

Ji et al. 2016, Nature

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

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

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

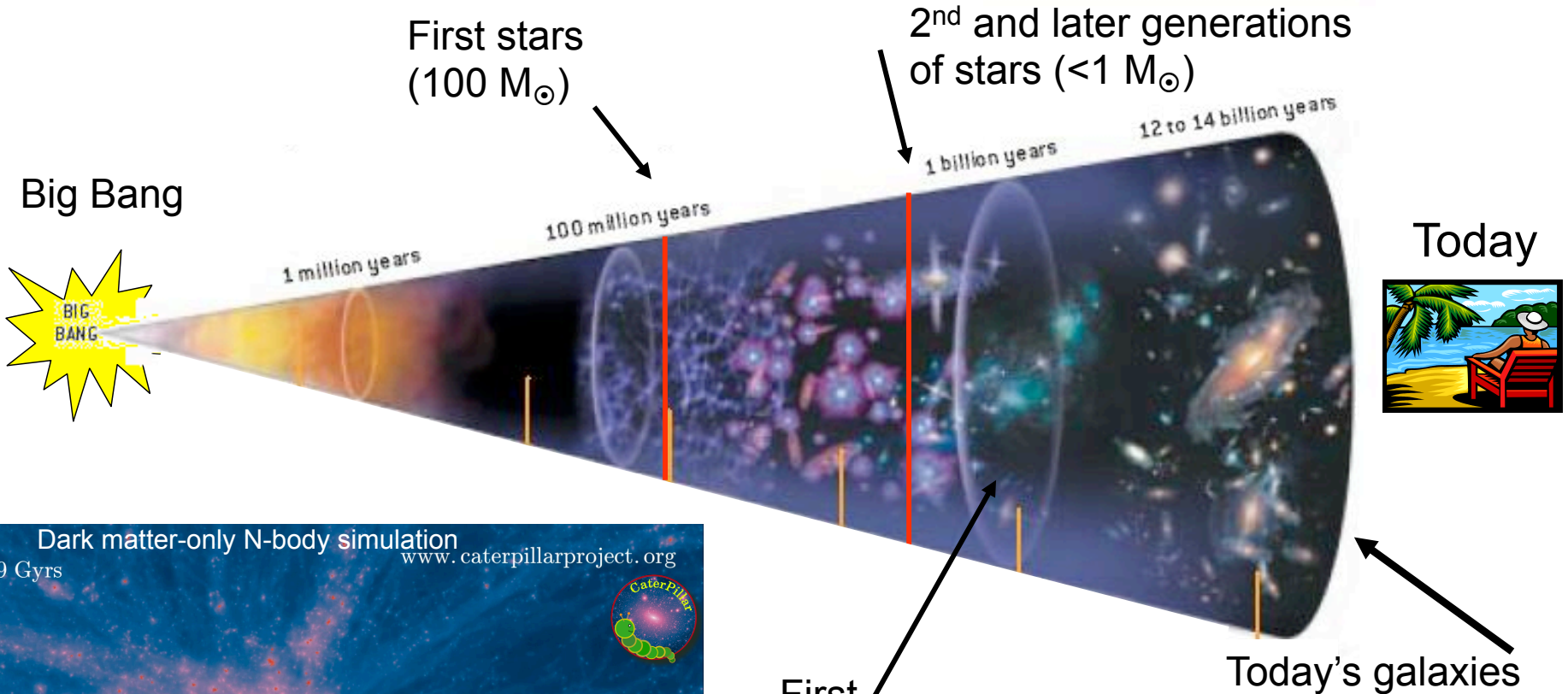
57 <b>La</b> Lanthanum 138.905	58 <b>Ce</b> Cerium 140.116	59 <b>Pr</b> Praseodymium 140.908	60 <b>Nd</b> Neodymium 144.243	61 <b>Pm</b> Promethium 144.913	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.964	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.925	66 <b>Dy</b> Dysprosium 162.500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

Anna Frebel

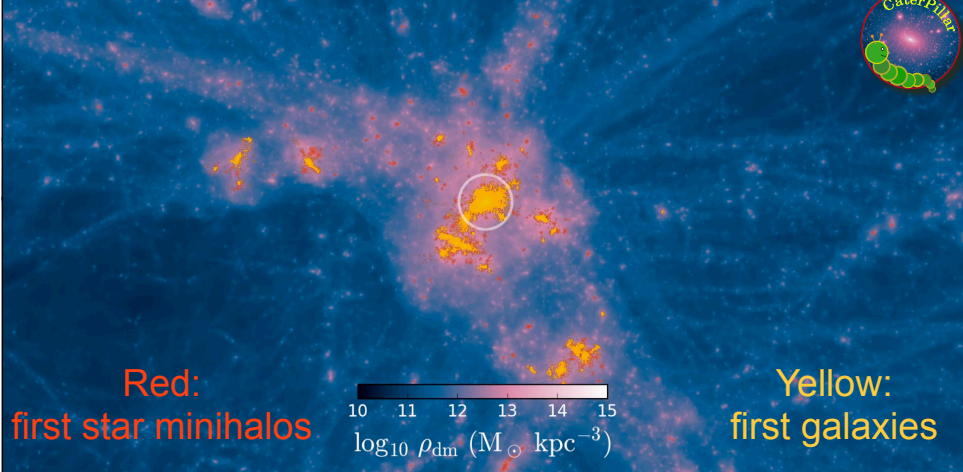




# A LONG TIME AGO...



$z = 4.155$  Dark matter-only N-body simulation  
 $t = 12.359$  Gyrs [www.caterpillarproject.org](http://www.caterpillarproject.org)



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

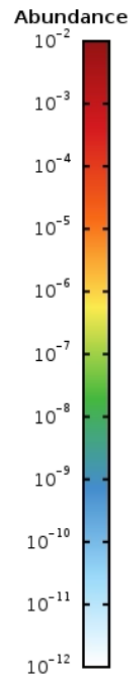


## Dwarf Galaxy Archaeology

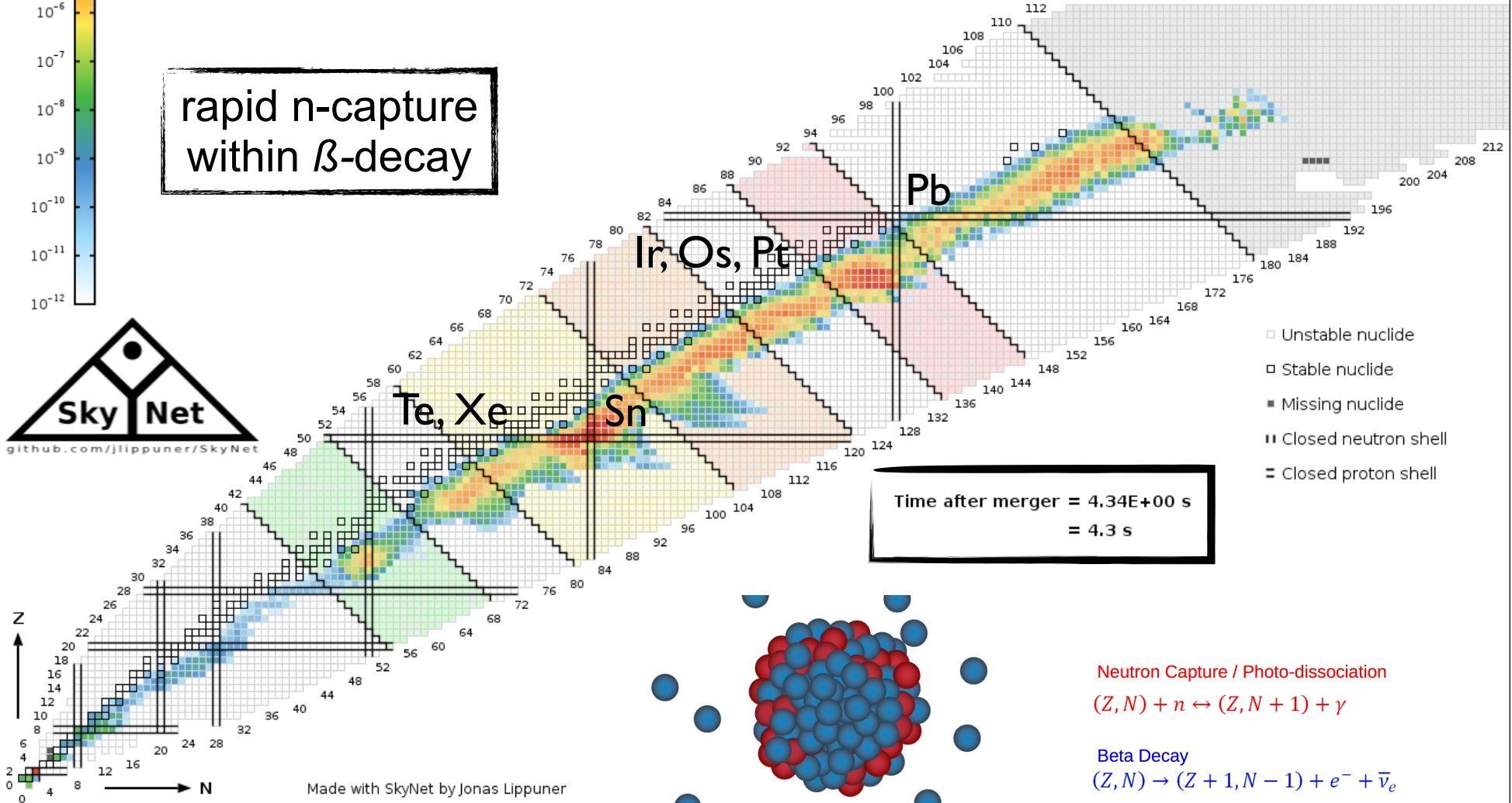
Ancient, clean  
chemical  
enrichment  
signatures

