

Ji et al. 2016, Nature

A rare and prolific r-process event observed in the ultra-faint dwarf galaxy Reticulum II

1 IA 1A																	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71 La Lanthanum 138.905	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Ac Actinium 227.028	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

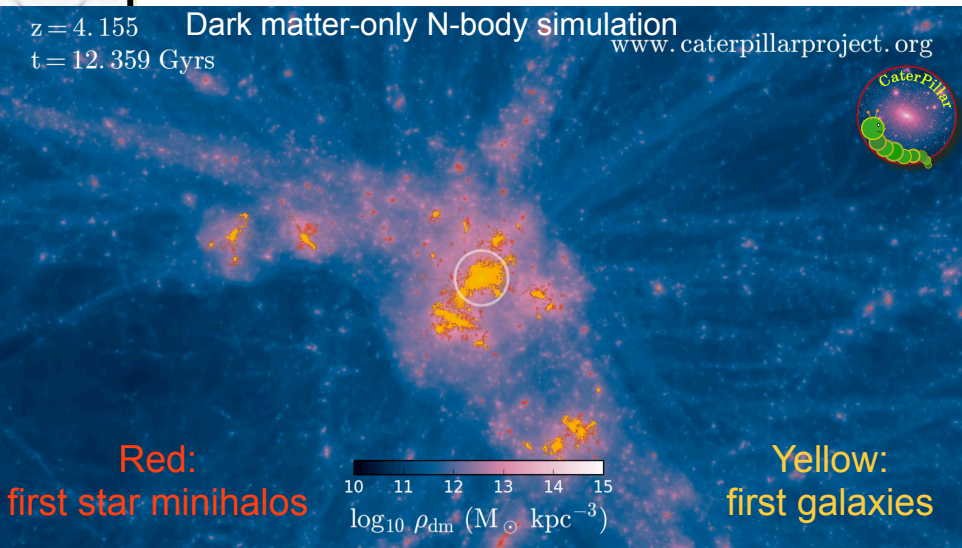
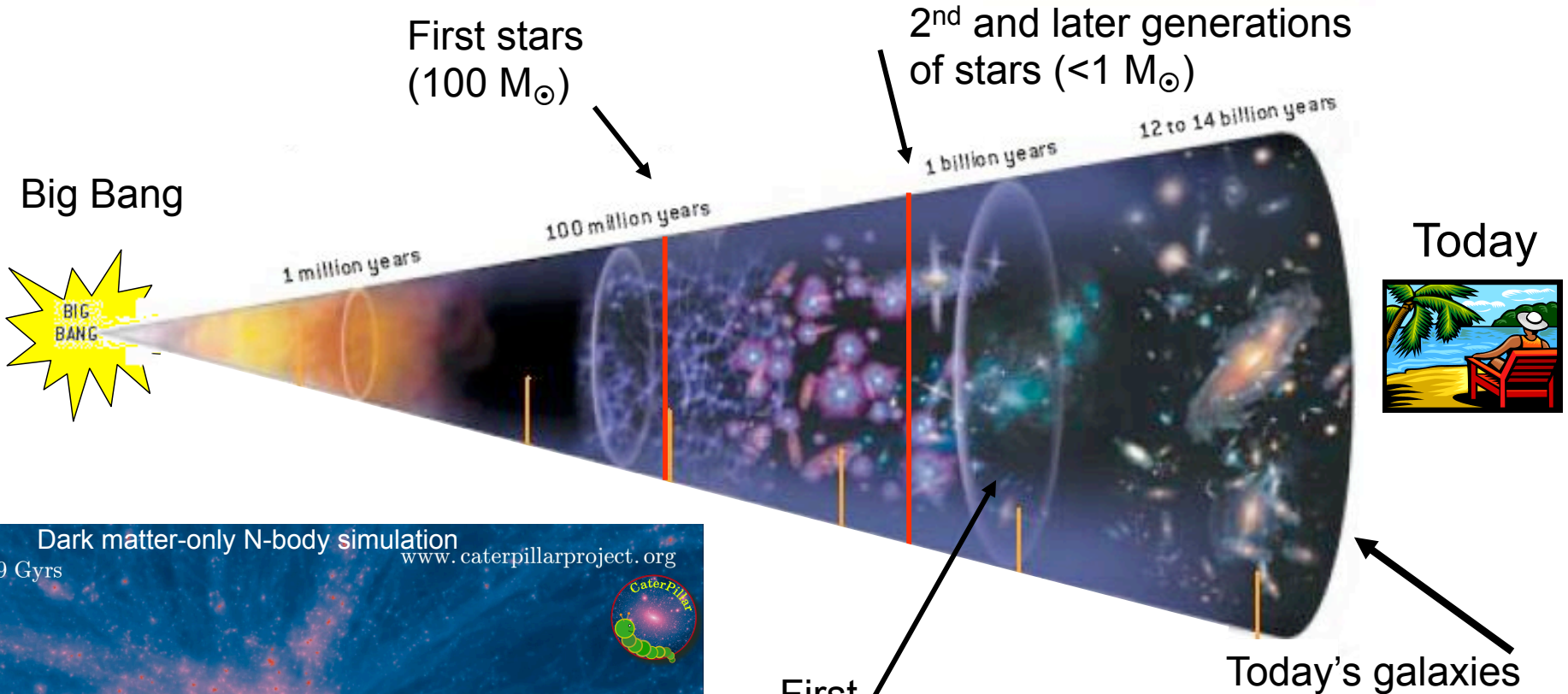
elements made in the rapid (r-) neutron-capture process

57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Anna Frebel



A LONG TIME AGO...



First galaxies

SCIENTIFIC AMERICAN
Larson & Bromm 2001

Cosmic time (not to scale)

THE STORY OF RETICULUM II



Nuclear Astrophysics

Cosmic origin of
the chemical
elements



Stellar Archaeology

Clues to the
astrophysical
site of r-process
nucleosynthesis

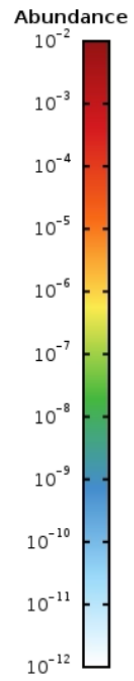


Dwarf Galaxy Archaeology

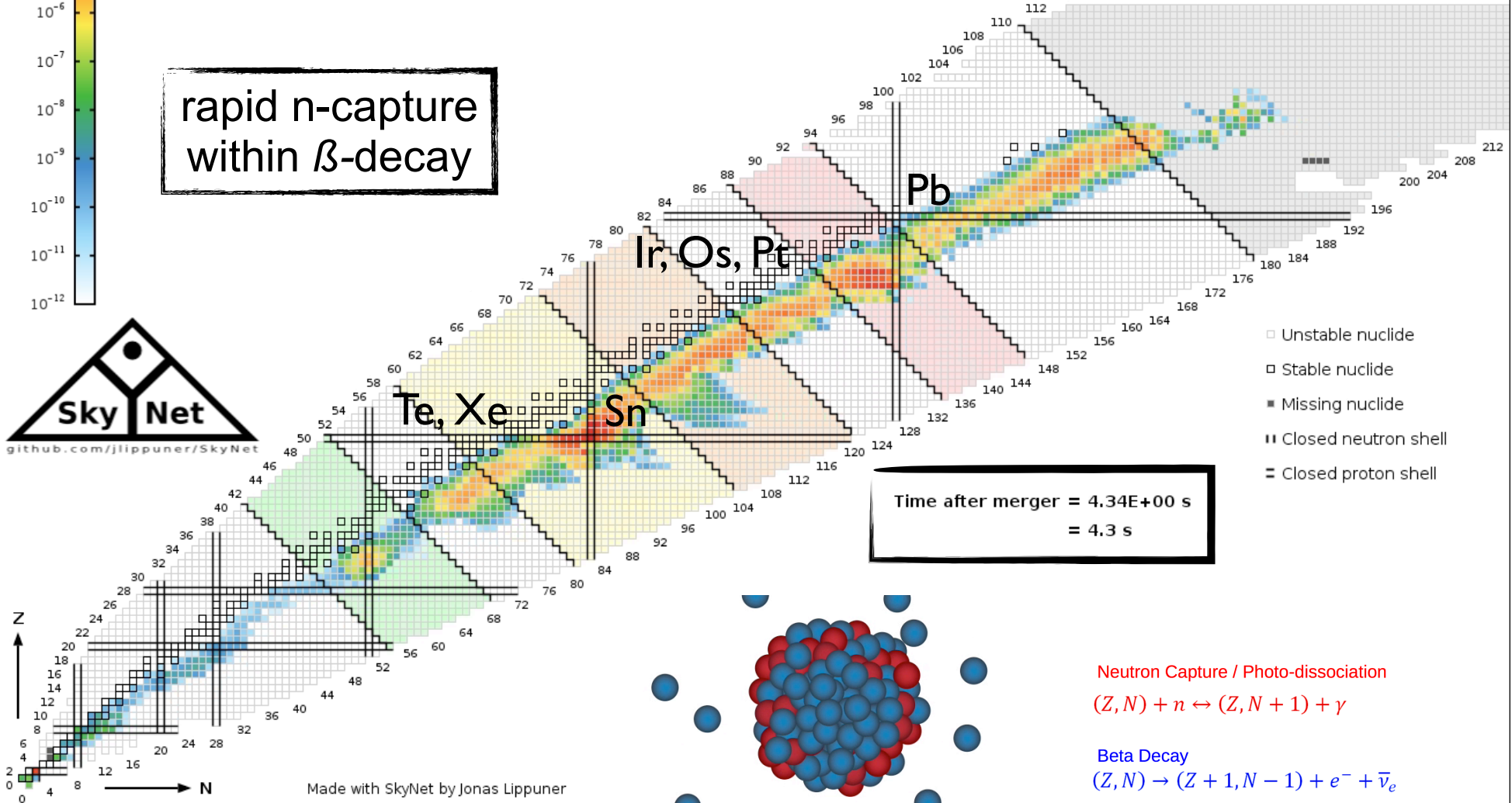
Ancient, clean
chemical
enrichment
signatures

