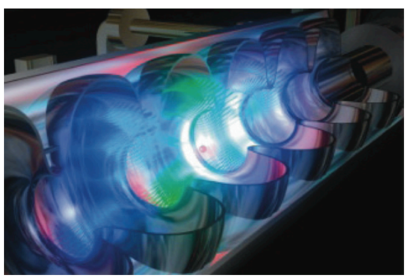
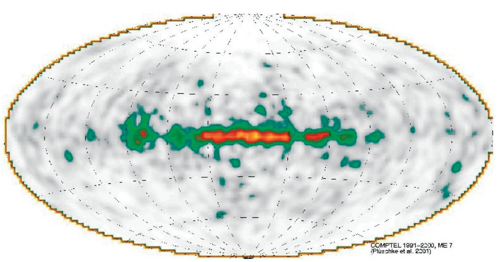
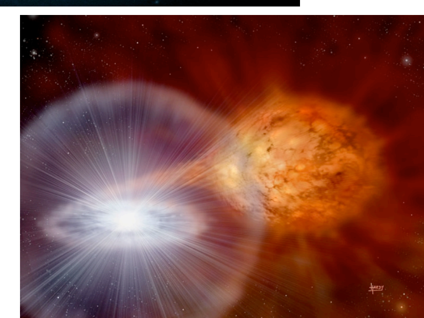
(Some)
Key Nuclear Uncertainties
(for Synthesis, Origins and Impacts)



Christian Aa. Diget
University of York

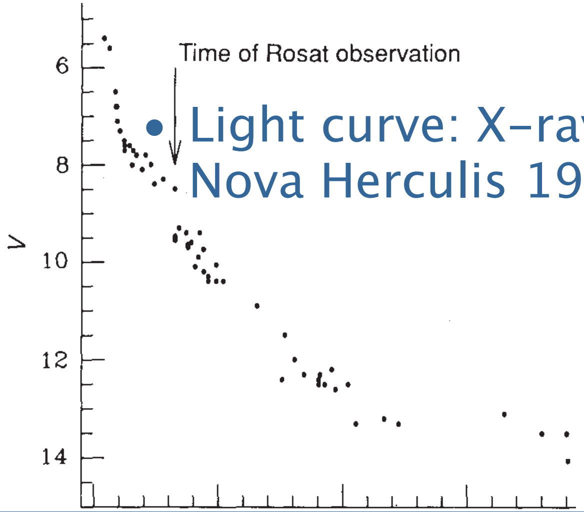




Nucleosynthesis:
Origins and Impacts
14th of February 2014

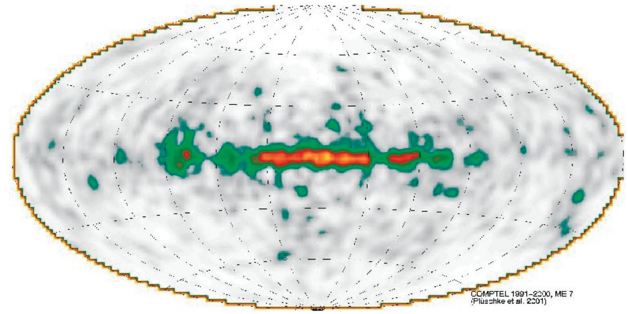
Stellar explosions and hydrostatic burning

- Novae and X-ray bursts
  - Thermo-nuclear run-away on surface of white dwarf / neutron star
  - Fuelled by material from red-giant companion
- Type-1a supernova: subsequent to novae in binary systems
- Core-collapse supernova: precursor to neutron stars (XRB)

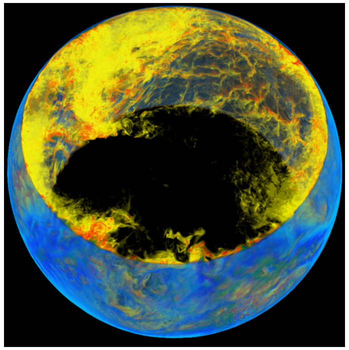


- Light curve: X-rays from Nova Herculis 1991

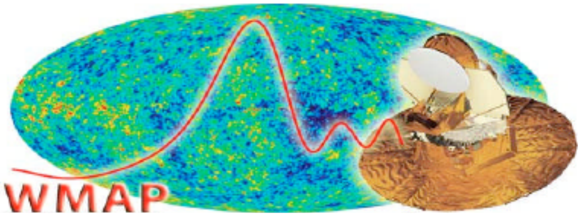
- COMPTEL/INTEGRAL: ^{26}Al decay spectroscopy survey, ESA



- Stellar fusion reactions in Asymptotic Giant Branch (AGB) stars [to the right a He-shell flash]



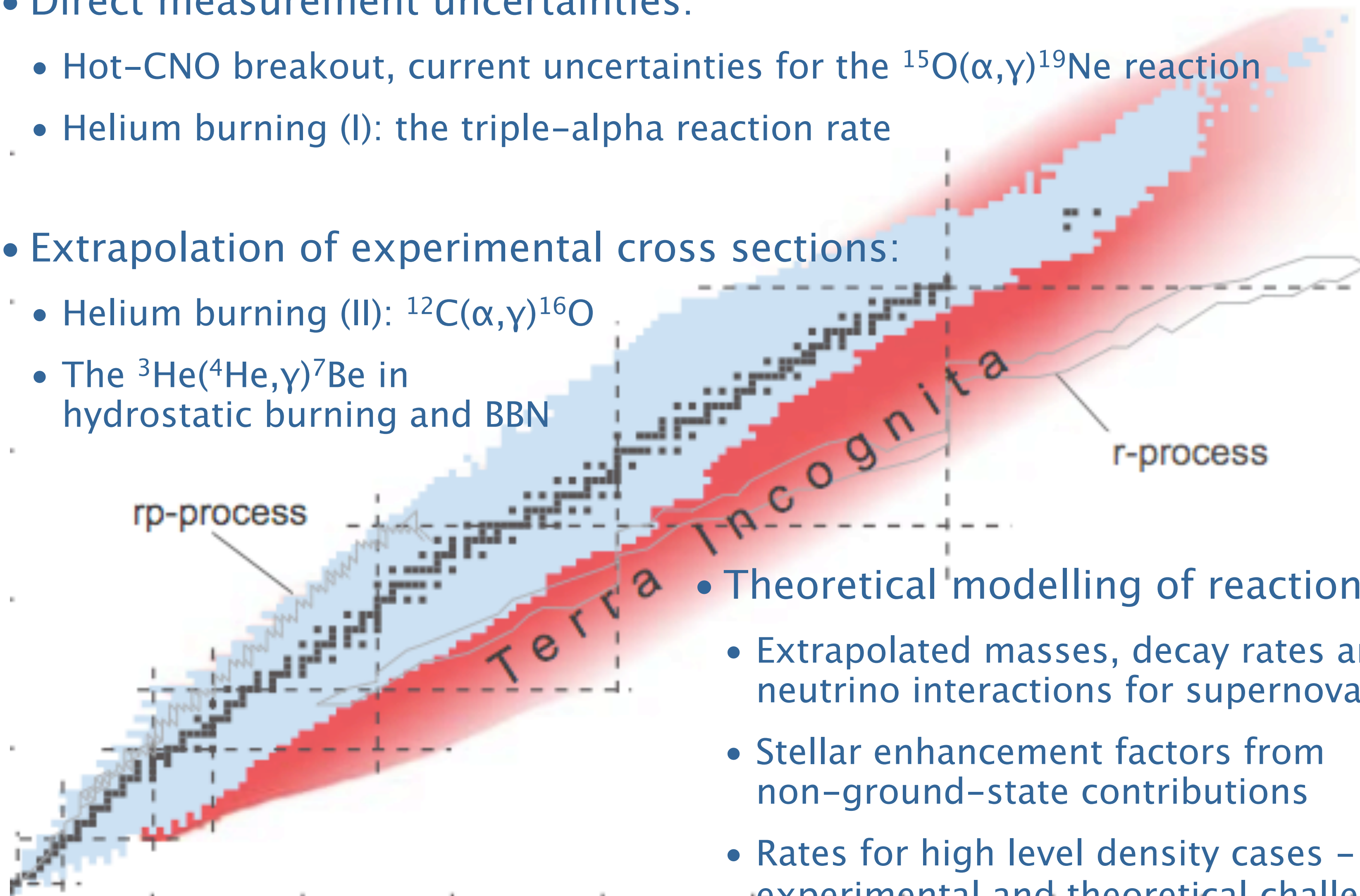
- Big Bang Nucleosynthesis



Lloyd et al., Nature, 356:222 (1992)
ESA, COMPTEL/INTEGRAL collaboration
Herwig, Pignatari, et al., APJ 727(2011)89

Key Nuclear Uncertainties for Origins and Impact

- Direct measurement uncertainties:
  - Hot-CNO breakout, current uncertainties for the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction
  - Helium burning (I): the triple-alpha reaction rate
- Extrapolation of experimental cross sections:
  - Helium burning (II): $^{12}C(\alpha,\gamma)^{16}O$
  - The $^{3}He(^{4}He,\gamma)^{7}Be$ in hydrostatic burning and BBN

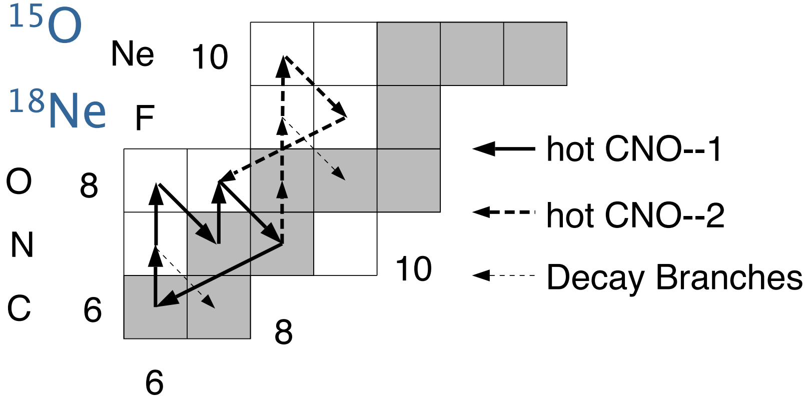


- Theoretical modelling of reaction rates
  - Extrapolated masses, decay rates and neutrino interactions for supernovae
  - Stellar enhancement factors from non-ground-state contributions
  - Rates for high level density cases – experimental and theoretical challenges

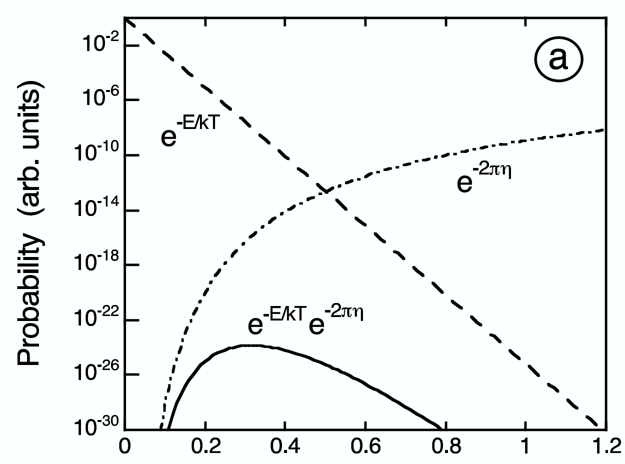
Gelbke et al., MSUCL-1345 (2006)
Langanke & Martínez-Pinedo, RMP 75:819 (2003)

Nuclear measurements of Hot-CNO breakout

- The CNO and Hot-CNO cycles
- Build-up of waiting-point nuclei in novae and X-ray bursts:
  - ^{14}O
  - ^{15}O
  - ^{18}Ne



- Breakout from Hot-CNO cycles:
  - ^{14}O(α,p)^{17}F
  - ^{15}O(α,γ)^{19}Ne
  - ^{18}Ne(α,p)^{21}Na