# RAPID NEUTRON-CAPTURE-NUCLEOSYNTHESIS

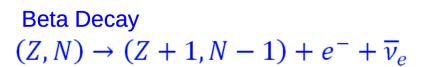
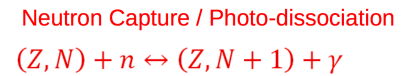
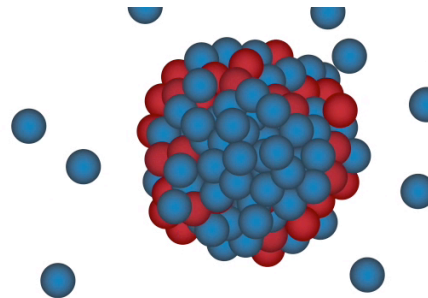
## (neutron star merger scenario)



rapid n-capture  
within  $\beta$ -decay



Made with SkyNet by Jonas Lippuner

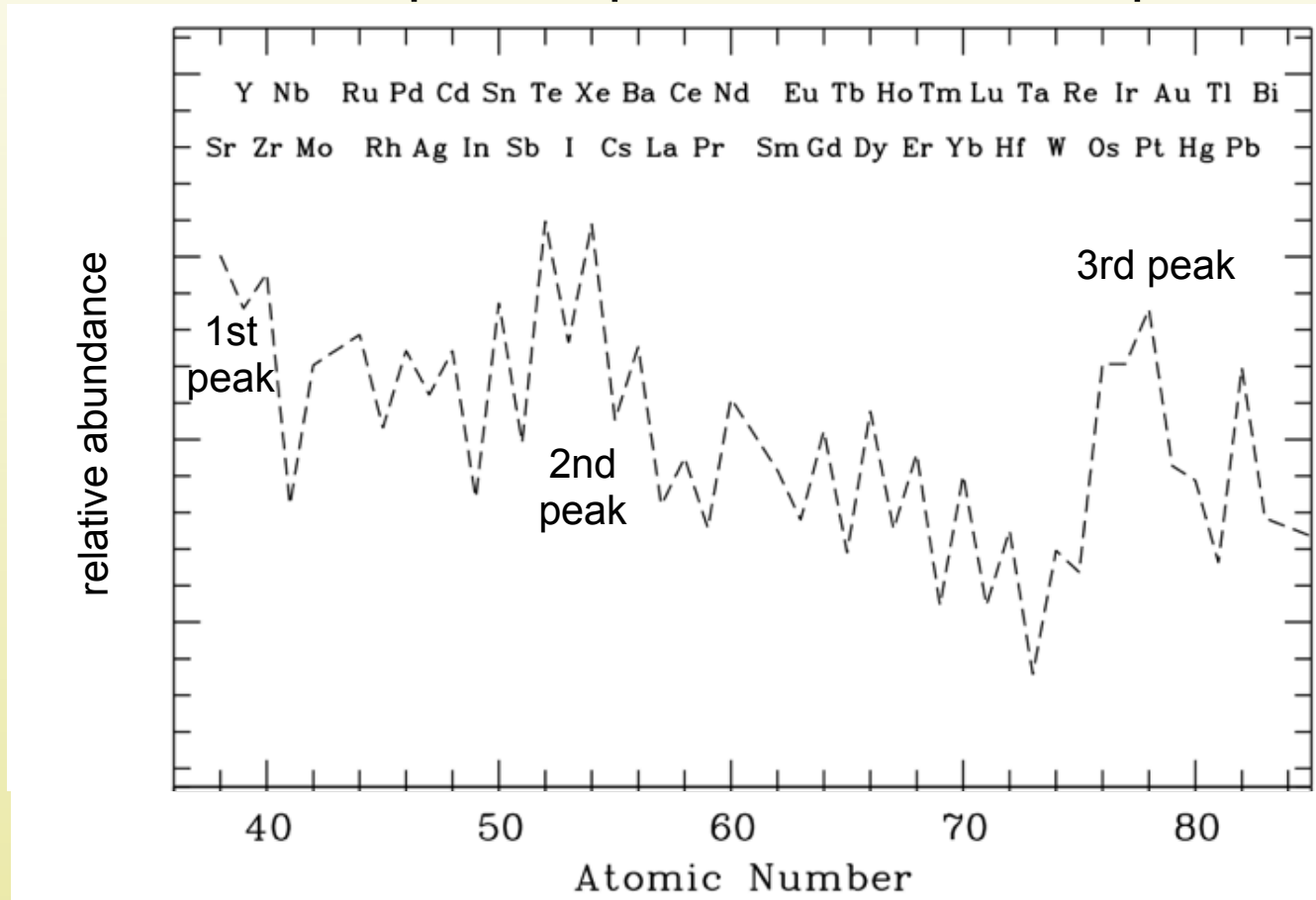


decay of unstable nuclides (to  $\beta$ -stable nuclides)  
to stability



# R-PROCESS PATTERN

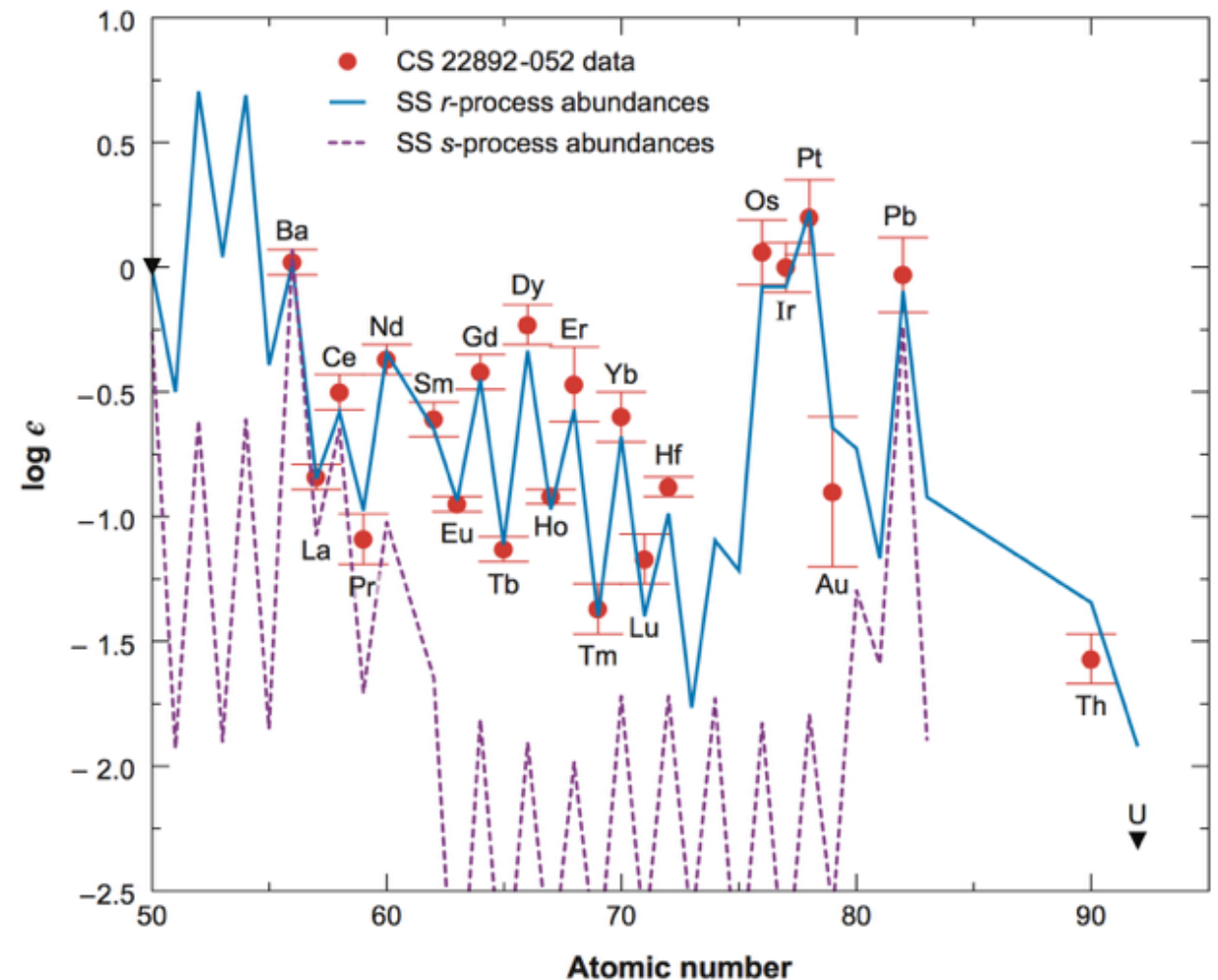
neutron-capture r-process elemental pattern



