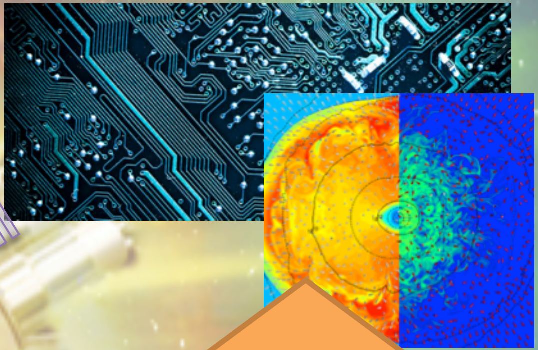
Nuclear Astrophysics

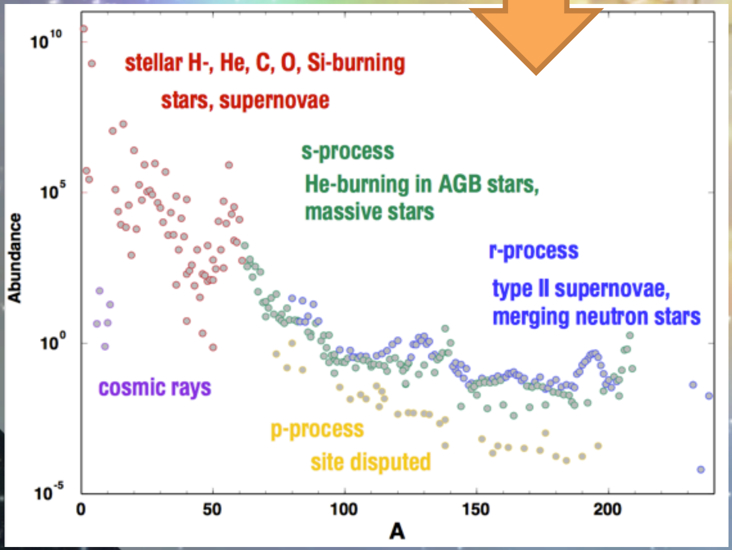
Artemis Spyrou

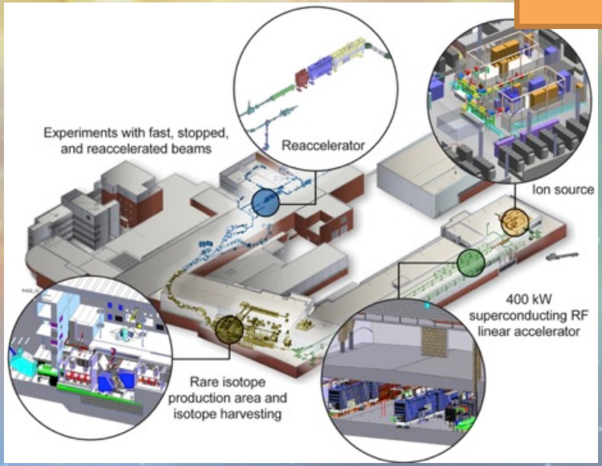
Observations

Models

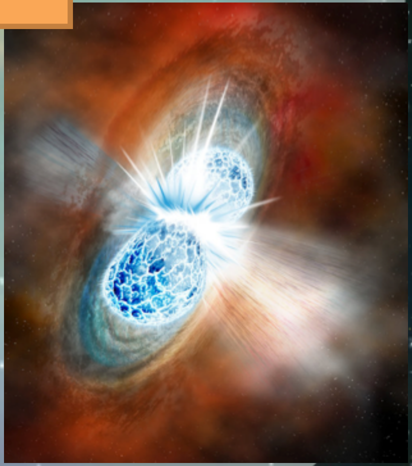


Input





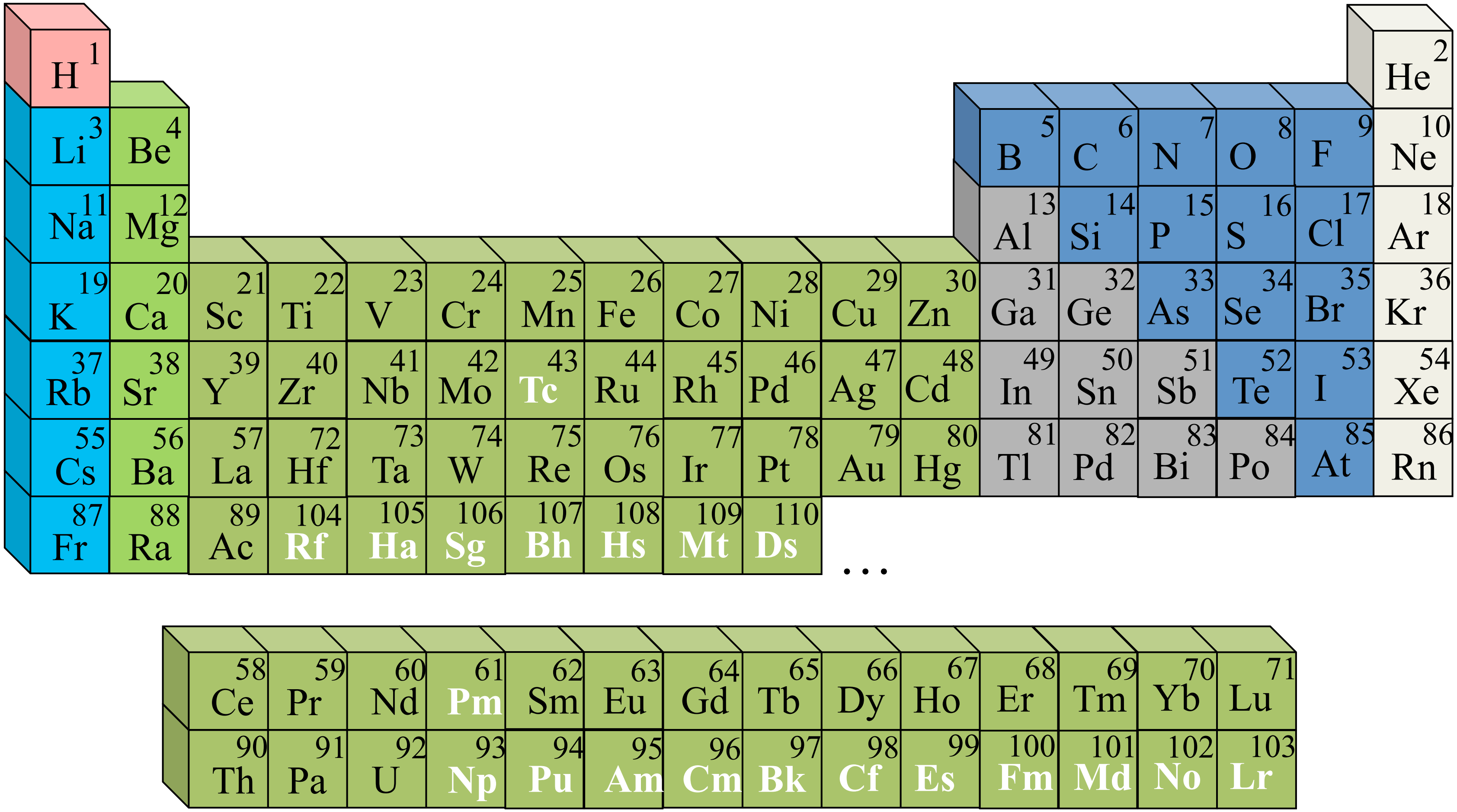
Nuclear



Astro

Figure Credit: Erin O'Donnel, NSCL

Elements in nature

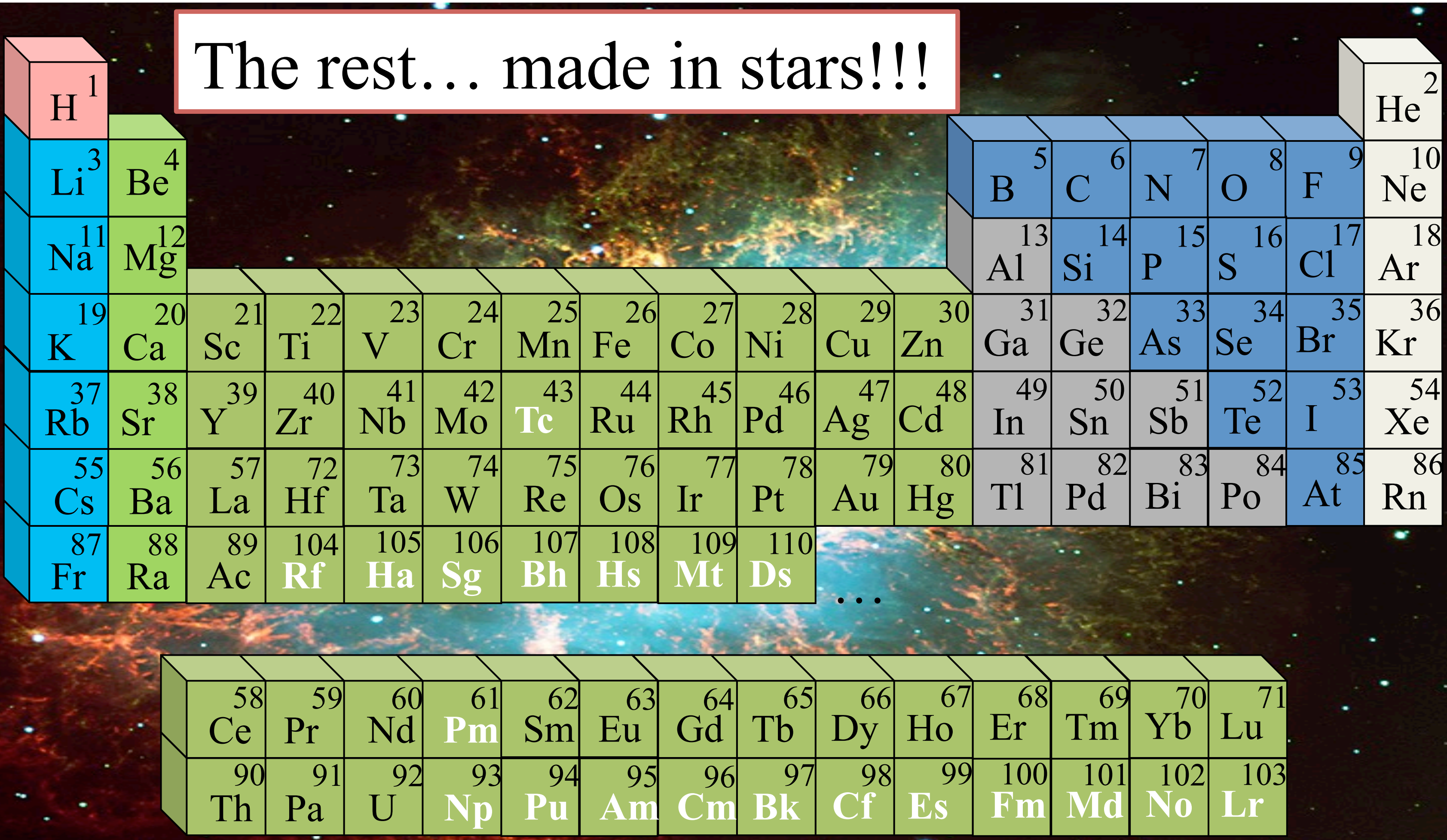


H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	**Tc** 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	La 57	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pd 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	Ac 89	**Rf** 104	**Ha** 105	**Sg** 106	**Bh** 107	**Hs** 108	**Mt** 109	**Ds** 110	…							

Ce 58	Pr 59	Nd 60	**Pm** 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
Th 90	Pa 91	U 92	**Np** 93	**Pu** 94	**Am** 95	**Cm** 96	**Bk** 97	**Cf** 98	**Es** 99	**Fm** 100	**Md** 101	**No** 102	**Lr** 103

