Nuclear Astrophysics Theory - I

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TRIUMF

FRIB Theory Alliance

NSERC CRSNG

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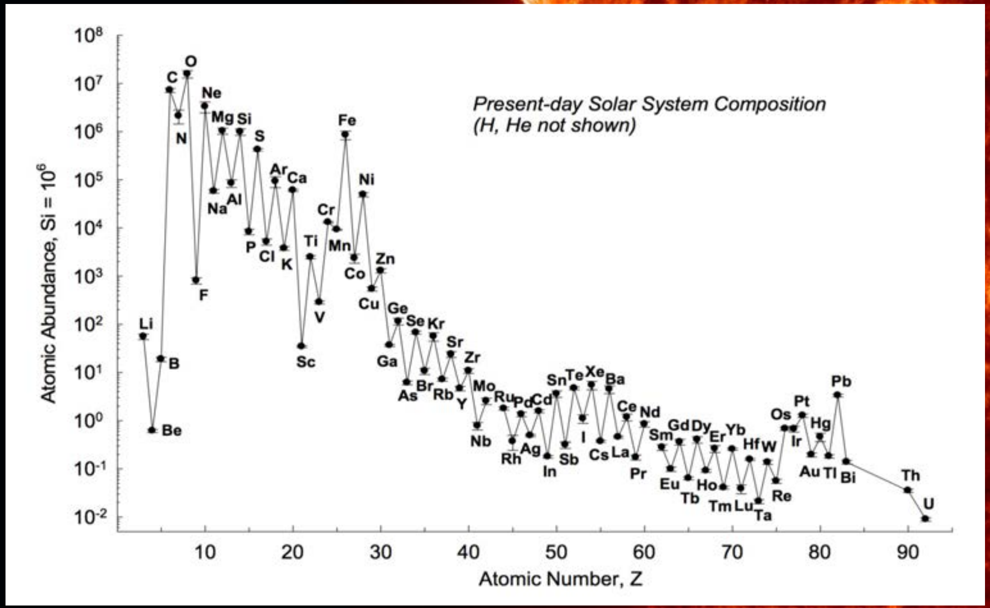
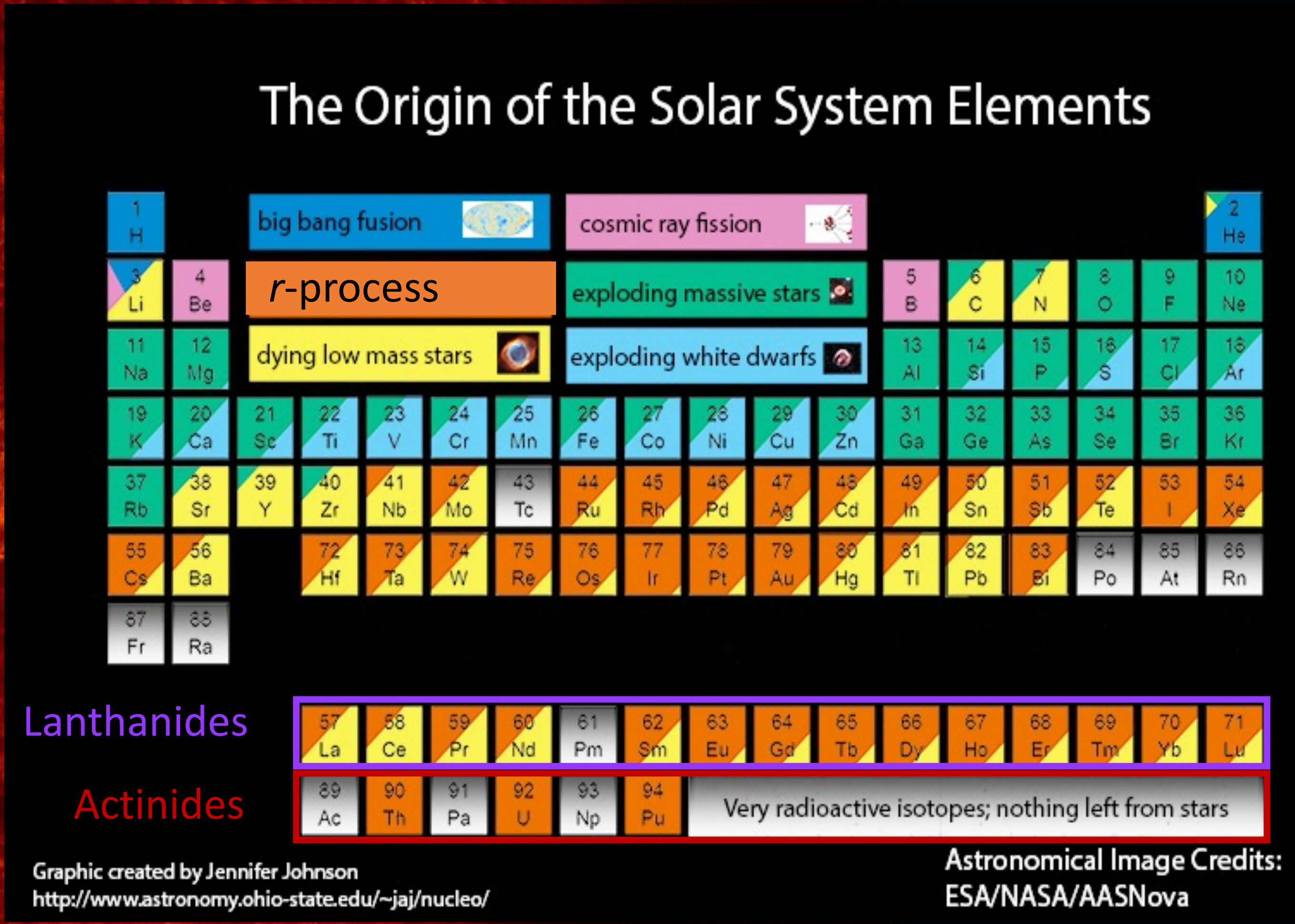
Outline for lecture I

- How can we study nuclear physics in astrophysics? Some observables [3-7]
- Some basic nuclear physics: masses, decays, reactions, reverse reaction rates, and equilibria [9-19]
- Reaction networks (BBN example and heavy element nucleosynthesis example) and using hydro simulations [21-30]
- Solar fusion [32-36]

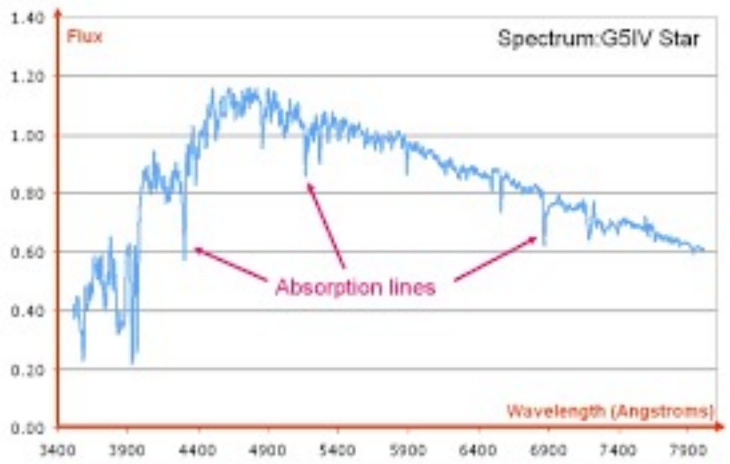
The solar composition can be decomposed into many processes → multiple nucleosynthesis sites enriched the solar system

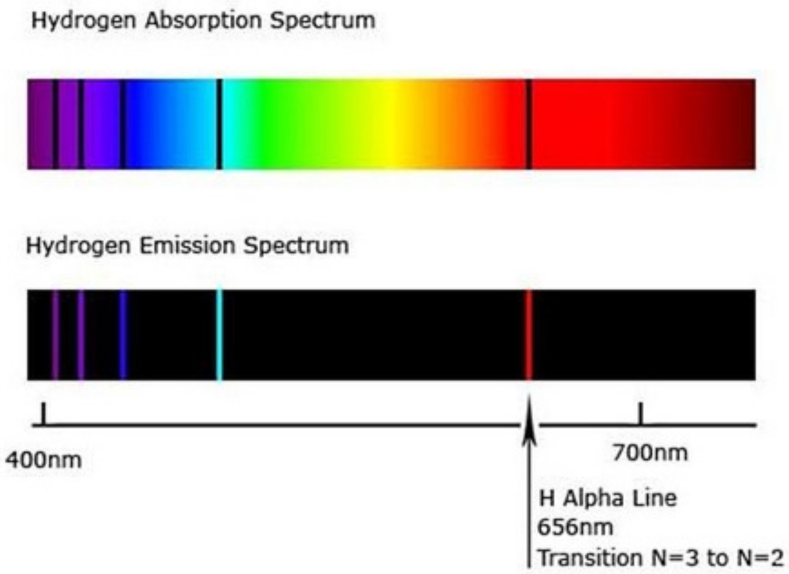


Lodders 10



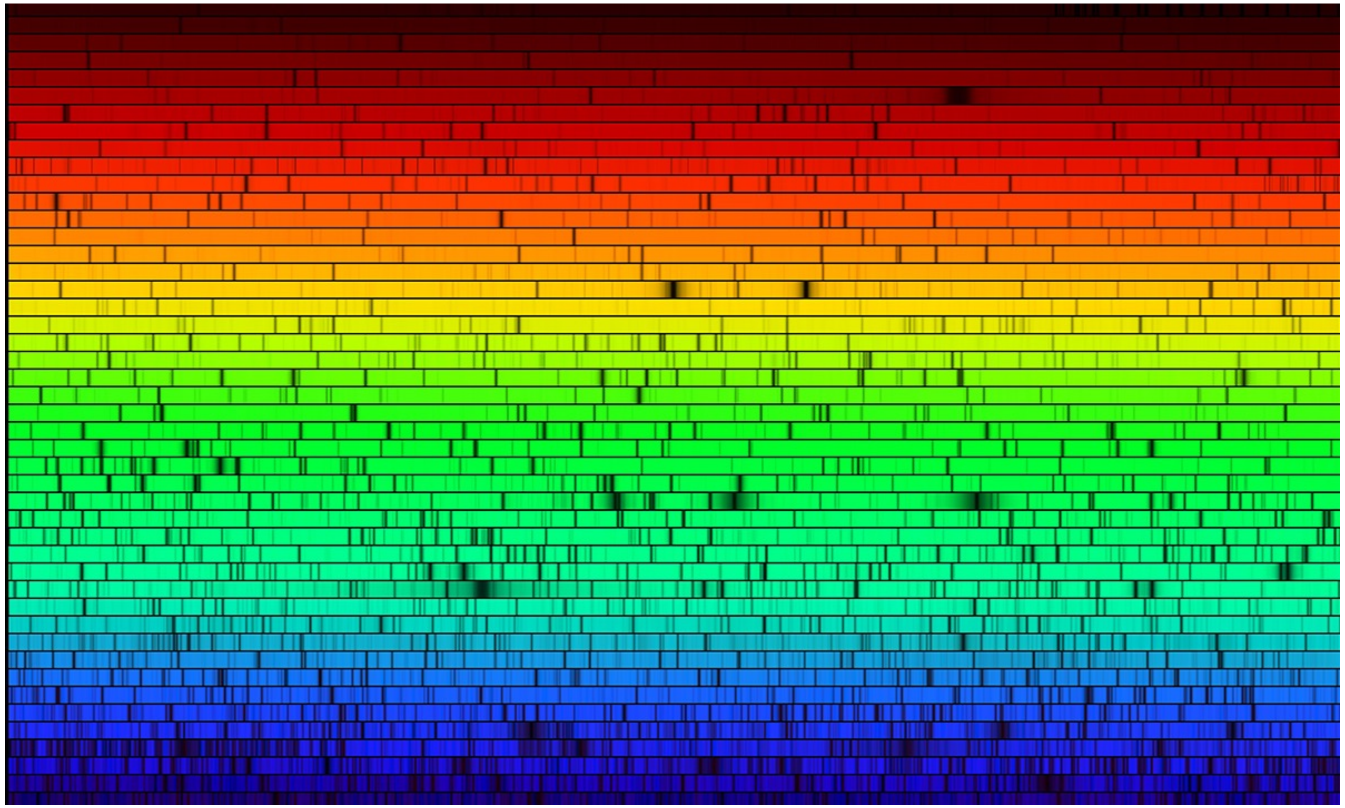
Stellar spectroscopy





High-resolution full visible spectrum of our Sun

(50 slices with wavelength increasing from left to right and bottom to top, starting at 4000-7000 Angstroms)



N.A.Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

Meteorites

- CI Chondrites: fragile and rare types of meteorites, most important for studying solar system composition
  (only 5 known of ~1000 recorded meteorites observed to fall)

- When comparing to spectroscopic abundances from the solar photosphere, CI chondrites show the best agreement

