# A bright-matter mystery: the quest for the origin of heavy elements

Background image: NASA

Ann-Cecilie Larsen

ERC-STG-2014 GA 637686

UiO : Department of Physics
University of Oslo

European Research Council
Established by the European Commission

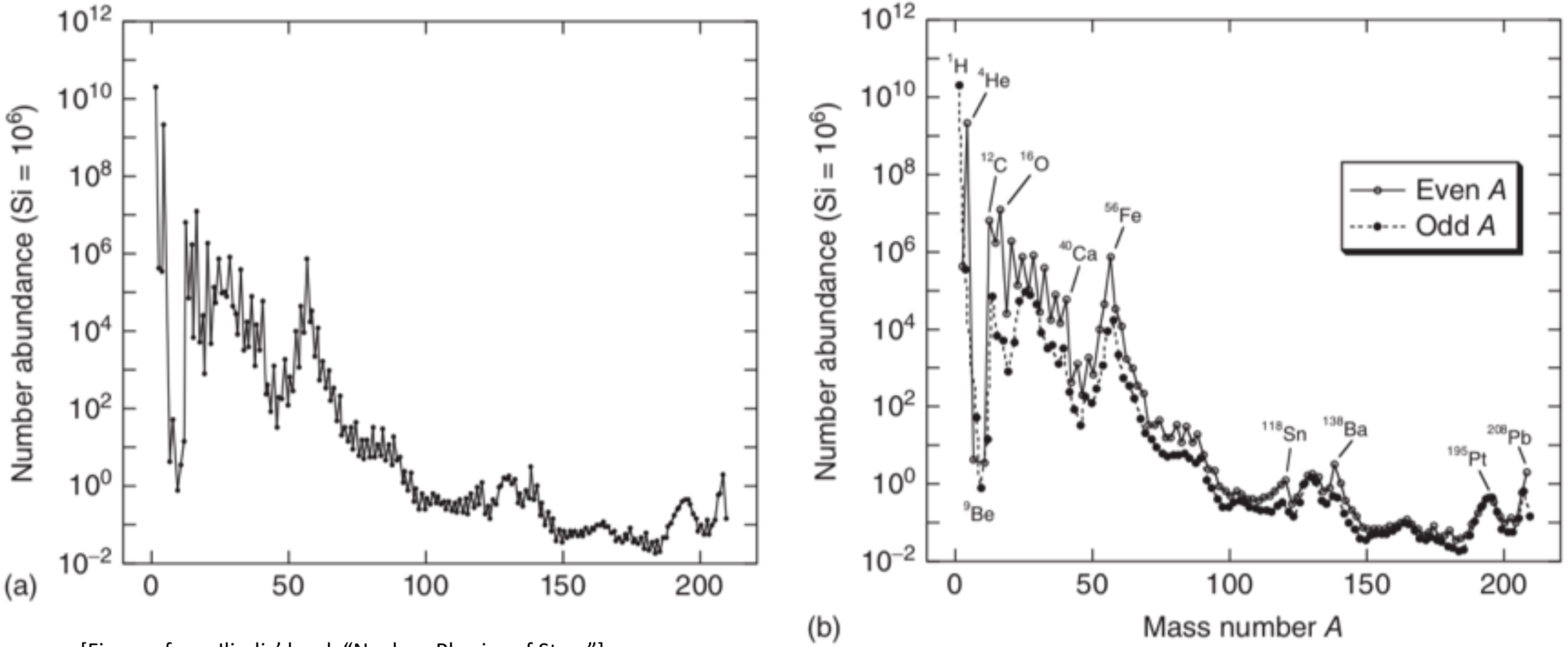
ChETEC Action

NSCL

JINA-CEE

# Element abundances in our solar system ☀️

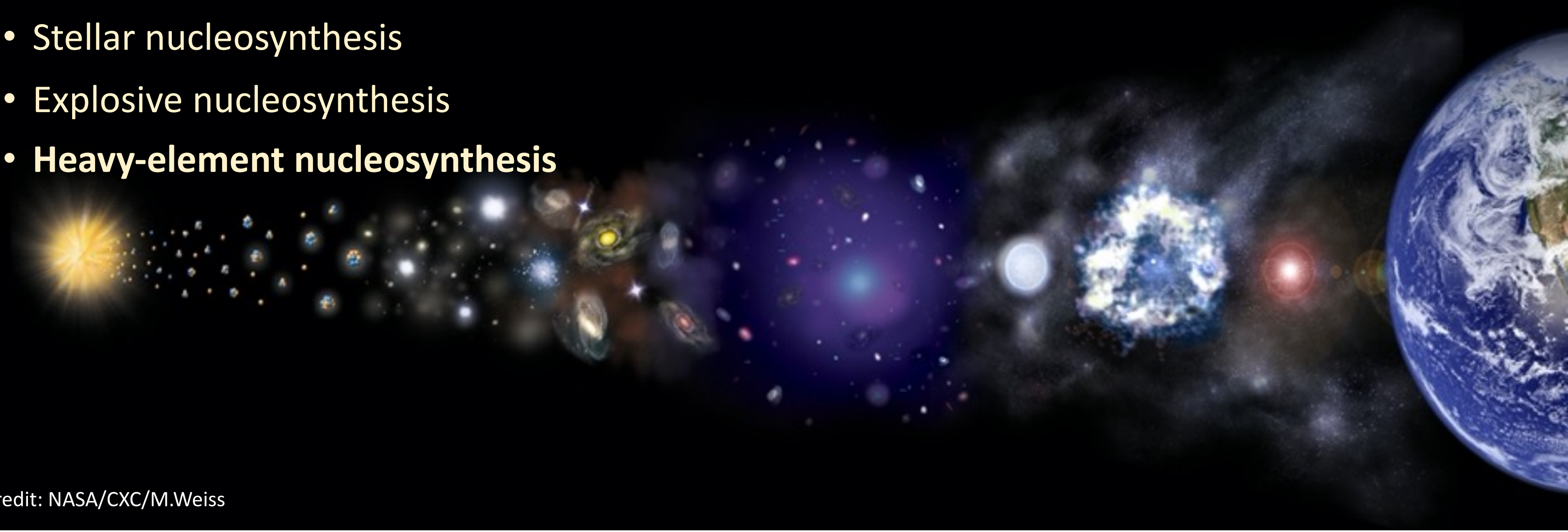
Where do they come from? 🤔




[Figures from Iliadis' book "Nuclear Physics of Stars"]

# From Big Bang until today

- Primordial nucleosynthesis and atomic formation
- Stellar nucleosynthesis
- Explosive nucleosynthesis
- **Heavy-element nucleosynthesis**



Credit: NASA/CXC/M.Weiss

# “We are star-stuff”

“The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars.

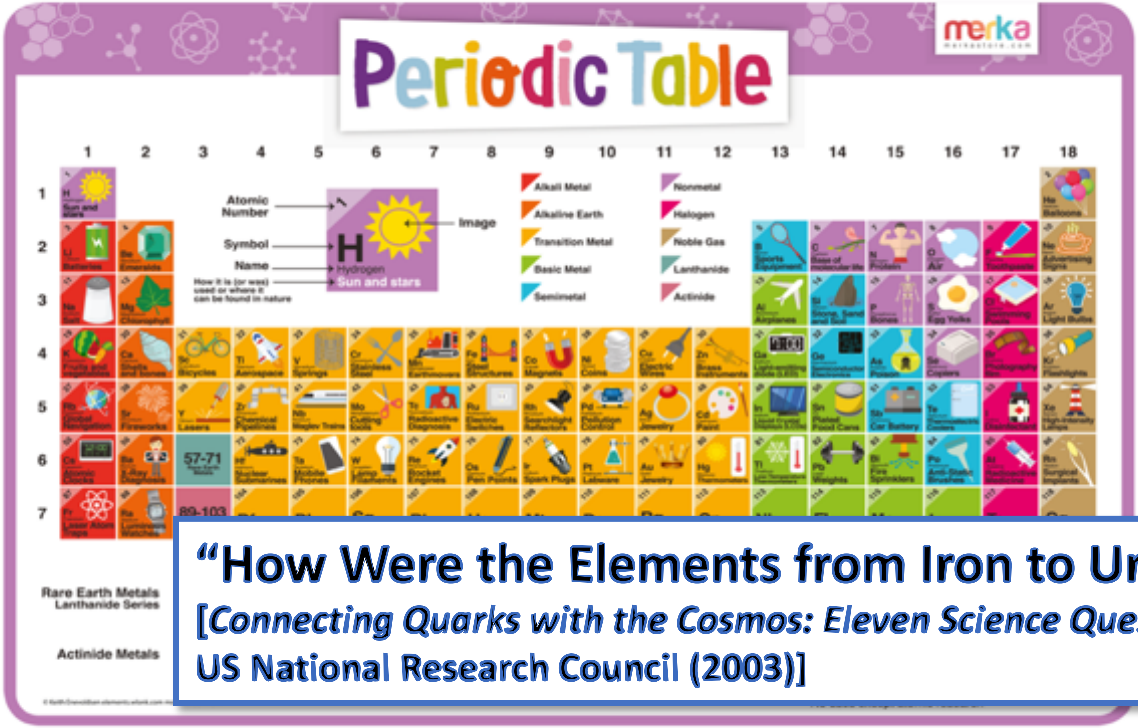
**We are made of star-stuff.”**

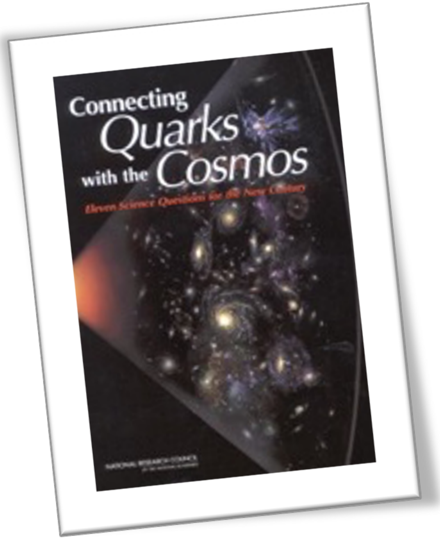
- Carl Sagan

*Big Bang*: hydrogen, helium, lithium
*Stellar and explosive nucleosynthesis*: up to iron/nickel

Credit: NASA

# The periodic table of elements




**"How Were the Elements from Iron to Uranium Made?"**

**[*Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century;* US National Research Council (2003)]**

https://merkastore.com/products/kids-periodic-table-of-elements

# Stars again ✨

REVIEWS OF

MODERN PHY

VOLUME 29, NUMBER 4

## Synthesis of the Elements in

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER

*Kellogg Radiation Laboratory, California Institute of Techno*
*Mount Wilson and Palomar Observatories, Carnegie Institution of*
*California Institute of Technology, Pasadena, Californ*

