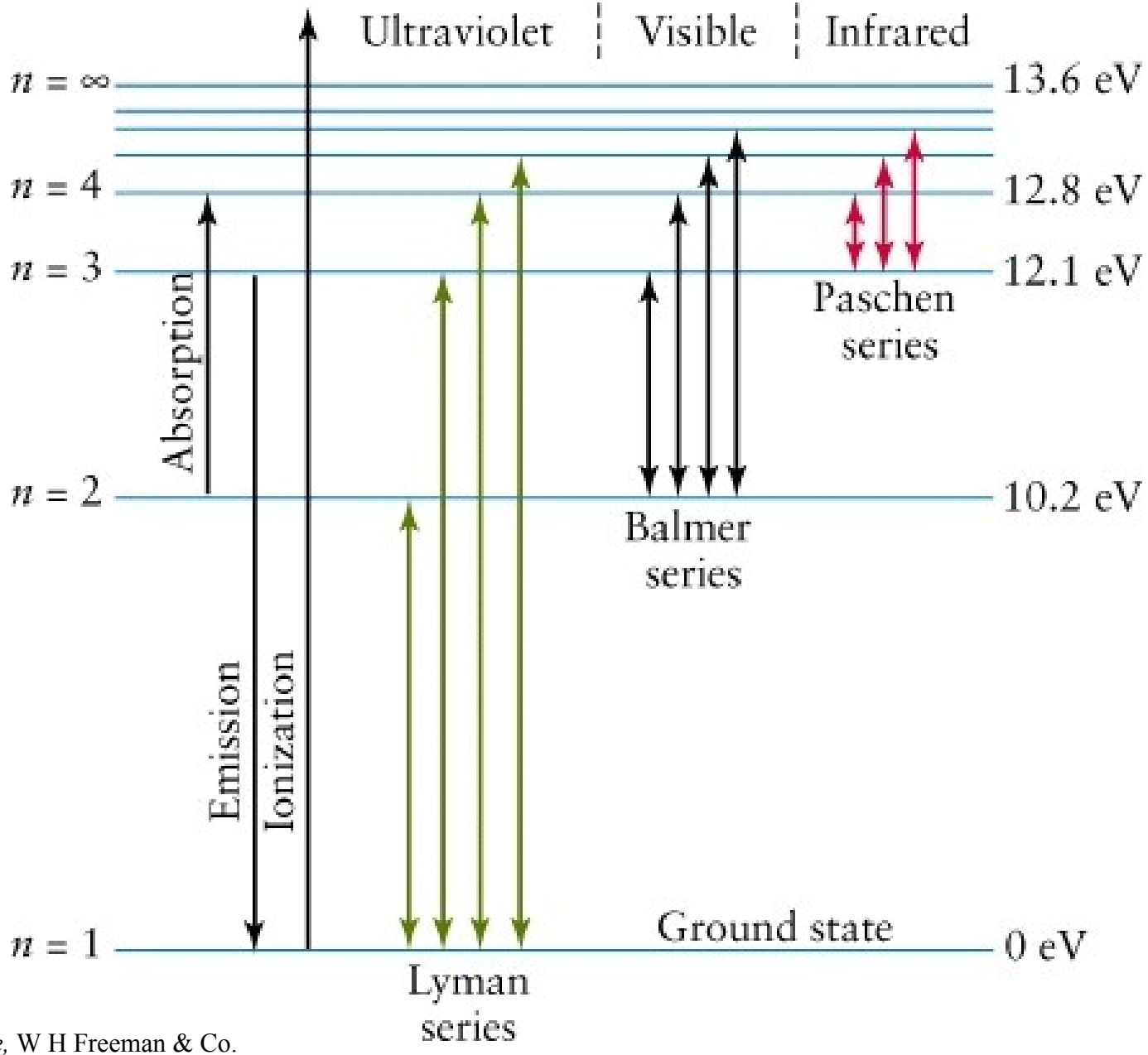
Opacity and Nuclear Reactions

- Sources of opacity
  - Absorption processes
  - Scattering
- Nuclear reactions
  - Proton-proton chain
  - CNO cycle
  - Triple alpha process

