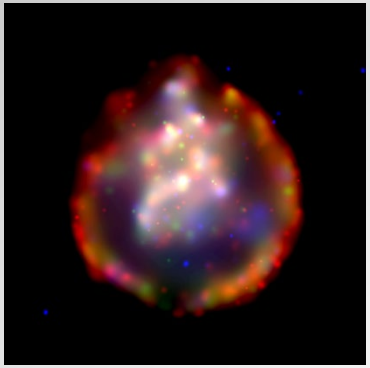
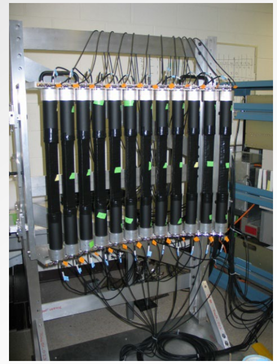




Constraining Weak Interaction Rates in Nuclear Astrophysics

(with a focus on core-collapse supernovae and electron captures)

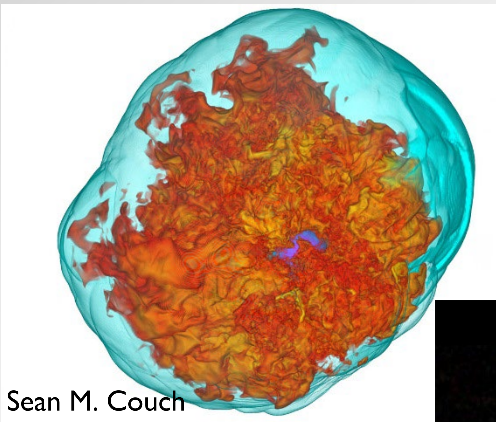
Remco G.T. Zegers

FRIB/Physics & Astronomy – Michigan State University

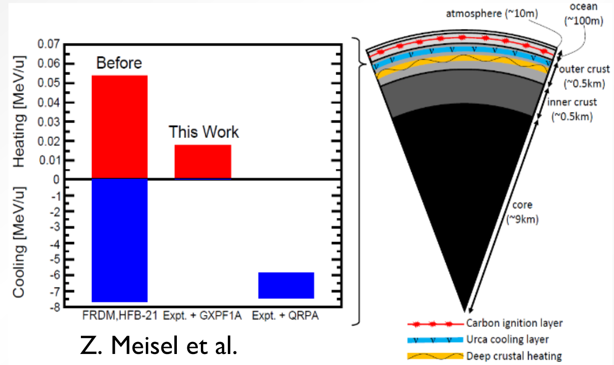
Recent review on Electron Captures in Stars:
K. Langanke, G. Martinez-Pínedo, R.G.T Zegers
Reports on Progress in Physics 84, 066301 (2021)

FRIB IReNA MICHIGAN STATE UNIVERSITY NSF U.S. DEPARTMENT OF ENERGY Office of Science

Transitions mediated by the weak force play important roles in astrophysical phenomena

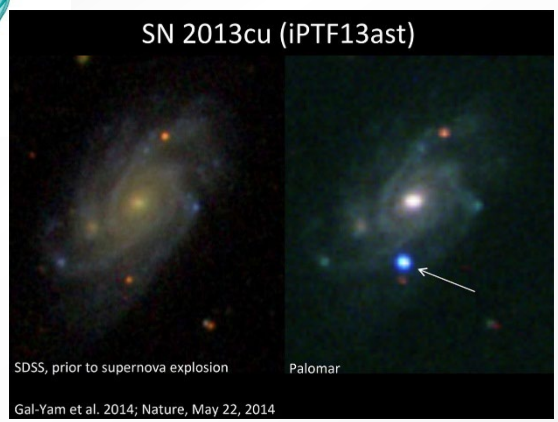


Core-collapse supernovae

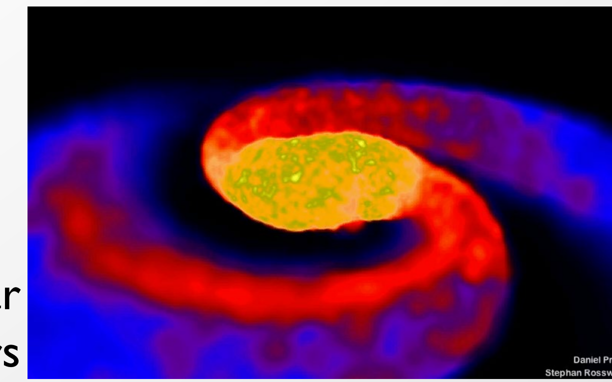


Cooling & heating in accreting neutron star crusts

Thermonuclear supernovae



Neutron-star mergers

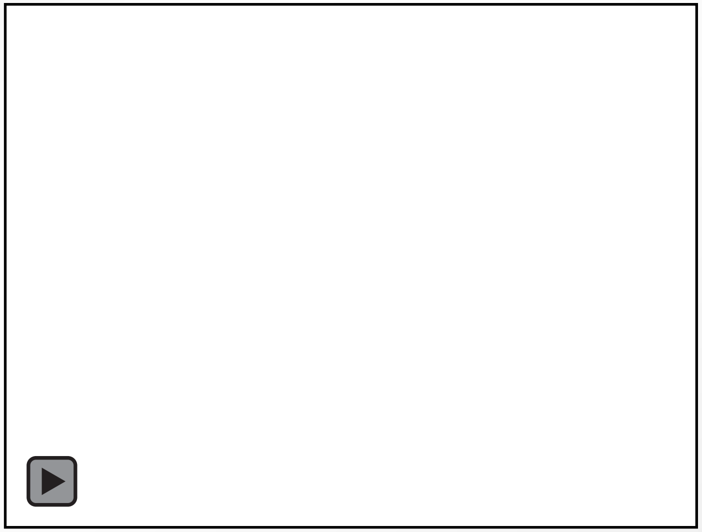


Electron capture, β-decay, and neutrino induced reaction rates serve as inputs in simulations and largely rely on theoretical calculations in which density and temperature dependencies are taken into consideration. The theoretical models must be developed, constrained, and benchmarked.

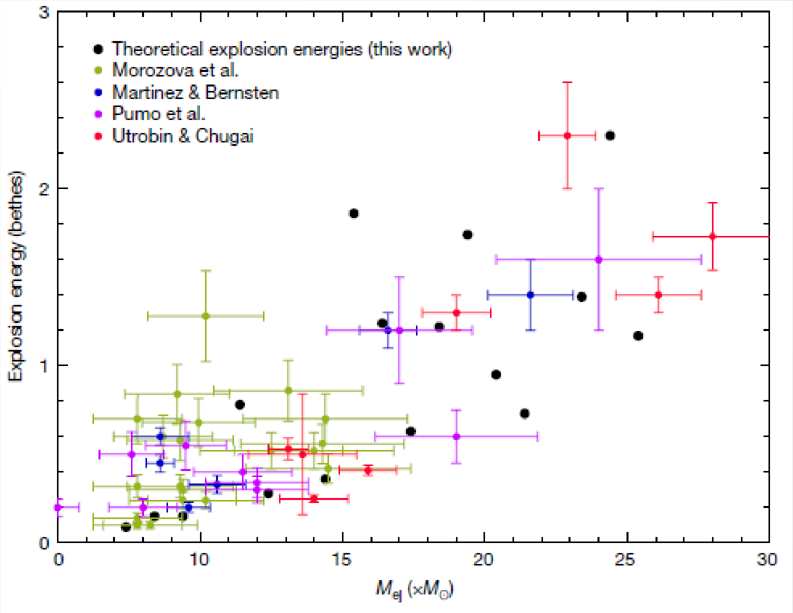
D. J. Price, S. Rosswog Scie

Core-collapse supernovae…

- Massive stars (> 8 M_{solar}) that explode and inject synthesized elements into the universe, leaving behind black holes and neutron stars
- Release ~10^{51} ergs (10^{44} joules or 1 Bethe) of energy, or more than ~10^{27} times the recent volcano in Tsonga



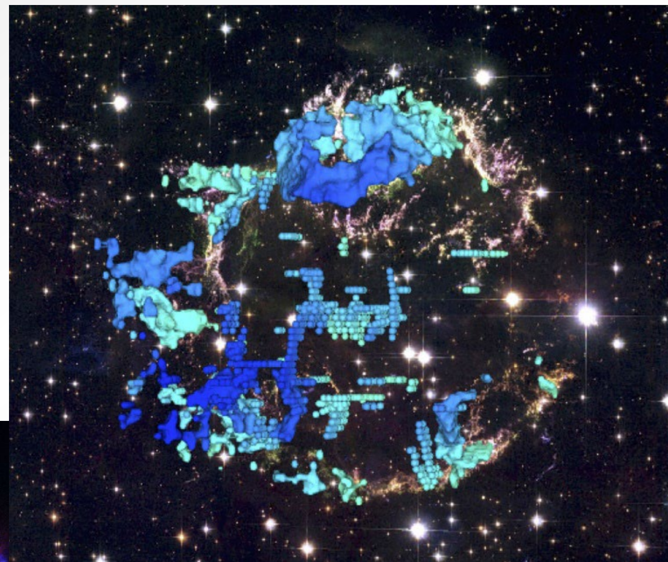
KMA / Simon Proud / NCEO



A. Burrows & D. Vartanyan Nature 589, 29 (2021)

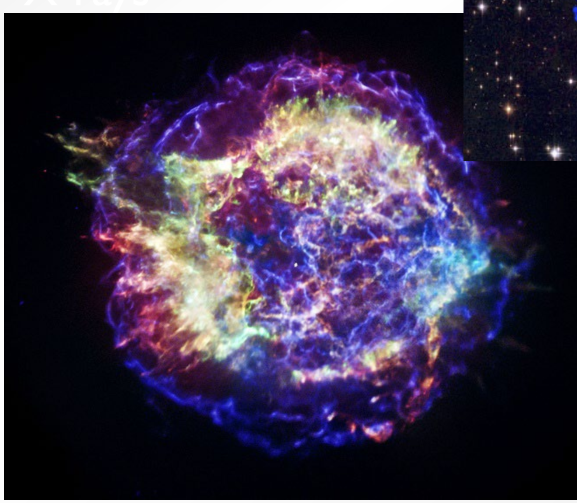
Cas(siopeia) A

- 11000 light years away in the Milky Way, exploded mid 1600's
- Expansion is ~4000-14000 km/s
- All elements necessary for life (H, C, N, O, P, S) identified in remnants

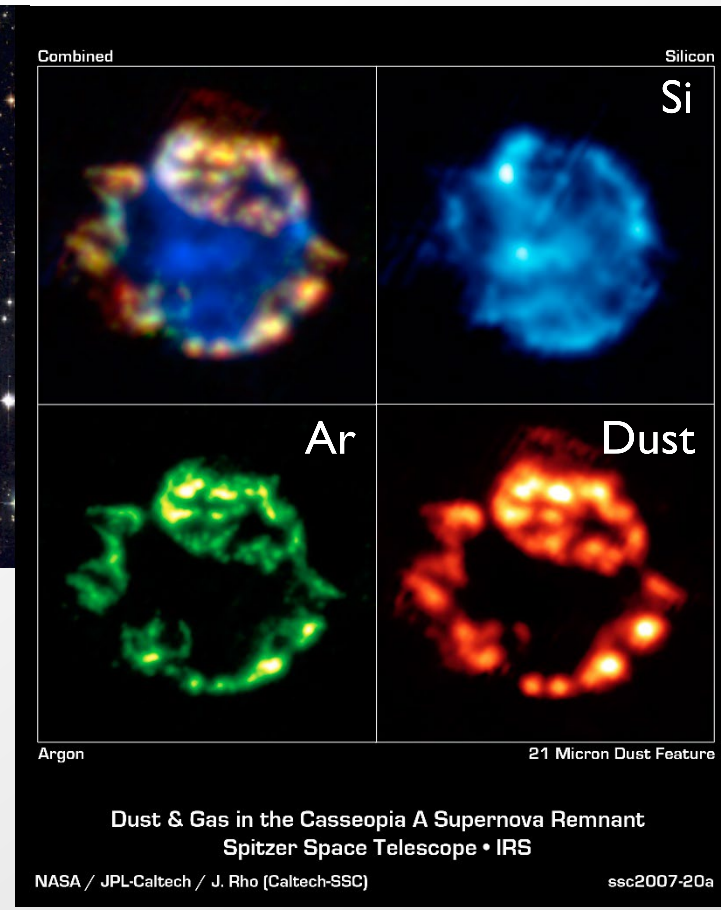


Velocity map
Dan Milisavljevic & Robert A. Fesen
Sience 347, 526 (2015)

X-rays



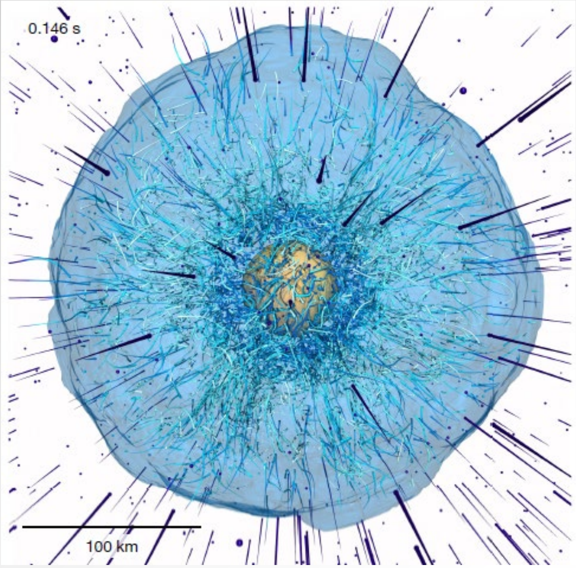
NASA's Chandra X-ray Observatory



By NASA/JPL-Caltech/J. Rho (Caltech-SSC) - http://www.spitzer.caltech.edu/images/1715-ssc2007-20a-Dusty-Celestial-Ornaments, Public Domain, https://commons.wikimedia.org/w/index.php?curid=15511949

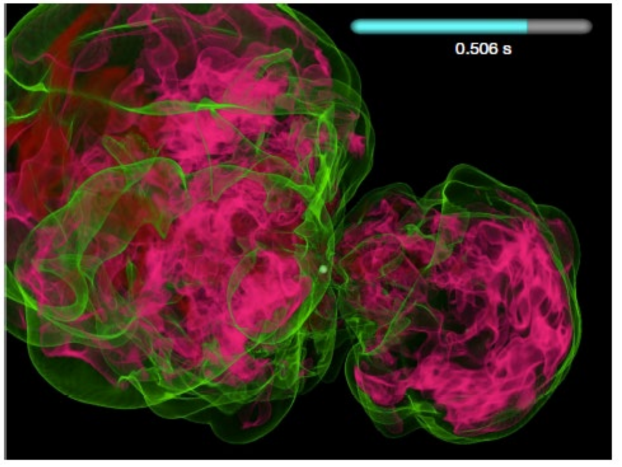
Core-collapse supernovae: a multi-physics problem

Hydrodynamics – Convection, Turbulence



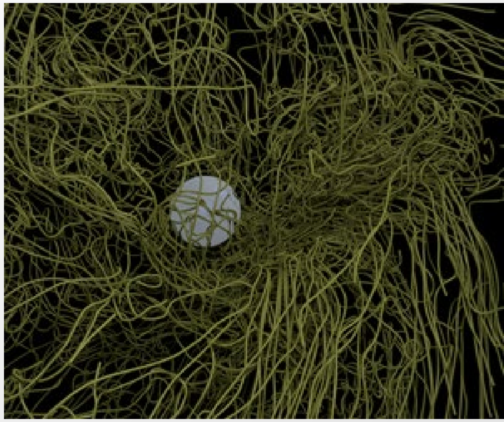
A. Burrows & D. Vartanyan Nature 589, 29 (2021)

Multi-Dimensional Effects - Asymmetries

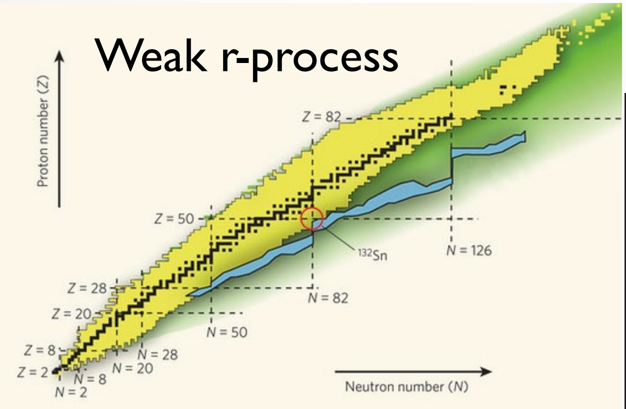


Neutrino physics (transport/ oscillations / interactions)

Magnetic fields

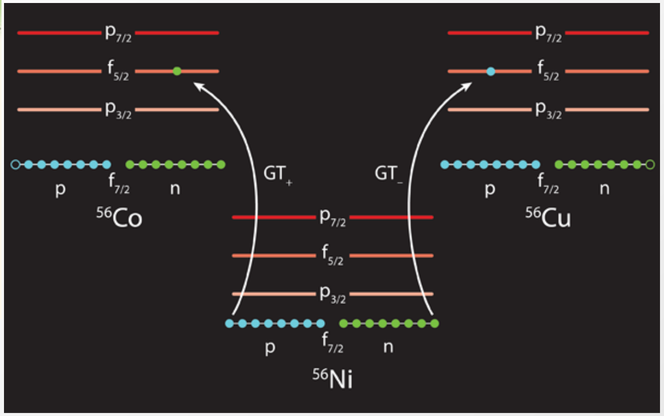


Pugmire et al., ORNL



P. Cottle Nature 465, 430–431 (2010)

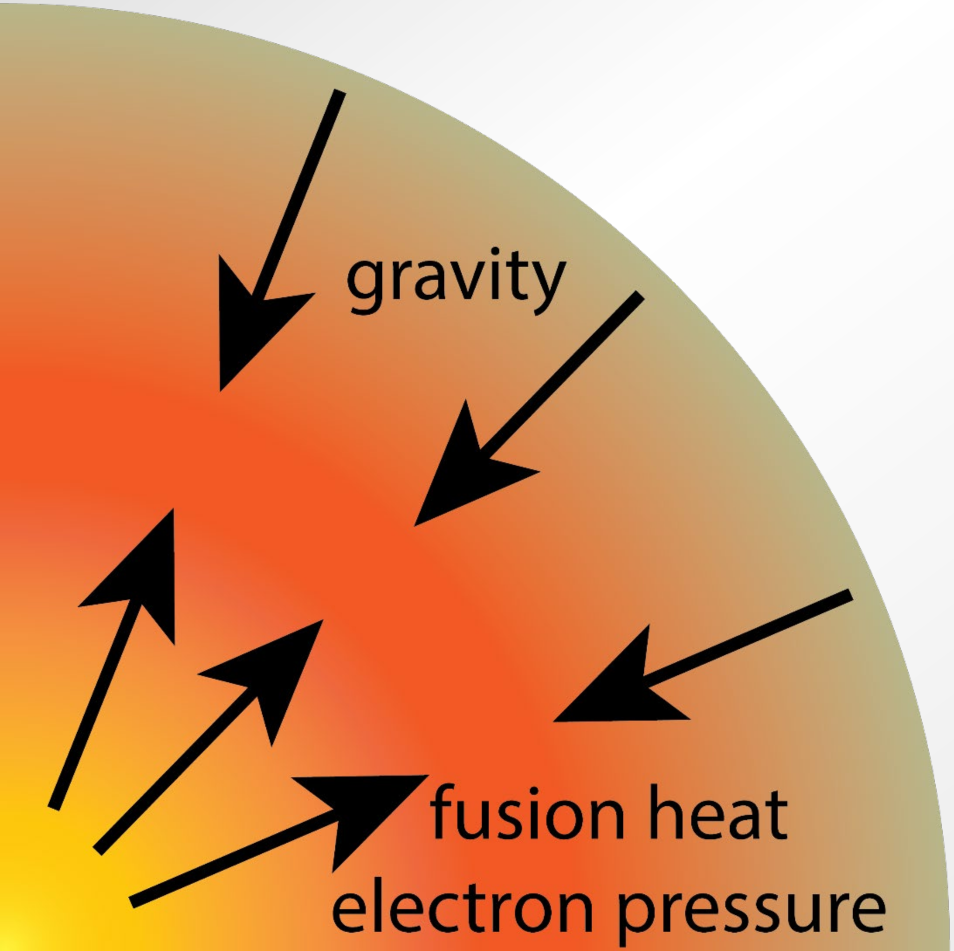
Electron captures and Neutrino production