"It is the stars, The stars above us, govern our condit
(*King Lear*, Act IV, Sc

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourse
(*Julius Caesar*, Act I, Sc

PUBLICATIONS OF THE
ASTRONOMICAL SOCIETY OF THE PACIFIC

Vol. 69 June 1957 No. 408

## NUCLEAR REACTIONS IN STARS AND NUCLEOGENESIS*

A. G. W. CAMERON
Atomic Energy of Canada Limited
Chalk River, Ontario

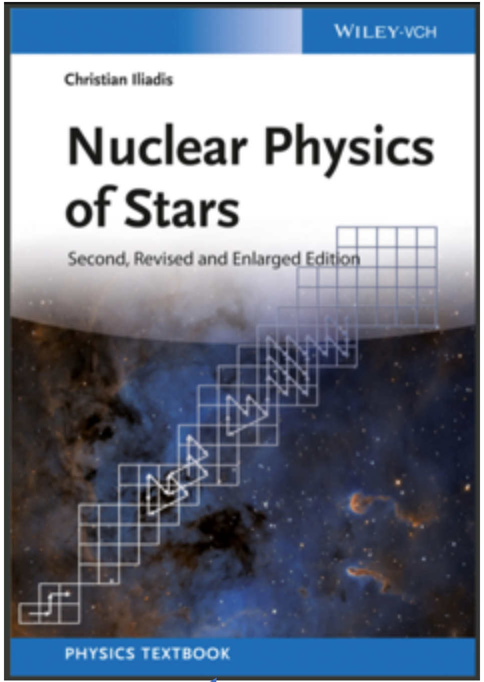
INTRODUCTION

It was once thought that the stars and the interstellar matter had a uniform chemical composition except for some of the lighter elements, which were destroyed by thermonuclear reactions in stellar interiors. This view has caused astronomers and physicists to look for extreme physical conditions in which all the mat-

Photo credit: Annie Gracy

# Notation and terminology

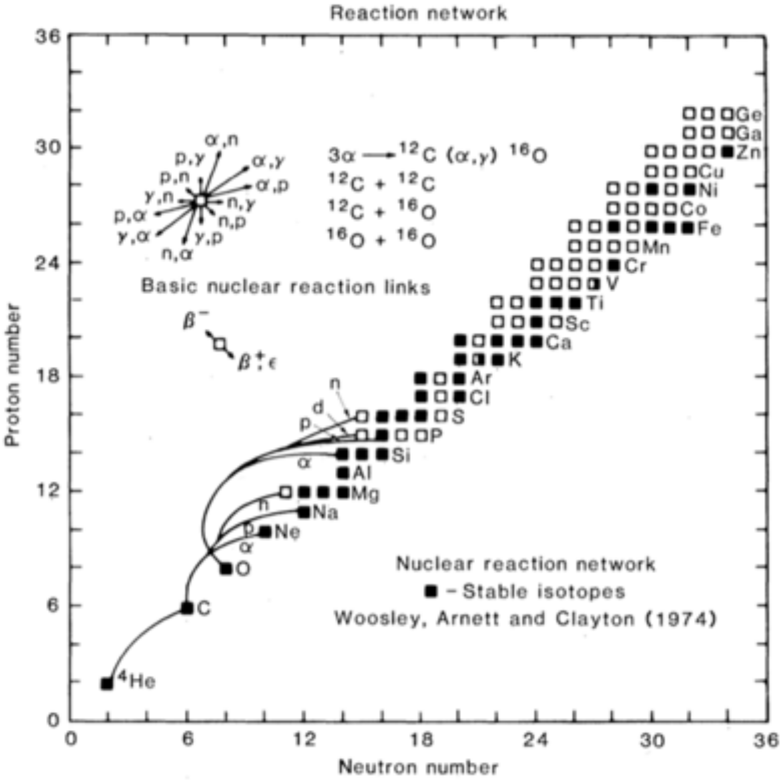
- **Radiative neutron capture reaction**: (n,$\gamma$) -> the "target" nucleus absorbs a neutron and emits $\gamma$ rays to get rid of the excess energy (Z equal, A+1)
- **Radiative proton capture reaction**: (p,$\gamma$) -> the "target" nucleus absorbs a proton and emits $\gamma$ rays (Z+1, A+1)
- **Beta decay**: either $\beta^-$ (electron + anti neutrino emission, element Z+1, A equal) or $\beta^+$ (positron + neutrino emission, element Z-1, A equal)
- **Photodisintegration**: ($\gamma$,n), ($\gamma$,p), ($\gamma$,$\alpha$) -> the inverse of radiative captures
- **Reaction network**: network including many different reactions connecting a set of nuclei, with the aim to reproduce observed elemental and isotopic abundances




Nice textbook!

# Example, nuclear reaction network 

Need to figure out which reactions are critical for producing (or destroying) a given nucleus
=> The **probability** or **rate ( cross section)** of a given reaction




From William Fowler, Science (1984)

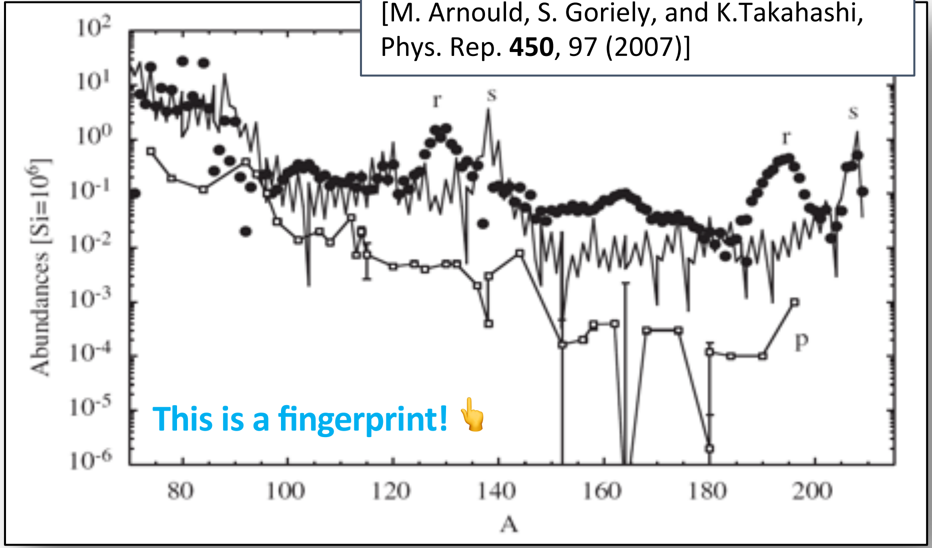
Fig. 3. Reaction network for nucleosynthesis involving the most important stable and radioactive nuclei with $N = 2$ to 34 and $Z = 2$ to 32. Stable nuclei are indicated by solid squares. Radioactive nuclei are indicated by open squares.

# How to “cook” heavy elements 🍳

**Slow** neutron capture (*s*) process (≈50%)

**Rapid** neutron-capture (*r*) process (≈50%)

*p* process: proton capture, photodisintegration, νp-process, … (~0.1-1%)

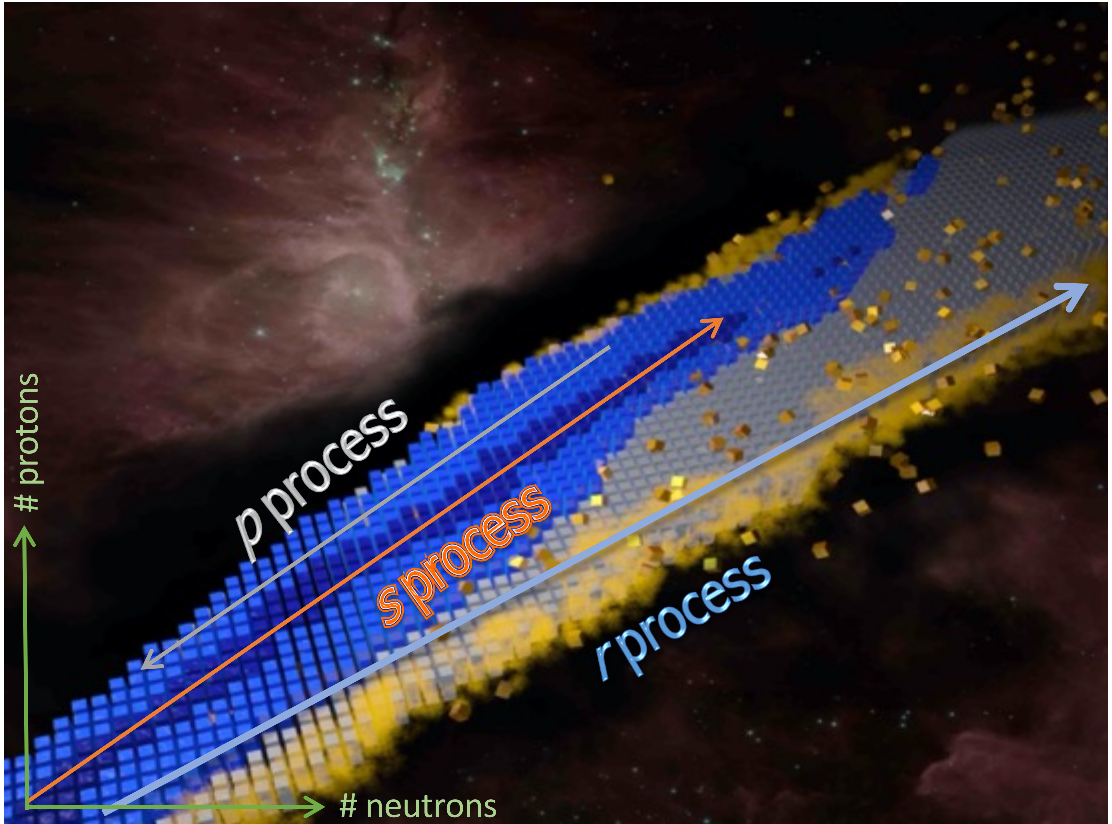



[M. Arnould, S. Goriely, and K.Takahashi, Phys. Rep. **450**, 97 (2007)]

Things to consider for *neutron capture* processes:

- No Coulomb barrier!
- Cross sections decrease with neutron energy, opposite to charged-particle reactions
- Free neutrons are *perishables* ($T_{1/2}$≈ 10 minutes)

# Processes contributing to the heavy-element yields – schematic "paths" in the nuclear chart




**In addition:**

- *Rapid proton-capture process* (probably not contributing to the observed abundances)
- *Intermediate neutron-capture process* (?!)