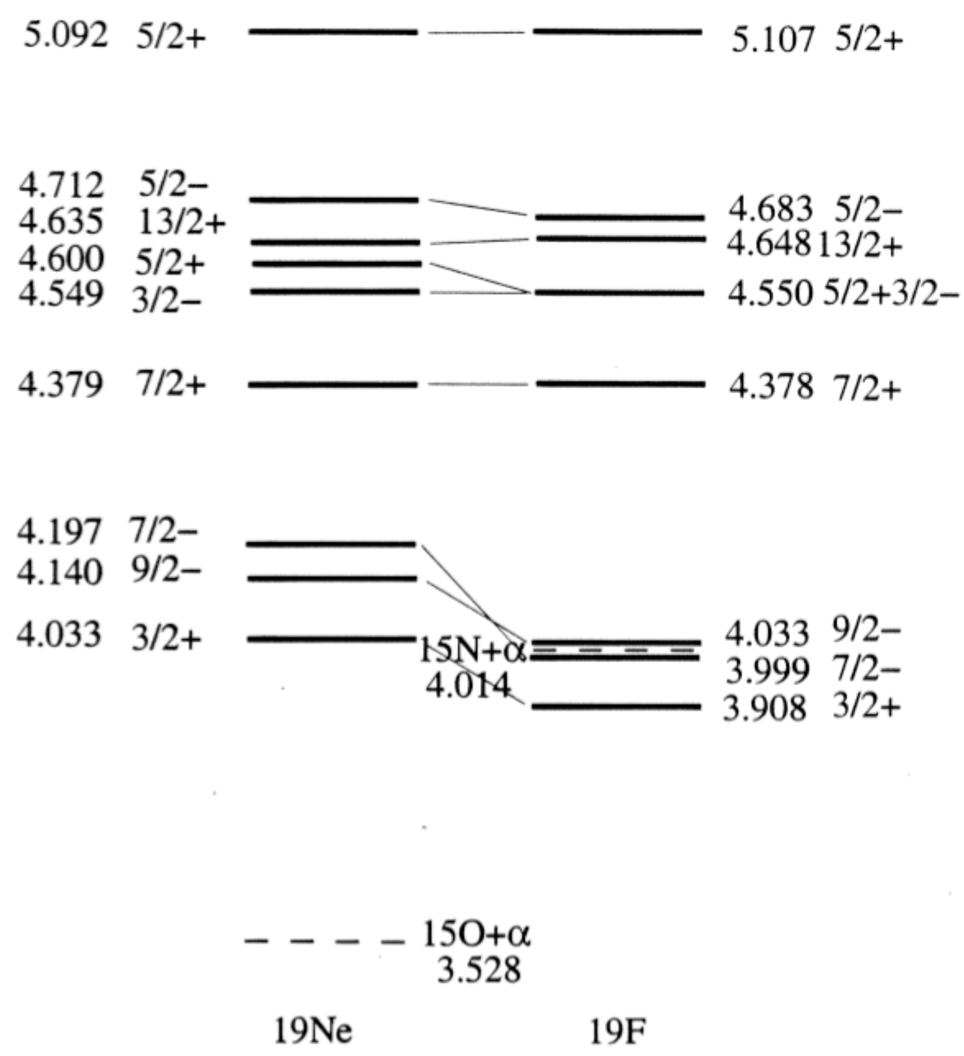


- Resonant reaction rate: velocity-weighted cross section.
- Resonant:
$$(2J+1)\frac{\Gamma_\alpha \Gamma_p}{\Gamma_{tot}}\exp(-\frac{E_r}{k_B T})$$
- Gamow-window: 0.7-2.0 MeV resonance energy for temperatures of 0.5-1.5 GK
- For ^{15}O(α,γ)^{19}Ne: Dominated by 4033 keV 3/2+ state in ^{19}Ne: $\Gamma_\alpha = 17 \pm 13$ μeV

Wiescher, et al. JPG, 25:R133 (1999)
C. Iliadis, Nuclear Physics of Stars (2007)
Rauscher, Phys. Rev. C, 81:045807 (2010)

Possible methods for reaction rate studies

- Direct measurement of resonant reaction cross section using a high-selectivity recoil separator
- Indirect: B_α and τ (presently most direct measurement of Γ_α)
- Indirect (mirror alpha transfer): $^{15}N(^{6}Li,d\gamma)^{19}F$ and $^{15}N(^{7}Li,t\gamma)^{19}F$ Measure S_α and Γ_α for ^{19}F states, Γ_α (^{19}Ne) inferred from mirror symmetry
- Indirect (alpha transfer): $^{15}O(^{6}Li,d\gamma)^{19}Ne$ and/or $^{15}O(^{7}Li,t\gamma)^{19}Ne$ to measure S_α and Γ_α for ^{19}Ne states without assumption of detailed mirror symmetry



Studies of the ^{19}Ne states (life time and alpha branch)

4033 keV (L=1) state:

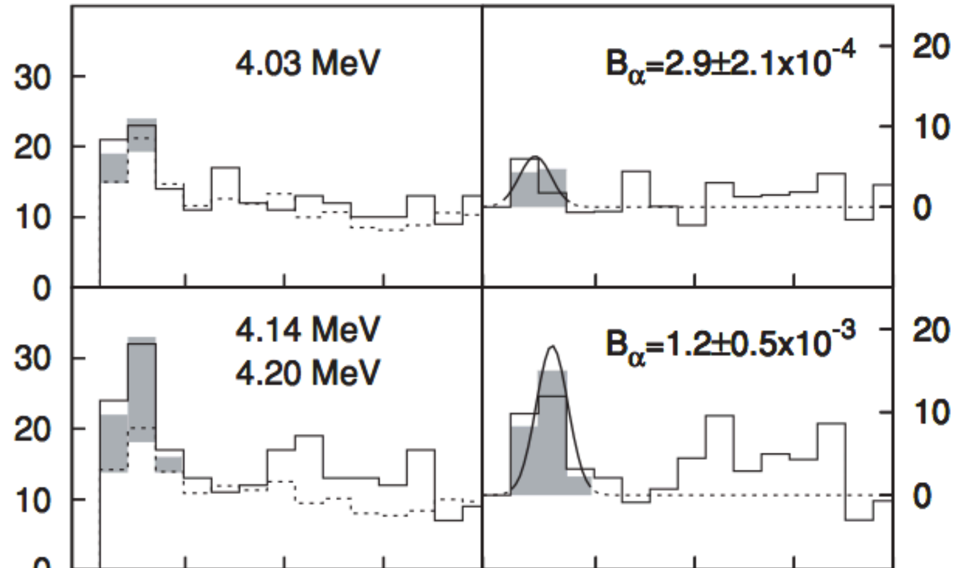
$$(2J+1)\frac{\Gamma_\alpha\,\Gamma_\gamma}{\Gamma_{tot}}\exp\left(-\frac{E_r}{k_B\,T}\right)$$

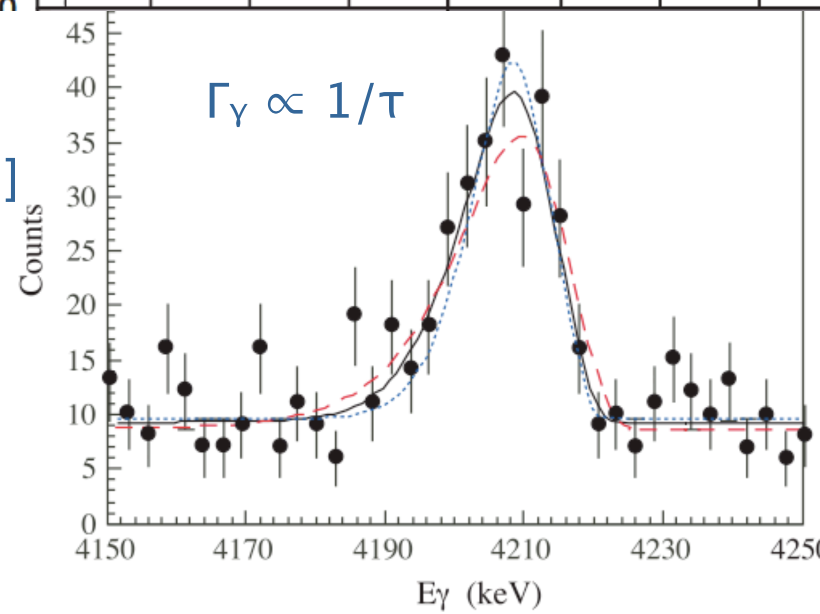
with $\Gamma_\alpha = B_\alpha \Gamma_{tot}$

- $B_\alpha = 2.9 \pm 2.1 \cdot 10^{-4}$ from:
  - ^{19}F(^{3}He,t)^{19}Ne*(,α)^{15}O
  - Difficult: 8 t–α events on background of 35
- $\Gamma_{tot} = \Gamma_\gamma \propto 1/\tau$ with
  - τ = 11(+4)(−3) fs from:
  - γ-ray Doppler-shift lineshape [2]
- $\Gamma_\alpha = 17 \pm 13$ μeV

4140, 4197 keV (L=4) doublet:

- Combined (unresolved) measurement of alpha branch [1]
- Disputed ordering [1,3]





[1] Tan et al., Phys. Rev. C, 79:055805 (2009)
[2] Kanungo et al., Phys. Rev. C, 74:045803 (2006)
[3] B. Davids, et al., APJ, 735:40 (2011)

The ^{12}C Hoyle state and α clustering in the continuum

- Nuclear structure deduced from triple-alpha reaction rate constraints

$$
\begin{aligned}
{}^{4}\mathrm{He} + {}^{4}\mathrm{He} &\rightleftharpoons {}^{8}\mathrm{Be(gs)} \\
{}^{8}\mathrm{Be(gs)} + {}^{4}\mathrm{He} &\rightarrow {}^{12}\mathrm{C} + \gamma
\end{aligned}
$$

- Prediction and subsequent measurement of ^{12}C Hoyle state at 7.65 MeV

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 $2He^4 \rightarrow Be^8$; $Be^8+He^4 \rightarrow C^{12}$; $C^{12}+He^4 \rightarrow O^{16}$. 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)

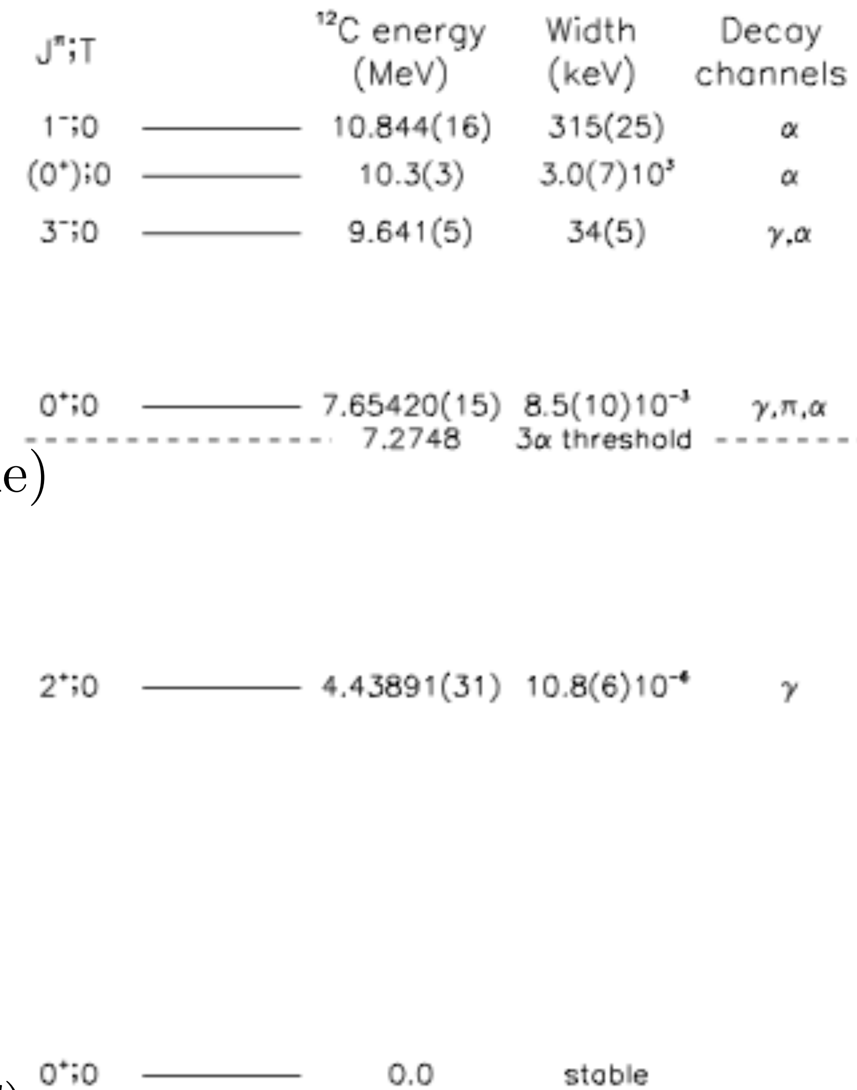
Stellar helium fusion (the triple-alpha process)

- Stellar helium fusion in Asymptotic Giant Branch (AGB) stars and supernova precursors
- Equilibrium population of the ^{8}Be(0^+,gs) and the ^{12}C (0^+) Hoyle state:

$$^4\mathrm{He} + {}^4\mathrm{He} \rightleftharpoons {}^8\mathrm{Be(gs)}$$
$$^8\mathrm{Be(gs)} + {}^4\mathrm{He} \rightleftharpoons {}^{12}\mathrm{C(Hoyle)}$$

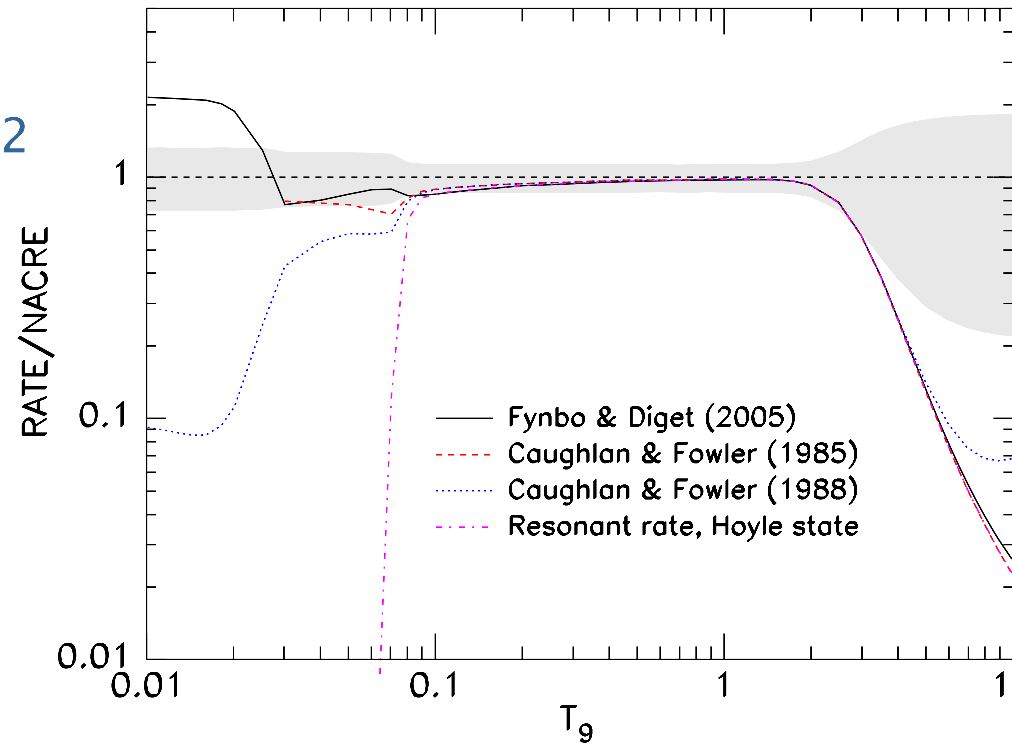
- ^{8}Be(gs) at 92 keV above threshold, Hoyle state at 379 keV above threshold.
- Subsequent gamma decay to the ground state through the intermediate 4.44 MeV (2^+) state
- Resonant reaction rate depends on radiative width and Q-value:

$$N_A^2 \langle \alpha\alpha\alpha \rangle \propto \Gamma_{\mathrm{rad}} \exp(-Q/k_B T).$$



