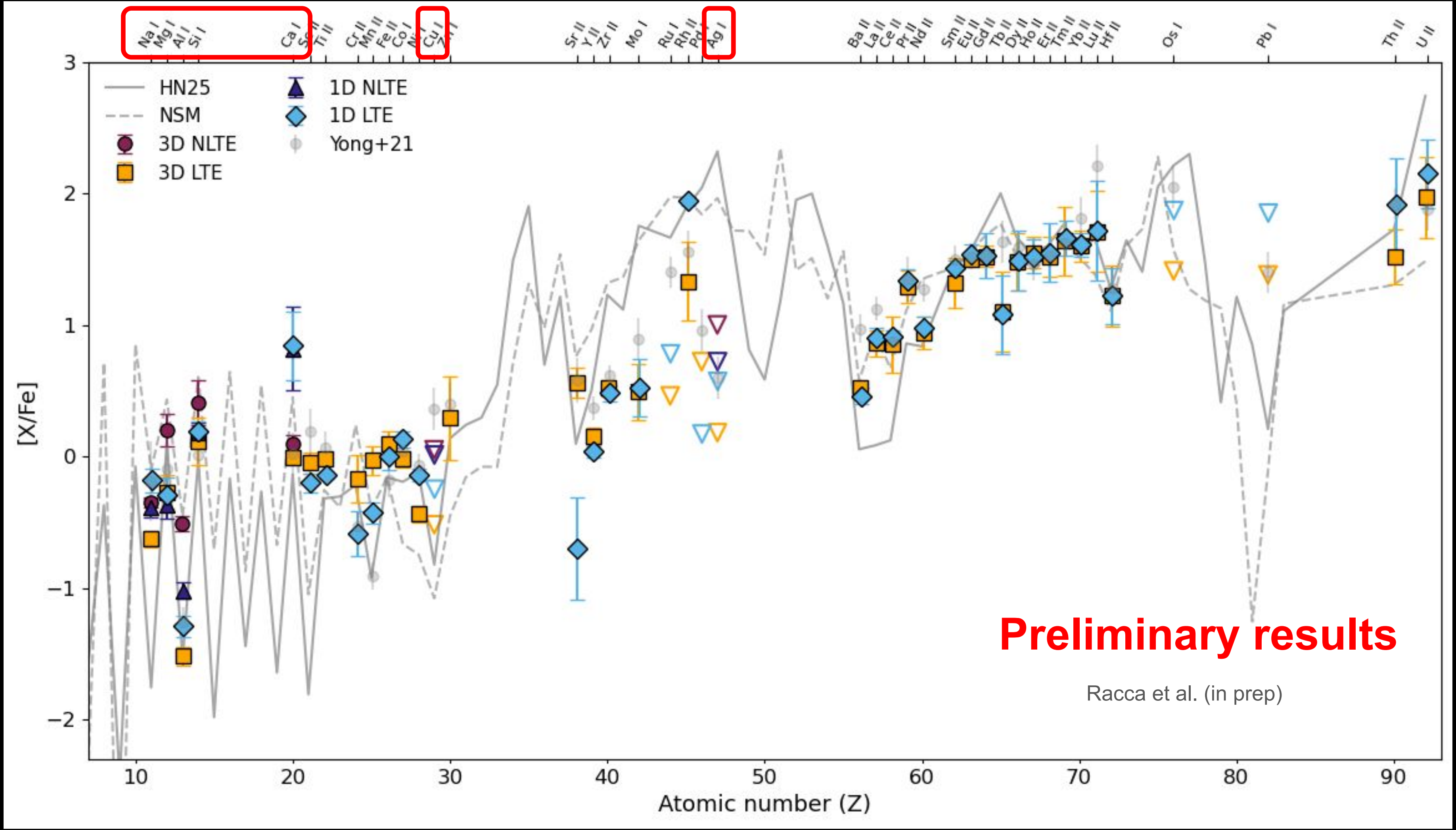
**1D LTE**

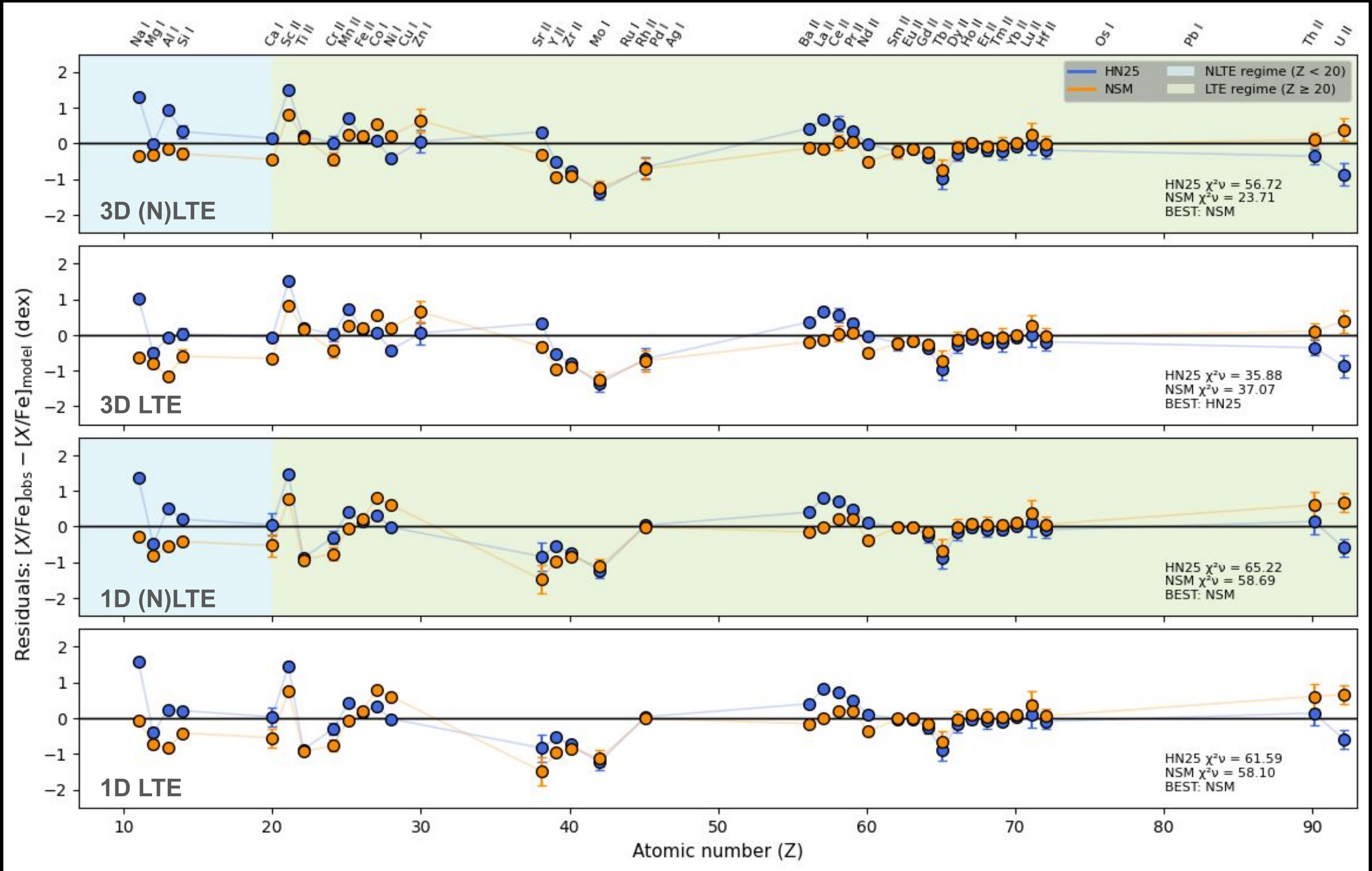

Model atmosphere
STAGGER (3D) (Rodriguez Diaz+24)
ATMO (1D) (Magic+18)
Radiative transfer
BALDER (NLTE) (Amarsi+18)
SCATE (LTE) (Hayek+11)
3D NLTE
1D NLTE
3D LTE
1D LTE


Model atmosphere
Radiative transfer
STAGGER (3D) (Rodriguez Diaz+24)
ATMO (1D) (Magic+18)
BALDER (NLTE) (Amarsi+18)
SCATE (LTE) (Hayek+11)
3D NLTE
1D NLTE
3D LTE
1D LTE

