SubirFest Oxford 13 Oct 31 2023

the riddle of Li many origins

Paolo Molaro

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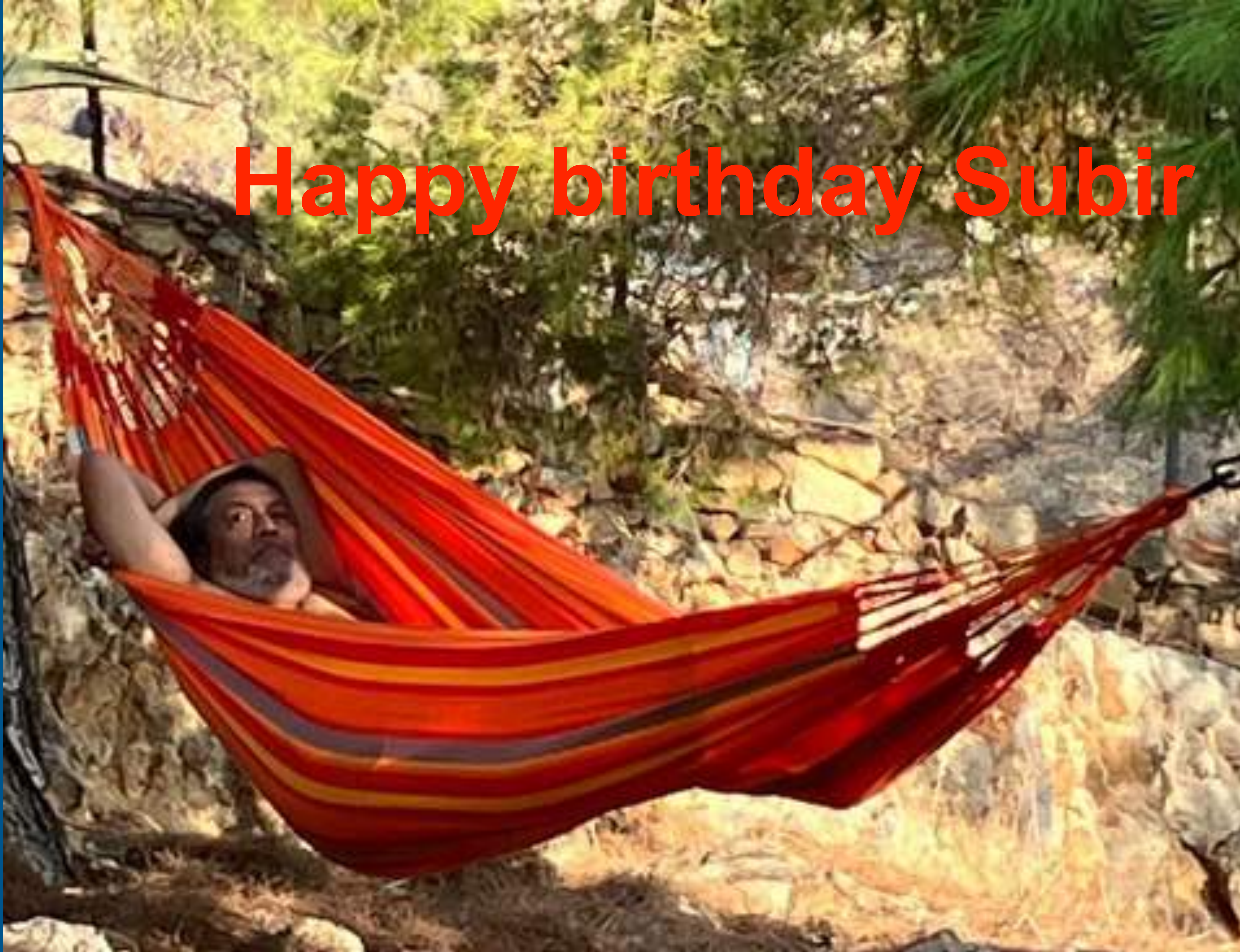
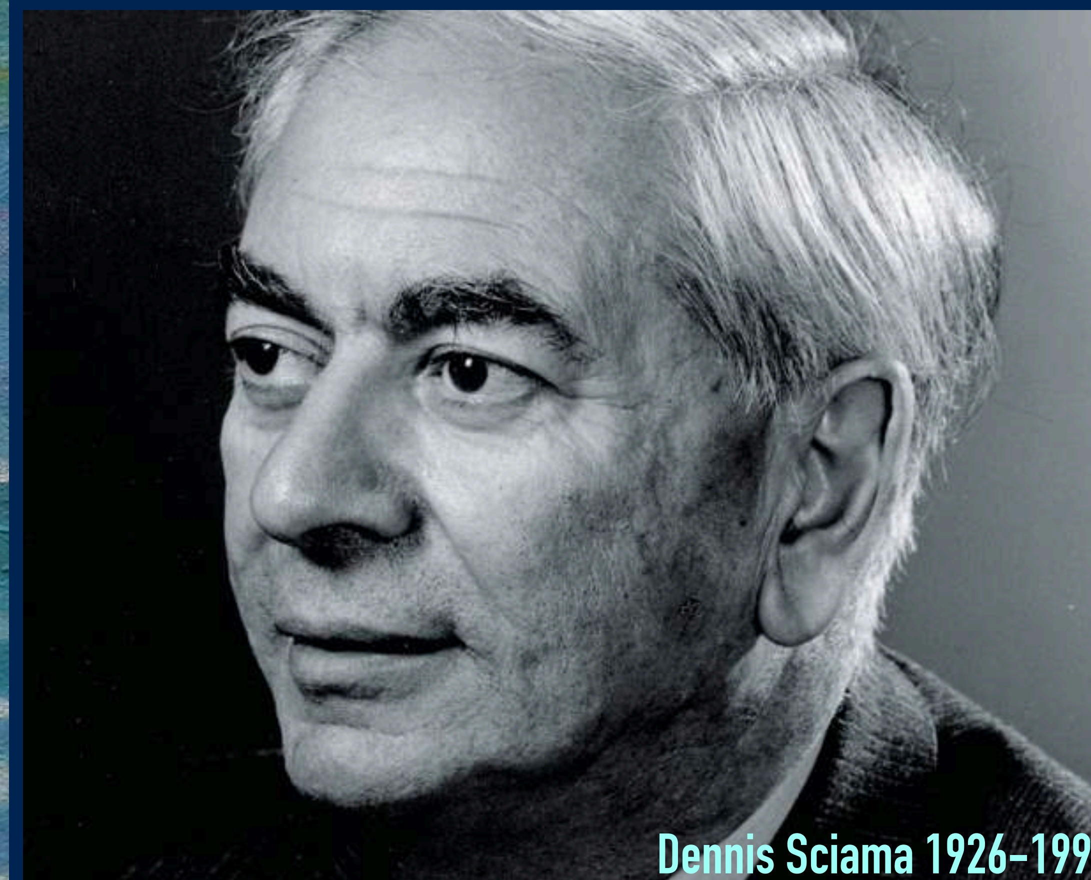

Happy birthday Subir

- 1983 at SISSA in Trieste
- 1987 in Oxford
- 2013-present PDG SBBN

Amanda Sarkar



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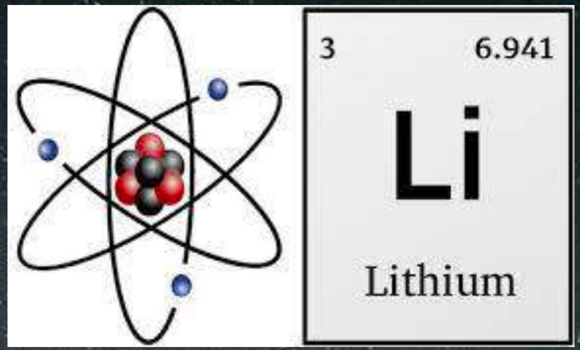

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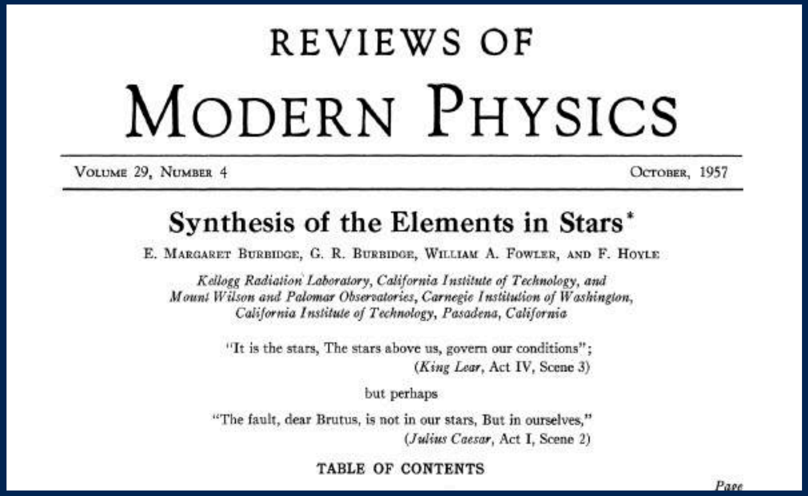
The X-mechanism

BBFH 1957



REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions"; (*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves," (*Julius Caesar*, Act I, Scene 2)

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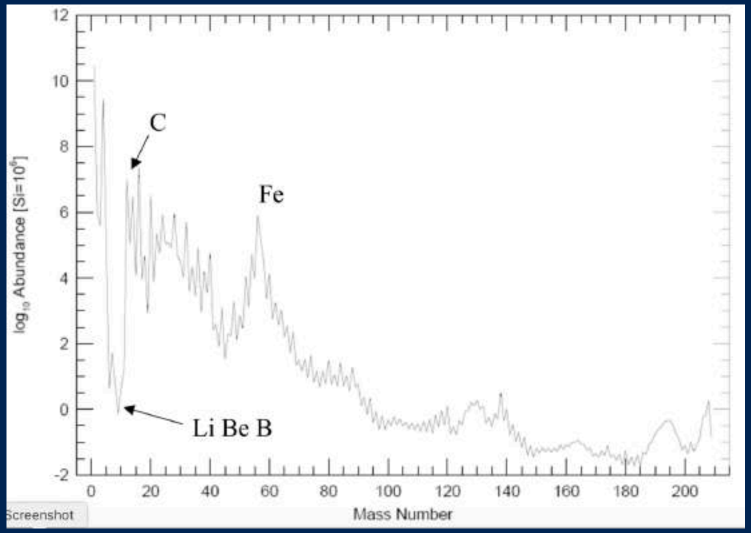
Page

- **Li destroyed inside stars**

  $^{7}Li(p,a)^{4}He$ ~ $2x10^{6}$ K
- **Li in meteorites A(Li) = 3.26 (+/- 0.05)**
- **Where does it comes from? *X-mechanism*:**

  ➡ spallation reactions in Flare Stars ?

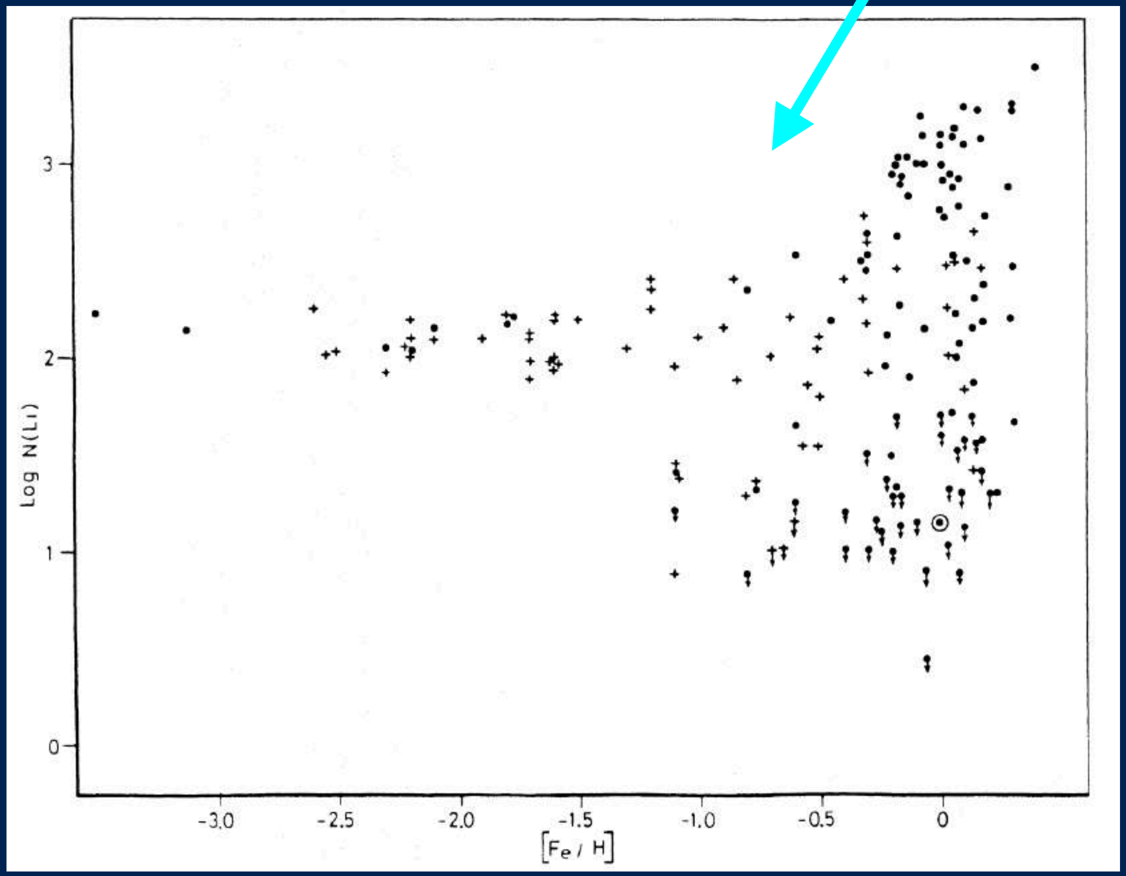
  ➡ TypeI SNae?



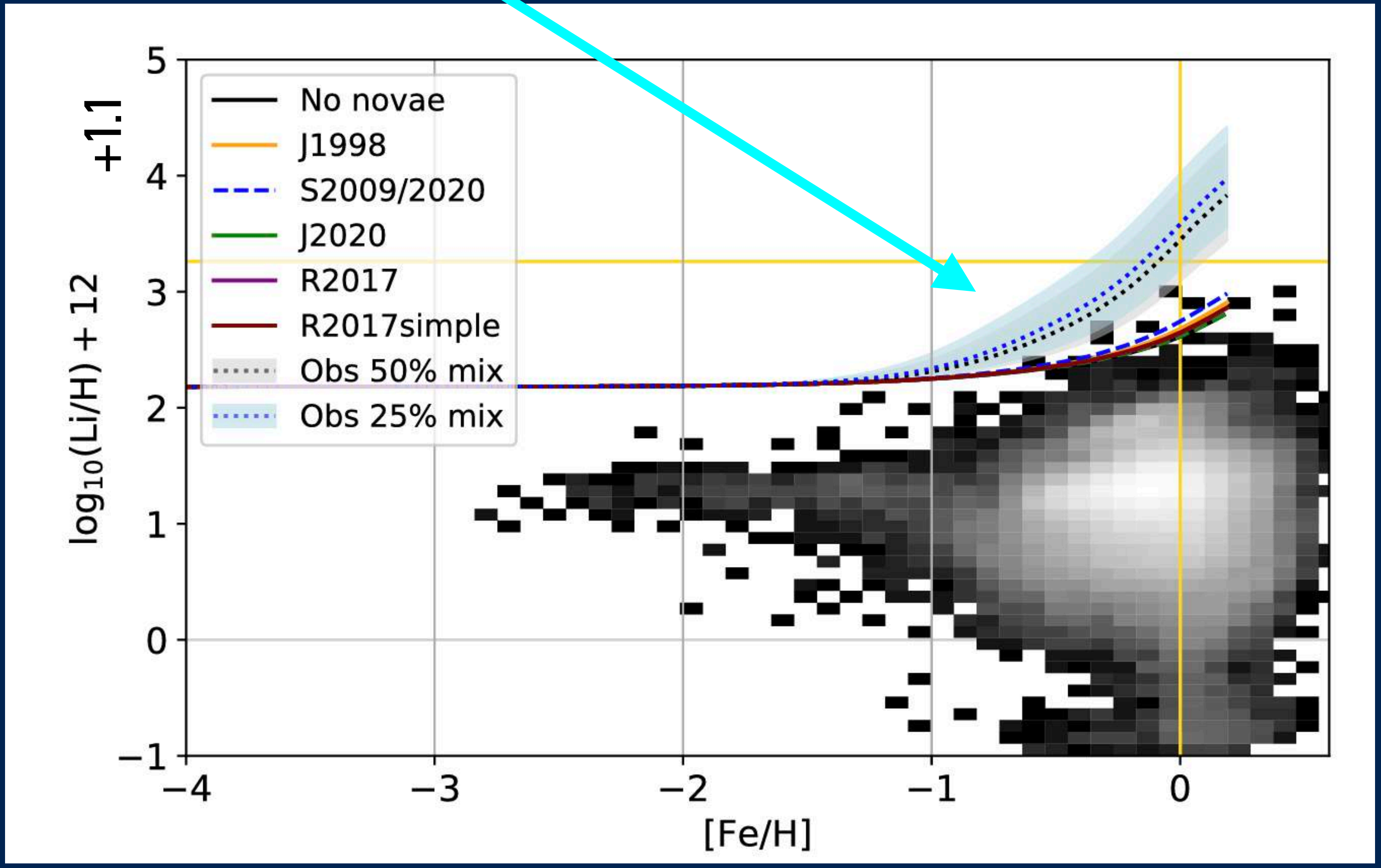
Still with us!

