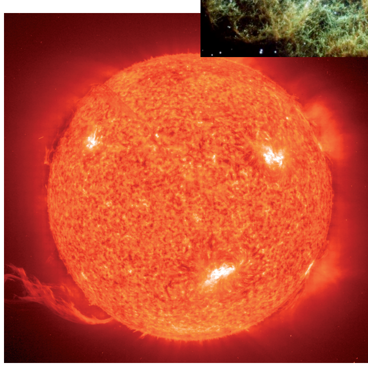
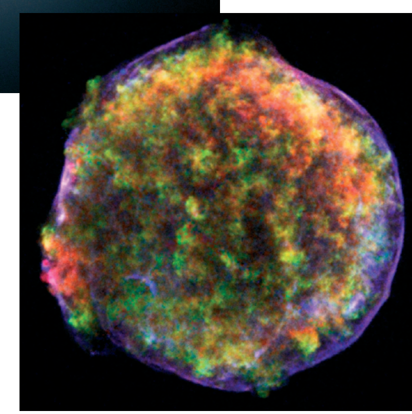
THE UNIVERSITY of York

Nuclear Astrophysics

Stellar explosions, nucleosynthesis and radioactive ion beams





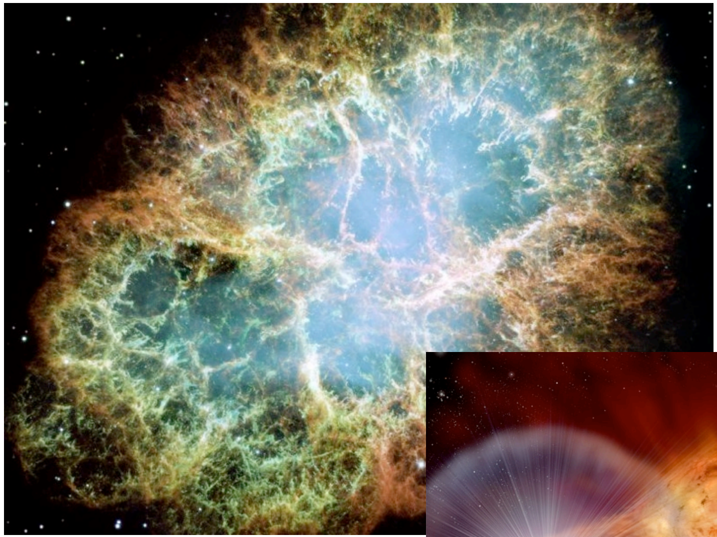
Christian Aa. Diget
University of York

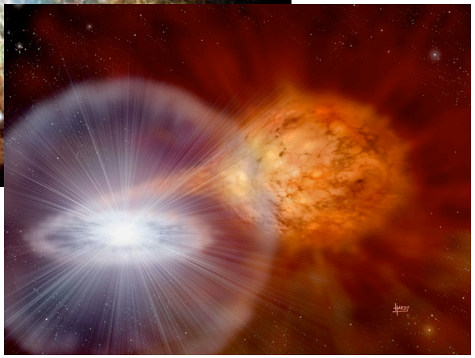
IoP HEPP-APP, 4th of April 2012

Stellar explosions and radioactive ion beams

Understanding stellar explosions:

- Observations
- Astrophysical modelling
- Nuclear theory and reaction modelling
- Nuclear experiments with radioactive ion beams





Core-Collapse Supernovae:

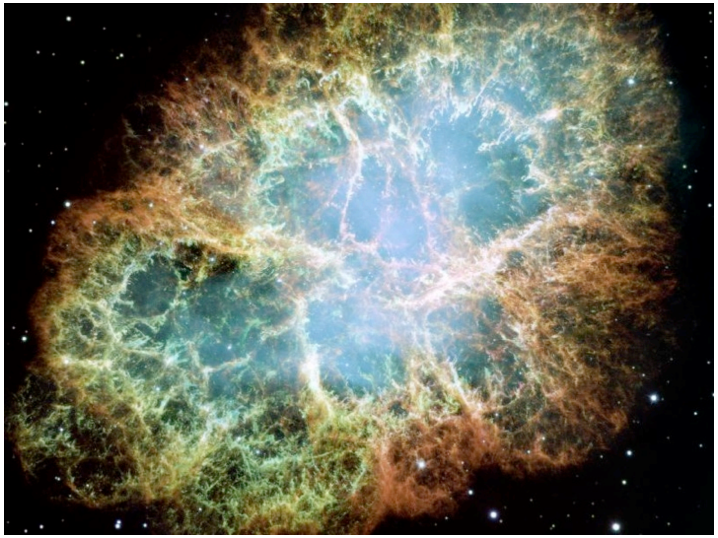
- Weak interactions in supernovae
- Critical for driving the explosion and for nucleosynthesis

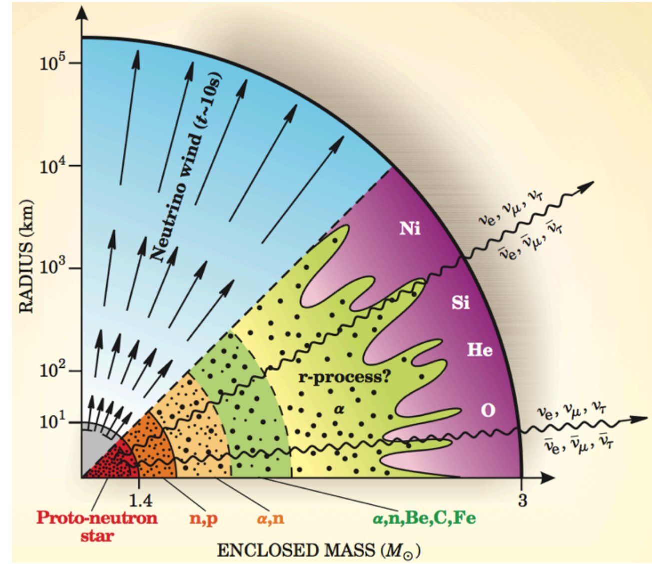
Novae and X-ray bursts

- Nuclear reactions driving explosions and nucleosynthesis
- Experiments, direct and indirect measurements of reaction rates with radioactive ion beams

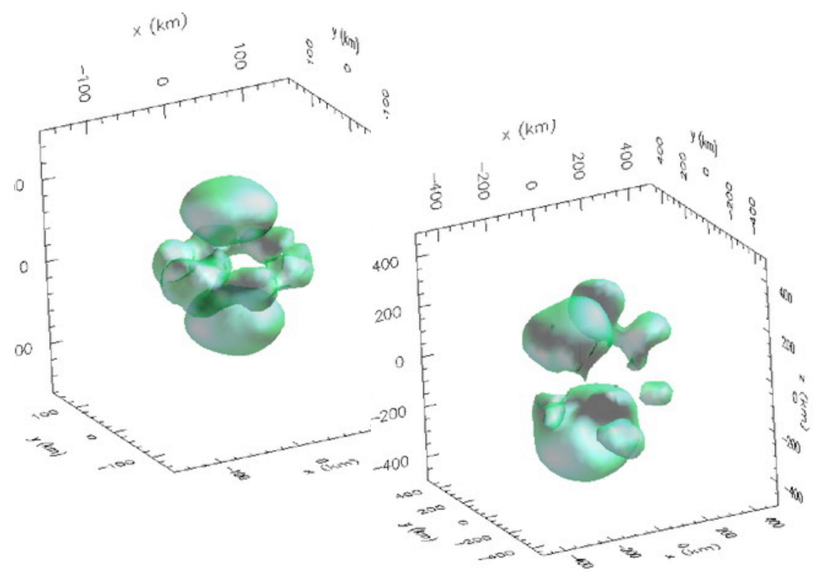
Crab Nebula image: NASA, ESA, and J. Hester (Arizona State U.)
Nova / X-ray burst illustration: David Hardy/PPARC
C. Iliadis, Nuclear Physics of Stars (2007)

Core-collapse supernovae





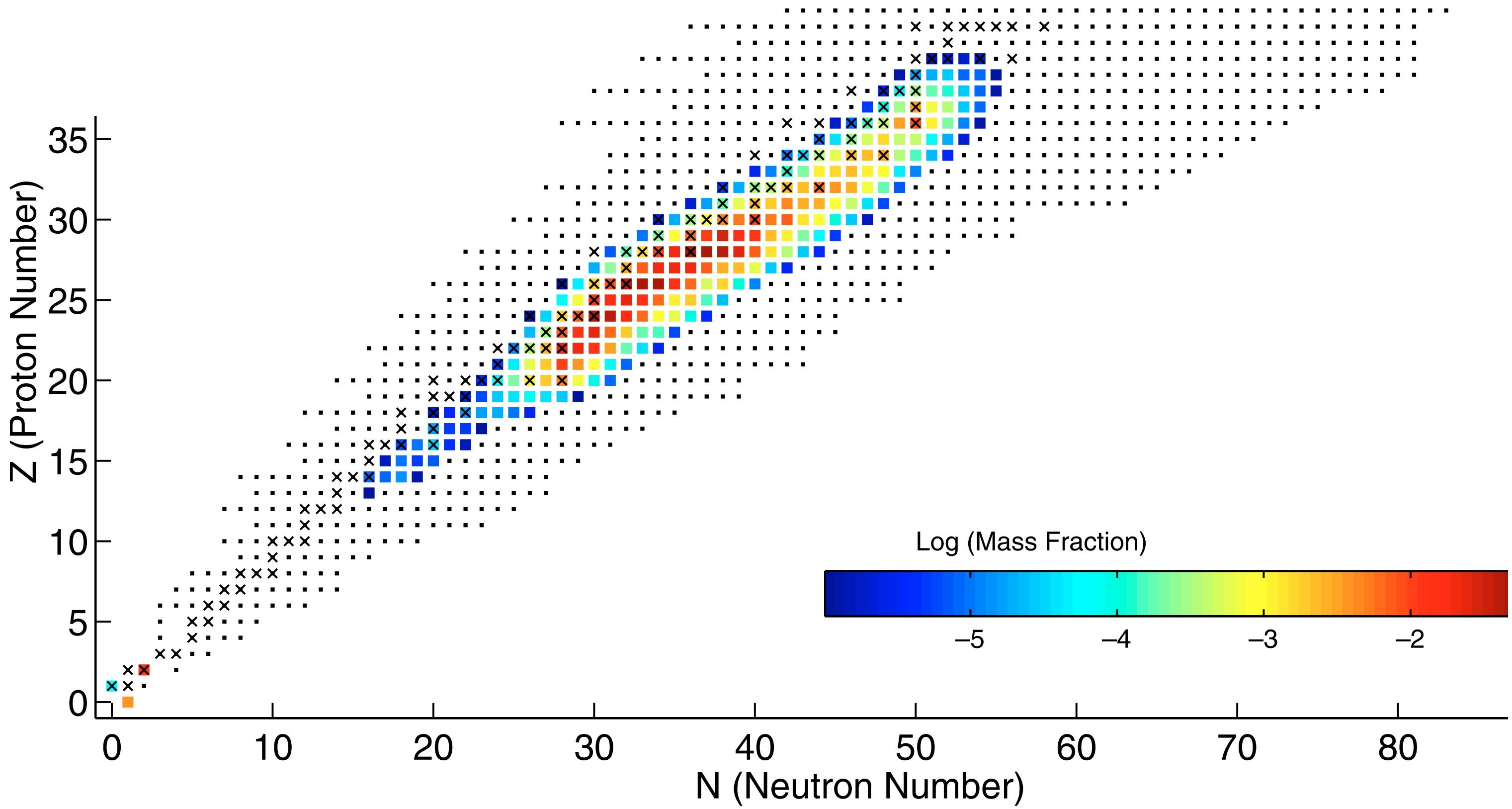
- Gravity-driven collapse of the core of massive star
- Rebounding shock wave driving an (often) asymmetric explosion
- Radiation emitted – material ejected
- Crab Nebula: Remnant of a Type-II (core-collapse) supernova (1054 AD)