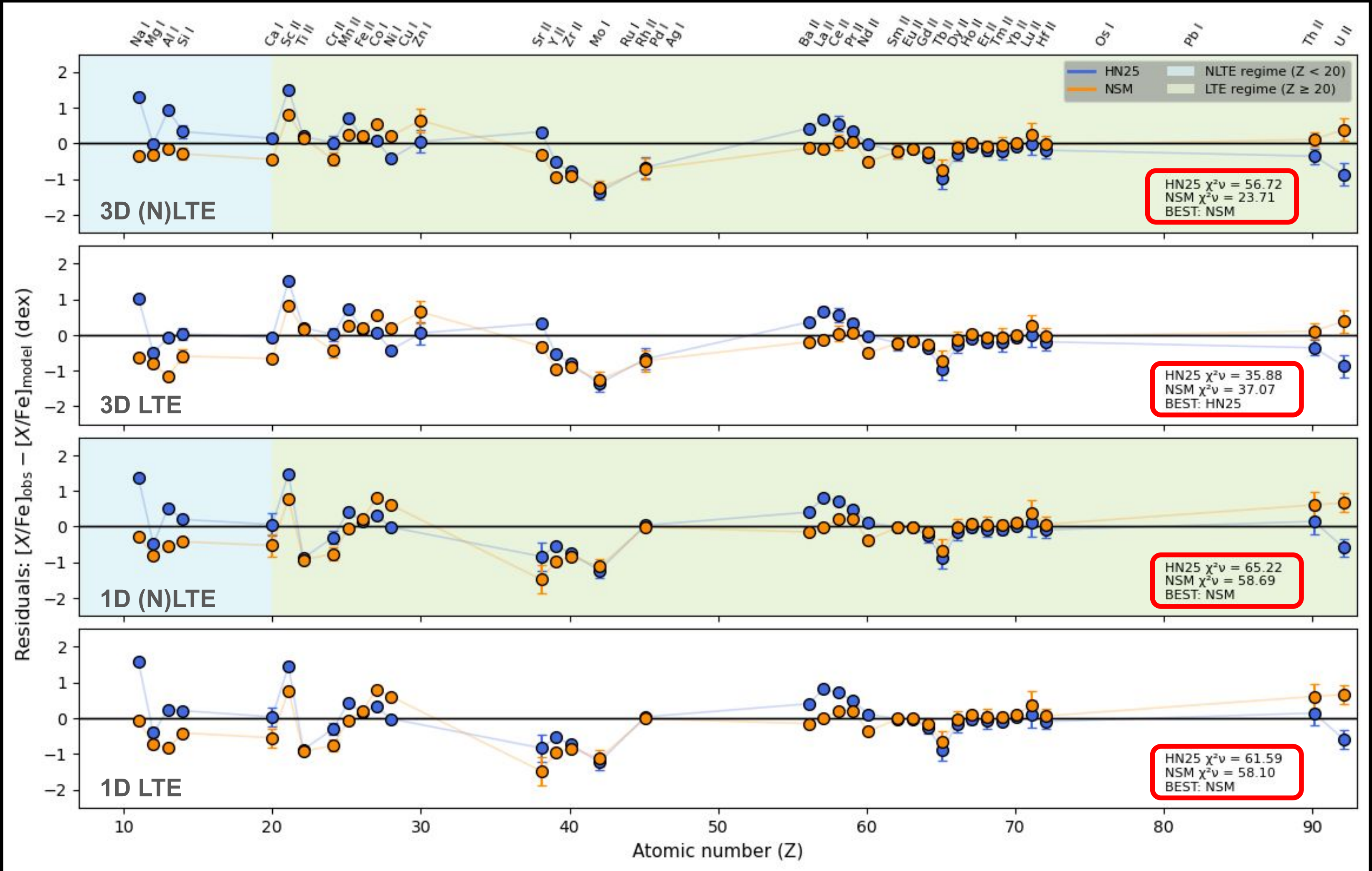


Na I
Mg I
Al I
Si I
Ca I
Sc II
Ti II
Cr II
Mn II
Fe II
Co I
Ni I
Cu I
Zn I
Sr II
Y II
Zr II
Mo I
Ru I
Rh II
Pd I
Ag I
Ba II
La II
Ce II
Pr II
Nd II
Sm II
Eu II
Gd II
Tb II
Dy II
Ho II
Er II
Tm II
Yb II
Lu II
Hf II
Os I
Pb I
Th II
U II
HN25
NSM
3D NLTE
3D LTE
1D NLTE
1D LTE
Yong+21
[X/Fe]
Atomic number (Z)
Preliminary results
Racca et al. (in prep)