The riddle of the Galactic Li

Galactic Lithium synthesis



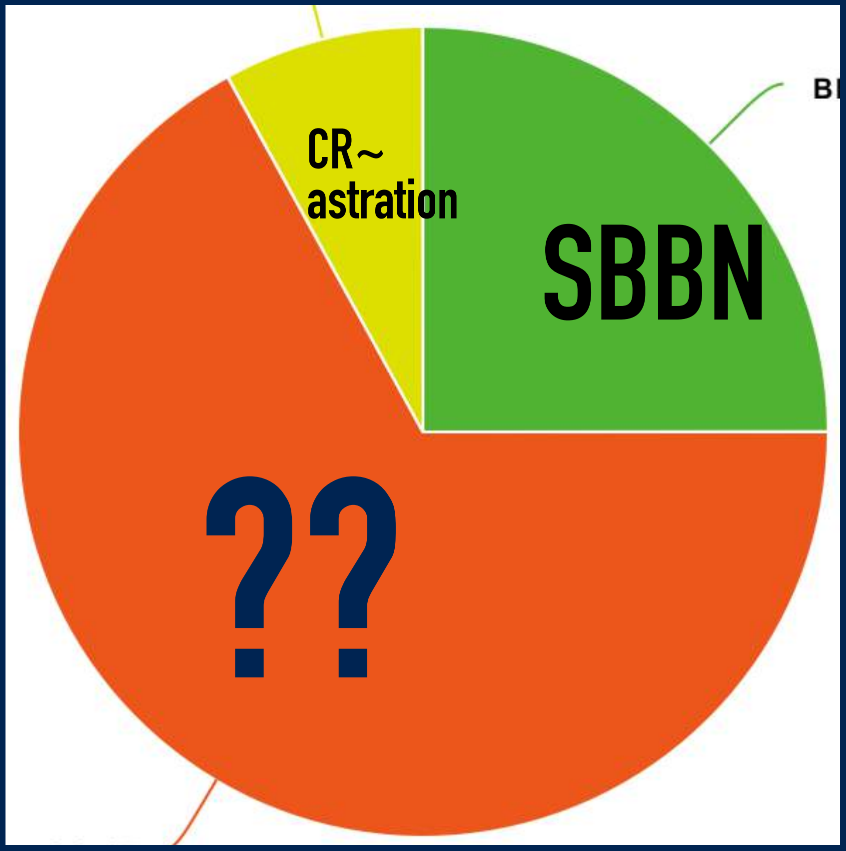
GALAH
1 million stars



- **Meteoritic: $(Li/H)_{mass}$ = 1.4×10^{-8}**

$$M_{Li} = 1.4\ 10^{-8} \times 10^{11} \times 0.71 \times \sim \mathbf{1000\ M_\odot}$$

- **Astration: - ~10%**
- **Spallation: ~10%** (from ^9Be)
- **SBBN: 25%** (CMB; D+SBBN)
- **~75% ??**



Rebolo, PM + 1987

Which sources?

- **AGB**: HBB 3.5-6.0 M⊙ (Smith & Lambert 1989,1990, Sackmann Boothroyd 1992) but too few!

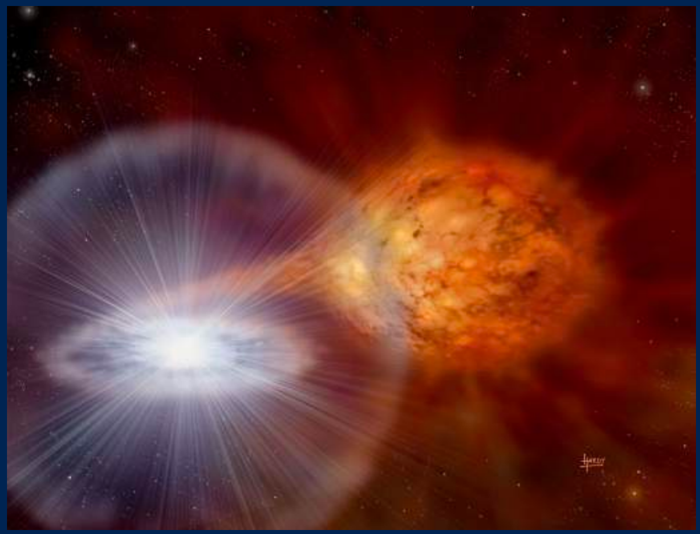
- **CCSN:** SN neutrino can break C nuclei in the C shell (Woosley+1990), ruled out by stellar evolution models

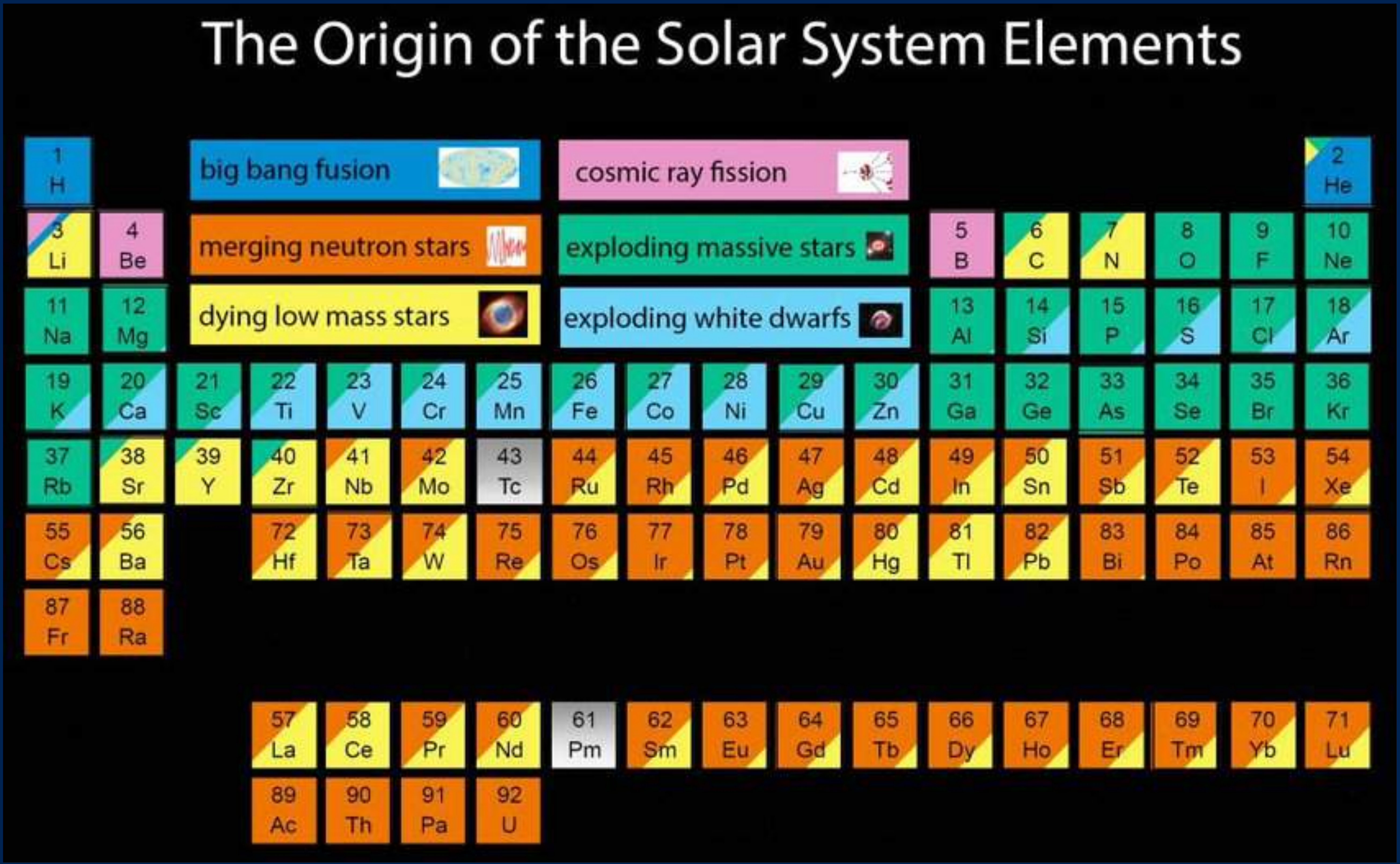
- **RED GIANTS:** 0.1% A(Li) > 3.3. (not clear origin) Romano+2001 But the model assume that all Giants (M<2 M⊙), produce A(Li) = 4 !

- NOVAE: in the Thermo Nuclear Runaway, at T ~ 10^7 K, ^{7}Be can be produced (Starrfield+ 1978)

^{3}He (α, γ) ^{7}Be

- **^{7}Be decays into ^{7}Li with a ~ 53 d**
- **LiI 6707 line search for decades but never observed**



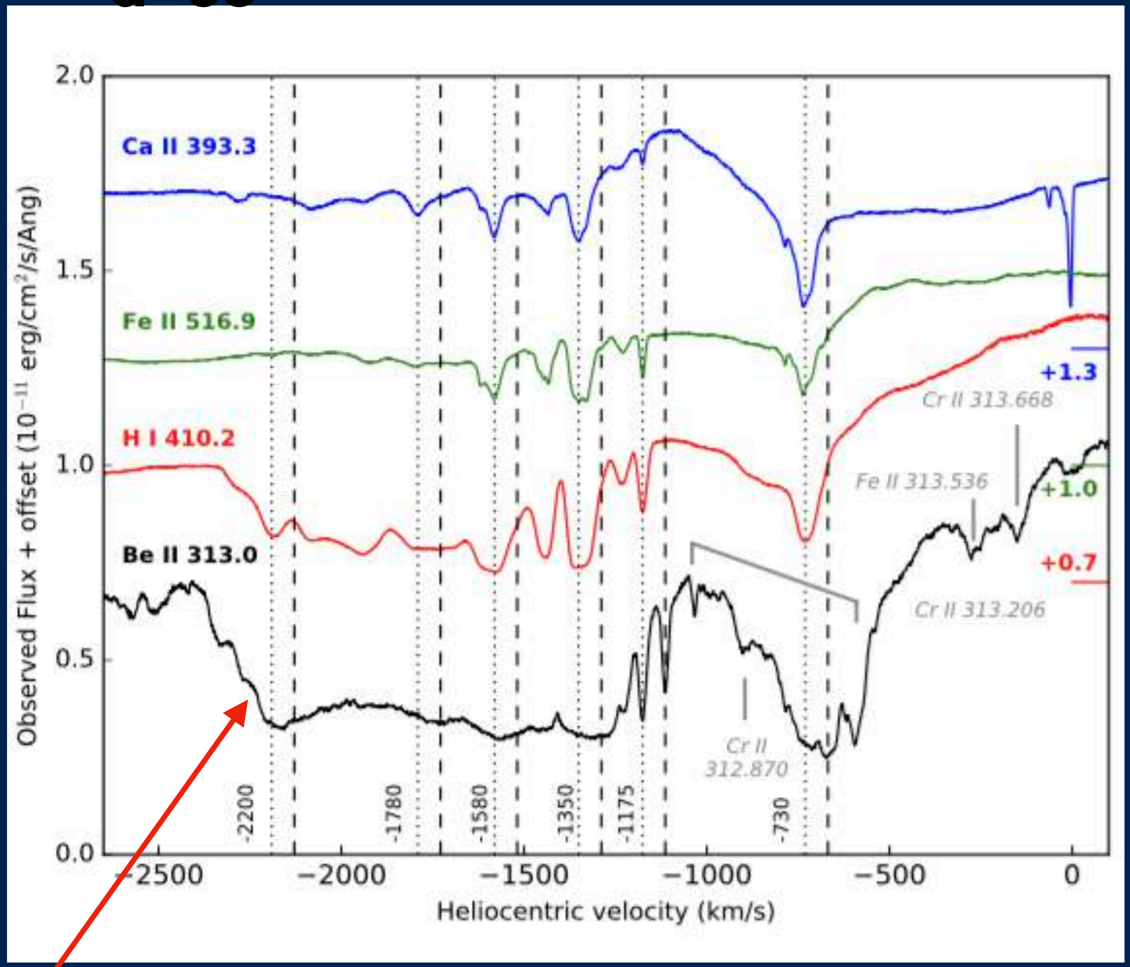


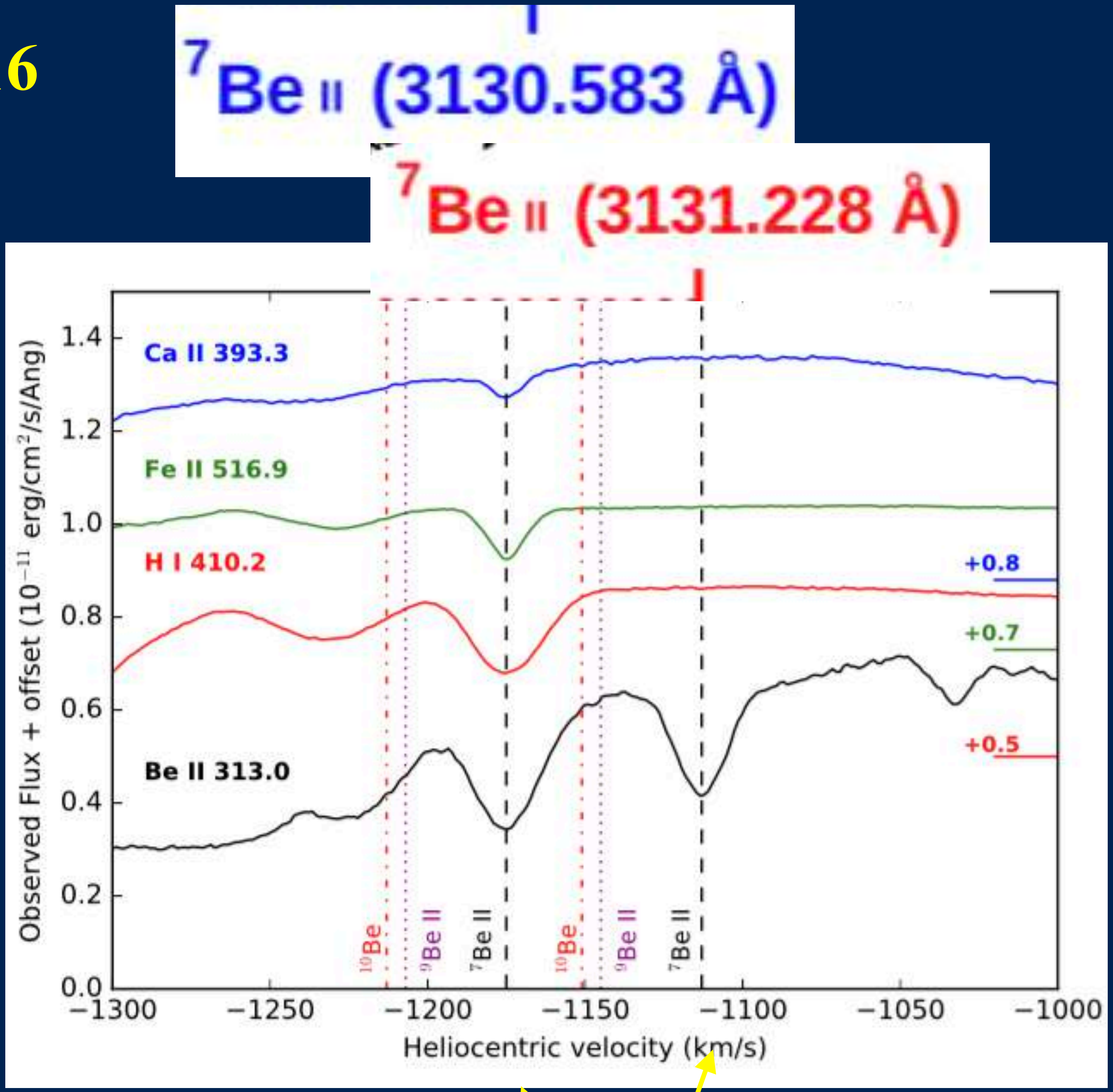
After 2019 year of the Table of elements
Li origin always wrong

Detection of ^{7}Be in novae

- **Li I in V1369 Cen (2013)** Izzo+15
- **^{7}Be in Nova Del 2013 (V339)** **Tajitsu+15**
- **^{7}Be in Nova Sgr 2015 (V5668)** **PM+16**

d=53





^{7}Be ?