RAPID NEUTRON-CAPTURE-NUCLEOSYNTHESIS

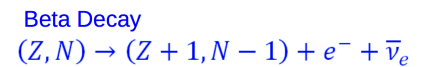
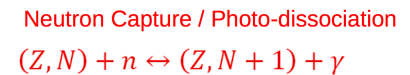
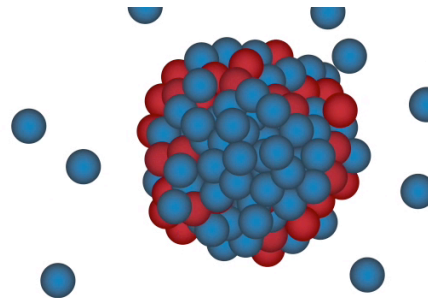
(neutron star merger scenario)



rapid n-capture
within β -decay



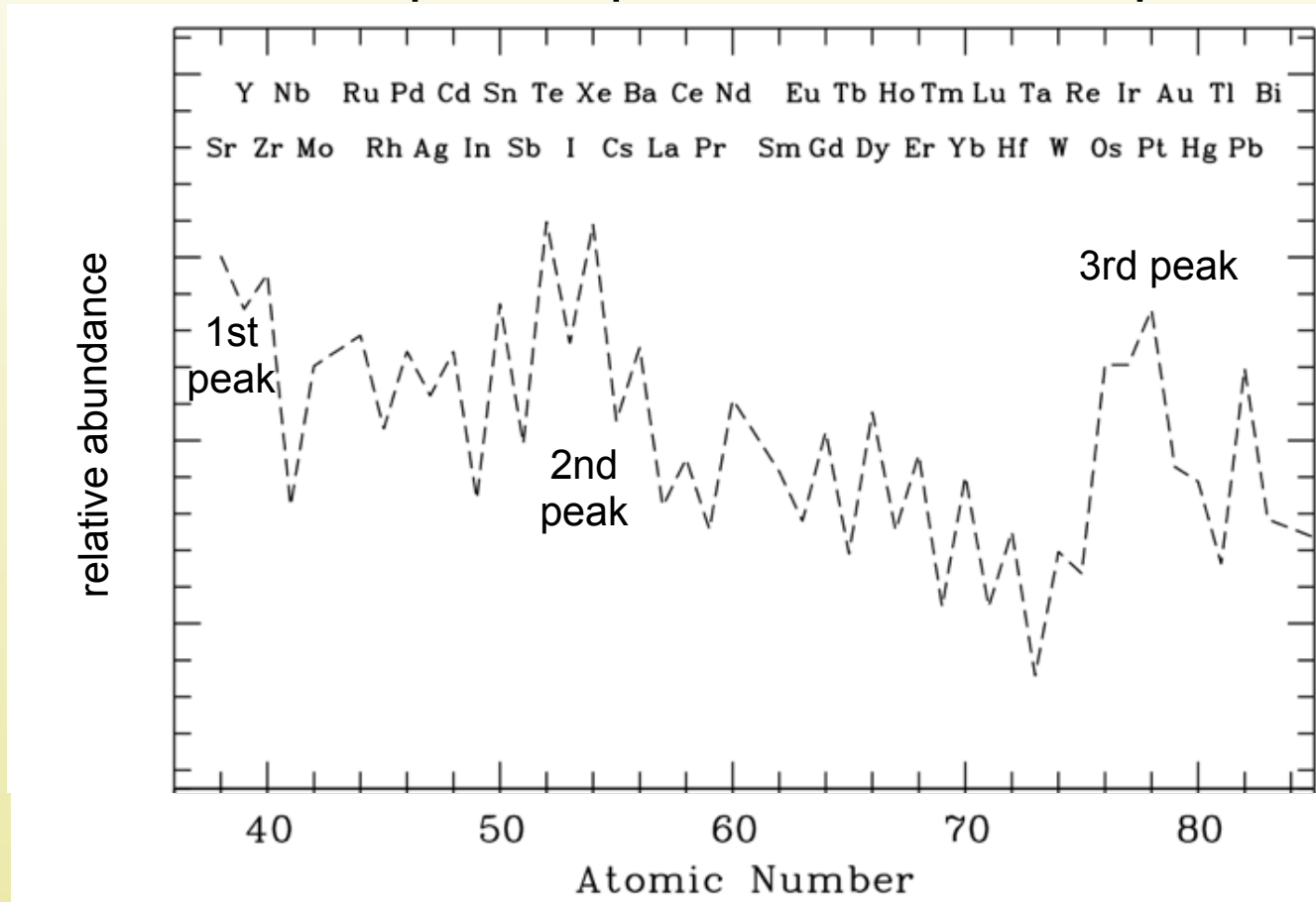
Made with SkyNet by Jonas Lippuner



decay of unstable nuclides (to β -stable nuclides)
to stability

R-PROCESS PATTERN

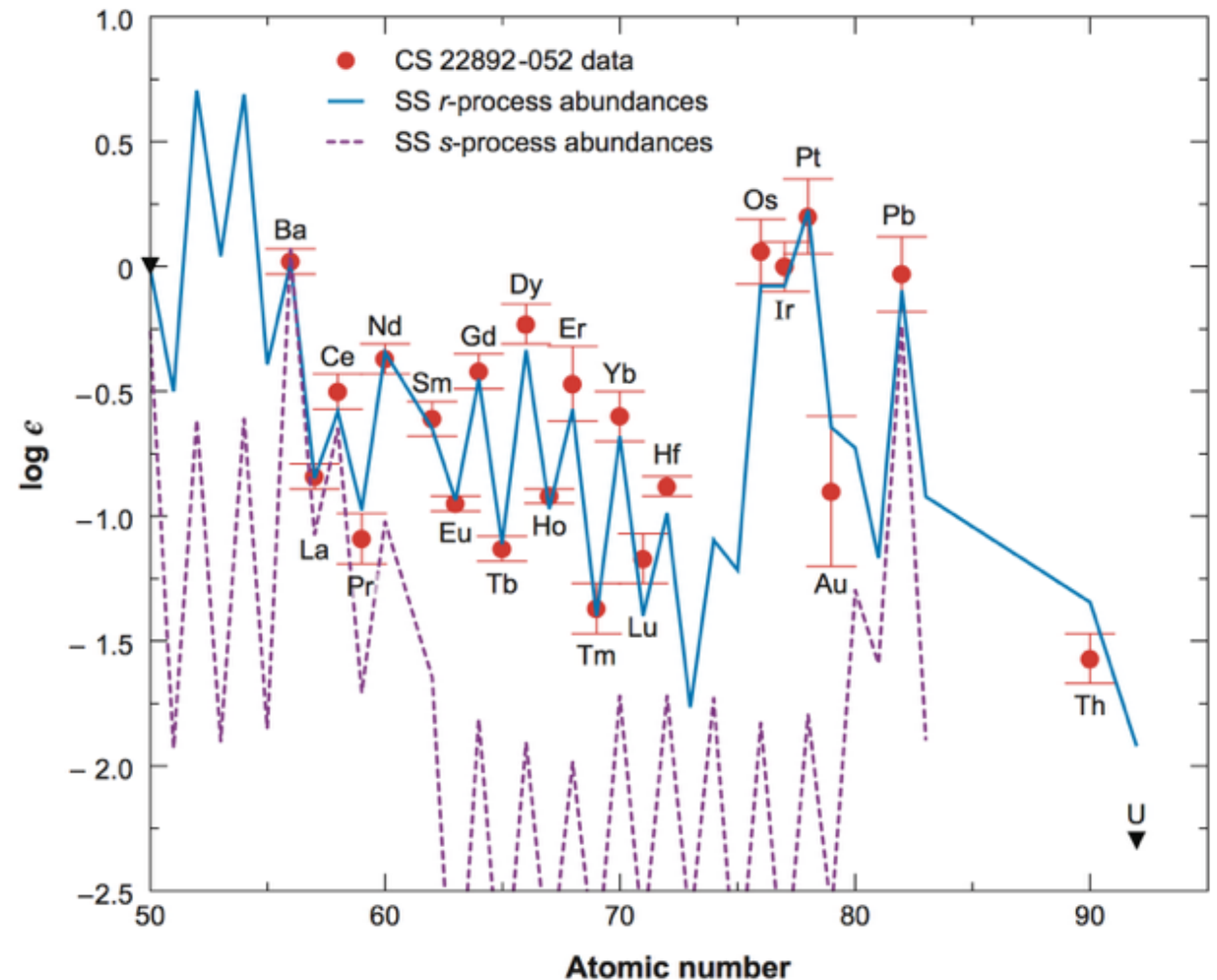
neutron-capture r-process elemental pattern



UNIVERSAL R-PROCESS PATTERN OBSERVED IN METAL-POOR STARS

r-process abundance **patterns** are the same in the Sun and old metal-poor stars

r-process stars are all extremely metal-poor:
 $[\text{Fe}/\text{H}] \sim -3.0$
 (= 1/1000th of solar Fe value)



Snedden et al. 2008

Definition: $[\text{Fe}/\text{H}] = \log_{10}(\text{N}_{\text{Fe}}/\text{N}_{\text{H}})_{\text{star}} - \log_{10}(\text{N}_{\text{Fe}}/\text{N}_{\text{H}})_{\text{Sun}}$

