

# 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	9 VIII 8	10	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

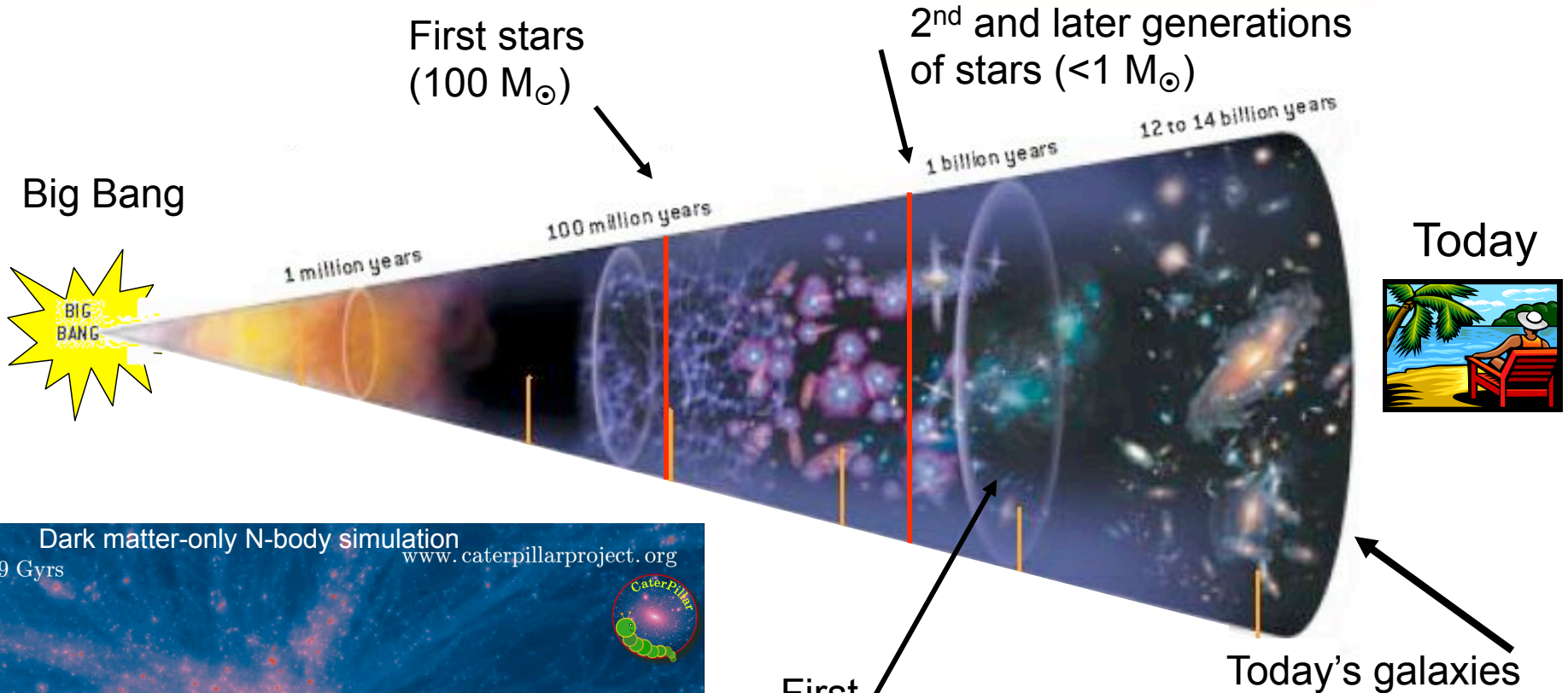
57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	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

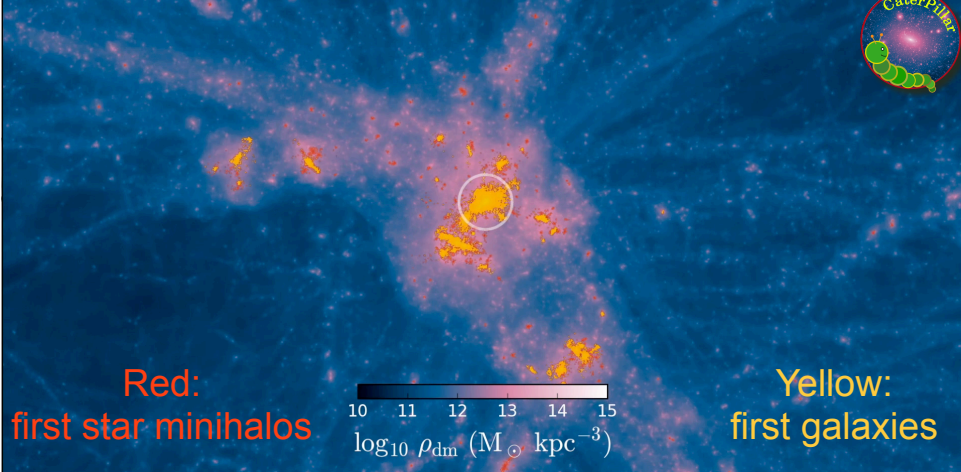




# A LONG TIME AGO...



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

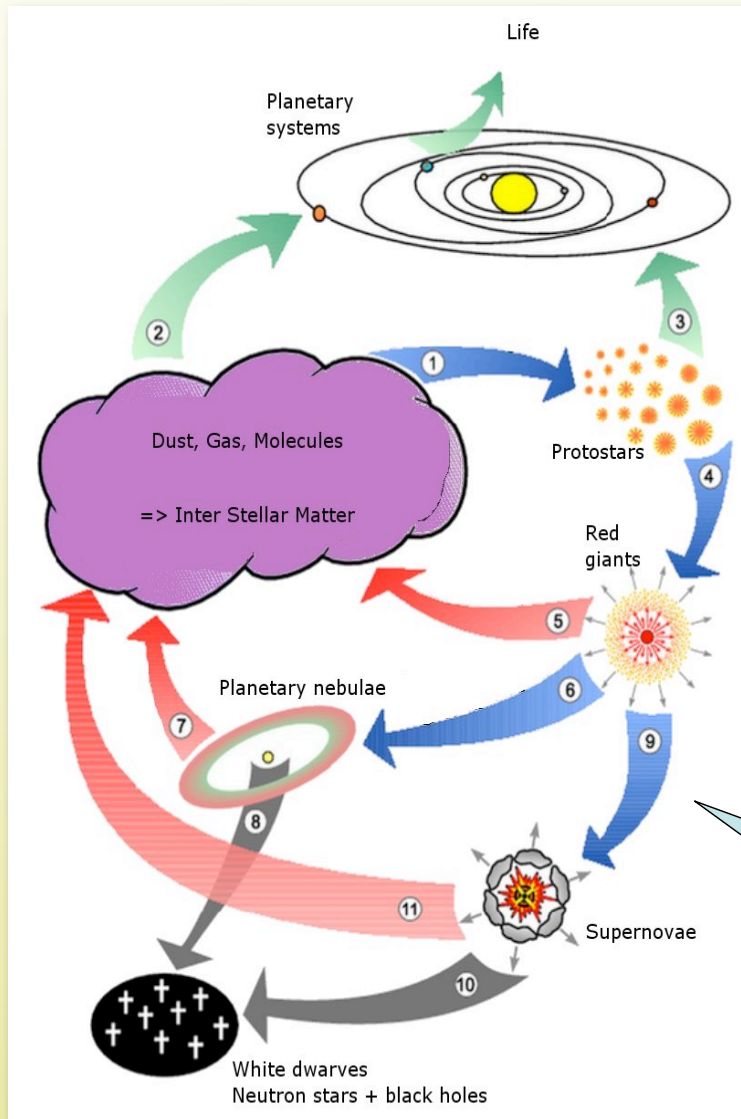


First galaxies

SCIENTIFIC AMERICAN  
Larson & Bromm 2001

Cosmic time (not to scale)

# CHEMICAL EVOLUTION



Stars are made from ~75% H and ~25% He, but:

⇒ Early stars contain little of all elements

⇒ Younger stars contain larger amounts

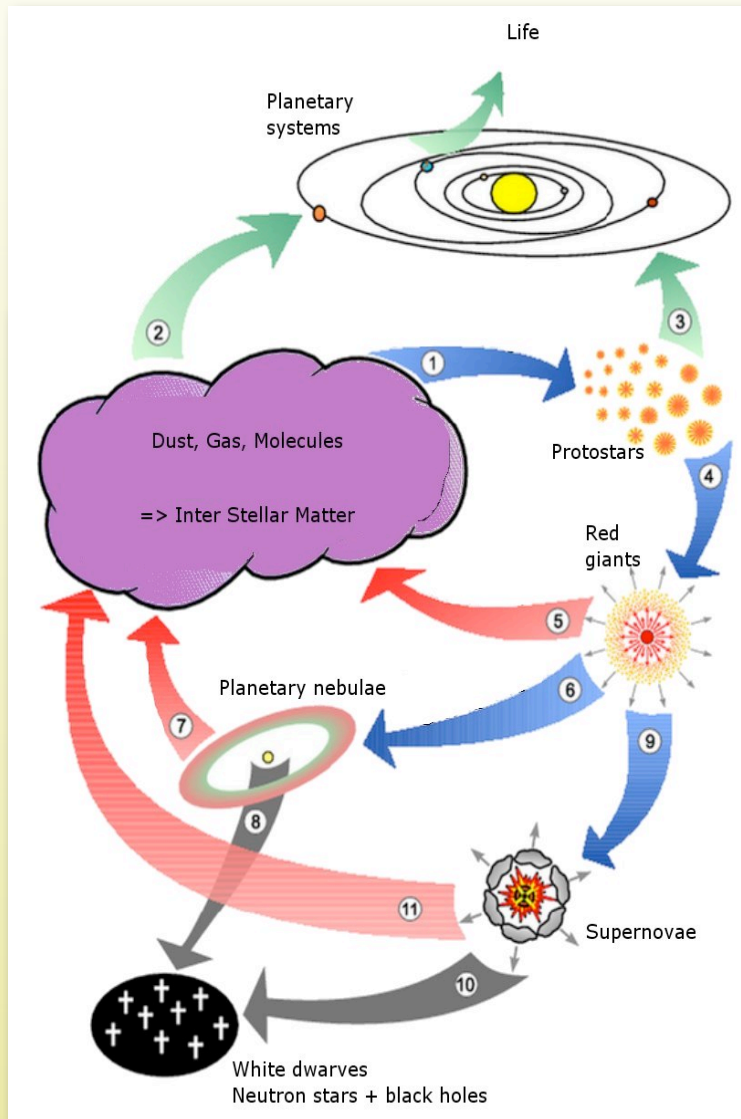
## Examples

Sun: contains 1.4 % heavy elements (by mass)

Oldest stars:  $10^{-4}$  to  $10^{-7}$  % heavy elements

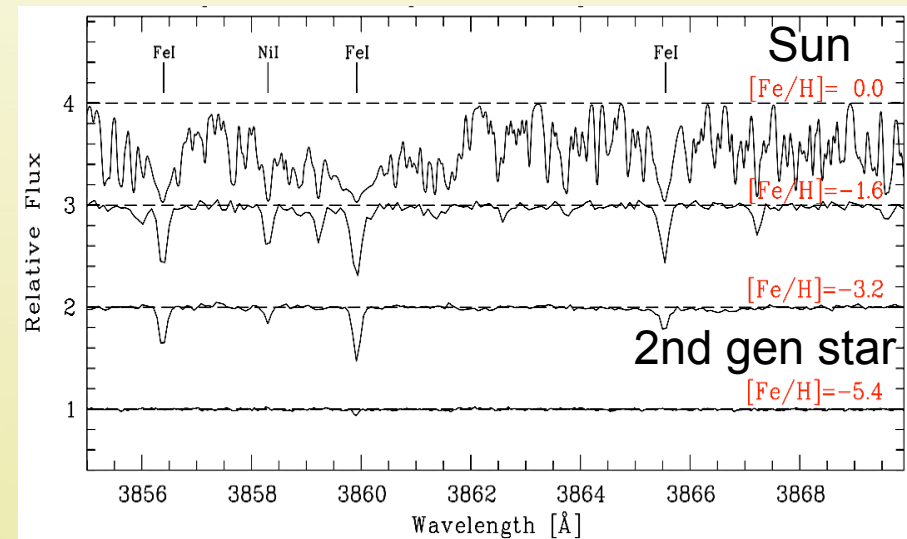
We look for stars with the least amounts of elements heavier than H and He!