# 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:  
[Fe/H]  $\sim$  -3.0  
(= 1/1000th of solar  
Fe value)



Sneden 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

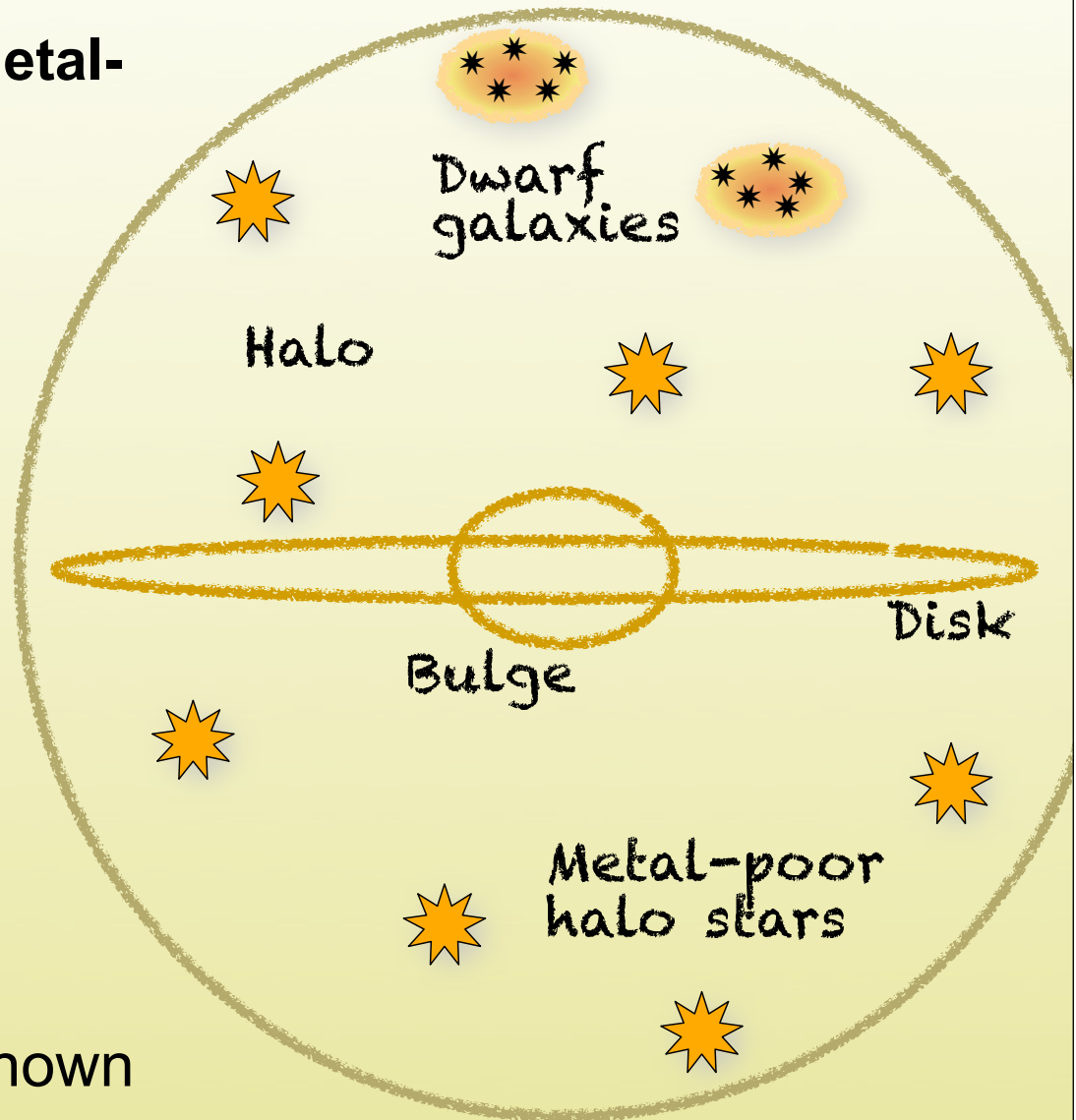
How common are r-process metal-poor stars in the Milky Way?

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

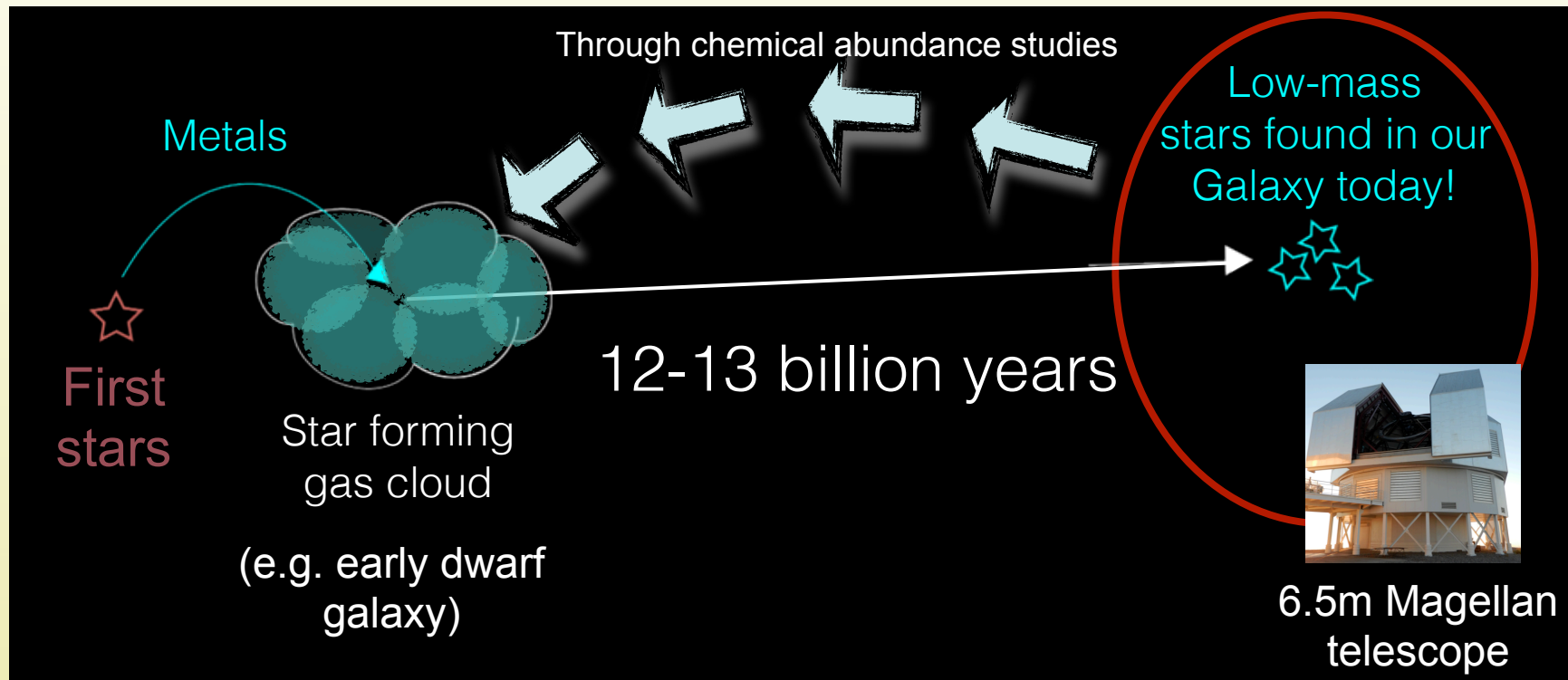
=> Origin of these stars is unknown



# 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  $\sim 1$  progenitor star produced that iron  
(= 1/1000th of solar Fe)  $\Rightarrow$  only  $\sim 1$  nucleosynthesis event made heavier elements



# THE (DETAILED) ASTRONOMER'S PERIODIC TABLE

**Big Bang nucleosynthesis**

**Spallation**

Evolved giant stars

**Odd-Z elements**

**$\alpha$ -elements**

**Iron group elements**

$\alpha$ -rich freezeout,  $\nu$ p-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 <b>H</b> 1.008																2 <b>He</b> 4.003					
2	3 <b>Li</b> 6.939	4 <b>Be</b> 9.012															5 <b>B</b> 10.811	6 <b>C</b> 12.011	7 <b>N</b> 14.007	8 <b>O</b> 15.999	9 <b>F</b> 18.998	10 <b>Ne</b> 20.183
3	11 <b>Na</b> 22.990	12 <b>Mg</b> 24.312															13 <b>Al</b> 26.982	14 <b>Si</b> 28.086	15 <b>P</b> 30.974	16 <b>S</b> 32.064	17 <b>Cl</b> 35.453	18 <b>Ar</b> 39.948
4	19 <b>K</b> 39.102	20 <b>Ca</b> 40.08	21 <b>Sc</b> 44.956	22 <b>Ti</b> 47.88	23 <b>V</b> 50.942	24 <b>Cr</b> 51.996	25 <b>Mn</b> 54.938	26 <b>Fe</b> 55.847	27 <b>Co</b> 58.933	28 <b>Ni</b> 58.69	29 <b>Cu</b> 63.54	30 <b>Zn</b> 65.37	31 <b>Ga</b> 69.72	32 <b>Ge</b> 72.59	33 <b>As</b> 74.922	34 <b>Se</b> 78.96	35 <b>Br</b> 79.909	36 <b>Kr</b> 83.80				
5	37 <b>Rb</b> 85.47	38 <b>Sr</b> 87.62	39 <b>Y</b> 88.905	40 <b>Zr</b> 91.22	41 <b>Nb</b> 92.906	42 <b>Mo</b> 95.94	43 <b>Tc</b> (99)	44 <b>Ru</b> 101.07	45 <b>Rh</b> 102.91	46 <b>Pd</b> 106.42	47 <b>Ag</b> 107.87	48 <b>Cd</b> 112.40	49 <b>In</b> 114.82	50 <b>Sn</b> 118.69	51 <b>Sb</b> 121.75	52 <b>Te</b> 127.60	53 <b>I</b> 126.90	54 <b>Xe</b> 131.30				
6	55 <b>Cs</b> 132.91	56 <b>Ba</b> 137.34	57 <b>La</b> 138.91	72 <b>Hf</b> 178.49	73 <b>Ta</b> 180.95	74 <b>W</b> 183.85	75 <b>Re</b> 186.2	76 <b>Os</b> 190.2	77 <b>Ir</b> 192.2	78 <b>Pt</b> 195.09	79 <b>Au</b> 196.97	80 <b>Hg</b> 200.59	81 <b>Tl</b> 204.38	82 <b>Pb</b> 208.17	83 <b>Bi</b> 208.98	84 <b>Po</b> (210)	85 <b>At</b> (210)	86 <b>Rn</b> (222)				
7	87 <b>Fr</b> (223)	88 <b>Ra</b> (226)	89 <b>Ac</b> (227)																			
„6“				58 <b>Ce</b> 140.12	59 <b>Pr</b> 140.91	60 <b>Nd</b> 144.24	61 <b>Pm</b> (145)	62 <b>Sm</b> 150.36	63 <b>Eu</b> 151.96	64 <b>Gd</b> 157.25	65 <b>Tb</b> 158.92	66 <b>Dy</b> 162.50	67 <b>Ho</b> 164.93	68 <b>Er</b> 167.26	69 <b>Tm</b> 168.93	70 <b>Yb</b> 173.04	71 <b>Lu</b> 174.97					
„7“				90 <b>Th</b> 232.04	91 <b>Pa</b> (231)	92 <b>U</b> 238.03	93 <b>Np</b> (237)	94 <b>Pu</b> (242)	95 <b>Am</b> (243)	96 <b>Cm</b> (247)	97 <b>Bk</b> (249)	98 <b>Cf</b> (251)	99 <b>Es</b> (254)	100 <b>Fm</b> (253)	101 <b>Md</b> (256)	102 <b>No</b> (253)	103 <b>Lr</b> (257)					

Isotope distribution of solar nebula (~8 billion yrs of chemical evolution)

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Big Bang nucleosynthesis  $\alpha$ -rich freezeout,  $\nu$ p-proc., weak s-proc.