Elements in nature

Elements in nature

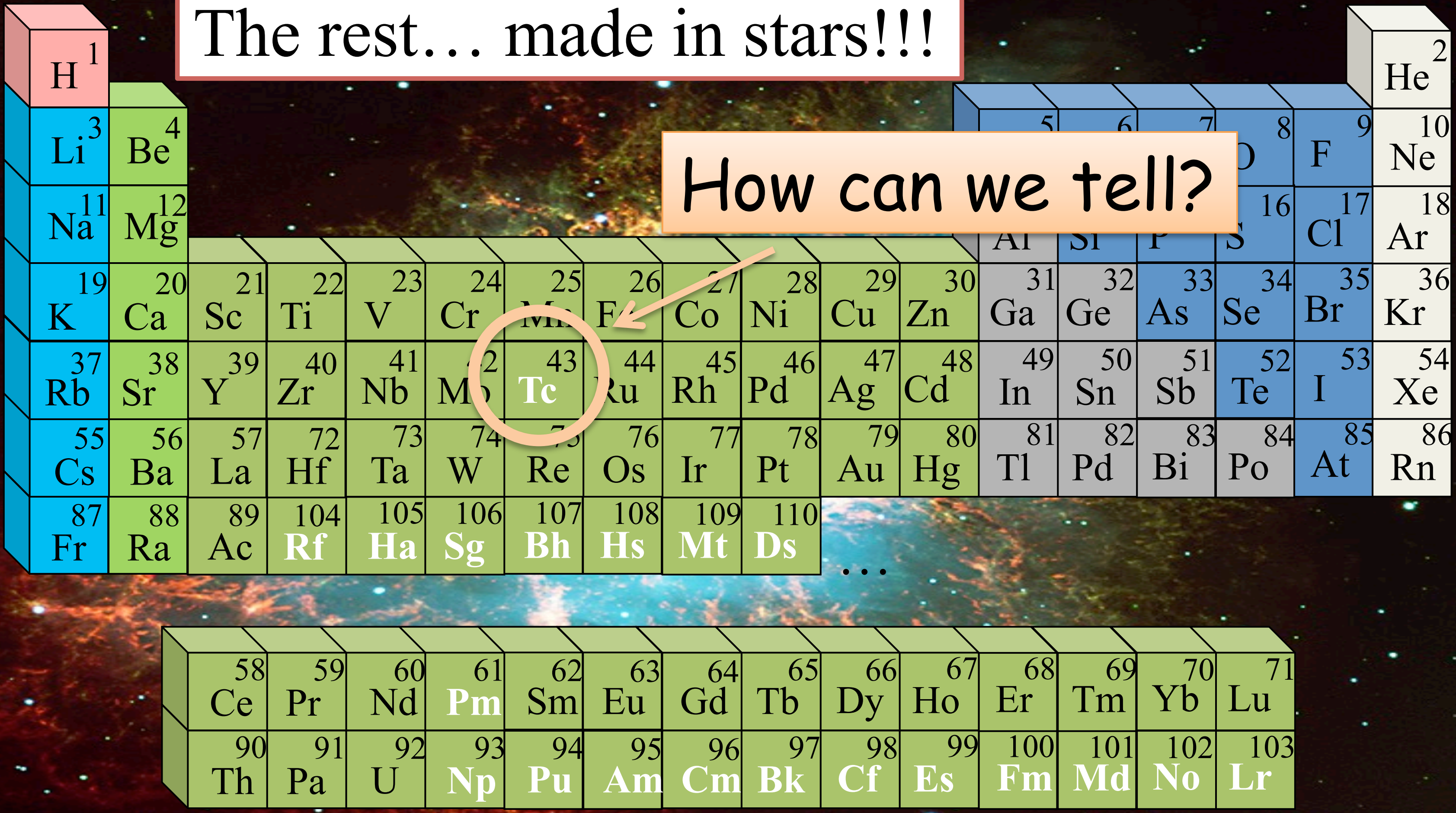


The rest… made in stars!!!

1 H																	2 He
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	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pd	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Ha	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	…							

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	71 Lu
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	103 Lr

Elements in nature

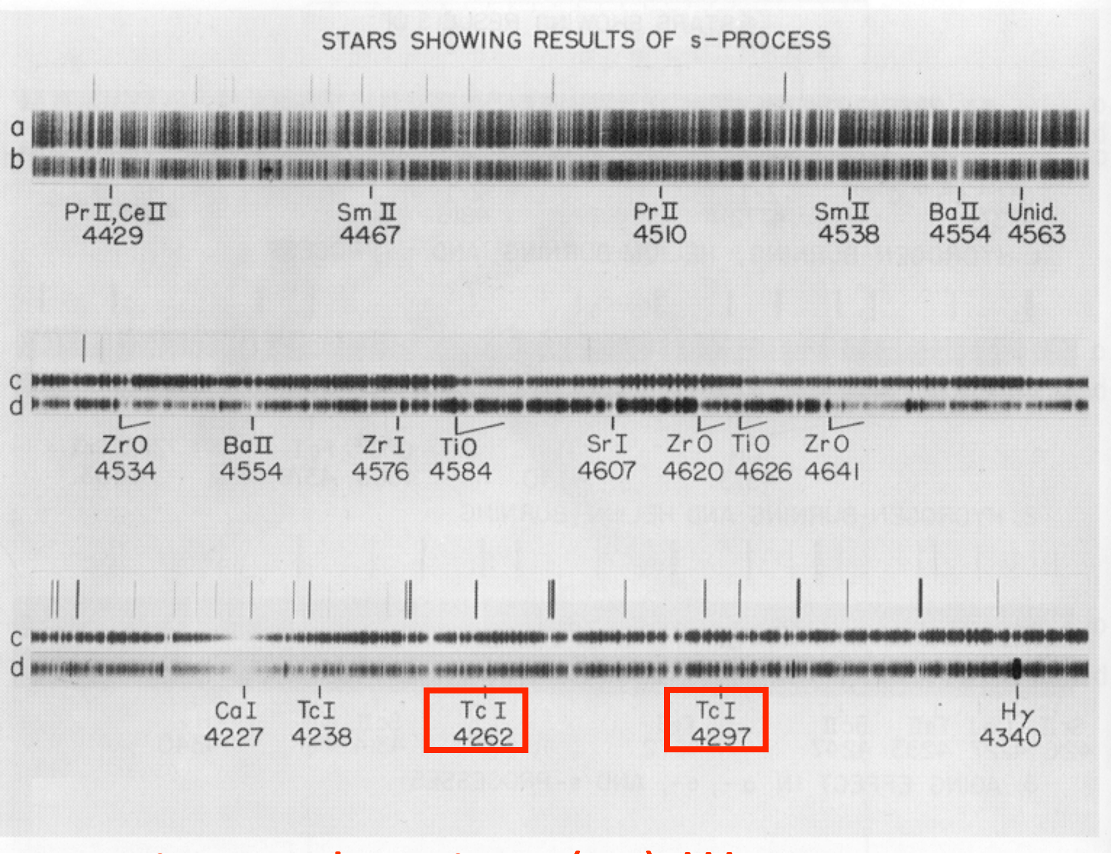


The rest… made in stars!!!

How can we tell?

How Can We Tell?

Light from a red giant (s-process):

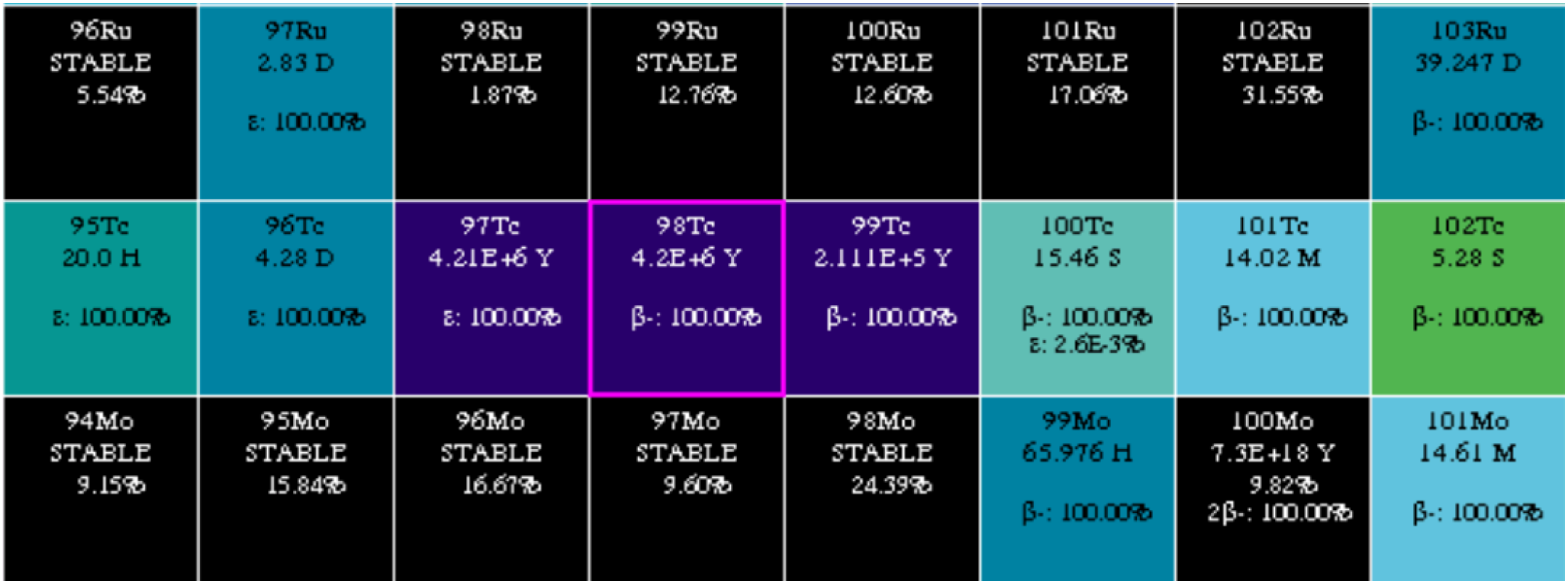


Star contains Technetium (Tc) !!!

(heavy element Z=43, $T_{1/2}$ = 4 Million years, Merrill 1952)

Merrill 1952

- Known at the time that Tc is an “artificial” element
- Artificial = someone has to make it