# CHEMICAL EVOLUTION



Stars are made from ~75% H and ~25% He, but:

- ⇒ Early stars contain little of all elements
- ⇒ Younger stars contain larger amounts

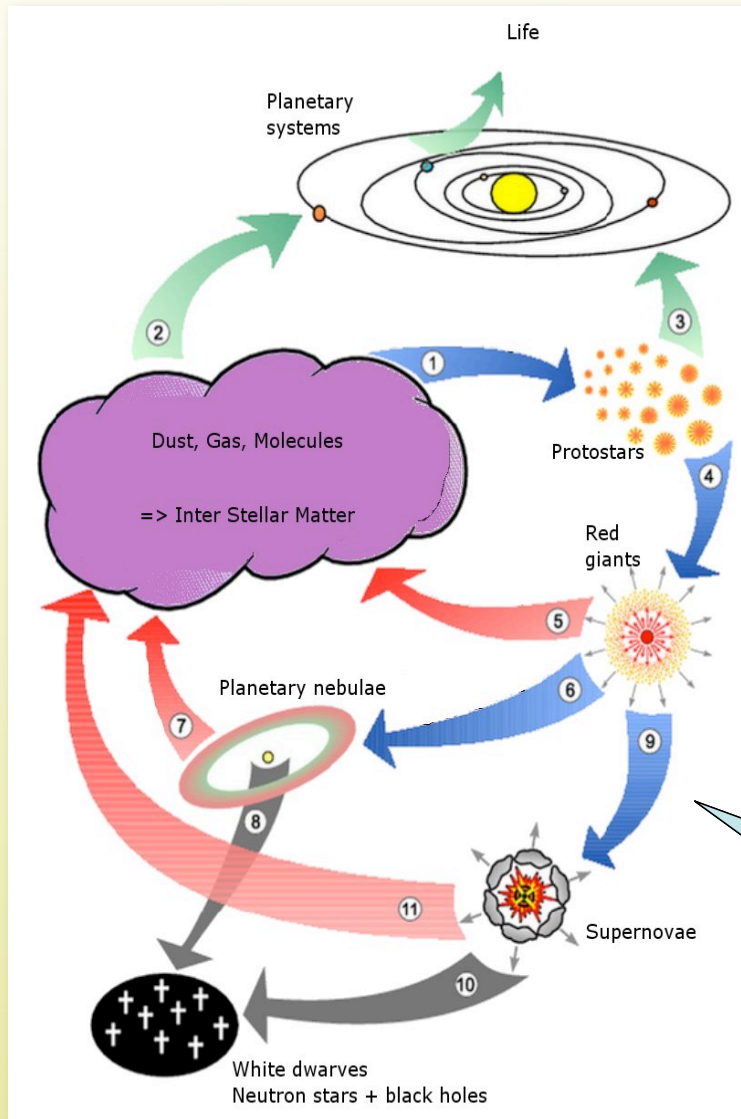


Abundances are derived from integrated absorption line strengths

$$[Fe/H] = \log(N_{Fe}/N_H)_* - \log(N_{Fe}/N_H)_\odot$$



# CHEMICAL EVOLUTION



*Periodic Table*

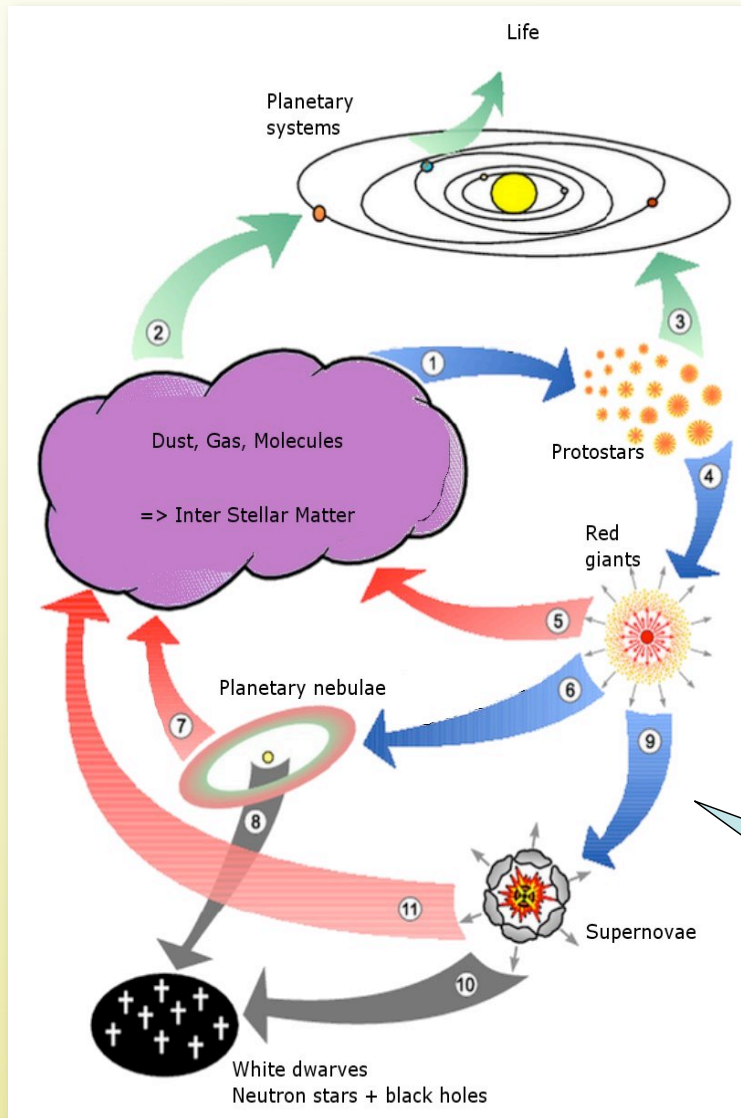
hydrogen 1 <b>H</b> 1.0079																		helium 2 <b>He</b> 4.0026	
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne		
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar		
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr		
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe		
55 Cs	56 Ba	* 71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn		
87 Fr	88 Ra	* 103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo		
		* 57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb				
		* 89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No				

With time, more and more of all elements were made!

We look for stars with the least amounts of elements heavier than H and He!

# CHEMICAL EVOLUTION

Zentrum fuer Astronomie und Astrophysik, TU Berlin



H: X

*Astronomers'*  
*Periodic Table*

He: Y

**Metals Z**

With time, more and more of  
all elements were made!

We look for stars  
that are metal-poor  
compared to the Sun's  
composition!



# THE STORY OF RETICULUM II



## Nuclear Astrophysics

Cosmic origin of  
the chemical  
elements



## Stellar Archaeology

Clues to the  
astrophysical  
site of r-process  
nucleosynthesis

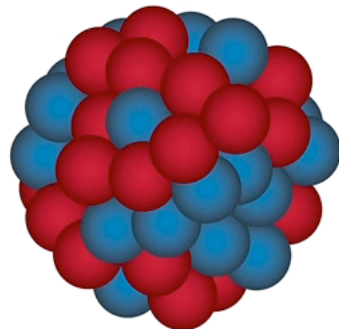


## Dwarf Galaxy Archaeology

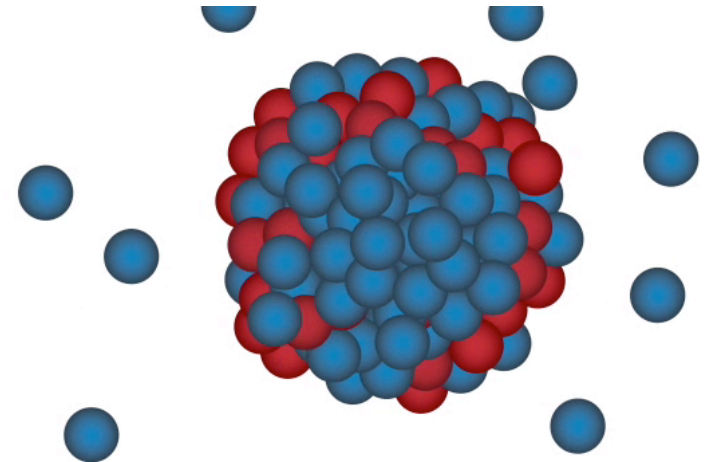
Ancient, clean  
chemical  
enrichment  
signatures

# NUCLEOSYNTHESIS IN STARS

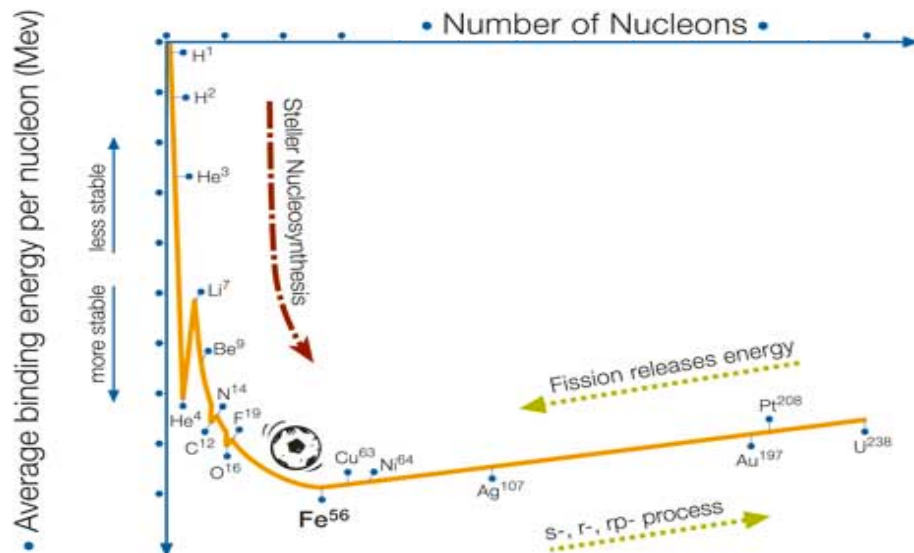
(Depends on stellar mass, stellar evolutionary status, others...)