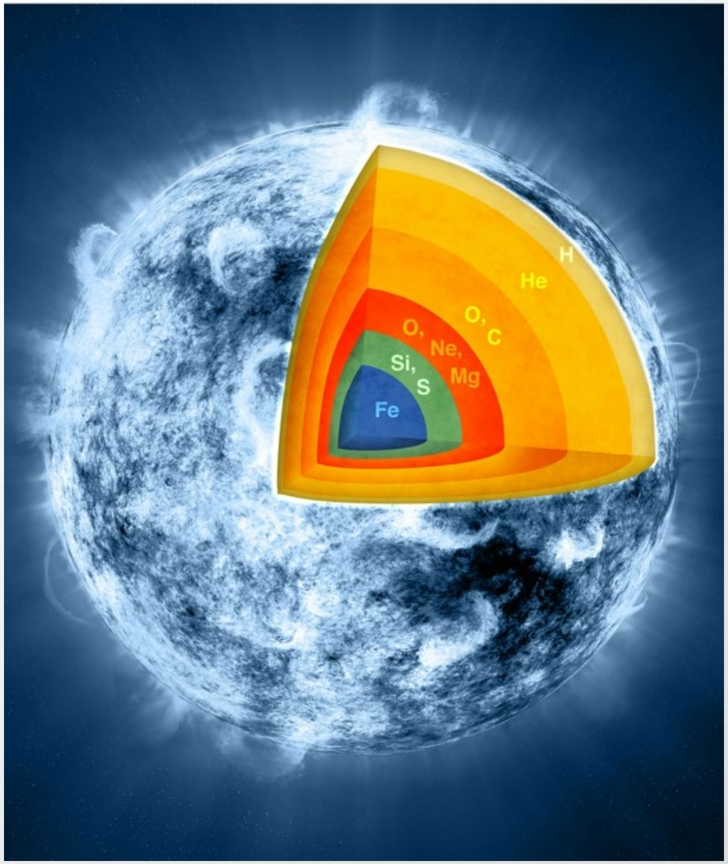


K. Langanke, Physics 4, 91 (2011)
Langanke, Martinez-Pinedo, RZ, RoPP 84, 066301

Core Collapse Supernova – A Cartoon

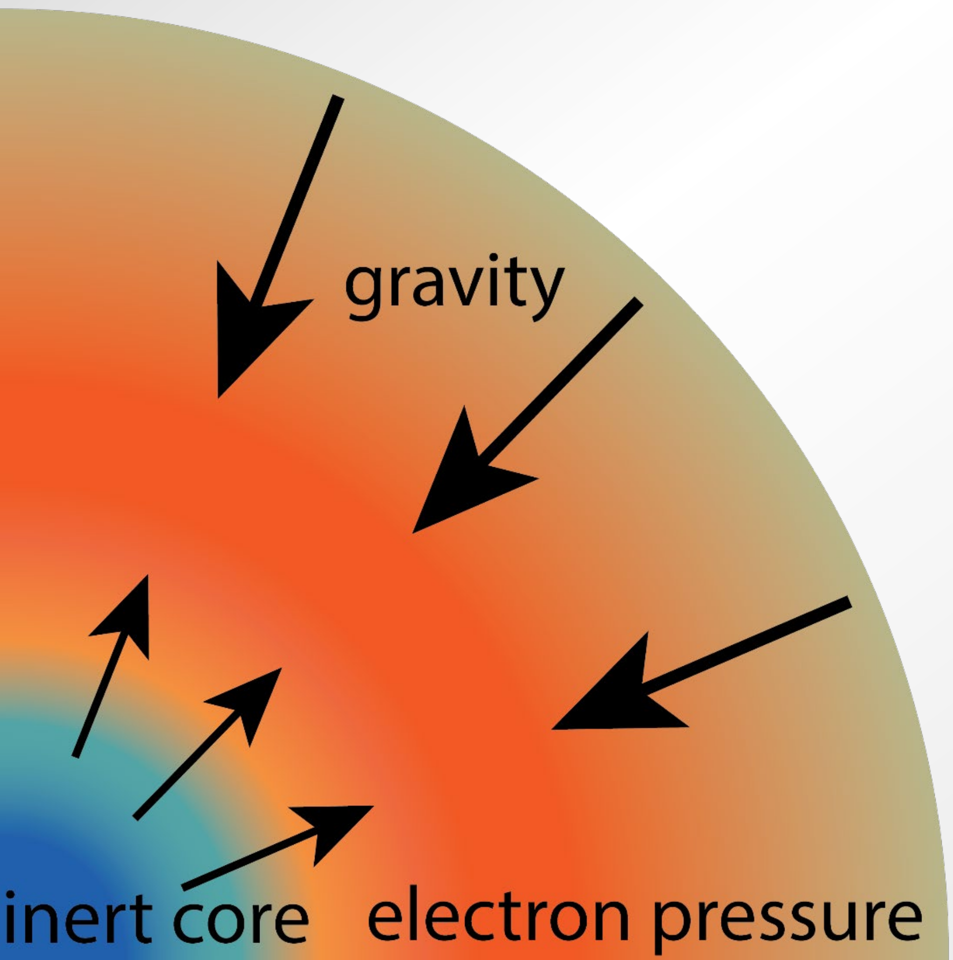
- Fusion in massive stars creates onion-like rings of elements ranging from Hydrogen (outer) to nuclei in the iron region (core)
- The gravitational force is countered by the degeneracy pressure of electrons and the energy generated by the fusion reactions

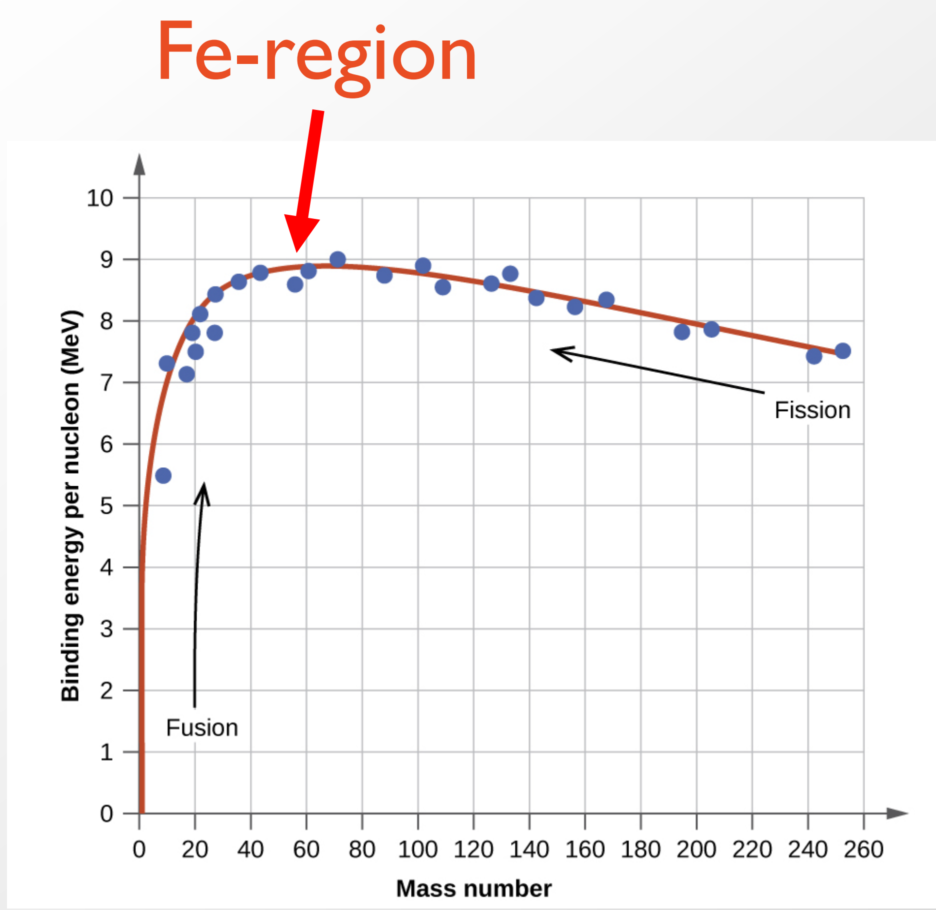




Core Collapse Supernova – A Cartoon

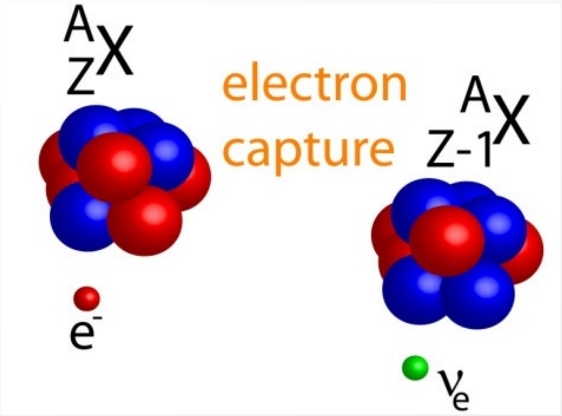
- Fusion ends when nuclei in the iron region are produced
- Reduction in fusion heat produced reduces the pressure

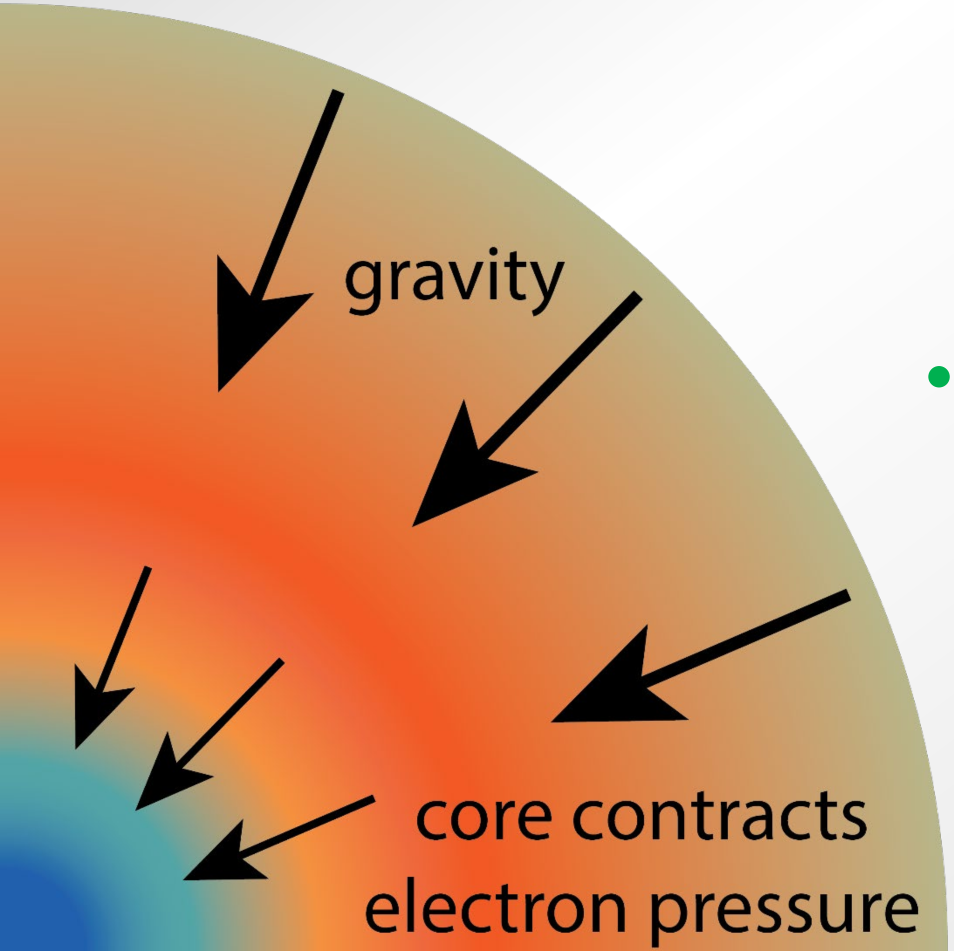


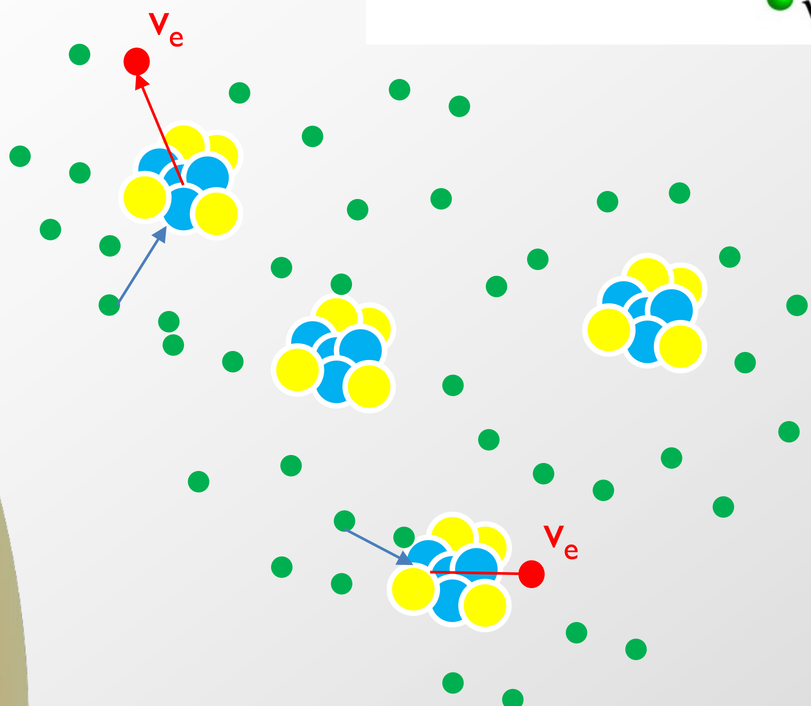


Core Collapse Supernova – A Cartoon

- Core starts to contract
- Electron captures on nuclei in the **iron region** reduce pressure further and remove energy from the core



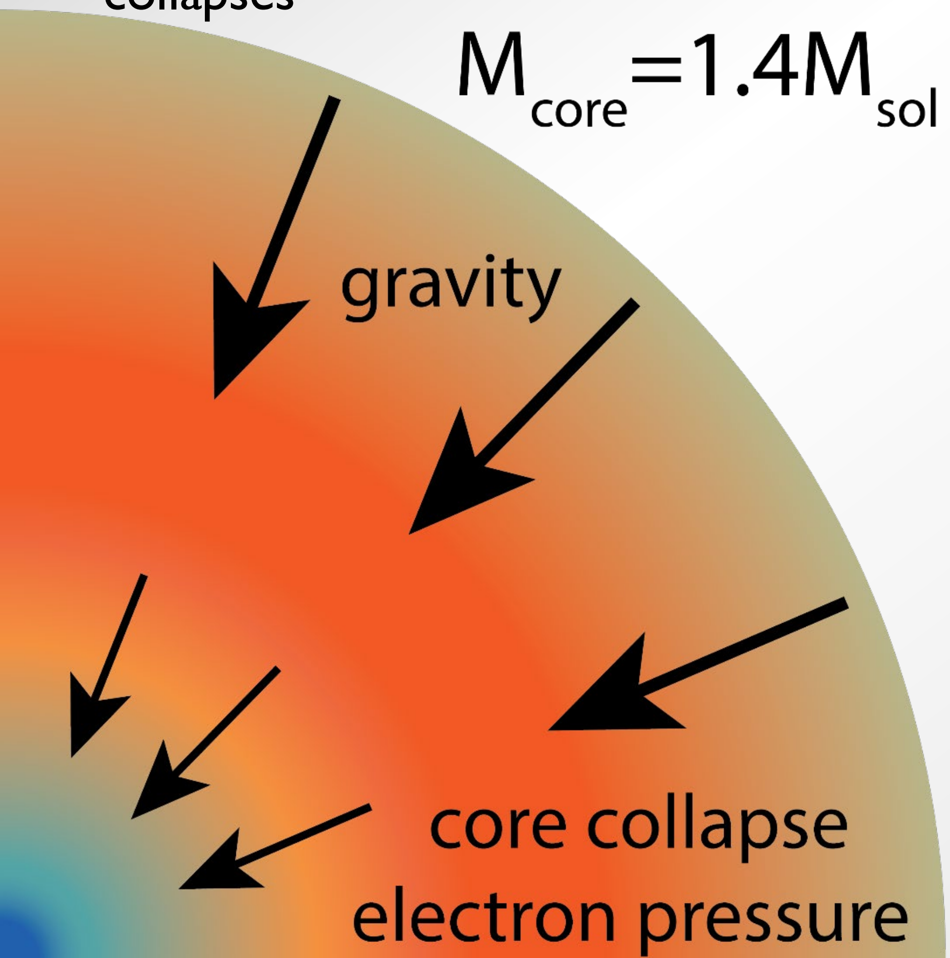




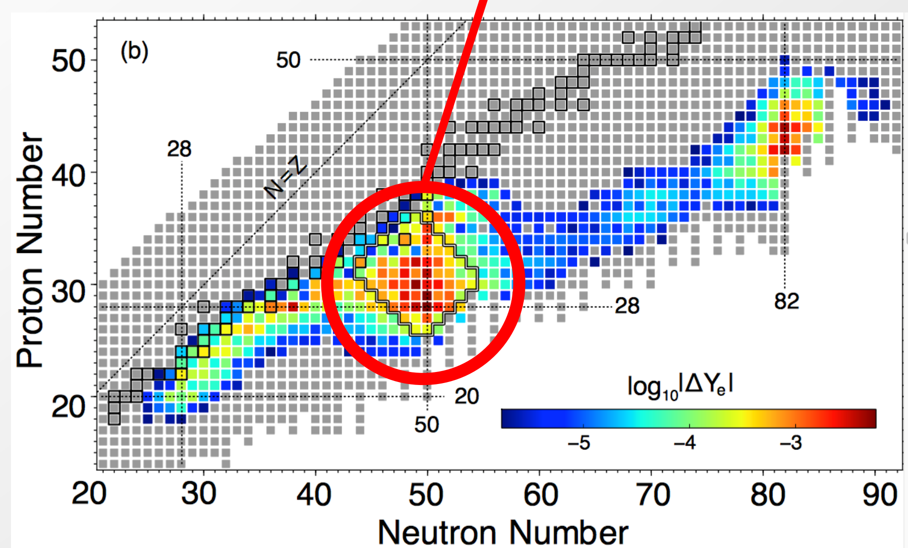
Core Collapse Supernova – A Cartoon

- Density of the core increases
- Electron captures on nuclei of mass ~80 are important regulators of the evolution
- When the core exceeds the Chandrasekhar limit of 1.4 solar masses, the electron degeneracy pressure is insufficient to counter the gravitational force and the core collapses

$$M_{core}=1.4M_{sol}$$



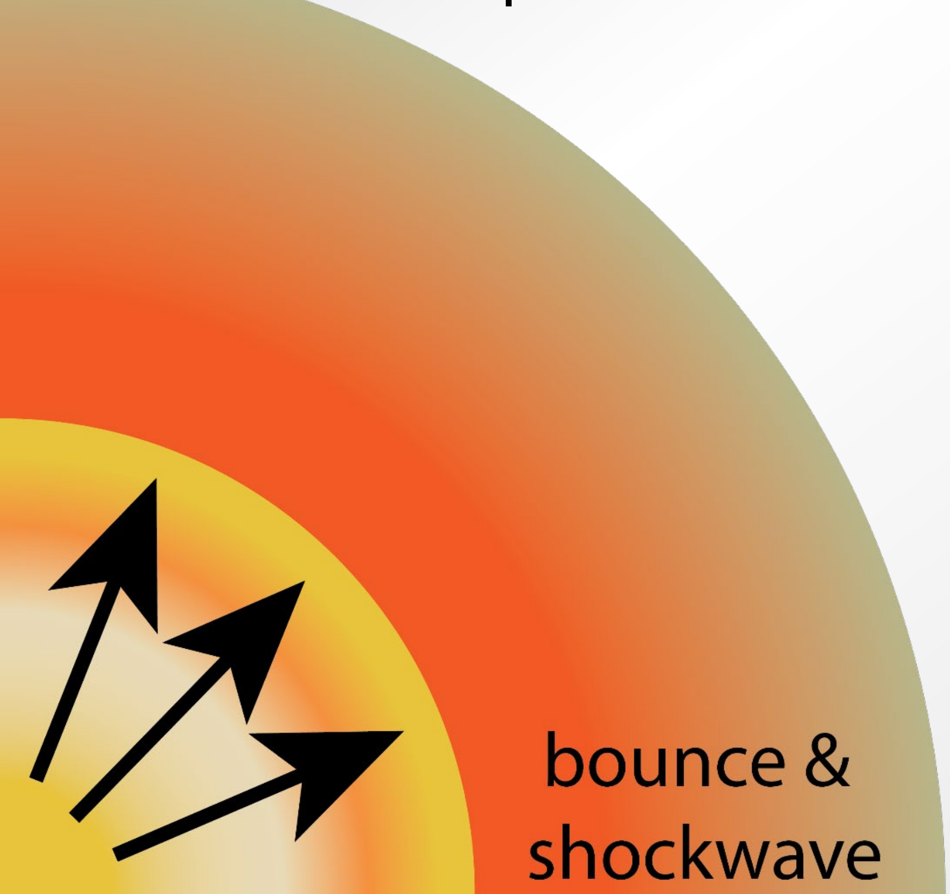
Electron captures on these nuclei change the electron fraction and generate neutrinos that carry away energy



