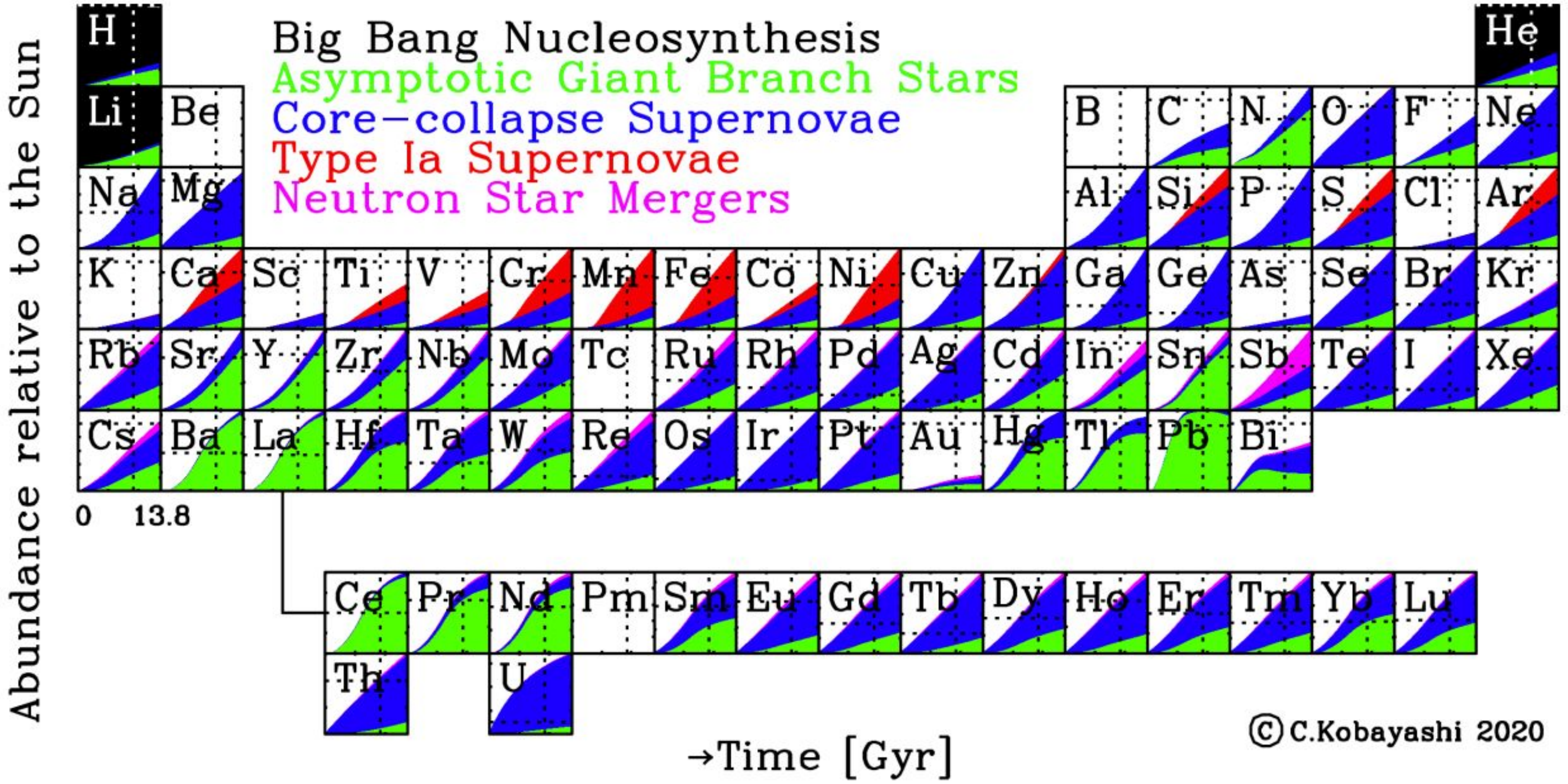
Probing the origins of the chemical elements

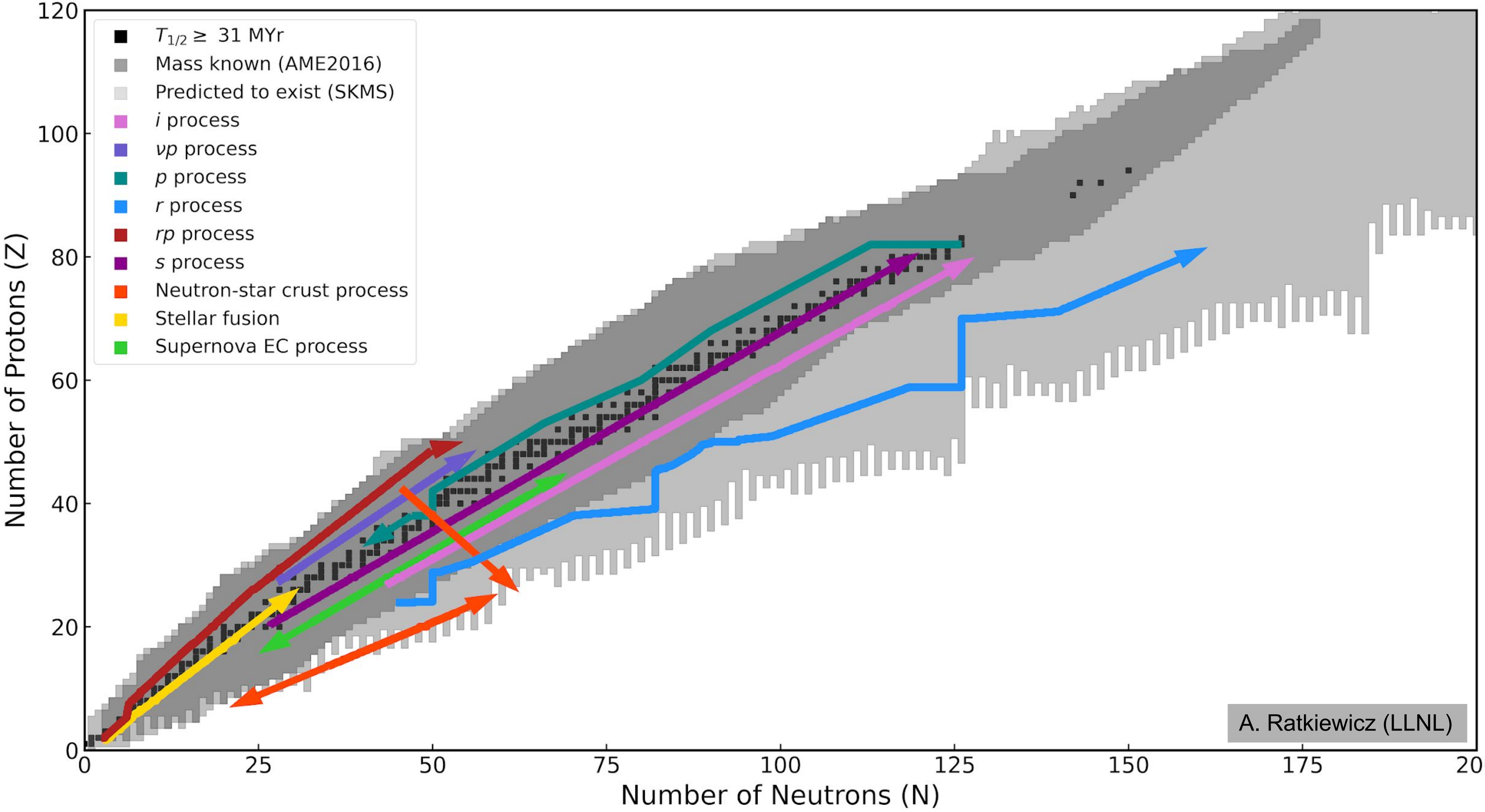
~~Kelly Chipps~~

Phil Adsley
padsley@tamu.edu

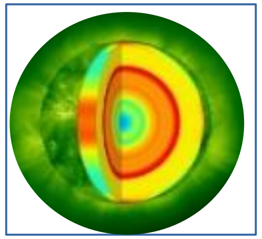
Where *and when* are the elements created?



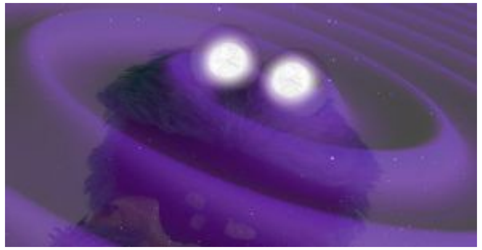
ⓒ C.Kobayashi 2020


$T_{1/2} \geq$ 31 MYr
Mass known (AME2016)
Predicted to exist (SKMS)
i process
νp process
p process
r process
rp process
s process
Neutron-star crust process
Stellar fusion
Supernova EC process
Number of Protons (Z)
Number of Neutrons (N)
0
20
40
60
80
100
120
0
25
50
75
100
125
150
175
200
A. Ratkiewicz (LLNL)

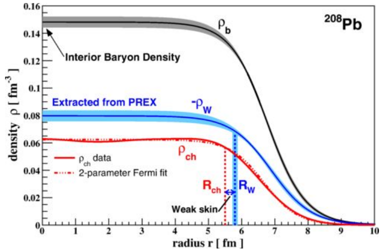
There are exciting opportunities in nuclear astro identified in the 2023 Long Range Plan!