Spallation

r-process

Evolved giant stars

Odd-Z elements

$\alpha$ -elements

Iron group elements

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19 <b>K</b> Potassium 39.098	20 <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.956	22 <b>Ti</b> Titanium 47.867	23 <b>V</b> Vanadium 50.942	24 <b>Cr</b> Chromium 51.996	25 <b>Mn</b> Manganese 54.938	26 <b>Fe</b> Iron 55.845	27 <b>Co</b> Cobalt 58.933	28 <b>Ni</b> Nickel 58.693	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.38	31 <b>Ga</b> Gallium 69.723	32 <b>Ge</b> Germanium 72.631	33 <b>As</b> Arsenic 74.922	34 <b>Se</b> Selenium 78.971	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 84.798
37 <b>Rb</b> Rubidium 84.468	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.906	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.906	42 <b>Mo</b> Molybdenum 95.95	43 <b>Tc</b> Technetium 98.907	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.906	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.868	48 <b>Cd</b> Cadmium 112.414	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.711	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.6	53 <b>I</b> Iodine 126.904	54 <b>Xe</b> Xenon 131.294
55 <b>Cs</b> Cesium 132.905	56 <b>Ba</b> Barium 137.328	57-71 <b>La</b> Lanthanum 138.905	72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.948	74 <b>W</b> Tungsten 183.84	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> Osmium 190.23	77 <b>Ir</b> Iridium 192.217	78 <b>Pt</b> Platinum 195.085	79 <b>Au</b> Gold 196.967	80 <b>Hg</b> Mercury 200.592	81 <b>Tl</b> Thallium 204.383	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.980	84 <b>Po</b> Polonium [208.982]	85 <b>At</b> Astatine 209.987	86 <b>Rn</b> Radon 222.018
87 <b>Fr</b> Francium 223.020	88 <b>Ra</b> Radium 226.025	89-103 <b>Ac</b> Actinium 227.028	104 <b>Rf</b> Rutherfordium [261]	105 <b>Db</b> Dubnium [262]	106 <b>Sg</b> Seaborgium [266]	107 <b>Bh</b> Bohrium [264]	108 <b>Hs</b> Hassium [269]	109 <b>Mt</b> Meitnerium [268]	110 <b>Ds</b> Darmstadtium [269]	111 <b>Rg</b> Roentgenium [272]	112 <b>Cn</b> Copernicium [277]	113 <b>Uut</b> Ununtrium unknown	114 <b>Fl</b> Flerovium [289]	115 <b>Uup</b> Ununpentium unknown	116 <b>Lv</b> Livermorium [298]	117 <b>Uus</b> Ununseptium unknown	118 <b>Uuo</b> Ununoctium unknown
			57 <b>La</b> Lanthanum 138.905	58 <b>Ce</b> Cerium 140.116	59 <b>Pr</b> Praseodymium 140.908	60 <b>Nd</b> Neodymium 144.243	61 <b>Pm</b> Promethium 144.913	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.964	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.925	66 <b>Dy</b> Dysprosium 162.500	67 <b>Ho</b> Holmium 164.930	68 <b>Er</b> Erbium 167.259	69 <b>Tm</b> Thulium 168.934	70 <b>Yb</b> Ytterbium 173.055	71 <b>Lu</b> Lutetium 174.967
			89 <b>Ac</b> Actinium 227.028	90 <b>Th</b> Thorium 232.038	91 <b>Pa</b> Protactinium 231.036	92 <b>U</b> Uranium 238.029	93 <b>Np</b> Neptunium 237.048	94 <b>Pu</b> Plutonium 244.064	95 <b>Am</b> Americium 243.061	96 <b>Cm</b> Curium 247.070	97 <b>Bk</b> Berkelium 247.070	98 <b>Cf</b> Californium 251.080	99 <b>Es</b> Einsteinium [254]	100 <b>Fm</b> Fermium 257.095	101 <b>Md</b> Mendelevium 258.1	102 <b>No</b> Nobelium 259.101	103 <b>Lr</b> Lawrencium [262]

# THE BIG QUESTION

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

➡ Core-collapse supernovae

➡ Neutron star mergers

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

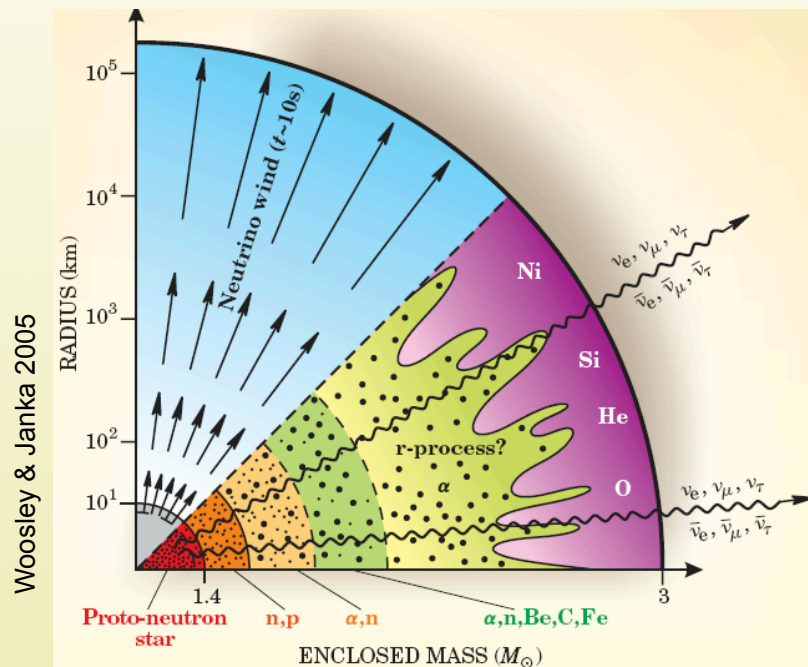
★ **What is the rate and yield of the event?**

★ **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)

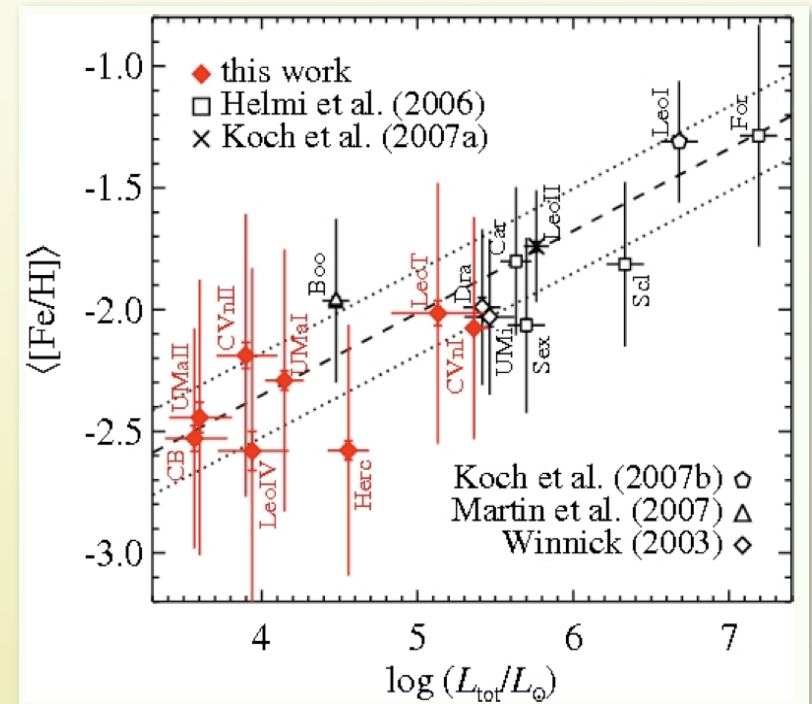
**=>  $\sim 10^{-4.5} M_{\text{sun}}$  of Eu (per event)**

### 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  $L_{\text{sun}}$ )
- Dark matter-dominated ( $M/L > 100$ )
- Metal-poor (mean  $[Fe/H] \sim -2$ )
- Stars are old (mean age  $13.3 \pm 1$  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