Y_e: electron fraction

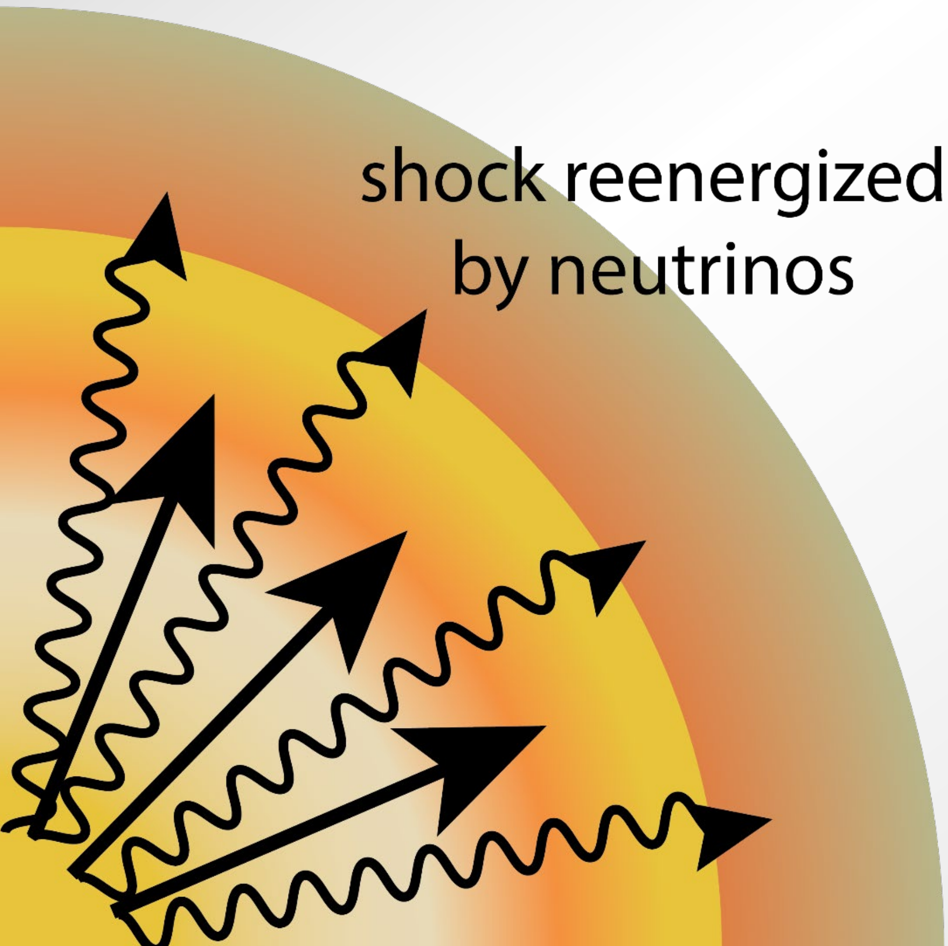
Core Collapse Supernova – A Cartoon

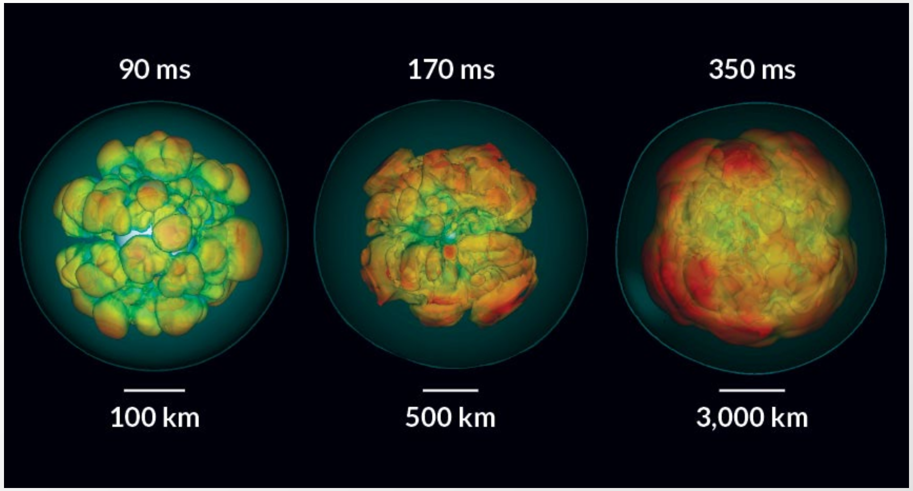
- When the density of the core exceeds that of nuclear matter, the core rebounds and produces a pressure wave against the in falling outer core
- It is generally thought that this shockwave by itself is not sufficient to cause the explosion



Core Collapse Supernova – A Cartoon

- Neutrinos produced by electron captures reenergize the shockwave
- Shockwave can travel all the way to the surface
- Convection processes in the star enhance the re-energization of the shockwave

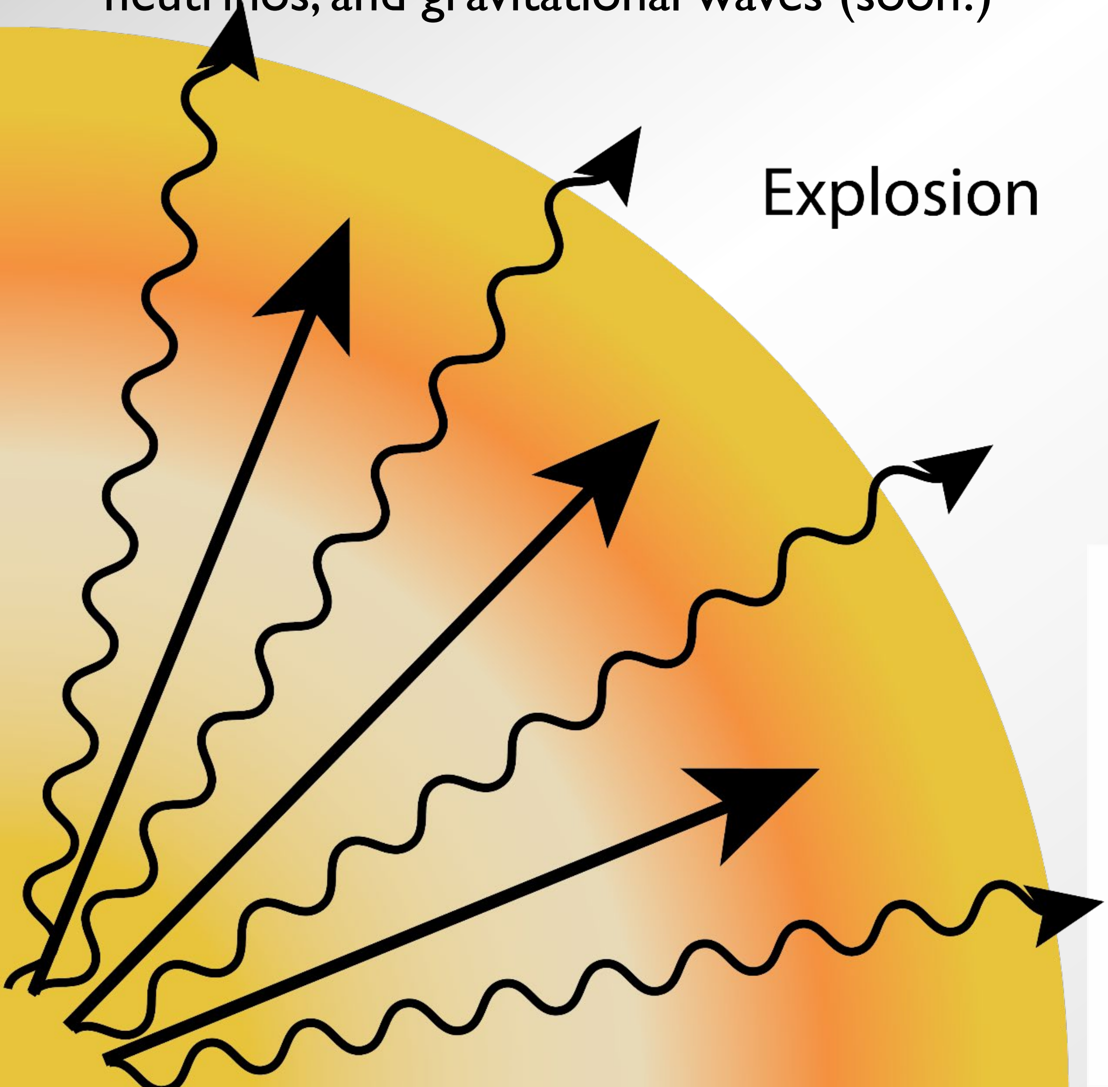




T. MELSON, H.-T. JANKA AND A. MAREK/*ASTROPHYS. J. LETT*. 2015

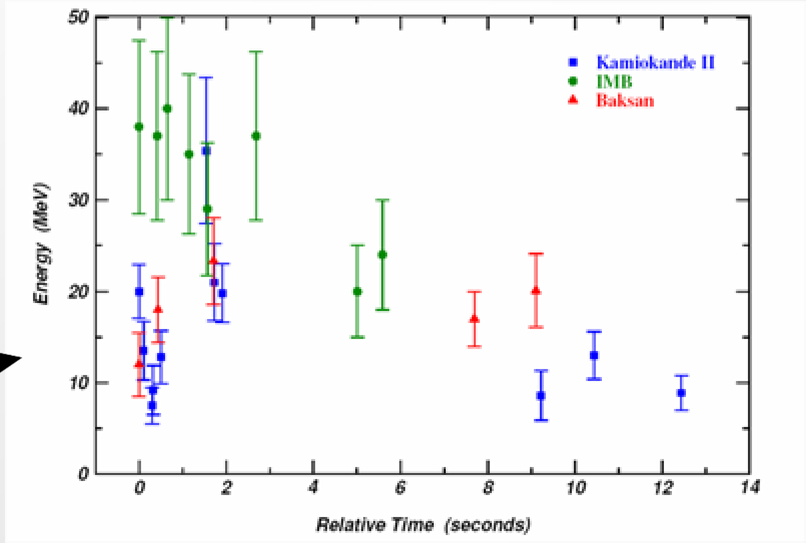
Core Collapse Supernova – A Cartoon

- Star explodes with a power of 10^{45} Watt (Sun: 4×10^{26} Watt)
- Supernovae can be detected through multi messenger signals: light (photons), neutrinos, and gravitational waves (soon!)



Explosion

Light and neutrinos from SN 1987A



electron capture rates on nuclei

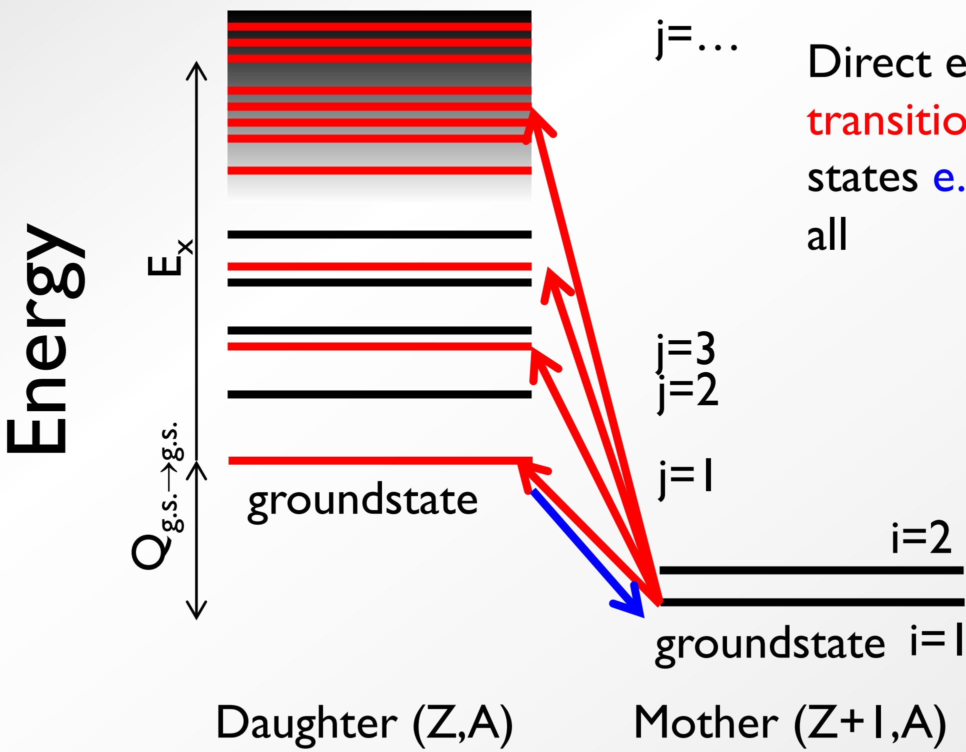
$$\lambda_{EC} = ln2 \sum_{ij} f_{ij}(T, \rho, U_F) B(GT)_{ij}$$

Gamow Teller Strength

EC — on groundstate

β^- — from groundstate

Dominated by allowed (Gamow-Teller ΔL=0, ΔS=1, ΔT=1) weak transitions between states in the initial and final nucleus. Each transition is characterized by a reaction Q-value and a strength, B(GT).

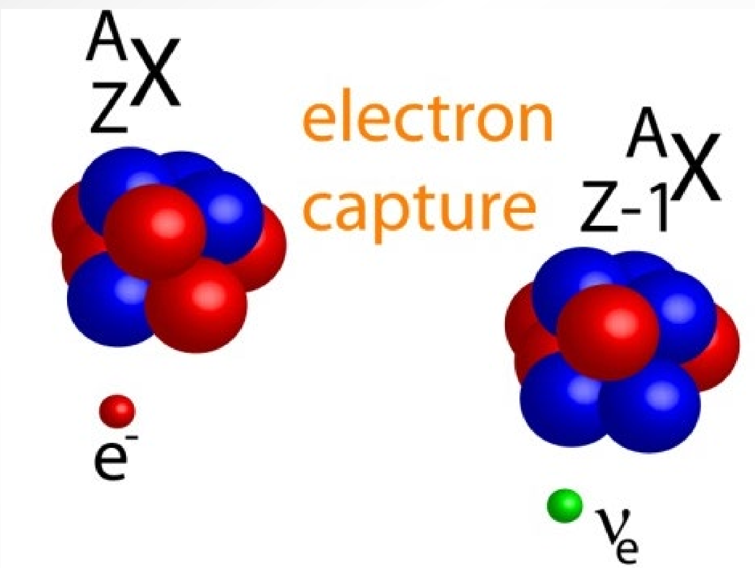


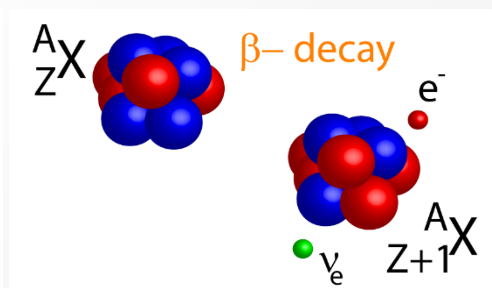
Direct empirical information on strength of transitions [B(GT)] is limited to low-lying excited states e.g. from the inverse (β-decay) transitions, if at all

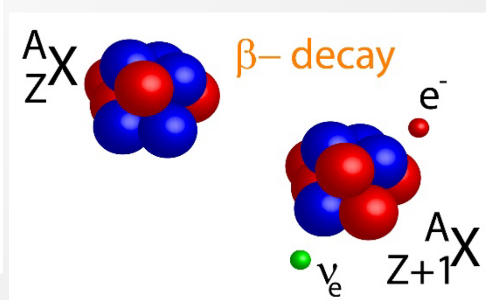
EC rates on many (unstable) nuclei are important. Only fraction of transitions can be measured. Must rely on theoretical models benchmarked by experiments.