# The *r* process … WHERE???

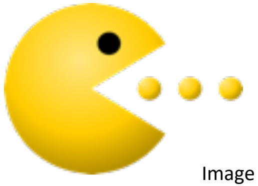
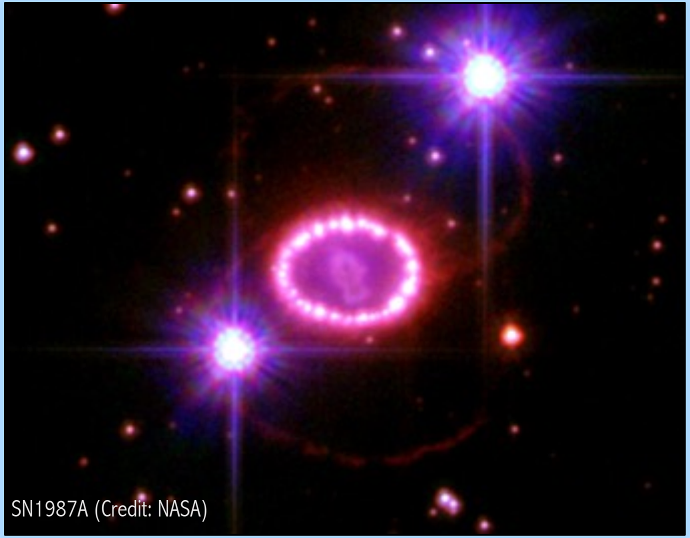


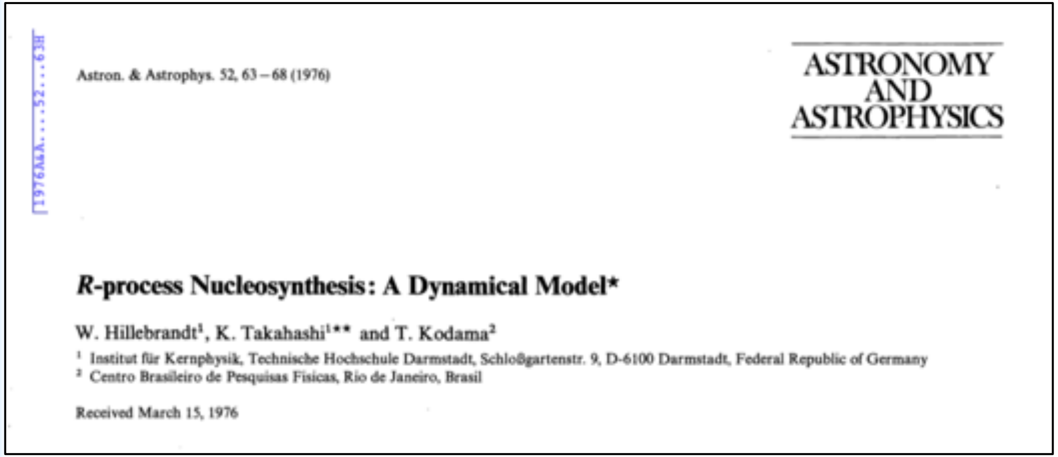
Image from pixabay.com

**Extremely** high neutron density ($10^{20}$ /cm$^3$ or more), maybe (?) high temperature (1-5 x $10^9$K), and **extremely** fast (≈ 1 second)



SN1987A (Credit: NASA)

For many years, core-collapse supernovae were favored



1976A&A....52...63H

Astron. & Astrophys. 52, 63 – 68 (1976)

ASTRONOMY AND ASTROPHYSICS

***R*-process Nucleosynthesis: A Dynamical Model***

W. Hillebrandt[1], K. Takahashi[1**] and T. Kodama[2]

[1] Institut für Kernphysik, Technische Hochschule Darmstadt, Schloßgartenstr. 9, D-6100 Darmstadt, Federal Republic of Germany
[2] Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brasil

Received March 15, 1976

… but modern simulations gave too few neutrons…

# The *r* process … WHERE???

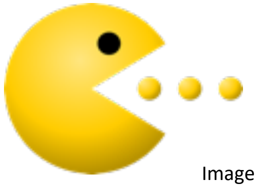
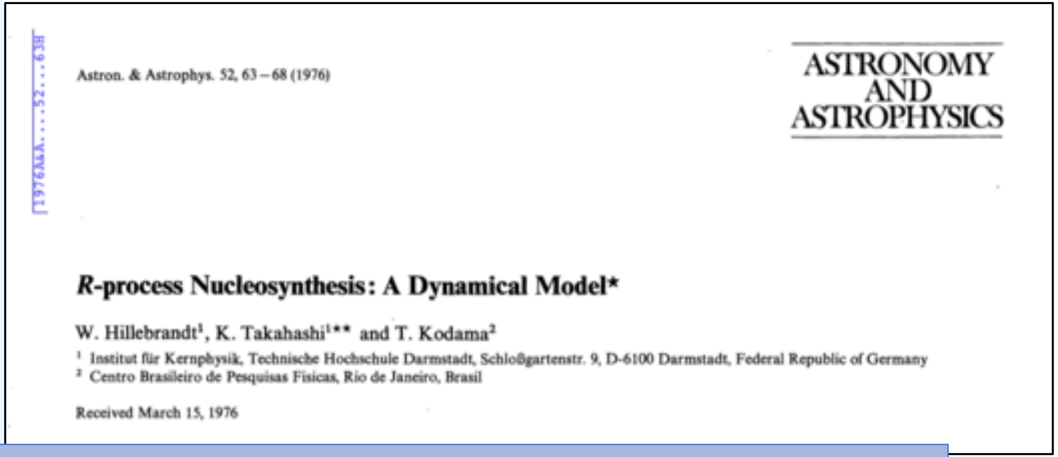


Image from pixabay.com

**Extremely** high neutron density ($10^{20}$ /cm$^3$ or more), maybe (?) high temperature (1-5 x $10^9$K), and **extremely** fast (≈ 1 second)

SN1987A (Credit: NASA)

For many years, core-collapse supernovae were favored



1976A&A....52...63H

Astron. & Astrophys. 52, 63 – 68 (1976)

ASTRONOMY AND ASTROPHYSICS

***R*-process Nucleosynthesis: A Dynamical Model***

W. Hillebrandt[1], K. Takahashi[1]** and T. Kodama[2]

[1] Institut für Kernphysik, Technische Hochschule Darmstadt, Schloßgartenstr. 9, D-6100 Darmstadt, Federal Republic of Germany
[2] Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brasil

Received March 15, 1976

"… our notion of supernova nucleosynthesis was shattered…"
[Hans-Thomas Janka, Annu. Rev. Nucl. Part. Sci. 62, 407 (2012)]

# The *r* process … WHERE???

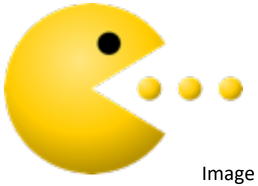


Image from pixabay.com

**Extremely** high neutron density ($10^{20}$ /cm$^3$ or more), maybe (?) high

PRL 109, 251104 (2012) PHYSICAL REVIEW LETTERS week ending 21 DECEMBER 2012

**Charged-Current Weak Interaction Processes in Hot and Dense Matter and its Impact on the Spectra of Neutrinos Emitted from Protoneutron Star Cooling**

G. Martínez-Pinedo,[1,2] T. Fischer,[2,1] A. Lohs,[1] and L. Huther[1]

[1]*Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstraße 2, 64289 Darmstadt, Germany*

[2]*GSI Helmholtzzentrum für Schwerioneneforschung, Planckstraße 1, 64291 Darmstadt, Germany*

(Received 12 May 2012; published 20 December 2012)

We perform three-flavor Boltzmann neutrino transport radiation hydrodynamics simulations covering a period of 3 s after the formation of a protoneutron star in a core-collapse supernova explosion. Our results show that a treatment of charged-current neutrino interactions in hot and dense matter as suggested by Reddy *et al.* [Phys. Rev. D **58**, 013009 (1998)] has a strong impact on the luminosities and spectra of the emitted neutrinos. When compared with simulations that neglect mean-field effects on the neutrino opacities, we find that the luminosities of all neutrino flavors are reduced while the spectral differences between electron neutrinos and antineutrinos are increased. Their magnitude depends on the equation of state and in particular on the symmetry energy at subnuclear densities. These modifications reduce the proton-to-nucleon ratio of the outflow, increasing slightly their entropy. They are expected to have a substantial impact on nucleosynthesis in neutrino-driven winds, even though they do not result in conditions that favor an *r* process. Contrary to previous findings, our results show that the spectra of

…ae were favored

ASTRONOMY AND ASTROPHYSICS

…, Federal Republic of Germany

…ered…"

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Physics Reports 442 (2007) 237–268

PHYSICS REPORTS

www.elsevier.com/locate/physrep

# Where, oh where has the *r*-process gone?

Y.-Z. Qian[a,*], G.J. Wasserburg[b]

[a] *School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*

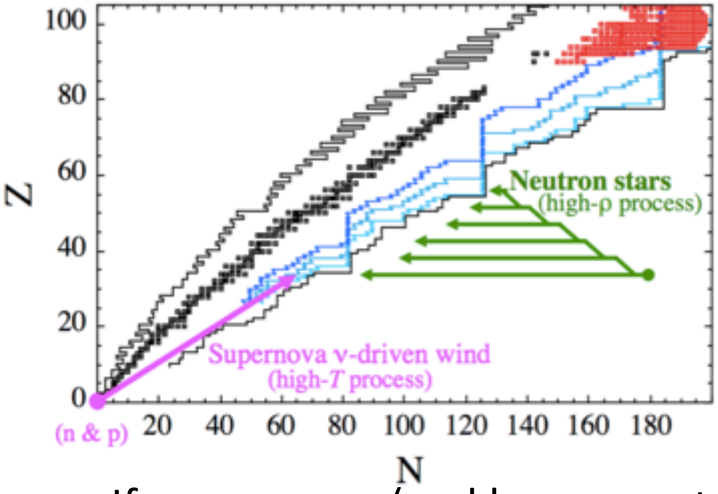
[b] *The Lunatic Asylum, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA*

Available online 16 February 2007

editor: G.E. Brown

# Problems, unknown *r*-process site

Figure from Stephane Goriely's talk at the 13th Nordic Meeting on Nuclear Physics, 2015




- We don't know the initial conditions (density, temperature, neutron flux, …)
- Because we don't know the conditions, we don't know exactly which nuclear-physics input is (most) relevant

In particular: **will there be an equilibrium between neutron capture (n,$\gamma$) and photodisintegration ($\gamma$,n) processes?**

If ***yes***, masses (and hence neutron separation energies) and beta-decay rates are most important

