OMEG 16 Oct. 25 - 28 2022
Hanoi, Vietnam

The Production of ^{10}Be in Core-Collapse Supernovae

And implications for the early solar system

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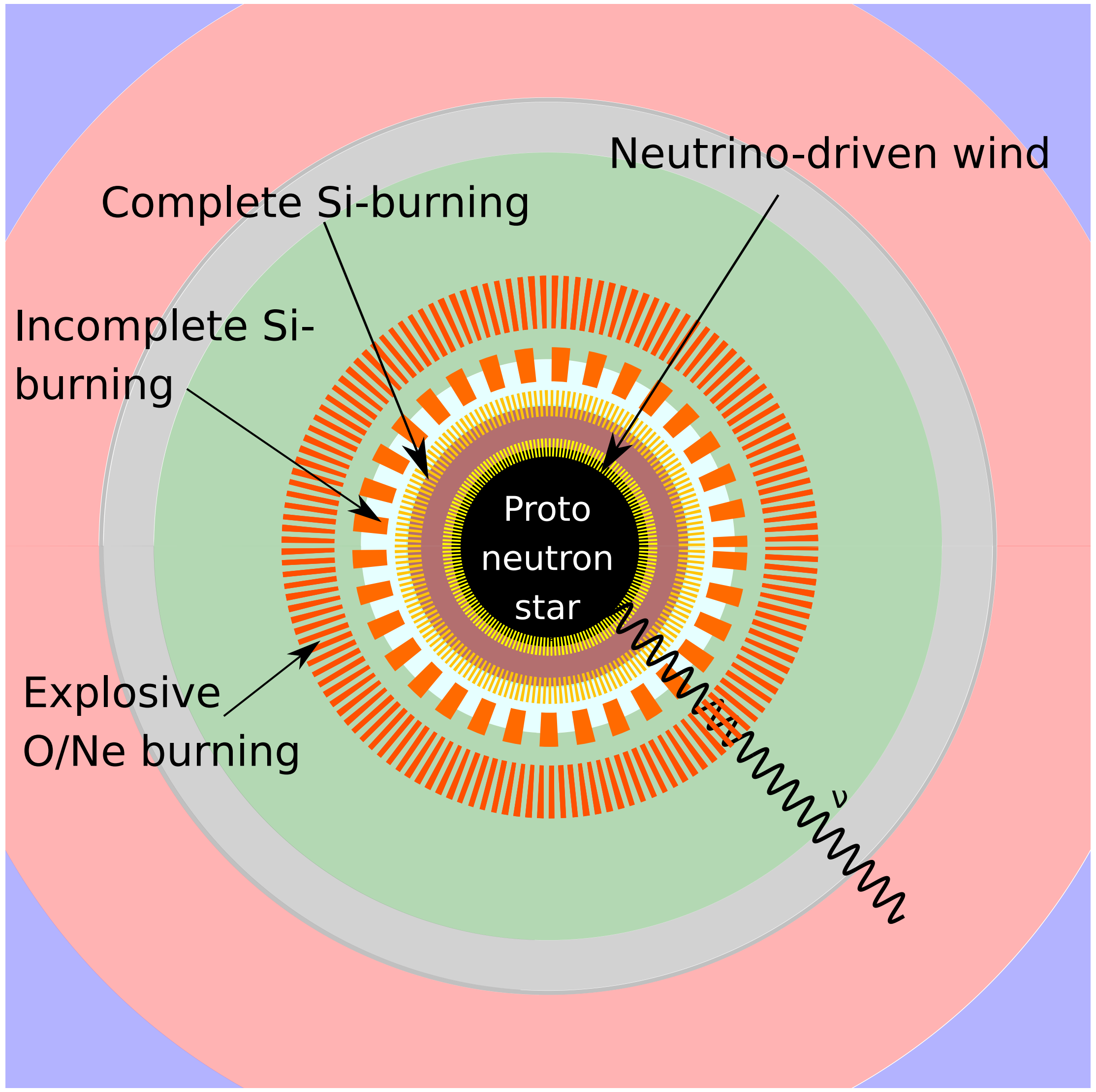
Research supported by US Department of Energy
and the National Science Foundation

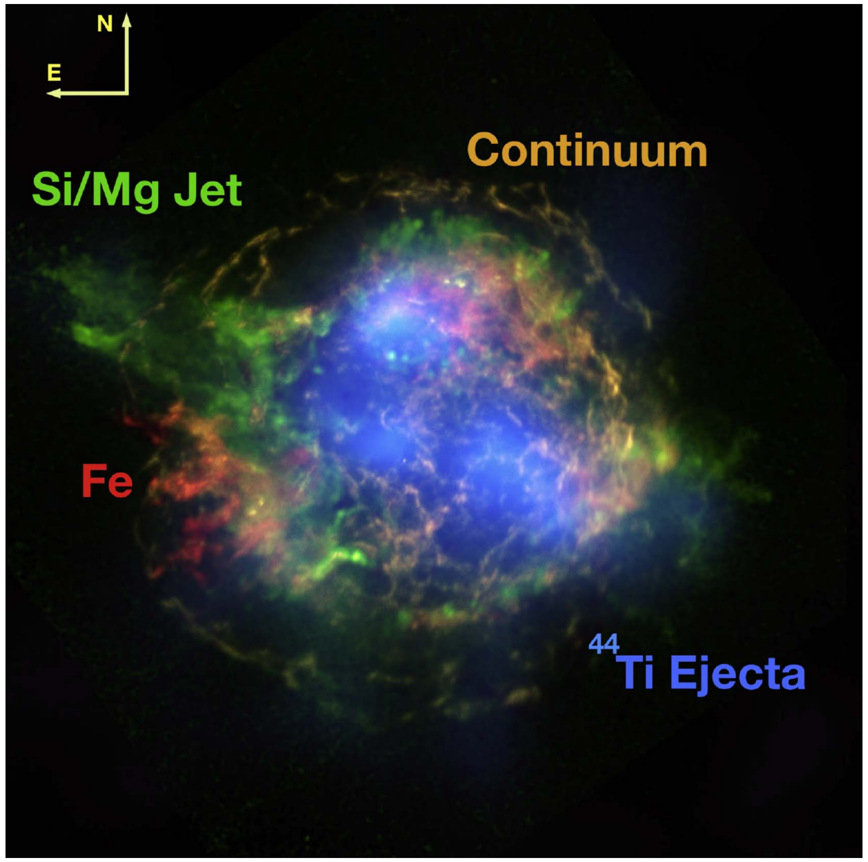
Core-Collapse Supernovae

- Massive stars form an Fe core that collapses
- Neutrino-driven supernova explosion
- Rich nucleosynthesis
  - *Neutrino heated ejecta*
  - *Explosive nuclear burning*
  - *Ejection of stellar nucleosynthesis products*
- Difficult multi-physics problem, very few self-consistent models

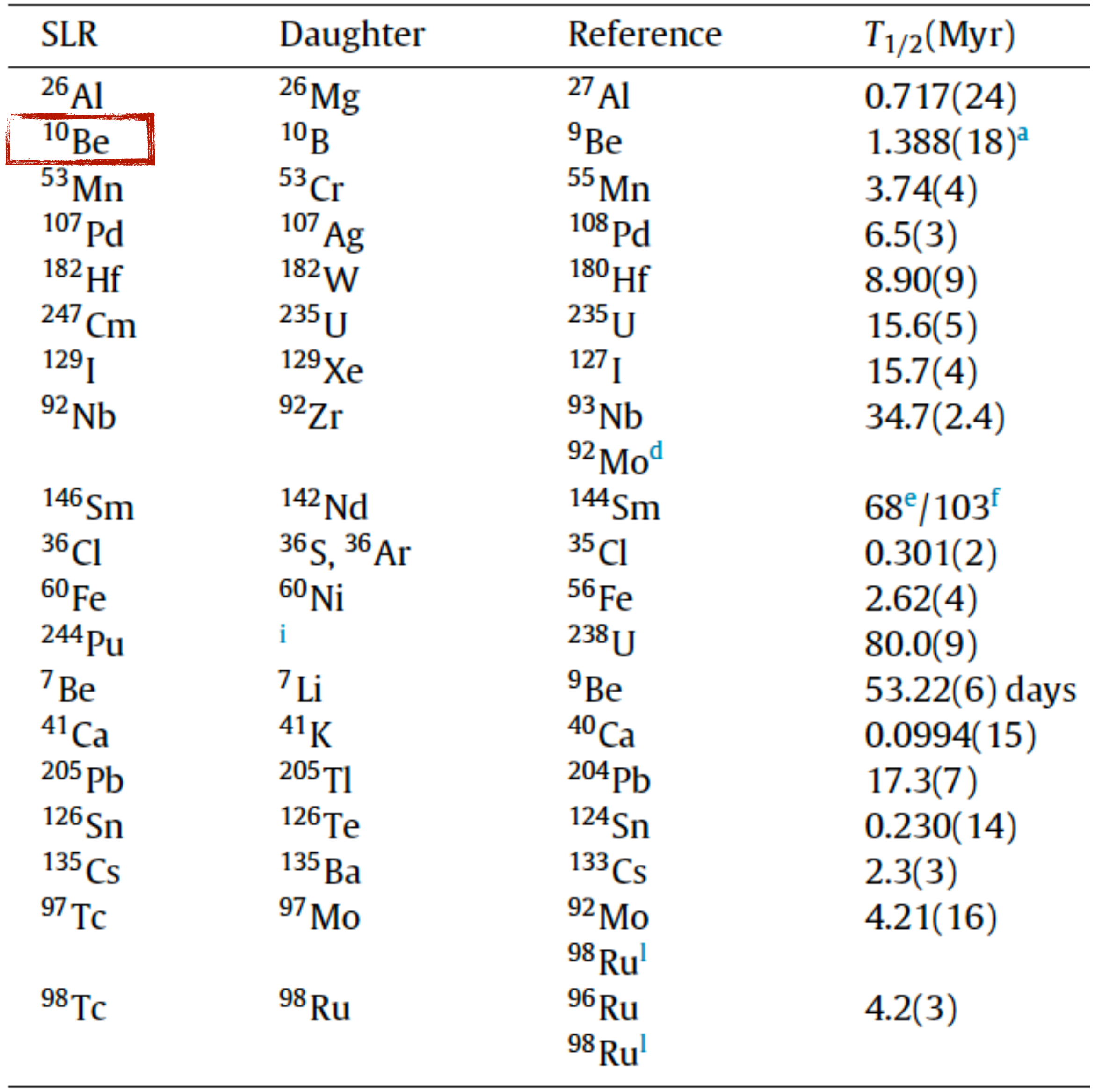


Radioactive isotopes

- Radioactive isotopes are indicators of active nucleosynthesis and provide key constraints for astrophysical models