Opacity

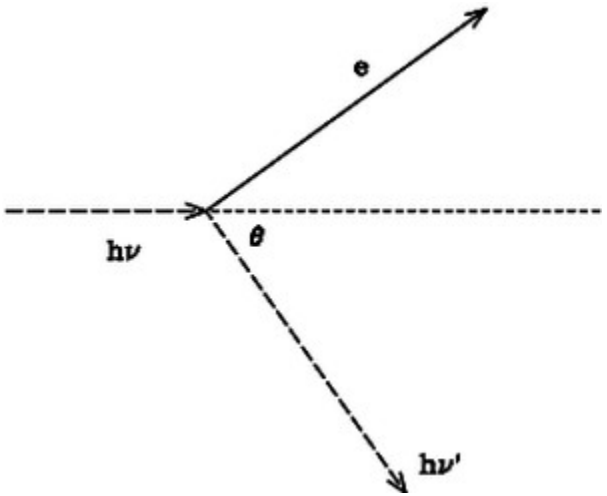
- Absorption processes
  - photon is absorbed (destroyed) (although usually re-emited a short time later, but in a random direction)
  - can be classifed by type of electron transition taking place in the particle doing the absorbing

- bound-bound
  - photon absorbed when e^- undergoes transition between two bound energy levels in an ion, atom or molecule - spectral lines
- bound-free
  - transition from bound level to free the e^- - photoionization – continuum with thresholds
- free-free
  - e^- absorbs photon energy and is accelerated in vicinity of an ion – bremsstrahlung - continuum



Scattering

- photon is re-directed, but frequency unchanged - elastic collision – continuum
- E.g. Thomson scattering by free electrons



Nuclear fusion of hydrogen

- fusion of two protons is difficult since no stable nucleus with two protons and no neutrons
- Takes place by one of two main routes

- Proton-proton chain
  - one proton has to decay to a neutron emitting a positron and a neutrino via the weak interaction whilst the two nuclei are still close enough to react
  - can occur at low temperatures ~ 4×10^6 K

$$ {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{2}_{1}\mathrm{H} + {}^{+}\mathrm{e} + \nu + \text{energy} $$

$$ {}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \longrightarrow {}^{3}_{2}\mathrm{He} + \gamma + \text{energy} $$

$$ {}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \longrightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{1}_{1}\mathrm{H} + \text{energy} $$

- CNO Cycle
  - reaction cross-sections with heavier nuclei are larger, but so is Coulomb barrier
  - needs higher temperatures ~ 10^7 K
  - resonances in cross-sections - reaction produces nucleus in excited state which then decays to ground state - fast reaction rates

