

The astrophysical r-process: what we are learning from gravitational waves, dwarf galaxies, and stellar archaeology



Ian U. Roederer

University of Michigan

and

Joint Institute for Nuclear Astrophysics and Chemical Evolution of the Elements

The astrophysical r-process: what we are learning from gravitational waves, dwarf galaxies, and stellar archaeology



I am grateful for the many contributions of my collaborators on these projects:

Jeb Bailey (Leiden)

Tim Beers (Notre Dame)

Eric Bell (Michigan)

John Cowan (Oklahoma)

Jeff Crane (Carnegie Obs.)

Anna Frebel (MIT)

Terese Hansen (Carnegie Obs.)

Kohei Hattori (Michigan)

Jim Lawler (Wisconsin)

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Mario Mateo (Michigan)

David Nidever (Montana St.)

Ed Olszewski (Arizona)

Vini Placco (Notre Dame)

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Hendrik Schatz (Michigan State)

Steve Sheckman (Carnegie Obs.)

Chris Sneden (Texas)

Jen Sobeck (Washington)

Yingyi Song (Michigan)

Ian Thompson (Carnegie Obs.)

Monica Valluri (Michigan)

Matt Walker (Carnegie Mellon)

The astrophysical r-process: what we are learning from gravitational waves, dwarf galaxies, and stellar archaeology



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National Science Foundation
WHERE DISCOVERIES BEGIN



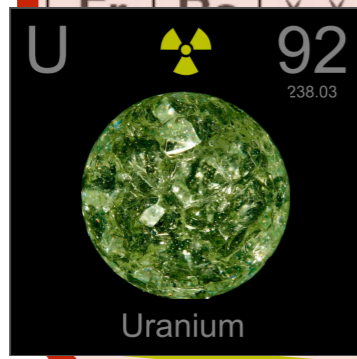
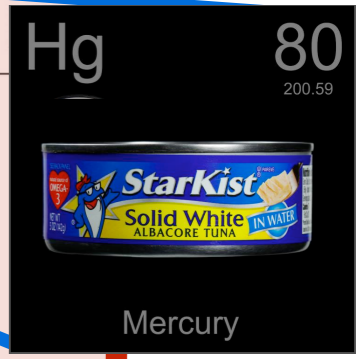
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lithium 3 Li 6.941	beryllium 4 Be 9.0122											boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180	
sodium 11 Na 22.990	magnesium 12 Mg 24.305											aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948	
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80	
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29	
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 **	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

* Lanthanide series

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

** Actinide series

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(most) images: periodictable.com

H

hydrogen 1 H 1.00794

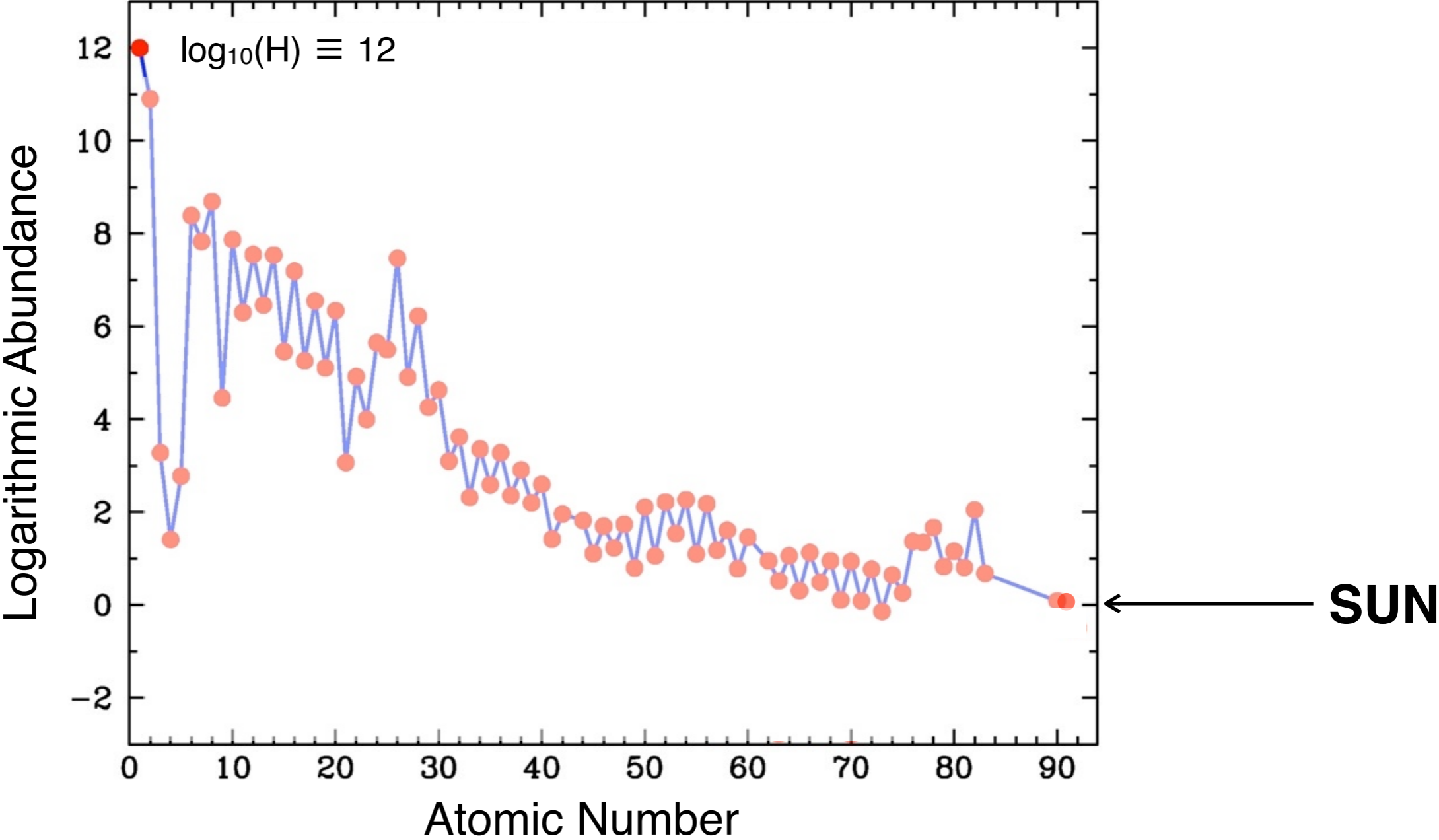
helium 2 He 4.002602

He

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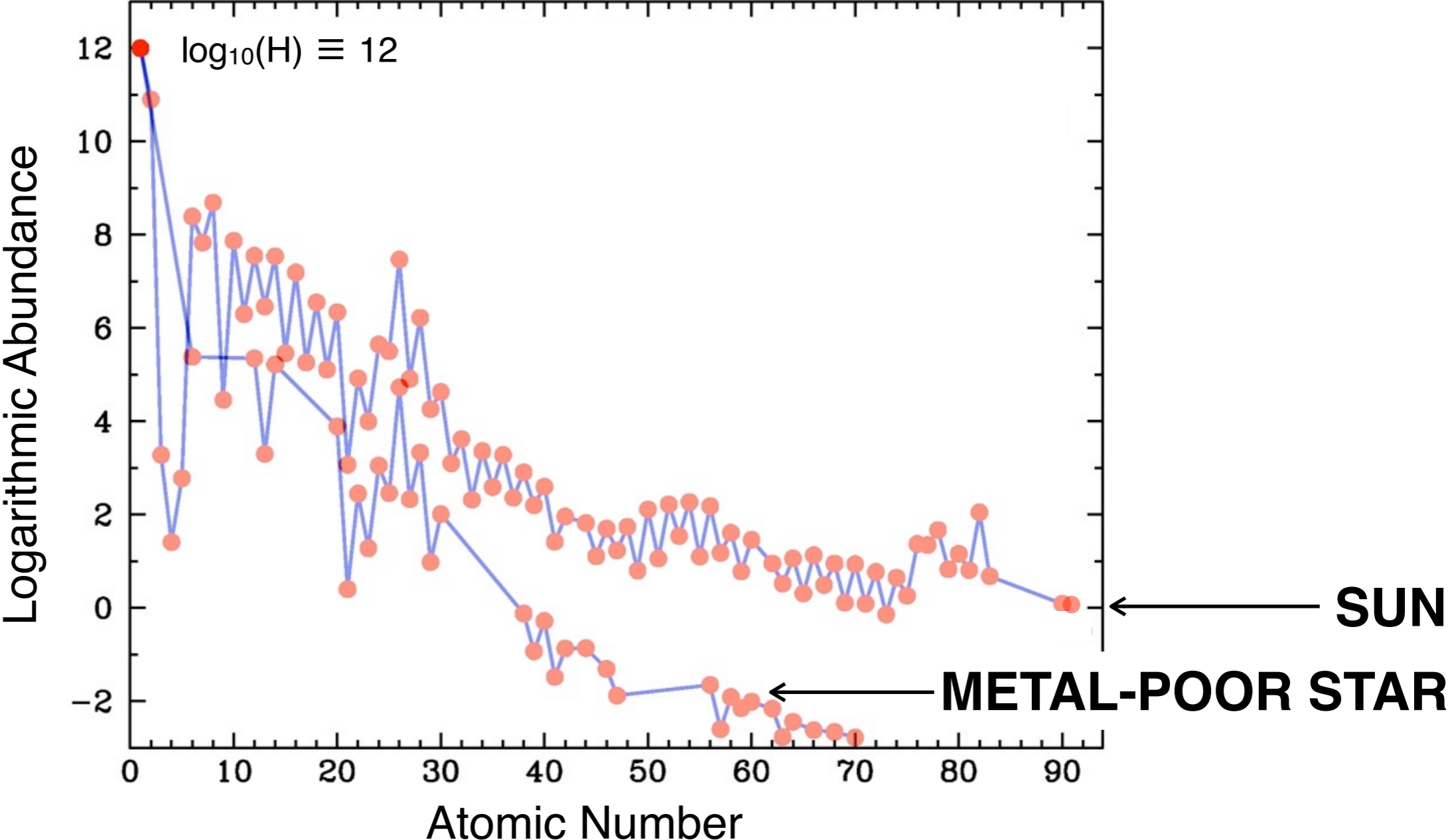
METALS

Why stars?



data: Lodders, Astrophys. J., 591, 1220 (2003)

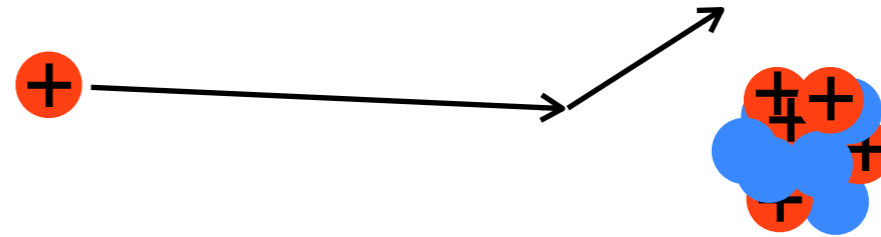
Why stars?



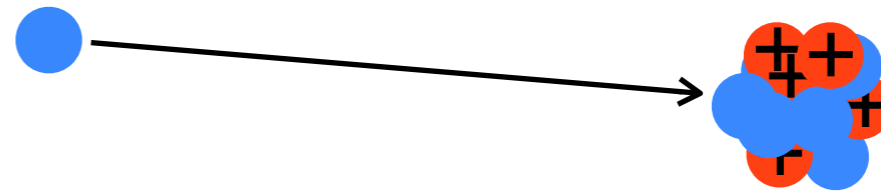
data: Lodders, Astrophys. J., 591, 1220 (2003)

What is known about the physics of heavy-element nucleosynthesis?

Charged-particle reactions are ineffective for heavy nuclei.

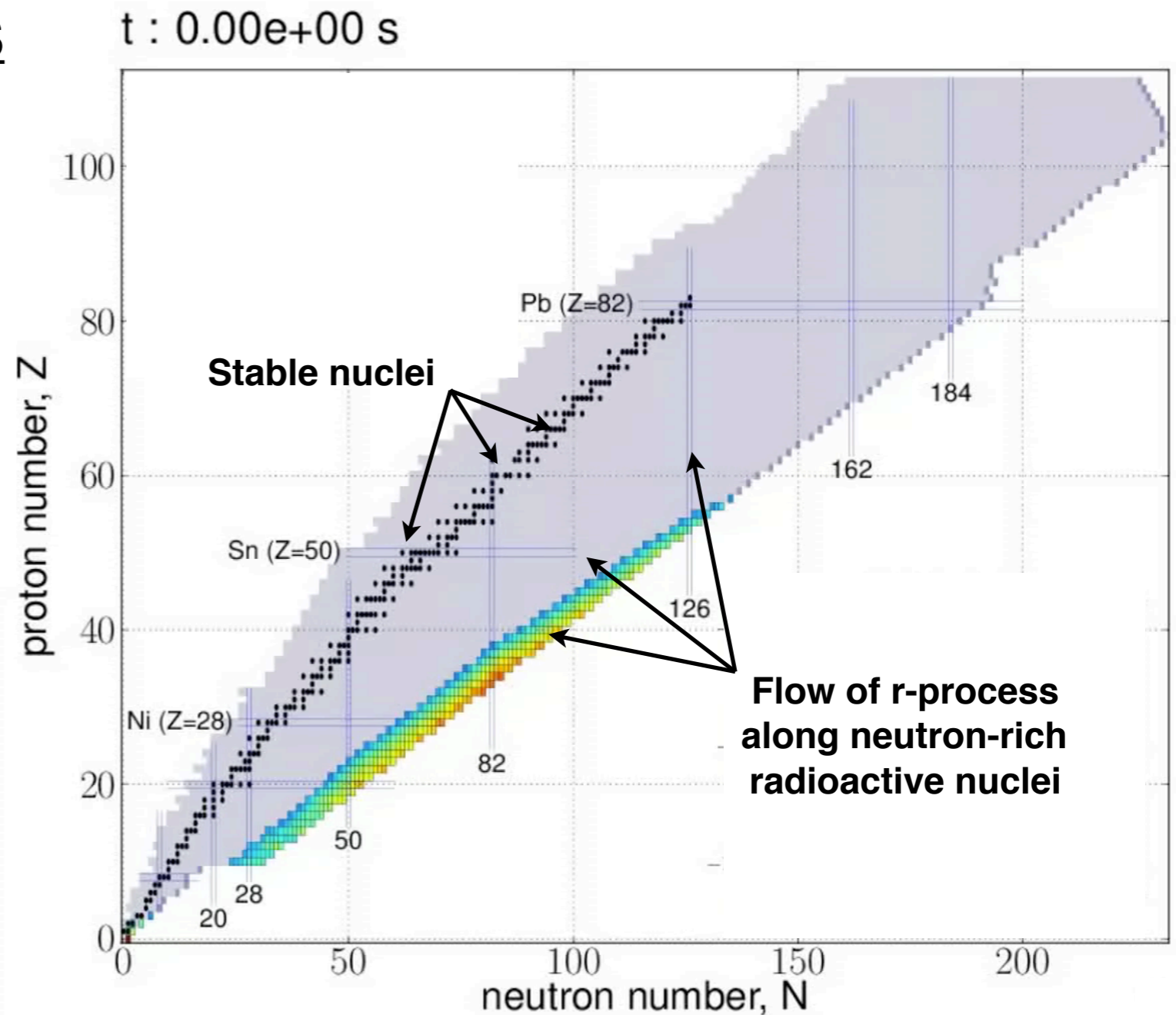


Neutron-capture reactions are effective for heavy nuclei.



r-process nucleosynthesis

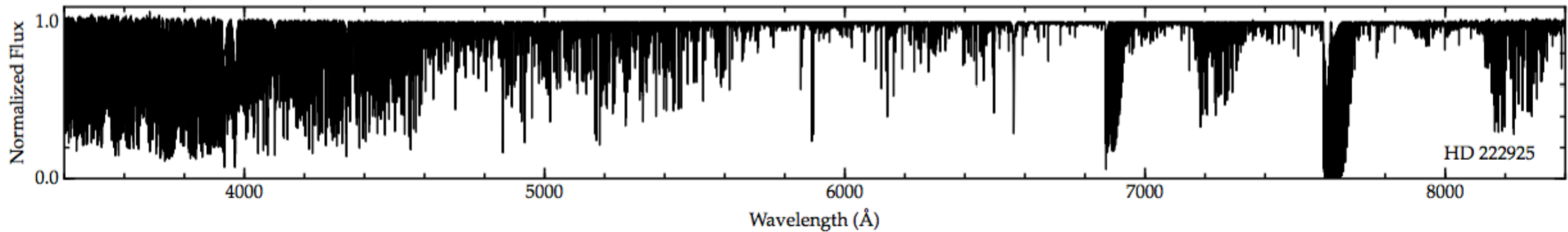
- * **r**apid addition of neutrons
- * explosive environment
- * $\sim 10^{22} - 10^{28} \text{ n cm}^{-3}$
- * produced most heavy elements in the oldest stars
- * produced about half of heavy elements found in the Sun

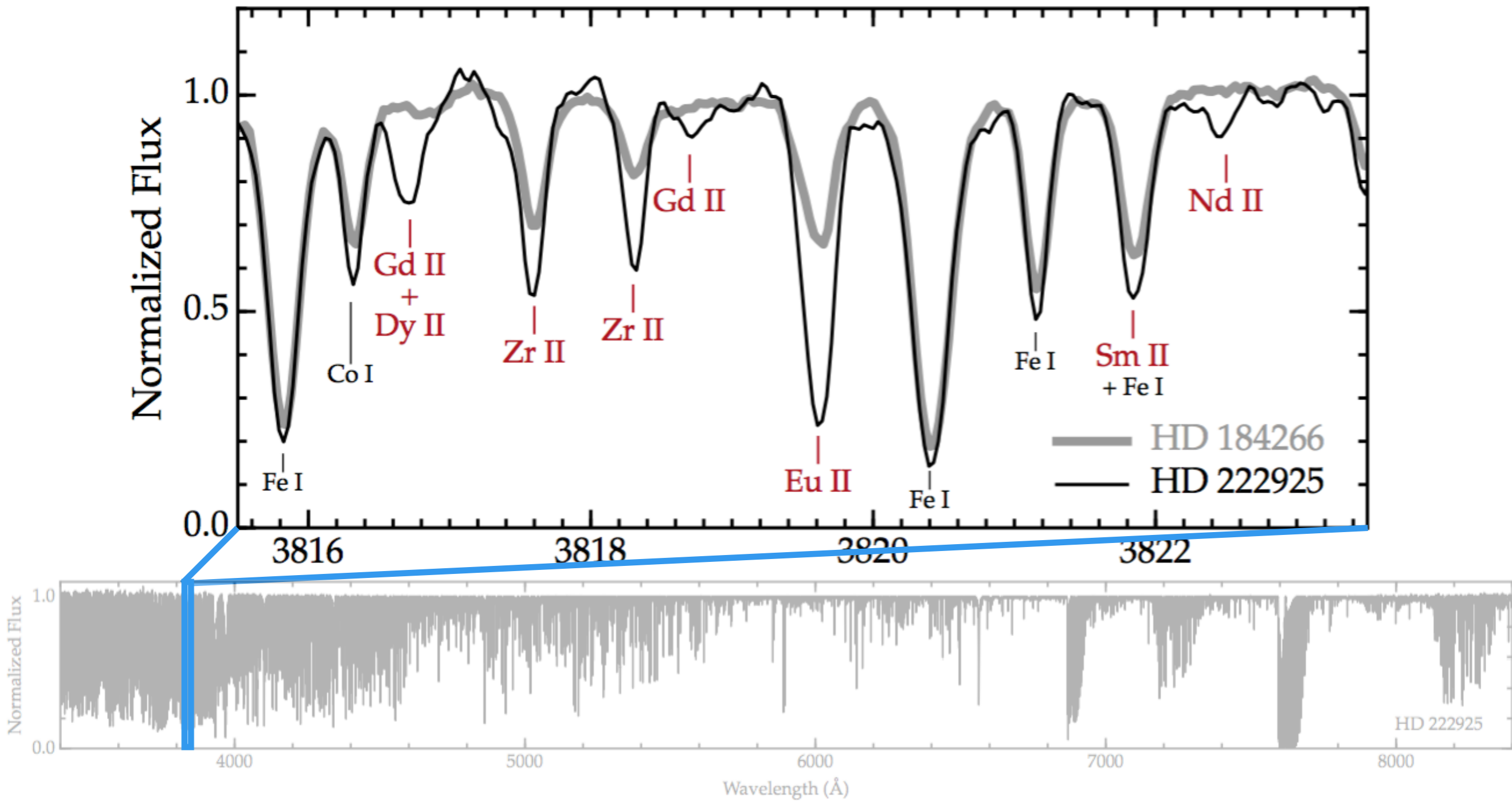


Burbidge, Burbidge, Fowler, & Hoyle, Rev. Mod. Phys., 29, 547 (1957)

Korobkin et al., Mon. Not. Roy. Astron. Soc., 426, 1940 (2012)

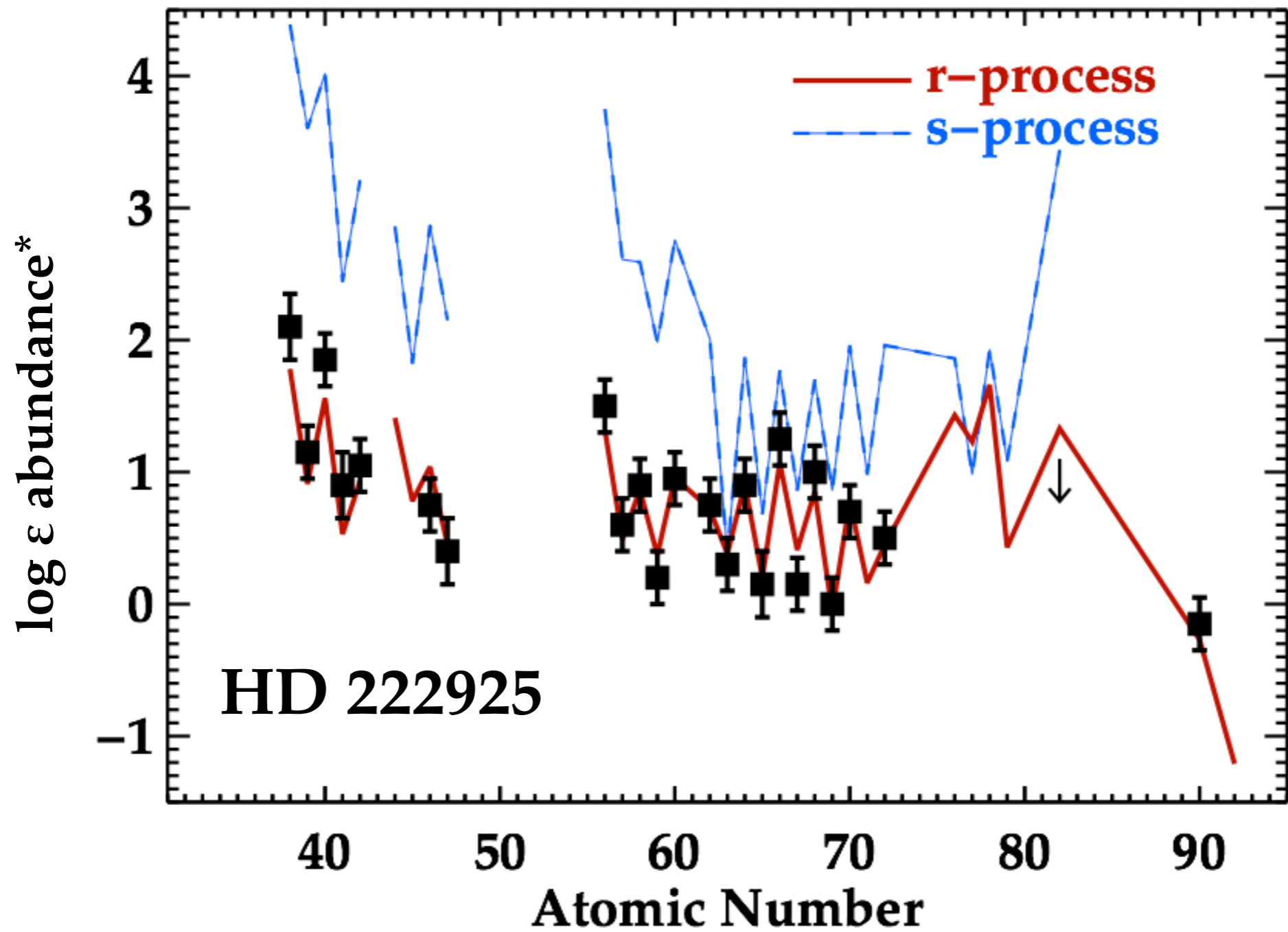
This is a high-resolution, high-S/N optical spectrum of a cool star.
Every line in this spectrum is real!





spectra obtained using Magellan/MIKE, Sept. 2017

Roederer et al., in prep.



* for a given element X, $\log \epsilon (X) = \log_{10}(X/H) + 12.0$

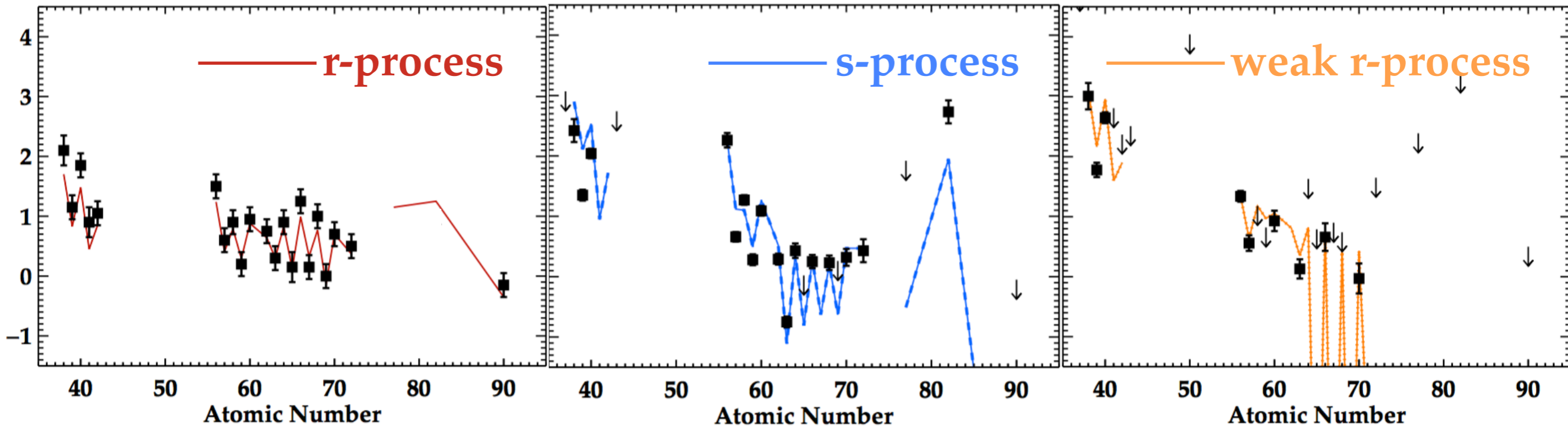
Abundance patterns produced by different nucleosynthesis processes are easily distinguishable.