Cowan & Thielemann, Phys. Today, 10 (2004) 47
Langanke & Martínez-Pinedo, RMP 75 (2003) 819
Fryer and Warren , APJ, 601 (2004) 391

Weak interactions in supernovae

- Weak interactions in supernovae:
  - gravitational collapse boosted by electron-capture on protons and iron-group nuclei: $p(e^-,\nu_e)n$



Cowan & Thielemann, Phys. Today, 10 (2004) 47
Martínez-Pinedo, Eur. Phys. J. Spec. Top. 156 (2008) 123
Fröhlich et al., PRL 96 (2006) 142502

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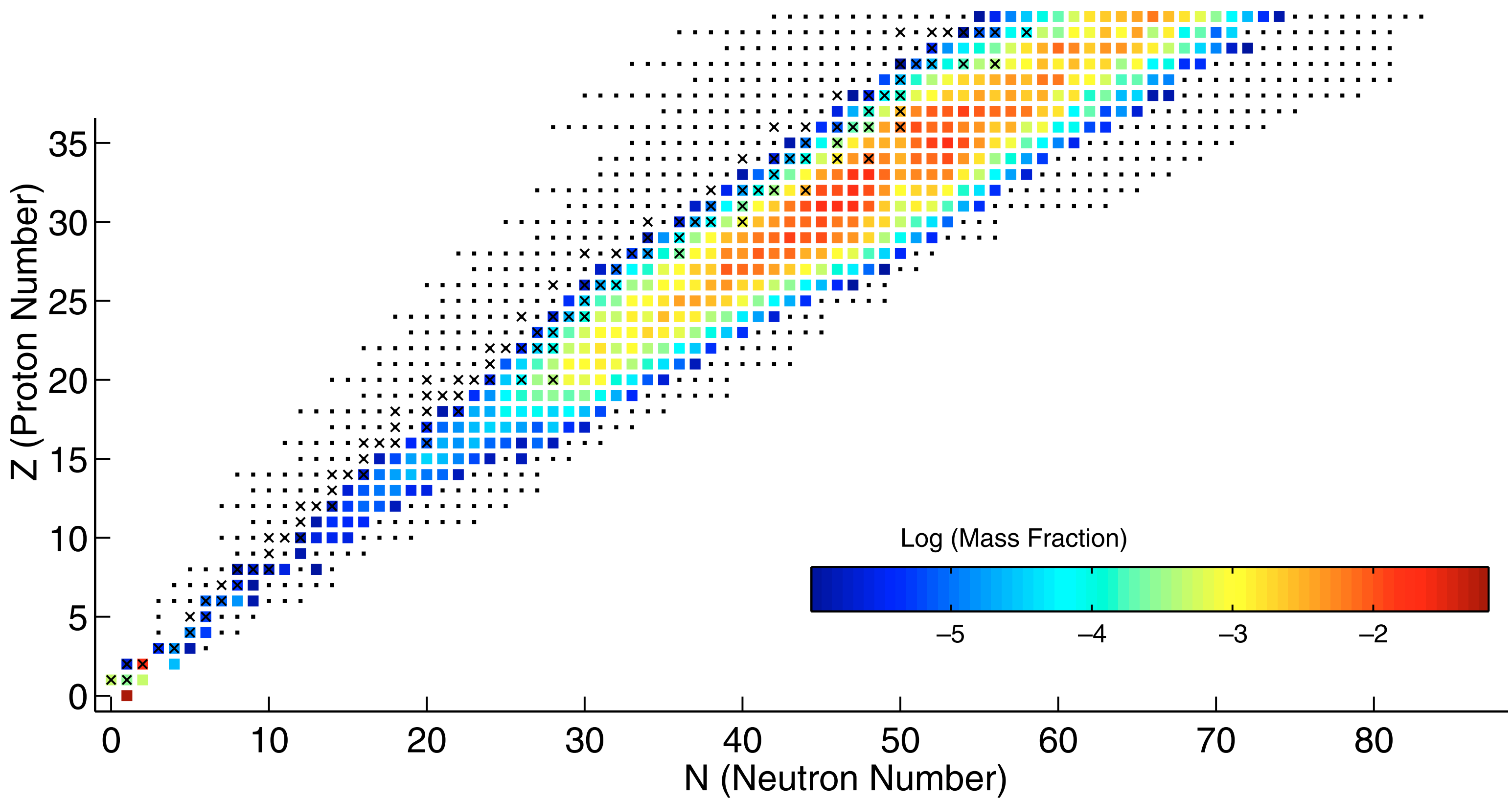

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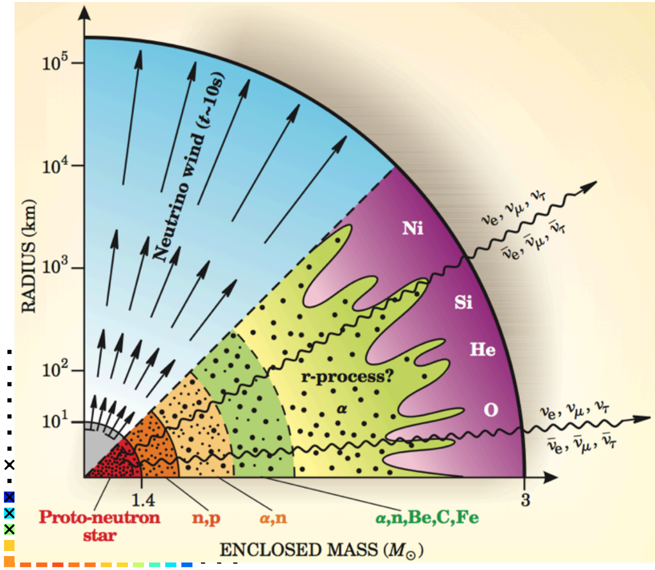
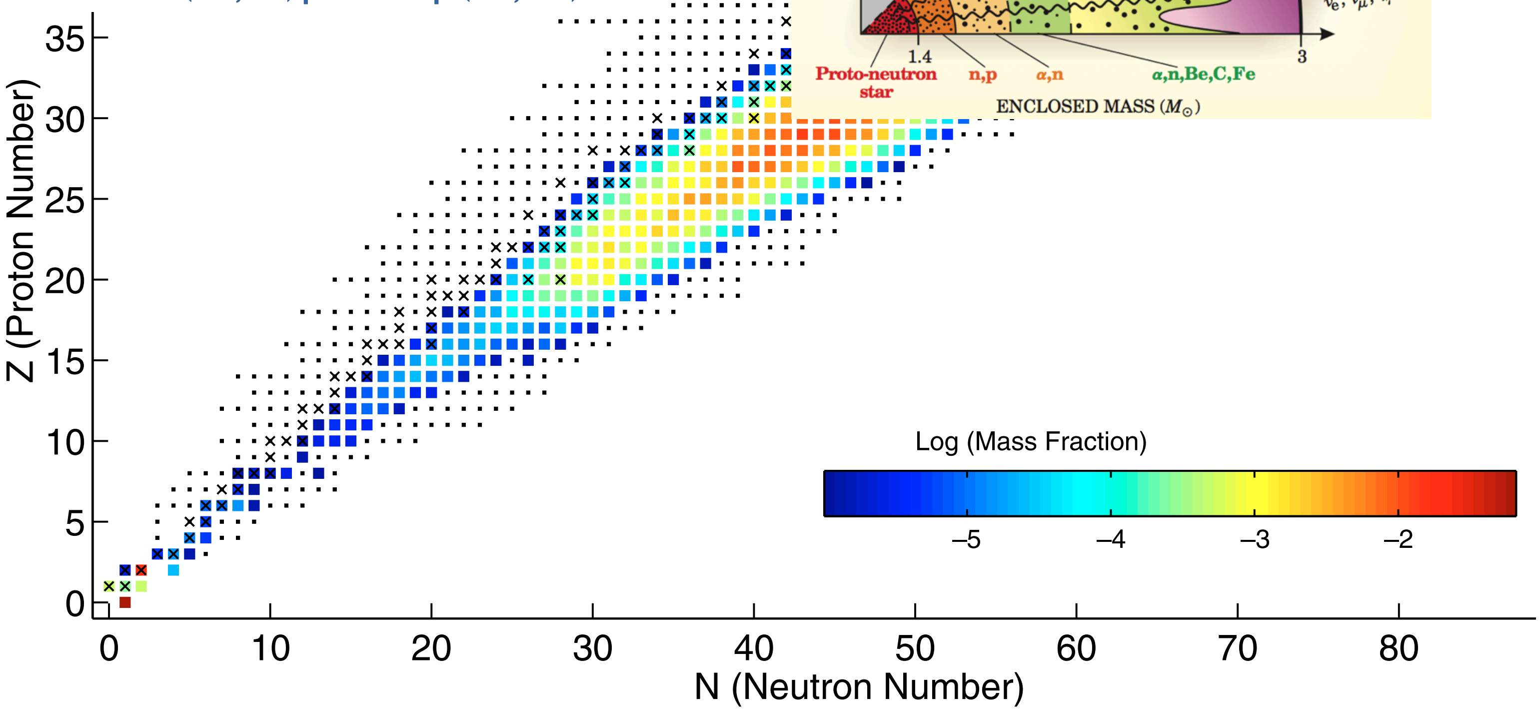
  - gravitational collapse boosted by electron-capture on protons and iron-group nuclei: $p(e^-,\nu_e)n$
  - neutrinos from the neutron star are trapped and revives the stalled shock-wave: $n(\nu_e,e^-)p$ and $p(\bar{\nu}_e,e^+)n$





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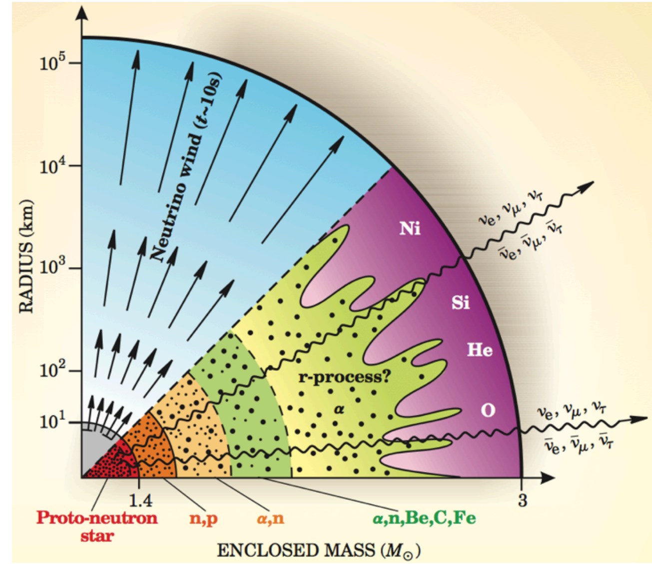
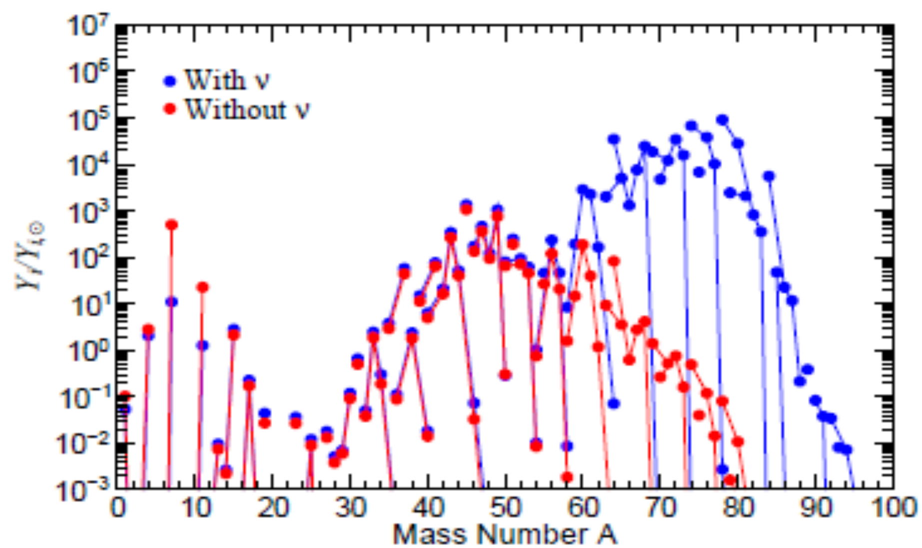
  - neutrinos from the neutron star are trapped and revives the stalled shock-wave: n(ν_e,e⁻)p and p($\bar{\nu}_e$,e⁺)n
  - proton and alpha-rich freeze-out produces neutron-deficient nuclei in the inner ejecta but terminates around ^{64}Ge ($T_{1/2}$ = 64s)