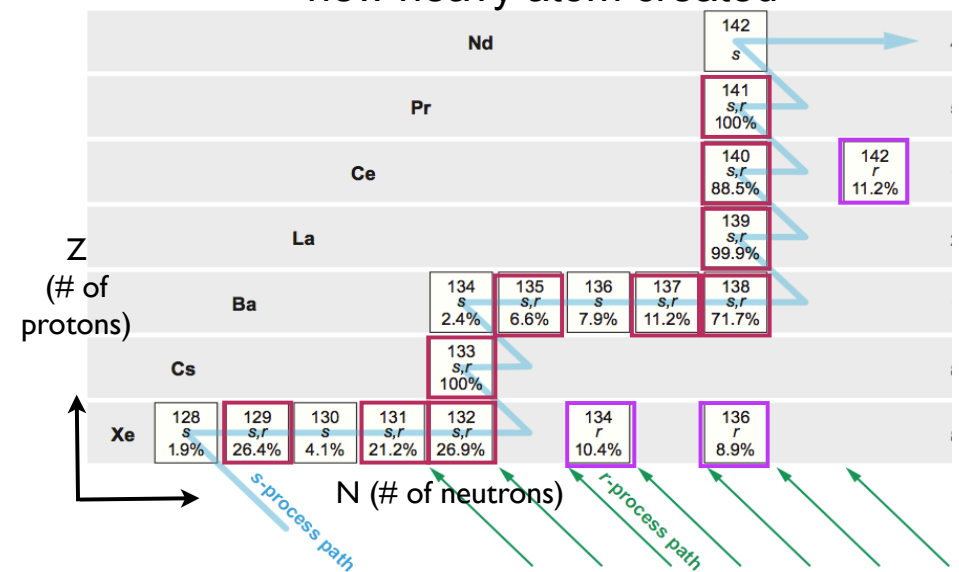
$^{56}\text{Fe}$  Iron



new heavy atom created



**Fusion: H to iron**  
*during stellar evolution*

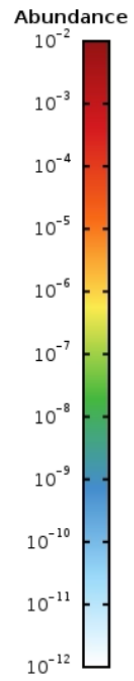


**Neutron-capture processes**  
*slow n-capture: advanced stellar evolution*  
*rapid n-capture: site undetermined(!)*

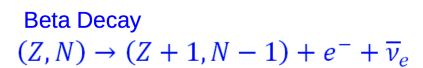
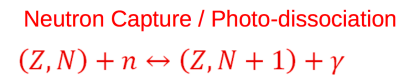
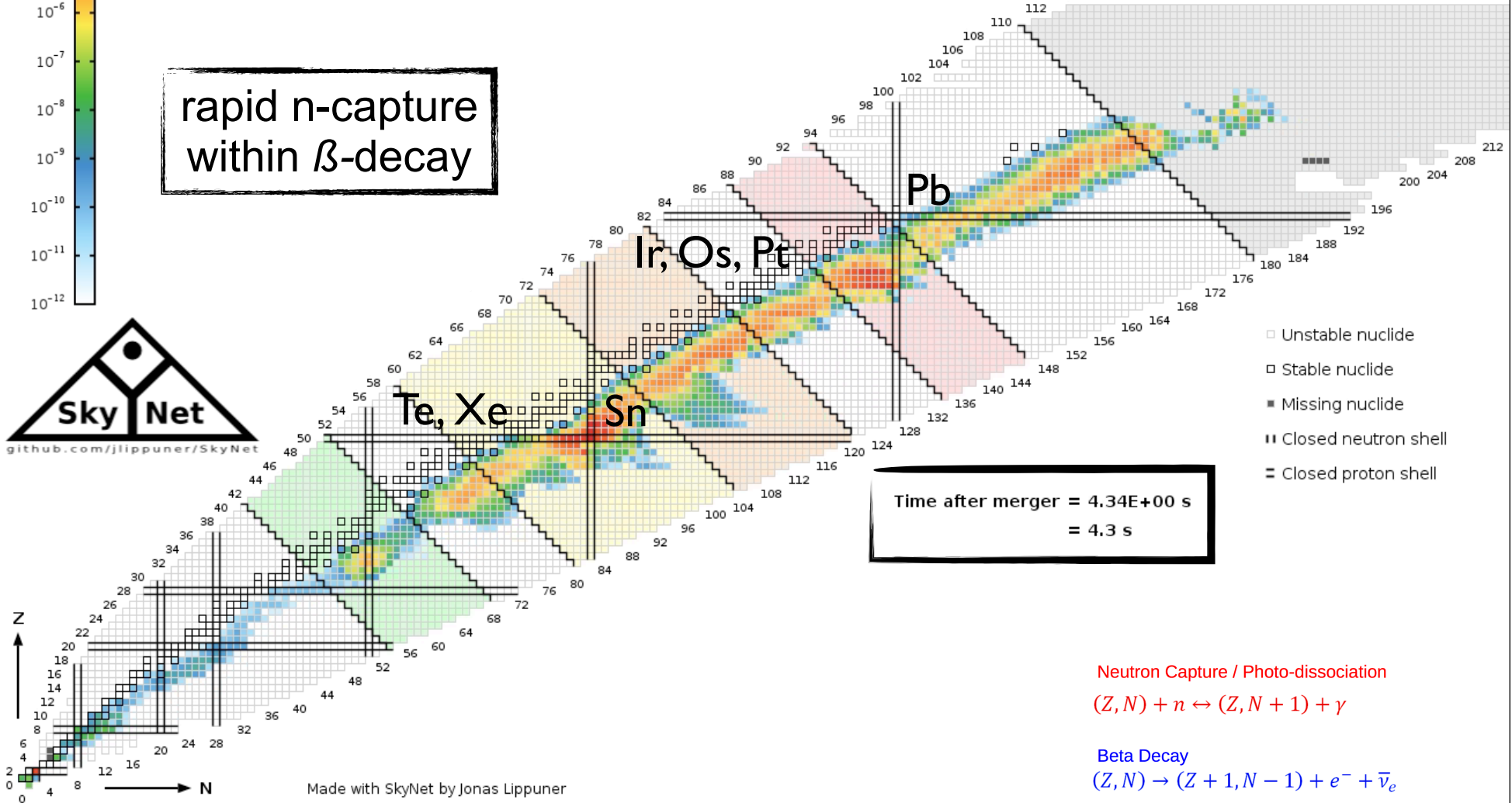


# RAPID NEUTRON-CAPTURE-NUCLEOSYNTHESIS

## (neutron star merger scenario)

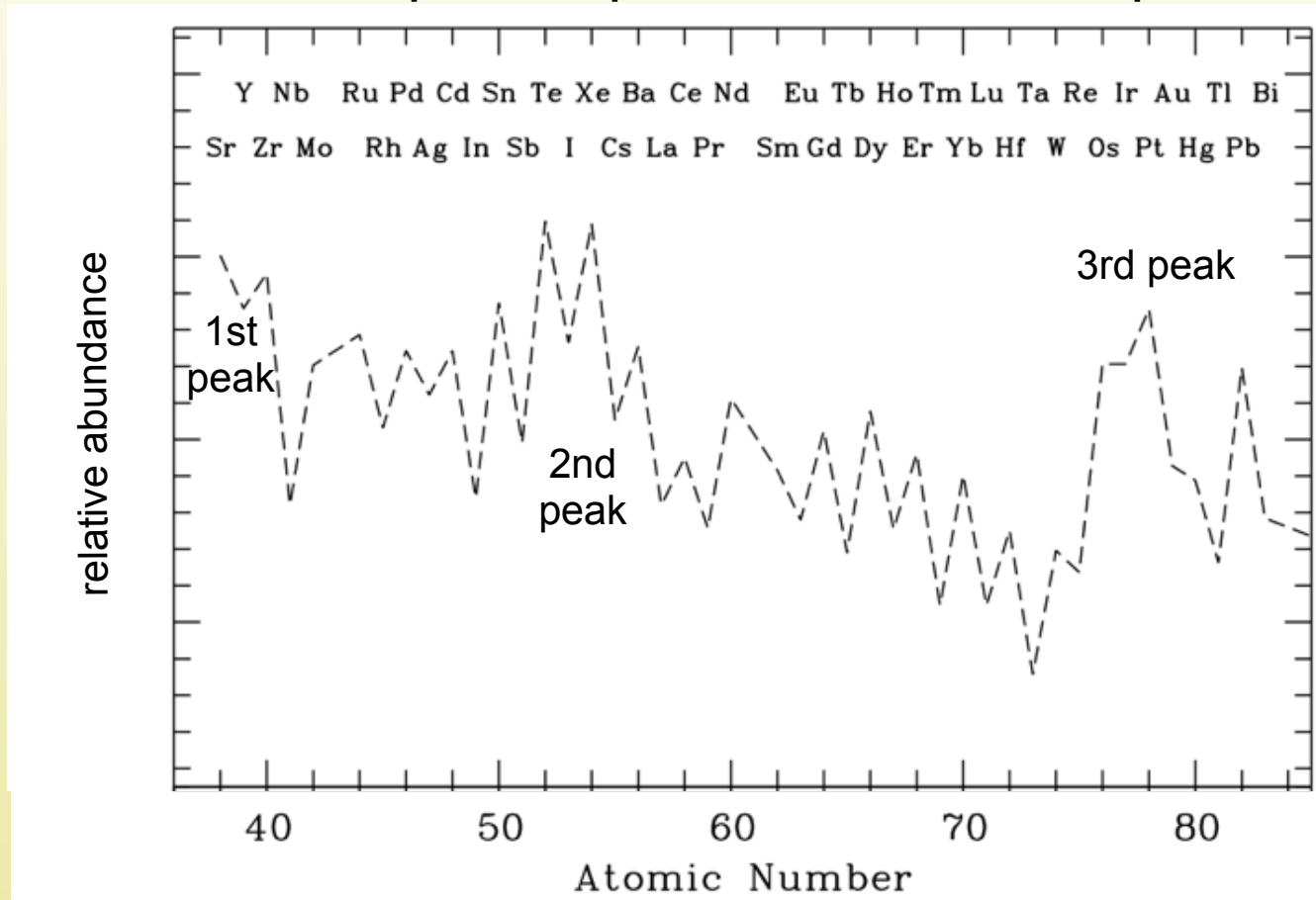


rapid n-capture  
within  $\beta$ -decay



# R-PROCESS PATTERN

neutron-capture r-process elemental pattern

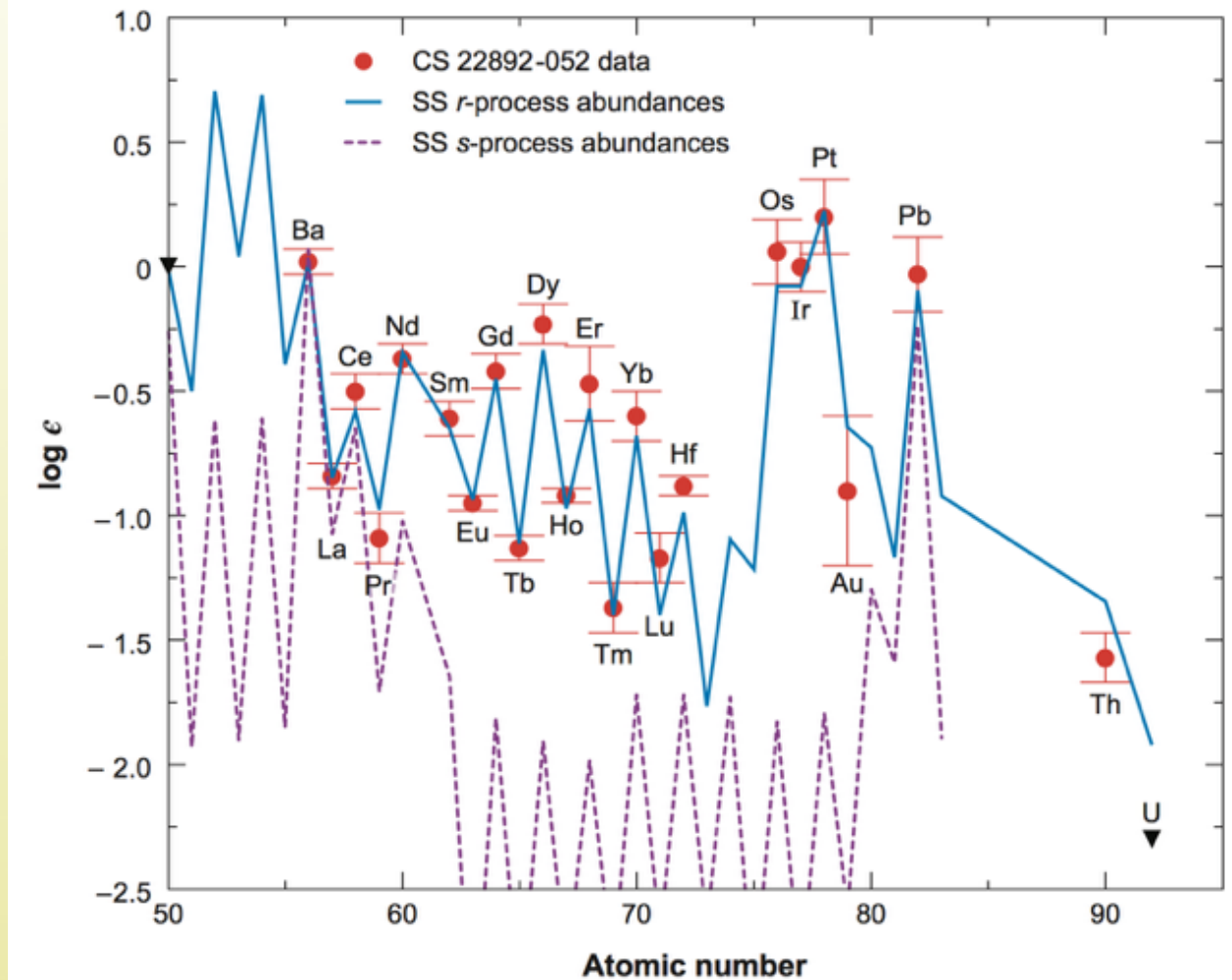




# UNIVERSAL R-PROCESS PATTERN OBSERVED IN METAL-POOR STARS

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)