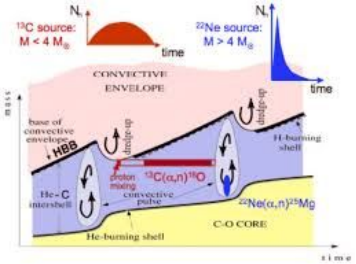
Neutrinos from the Sun and isotopic signatures of the oldest stars



Interpretation of transients from all-sky surveys

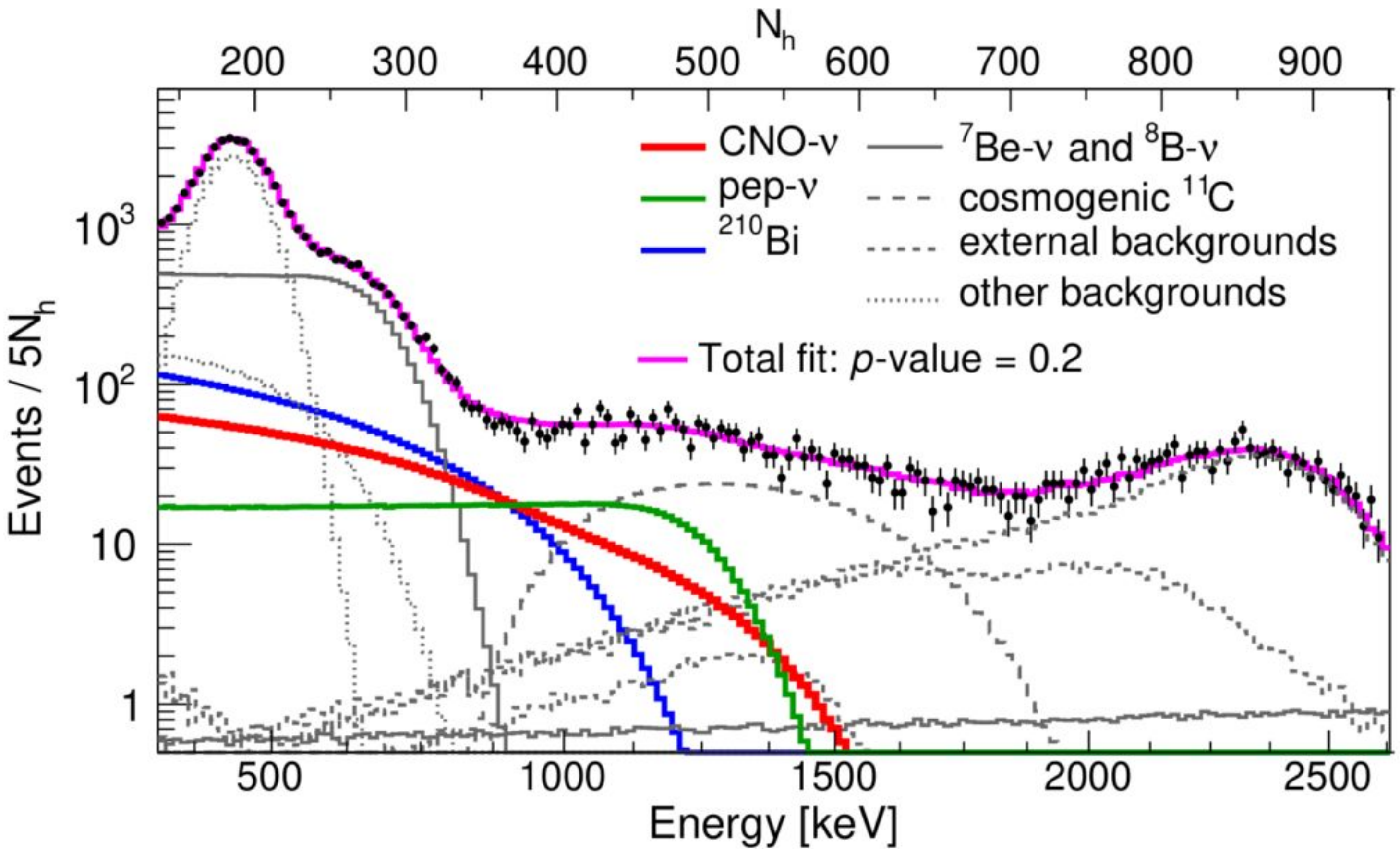


Constraint of the nuclear equation of state



Heavy element nucleosynthesis in the multimessenger era

First observation of neutrinos from the Sun's CNO cycle

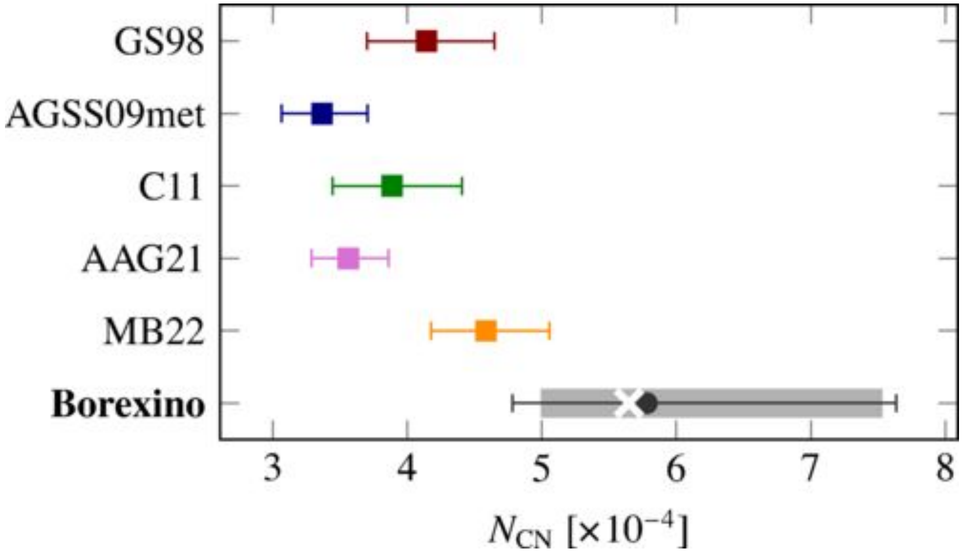


Appel et al, PRL129, 252701 (2022)

Measuring the neutrinos produced by the Sun can tell us not only about the properties of neutrinos themselves, but also about the solar composition

→ recent Borexino result seems to indicate that the Sun has more "heavy" elements inside it than are visible at the solar surface

→ additional precision in the underlying CNO cycle reaction rates is needed



Can nuclear reactions critical to the CNO neutrino flux be measured with the required precision?

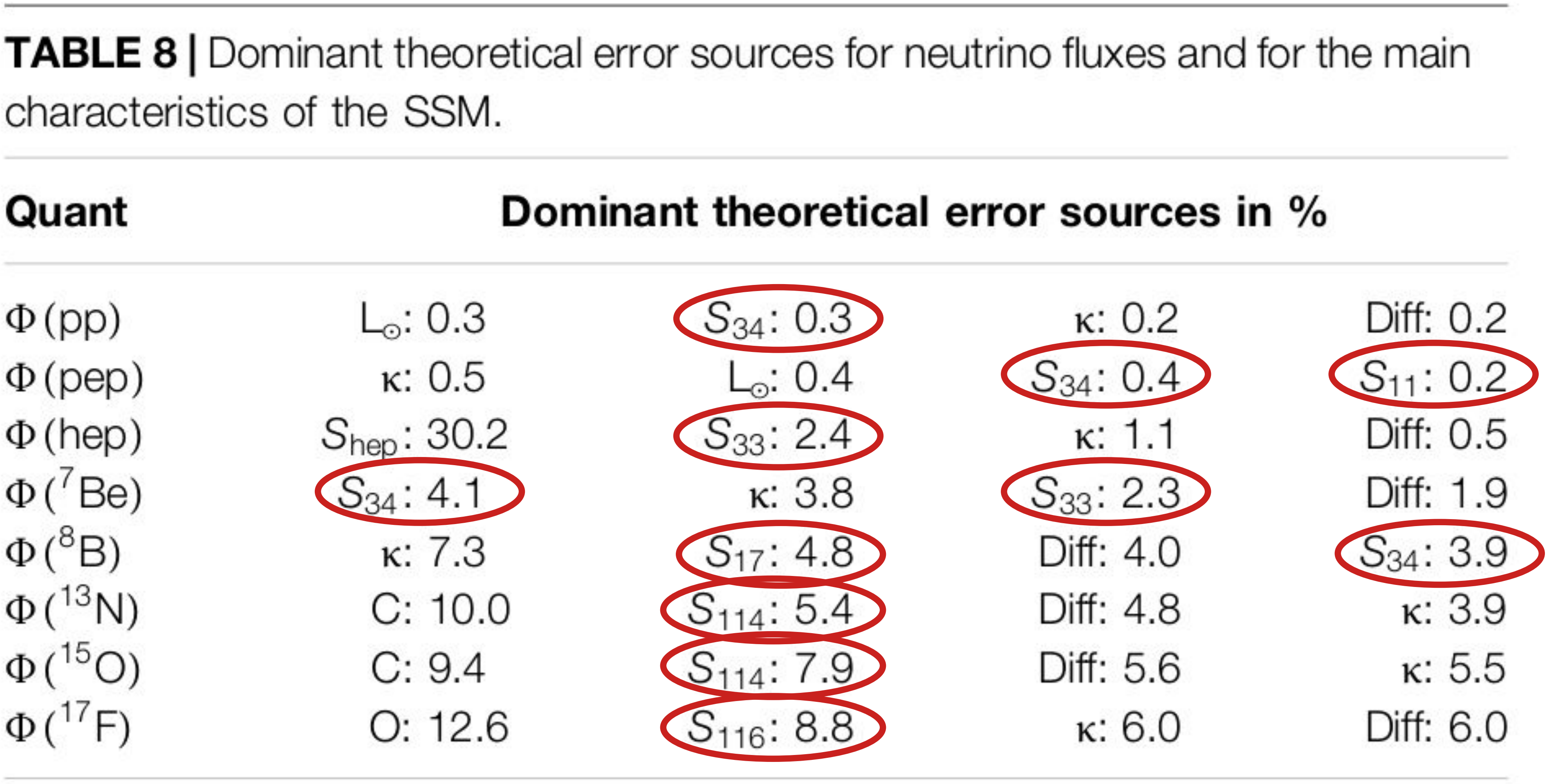


TABLE 8 | Dominant theoretical error sources for neutrino fluxes and for the main characteristics of the SSM.