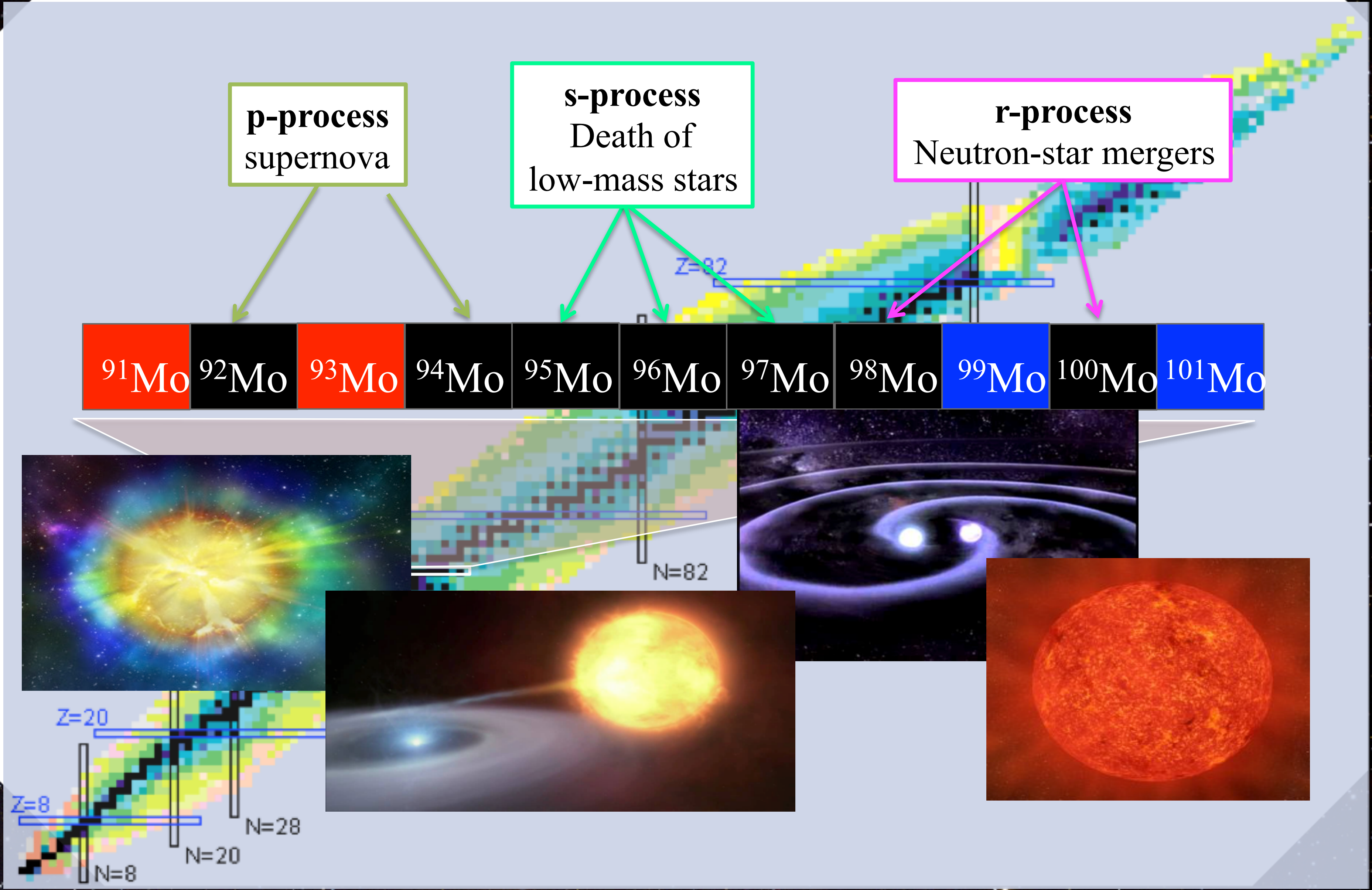


96Ru STABLE 5.54%	97Ru 2.83 D ε: 100.00%	98Ru STABLE 1.87%	99Ru STABLE 12.76%	100Ru STABLE 12.60%	101Ru STABLE 17.06%	102Ru STABLE 31.55%	103Ru 39.247 D β-: 100.00%
95Tc 20.0 H ε: 100.00%	96Tc 4.28 D ε: 100.00%	97Tc 4.21E+6 Y ε: 100.00%	98Tc 4.2E+6 Y β-: 100.00%	99Tc 2.111E+5 Y β-: 100.00%	100Tc 15.46 S β-: 100.00% ε: 2.6E-3%	101Tc 14.02 M β-: 100.00%	102Tc 5.28 S β-: 100.00%
94Mo STABLE 9.15%	95Mo STABLE 15.84%	96Mo STABLE 16.67%	97Mo STABLE 9.60%	98Mo STABLE 24.39%	99Mo 65.976 H β-: 100.00%	100Mo 7.3E+18 Y 9.82% 2β-: 100.00%	101Mo 14.61 M β-: 100.00%

- Merril 1952: “It is surprising to find an unstable element in the stars”

…“(1) A stable isotope (of technetium) actually exists although not yet found on Earth; or (2) S-type stars somehow produce technetium as they go along; or (3) S-type stars represent a comparatively transient phase of stellar existence”

Nuclear Landscape



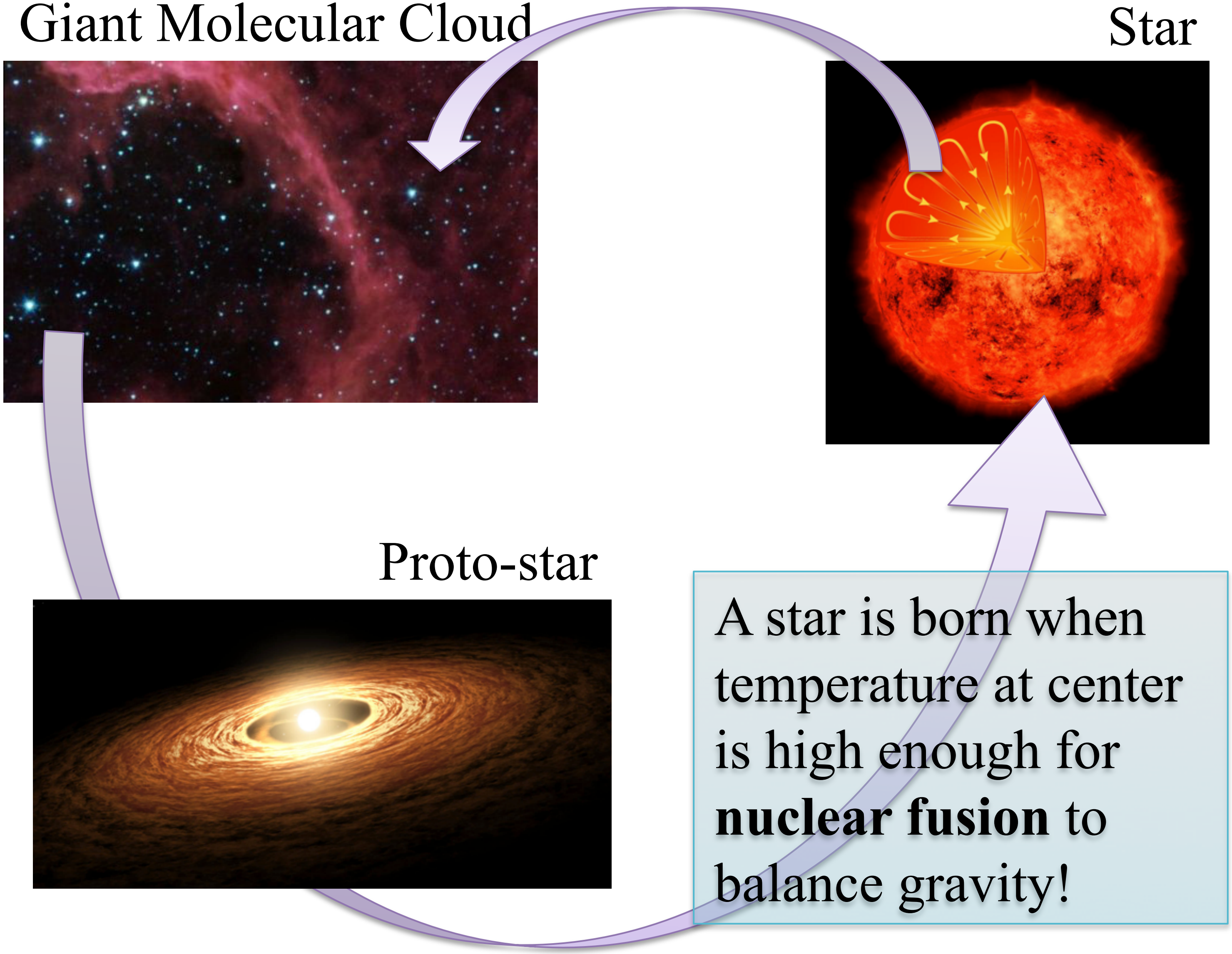
p-process
supernova

s-process
Death of
low-mass stars

r-process
Neutron-star mergers

^{91}Mo ^{92}Mo ^{93}Mo ^{94}Mo ^{95}Mo ^{96}Mo ^{97}Mo ^{98}Mo ^{99}Mo ^{100}Mo ^{101}Mo

Stellar Evolution



Giant Molecular Cloud

Star

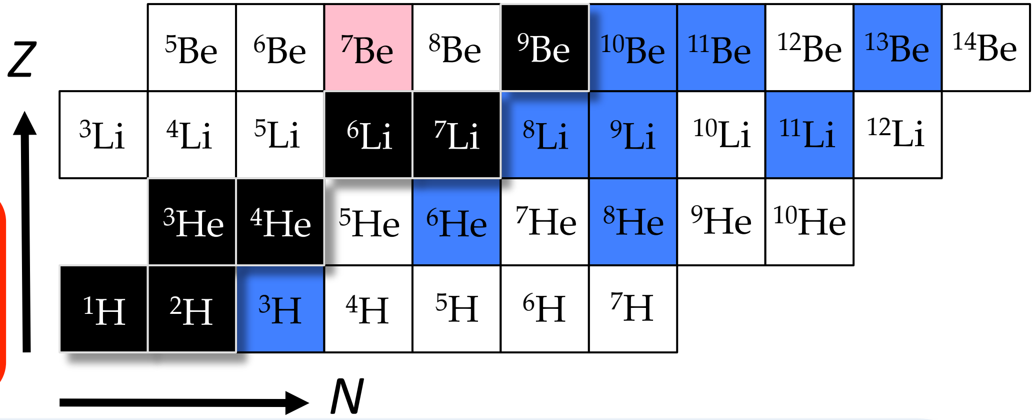
Proto-star

A star is born when temperature at center is high enough for **nuclear fusion** to balance gravity!

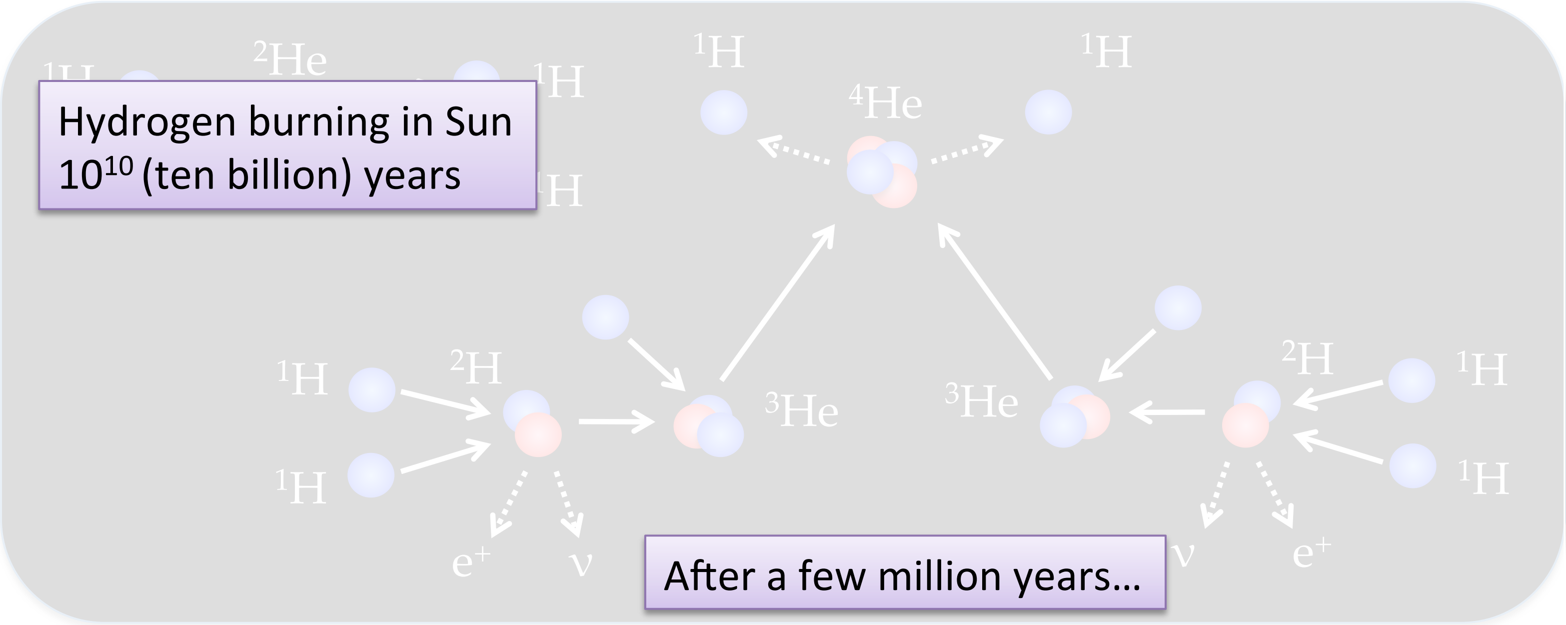
Nuclear-Astro-physics

Interstellar medium :
~ 1 particle per cm^{3}

Main ingredients
H (Hydrogen/protons)
He (Helium)