RARE R-PROCESS STARS IN THE MILKY WAY

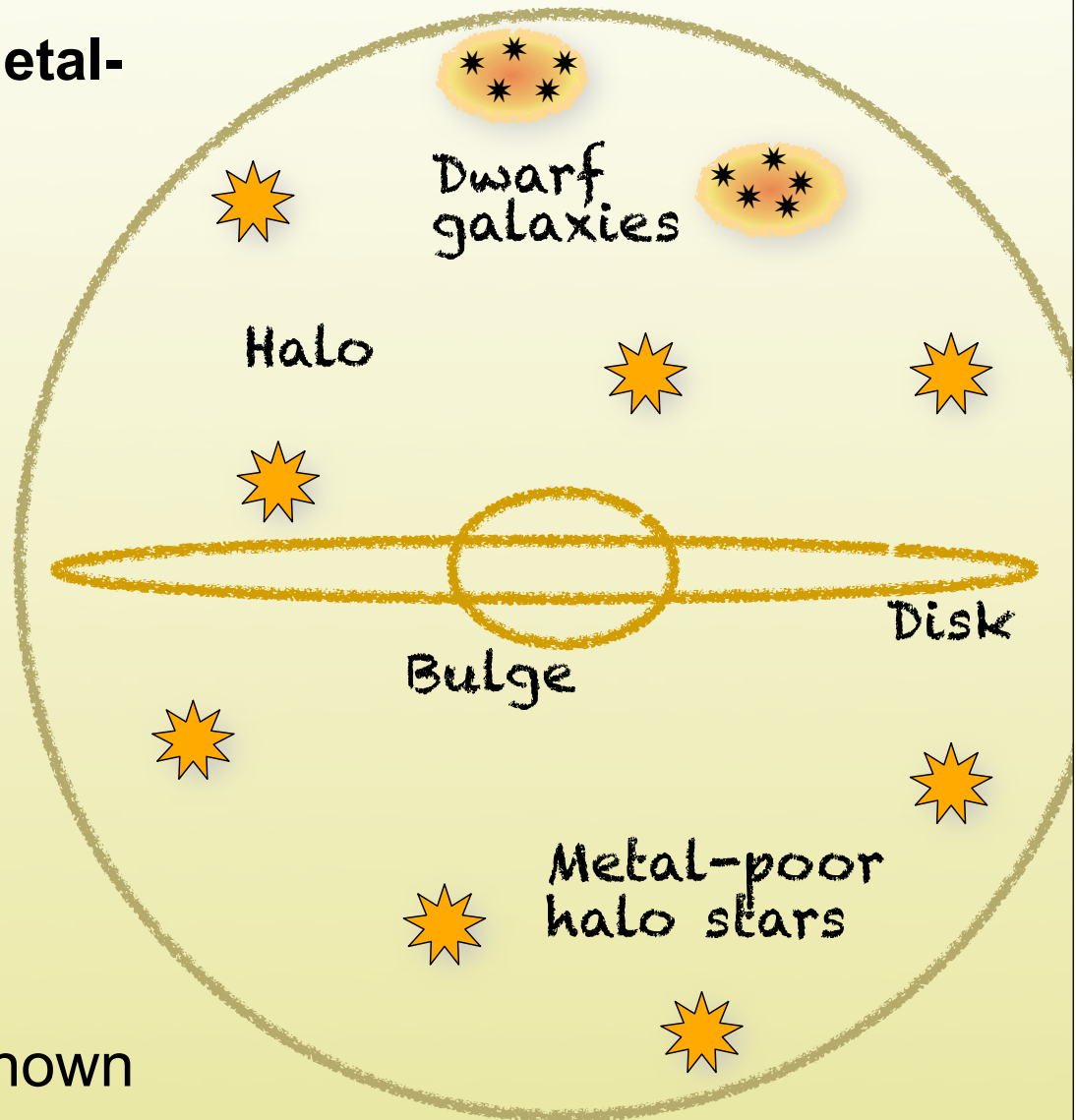
How common are r-process metal-poor stars in the Milky Way?

3 to 5% of metal-poor stars w/
 $[Fe/H] < -2.5$ (Barklem et al. 05)

Only ~30 stars known so far w/
 $[Eu/Fe] > 1.0$; i.e. clear r-
process pattern above Ba

More stars known with lower
levels of $0.3 < [Eu/Fe] < 1.0$;
unclear what lowest level is

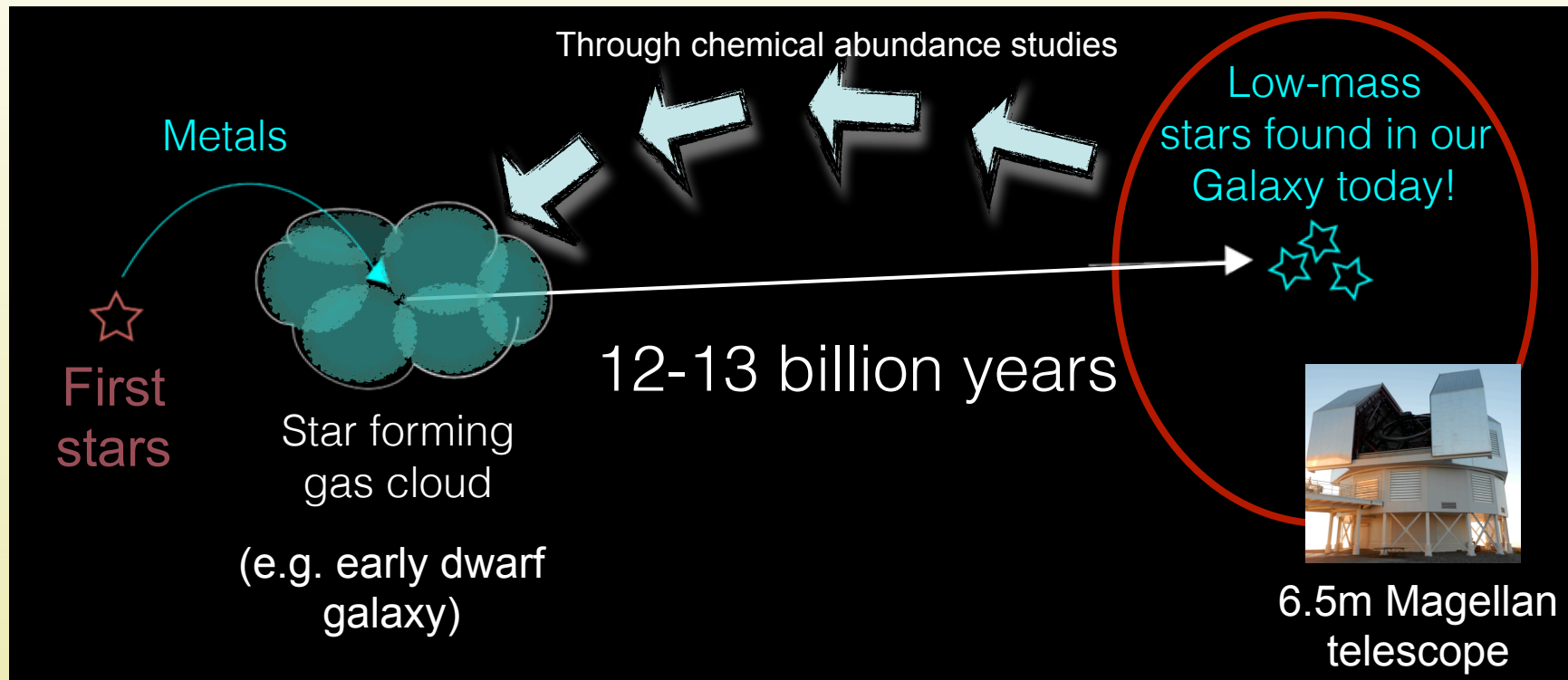
=> Origin of these stars is unknown



STELLAR ARCHAEOLOGY

Using metal-poor stars to probe the early universe

Low-mass stars with $M < 1 M_{\odot}$: Lifetimes > 10 billion years \Rightarrow they are still around!



$[Fe/H] \leq -3$ \Rightarrow only ~ 1 progenitor star produced that iron
(= 1/1000th of solar Fe) \Rightarrow only ~ 1 nucleosynthesis event made heavier elements

THE (DETAILED) ASTRONOMER'S PERIODIC TABLE

Big Bang nucleosynthesis

Spallation

Evolved giant stars

Odd-Z elements

α -elements

Iron group elements

α -rich freezeout, νp -proc., weak s-proc.

s-process

Weak r-proc., light n-cap. primary proc.

r-process

Long-lived

radioactive

(also r-process)

	IA	IIA															VIIIA					
1	1 H 1.008																2 He 4.003					
2	3 Li 6.939	4 Be 9.012															5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.183
3	11 Na 22.990	12 Mg 24.312															13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
4	19 K 39.102	20 Ca 40.08	21 Sc 44.956	22 Ti 47.88	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.847	27 Co 58.933	28 Ni 58.69	29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.909	36 Kr 83.80				
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.905	40 Zr 91.22	41 Nb 92.906	42 Mo 95.94	43 Tc (99)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.90	54 Xe 131.30				
6	55 Cs 132.91	56 Ba 137.34	57 La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.09	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 208.98	83 Bi 208.98	84 Po (210)	85 At (210)	86 Rn (222)				
7	87 Fr (223)	88 Ra (226)	89 Ac (227)															<p>Isotope distribution of solar nebula (~8 billion yrs of chemical evolution)</p>				
„6“				58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.92	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97					
„7“				90 Th 232.04	91 Pa (231)	92 U 238.03	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (249)	98 Cf (251)	99 Es (254)	100 Fm (253)	101 Md (256)	102 No (253)	103 Lr (257)					

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THE BIG QUESTION

★ **What is the (dominant) astrophysical site of the r-process?**

➡ Core-collapse supernovae

➡ Neutron star mergers

➡ Others (e.g., jet-driven supernovae)