Triple-α reaction rate: status and resonances

- The Hoyle state resonant reaction rate:
  - Dominant rate at $T_9=0.1-2$
  - Combined uncertainty of 10% dominated by pair-branch
- Other resonances, important above $T_9=2$:
  - 2^+ state at 9.1–11 MeV
  - 3^- state at 9.6 MeV



$$\langle\alpha\alpha\alpha\rangle_{res} \propto \frac{\Gamma_{\alpha_0}\Gamma_{rad}}{\Gamma}\exp\left(-Q/k_BT\right) = \frac{\Gamma_\gamma+\Gamma_\pi}{\Gamma}\frac{\Gamma}{\Gamma_\pi}\Gamma_\pi\exp\left(-Q/k_BT\right)$$

9.2% [Alburger:1977]

1.2% @ $T_9=0.2$ [Nolen:1976]

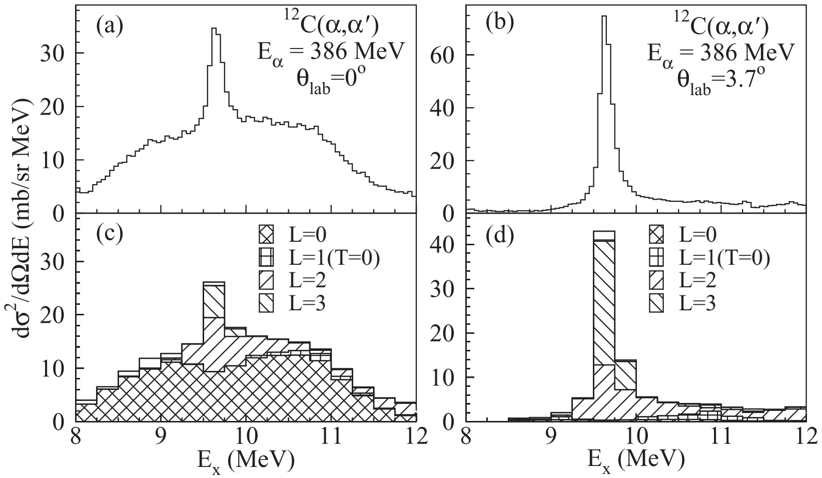
2.7% [Markham:1976]

3.2% [Chernykh:2010]

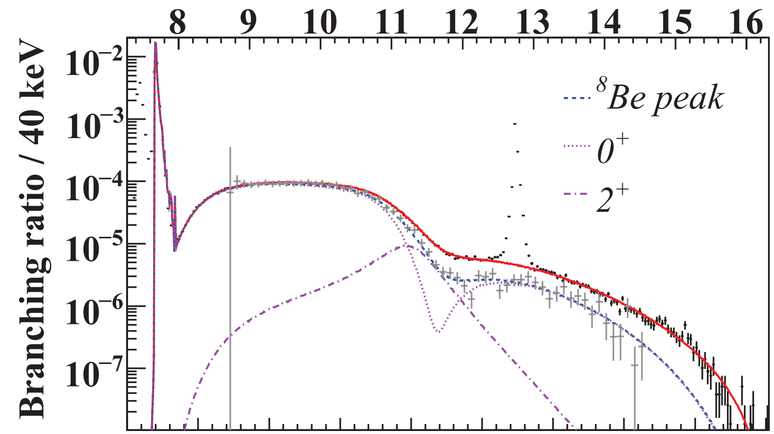
Fynbo, Diget, et al., Nature 433 (2005) 136
Fynbo & Diget, Hyperfine Interactions (2012) 1, doi:10.1007/s10751-012-0611-x

Recent suggestions of 2^+ state observation

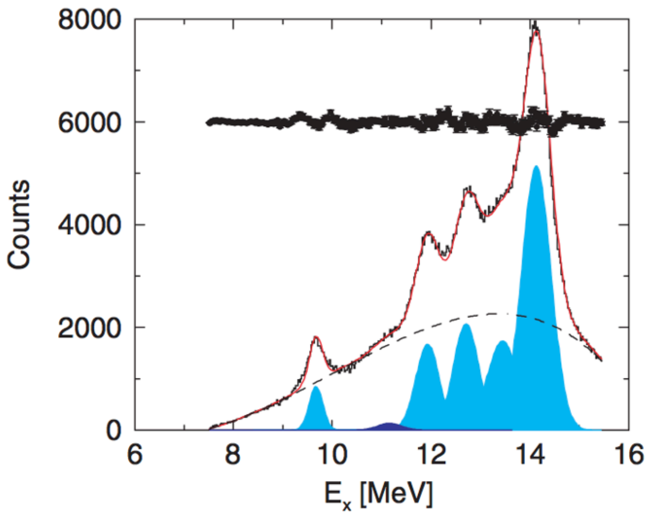
Itoh (2011): $^{12}C(\alpha, \alpha')^{12}C$



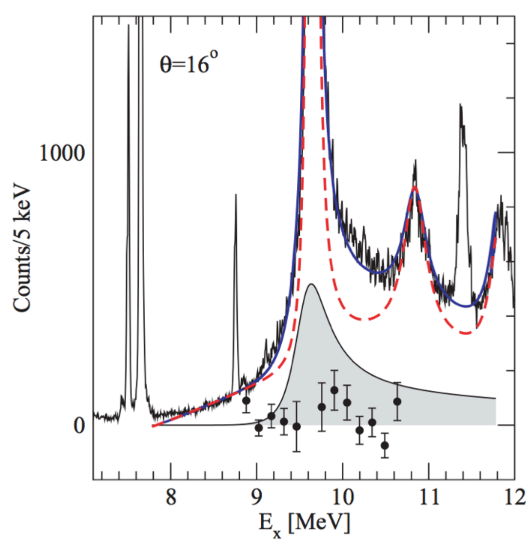
Hyldegaard (2010): $^{12}N/^{12}B(,\beta)3\alpha$



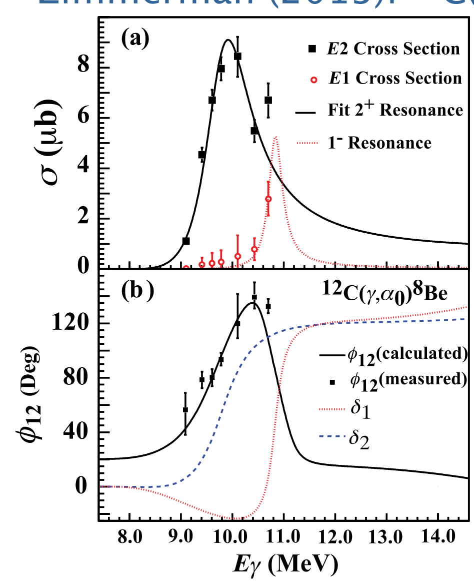
Freer (2007): $^{12}C(^{12}C,3\alpha)\ ^{12}C$



Freer et al. (2009): $^{12}C(p,p')^{12}C$



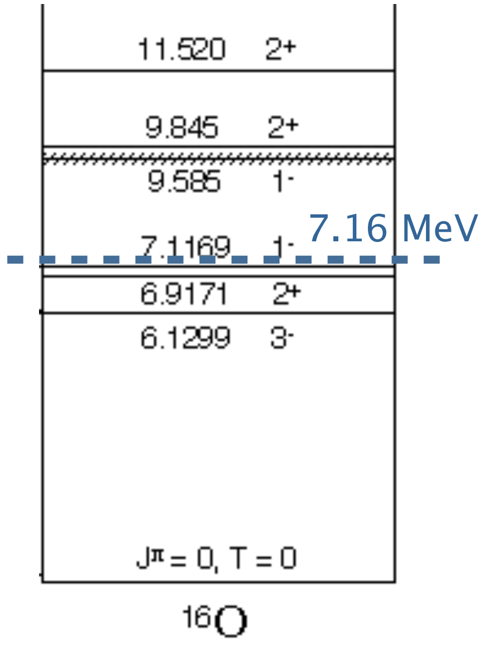
Zimmerman (2013): $^{12}C(\gamma,3\alpha)$



Itoh, PRC 84(2011)054308
Hyldegaard, PRC 81(2010)024303
Freer, PRC 76(2007)034320
Freer, PRC 80 (2009) 041303
Zimmerman, PRL 110 (2013) 152502

Extrapolation of $^{12}C(\alpha,\gamma)^{16}O$: S_{E1} and S_{E2} at 300 keV

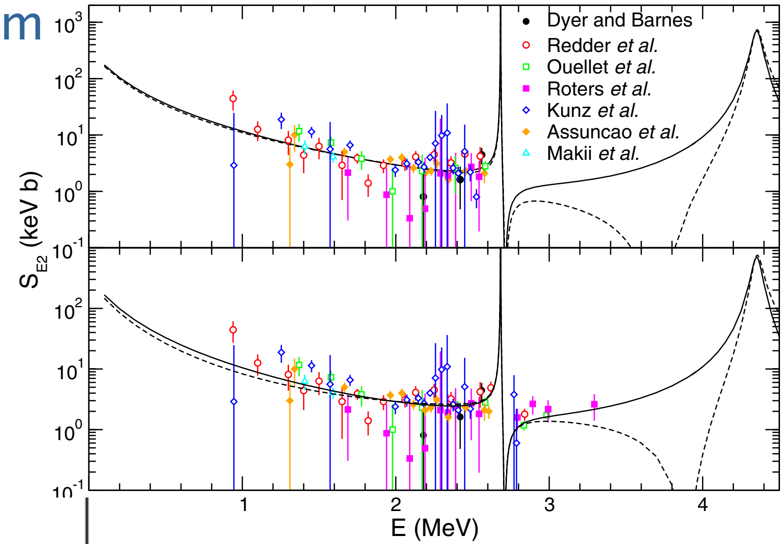
- Extrapolation of E1 and E2 S-factors from the measured S(1 MeV) to S(300 keV)
  - Detailed study of interference in S_{E2}
  - Dedicated beta-decay study of S_{E1}
  - Combined fit to all reactions that proceed through the ^{16}O states: $^{12}C(\alpha,\alpha)$, $^{12}C(\alpha,p)$, $^{12}C(\alpha,\gamma)$, $^{15}N(p,p)$, $^{15}N(p,\alpha)$, $^{16}N(\beta\alpha)$ and $^{15}N(p,\gamma)$

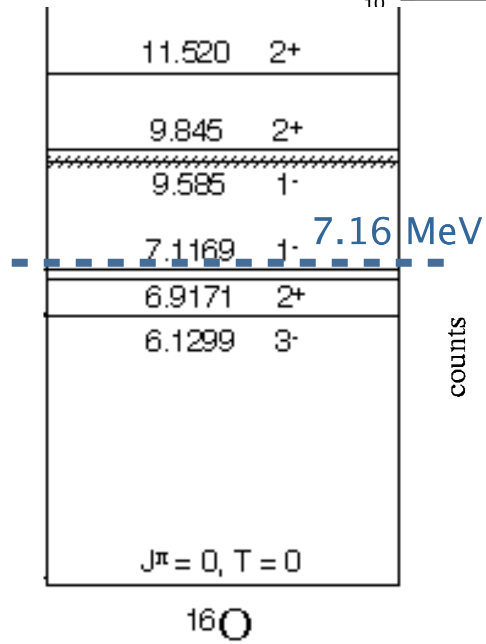


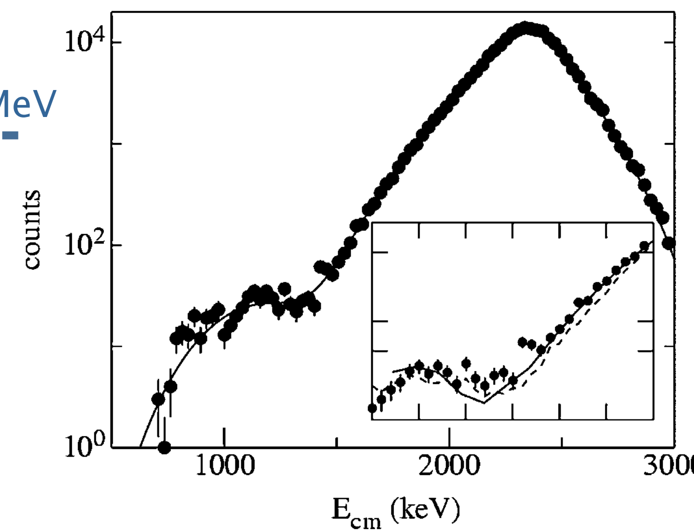
Sayre, et al., PRL, 109(2012)142501
Tang, et al., PRL 99(2007)052502
deBoer, et al., PRC, 87(2013)015802