HD 222925

HD 196944

CS 22891-209

log abundance, arbitrary scale

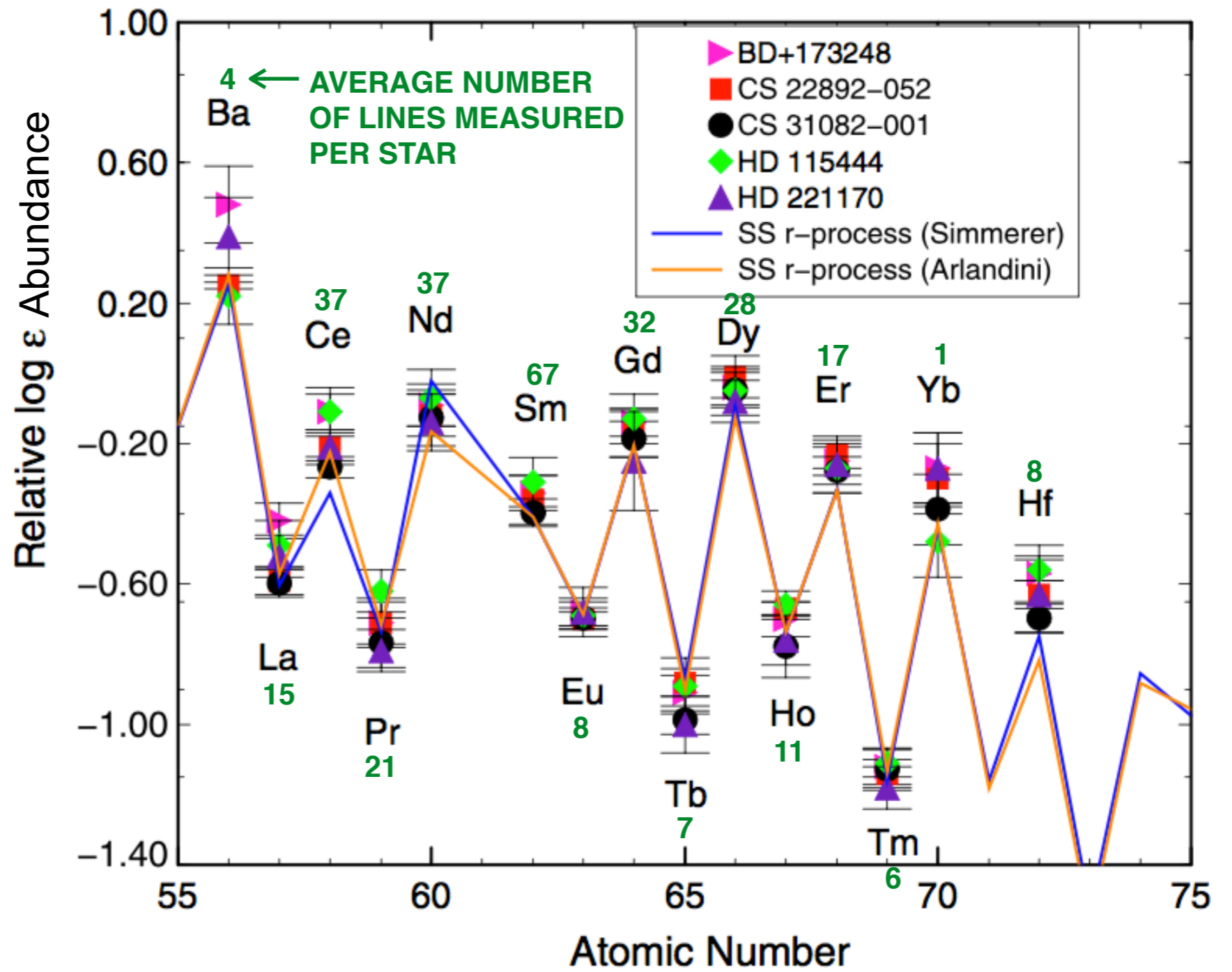


~ 5% of metal-poor stars

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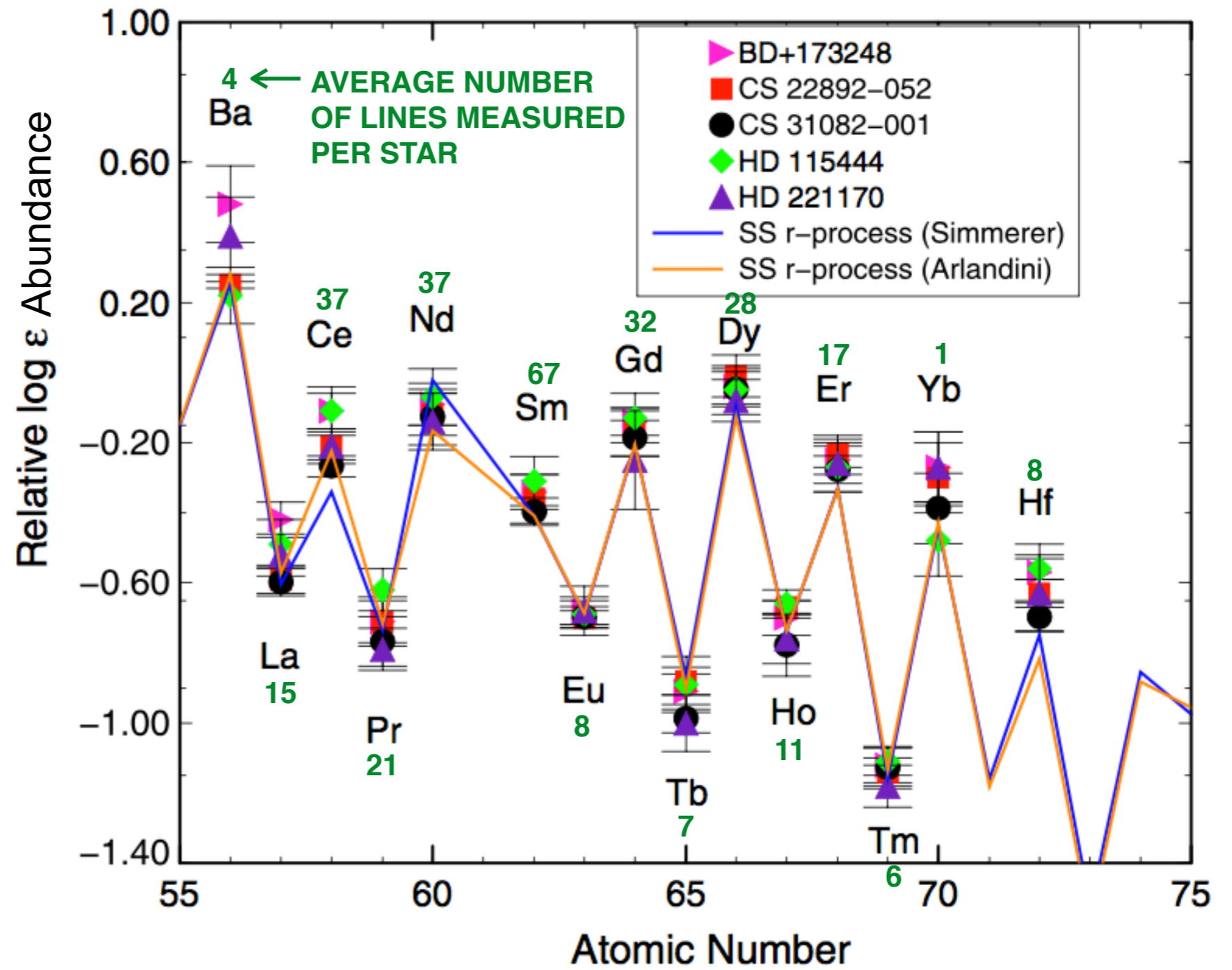
~ 25% of metal-poor stars

Most other metal-poor stars show composite signatures of these processes.

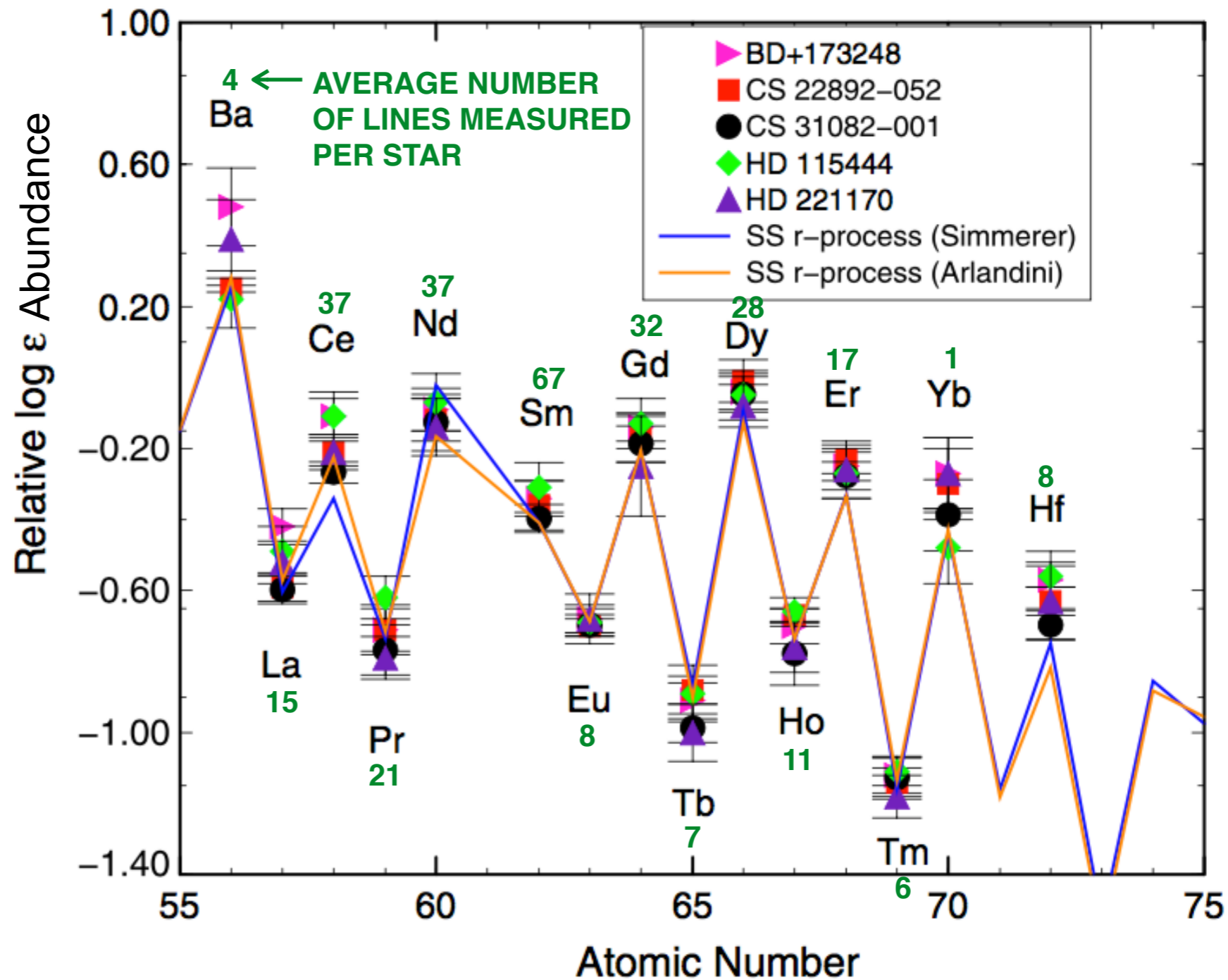


Sneden et al., *Astrophys. J. Sup. Ser.*, 182, 80 (2009)

1. Small observational uncertainties

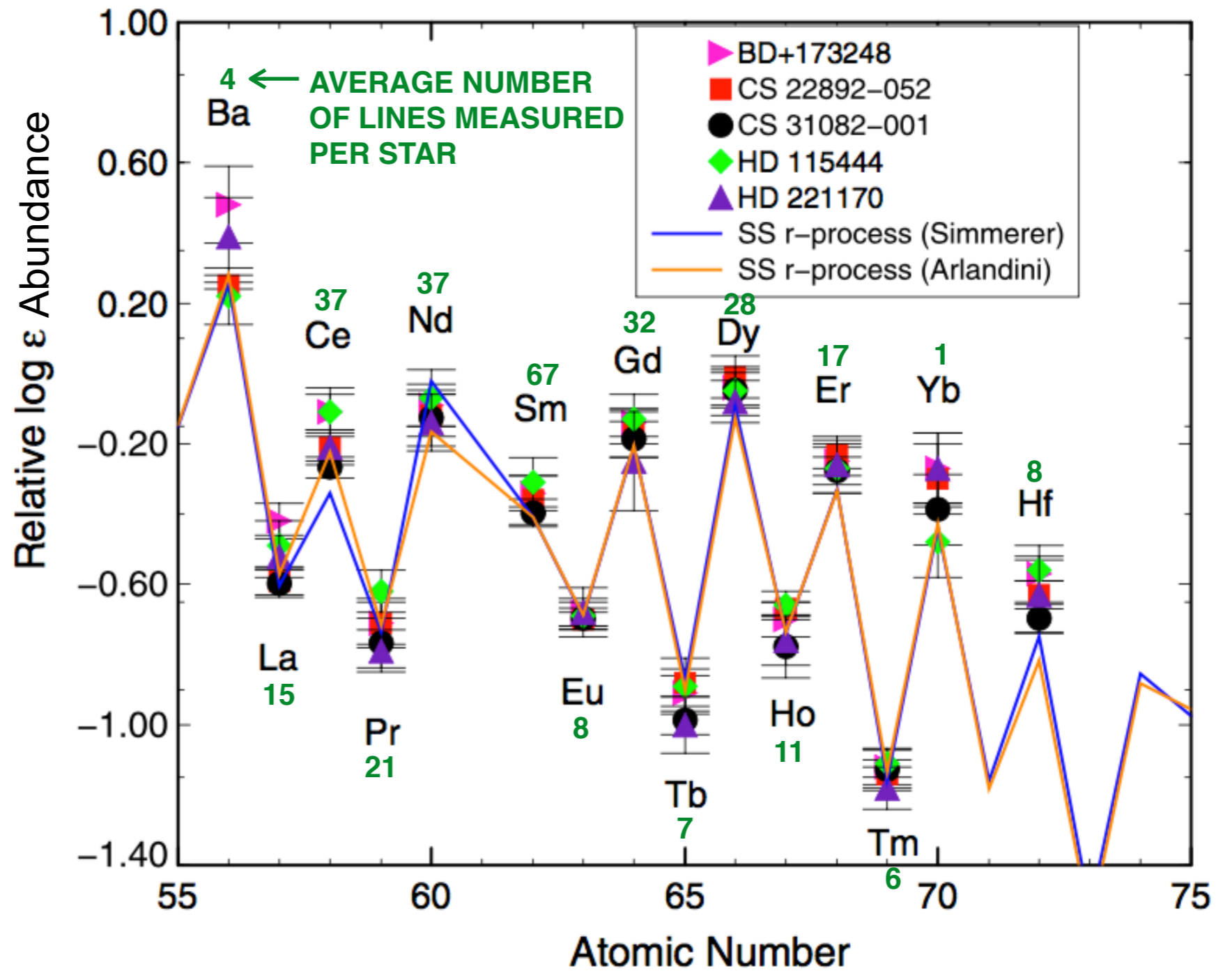


1. Small observational uncertainties
2. Virtually identical patterns ...



Sneden et al., *Astrophys. J. Sup. Ser.*, 182, 80 (2009)

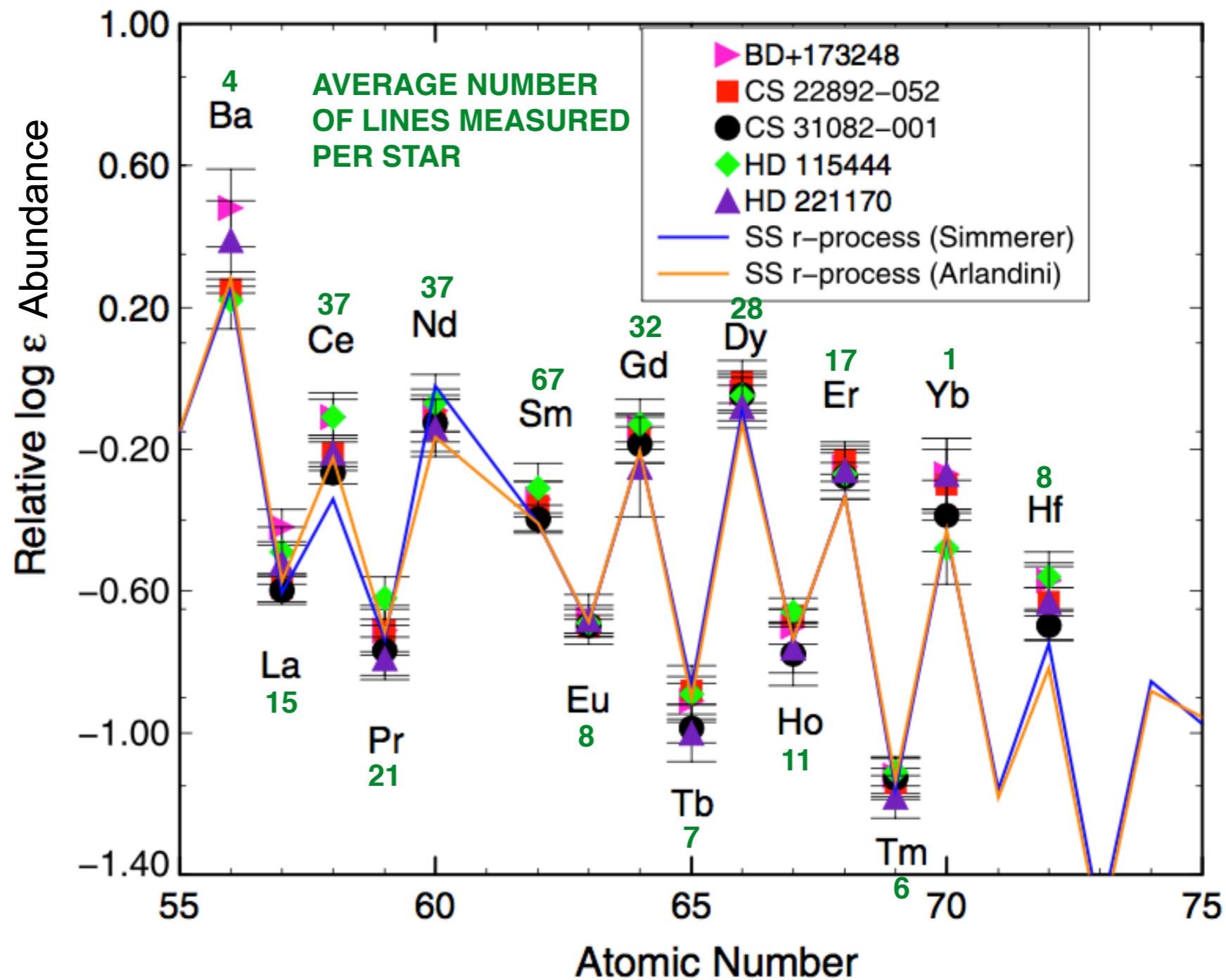
1. Small observational uncertainties
2. Virtually identical patterns ...
3. ... that are basically unchanged across ~ 9 billion years of cosmic time



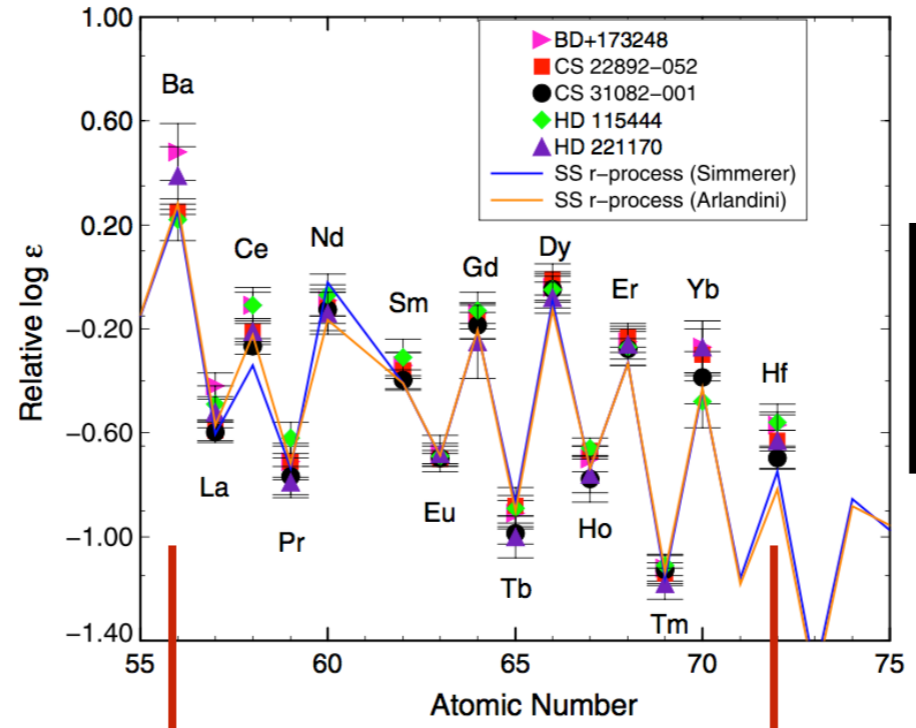
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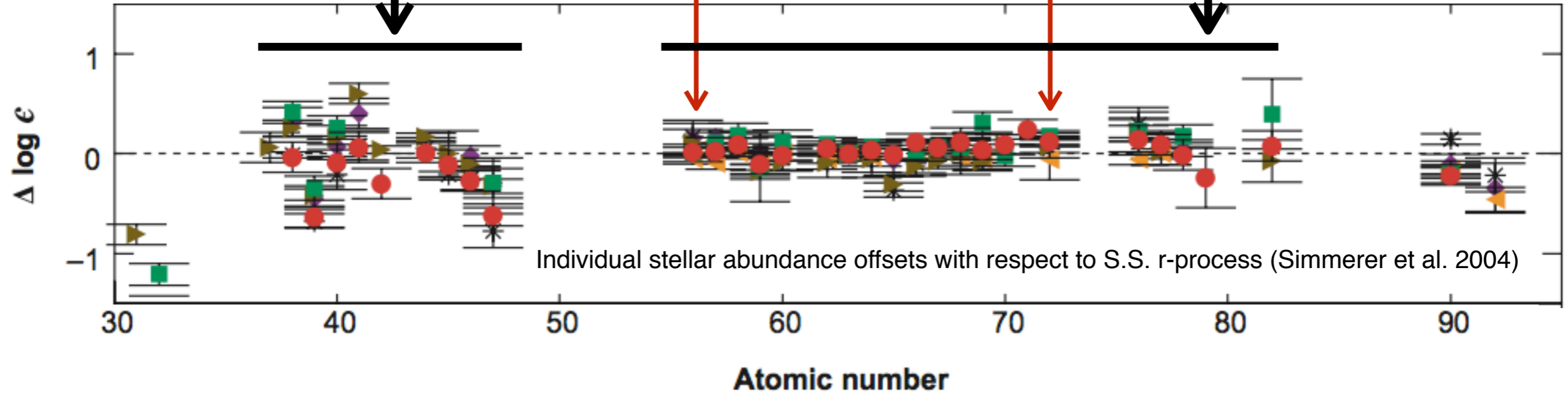
**The
“universality”
of the r-process**