^{7}Be not ^{9}Be!

Perfect separation 61.8 km/s

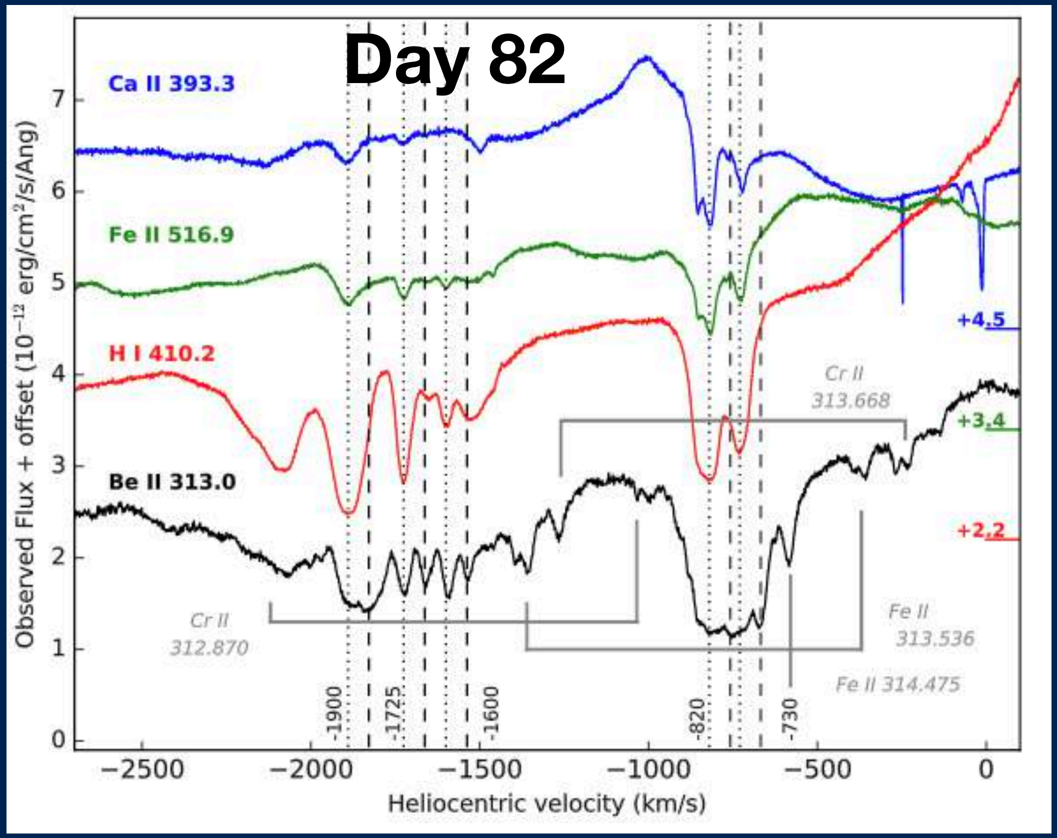
➡ **TNR reactions make ^{7}Be!**

➡ **(the only place where you can see ^{7}Be !)**

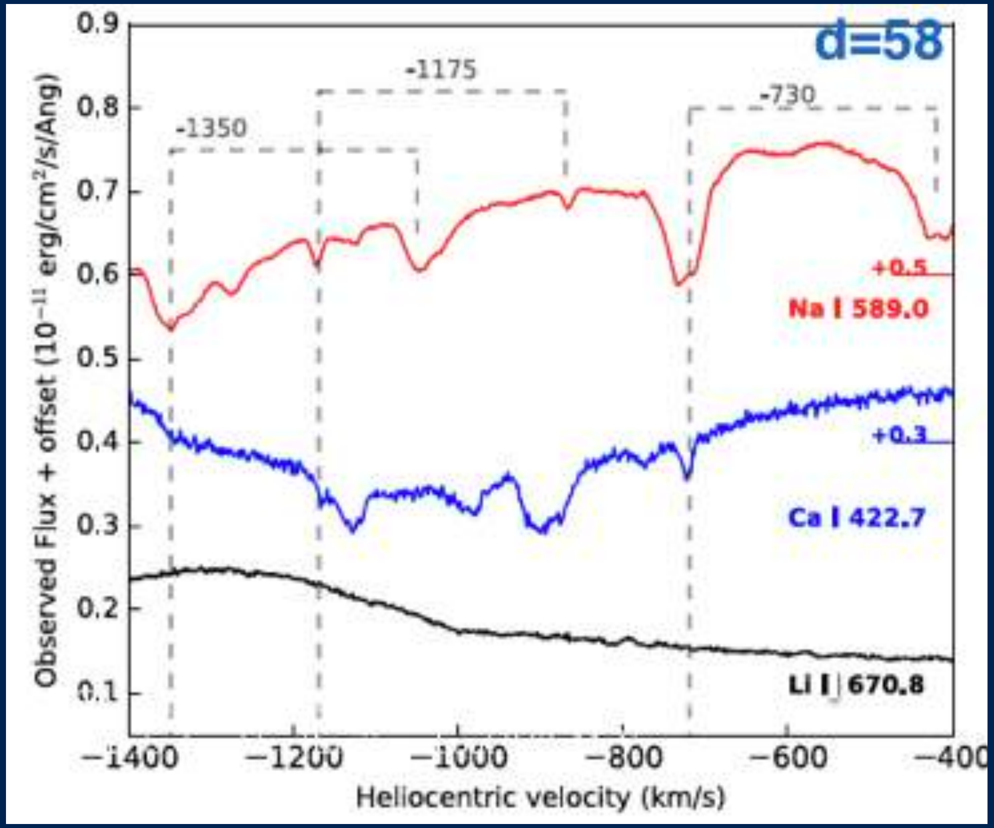
and ^{7}LiI 6707?

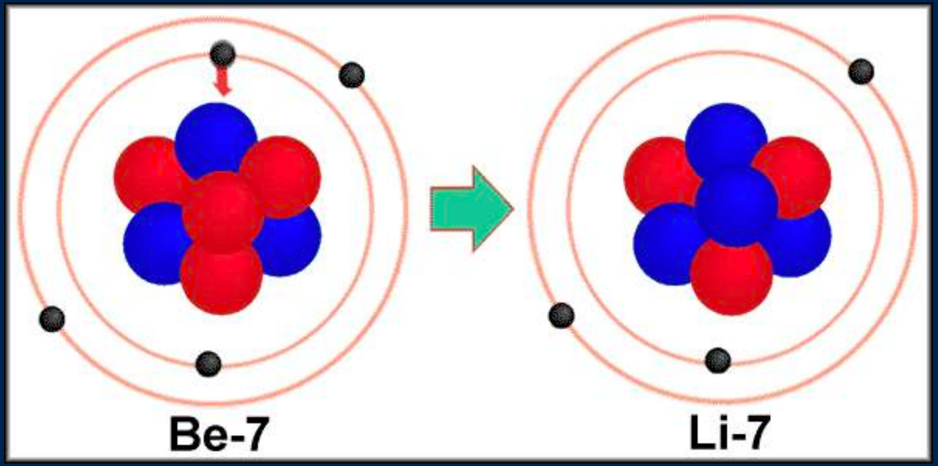
- At day 82 the line optically thin and shows several components of ^{7}Be in the bulk absorption (with some blends of CrII, FeII)

Huge ^{7}BeII line



- **but LiI 670.7 nm not detected!**





^{7}BeII => ^{7}Li II

- LiII has no lines in the optical!

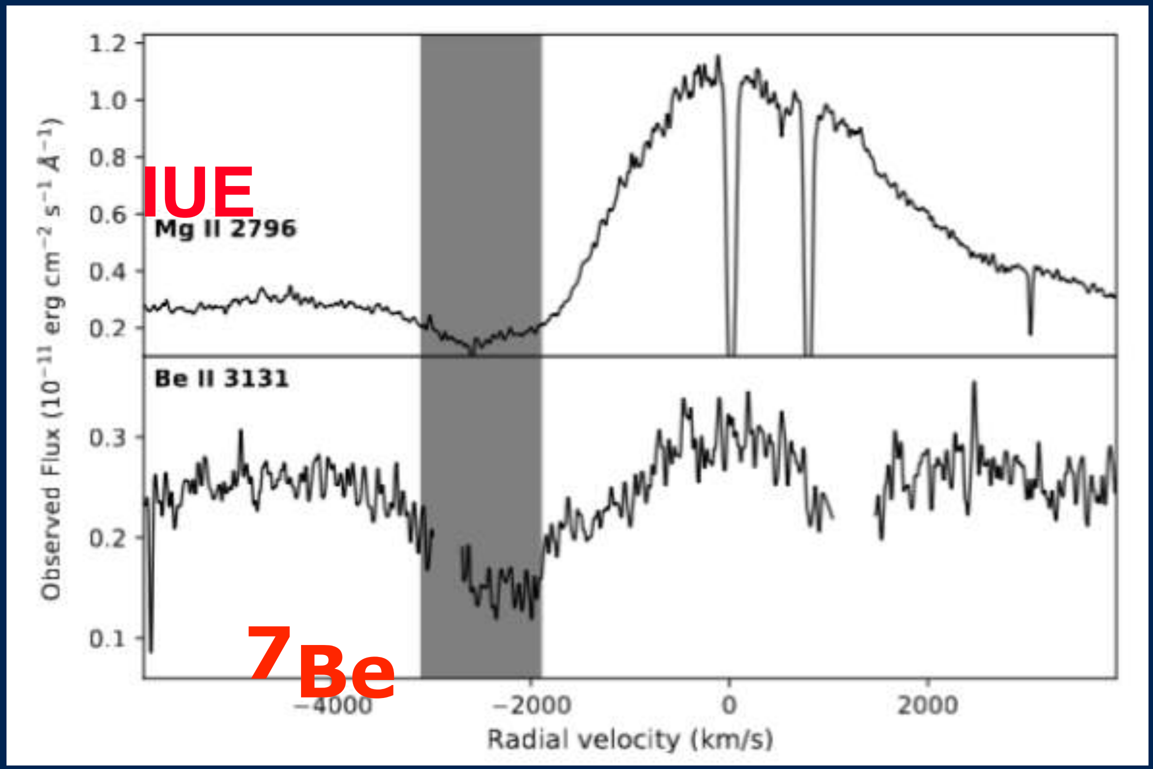
ToO for ^{7}Be

- ToO for bright novae, V< 9 mag at max, with UVES, since 2016, with gaps
  - 9 novae by our group (UVES@VLT)
  - 4 from Tajitsu group (SUBARU)
  - I from archive IUE

Nova Herculis 1991

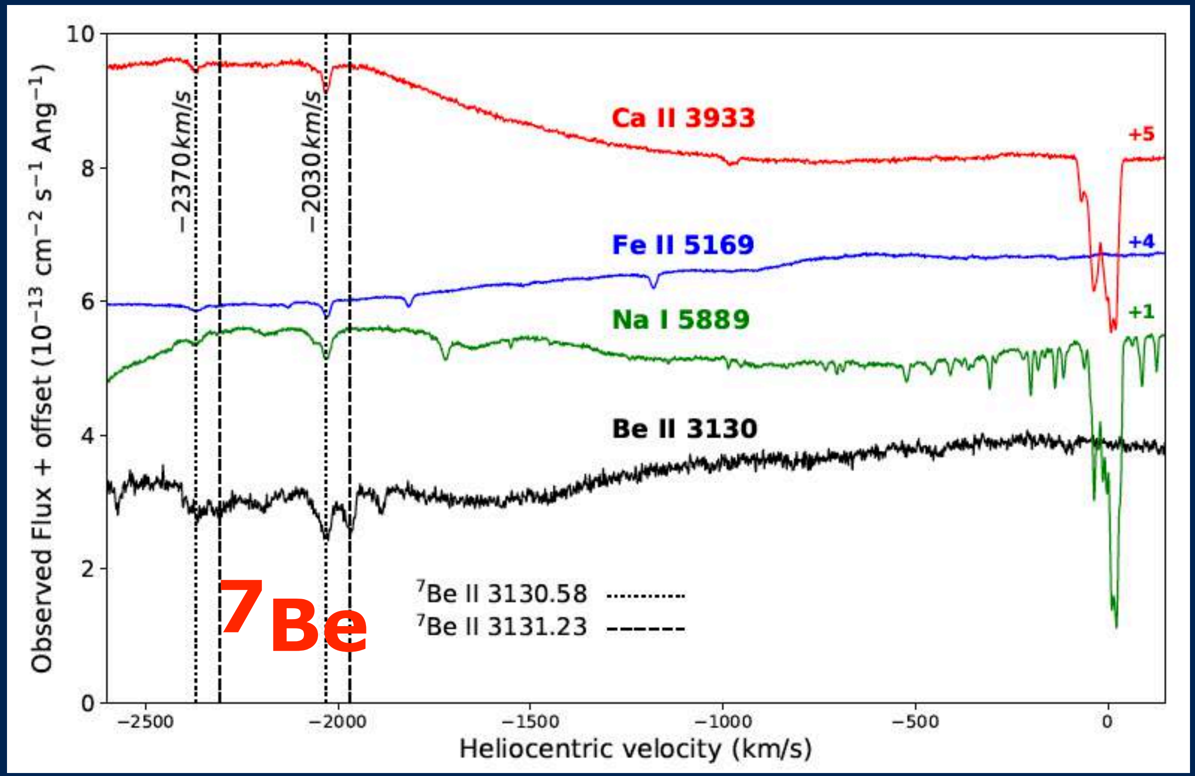
From IUE archive:

Selvelli+19



Nova Lupi 2017

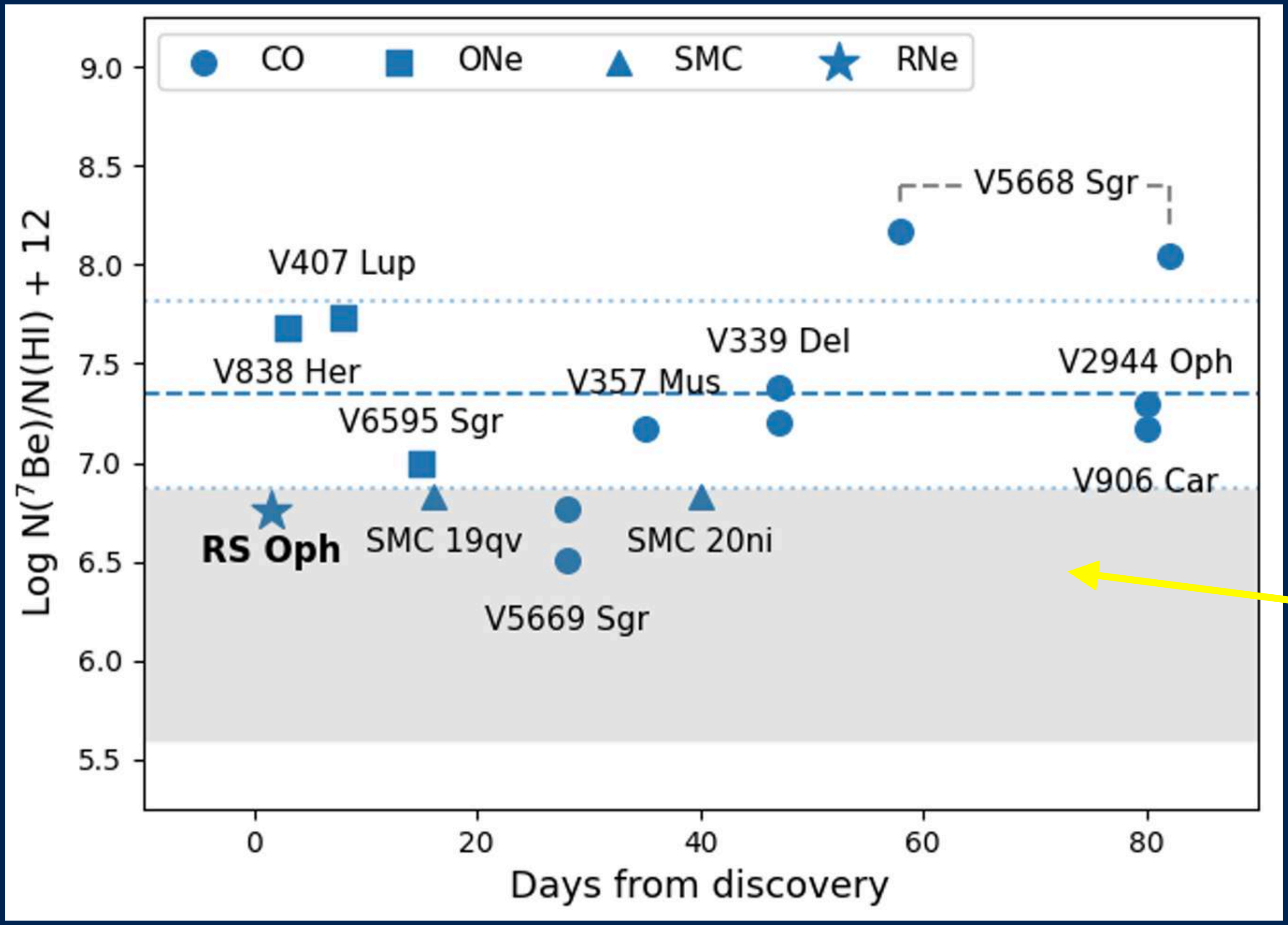
Izzo+18



^{7}Be (= ^{7}Li) yields

- Unsaturated and resolved components
- Relative to CaII, or MgII (assumed solar)
- CaII and BeII dominant ionisation stage

PM, Izzo, L.; Selvelli, P.; Bonifacio, P.; Aydi, E.; Cescutti, G.; Guido, E.; Harvey, E. J.; Hernanz, M.; Della Valle, M. 2023



Nova Models Much lower Starrfield+20,23

- <A(Li)> ~ 7.4,
- 4 orders of magnitude >> meteoritic A(Li) = 3.3,
- Tension in the yields: models << observations

Nova contribution to the Galactic Li ??