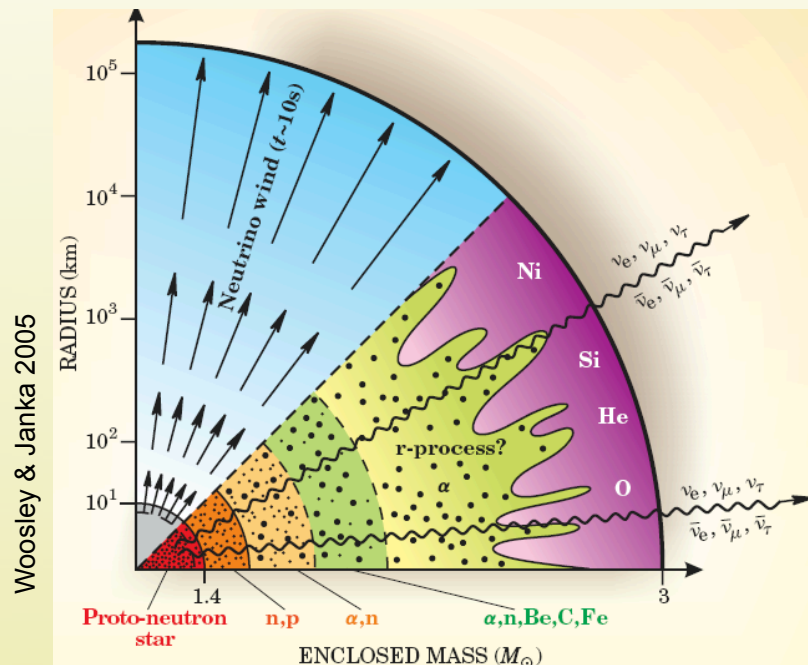
★ **What is the rate and yield of the event?**

★ **Is the dominant site changing over cosmic time?**

CORE-COLLAPSE SUPERNOVA

(DEATH OF A MASSIVE STAR WITH $M > 8 M_{\odot}$)

Supernovae are common; produce light elements w/ $Z < 30$ in their cores
Responsible for these light elements when observed in metal-poor stars



Theoretical element yield:

$\sim 10^{-6} M_{\text{sun}}$ of total r-process material

$\Rightarrow \sim 10^{-7.5} M_{\text{sun}}$ of Eu (per event)

Pros

- ✓ Metal-poor stars only have one/few progenitors
- ✓ Provides the fast enrichment needed; small & steady r-process yields

Con Theoretical difficulties for r-process nucleosynthesis to produce elements heavier than Ba (e.g. Arcones et al.)

NEUTRON STAR BINARY MERGER

(TWO COMPACT SUPERNOVA REMNANTS)

Pros Easily produces elements heavier than Ba

Cons Rare One binary per ~1000- 2000 supernovae
Long(er) enrichment timescale => Inspiral time >100 Myr



Yield: $\sim 10^{-3} - 10^{-2} M_{\text{sun}}$ of r-process material (across all n-cap elements)

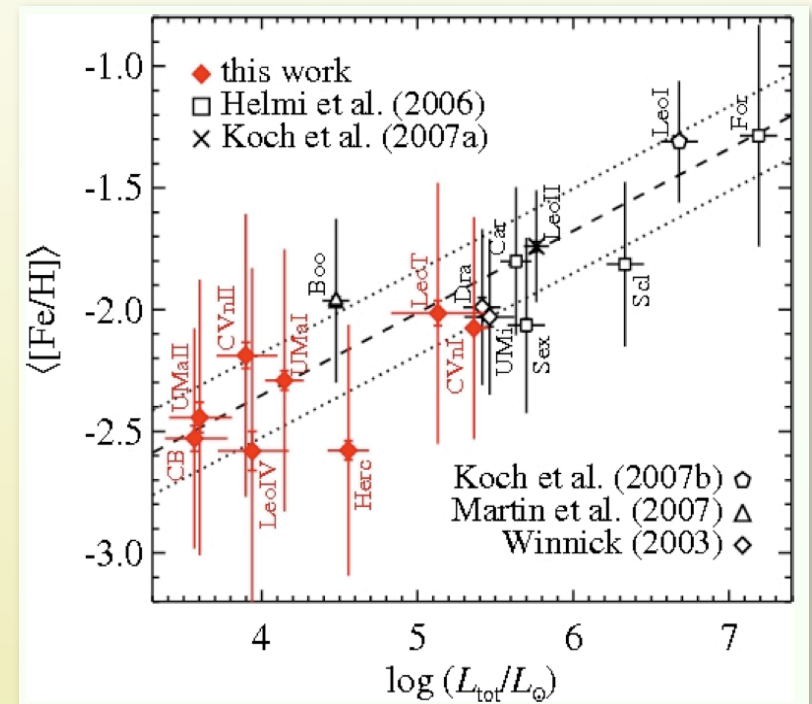
=> $\sim 10^{-4.5} M_{\text{sun}}$ of Eu (per event)

Additional (indirect) evidence for local r-process nucleosynthesis

- 1) Short gamma-ray bursts: Afterglow from decay of radioactive r-process elements detected (Tanvir et al. 13)
- 2) Radioactive deep sea measurements suggest local neutron star mergers (Wallner et al. 15, Hotokezaka et al.15)

ULTRA-FAINT DWARF GALAXY PROPERTIES (UFDS)

- Low luminosity (300 - 3,000 L_{sun})
- Dark matter-dominated ($M/L > 100$)
- Metal-poor (mean $[Fe/H] \sim -2$)
- Stars are old (mean age 13.3 ± 1 Gyr)
- Few bursts of star formation



Ultra-faint dwarfs

Classical dSphs

Ideal targets for Dwarf Galaxy Archaeology

Use entire galaxy as fossil record of the early universe.

Bonus: get environmental information because we know where stars were born

MEET RETICULUM II



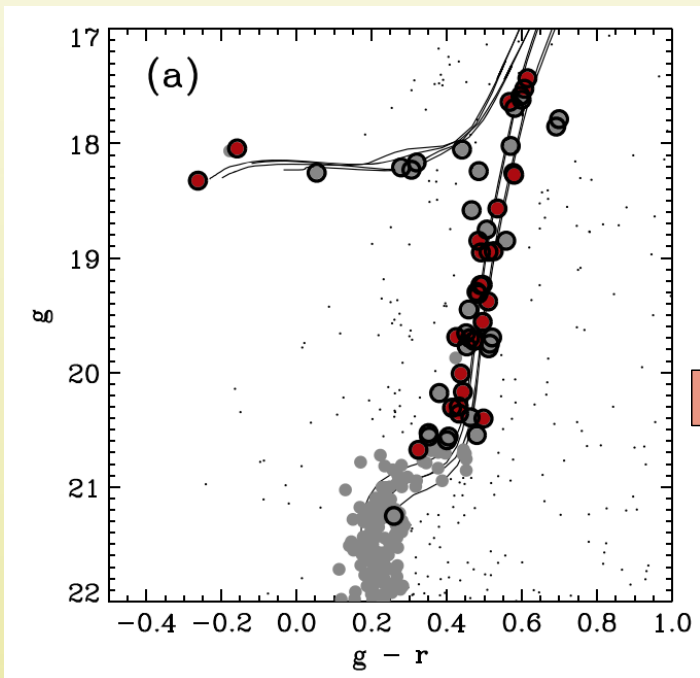
All stars

Reticulum II stars

(Dark Energy Survey, 2015)

MAGELLAN OBSERVATIONS

Simon et al. 2015: radial velocity members confirm Ret II to be a galaxy
Brightest members ($V=17-19$) observable with high-resolution spectroscopy
=> Ji et al. (2015) spent 2-3 hours on each of 9 brightest targets (~23h)



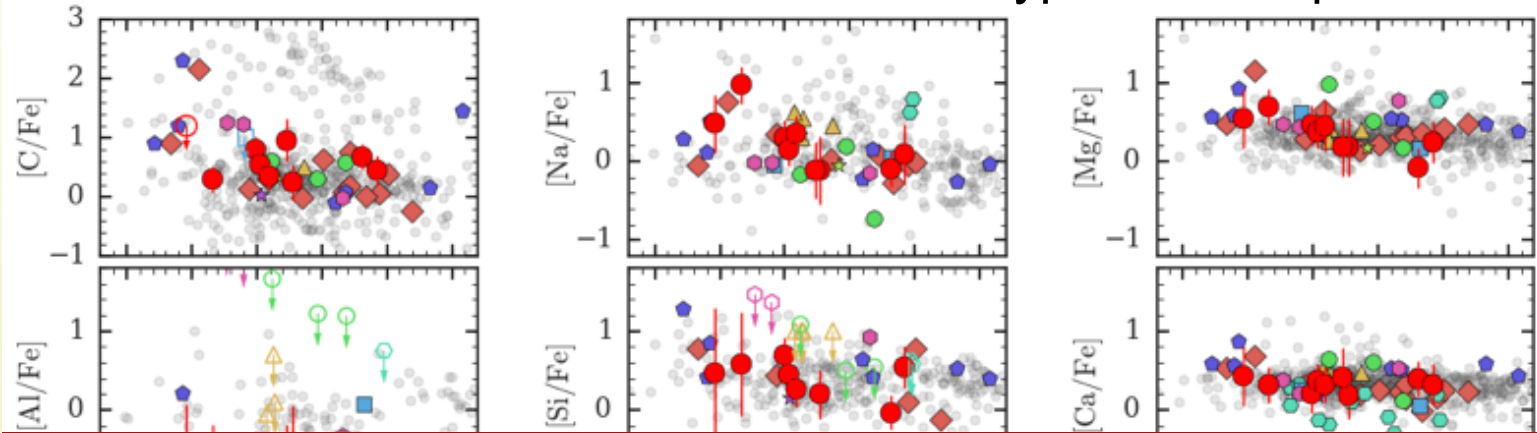
Color-magnitude-diagram of Ret II
(red = confirmed members)