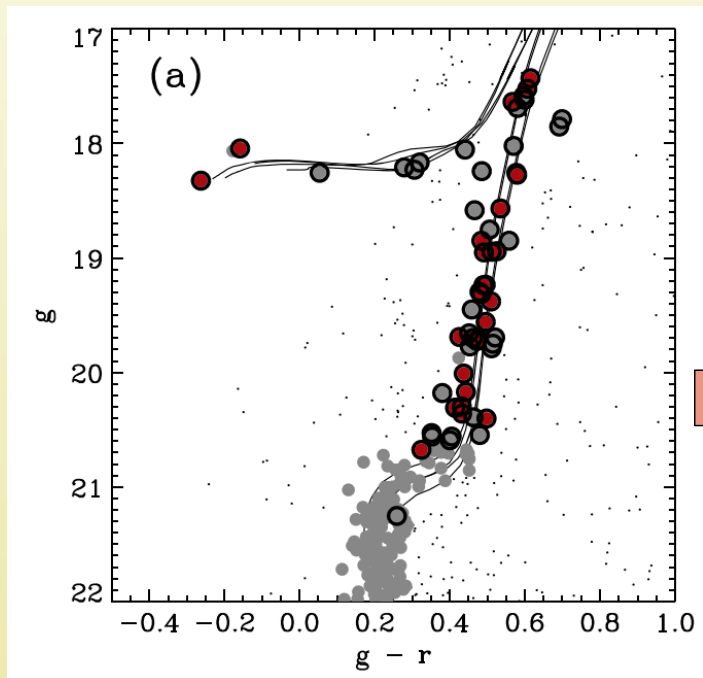
Reticulum II stars

(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 ( $\sim 23\text{h}$ )



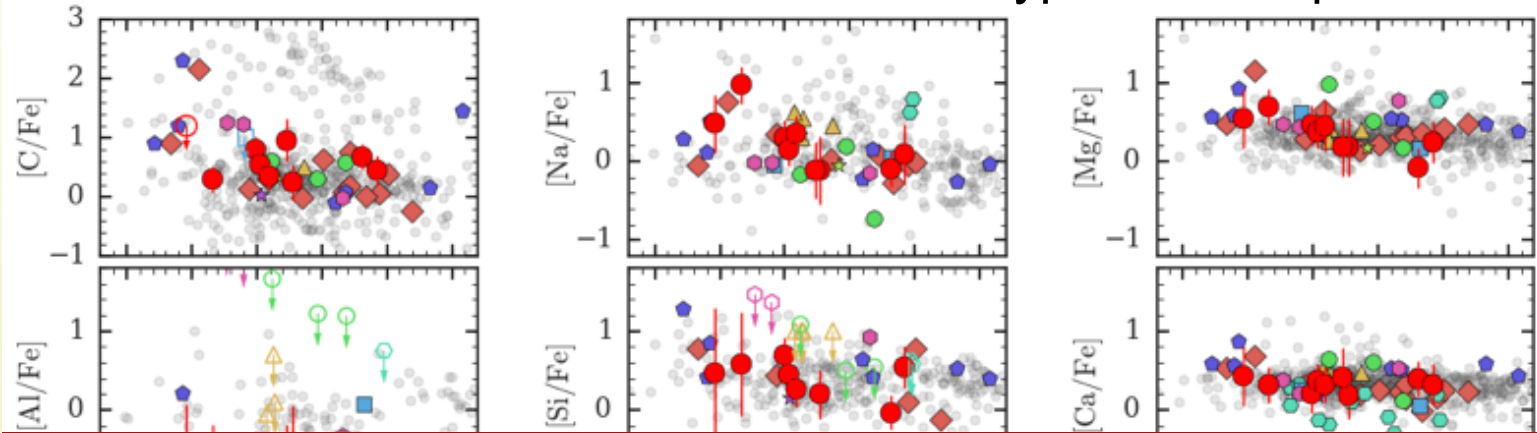
Color-magnitude-diagram of Ret II  
(red = confirmed members)

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

# LIGHT ELEMENT ABUNDANCES

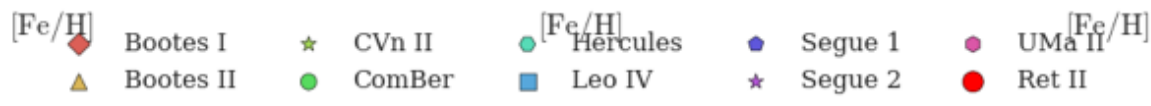
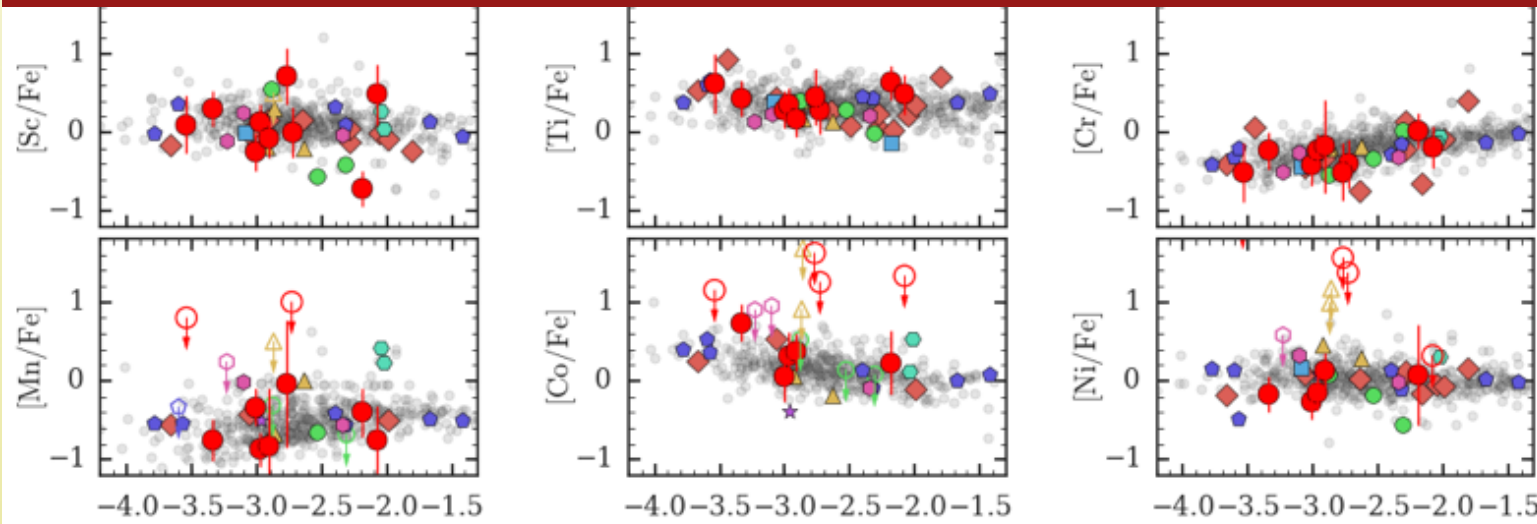
(C, NA, MG, AL, SI, CA, SC, TI, CR, MN, CO, NI)

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

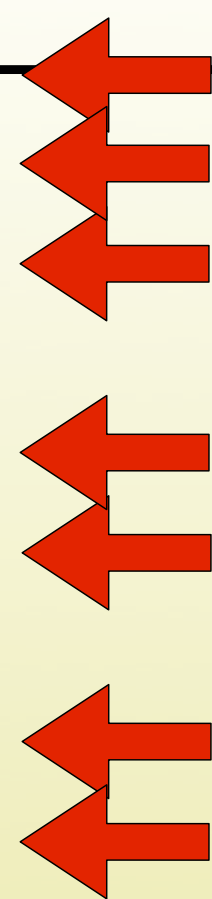
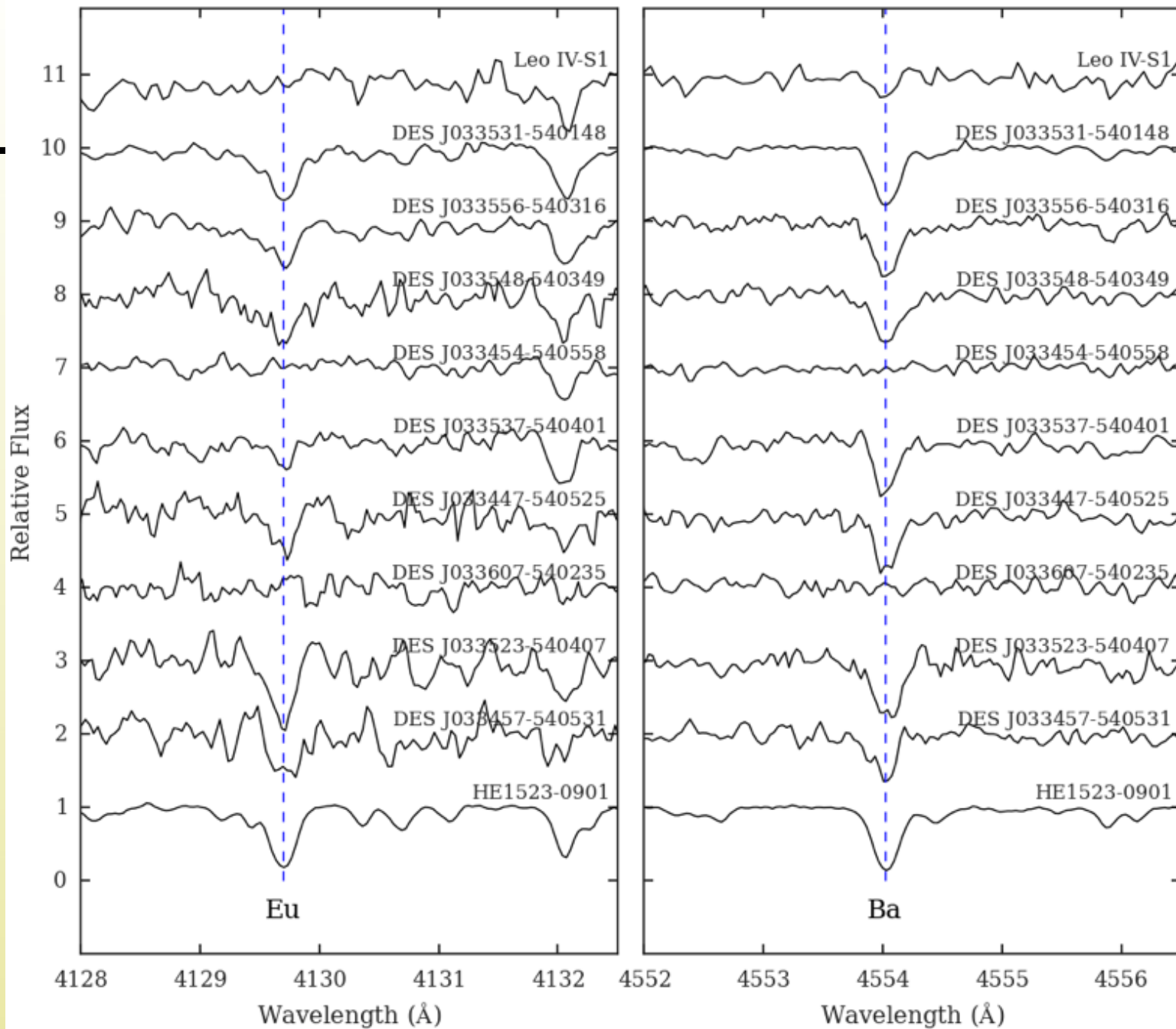