Quant	**Dominant theoretical error sources in %**			
$\Phi(pp)$	$L_\odot$: 0.3	S_{34}: 0.3	κ: 0.2	Diff: 0.2
$\Phi(pep)$	κ: 0.5	$L_\odot$: 0.4	S_{34}: 0.4	S_{11}: 0.2
$\Phi(hep)$	S_{hep}: 30.2	S_{33}: 2.4	κ: 1.1	Diff: 0.5
$\Phi(^7Be)$	S_{34}: 4.1	κ: 3.8	S_{33}: 2.3	Diff: 1.9
$\Phi(^8B)$	κ: 7.3	S_{17}: 4.8	Diff: 4.0	S_{34}: 3.9
$\Phi(^{13}N)$	C: 10.0	S_{114}: 5.4	Diff: 4.8	κ: 3.9
$\Phi(^{15}O)$	C: 9.4	S_{114}: 7.9	Diff: 5.6	κ: 5.5
$\Phi(^{17}F)$	O: 12.6	S_{116}: 8.8	κ: 6.0	Diff: 6.0

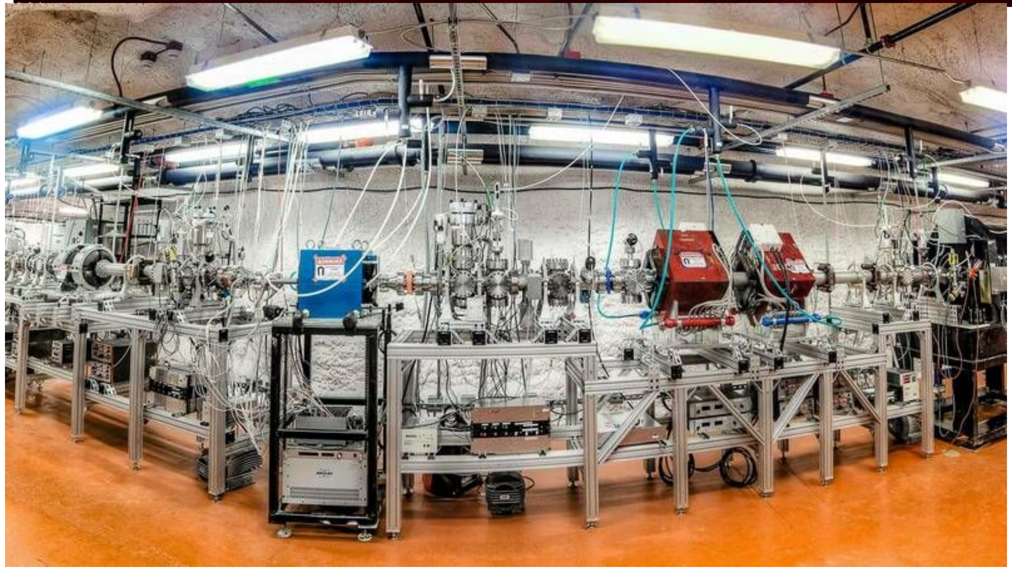
Villante Frontiers 618356 (2021)

Astrophysical cross section differences of just a few percent can cause solar models to disagree with observations by >1σ

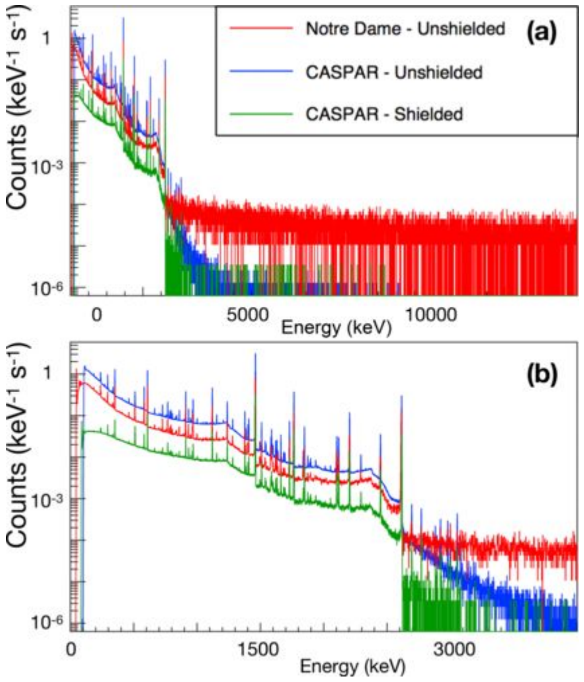
→ 1/3rd of major sources of uncertainty in neutrino flux are nuclear physics

→ measurements are needed at 10s of keV; extrapolations can be unreliable due to lack of structure info, plasma effects...

New techniques coupled with old tricks can help us understand these critical reaction rates



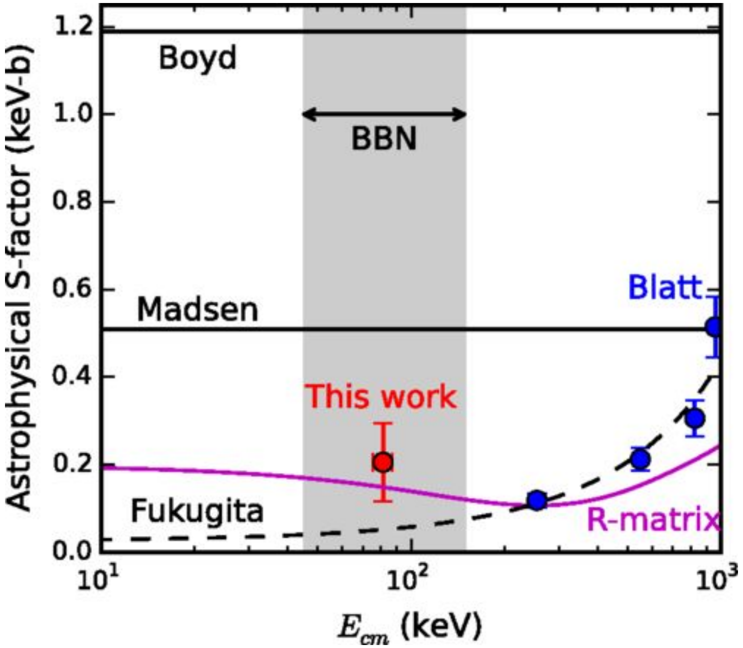
Going underground in conventional experiments can reduce the cosmic-ray background e.g. CASPAR



Frentz++
Phys. Rev. C 106, 065803

Laser-driven fusion experiments probing cross sections at astrophysical temperatures

Zylstra++
Phys. Rev. Lett. 117, 035002



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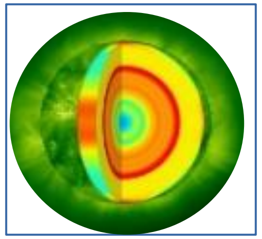

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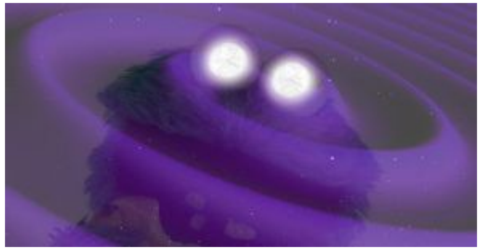

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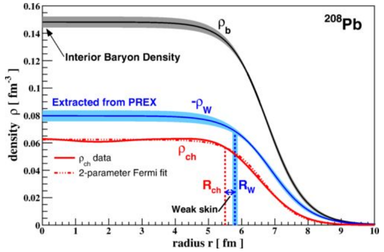

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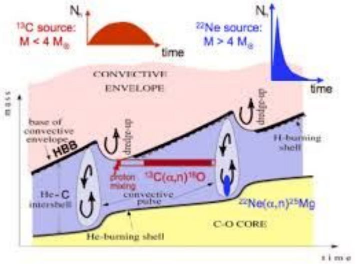
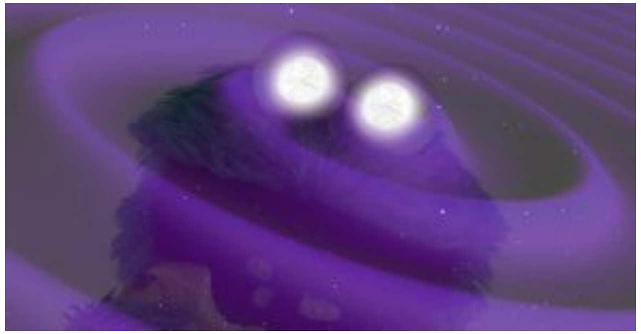


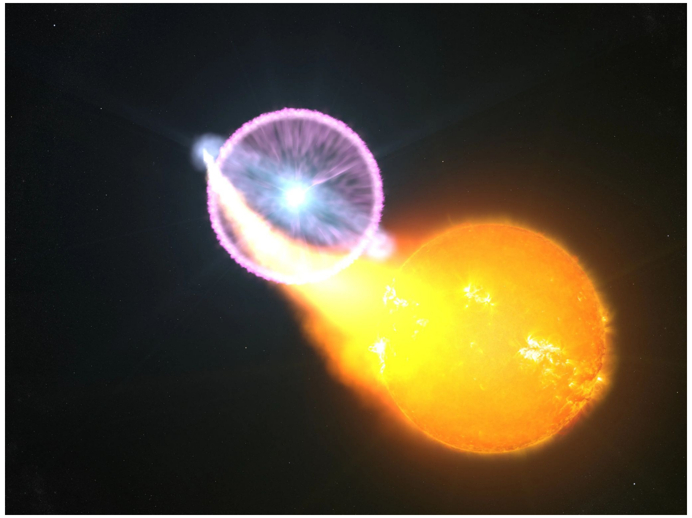
Heavy element nucleosynthesis in the multimessenger era