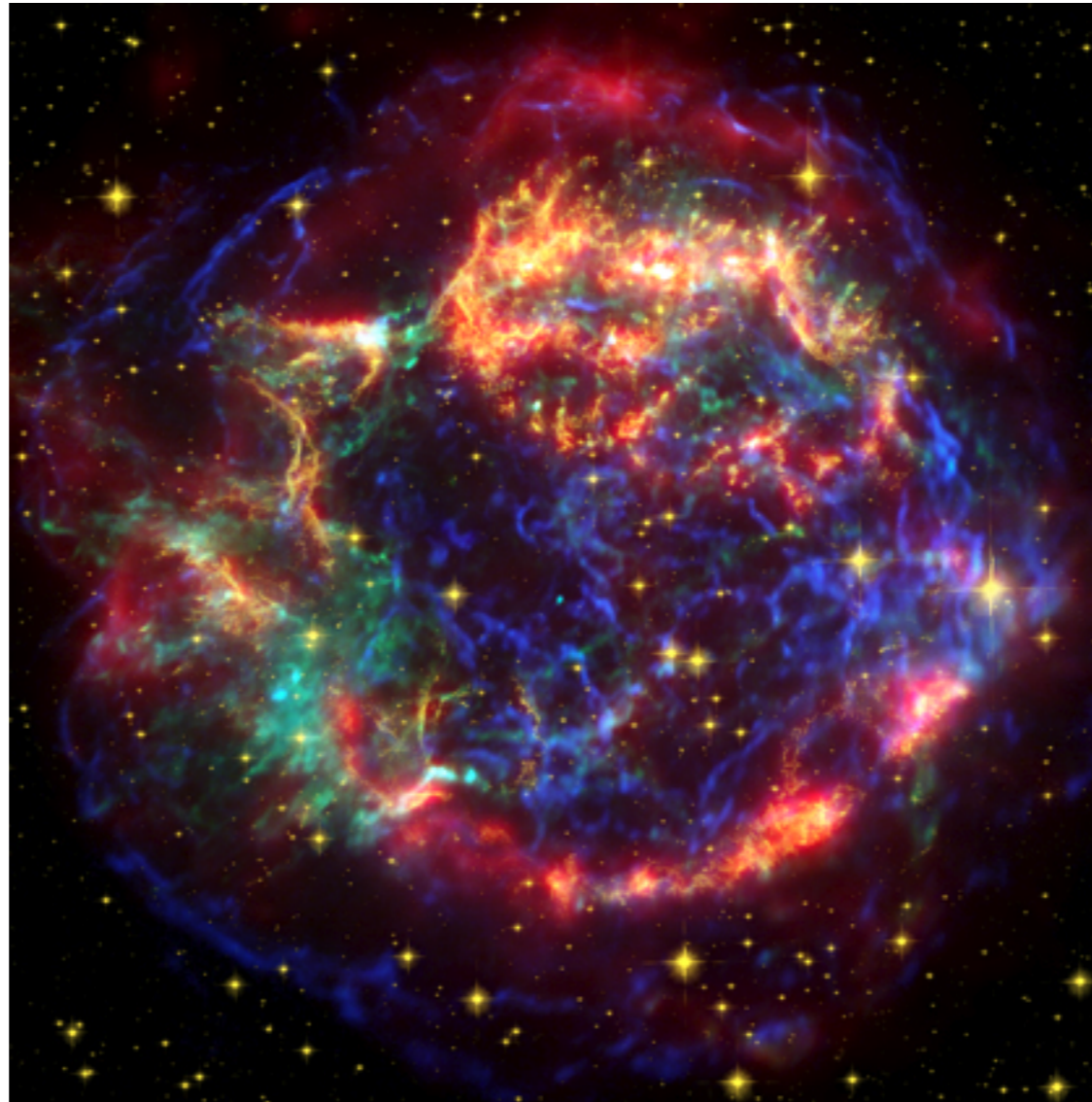
**“universality”
not applicable**



**“universality”
applicable**

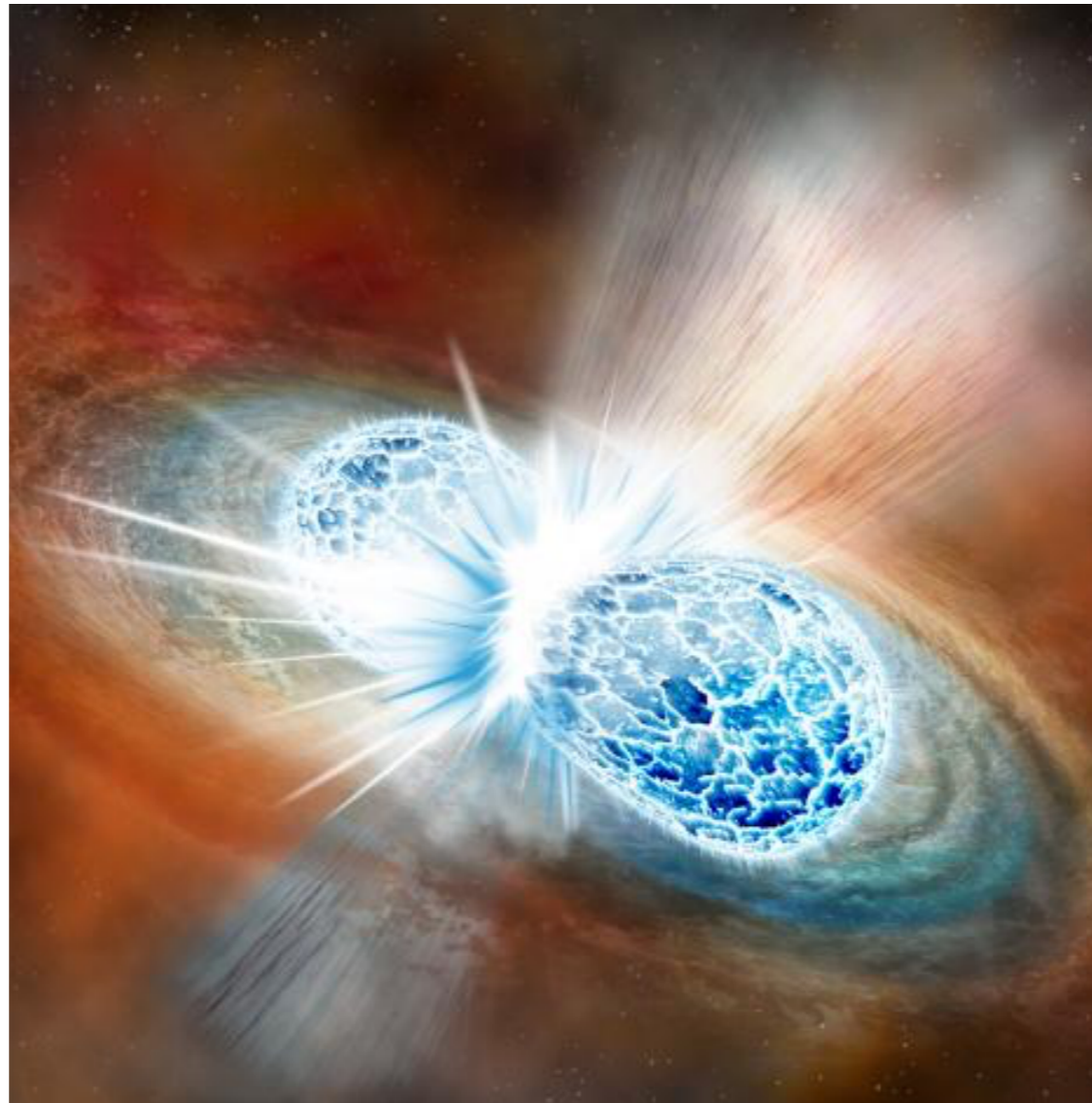


Sneden et al., *Astrophys. J. Sup. Ser.*, 182, 80 (2009)
Sneden et al., *Ann. Rev. Astron. Astrophys.*, 46, 241 (2008)



$\sim 10^{-5} M_{\odot}$ of r-process material

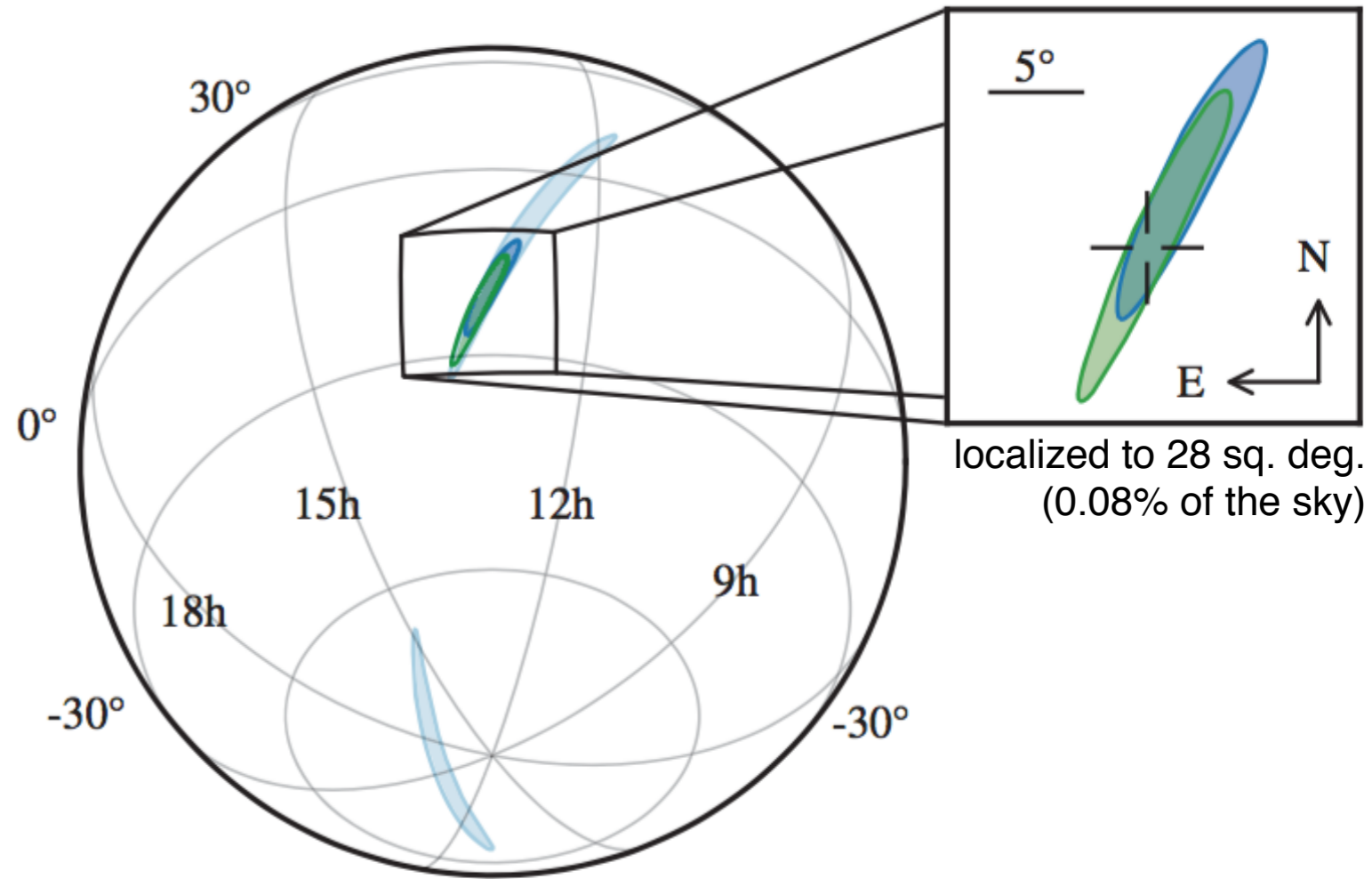
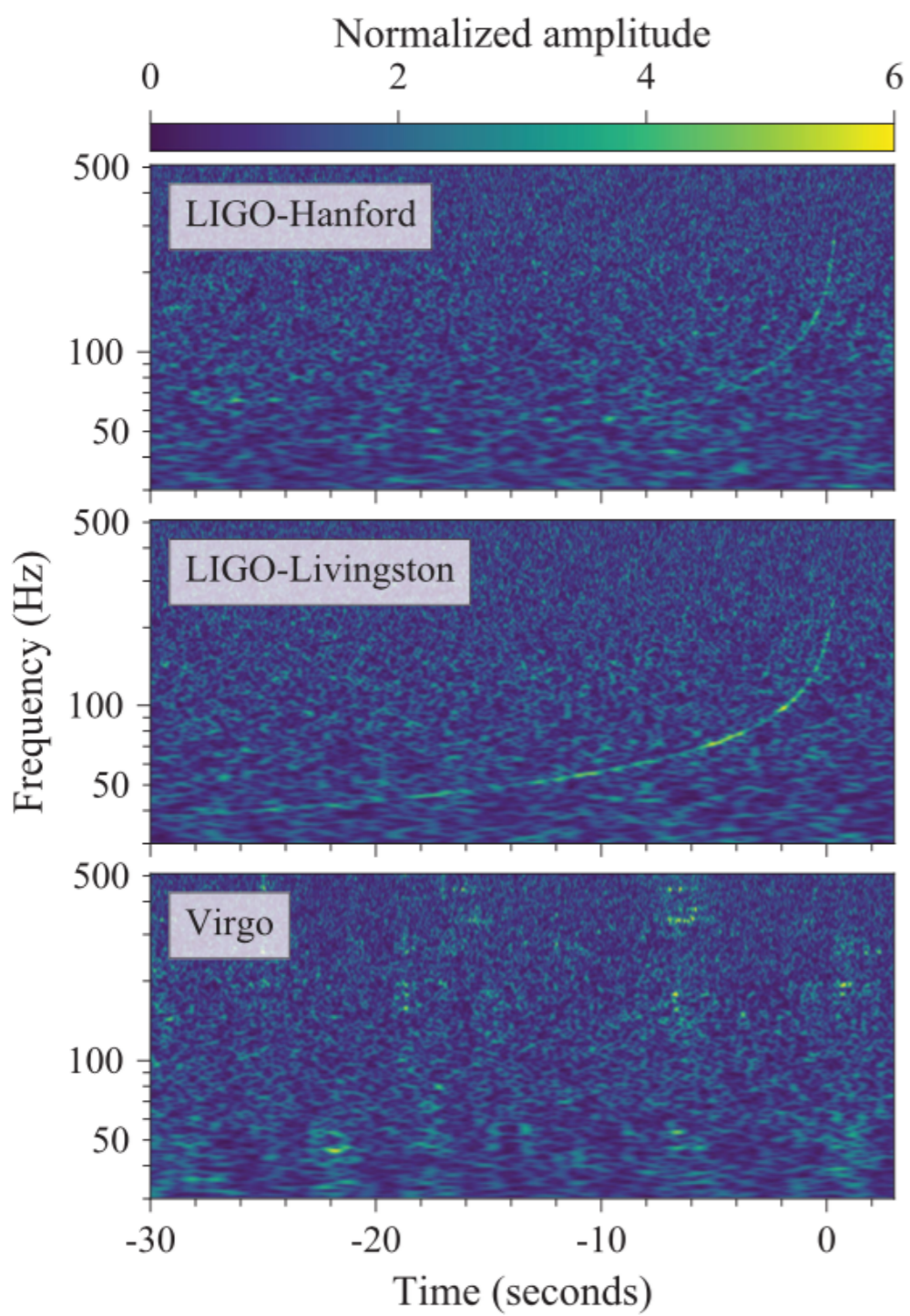
image: NASA/CXC



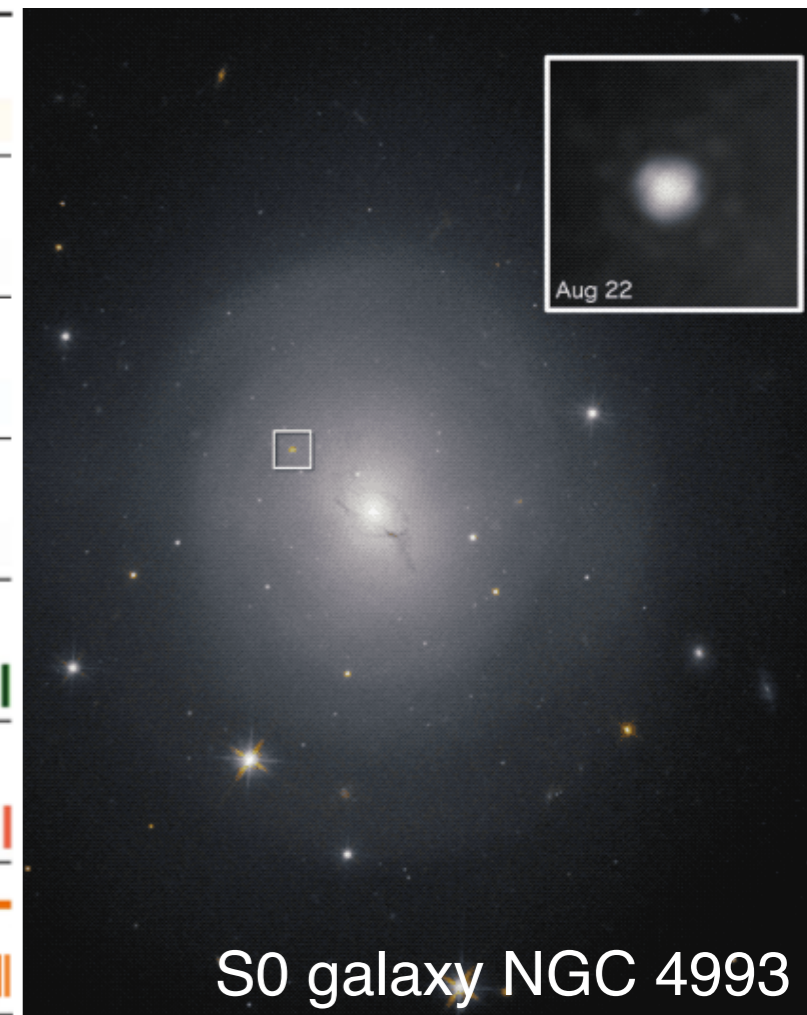
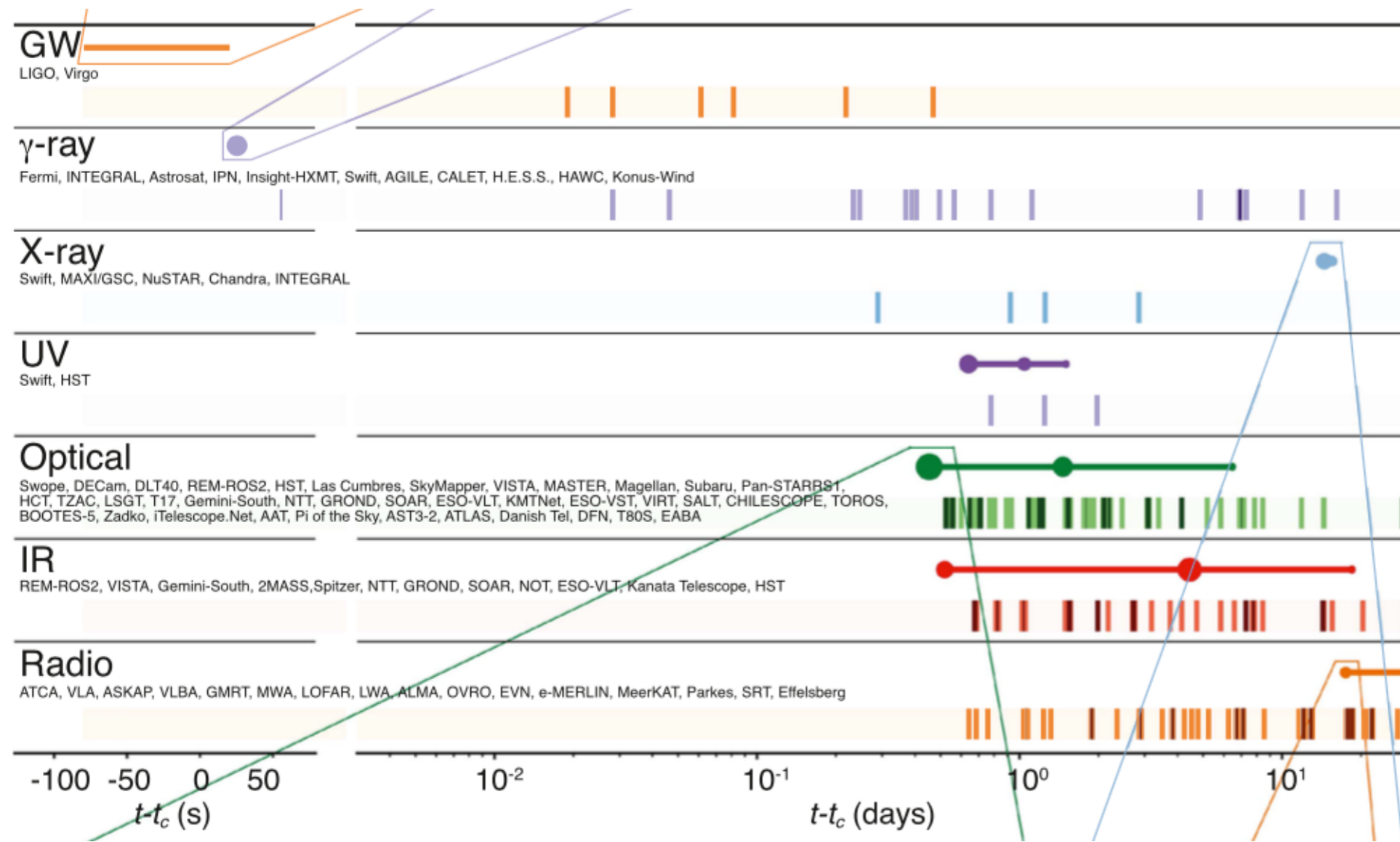
$\sim 10^{-2} M_{\odot}$ of r-process material
1 event per few thousand supernovae

image: Carnegie Institution for Science

GW170817: a binary neutron star merger detected in gravitational waves

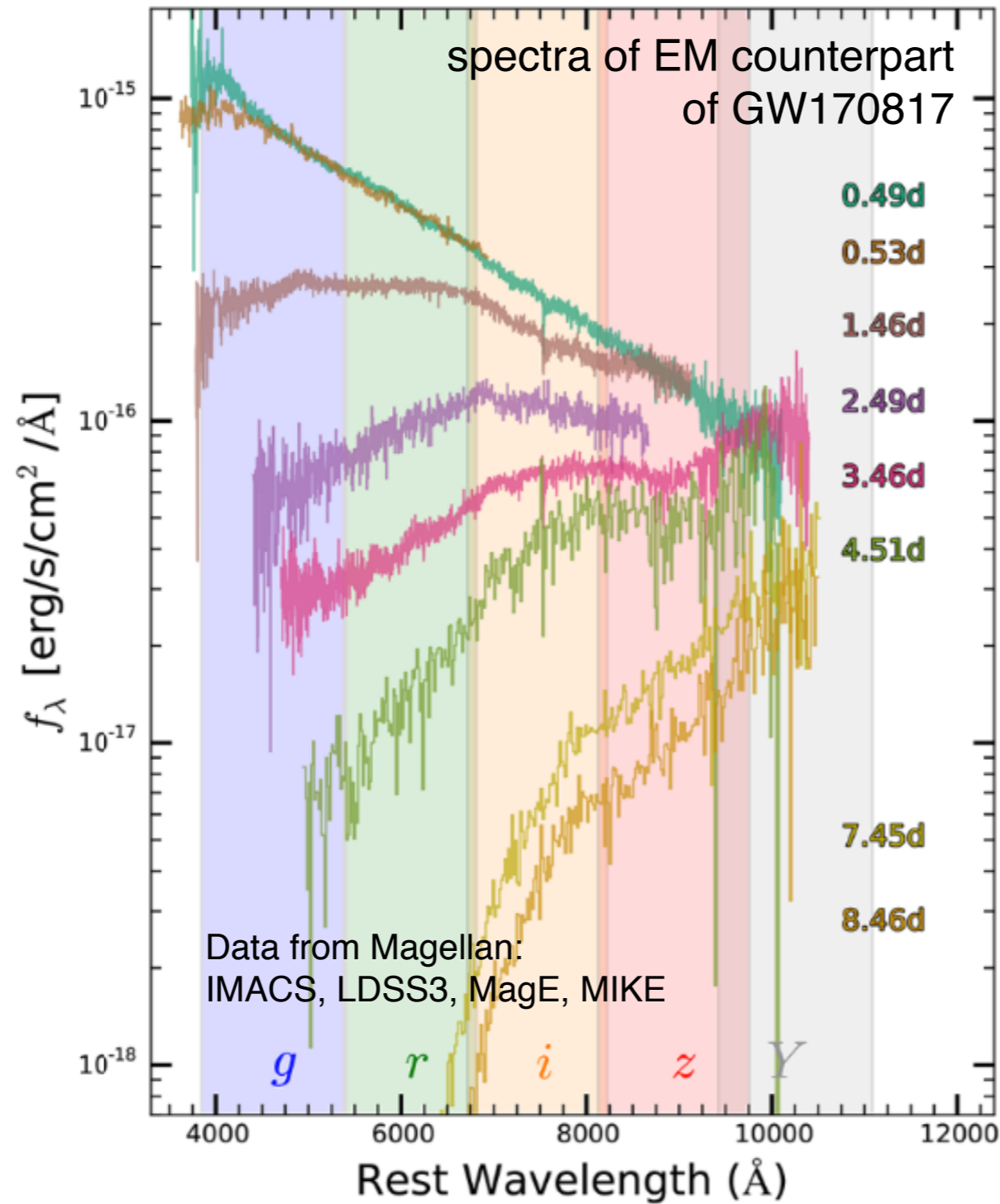


LIGO Scientific Collaboration and Virgo Collaboration, Abbott et al., Phys. Rev. Lett., 119, 161101 (2017)



S0 galaxy NGC 4993

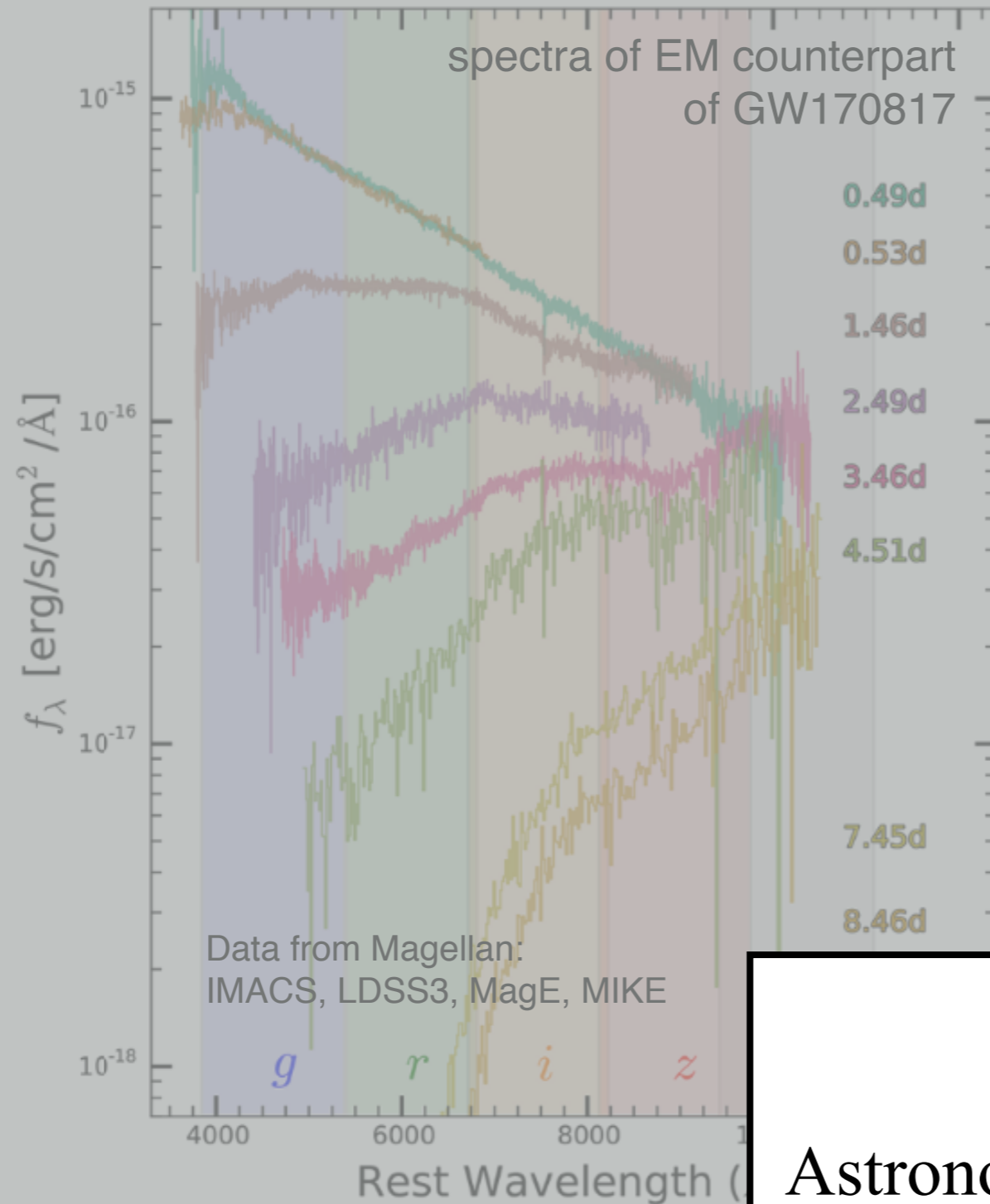
LIGO Scientific Collaboration and Virgo Collaboration, *Astrophys. J. Lett.*, 848, L12 (2017)
 optical image credit: HST/NASA/ESA



← 0.5 - 1.5 days: brighter in blue

← 3.5 - 8.5+ days: brighter in red

This is a **kilonova**, which is powered by the radioactive decay of a few $10^{-2} M_\odot$ of r-process elements.