Core-collapse supernovae are primary light element source

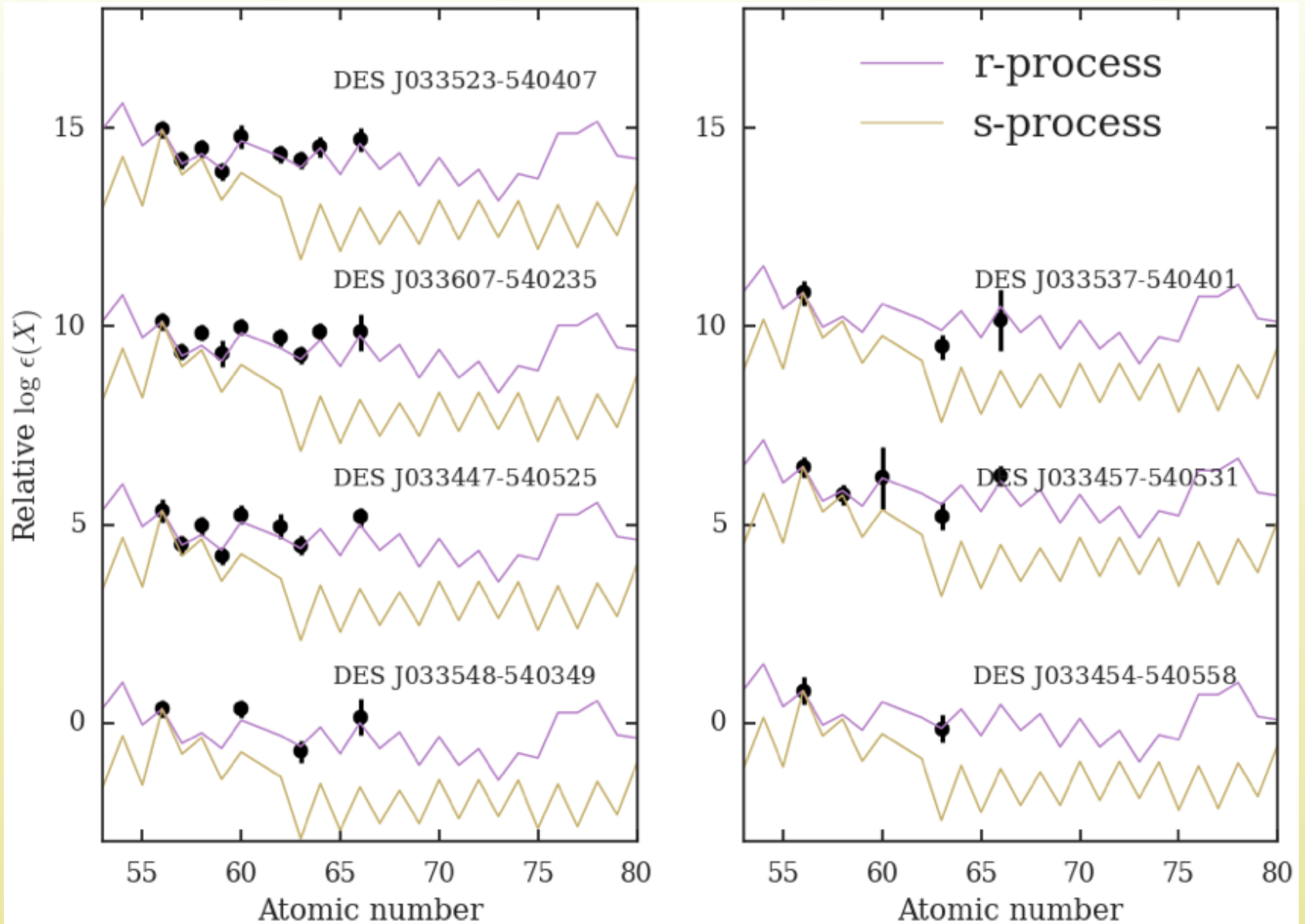
Ji et al 2016, Nature, 531, 610



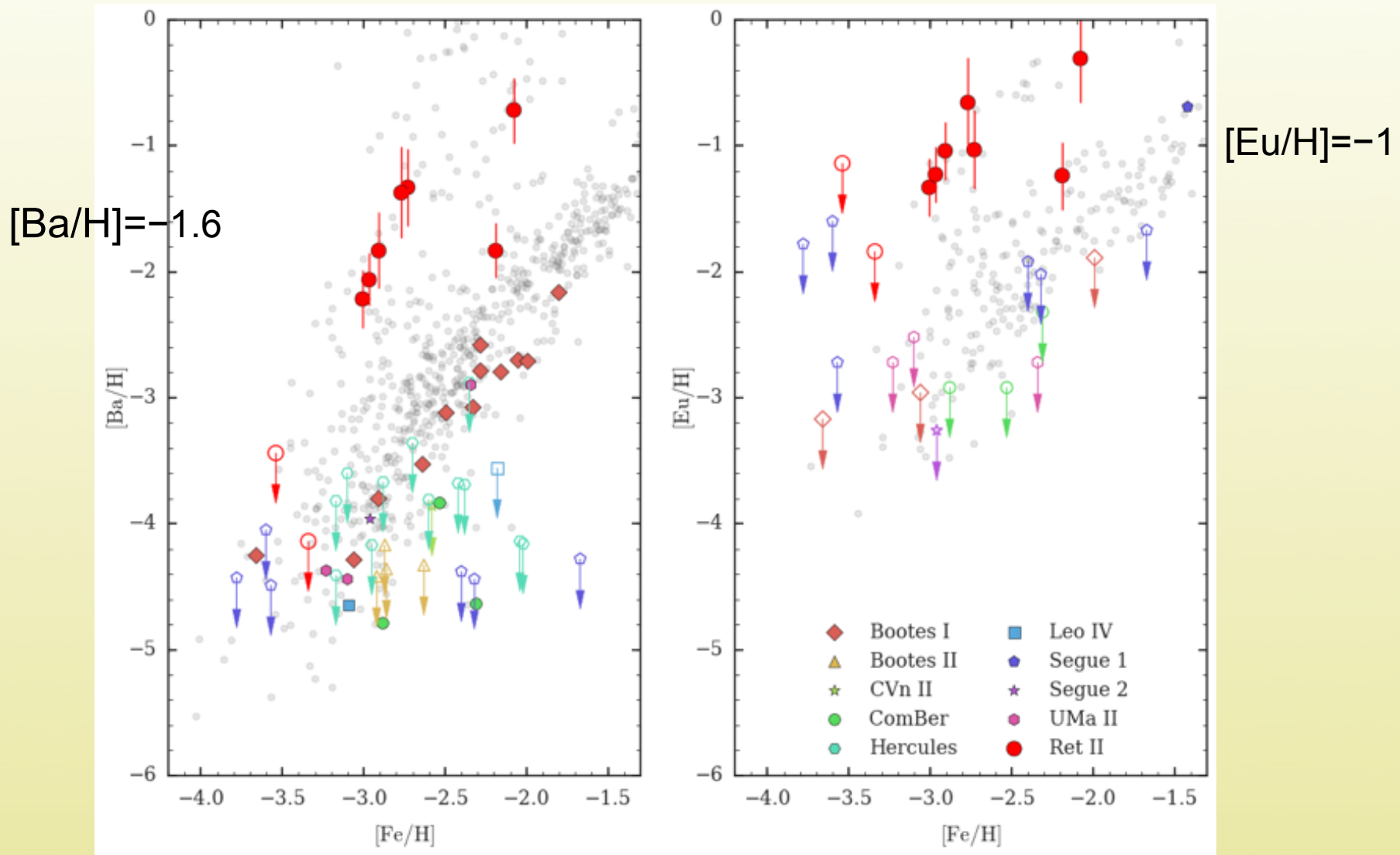
gray dots  
metal-poor  
halo  
stars





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!**

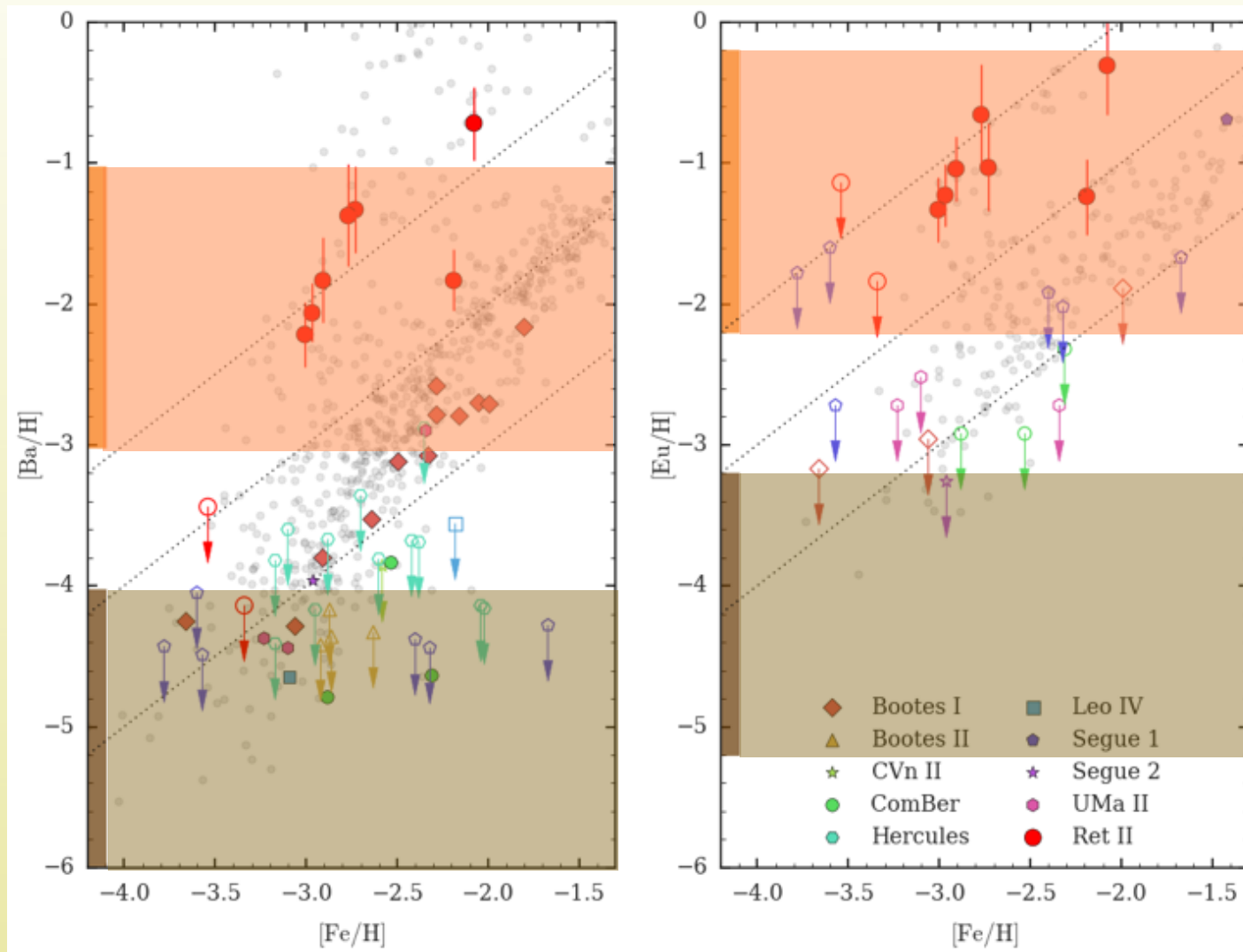




# RET II ABUNDANCES CONSISTENT W/ NEUTRON-STAR MERGER YIELD

Neutron  