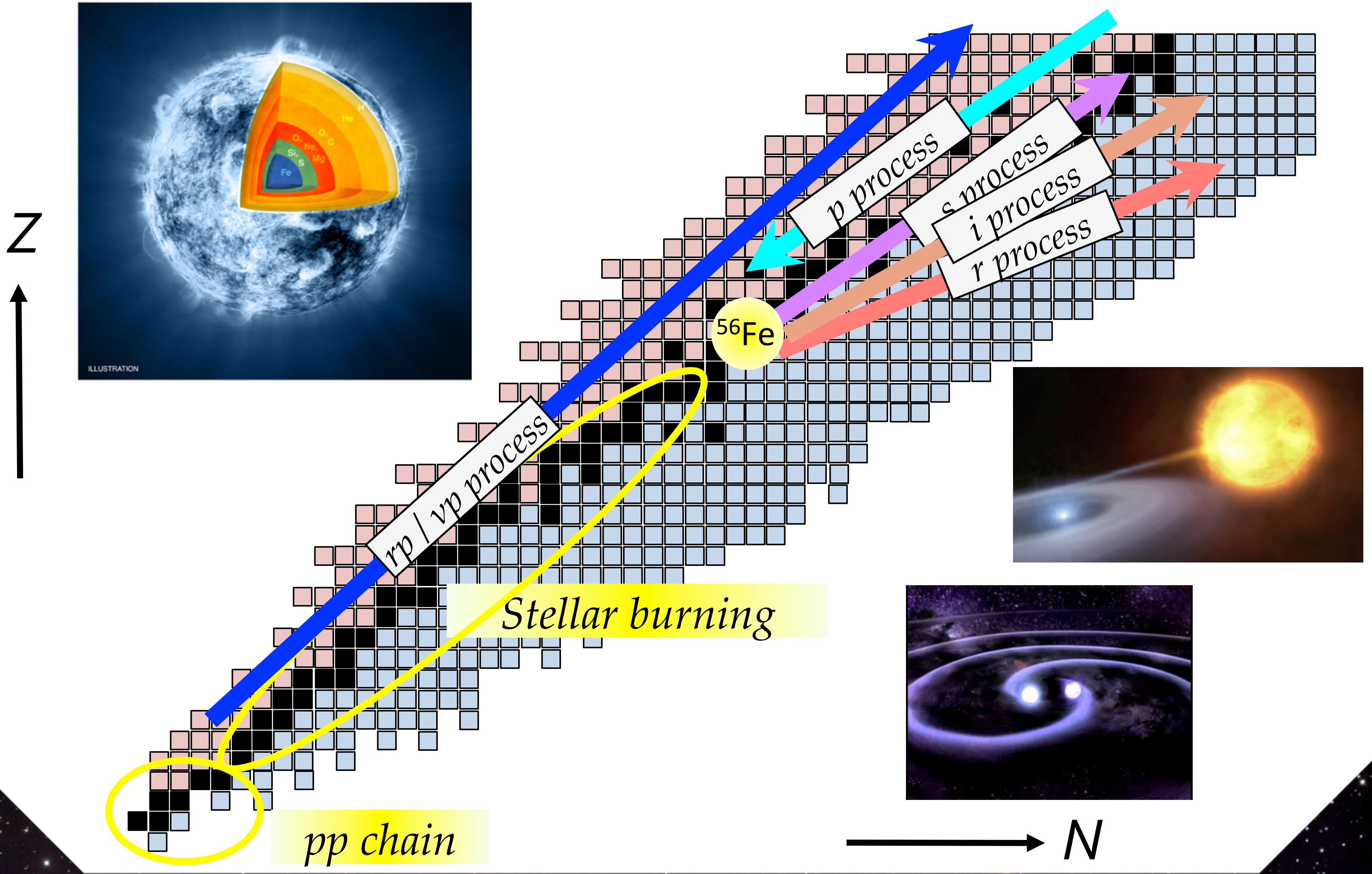
	^{5}Be	^{6}Be	^{7}Be	^{8}Be	^{9}Be	^{10}Be	^{11}Be	^{12}Be	^{13}Be	^{14}Be
^{3}Li	^{4}Li	^{5}Li	^{6}Li	^{7}Li	^{8}Li	^{9}Li	^{10}Li	^{11}Li	^{12}Li	
	^{3}He	^{4}He	^{5}He	^{6}He	^{7}He	^{8}He	^{9}He	^{10}He		
^{1}H	^{2}H	^{3}H	^{4}H	^{5}H	^{6}H	^{7}H				



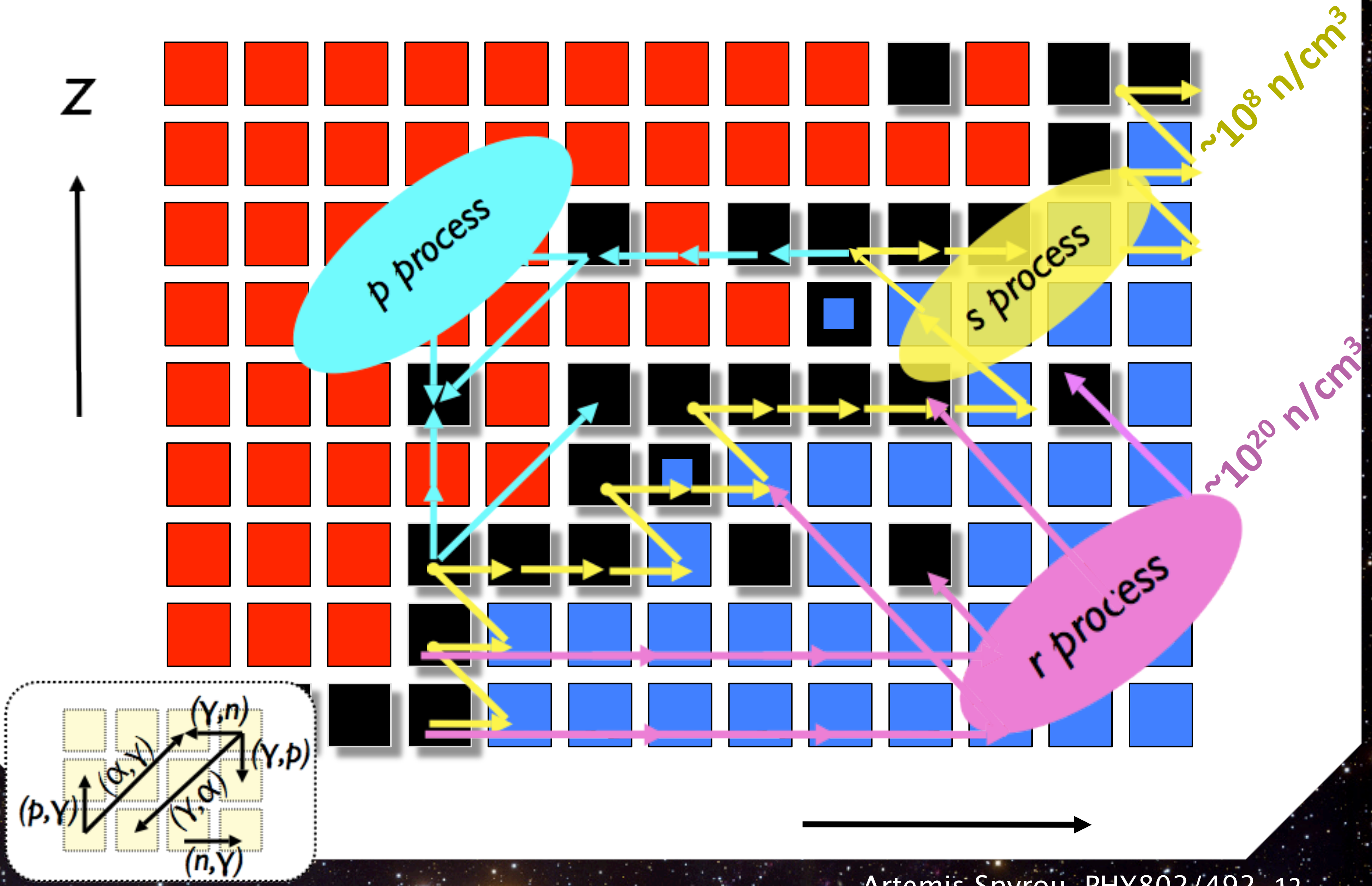
Hydrogen burning in Sun
10^{10} (ten billion) years