- Allende meteorite most studied and dated (Mexico 1969): 4.6 billion years old

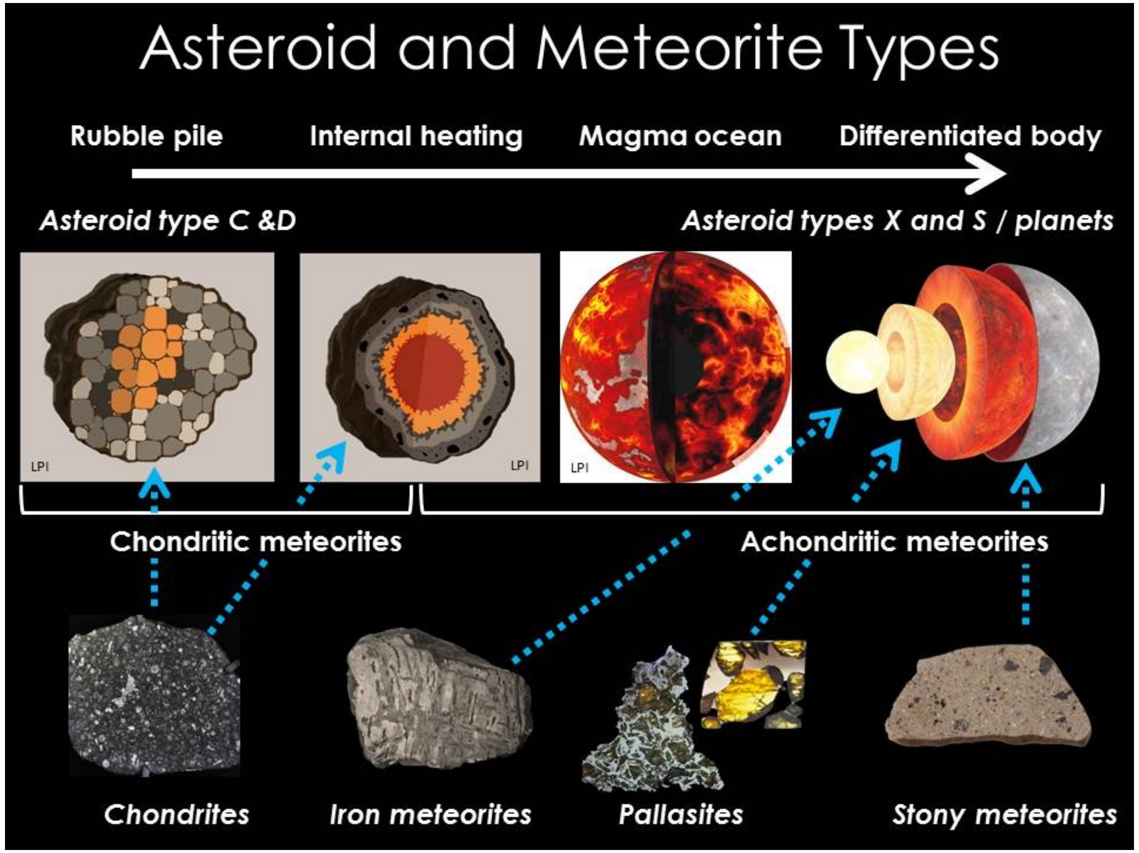
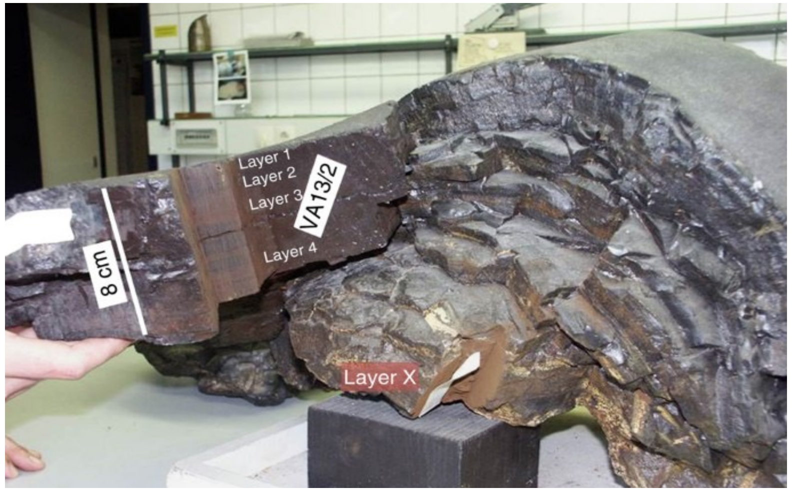


Image by K Joy adapted from images at LPI / E&SS / NASA

Deep sea ocean crusts

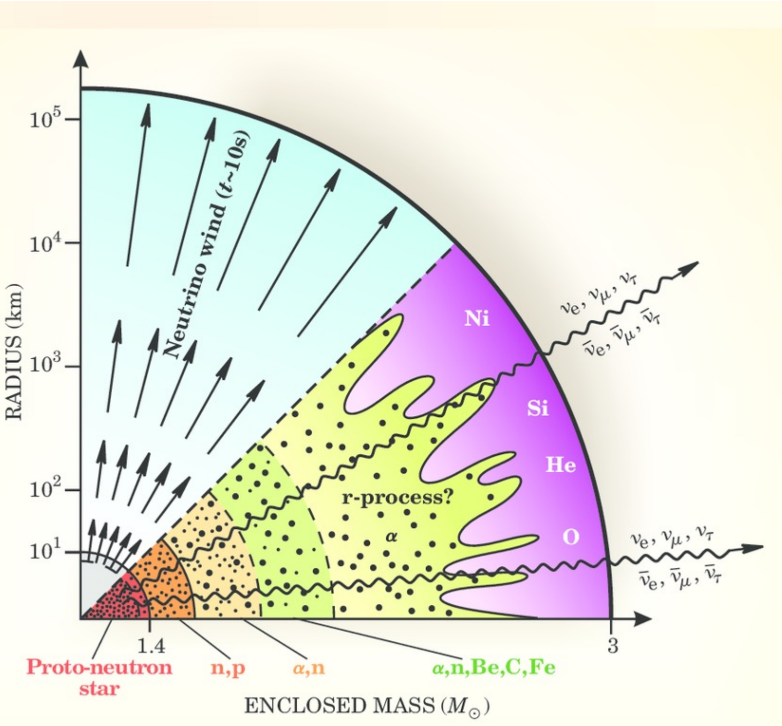
- Plutonium-244 (half-life 81 Myr) detection in Earth's deep sea ocean floor implies an extraterrestrial source of Pu arriving on Earth during the last ~25 Myr



Wallner+2015

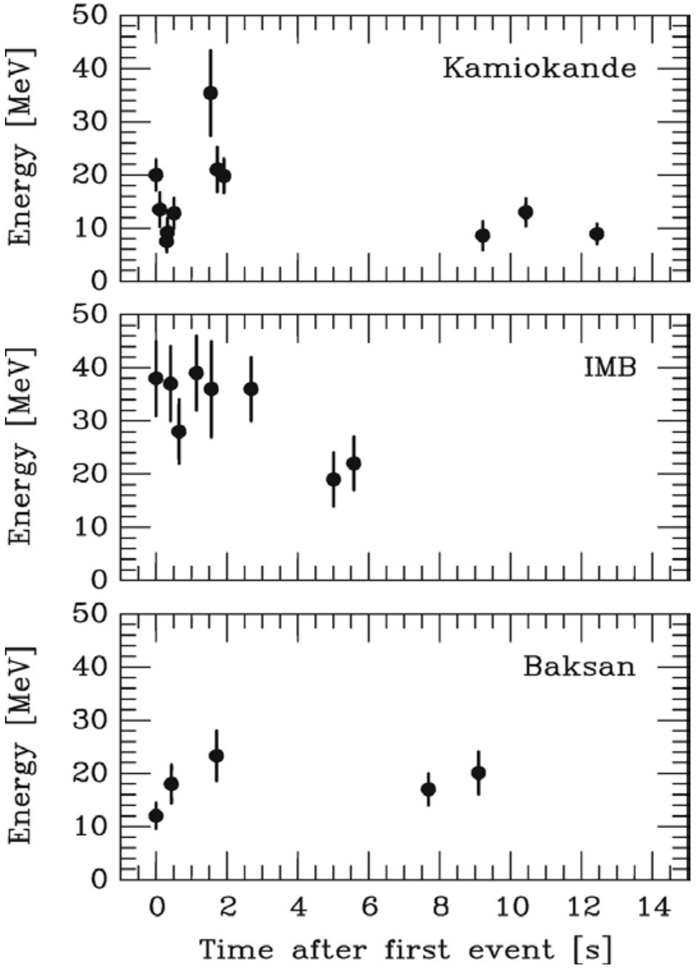
Multi-messenger events

SN1987A:
A famous core-collapse supernova

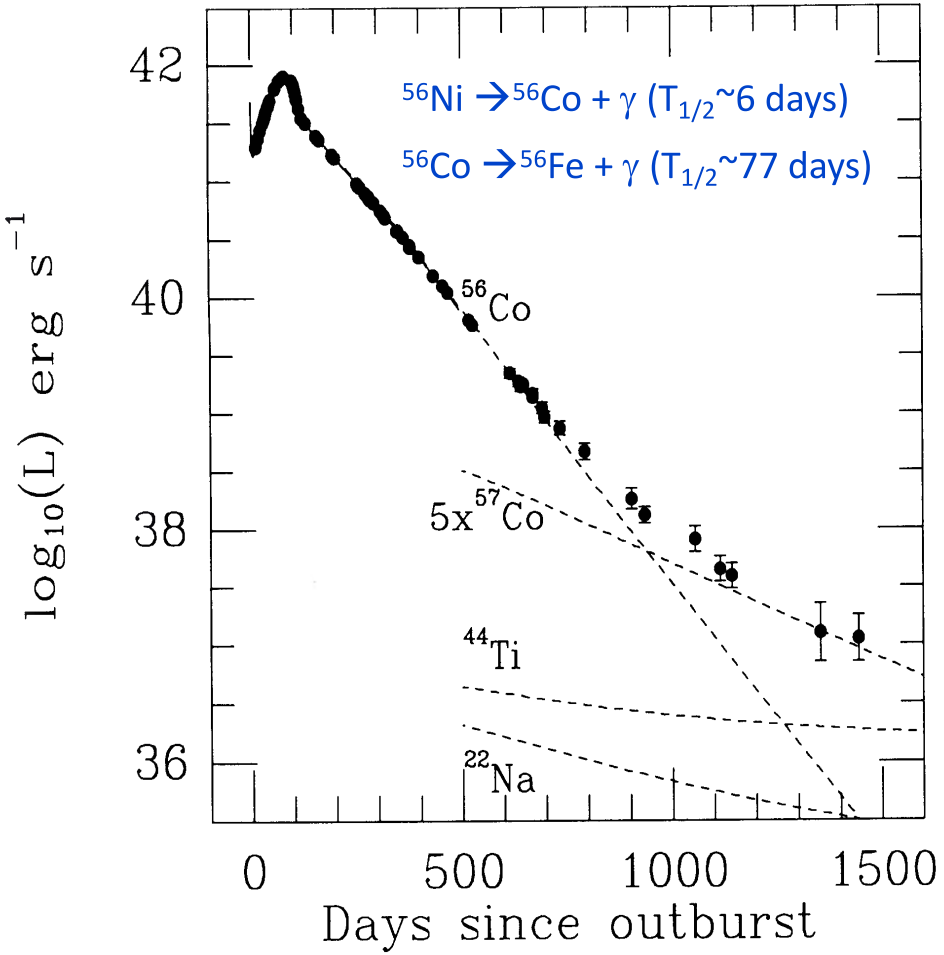


Woosley&Janka 06

Neutrinos



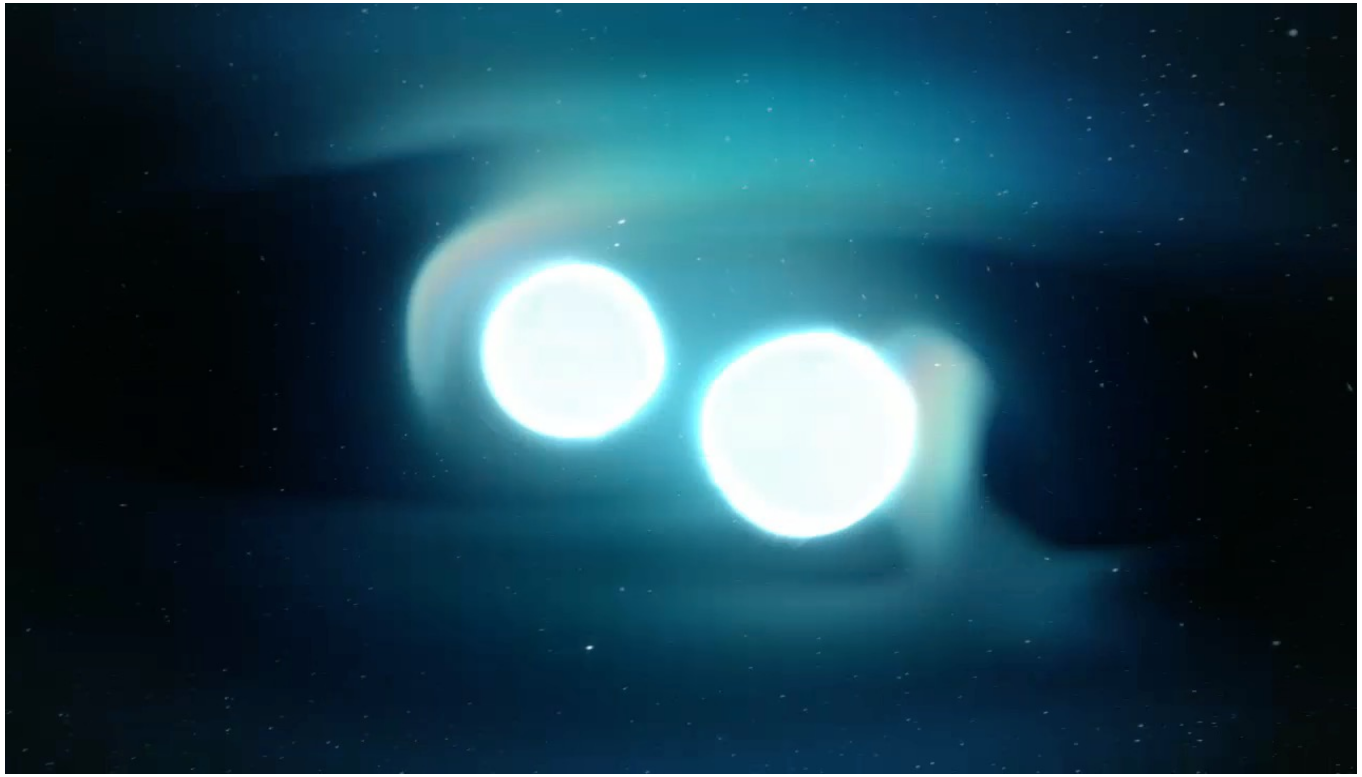
Light curve



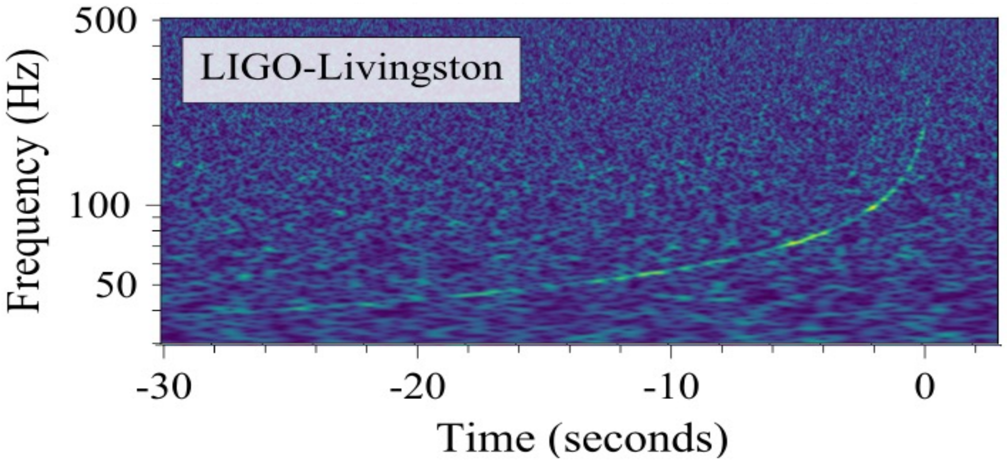
Suntzeff+92

A new kind of messenger: gravitational waves

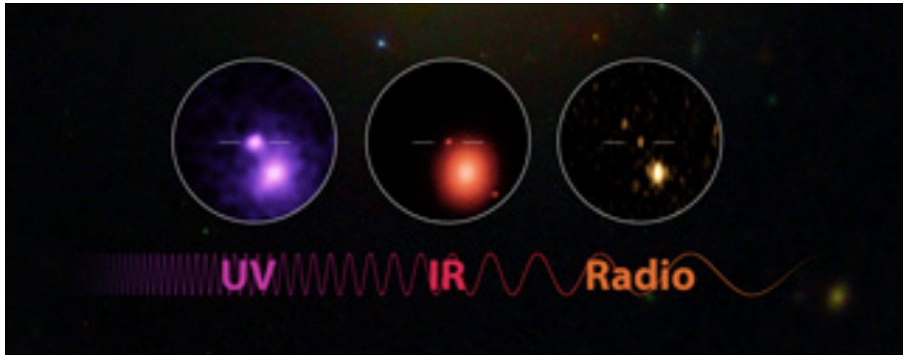
GW170817 & AT2017gfo:
Binary neutron star merger



NASA Goddard



Abbott+17



Hurt/Kasliwal/Hallinan, Evans, and the GROWTH collab.