Cassiopeia A : Supernova remnant
[Greffenstette et al. 2017]

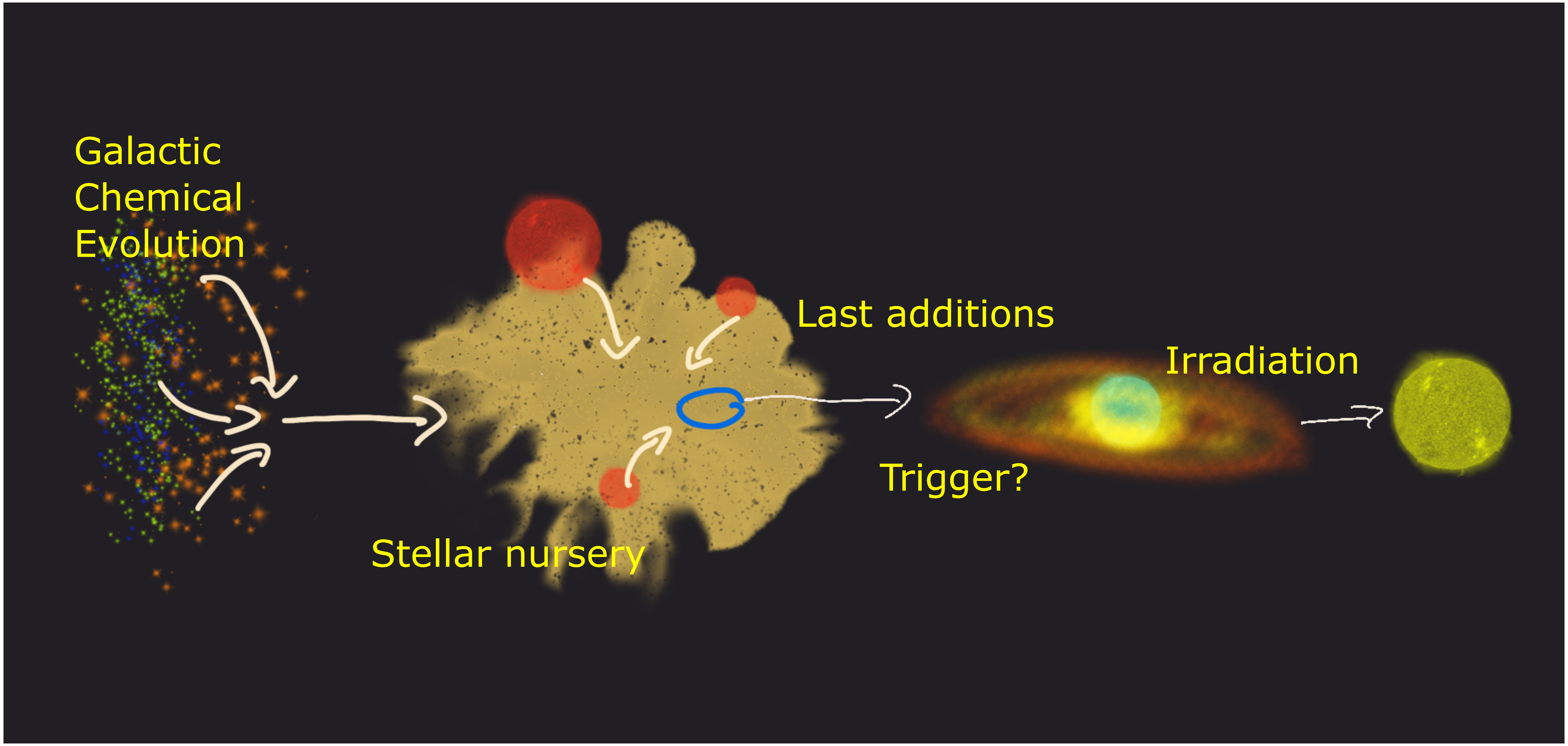


SLR	Daughter	Reference	$T_{1/2}$(Myr)
^{26}Al	^{26}Mg	^{27}Al	0.717(24)
^{10}Be	^{10}B	^{9}Be	1.388(18)[a]
^{53}Mn	^{53}Cr	^{55}Mn	3.74(4)
^{107}Pd	^{107}Ag	^{108}Pd	6.5(3)
^{182}Hf	^{182}W	^{180}Hf	8.90(9)
^{247}Cm	^{235}U	^{235}U	15.6(5)
^{129}I	^{129}Xe	^{127}I	15.7(4)
^{92}Nb	^{92}Zr	^{93}Nb ^{92}Mo[d]	34.7(2.4)
^{146}Sm	^{142}Nd	^{144}Sm	68[e]/103[f]
^{36}Cl	^{36}S, ^{36}Ar	^{35}Cl	0.301(2)
^{60}Fe	^{60}Ni	^{56}Fe	2.62(4)
^{244}Pu	[i]	^{238}U	80.0(9)
^{7}Be	^{7}Li	^{9}Be	53.22(6) days
^{41}Ca	^{41}K	^{40}Ca	0.0994(15)
^{205}Pb	^{205}Tl	^{204}Pb	17.3(7)
^{126}Sn	^{126}Te	^{124}Sn	0.230(14)
^{135}Cs	^{135}Ba	^{133}Cs	2.3(3)
^{97}Tc	^{97}Mo	^{92}Mo ^{98}Ru[l]	4.21(16)
^{98}Tc	^{98}Ru	^{96}Ru ^{98}Ru[l]	4.2(3)

Ratios of short-lived radioactive isotopes in the early solar system
[Lugaro et al. 2018]

See also talks by B. Wehmeyer, M. Lugaro and others

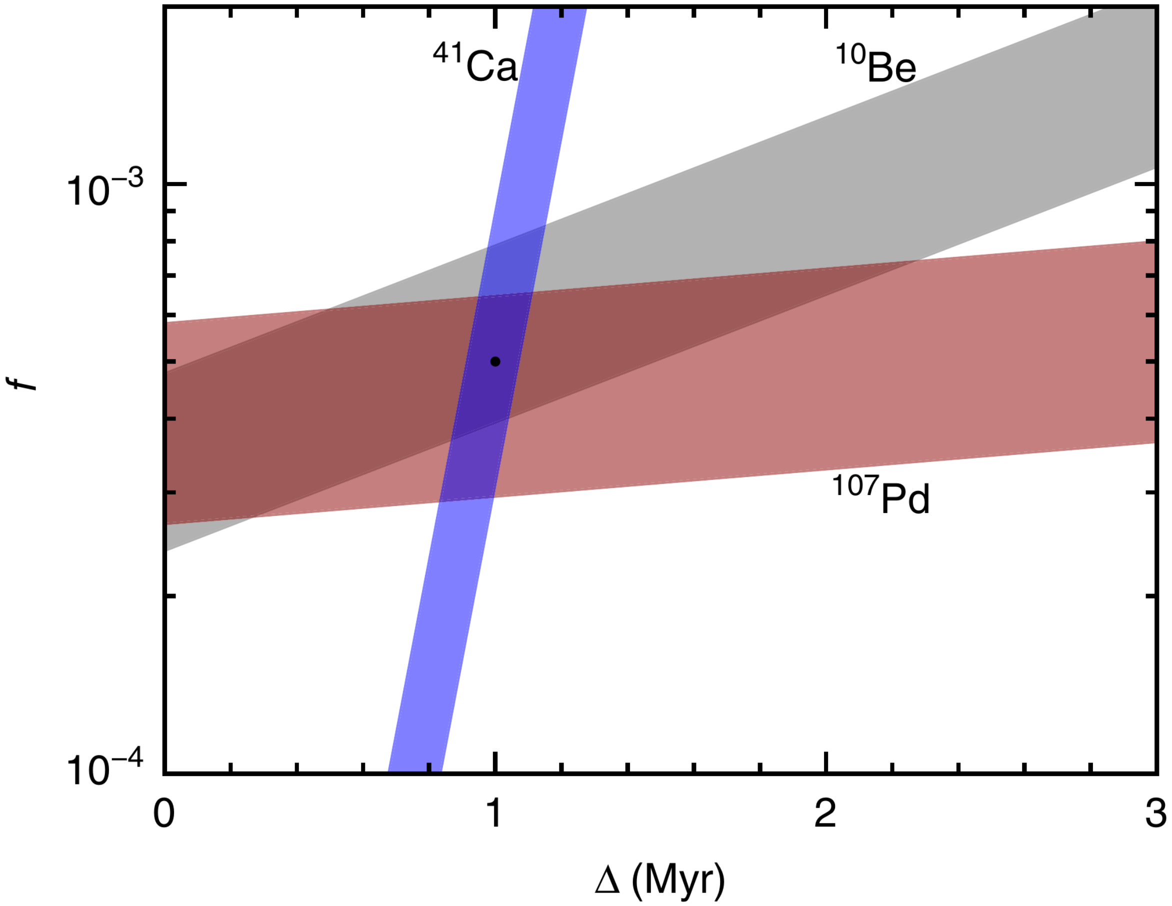
Birth of the Solar System



- Fingerprint of an individual supernova? Trigger? [Cameron & Truran 1977]