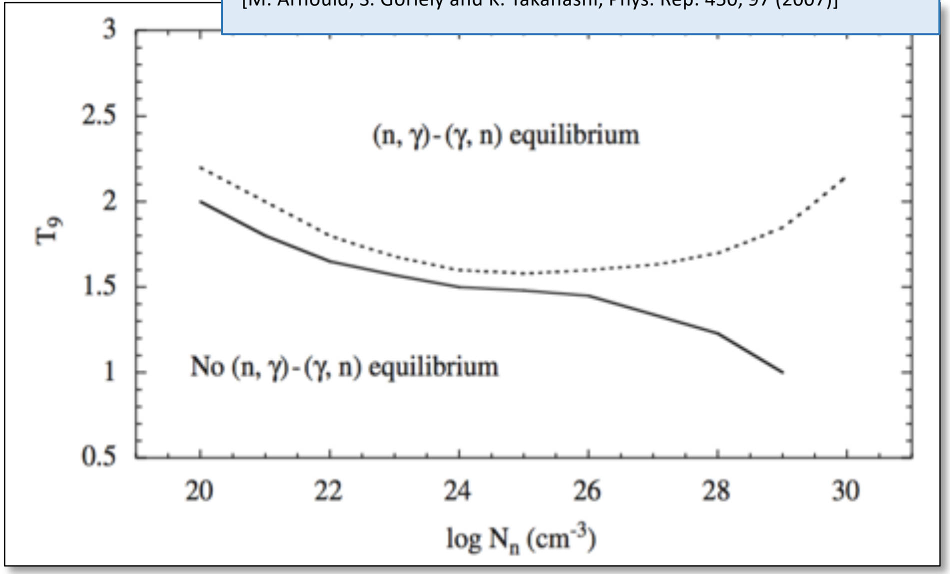
If ***no***, neutron-capture rates and fission rates are also important (=> much more complicated reaction network)

# (n,γ)-(γ,n) equilibrium: to be or not to be ⚖️

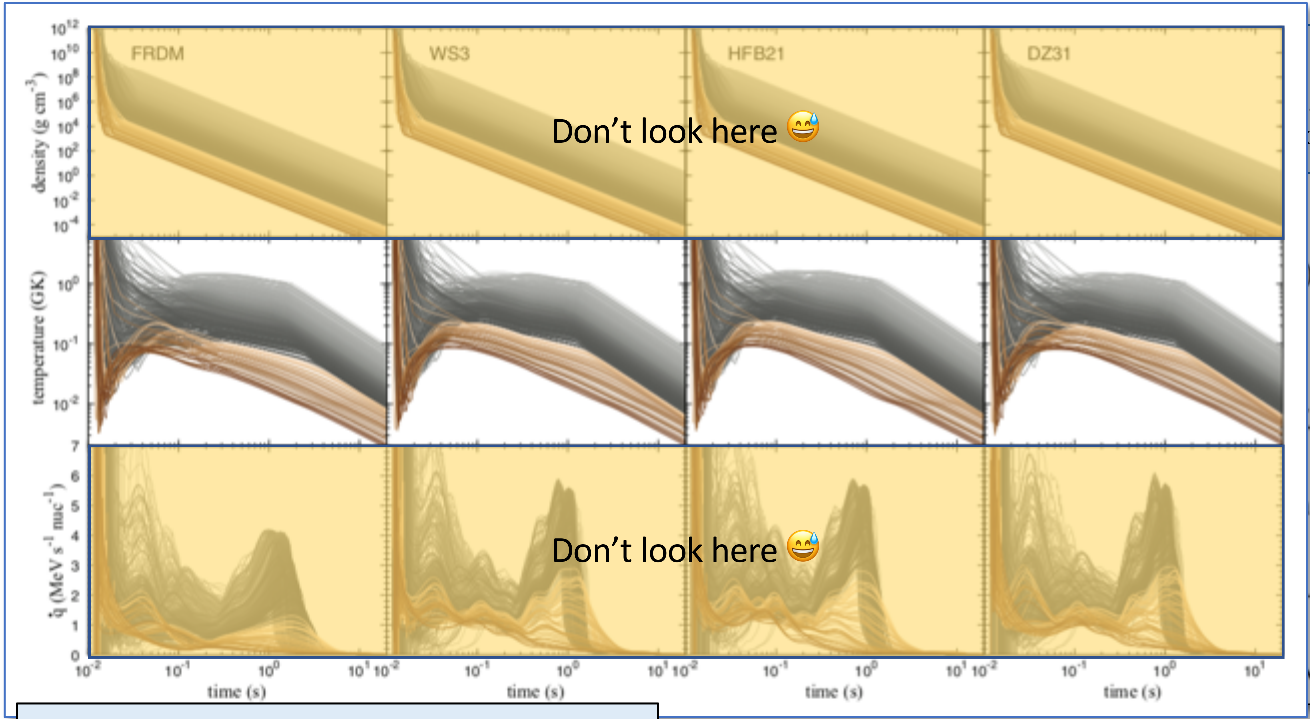
- Near and at the neutron drip line, the neutron separation energies are very low (~keV range)
- In the *r* process, both (n,γ) and (γ,n) are faster than $\beta^-$ decay
- BUT: there is a strong interplay between temperature, neutron density, and nuclear-physics properties (capture cross sections!) that must be considered

Solid line: pure Hauser-Feshbach; dashed line: also **direct capture**

[M. Arnould, S. Goriely and K. Takahashi, Phys. Rep. 450, 97 (2007)]

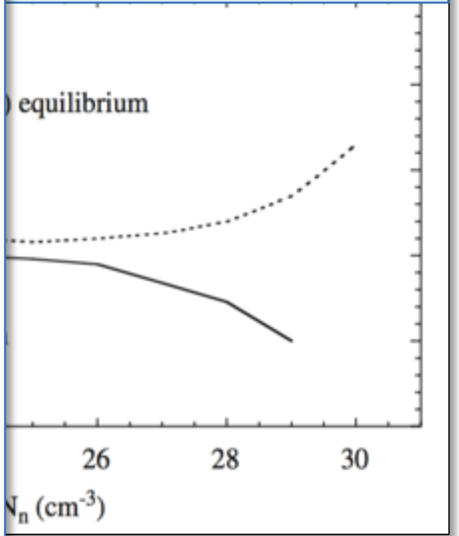


# (n,γ)-(γ,n) equilibrium: to be or not to be ⚖️

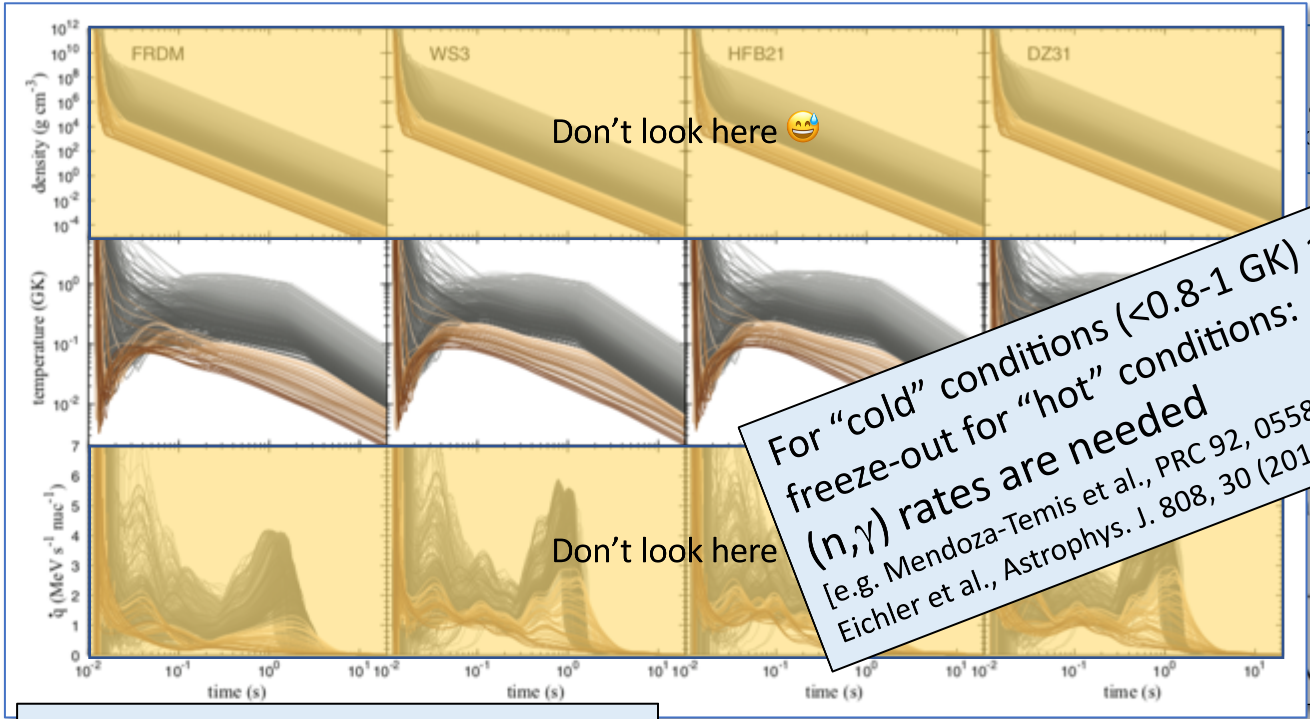



Mendoza-Temis et al., PRC 92, 055805 (2015);

…auser-Feshbach; dashed
**…apture**
[… Takahashi, Phys. Rep. 450, 97 (2007)]



# (n,γ)-(γ,n) equilibrium: to be or not to be ⚖️

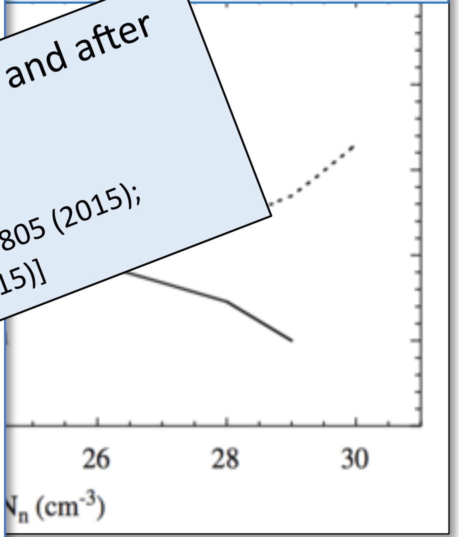



Don't look here 😅

Don't look here

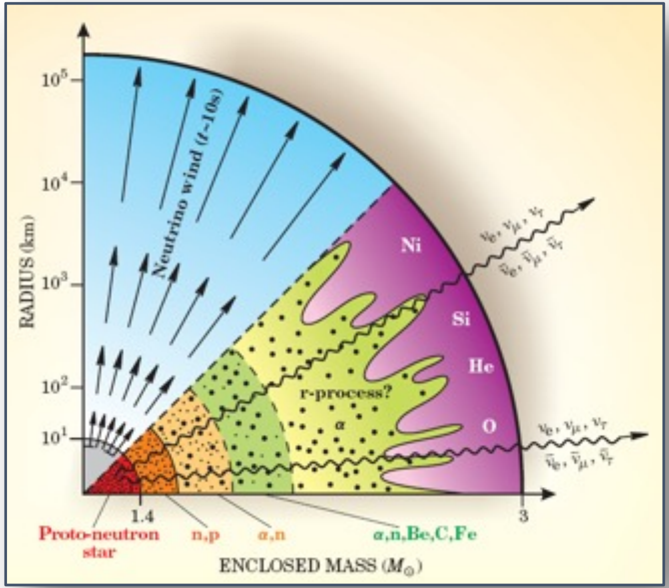
Mendoza-Temis et al., PRC 92, 055805 (2015);

auser-Feshbach; dashed
**apture**
. Takahashi, Phys. Rep. 450, 97 (2007)]