star merger

Supernova

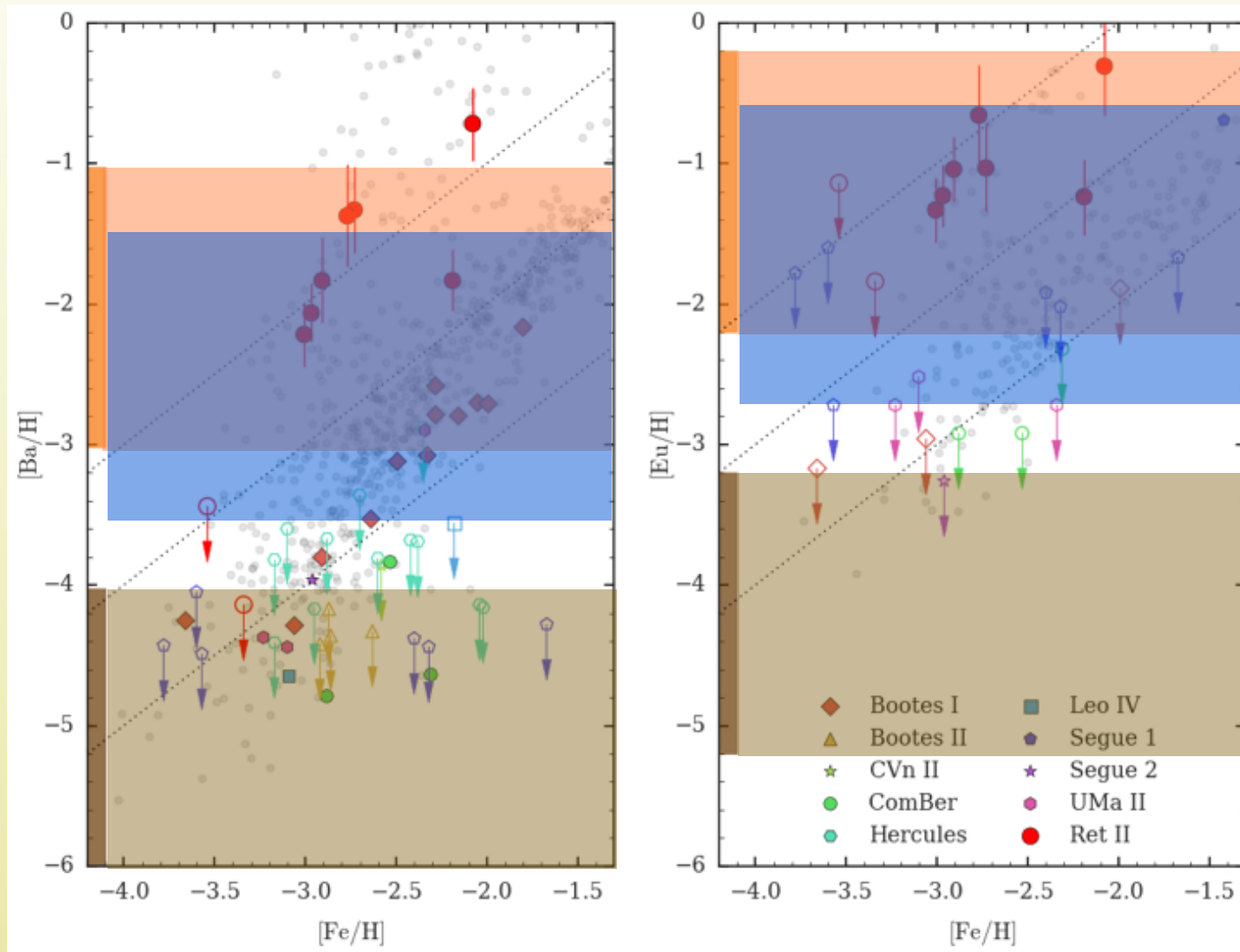


Ji et al 2016, *Nature*, 531, 610

# RARE AND PROLIFIC JET-DRIVEN SUPERNOVA REMAINS POSSIBILITY

Neutron  
star merger

Supernova

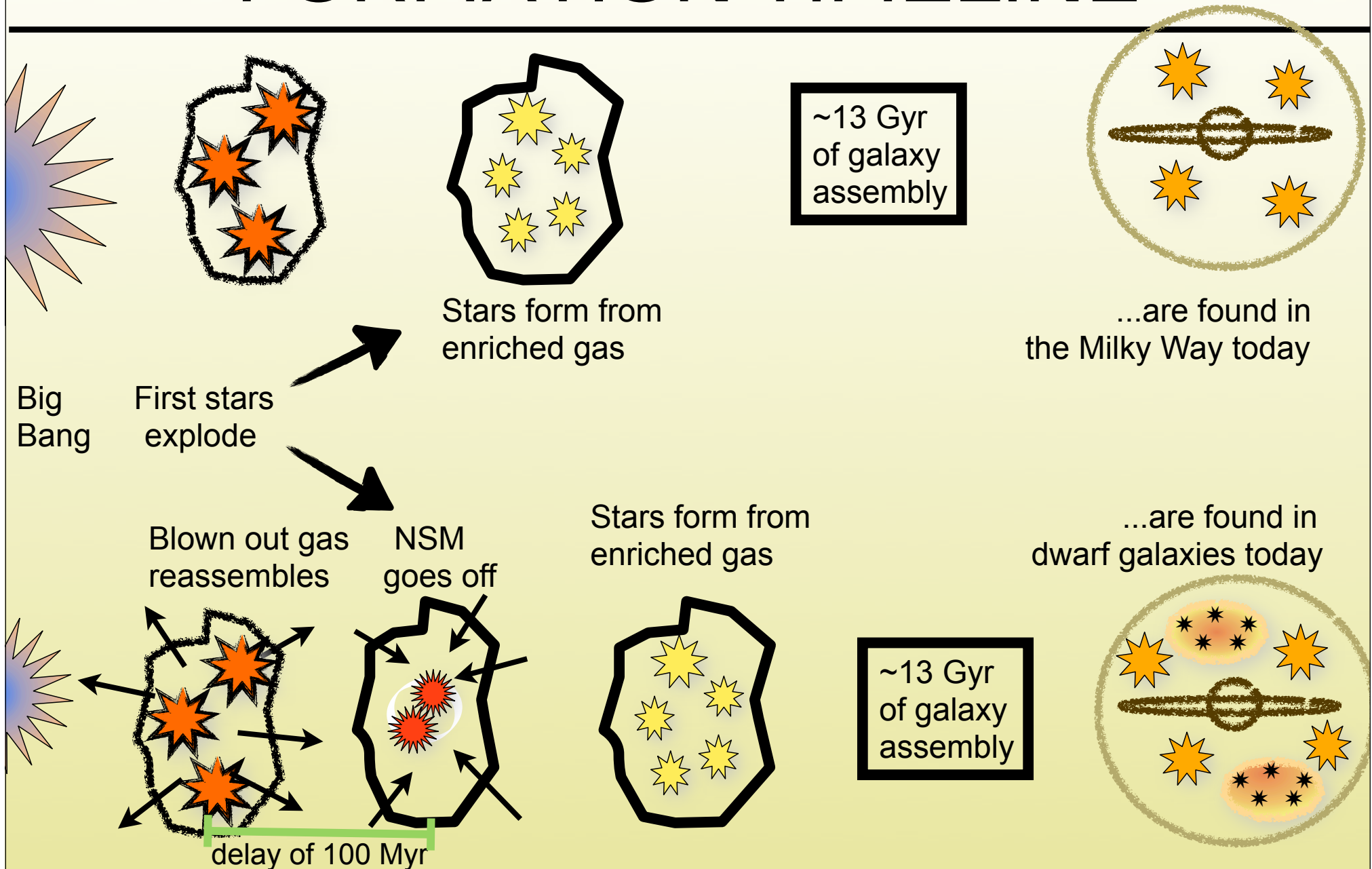


(e.g. Winteler et al. 2012)

Jet-driven  
supernova

...but ordinary supernovae remain ruled out!