Transients

Many different transients
-Kilonovae
-Classical Novae
-Supernovae
-X-ray bursts



r-process nucleosynthesis
Own artwork on ESA base



CNe are important sources of Li, maybe P - need good yields from models for GCE

NASA artist's impression

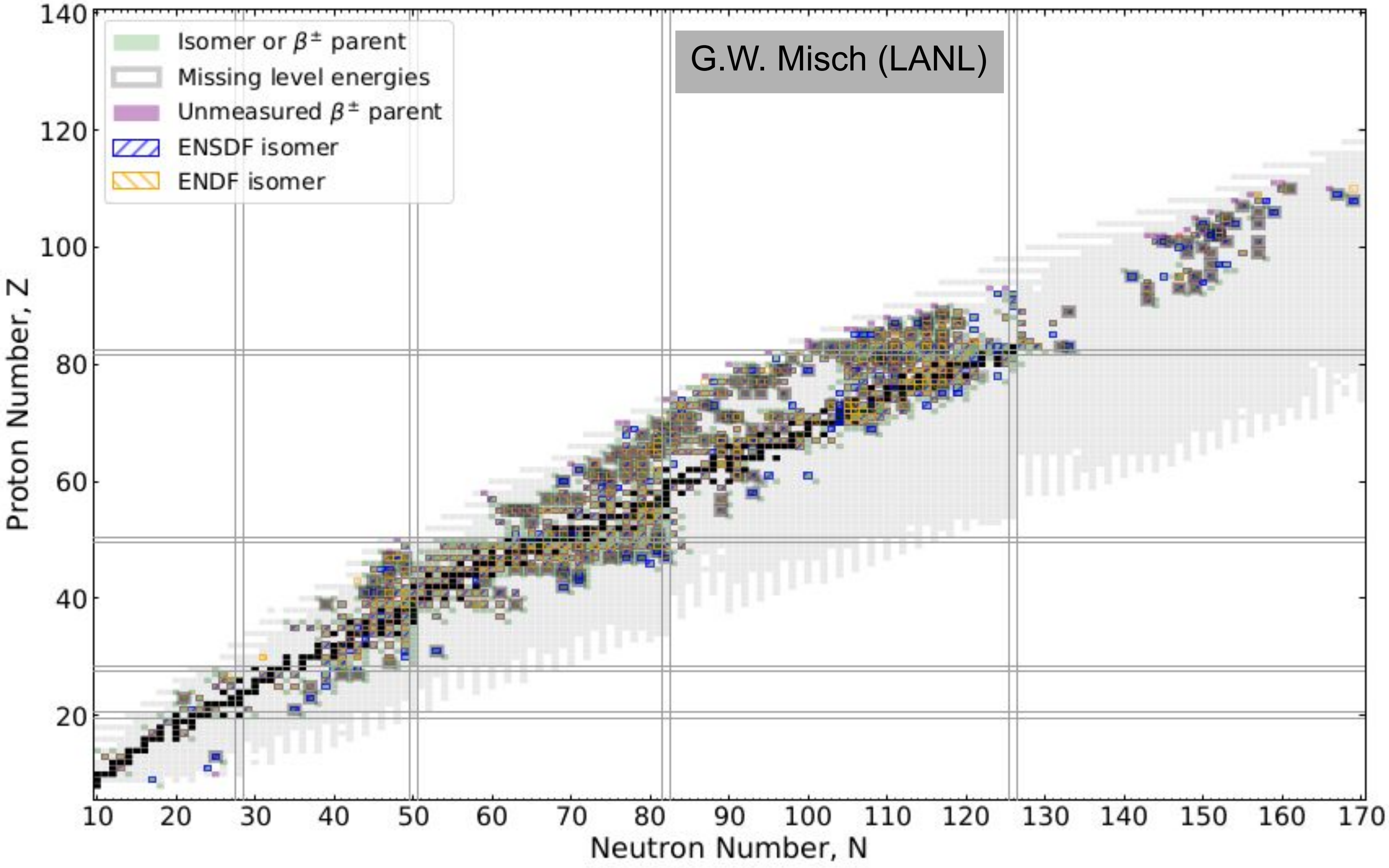
What is the role of “astromers” in proton-rich nucleosynthesis?

^{26}Al is the most well-known, but many isomers exist along the rp-process path

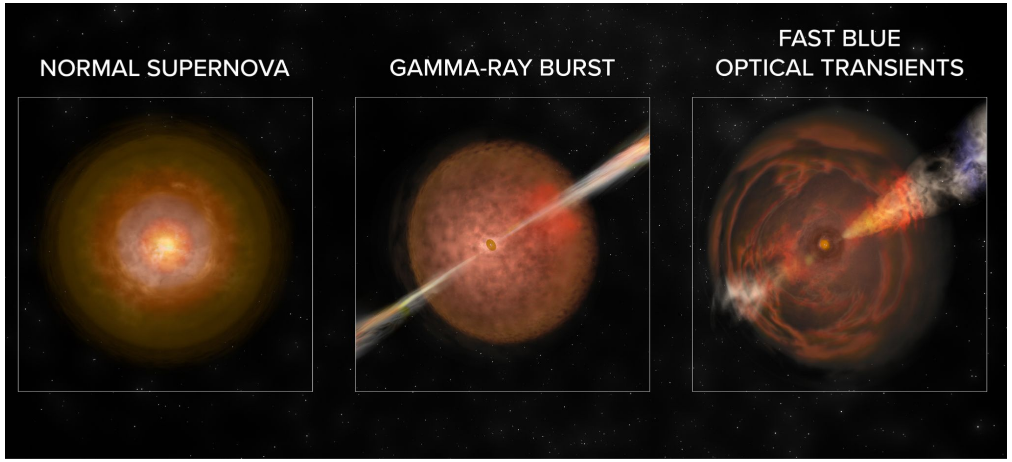
→ long-lived isomers can be populated thermally or as a decay endproduct

→ assumptions of thermal equilibrium may not be valid due to high angular momentum barriers, large differences in lifetime, coupling through higher-lying states needs large partial widths

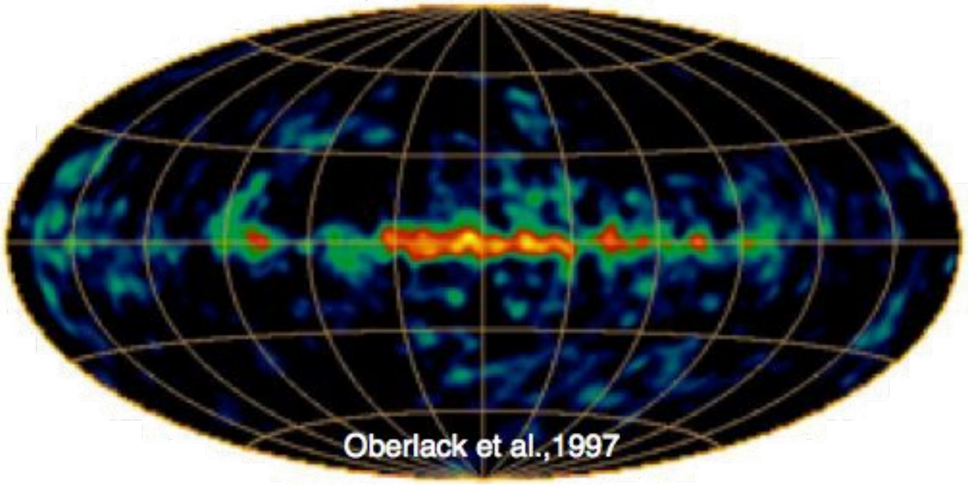
→ mixed populations impact effective lifetimes and stellar enhancement factors



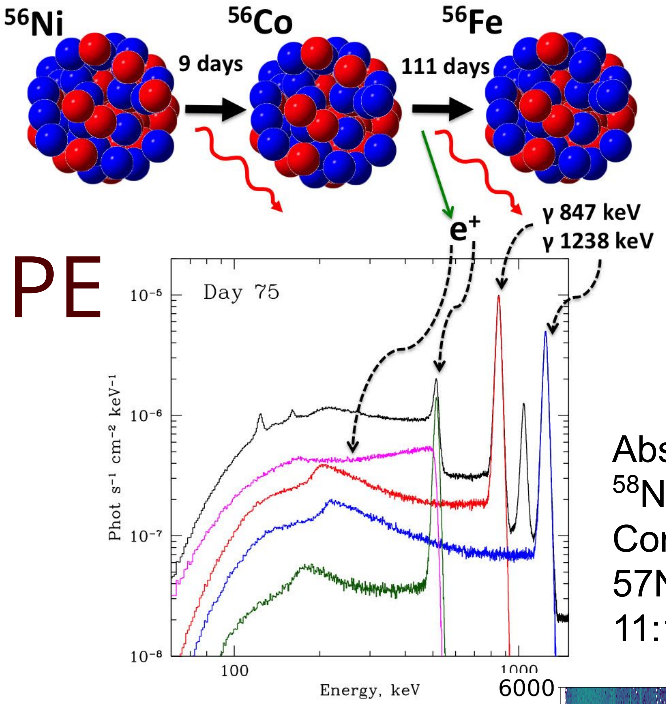
Supernovae



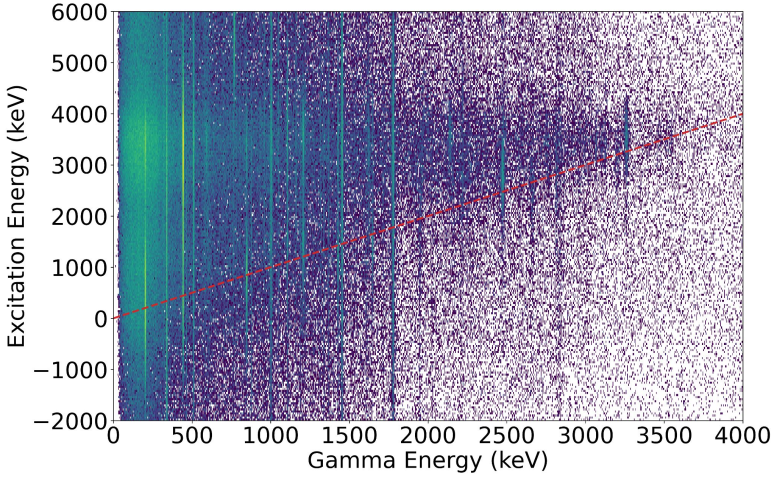
NRAO



MPE



Abstract: R06.00005 :
^{58}Ni(^{3}He,t)^{58}Cu Measurements to Constrain the Astrophysical Rate of 57Ni(p,γ)58Cu*
11:18 AM–11:30 AM Thursday



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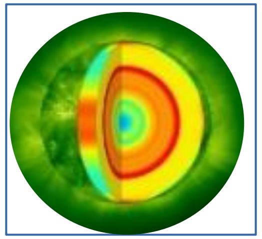

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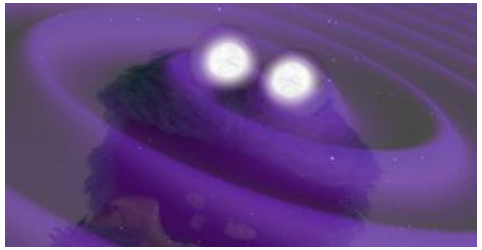