$$^{12}C + {}^{1}H \rightarrow {}^{13}N + \text{energy}$$

$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu$$

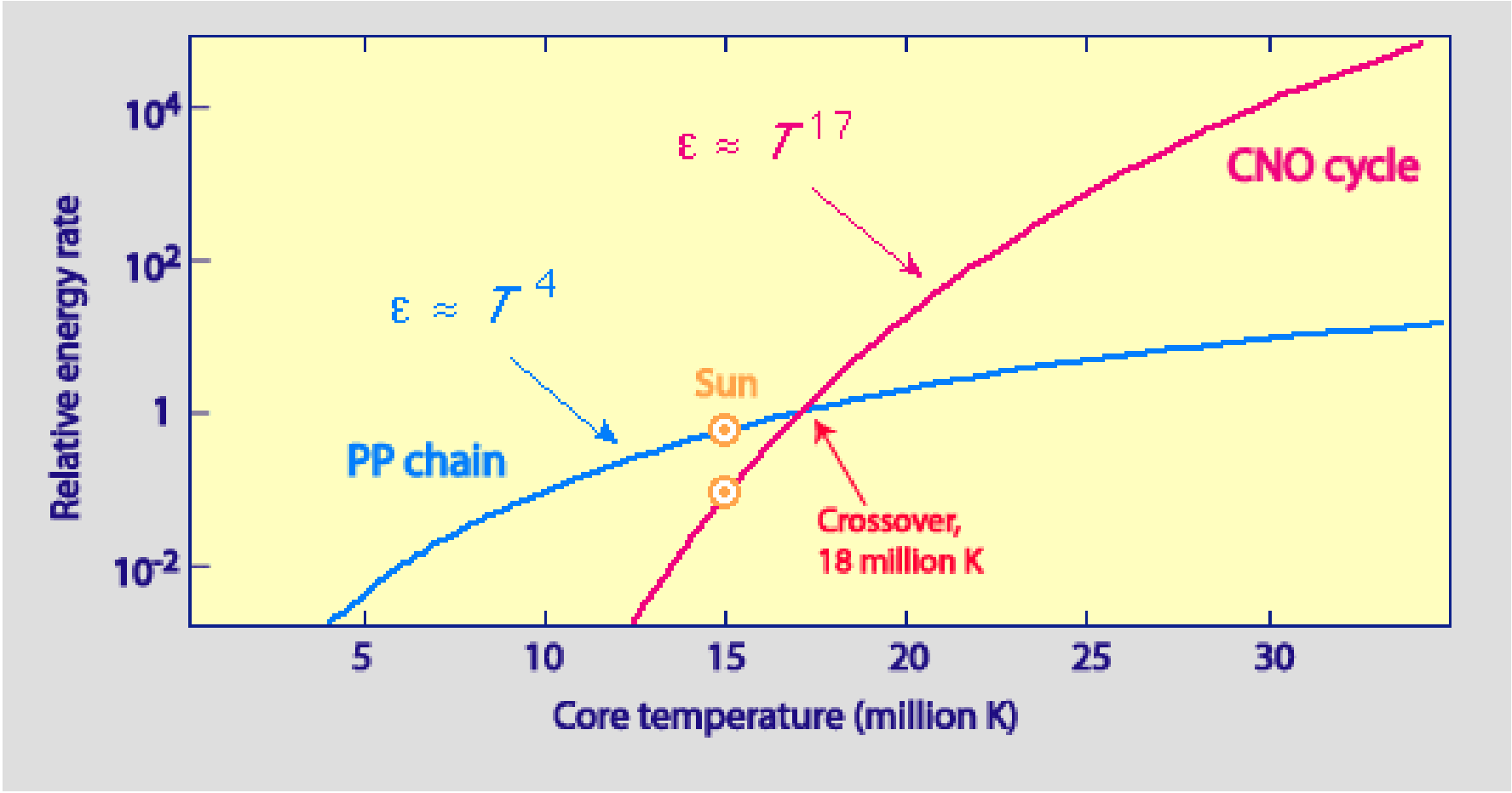
$$^{13}C + {}^{1}H \rightarrow {}^{14}N + \text{energy}$$