Electron capture

- Mediated by the weak nuclear force
- Dominated by "Allowed" Gamow-Teller transitions: transfer of spin ($\Delta S=1$), transfer of isospin ($\Delta T=1$), and no transfer of angular momentum ($\Delta L=0$)
- If ground state is a 0^+ state then the final state is a 1^+ state
- At high densities and temperatures, contributions from "Forbidden" transitions ($\Delta L>0$) can become significant







$$\frac{K}{ft} = \left(\frac{g_A}{g_v}\right)^2 B(GT)$$

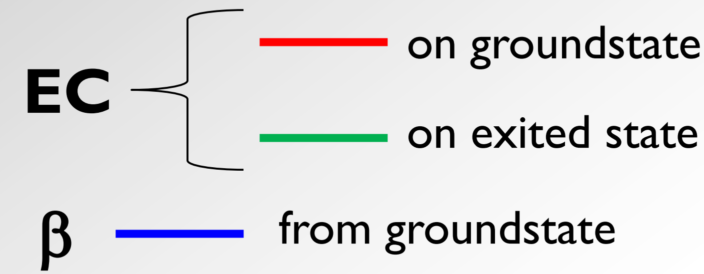
Half life ↑ (t) GT strength ↑ ($B(GT)$)

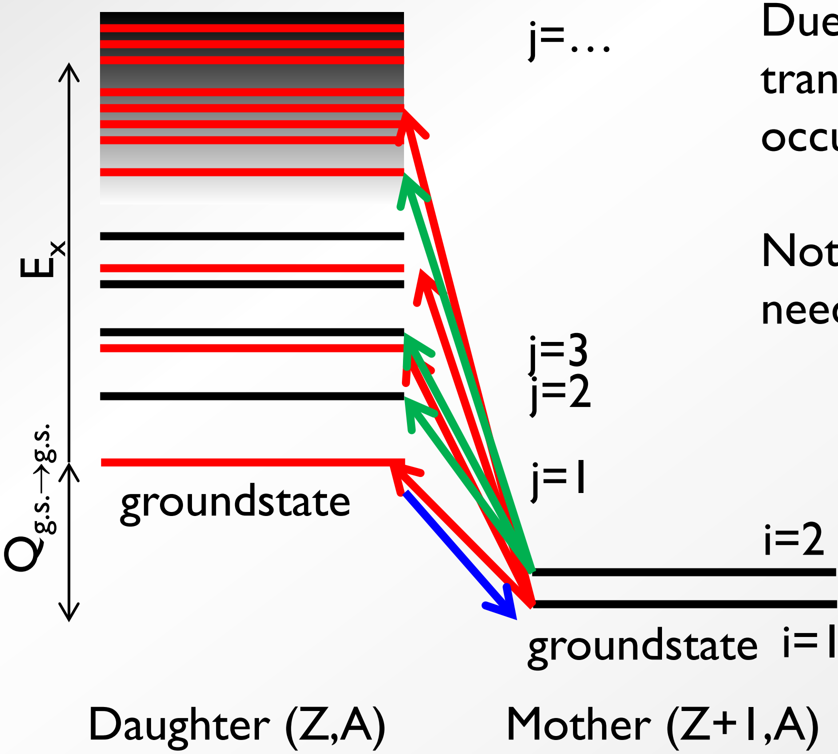
Half life

GT strength

electron capture rates on nuclei

$$\lambda_{EC} = ln2 \sum_{ij} f_{ij}(T, \rho, U_F) \boxed{B(GT)_{ij}}$$



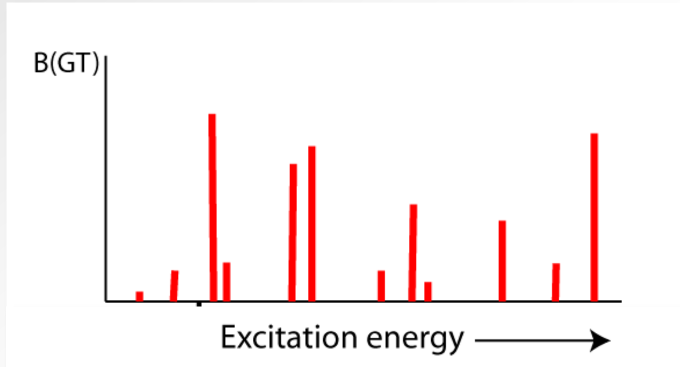


Dominated by allowed (Gamow-Teller ΔL=0, ΔS=1, ΔT=1) weak transitions between states in the initial and final nucleus. Each transitions is characterized by a Q-value and a strength, B(GT).

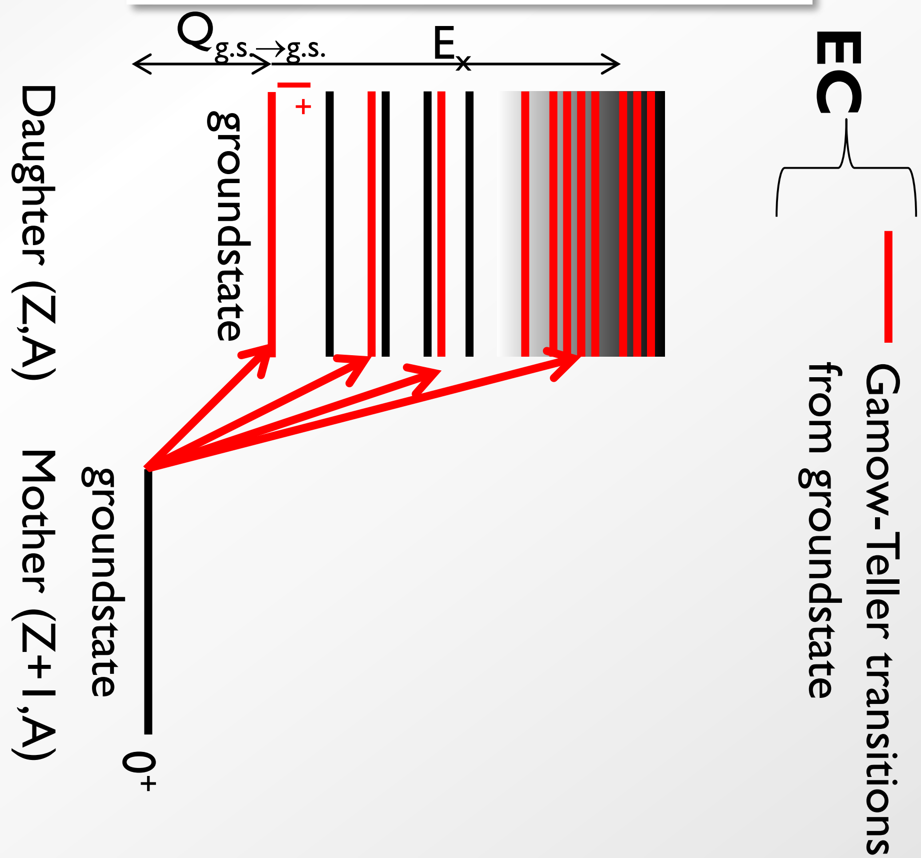
Due to finite temperature in stars, Gamow-Teller transitions from excited states in the mother nucleus can occur

Not all data can be obtained from experiments – we need to test and develop theory!

Gamow-Teller Strength Distribution



Need to know this spectrum

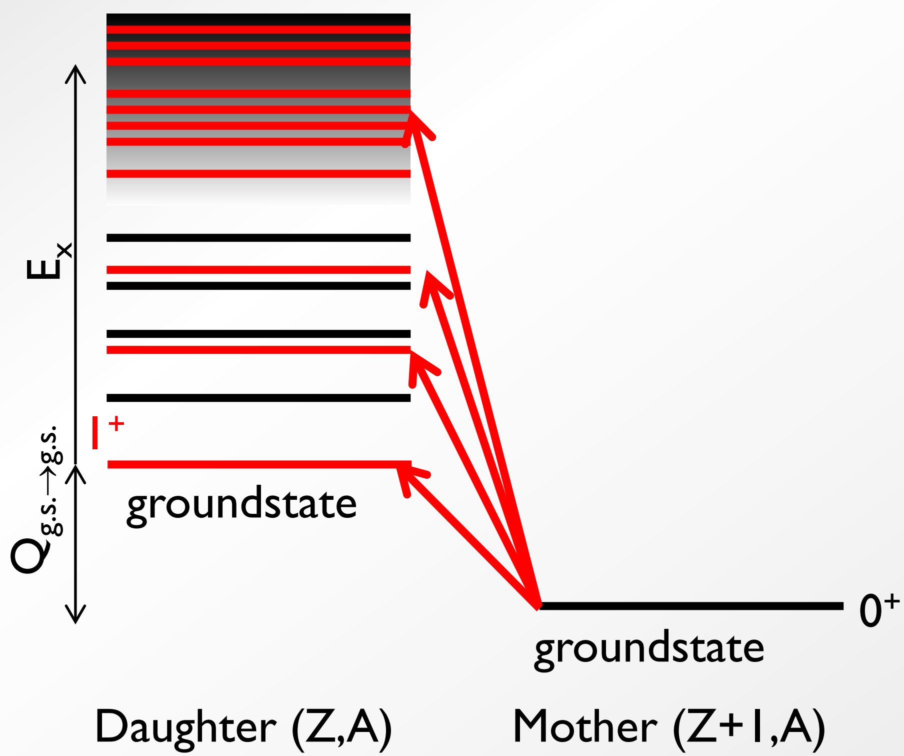


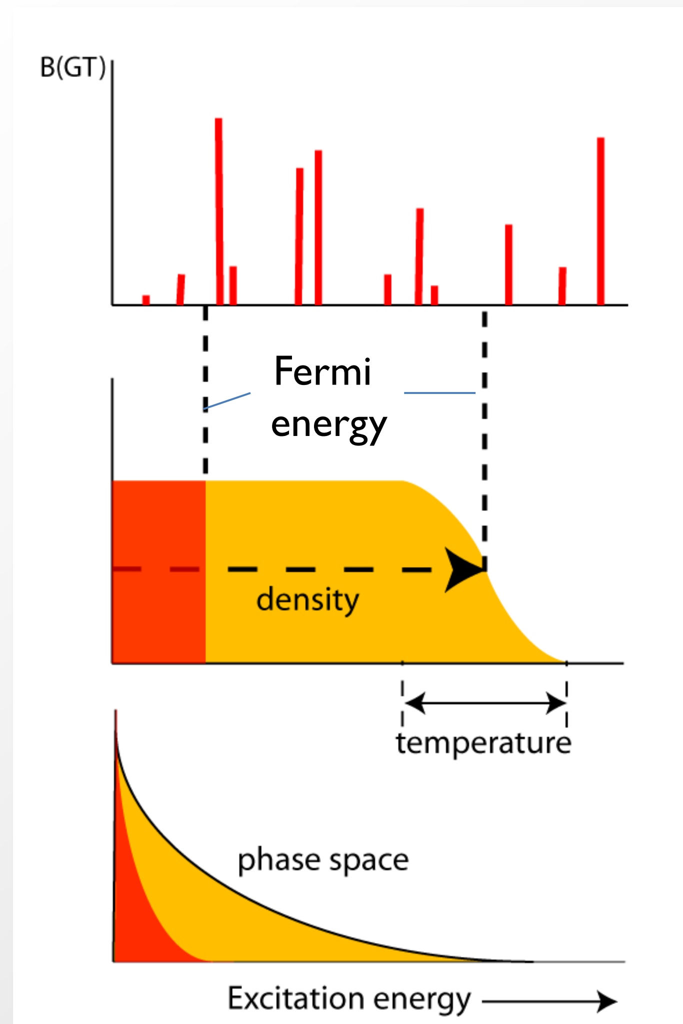
Electron captures in stars

rate ← $$\lambda_{EC} = ln2 \sum_{ij} f_{ij}(T, \rho, U_F) B(GT)_{ij}$$

→ Phase space available for electron

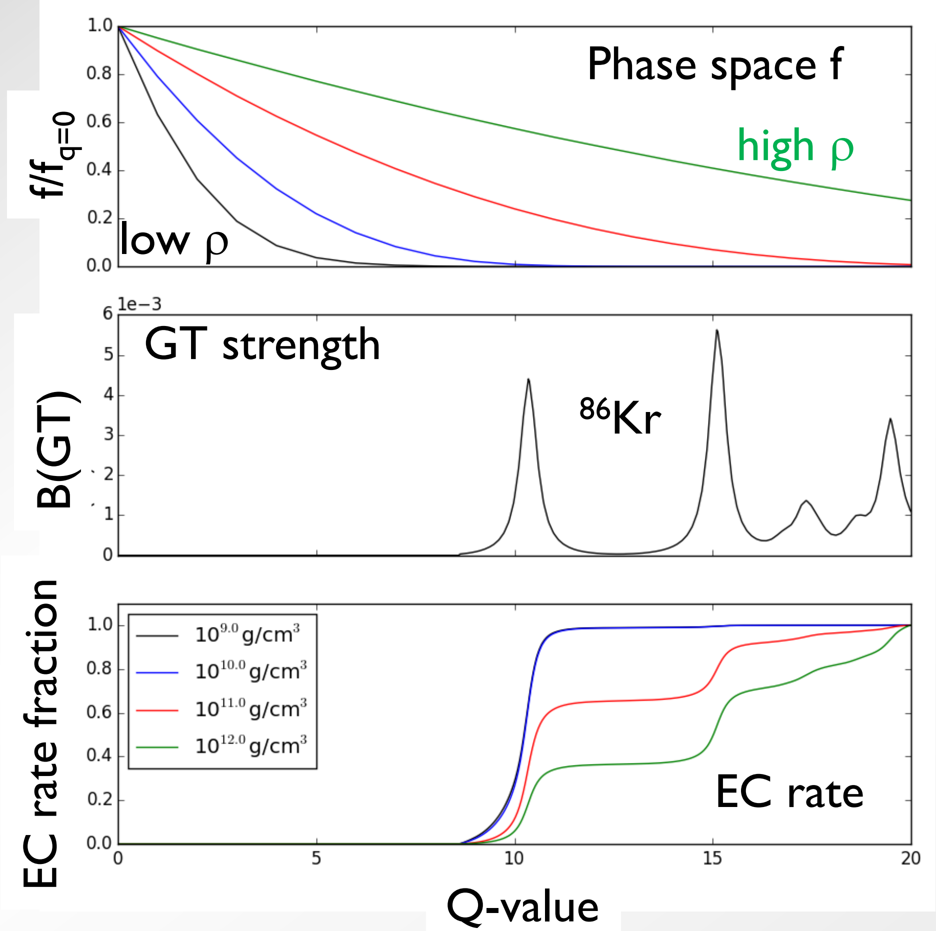
EC — Gamow-Teller transitions from groundstate

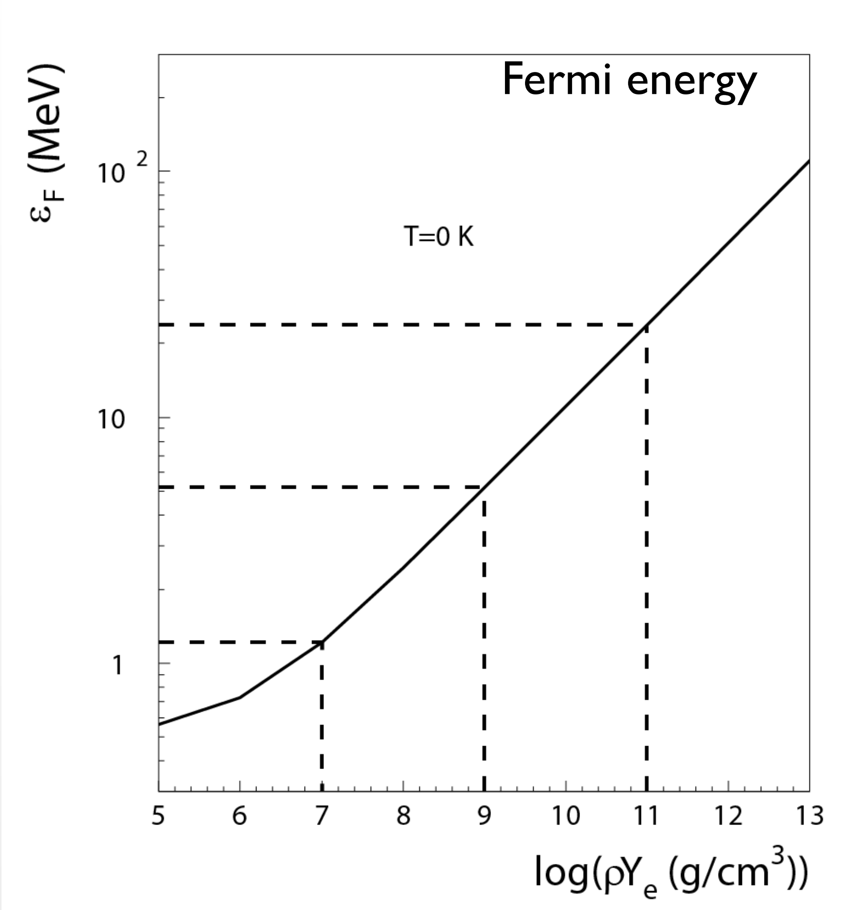




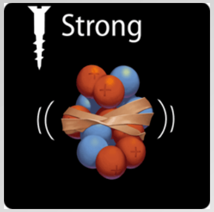
$$\lambda_{EC} = ln2 \sum_{ij} f_{ij}(T, \rho, U_F) B(GT)_{ij}$$

- At high stellar densities, the Fermi energy increases, making the EC rates less sensitive to details of the GT strength distribution.
- However, for neutron-rich nuclei important during the collapse the Q value also strongly increases, countering such effects

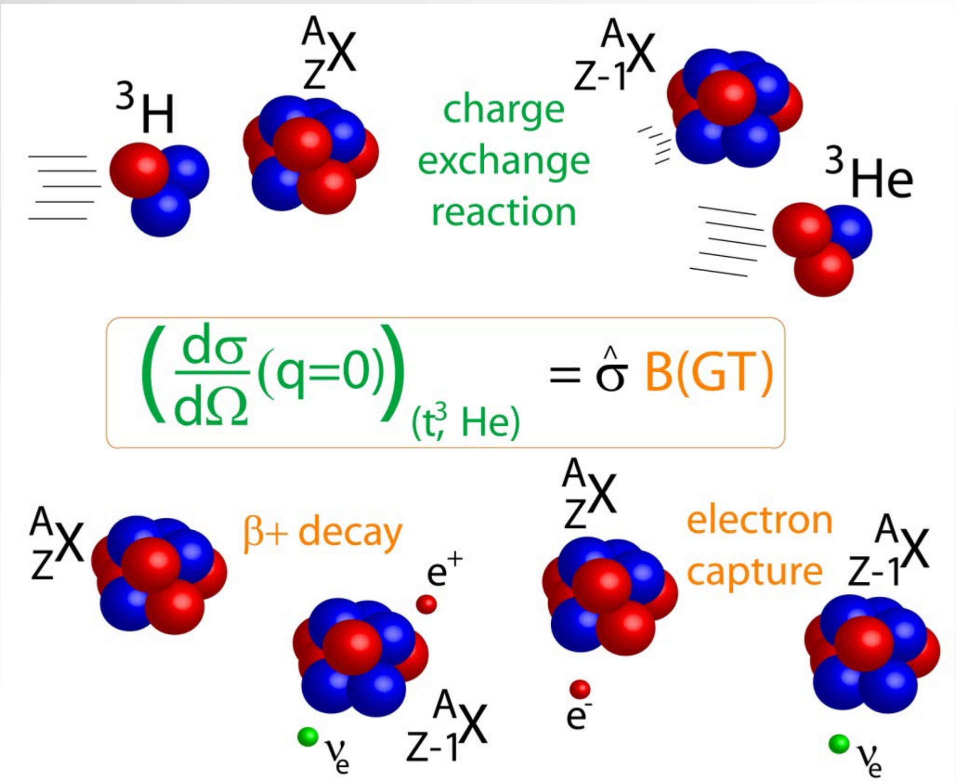




Charge-exchange reactions & β/EC-decay



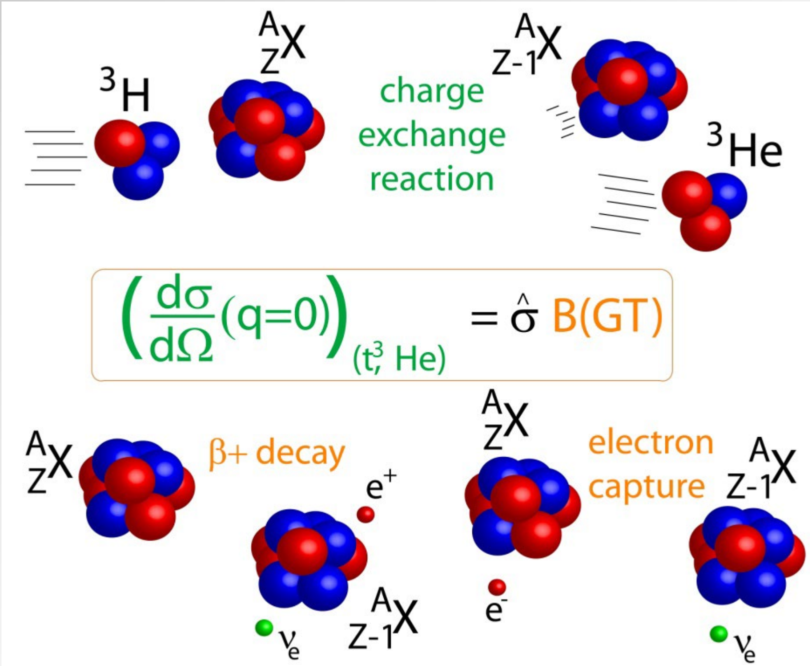
$$\left(\frac{d\sigma}{d\Omega}\right)_{q=0} = \hat{\sigma} B(GT)$$