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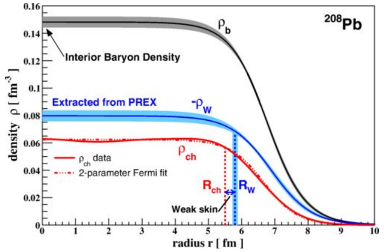

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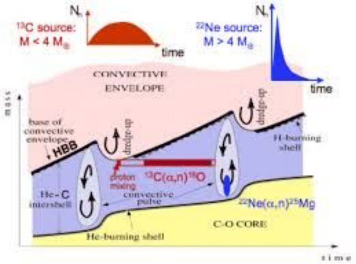


Heavy element nucleosynthesis in the multimessenger era

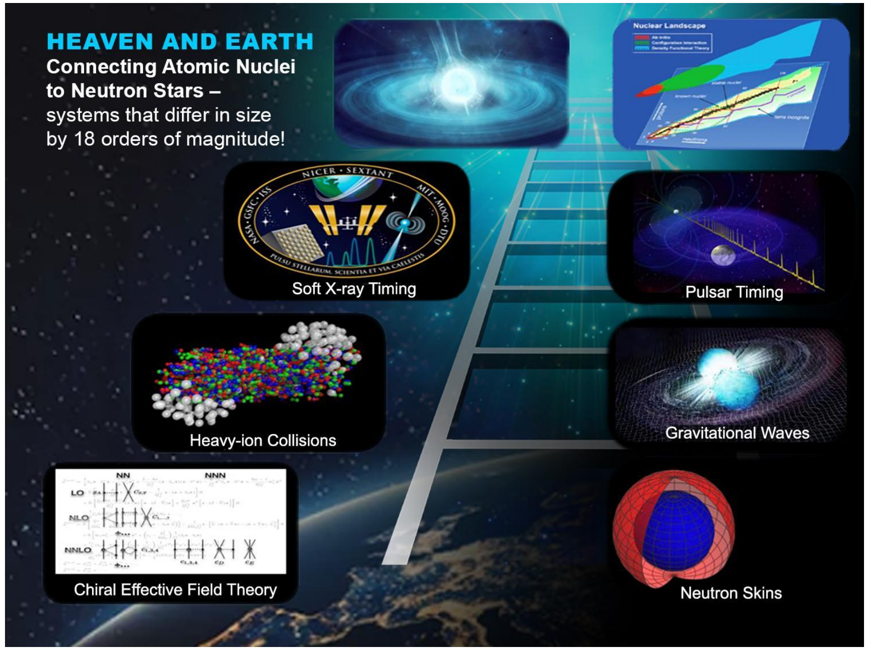
EoS and the symmetry energy

EoS physics links microscopic nuclear physics (ISGMR, IVGDR, masses, GT response, HIC, neutron skins etc) to behaviour of neutron stars

Observations - NICER data, GWs, NS cooling, X-ray bursts

NS cooling needs information on Urca processes (weak rates including between excited states!)

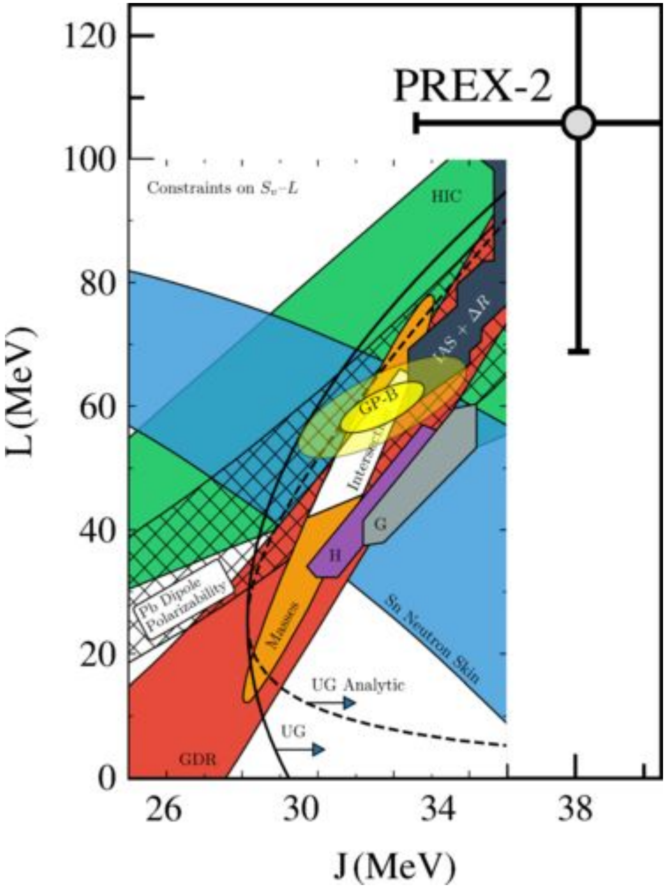
XRBs require accurate reaction rates for many reactions (Gavin's talk!)



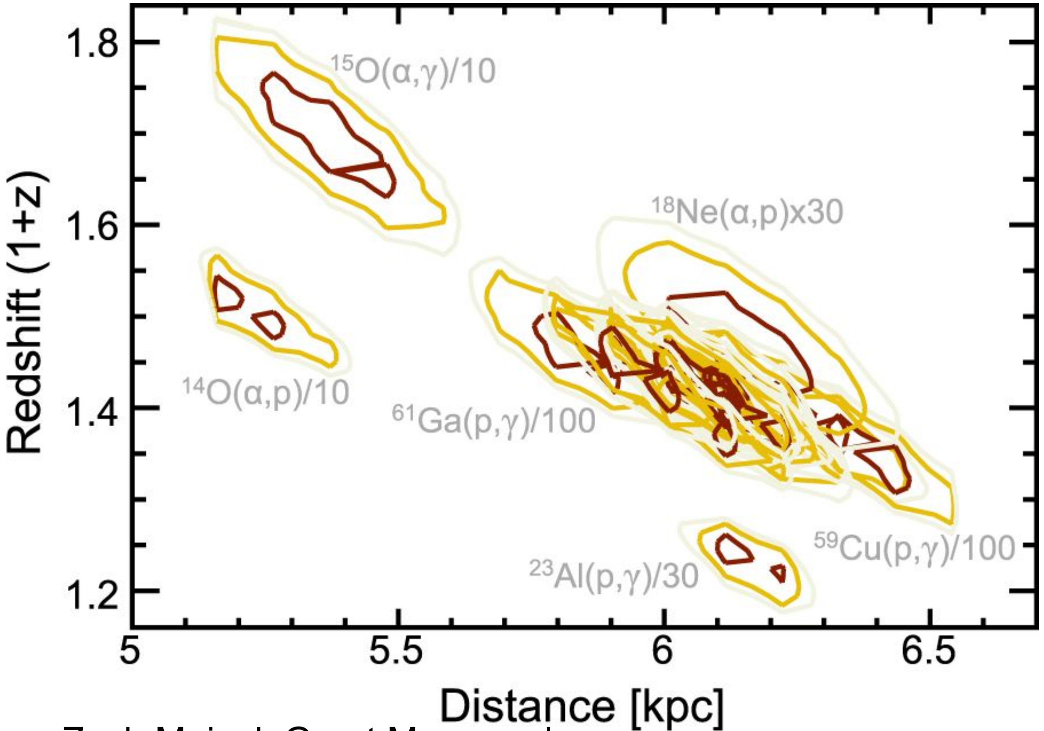
HEAVEN AND EARTH

Connecting Atomic Nuclei to Neutron Stars –

systems that differ in size by 18 orders of magnitude!

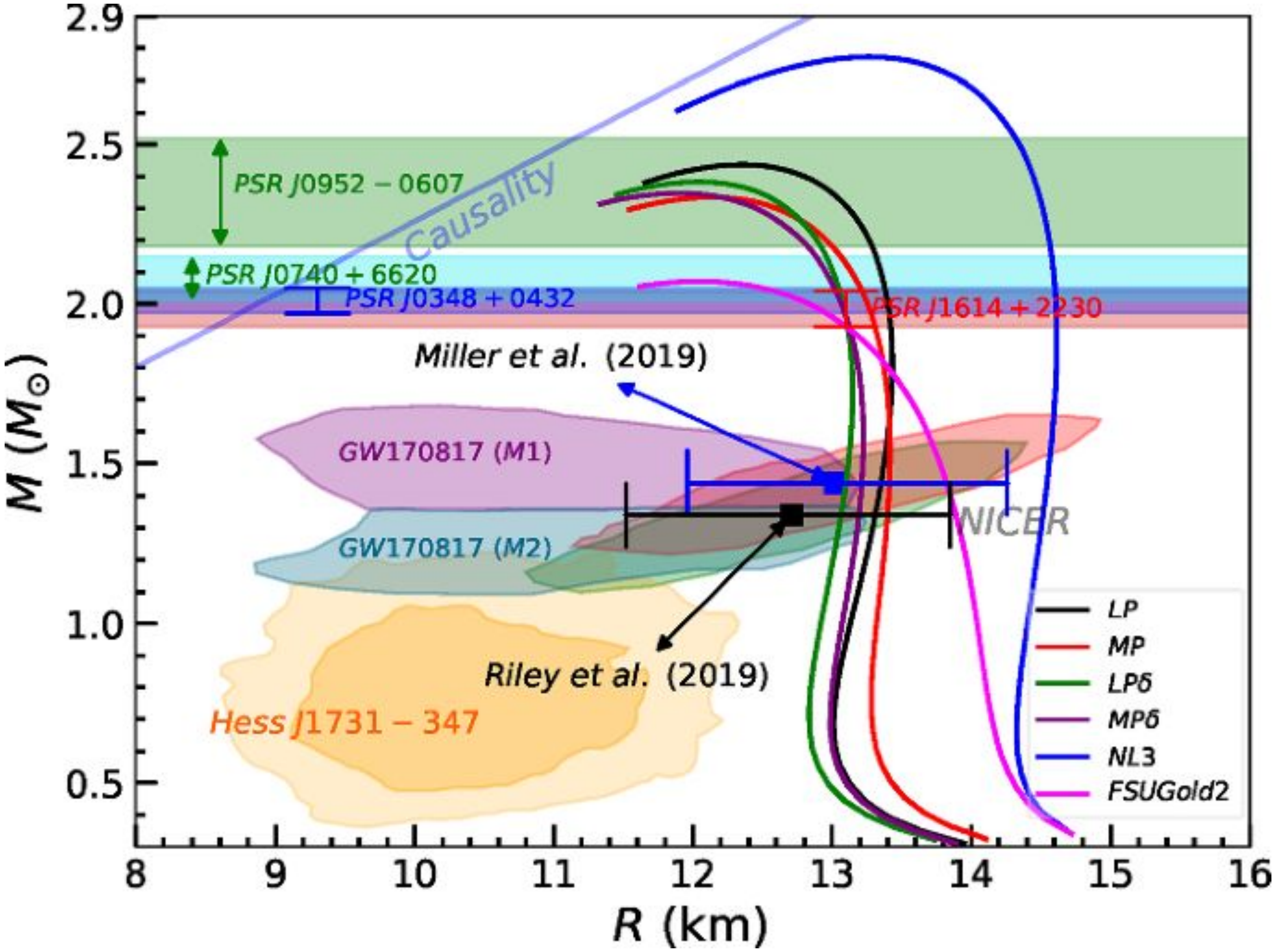


Brendan T. Reed, F. J. Fattoyev,
C. J. Horowitz, and J. Piekarewicz
Phys. Rev. Lett. 126, 172503