Over ~70 observing teams (~1/3 of the worldwide astronomical community) followed up on the merger event!

Ultraviolet (left, NASA Swift satellite)
Infrared (middle, Gemini South telescope)
Radio (right, Very Large Array)
γ-ray, X-ray, and optical also observed

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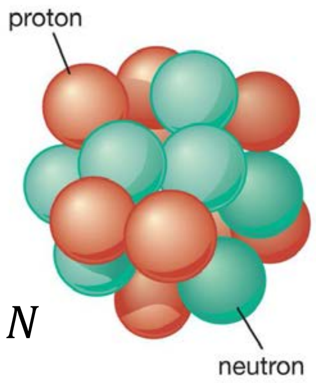
Nuclear masses and binding energy

Z



$A = Z + N$

N

The total nuclear masses is *less than* the sum of the masses of its constituent neutrons and protons:

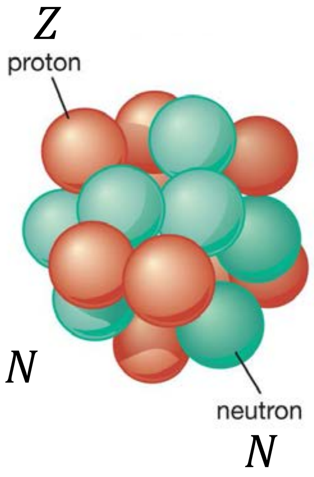
$$M_{nuc} = Z\, M_p + N\, M_n - \Delta m$$

“mass defect” defines binding energy through $\Delta E = \Delta m\, c^2$; that is

$$BE(Z, N) = (Z\, M_p + N\, M_n - M_{nuc})c^2$$

*Nuclear processes liberate energy as long as the binding energy per nucleon of the final products exceeds the binding energy per nucleon of the initial constituents

Nuclear masses and binding energy



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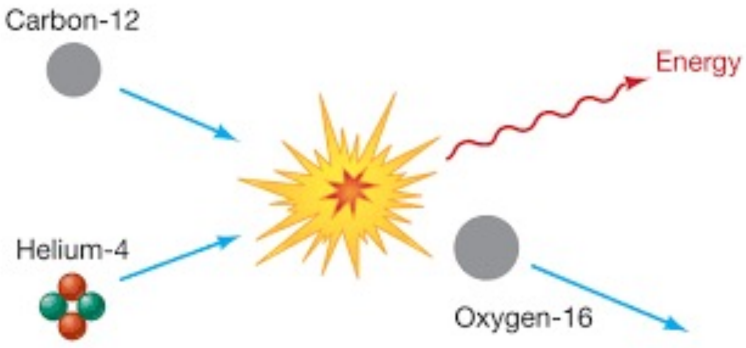
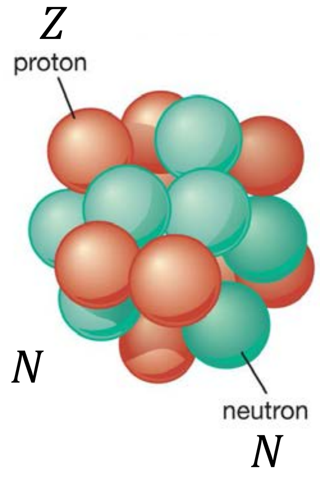
Example 1



$$\frac{BE}{A}(^{12}C) = 7.68 \text{ MeV}$$
$$\frac{BE}{A}(^{4}He) = 7.07 \text{ MeV}$$
$$\frac{BE}{A}(^{16}O) = 7.98 \text{ MeV}$$

The energy release is:
(127.68 – 92.16 – 28.28) MeV = 7.24 MeV

Nuclear masses and binding energy

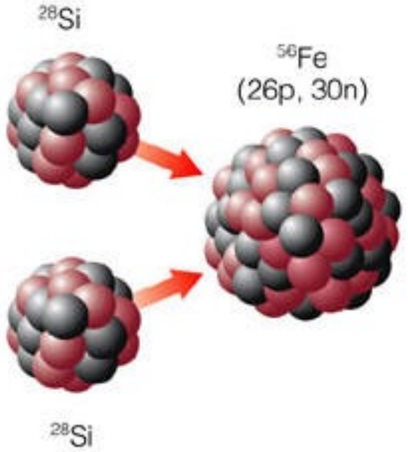


$A = Z + N$

Example 2

$\frac{BE}{A}(^{28}Si) = 8.45$ MeV

$\frac{BE}{A}(^{56}Fe) = 8.79$ MeV



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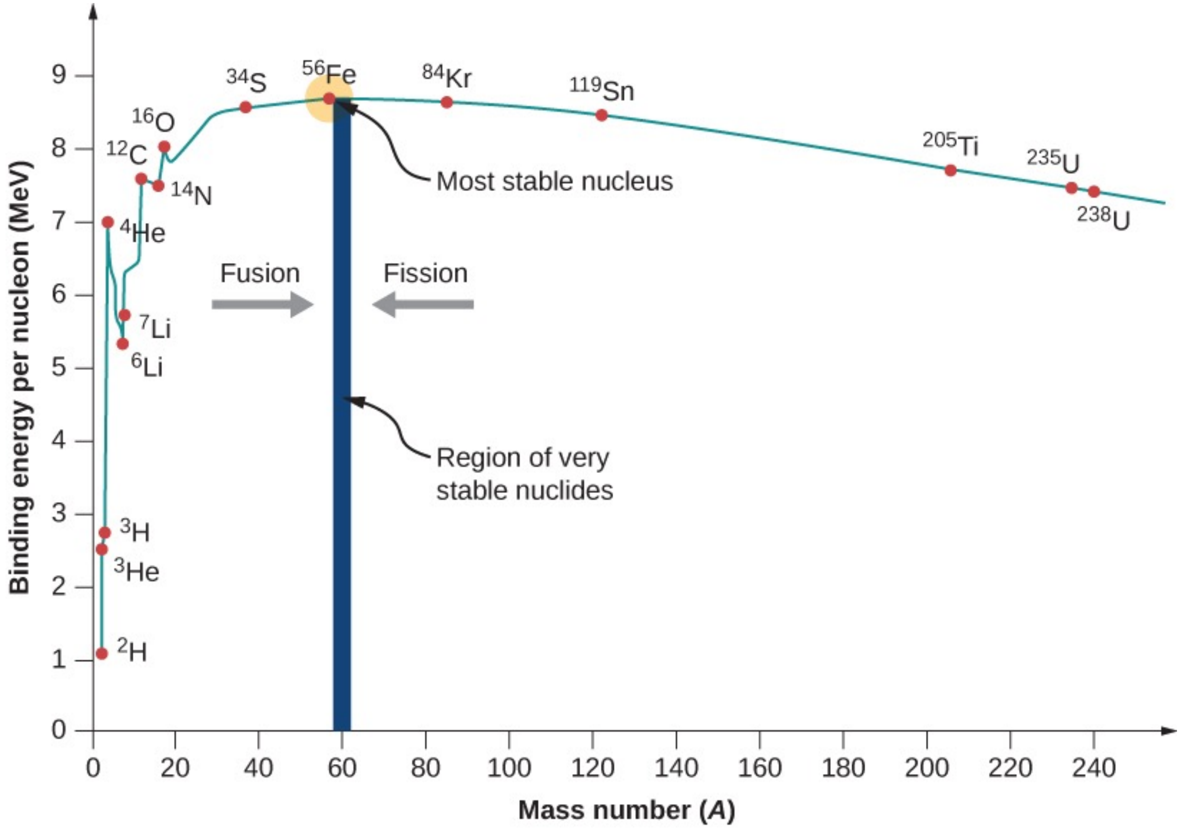
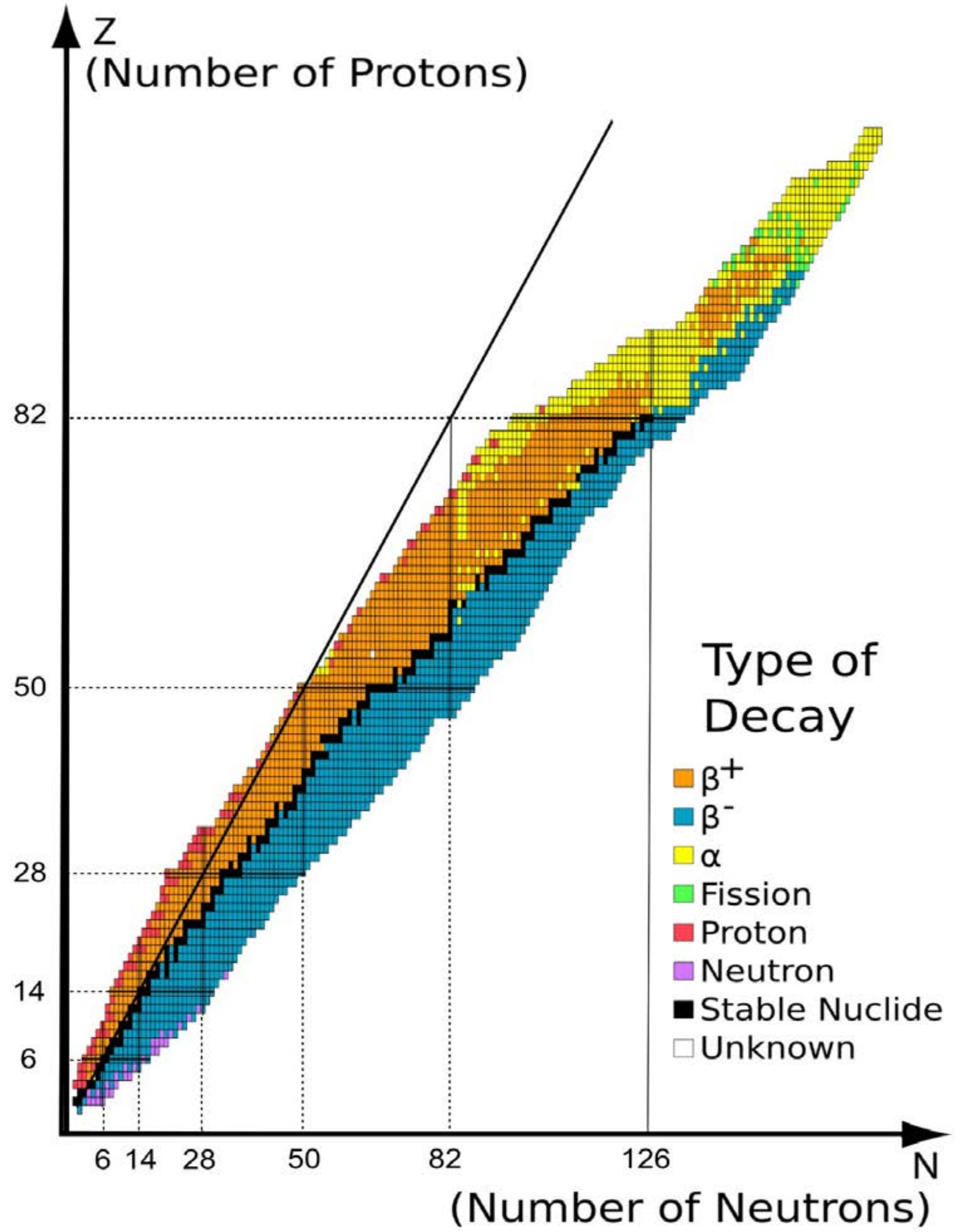
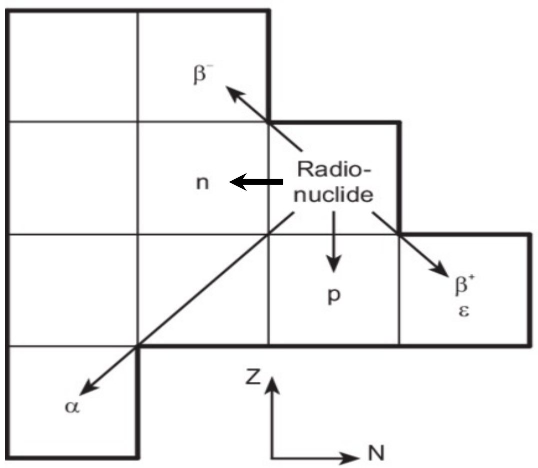
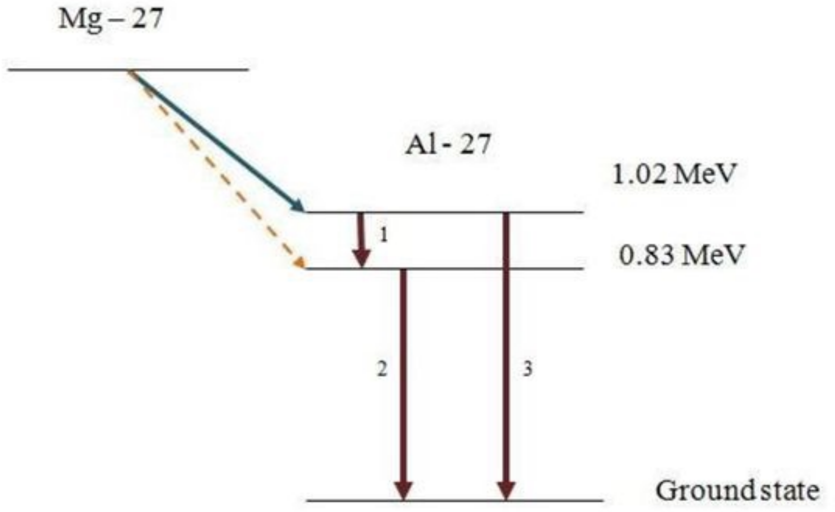


Nuclear Decays







Decay constant (decay rate) λ (and half-life $T_{1/2} = \ln(2)\,/\lambda$) defined by:

$$N_0 e^{-\lambda t}$$

Fermi’s Golden Rule:

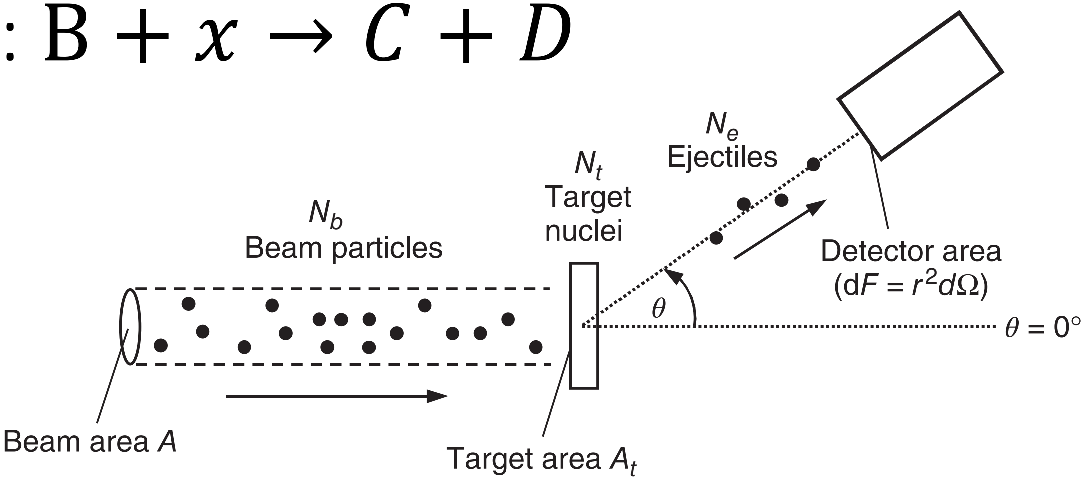
$$\lambda = \frac{2\pi}{\hbar} |\langle f|H_{\text{int}}|i\rangle|^2 \rho(E)$$

f, i are final and initial state wavefunctions and $M_{fi} = \langle f|H_{\text{int}}|i\rangle$ is the “matrix element”

H_{int} is the weak interaction Hamiltonian

$\rho(E)$ is the density of states of the final particles (a process is more likely to happen if there is a larger choice of final states)

Cross sections and stellar reaction rates: $\mathrm{B} + x \rightarrow C + D$



The cross section depends on the matrix element $M_{fi} = \langle f | H_{\mathrm{int}} | i \rangle$ and can be understood schematically as:

$$\sigma = \frac{\text{\# of interactions per time}}{(\text{\# of incident particles per area per time})(\text{\# of target nuclei in beam})}$$

Since cross sections are dependent on the incident energy (velocity), *in astrophysical plasmas must average over a velocity distribution* to get the thermally averaged cross section:

$$\langle \sigma v \rangle = \int \sigma \ v\, f(v)\, dv$$

where if nuclei are non-relativistic and non-degenerate velocities described by Maxwell-Boltzmann distribution ($\sim e^{-E/kT}$) giving

$$f(v) = \left(\frac{m}{2\pi kT}\right)^{3/2} 4\pi v^2 e^{-\frac{mv^2}{2kT}} \quad \text{with} \quad m = \frac{m_B m_x}{m_B + m_x} \text{ (the reduced mass)}$$

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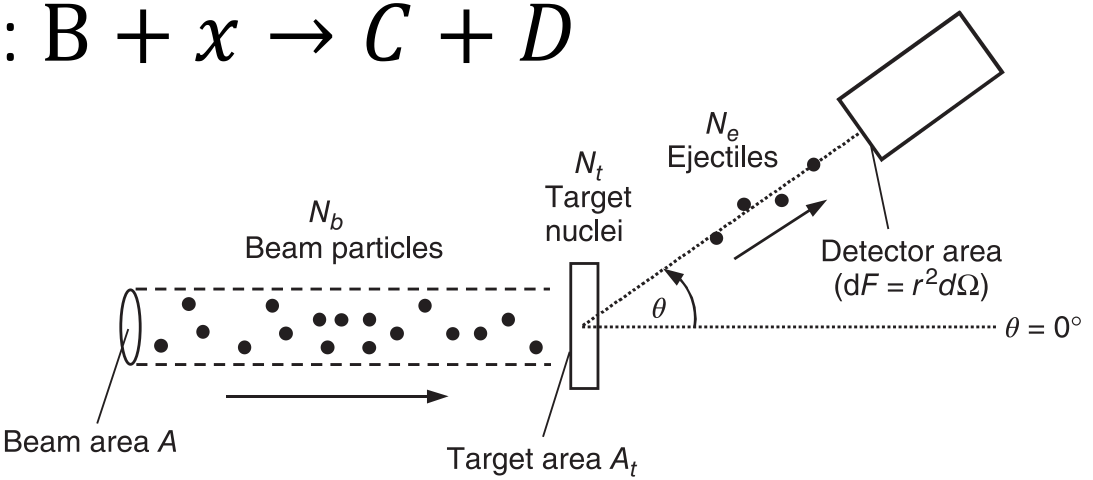

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Interaction rate or reaction rate [$\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$]:

$$r_{Bx} = \frac{n_B n_x}{1 + \delta_{Bx}} \langle \sigma v \rangle$$

"Stellar reaction rate" (per target nucleus) [s^{-1}]:

$$\lambda_{Bx} = \frac{1}{1 + \delta_{Bx}} n_B \langle \sigma v \rangle$$

Putting it all together: consider $\mathrm{B} + x \rightarrow C + D$

$Q = (M_B + M_x - M_c - M_D)c^2$

$Q =$ energy released (+) or absorbed (-), aka Q-value [MeV]

$S_n(Z, A+1) = M_{Z,A} + M_n - M_{Z,A+1}$

S_n = one neutron separation energy [MeV]

$n_B = \rho N_A \frac{X_B}{A_B} = \rho N_A Y_B$

n_B = number density [cm^{-3}], ρ = density [g $\cdot$ cm^{-3}], N_A= Avogadro's number (6.022×10^{23}) [g^{-1}]

$\frac{X_B}{A_B} = \frac{\text{mass fraction } (\sum_i X_i = 1)}{\text{mass number (\# protons + \# neutrons)}}$, Y_B = abundance

$Y_e = \sum_i Z_i Y_i = \frac{n_p}{n_p + n_n}$

Y_e = electron fraction (formula assumes charge neutrality); lower Y_e is more neutron rich

$r_{Bx} = \frac{n_B n_x}{1+\delta_{Bx}} \langle \sigma v \rangle$

$\langle \sigma v \rangle$ = thermally averaged cross section = $\int \sigma \; v \, f(v) \, dv$ where $f(v) = \left(\frac{m}{2\pi kT}\right)^{3/2} 4\pi v^2 e^{-\frac{mv^2}{2kT}}$ is the Maxwell-Boltzmann distribution ($\sim e^{-E/kT}$) and $m = \frac{m_B m_x}{m_B + m_x}$ (the reduced mass)

$\lambda_{Bx} = \frac{1}{1+\delta_{Bx}} Y_B \rho N_A \langle \sigma v \rangle$

r = interaction rate or reaction rate [cm^{-3} s^{-1}],
λ = "stellar reaction rate"(per target nucleus) [s^{-1}] (Note units of $N_A \langle \sigma v \rangle$=cm^3/s/g)

Recall definitions for $\mathrm{B} + x \rightarrow C + D$

$Q = (M_B + M_x - M_c - M_D)c^2$

$r_{Bx} = \frac{n_B n_x}{1+\delta_{Bx}} \langle \sigma v \rangle$

$n_B = \rho N_A \frac{X_B}{A_B} = \rho N_A Y_B$

$\lambda_{Bx} = \frac{1}{1+\delta_{Bx}} Y_B \rho N_A \langle \sigma v \rangle$

Reverse rate for $C + D \rightarrow \mathrm{B} + x$ from detailed balance (equilibrium): Saha Equation

If $B \neq x$ and $\mathrm{C} \neq D$ with all being nuclei:

$r_{Bx} = r_{CD} \Rightarrow \frac{n_C n_D}{n_B n_x} = \frac{\langle \sigma v \rangle_{Bx}}{\langle \sigma v \rangle_{CD}}$ along with $\frac{\sigma_{Bx}}{\sigma_{CD}} = \frac{g_C g_D}{g_B g_X} \frac{A_C A_D E_{CD}}{A_B A_x E_{Bx}}$

where g=2J+1; can then obtain:

$$\frac{n_C n_D}{n_B n_x} = \frac{\langle \sigma v \rangle_{Bx}}{\langle \sigma v \rangle_{CD}} = \frac{g_C g_D}{g_B g_X} \left(\frac{A_C A_D}{A_B A_x} \right)^{3/2} e^{+Q/kT}$$

*See Fowler, Caughlan, and Zimmerman (1967) for more details

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$$n_B = \rho N_A \frac{X_B}{A_B} = \rho N_A Y_B \qquad \lambda_{Bx} = \frac{1}{1+\delta_{Bx}} Y_B \rho N_A \langle\sigma v\rangle$$

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$$\frac{n_C n_D}{n_B n_x} = \frac{\langle\sigma v\rangle_{Bx}}{\langle\sigma v\rangle_{CD}} = \frac{g_C g_D}{g_B g_X}\left(\frac{A_C A_D}{A_B A_x}\right)^{3/2} e^{+Q/kT}$$

If instead C is a photon:

$$r_{Bx} = r_{D\gamma} \Rightarrow \frac{n_D}{n_B n_x} = \frac{\langle\sigma v\rangle_{Bx}}{\lambda_\gamma}$$

Gives:

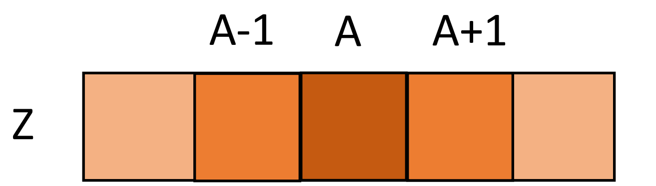
$$\frac{n_D}{n_B n_x} = \frac{\langle\sigma v\rangle_{Bx}}{\lambda_\gamma} = \frac{g_D}{g_B g_X}\left(\frac{A_D}{A_B A_x}\right)^{3/2}\left(\frac{2\pi\hbar^2}{mkT}\right)^{3/2} e^{+Q/kT}$$

*See Fowler, Caughlan, and Zimmerman (1967) for more details

Example: $(n,\gamma) \rightleftarrows (\gamma,n)$ equilibrium + steady β flow

Assume $(\mathrm{n},\gamma) \rightleftarrows (\gamma,\mathrm{n})$ equilibrium to obtain relative abundances of neighboring isotopes:

$$\frac{Y_{A+1}}{Y_A} = \frac{n_{A+1}}{n_A} \approx n_n \frac{g_{A+1}}{g_A g_n}\left(\frac{A+1}{A}\right)^{3/2}\left(\frac{2\pi\hbar^2}{A m_n m_n kT}(A+1)m_n\right)^{3/2} e^{+S_n/kT}$$

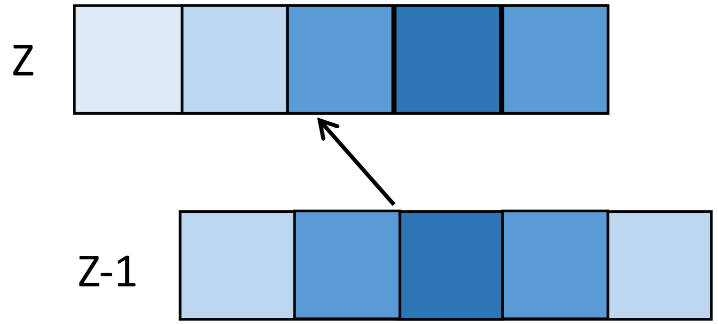


*Sets the relative abundances along an isotopic chain

The evolution of abundances is determined from flow of β-decay:

$$\frac{dn(Z)}{dt} = \lambda_{Z-1} n(Z-1) - \lambda_z n(Z) \quad \text{where} \quad \lambda_z = \textstyle\sum_A n(Z,A)\lambda_\beta(Z,A)$$

Steady flow equilibrium (or β-flow equilibrium) assumes $\lambda_z n(Z) \sim$ constant



*Allows for the chain to move to elements with higher proton numbers or in the case of steady flow sets relative Z abundances

Nuclear Statistical Equilibrium (NSE)

If the environment is hot enough to overcome Coulomb barriers and has high energy photons, neutron and proton captures on (Z,N) are in chemical equilibrium with reverse photodissociations:

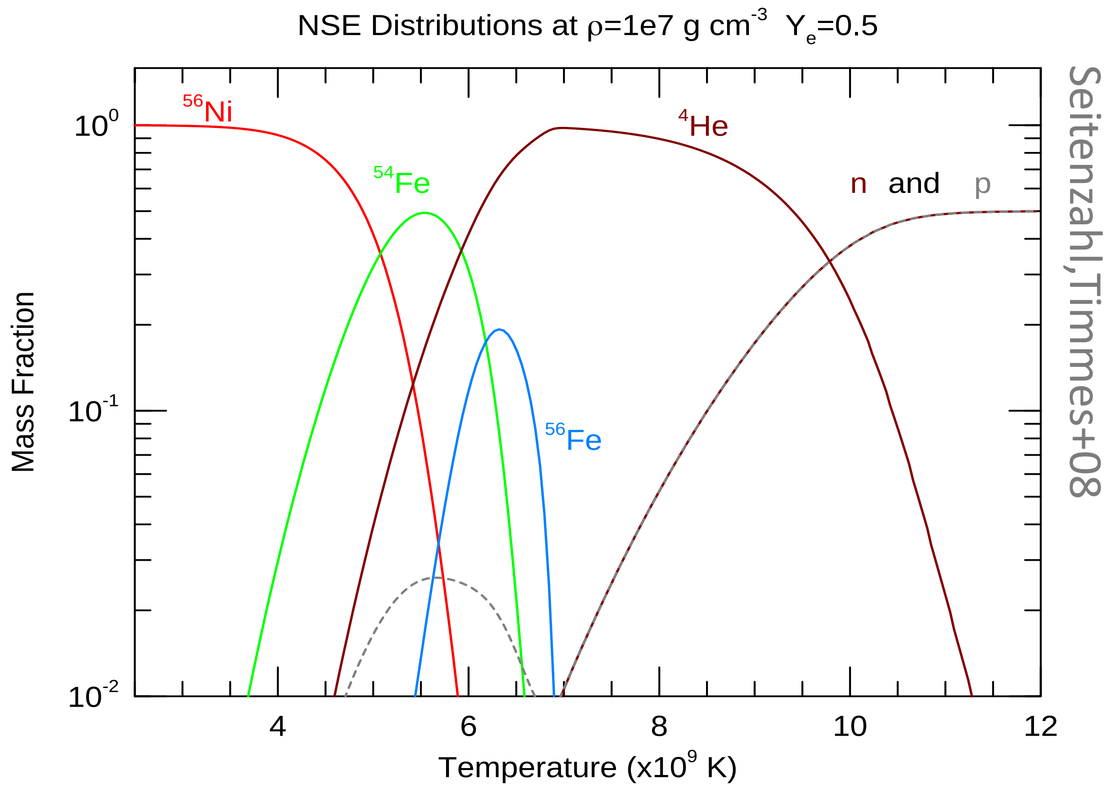
$$N \text{ neutrons} + Z \text{ protons} \rightleftarrows (Z,N)$$

$$N\mu_n + Z\mu_Z = \mu_{Z,N}$$

where μ is the chemical potential; nucleons and nuclei are described by Maxwell-Boltzmann distributions (note G_i is the partition function):

$$\mu_i = m_i c^2 + kTln\left[\rho N_A \frac{Y_i}{G_i}\left(\frac{2\pi\hbar^2}{m_i kT}\right)^{3/2}\right]$$