CCSN contribution to the early solar system

- Estimate ESS ratio from supernova yield:
- $$(N_A/N_B)_{\mathrm{ESS}} = f\,\frac{Y_A/M_\odot}{X_{B,\odot}}\,e^{\Delta/\tau_A}$$
- Two free parameters: f, Δ
  Require concurrent match with multiple isotopes
- Low-mass CCSN is most likely candidate, to avoid unobserved anomalies of stable isotopes

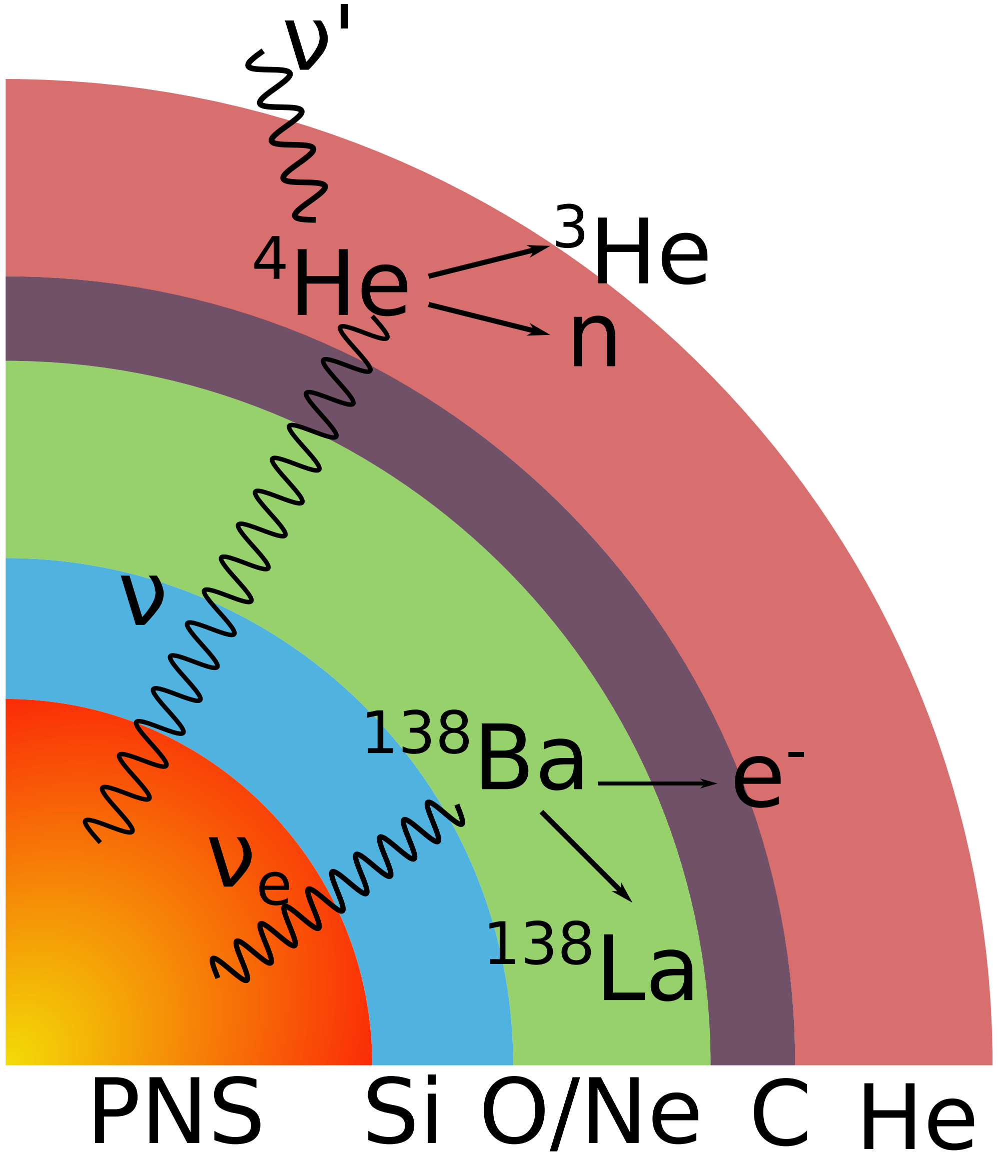


[Figure from Banerjee et al. 2016]

A low-mass (11.8 $M_\odot$) supernova provides a good match *[Banerjee et al. 2016]*

Including ^{10}Be ($T_{1/2}$=1.5 Myr)

The ν process



- High energy neutrinos (~10 MeV) induce reaction on abundant nuclei *[Woosely et al. 1990 …]*
  - Inverse β decay
  - Spallation reactions
  - Supply of light particles
- Contributions to ^{7}Li, ^{11}B, ^{22}Na, ^{26}Al, ^{92}Nb, ^{98}Tc, ^{138}La, ^{180}Ta … and ^{10}Be

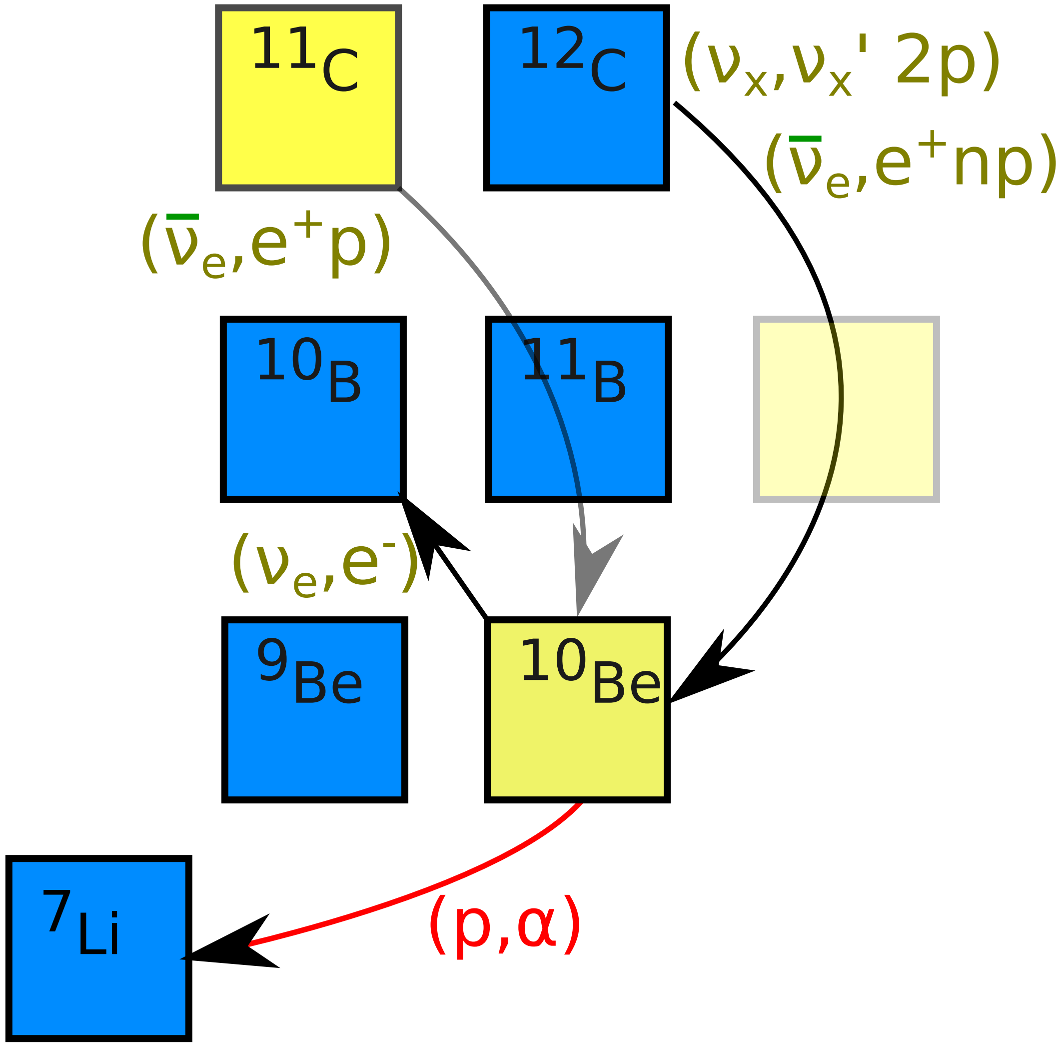
[Ko et al. 2022, Kusakabe et al. 2019, AS et al. 2019 …]

Neutrino spectra (energies) are the largest uncertainty

Flavor transformations? Mass hierarchy?

