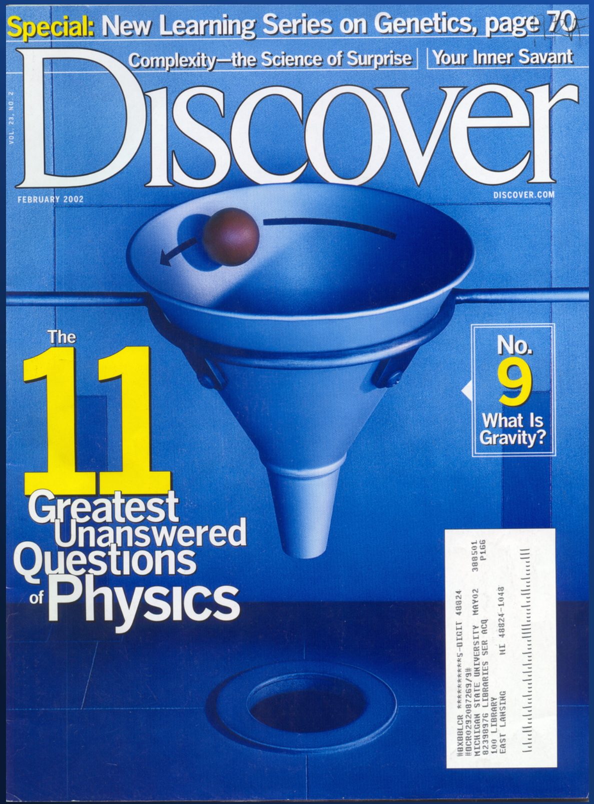
New Physics with GAMKA

Breaking Heavens Code

How were/are the elements made?



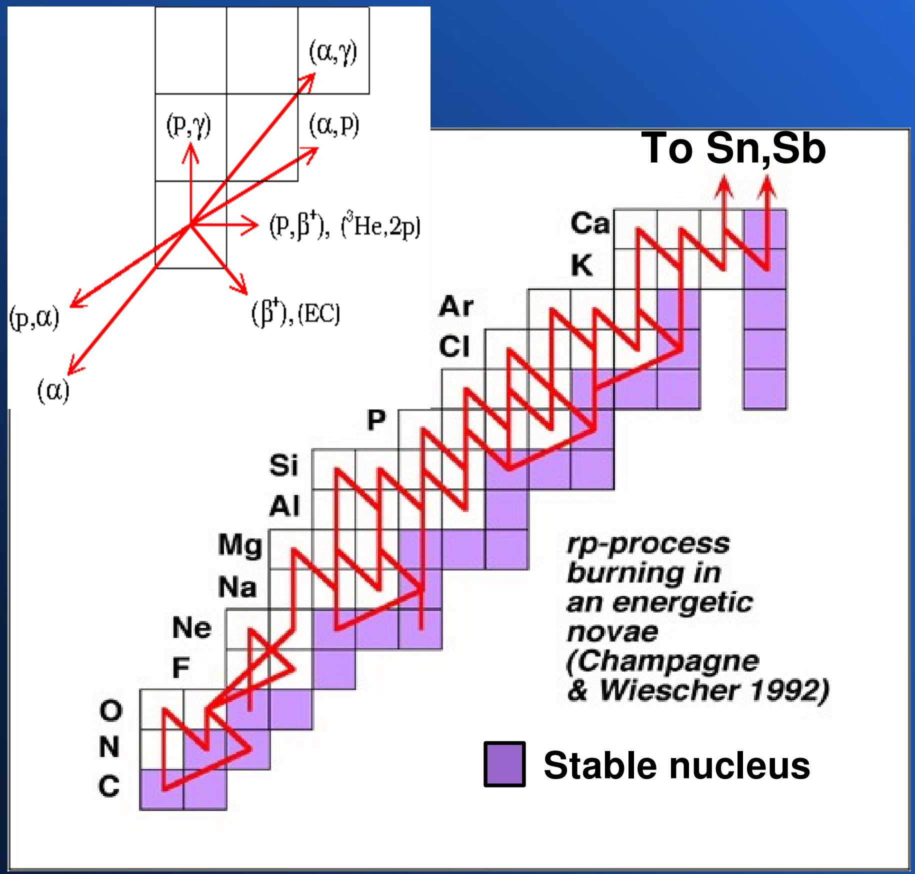
Question 3

How were the elements from iron to uranium made?

Based on National Academy of Science Report [Committee for the Physics of the Universe (CPU)]

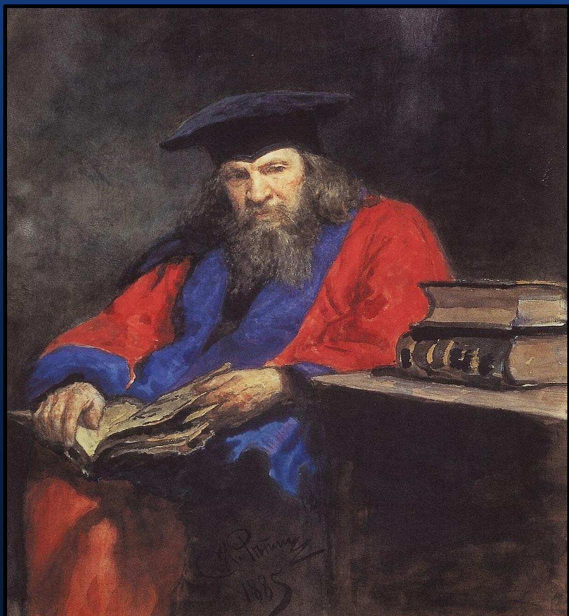
Breaking the Heavens Code

How are elements made?



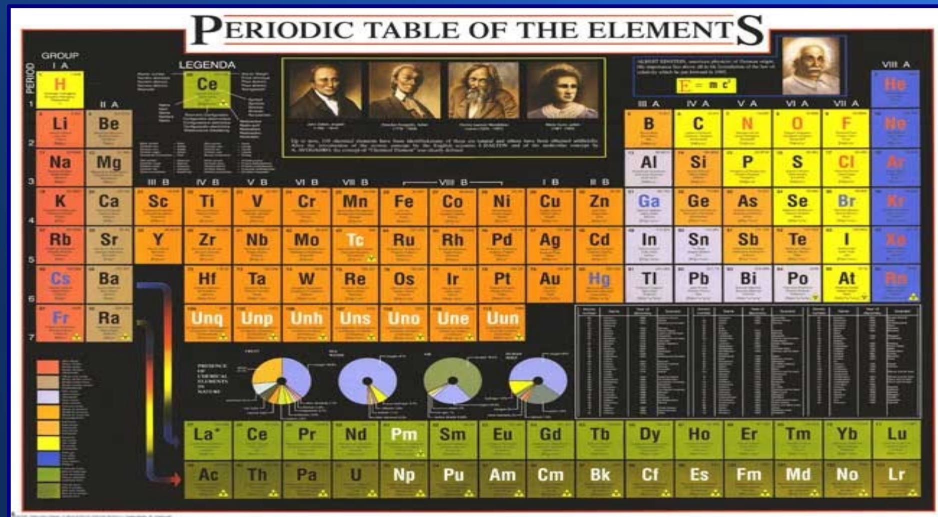
Putting things together...

The Periodic Table



A. Mendeleev, our 1st hero

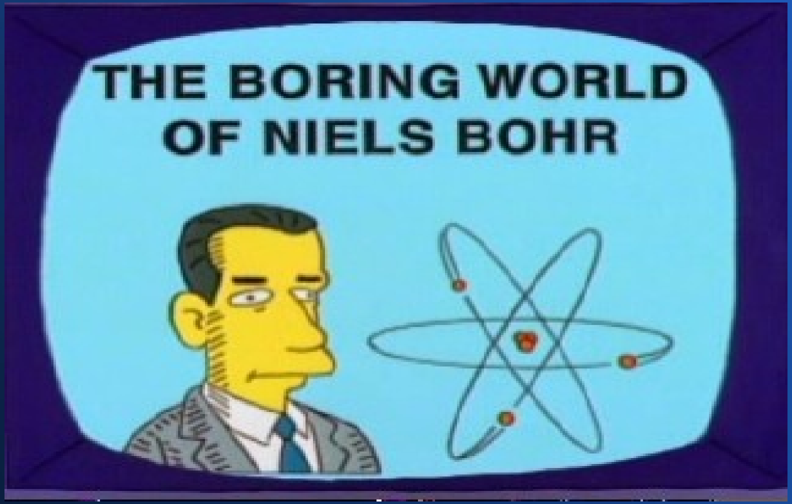
" The elements, if arranged according to their atomic weights, exhibit an evident periodicity of properties "



This is what happened so far...

The atomic puzzle

"This is the highest form of musicality in the sphere of thought."



Niels Bohr, our 2nd hero

Putting things together...

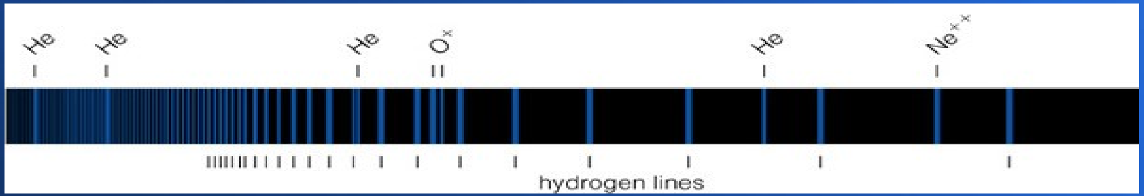
The atomic puzzle

That this insecure and contradictory foundation was sufficient to enable a man of Bohr's unique instinct and sensitivity to discover the principal laws of the spectral lines and of the electron shell of the atoms, together with their significance for chemistry, appeared to me as a miracle – and appears to me a miracle even today.

Albert Einstein (Autobiographical Notes)

Putting things together...