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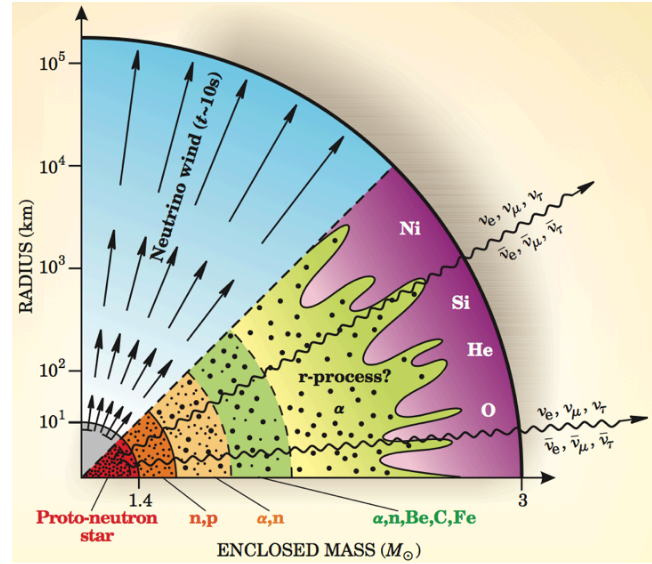

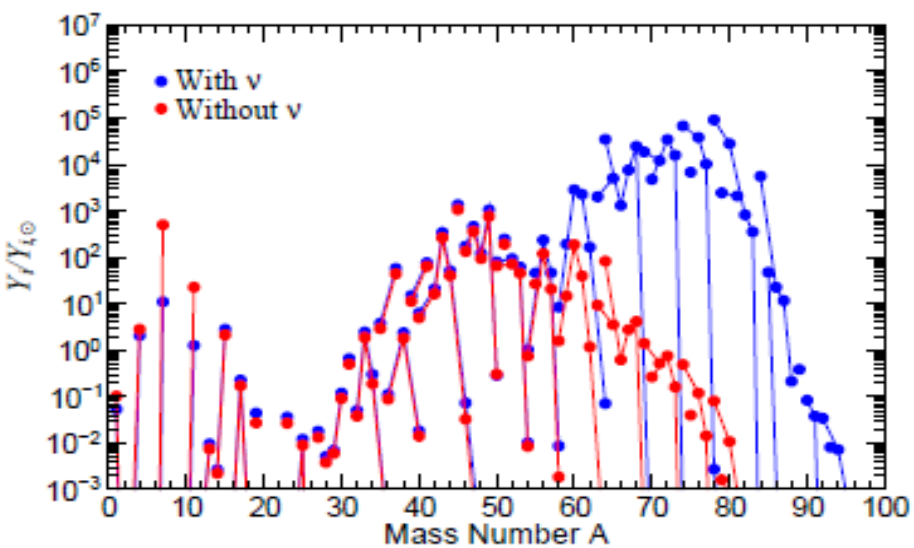

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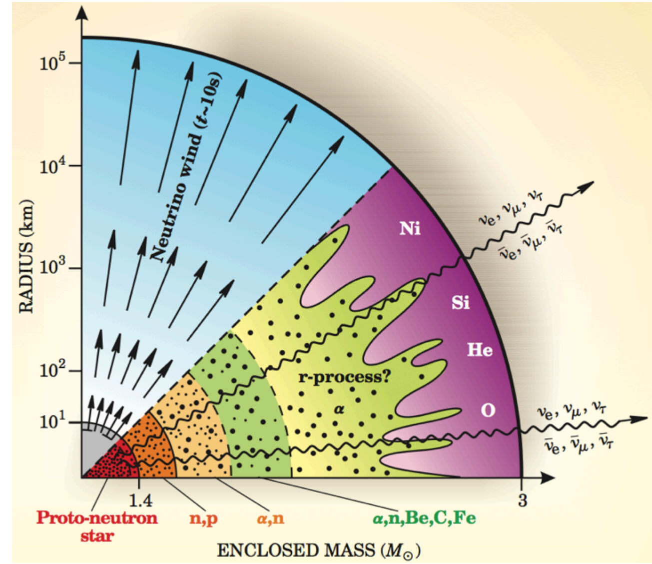
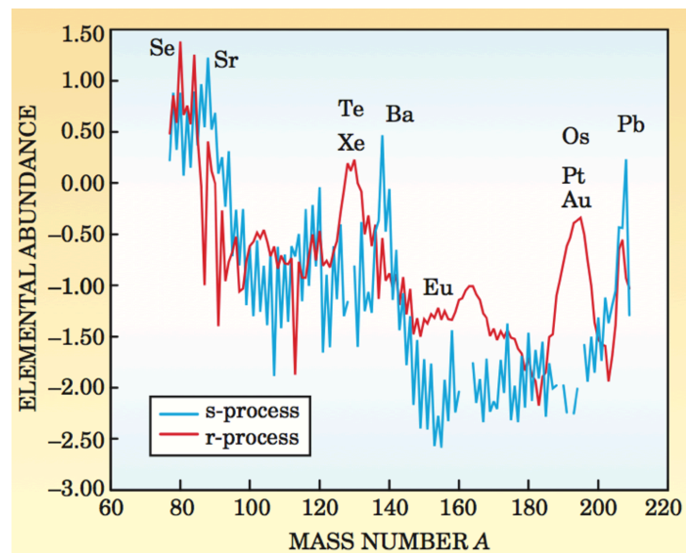
  - Prime-candidate for rapid neutron-capture (r-process) nucleosynthesis (outer ejecta).

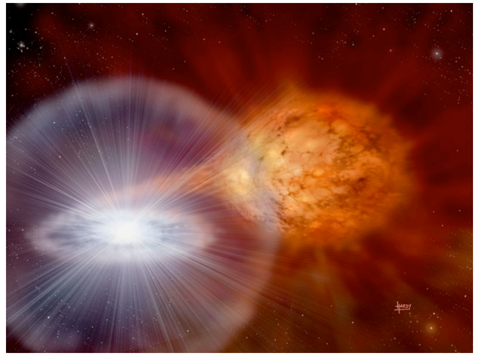


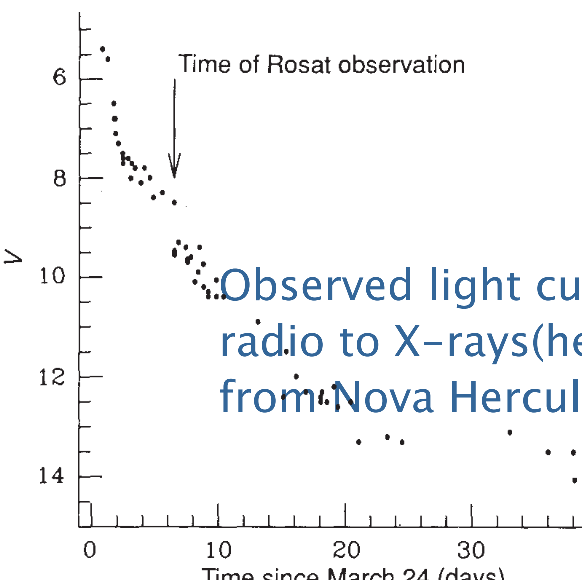


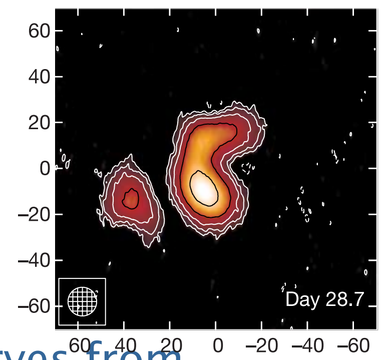
Cowan & Thielemann, Phys. Today, 10 (2004) 47
Martínez-Pinedo, Eur. Phys. J. Spec. Top. 156 (2008) 123
Fröhlich et al., PRL 96 (2006) 142502

Novae and X-ray bursts

- Thermo-nuclear run-away
  - Surface of white dwarf or neutron star
  - Fuelled by material from red-giant companion
  - Recurrent in time scales of hours-days (X-ray bursts) up to 10^4–10^5 years (classical novae)







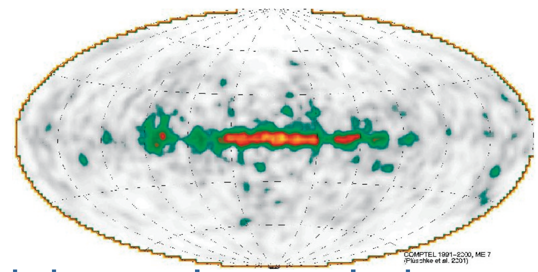
- Observed light curves from radio to X-rays(here: X-rays from Nova Herculis 1991)

GAMMA-RAY LINES FROM NOVAE

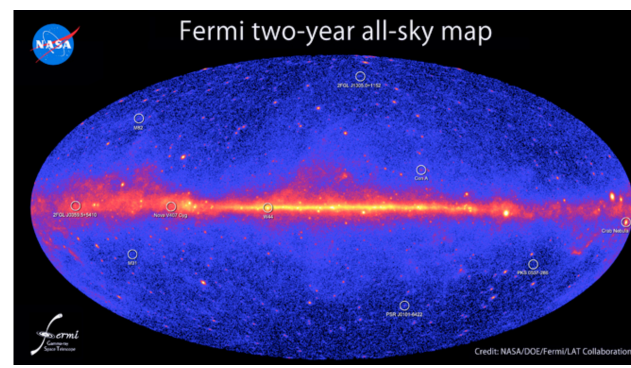
DONALD D. CLAYTON AND FRED HOYLE*
Department of Space Physics and Astronomy, Rice University

Received 1973 November 12

- Gamma-ray telescopes:
  - COMPTEL/INTEGRAL: ^{26}Al (7e5 y) decay spectroscopy survey, ESA