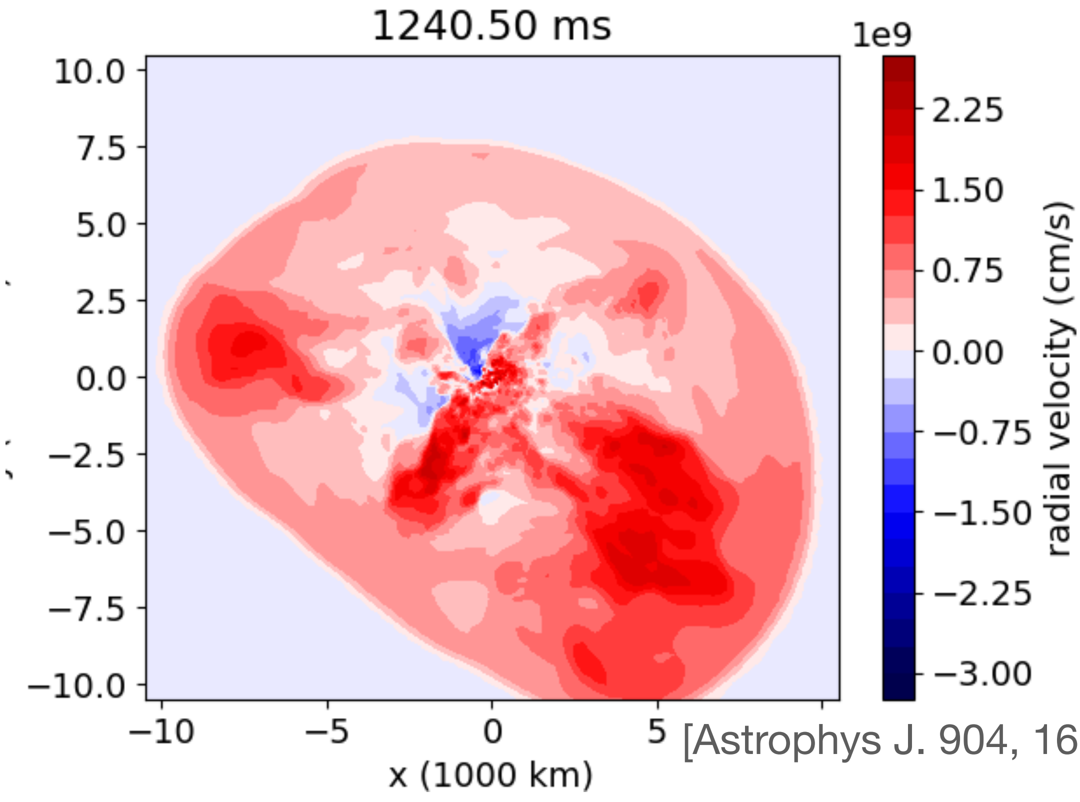
Reaction relevant for ^{10}Be

- Production from ^{12}C
- Production reactions:
  $^{12}\mathrm{C}(\nu_x, \nu_x' \, 2\mathrm{p})$, $^{12}\mathrm{C}(\bar{\nu}_e, e^+\mathrm{np})$
  [Cross section from Yoshida et al. 2008]
- Main destruction channel
  $^{10}\mathrm{Be}(p, \alpha)^7\mathrm{Li}, ^{10}\mathrm{Be}(\alpha, n)^{13}\mathrm{C}$

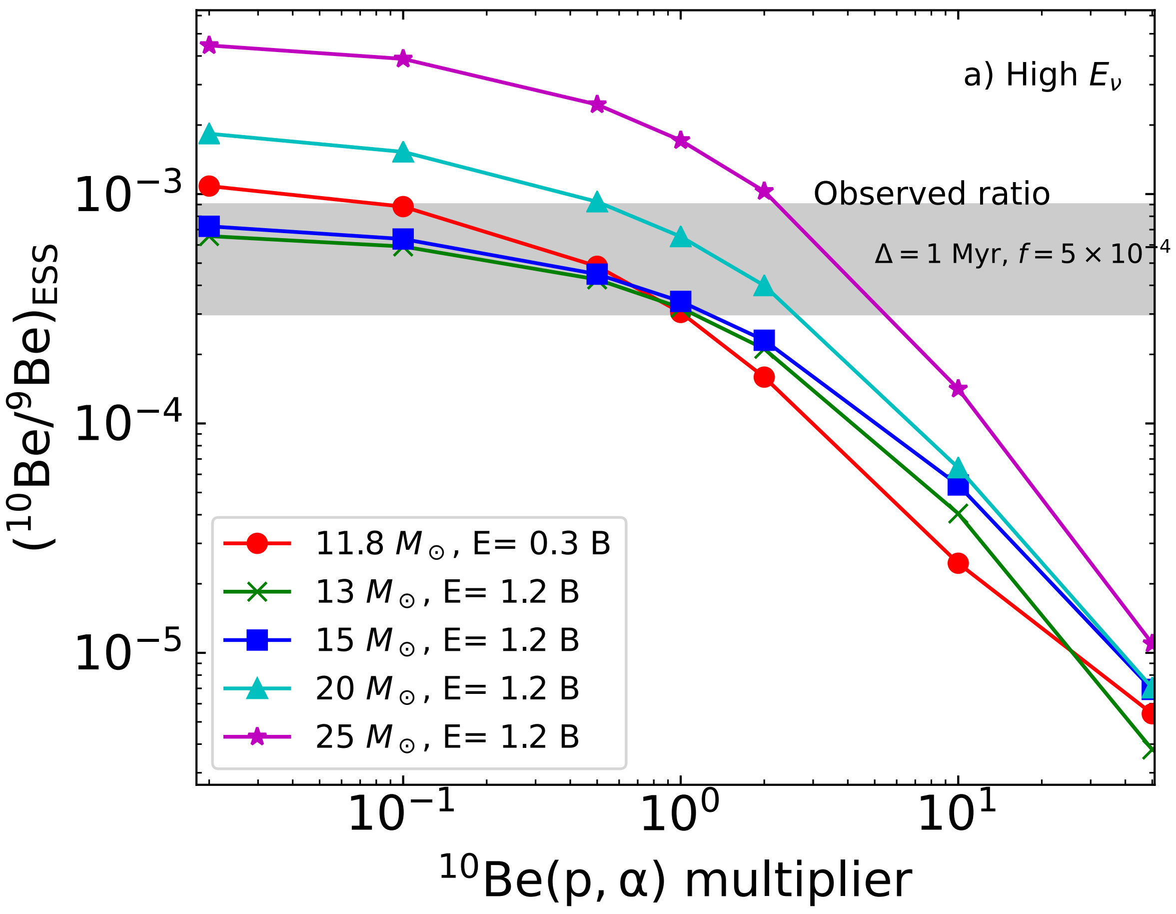


New results with a 3D simulation

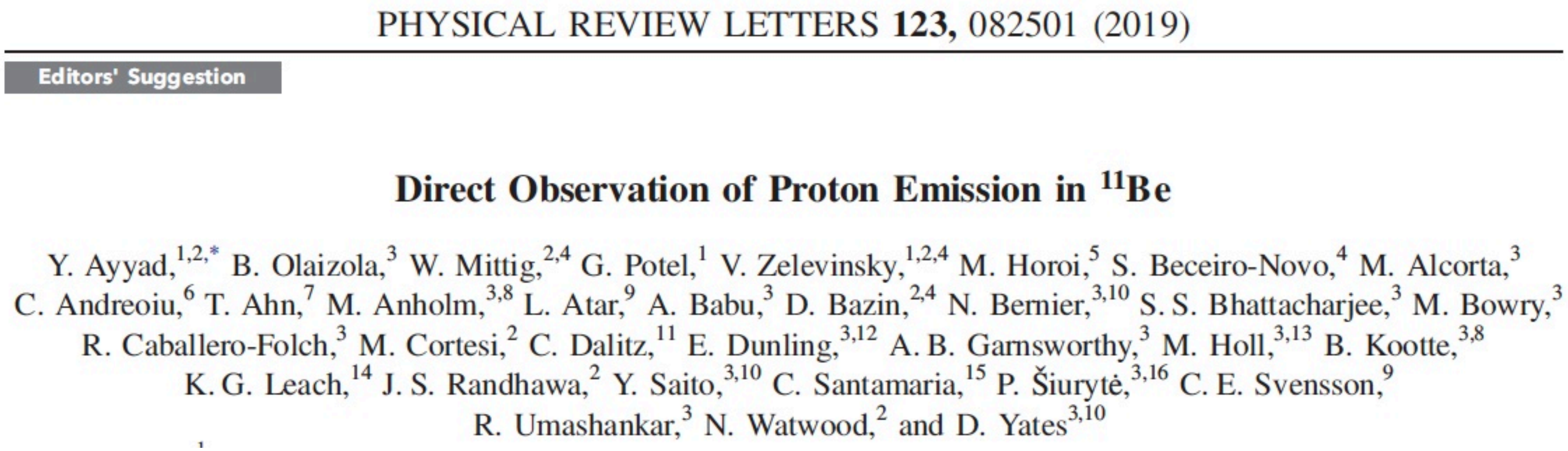
- Post-processing of 3D simulation of the 11.8 $M_\odot$ progenitor *[AS et al 2020,Müller et al. 2019]*
- Lower neutrino energies, extended reaction network
- **Only enough if the rate of the ^{10}Be$(p,\alpha)^7$Li reaction rate is reduced**
- Confirmation by sensitivity study (1D calculations)



[Astrophys J. 904, 163]