*The above equations are used along with $\sum_i A_i Y_i = 1$ and $\sum_i Z_i Y_i = Y_e$ to solve for abundances at a given ρ, T, Y_e



For high temperatures, favors a composition of n, p, and α due to photodissociation, for lower temperatures nuclei with the highest binding energy are favored
(^{56}Fe for $Y_e < 0.5$ and ^{56}Ni for $Y_e = 0.5$)

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A short intro to reaction networks

$$Q = (M_B + M_x - M_c - M_D)c^2 \qquad r_{Bx} = \frac{n_B n_x}{1+\delta_{Bx}}\langle\sigma v\rangle$$

$$n_B = \rho N_A \frac{X_B}{A_B} = \rho N_A Y_B \qquad \lambda_{Bx} = \frac{1}{1+\delta_{Bx}} Y_B \rho N_A \langle\sigma v\rangle$$

For the two-body reaction

B + x → C

$$\frac{dn_B}{dt} = -n_B\lambda_{Bx} = -n_B Y_x \rho N_A \langle\sigma v\rangle$$

$$\frac{dn_C}{dt} = +n_B\lambda_{Bx}$$

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Now if a one-body decay produces B

$D \rightarrow B + z$

$$\frac{dn_B}{dt} = -n_B Y_x \rho N_A \langle\sigma v\rangle + n_D\lambda_D$$

$$\frac{dn_D}{dt} = -n_D\lambda_D$$

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$$\frac{dn_D}{dt} = -n_D\lambda_D$$

Thus network equations can be written as:

$$\dot{Y}_i = \sum_j \xi^i_j \lambda_j Y_j + \sum_{j,k} \xi^i_{j,k} \rho N_A \langle\sigma v\rangle_{j,k} Y_j Y_k + \sum_{j,k,l} \xi^i_{j,k,l} \rho^2 {N_A}^2 \langle\sigma v\rangle_{j,k,l} Y_j Y_k Y_l$$

Where ξ is + when i created, - when i consumed, and corrects for overcounting in a reaction involving identical particles

*Coupled differential equations can be put into matrix form so networks use matrix solvers

A short intro to reaction networks

$$Q = (M_B + M_x - M_c - M_D)c^2 \qquad r_{Bx} = \frac{n_B n_x}{1+\delta_{Bx}}\langle\sigma v\rangle$$

$$n_B = \rho N_A \frac{X_B}{A_B} = \rho N_A Y_B \qquad \lambda_{Bx} = \frac{1}{1+\delta_{Bx}} Y_B \rho N_A \langle\sigma v\rangle$$

Written out in a more schematic way:

$\dot{Y}_i = \sum(\text{2body reactions into } i) - \sum(\text{2body reactions out of } i)$ (ex: n capture, photodissociation)

$+\sum(\text{3body reactions into } i) - \sum(\text{3body reactions out of } i)$ (ex: $\alpha\alpha$n, (n,2n))

$+\sum(\text{decays into } i) - \sum(\text{decays out of } i)$ (ex: β-decay, β-delayed n emission, α-decay)

$+\sum(\text{fission into } i)$ OR $-\sum(\text{fission out of } i)$ (ex: neutron-induced, β-delayed, spontaneous fission)

See e.g. Hix&Meyer 06, Lippuner&Roberts 18 for discussions of solving network equations

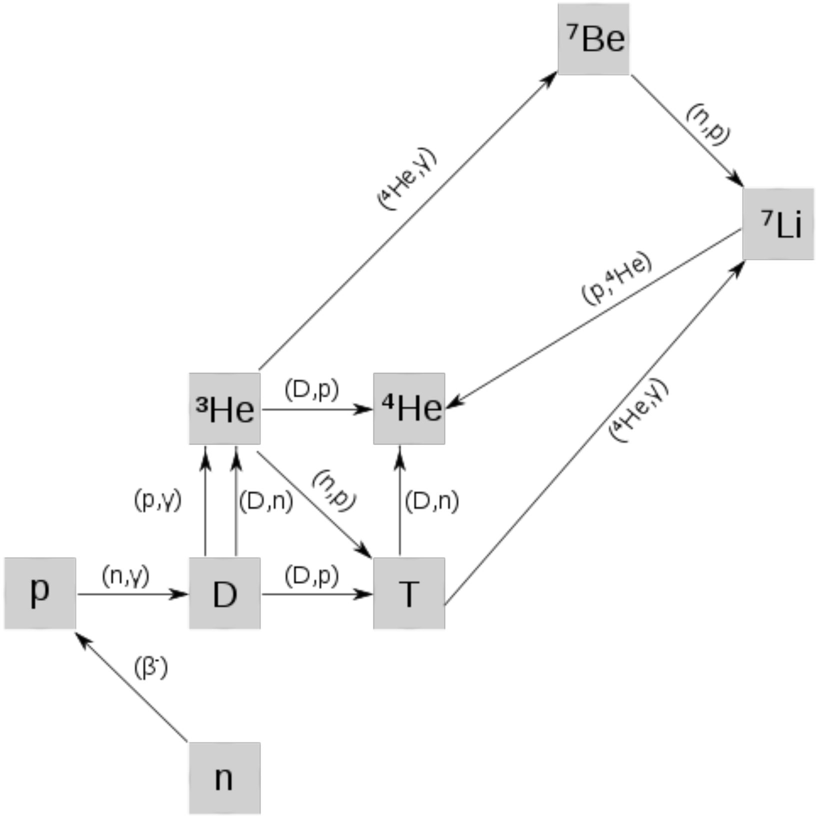
Thus network equations can be written as:

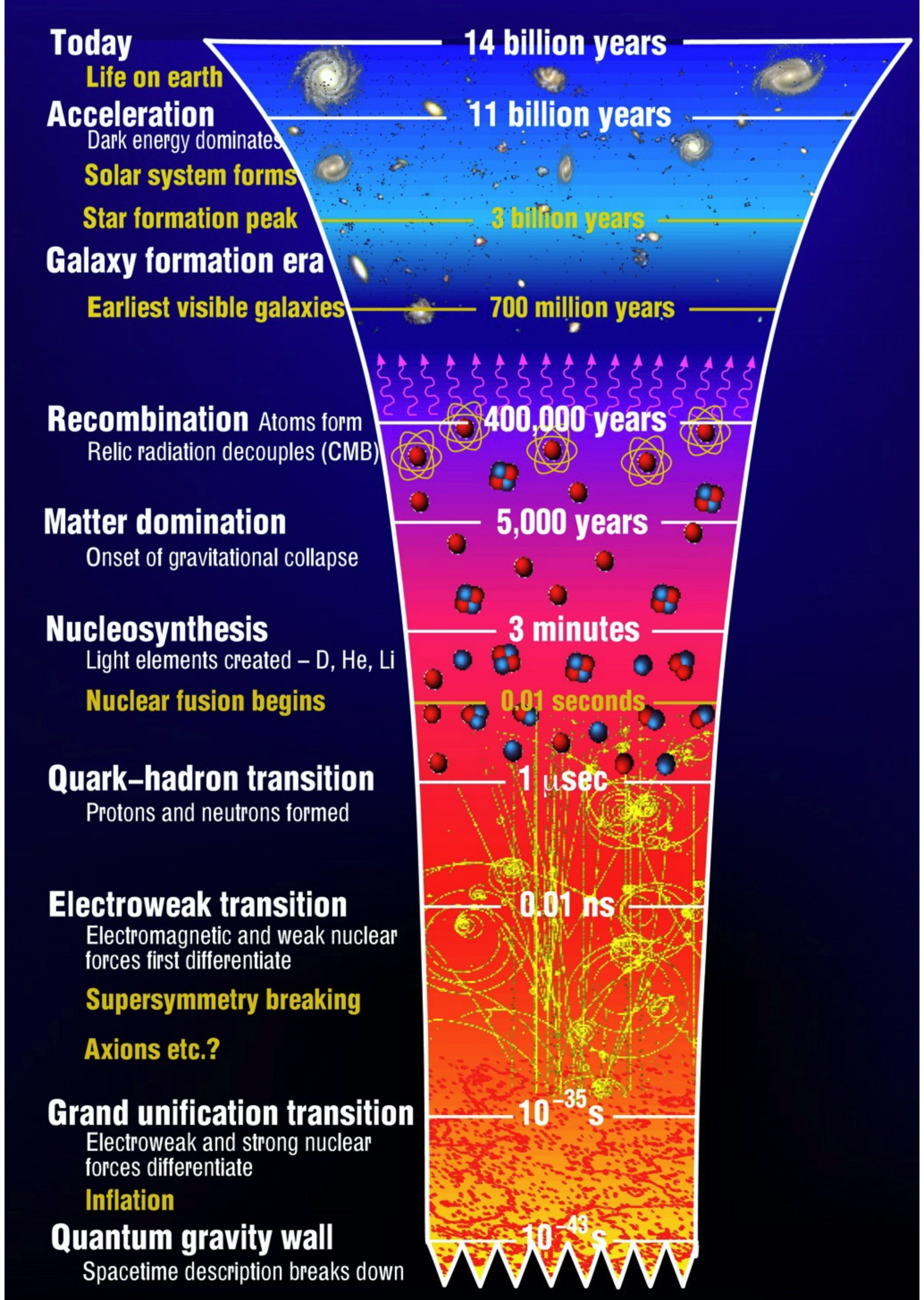
$$\dot{Y}_i = \sum_j \xi^i_j \lambda_j Y_j + \sum_{j,k} \xi^i_{j,k} \rho N_A \langle\sigma v\rangle_{j,k} Y_j Y_k + \sum_{j,k,l} \xi^i_{j,k,l} \rho^2 {N_A}^2 \langle\sigma v\rangle_{j,k,l} Y_j Y_k Y_l$$

Where ξ is + when i created, - when i consumed, and corrects for overcounting in a reaction involving identical particles

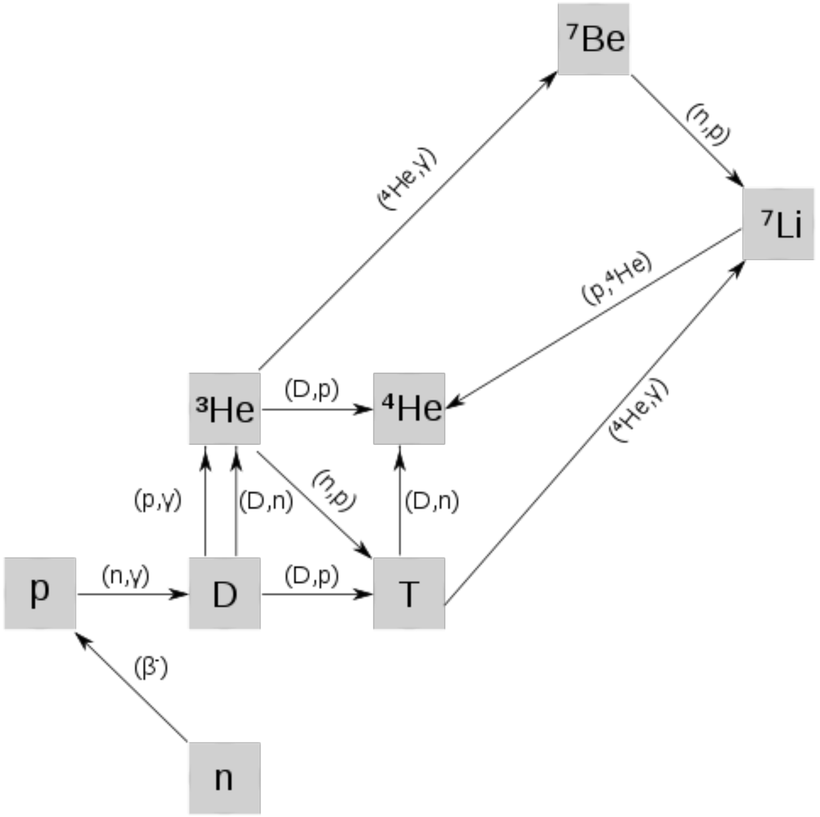
*Coupled differential equations can be put into matrix form so networks use matrix solvers

Big Bang Nucleosynthesis network of reactions





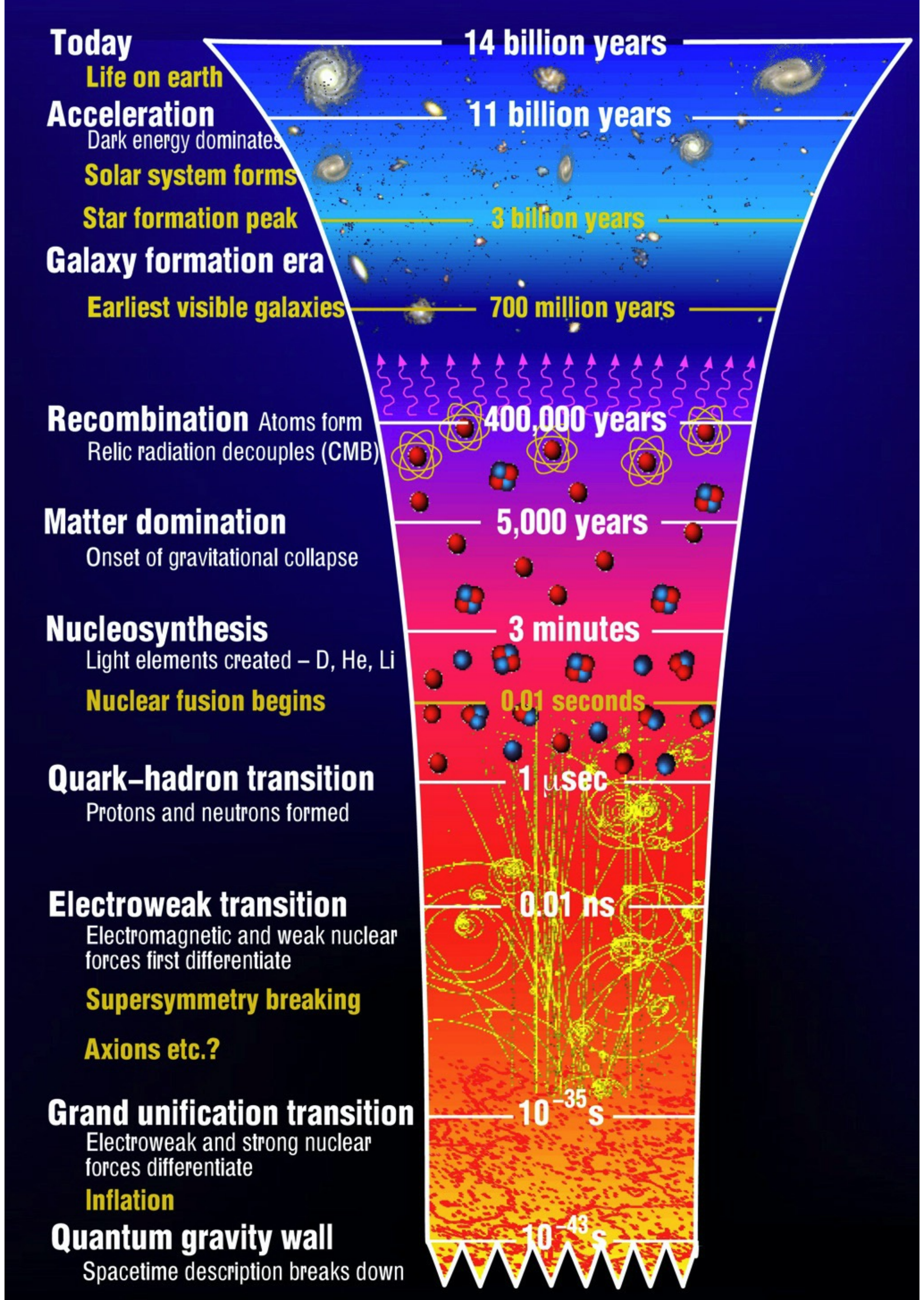
Big Bang Nucleosynthesis network of reactions