Extrapolation of $^{12}C(\alpha,\gamma)^{16}O$: S_{E1} and S_{E2} at 300 keV

- Extrapolation of E1 and E2 S-factors from the measured S(1 MeV) to S(300 keV)
  - Detailed study of interference in S_{E2}
  - Dedicated beta-decay study of S_{E1}
  - Combined fit to all reactions that proceed through the ^{16}O states: $^{12}C(\alpha,\alpha)$, $^{12}C(\alpha,p)$, $^{12}C(\alpha,\gamma)$, $^{15}N(p,p)$, $^{15}N(p,\alpha)$, $^{16}N(\beta\alpha)$ and $^{15}N(p,\gamma)$



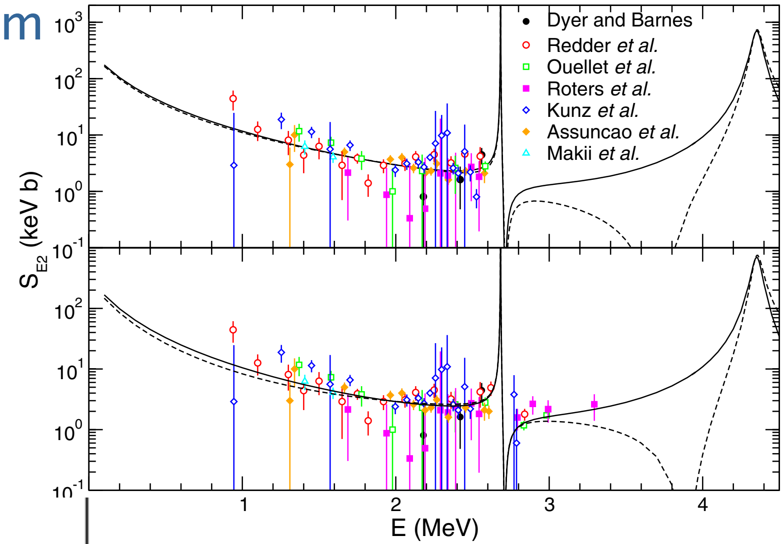


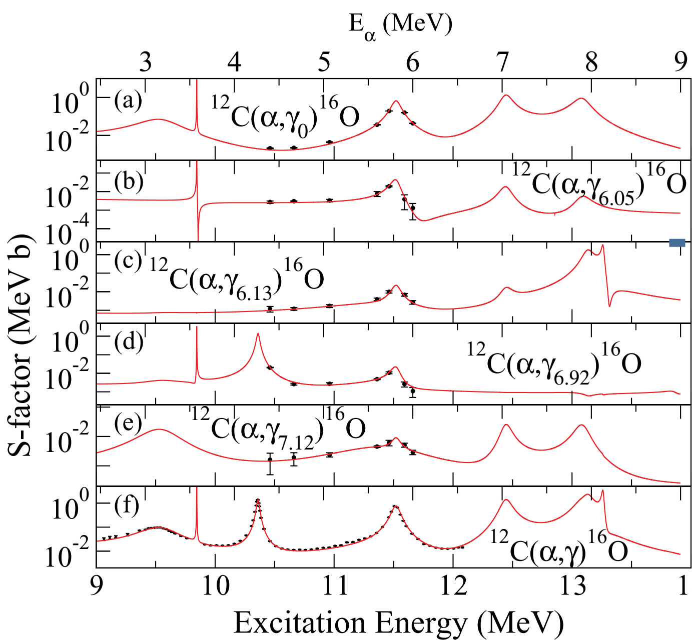


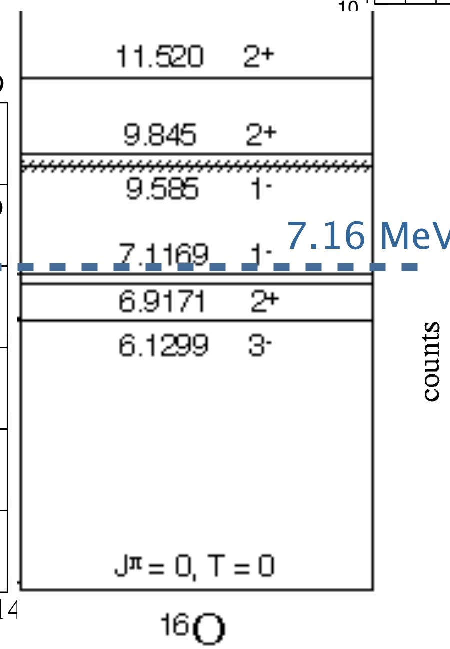
Sayre, et al., PRL, 109(2012)142501
Tang, et al., PRL 99(2007)052502
deBoer, et al., PRC, 87(2013)015802

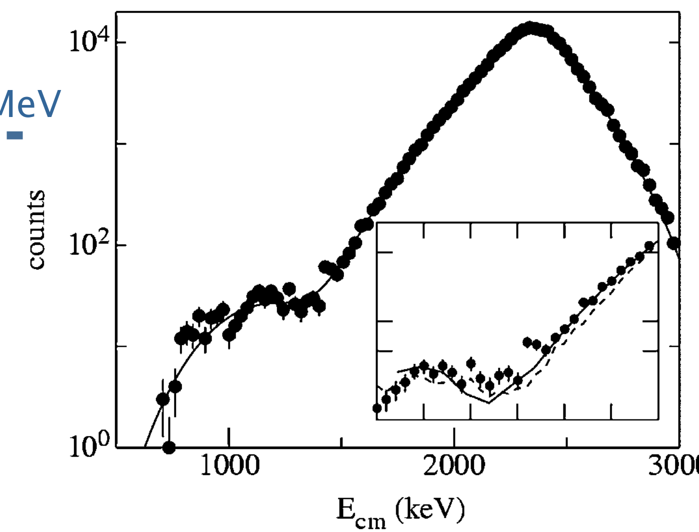
Extrapolation of $^{12}C(\alpha,\gamma)^{16}O$: S_{E1} and S_{E2} at 300 keV

- Extrapolation of E1 and E2 S-factors from the measured S(1 MeV) to S(300 keV)
  - Detailed study of interference in S_{E2}
  - Dedicated beta-decay study of S_{E1}
  - Combined fit to all reactions that proceed through the ^{16}O states: $^{12}C(\alpha,\alpha)$, $^{12}C(\alpha,p)$, $^{12}C(\alpha,\gamma)$, $^{15}N(p,p)$, $^{15}N(p,\alpha)$, $^{16}N(\beta\alpha)$ and $^{15}N(p,\gamma)$





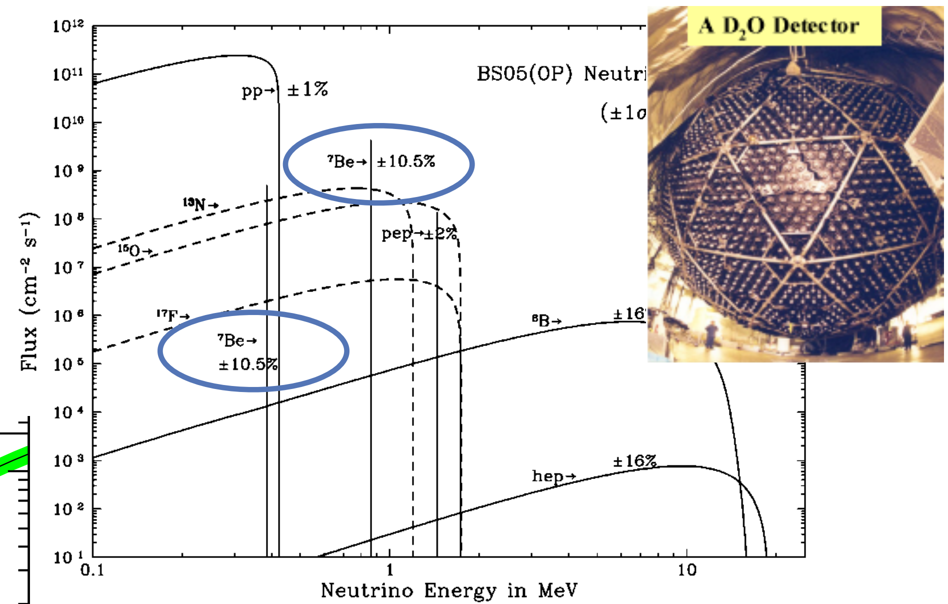


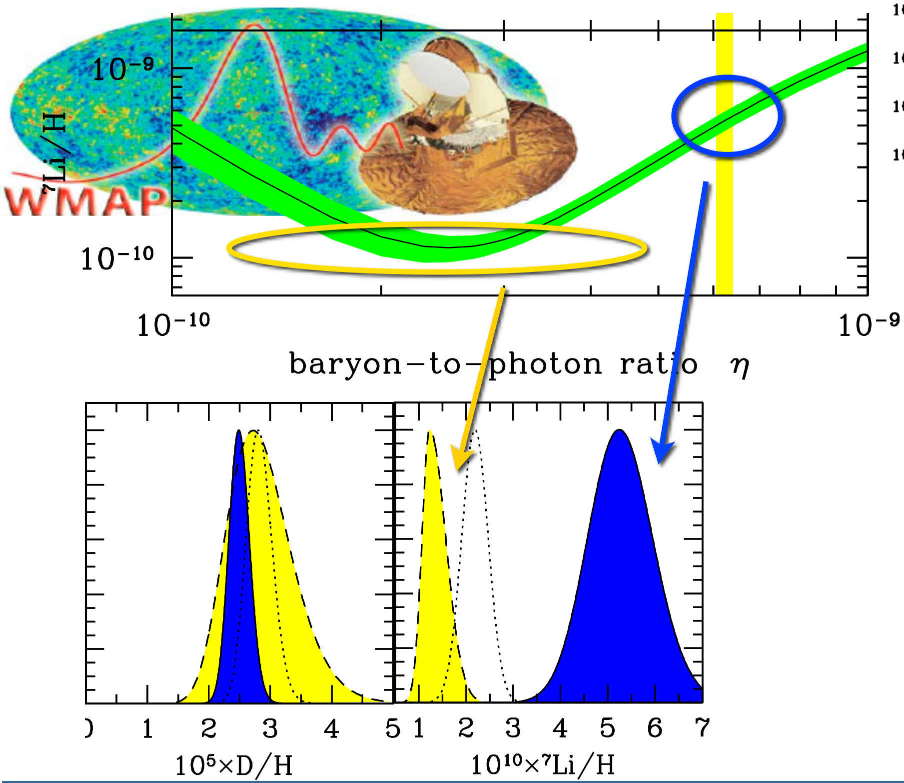


Sayre, et al., PRL, 109(2012)142501
Tang, et al., PRL 99(2007)052502
deBoer, et al., PRC, 87(2013)015802

Uncertainties in S_{34}, the $^3He(^4He,\gamma)^7Be$ reaction rate

- Stable burning in stars (cross section uncertainty produces largest uncertainty in solar neutrino yield)
- Big Bang Nucleosynthesis (cross section critical for interpreting the Li problem)



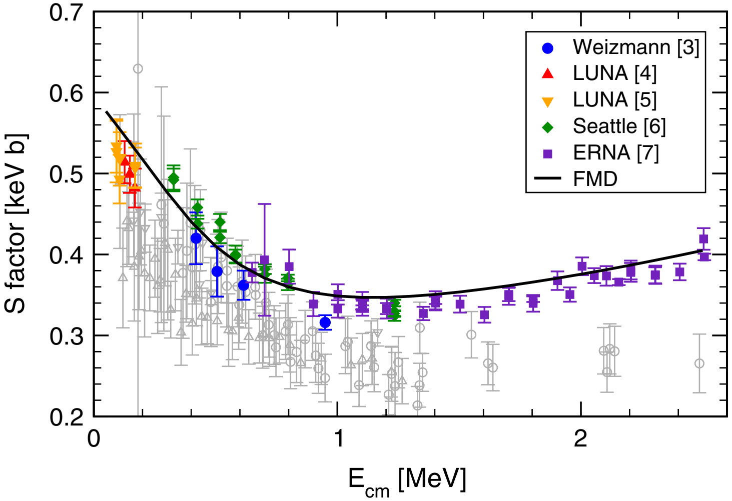


- Choices for measurement of $^3He(^4He,\gamma)^7Be$:
  - Detect gamma rays from reaction
  - Detect recoiling ^7Be in separator
  - Collect recoiling ^7Be and later count β–decays to ^7Li

Bahcall, Serenelli, & Basu, APJL 621(2005)L85
Fields, Annu. Rev. Nucl. Part. Sci., 61(2011)47