New experimental data



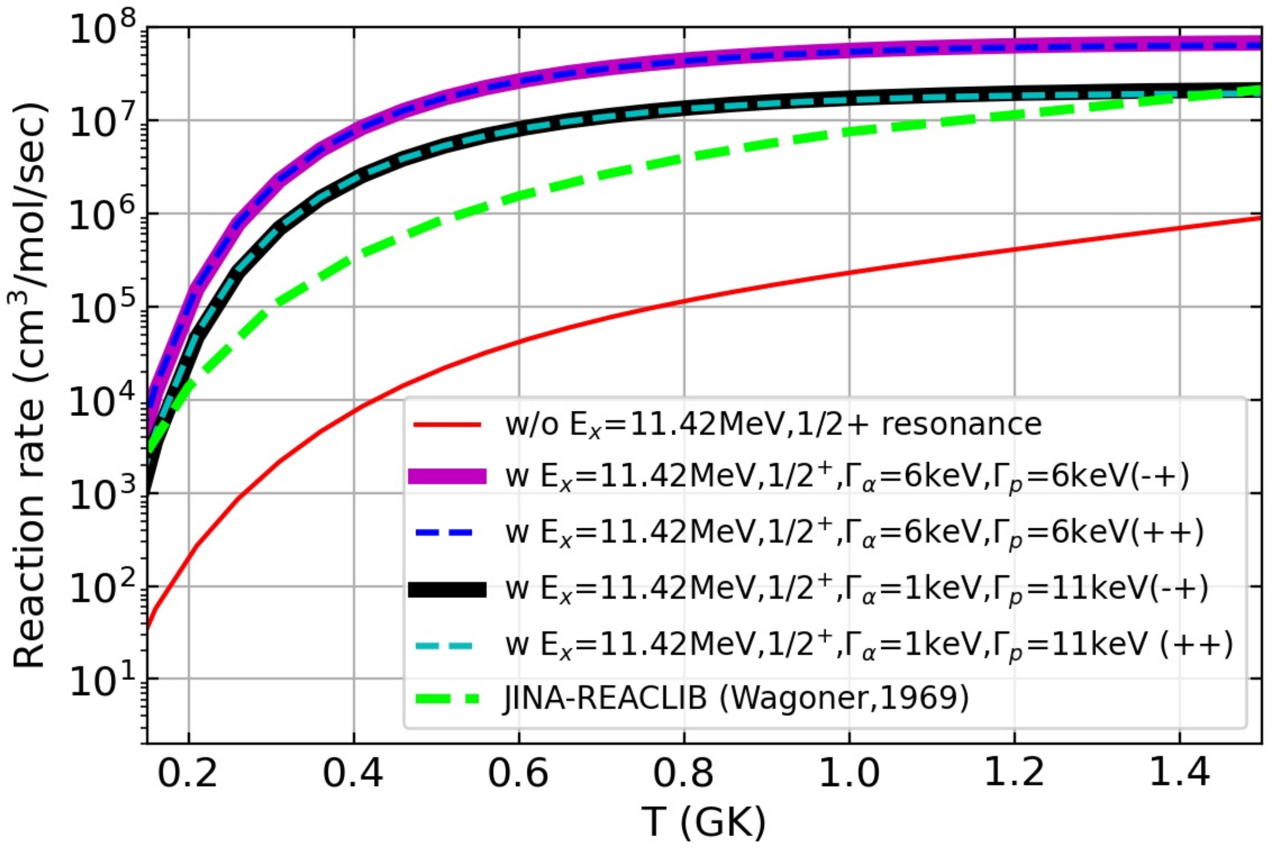
PHYSICAL REVIEW LETTERS **123,** 082501 (2019)

Editors' Suggestion

Direct Observation of Proton Emission in ^{11}Be

Y. Ayyad,[1,2,*] B. Olaizola,[3] W. Mittig,[2,4] G. Potel,[1] V. Zelevinsky,[1,2,4] M. Horoi,[5] S. Beceiro-Novo,[4] M. Alcorta,[3]
C. Andreoiu,[6] T. Ahn,[7] M. Anholm,[3,8] L. Atar,[9] A. Babu,[3] D. Bazin,[2,4] N. Bernier,[3,10] S. S. Bhattacharjee,[3] M. Bowry,[3]
R. Caballero-Folch,[3] M. Cortesi,[2] C. Dalitz,[11] E. Dunling,[3,12] A. B. Garnsworthy,[3] M. Holl,[3,13] B. Kootte,[3,8]
K. G. Leach,[14] J. S. Randhawa,[2] Y. Saito,[3,10] C. Santamaria,[15] P. Šiurytė,[3,16] C. E. Svensson,[9]
R. Umashankar,[3] N. Watwood,[2] and D. Yates[3,10]

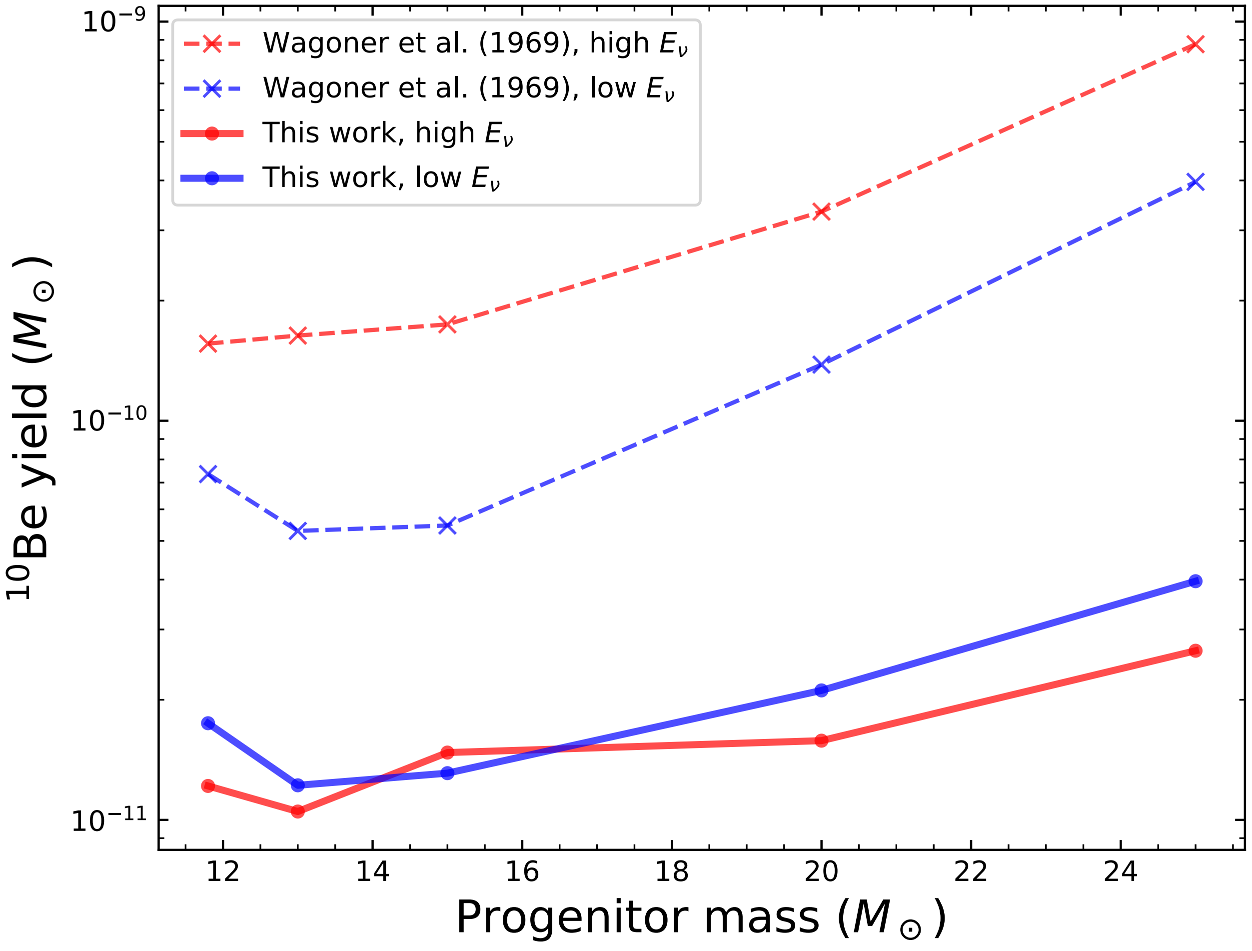
- Experiments at TRIUMF have shown the existence of a resonance in ^{11}B
- Properties of the resonance have been confirmed by scattering experiments
- **Significant increase of the ^{10}Be$(p,\alpha)^{7}$Li rate**