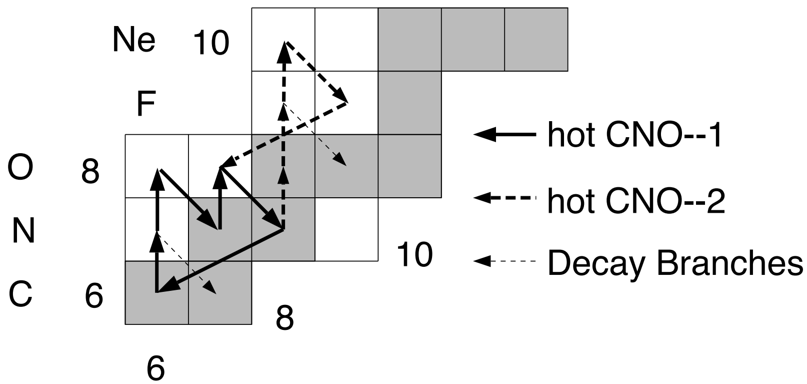
  - Fermi: high angular resolution and coverage, NASA



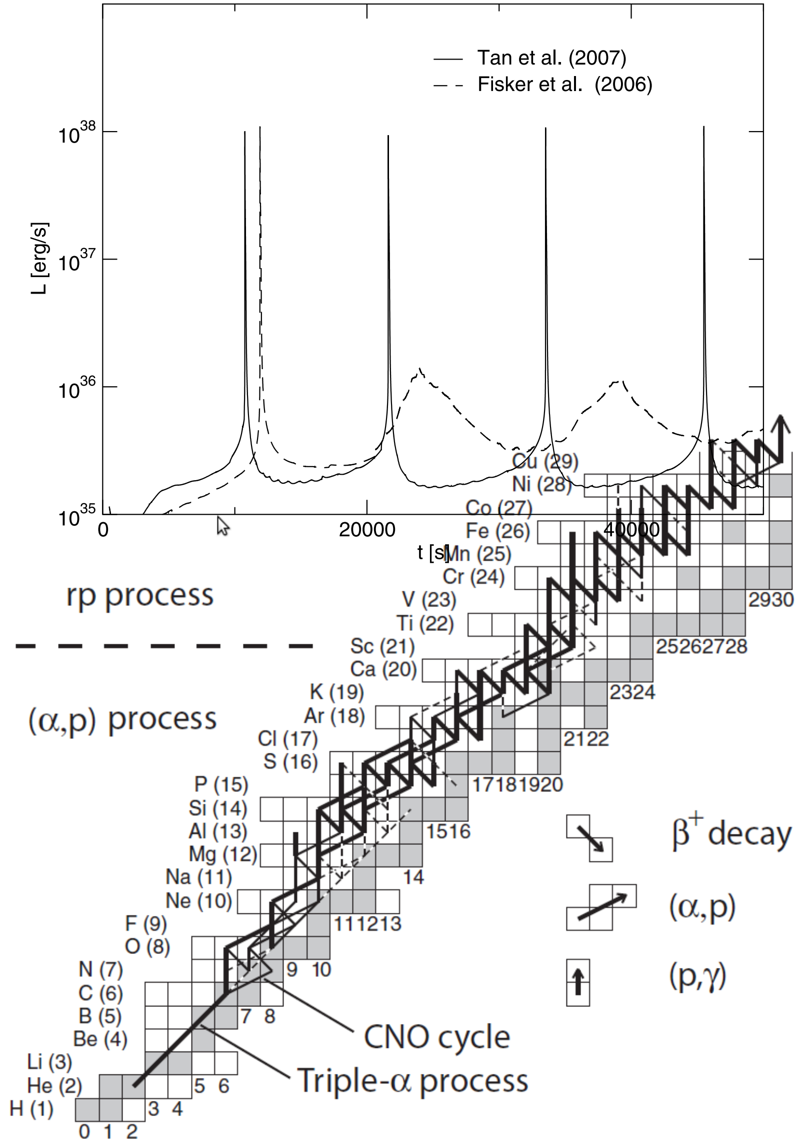
O'Brien, et al., Nature, 442:279 (2006); Lloyd et al., Nature, 356:222 (1992); Clayton & Hoyle., APJ, 187:L101 (1974); S. Plüschke, et al., in Exploring the Gamma-Ray Universe, 459:55 (2001); NASA/DOE/Fermi/LAT Coll.

Hot-CNO breakout in X-ray bursts

- The CNO and Hot-CNO cycles

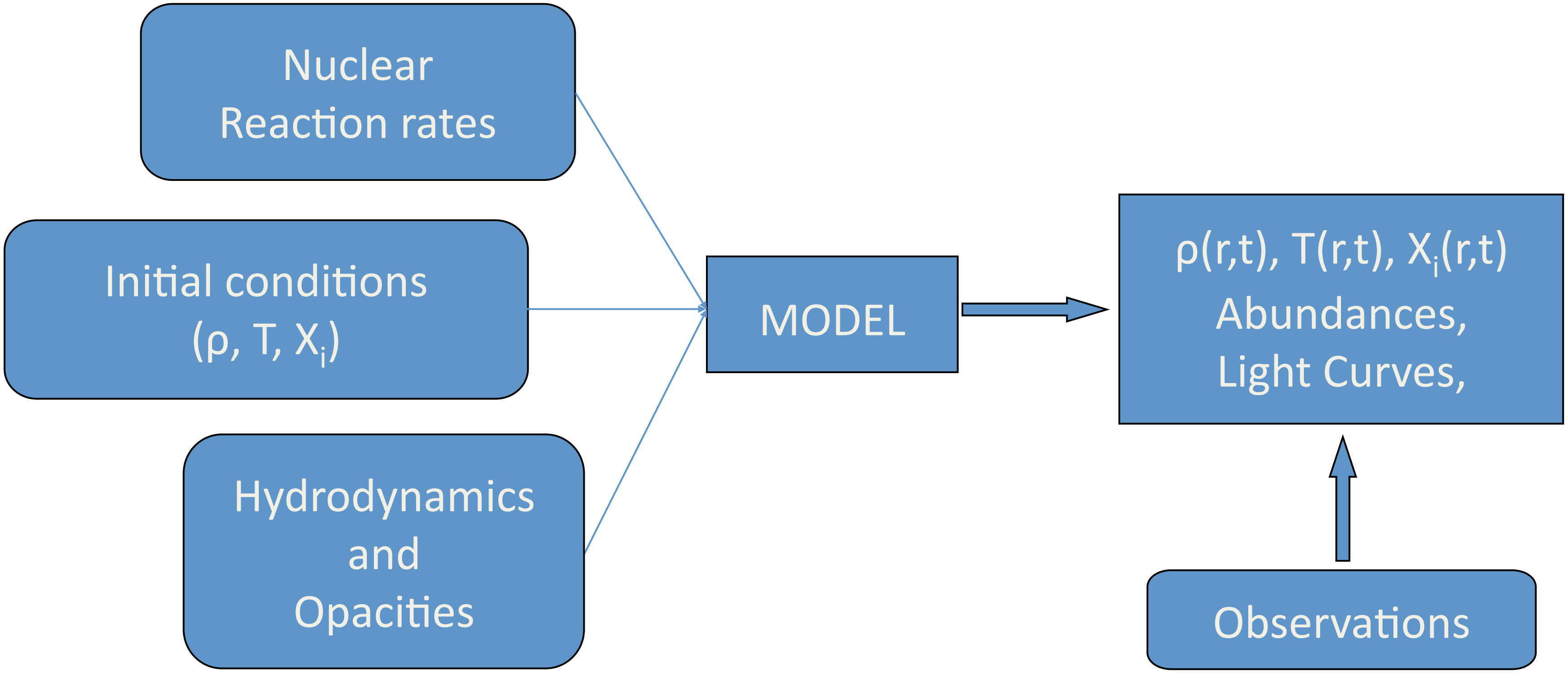


- Build-up of waiting-point nuclei in novae and X-ray bursts: ^{14}O, ^{15}O, and ^{18}Ne
- Breakout from Hot-CNO cycles:
  - ^{15}O(α,γ)^{19}Ne
  - ^{18}Ne(α,p)^{21}Na
  - ^{14}O(α,p)^{17}F
- Followed by rp- and (α,p) processes:



Wiescher, et al. JPG, 25:R133 (1999)
J.L. Fisker, et al., APJ, 665(2007)637
H. Schatz, NSCL-MSU

Interdisciplinary nature of the field



- **Astronomers:** Observe astrophysical sites: energy, abundances, …
- **Astrophysicists:** Develop stellar models in terms of material dynamics and nuclear reactions
- **Nuclear physicists:** Measure (experimentalists) or calculate (theorists) the reaction or decay rates

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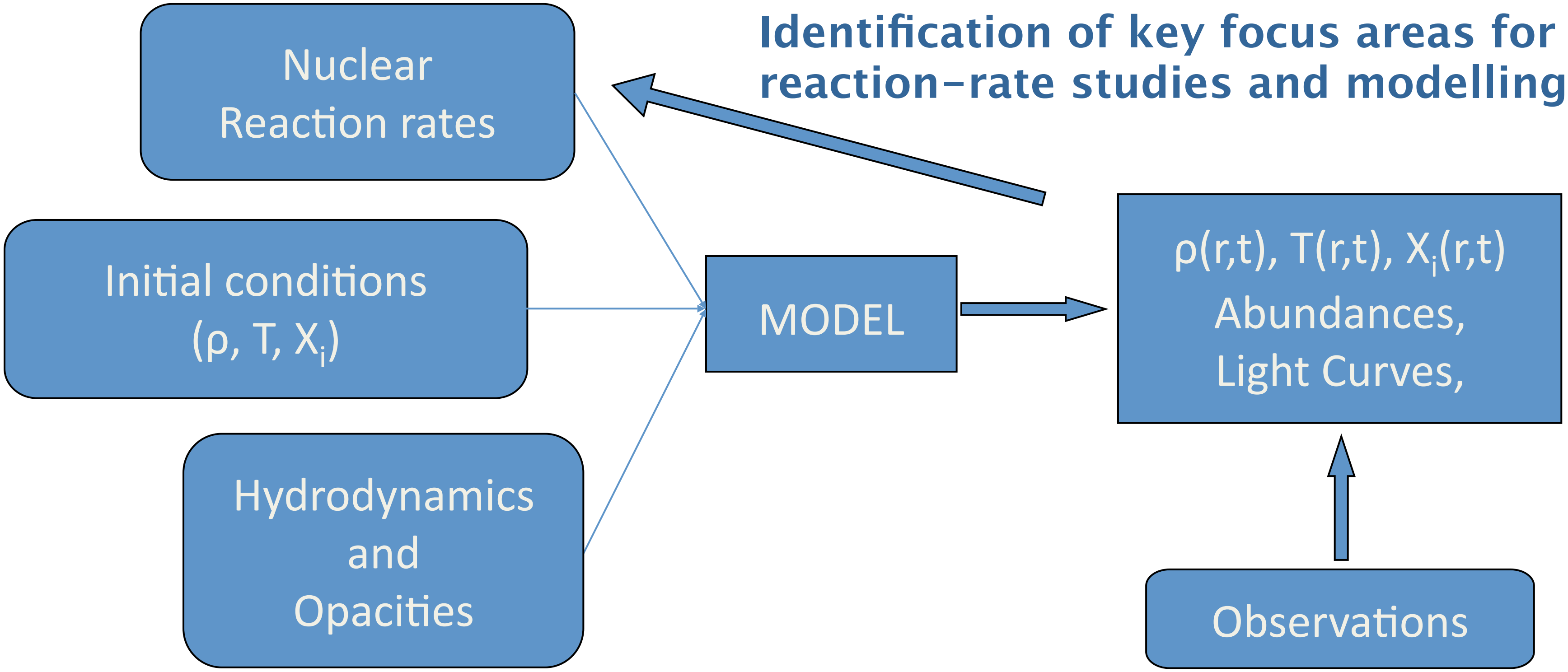