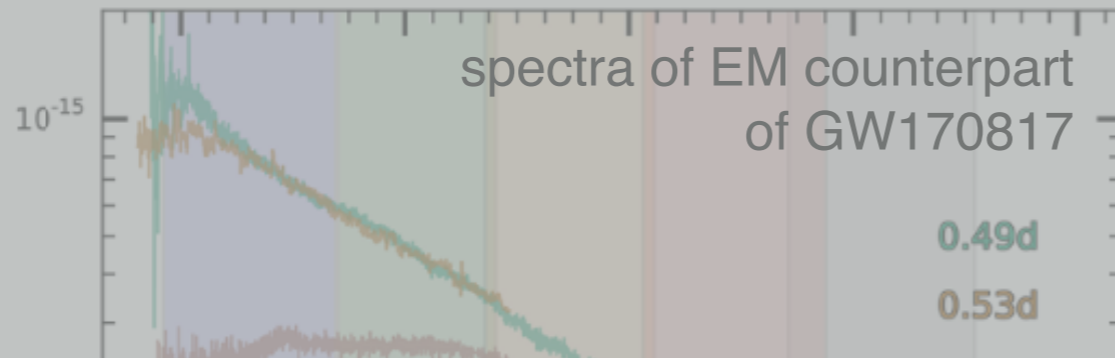
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Los Angeles Times

10/17/2017

Astronomers strike gold—and platinum—
as they watch two neutron stars collide



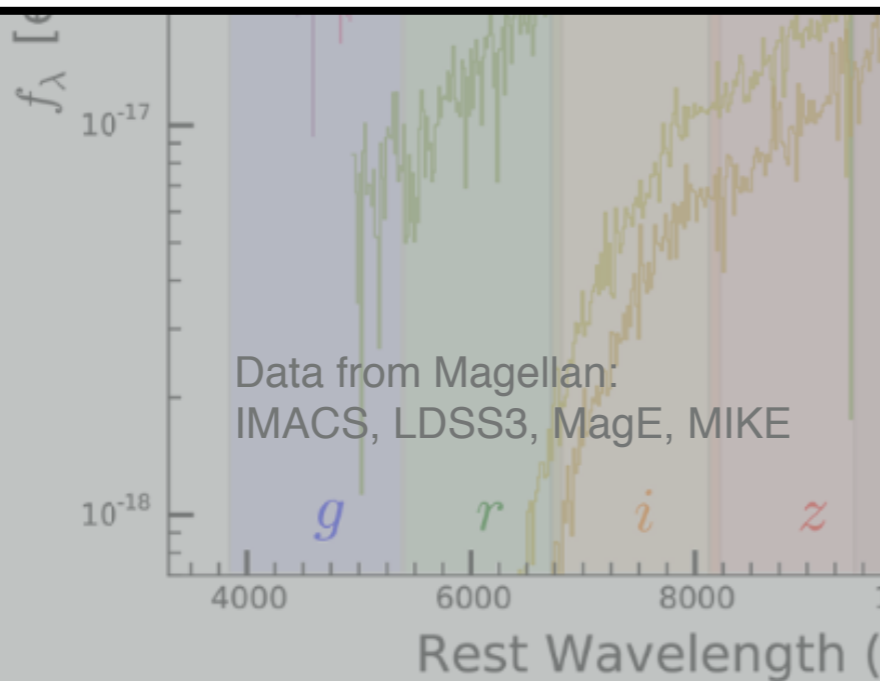
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10/16/2017

First-seen neutron star collision creates light, gravitational waves and gold

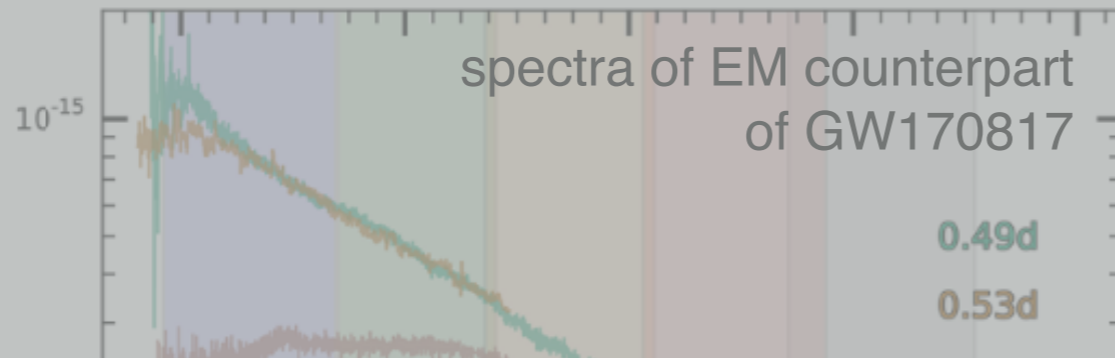
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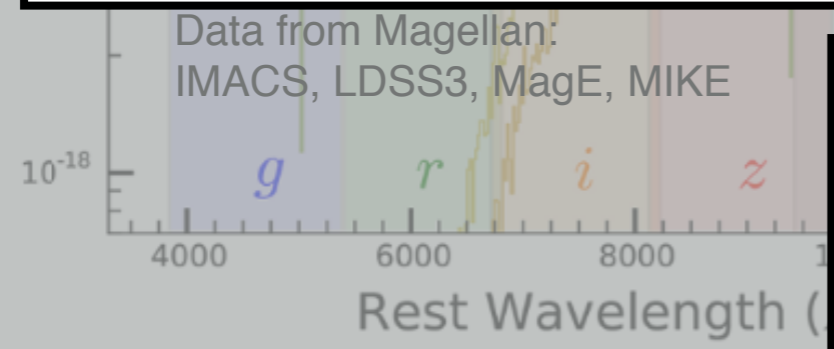
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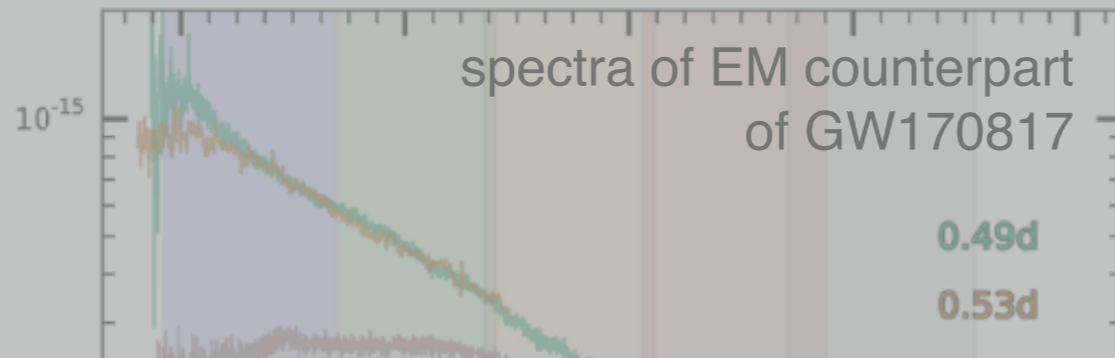
Astronomers Strike Gravitational Gold in Colliding Neutron Stars



Los Angeles Times

10/17/2017

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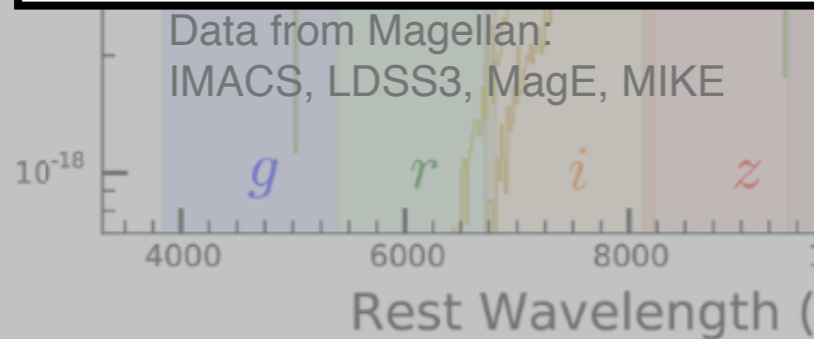
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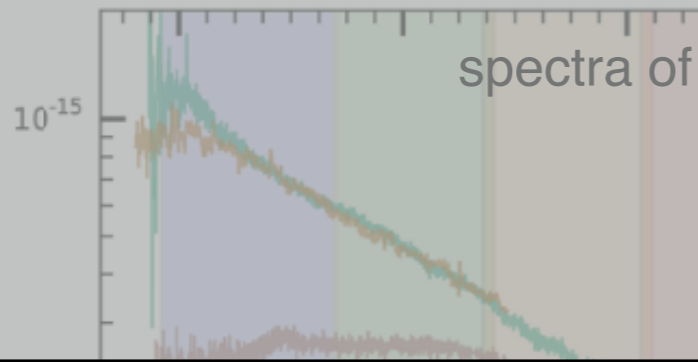
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10/17/2017

How Gravitational Waves Led Astronomers to Cosmic Gold



10/16/2017

Gravitational waves just led us to the incredible origin of gold in the universe



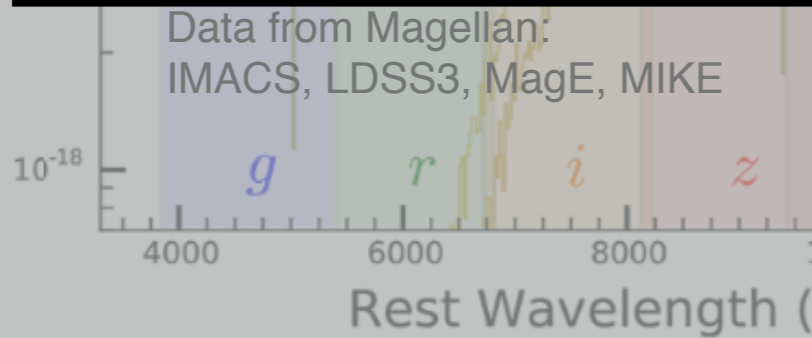
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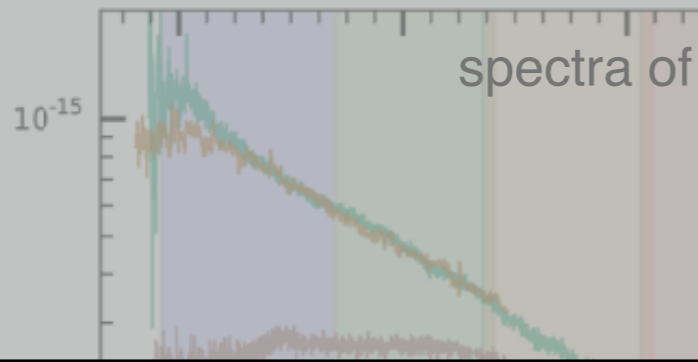
10/17/2017

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10/17/2017

How Gravitational Waves Led Astronomers to Cosmic Gold



10/16/2017

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Data from Magellan:
IMACS, LDSS3, MagE, MIKE

Los Angeles Times

10/17/2017

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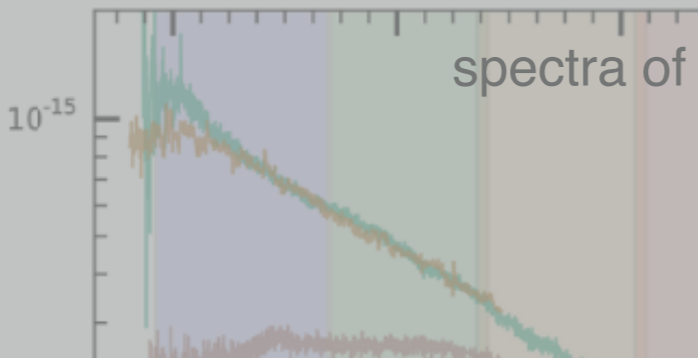
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...two neutron stars collide

Astronomers just proved the incredible origin of nearly all gold, platinum, and silver in the universe

10/17/2017



How Gravitational Waves Led Astronomers to Cosmic Gold



spectra of



10/16/2017

Gravitational waves just led us to the incredible origin of gold in the universe



First-seen neutron star collision creates light, gravitational waves and gold

3.5 - 8.5+ days: brighter in red



10/16/2017



10/17/2017

Neutron-Star Collision Reveals Origin of Gold, Astronomers Say

Stars



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Secret of gold finally found: precious metals are forged in cataclysmic collision of neutron stars

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LIVESCIENCE

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Los Angeles Times

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First-

The Mercury News

10/16/2017

A bright light seen across the universe, proving Einstein right: Violent collisions source of our gold, silver

2017



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Neutron collision tells us about how gold is made—and possibly the secrets of the universe

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Queen's boffins help find gold in space during research into gravitational waves

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Neutron collision tells us about how gold is made

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Scientists discover neutron star collisions produce gold, platinum, and other elements

How Gravitational Waves Led Astronomers to Cosmic Gold

spectra of

10/16/2017

The Telegraph

10/16/2017

Secret of gold fin

10/16/2017

Be

 **USA TODAY**

Queen's boffins

Scientists witness huge cosmic crash, find origins of gold

during research into gravitational waves

10/16/2017

The Mercury News

10/17/2017

DECCAN
Chronicle

Indian scientist part of team that taps gold origins from gravitational waves

10/22/2017

Astronomers Say

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 **CNBC**

ASTRONOMERS

nearly all gold

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sometimes detectable in cool stars
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hydrogen 1 H 1.0079																	helium 2 He 4.0026						
lithium 3 Li 6.941	beryllium 4 Be 9.0122																	boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305																	aluminum 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.38	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80						
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.6	iodine 53 I 126.90	xenon 54 Xe 131.29						
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.967	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]					
francium 87 Fr [223]	radium 88 Ra [226]	89-102 **	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]						ununquadium 114 Uuq [289]					

* Lanthanide series

** Actinide series

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.05
actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

★ atomic spectroscopy and/or expertise contributed by Wisconsin group

hydrogen 1 H 1.0079	sometimes detectable in cool stars (not always simultaneously)																helium 2 He 4.0026															
lithium 3 Li 6.941	beryllium 4 Be 9.0122	Hubble Space Telescope UV required (or makes big improvement)																boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180									
sodium 11 Na 22.990	magnesium 12 Mg 24.305	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.38	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	argon 18 Ar 39.948	krypton 36 Kr 83.80														
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UV spectra → 40% increase in number of elements detectable

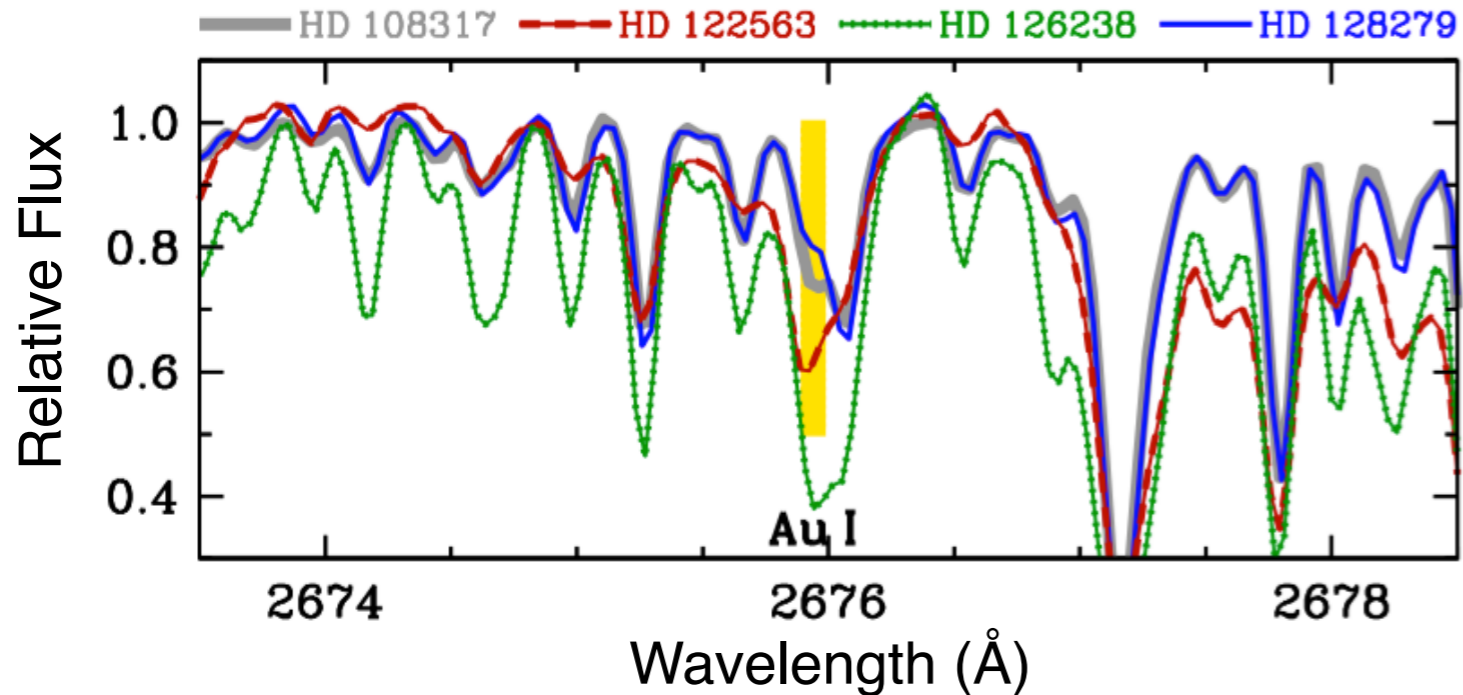
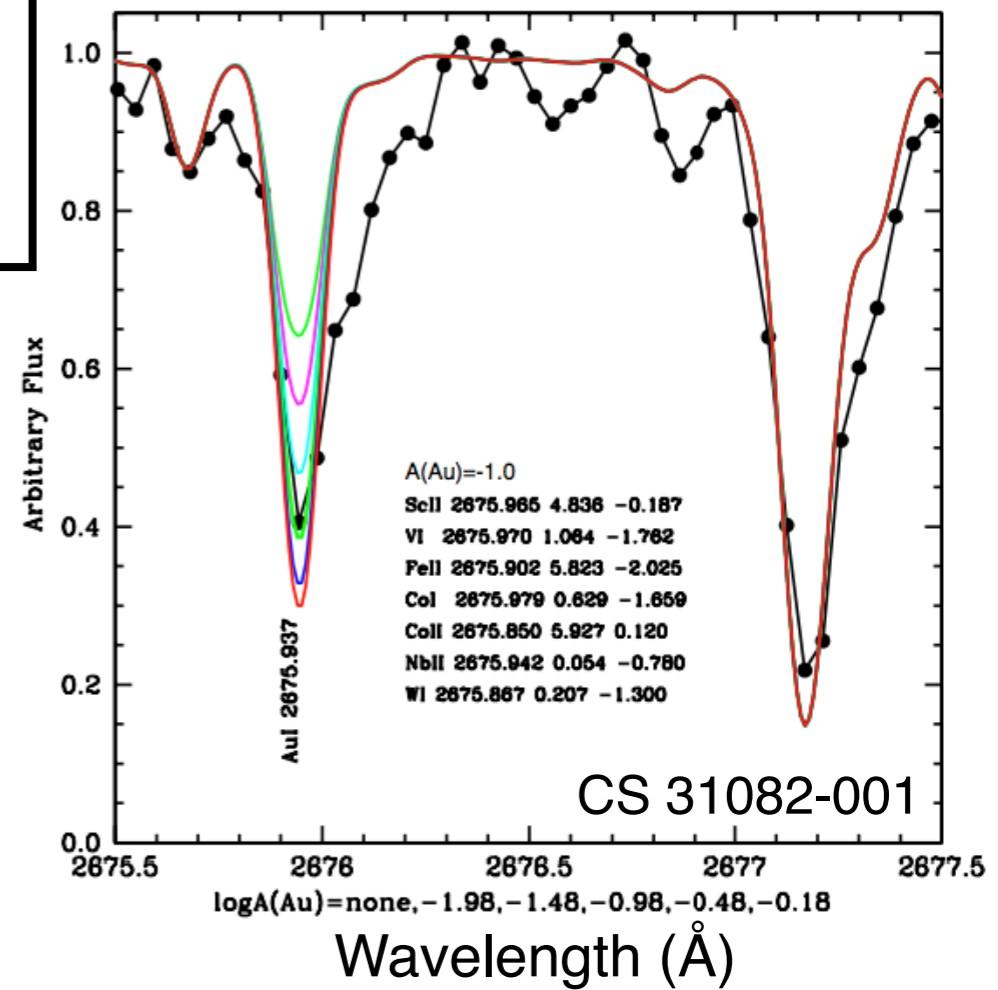
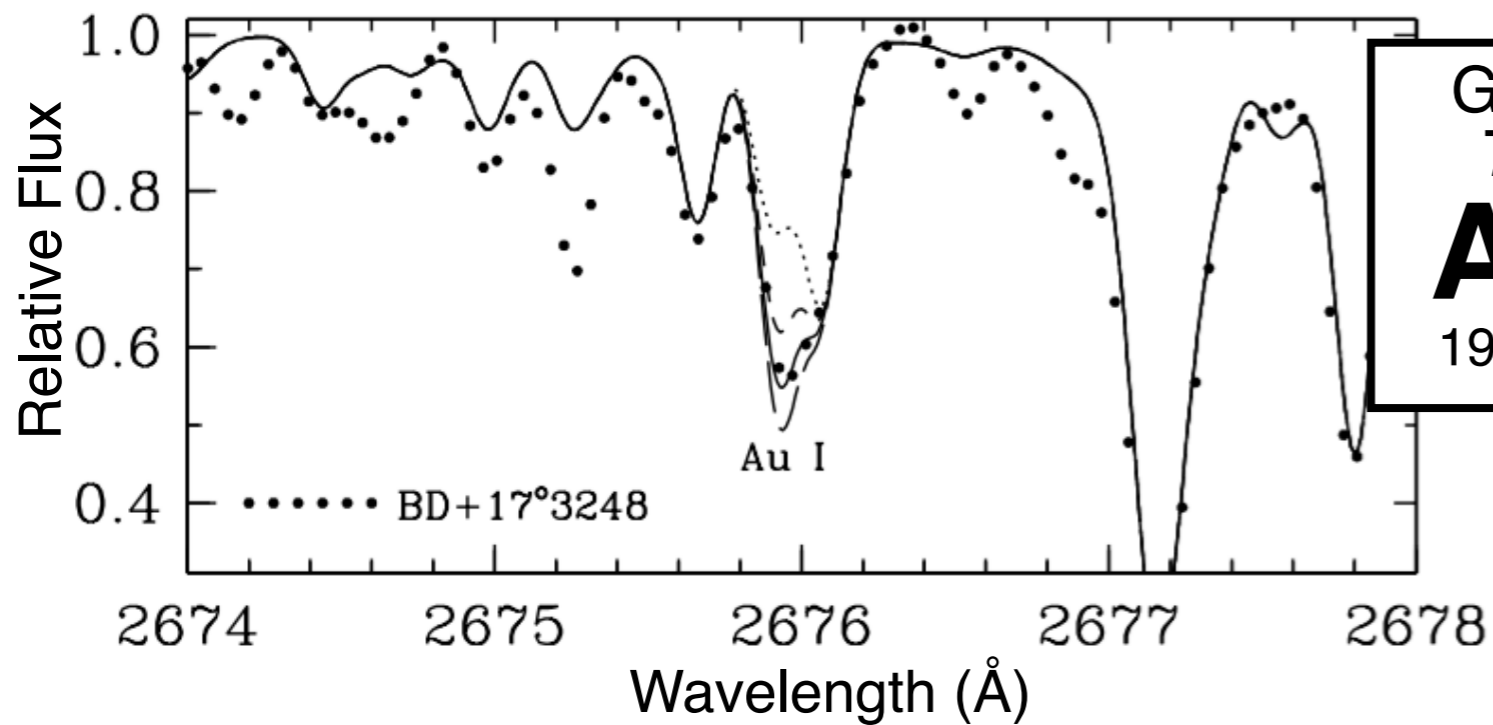
* Lanthanide series

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
138.91	140.12	140.91	144.24	[145]	150.36	151.96	157.25	158.93	162.50	164.93	167.26	168.93	173.05

** Actinide series

Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No
[227]	232.04	231.04	238.03	[237]	[244]	[243]	[247]	[247]	[251]	[252]	[257]	[258]	[259]

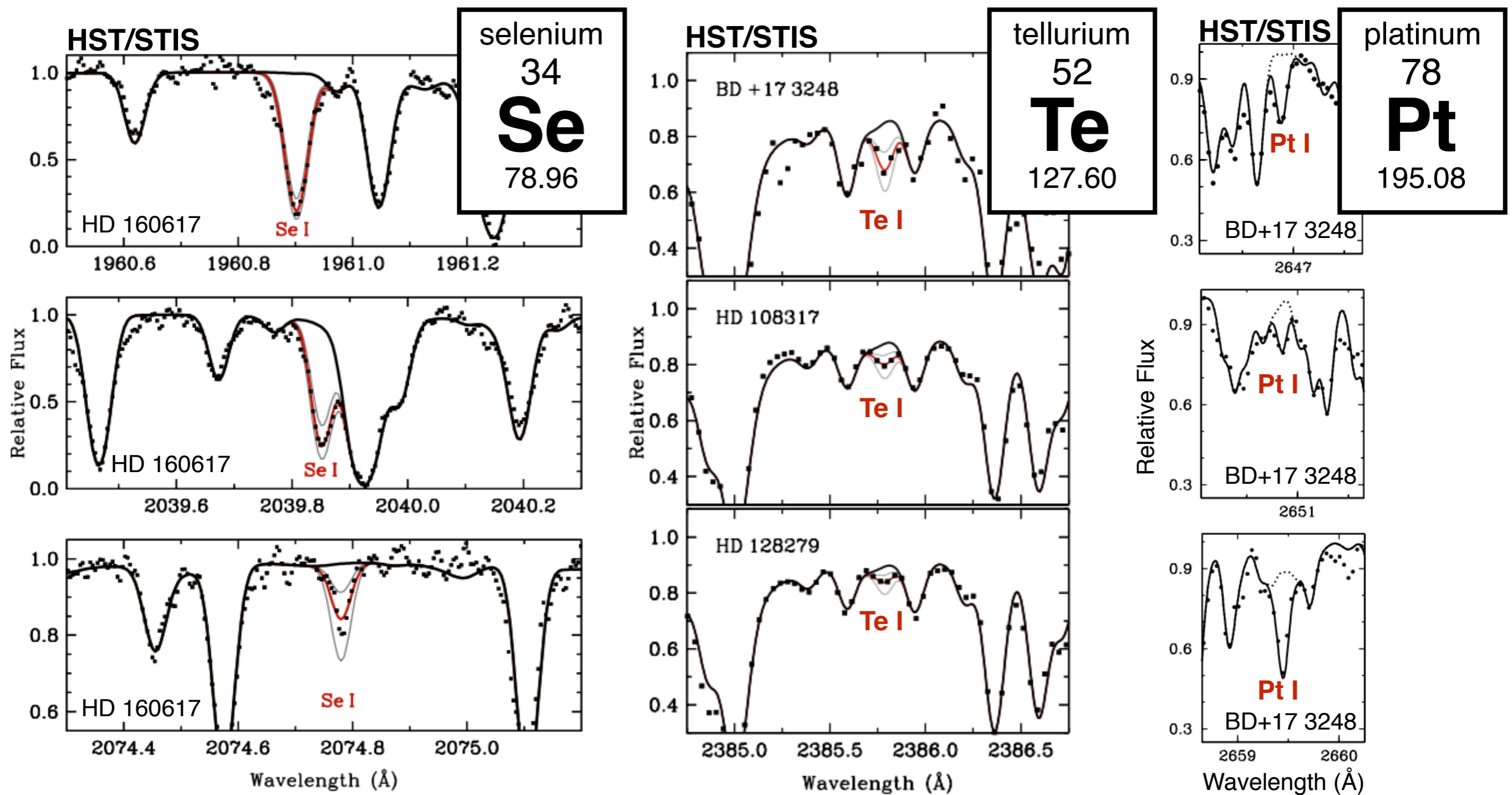
★ atomic spectroscopy and/or expertise contributed by Wisconsin group