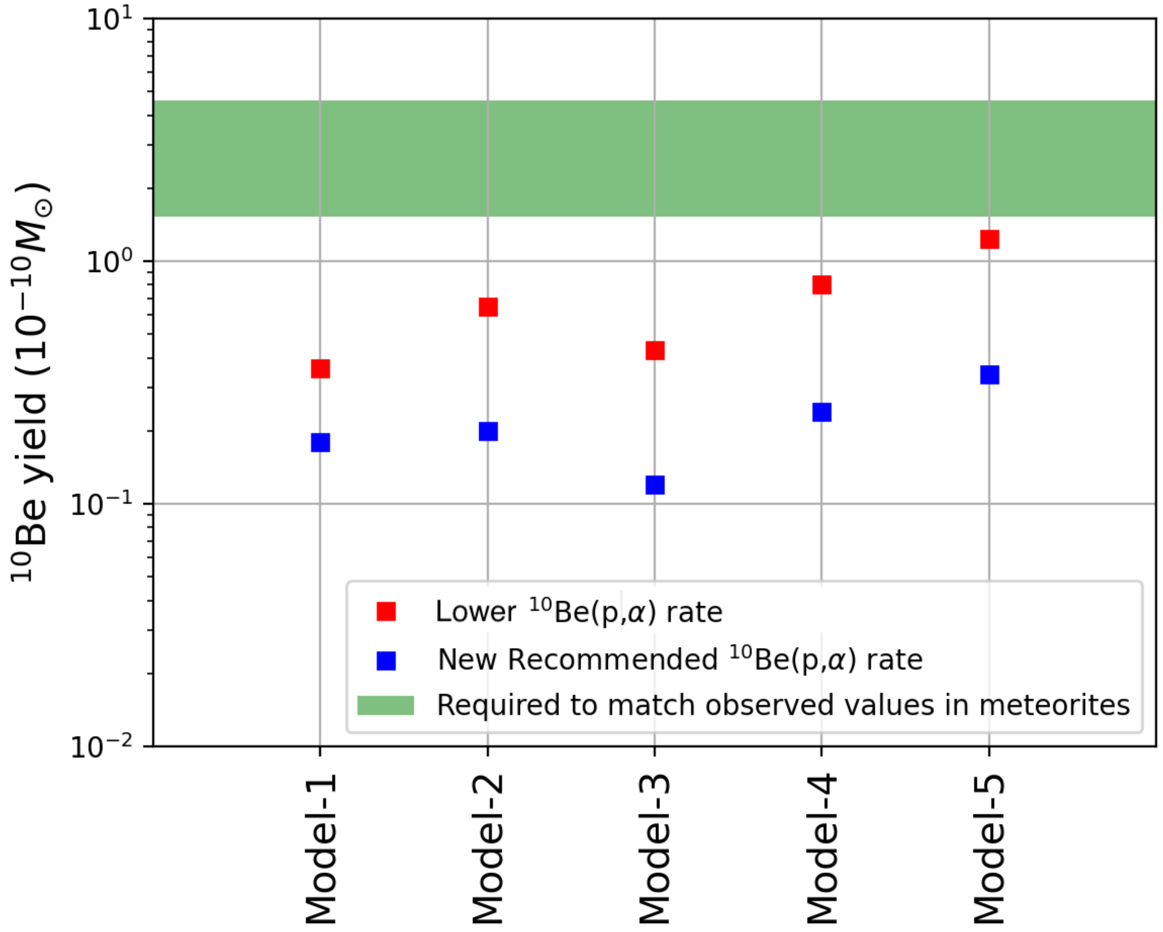


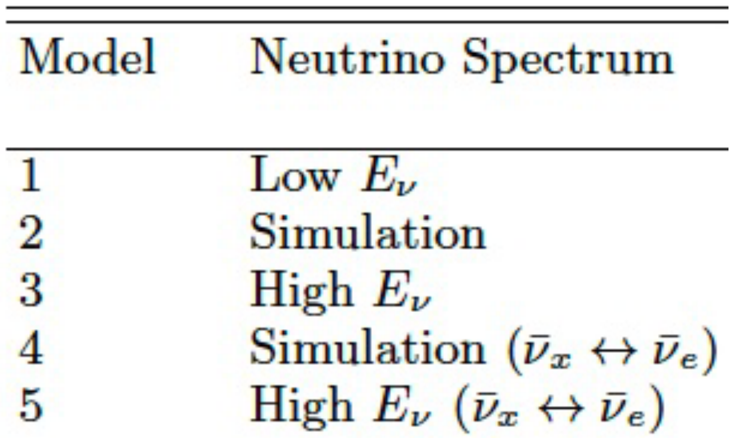
[AS et al. 2022]

Results with new reaction rate

- With the new ${}^{10}\mathrm{Be}(p,\alpha)^{7}\mathrm{Li}$ reaction rate, the 11.8 $M_\odot$ supernova does not produce enough ^{10}Be
- Sensitivity to stellar models?





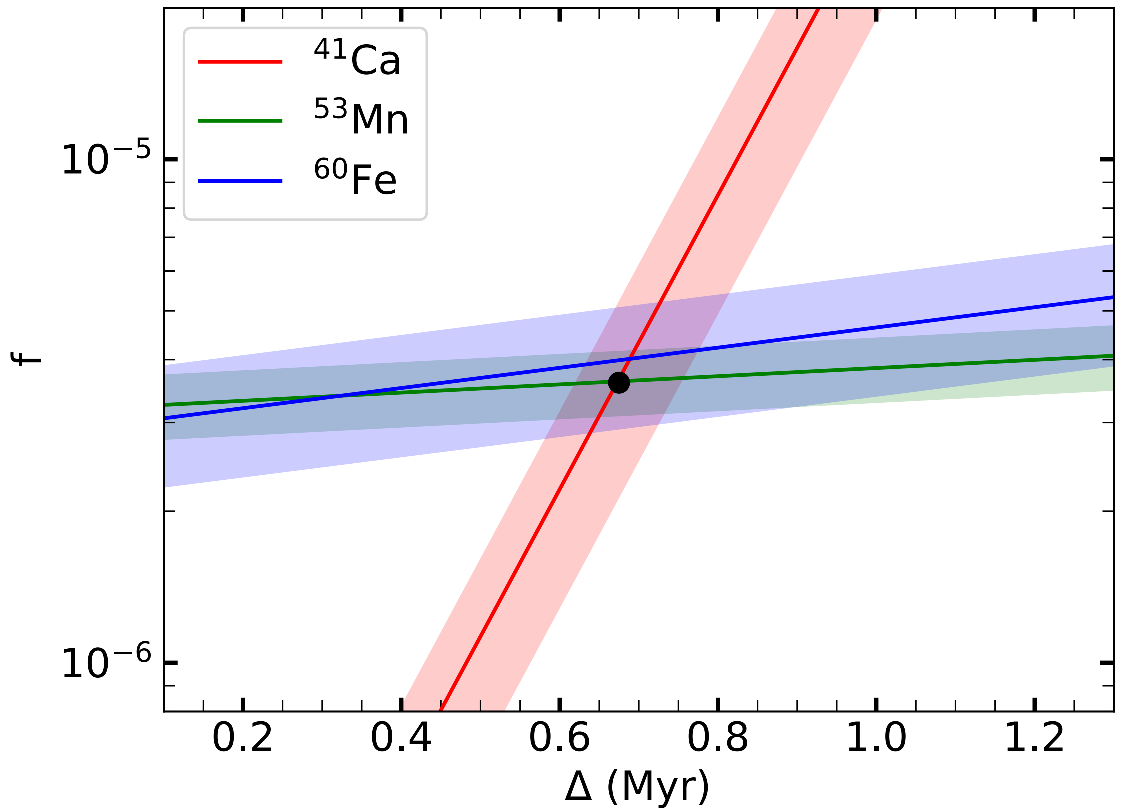


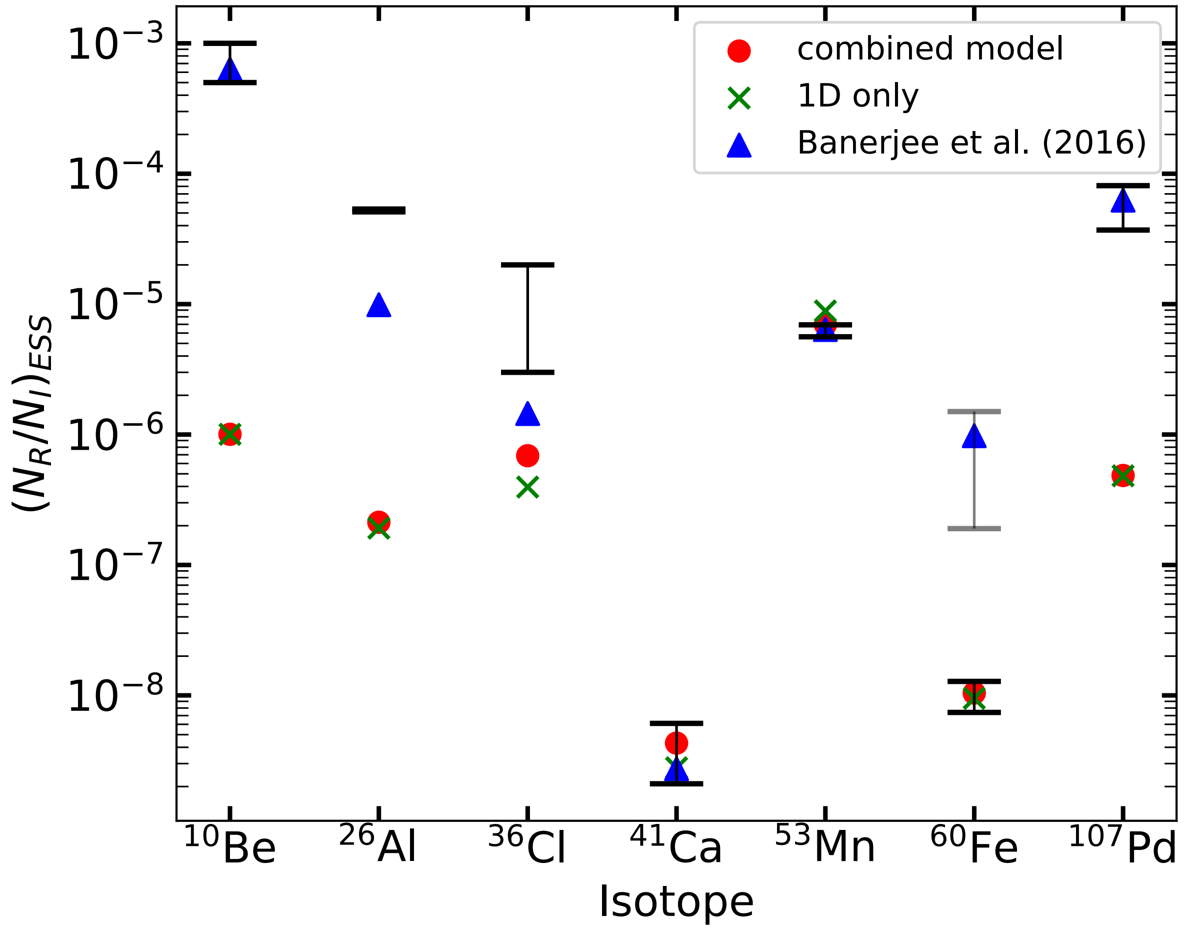
Model	Neutrino Spectrum
1	Low E_ν
2	Simulation
3	High E_ν
4	Simulation ($\bar{\nu}_x \leftrightarrow \bar{\nu}_e$)
5	High E_ν ($\bar{\nu}_x \leftrightarrow \bar{\nu}_e$)