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

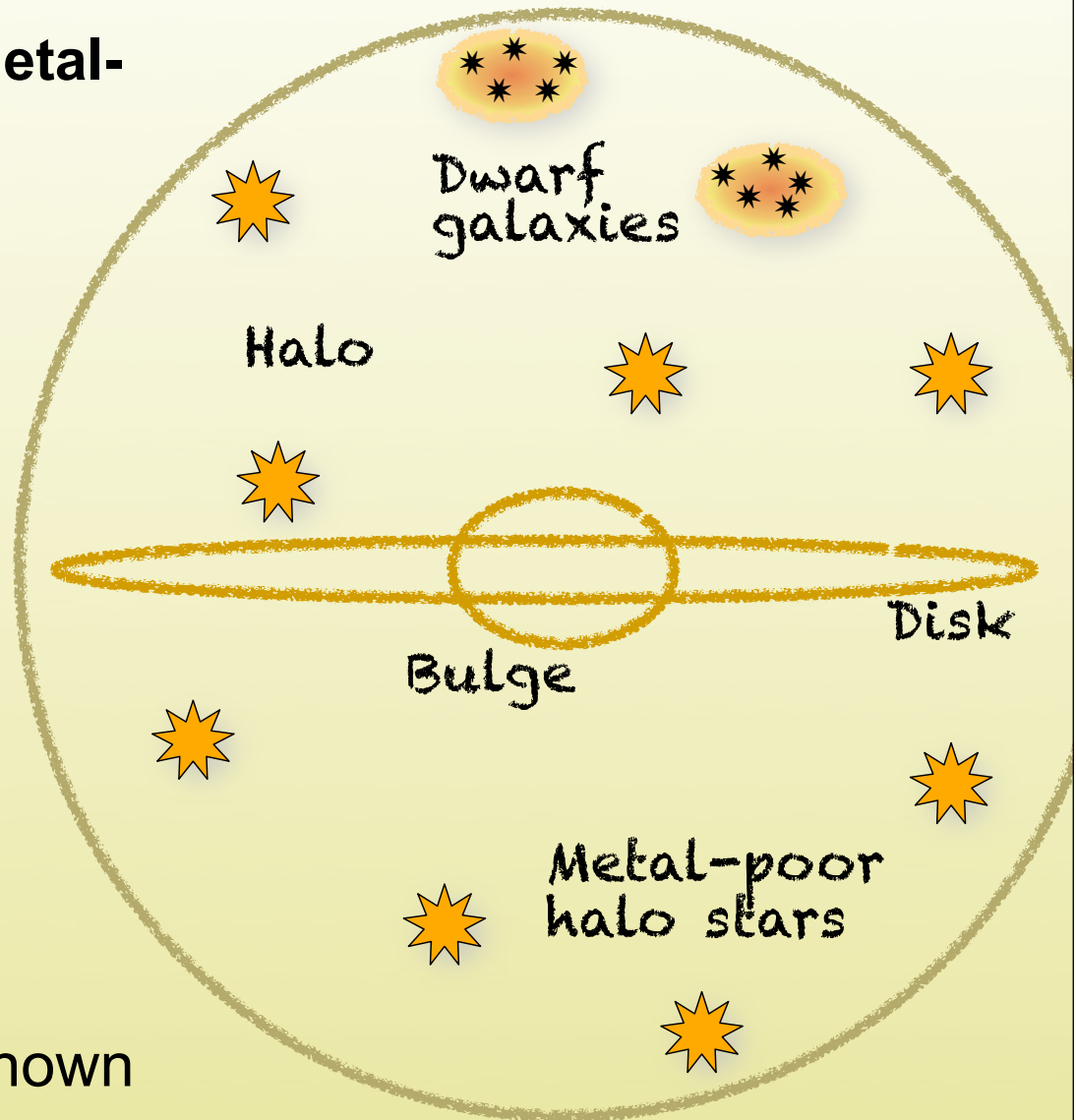
How common are r-process metal-poor stars in the Milky Way?

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

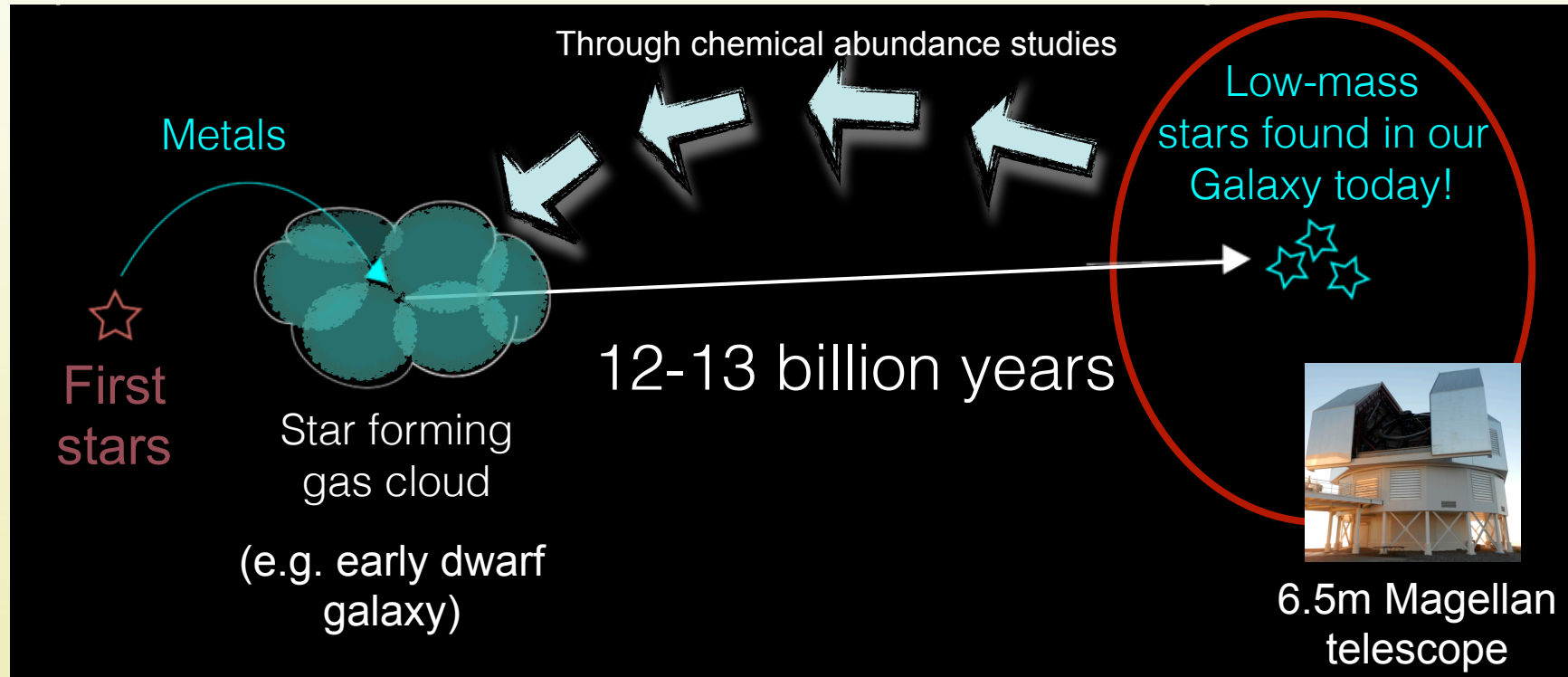




# STELLAR ARCHAEOLOGY

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!



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

***Galactic metal-poor stars are a great tool for near-field cosmology because they are the local equivalent of the high-redshift Universe!***

# THE (DETAILED) ASTRONOMER'S PERIODIC TABLE

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

1 IA 1A <b>H</b> Hydrogen 1.008																	2 VIIIA 8A <b>He</b> Helium 4.003															
3 <b>Li</b> Lithium 6.941	4 IIA 2A <b>Be</b> Beryllium 9.012											5 IIIA 3A <b>B</b> Boron 10.811	6 IVA 4A <b>C</b> Carbon 12.011	7 VA 5A <b>N</b> Nitrogen 14.007	8 VIA 6A <b>O</b> Oxygen 15.999	9 VIIA 7A <b>F</b> Fluorine 18.998	10 VIIIA 8A <b>Ne</b> Neon 20.180															
11 <b>Na</b> Sodium 22.990	12 IIA 2A <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															
																		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 (DETAILED) ASTRONOMER'S PERIODIC TABLE

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

Spallation

s-process

Evolved giant stars

Odd-Z elements

$\alpha$ -elements

Iron group elements

1 IA 1A <b>H</b> Hydrogen 1.008																	2 IIIA 8A <b>He</b> Helium 4.003
3 <b>Li</b> Lithium 6.941	4 IIA 2A <b>Be</b> Beryllium 9.012											5 IIIA 3A <b>B</b> Boron 10.811	6 IVA 4A <b>C</b> Carbon 12.011	7 VA 5A <b>N</b> Nitrogen 14.007	8 VIA 6A <b>O</b> Oxygen 15.999	9 VIIA 7A <b>F</b> Fluorine 18.998	10 VIIIA 8A <b>Ne</b> Neon 20.180
11 <b>Na</b> Sodium 22.990	12 IIA 2A <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
			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 (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> 208.98	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)															<p>Isotope distribution of solar nebula (~8 billion yrs of chemical evolution)</p>				
„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)					

# 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)

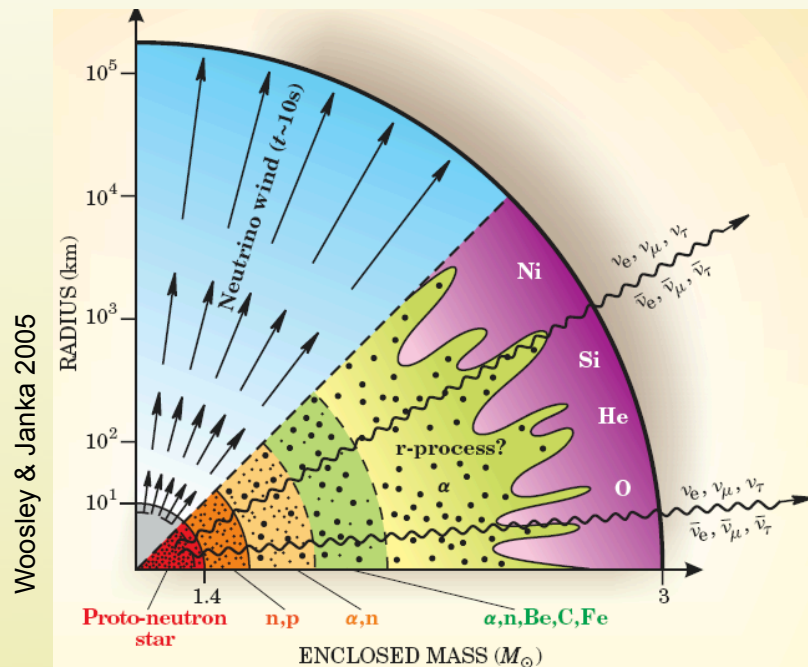
★ **What is the rate and yield of the event?**

★ **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.)