Na I
Mg I
Al I
Si I
Ca I
Sc II
Ti II
Cr II
Mn II
Fe II
Co I
Ni I
Cu I
Zn I
Sr II
Y II
Zr II
Mo I
Ru I
Rh II
Pd I
Ag I
Ba II
La II
Ce II
Pr II
Nd II
Sm II
Eu II
Gd II
Tb II
Dy II
Ho II
Er II
Tm II
Yb II
Lu II
Hf II
Os I
Pb I
Th II
U II
HN25
NSM
3D NLTE
3D LTE
1D NLTE
1D LTE
Yong+21
[X/Fe]
Atomic number (Z)
Preliminary results
Racca et al. (in prep)



Na I Mg I Al I Si I Ca I Sc II Ti II Cr II Mn II Fe II Co I Ni I Cu I Zn I Sr II Y II Zr II Mo I Ru I Rh II Pd I Ag I Ba II La II Ce II Pr II Nd II Sm II Eu II Gd II Tb II Dy II Ho II Er II Tm II Yb II Lu II Hf II Os I Pb I Th II U II
HN25
NSM
NLTE regime (Z < 20)
LTE regime (Z ≥ 20)
3D (N)LTE
HN25 χ²ν = 56.72
NSM χ²ν = 23.71
BEST: NSM
3D LTE
HN25 χ²ν = 35.88
NSM χ²ν = 37.07
BEST: HN25
1D (N)LTE
HN25 χ²ν = 65.22
NSM χ²ν = 58.69
BEST: NSM
1D LTE
HN25 χ²ν = 61.59
NSM χ²ν = 58.10
BEST: NSM
Residuals: [X/Fe]obs − [X/Fe]model (dex)
Atomic number (Z)



Na I Mg I Al I Si I Ca I Sc II Ti II Cr II Mn II Fe II Co I Ni I Cu I Zn I Sr II Y II Zr II Mo I Ru I Rh II Pd I Ag I Ba II La II Ce II Pr II Nd II Sm II Eu II Gd II Tb II Dy II Ho II Er II Tm II Yb II Lu II Hf II Os I Pb I Th II U II
HN25
NSM
NLTE regime (Z < 20)
LTE regime (Z ≥ 20)
3D (N)LTE
HN25 χ²ν = 56.72
NSM χ²ν = 23.71
BEST: NSM
3D LTE
HN25 χ²ν = 35.88
NSM χ²ν = 37.07
BEST: HN25
1D (N)LTE
HN25 χ²ν = 65.22
NSM χ²ν = 58.69
BEST: NSM
1D LTE
HN25 χ²ν = 61.59
NSM χ²ν = 58.10
BEST: NSM
Residuals: [X/Fe]obs − [X/Fe]model (dex)
Atomic number (Z)