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Interdisciplinary nature of the field

Interplay between:
- Astronomical observations
- Astrophysical modelling
- Nuclear reaction models
- Nuclear experiment

1) Assuming that oxygen and carbon is produced in stars
2) Constraints on reaction rate from observed abundances and astrophysical modelling
3) Constraints on nuclear resonances
4) Measurement of nuclear resonance and key properties
5) Precise determination of reaction rate

A State in C^{12} Predicted from Astrophysical Evidence

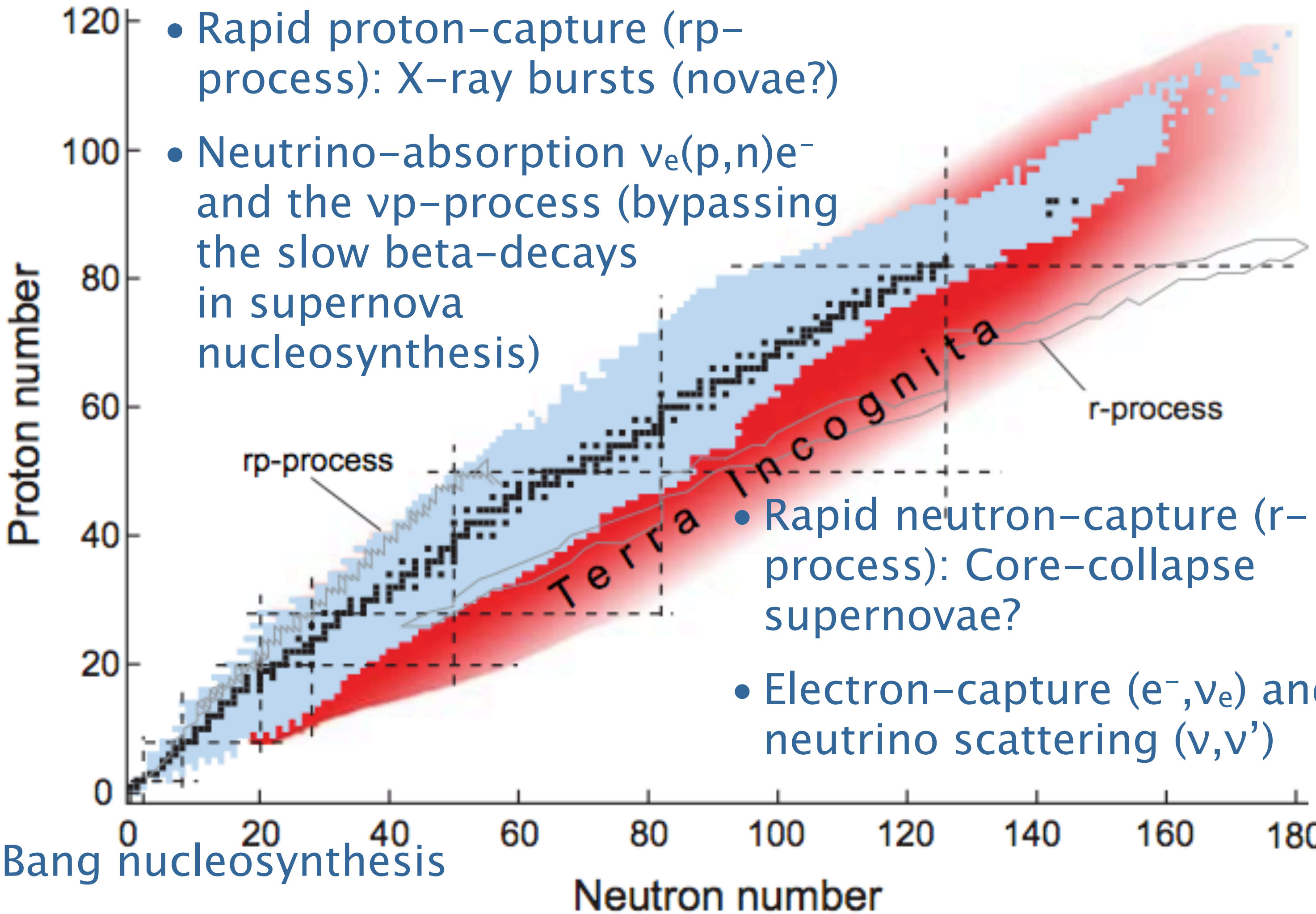
F. Hoyle, D.N.F. Dunbar, W.A. Wenzel, and W. Whaling,
Phys. Rev. 92:1095c (1953)

"It is assumed that oxygen and carbon are produced in stars … by the reactions $2He^4 \to Be^8$; $Be^8+He^4 \to C^{12}$; $C^{12}+He^4 \to O^{16}$. The observed cosmic abundance ratio of He:C:O can be made to fit the yields calculated for these reactions if the reaction $Be^8(\alpha,\gamma)C^{12}$ has a resonance near 0.31 MeV, corresponding to a level at 7.68 MeV in C^{12}."

Hoyle, Astrophys. J. Suppl. Ser. 1:121 (1954)
Maddox, Nature 413:270 (2001)
H. Kragh, Archive for History of Exact Sciences, 64:721, (2010)

Nuclear synthesis in stellar explosions

- Rapid proton-capture (rp-process): X-ray bursts (novae?)
- Neutrino-absorption $\nu_e(p,n)e^-$ and the νp-process (bypassing the slow beta-decays in supernova nucleosynthesis)

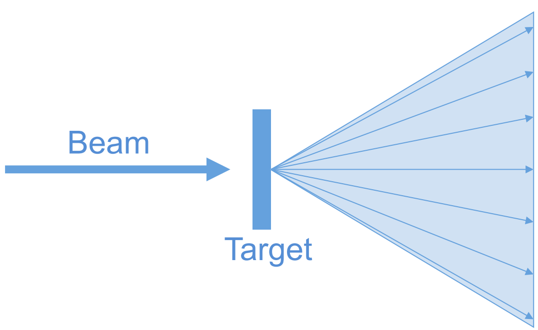


- Rapid neutron-capture (r-process): Core-collapse supernovae?
- Electron-capture (e^-,ν_e) and neutrino scattering (ν,ν')

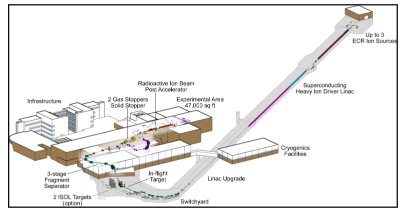
- Big-Bang nucleosynthesis
- Stellar burning and Hot-CNO in novae
- Hot-CNO breakout in X-ray bursts (novae?)

Taking nuclear astrophysics down-to-earth

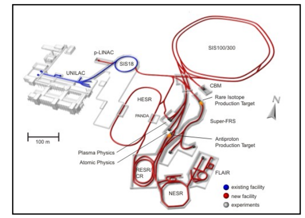
- Measurement of key nuclear reactions using radioactive ion beams (RIBs):
- Intense
- Pure
- Accelerated
- Setup for reaction studies



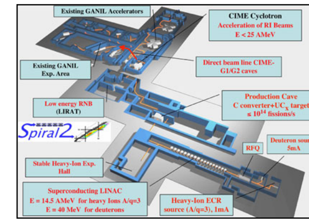
FRIB-MSU



FAIR-GSI



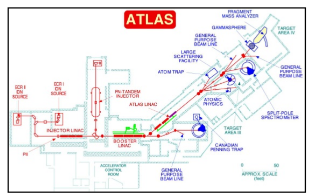
SPIRAL2-GANIL



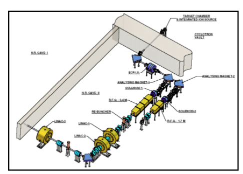
New Facilities

UNDER CONSTRUCTION

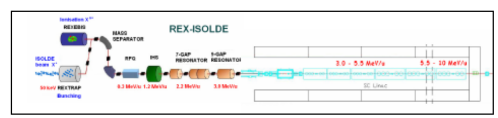
Upgrades



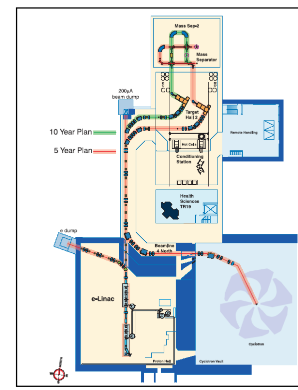
CARIBU (Argonne)



VECC-RIB (Calcutta)



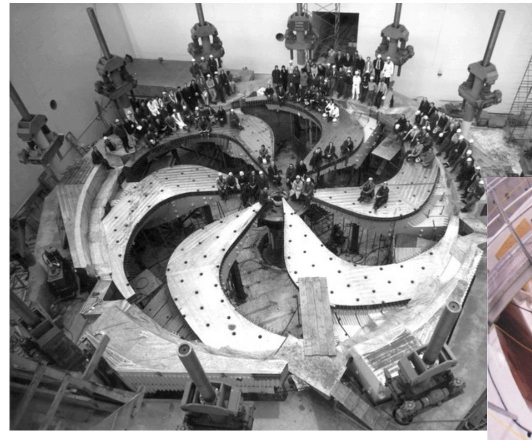
HIE-ISOLDE (CERN)

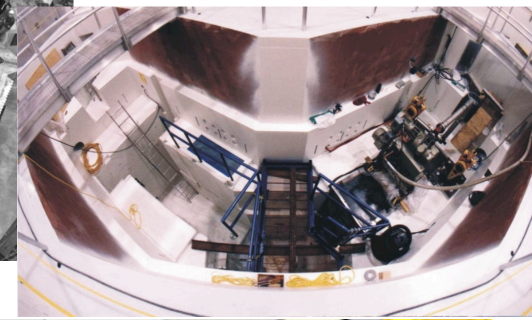


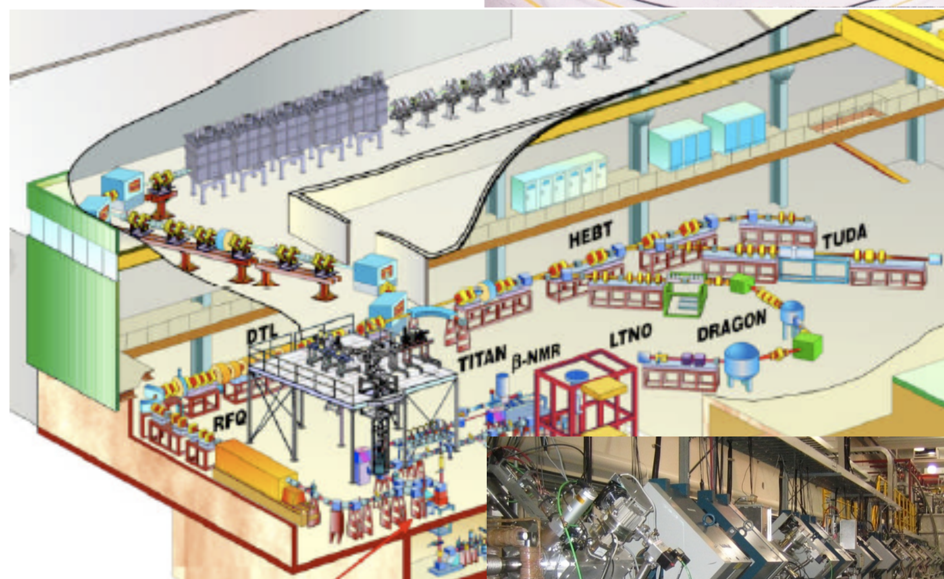
E-fission (TRIUMF)