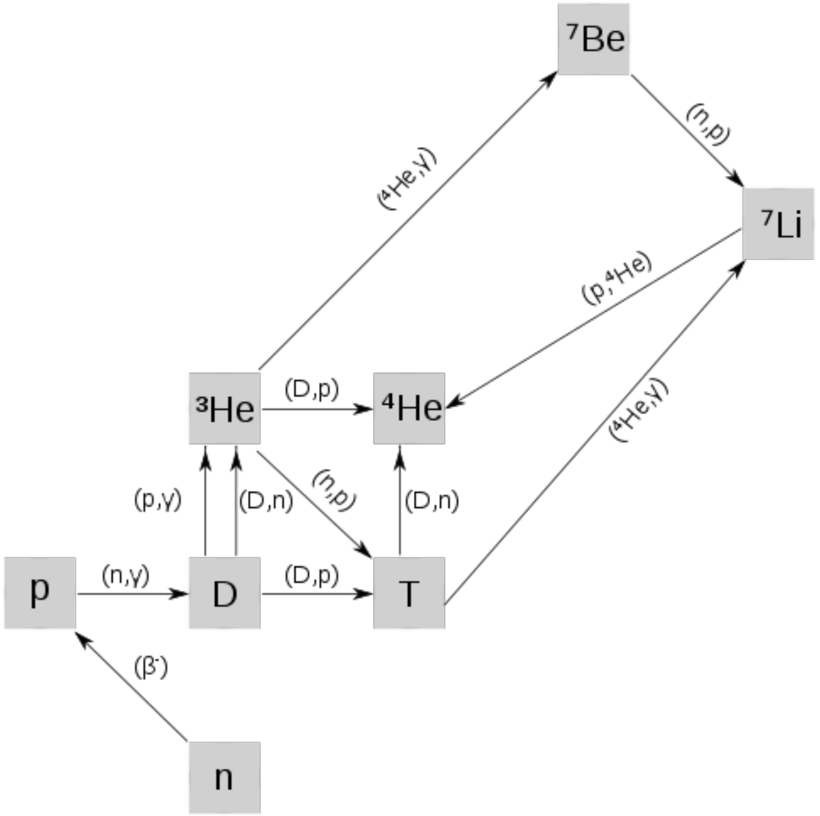
Let's write down some of the coupled differential equations:

$$\frac{dY_p}{dt} = Y_n \lambda_{n\to p} - Y_p Y_n \rho N_A \langle\sigma v\rangle_{p(n,\gamma)}$$

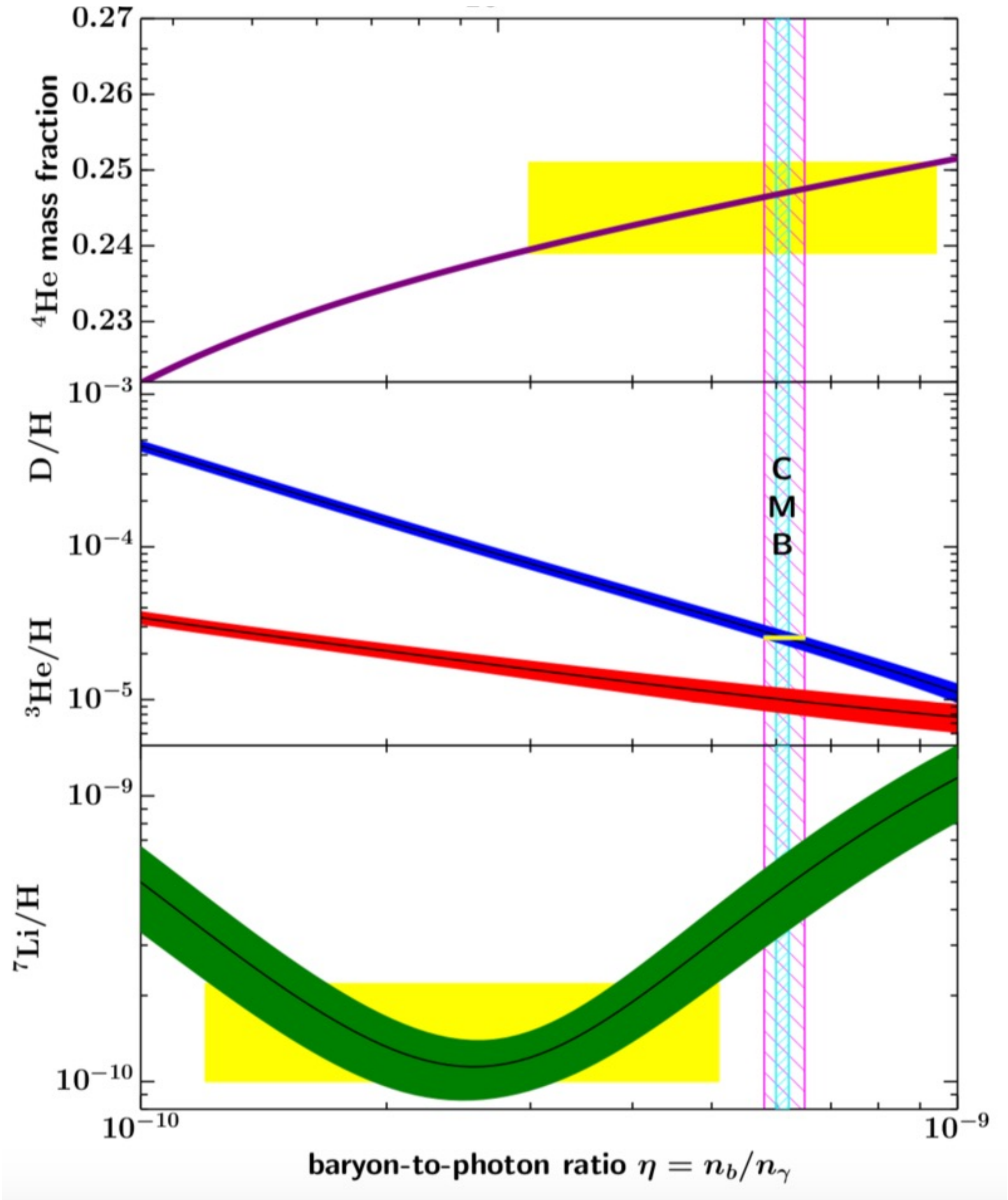
$$\frac{dY_{Li}}{dt} = Y_{Be} Y_n \rho N_A \langle\sigma v\rangle_{Be(n,p)} + Y_T Y_\alpha \rho N_A \langle\sigma v\rangle_{T(\alpha,\gamma)} - Y_{Li} Y_p \rho N_A \langle\sigma v\rangle_{Li(p,\alpha)}$$



Big Bang Nucleosynthesis network of reactions

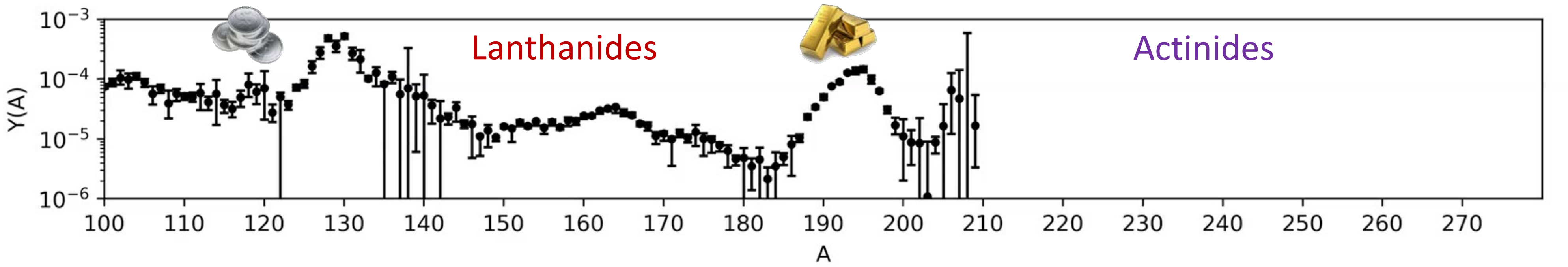


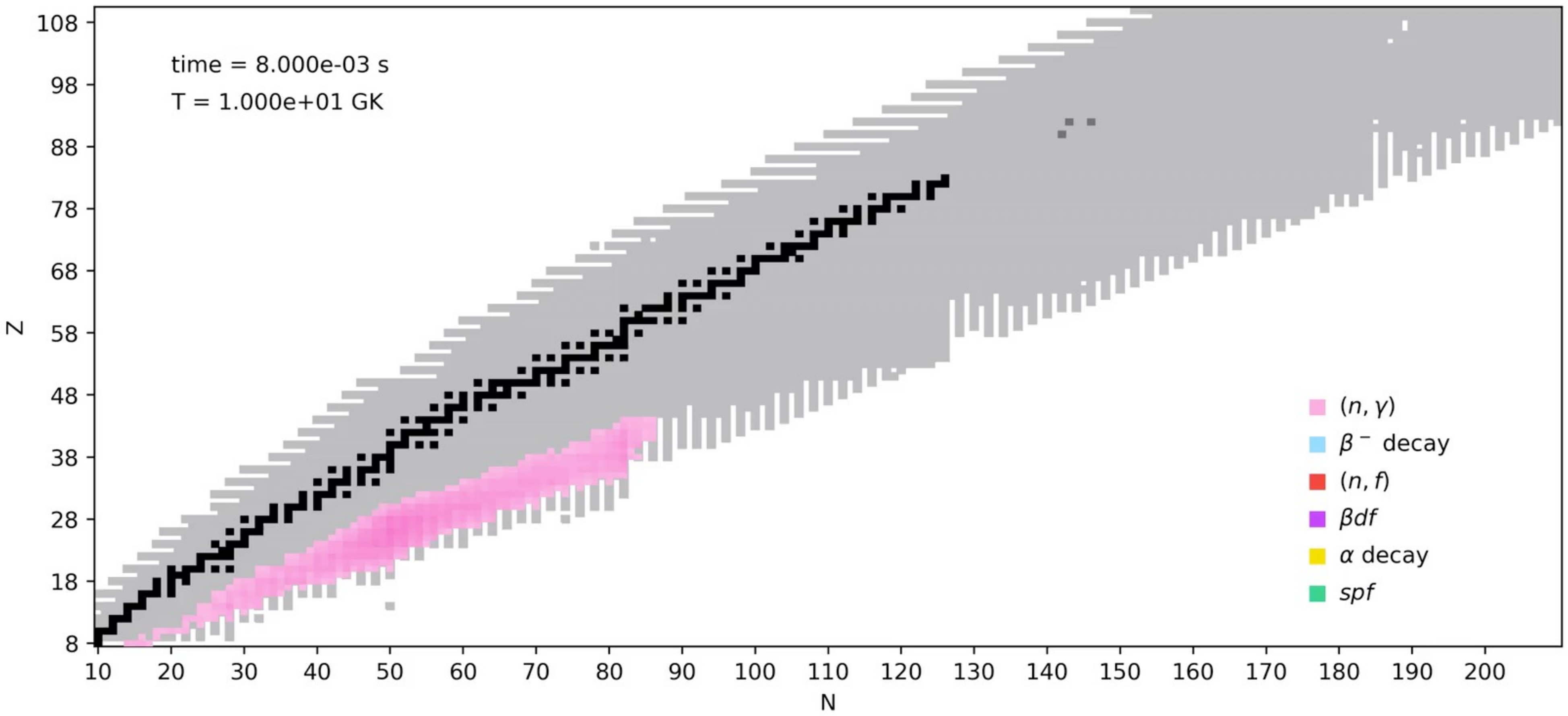
BBN abundances



- BBN primarily makes hydrogen (~75%) and helium (~25%)
- BBN abundances are a probe of new physics (ex sterile neutrinos, dark matter) in the early universe
- Ongoing work (ex: Fields+22) with BBN abundances: Li problem - abundances observed in metal poor stars lower than prediction
- Ongoing measurements of BBN reaction rates (ex: recently updated ^{7}Be(n,p)^{7}Li measurement Damone+18)