Phys. Rev. C, 106, 015803

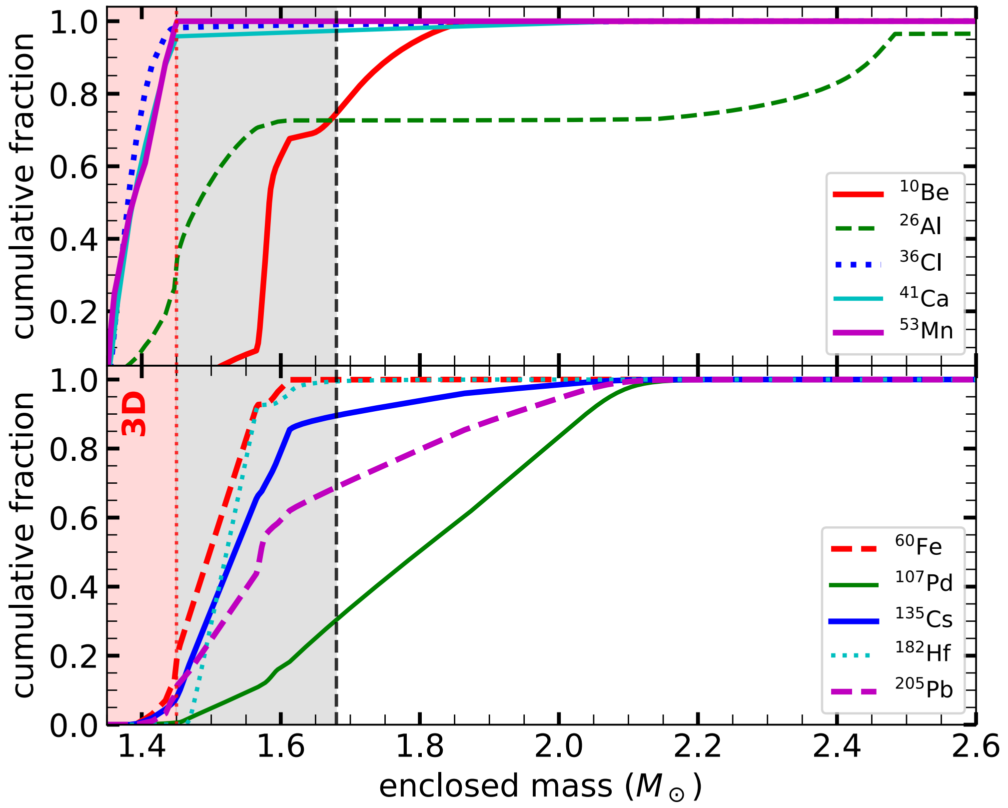
Contribution of supernovae to other radioactive isotopes

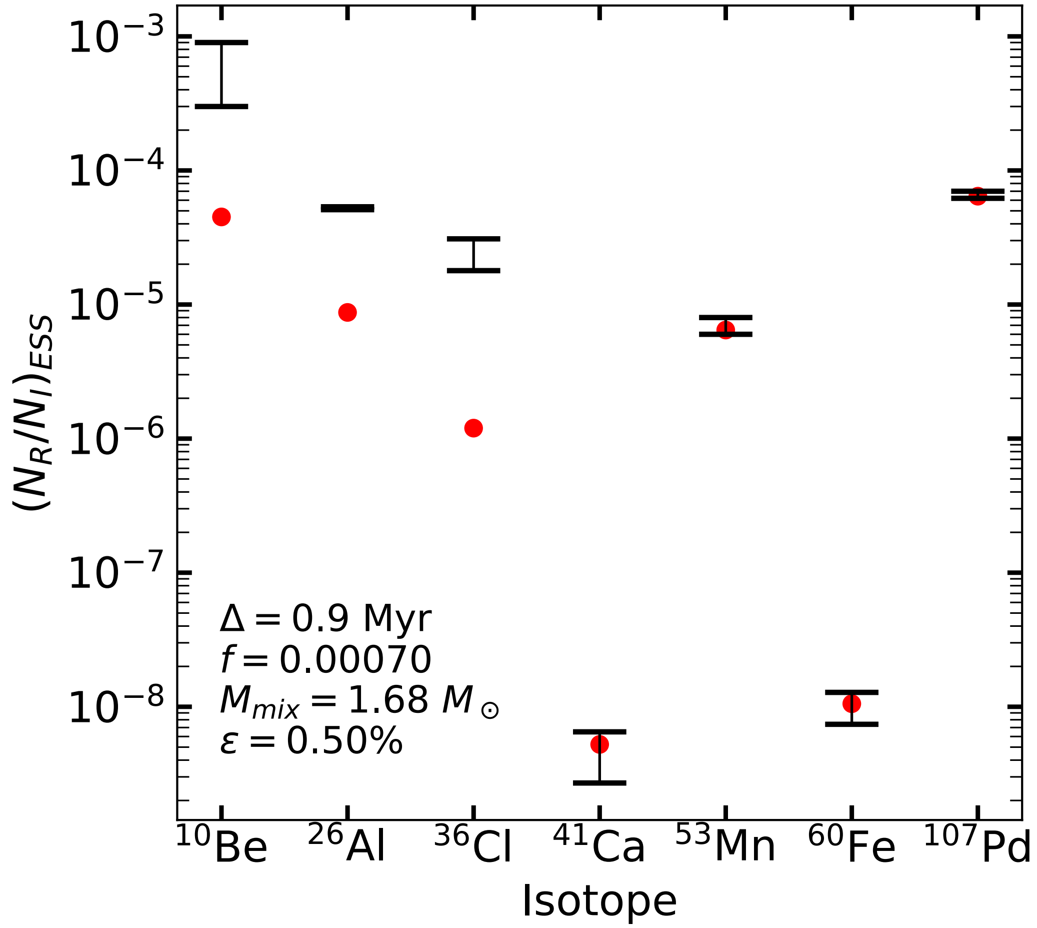
- Low ^{60}Fe/^{56}Fe ratio limits CCSN contribution
- Can still match ^{60}Fe, ^{53}Mn and ^{41}Ca simultaneously
- ^{60}Fe and ^{53}Mn in the right proportions by the 11.8 $M_\odot$ model
- Most short-lived radioactive isotopes from other sources