After a few million years…

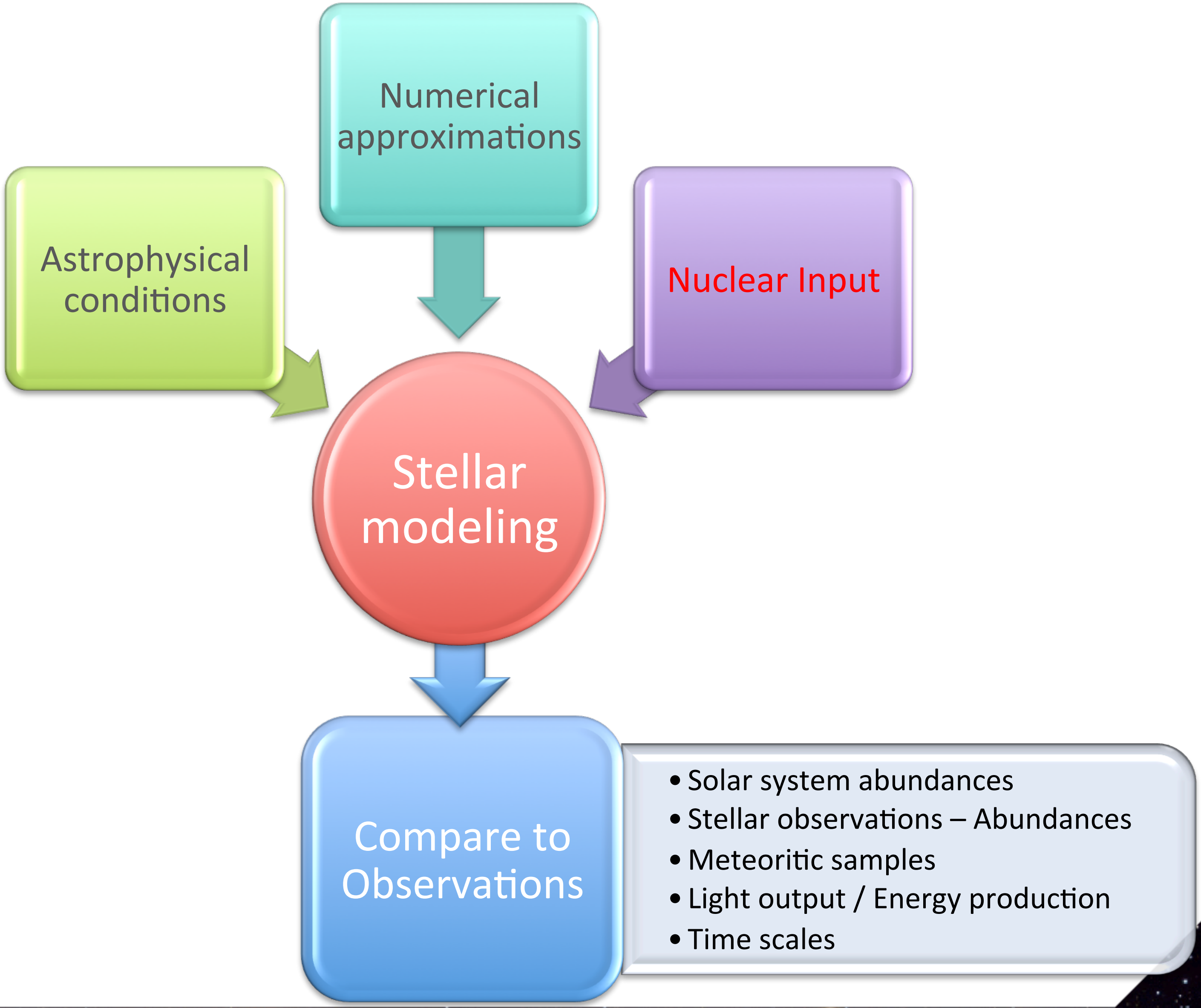
Nucleosynthesis paths



Paths beyond Iron



Nuclear Astrophysics Connections



Numerical approximations

Astrophysical conditions

Nuclear Input

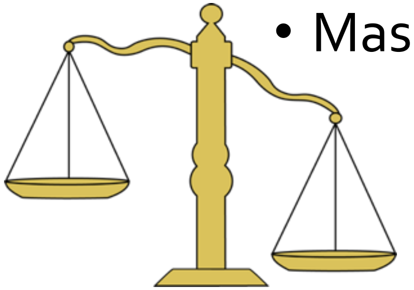
Stellar modeling

Compare to Observations

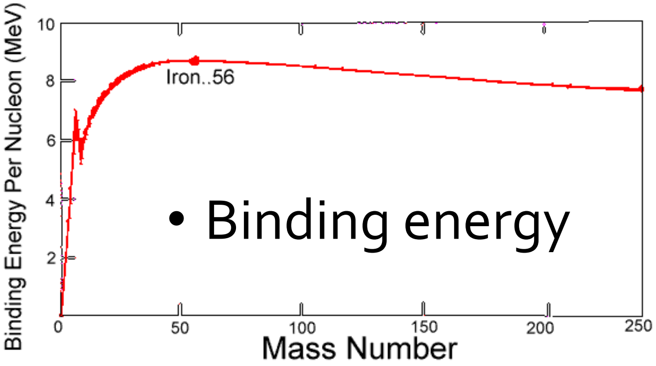
- Solar system abundances
- Stellar observations – Abundances
- Meteoritic samples
- Light output / Energy production
- Time scales

Nuclear input: What do we need?