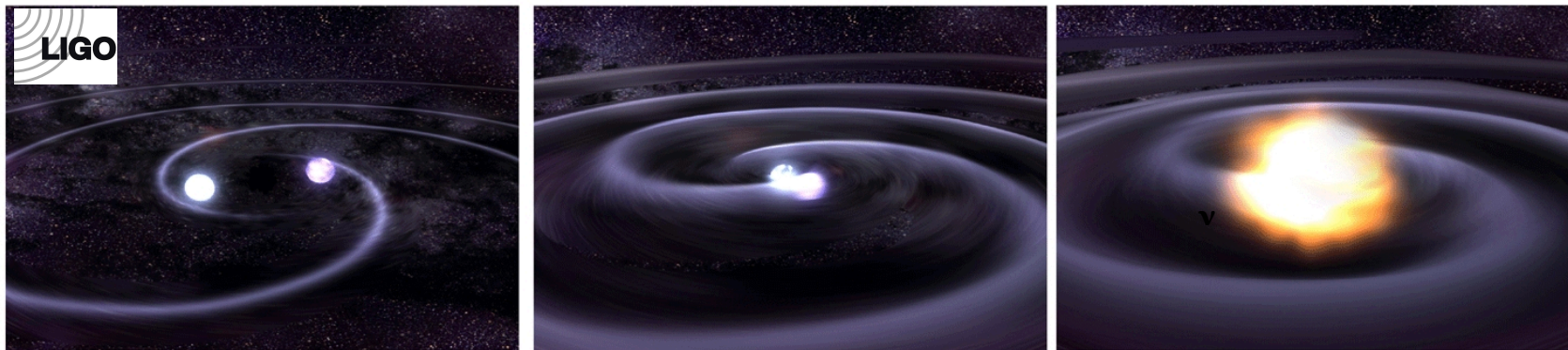


# NEUTRON STAR BINARY MERGER

(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

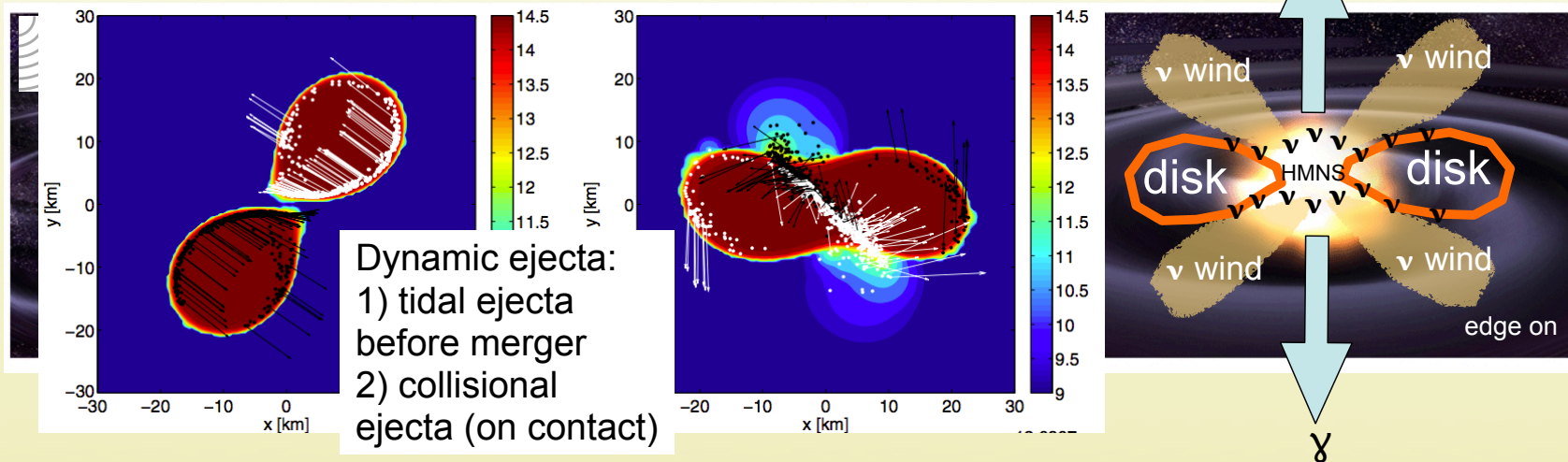
- 1) Short gamma-ray bursts: Afterglow from decay of radioactive r-process elements detected (Tanvir et al. 13)
- 2) Radioactive deep sea measurements suggest local neutron star mergers (Wallner et al. 15, Hotokezaka et al.15)

# 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



**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)

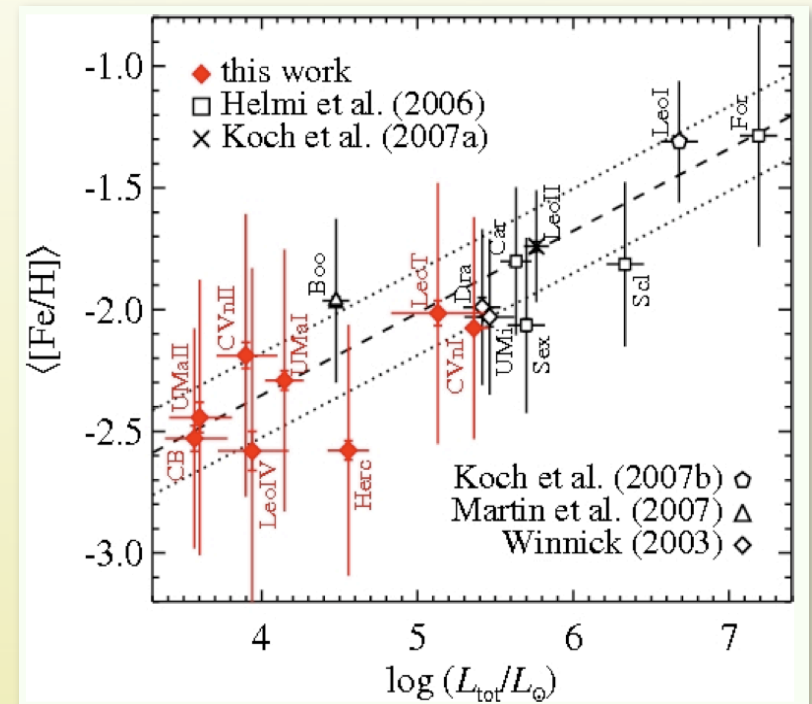






# ULTRA-FAINT DWARF GALAXY PROPERTIES (UFDs)

- 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

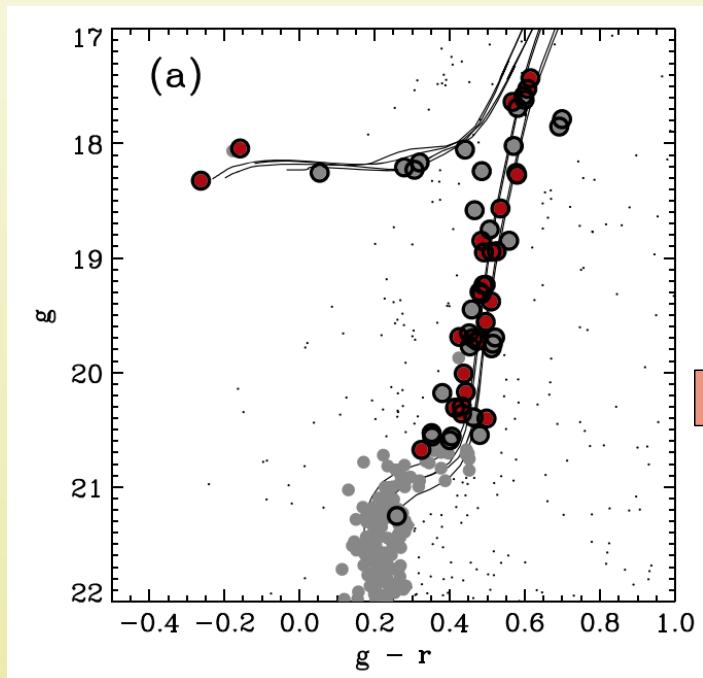
Reticulum II stars

(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 (~23h)



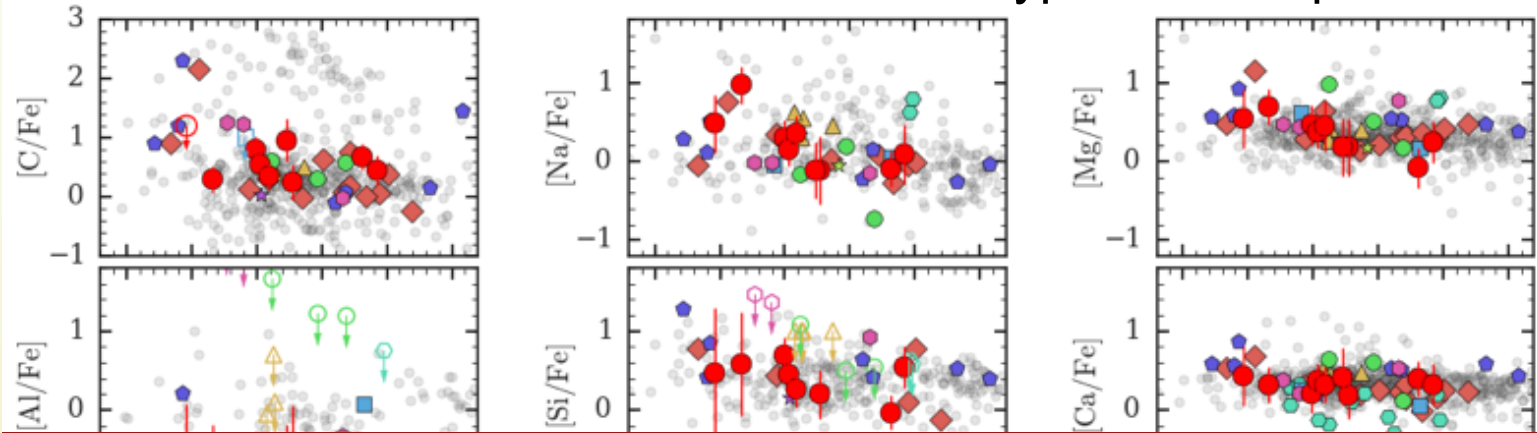
Color-magnitude-diagram of Ret II  
(red = confirmed members)

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

# LIGHT ELEMENT ABUNDANCES

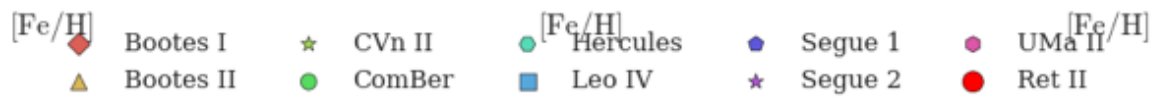
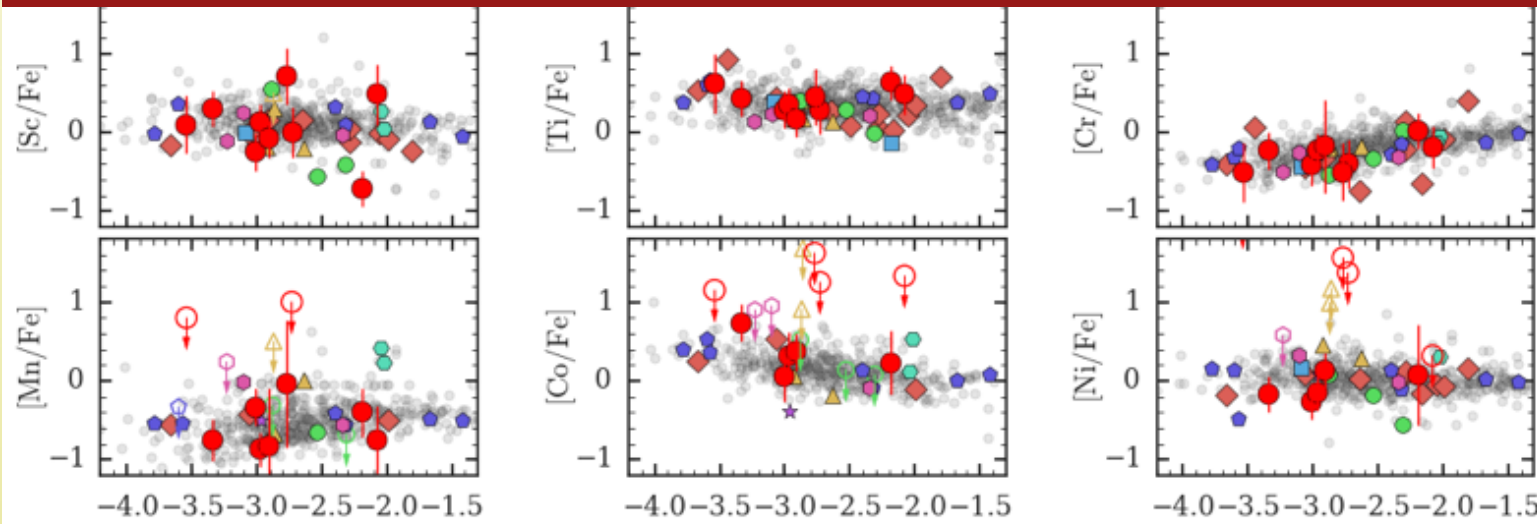
(C, NA, MG, AL, SI, CA, SC, TI, CR, MN, CO, NI)