A (much) bigger network: rapid neutron capture and the heaviest elements

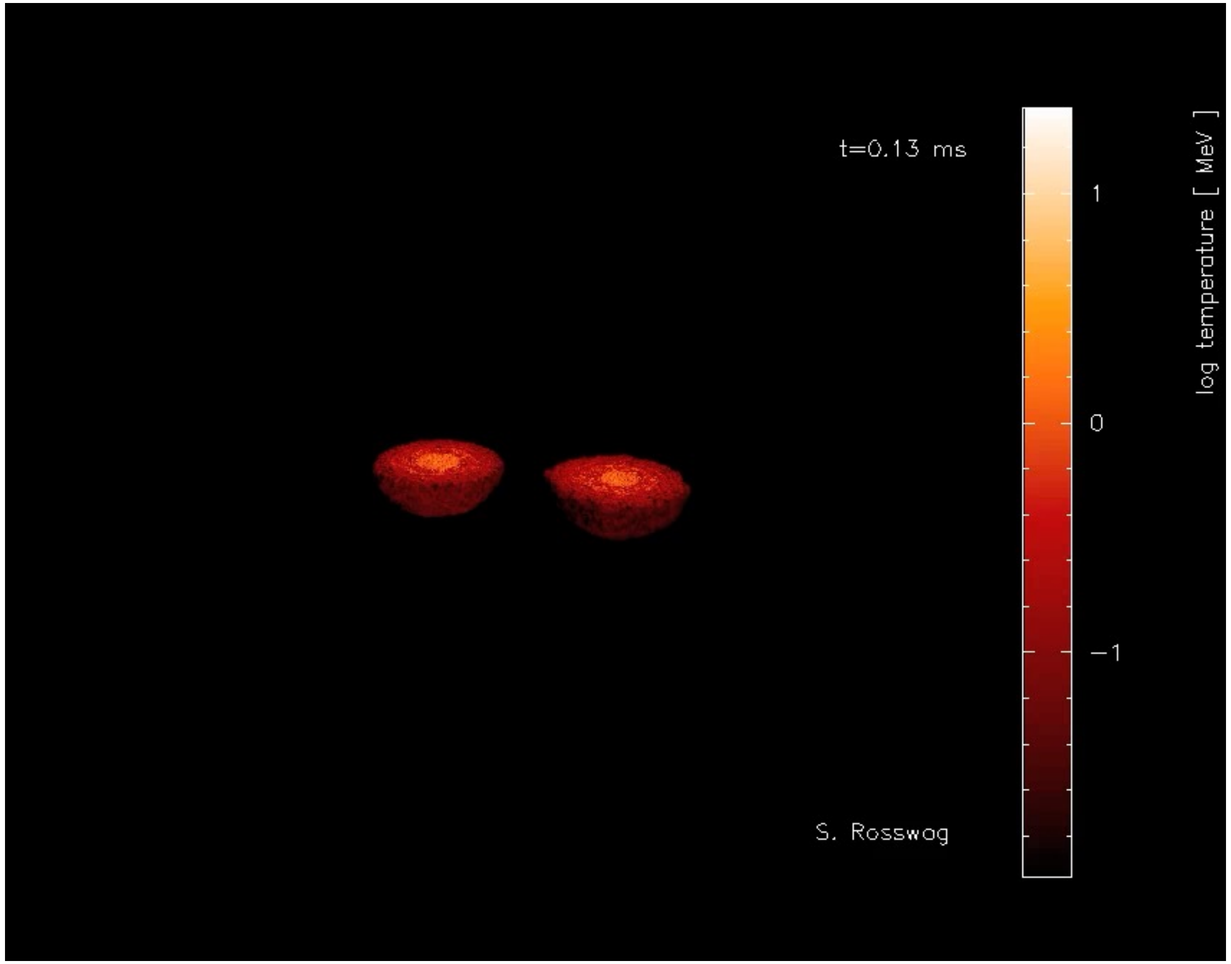


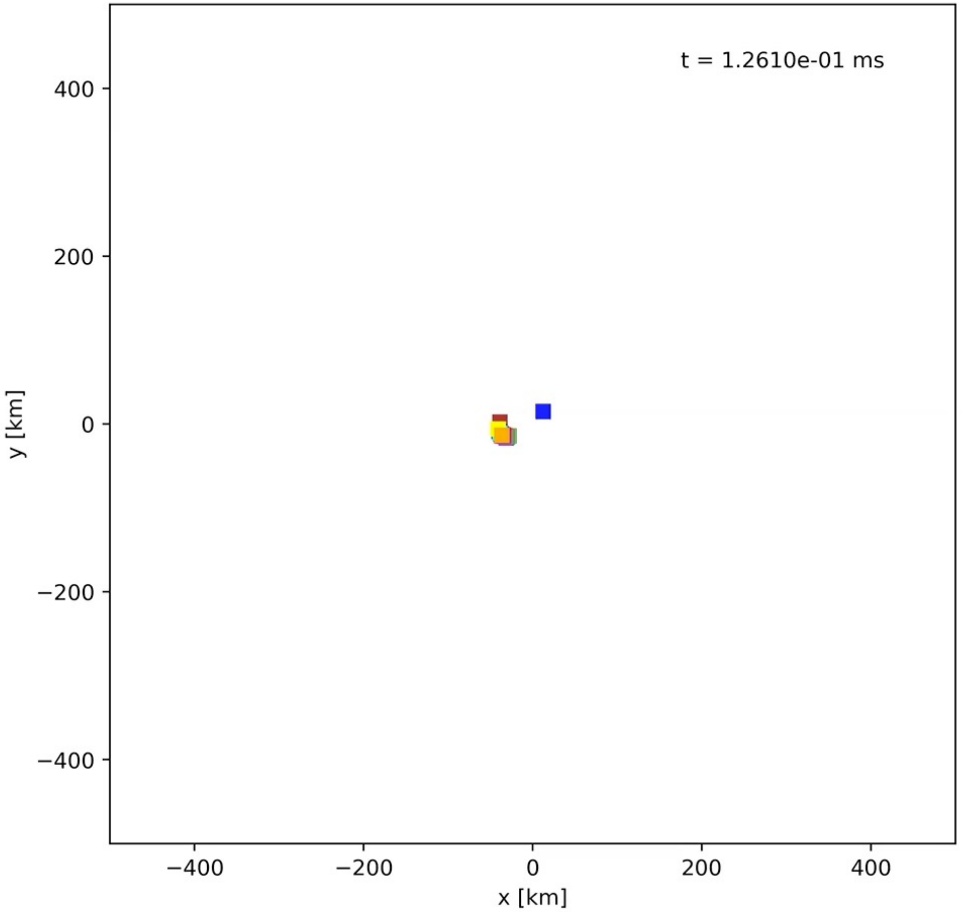


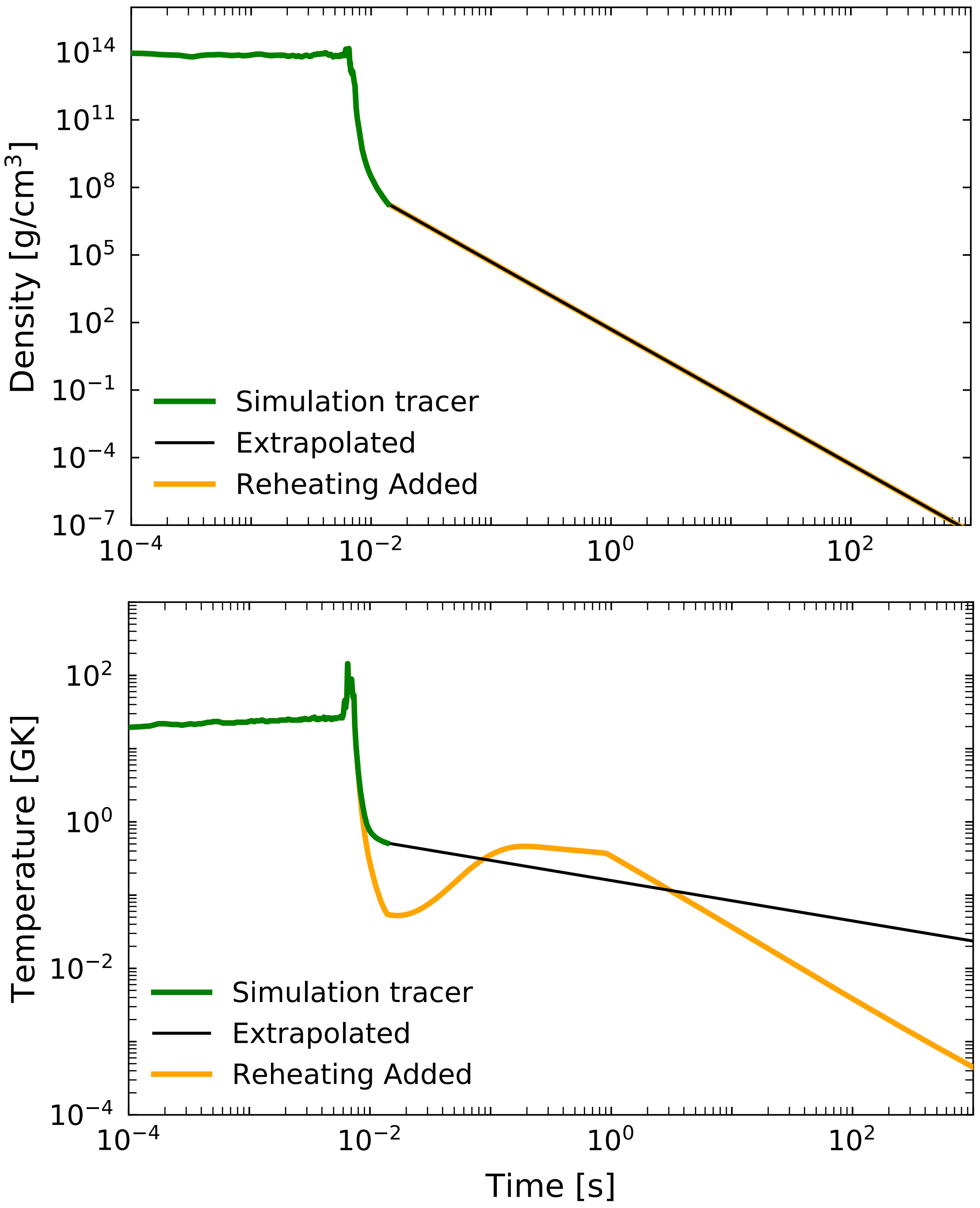
Movie by Vassh

Using simulation tracers

Networks permit nucleosynthesis calculations to account for the *time evolution of the temperature and density of a particular mass element in an astrophysical environment (aka trajectory)*







Using simulation tracers: Extrapolating trajectories and reheating

The density beyond the ~ms timescale considered in hydrodynamic simulations is typically extrapolated assuming "free expansion" (homologous expansion such that $r = vt$):

$$\rho(t) = \rho_0 \left(\frac{t}{t_0}\right)^{-3}$$

Given $\rho(t)$, the composition, and the entropy s_0, the change in entropy can be calculated via the nuclear equation of state (EOS) which is then linked to temperature $\left(\Delta s = \frac{\Delta Q}{T}\right)$ thus

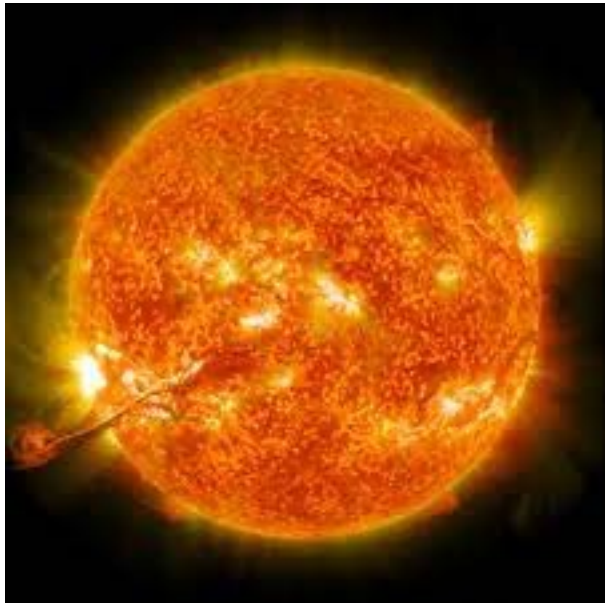
$$T(t) = \mathrm{EOS}[s_0, \rho(t), \mathrm{Y}(t)]$$

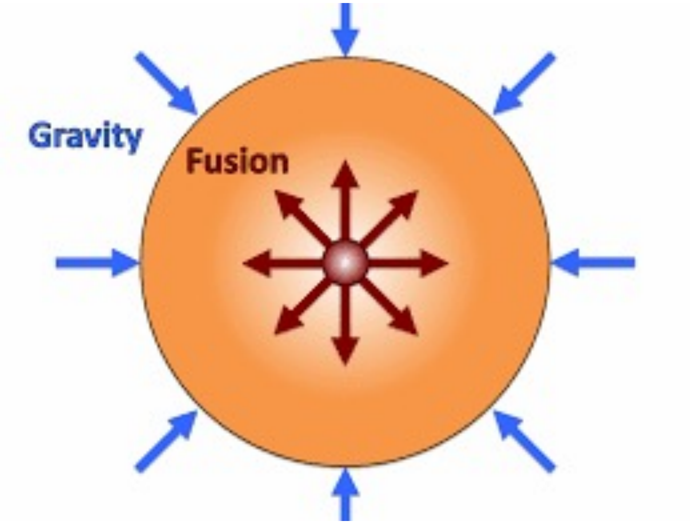
This is called "reheating" or "self-heating" since the changes in the composition from nuclear reactions heat the system

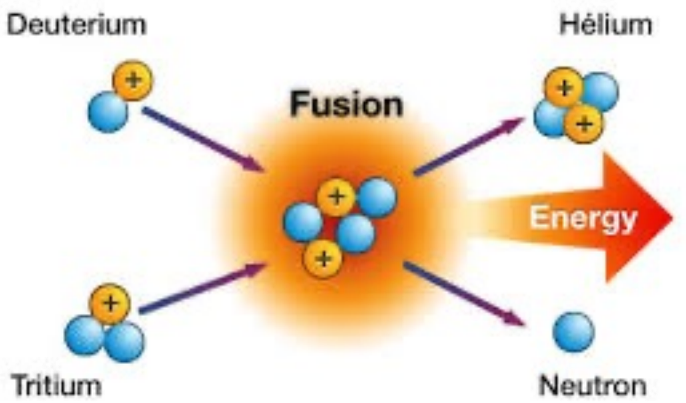
Outline for lecture I

- How can we study nuclear physics in astrophysics? Some observables [3-7]
- Some basic nuclear physics: masses, decays, reactions, reverse reaction rates, and equilibria [9-19]
- Reaction networks (BBN example and heavy element nucleosynthesis example) and using hydro simulations [21-30]
- Solar fusion [32-36]

Stellar fusion







- The Sun was first a cloud of gas that underwent gravitational collapse, causing the core to become hot and dense enough* for fusion to begin
  *have to overcome the Coulomb barrier (proton repulsion)