- ^{7}Li per event:

  yield (in mass) x ejecta ~ 1.4×10^{-4} x ~ 10^{-5} $M_\odot$

  $< {}^{7}Li > \sim 1.4 \times 10^{-9}\, M_\odot$

- Li Galactic production

  Li-event x nova rate x Age of the Galaxy

  $1.4 \times 10^{-9} \times 30 \times 10^{10} \sim 420\, M_\odot$

➡ Novae are an important Galactic ^{7}Li source!

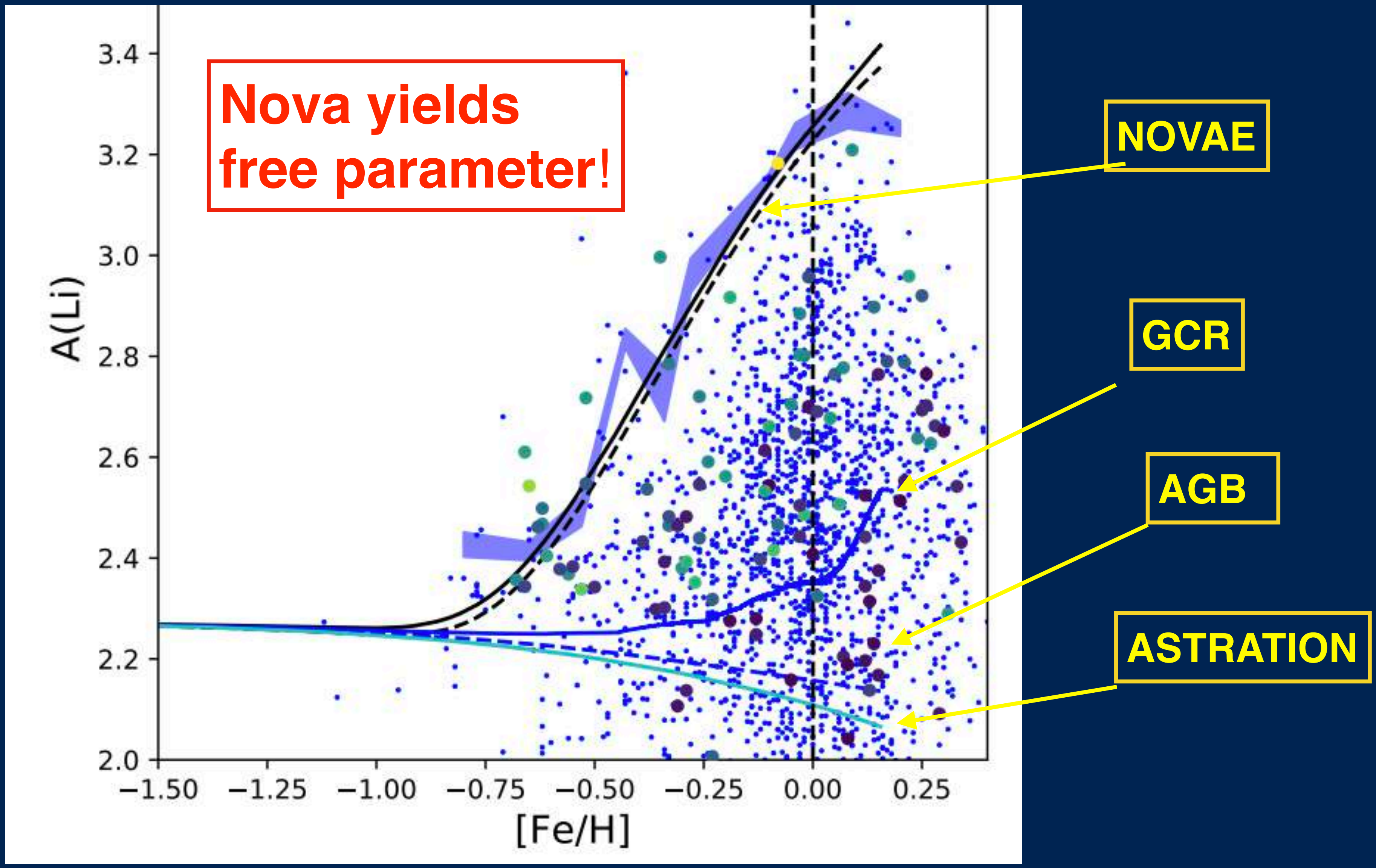
➡ But with the observed yields (theoretical yields 1dex lower)!

Galactic Li evolution

- **State of the art CE model (Romano+01)**
- **Novae yields free**
- **Li Sources:**
  - **- AGB,**
  - **- GCR**

Cescutti & PM, 2019

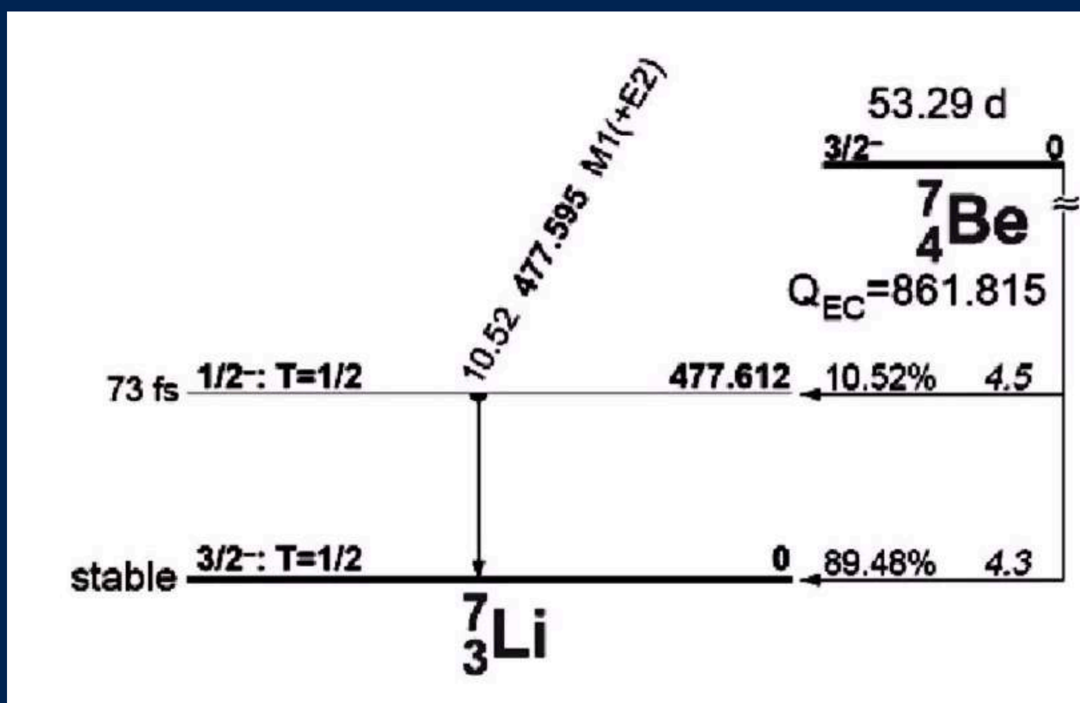
- Li database: AMBRE Guiglion+16



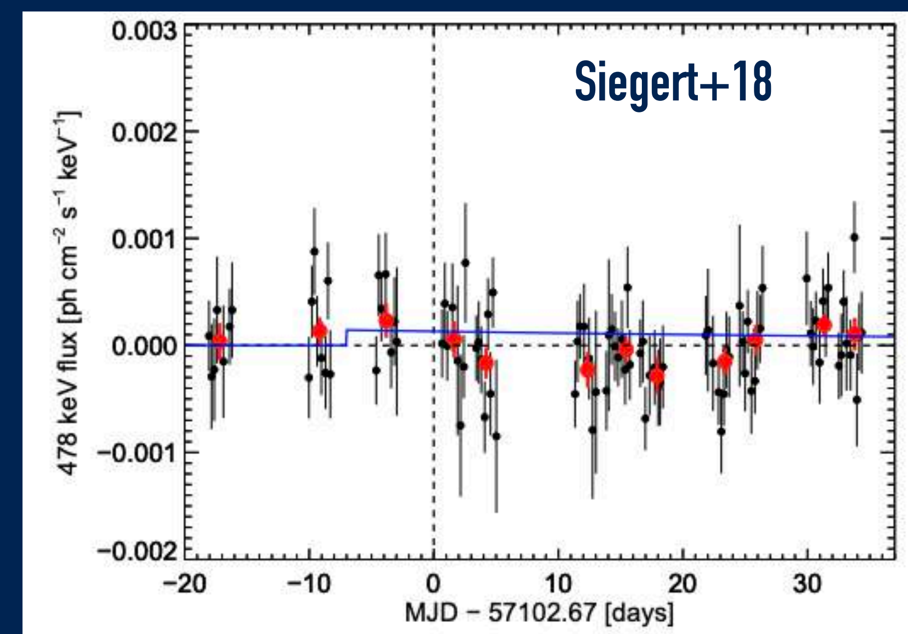
- **Results:**
  - **- Li single burst: 1.8 10^{-9} M$\odot$**
  - **- delay contribution: 1 Gyr**
  - **- Initial value of Li non important**

478 KeV emission line

- ^{7}Be decays into ^{7}Li with an emission at 478 KeV.
- Not yet detected



- The SPectrometer on INTEGRAL (SPI) pointed V5668 Sgr by chance



(b) 478 keV line.

- No significant flux at 478 KeV.

➡ ^{7}Be mass is < 4.8 x 10^{-9} (d/Kpc)^{2} M☉.

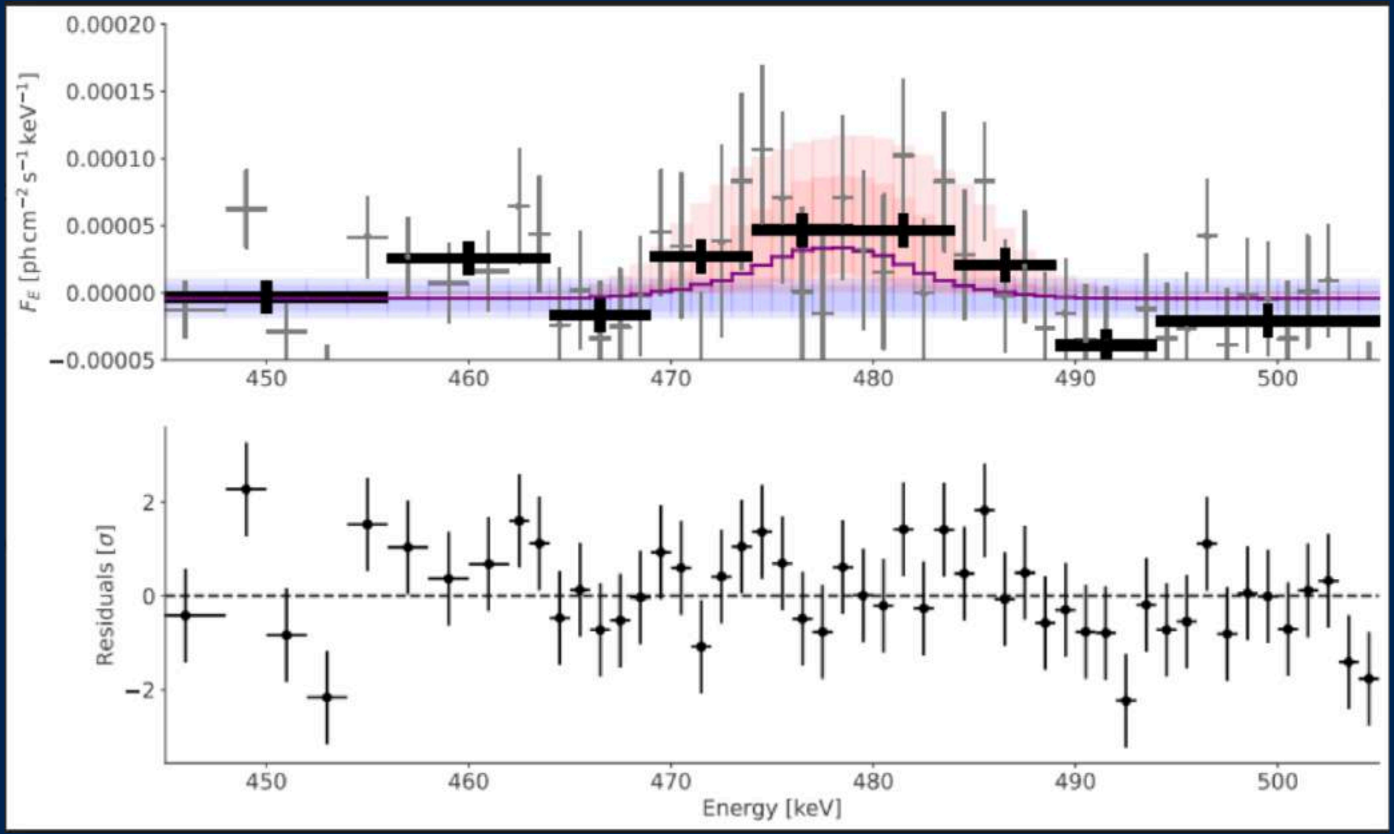
➡ d > 1.1 kpc consistent with d = 1.54 kpc (Banerjiee+ 2016)

- ToO with INTEGRAL for novae with d < 0.5 kpc P.I. Margarita Hernanz.

478 KeV emission line

Another nova at d=317(+/-55) pc
In the field of the SPectrometer on INTEGRAL (SPI)

Courtesy:
Luca Izzo, Thomas Siegert, Pierre Jean, Margarita Hernanz, PM, in prep.



Gaussian 8KeV FWHM

➡ 480 +/- 1.8 KeV

➡ Flux: (4.35 +/- 1.74) x10^{-4} ph/cm/s

➡ ^{7}Be =^{7}Li mass~ 2.7(+/- 1) x10^{-9} M☉

stay tuned!