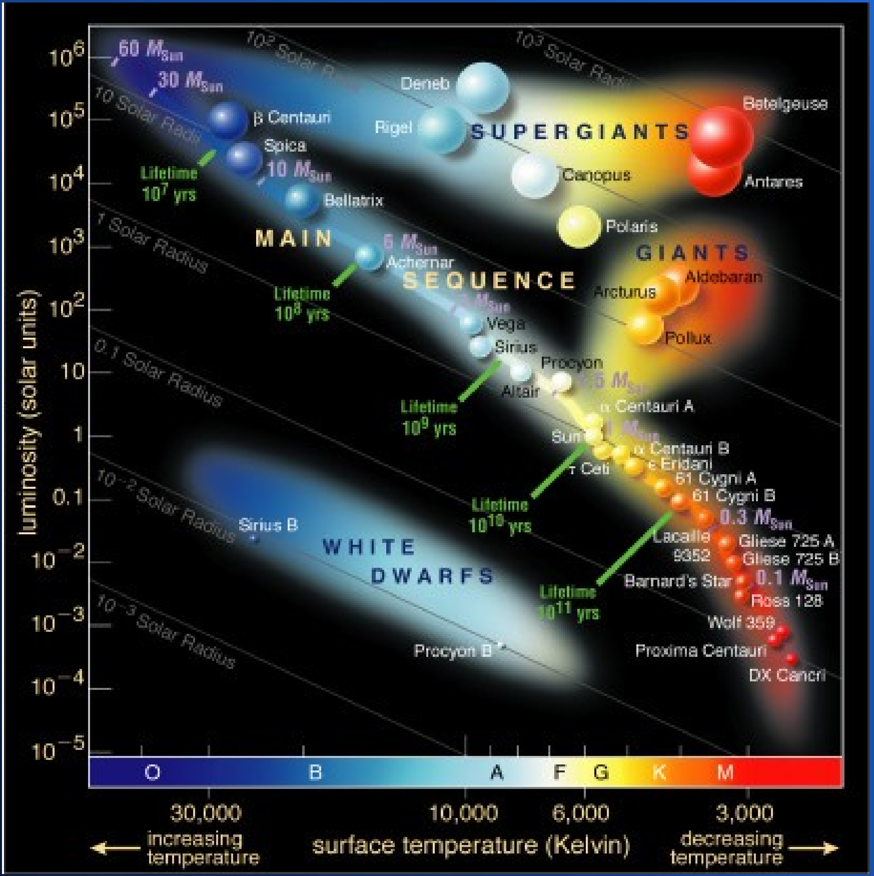
Emission Line Spectrum: e.g., the Sun hot upper atmosphere or the Orion Nebula



Orion Nebula

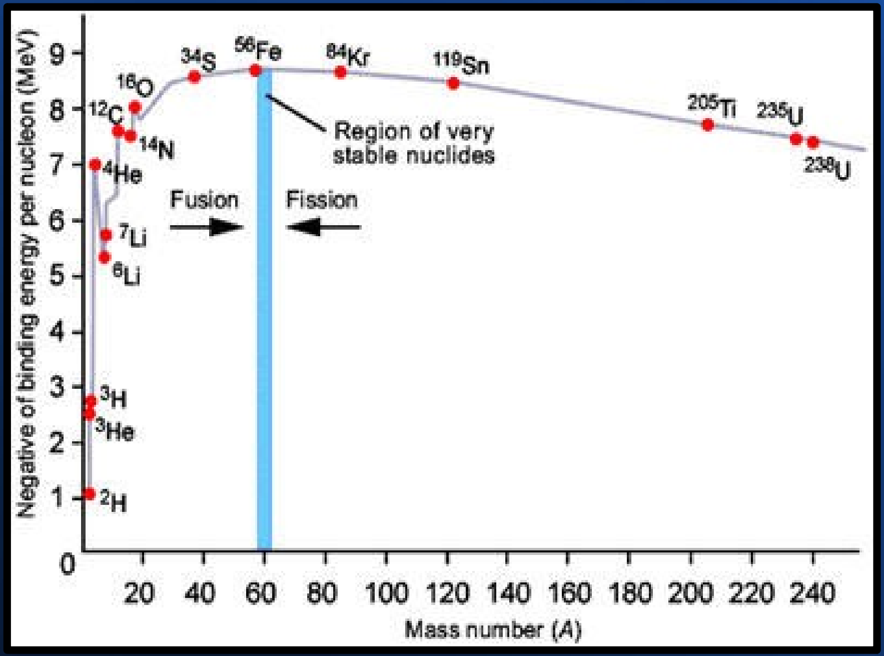
Putting things together...

How Stars Live and Die: The Hertzsprung-Russell Diagram

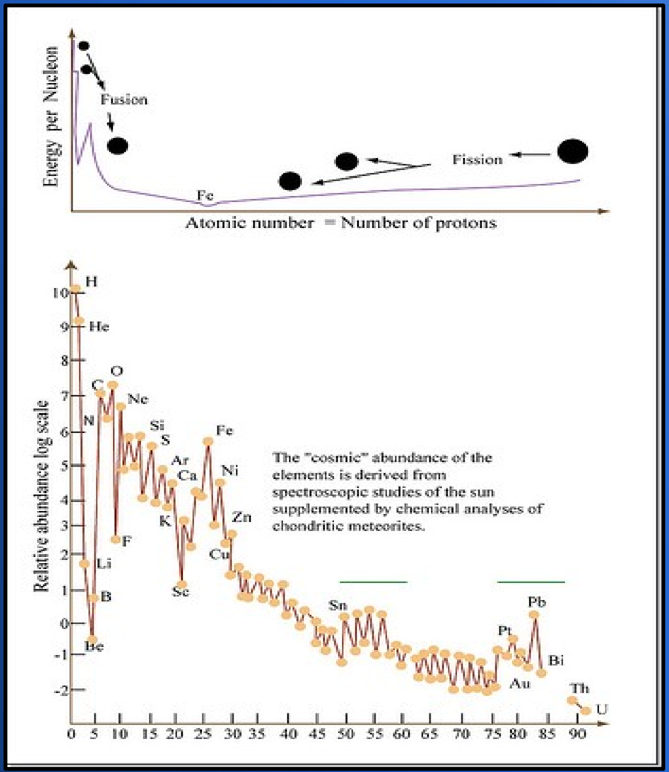


Putting things together...

How stars shine



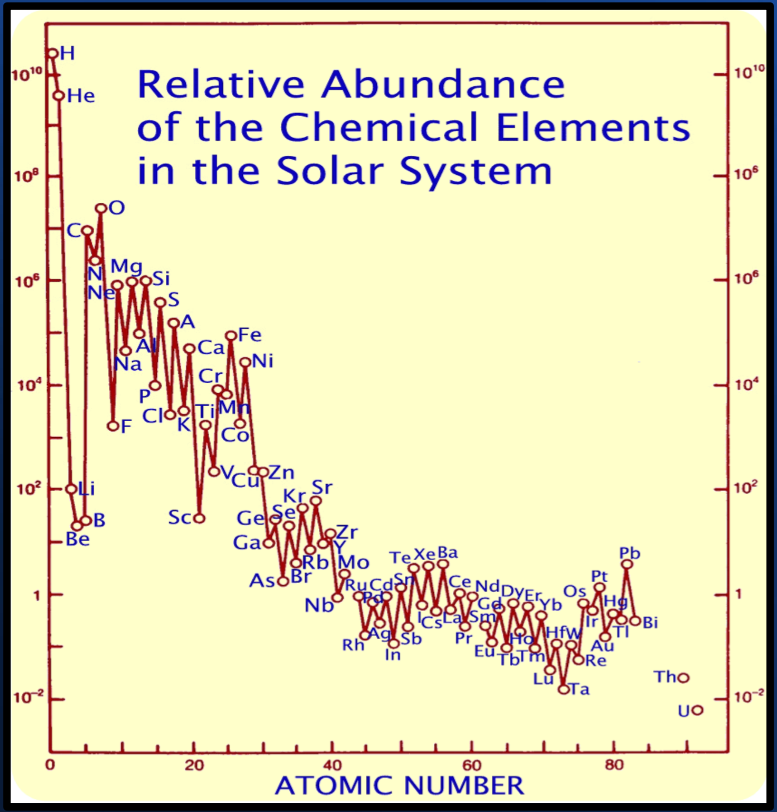
Binding energy per nucleon



Abundances in our Solar system

Experimental abundances

A meeting between our Cosmos and the microscopic world

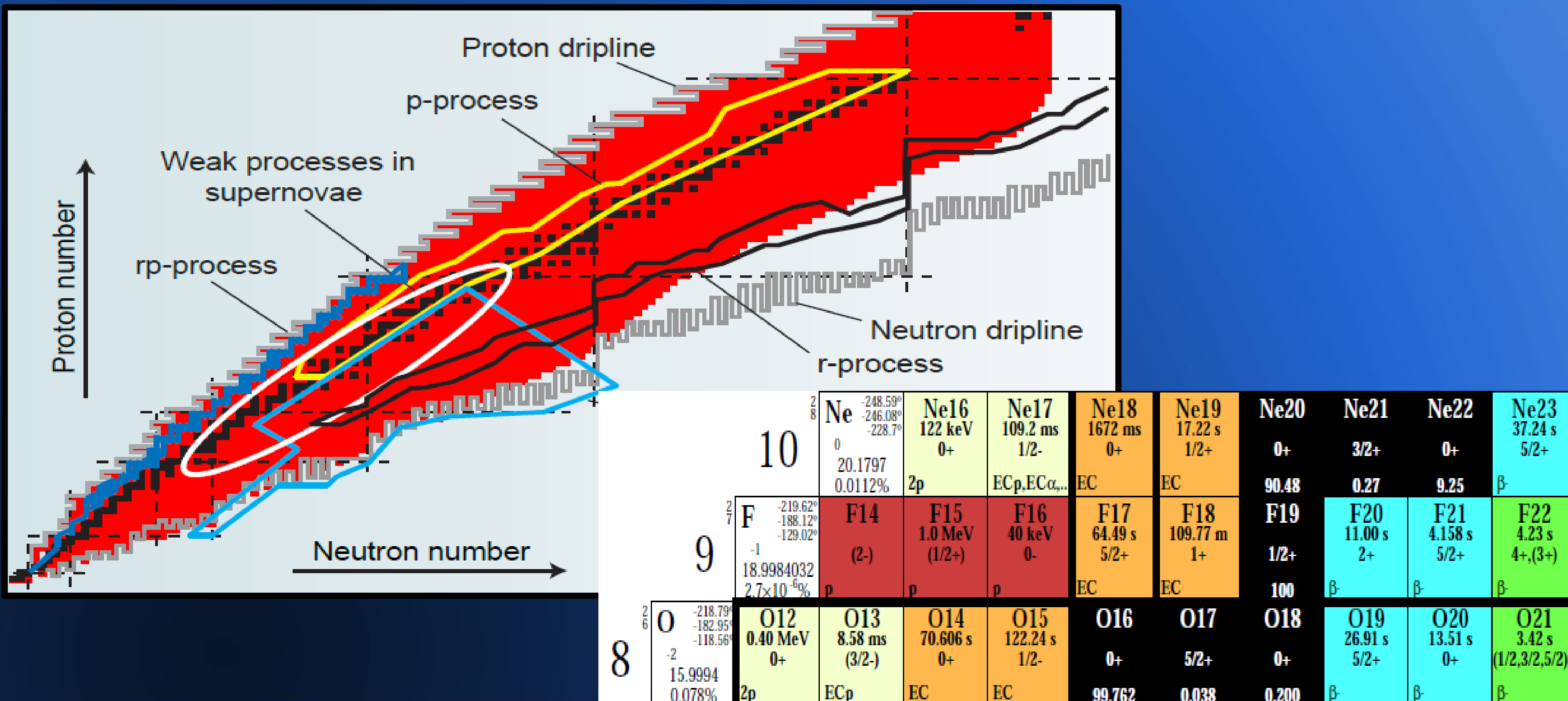


" I cannot better illustrate the interconnection of all facts of nature than by pointing to the chart of *abundances of elements*. Each maximum and minimum in the curve of abundances corresponds to some trait of nuclear dynamics, here a closed shell, there a strong neutron cross section, or a low binding energy."