- The energy released by fusion provides an outward pressure, combating the gravitational inward pull

$$^2H + {}^3H \rightarrow {}^4He + n\ ,\ \ \mathrm{Q} = 17.6\ \mathrm{MeV}$$

Energy released by fusion ~10-30 MeV

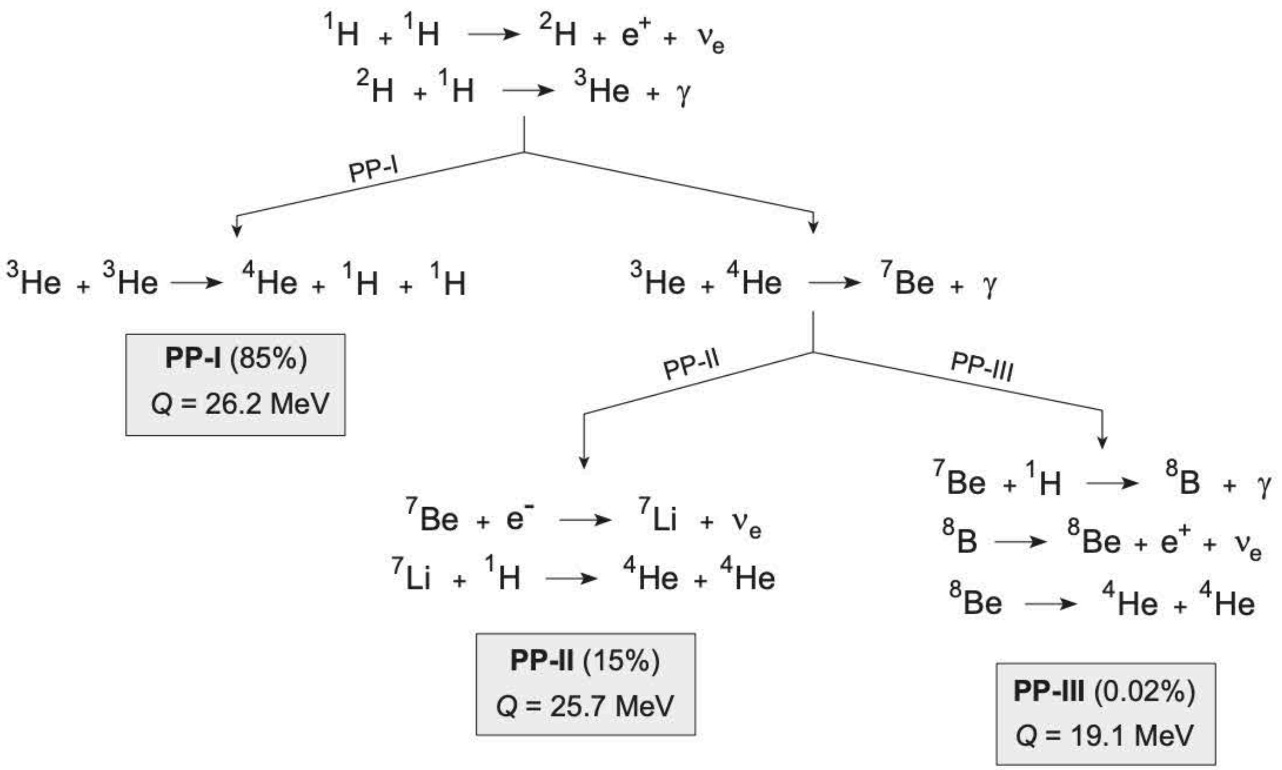
The pp chain

The Sun is mostly hydrogen and helium

Present day Solar composition (mass %)

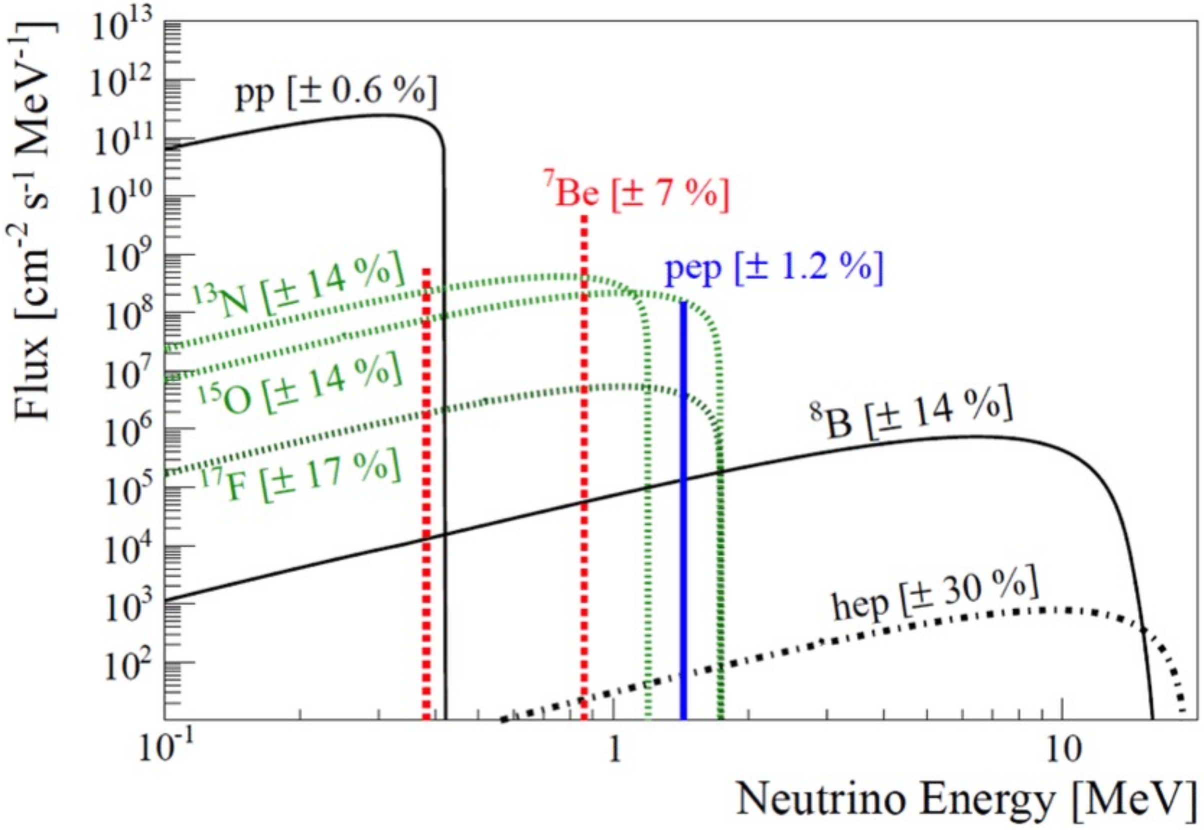
	this work	[05A1,07G]
H (=X)	73.90	73.92
He (=Y)	24.69	24.86
O	0.63	0.54
C	0.22	0.22
Ne	0.17	0.10
Fe	0.12	0.12
N	0.07	0.06
Si	0.07	0.07
Mg	0.06	0.06
S	0.03	0.03
all other elements	0.04	0.02
total heavy elements (=Z)	1.41	1.22

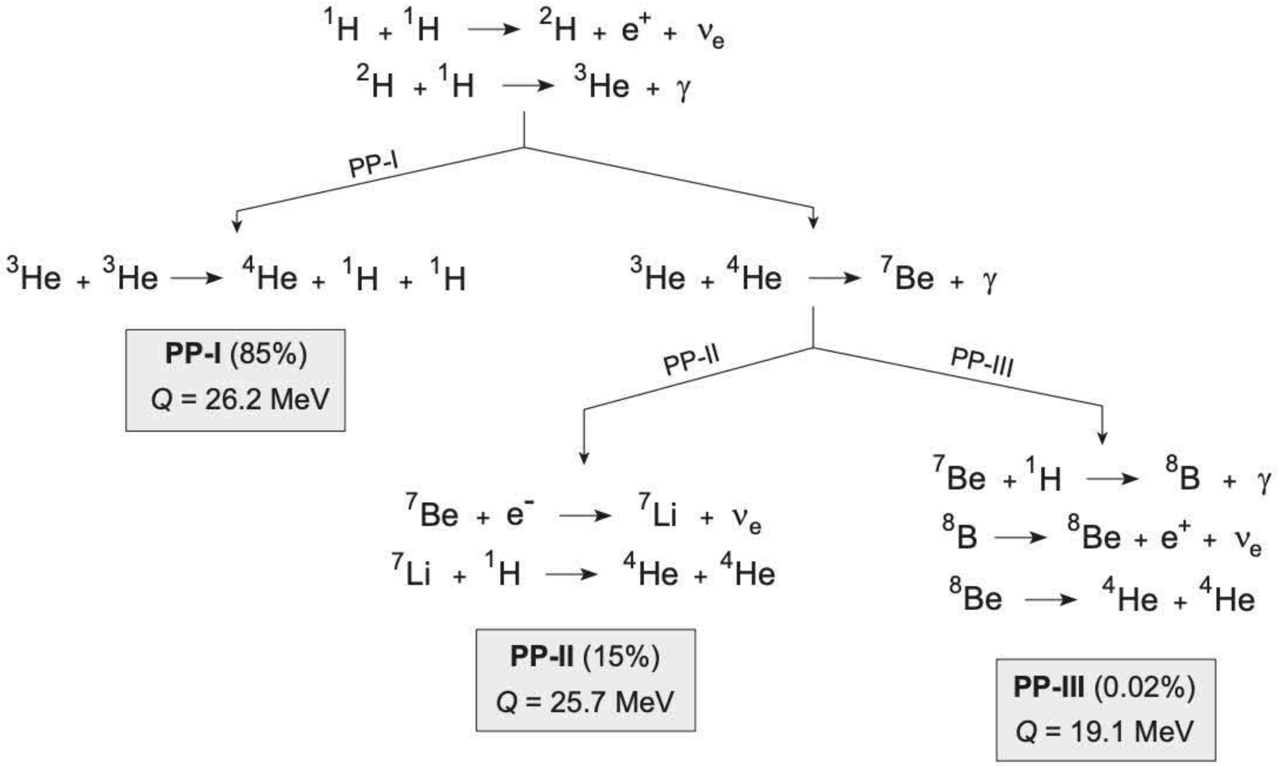
Lodders+ 2009



The pp chain

Solar Neutrino Spectrum

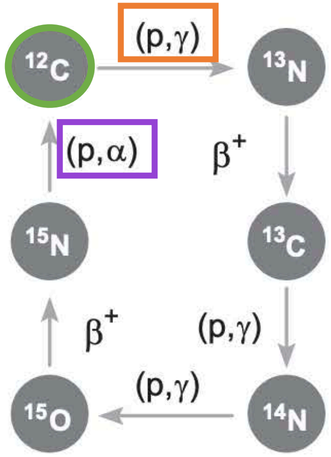




*pp chain is the primary energy source for the Sun

CNO cycle

Uses carbon-12 as a catalyst to convert hydrogen (p) into helium (α)



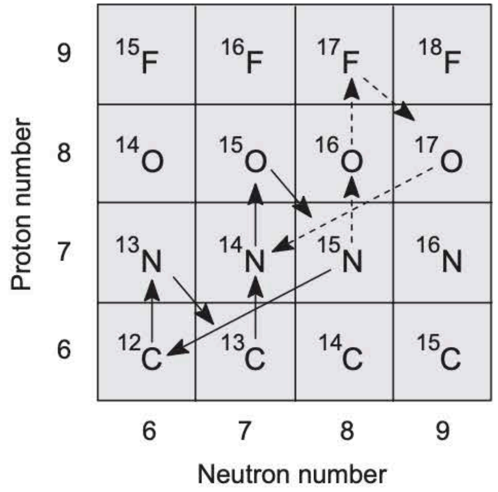
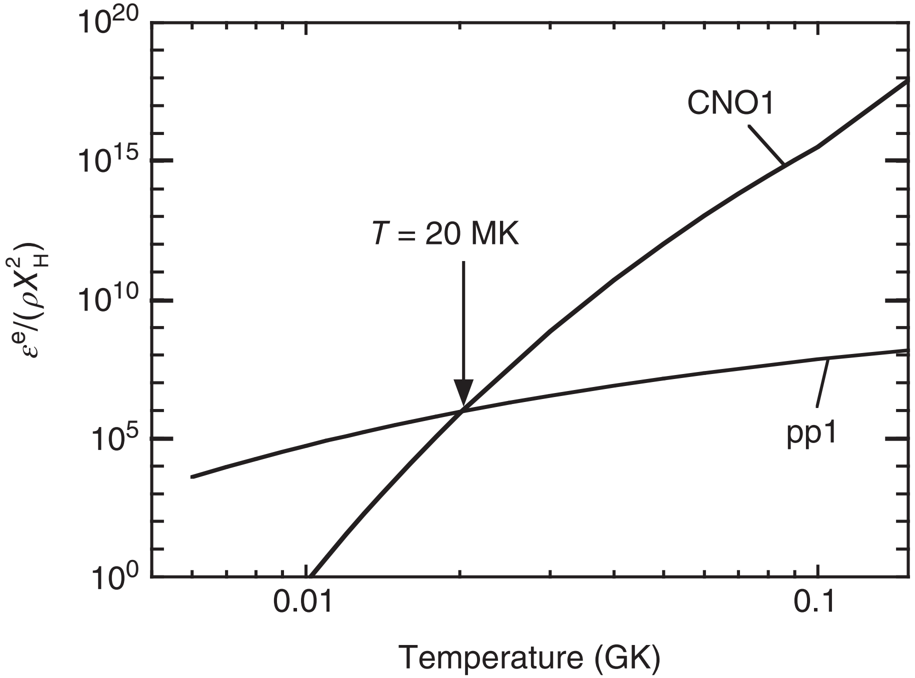


Table 6.1: Effective Q-values

Process	Q_{eff} (MeV)	% Solar energy
PP-I	26.2	83.7
PP-II	25.7	14.7
PP-III	19.1	0.02
CNO	23.8	1.6

- With a core temperature ~15 MK, CNO subdominant to pp in the Sun
- For stars heavier than the Sun with carbon-12 present, the CNO cycle becomes the dominant hydrogen burning process



Iliadis 15

Article | Published: 25 November 2020

Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun

The Borexino Collaboration

Nature **587**, 577–582 (2020) | Cite this article

Abstract

For most of their existence, stars are fuelled by the fusion of hydrogen into helium. Fusion proceeds via two processes that are well understood theoretically: the proton–proton (*pp*) chain and the carbon–nitrogen–oxygen (CNO) cycle[1,2]. Neutrinos that are emitted along such fusion processes in the solar core are the only direct probe of the deep interior of the Sun. A complete spectroscopic study of neutrinos from the *pp* chain, which produces about 99 per cent of the solar energy, has been performed previously[3]; however, there has been no reported experimental evidence of the CNO cycle. Here we report the direct observation, with a high statistical significance, of neutrinos produced in the CNO cycle in the Sun. This experimental evidence was obtained using the highly radiopure, large-volume, liquid-scintillator detector of Borexino, an experiment located at the underground Laboratori Nazionali del Gran Sasso in Italy. The main experimental challenge was to identify the excess signal—only a few counts per day above the background per 100 tonnes of target—that is attributed to interactions of the CNO neutrinos. Advances in the thermal stabilization of the detector over the last five years enabled us to develop a method to constrain the rate of bismuth-210 contaminating the scintillator. In the CNO cycle, the fusion of hydrogen is catalysed by carbon, nitrogen and oxygen, and so its rate—as well as the flux of emitted CNO neutrinos—depends directly on the abundance of these elements in the solar core. This result therefore paves the way towards a direct measurement of the solar metallicity using CNO neutrinos. Our findings quantify the relative contribution of CNO fusion in the Sun to be of the order of 1 per cent; however, in massive stars, this is the dominant process of energy production. This work provides experimental evidence of the primary mechanism for the stellar conversion of hydrogen into helium in the Universe.