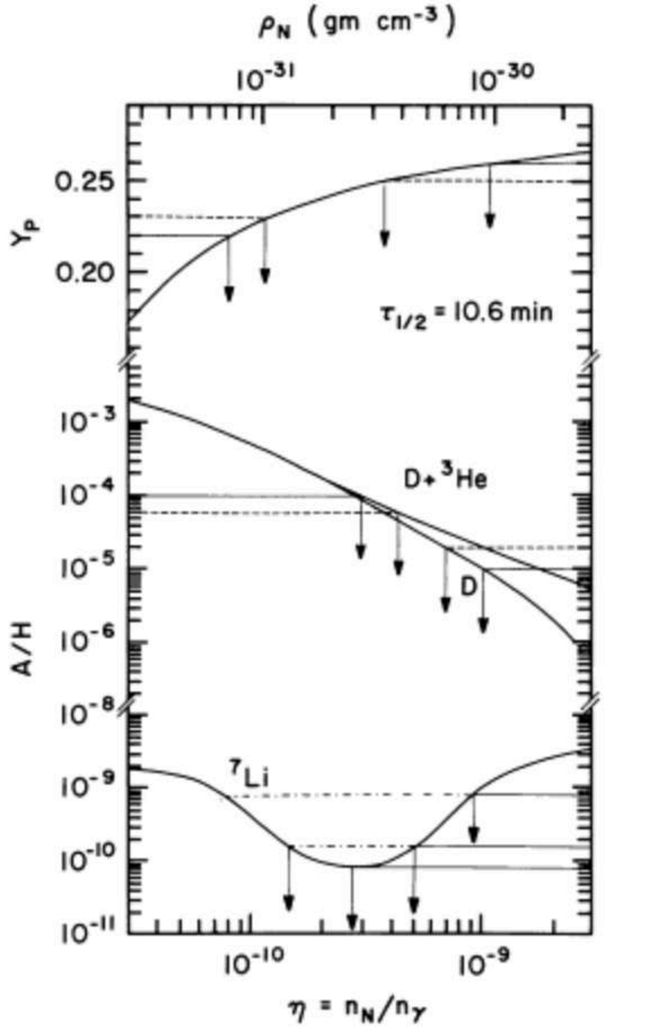
Summary part 1

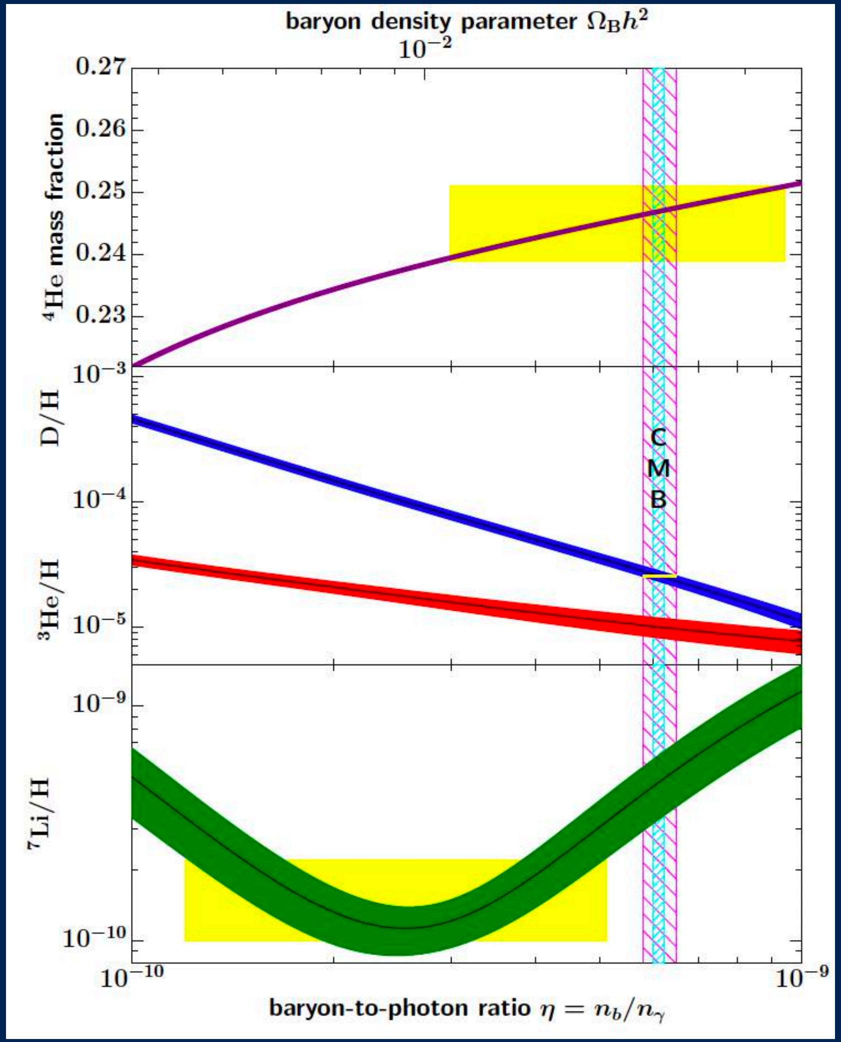
- **Riddle of Galactic Lithium solved?**
  - Novae are the only viable source
  - They could make it all
  - If observational yields are right

Part 2: the riddle of primordial Li

1985

2023



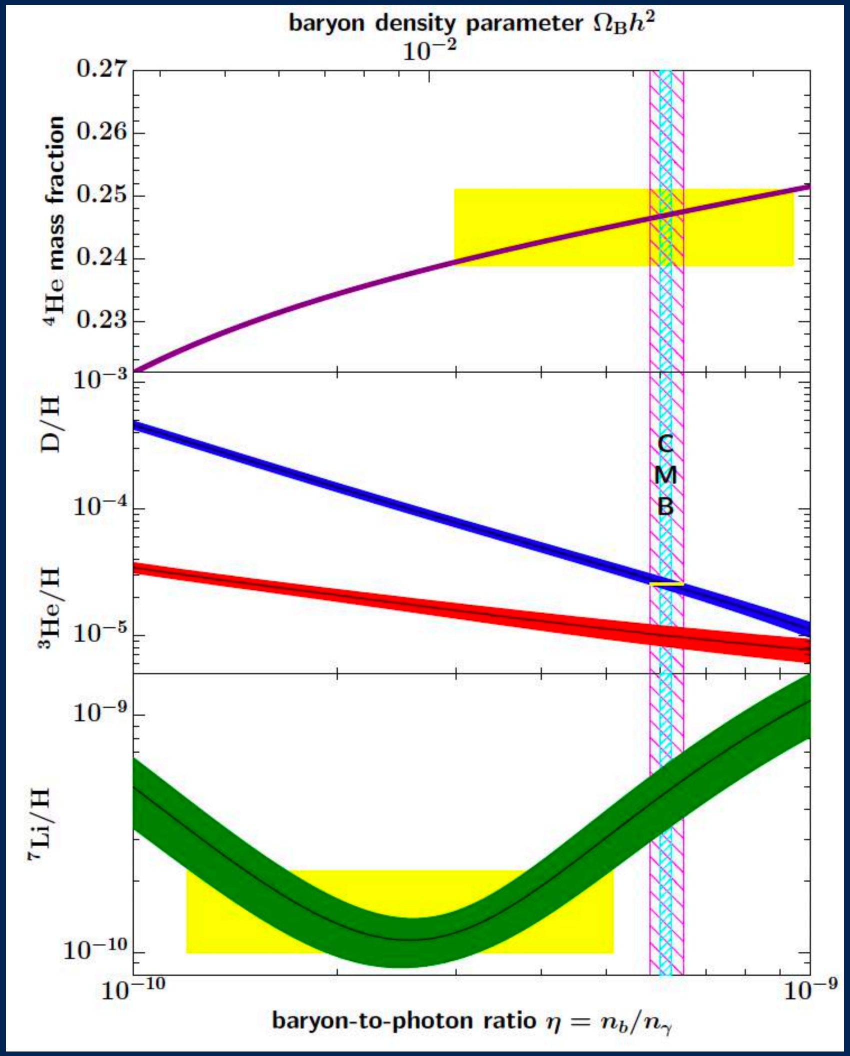


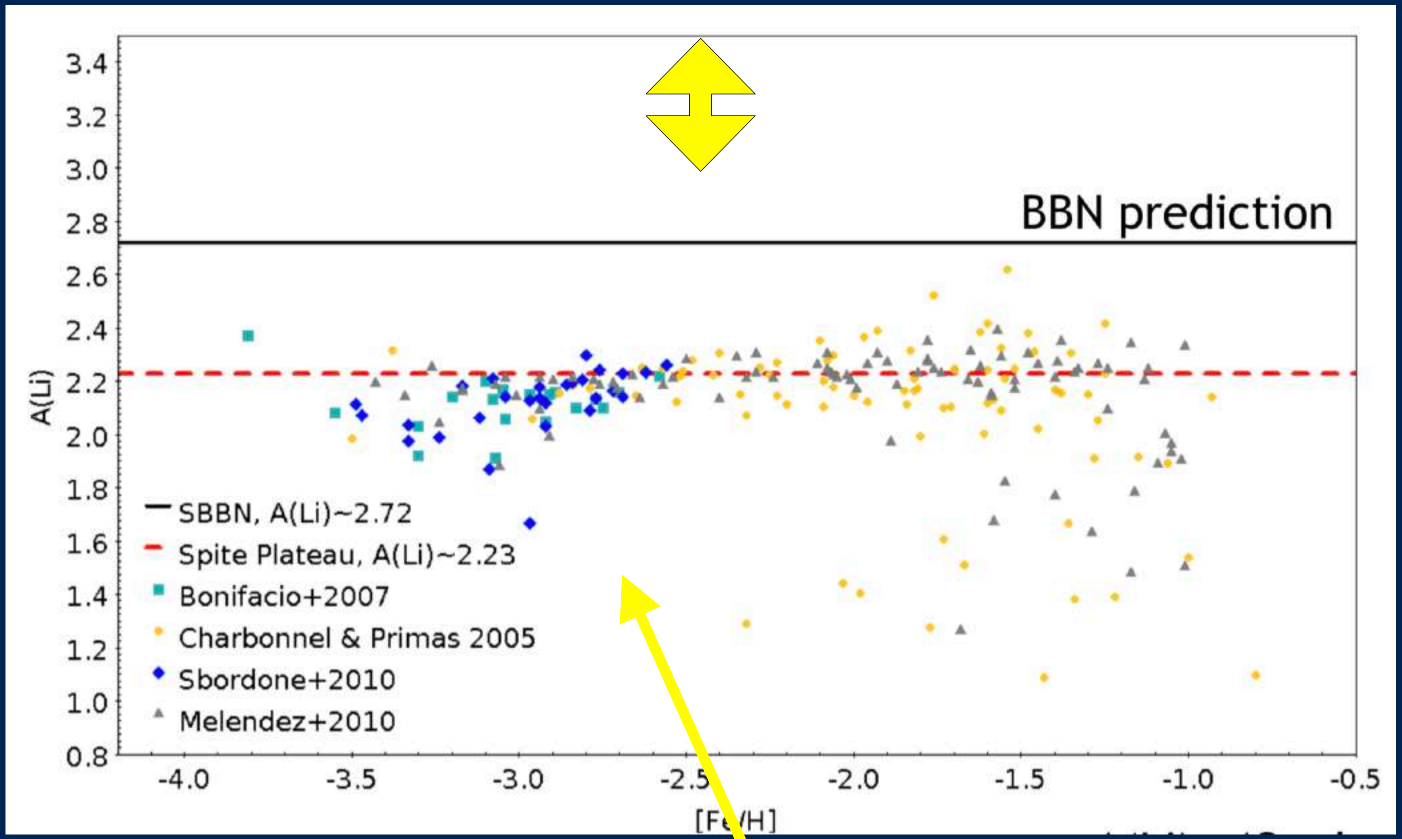
Boesgaard Steigman 1985. AAAR

Part 2: the riddle of primordial Li

Stellar abundances
3 x lower than BBN

- **$A(\mathrm{Li})_{BBN}$ = 2.69 ±0.02 (Yeh+21)**
- **$A(\mathrm{Li})_{stars}$ = 2.22 ±0.02 -3.0<[Fe/H]<-1.5 (Sbordone+1**



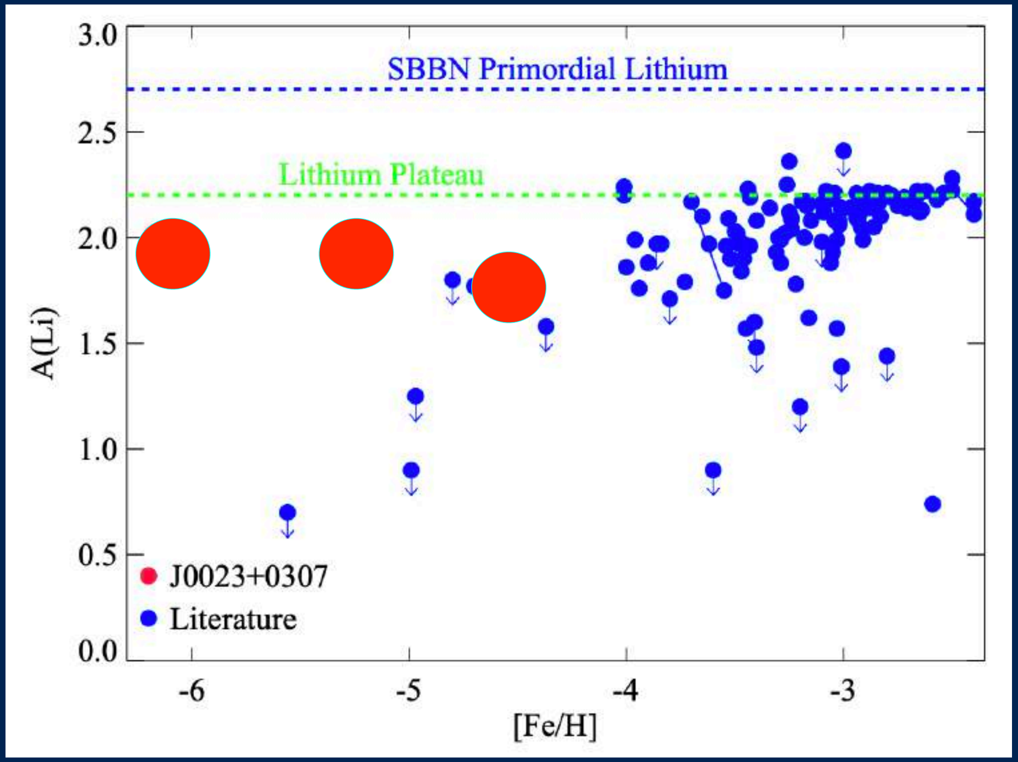


- **"*meltdown*" for [Fe/H]<-3.0 (Sbordone+10)**

Meltdown at [Fe/H]<-3.0

- **What's happening at the lowest metallicities?**
  - **[Fe/H]<-4: 8 stars, 3 Li detection, 4 upper limits**

Aguado+19



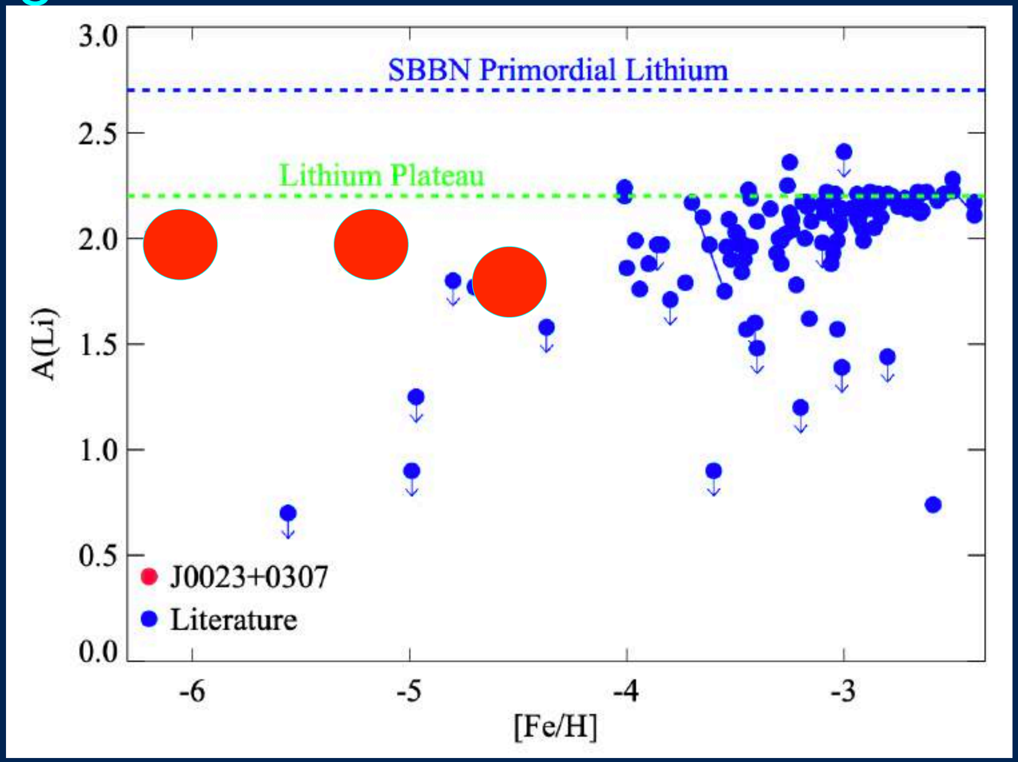
- **CEMP (carbon enhance metal poor):**
  - **100% [Fe/H] < -5**
  - **~50% -5<[Fe/H] < -4**
  - **~30% -4<[Fe/H] < -3**

Meltdown at [Fe/H]<-3.0

- **What's happening at the lowest metallicities?**
  - **Increase of scatter"*meltdown*" for [Fe/H]<-3.0 (Sbordone+10)**
  - **[Fe/H]<-4: 8 stars, 3 Li detection, 5 upper limits**