Zach Meisel, Grant Merz, and
Sophia Medvid

The Astrophysical Journal, Volume
872, Number 1



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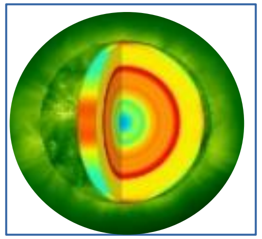

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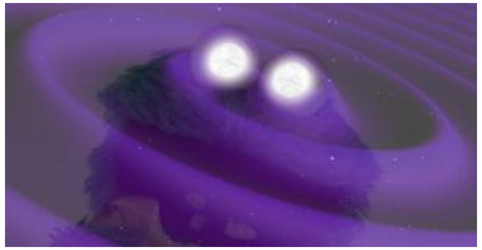

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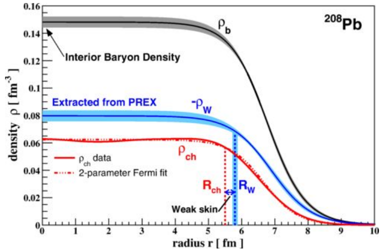

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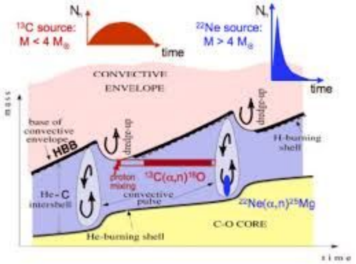

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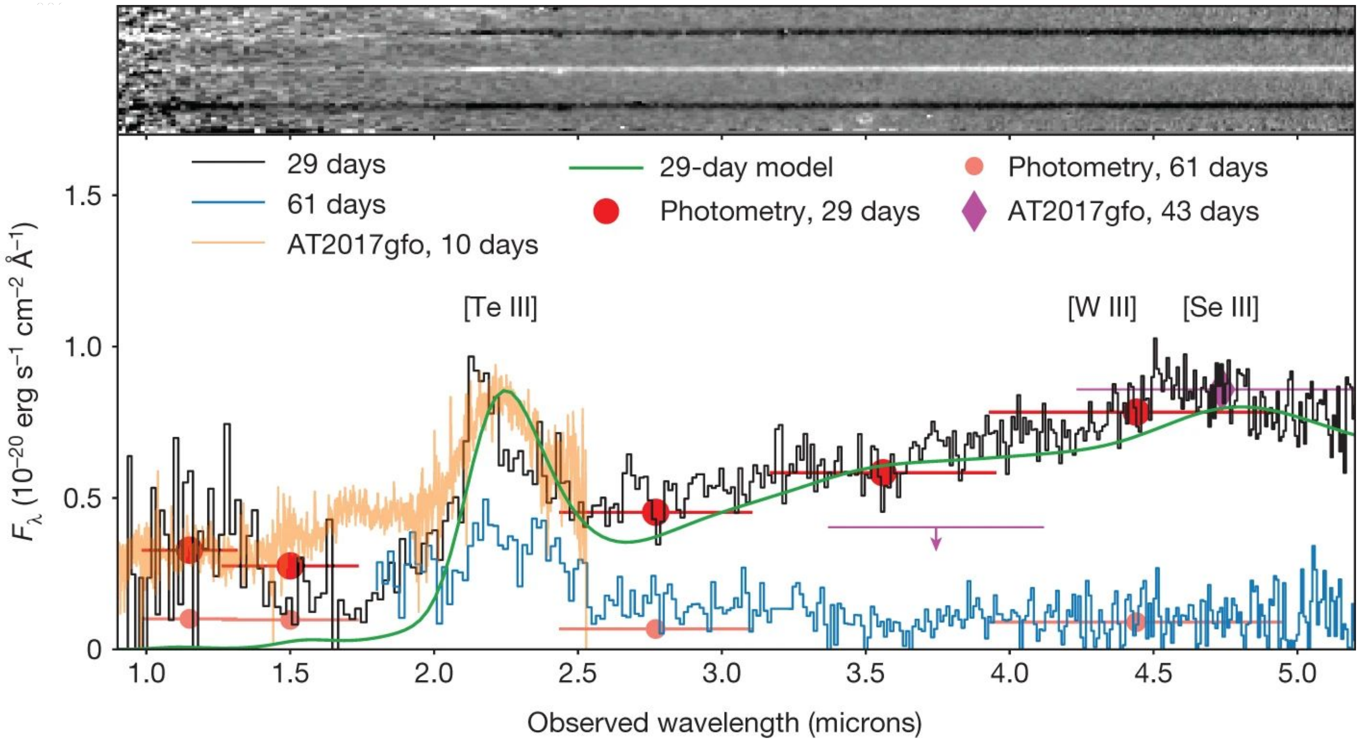
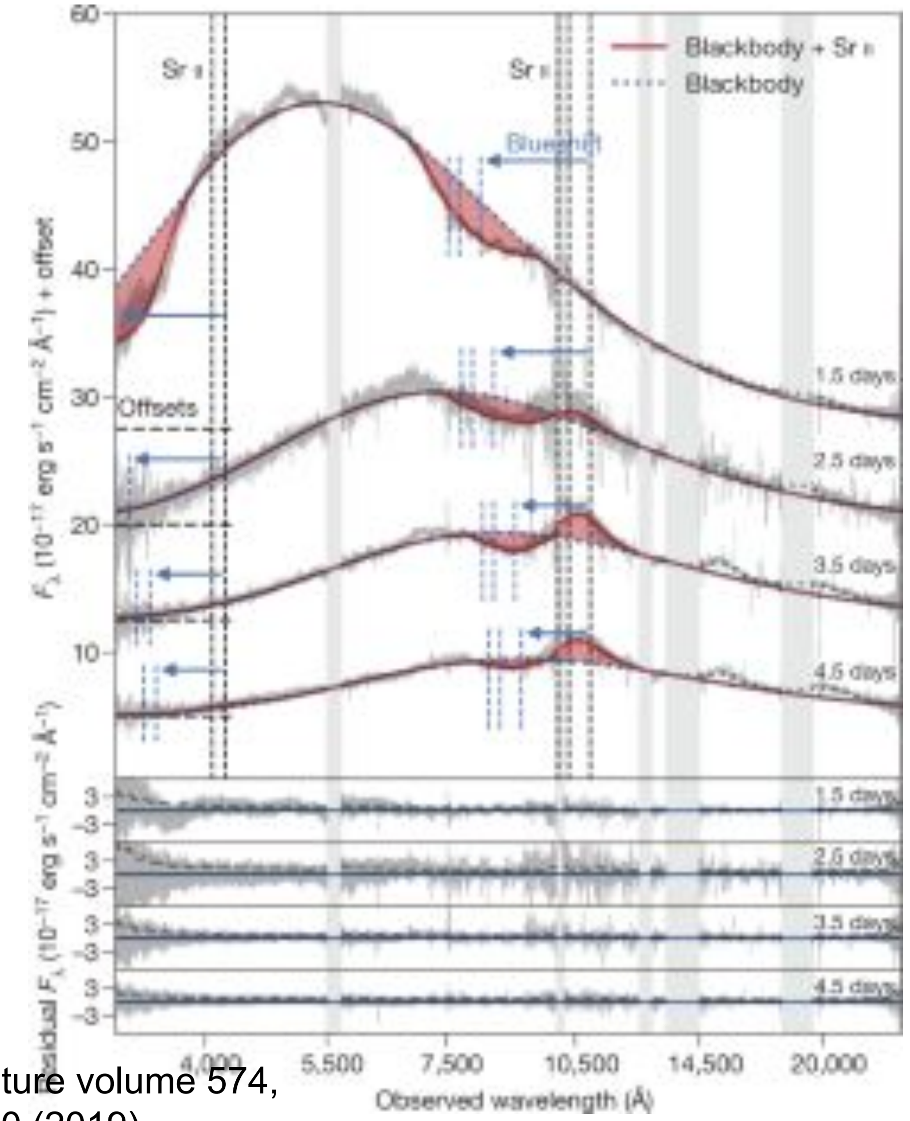