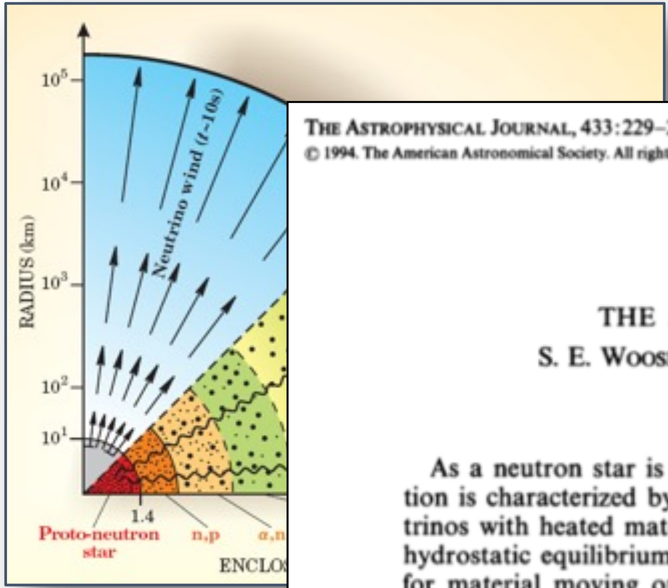

For "cold" conditions (<0.8-1 GK) and after freeze-out for "hot" conditions:
**(n,γ) rates are needed**
[e.g. Mendoza-Temis et al., PRC 92, 055805 (2015); Eichler et al., Astrophys. J. 808, 30 (2015)]

# Alternative sites for the *r* process: neutrino-driven wind from a baby neutron star




Equilibrium between (n,$\gamma$) and ($\gamma$,n) most of the time, only moderately neutron rich

# Alternative sites for the *r* process: neutrino-driven wind from a baby neutron star




Equilibrium between (n,γ) and (γ,n) most

THE ASTROPHYSICAL JOURNAL, 433:229–246, 1994 September 20

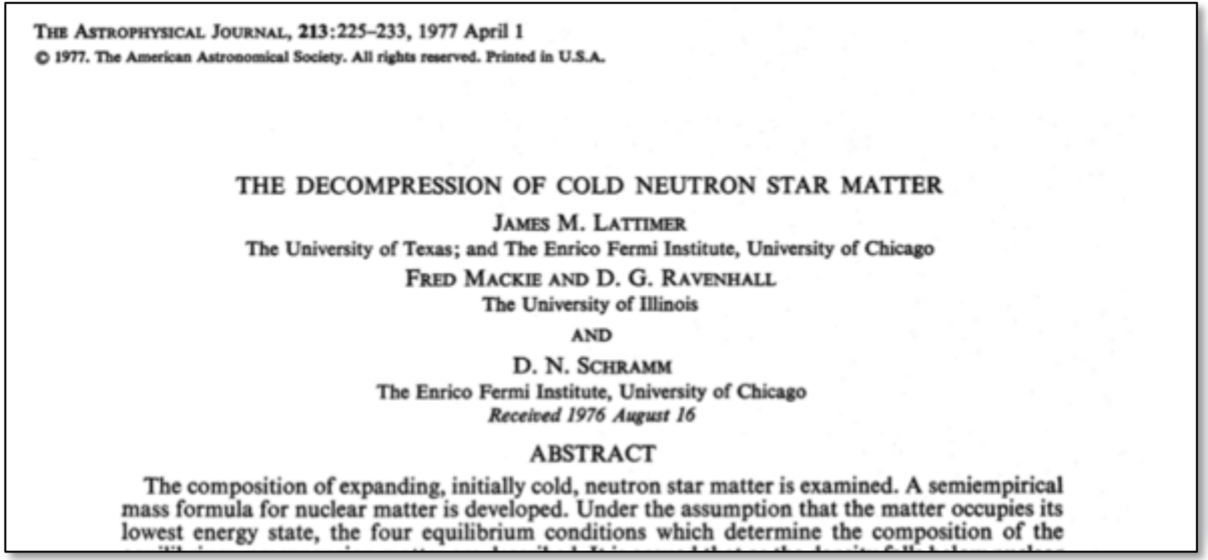

## THE *r*-PROCESS AND NEUTRINO-HEATED SUPERNOVA EJECTA

S. E. WOOSLEY,[1,2] J. R. WILSON,[2] G. J. MATHEWS,[2] R. D. HOFFMAN,[1] AND B. S. MEYER[3]
*Received 1993 October 22; accepted 1994 March 24*


### ABSTRACT

As a neutron star is formed by the collapse of the iron core of a massive star, its Kelvin-Helmholtz evolution is characterized by the release of gravitational binding energy as neutrinos. The interaction of these neutrinos with heated material above the neutron star generates a hot bubble in an atmosphere that is nearly in hydrostatic equilibrium and heated, after ~10 s, to an entropy of $S/N_A k \gtrsim 400$. The neutron-to-proton ratio for material moving outward through this bubble is set by the balance between neutrino and antineutrino capture on nucleons. Because the electron antineutrino spectrum at this time is hotter than the electron neutrino spectrum, the bubble is neutron-rich ($0.38 \lesssim Y_e \lesssim 0.47$). Previous work using a schematic model has shown that these conditions are well suited to the production of heavy elements by the *r*-process. In this paper

# Alternative sites for the *r* process: neutron star collision 💥


THE ASTROPHYSICAL JOURNAL, **213**:225–233, 1977 April 1


THE DECOMPRESSION OF COLD NEUTRON STAR MATTER

JAMES M. LATTIMER
The University of Texas; and The Enrico Fermi Institute, University of Chicago
FRED MACKIE AND D. G. RAVENHALL
The University of Illinois
AND
D. N. SCHRAMM
The Enrico Fermi Institute, University of Chicago
*Received 1976 August 16*

ABSTRACT

The composition of expanding, initially cold, neutron star matter is examined. A semiempirical mass formula for nuclear matter is developed. Under the assumption that the matter occupies its lowest energy state, the four equilibrium conditions which determine the composition of the

Credit: Dana Berry, SkyWorks Digital, Inc

# First live observation of the *r* process in 2017


NS merger observed **live!**

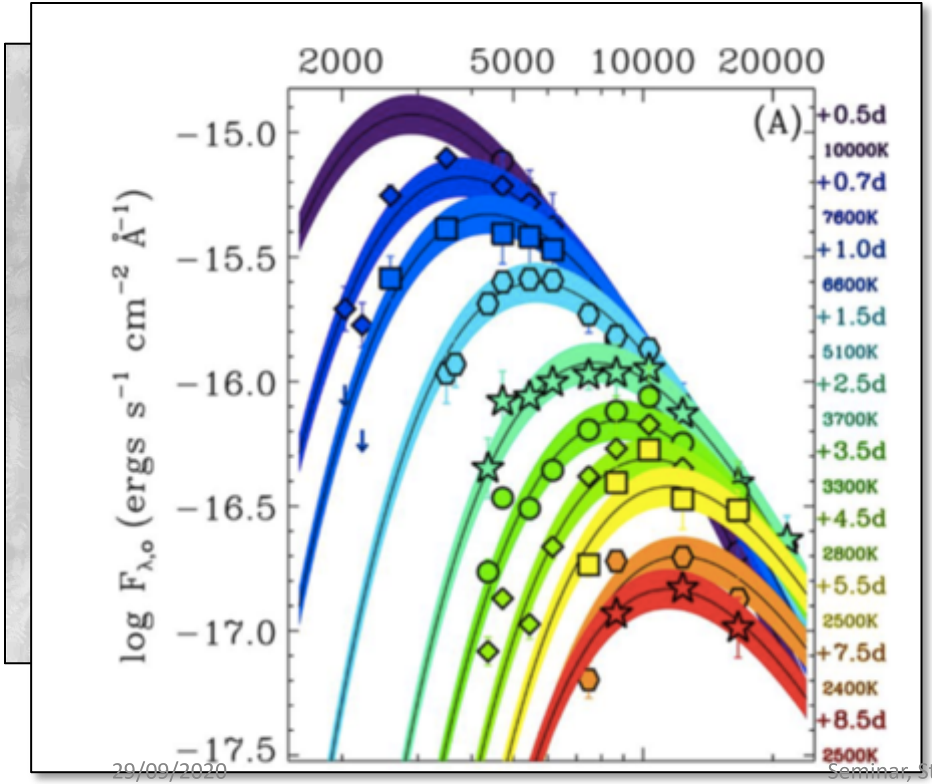
17 Aug 2017 by Adv. LIGO & Adv. Virgo

[Abbott et al., Phys. Rev. Lett. **119**, 161101 (2017)]

**"Afterglow" consistent with *r*-process nucleosynthesis**

[Kasen et al., Nature **551**, 80 (2017), E. Pian et al., Nature **551**, 67(2017) +++]