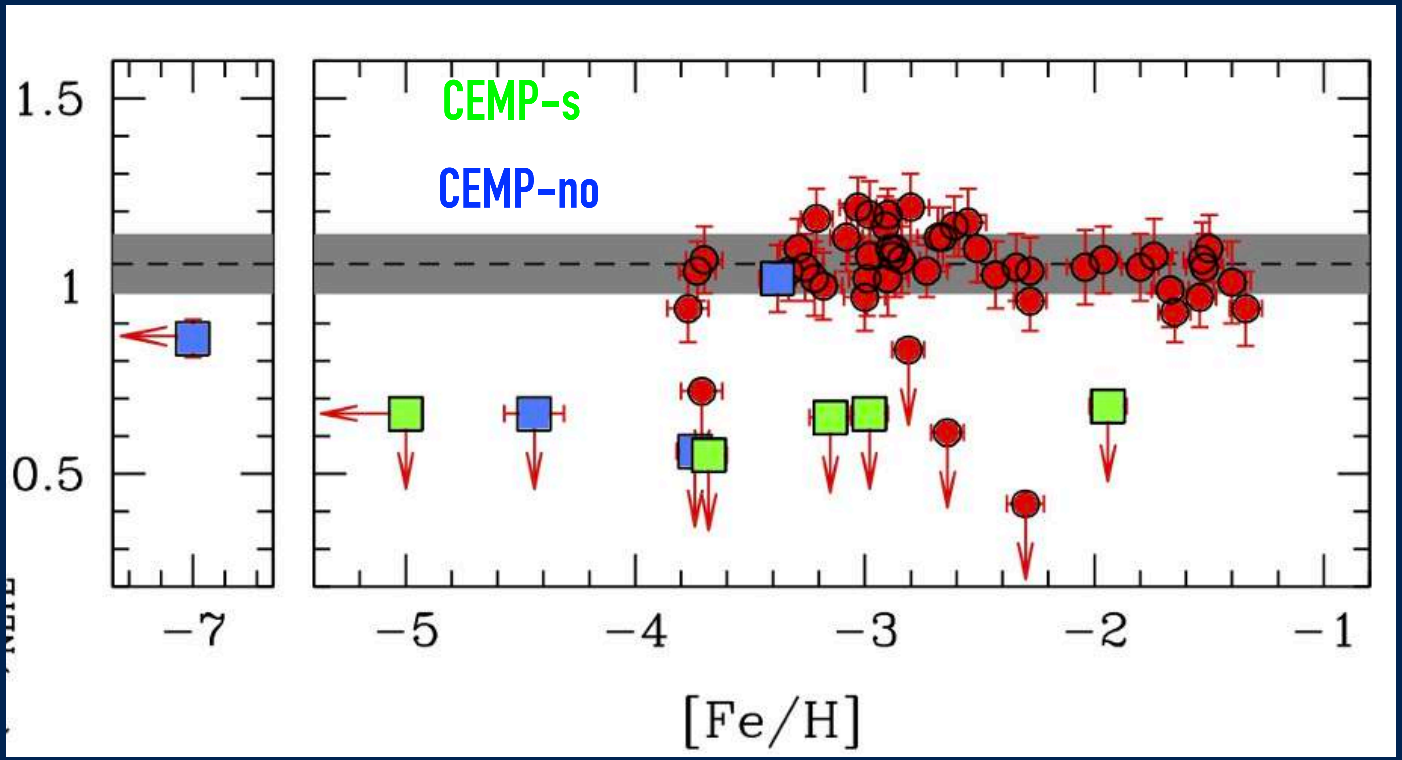
Aguado+19

DWARFS



GIANTS

Mucciarelli + 22



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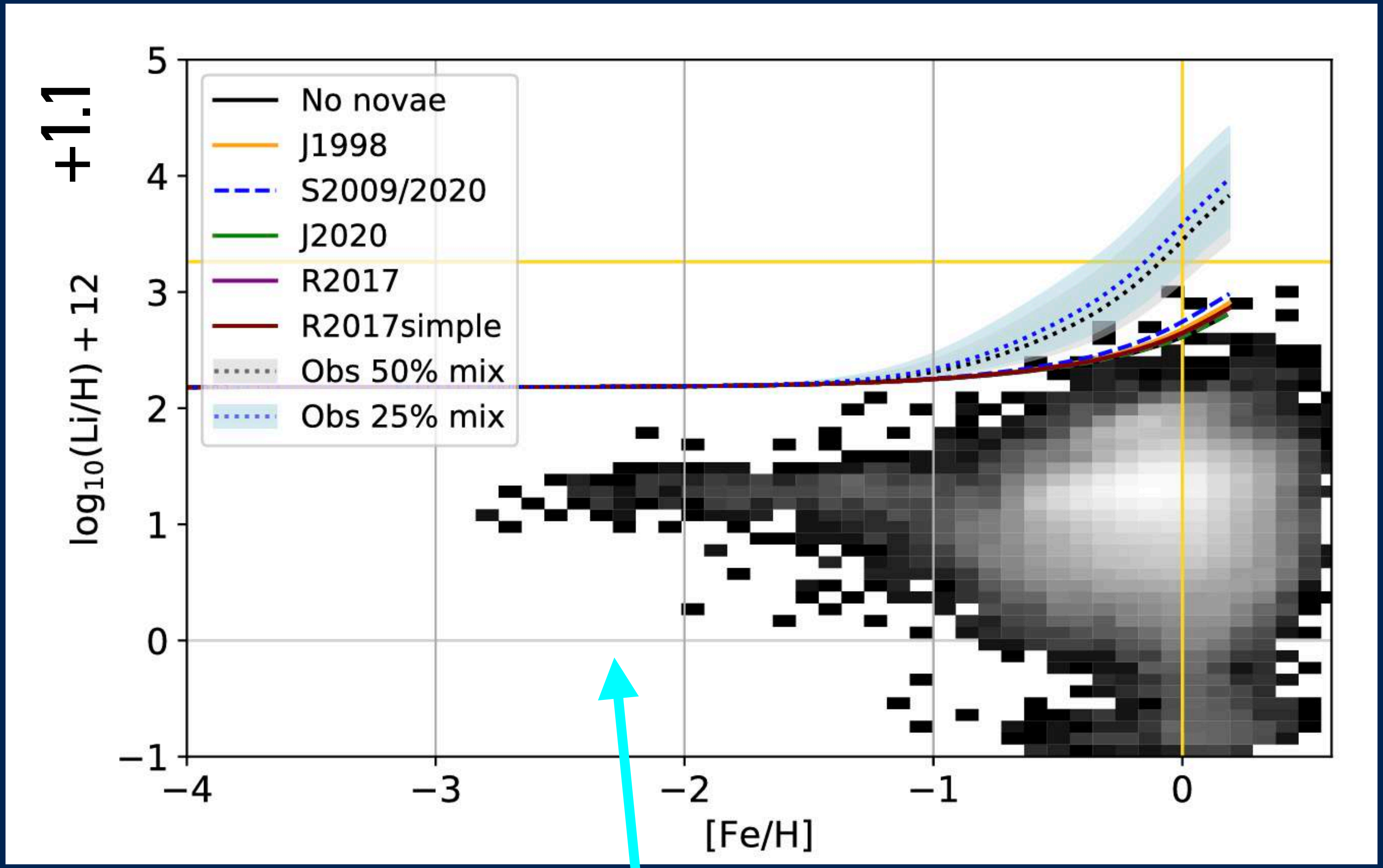
  - **100% [Fe/H] < -5**
  - **~50% -5<[Fe/H] < -4**
  - **~30% -4<[Fe/H] < -3**

- **Plateau of giants (mirror of the Spite plateau)**
- **Li depleted mostly CEMP-s and CEMP-no**
- **Smaller masses i.e. more PMS depletion**
- **More compact , i.e. smaller distance between CZ and burning layer**

GALAH
1 million stars

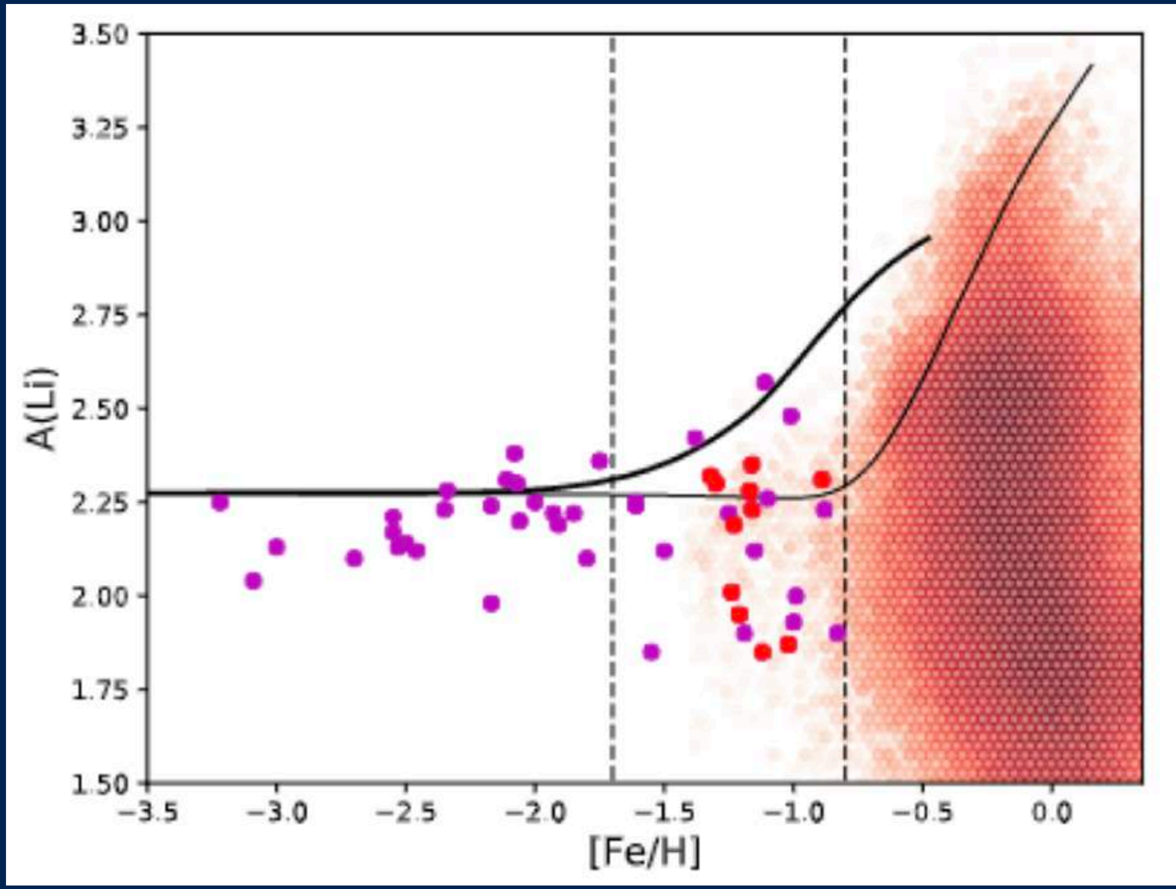


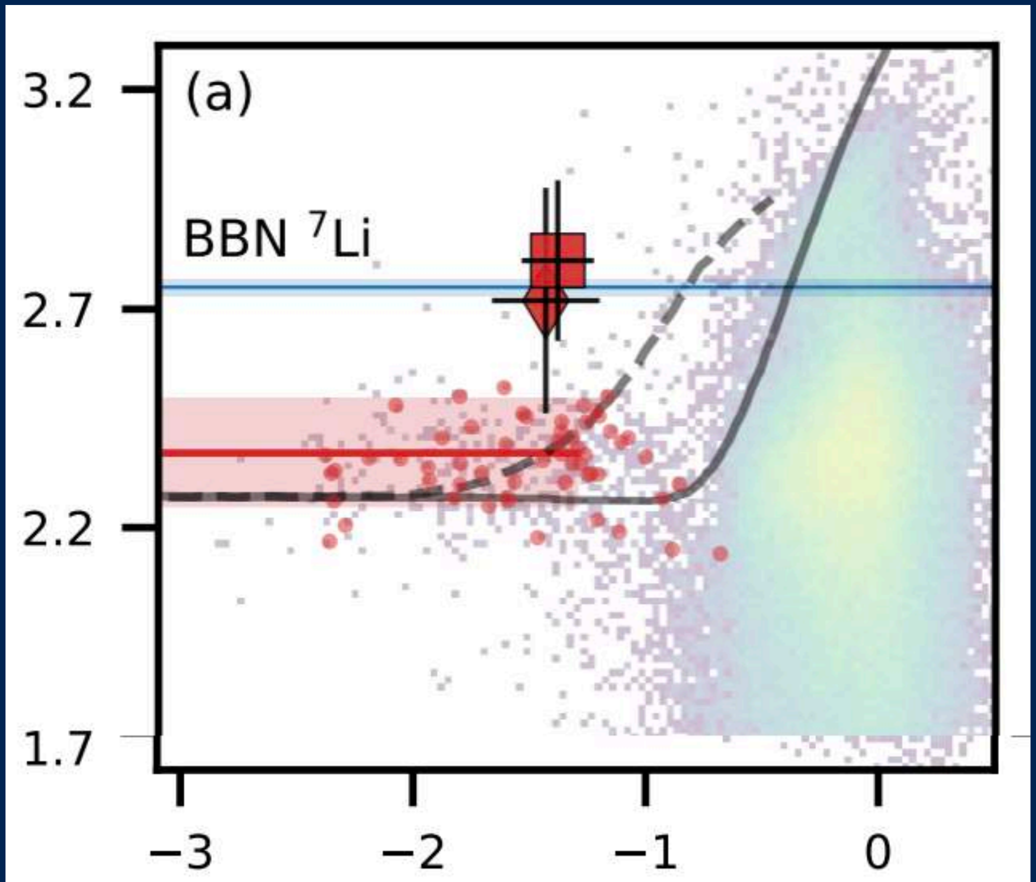
Spite plateau is still alive with
A(Li) ~ 2.2 for [Fe/H]<-1.5

Li in other galaxies?

- **MS stars out of reach**
- **Proxy: GAIA-Sousage-Enceladus: ancient satellite that merged with the MW kinematic & chemical signatures** (Belokurov+18, Helmi+18,Haywood+18)

PM Cescutti Fu, 2020;