Victor Weisskopf

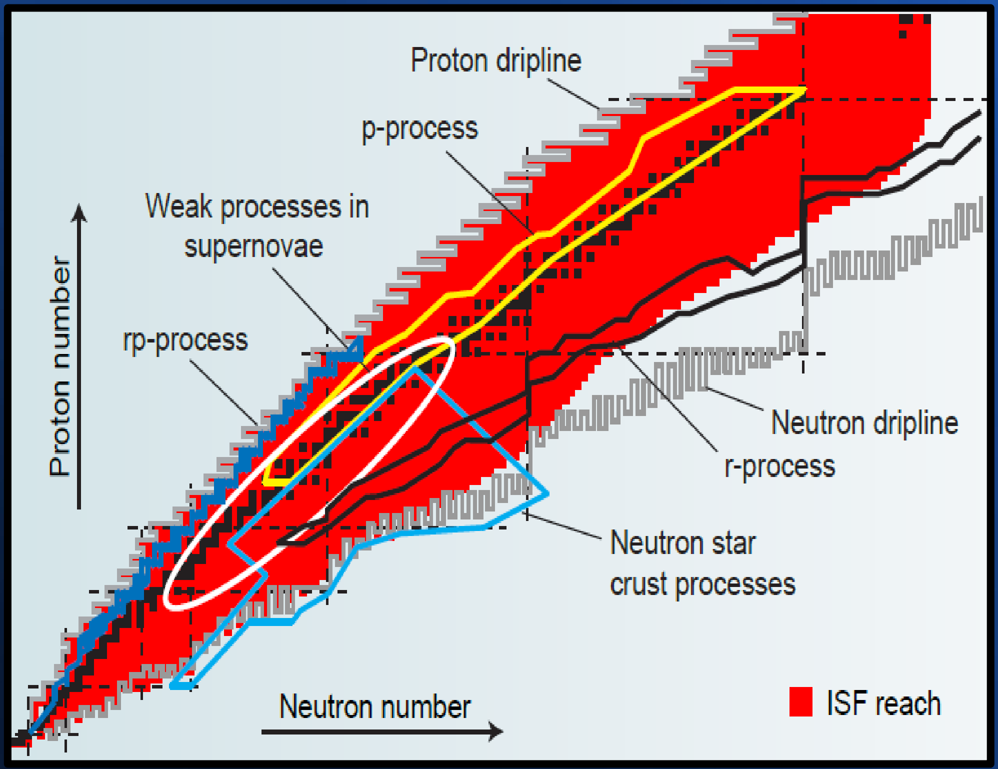
Putting things together...

The nuclear landscape



Breaking the Heavens Code

Explosive nucleosynthesis: the nuclear paths



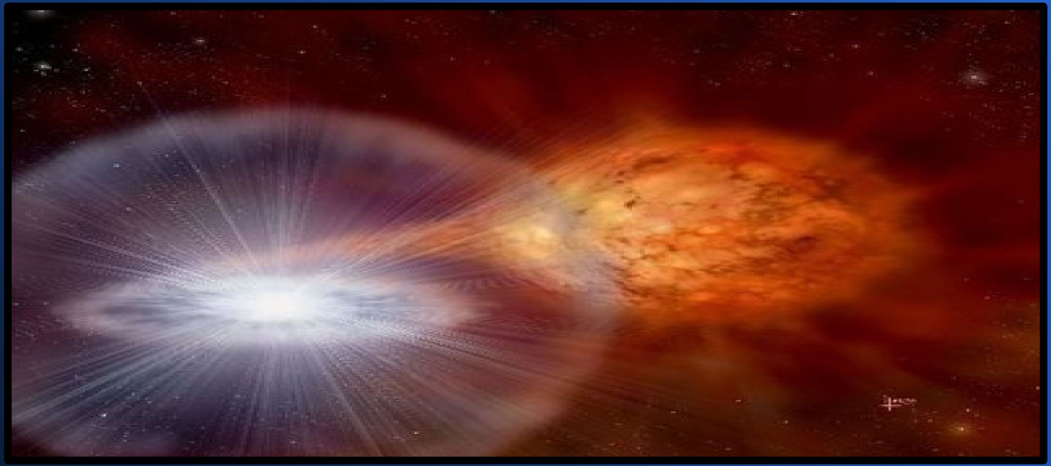
- Novae (hot CNO, NeNa, MgAl cycles)
- X-ray bursts (rapid-proton capture process)
- Supernovae (r-process,...)

Breaking the Heavens Code

Novae ($T < 4 \times 10^8$ K)

Binary system:

white dwarf + normal (often giant) star



- Recurrent: periods of 1 year to 1 million years depending on mass transfer rate
- ~50/year observed in our galaxy

Breaking the Heavens Code

Novae (T < 4 x 10^8 K)

Cosmic abundances (not well understood)

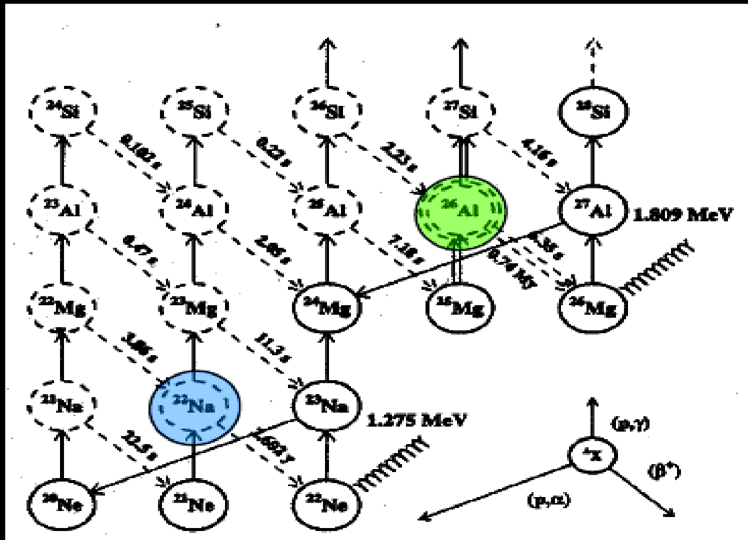


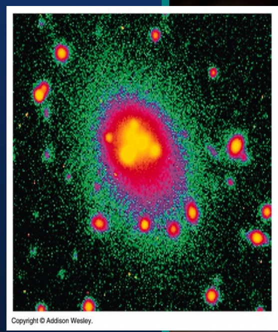
FIG. 2.—Main nuclear paths in both NeNa and MgAl cycles

- Anomalous ^{22}Ne/^{20}Ne excess in meteorites
- ^{26}Al excess in our galaxy

Breaking the Heavens Code

X-ray bursts (high-T > 10^9 K)

Binary system: neutron star + normal (often giant) star

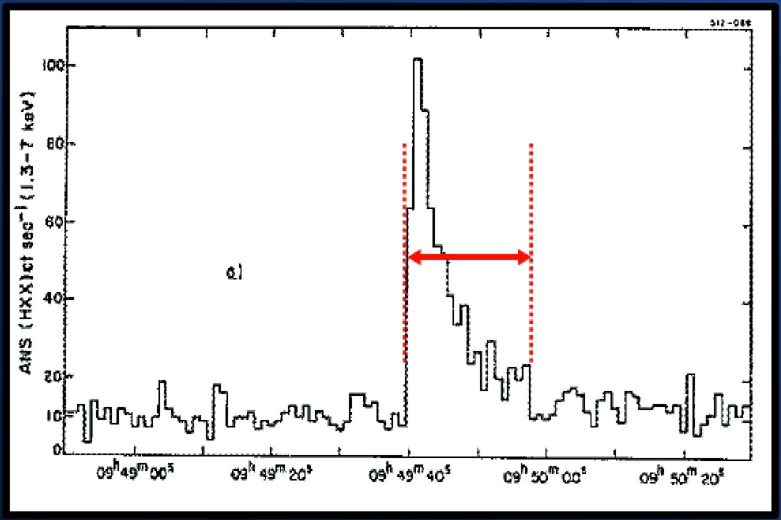


- The most recurrent explosion in the Universe: periods of hours to days!
- Cosmic abundances??

Breaking the Heavens Code

X-ray bursts and rp-process

Duration of X-ray burst: 10-100 seconds

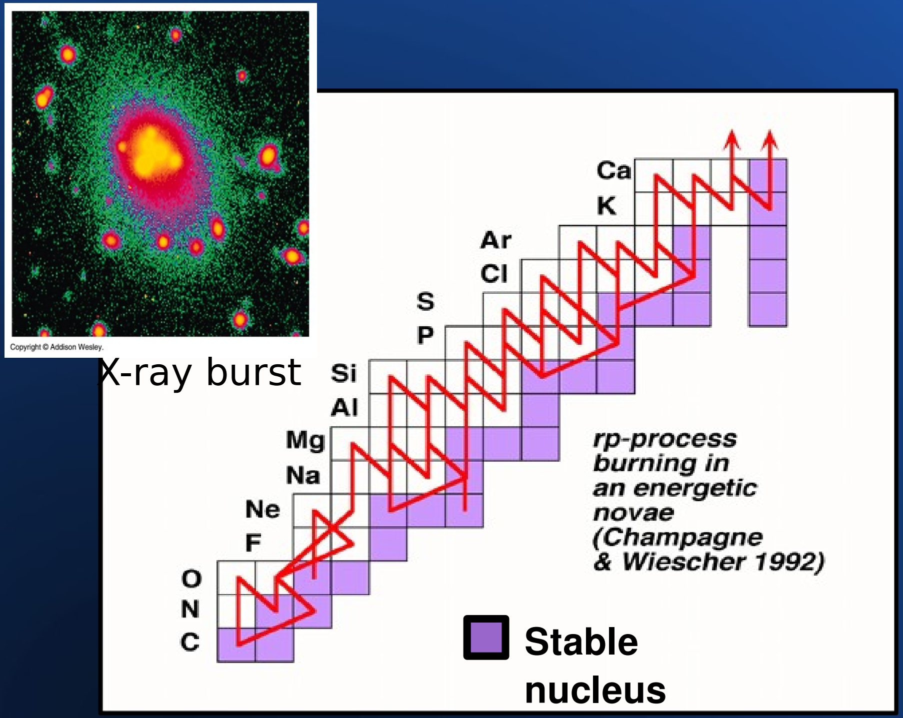


Old talk by D. Jenkins (York)

Waiting-point nuclide	β-decay half-life
^{64}Ge	63.7 s
^{68}Se	35.5 s
^{72}Kr	17.2 s
^{76}Sr	8.9 s
^{80}Zr	4.6 s