Au I also detected in CS 22892-052
Snedden et al., *Astrophys. J.*, 591, 936 (2003)

Cowan et al., *Astrophys. J.*, 572, 861 (2002)
Roederer et al., *Astrophys. J. Sup. Ser.*, 203, 27 (2012)

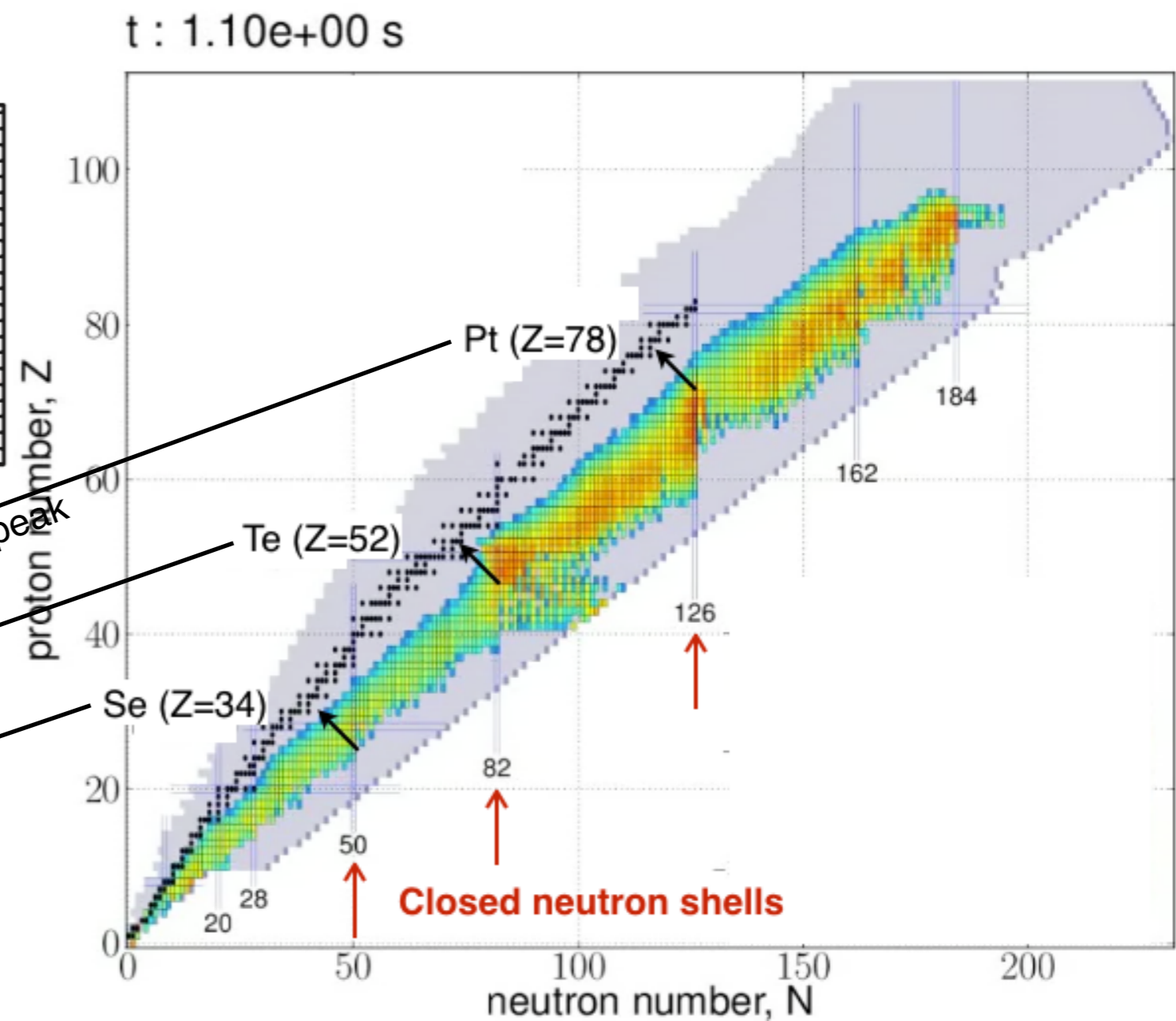
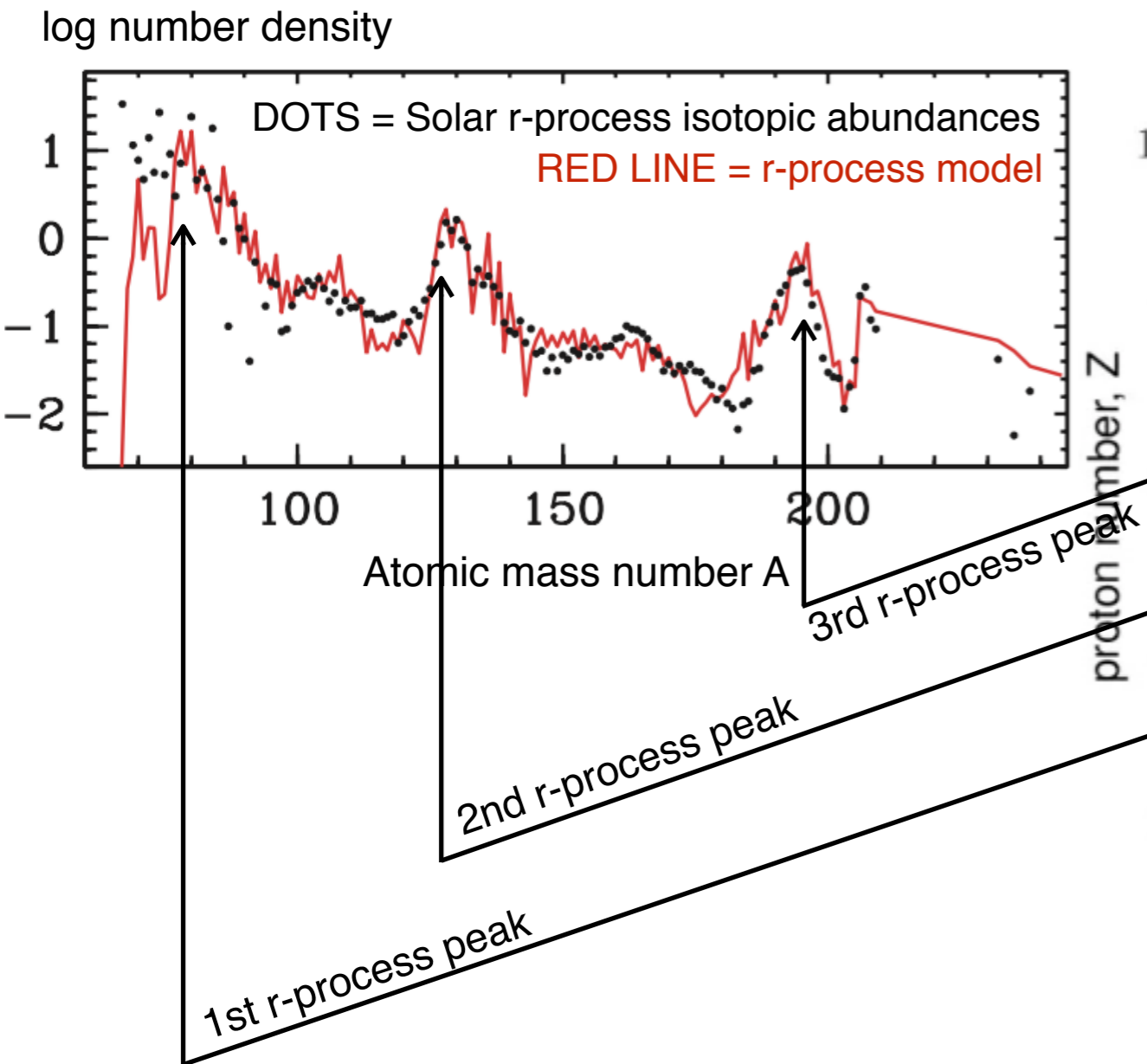
Barbuy et al., *Astron. & Astrophys.*, 534, A60 (2011)



Roederer & Lawler, *Astrophys. J.*, 750, 76 (2012)

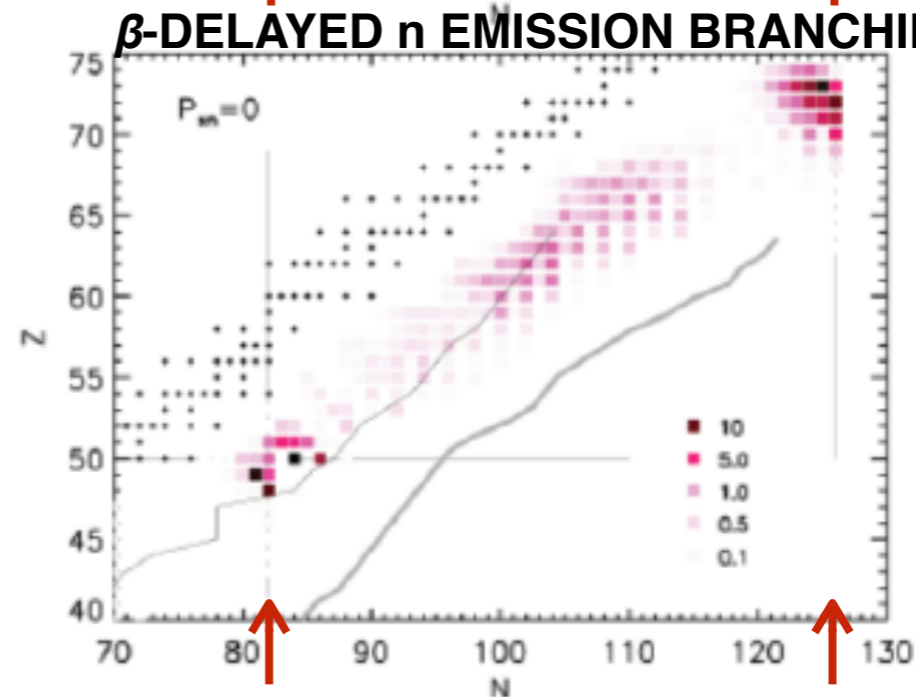
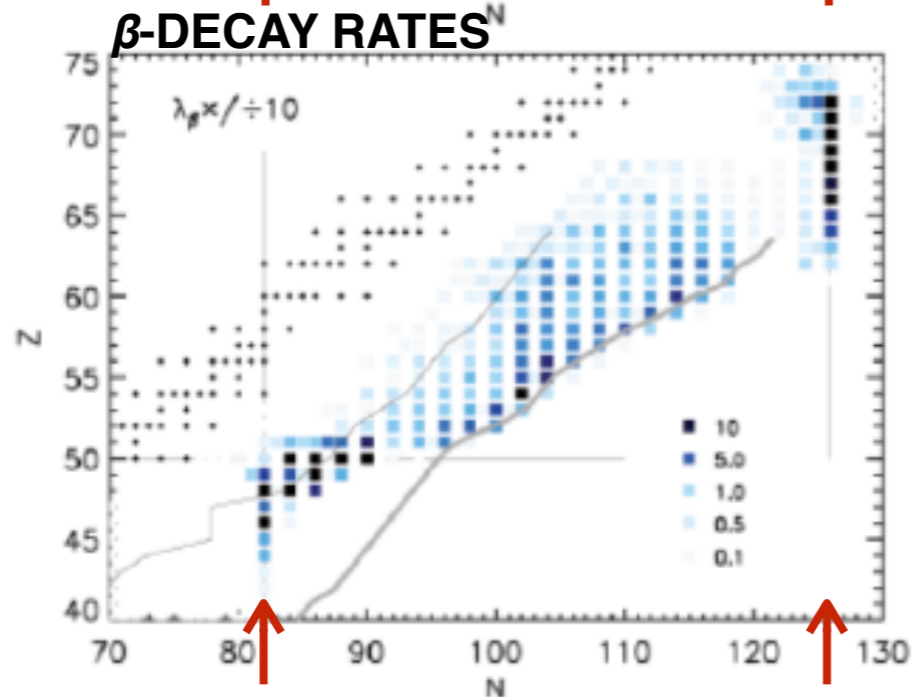
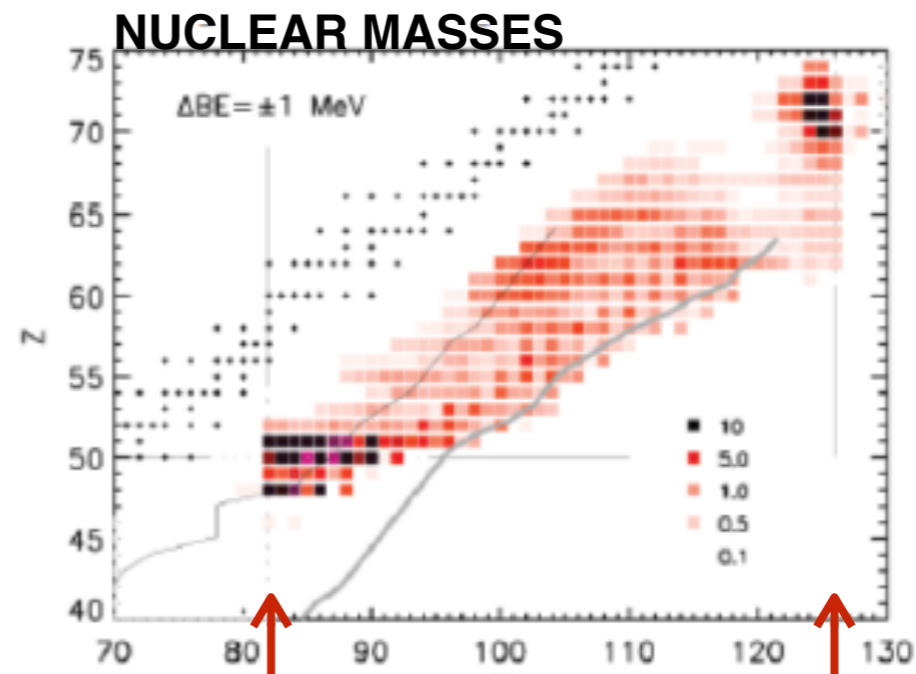
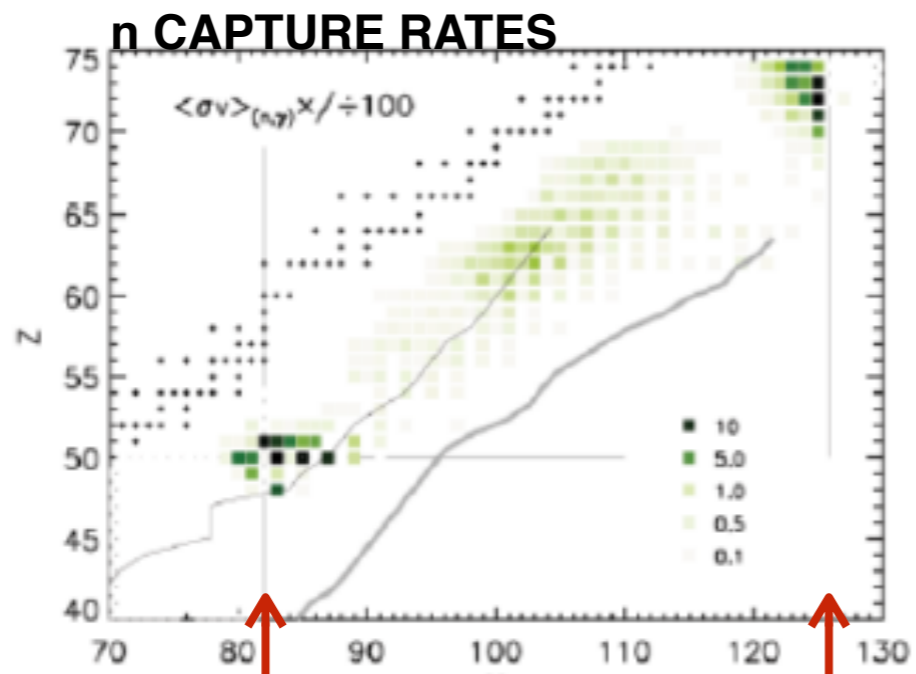
Den Hartog et al., *Astrophys. J.*, 619, 639 (2005)

Roederer et al., *Astrophys. J. Lett.*, 747, L8 (2012)



Kratz et al., *Astrophys. J.*, 662, 39 (2007)

Korobkin et al., *Mon. Not. Roy. Astron. Soc.*, 426, 1940 (2012)



Accessibility Limits

— CARIBU

— Predicted FRIB

R. Surman, in summary of ICNT workshop, C. Horowitz et al., J. Phys. G: Nucl. Part. Phys, submitted

ABUNDANCES

(astronomical observations)

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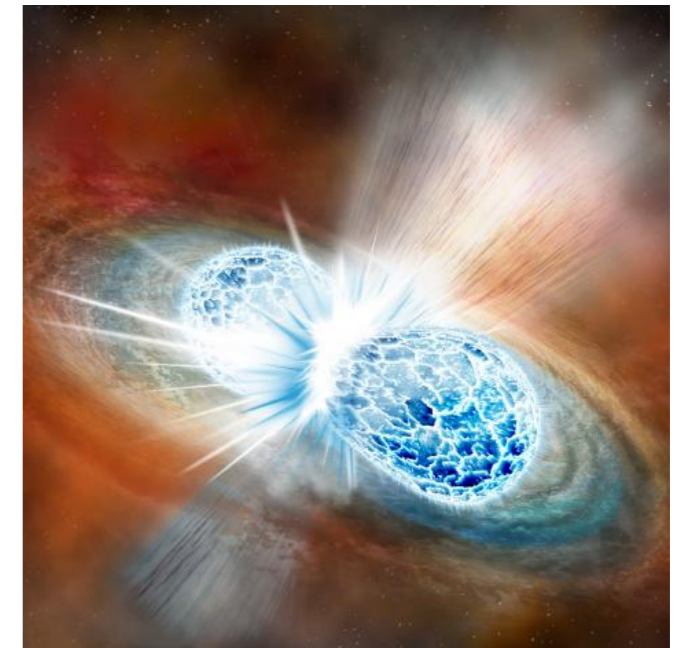
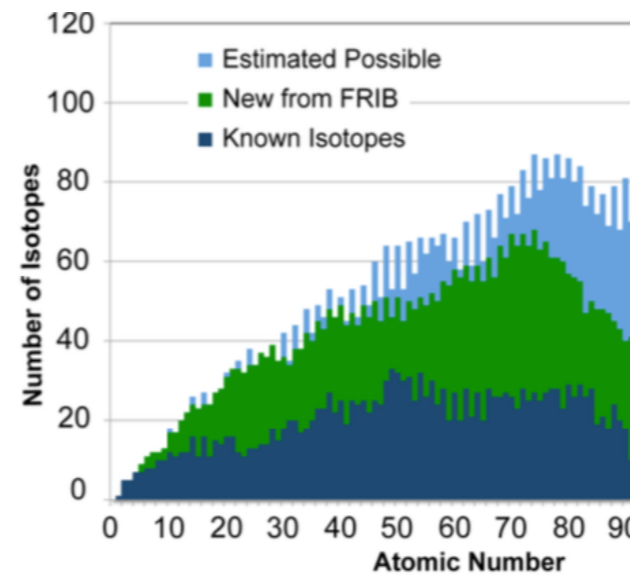
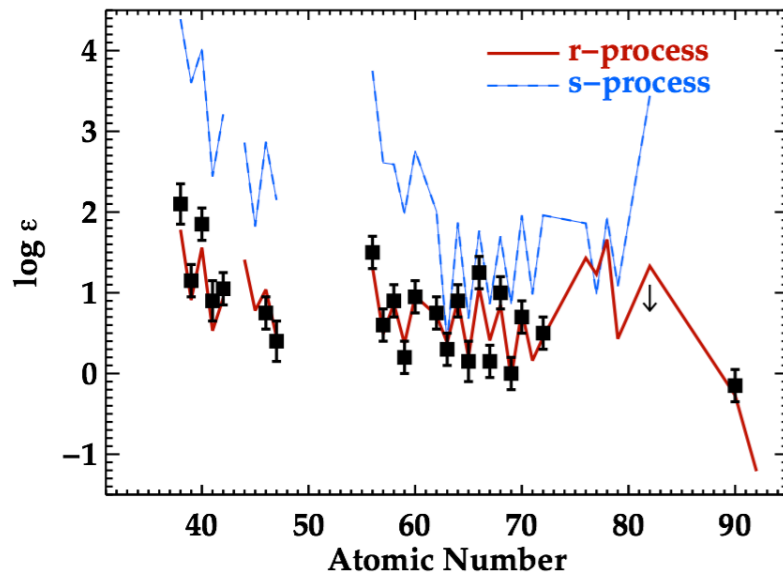
NUCLEAR PROPERTIES

(accelerator experiments)

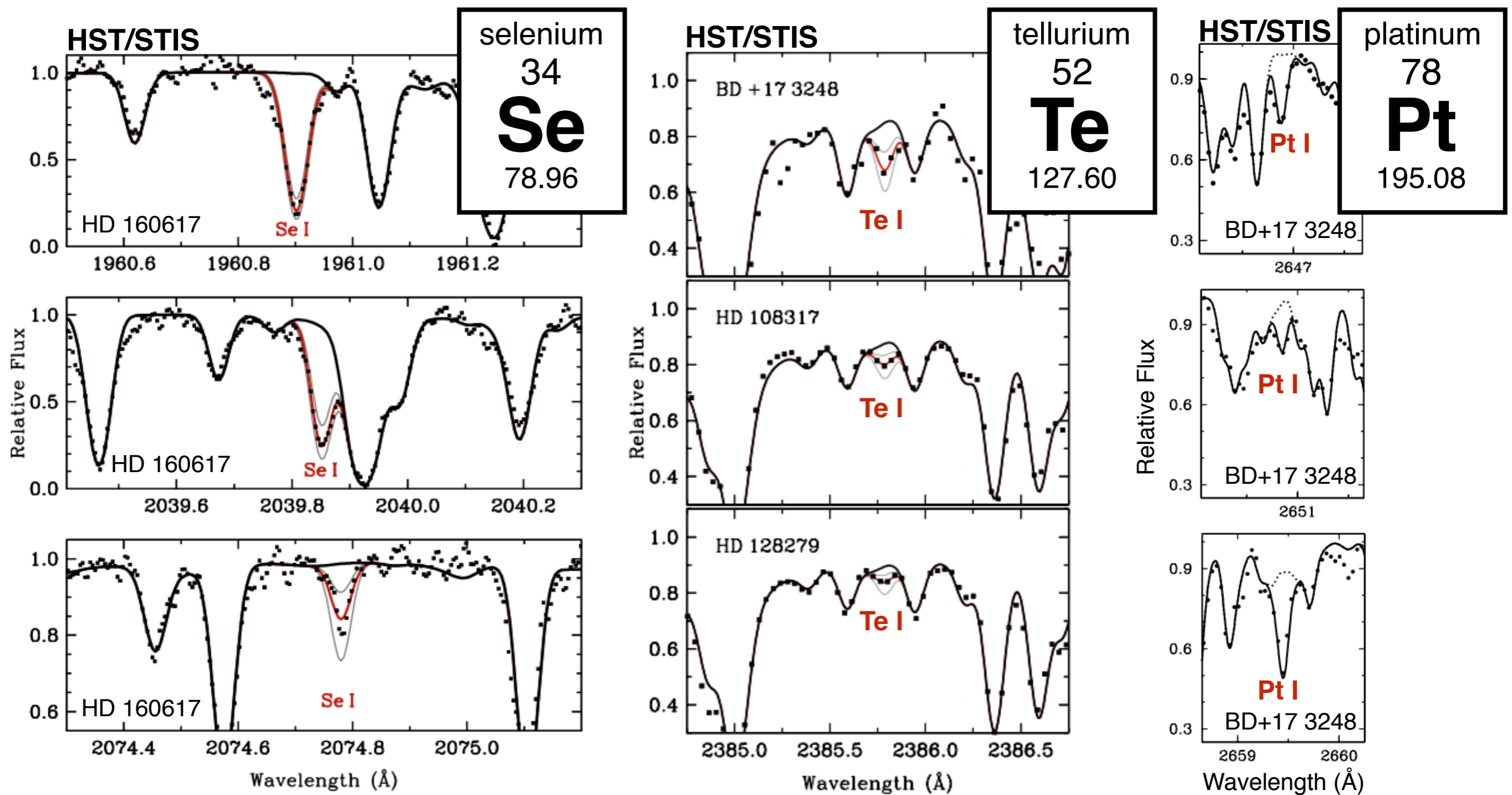
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CONDITIONS

(astrophysical sites)



images: IUR, B. Sherrill (NSCL/MSU), Carnegie Institution for Science



Roederer & Lawler, *Astrophys. J.*, 750, 76 (2012)

Den Hartog et al., *Astrophys. J.*, 619, 639 (2005)

Roederer et al., *Astrophys. J. Lett.*, 747, L8 (2012)

The R-Process Alliance:

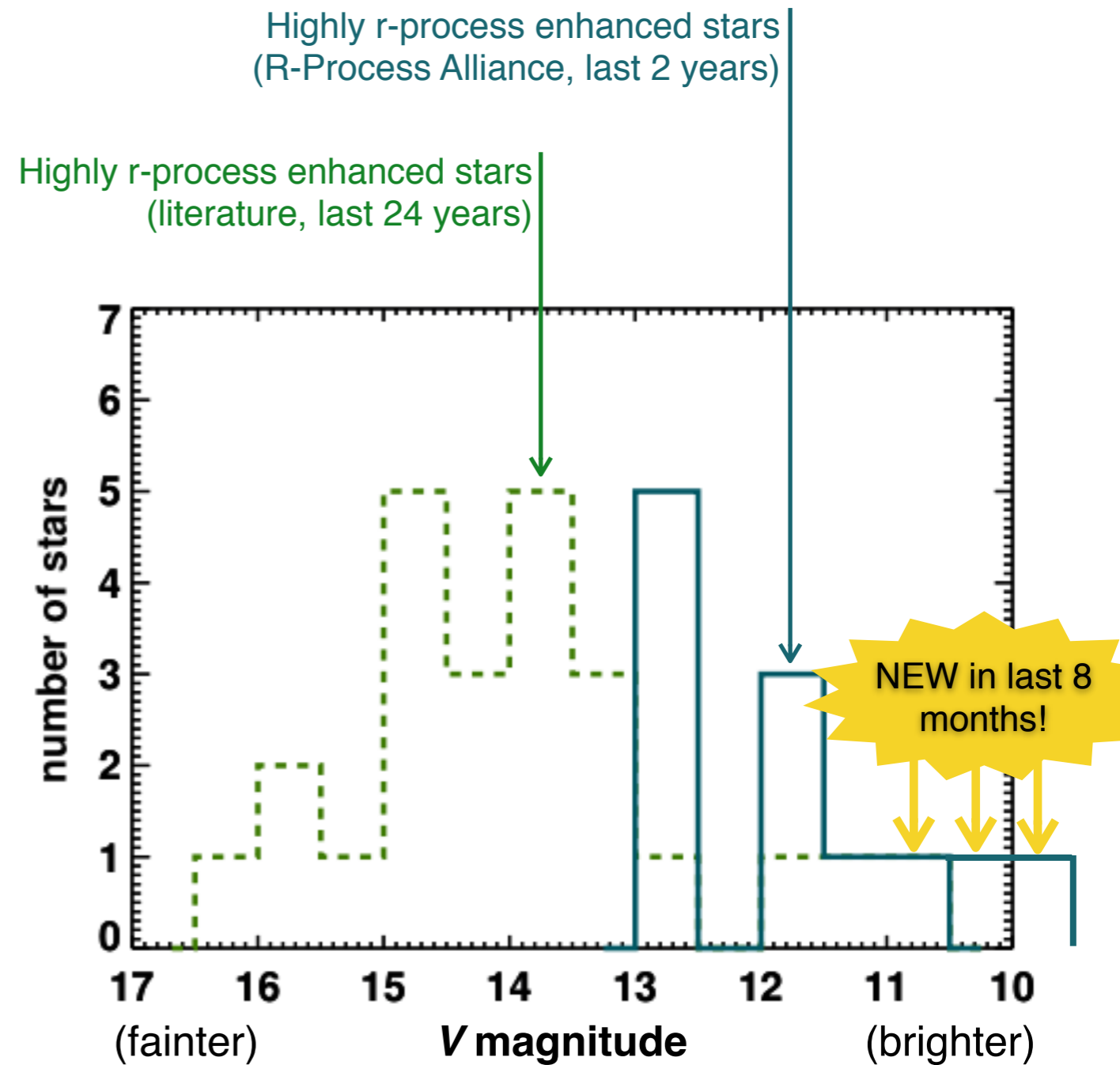
a multi-stage, multi-year effort to provide observational, theoretical, and laboratory constraints on the nature and origin of the astrophysical r-process