Fallback or partial injection

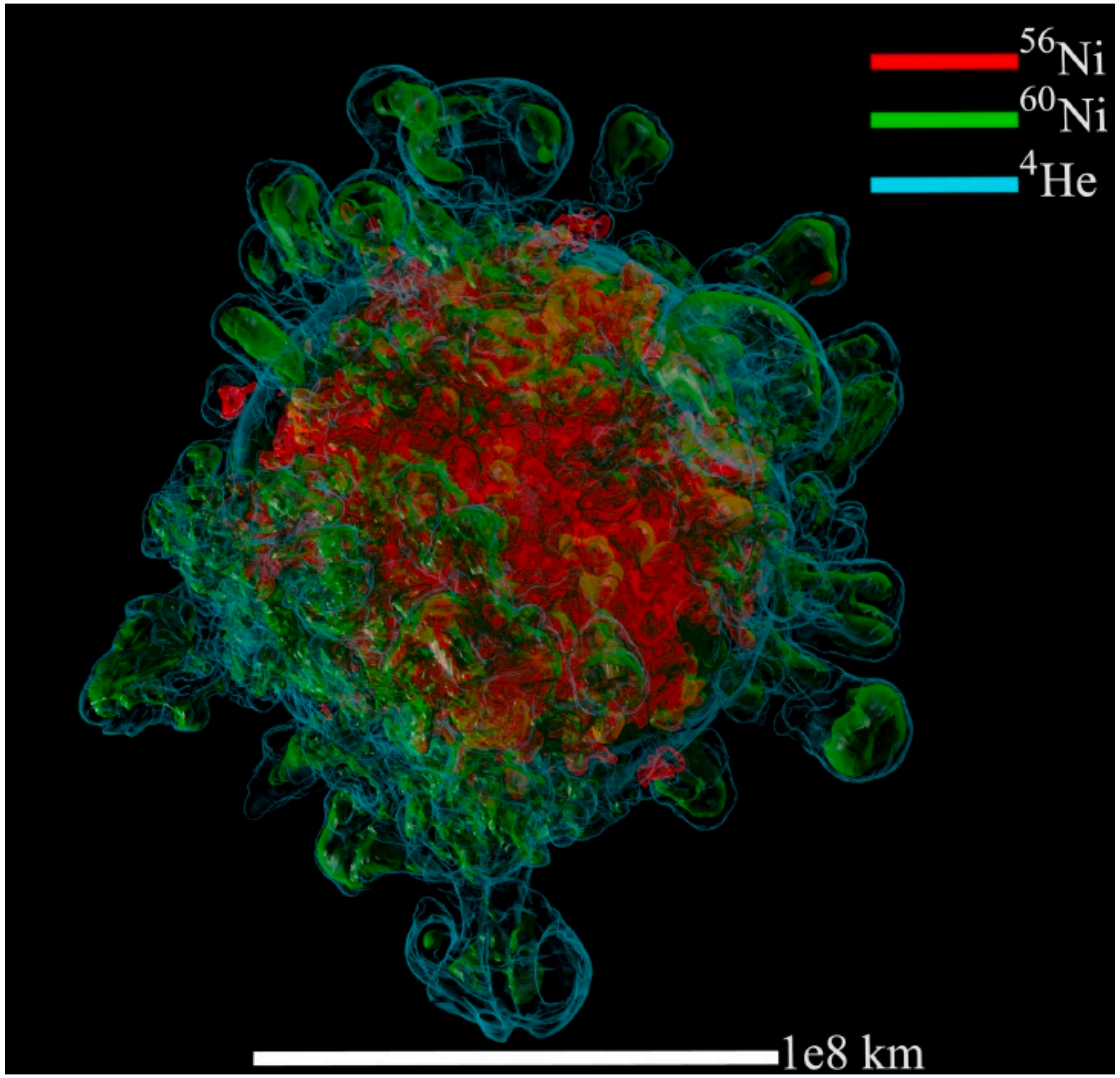




- Isotopes are produced in different regions of the star
- If part of the star falls back or is not mixed into the ESS, other solutions are possible
- At least two additional free parameters: Mixing mass and efficiency *[e.g. Heger et al. 2010]*
- Allows to fit four isotope ratios at the same time with the 11.8 $M_\odot$ model
- Self-consistent, long-term SN simulations with nucleosynthesis are required

Future Work

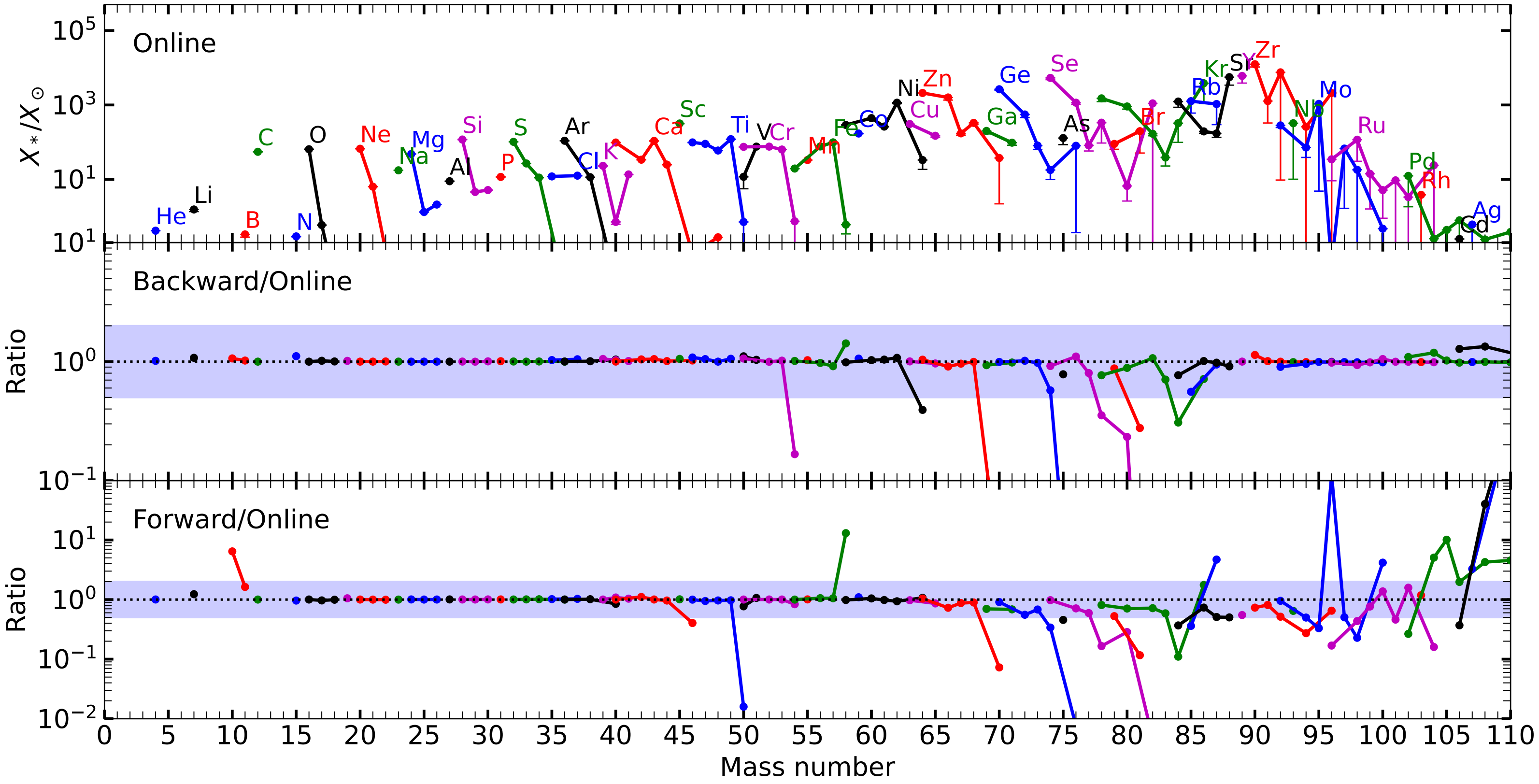
- Nucleosynthesis from long-term, self-consistent 3D simulations
- Evolution to shock breakout
- Observational signatures
- Morphology and mixing in the supernova ejecta

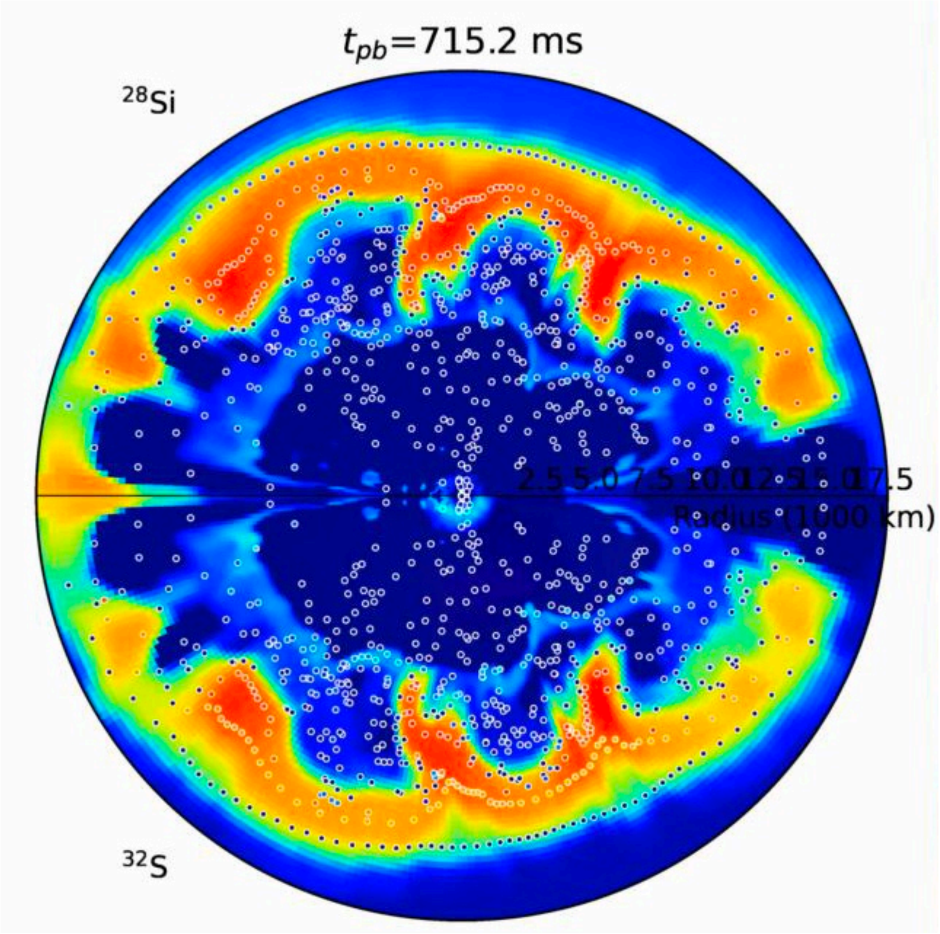


[Sandoval et al. 2021]

Open Questions

- Modern multi-dimensional simulations require nucleosynthesis post-processing
- Methods for tracer particle extraction
- Role of mixing and convective burning





Summary

- Radioactive ^{10}Be in the early solar system could be evidence for a CCSN contribution, but it strongly depends on the ^{10}Be$(p,\alpha)^7$Li reaction rate

- Calculations with new reaction rate suggest, other sources for ^{10}Be are required, e.g., cosmic ray irradiation

- Constraints on ^{60}Fe strongly limit the supernova contribution or require special assumptions

- ^{60}Fe, ^{53}Mn and ^{41}Ca could be from a CCSN explosion

- Upcoming improvements of CCSN nucleosynthesis predictions with multi-dimensional, long-term simulations

Thanks!

Production of ^{10}Be

- Progenitor structure determines production region
- Mostly produced after the SN shock has passed
- Too strong neutrino irradiation produces additional protons, that reduce the production