# NSM becomes the favourite model!

# A different approach:

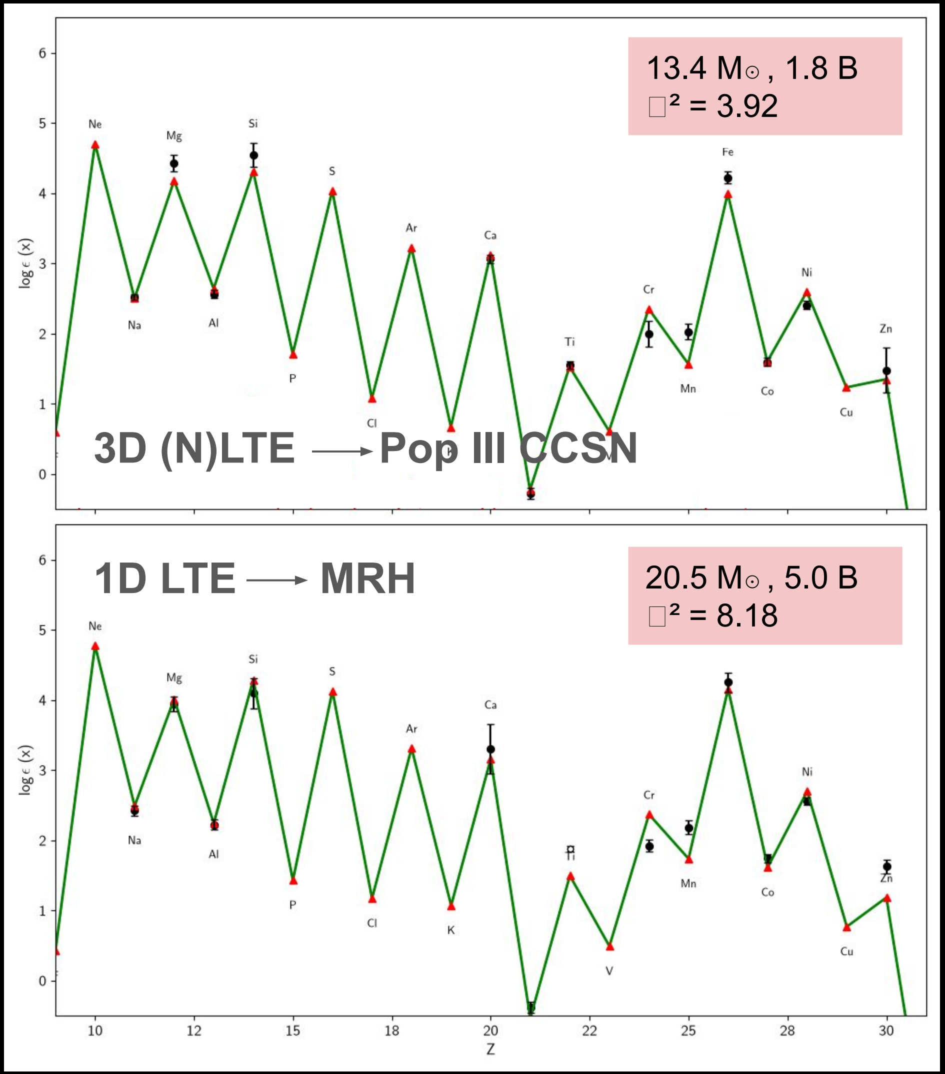
Light elements first

Neutron capture elements

# A different approach:

Light elements first

Neutron capture elements

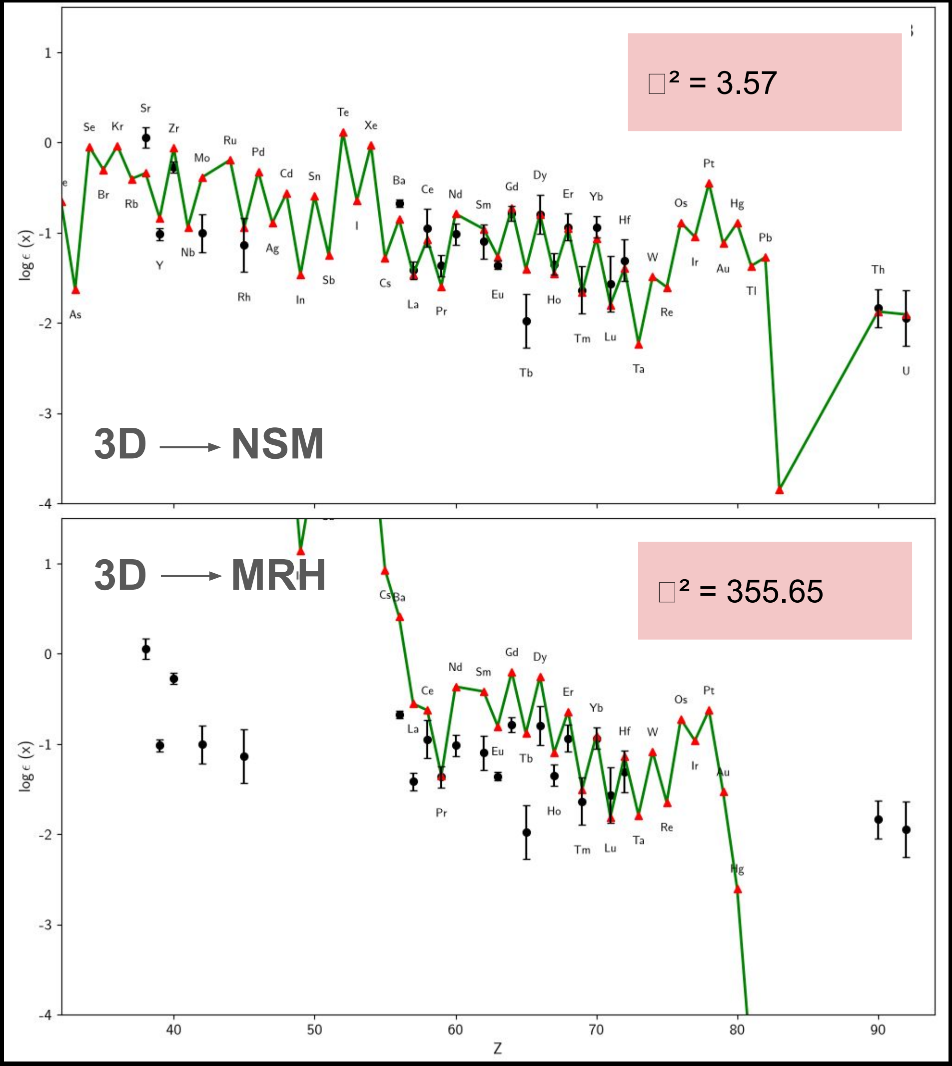



Credits: Marco Palla

# A different approach:

Light elements first

Neutron capture elements




Credits: Marco Palla

# SUMMARY

**Stellar abundances can be MODEL DEPENDENT**

→

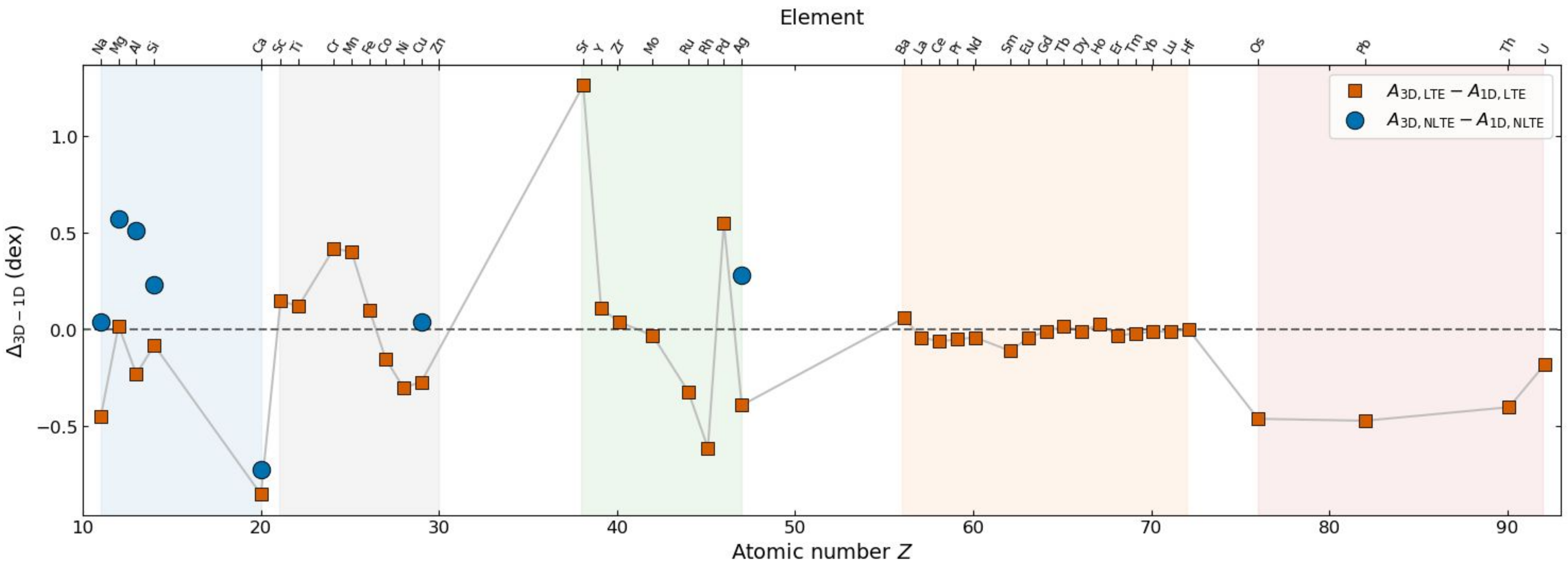
**Reliable abundances provide better constraint on nucleosynthesis models**

↓

**First comprehensive analysis of a very metal poor star in 3D (N)LTE**

←

**From MRH to NSM as the nucleosynthesis**



Element
Na
Mg
Al
Si
Ca
Sc
Ti
Cr
Mn
Fe
Co
Ni
Cu
Zn
Sr
Y
Zr
Mo
Ru
Rh
Pd
Ag
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Os
Pb
Th
U
$A_{3D,LTE} - A_{1D,LTE}$
$A_{3D,NLTE} - A_{1D,NLTE}$
$\Delta_{3D-1D}$ (dex)
1.0
0.5
0.0
−0.5
10
20
30
40
50
60
70
80
90
Atomic number $Z$

# A different approach:

**Light elements first**

**Neutron capture elements**

1. **MRH:**


2. **CCSN + NSM:**


+

# Revisiting r-process element origins through 3D NLTE stellar abundance analysis

(In prep)