Duration determined by lifetimes in β-decay processes

X-ray bursts and rp-process

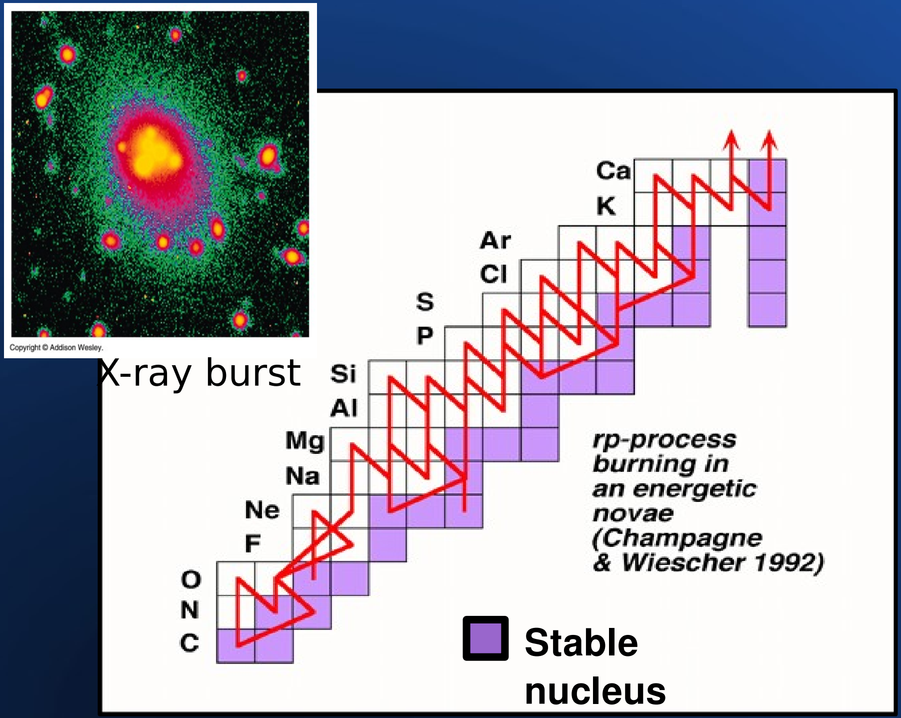


Cosmic abundances

The rp-process could be responsible for producing many of the isotopes occurring naturally that are found on the proton-rich side of the valley of stability.

Breaking the Heavens Code

X-ray bursts and rp-process

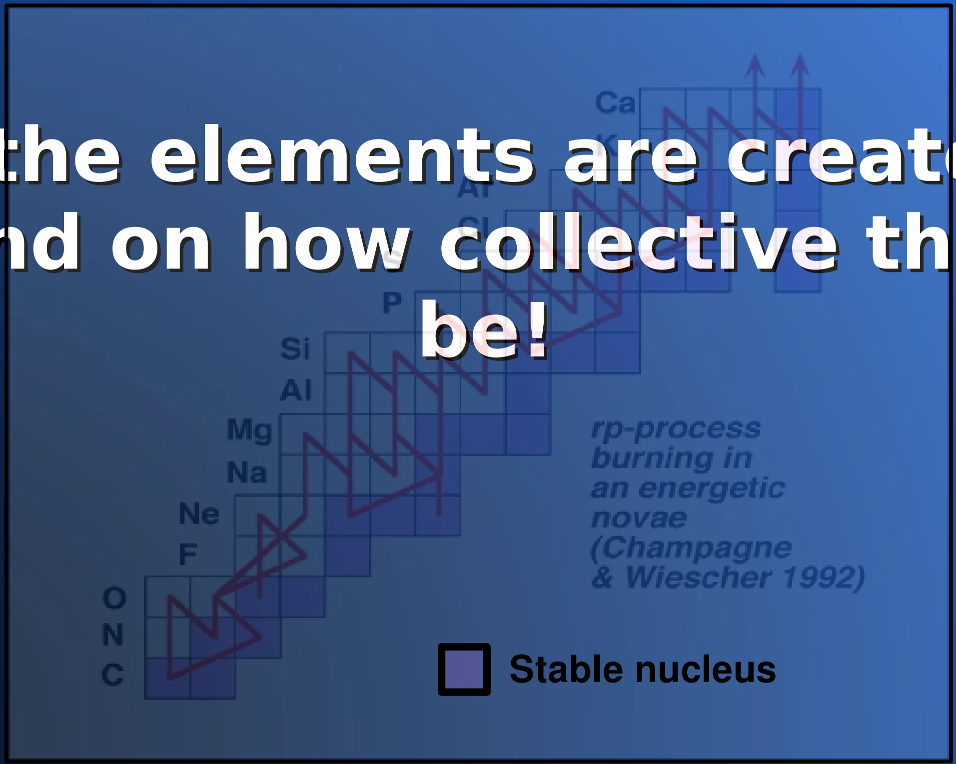


<u>The same Big Question (x3):</u>

- Has the rp-process anything to do with Cosmic abundances?
- Can the rp-process lead to the ejection of the synthesized elements into the interstellar medium?
- Can the rp-process overcome the strong gravitation field of a neutron star?

We need a bold guess

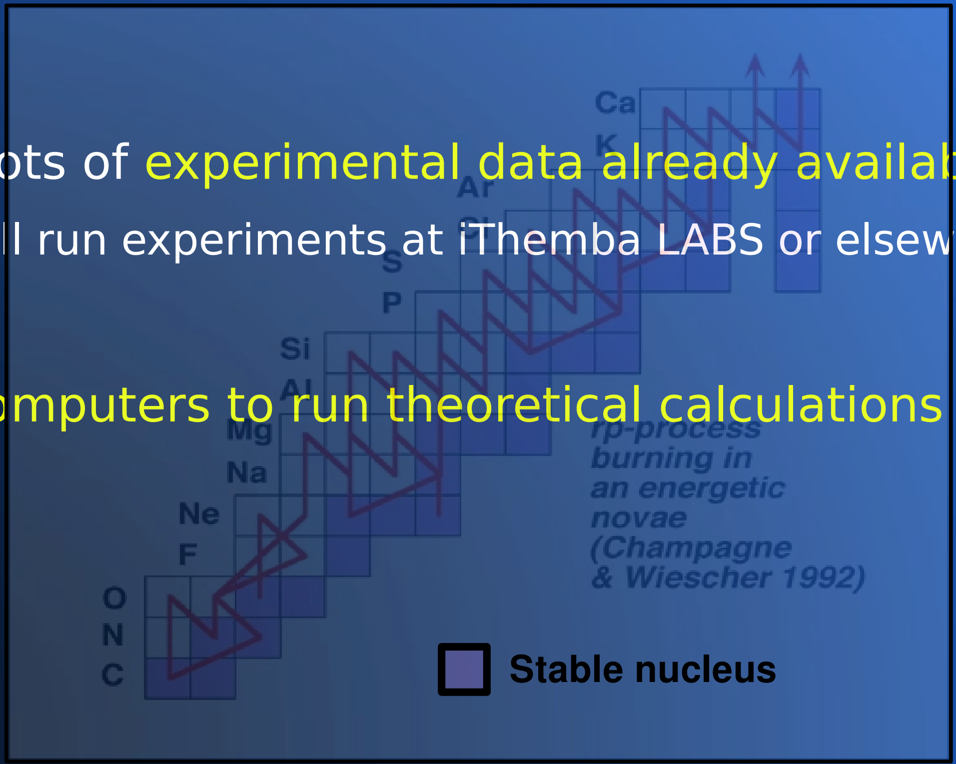
Nuclear collectivity is related to how the elements are created!



How the elements are created may depend on how collective they can be!

What's the goal of this game?

To find and explain **NEW** trends/relations/systematics (*ala Mendeleev*)



- Lots of experimental data already available

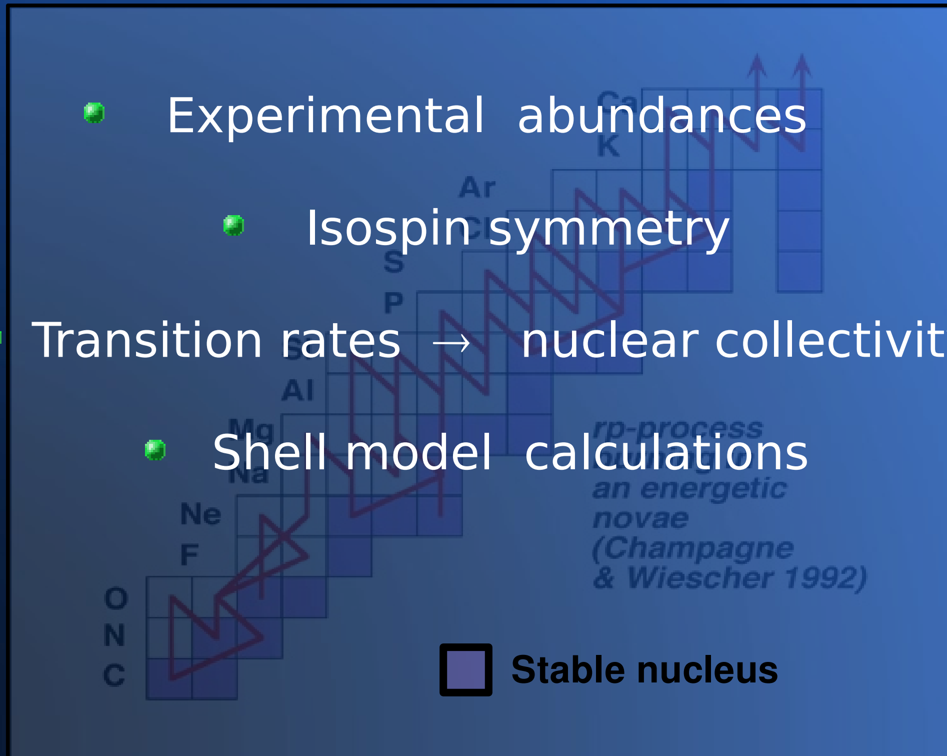
(if not available, we'll run experiments at iThemba LABS or elsewhere in the world)

- We've got supercomputers to run theoretical calculations (e.g., shell model)

Which tools shall we use?