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



Core-collapse supernovae are primary light element source

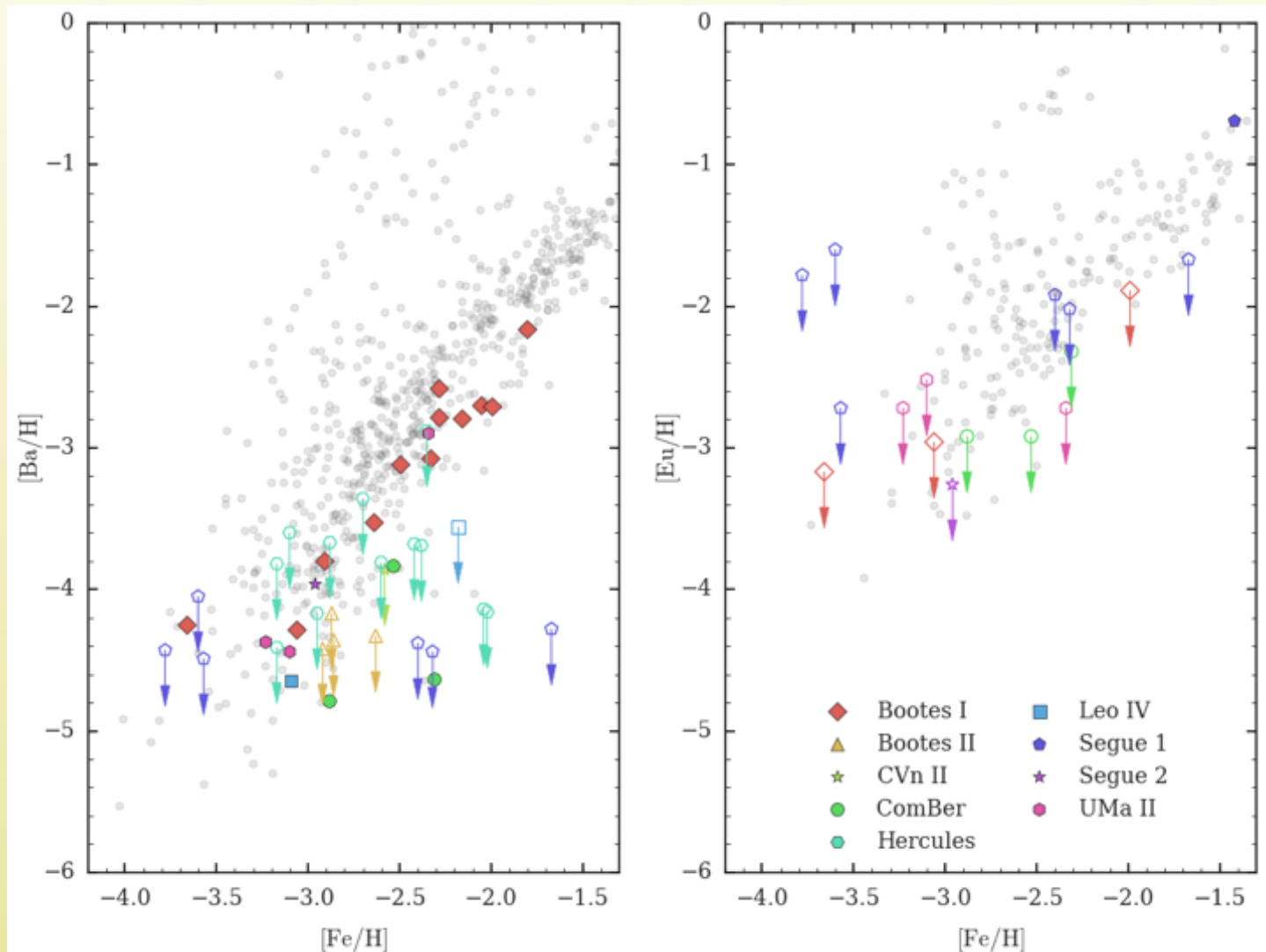
Ji et al 2016, Nature, 531, 610

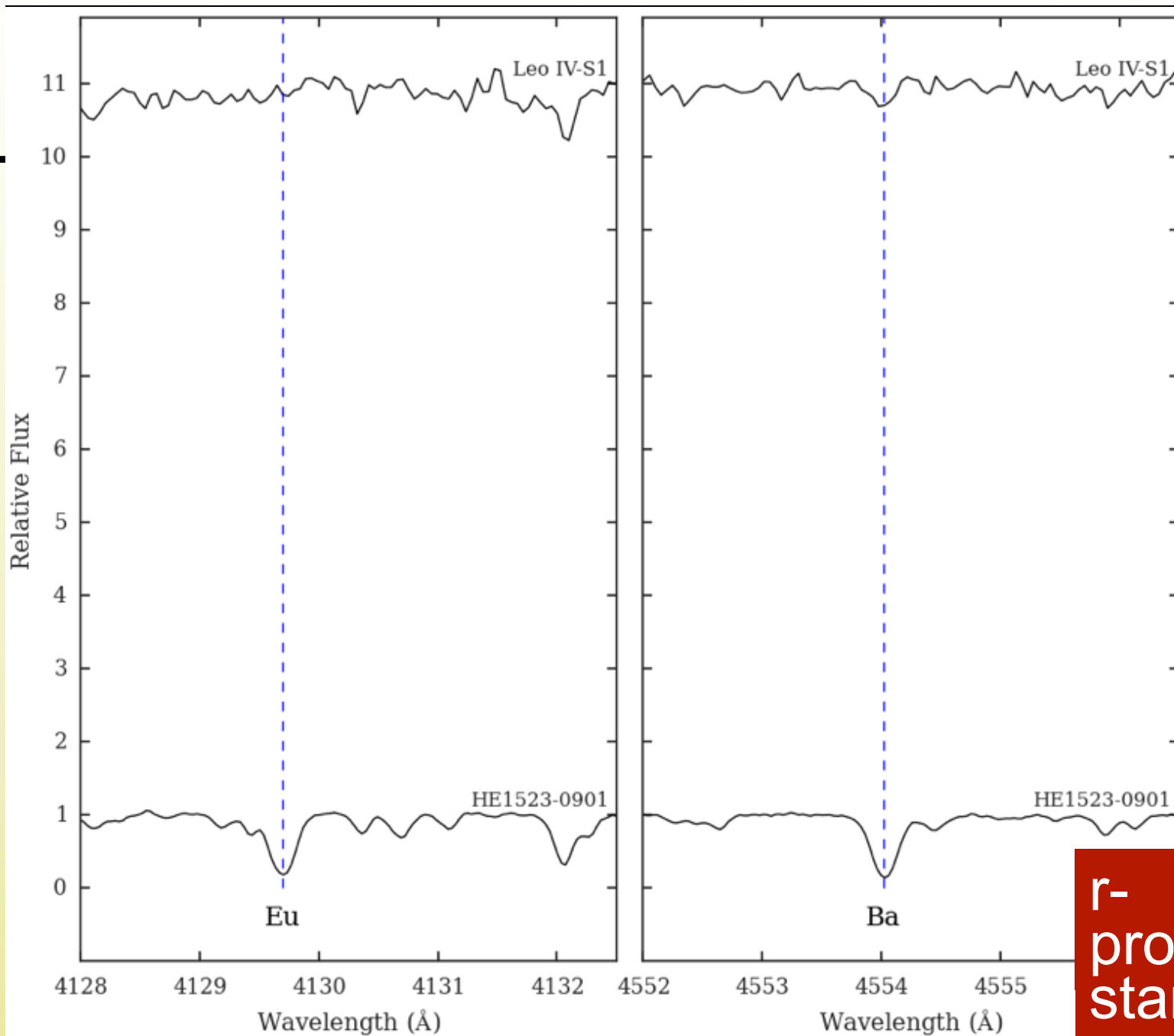


gray dots  
metal-poor  
halo  
stars

# NEUTRON-CAPTURE ELEMENT ABUNDANCES (BA AND EU)

The **other ten** UFDs have **uniquely low** neutron-capture element abundances!