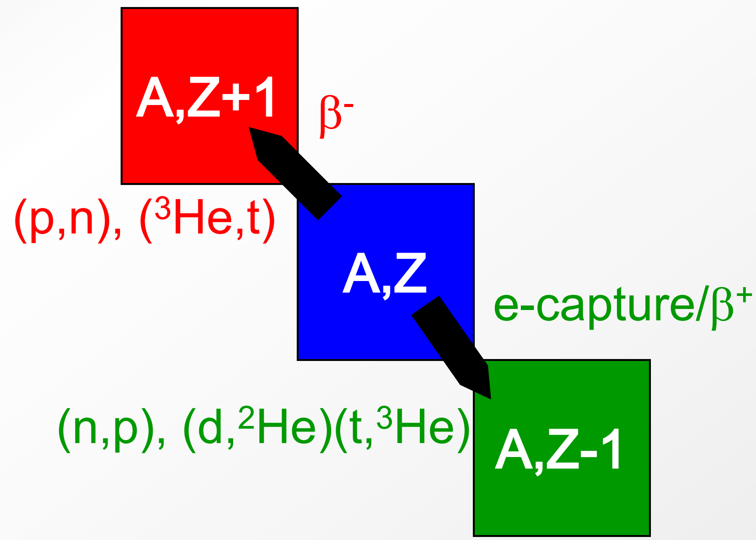
$$\frac{K}{ft} = \left(\frac{g_A}{g_v}\right)^2 B(GT)$$

- Perform experiments ~ 100 MeV/nucleon or above where reaction mechanism is simple
- Extract the differential cross section for Gamow-Teller transitions at 0-degree scattering angles (momentum transfer q~0)
- Extract Gamow-Teller strength B(GT) by using the unit cross section $\hat{\sigma}$
- $\hat{\sigma}$ is calibrated with a transition for which B(GT) is know from β decay half-life measurement

Gamow-Teller strengths and CE cross sections



Model-independent extraction of GT strengths



$$B(GT_+) = \sum_{i,f} \frac{n_i^p n_f^h}{(2j_i+1)(2j_f+1)} \left| \langle f | \vec{\sigma}\tau_+ | i \rangle \right|^2$$

β-decay weak

$$\frac{d\sigma}{d\Omega}(q=0) = \left[\frac{\mu}{2\pi\hbar}\right]^2 \frac{k_f}{k_i} N_D \left|V_{\sigma\tau}\right|^2 \left| \left\langle f \left| \sum_k \sigma_k \tau_k \right| i \right\rangle \right|^2$$

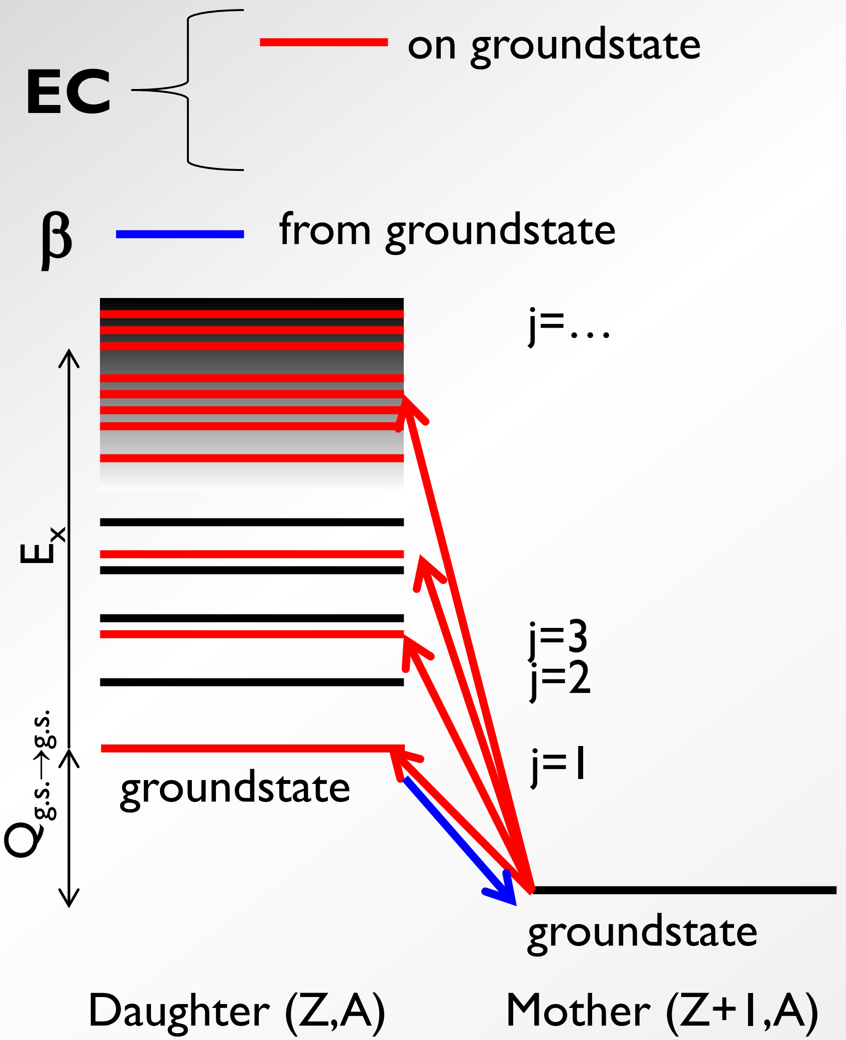
charge-exchange strong

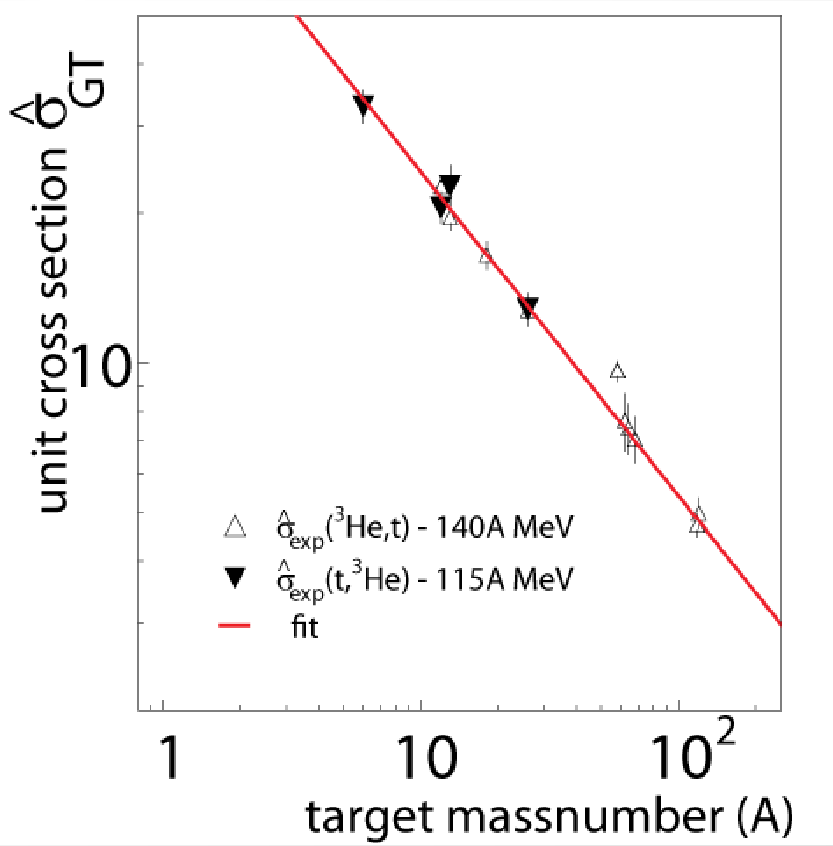
$\hat{\sigma}$: **unit cross section**

Taddeucci et al. NPA 469, 125 (1987)

Unlike β-decay CE experiments do not suffer from Q-value restrictions

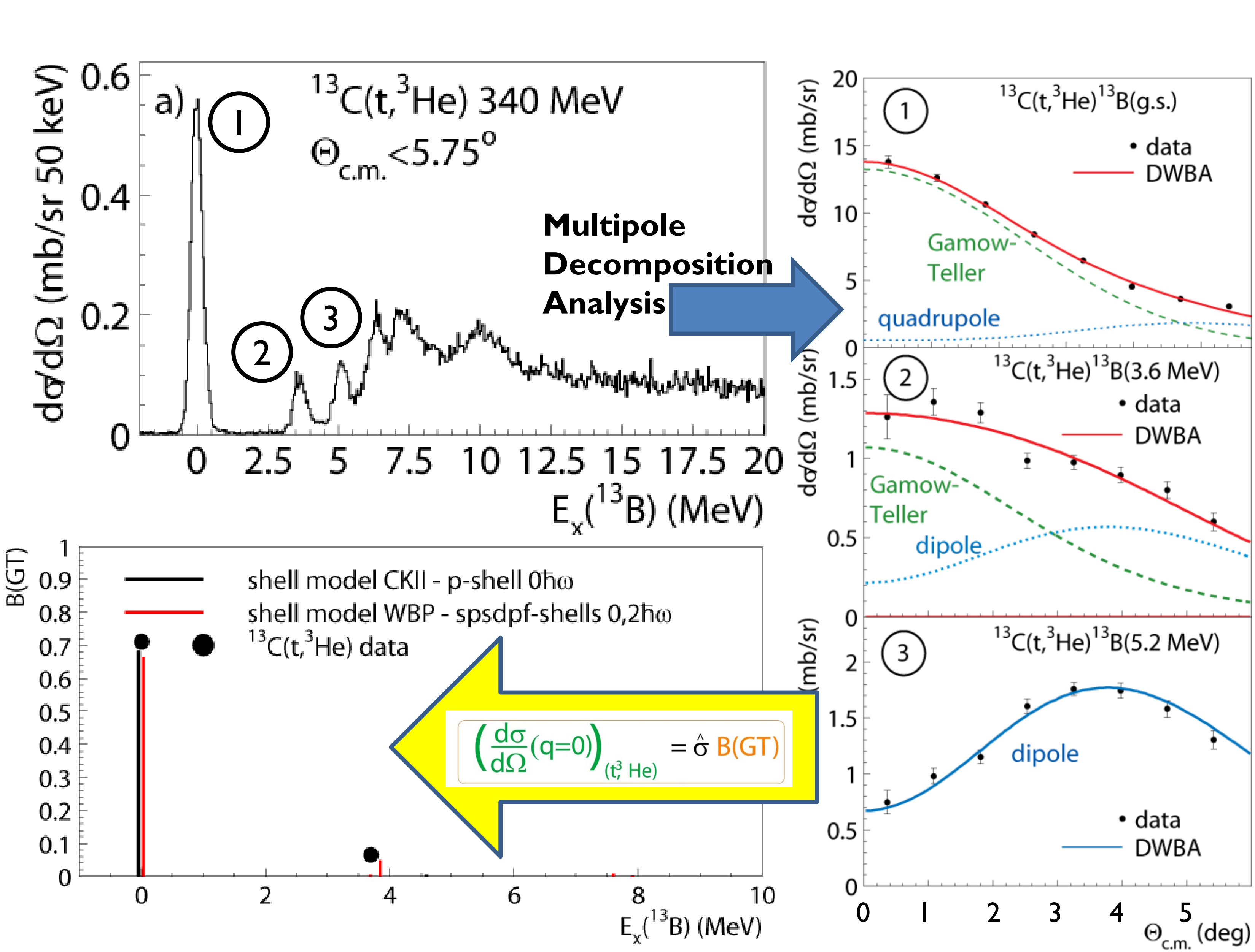
Extract B(GT) for many states





The unit cross section is calibrated against transitions for which β-decay data are available

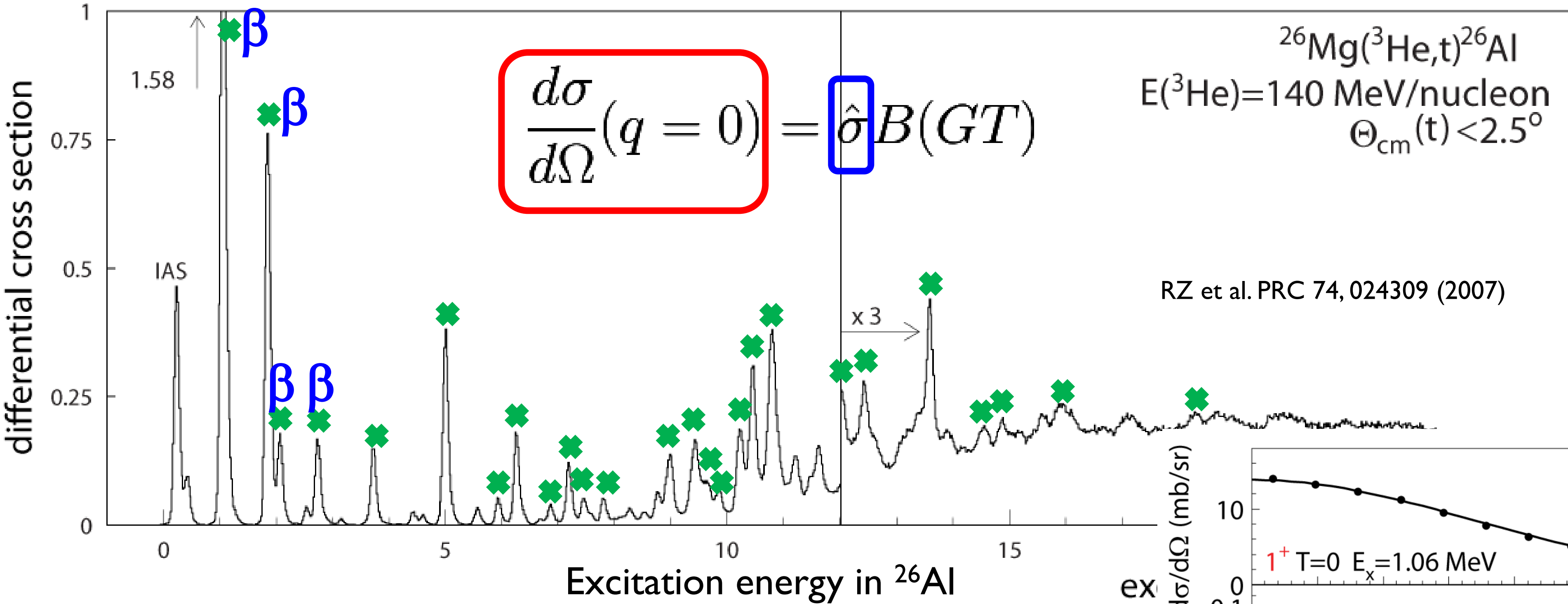
Extraction of GT strength



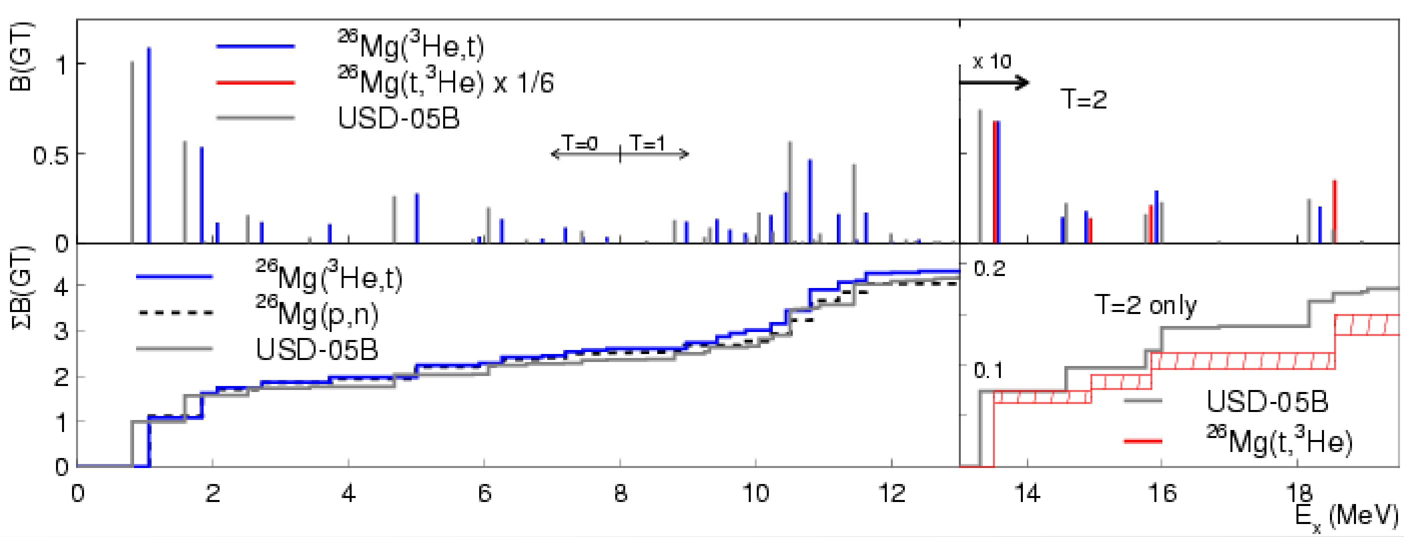
$$\left(\frac{d\sigma}{d\Omega}(q=0)\right)_{(t,^3He)} = \hat{\sigma}\, B(GT)$$

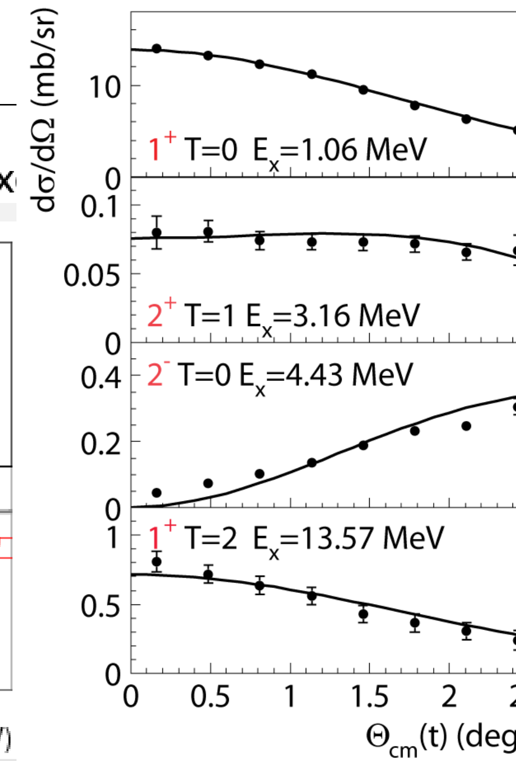
C. Guess et al., Phys. Rev. C 80, 024305 (2009)