- **In Enceladus stars [Fe/H] < -2:**
A(Li) = 2.18 ± 0.10

- **Simpson+ 2021, with GALAH**
A(Li) = 2.3

➡ The Li problem is not only a Galactic feature

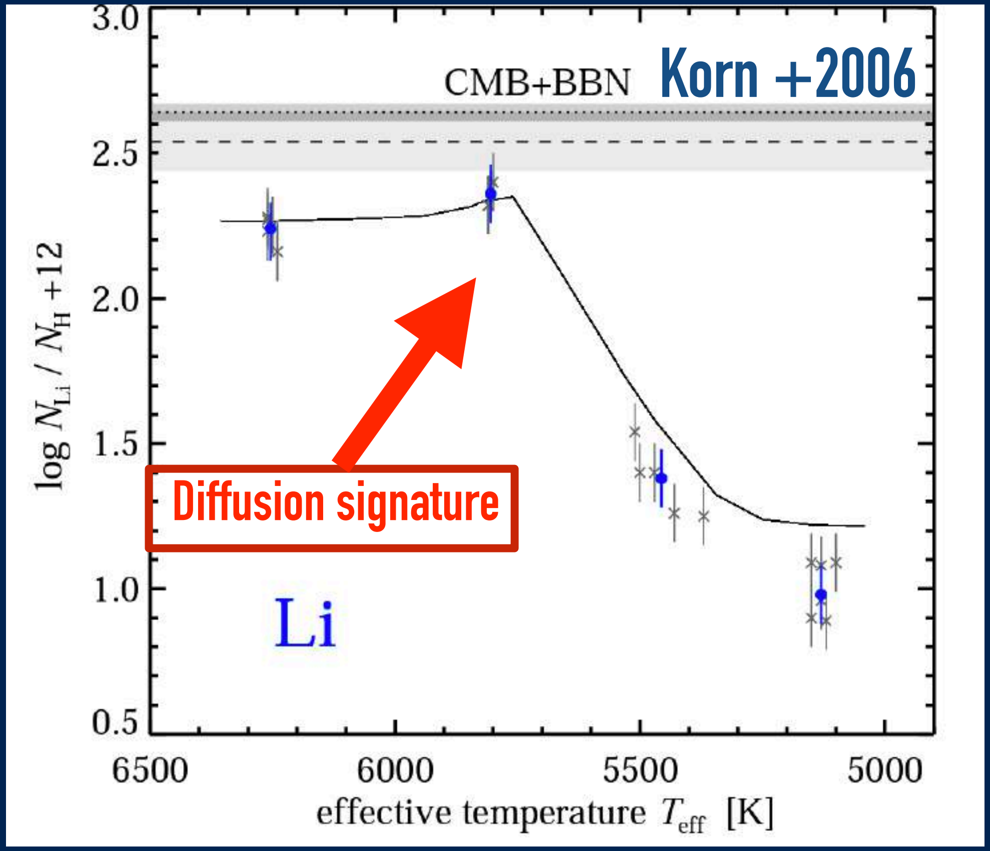
Stellar fix1: diffusion+mixing

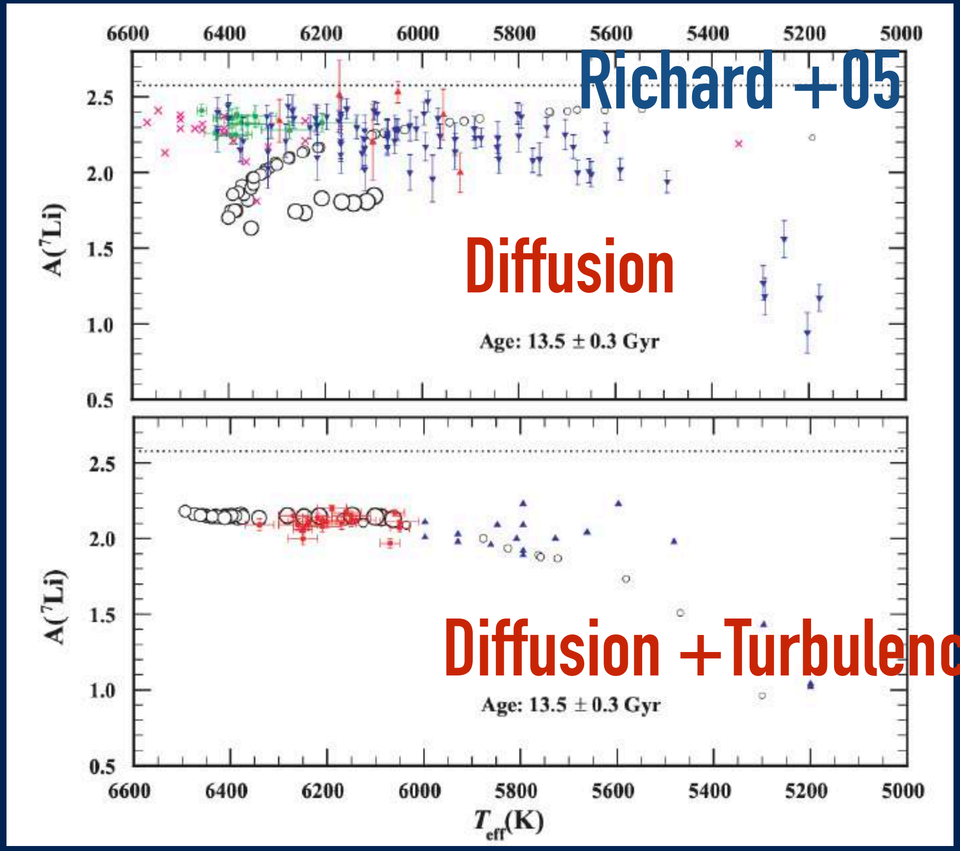
PARSEC code

- $^{6}Li / ^{7}Li < 0.02$ (Wang+ 22)
  - ➡ Stellar ^{7}Li depletion possible (Fields Olive+22)

- Hydrodinamical Mixing due to rotation (Pinsonneault+92,+02
- Gravitational settling -diffusion Vauclair & Charbonelle 1998
- Turbulent diffusion (Richard +02,05, Deal+ 21)

turbulence + gravitational settling



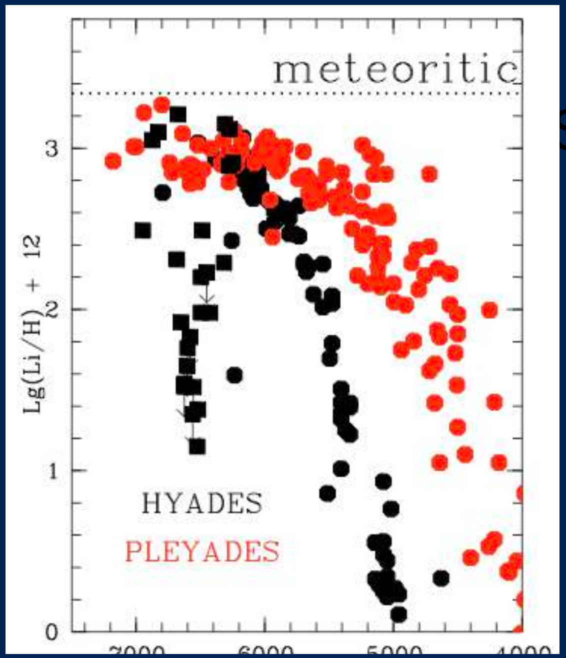


➡ fine tuning required

➡ easy for 1 star, more difficult for 100 field stars, still to be demonstrated

Stellar fix 2:   PMS depletion

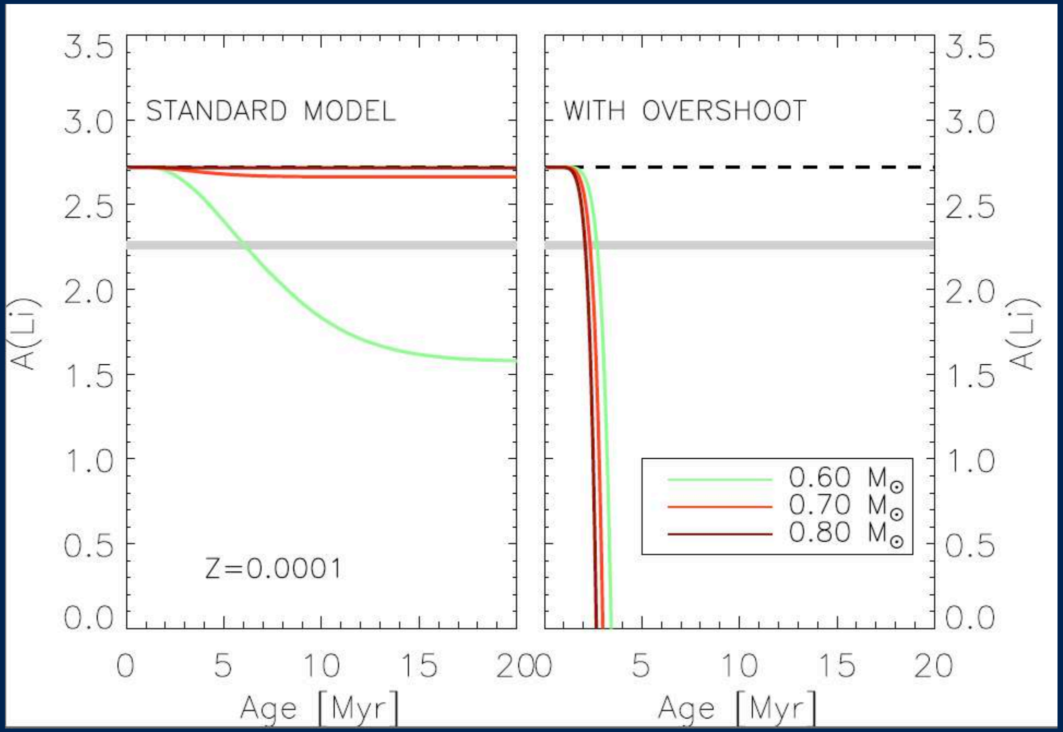
- Young clusters show already depletion
  - ➡ PMS Li destruction (with overshooting)
  - ➡ Followed by accretion of primordial Li material

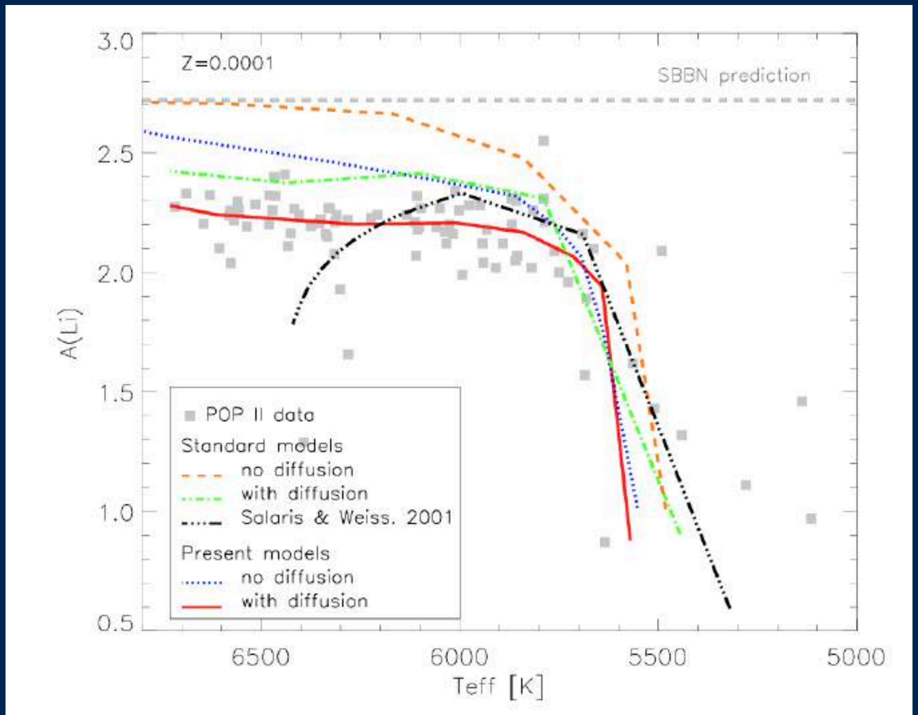


SEC code

Hyades:670 Myrs
Pleiades:100 Myrs

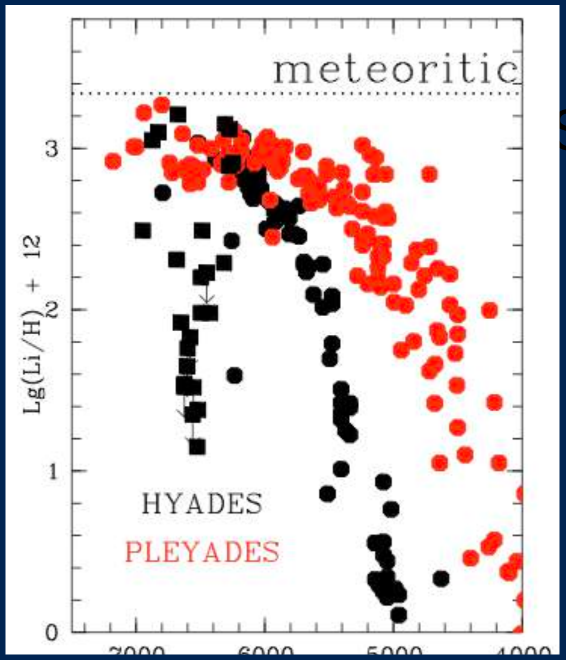
Fu, Bressan , PM Marigo 15





- self-regulating mechanism:
  - less accretion where there is less depletion (hotter stars)
  - More accretion where there is more depletion (cooler stars)
- Testable! Li in very young cluster (<20 Myrs) should reveal Li depletion

Stellar fix 2:   PMS depletion



SEC code

Hyades:670 Myrs
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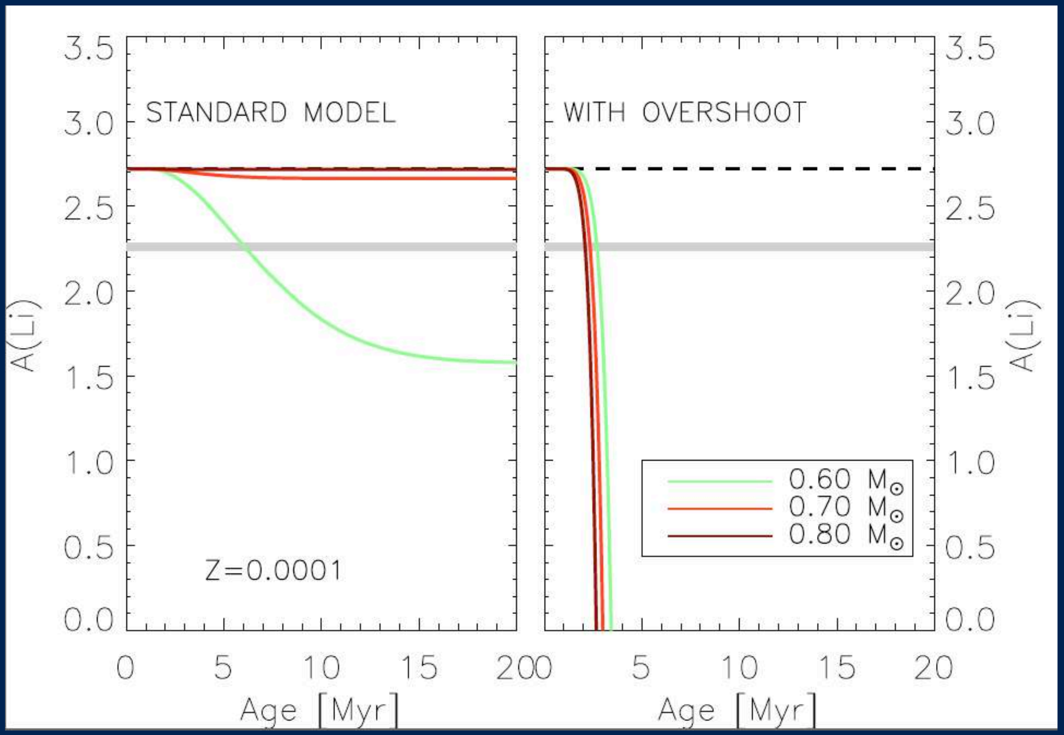
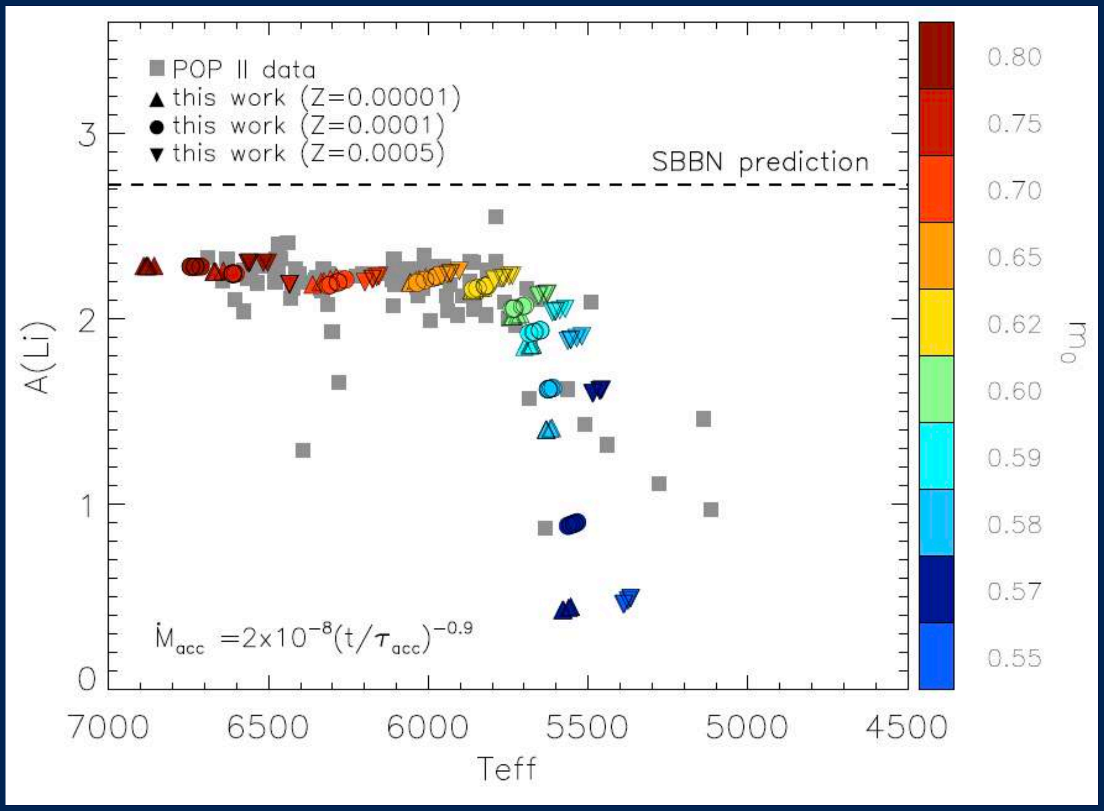
Fu, Bressan , PM Marigo 15