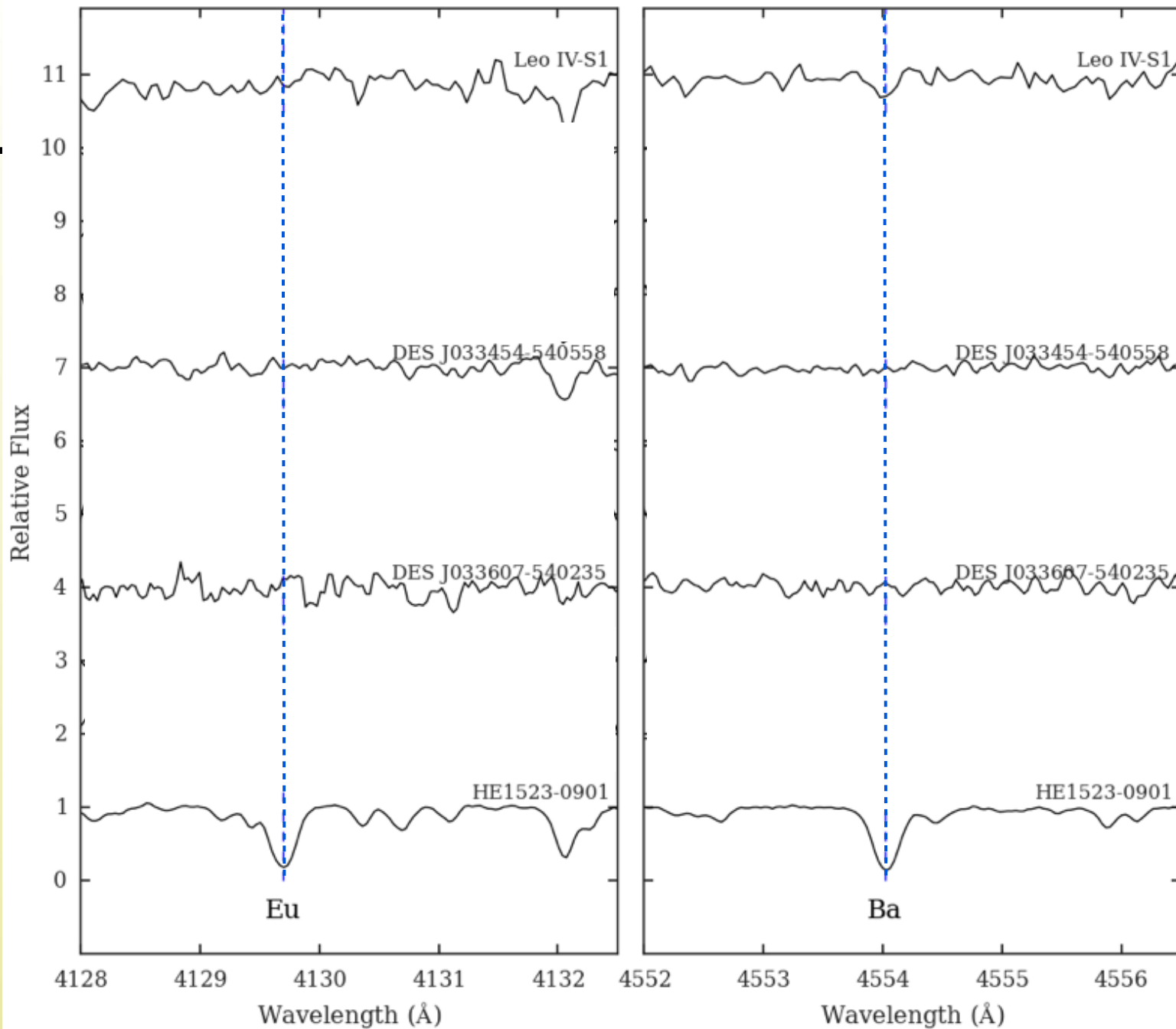


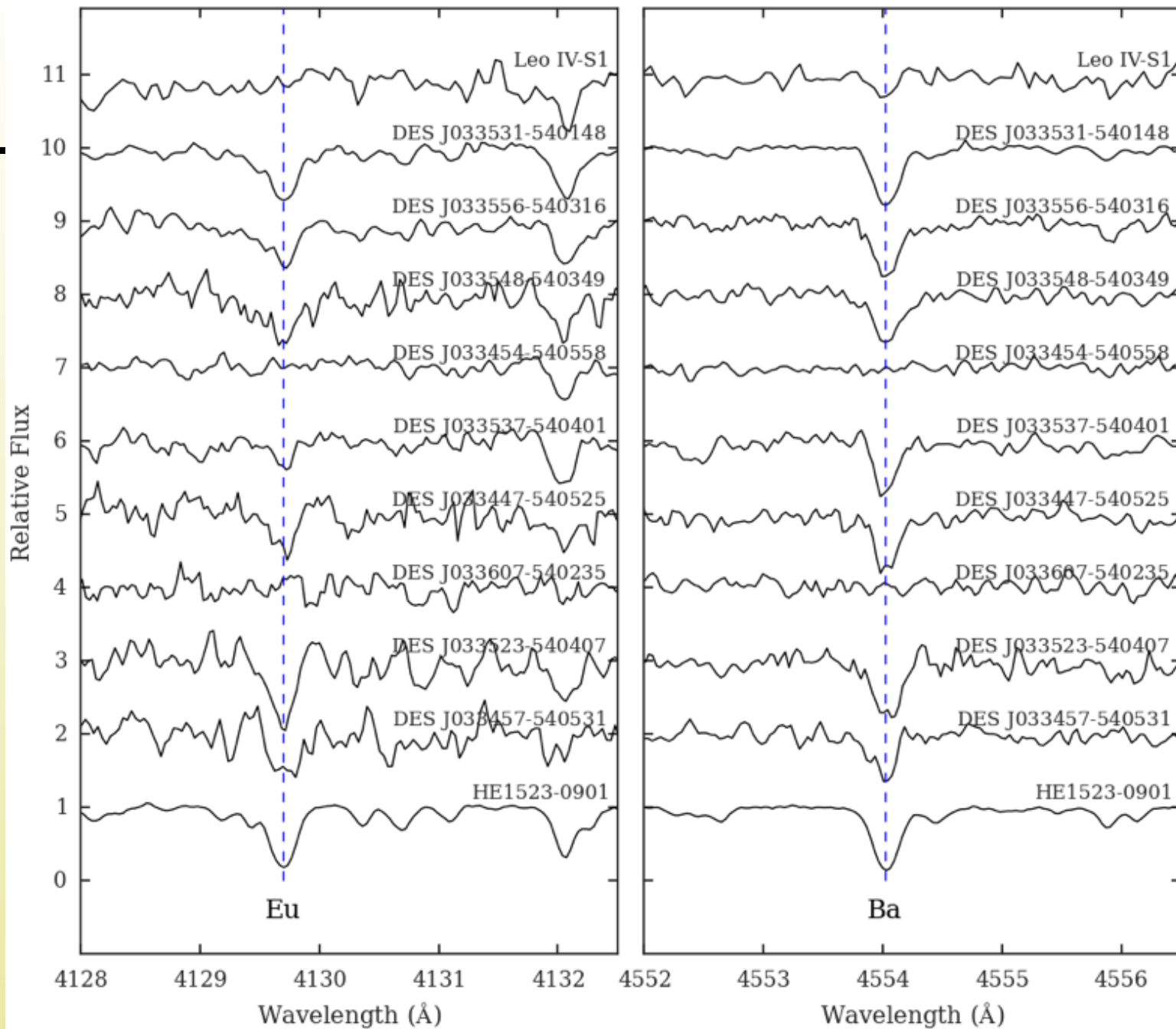


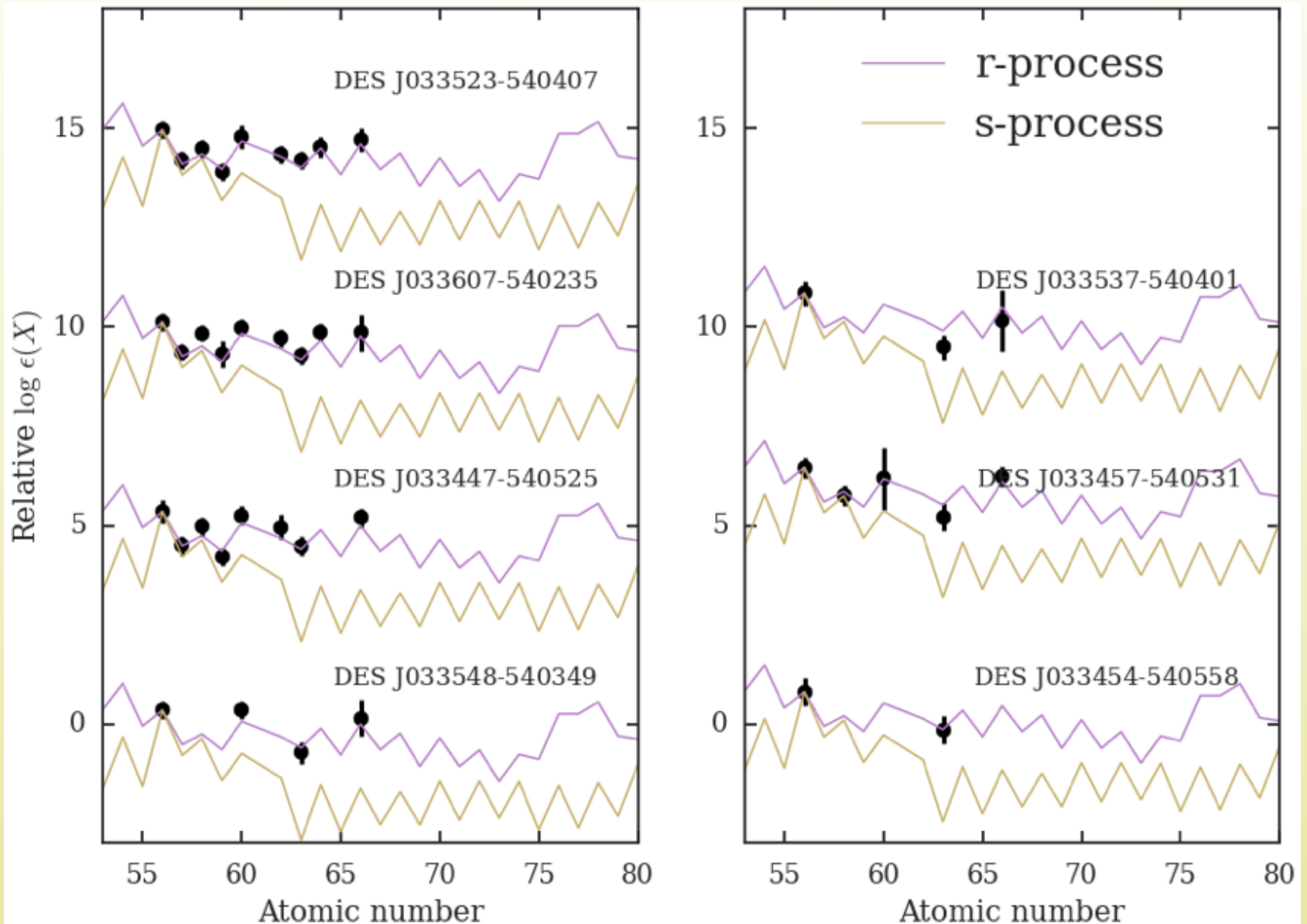
UFD  
star

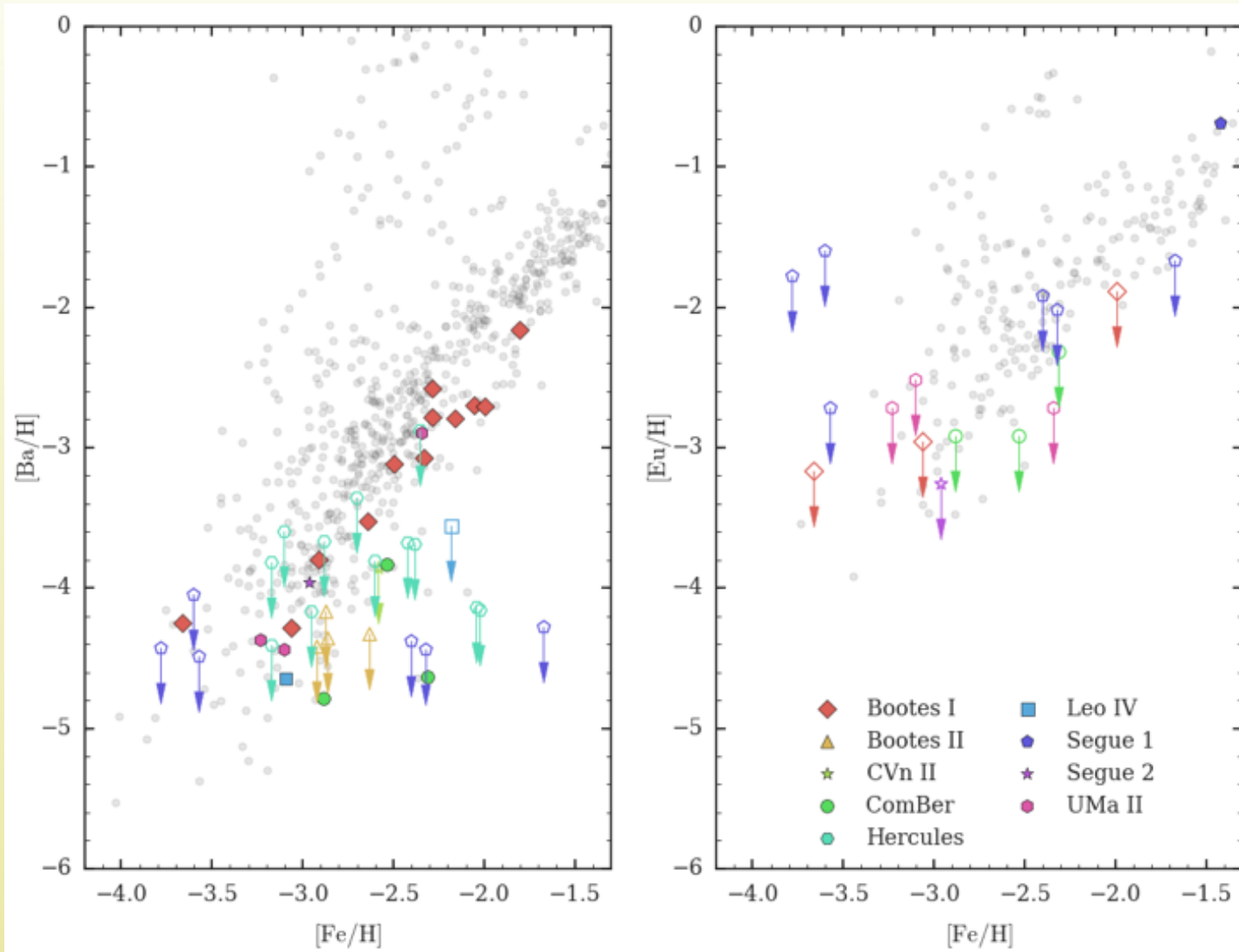
r-  
process  
star





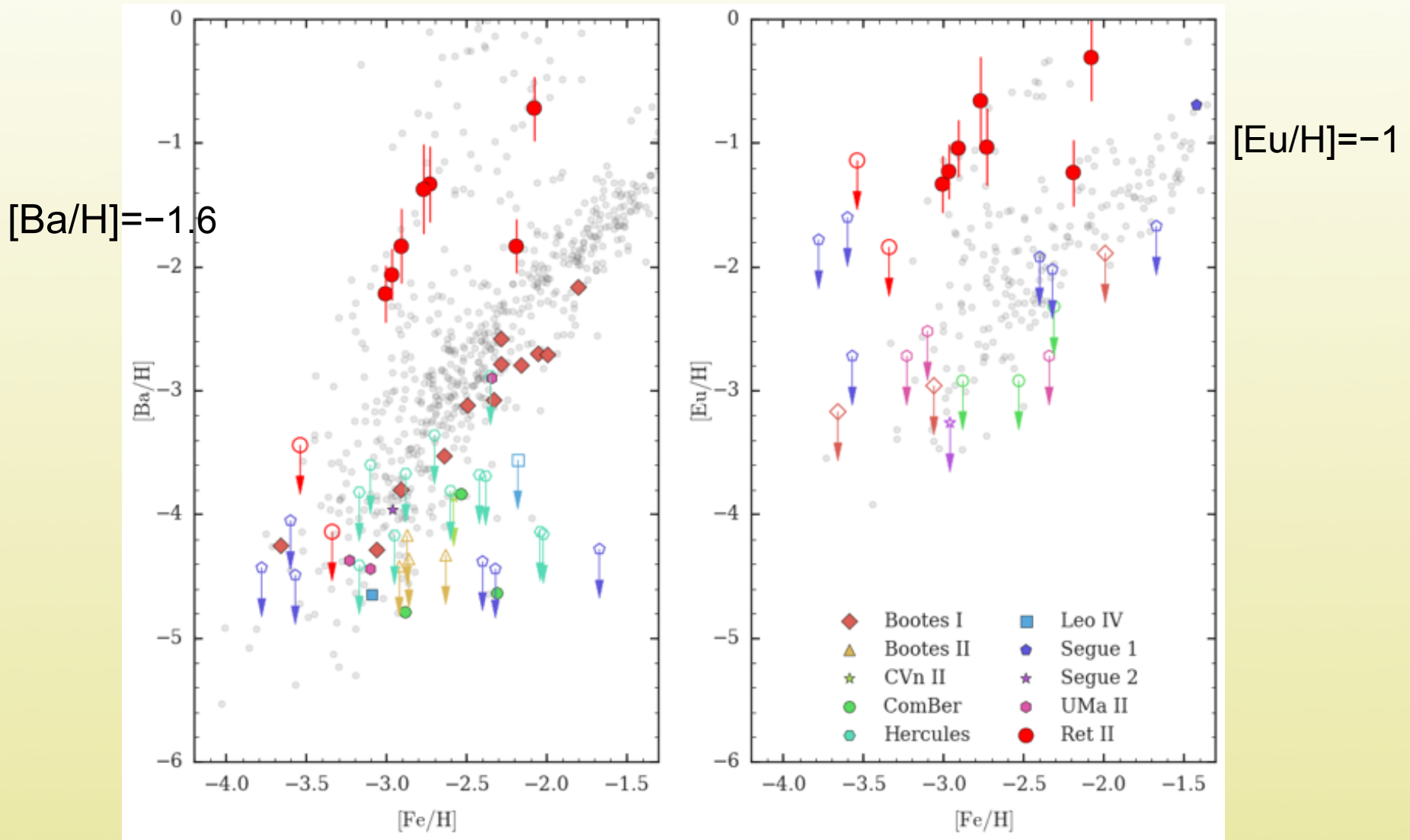


ALL SEVEN RET II STARS DISPLAY  
THE R-PROCESS PATTERNJi et al 2016, *Nature*, 531, 610

NEUTRON-CAP. ELEMENTS IN  
UFD STARS (BEFORE ADDING RET II)