Extracting GT strength from scattering data

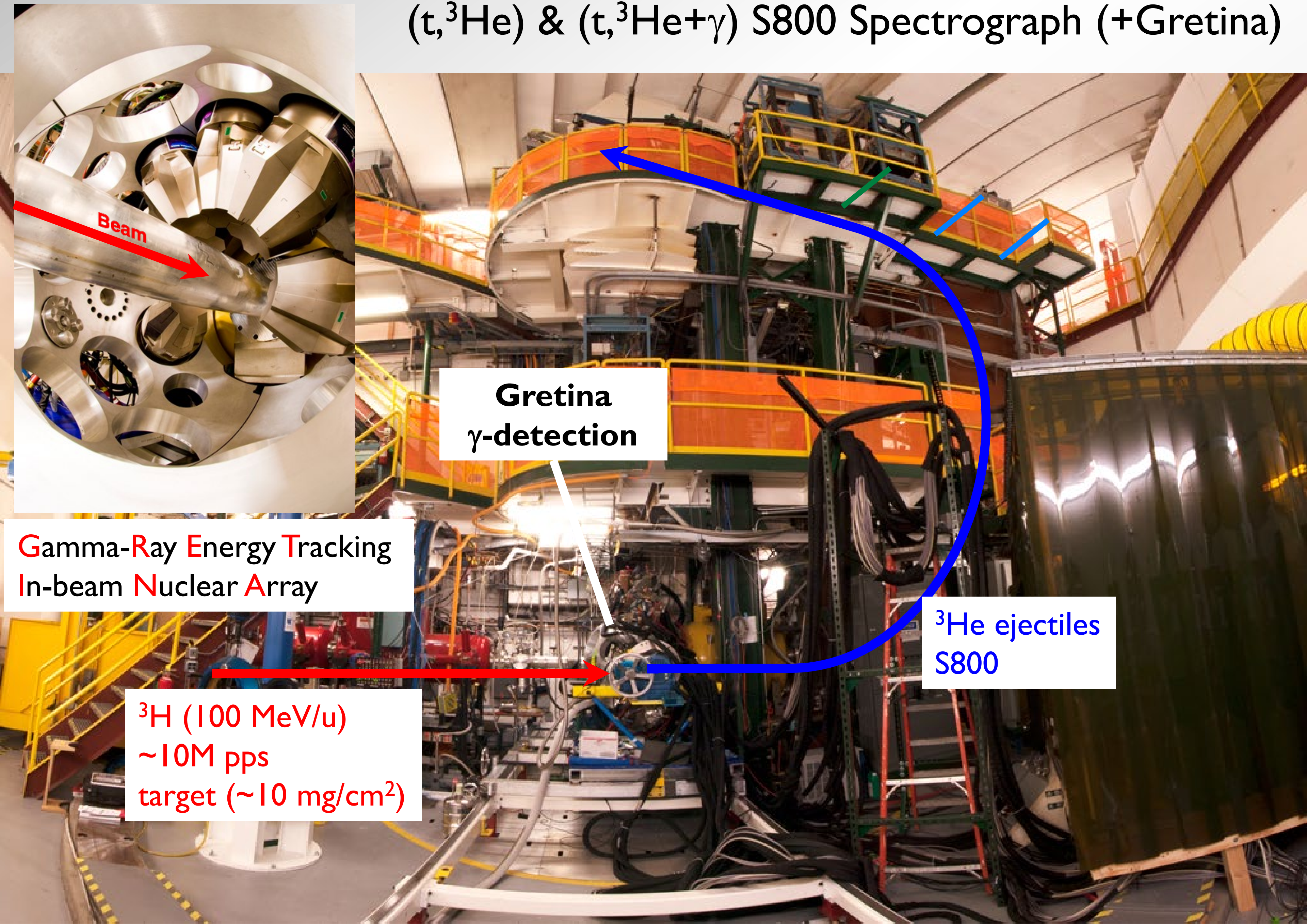


$$\frac{d\sigma}{d\Omega}(q=0) = \hat{\sigma} B(GT)$$

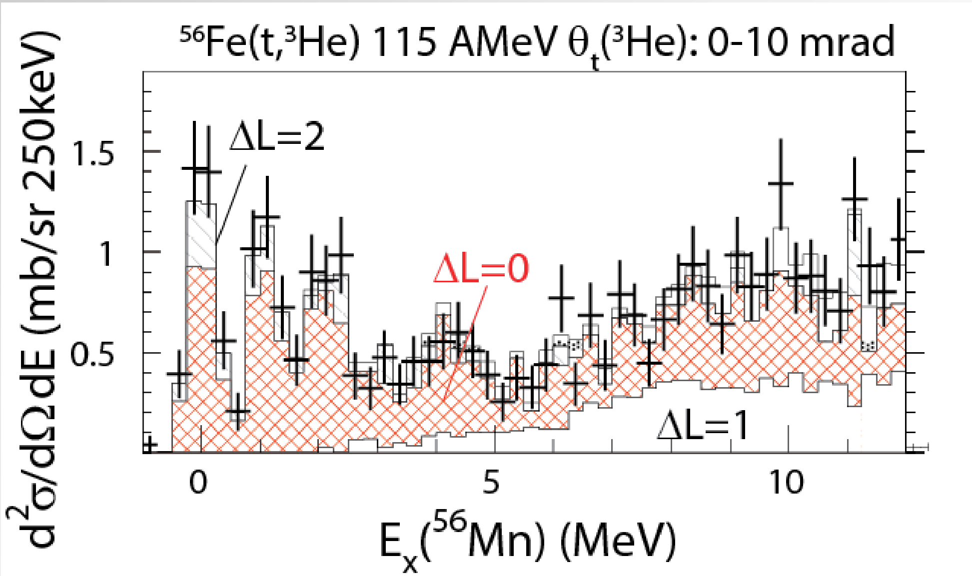




(t,^{3}He) & (t,^{3}He+γ) S800 Spectrograph (+Gretina)



$^{56}Fe(t,^{3}He)$



Result from multipole decompositions analysis

Experiment

$^{56}Fe(t,^{3}He)$ - M. Scott et al., PRC 90, 025801 (2014)

$^{56}Fe(n,p)$ - S. El-Kateb et al., PRC 49, 3128 (1994)

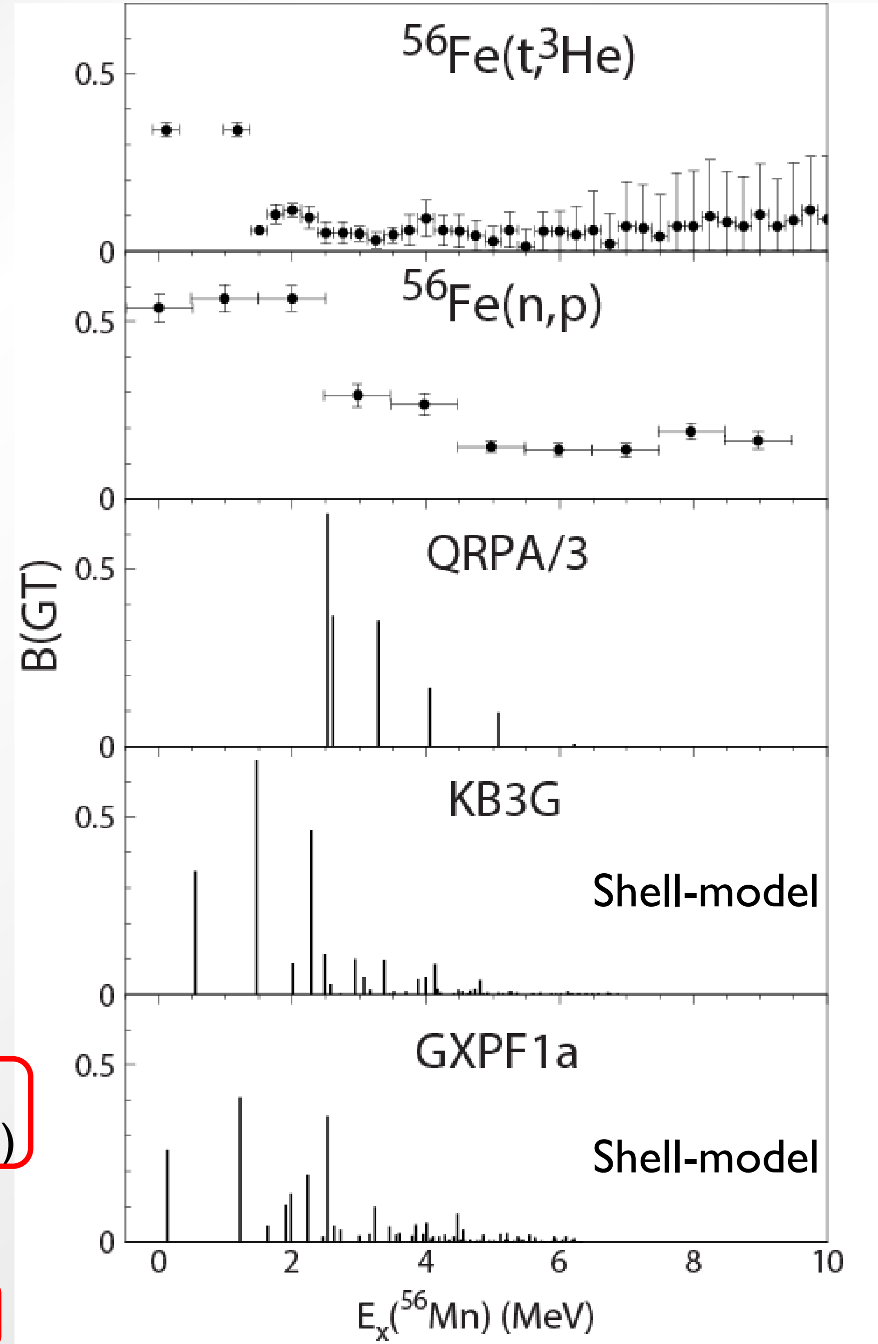
Theory – Shell model

KB3G - A. Poves et al., NPA694, 157 (2001)

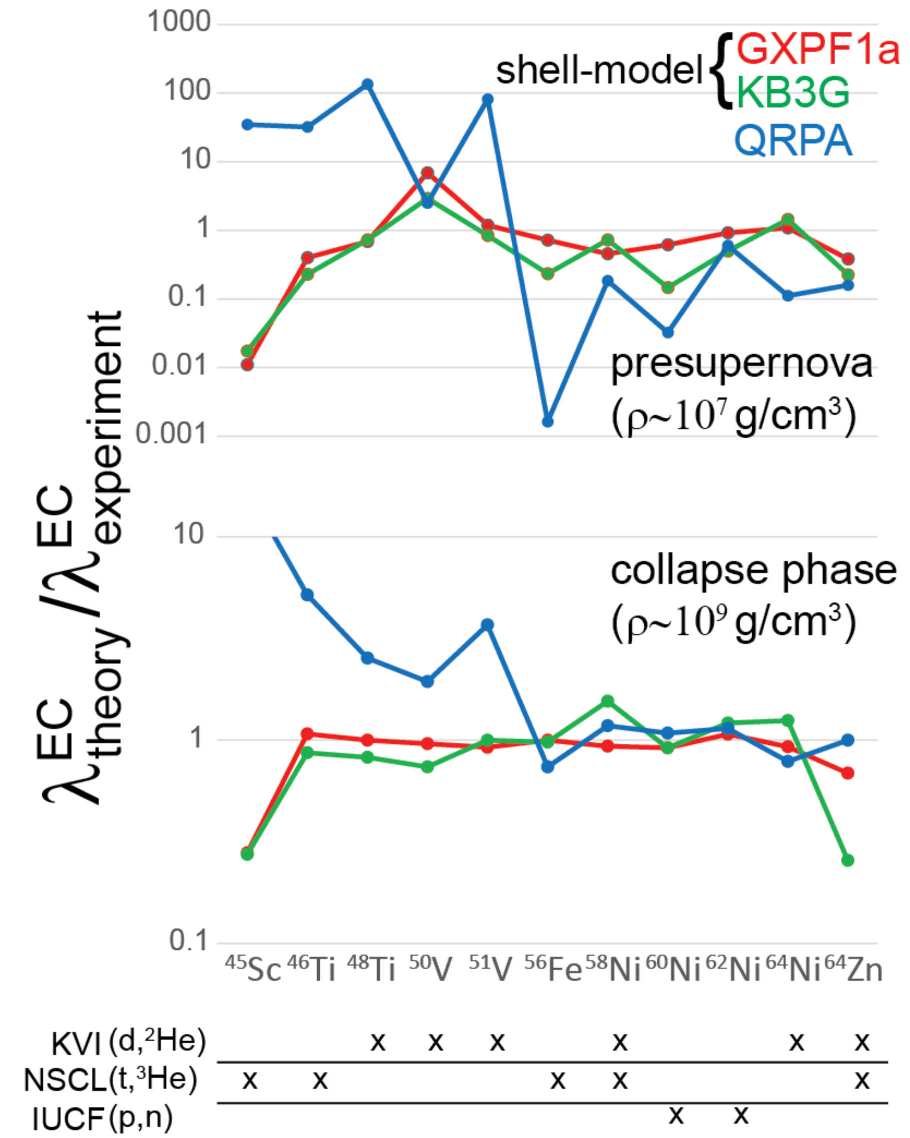
GXPF1a - M. Honma et al. PRC 65, 061301(R) (2002)

Theory – QRPA

P. Moller and J. Randrup, NPA514, 1 (1990); S. Gupta



Systematic EC rate comparisons



A.L. Cole et al., PRC 86, 015809 (2012)

Systemic comparison of EC rates calculated from theory and derived from data provide framework for error estimation of theoretical rates

(d,^{2}He) data – KVI, the Netherlands
(t,^{3}He) data – NSCL/MSU
(p,n) data IUCF (isospin symmetry)

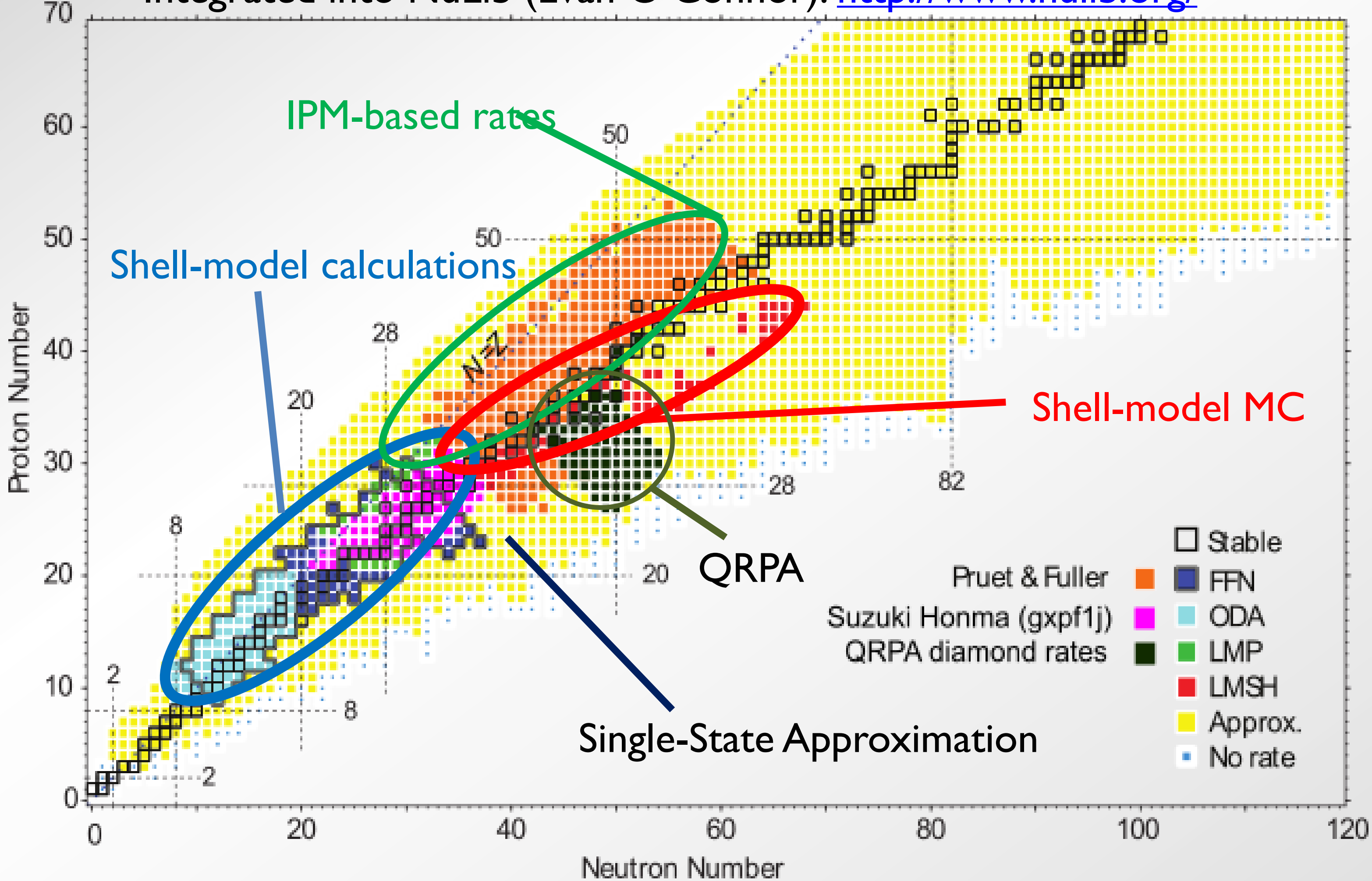
Systematic studies provide a way to benchmark and improve theoretical calculations

Experimental results from different facilities and probes are combined to perform comprehensive comparisons

Electron-capture rate library

http://groups.nscl.msu.edu/charge_exchange/weakrates.html

Integrated into NuLib (Evan O'Connor): http://www.nulib.org/



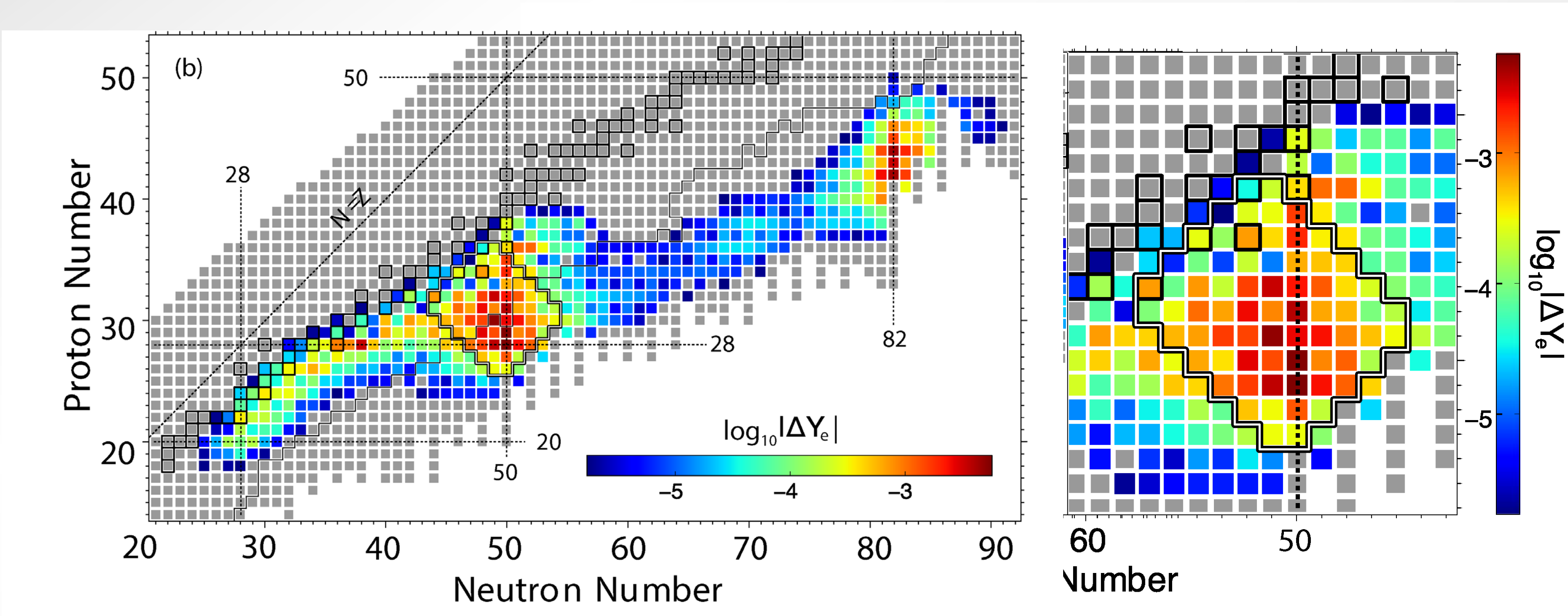
Library is already used in GR1D (1D), CoCoNuT (2D), FLASH (3D) core-collapse simulation codes

Sensitivity Study of Core Collapse Supernovae

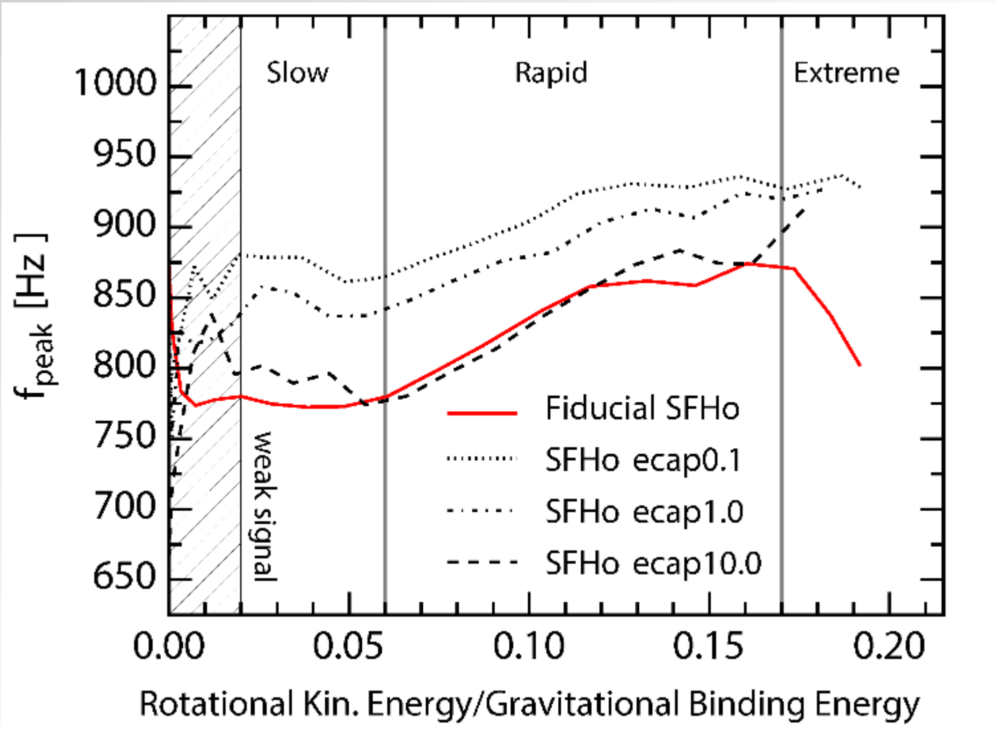
C. Sullivan et al., Ap. J., 816, 44 (2015)

- 1D core-collapse supernovae simulation (GR1D) simulation with modern weak rate estimates up to 100 ms after bounce
- Simulation allows for explicit simulation involving all isotope species.