Radioactive ion beams for nuclear astrophysics

- Example: TRIUMF facility, Vancouver:
  - Cyclotron 500-MeV 100-μA continuous proton beam
- Radioactive isotope separation with subsequent acceleration:
  - Radioactive-ion production targets (e.g. SiC and UCx)
  - Chemical selectivity in ion source (e.g. laser).
  - Magnetic separation of beams (A/q)
  - Secondary acceleration of radioactive ions (10.0 MeV/u)
- Nuclear-reaction studies for reactions in stellar explosions



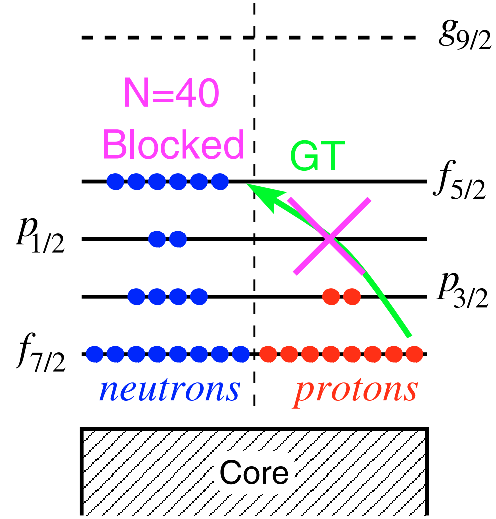


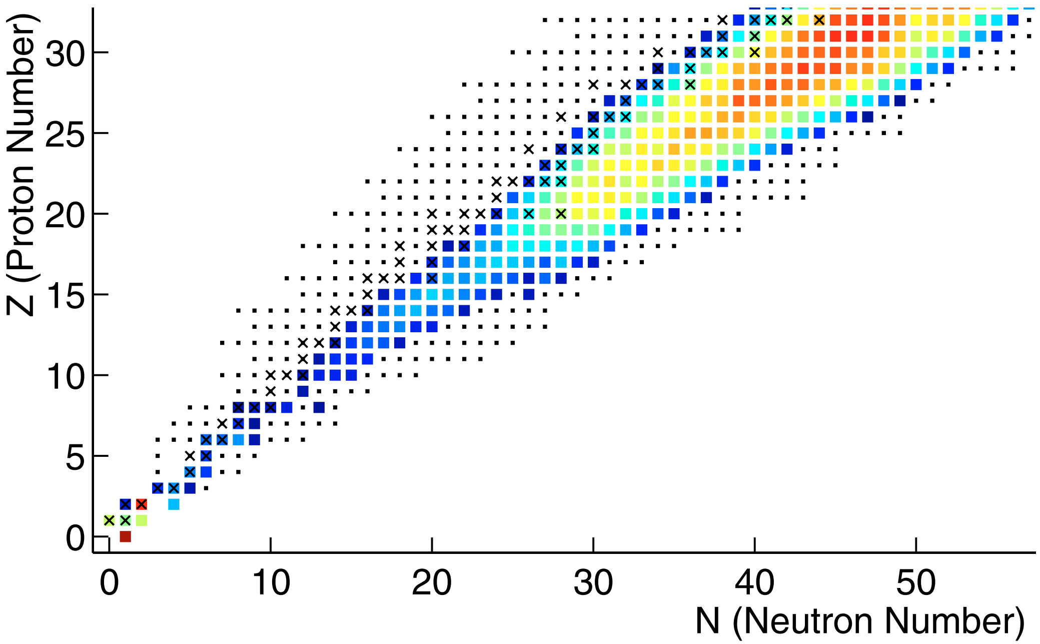


Bricault et al. NIMB, 126:231 (1997)
Laxdal, et al., proc. of LINAC08, p. 97 (2008)

Electron capture in core-collapse supernovae

- GT electron capture blocked for neutron-$g_{9/2}$ nuclei
- Unblocked if proton-$g_{9/2}$ states are partly filled or neutron-fp shell partly emptied
- Potentially lifted by T>0 or configuration mixing





Dzhioev et al., PRC 81 (2010) 015804
Langanke & Martínez-Pinedo, RMP 75 (2003) 819
Q. Zhi, el al., Nucl. Phys. A, 859(2011)172

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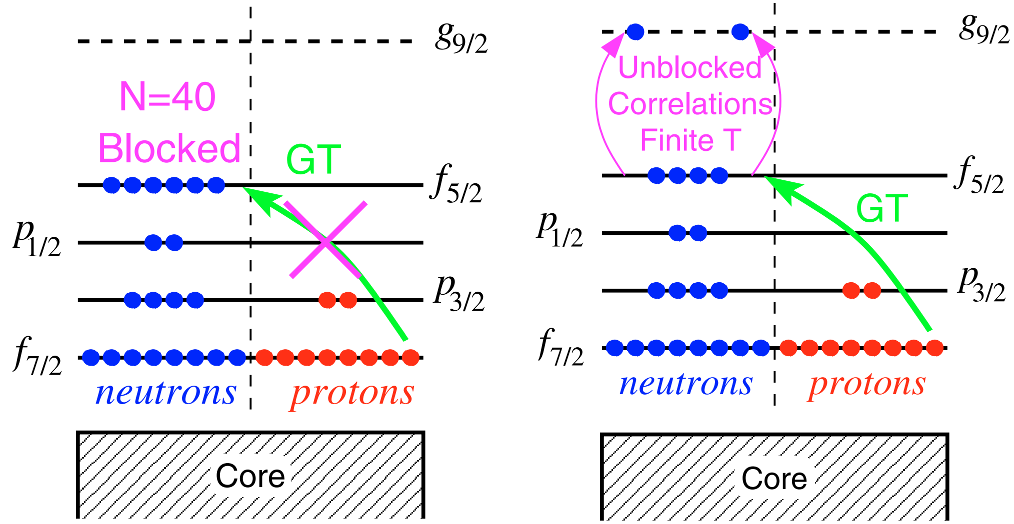

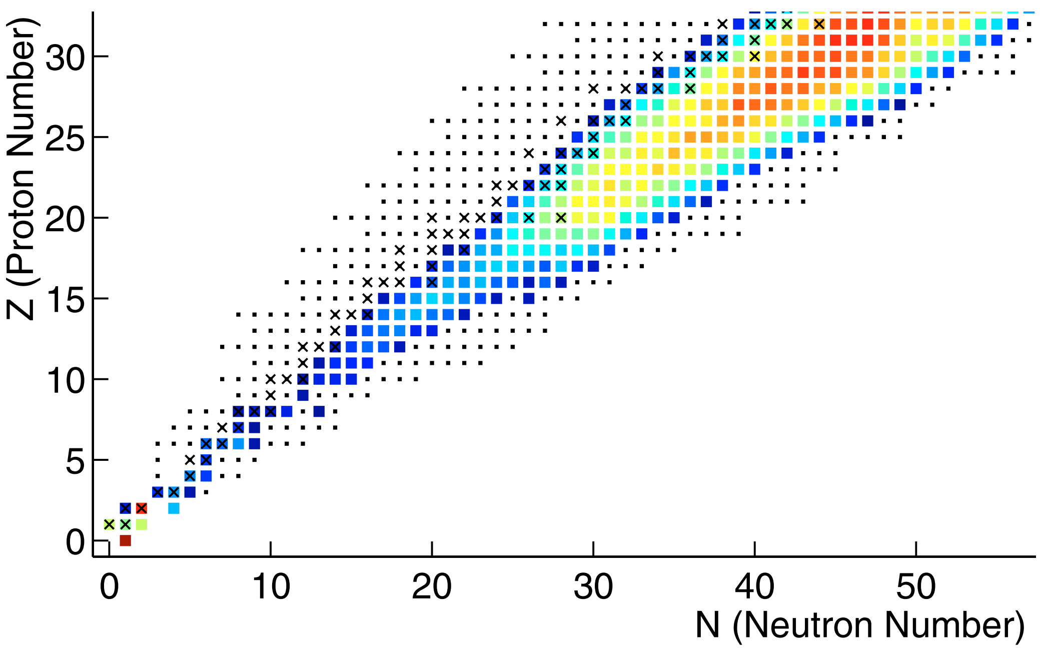

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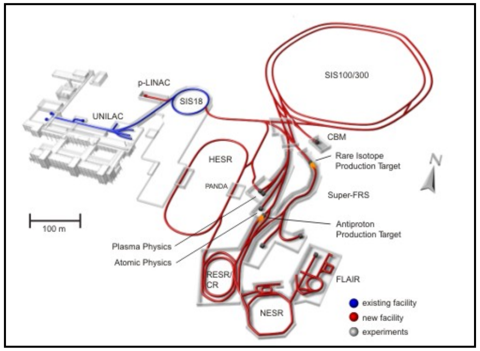


- Nuclear structure studies of exotic nuclei at GSI-FAIR (Germany)

Dzhioev et al., PRC 81 (2010) 015804
Langanke & Martínez-Pinedo, RMP 75 (2003) 819
Q. Zhi, el al., Nucl. Phys. A, 859(2011)172

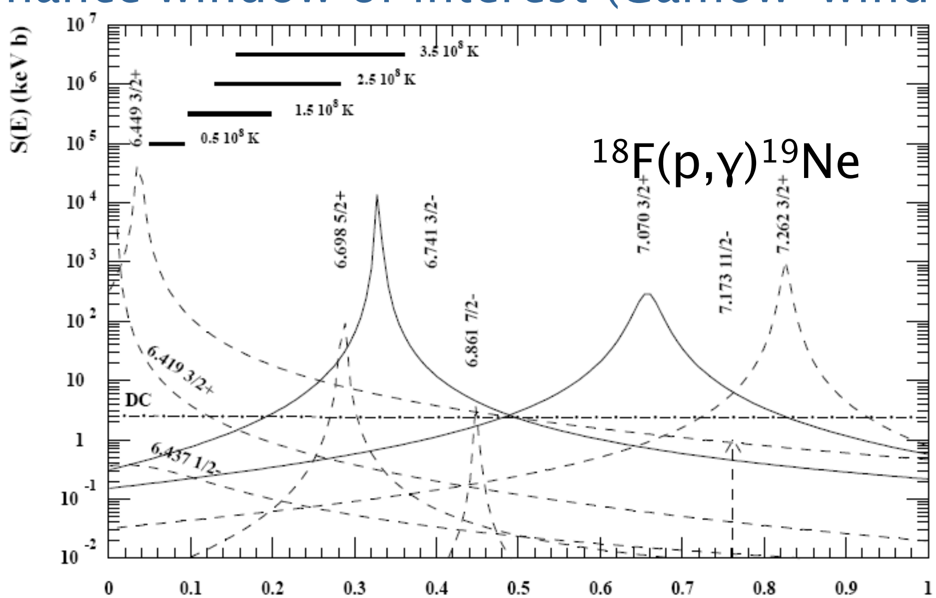
Charged particle reaction rates (Novae / X-ray bursts)