# First live observation of the *r* process in 2017

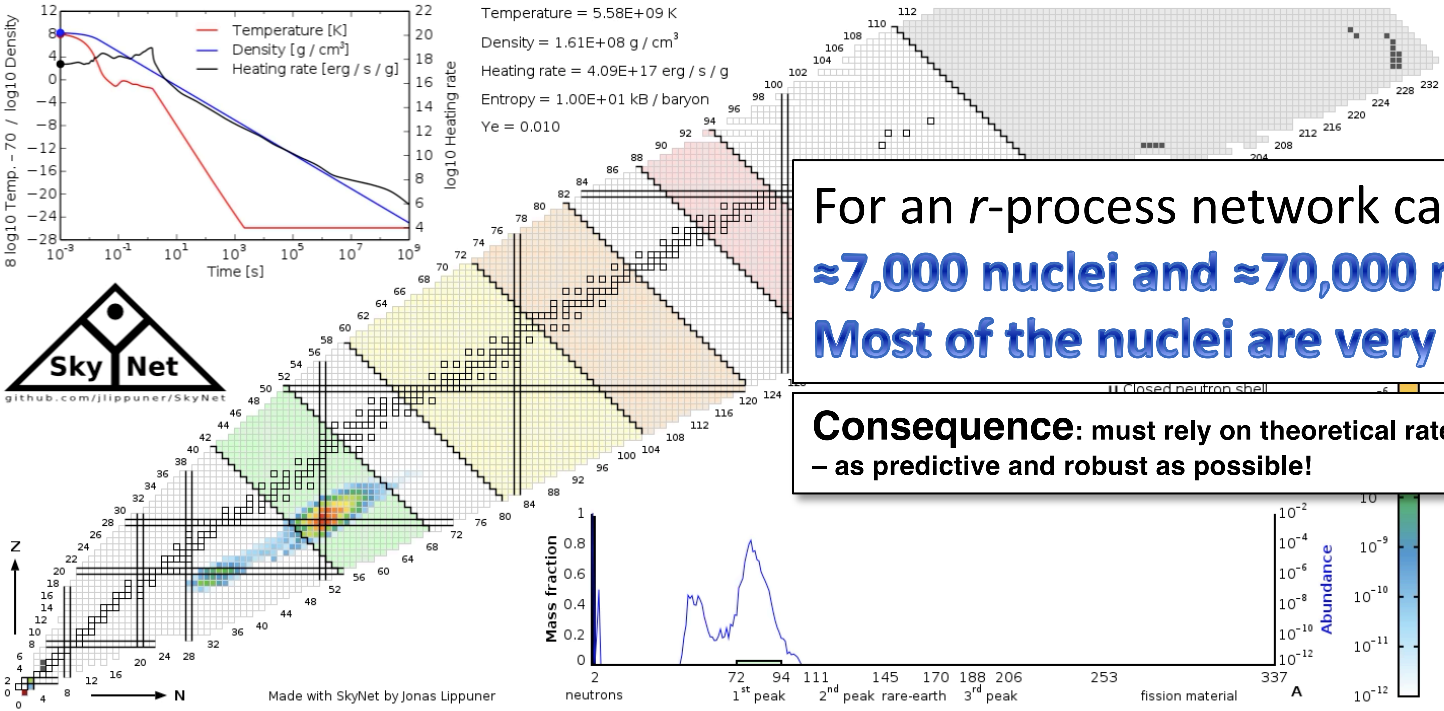



NS merger observed **live!**
17 Aug 2017 by Adv. LIGO & Adv. Virgo
[Abbott et al., Phys. Rev. Lett. **119**, 161101 (2017)]

**“Afterglow” consistent with *r*-process nucleosynthesis**
[Kasen et al., Nature **551**, 80 (2017), E. Pian et al., Nature **551**, 67(2017) +++]

M.R. Drout et al., Science **358**, 1570 (2017)

# Nuclear reaction network simulation for the *r* process – NS merger conditions




For an *r*-process network calculation:

**≈7,000 nuclei and ≈70,000 rates;**

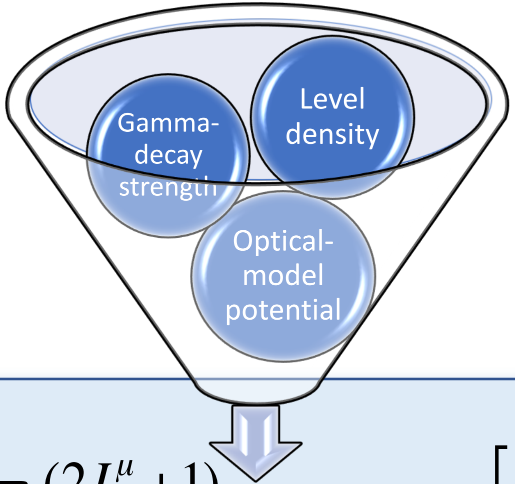
**Most of the nuclei are very short-lived**

**Consequence: must rely on theoretical rates – as predictive and robust as possible!**

Jonas Lippuner, Skynet https://jonaslippuner.com/research/skynet/

# How to calculate radiative neutron-capture rates?

We still rely on Hauser-Feshbach theory!
-> “Compound nucleus” picture of Bohr
[W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952)]




$$N_A\langle\sigma v\rangle(T) = \left(\frac{8}{\pi m}\right)^{1/2} \frac{N_A}{(kT)^{3/2}G(T)} \int_0^\infty \sum_\mu \frac{(2I^\mu+1)}{(2I^0+1)} \sigma^\mu(E) E \exp\left[-\frac{(E+E_x^\mu)}{kT}\right] dE$$

$$G(T) = \sum_\mu (2I^\mu+1)/(2I^0+1)\exp(-E_x^\mu/kT)$$

**Uncertain input → Uncertain output (orders of magnitude!)**
[E.g. Mumpower et al., PPNP 86, 86 (2016)]

# Level density and γ-ray strength function 😎

**Level density:**

Number of quantum levels per energy unit as function of $E_x$, $J$, $\pi$:

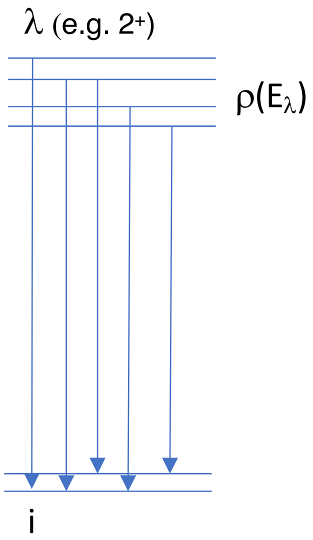
$$\rho = \rho(E_x, J, \pi)$$

**Gamma strength function:**

Average, nuclear electromagnetic response

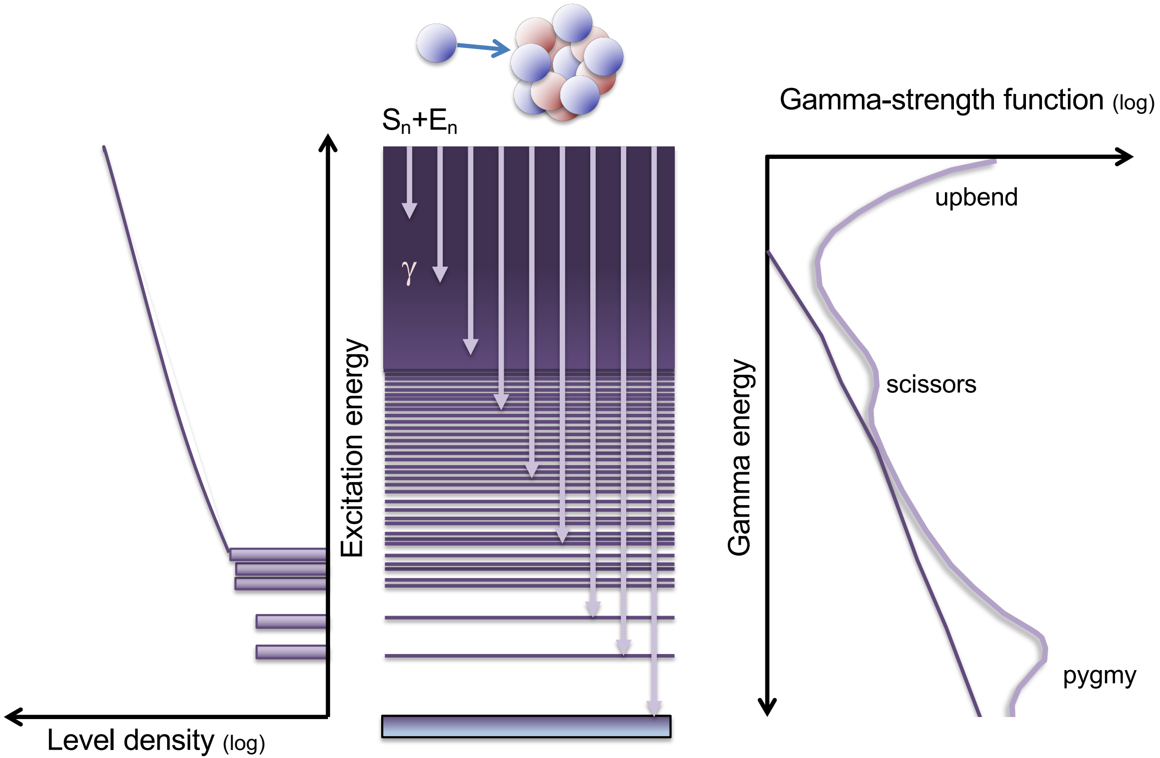
**Distribution** of average, reduced partial widths as function of γ-ray energy

$$f^J_{i\lambda XL}(E_\gamma) = \frac{\bar{\Gamma}^J_{\gamma i\lambda XL}}{E_\gamma^{2L+1}} \rho(E_\lambda)$$



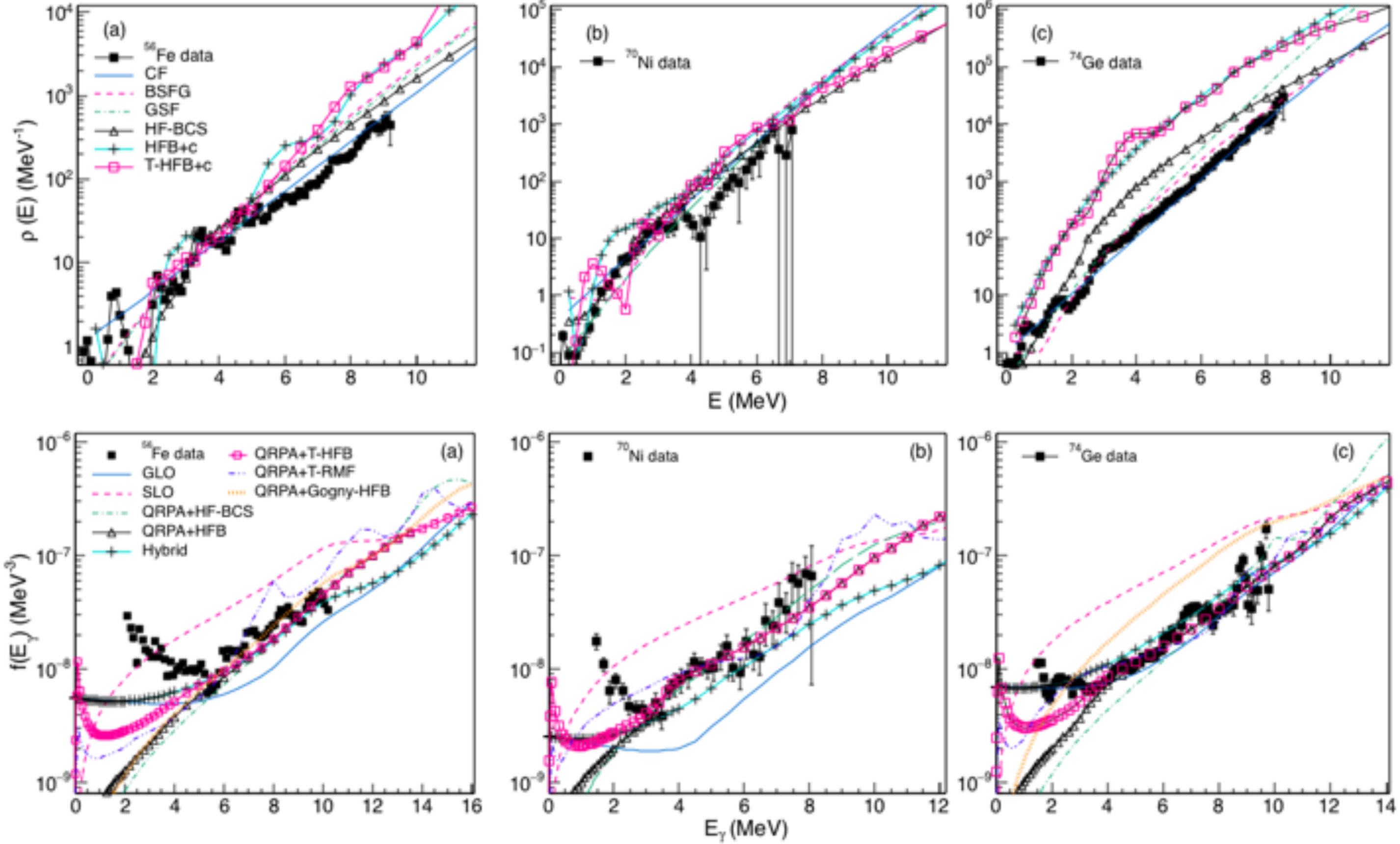

[Bartholomew et al., Adv. Nucl. Phys. **7**, 229 (1973)]