Which nuclei contribute most to the change in electron fraction and neutrino emission during the late stage of core-collapse supernovae?

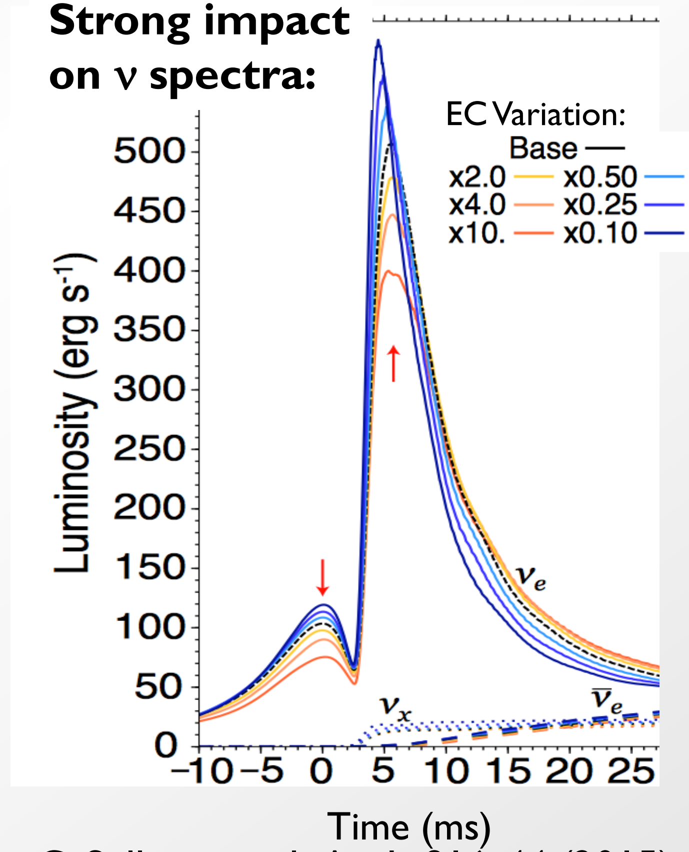


Library allows for the study of uncertainties in messenger signal due to uncertainties in the electron capture rates



S. Richers et al., Phys. Rev. D 95, 063019 (2017)
Using the CoCoNut (2D) code

Strong impact on ν spectra:



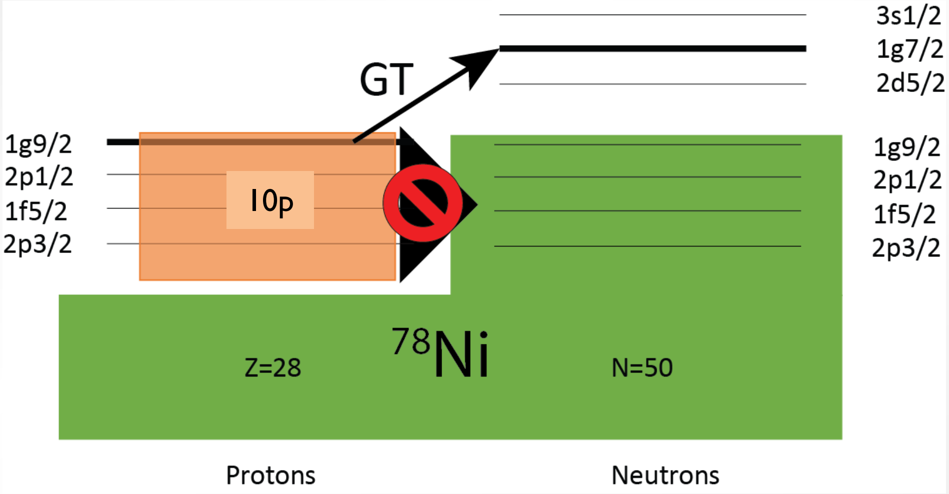
C. Sullivan et al., Ap. J., 816, 44 (2015)

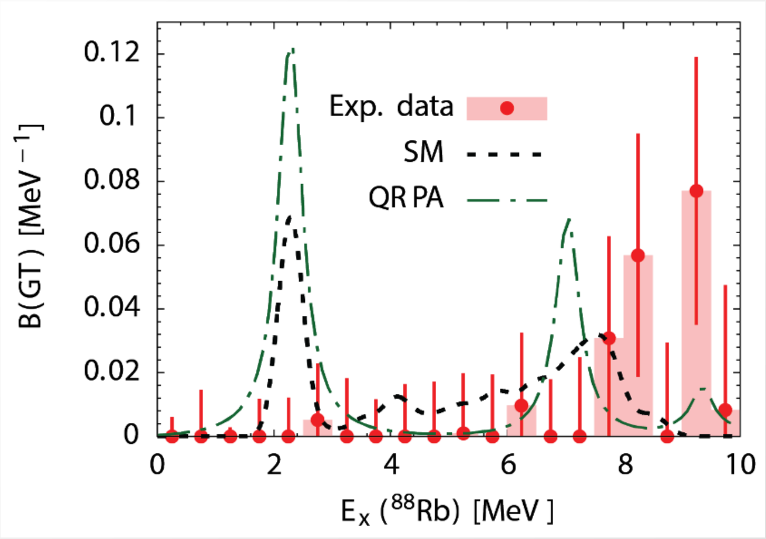
Uncertainties in frequency of gravitational waves from CCSNe due to uncertainties in EC rates is comparable to the uncertainties in Equation of States

EC rates strongly affect neutrino peak luminosity

GT strengths on neutron-rich nuclei

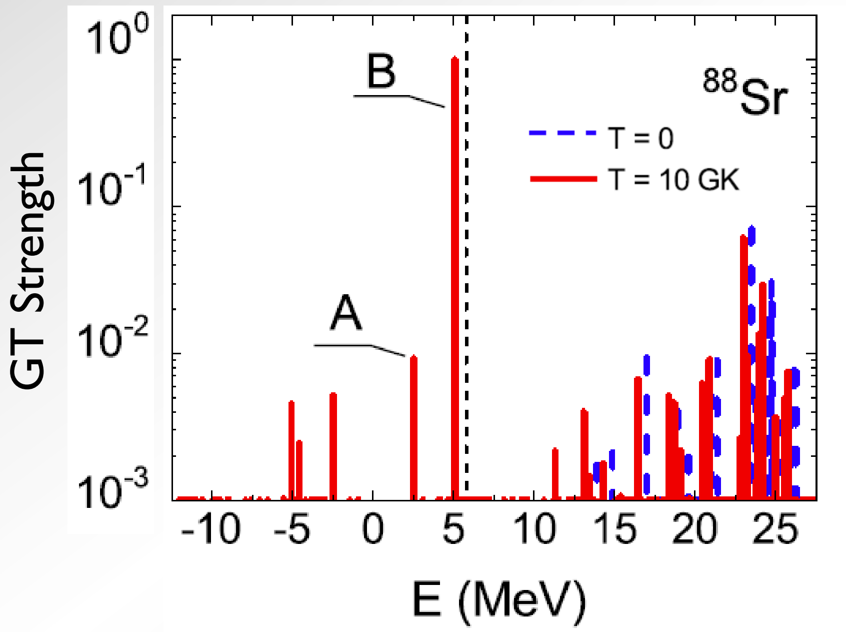
- Due to Pauli Blocking, GT transitions are (strongly) suppressed in certain neutron-rich areas of the chart of nuclei
- At high stellar temperatures, un-blocking can occur, rapidly increasing the transition strength and thus the electron-capture rates





Electron capture on ^{88}Sr - experiment ^{88}Sr(t,^{3}He)

Improvement of theoretical models & temperature dependence

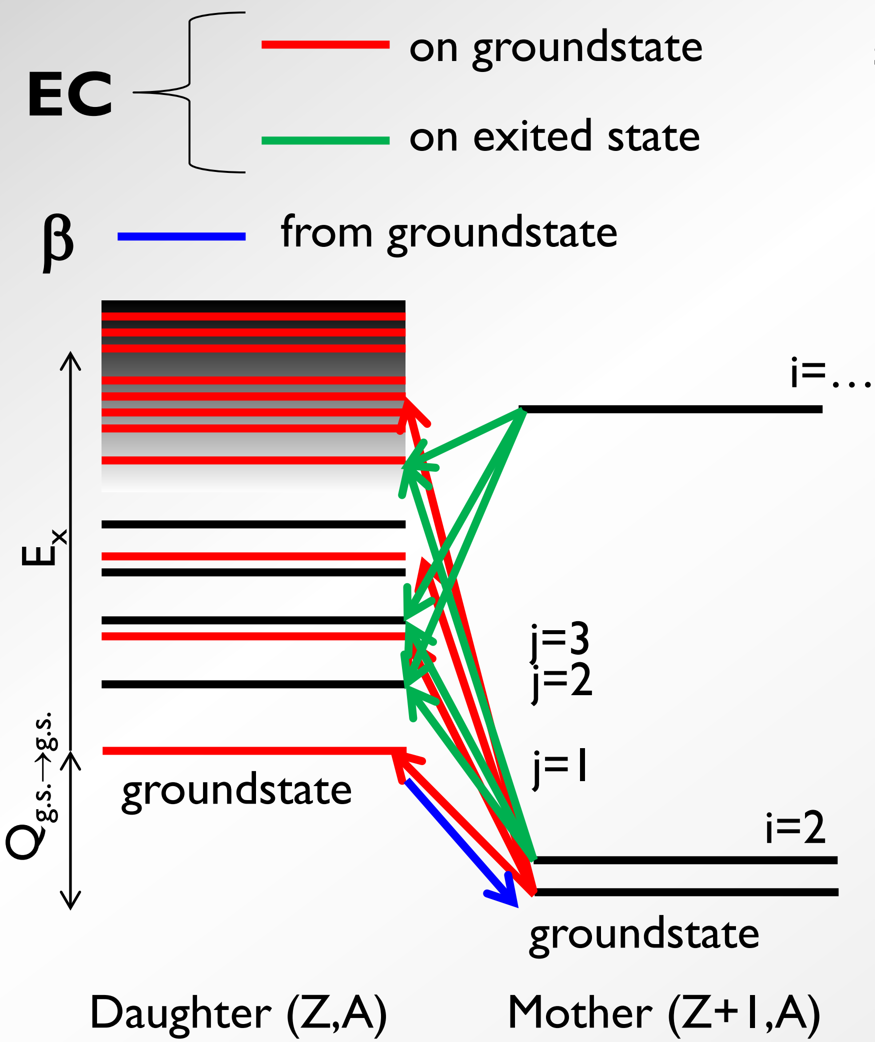


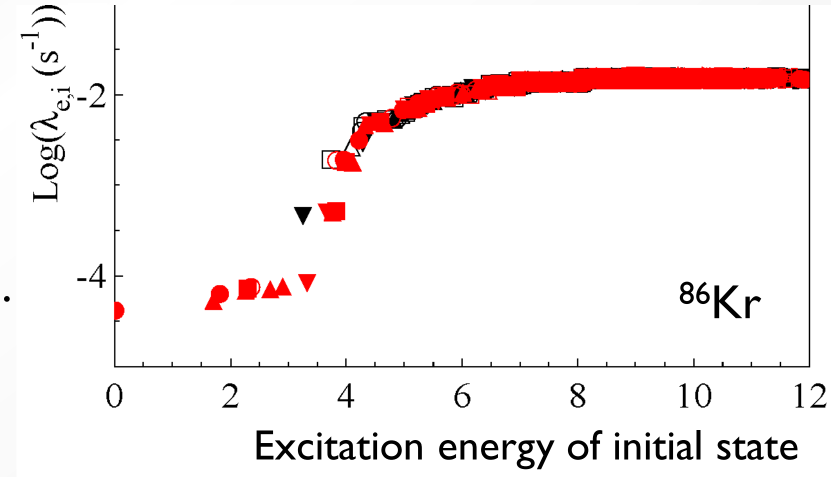
Dzhioev et al., Phys. Rev. C **101**, 025805 (2020)

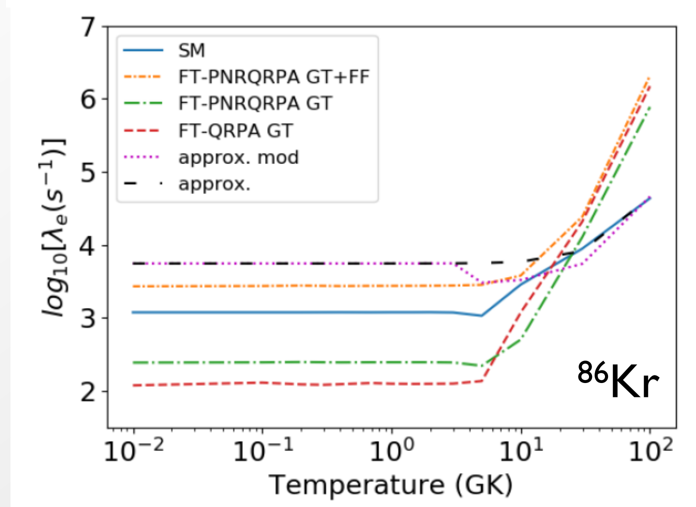
At high temperatures, GT transition to low-lying states appear…..

At high stellar temperatures: transitions from excited states

Although transitions from excited states are suppressed as they are only weakly populated, at high T inside the collapse (~10 GK) it becomes significant: Electron capture Q value is favorable!





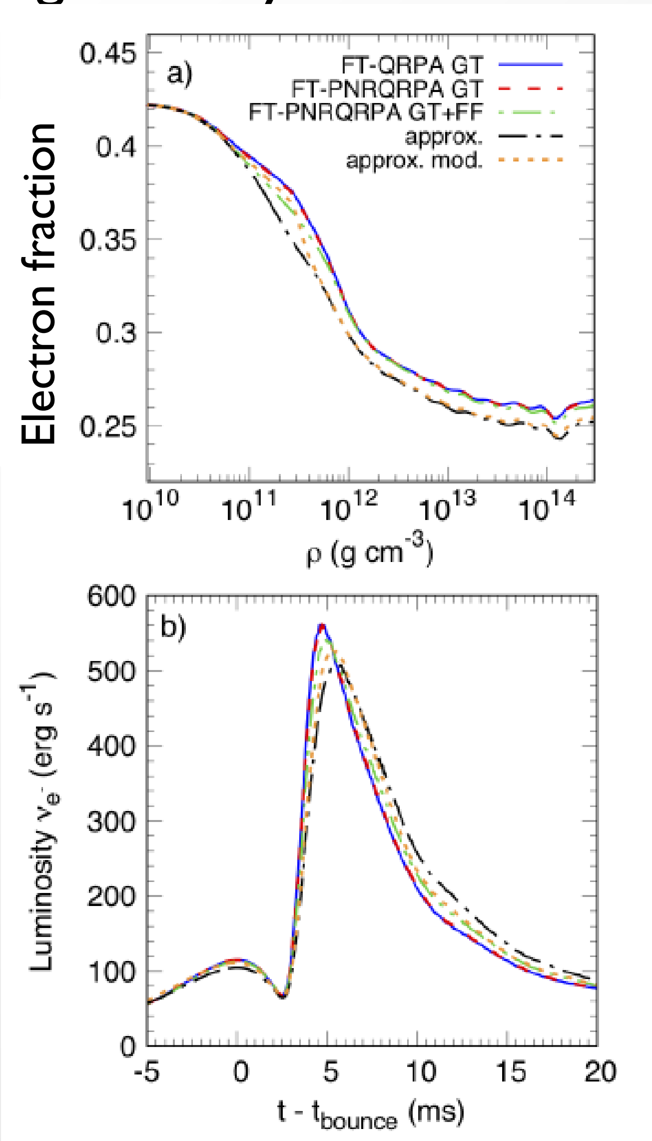


Giraud et al., Phys. Rev. C **105**, 055801 (2022)

Uncertainties in Core Collapse Supernovae Simulations due to Uncertainties in Electron Capture Rates Significantly Reduced

- EC rates at finite temperature estimated in multiple ways to study model dependence and uncertainties (benefits from IReNA):
  - Shell model: CE group, Alex Brown (MSU)
  - QRPA: Evan Ney, Jon Engel (UNC)
  - pnRQRPA: Ante Ravlic, Nils Paar (U. Zagreb)

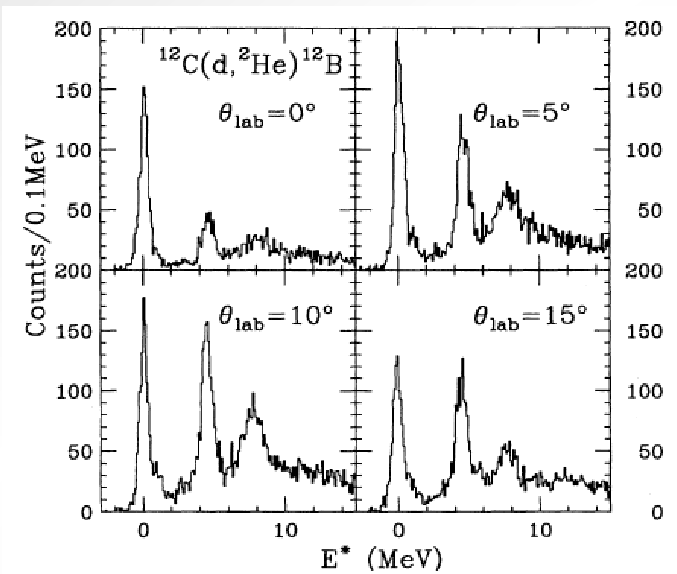
- Simulations in GR1D – EC rates included in NuLiB (Evan O'Connor)
- Differences in e.g. ν luminosity <10% compared to 30% a few years ago
- **Caveat: Almost all experimental tests on stable nuclei…**



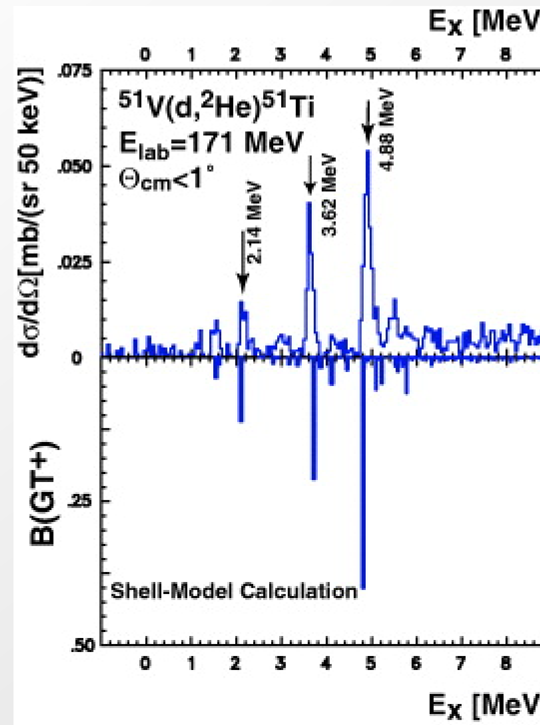
S. Giraud et al. Phys. Rev. C **105**, 055801 (2022) (2022)

(n,p)-type charge exchange on unstable nuclei?