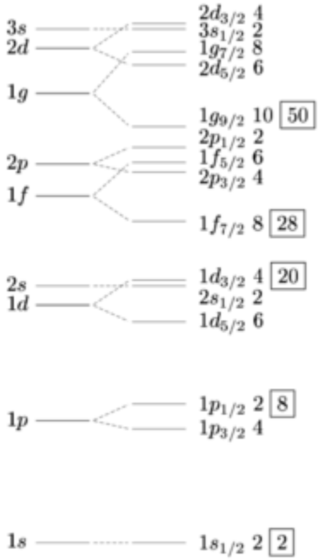
- Basic nuclear properties



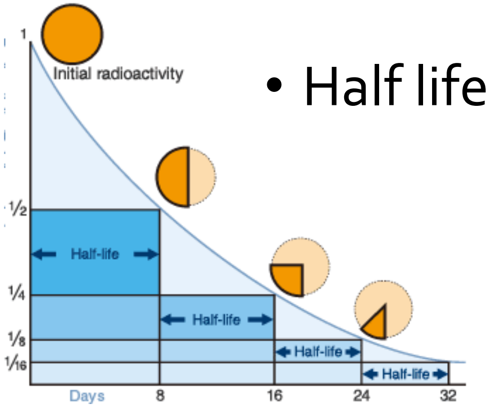
- Mass



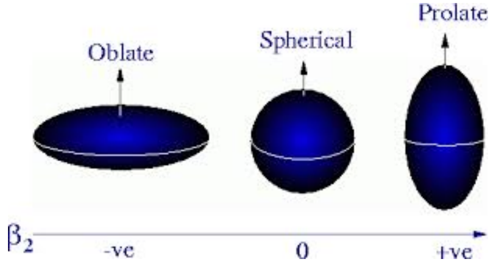
- Binding energy



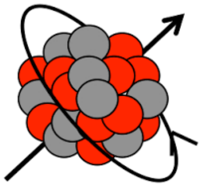
- Level structure



- Half life

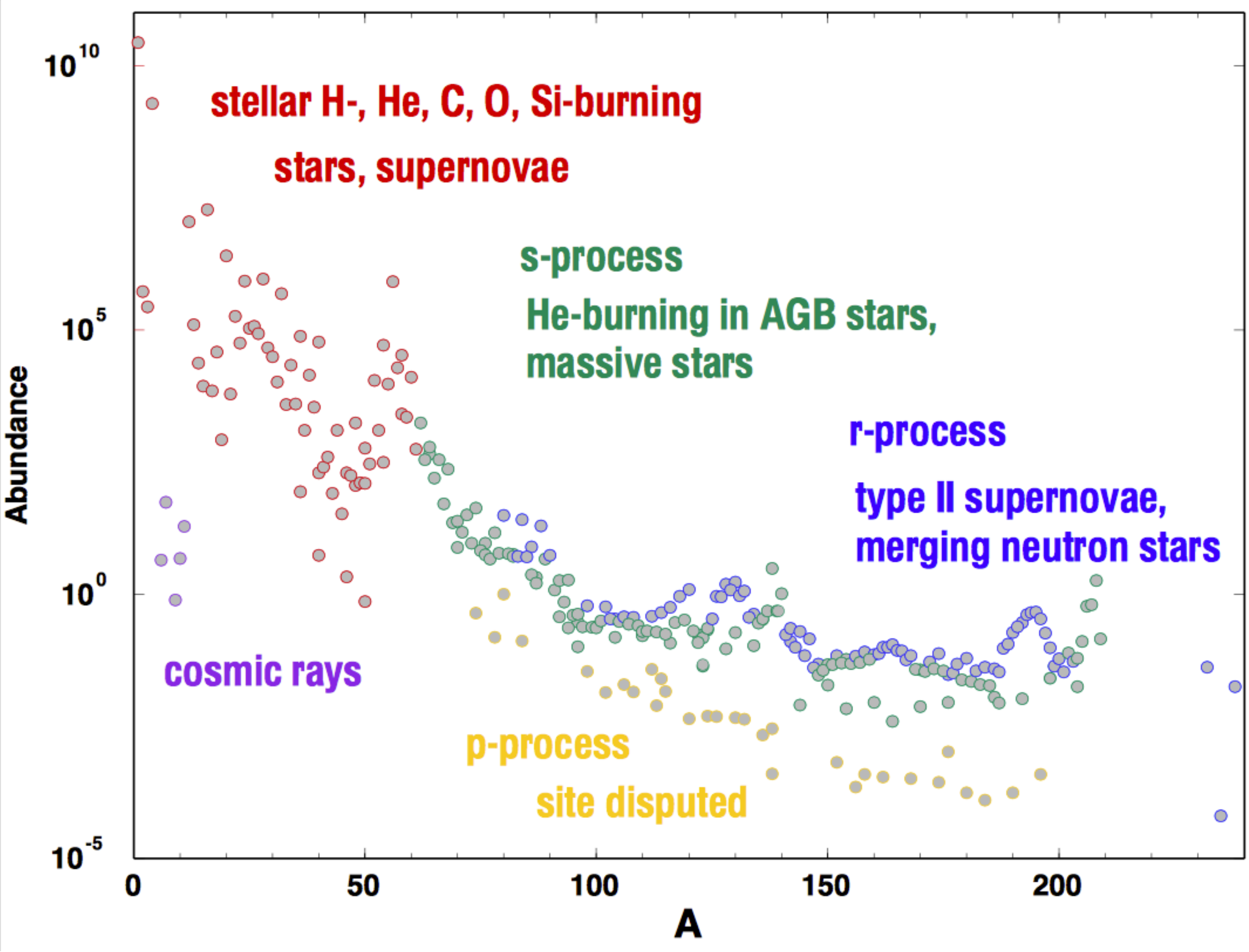


- Nuclear radius/shape



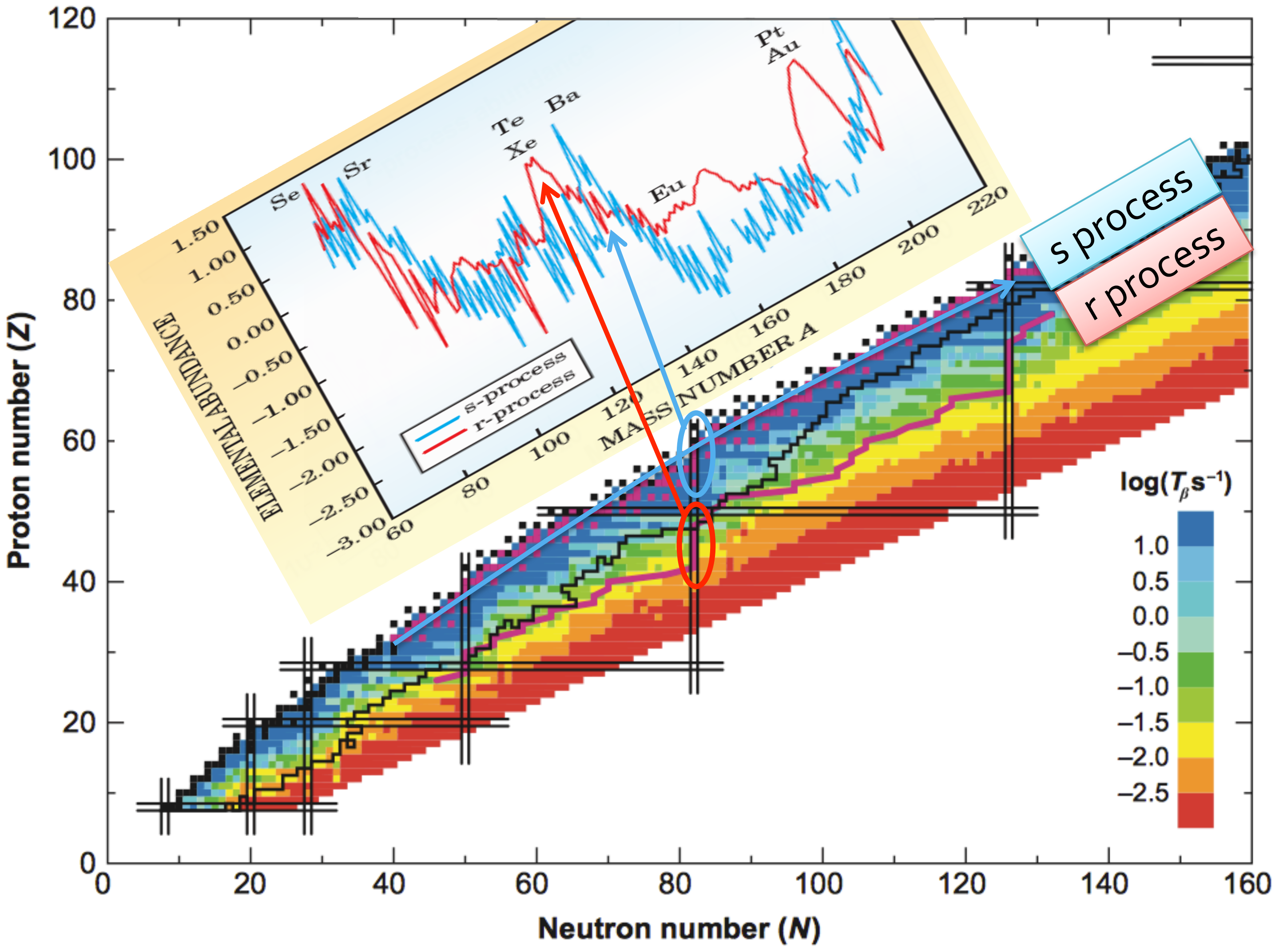
- Angular Momentum

Abundances



From M. Wiescher, JINA web

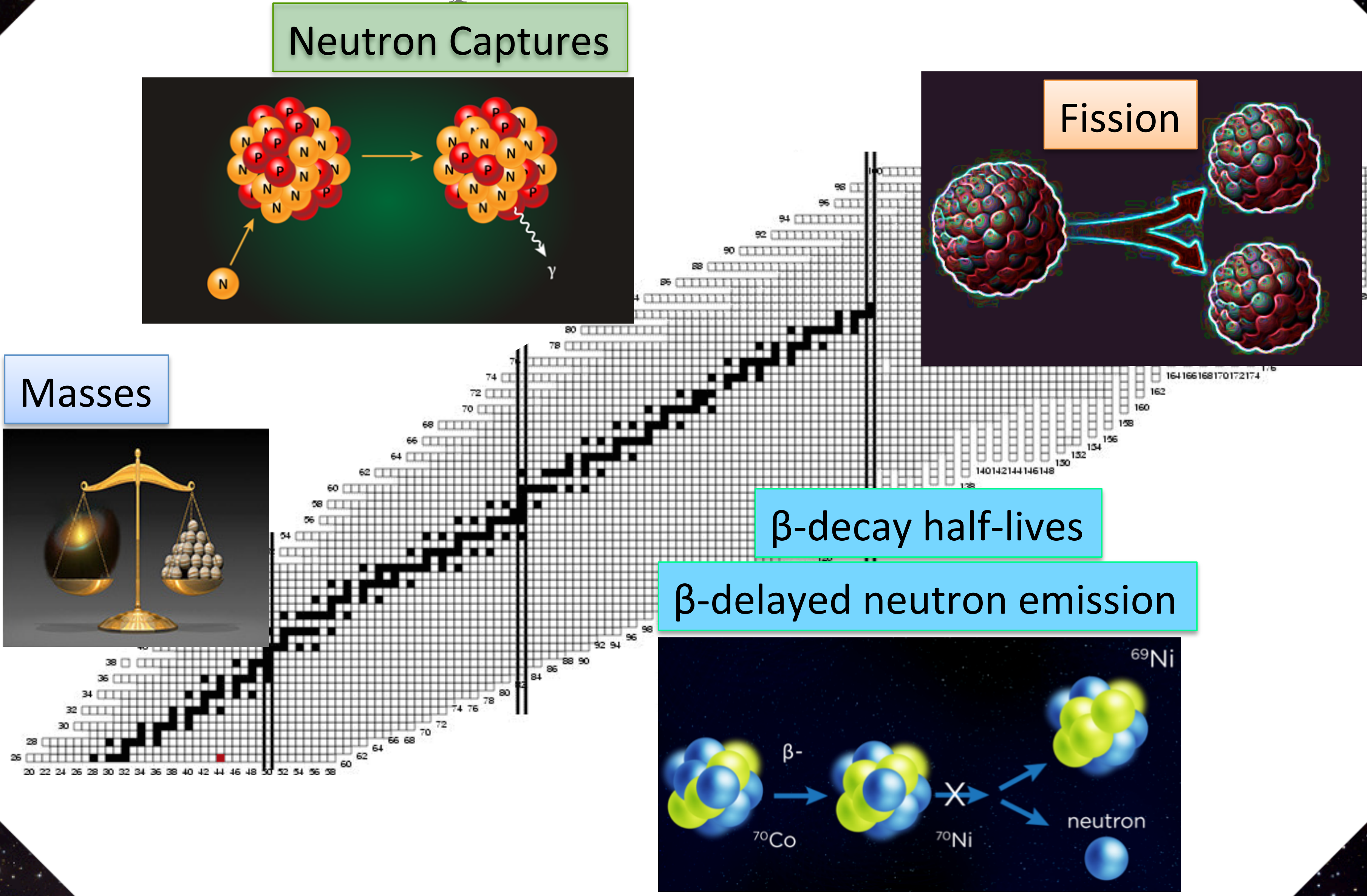
s/r-process paths and abundances



Sneden, C., Cowan, J. J., & Gallino, R., *Ann. Rev. Ast. Ap.* **46** (200

Cowan and Thielemann, Physics Today, 2004

r-process simulation



Neutron Captures

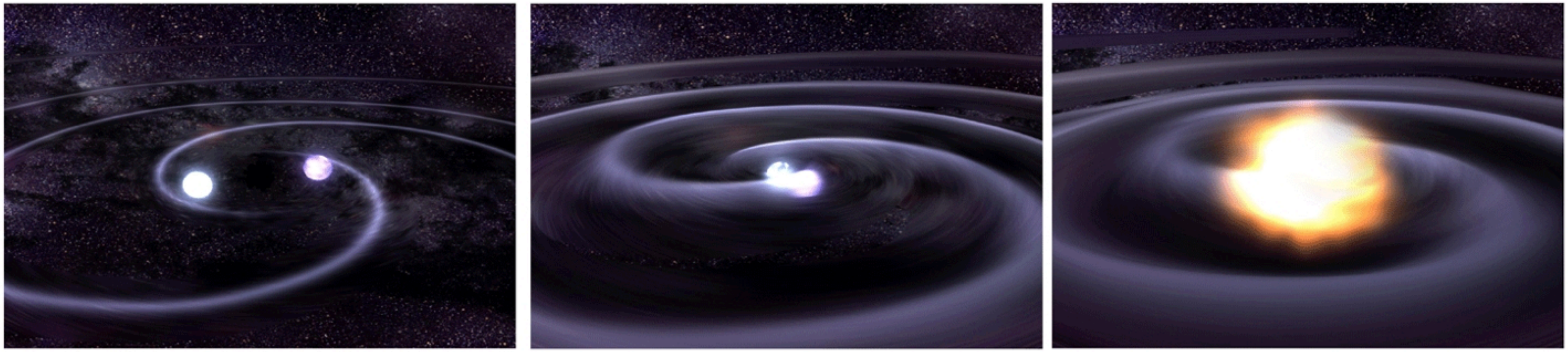
Fission

Masses

β-decay half-lives

β-delayed neutron emission

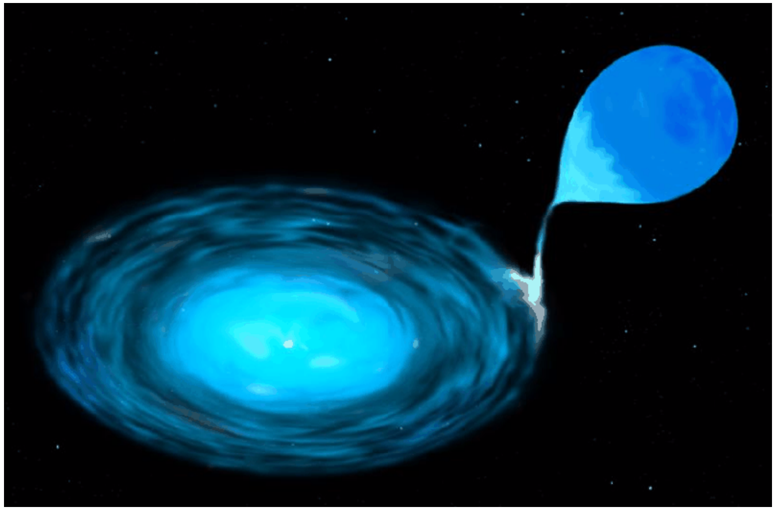
GW170817

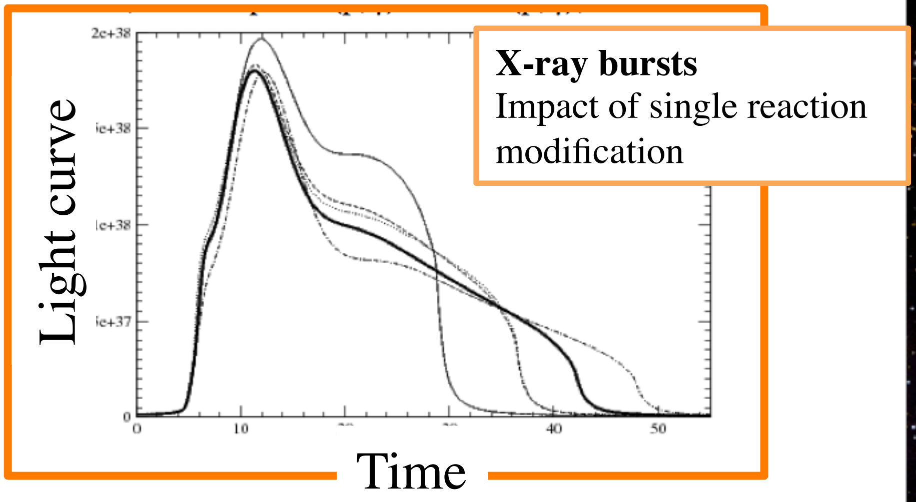


- First observation of neutron-star merger
- Multi-messenger astronomy: 3 GW detectors + 90 telescopes observed the event
- Observation of Heavy elements!!! A LOT of them: ~100 Earth Masses of gold.
- What does this mean for nuclear astrophysics?
  - We know neutron-star mergers is **at least one of the sites** for the r-process
  - Better constraint on astrophysical conditions, need to **constrain nuclear input**.
  - Tidal tails: Cold and neutron rich-> (n,γ) – (γ,n) equilibrium is not reached: **neutron-capture reactions more important than ever**
  - More neutron-rich than expected->need to reach **even farther** from the valley of stability

X-ray bursts

Accreting Neutron Star





X-ray bursts
Impact of single reaction modification

- X-ray bursts: most frequent explosions
- Neutron star + companion
- NS accretes H and He-rich material
- Large gravitational attraction!!!
- Material compresses, heated and eventually undergoes thermonuclear burning
- BOOM: X-ray burst
- Process repeated every few hours - days