Our physics ingredients (4+)

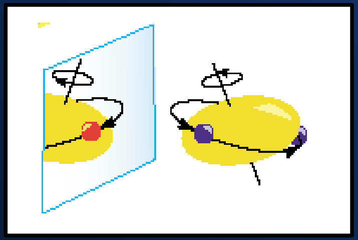
- Experimental abundances
- Isospin symmetry
- Transition rates → nuclear collectivity
- Shell model calculations



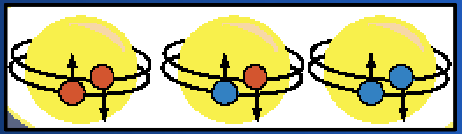
Isospin symmetry

Charge symmetry and charge independence of the nuclear force

In the absence of Coulomb interactions between the protons, a perfectly charge-symmetric and charge-independent nuclear force would result in **structurally identical nuclei.**



Charge symmetry

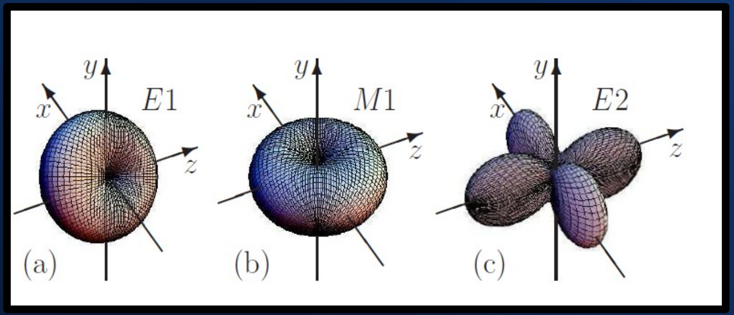


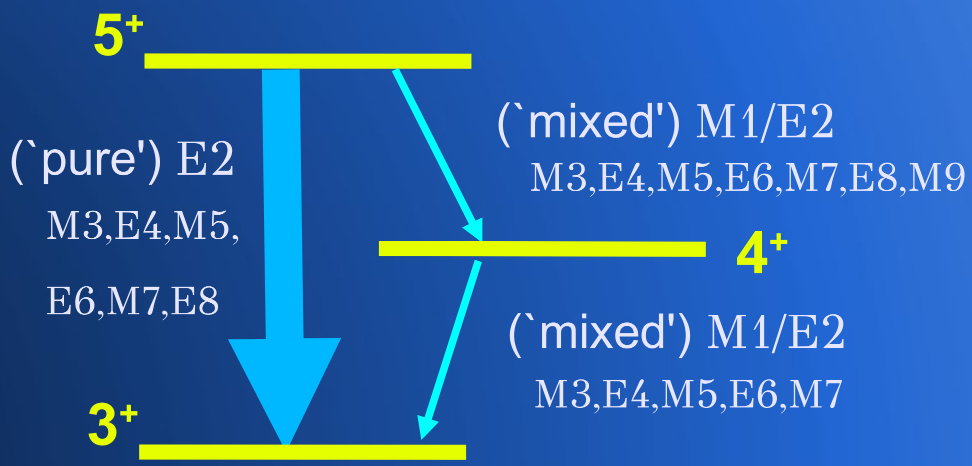
Charge independence

Transition rates → nuclear collectivity

Overlap of wave functions between initial and final states

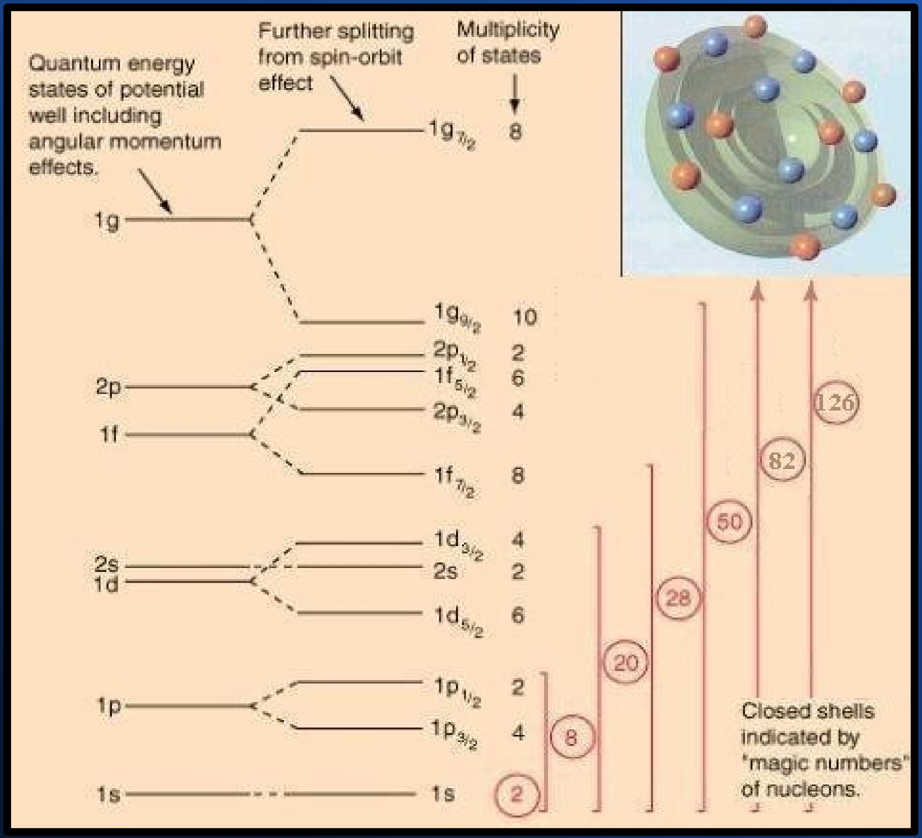
Gamma-ray decay selection rules: the decay can proceed by a photon of electric and magnetic multipole order $E\lambda$ or $M\lambda$, where $|J_i + J_f| \geq \lambda \geq |J_i - J_f|$





Shell model calculations

Confront experiment with theoretical calculations



Basic ingredients: harmonic oscillator, spin-orbit, tensor force

`Magic' numbers
Especially stable/bound nuclei/atoms

Single-particle or collective properties

Shell model calculations

Confront experiment with theoretical calculations

$$B(M\lambda/E\lambda;\ J_i \rightarrow J_f) = (2J_i + 1) \quad |\langle \Psi_f \| \hat{M}\lambda/\hat{E}\lambda \| \Psi_i \rangle|^2$$

We'll use shell-model calculations to compare transition rates:

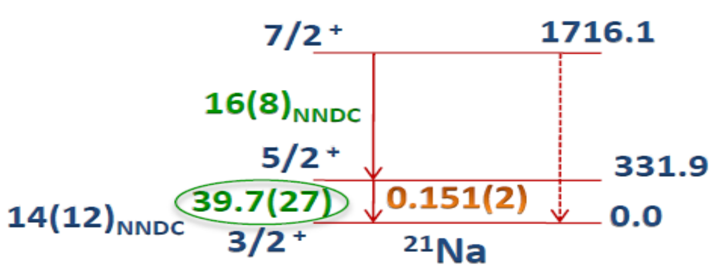
how collective the states are

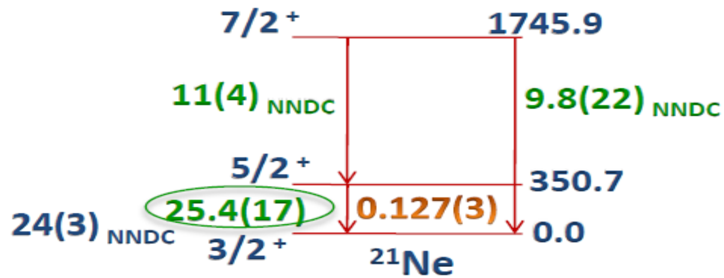
My bold guess

Nuclear collectivity is related to how the elements are created!

$^{21}_{10}$Ne much less E2 collective than $^{21}_{11}$Na

M1 (μ_N^2) and E2 (W.u.) strengths in ^{21}Na - ^{21}Ne





PSD & USDB Shell Model (similar results)		
B(E2; 5/2$^+$ → 3/2$^+$)		
e_p=1.5e,e_n=0.5e	36.4 W.u.	✓
e_p=1.7e,e_n=0.3e*	37.5 W.u.	✓
B(M1; 5/2$^+$ → 3/2$^+$)		
(standard) g_p=3.91, g_n=-2.678	0.105 μ_N^2	✗
g_p=4.748, g_n=-3.252*	0.155 μ_N^2	✓

PSD & USDB Shell Model (similar results)		
B(E2; 5/2$^+$ → 3/2$^+$)		
e_p=1.5e,e_n=0.5e	30.8 W.u.	✗
e_p=1.7e,e_n=0.3e*	29.6 W.u.	✗
B(M1; 5/2$^+$ → 3/2$^+$)		
(standard) g_p=3.91, g_n=-2.678	0.105 μ_N^2	✗
g_p=4.748, g_n=-3.252*	0.125 μ_N^2	✓

* Best SM agreement

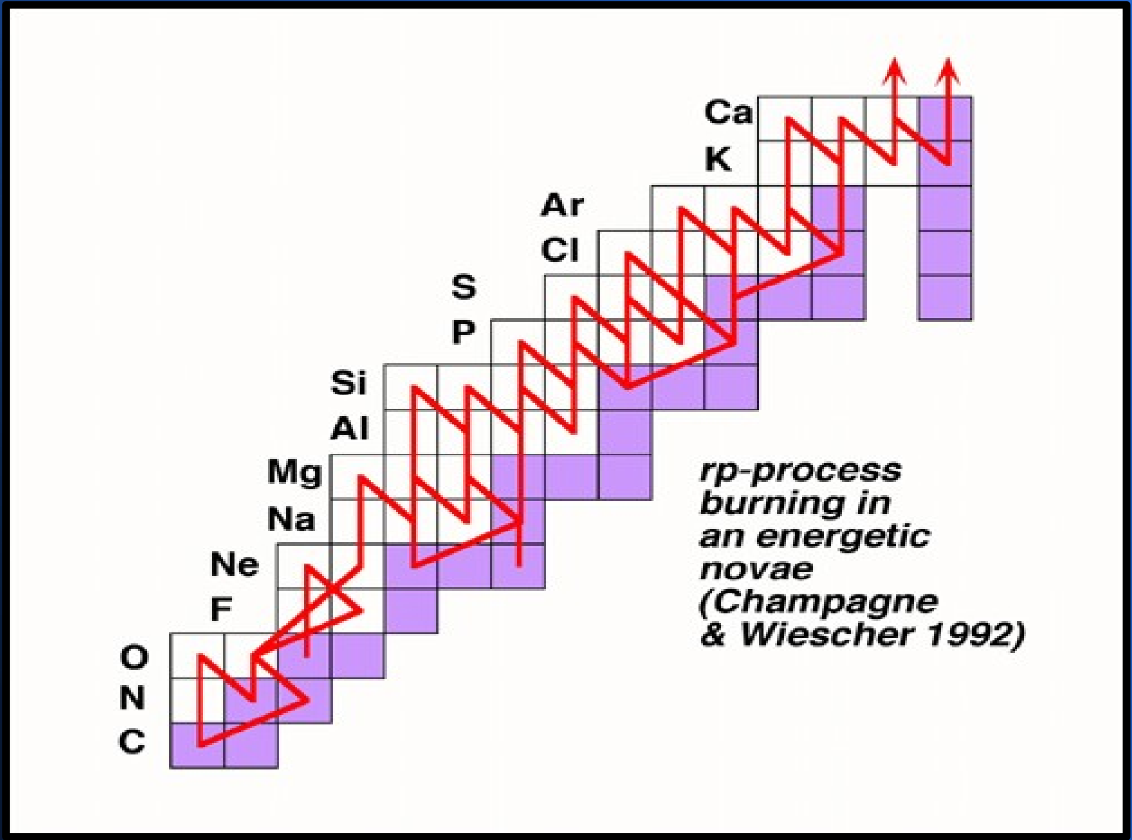
Standard g-factors (g_p = 3.91, g_n = - 2.678, quenching factor = 0.7)

SM cannot comparatively reproduce discrepant E2 strengths

Coulomb excitation of ^{21}Na - ^{21}Ne, M.A. Schumaker *et al.*, Phys. Rev. C 78, 044321 (2008)

My bold guess

Nuclear collectivity is related to how the elements are created!