Clay 6.5m Magellan telescope
(on left) at Las Campanas Observatory, Chile

LIGHT ELEMENT ABUNDANCES

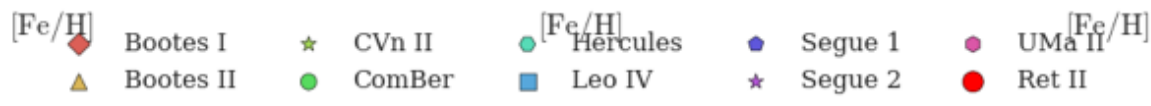
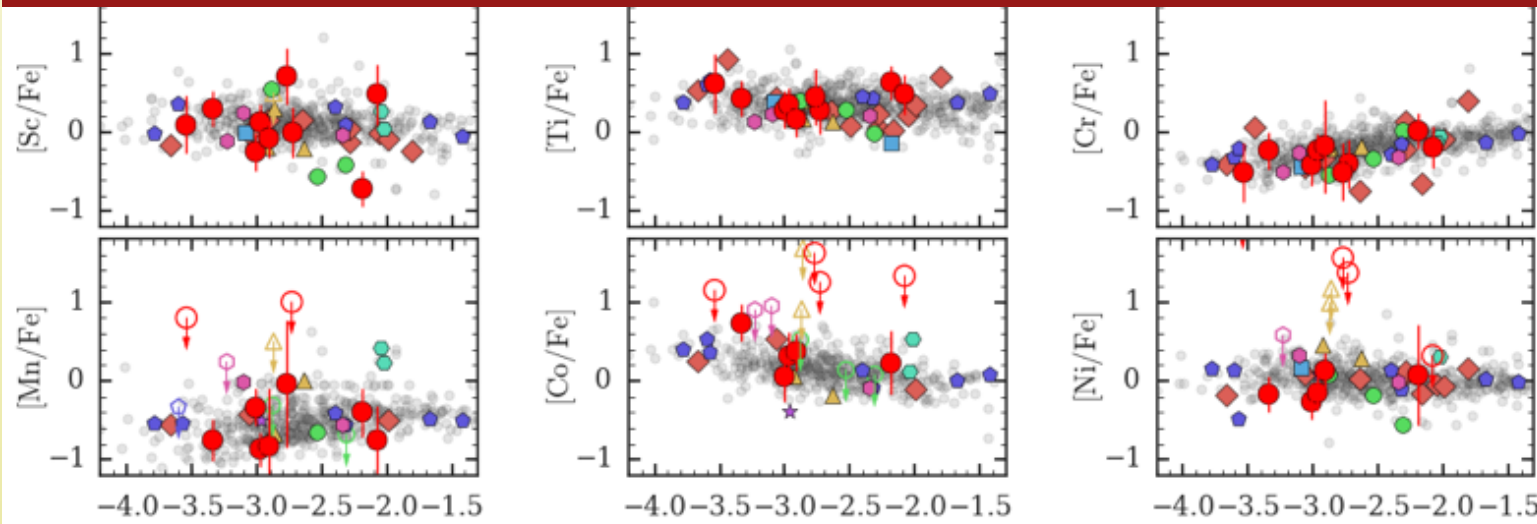
(C, NA, MG, AL, SI, CA, SC, TI, CR, MN, CO, NI)

Reticulum II stars have same abundances as typical metal-poor halo stars

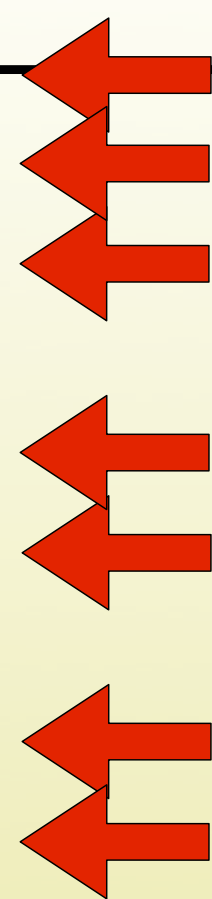
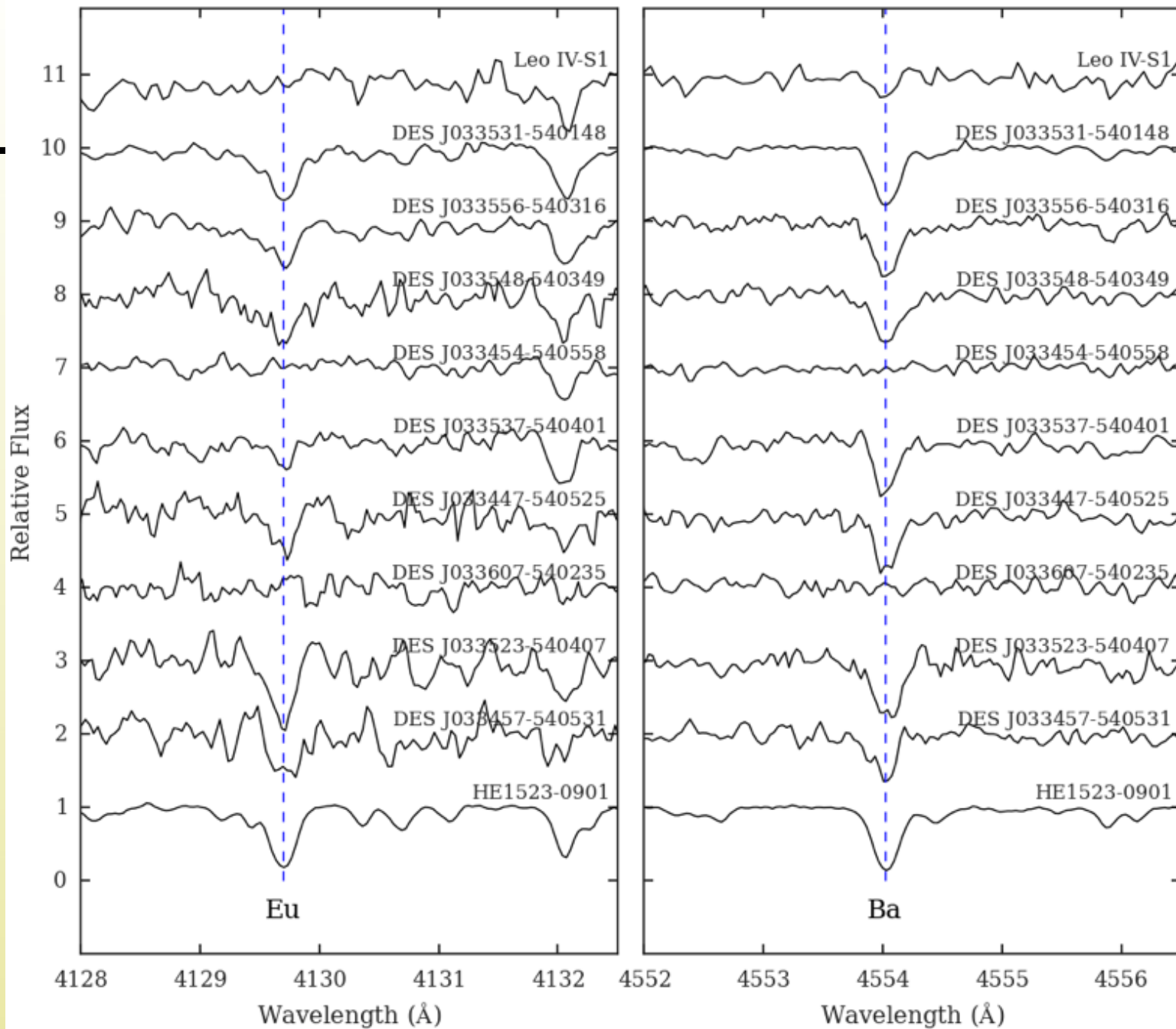


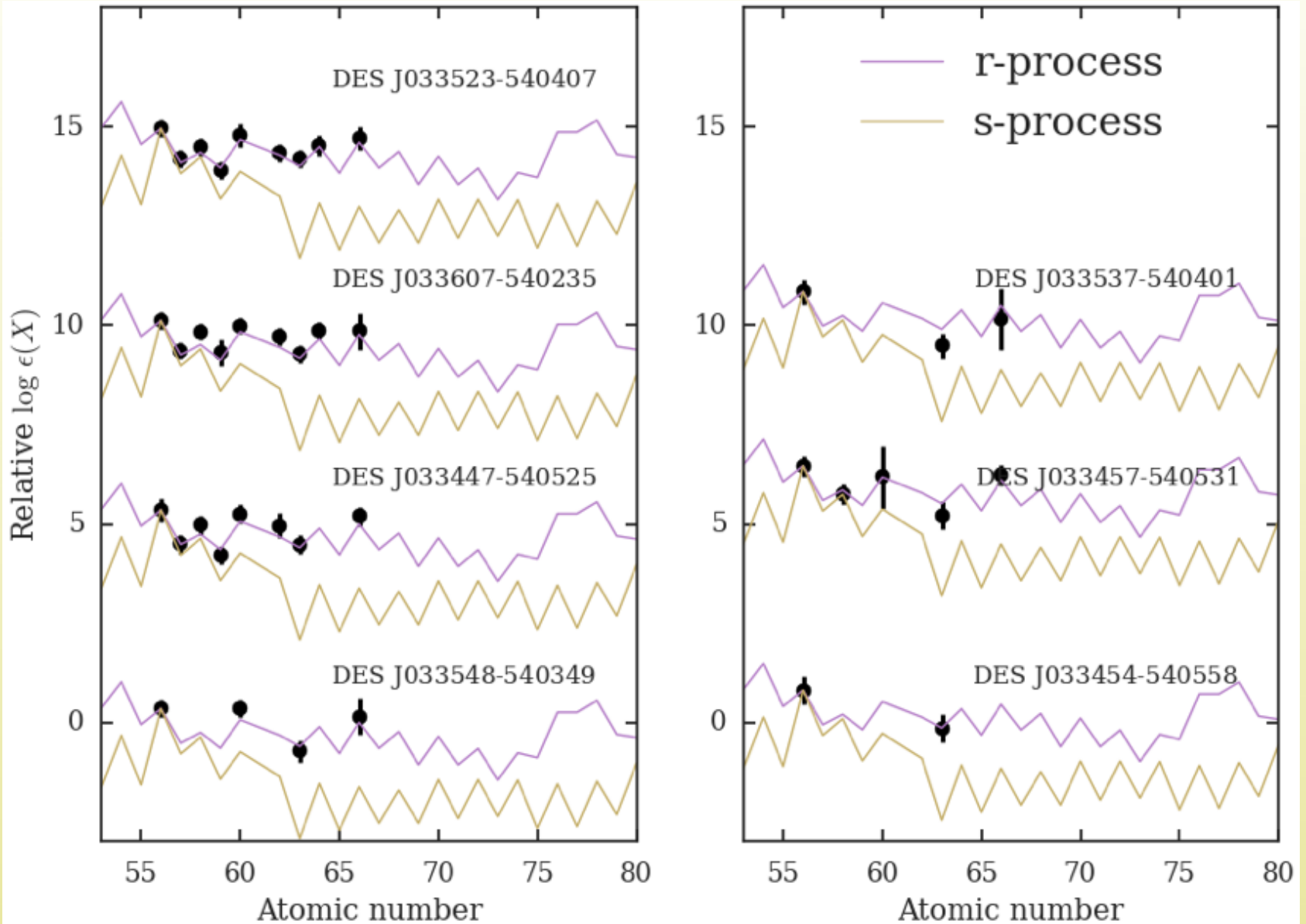
Core-collapse supernovae are primary light element source