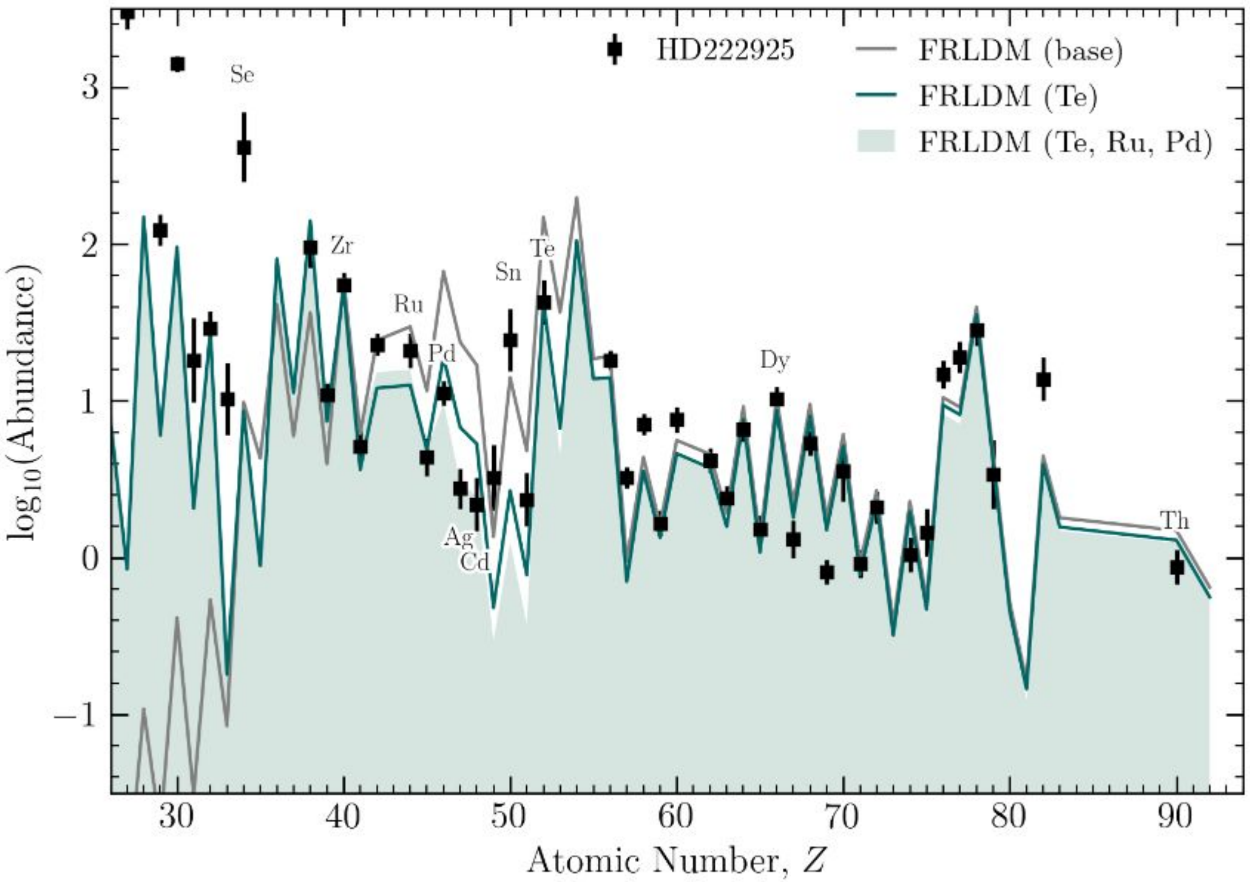
Levan++ Nature volume 626, pages737–741 (2024)

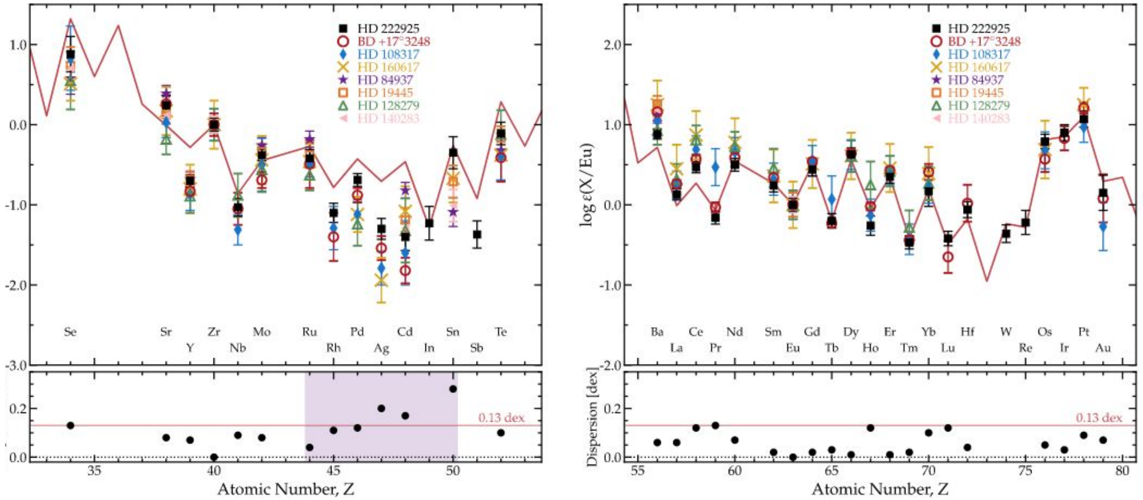
Definite production of heavy elements following the kilonova



Watson++ Nature volume 574, pages497–500 (2019)

Can we constrain the various astro contributions to r-process abundances with improved nuclear data?





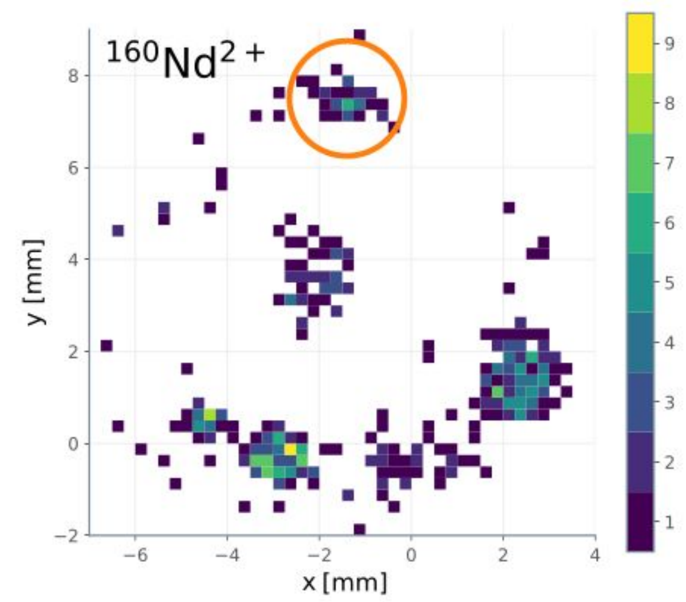
More precise knowledge of nuclear masses, decay branches, neutron capture, fission probabilities, spallation reactions can help pin down the astrophysics behind r-process sites

→ still some places, like the first r-process peak, where the uncertainty in the masses are driving abundance pattern changes on par with the uncertainties in the astrophysics

→ reverse engineering from the nuclear physics data and the observational data are allowing more meaningful constraints on the astrophysical conditions

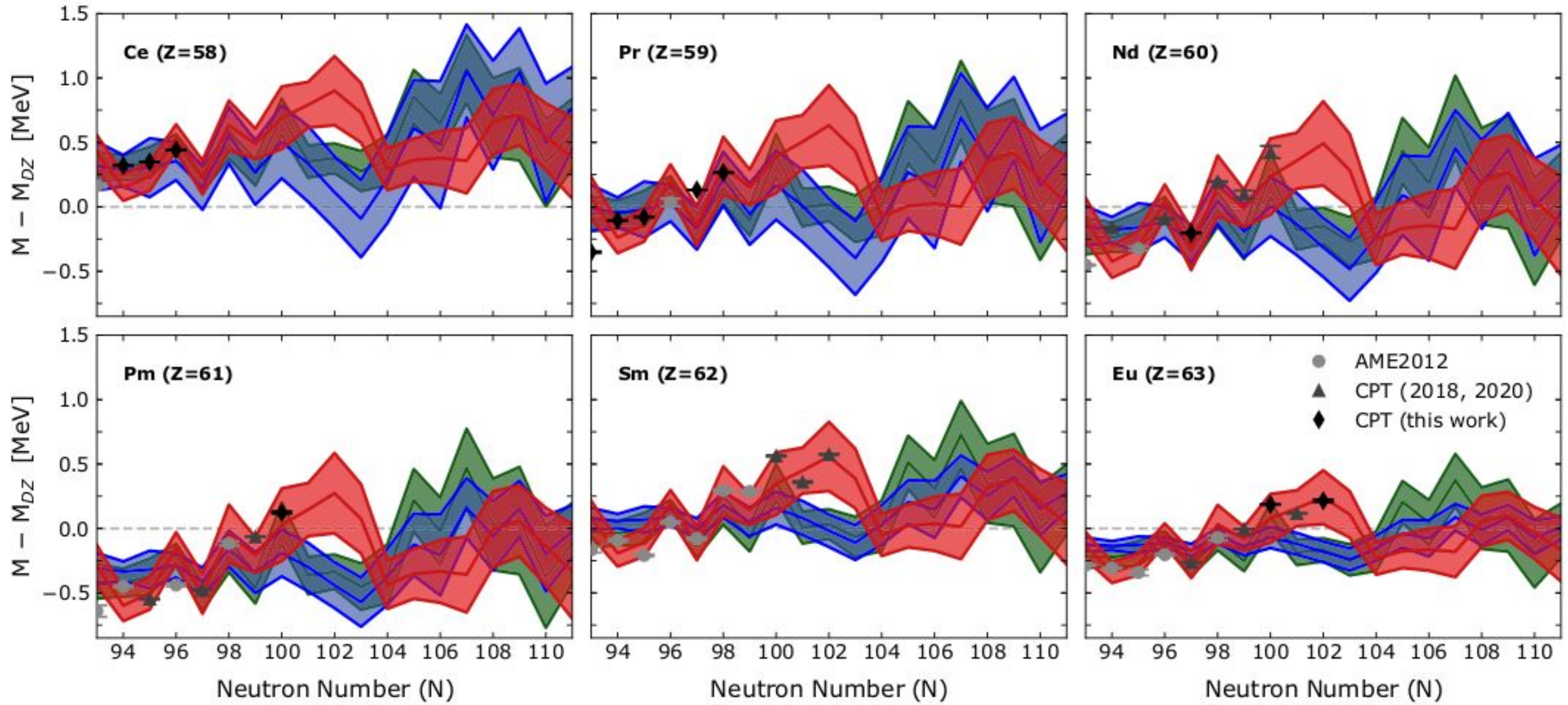
Holmbeck arxiv2210:10122,
Roederer ApJ 936:84 (2022)

Nuclear physics is improving astro predictions!