Uncertainties in S_{34}, the $^3He(^4He,\gamma)^7Be$ reaction rate

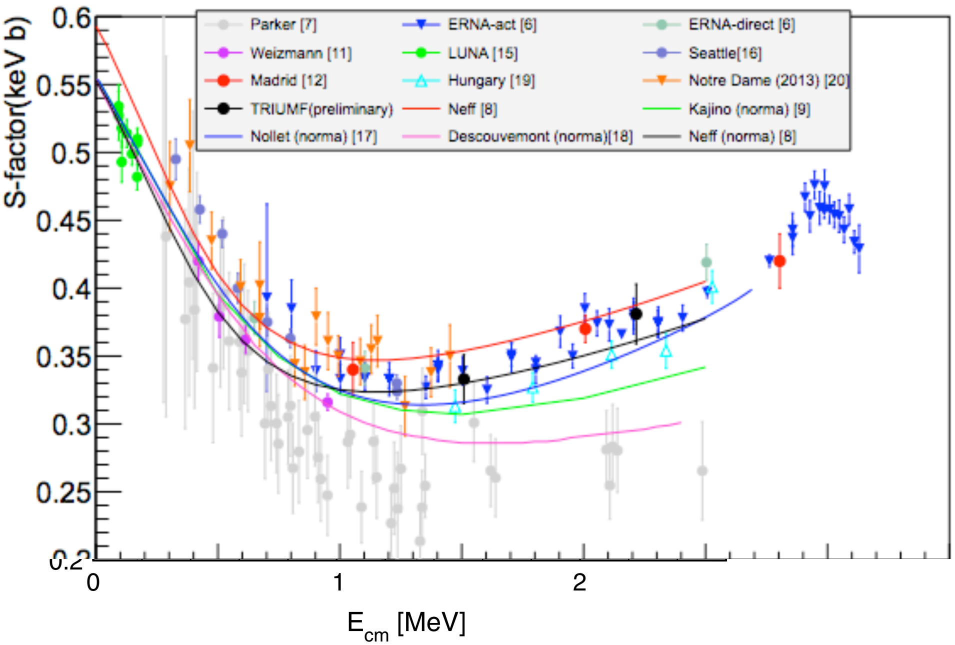
- Recent measurement by the ERNA group using a new method of recoil detection suggested different energy dependency of S_{34} above 1 MeV
- Tested independently through recoil collection [Madrid] and direct recoil detection [TRIUMF]
- S_{34} reproduced by microscopic calculations [T Neff]
- However, the same microscopic calculation should reproduce the mirror reaction $^3H(^4He,\gamma)^7Li$
- Plans for new measurement of triton-induced (mirror) reaction [Nara Singh, Fulton and the TRIUMF collaboration]



[TRIUMF] Sjue, Nara Singh, et al., NIMA 700(2013)179
[Madrid] Carmona-Gallardo, Nara Singh, et al., PRC-R, 86(2012)032801
Neff, PRL, 106(2011)042502

Uncertainties in S_{34}, the $^3He(^4He,\gamma)^7Be$ reaction rate

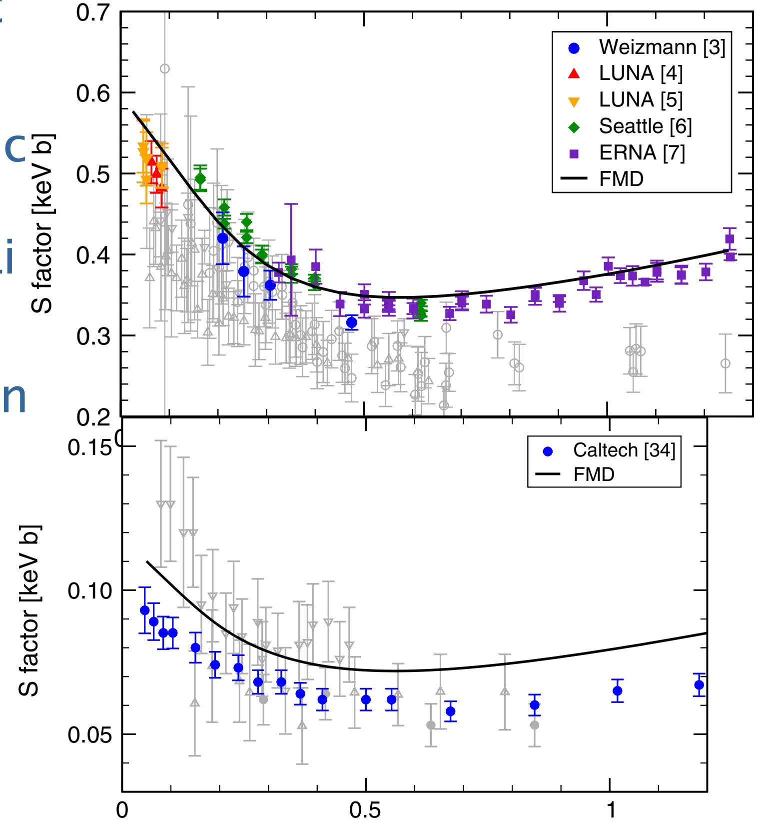
- Recent measurement by the ERNA group using a new method of recoil detection suggested different energy dependency of S_{34} above 1 MeV
- Tested independently through recoil collection [Madrid] and direct recoil detection [TRIUMF]
- S_{34} reproduced by microscopic calculations [T Neff]
- However, the same microscopic calculation should reproduce the mirror reaction $^3H(^4He,\gamma)^7Li$
- Plans for new measurement of triton-induced (mirror) reaction [Nara Singh, Fulton and the TRIUMF collaboration]



[TRIUMF] Sjue, Nara Singh, et al., NIMA 700(2013)179
[Madrid] Carmona-Gallardo, Nara Singh, et al., PRC-R, 86(2012)032801
Neff, PRL, 106(2011)042502

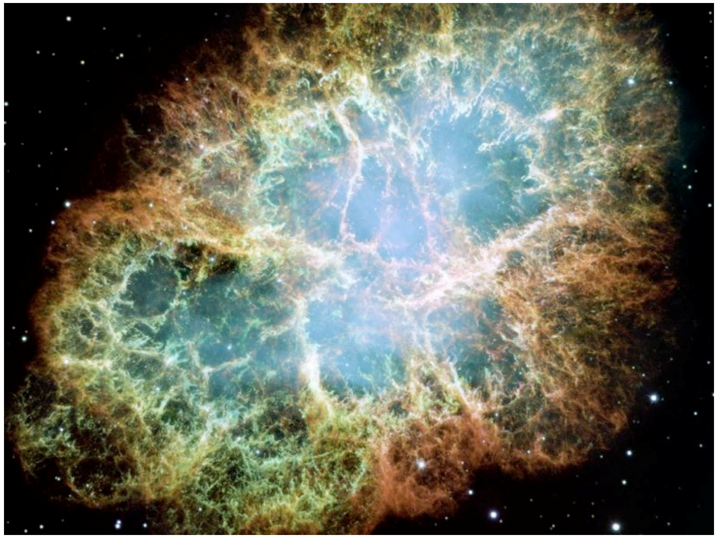
Uncertainties in S_{34}, the $^3He(^4He,\gamma)^7Be$ reaction rate

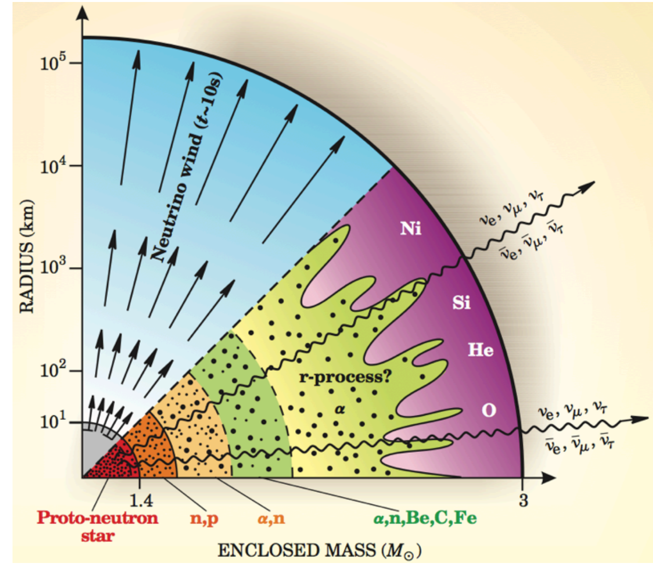
- Recent measurement by the ERNA group using a new method of recoil detection suggested different energy dependency of S_{34} above 1 MeV
- Tested independently through recoil collection [Madrid] and direct recoil detection [TRIUMF]
- S_{34} reproduced by microscopic calculations [T Neff]
- However, the same microscopic calculation should reproduce the mirror reaction $^3H(^4He,\gamma)^7Li$
- Plans for new measurement of triton-induced (mirror) reaction [Nara Singh, Fulton and the TRIUMF collaboration]



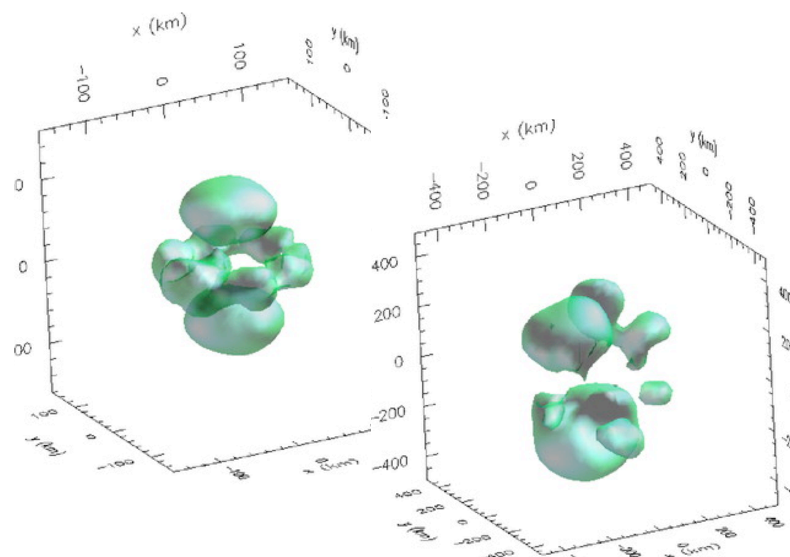
[TRIUMF] Sjue, Nara Singh, et al., NIMA 700(2013)179
[Madrid] Carmona-Gallardo, Nara Singh, et al., PRC-R, 86(2012)032801
Neff, PRL, 106(2011)042502

Theoretical evauations for CC-SN nuclear reactions





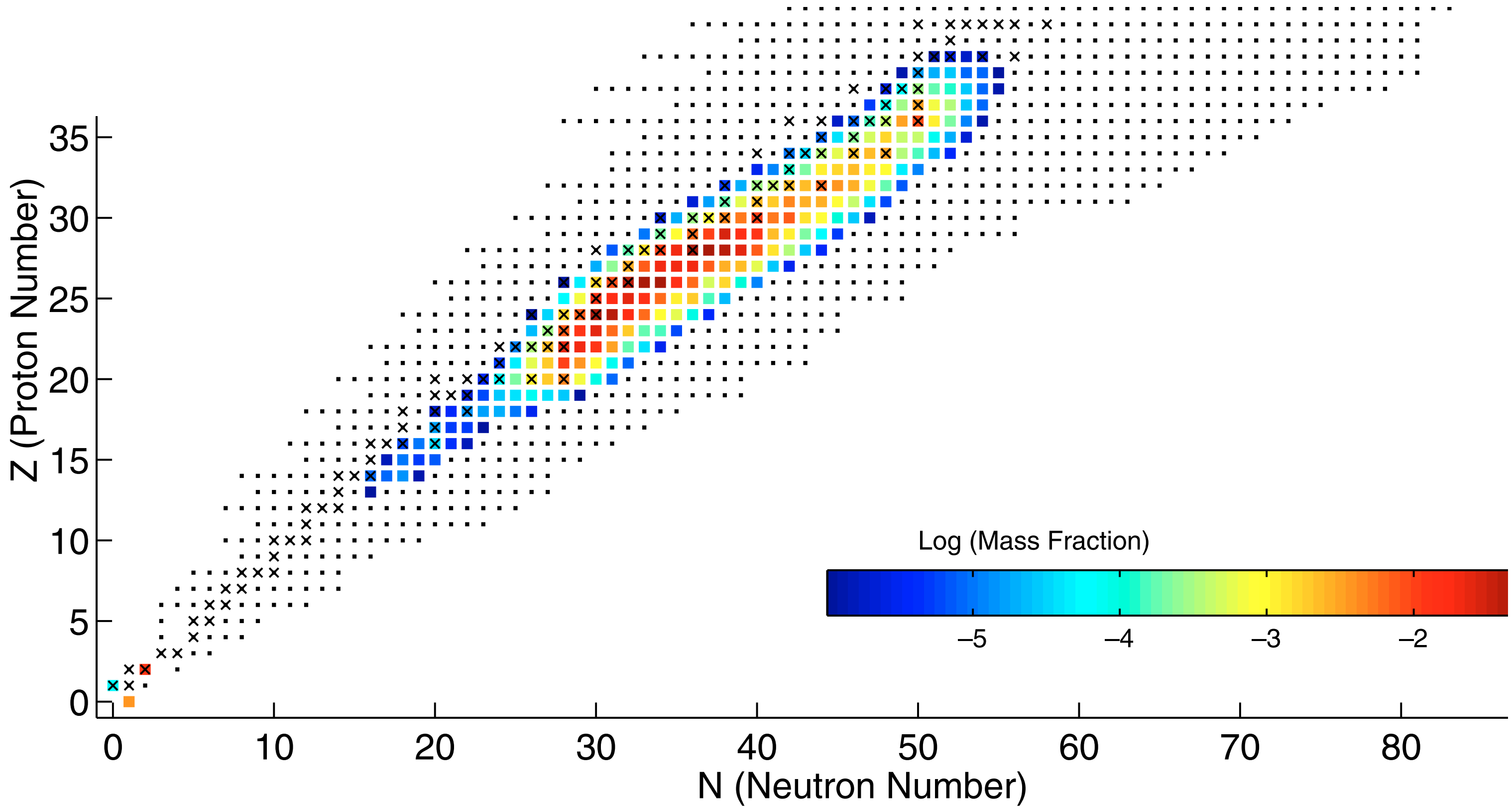
- Core-Collapse SN: gravity-driven massive-star core collapse
- Rebounding shock wave driving an (often) asymmetric explosion
- Radiation emitted – material ejected
- Crab Nebula: Remnant of a Type-II (core-collapse) supernova (1054 AD)