- self-regulating mechanism:
  - less accretion where there is less depletion (hotter stars)
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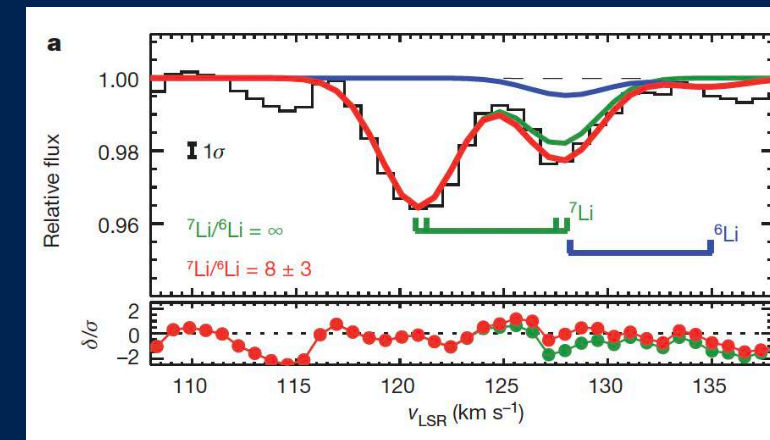
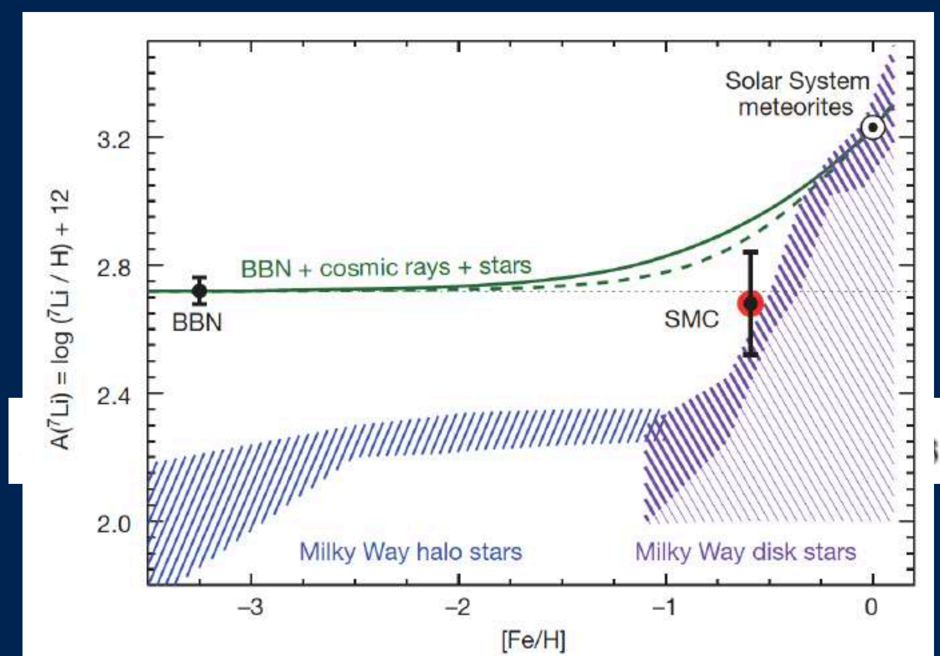
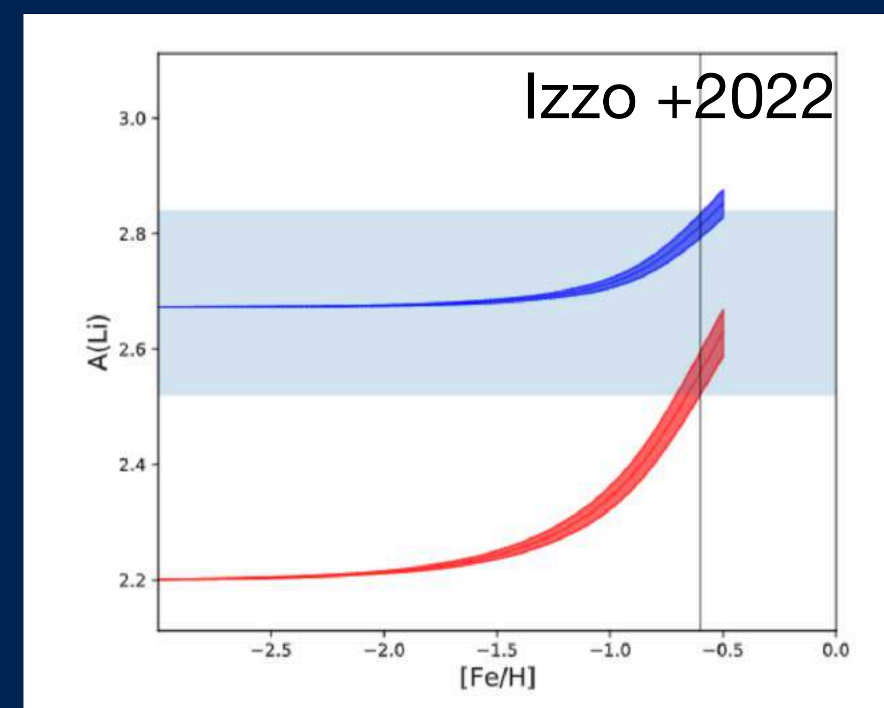
Interstellar Li in metal poor gas



- **Interstellar Li is free from "stellar complications"**
- **IS Li towards SK 143 in the SMC (Howk et al 2012)**





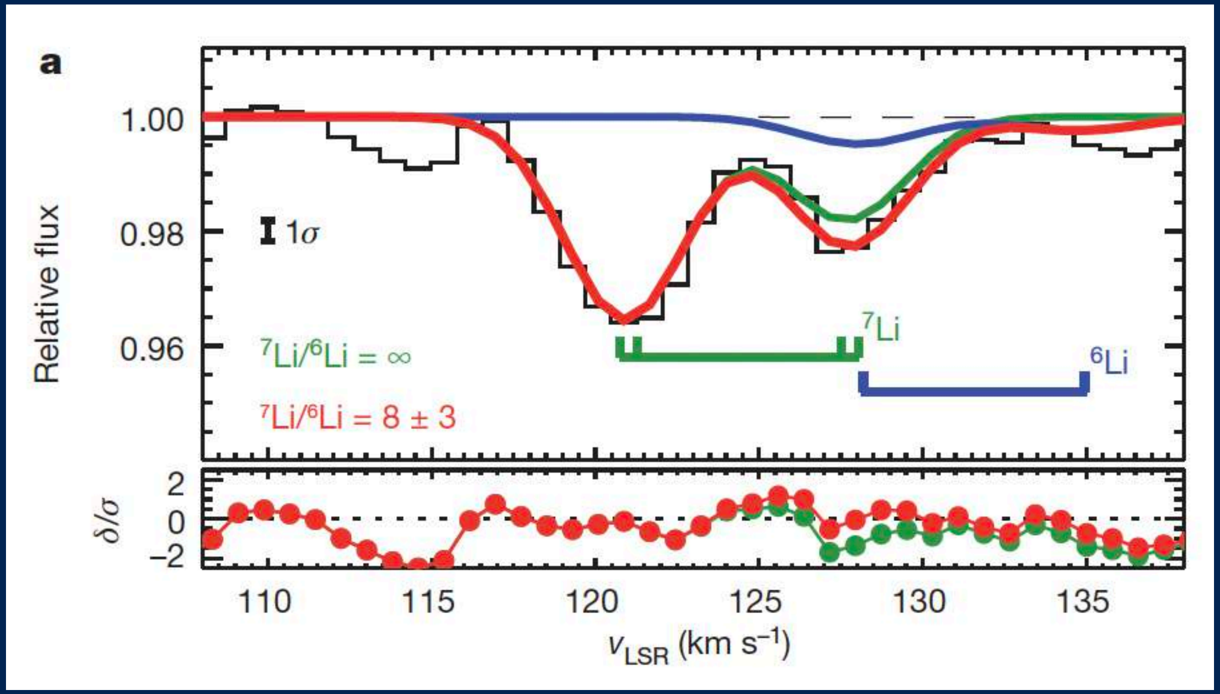
- **KI is used for dust & ionisation corrections**
- **K stellar abundance [K/H]=-0.6**

- **A(Li) = 2.68+/- 0.16 ~ the CMB+BBN value**

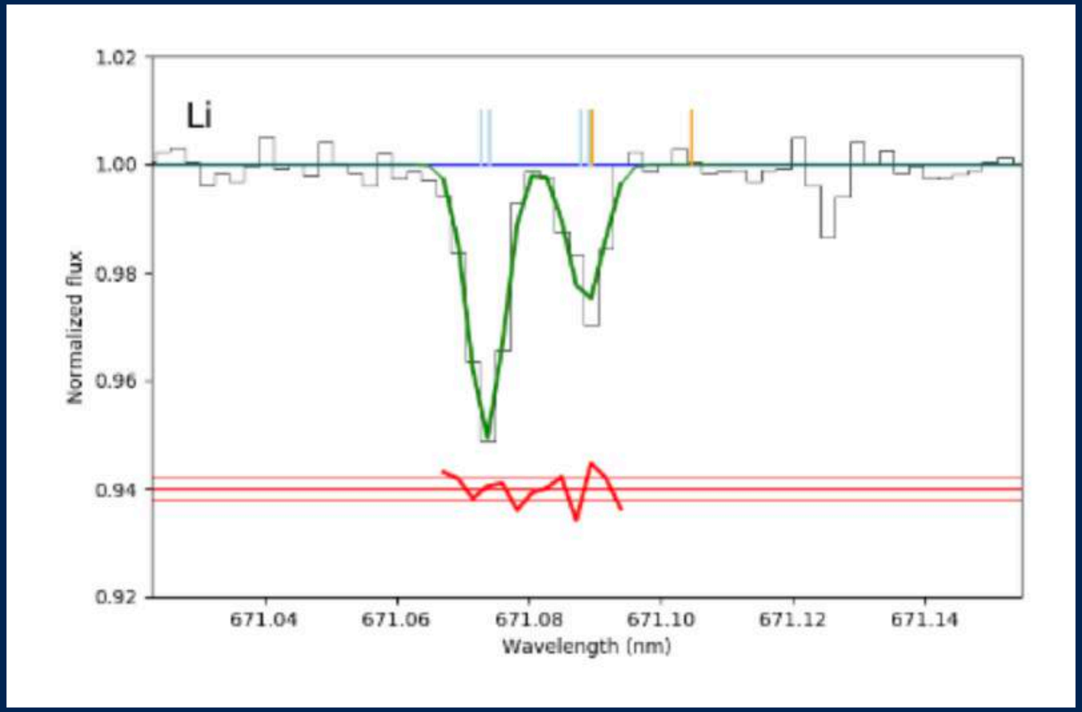
With some Li from novae

• **New Analysis with ESPRESSO spectra R~ 145000**

Howk, Lehneer Fields Mathiews2012



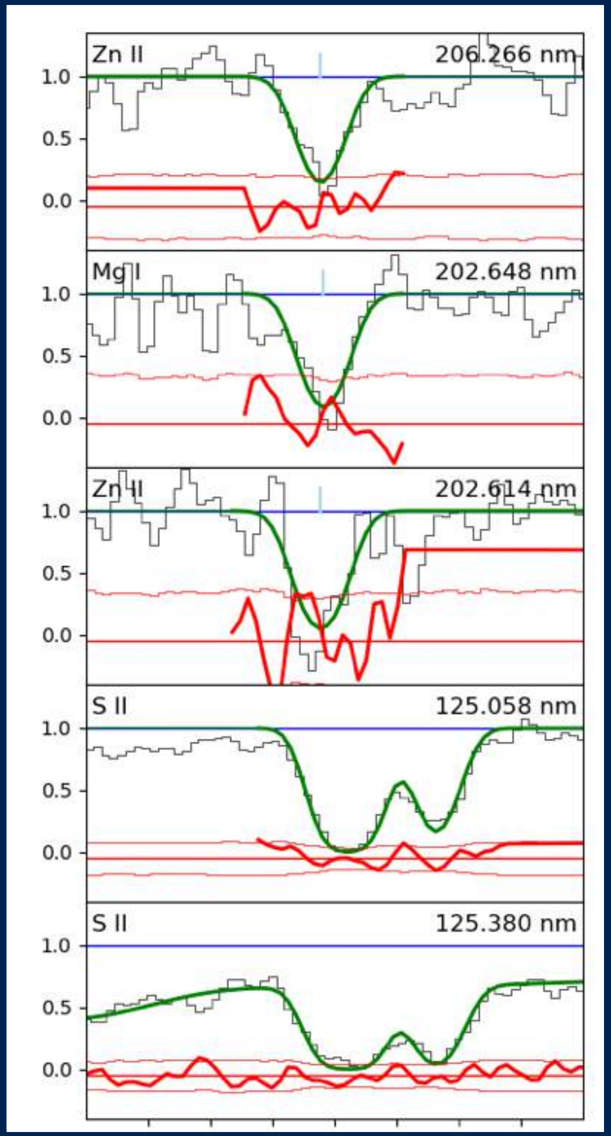
PM + in preparation



$^{7}Li/^{6}Li$ =8+/- 3

$^{7}Li/^{6}Li$ > 10

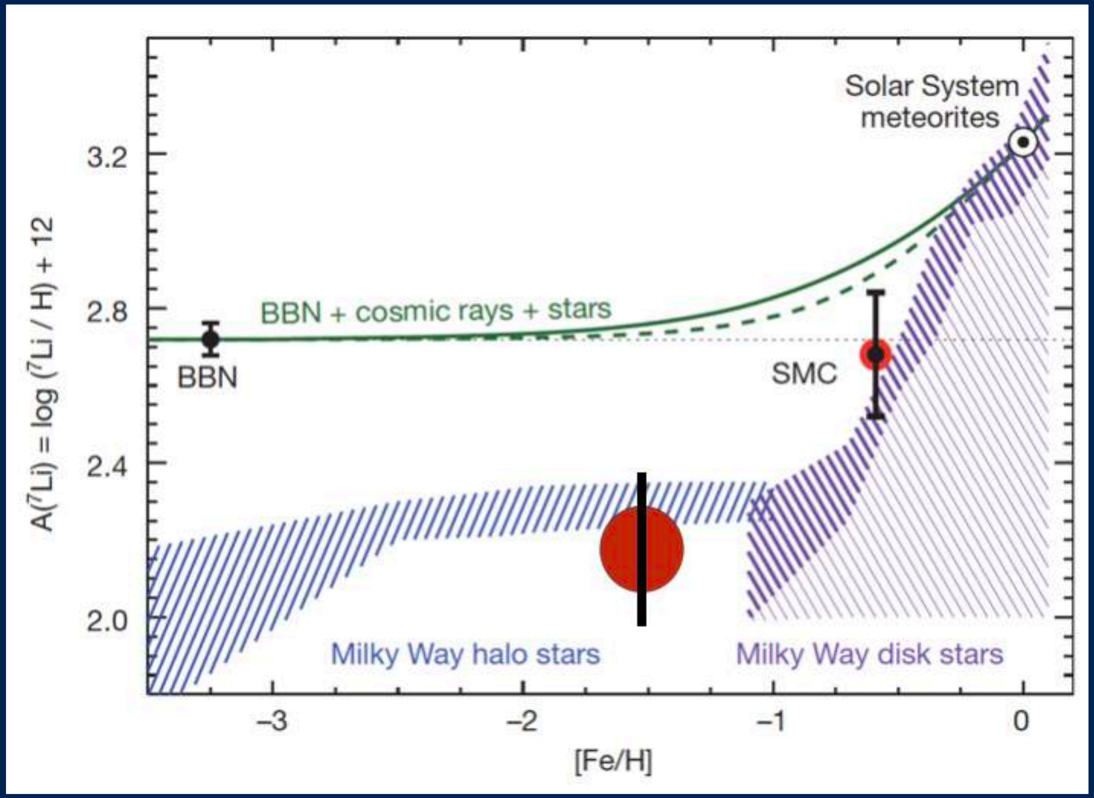
- **Metallicities measured in the cloud at VR = +132 km/s (from STIS HST data)**



[Zn/H] = -1.15 (+/- 0.09)

[S/H] = -0.6(+/- 0.11)

With [K/Zn]=0



A(Li)~2.2+/- 0.12

Summary

- Riddle of Galactic Lithium solved?
  - Novae are the ONLY potential source..
  - but observational yields "need" to be right ones..
  - Theoretical yields are too low

- Riddle of primordial lithium, solved?
  - SBBN (without Li) is looking good,
  - Li shows a tension
  - Stellar fix is possible, but fine tuning required
  - Interstellar Li towards SK143 exacerbates the tension

Thank you Subir!