$$^{14}N + {}^{1}H \rightarrow {}^{15}O + \text{energy}$$

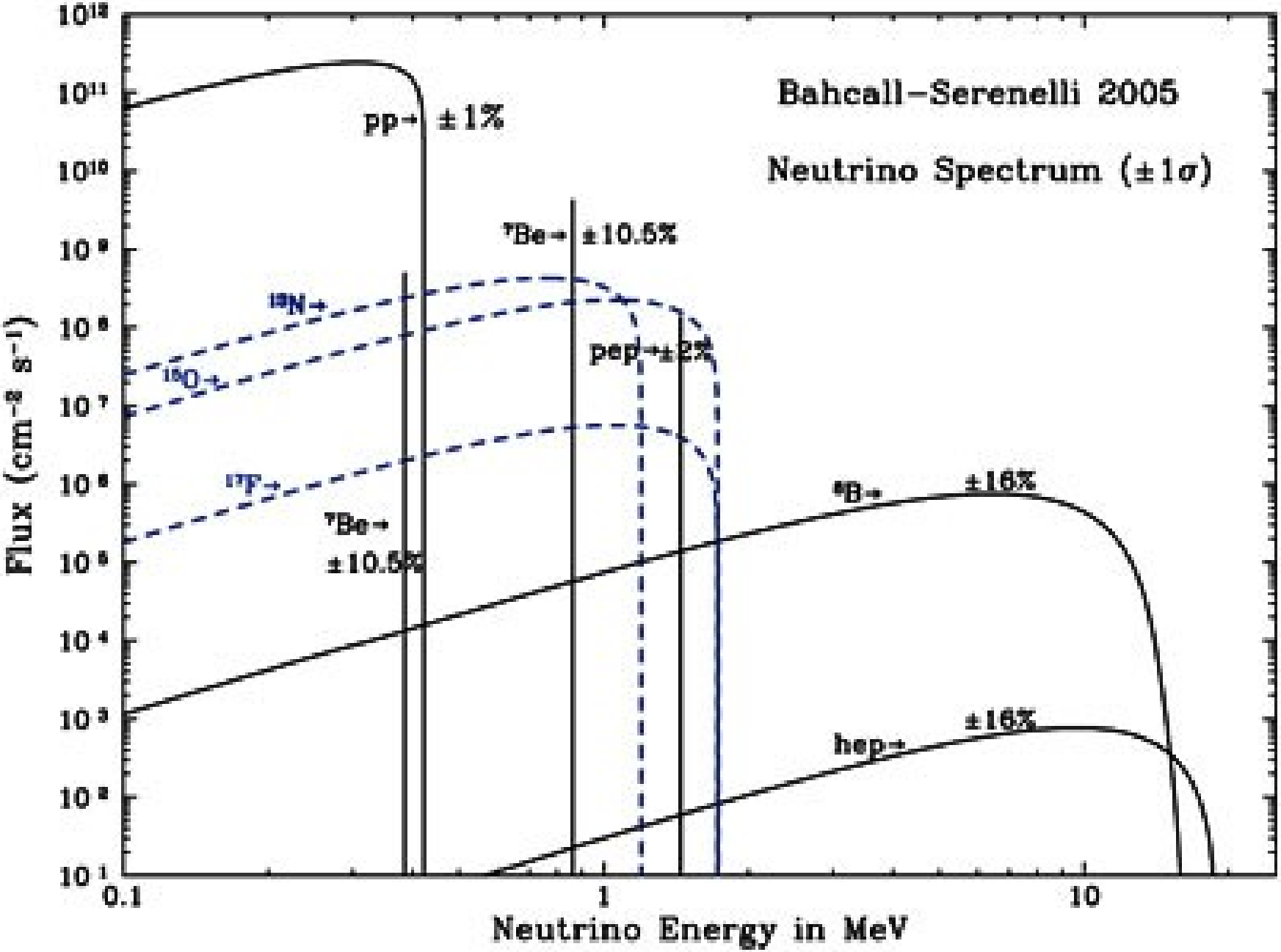
$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu$$

$$^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He + \text{energy}$$

  - C, N, O nuclei are catalysts (C+N+O=constant) although isotope ratios change
  - isotopes destroyed by slow reactions are enhanced e.g. ^{13}C and ^{14}N
- Evidence of these reactions comes from
  - observations of solar neutrinos
  - surface abundances of products convected to the surface or revealed by mass-loss during stellar evolution



www.atnf.csiro.au/outreach/education/senior/astrophysics/stellarevolution_mainsequence.html