Ji et al 2016, Nature, 531, 610

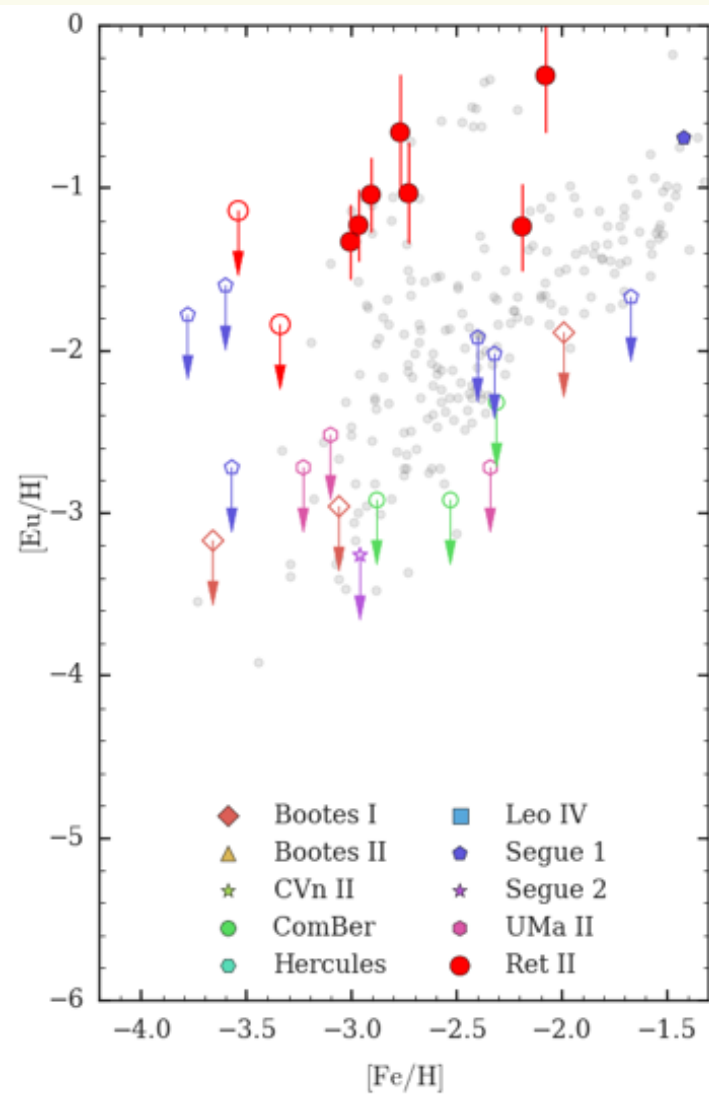
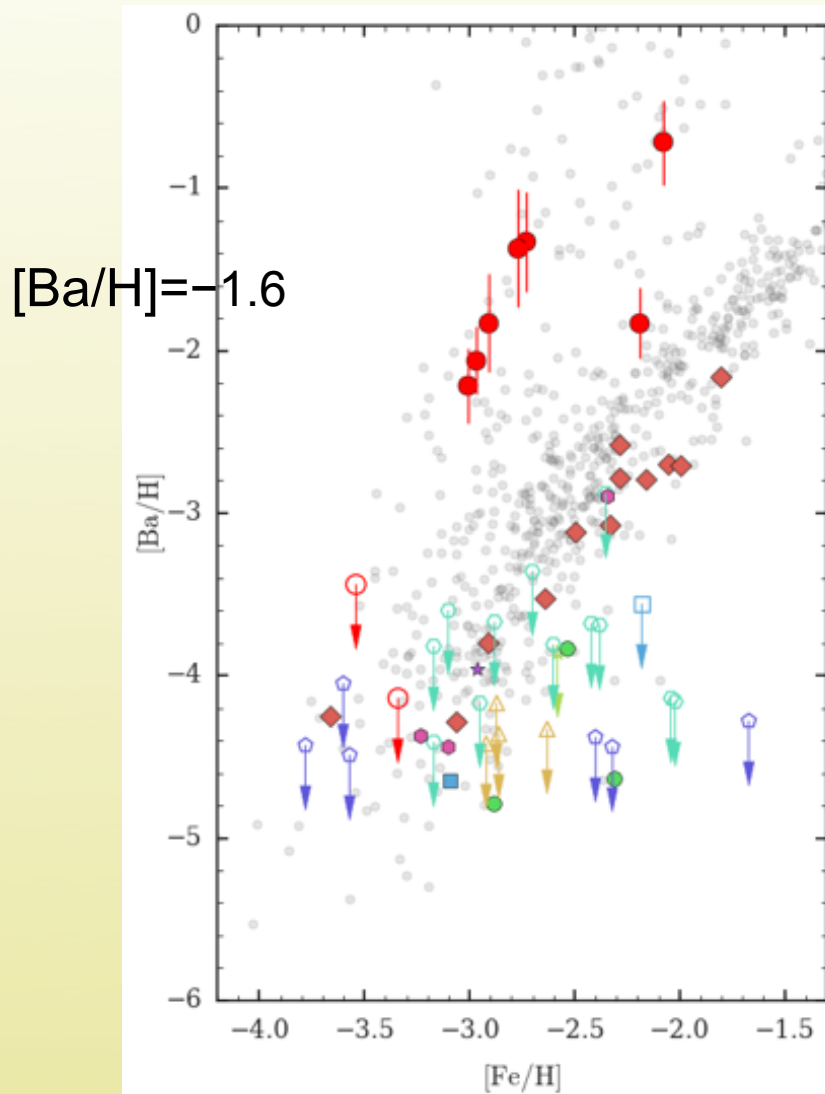


gray dots
metal-poor
halo
stars



ALL SEVEN RET II STARS DISPLAY
THE R-PROCESS PATTERNJi et al 2016, *Nature*, 531, 610

RET II STARS: > 100X HIGHER N-CAPTURE ELEMENT ABUNDANCES THAN OTHER UFDs



DWARF GALAXY ARCHAEOLOGY

(= USING AN ENTIRE DWARF GALAXY TO STUDY THE EARLY UNIVERSE)

How Rare?

Population of 10 UFDs:

➔ **1 of 10** r-process events

➔ Est. stellar mass of **all** UFDs:
~2000 SNe expected

➔ Consistent w/ expected NSM
rate of **1 per 1000-2000** SNe
(*LIGO will deliver answer in 2+ yrs*)

How Prolific?

Estimate gas mass of UFD:

Total gas in UFD galaxy

➔ Max. dilution mass: **$\sim 10^7 M_{\text{sun}}$**

Gas swept up by a 10^{51} erg
energy injection into typical ISM

➔ Min. dilution mass: **$\sim 10^5 M_{\text{sun}}$**

Back-of-the-envelope calculation

Mix NSM yield mass of $10^{-4.5} M_{\text{sun}}$ into $10^6 M_{\text{sun}}$ of H gas (can NOW be estimated!)