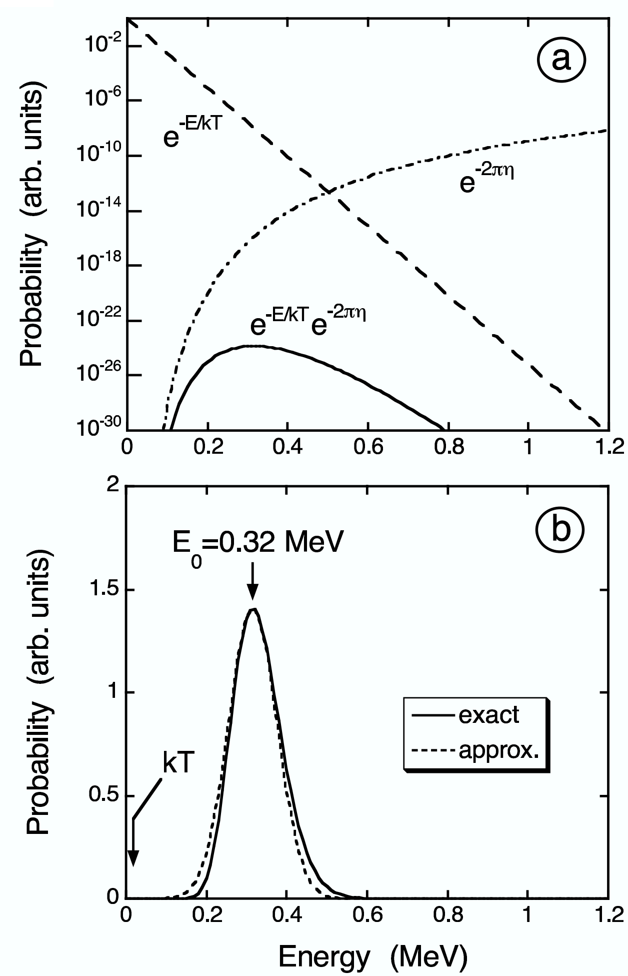
Rate is σv weighed by Maxwell-Boltzmann distribution, P(E):

$$\langle \sigma v \rangle = \int_0^{\infty} v\sigma(E)P(E)dE \;\propto \int_0^{\infty} E\sigma(E)e^{-E/kT}dE \qquad \sigma(E) \equiv \frac{1}{E}e^{-2\pi\eta}S(E)$$

where S(E) changes slowly except where resonances dominate the cross section

Peak in exp(−E/kT)·exp(2πη) defines the resonance window of interest (Gamow-window)





$$\langle \sigma v \rangle \propto (2J+1)\frac{\Gamma_{initial}\Gamma_{final}}{\Gamma_{total}}\exp\left(-\frac{E_r}{k_B T}\right)$$

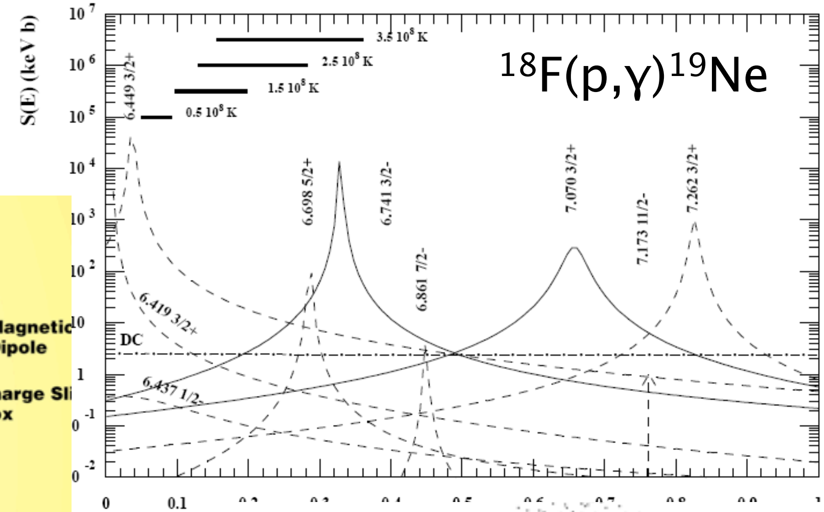
C. Iliadis, Nuclear Physics of Stars (2007)
Rauscher, Phys. Rev. C, 81:045807 (2010)
A.M. Laird, et al. (experiment proposal 2007)

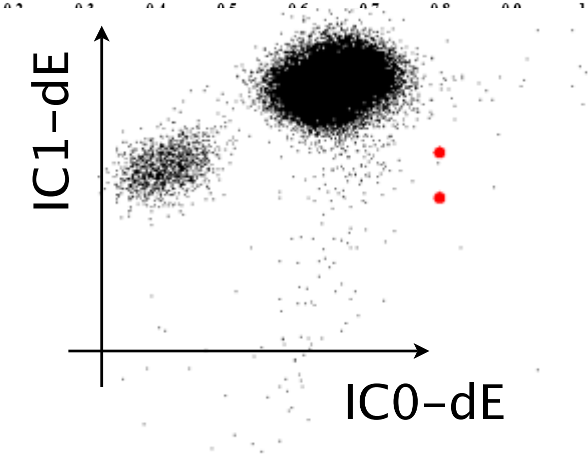
Methods for reaction-rate studies

- Direct: measurement of resonant-reaction cross section, DRAGON Selectivity of 10^{10}

$$\langle \sigma v \rangle \propto (2J+1)\frac{\Gamma_{initial}\Gamma_{final}}{\Gamma_{total}}\exp\left(-\frac{E_r}{k_B T}\right)$$

Gas-target (^1H or ^4He)
Electrostatic and magnetic separation
γ-rays and dE-dE-TOF particle-ID





N. de Sereville, et al., Phys. Rev. C, 79(2009)015801; C. E. Beer, et al., Phys. Rev. C, 83(2011)042801; M. Taggart, et al., PoS (NIC-XI, 2010)045; C. Akers, A.M. Laird, et al. (Dec 2011)

Methods for reaction-rate studies

$$\langle \sigma v \rangle \propto (2J+1)\,\frac{\Gamma_{initial}\Gamma_{final}}{\Gamma_{total}}\,\exp\left(-\frac{E_r}{k_B T}\right)$$

- Direct: measurement of resonant-reaction cross section, DRAGON Selectivity of 10^{10}
- Indirect: state in ^{19}Ne, $\Gamma_\alpha = B_\alpha \Gamma_{tot} \propto B_\alpha/\tau$, with
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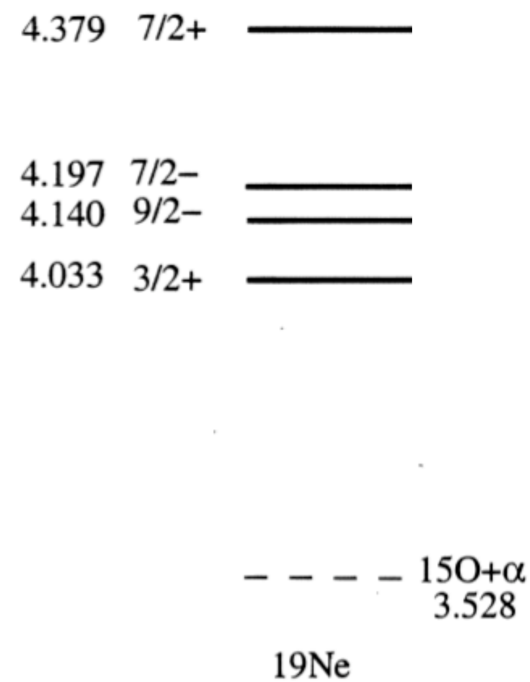
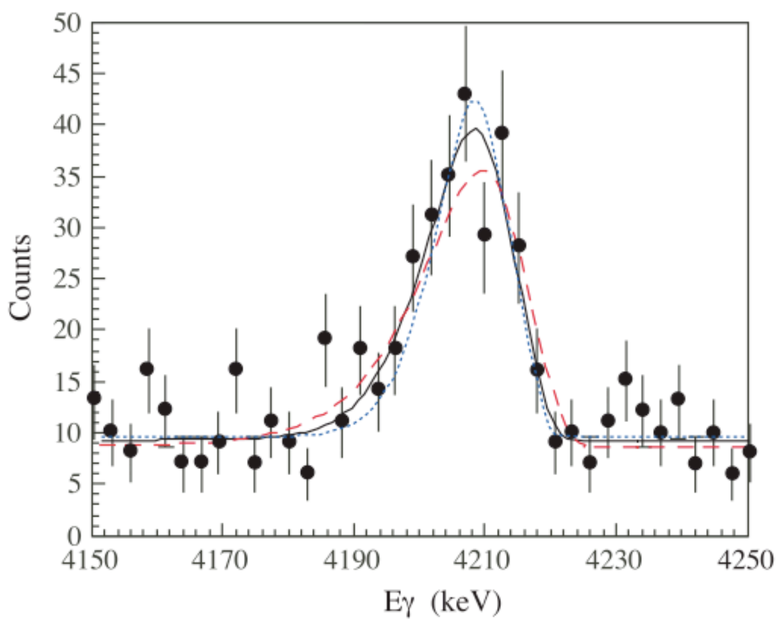
  - $B_\alpha = 3 \pm 2 \cdot 10^{-4}$ from identification of weak α-branch of state





- Breakout from Hot-CNO cycles: ^{15}O(α,γ)^{19}Ne

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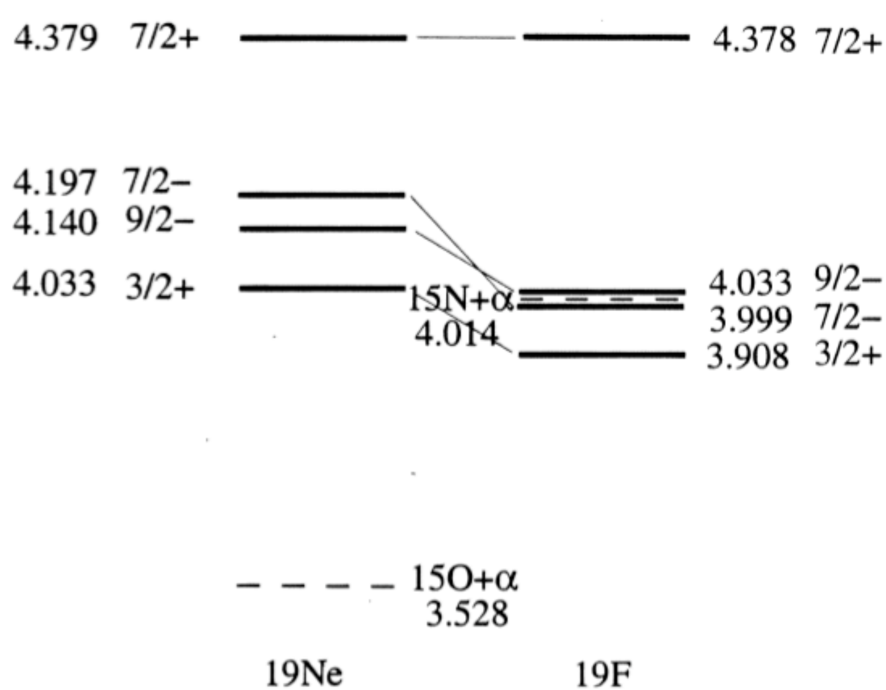