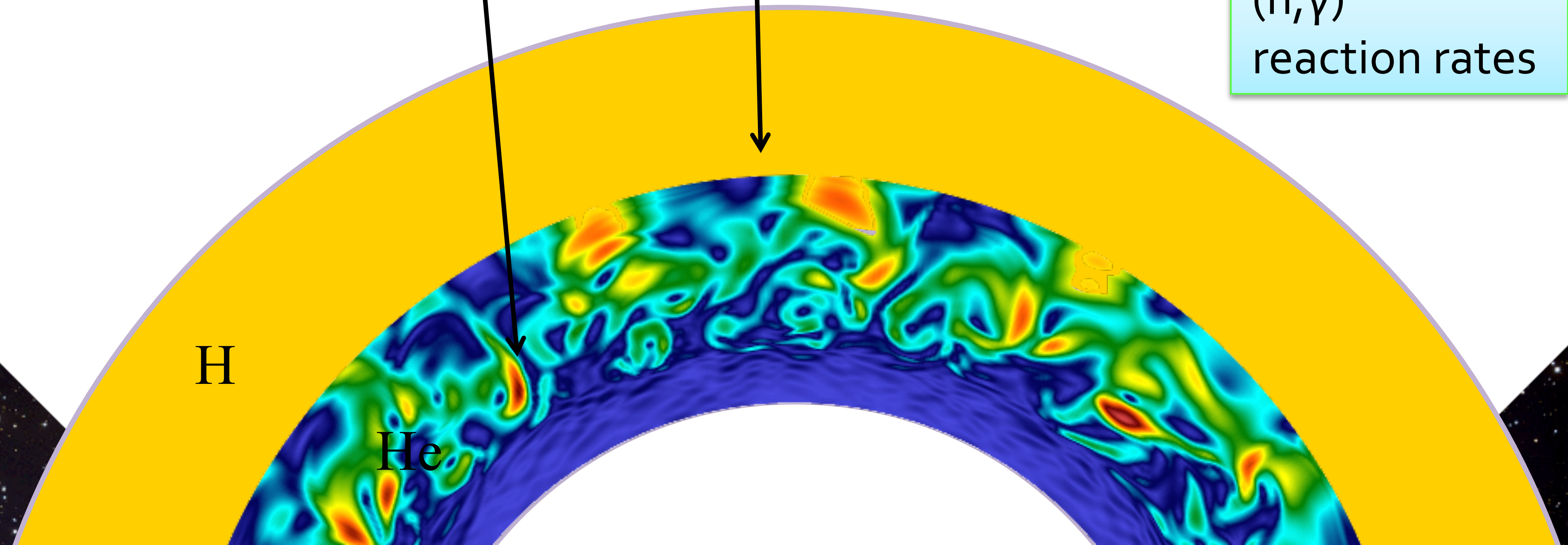
(p,γ) reaction rates

i-process

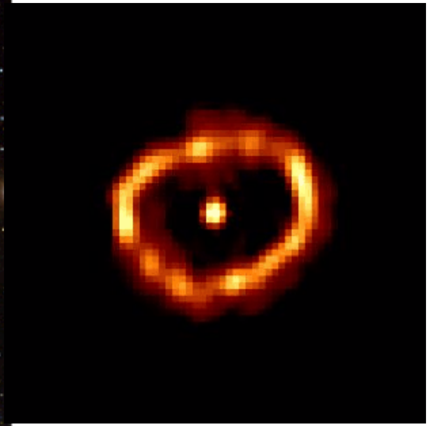
- **Neutron density: 10^{15} cm^{-3}**

  (intermediate between s process (<10^{11} cm^{-3}), and r process (>10^{22} cm^{-3}))
- Proposed in the 1970s and revived recently to explain observations of "strange" abundance distributions (post-AGB and CEMP stars)
- Neutron production: $^{13}C(\alpha,n)^{16}O$ reaction like s process
- Replenishment of ^{13}C via $^{12}C(p,\gamma)^{13}N$ and $^{13}N(e^+)^{13}C$ with $T_{1/2}$~10 minutes.

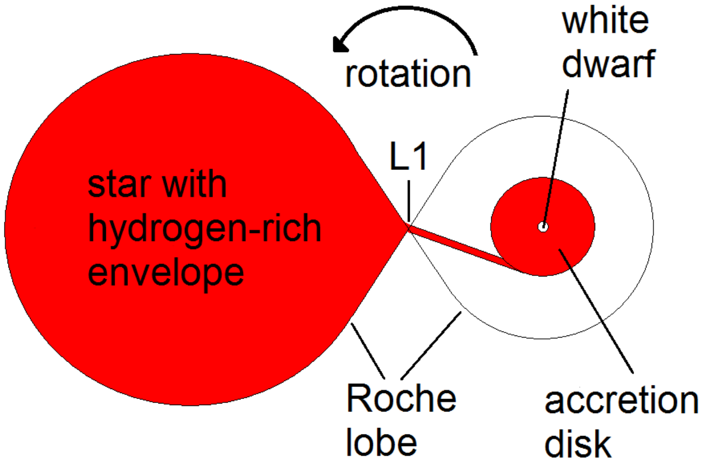
(n,γ) reaction rates



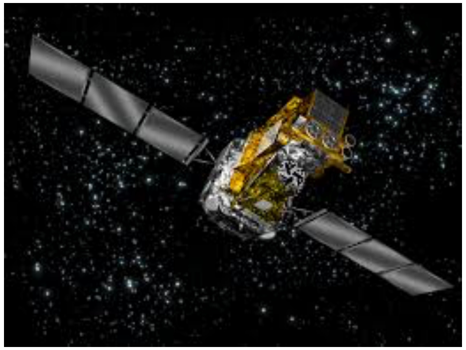
Nova contribution to Galactic ^{26}Al?

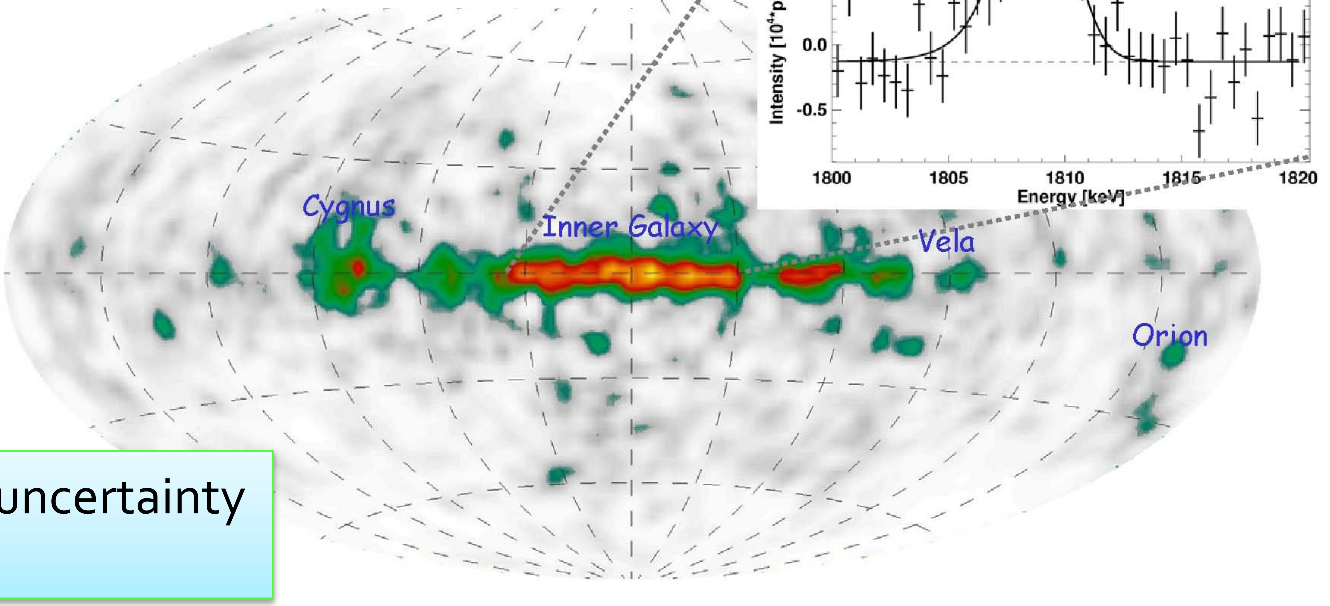


Nova Cygni 1992 (in 1994)
NASA, ESA, HST



Similar observations for ^{60}Fe





Last nuclear-physics uncertainty is ^{25}Al(p,γ)^{26}Si rate

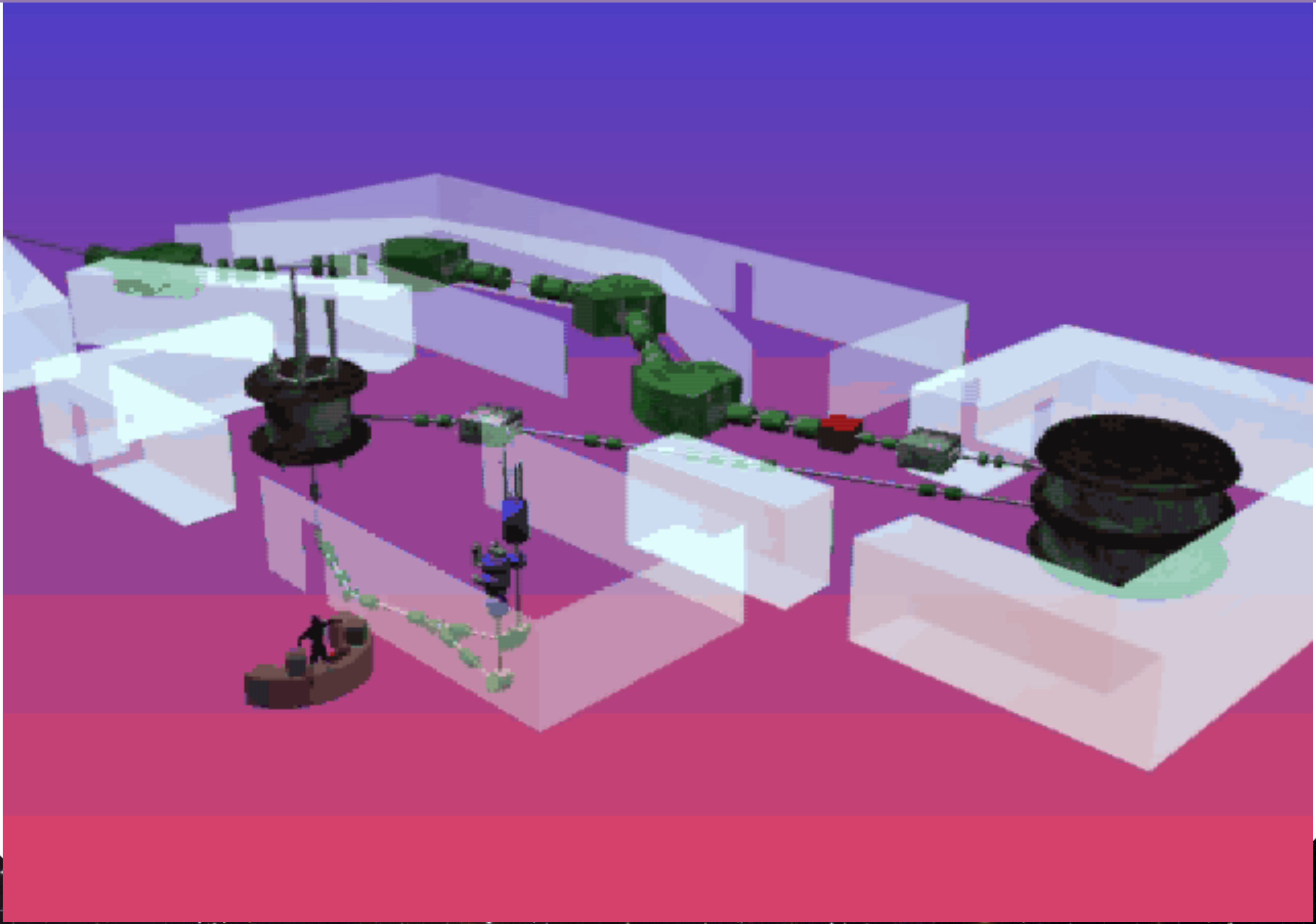
Data from COMPTEL & INTEGRAL-SPI (MPE Garching / Roland Diehl)

Nuclear Input: How to get it!