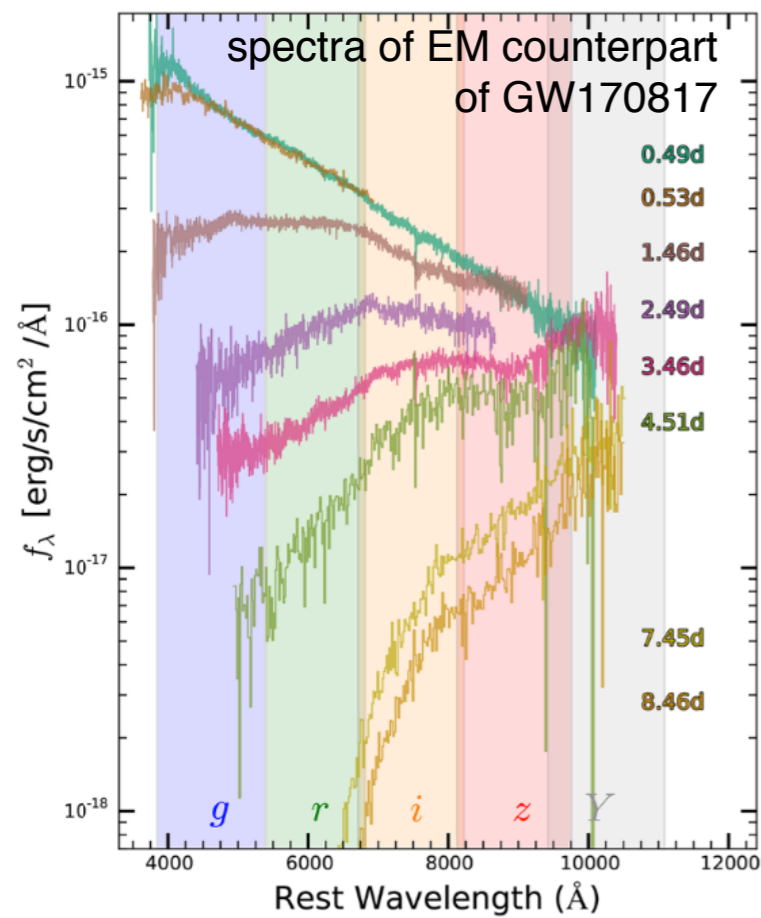
Tim Beers	(Notre Dame)
Maddie Cane	(MIT)
Julio Chaname	(P. U. Católica)
Anna Frebel	(MIT)
Maud Gull	(MIT)
Terese Hansen	(Carnegie Obs.)
Erika Holmbeck	(Notre Dame)
Honggeun Kim	(MIT)
Jennifer Marshall	(Texas A&M)
Maria Paz Sepúlveda	(P. U. Católica)
Vini Placco	(Notre Dame)
Kaitlin Rasmussen	(Notre Dame)
Ian Roederer	(Michigan)
Charli Sakari	(Washington)
Rafael Santucci	(U. F. de Goiás)
Chris Sneden	(Texas)
Sandro Villanova	(Concepción)
Devin Whitten	(Notre Dame)

This is a loose affiliation and will likely grow as the project moves into later phases

The R-Process Alliance:

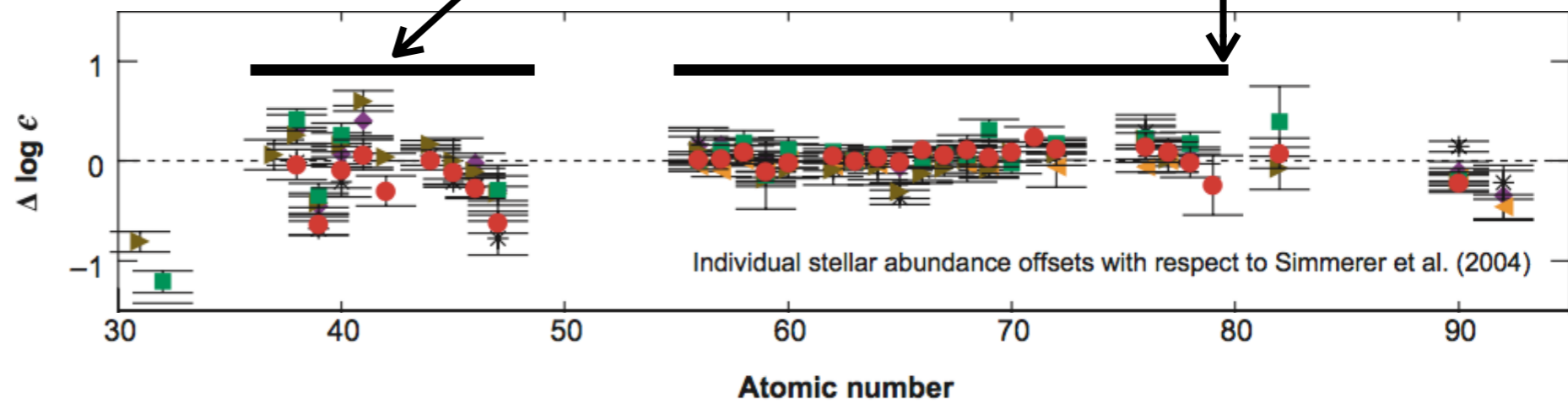
a multi-stage, multi-year effort to provide observational, theoretical, and laboratory constraints on the nature and origin of the astrophysical r-process





→ 0.5 - 1.5 days: brighter in blue → ? → non “universality”

→ 3.5 - 8.5+ days: brighter in red → ? → “universality”



Hubble Space Telescope

COS
STIS

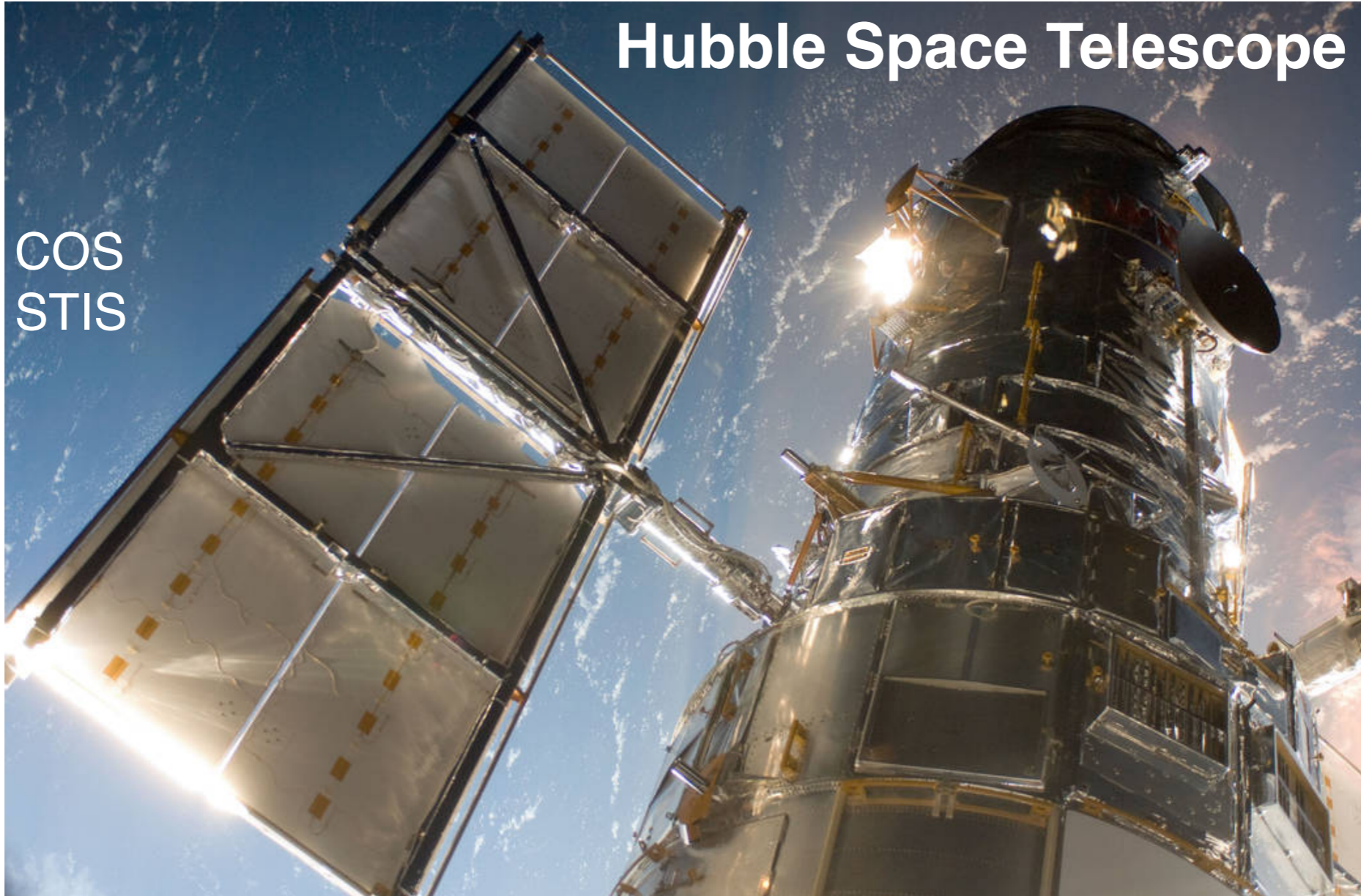


image: NASA

Habitable Exoplanet Imaging Mission (HabEx)

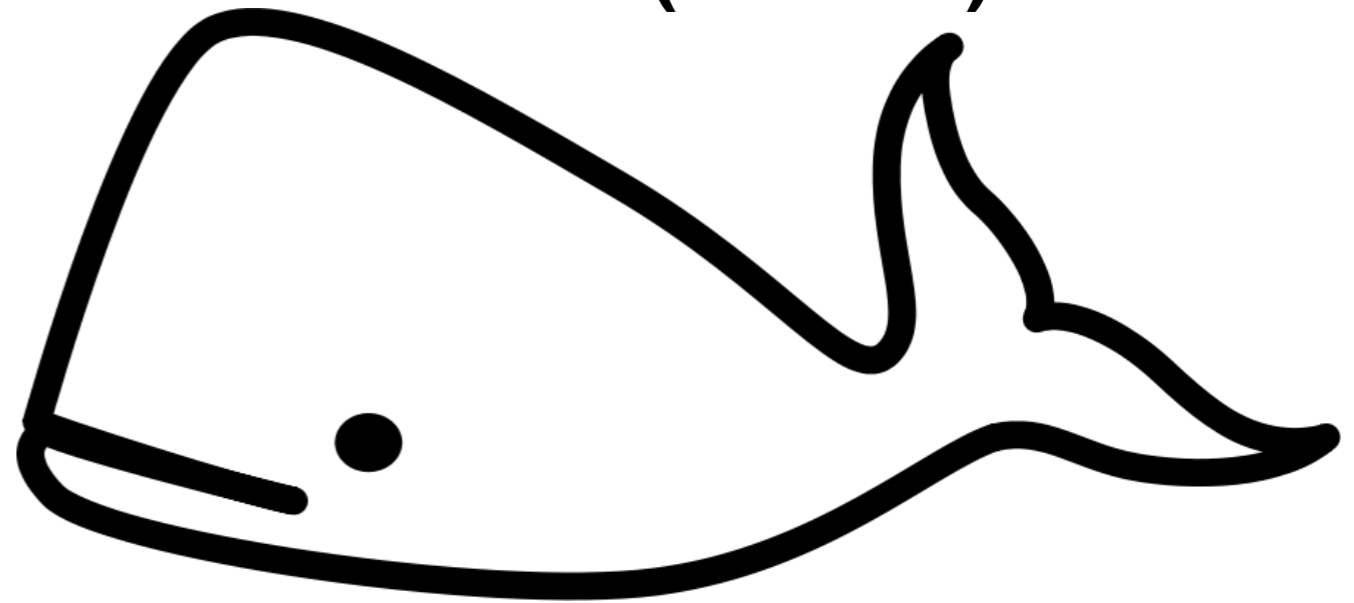
concept:

4m (6.5m considered) off-axis primary mirror
starshade, coronagraph,
UVOIR imager, high-res UV spectrograph
(report ready for 2020 decadal)



artist's rendition, credit NASA

Cosmic Evolution Through UV Spectroscopy (CETUS)



proposed concept:

1.5m primary mirror

NUV+FUV cameras

wide FOV (17' x 17') NUV low-res multi-object spectrograph

NUV+FUV med- and high-res spectrograph

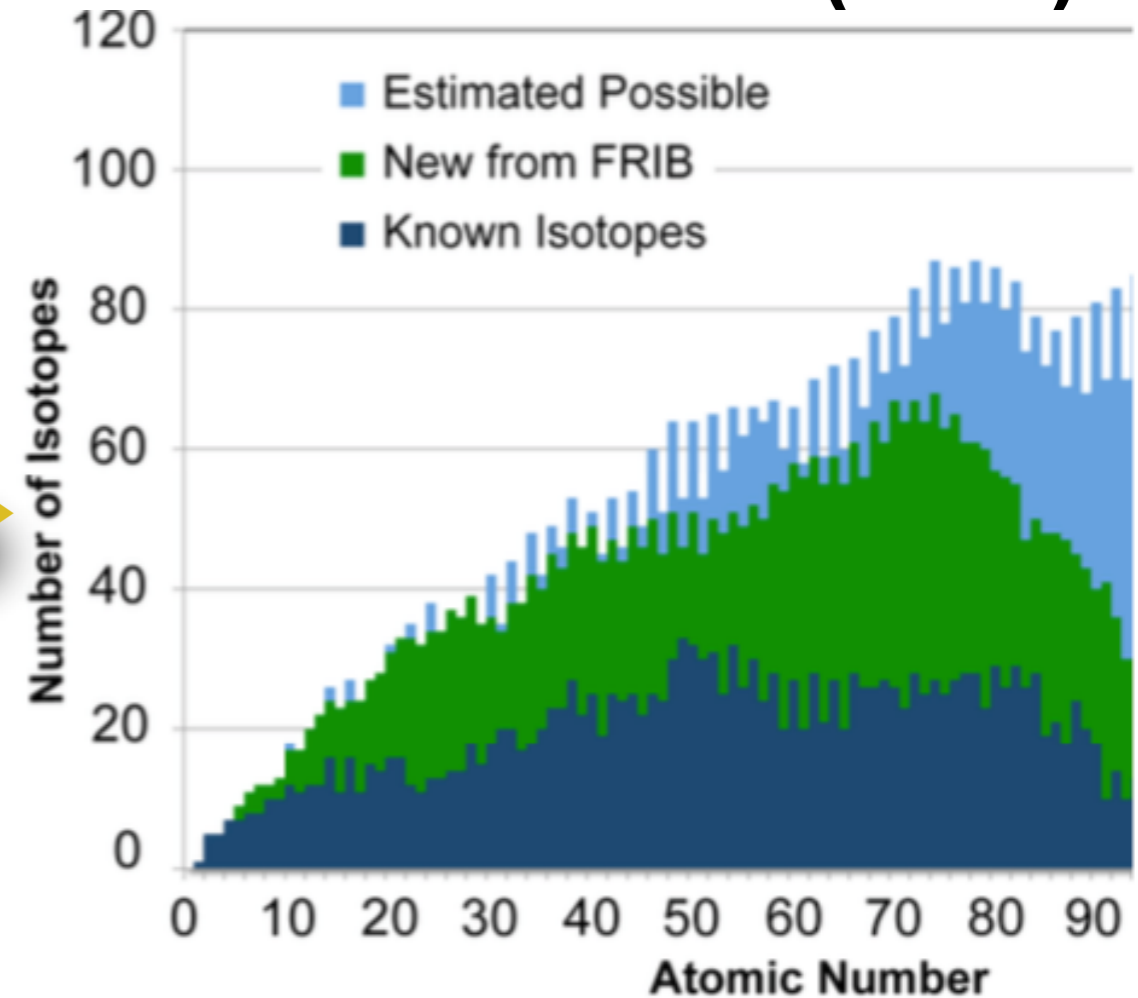
(PI = W. Danchi)

< \$1B

Facility for Rare Isotope Beams (FRIB)



under construction at Michigan State University
(completion ~2022)



images: FRIB/MSU/DOE; F. Nunes and B. Sherrill (NSCL/MSU)

ABUNDANCES

(astronomical observations)

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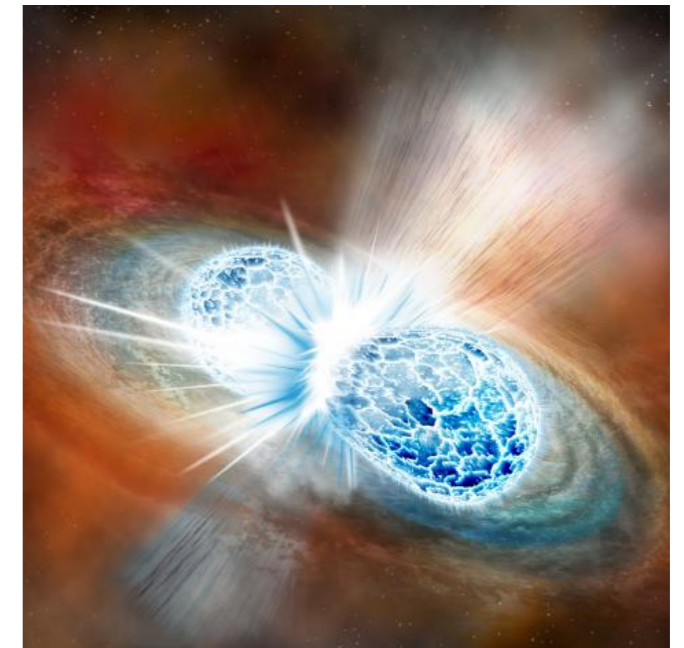
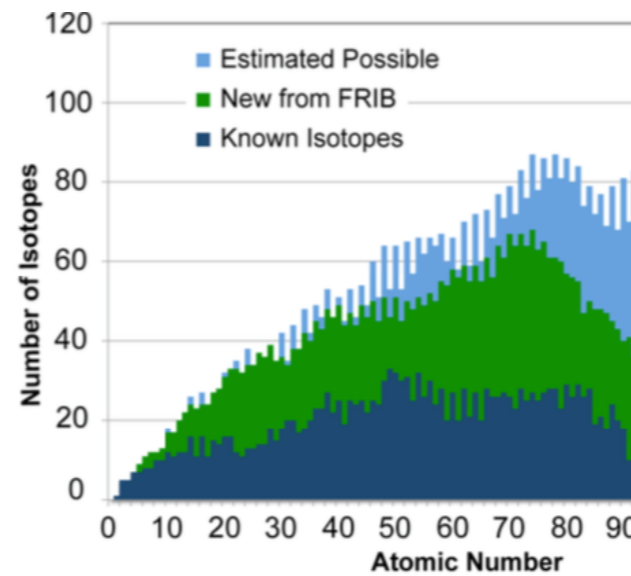
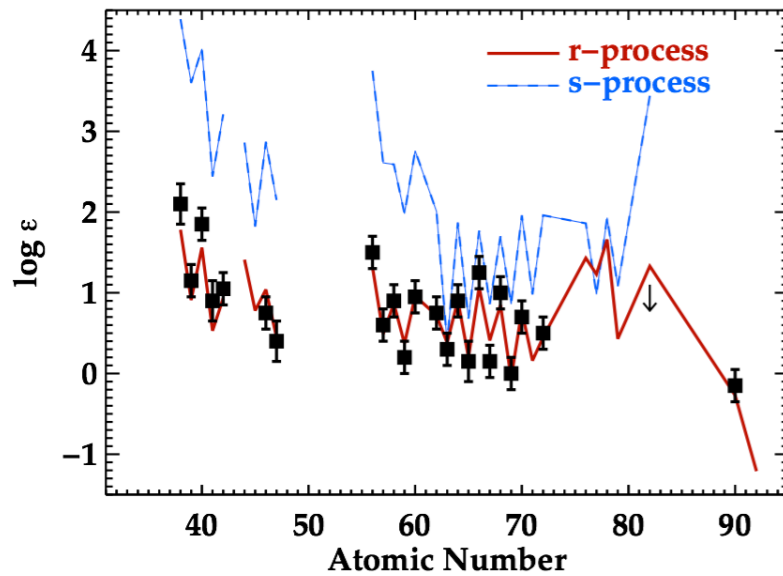
NUCLEAR PROPERTIES

(accelerator experiments)

*

CONDITIONS

(astrophysical sites)



images: IUR, B. Sherrill (NSCL/MSU), Carnegie Institution for Science

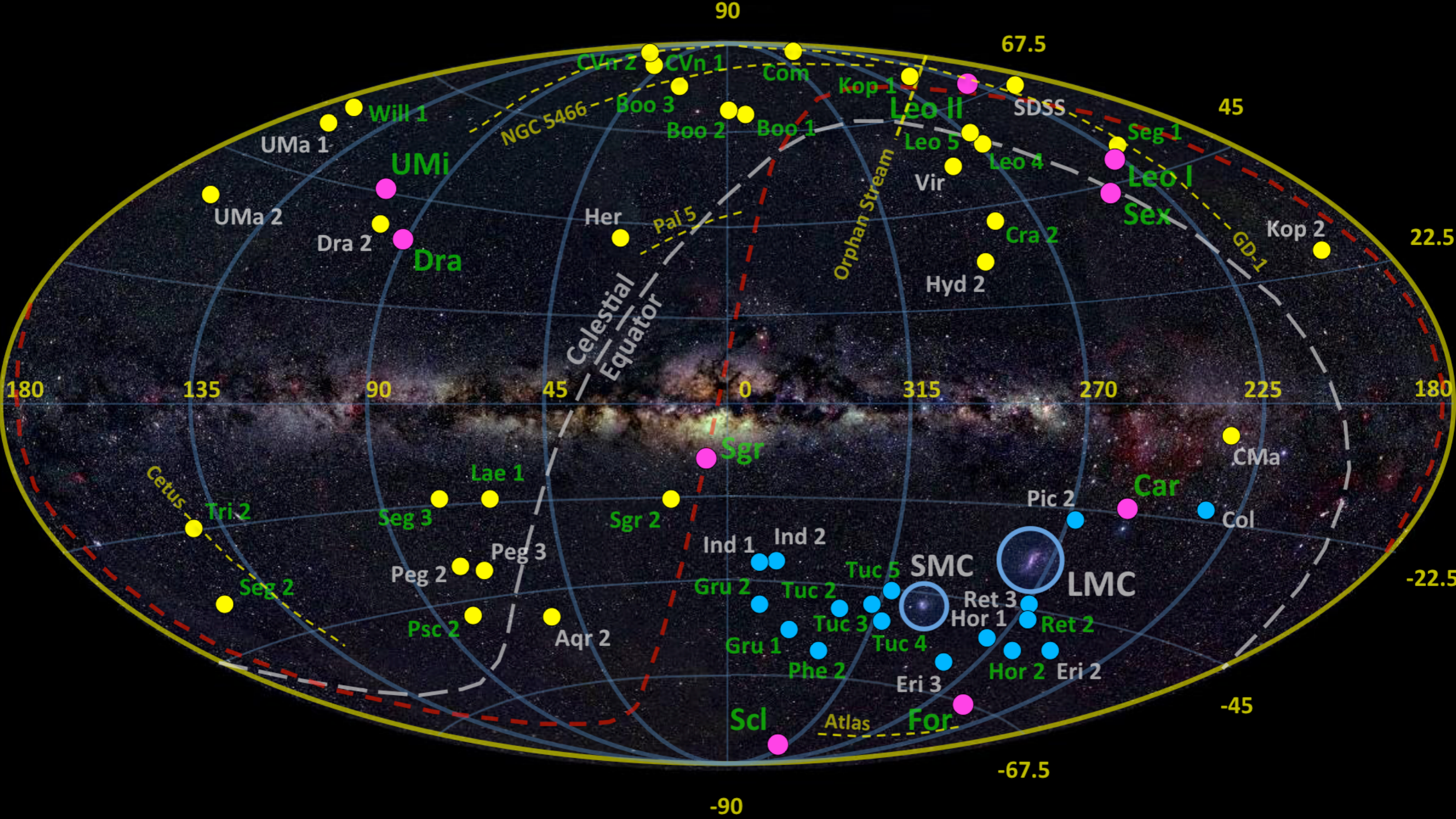
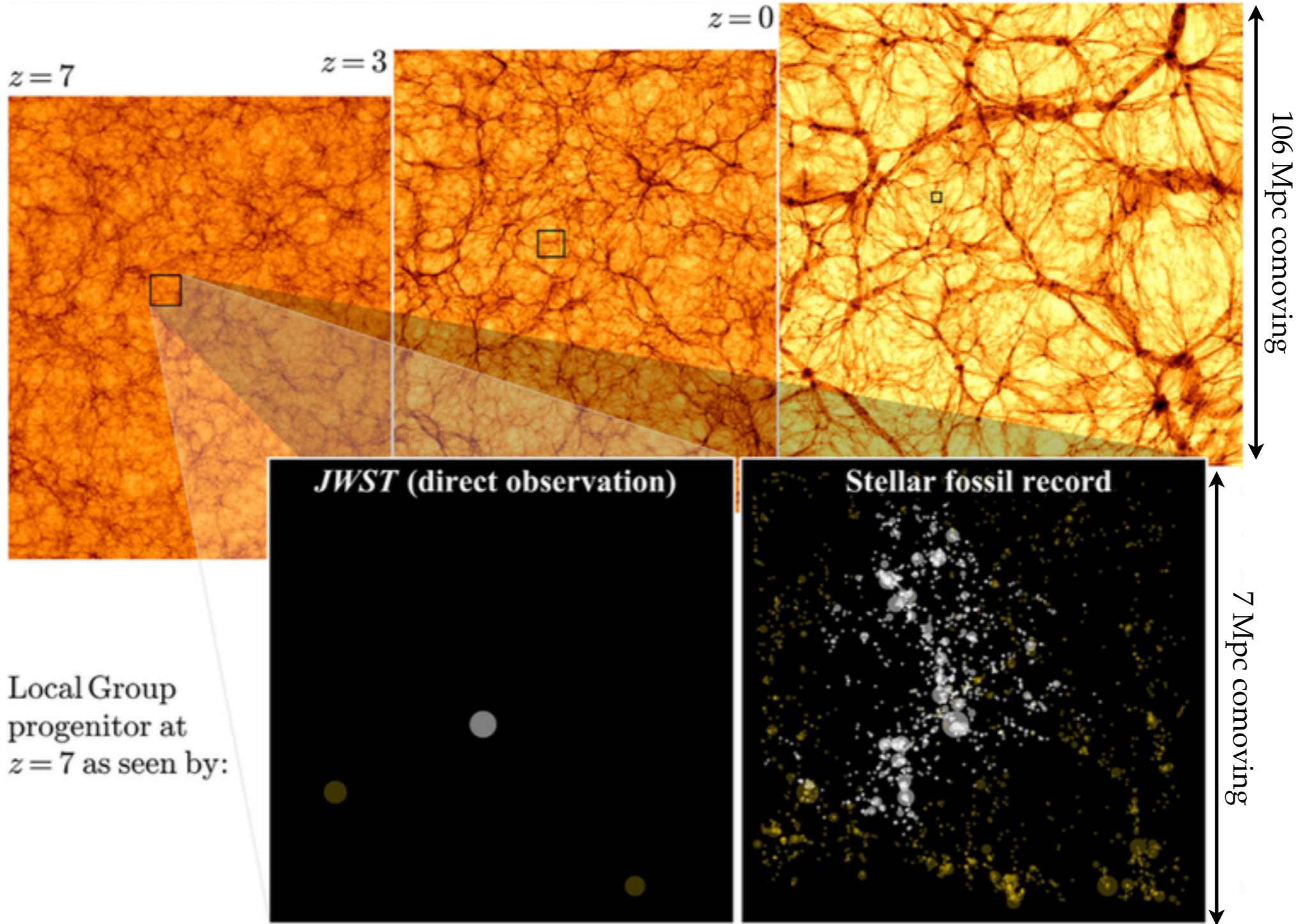


image: A. Mellinger (Central Michigan U.), M. Mateo (U. Michigan)

How (cosmologically) representative is the Local Group of galaxies?