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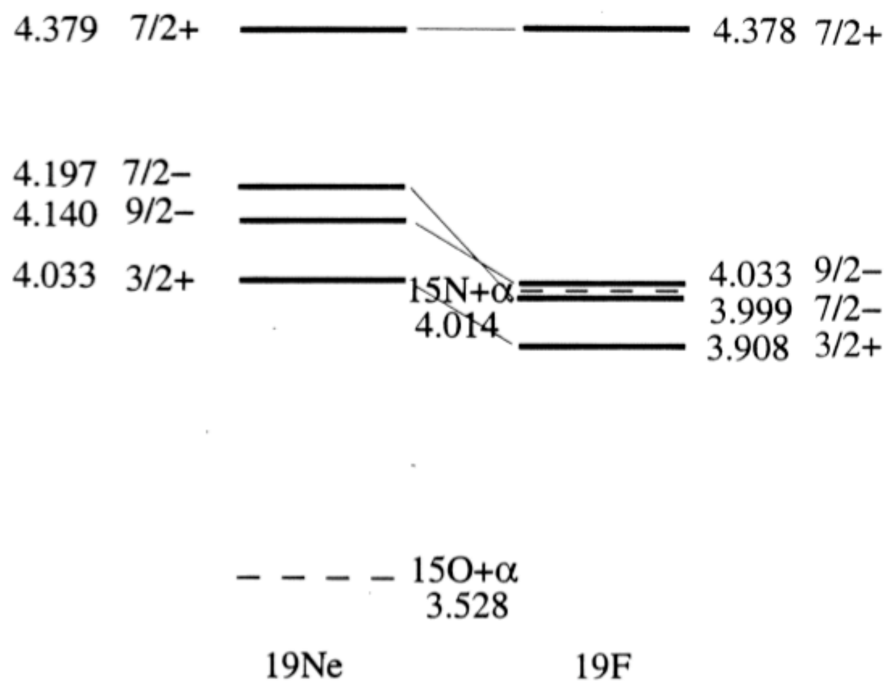

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Combined setup for γ-ray and particle spectroscopy

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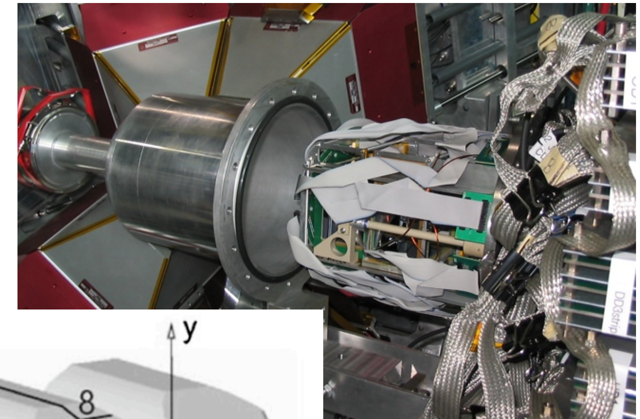
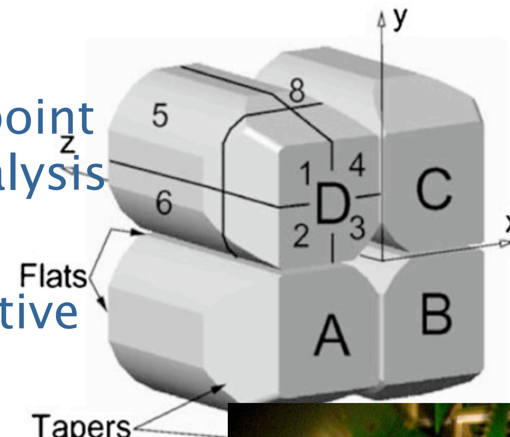
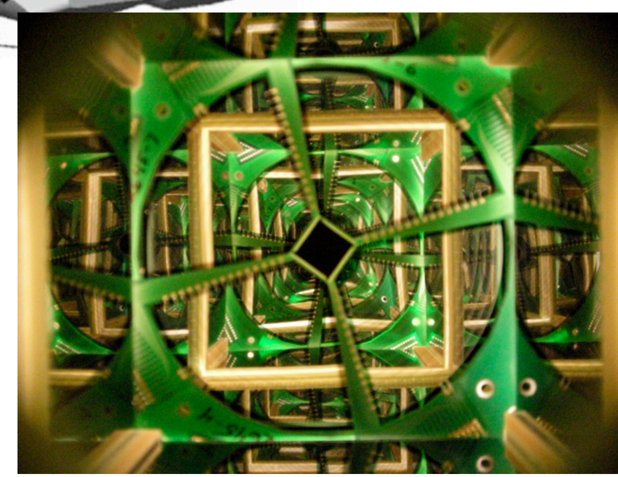


- TIGRESS: TRIUMF-ISAC Gamma-Ray Escape-Suppressed Spectrometer:
  - Array of 12 HPGe γ-ray detectors
  - Segmented contacts, interaction point determined from pulse-shape analysis
  - Doppler corrected γ-ray energies FWHM < 1% for 10 MeV/u radioactive ion beam; 5% efficiency at 4 MeV



- SHARC: Silicon Highly-segmented Array for Reactions and Coulex:
  - Reaction target at centre of silicon array, surrounded by HPGe array
  - Identification of reaction channel (PID), angular distributions, and cross sections



Svensson JPG, 31:S1663 (2005); Schumaker NIMA, 570:437 (2007)
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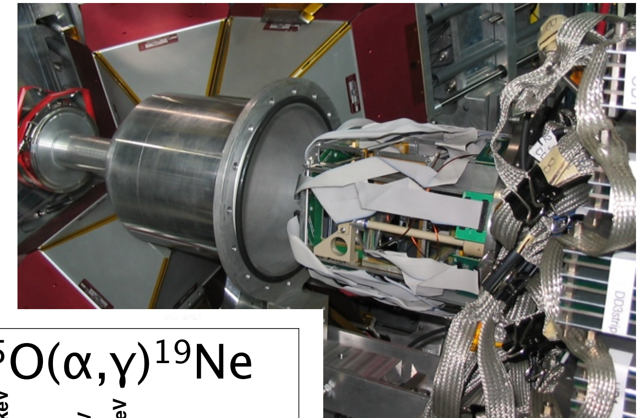

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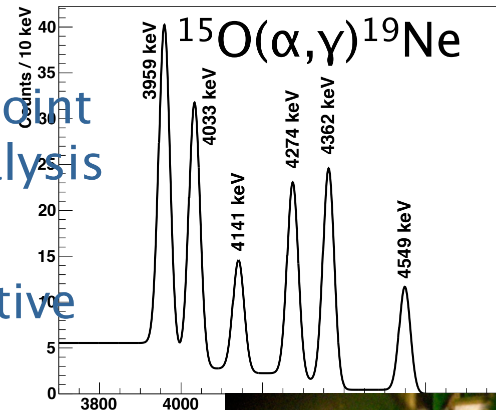

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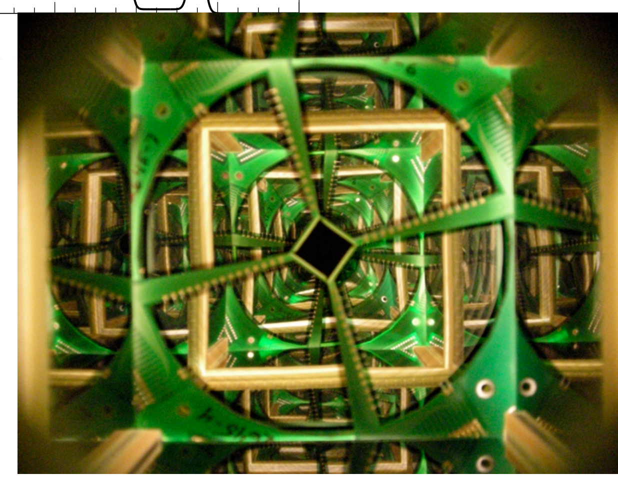

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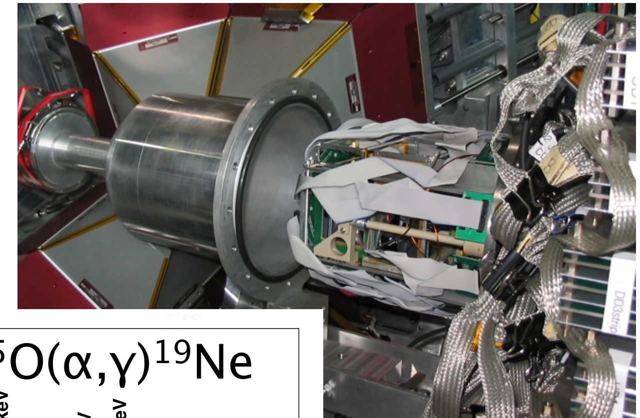

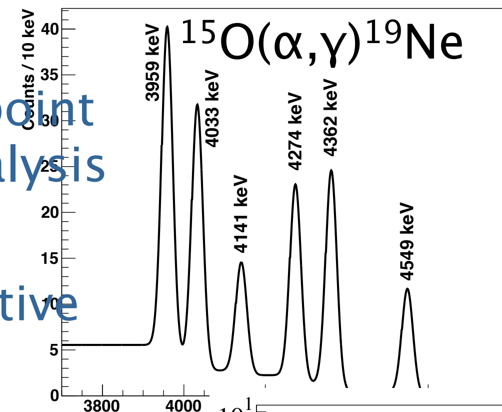

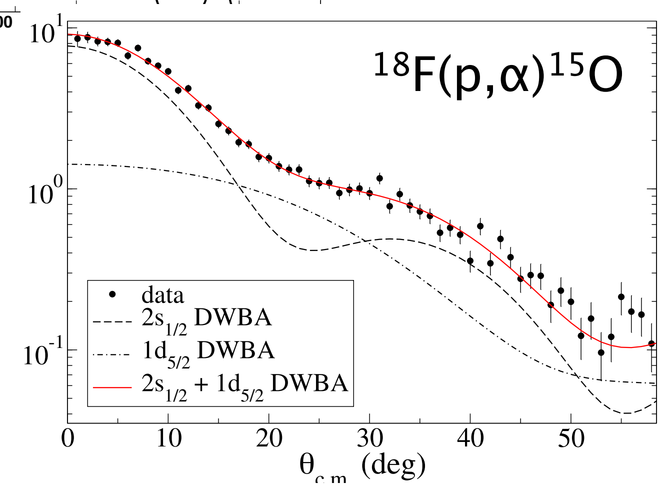

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Exiting prospects for nuclear astrophysics

- Next generation radioactive-ion-beam facilities online 2015-2020 (e.g. GSI-FAIR, TRIUMF-ARIEL):
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  - dedicated detectors for nuclear astrophysics
  - direct and indirect studies of key nuclear reactions in stellar explosions

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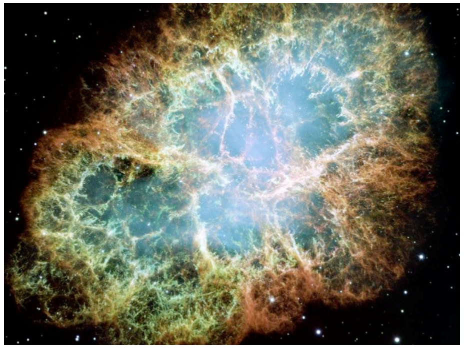

- Yielding combined probes of driving factors in stellar explosions

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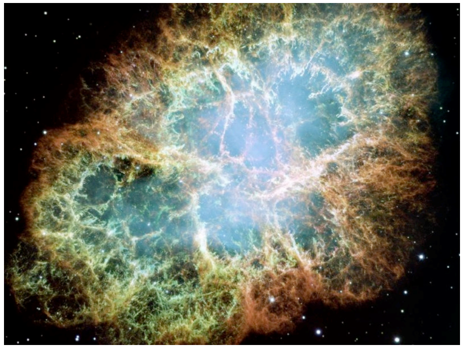

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Thanks to collaborators from

- United Kingdom:
  - University of York
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  - University of Edinburgh
  - University of Liverpool
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  - McMaster University, ON
  - Simon Fraser University, BC
  - Université de Montréal, QC
  - University of Guelph, ON
- USA:
  - Colorado School of Mines, CO
  - Louisiana State University, LA
  - NSCL, Michigan State University, MI
- France:
  - GANIL, Caen
  - LPC, Université de Caen
  - IPN-Orsay, Université Paris Sud
- Germany:
  - GSI-FAIR
- Spain:
  - IFC-CSIC, Universidad de Valencia
- Italy:
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