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

Weak interactions and groß properties for supernovae

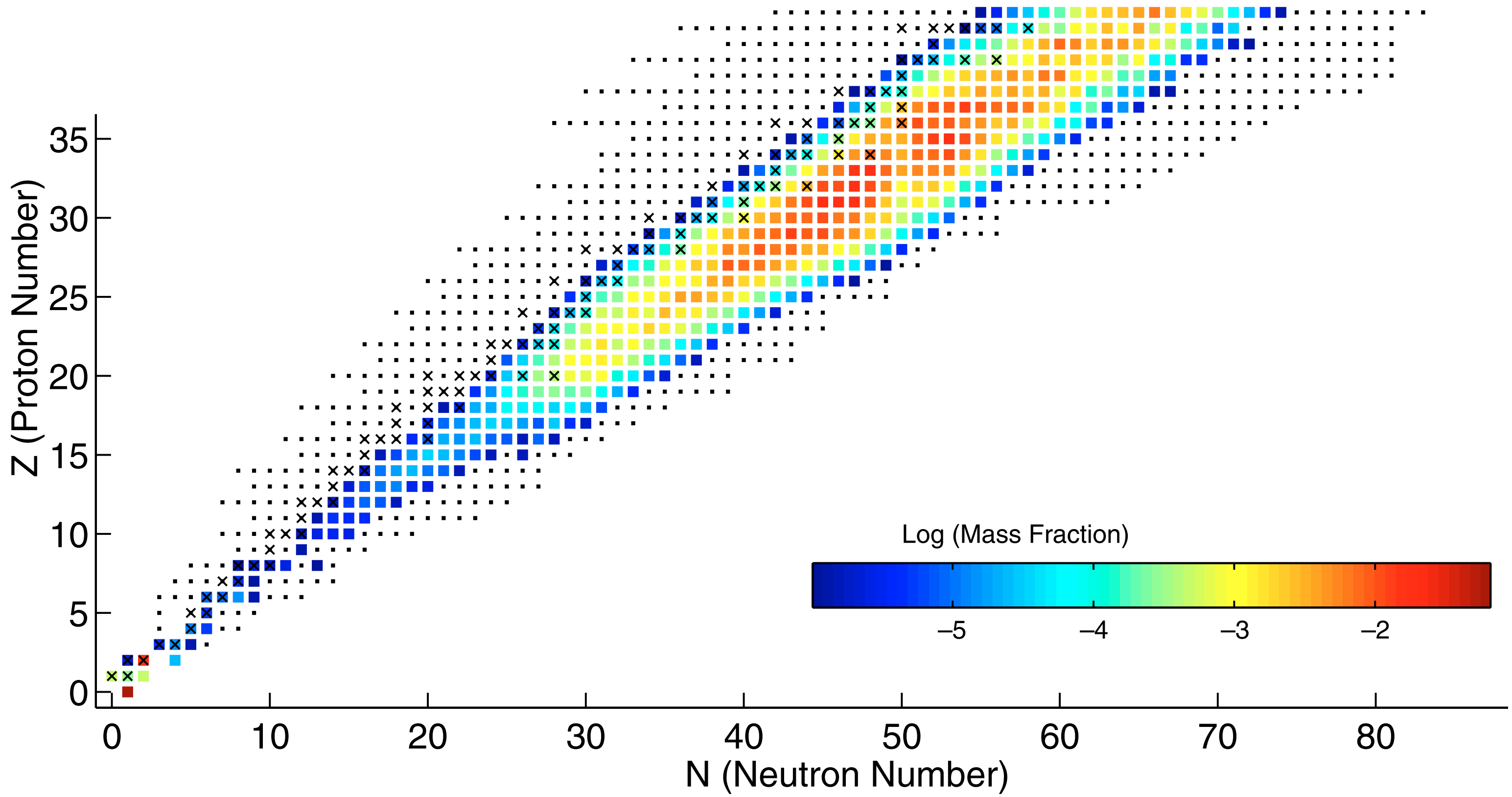
- Weak interactions in supernovae:
  - gravitational collapse boosted by electron-capture on protons and iron-group nuclei: $p(e^-,\nu_e)n$
- Groß properties (masses and lifetimes) for exotic nuclei
  - Next-generation radioactive ion beam facilities: r-process nuclei up to around mass 130



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

Weak interactions and groß properties for supernovae

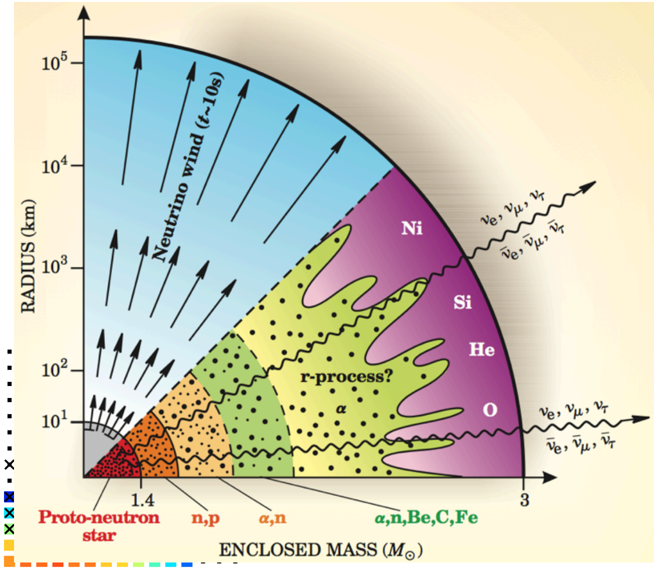
- Weak interactions in supernovae:
  - gravitational collapse boosted by electron-capture on protons and iron-group nuclei: $p(e^-,\nu_e)n$
- Groß properties (masses and lifetimes) for exotic nuclei
  - Next-generation radioactive ion beam facilities: r-process nuclei up to around mass 130

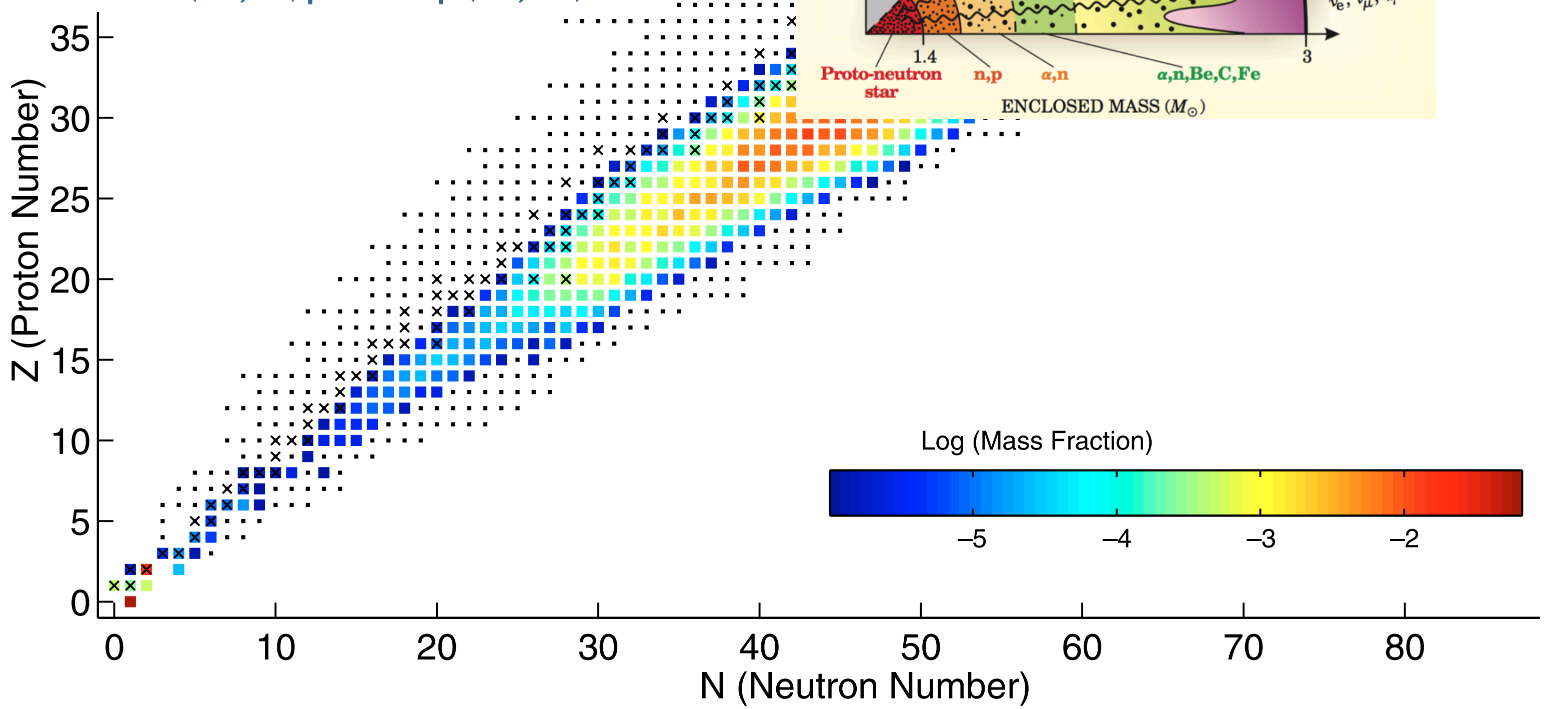


Cowan & Thielemann, Phys. Today, 10 (2004) 47
Martínez-Pinedo, Eur. Phys. J. Spec. Top. 156 (2008) 123
Fröhlich et al., PRL 96 (2006) 142502

Weak interactions and groß properties for supernovae

- Weak interactions in supernovae:
  - 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 $p(\bar{\nu}_e,e^+)n$

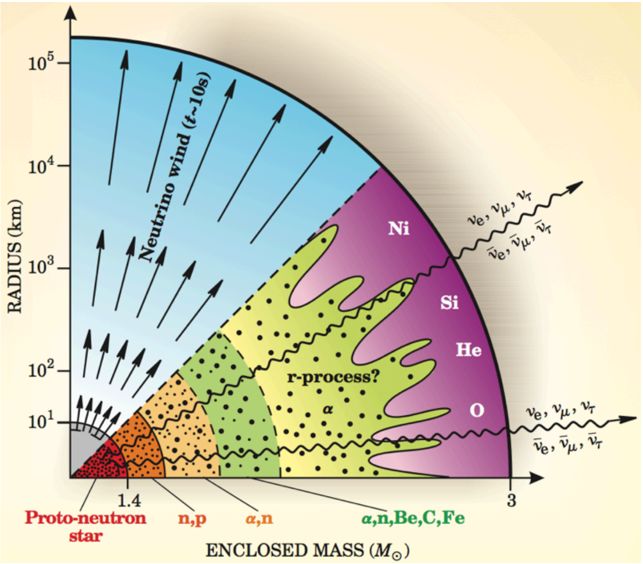


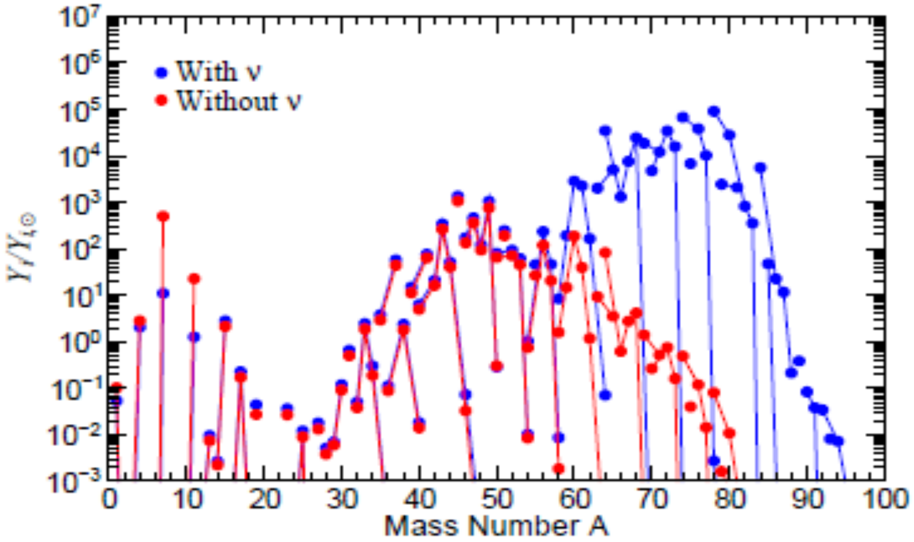


Cowan & Thielemann, Phys. Today, 10 (2004) 47
Martínez-Pinedo, Eur. Phys. J. Spec. Top. 156 (2008) 123
Fröhlich et al., PRL 96 (2006) 142502

Weak interactions and groß properties for supernovae

- Weak interactions in supernovae:
  - 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 $p(\overline{\nu}_e,e^+)n$
  - proton and alpha-rich freeze-out produces neutron-deficient nuclei in the inner ejecta but terminates around ^{64}Ge ($T_{1/2}$ = 64s)