# 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

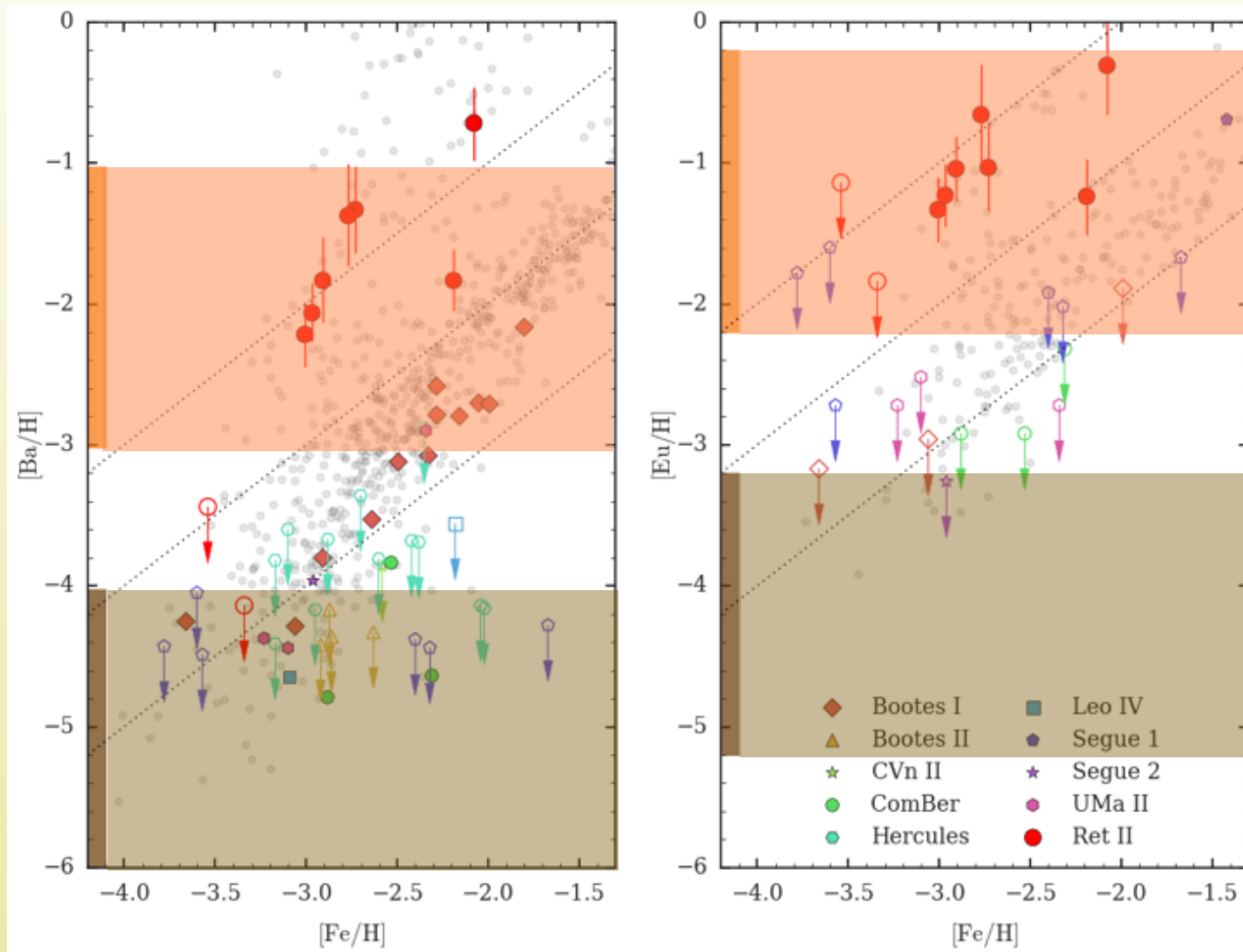
**=> Agrees with Ret II abundance results!**



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

Neutron  
star merger

Supernova

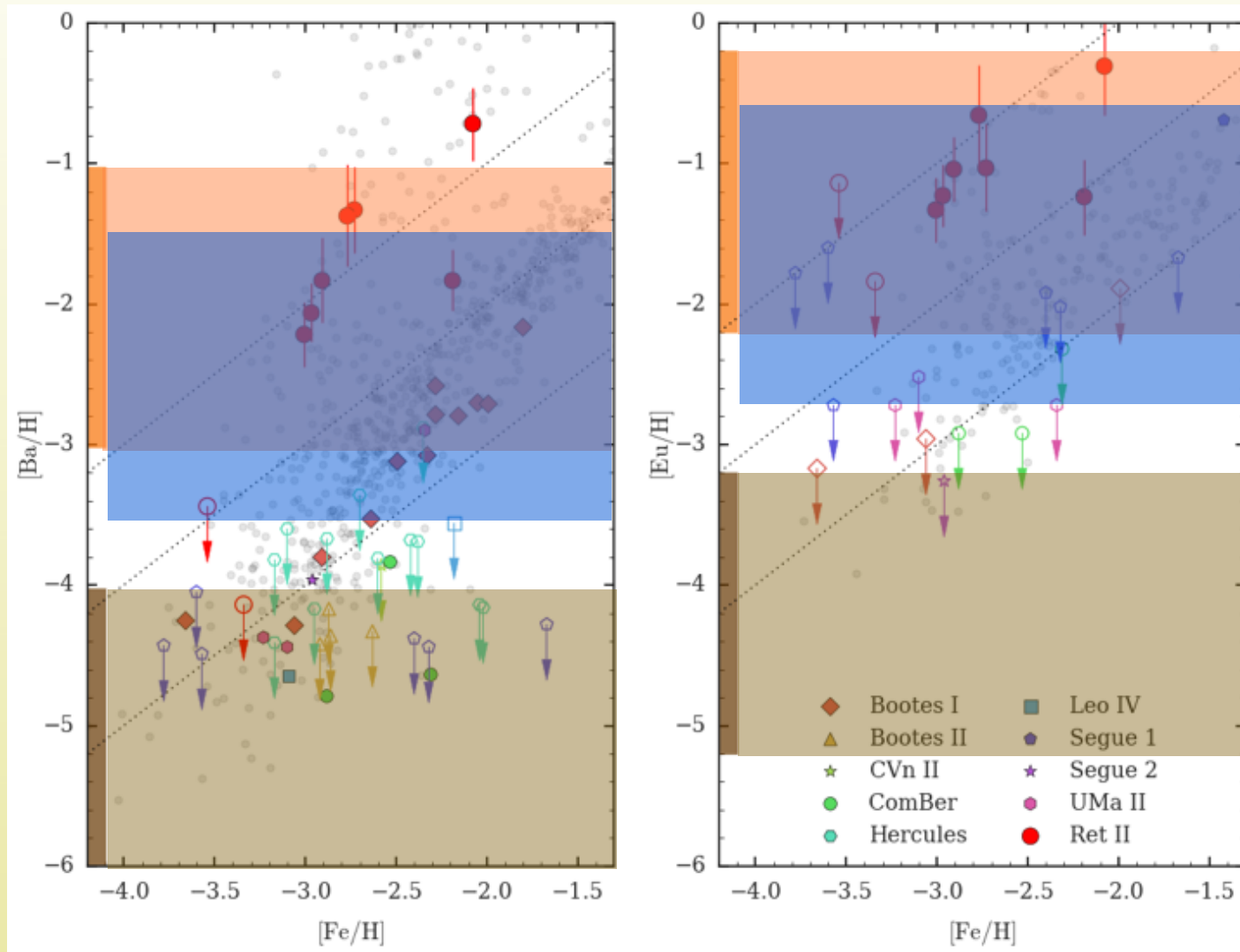


Ji et al 2016, *Nature*, 531, 610

# 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!**

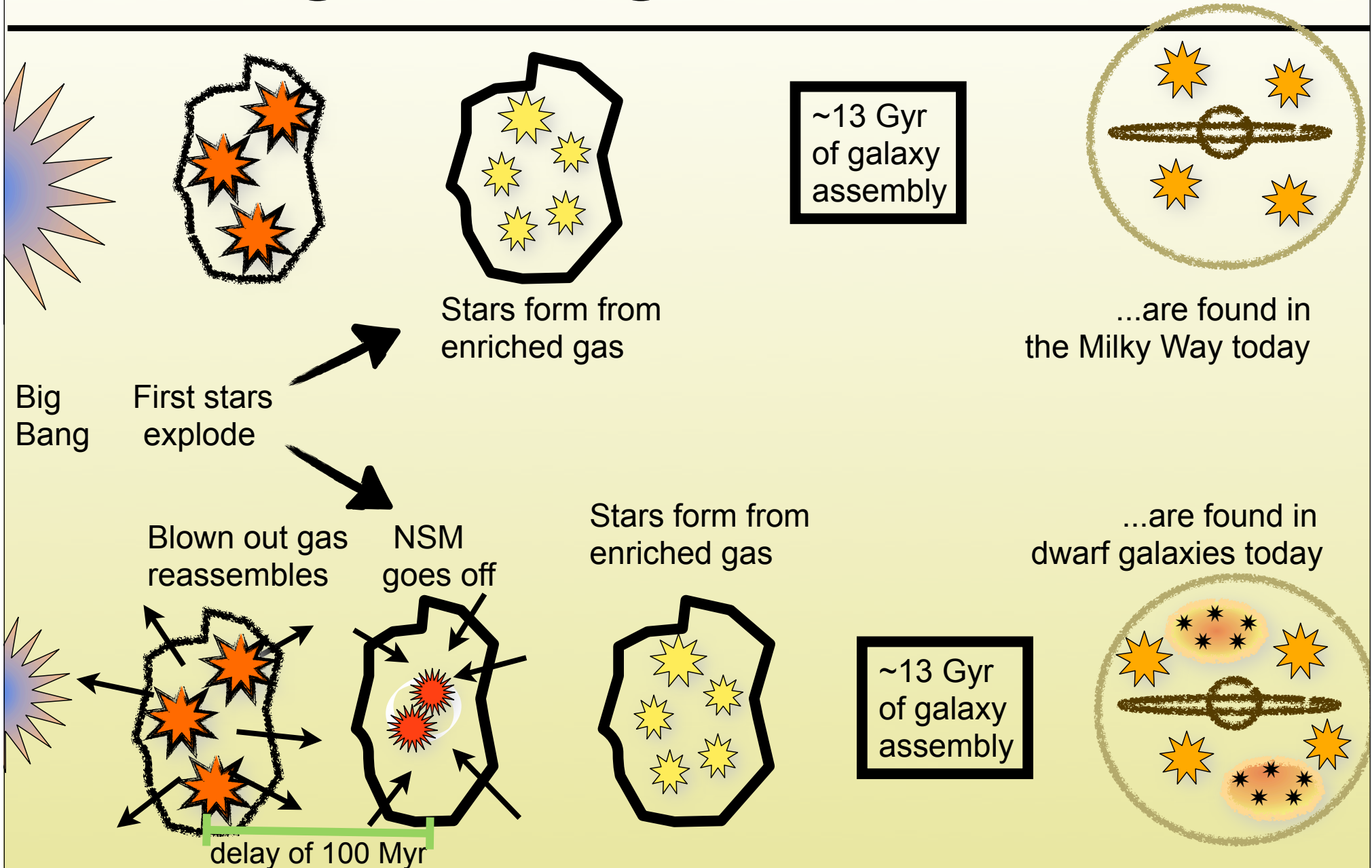
Can't you increase the # of supernovae to get higher yield?

- ➡ 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!