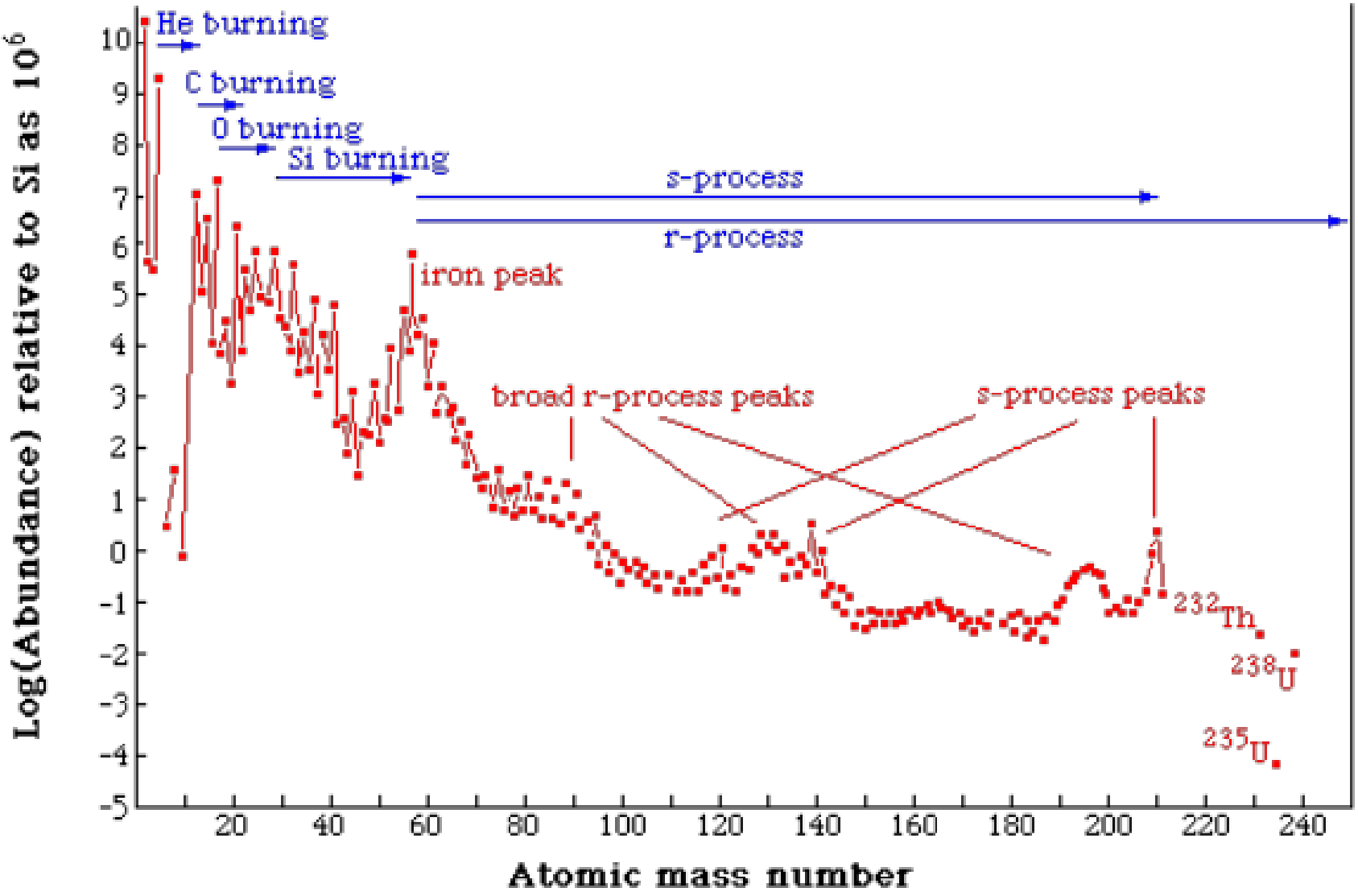

Bahcall-Serenelli 2005
Neutrino Spectrum (±1σ)
pp → ±1%
⁷Be → ±10.5%
pep → ±2%
¹³N →
¹⁵O →
¹⁷F →
⁸B → ±16%
⁷Be →
±10.5%
hep → ±16%
Flux (cm⁻² s⁻¹)
Neutrino Energy in MeV
0.1
1
10

Triple alpha process

- direct conversion of 3 ^{4}He nuclei (alpha particles) to ^{12}C
- needs high temperatures ~ 10^{8} K
- produces carbon - important for nucleosynthesis

Heavier elements

- Massive stars fuse elements successively up to iron
- Heavier elements are built up by slow neutron capture followed by beta decay (s-process) in He-burning red giants
- Also by rapid neutron capture (r-process) in supernova explosions



www.gly.fsu.edu/~odom/ng/nucleosynthesis/s%26r.html

Summary

- Opacities determine how photons interact with matter (atomic and molecular physics)
- Spectroscopy of stars, nebulae and galaxies can be used to determine the abundances of elements using their opacities
- Stellar nucleosynthesis can be used to explain the pattern of abundances (nuclear physics)