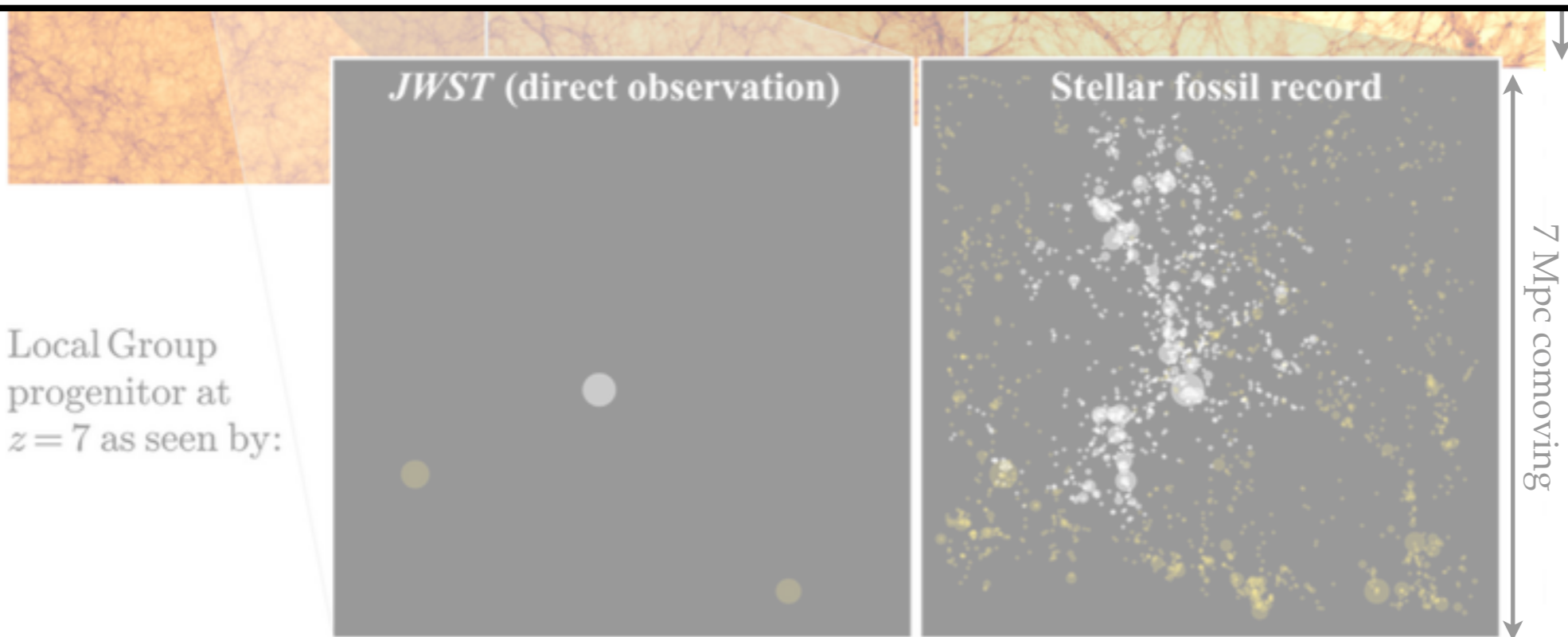
JWST = James Webb Space Telescope

Boylan-Kochin et al., Mon. Not. Roy. Astron. Soc., 462, L51 (2016)
 slices from the *Illustris* simulation



The Local Group spans a larger volume than the HUDF at $z < 3$.

It is representative of matter density and number of halos with $M_{\text{vir}}(z = 7) \approx 2 \times 10^9 M_{\odot}$



Local Group progenitor at $z = 7$ as seen by:

JWST = James Webb Space Telescope

Boylan-Kochin et al., Mon. Not. Roy. Astron. Soc., 462, L51 (2016)
slices from the *Illustris* simulation

ultra-faint dwarf (UFD) galaxies

- * have low luminosity ($M_V > -7$ or so)
- * are dark-matter dominated (mass-to-light ratios $\gtrsim 10^2 - 10^3$)
- * contain no detectable gas
- * contain only old stars (formed before reionization?)

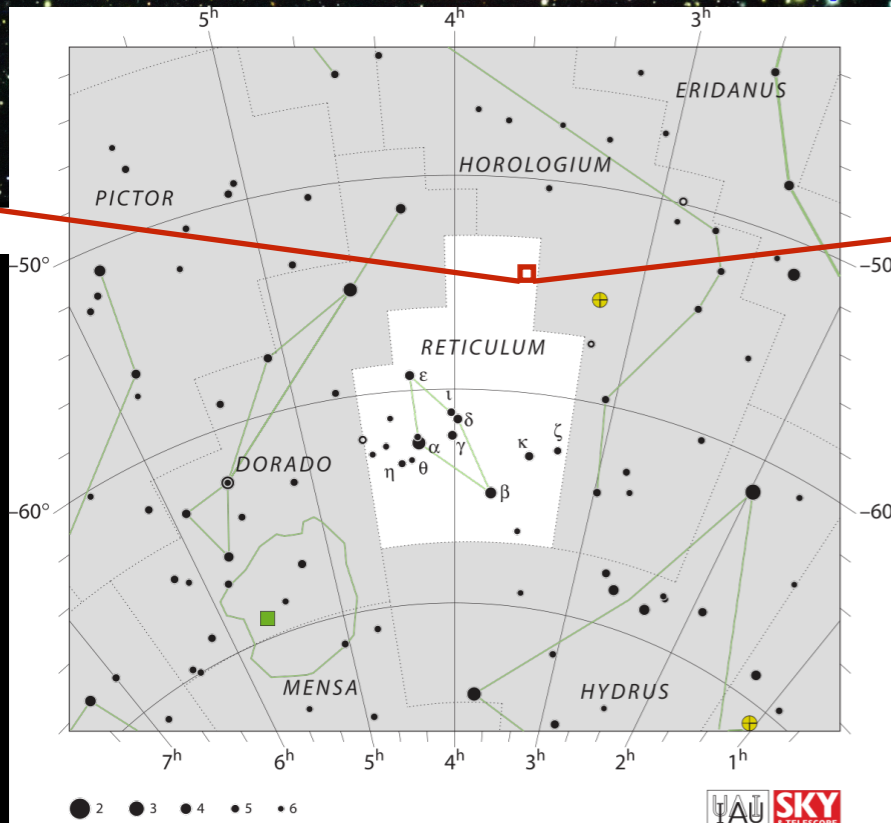
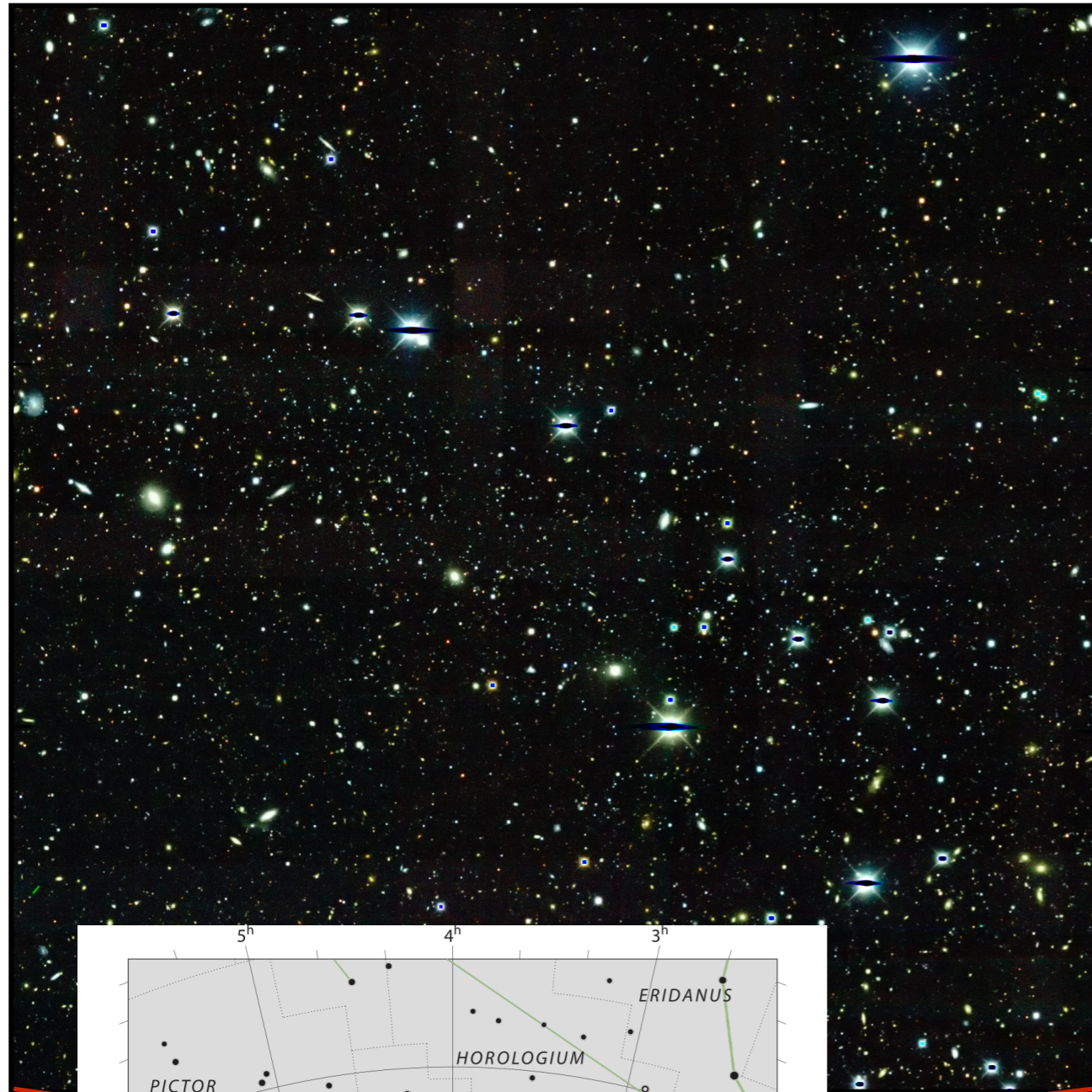
e.g.,

Simon & Geha, *Astrophys. J.*, 670, 313 (2007)

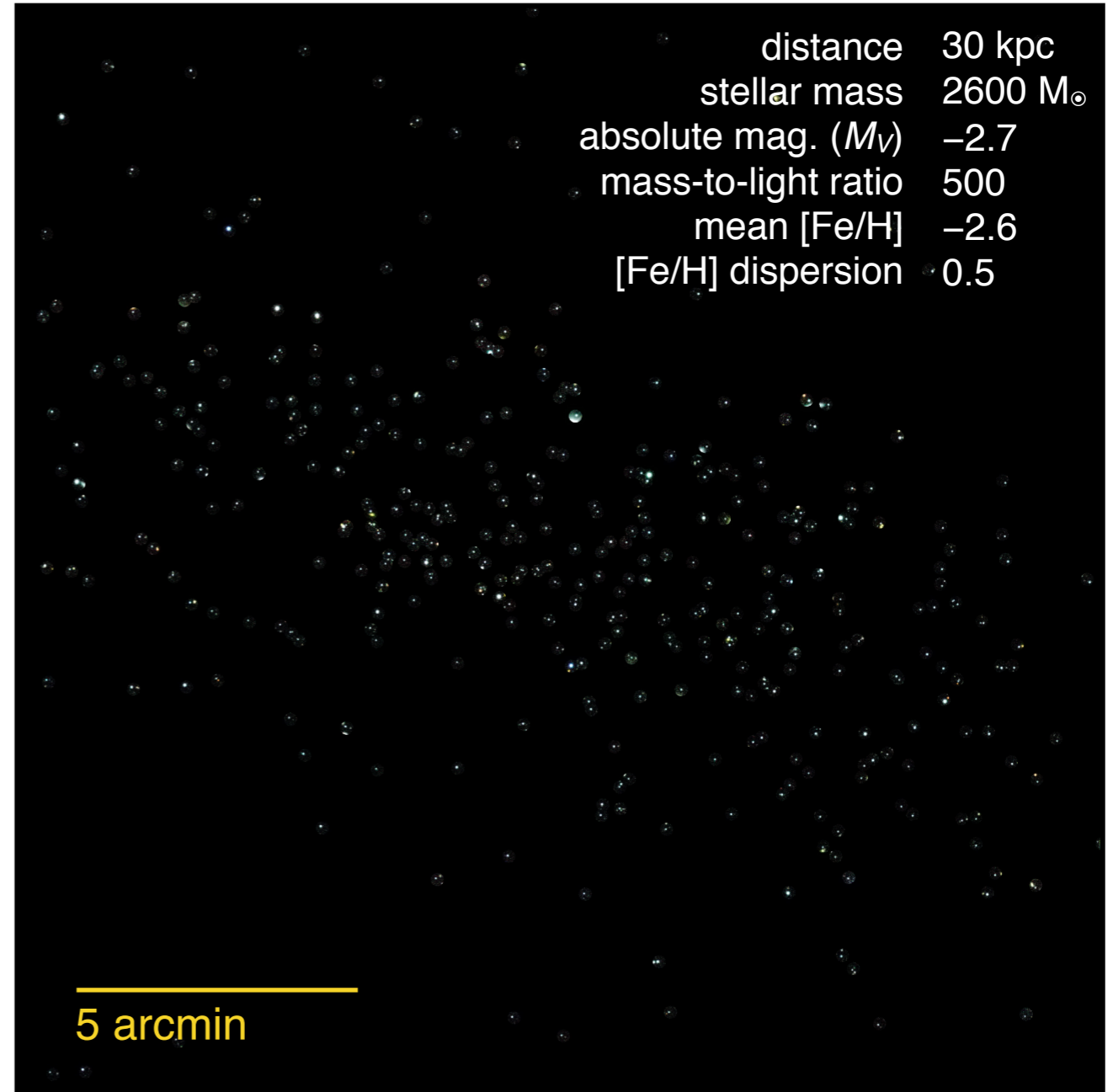
Brown et al., *Astrophys. J.*, 796, 91 (2014)

Westmeier et al., *Mon. Not. Roy. Astron. Soc.*, 453, 338 (2015)

All stars and background galaxies



Stars in the Reticulum II galaxy only



distance	30 kpc
stellar mass	2600 M_{\odot}
absolute mag. (M_V)	-2.7
mass-to-light ratio	500
mean [Fe/H]	-2.6
[Fe/H] dispersion	0.5

5 arcmin

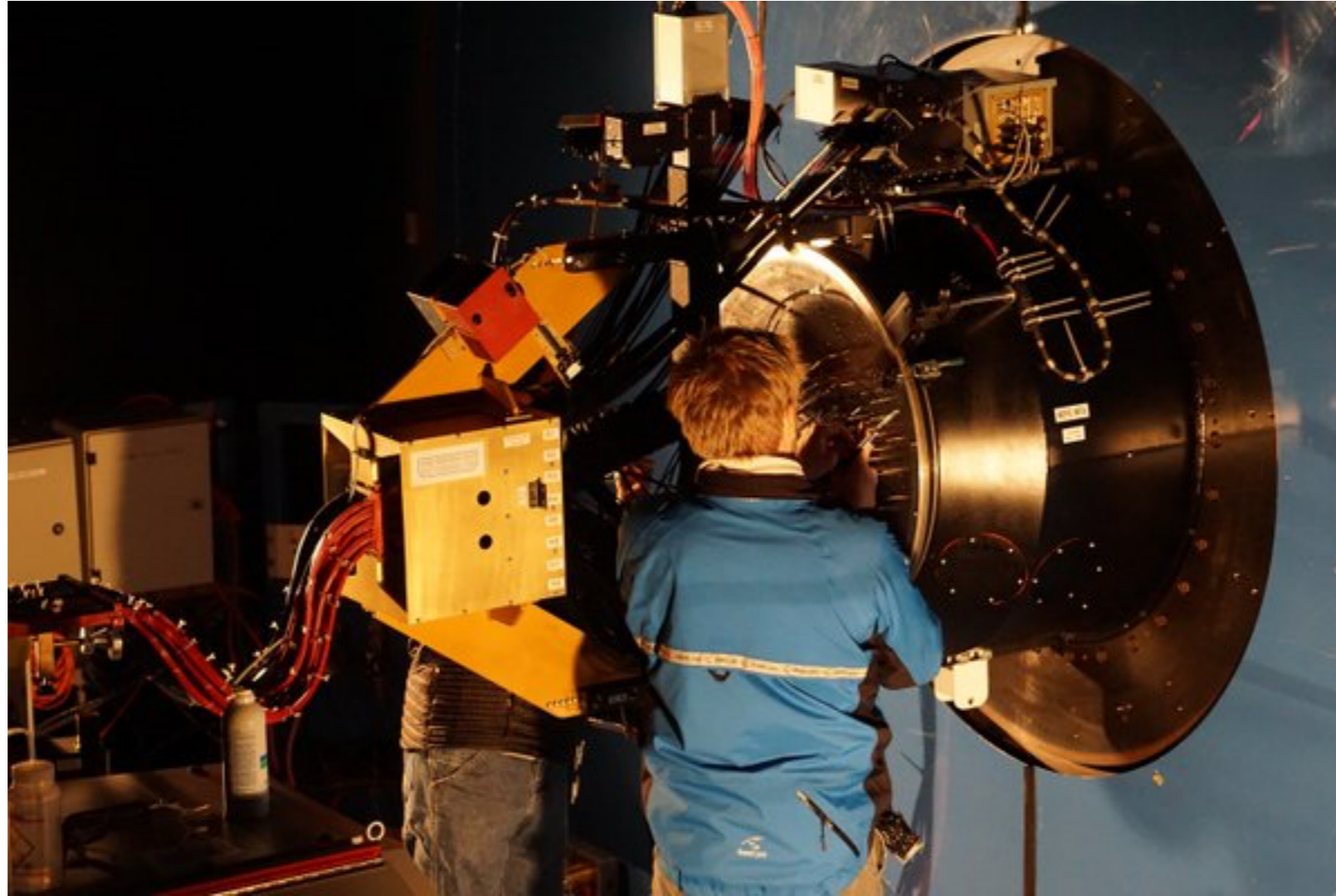
images:

Fermilab / Dark Energy Survey
IAU / Sky and Telescope

properties:

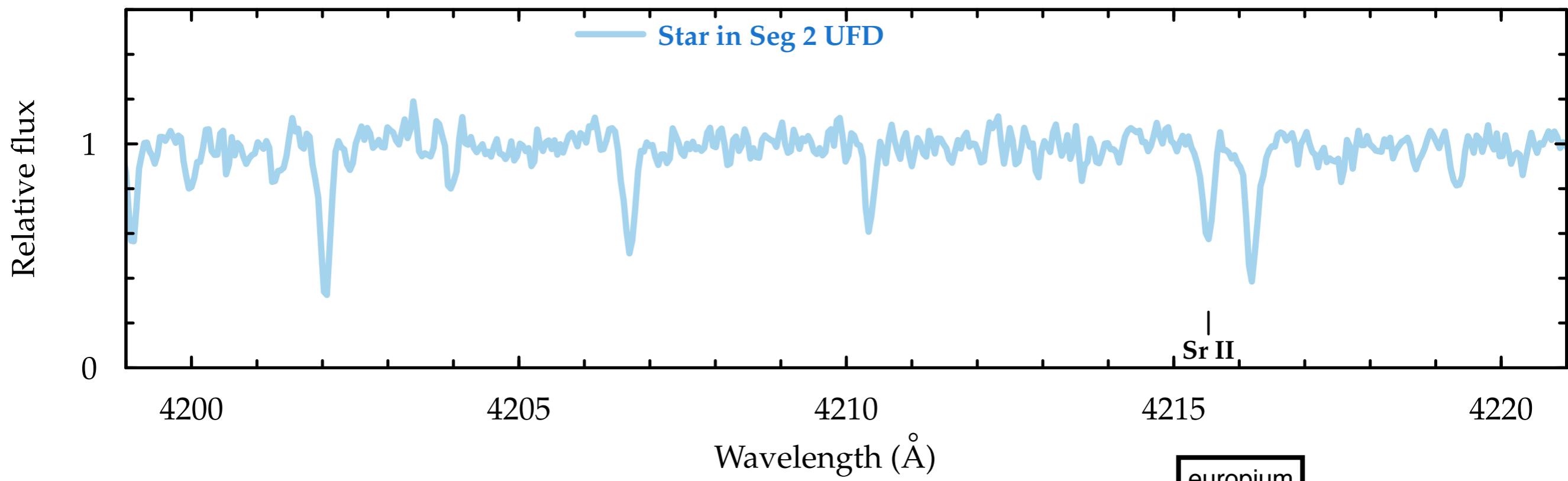
Koposov et al., *Astrophys. J.* 805, 130 (2015)
Bechtol et al., *Astrophys. J.* 807, 50 (2015)
Walker et al., *Astrophys. J.* 808, 108 (2015)

The Michigan/Magellan Fiber System (M2FS) is well-suited for this followup.

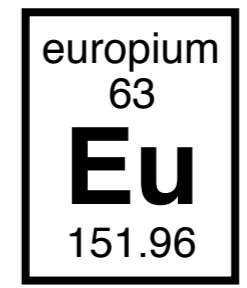


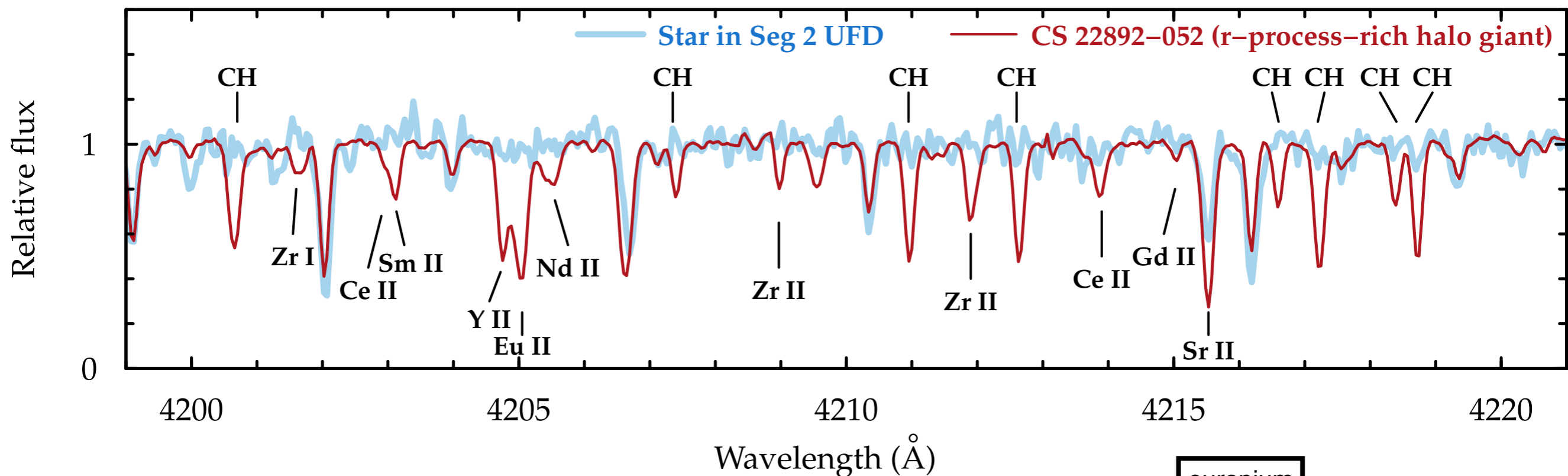
versatile high/medium/low-resolution modes
wide-field (30 arcmin diameter)
multi-object (up to 256 targets)

photo: C. Hull (Carnegie Obs.) and J. Bailey (Leiden)



	[Fe/H]	[Eu/Fe]
Seg 2	-2.9	< -0.3

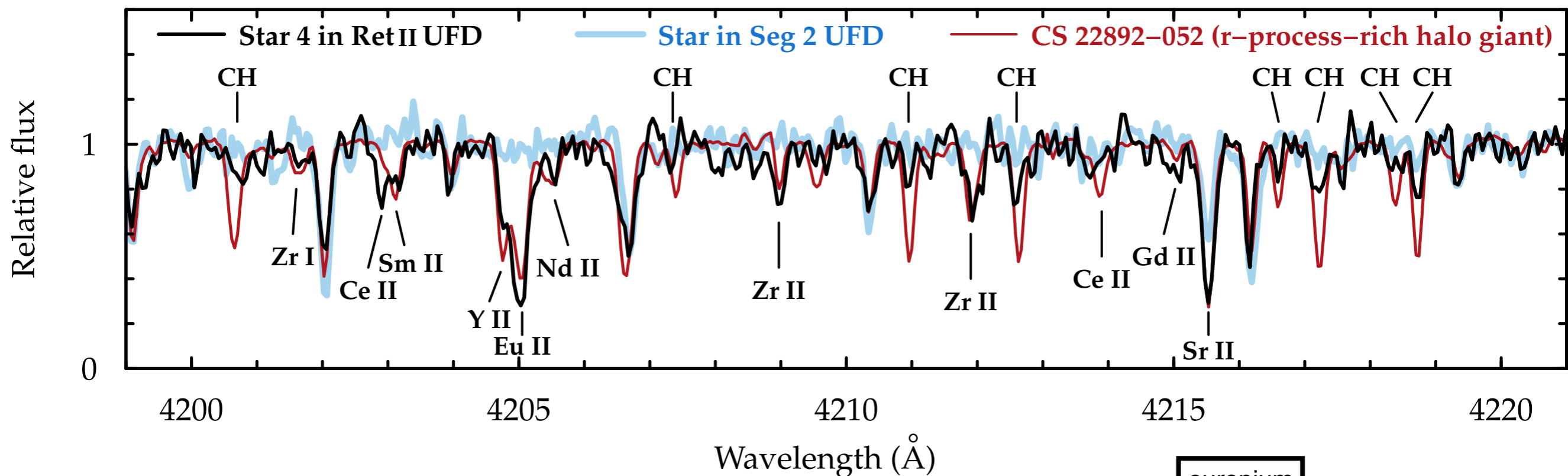




	[Fe/H]	[Eu/Fe]
Seg 2	-2.9	< -0.3
CS 22892-052	-3.1	+1.6

europium
63
Eu
151.96

Highly enhanced in r-process material!