- Identify necessary properties ✓
- Identify nuclei that matter ✓
- For nuclear reactions – identify appropriate conditions
  - Which astrophysical environment?
  - What is the temperature → Lab Energy
    - Mega Kelvin → A few keV
    - Giga Kelvin → A few MeV
- Find a lab that can produce the right nuclei at the right energy

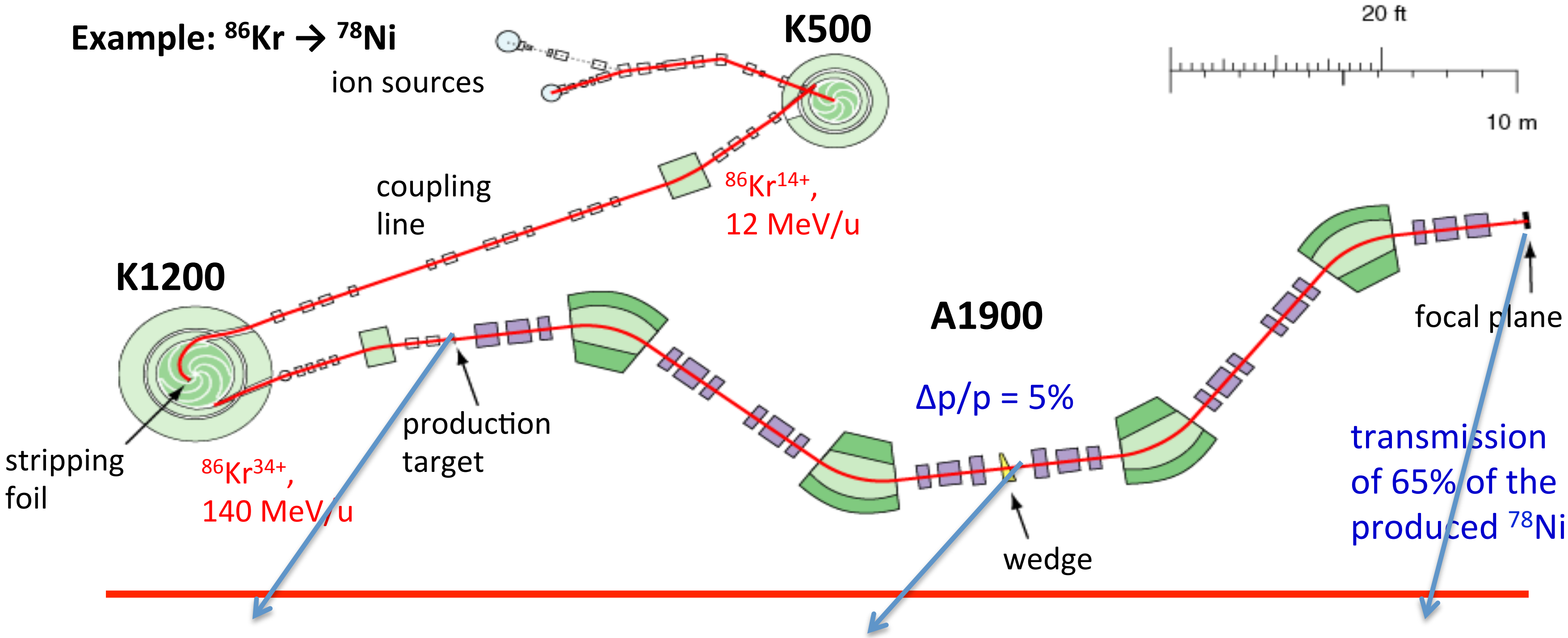
Welcome to NSCL and FRIB ☺

Coupled Cyclotron Facility



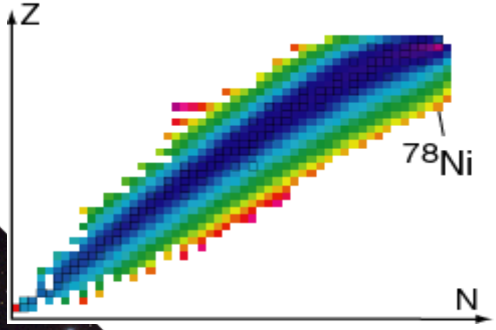
Coupled Cyclotron Facility

Example: $^{86}Kr \rightarrow {}^{78}Ni$

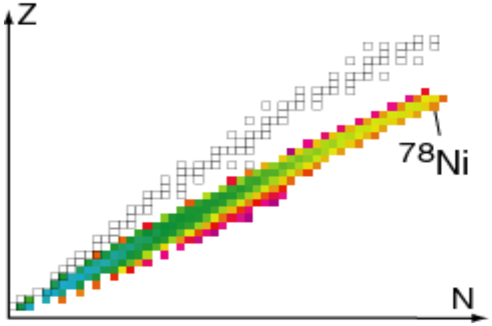


transmission of 65% of the produced ^{78}Ni

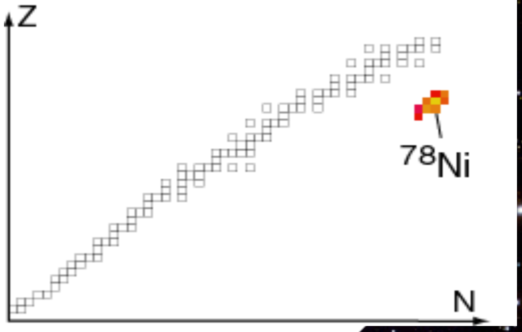
fragment yield after target



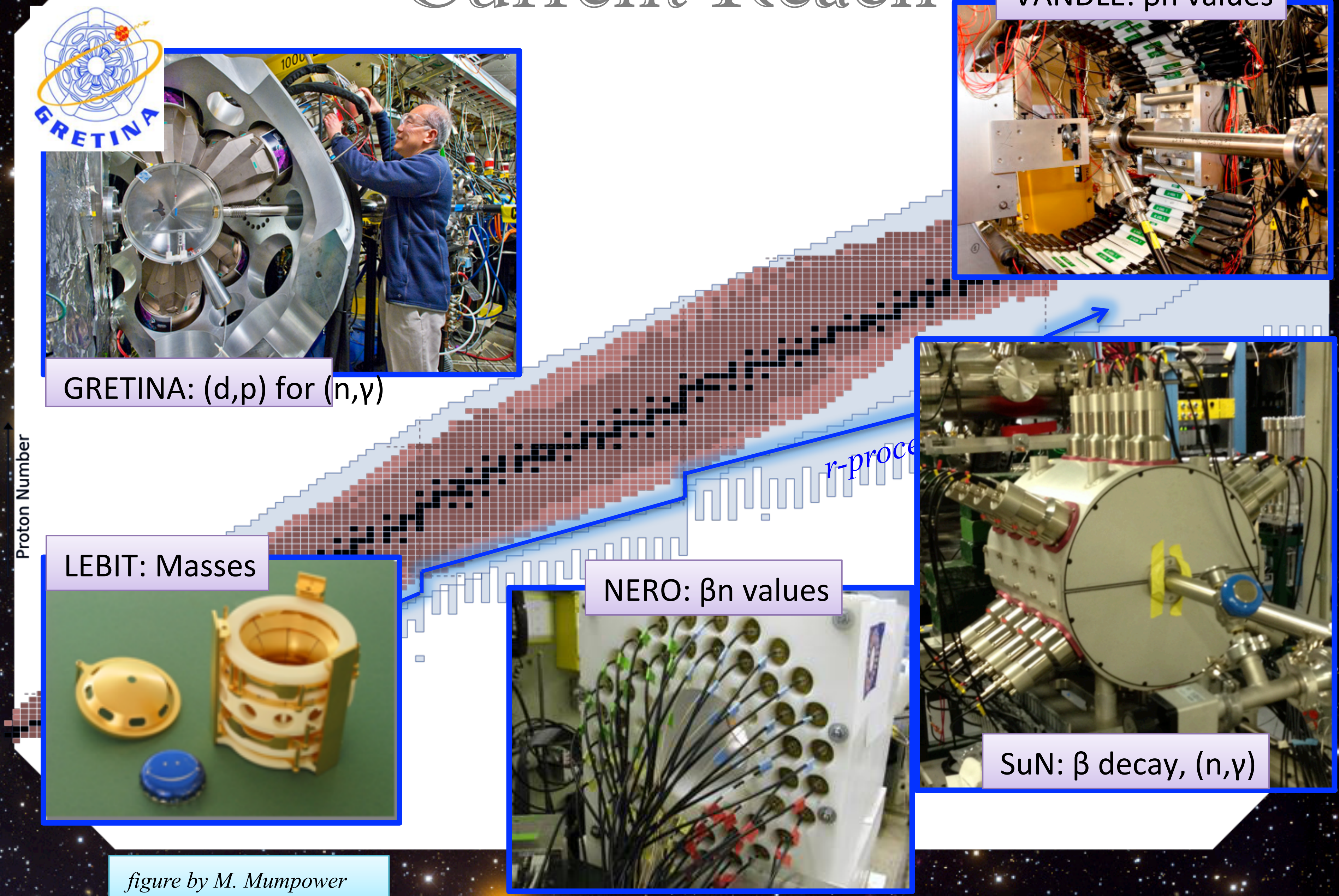
fragment yield after wedge



fragment yield at focal plane



Current Reach



GRETINA: (d,p) for (n,γ)

VANDLE: βn values

LEBIT: Masses

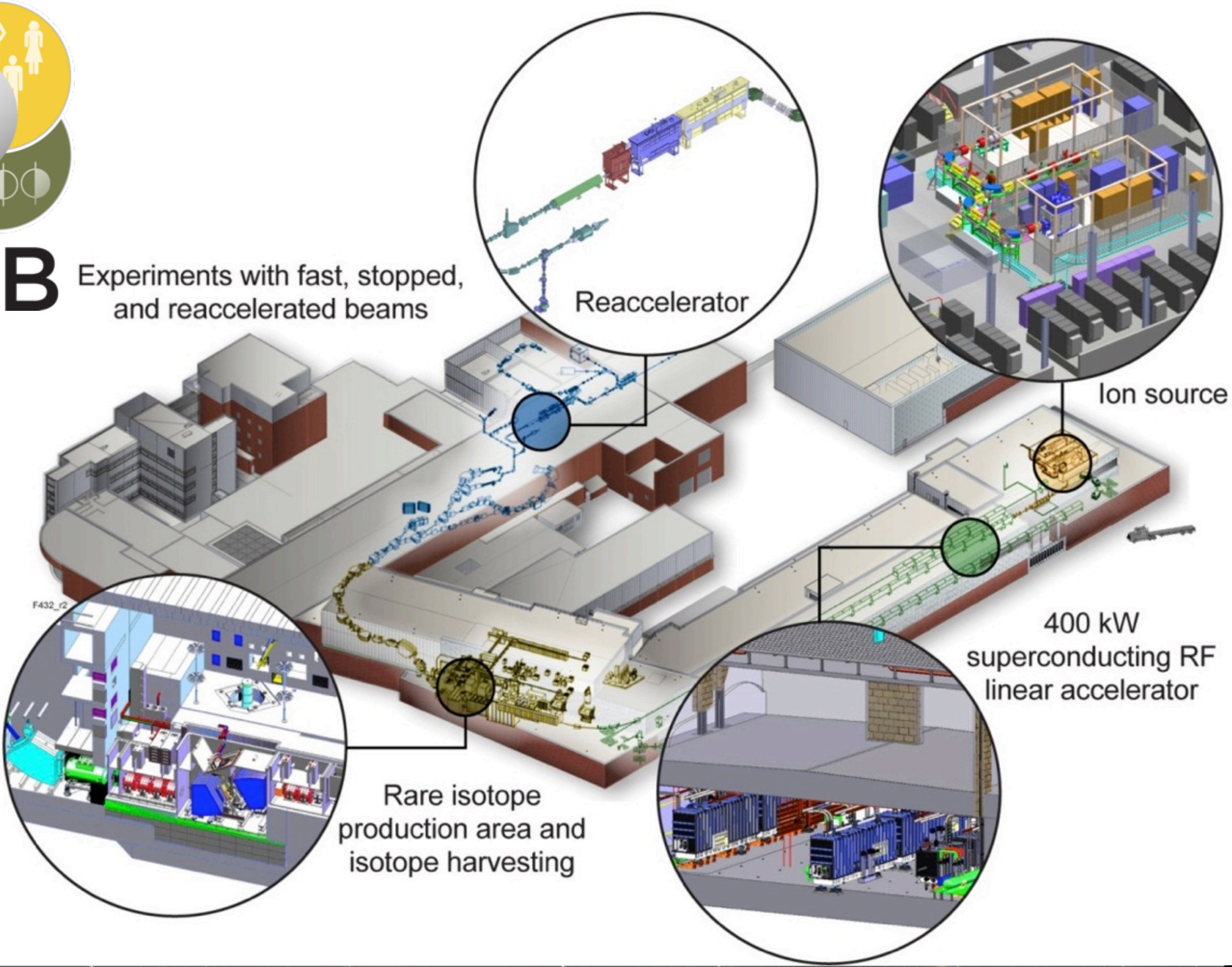
NERO: βn values

SuN: β decay, (n,γ)

figure by M. Mumpower

Facility for Rare Isotope Beams

FRIB



Experiments with fast, stopped, and reaccelerated beams

Reaccelerator

Ion source

400 kW superconducting RF linear accelerator

Rare isotope production area and isotope harvesting