# 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!

# 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.)

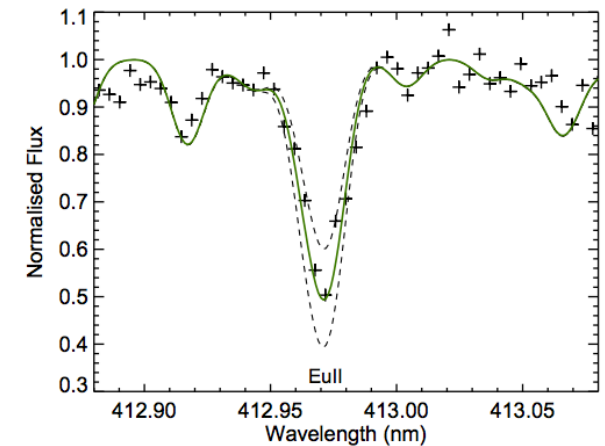
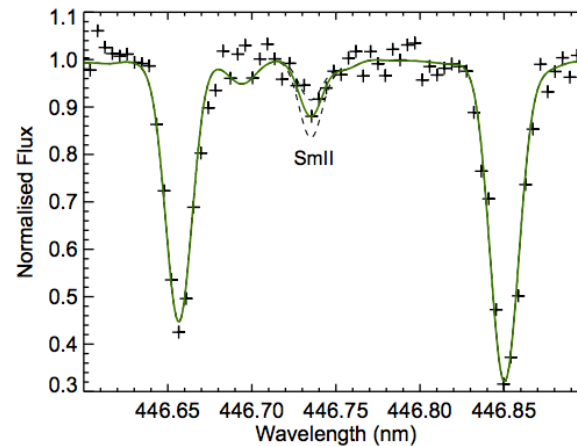
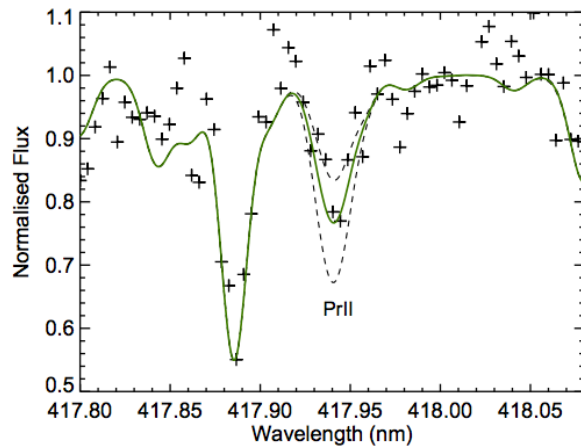
**Ideal system to model given all these obs constraints!**

# 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**





# R-PROCESS OPERATES IN DWARF GALAXIES

20 rI stars in

- Tucana III
- Ursa Minor
- Draco
- Sculptor
- Fornax
- Carina

$-2.5 < [\text{Fe}/\text{H}] < -0.8$

$0.3 < [\text{Eu}/\text{Fe}] < 1.0$

13 rII stars in

- Reticulum II  $-3.0 < [\text{Fe}/\text{H}] < -2.1$
- Ursa Minor  $1.0 < [\text{Eu}/\text{Fe}] < 2.1$
- Draco
- Fornax

$-2.6 < [\text{Fe}/\text{H}] < -0.8$

$1.1 < [\text{Eu}/\text{Fe}] < 1.7$

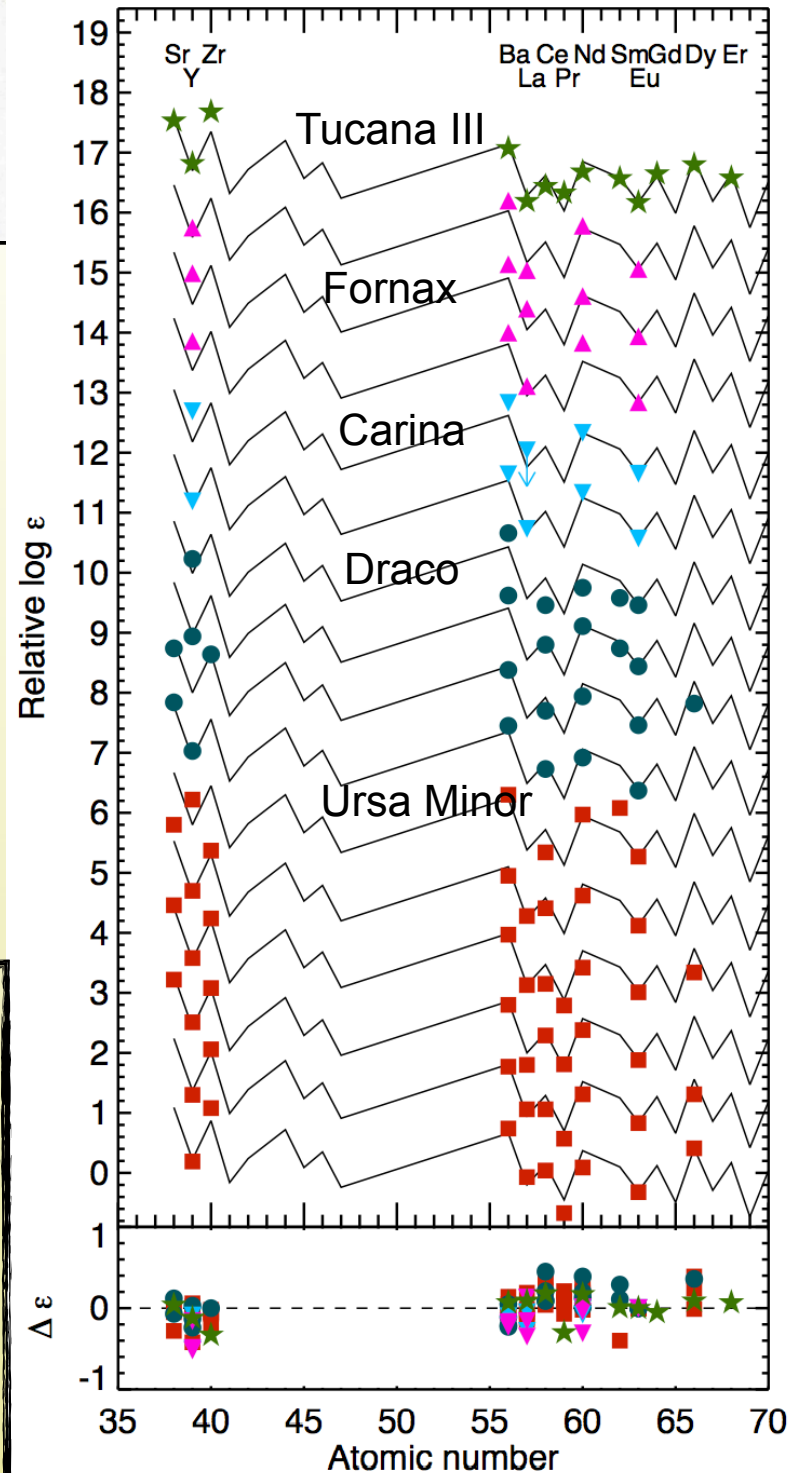
How can a variety of dwarfs have so different r-process levels?

=> Internal or external enrichment?

=> Different dilution masses?

=> Different accretion history

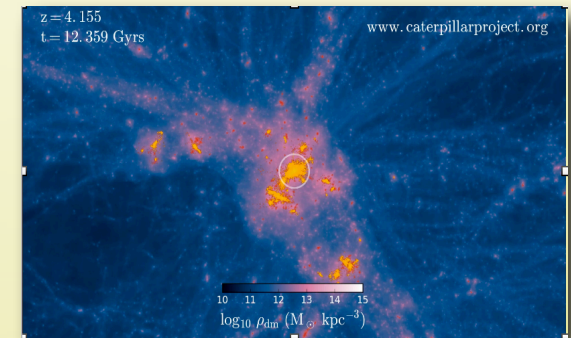
(accreted r-process stars)?



# A NEW KIND OF CHEMICAL TAGGING

## Tracing galaxy assembly w/ r-process stars & r-process galaxies

- Recall: The halo formed from accreted systems:
- r-process stars trace that assembly process: i.e., they trace the fraction of r-process dwarfs! -- we can determine that fraction
- Significant r-process enrichment in
  - 2/12 ultra-faint dwarf galaxies: **~15%** of all UFD
  - 5/12 classical dwarf galaxies: **~40%** of all dSph
- In the halo:
  - ~25-30 rII stars (published): **~5%** of metal-poor stars
  - ~40 rI stars (publ) + dozens (unpubl.): **~20-30%** of metal-poor stars



**Use existence of r-process pattern as a tag**







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

# 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