=> [Eu/H] = -1.2 is abundance of next-generation star

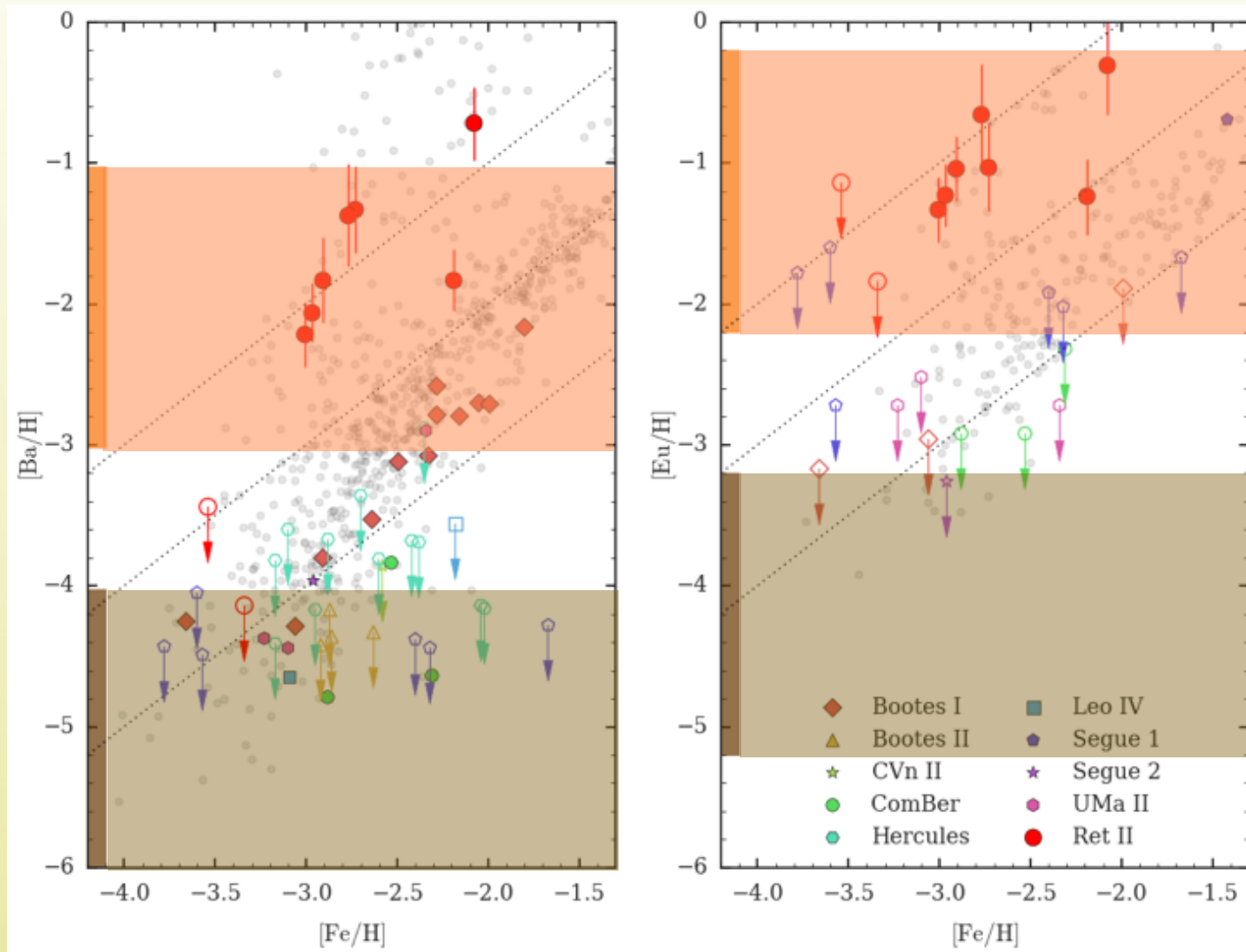
=> **Agrees with Ret II abundance results!**



RET II ABUNDANCES CONSISTENT W/ NEUTRON-STAR MERGER YIELD

Neutron
star merger

Supernova

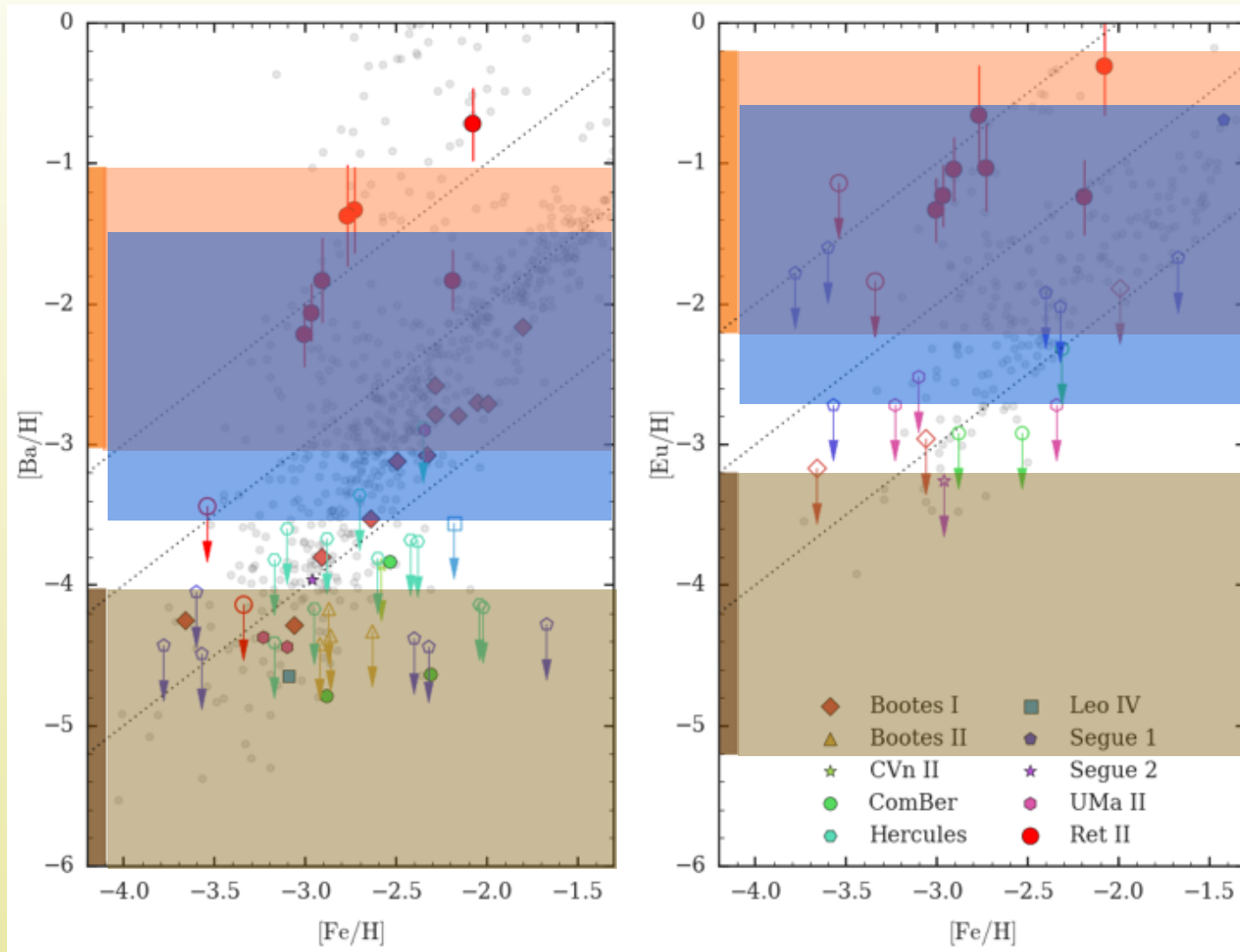


Ji et al 2016, *Nature*, 531, 610

RARE AND PROLIFIC JET-DRIVEN SUPERNOVA REMAINS POSSIBILITY

Neutron
star merger

Supernova



(e.g. Winteler et al. 2012)

Jet-driven
supernova

...but ordinary supernovae remain ruled out!

RETICULUM II WAS ENRICHED BY A RARE, PROLIFIC AND DELAYED R-PROCESS EVENT

A typical core-collapse supernova could not be responsible for the Ret II r-process signature!

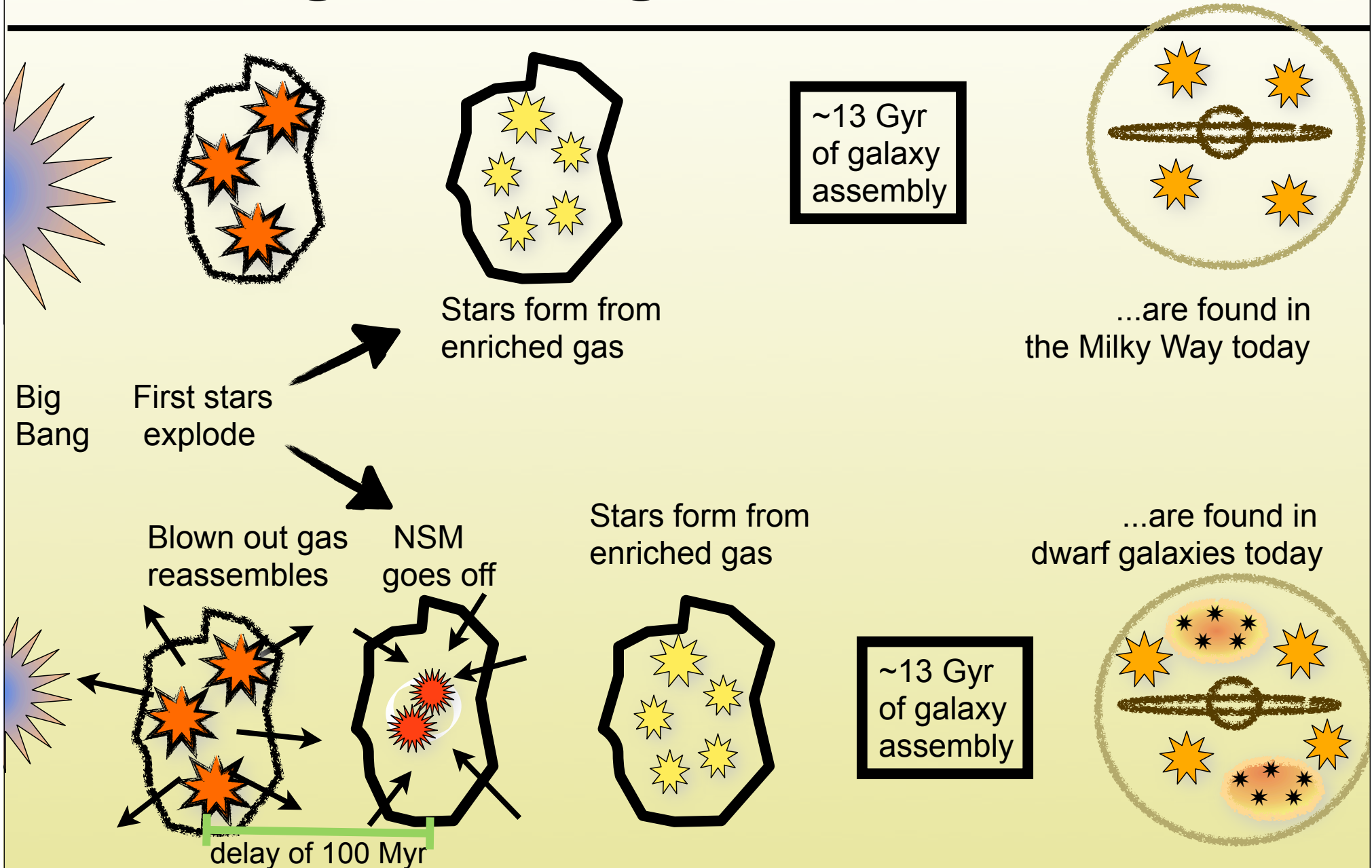
Can't you increase the # of supernovae to get higher yield?