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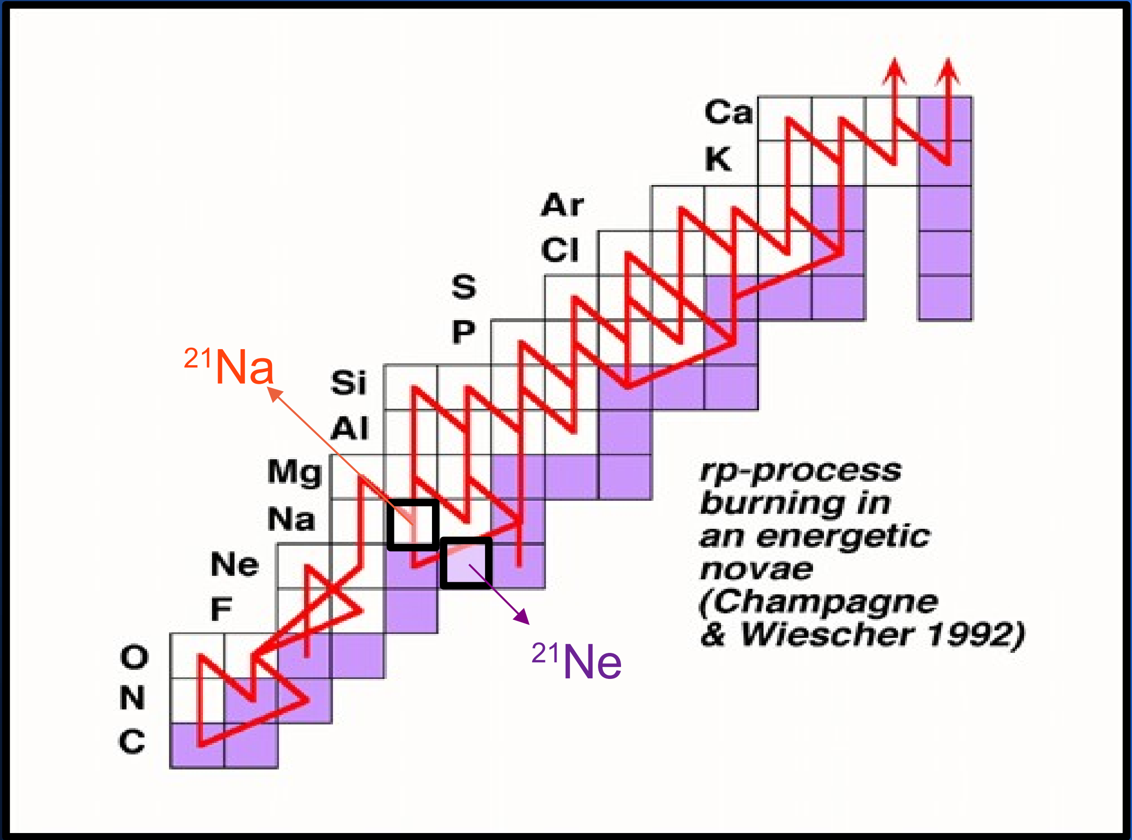


My bold guess

Nuclear collectivity is related to how the elements are created!

$^{20}_{9}$F less M1 collective than $^{20}_{11}$Na

M1 (μ_N^2) and E2 (W.u.) strengths in ^{20}Na (this work) - ^{20}F (NNDC)

PSD & USDB Shell Model (similar results)	
B(E2; 3⁺ → 2⁺)*	26.59 W.u. ✖
B(E2; 4⁺ → 2⁺)*	12.57 W.u. ✓
B(M1; 4⁺ → 3⁺)**	0.05 μ_N ✖
B(M1; 4⁺ → 3⁺) ***	0.10 μ_N ✖

PSD & USDB Shell Model (similar results)	
B(E2; 3⁺ → 2⁺)*	12.6 W.u. ?
B(E2; 4⁺ → 2⁺)*	4.76 W.u. ✓
B(M1; 4⁺ → 3⁺)**	0.05 μ_N^2 ✖
B(M1; 4⁺ → 3⁺)***	0.08 μ_N^2 ✓

* *Best SM agreement with standard e_p=1.5e, e_n=0.5e*

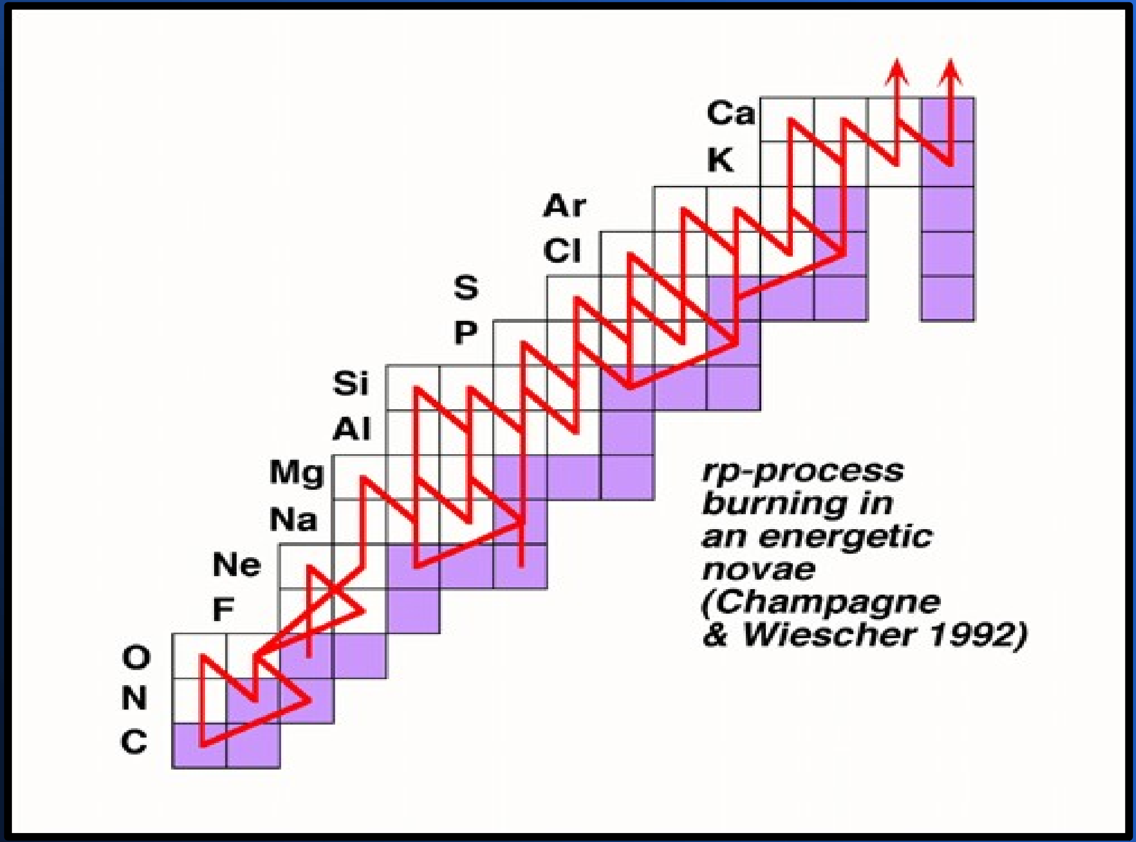
** Standard g-factors (g_p = 3.91, g_n = - 2.678, quenching factor = 0.7)

*** Best agreement with free g_p= 5.586 and g_n= - 3.826

SM cannot comparatively reproduce discrepant M1 strengths

My bold guess

Nuclear collectivity is related to how the elements are created!



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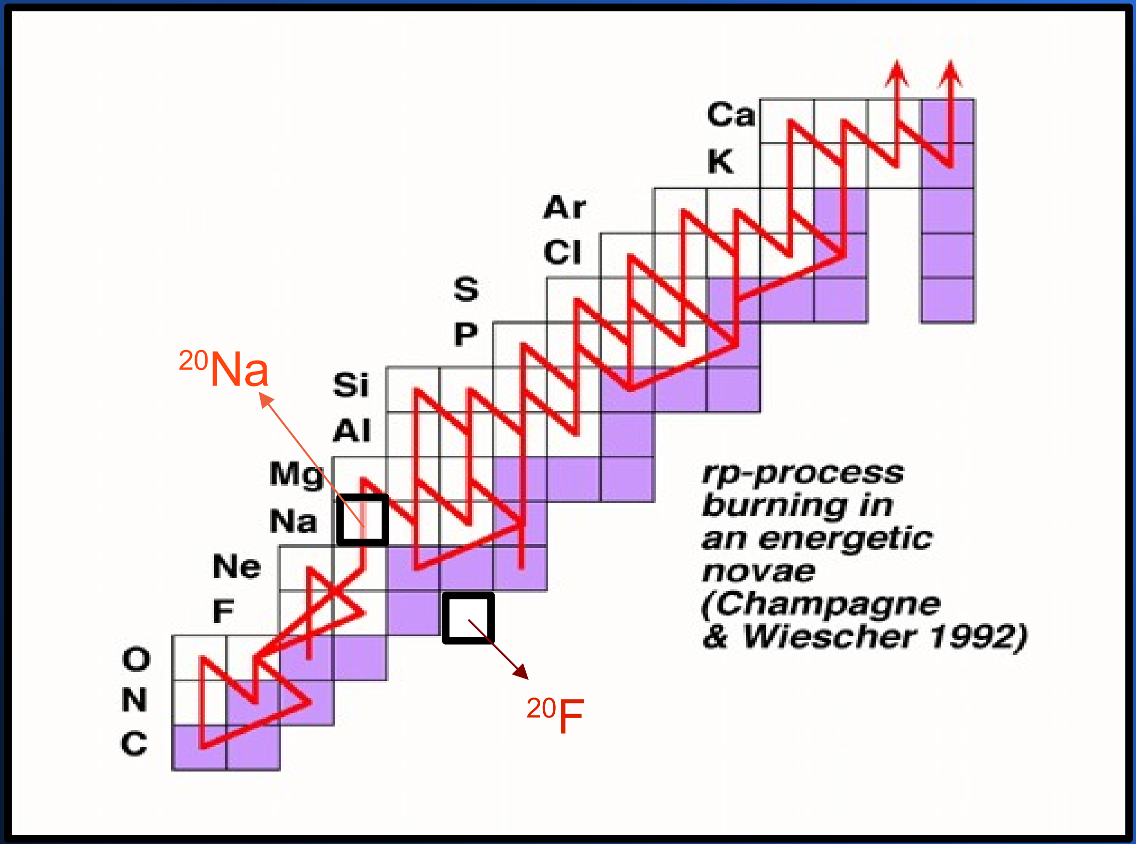