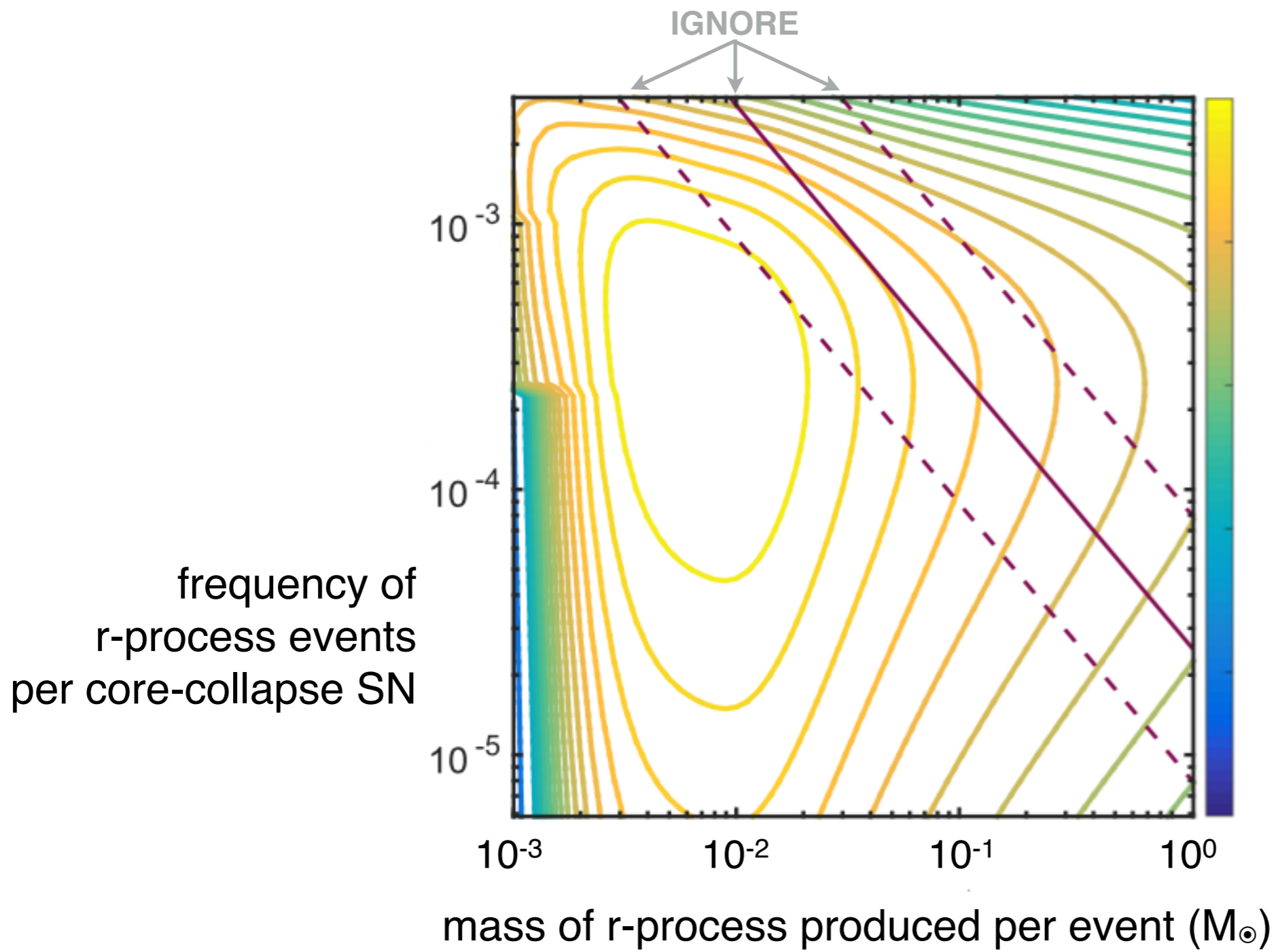
	[Fe/H]	[Eu/Fe]	
Seg 2	-2.9	< -0.3	<div style="border: 1px solid black; padding: 5px; display: inline-block;"> europium 63 Eu 151.96 </div> <div style="border: 1px solid black; padding: 5px; display: inline-block;"> Highly enhanced in r-process material! </div>
CS 22892-052	-3.1	+1.6	
Ret II	-2.9	+1.6	

Roederer et al., *Astronom. J.* 151, 82 (2016)
 see also Ji et al., *Astrophys. J.*, 830, 93 (2016)

Something happened in Ret II—an r-process event—that did not happen in other dwarf galaxies.

Where?	% of stars that are highly r-process enhanced
Ret II ultra-faint dwarf galaxy	$83 \pm 8\%^*$
Other ultra-faint dwarf galaxies	0%
Milky Way halo	$\sim 5\%$
Milky Way (all stars)	$\lesssim 0.05\%$ (?)

* Roederer et al., in prep.

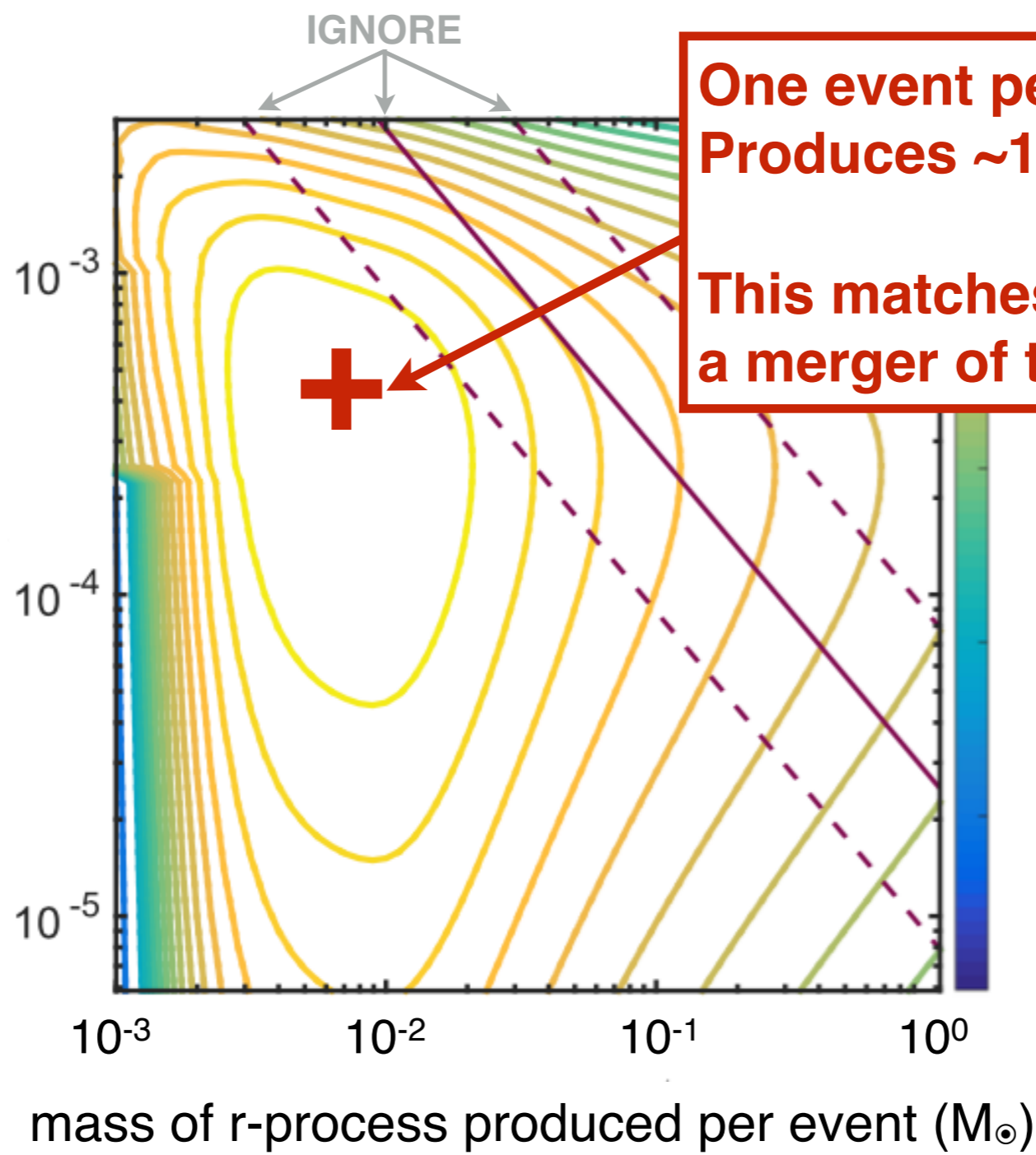


Beniamini et al., *Astrophys. J.*, 832, 149 (2016) [plus annotations]



core-collapse SN:
 $\sim 10^{-5} M_{\odot}$ of r-process

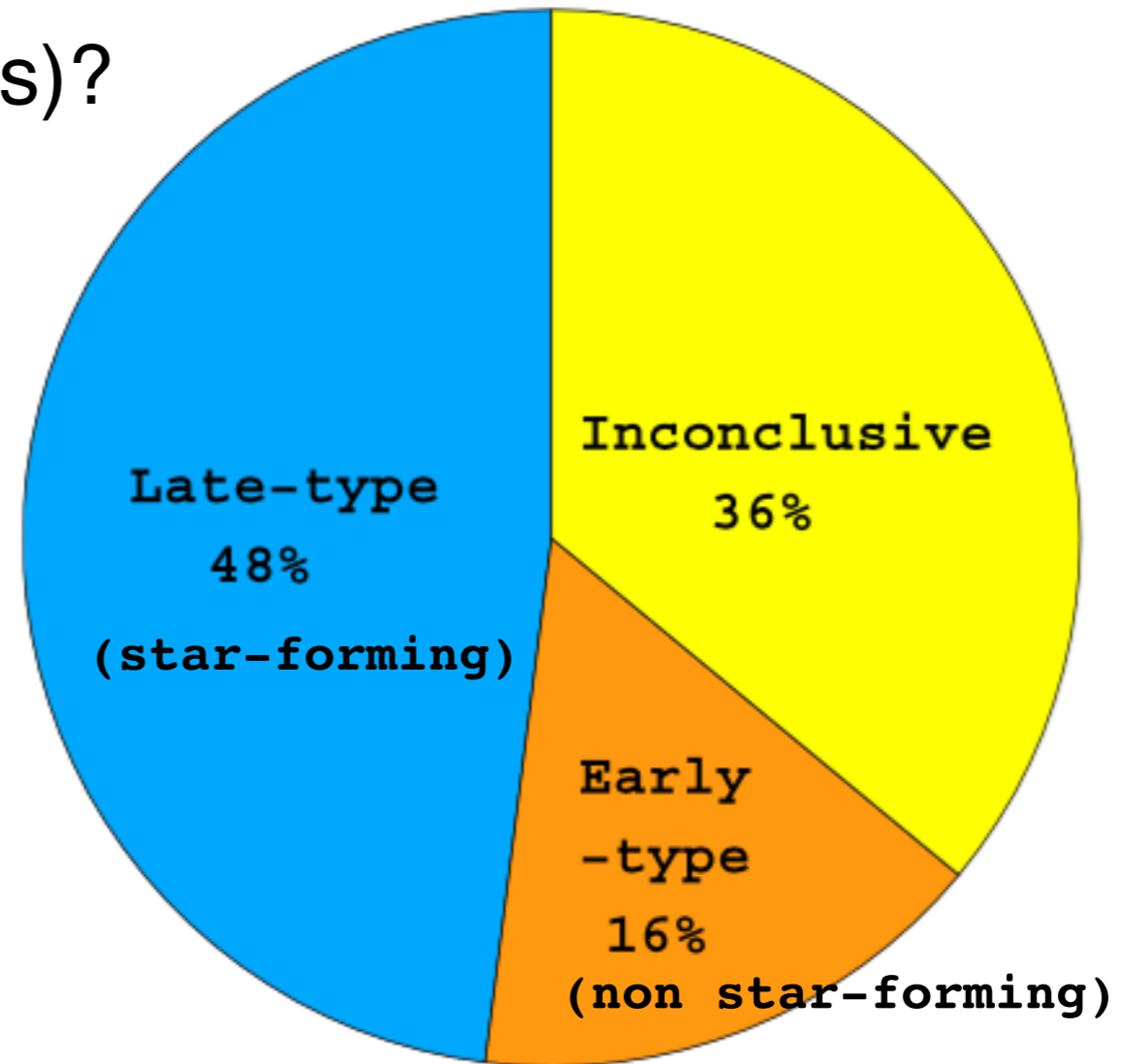
frequency of
r-process events
per core-collapse SN



**One event per ~ 5000 CCSN.
Produces $\sim 10^{-2} M_{\odot}$ of r-process.
This matches expectations for
a merger of two neutron stars.**

What are the host galaxies of short gamma-ray bursts (GRBs)?

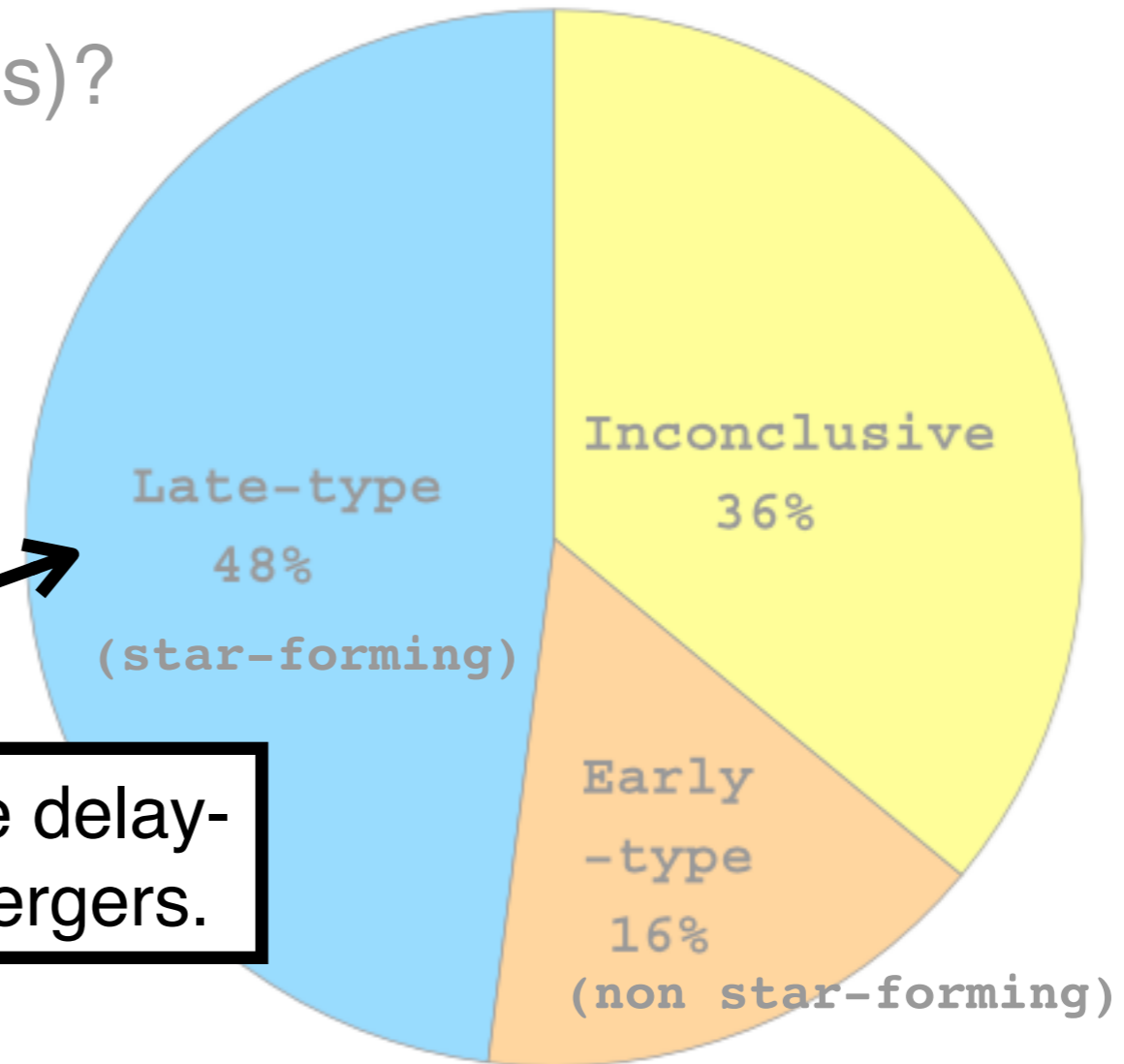
Sub-arcsec loc.
Host-less Assigned
Sample: 25



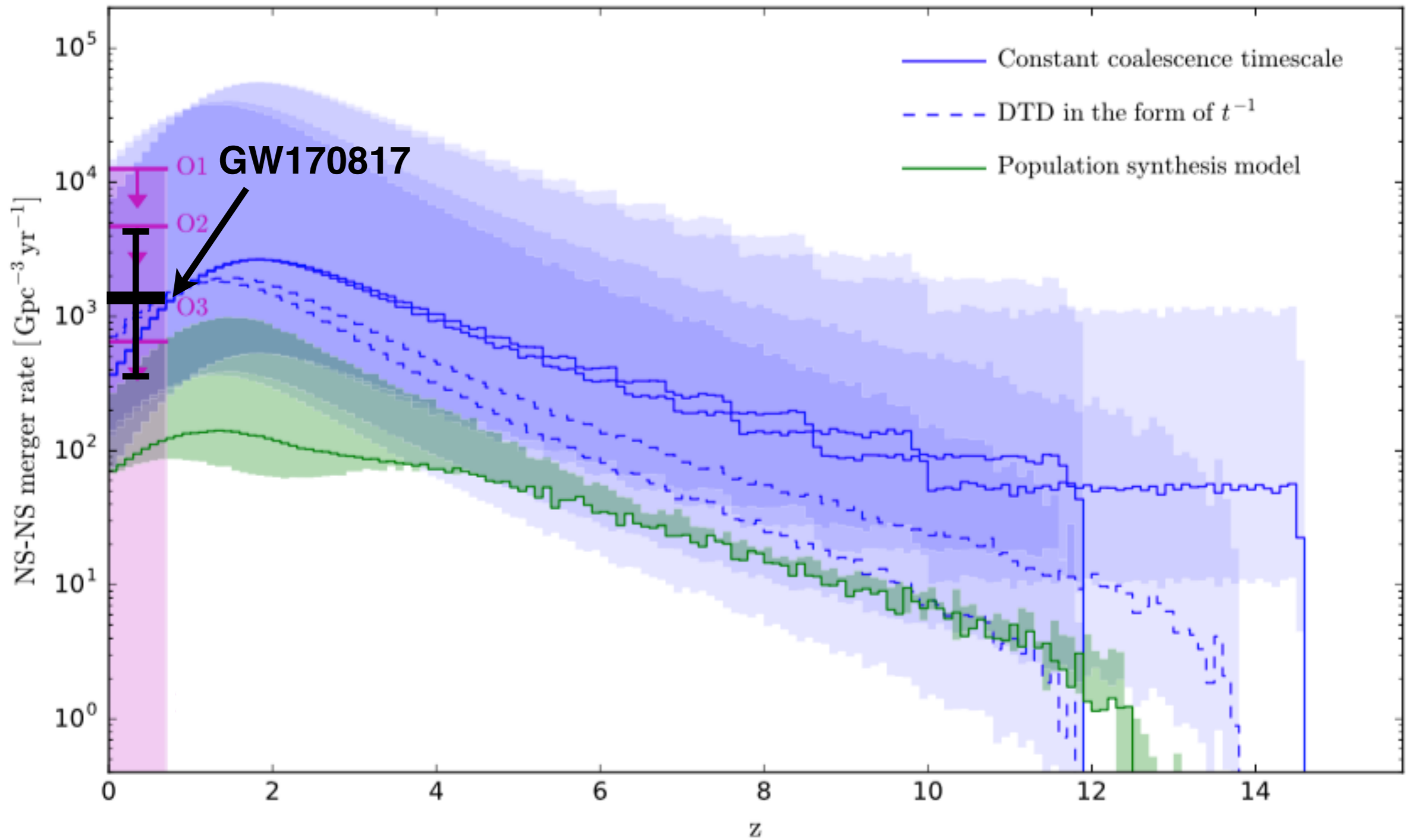
Fong et al., *Astrophys. J.*, 769, 56 (2013) [plus annotations]

What are the host galaxies of short gamma-ray bursts (GRBs)?

Sub-arcsec loc.
Host-less Assigned
Sample: 25

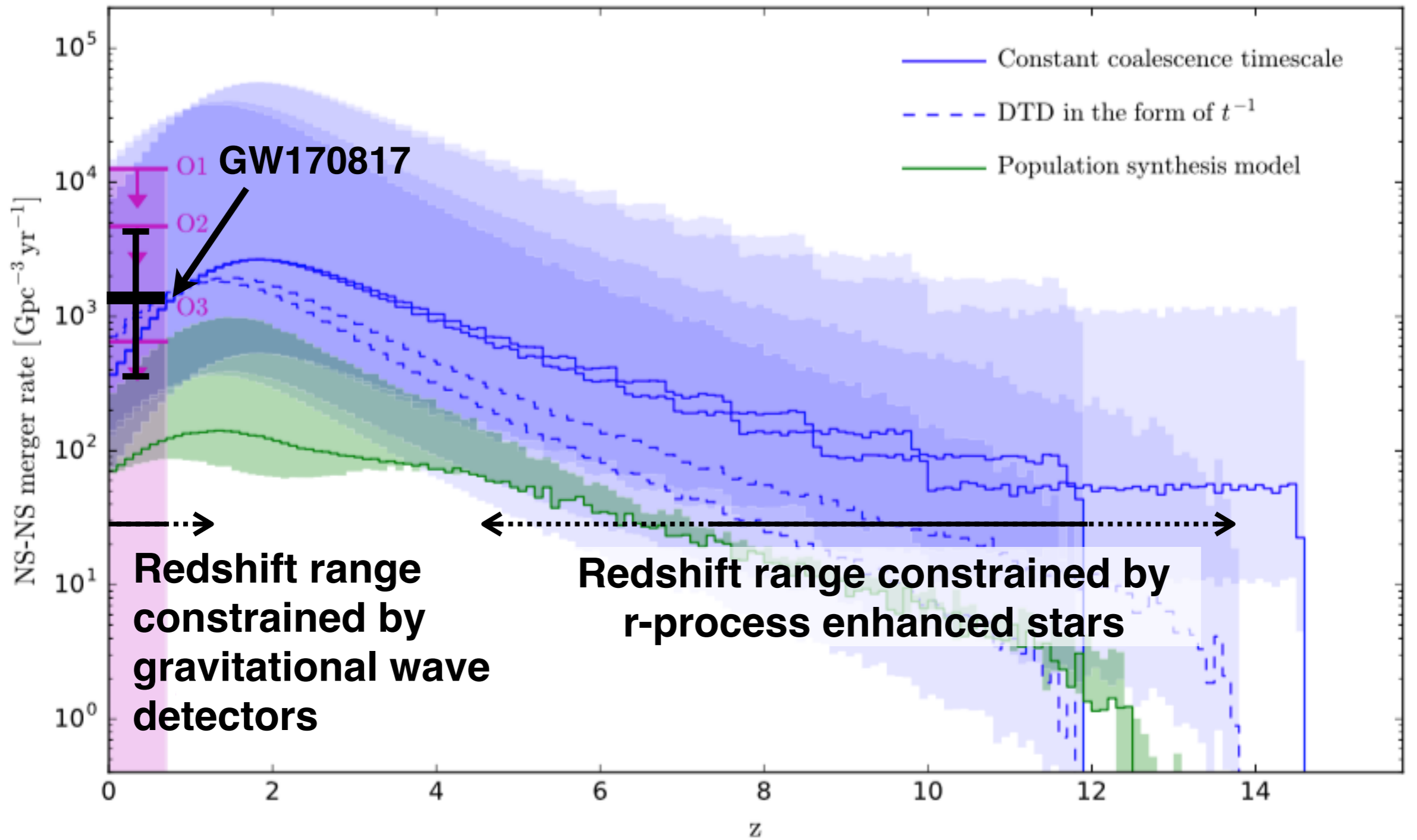


This may indicate a “fast” tail of the delay-time distribution of neutron star mergers.



Côté et al., *Astrophys. J.*, 836, 230 (2017)

NS-NS rate measurement: Abbott et al. (LIGO & Virgo Collab.), *Phys. Rev. L.*, 119, 161101 (2017)



Côté et al., *Astrophys. J.*, 836, 230 (2017)

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CONCLUSIONS

Laboratory atomic spectroscopy from the Wisconsin group has effectively removed the atomic data as a source of uncertainty in stellar abundance derivations for r-process elements.

Observations from dwarf galaxies and the EM counterpart of GW170817 indicate that neutron star mergers are capable of hosting the r-process.

Answering the next level of questions will (continue to) require a wide variety of observational and experimental data:

- * surveys for highly r-process enhanced stars (R-Process Alliance)
- * surveys for Local Group dwarf galaxies (DES, Gaia, LSST)
- * access to high-quality UV spectra (HST, CETUS, HabEx)
- * gravitational wave detectors and telescopes for EM followup (Advanced LIGO, Virgo, ...)
- * rare isotope accelerators (FRIB, FAIR, TRIUMF/ARIEL, RIKEN/RIBF, ...)