- ➡ No, 1000+ supernovae would disrupt the system
- ➡ Need to be just one/few massive events

Aren't NSM taking too long to enrich the galaxy?

- ➡ After the few (initial) supernovae, it takes time for the system to reassemble again (~100 Myr)
- ➡ Minimum time scales for coalescence is ~100 Myr

ENRICHMENT AND STAR FORMATION TIMELINE



ANSWERS TO THE BIG QUESTION

★ What is the (dominant) astrophysical site of the r-process?

- ➔ Core-collapse supernovae → No, but a rare and prolific site
- ➔ Neutron star mergers → Consistent w/ Ret II abundances
- ➔ Others (e.g., jet-driven supernovae) → Remain possible

★ What is the rate and yield of the event?

→ ~1 event per 2000 SN; $\sim 10^{-2.5} M_{\text{sun}}$ of r-process

★ Is the dominant site changing over cosmic time?

→ Probably not!

COMMON NOMENCLATURE (FOCUSSED ON PHYSICS PROCESS)

Enables astronomers to identify nuclear physics processes among stellar observational data!

Table 2 Nucleosynthesis processes that can contribute to neutron-capture element patterns observed in metal-poor stars

Name	Description	Elements produced	Y_e	Site(s)	References	Star(s)
Terminal QSE	insufficient n-rich α -, n-, p-capture and reverse extension from hot, dense state	Sr \rightarrow Ag	< 0.5	“standard” proto-NS wind in CCSN shock-heated/disk ejecta	TBD	? light el. of rI/rII stars?
ν p-process	p-rich, $\bar{\nu}_e$ -rich QSE + $\bar{\nu}_e$ -capture	Sr \rightarrow Ag \rightarrow Mo	> 0.5	“standard” proto-NS wind in CCSN shock-heated/disk ejecta		? light el. of rI/rII stars?
Limited ^a r-process	n/s \sim 100 QSE + (limited) n-capture no fission cycling	Sr \rightarrow Ba (limited production towards Ba)	< 0.5	modified proto-NS wind(?) NSM disk (after merger) ^b shock-heated ejecta (during merger) ^c		HD122563 ? light el. of rI/ rII stars?
Main r-process	n/s \gg 100; QSE + n-capture any fission cycling	Ba \rightarrow U	< 0.2	NSM tidal ejecta (during interaction) dynamical ejecta during merger		r/II stars
Robust (main) r-process	n/s \gg 100; QSE + n-capture fission cycling limit	Ba \rightarrow U	< 0.2	NSM tidal ejecta (during interaction) dynamical ejecta during merger		r/II stars

^a Sometimes referred to as weak r-process of Light Element Primary Process (LEPP); “Weak”, however, does not well describe the nature of the actual r-process physics, and “LEPP” does not refer to a specific nuclear physics process.

^b On “viscous”/wind timescales.

^c On dynamical timescales.

ANYTHING ELSE TO LEARN?

A puzzle: Chemical Enrichment in Ret II

Need to explain: 7+1 r-process-rich, 2 n-capture poor stars

- ➔ Sequential bursts of star formation?
n-cap poor stars have lower $[Fe/H]$
- ➔ Inhomogeneous metal mixing?
Seems unlikely given homogeneity of light elements
- ➔ Accretion of other, smaller galaxy?
No more than 1 accreted galaxy possible (Griffen et al. 2016, subm.)

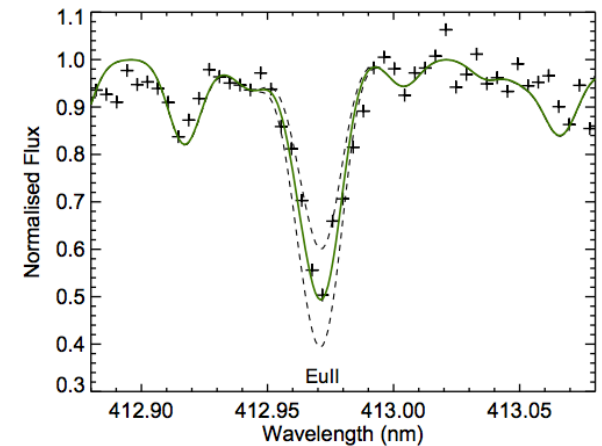
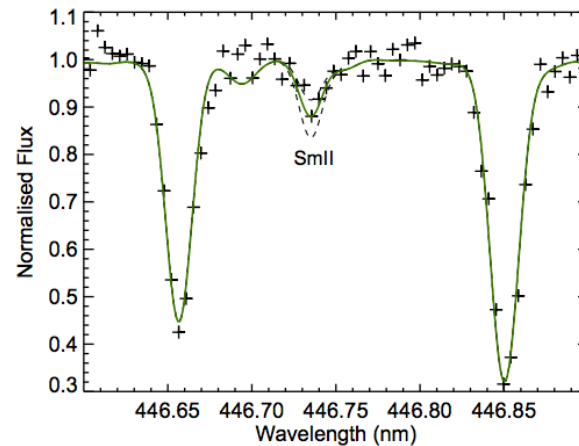
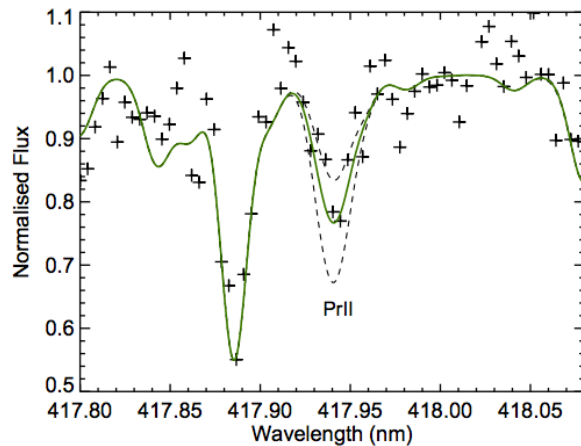
Ideal system to model given all these obs constraints!

IS RETICULUM II THE ONLY R-PROCESS GALAXY?

Nope!

Feb 2017: newly discovered UFD Tucana III hosts at least 1 mildly r-process enriched star with $[\text{Fe}/\text{H}] = -2.25$!

=> 2/12 UFDs show strong r-process enrichment





Abdu
Abohalima

JINABASE

A NEW DATABASE OF METAL-POOR STARS

The Joint Institute for Nuclear Astrophysics
EMP Database



Home

Query/Plot

Search

References

Contact

Query data from database!

Data for axes

x-axis / From To

y-axis / From To

Solar abundance for normalization

User defined criteria

Filters

Location of stars

- Select/Deselect All
- MW Halo
- Bulge
- Classical Dwarfs
- Ultra-faint Dwarfs

Stellar phase

- Select/Deselect All
- Giants
- Subgiants
- Dwarfs
- Horizontal branch

Specific element signatures

- Select/Deselect All
- no signatures
- r-I rich
- r-II rich
- s-rich
- r/s stars
- CEMP
- CEMP-no

References

Select by Author and year: First Author/s Year range: From To

- Select/Deselect All
- Afsar et al. (2016)
- Allen et al. (2012)
- Andrievsky et al. (2009)
- Andrievsky et al. (2010)
- Aoki et al. (2001)
- Aoki et al. (2002a)

- Cohen & Huang(2009)
- Cohen et al. (2013)
- Collet et al. (2006)
- Cowan et al. (2002)
- Cui et al. (2013)
- Feltzing et al. (2009)
- Francois (2016)

- Ji et al. (2016a)
- Ji et al. (2016b)
- Johnson & Bolte(2002a)
- Johnson & Bolte(2002b)
- Johnson & Bolte (2004)
- Jonsell et al. (2005)
- Jonsell et al. (2006)

- Ren et al. (2012)
- Rich et al. (2009)
- Roederer et al. (2008)
- Roederer et al. (2009)
- Roederer et al. (2010)
- Roederer et al. (2012a)
- Roederer et al. (2012b)

Customize output table

- Select/Deselect All
- ID
- Priority key
- Reference
- Star name

- Science key
- CEMP key
- Location
- Stellar type
- RA

- Radial velocity
- RV bibcode
- U mag
- B mag
- V mag

- I mag
- J mag
- H mag
- K mag
- Teff

- Z
- Vmic
- Upper limits key

Customize plot

- Plot/Show duplicate stars
- Plot upper limits
- Show legend for plot

Plot

Show data table

THE FUTURE IS HERE

The first glimpse of the incredible potential of UFDs for early universe studies

From nuclear astrophysics to near-field cosmology

✓ Clean nucleosynthesis event(s) w/ actual information on the site and environment

➔ Unprecedented astrophysics constraints for nuclear physics, early chemical evolution, first galaxy formation, metal mixing processes, galaxy assembly, etc.

✓ New dwarf galaxies are still being discovered (e.g. in Dark Energy Survey)

➔ New observable target stars; firm up fraction of r-process ultra-faint dwarf galaxies

✓ Only stars w/ $V \leq 19$ mag can be observed w/ current telescopes (= only few stars per galaxy!)

➔ New telescopes are needed with high-resolution spectrographs, i.e. GCLEF on GMT



25m Giant Magellan Telescope (GMT), from 2020