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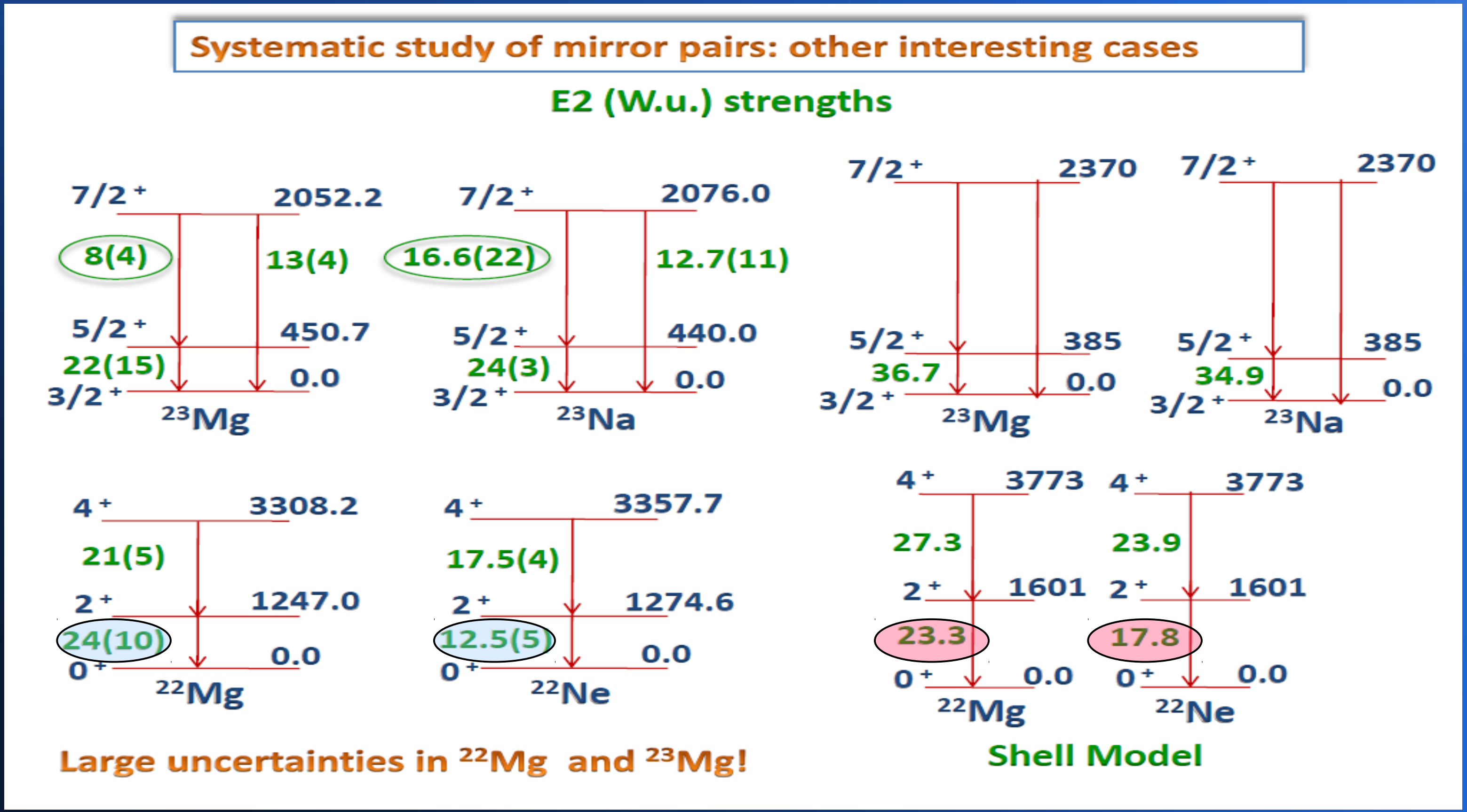
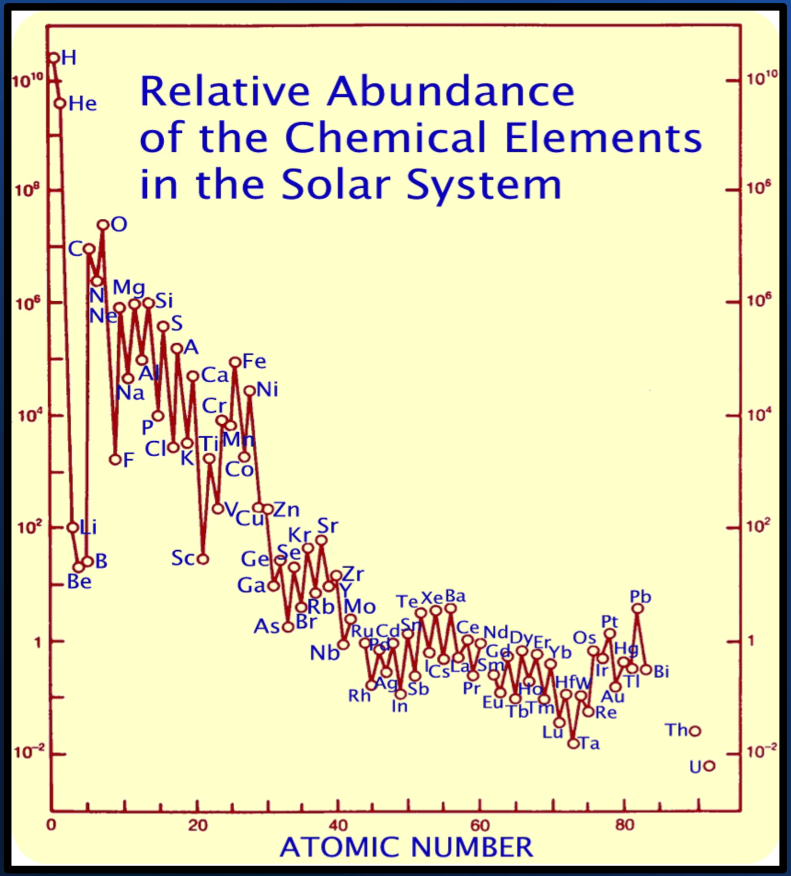


Experimental abundances

A meeting between our Cosmos and the microscopic world

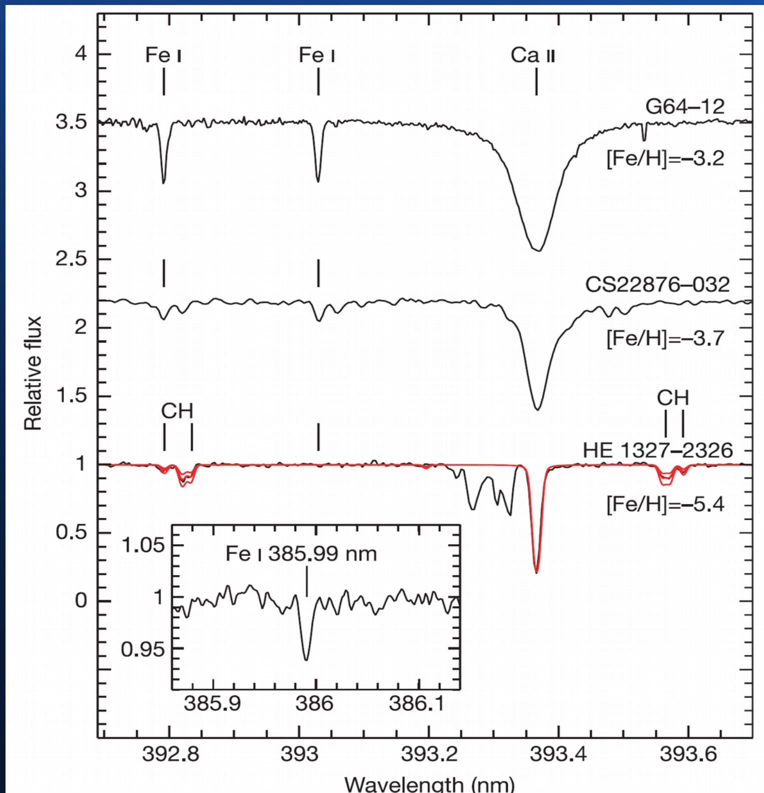


But not everything is well understood!

For instance, there is a cosmic “excess” of ^{22}Na and ^{26}Al produced in nova and supernova.

Metal-poor stars

A simple yet unexplained abundance pattern



But not everything is well understood!

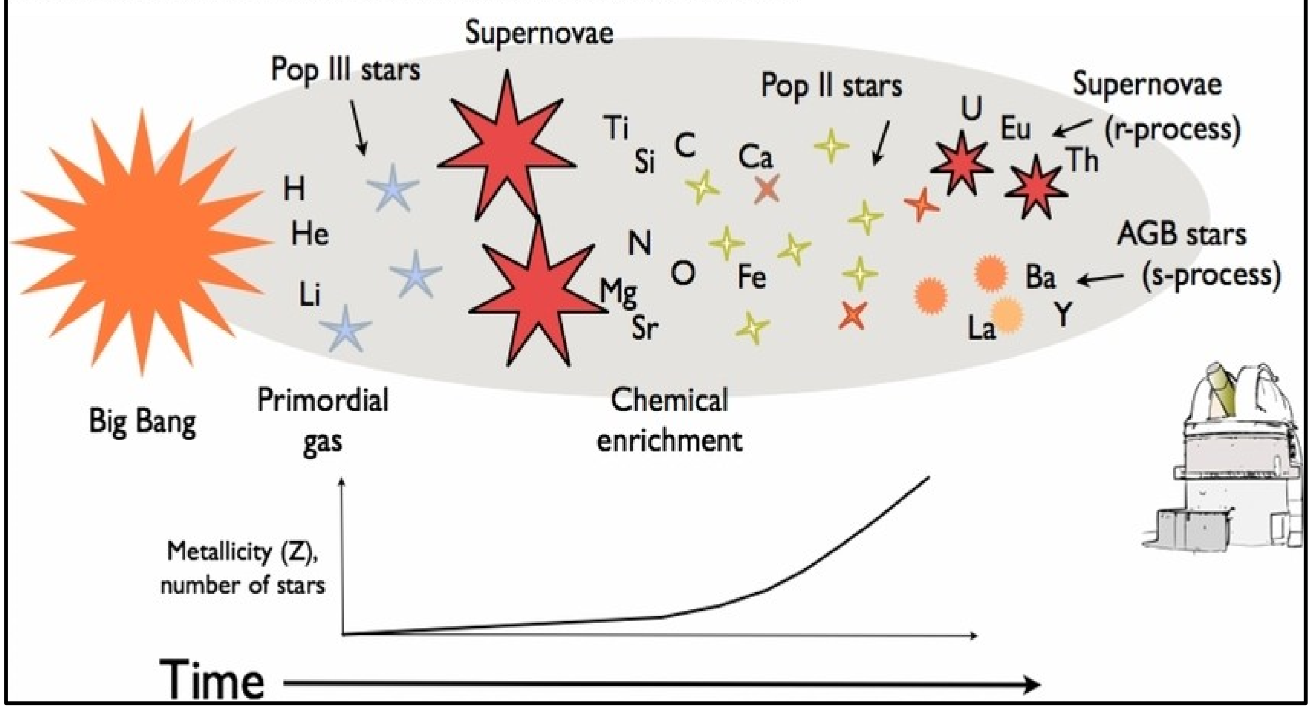
Sr and Ba in metal-poor stars

High-resolution observational nuclear astrophysics @ SALT

The Southern African Large Telescope (SALT) is a 10-meter class optical telescope designed mainly for spectroscopy