- Not possible to make a viable neutron target
- It is very difficult to come up with a technique for (t,^{3}He) or heavy-ion charge-exchange in inverse kinematics
- (d,^{2}He) in inverse kinematics?



Successfully used in forward kinematics RIKEN/Texas A&M/KVI

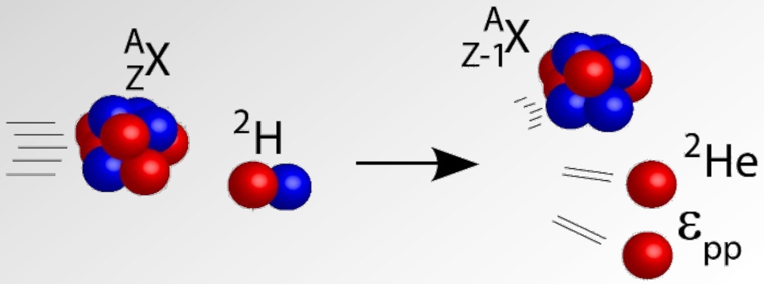


(*d*, ^{2}He) reactions at E_d=125.2 MeV

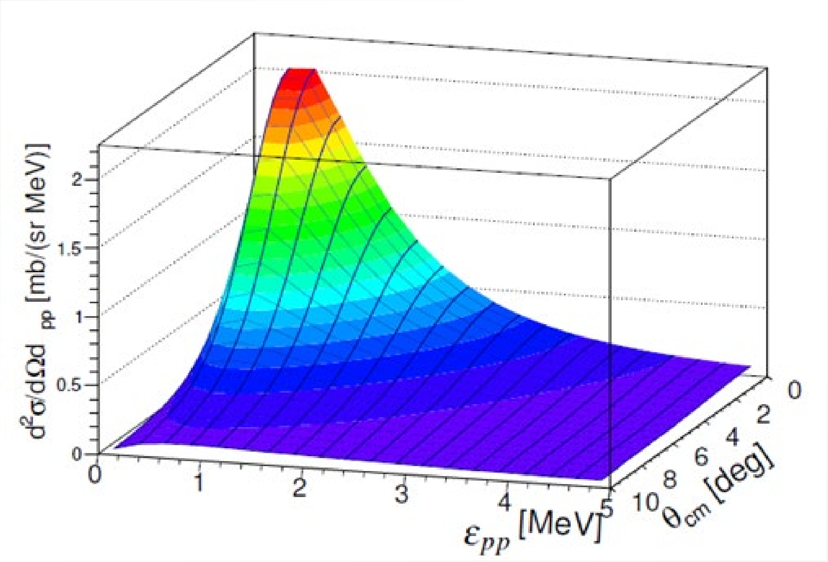
H.M. Xu, G.K. Ajupova, A.C. Betker,* C.A. Gagliardi, B. Kokenge, Y.-W. Lui, and A.F. Zaruba
Cyclotron Institute, Texas A&M University, College Station, Texas 77843
(Received 5 May 1995)

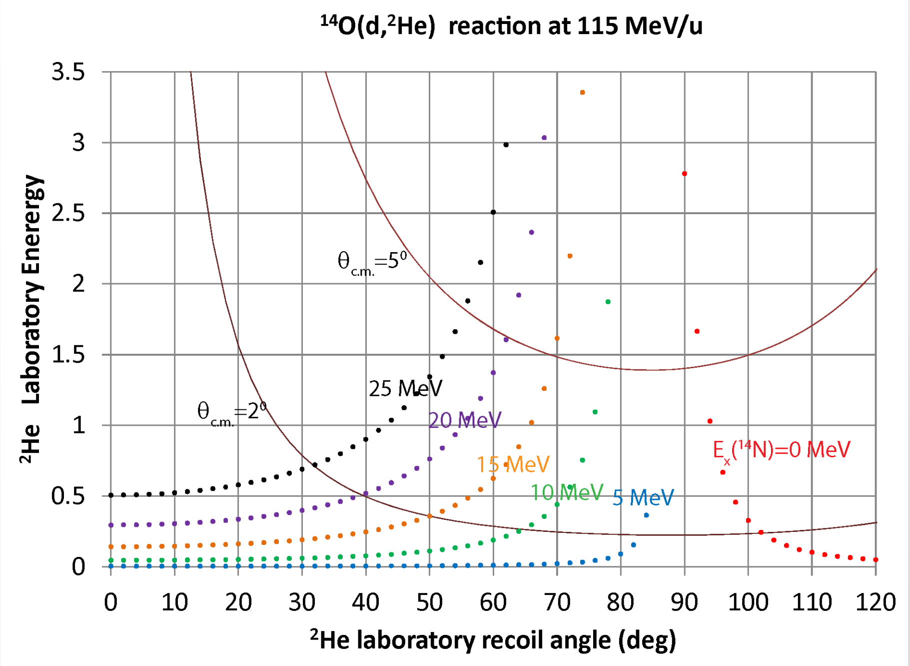
Bäumer et al, PRC 68, 031303 (2003)

EC rates on unstable nuclei: (d,^{2}He) in inverse kinematics



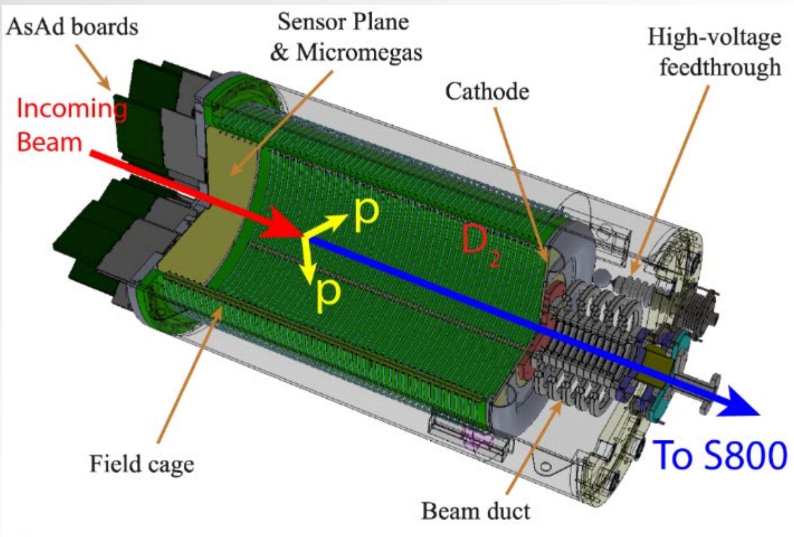
- ^{2}He is an unbound 2-p system
- If the relative energy between the two protons is small (ε_{pp}<1 MeV), ΔS=1 is ensured and a pure spin-transfer probe is created
- Successfully used in forward kinematics (Tokyo, Texas A&M, KVI)
- In inverse kinematics, the two protons have very low energy if the momentum transfer is small: difficult to measure

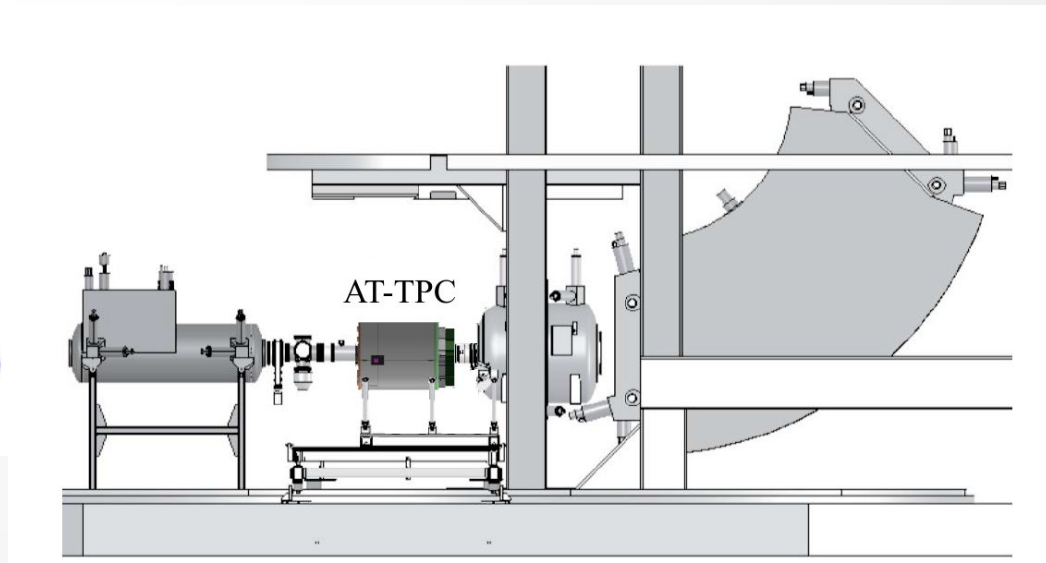


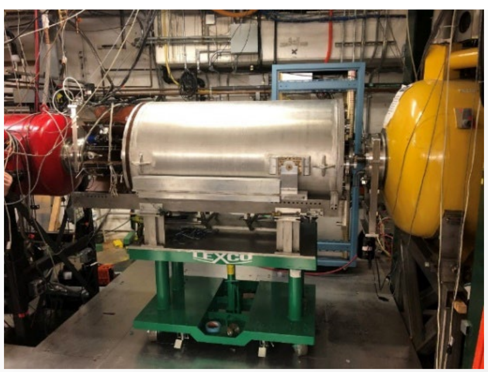


(d,^{2}He) in inverse kinematics

- Protons from ^{2}He detected in Active-Target Time Projection Chamber (AT-TPC)
- Heavy charge-exchange residue detected in S800;
- Tracked protons are used to reconstruct excitation energy and scattering angle

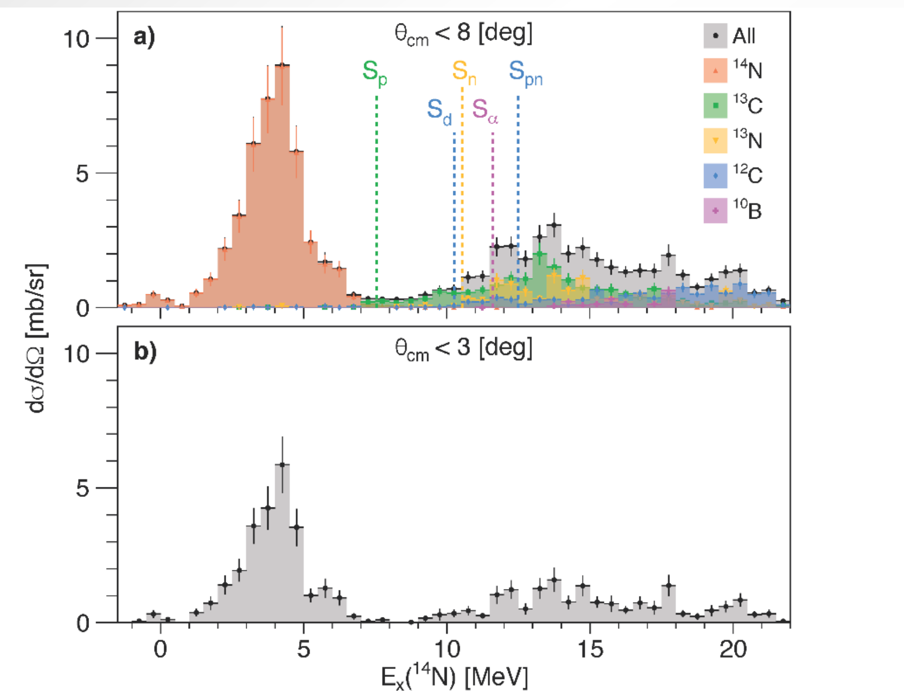


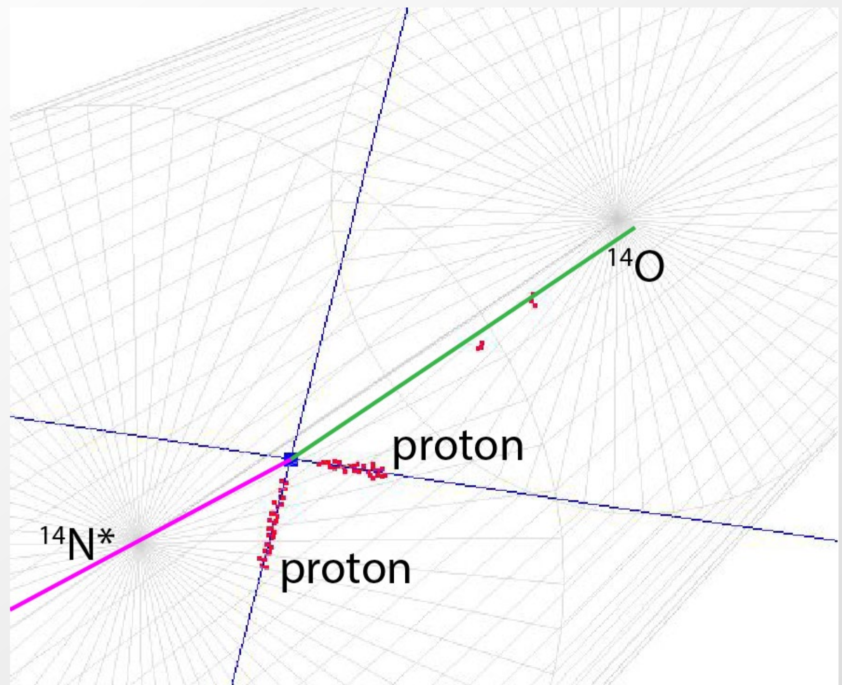




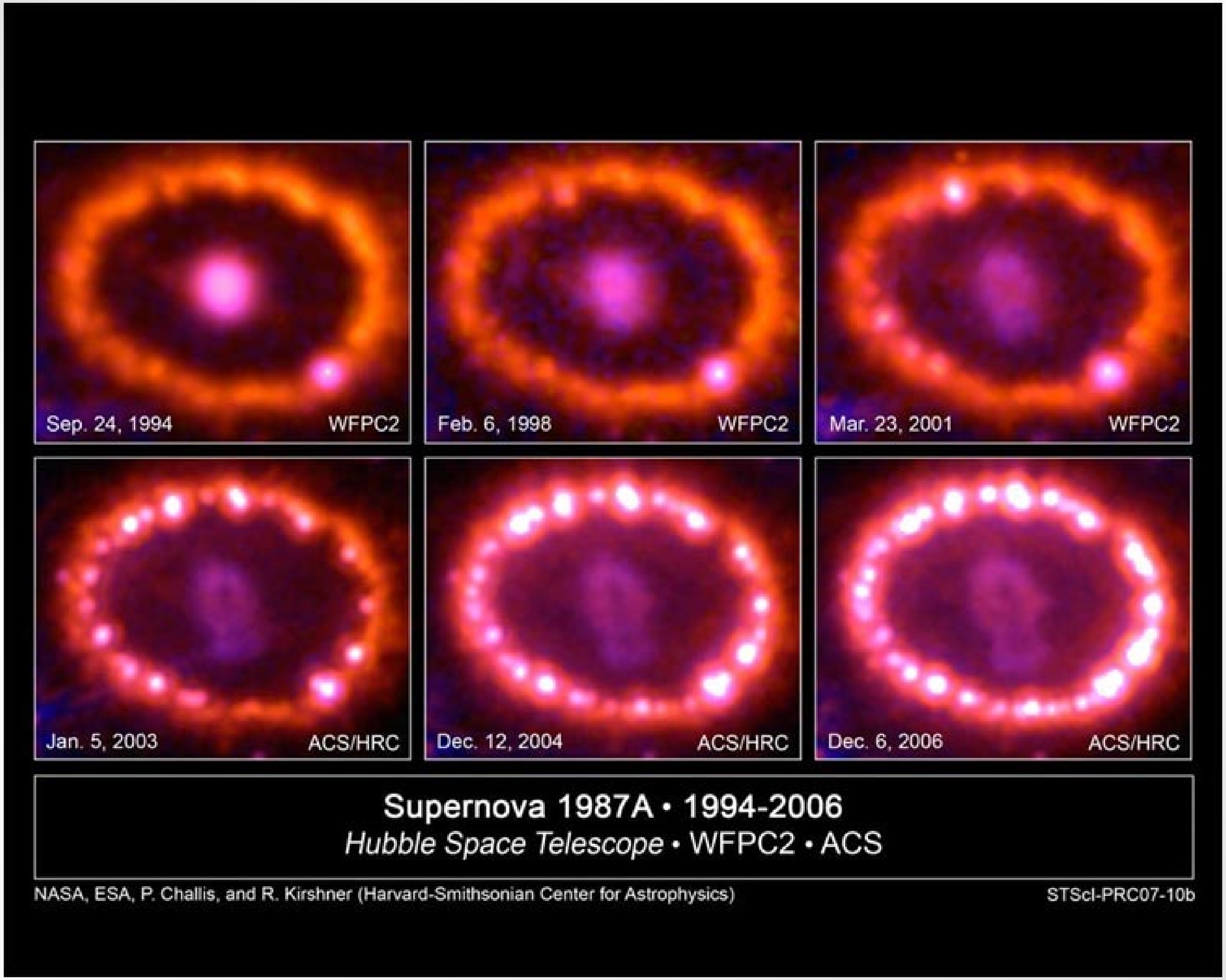
Pilot experiment: $^{14}O(d,^{2}He)$ in inverse kinematics

- Performed October 2020
- Beam intensities up to ~700,000 pps (detector is insensitive around beam path)
- Trigger by spectrometer and identification of 2 tracks from a single vertex: very clean spectra
- Successful extraction of excitation energy spectrum up to about $E_x(^{14}N)$=25 MeV





Thank you!



Sep. 24, 1994
WFPC2
Feb. 6, 1998
WFPC2
Mar. 23, 2001
WFPC2
Jan. 5, 2003
ACS/HRC
Dec. 12, 2004
ACS/HRC
Dec. 6, 2006
ACS/HRC
Supernova 1987A • 1994-2006
Hubble Space Telescope • WFPC2 • ACS
NASA, ESA, P. Challis, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)
STScI-PRC07-10b