# Why are level densities and γ-ray strength functions important for (n,γ) reaction rates?



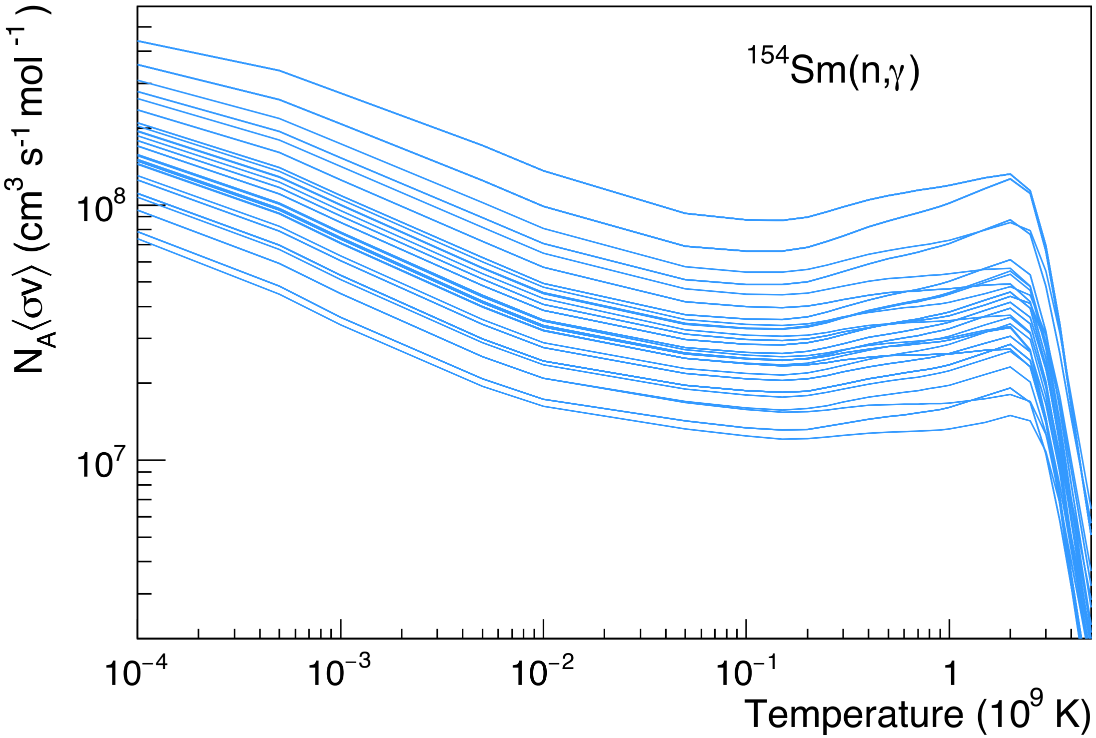
# … but don't we know how to calculate level densities and γ-decay strength functions? 🤔

Data (+ all refs) available at ocl.uio.no




Calculations are models included in TALYS-1.8 www.talys.eu

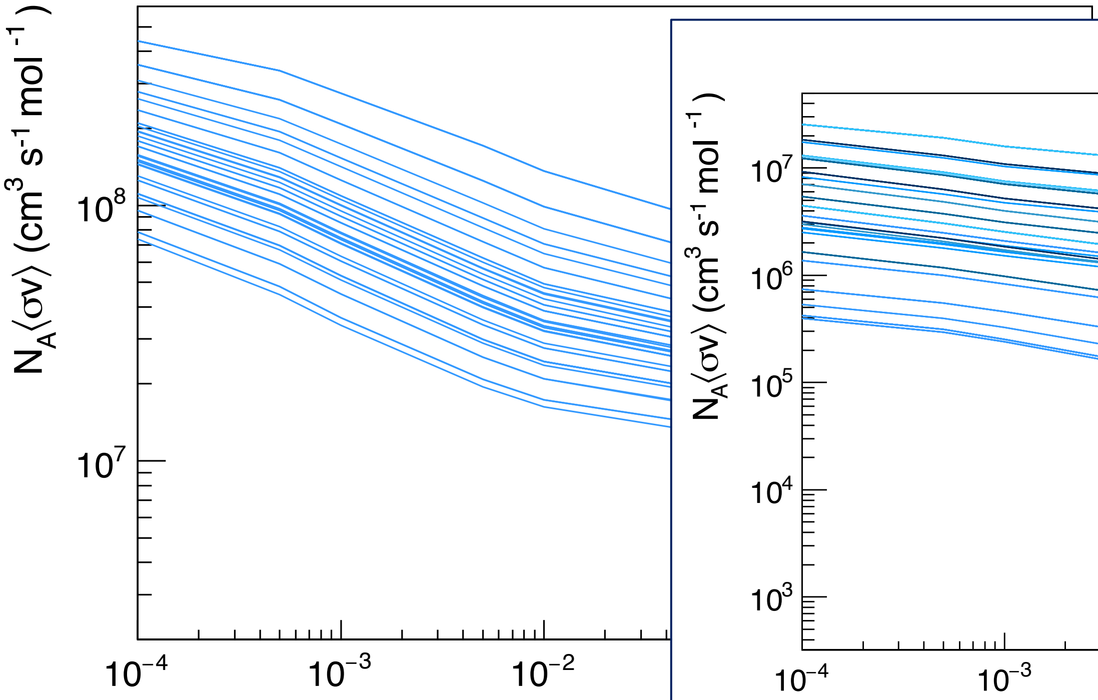
# Example: $^{154}$Sm(n,$\gamma$) and $^{175}$Sm(n,$\gamma$) reaction rates

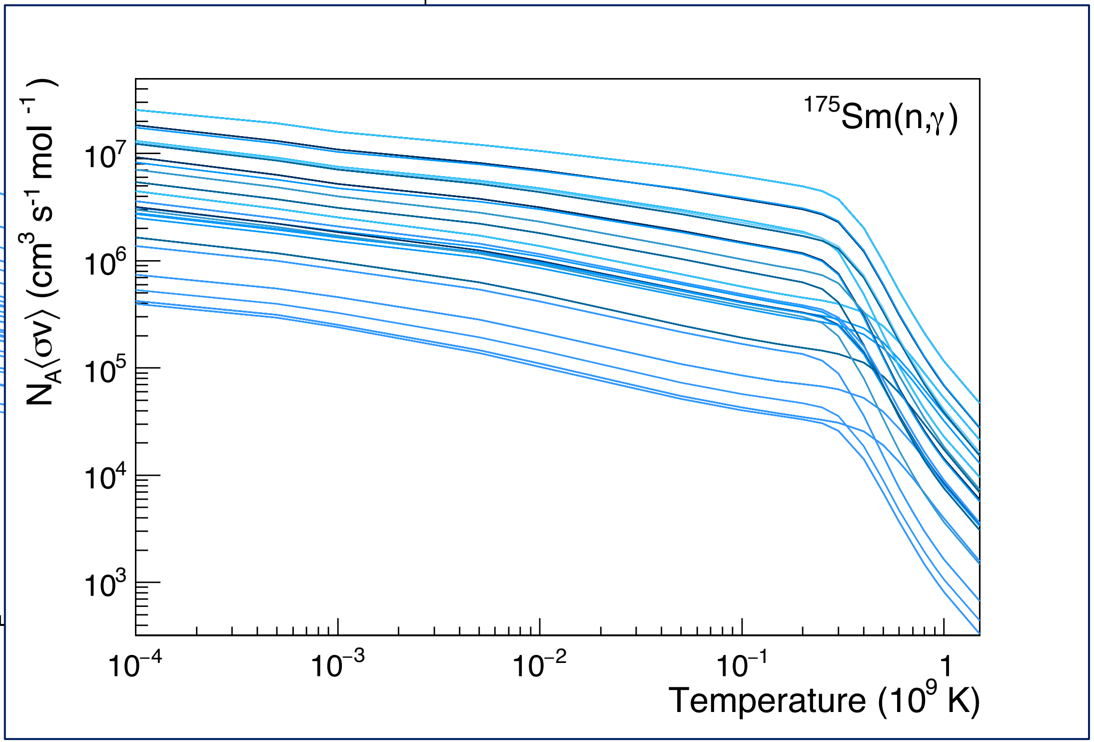



Calculated with TALYS-1.8

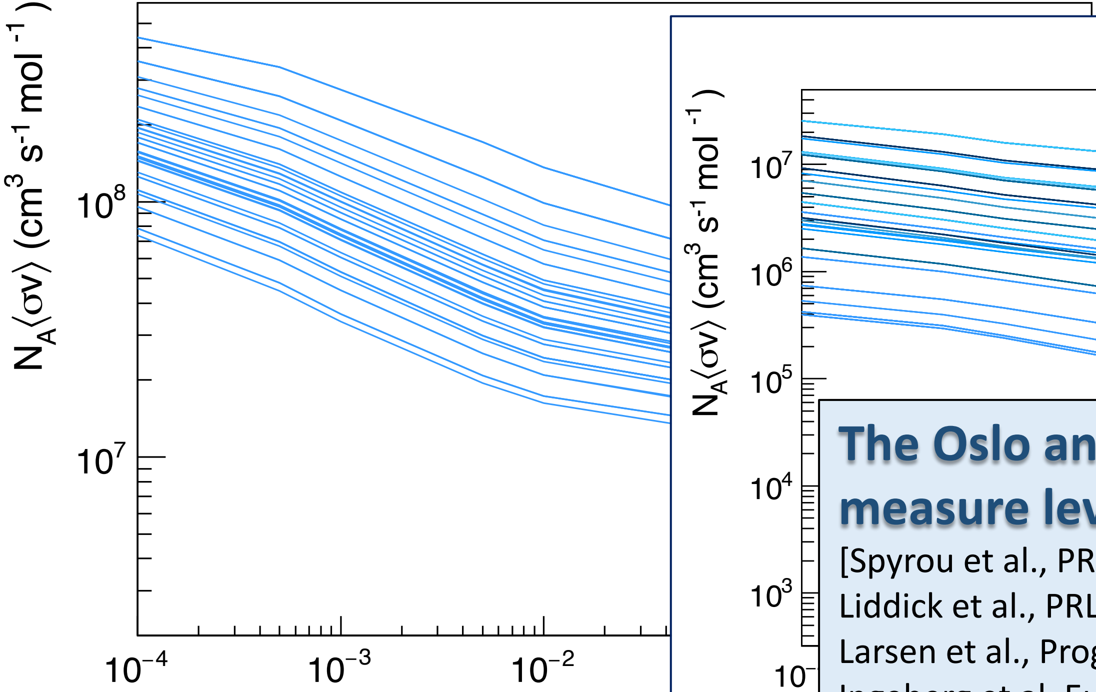
Each line is one specific combination of a level density model and $\gamma$-strength function model