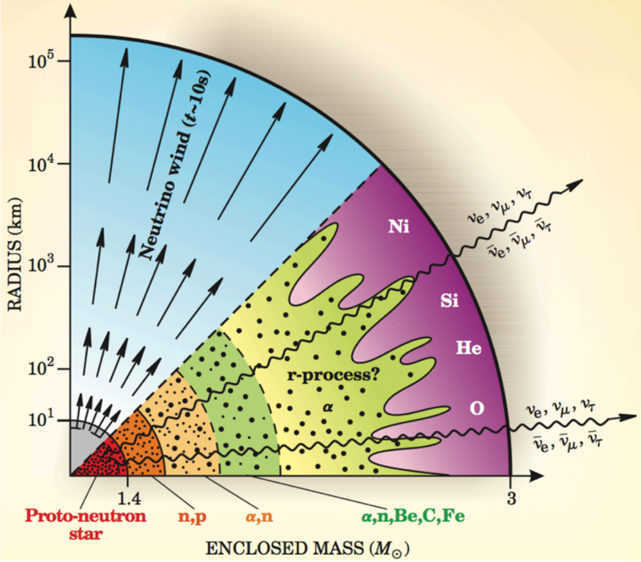


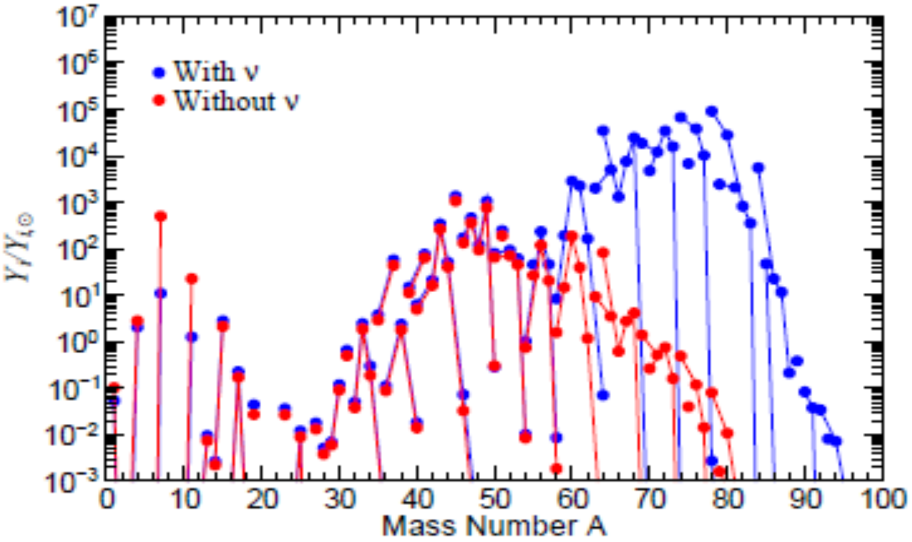


Cowan & Thielemann, Phys. Today, 10 (2004) 47
Martínez-Pinedo, Eur. Phys. J. Spec. Top. 156 (2008) 123
Fröhlich et al., PRL 96 (2006) 142502

Weak interactions and groß properties for supernovae

- Weak interactions in supernovae:
  - 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 $p(\overline{\nu}_e,e^+)n$
  - proton and alpha-rich freeze-out produces neutron-deficient nuclei in the inner ejecta but terminates around ^{64}Ge ($T_{1/2}$ = 64s)
  - νp-process: in the strong neutrino-wind these neutron-deficient nuclei capture neutrinos on the time-scale of seconds

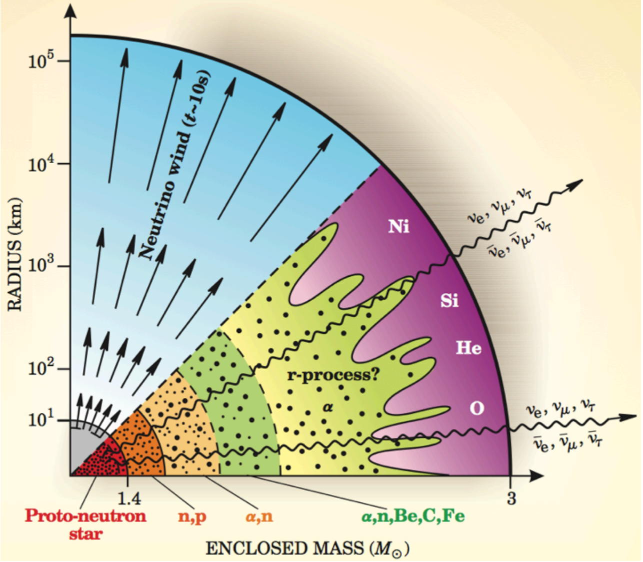


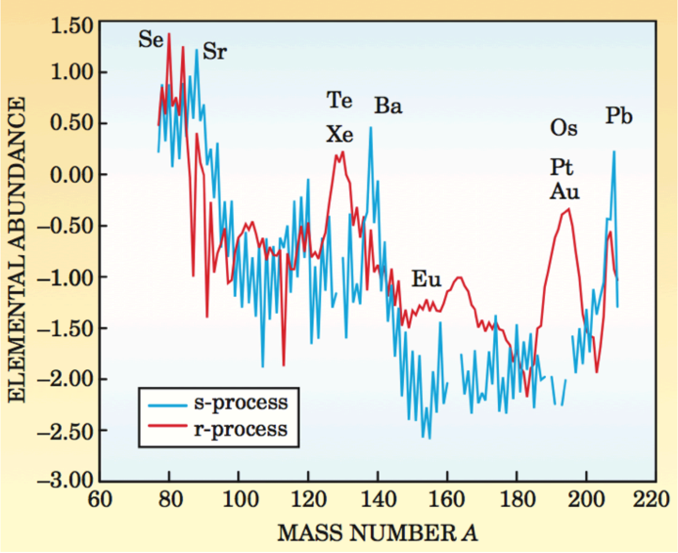


Cowan & Thielemann, Phys. Today, 10 (2004) 47
Martínez-Pinedo, Eur. Phys. J. Spec. Top. 156 (2008) 123
Fröhlich et al., PRL 96 (2006) 142502

Weak interactions and groß properties for supernovae

- Weak interactions in supernovae:
  - 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 $p(\overline{\nu}_e,e^+)n$
  - proton and alpha-rich freeze-out produces neutron-deficient nuclei in the inner ejecta but terminates around ^{64}Ge ($T_{1/2} = 64$s)
  - νp-process: in the strong neutrino-wind these neutron-deficient nuclei capture neutrinos on the time-scale of seconds
  - Prime-candidate site for rapid neutron-capture (r-process) nucleosynthesis (outer ejecta).





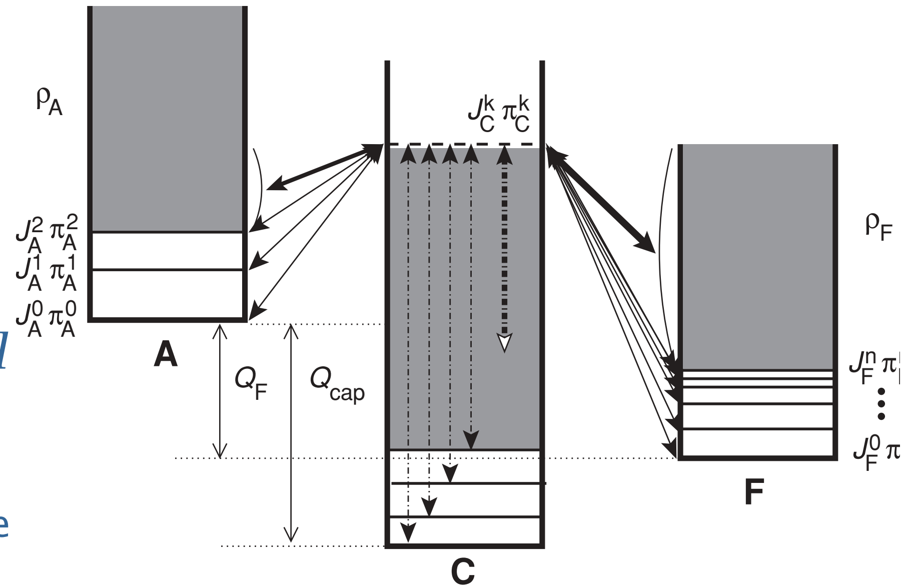
Cowan & Thielemann, Phys. Today, 10 (2004) 47
Martínez-Pinedo, Eur. Phys. J. Spec. Top. 156 (2008) 123
Fröhlich et al., PRL 96 (2006) 142502

Stellar Enhancement Factors

- Stellar Enhancement Factor (SEF) defined as:

$$f = \frac{r^*}{r^{\text{g.s.}}} = \frac{r^*}{r^{\text{lab}}}$$

- *Assuming a similar level structure in all involved nuclei, it is expected that the SEF of a given reaction will be smaller for the exothermic direction f_{forw} than for the endothermic f_{rev}.* [Forward direction here defined as positive Q value, Rauscher 2009]
- However: Coulomb suppression of the SEF found for charged-particle reactions with Q < 0 but low |Q|
- 1200 reactions: including (α,γ) for the p process and (p,γ) for the rp process; as well as (p,n) reactions

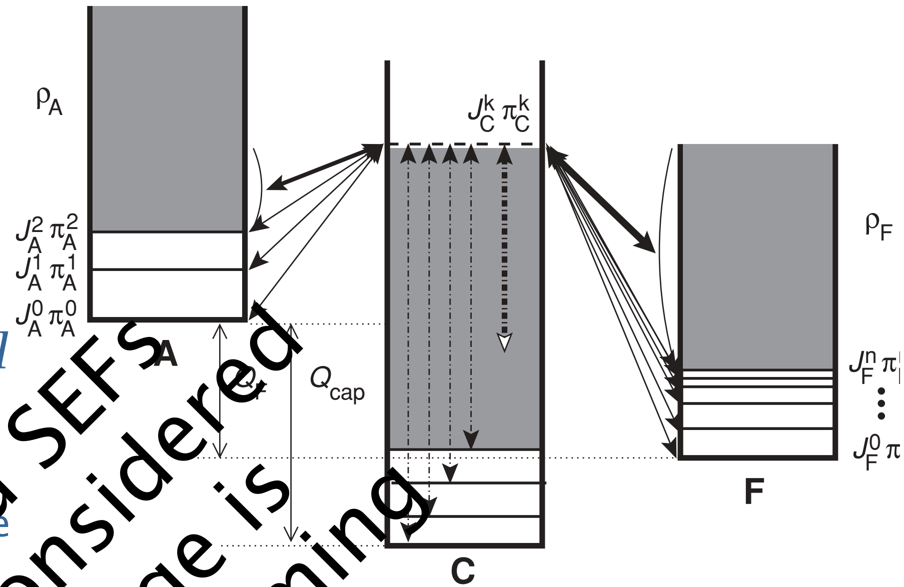


- Strong suppression for charged particles due to Coulomb barrier:
  - A(n,p)F or A(p,α)F reactions with Q>0
  - Suppress transitions to/from final state nucleus (higher Coulomb barrier)
  - SEF suppressed the most for the reverse reaction (Q<0) with a larger SEF in the forward direction (Q>0).

Kiss, et al., PRL, 101(2008)191101
Rauscher et al., PRC 80(2009)035801
Rauscher, PRC, 88(2013)035803

Stellar Enhancement Factors

- Stellar Enhancement Factor (SEF) defined as: $$f = \frac{r^*}{r^{\mathrm{g.s.}}} = \frac{r^*}{r^{\mathrm{lab}}}$$
- *Assuming a similar level structure in all involved nuclei, it is expected that the SEF of a given reaction will be smaller for the exothermic direction f_{forw} than for the endothermic f_{rev}.* [Forward direction here defined as positive Q value, Rauscher 2009]



- However: Coulomb suppression of the SEF found for charged-particle reactions with Q < 0 but low |Q|
- 1200 reactions: including (α,γ) for the p process and (p,γ) for the rp process; as well as (p,n) reactions

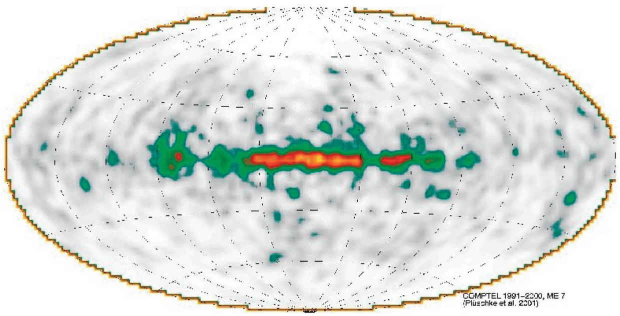
- Strong suppression for charged particles due to Coulomb barrier:
  - A(n,p)F or A(p,α)F reactions with Q>0
  - Suppress transitions to/from final state nucleus (higher Coulomb barrier)
  - SEF suppressed the most for the reverse reaction (Q<0) with a larger SEF in the forward direction (Q>0).