Precision mass measurements of most neutron-rich CARIBU isotopes using PI-ICR at the CPT pins down astrophysical outflow conditions

→ masses near N=100, A=164 r-process “rare earth peak”
→ data compared to MCMC reverse engineering of mass surface needed to reproduce observed solar abundance patterns given a particular NSM outflow model (hot, cold, mixed)

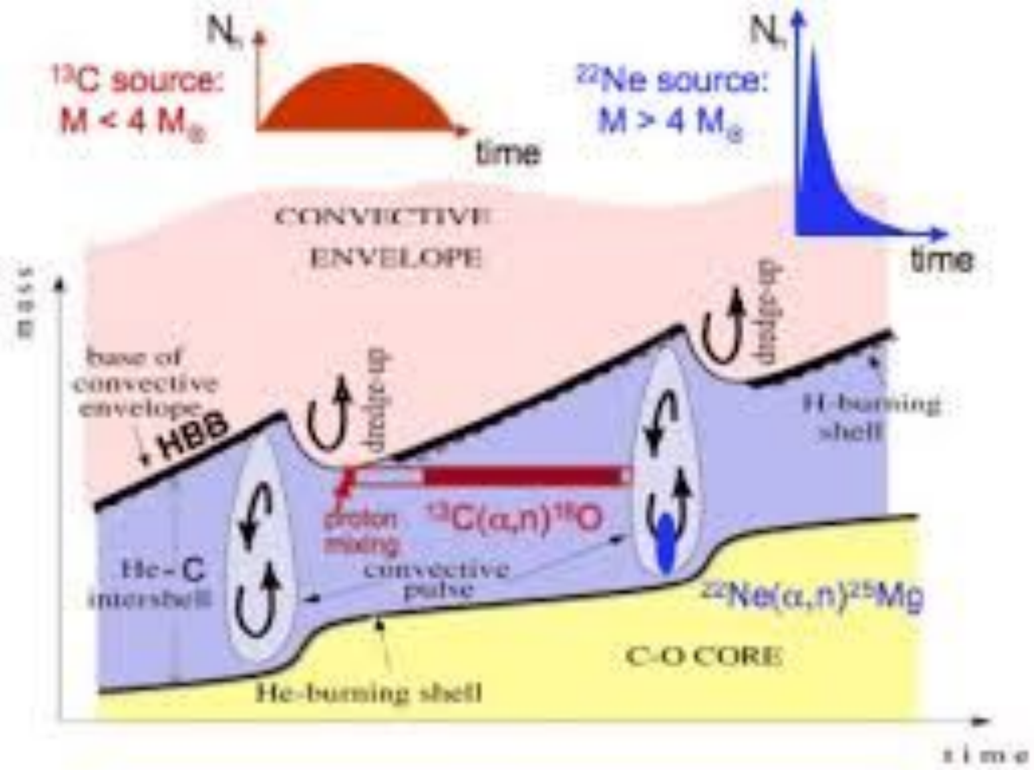


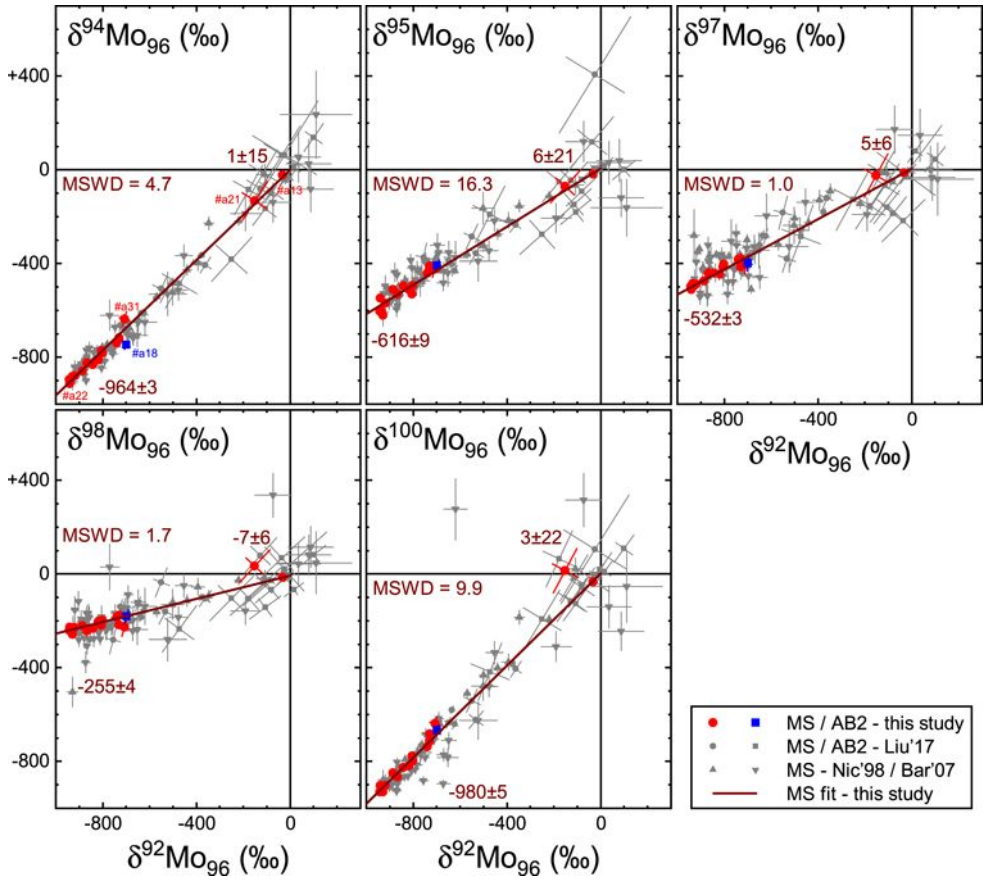
PRL120, 262702
& PRC105, L052802

Heavy element nucleosynthesis in the multimessenger era

Prof Surman will talk about the r-process in a moment but I like the s-process

Need to understand the s-process to confirm r-process models





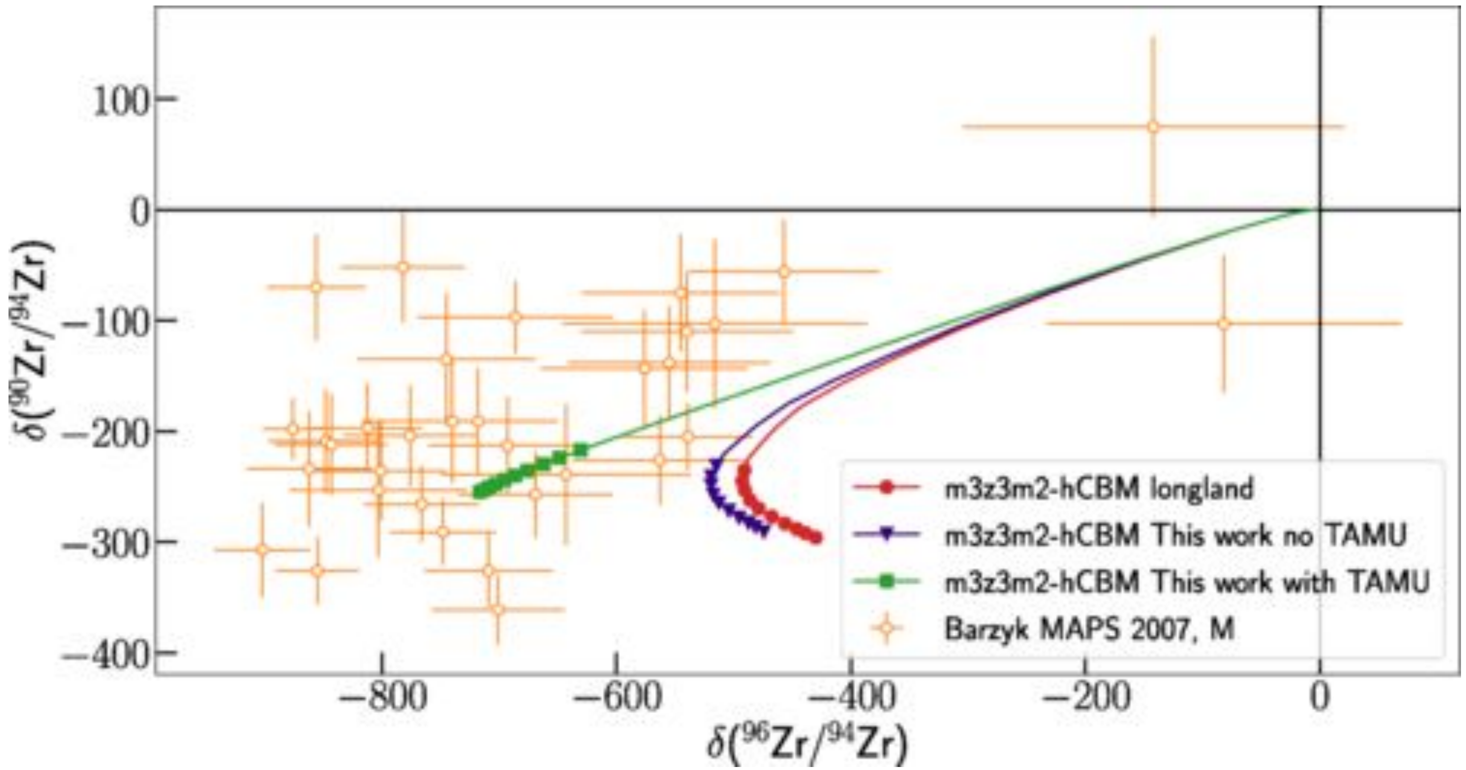
Rightly much focus on observations - GWs, ν, optical, presolar grains and isotopic ratios also vital to models of GCE

As an example: ^{96}Zr can be made in s-process since ^{95}Zr is long lived

It’s a probe of the neutron density in e.g. AGB stars

Strong dependence on the ^{22}Ne(α,n) rate (oh no)

Most ^{96}Zr is produced in the r-process but how much? Need to know the s-process



Any questions?

Blame Kelly for any mistakes :)

(She gave me a lot of the slides so also I should say “thanks”, I guess)