Low-mass, old, metal poor stars: the simplest case scenario

Figure 1 from Heather R Jacobson and Anna Frebel 2014 J. Phys. G: Nucl. Part. Phys. 41 044001

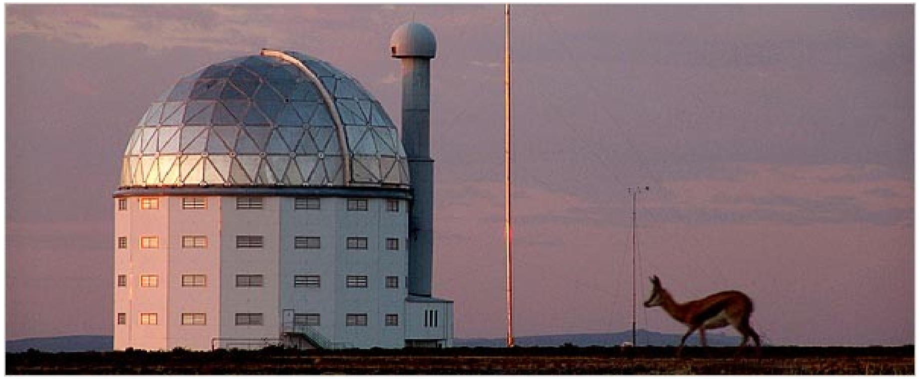


Layers of chemical evolution are difficult to disentangle:

Low-mass, metal poor, old stars (Pop II) still shine (lifetime > 10Gyr, population < 0.1%)

High-resolution observational nuclear astrophysics @ SALT

Search for extreme metal poor stars in the Edinburgh-Cape Blue Object Survey



HRS at SALT

Title					
Search for extreme metal poor stars in the Edinburgh–Cape Blue Object Survey					
PID	**Code**	**Phase**	**Semester**	**First Submission**	**Current Submission**
1556-2	2014-2-SCI-053	1	2 / 2014	2014-08-01	**2014/08/18 (#2)**

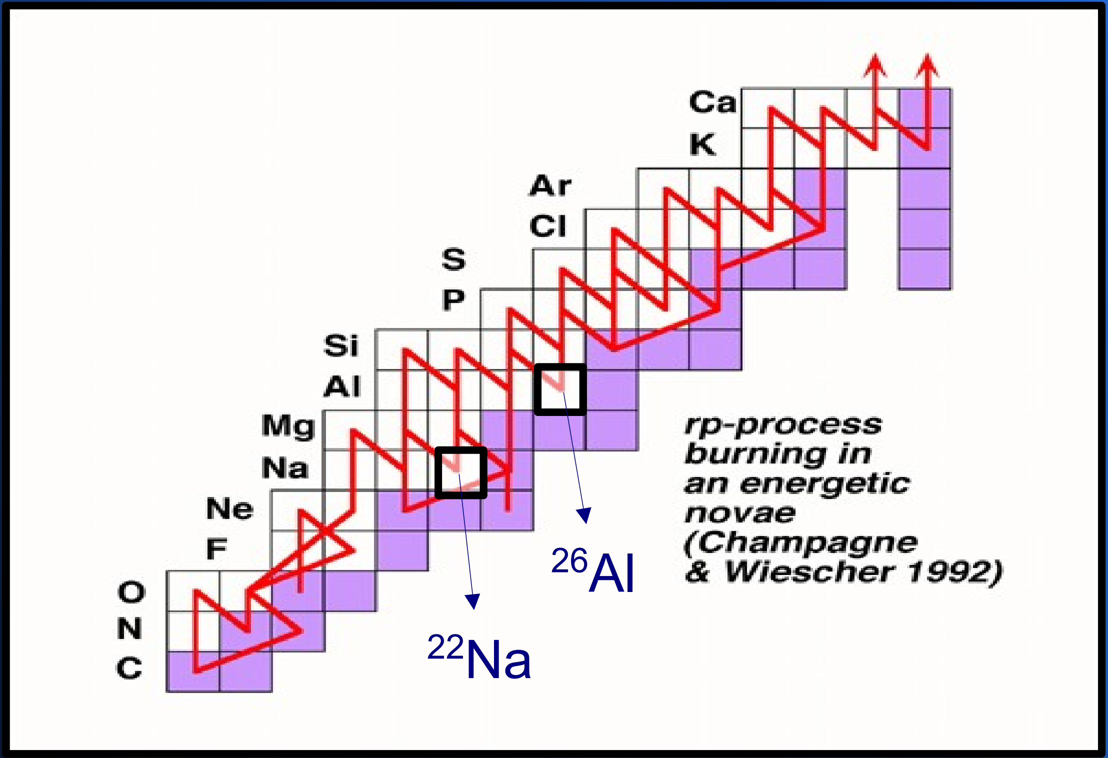
Abstract

The most iron-deficient stars provide an excellent testing ground to study early star formation and the synthesis of elements in stellar processes. We propose a search for spectral lines in extremely metal-poor candidates from the recently published Edinburgh–Cape Blue Object Survey using the SALT HRS. Some of these target stars could have [Fe/H] less than the most metal-poor stars found to date. High-resolution and high S/N spectra of these stars could also provide constaints on the origin of heavy metals.

Experimental abundances

A meeting between our Cosmos and the microscopic world

Another relation ?

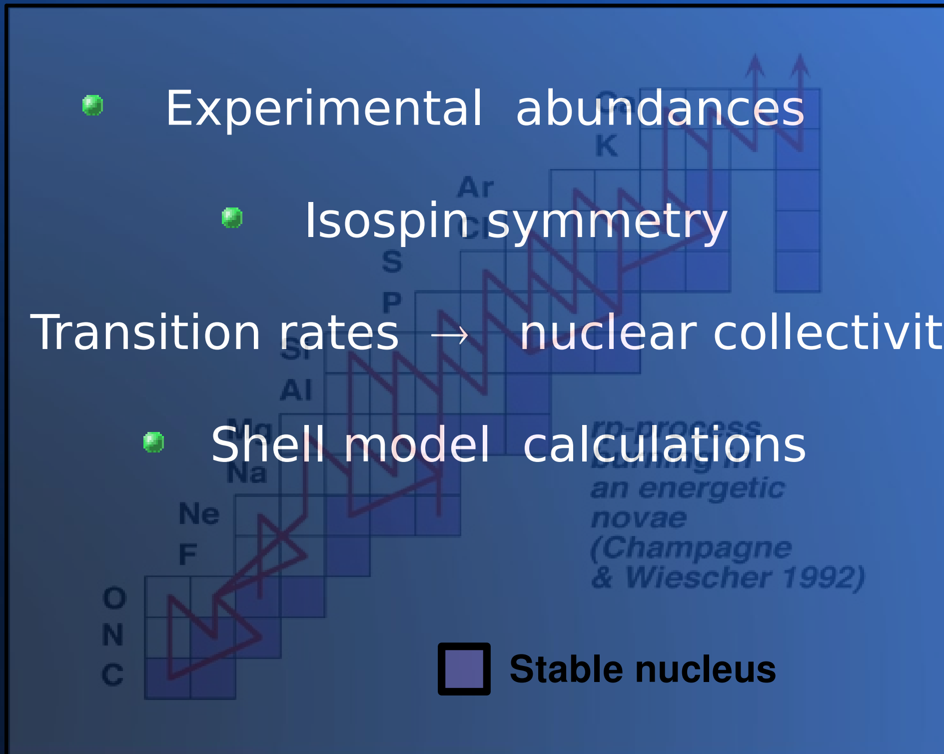


Summarizing, our Physics game is about...

To find and explain **NEW** trends/relations/systematics

Follow our physics ingredients and your `physics' intuition!

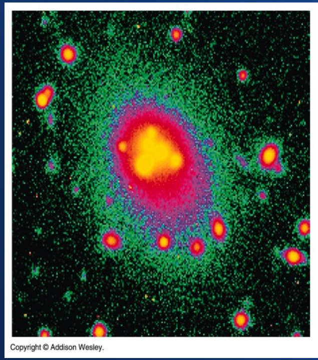
- Experimental abundances
- Isospin symmetry
- Transition rates → nuclear collectivity
- Shell model calculations



And maybe...

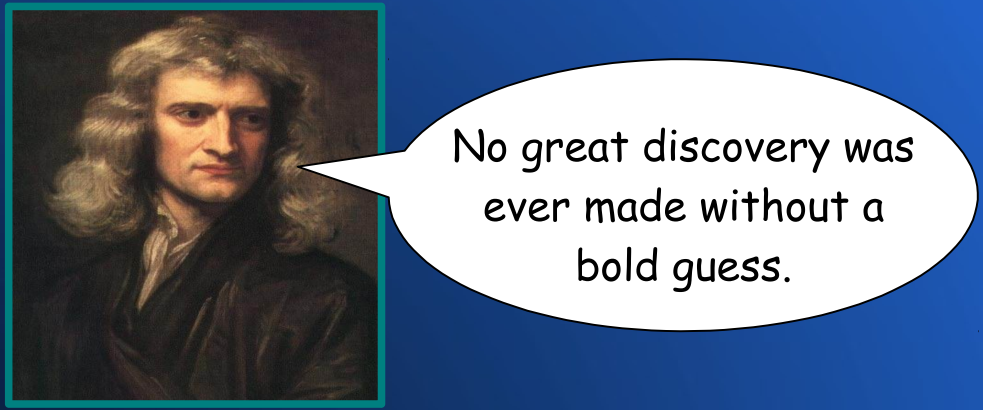
We may find an answer to the big question:

Are X-ray bursts the nurseries of many elements we know?



My bold guess

Nuclear collectivity is related to how the elements are created!



Sir Isaac Newton