Non-standard SEFs should be considered when the charge is different in incoming and outgoing channels

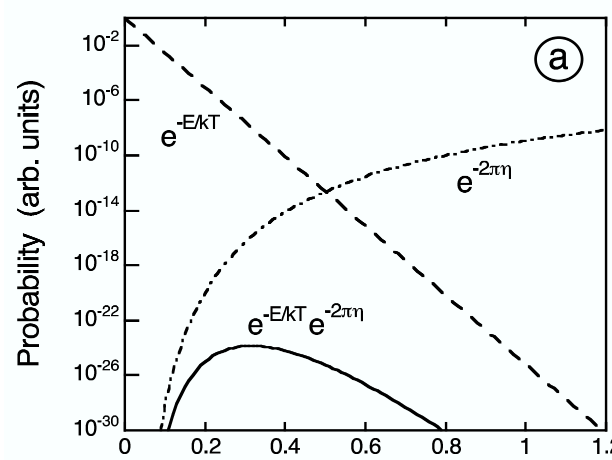
Kiss, et al., PRL, 101(2008)191101
Rauscher et al., PRC 80(2009)035801
Rauscher, PRC, 88(2013)035803

Rates at high level density: ^{26}Al destruction

- COMPTEL/INTEGRAL: ^{26}Al decay spectroscopy survey, ESA



- Next-generation satellite missions: observation of ^{26}Al from individual stellar explosions
- ^{26}Al creation via proton capture: ^{25}Mg(p,γ)^{26}Al
- ^{26}Al destruction via β-decay and neutron induced reactions: ^{26}Al(n,p)^{26}Mg, ^{26}Al(n,α)^{26}Mg



- Resonant reaction rate: velocity-weighted cross section:

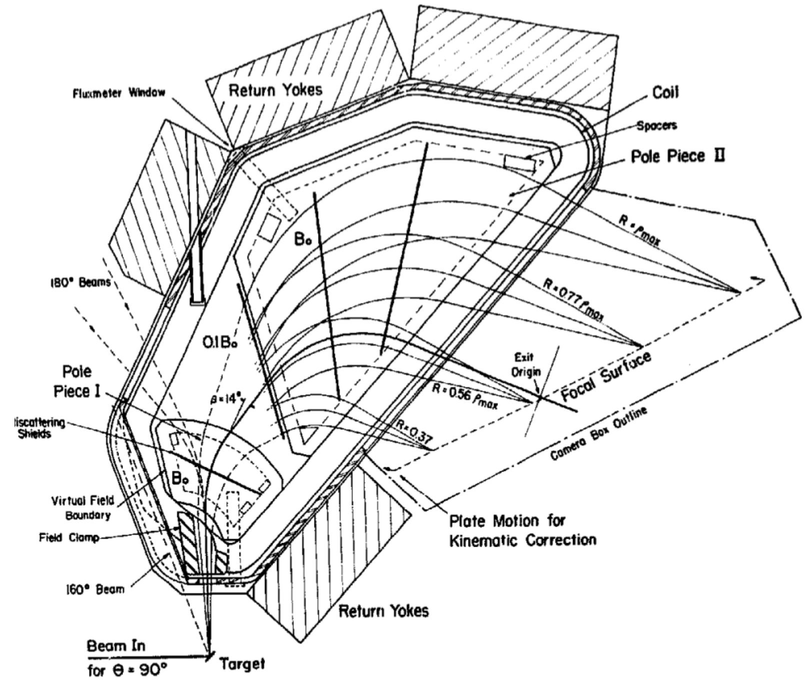
$$(2J+1)\frac{\Gamma_\alpha \Gamma_p}{\Gamma_{tot}} \exp\left(-\frac{E_r}{k_B T}\right)$$

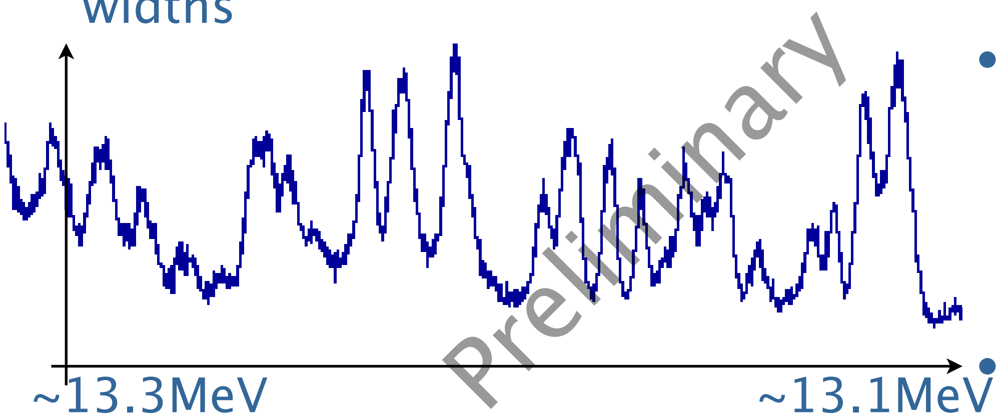
- Gamow-window: 0.7–2.0 MeV resonance energy for alpha-induced reactions at temperatures of 0.5–1.5 GK
- Significant corrections for neutron induced reactions but still dependent on spin-parity and partial widths

Iliadis, Nuclear Physics of Stars (2007)
Iliadis et al., APJSS 193:23 (2011)
Rauscher, Phys. Rev. C, 81:045807 (2010)

Indirect measurement of ^{26}Al destruction

- ^{26}Al destruction via β-decay and neutron induced reactions: ^{26}Al(n,p)^{26}Mg, ^{26}Al(n,α)^{26}Mg
- Observables for ^{26}Al destruction:
- States in the region immediately above the 13.06MeV n-threshold
- High level density (~ one per 10keV observed, more predicted)
- Spin-parities
- Proton- alpha- and neutron widths

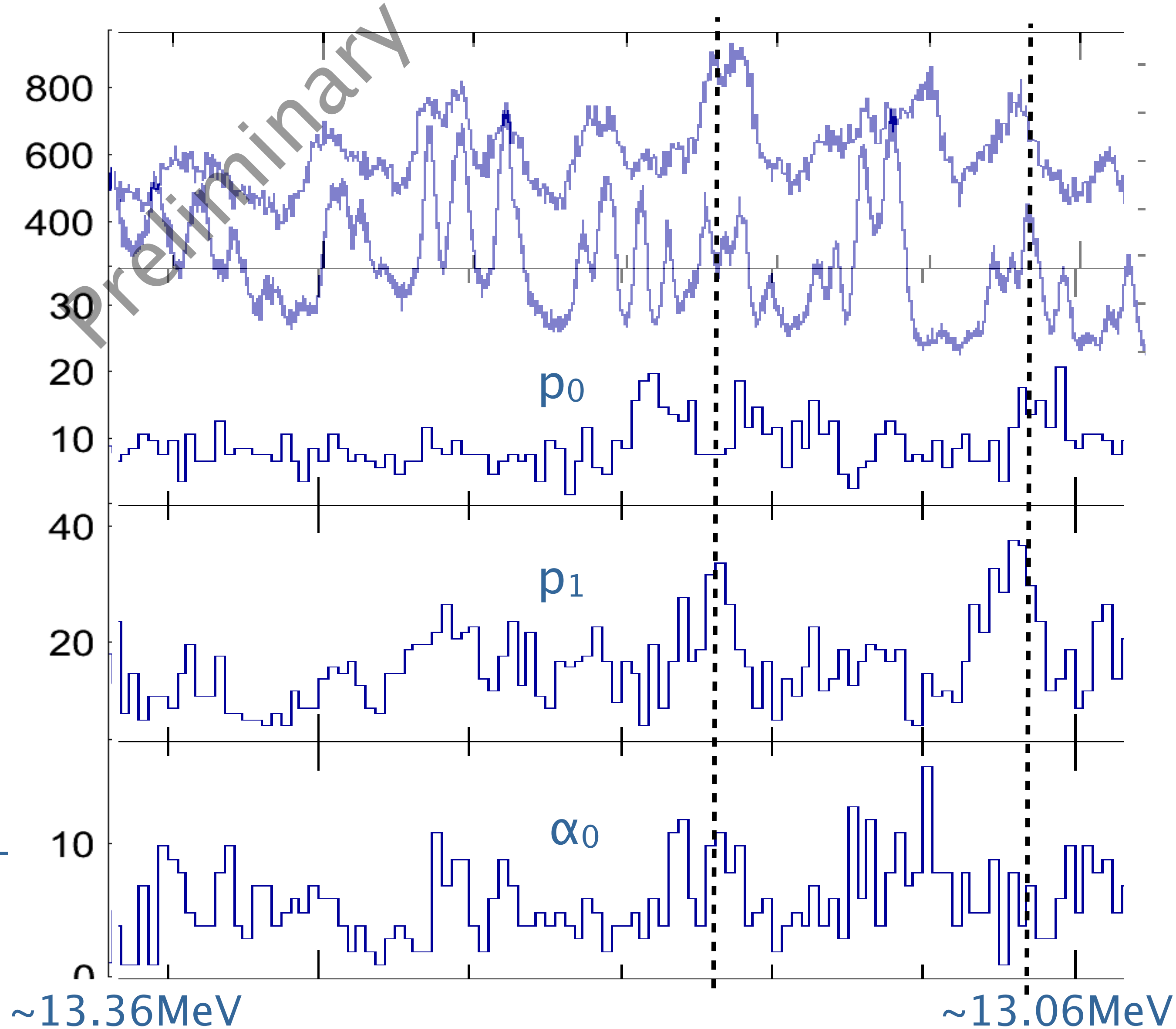




- Measurements of the states in question using the Orsay Enge spectrometer and the Munich Q3D (spin parities from angular distributions).
- Coincident silicon array for proton and alpha branching ratios

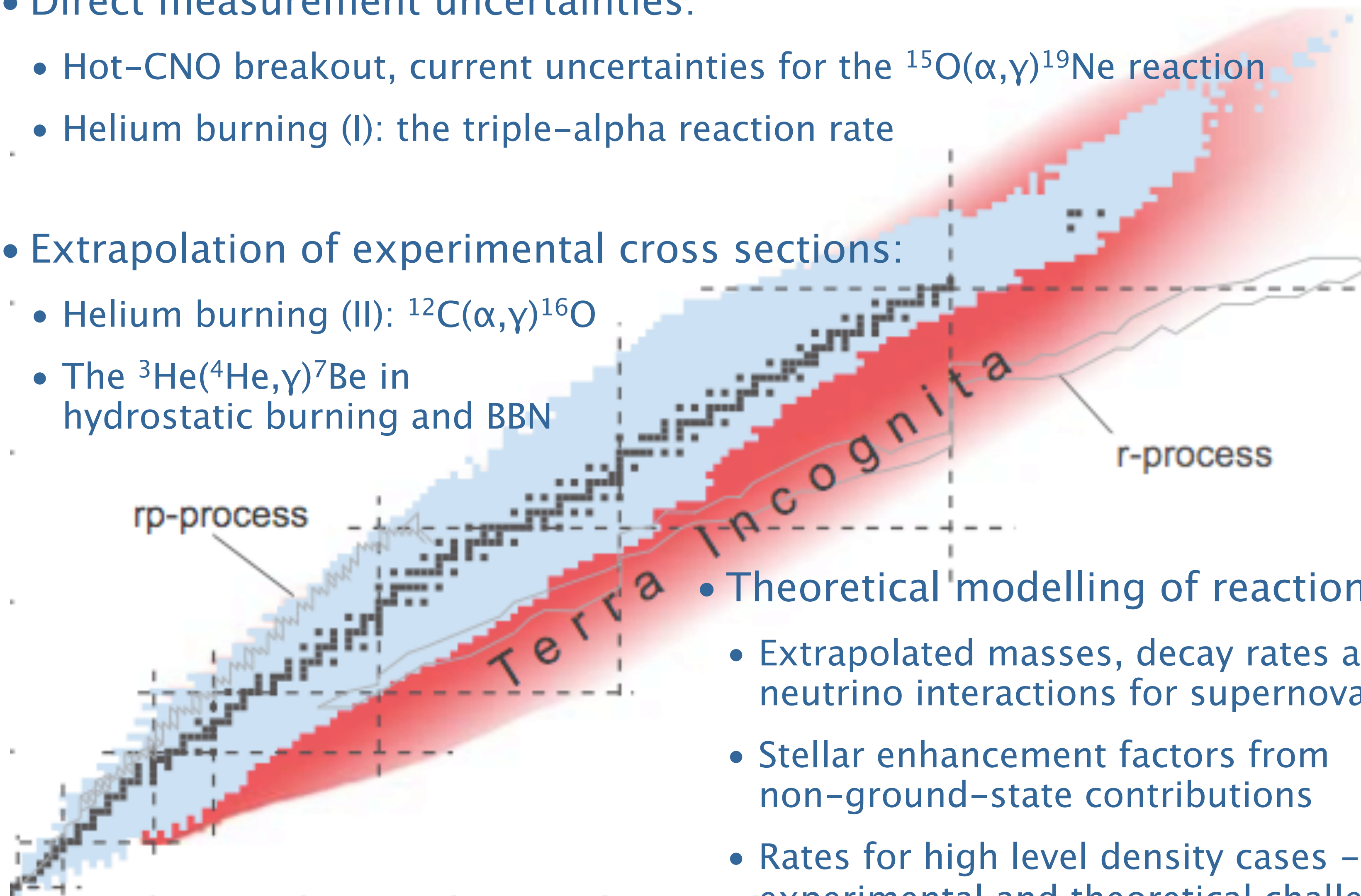
Indirect measurement of ^{26}Al destruction

- Branching ratios from secondary channel coincidences:
- $\Gamma_\alpha/\Gamma_{tot}$ and $\Gamma_\alpha/\Gamma_{tot}$
- Separation of decays to individual (excited) states, e.g. ^{26}Mg first excited:
- ^{27}Al(,p_0)^{26}Mg(gs)
- ^{27}Al(,p_1)^{26}Mg(1st)
- ^{27}Al(,α_0)^{23}Na(gs)
- Compare to high-resolution spectroscopy



Key Nuclear Uncertainties for Origins and Impact

- Direct measurement uncertainties:
  - Hot-CNO breakout, current uncertainties for the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction
  - Helium burning (I): the triple-alpha reaction rate
- Extrapolation of experimental cross sections:
  - Helium burning (II): $^{12}C(\alpha,\gamma)^{16}O$
  - The $^{3}He(^{4}He,\gamma)^{7}Be$ in hydrostatic burning and BBN



- Theoretical modelling of reaction rates
  - Extrapolated masses, decay rates and neutrino interactions for supernovae
  - Stellar enhancement factors from non-ground-state contributions
  - Rates for high level density cases – experimental and theoretical challenges

Gelbke et al., MSUCL-1345 (2006)
Langanke & Martínez-Pinedo, RMP 75:819 (2003)