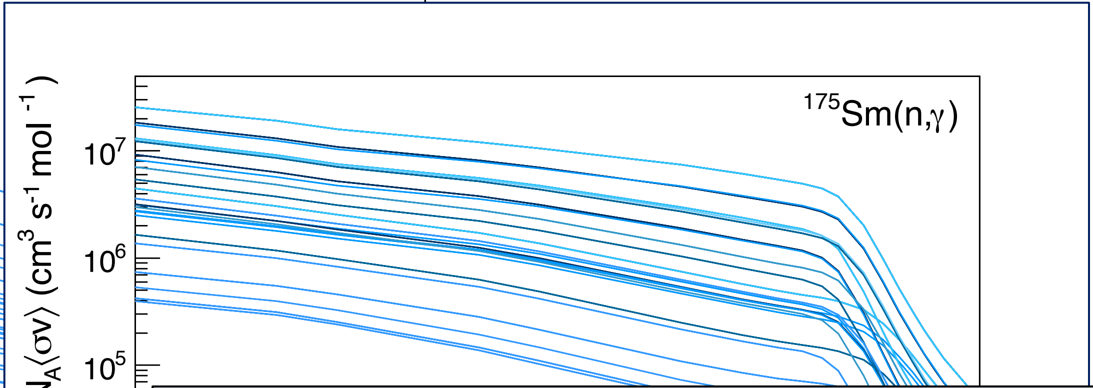
# Example: $^{154}$Sm(n,γ) and $^{175}$Sm(n,γ) reaction rates



# Example: $^{154}$Sm(n,$\gamma$) and $^{175}$Sm(n,$\gamma$) reaction rates

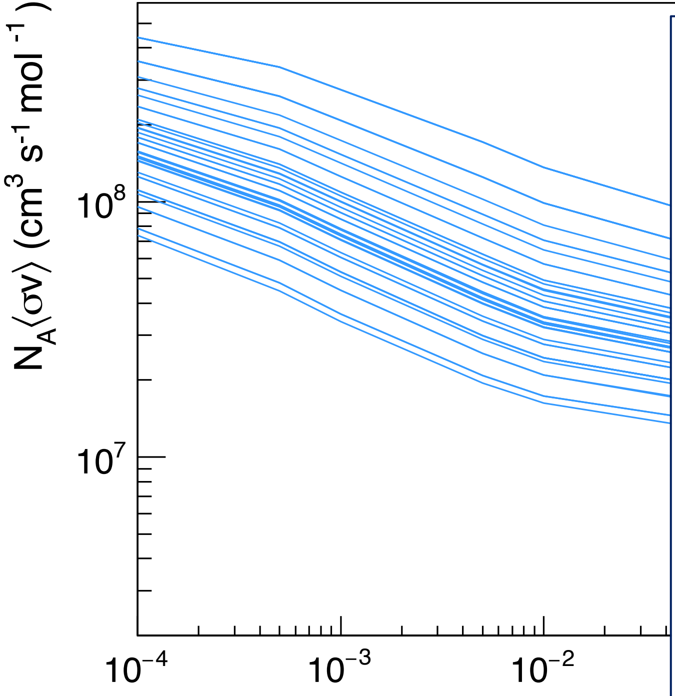


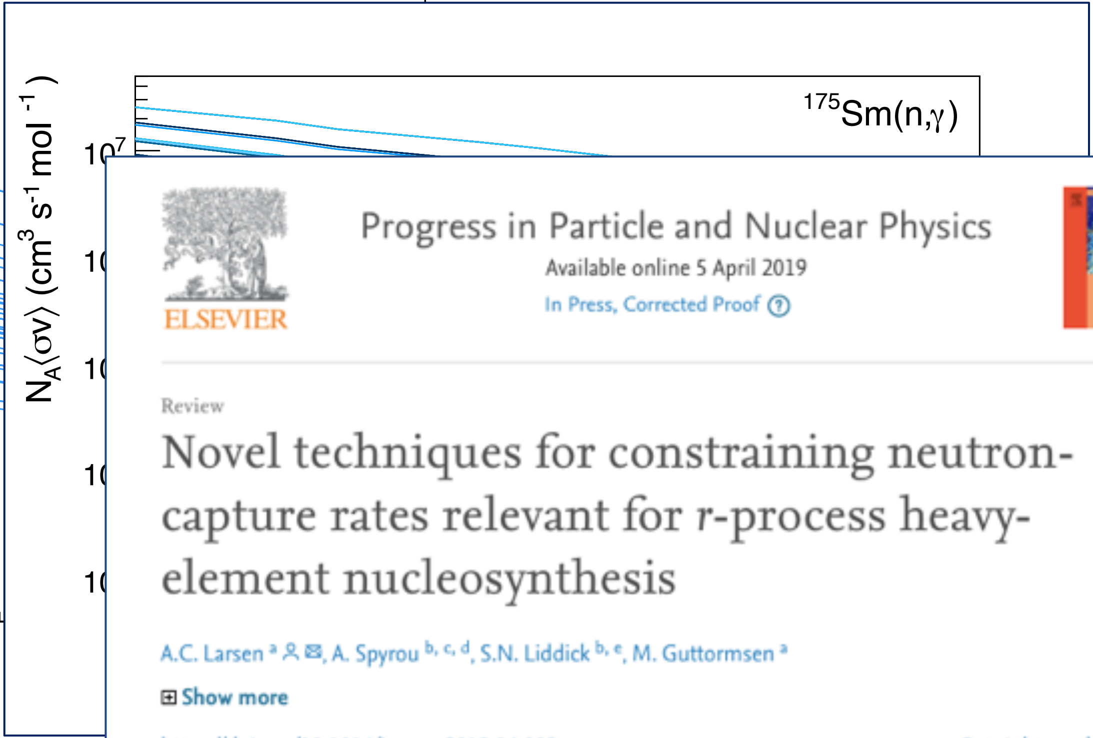




**The Oslo and beta-Oslo method: measure level density and $\gamma$-decay strength**

[Spyrou et al., PRL **113**, 232502 (2014);
Liddick et al., PRL **116**, 242502 (2016);
Larsen et al., Prog. Part. Nucl. Phys. (2019);
Ingeberg et al. Eur. Phys. J. A **56**, 68 (2020)]

# Example: $^{154}$Sm(n,$\gamma$) and $^{175}$Sm(n,$\gamma$) reaction rates





Progress in Particle and Nuclear Physics
Available online 5 April 2019
In Press, Corrected Proof


Review

## Novel techniques for constraining neutron-capture rates relevant for *r*-process heavy-element nucleosynthesis


A.C. Larsen [a], A. Spyrou [b, c, d], S.N. Liddick [b, e], M. Guttormsen [a]

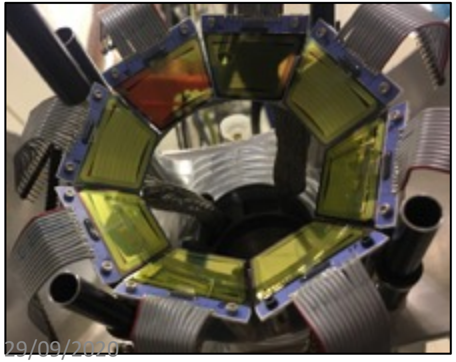

Show more


https://doi.org/10.1016/j.ppnp.2019.04.002

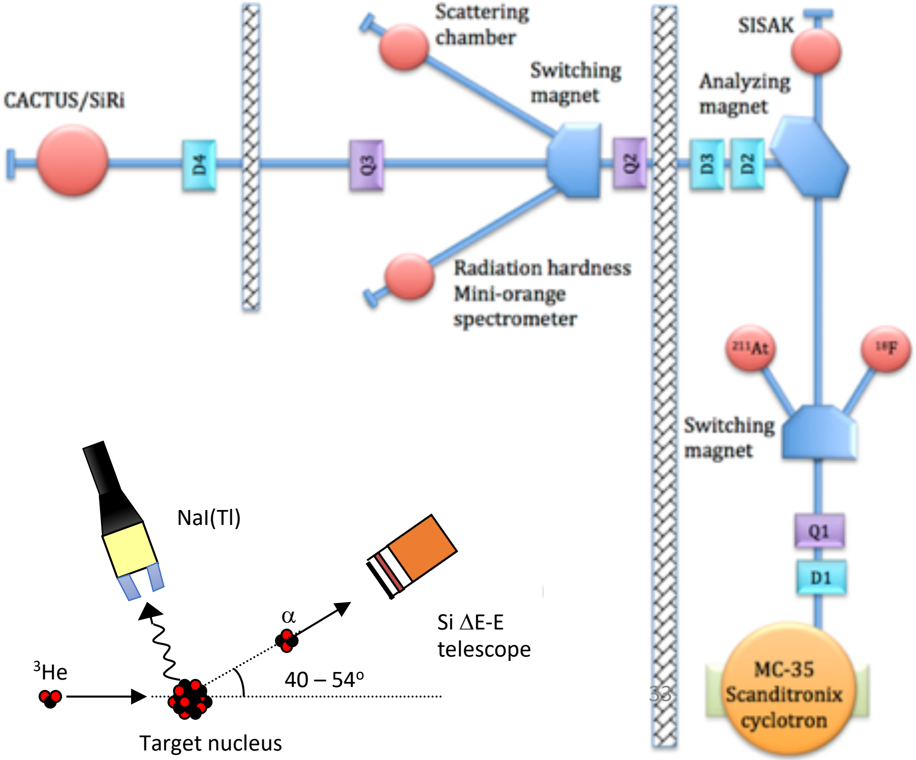

Get rights and content

# Experiments at the Oslo Cyclotron Laboratory

CACTUS:
26
collimated
NaI(Tl)
crystals,
5'' x 5''

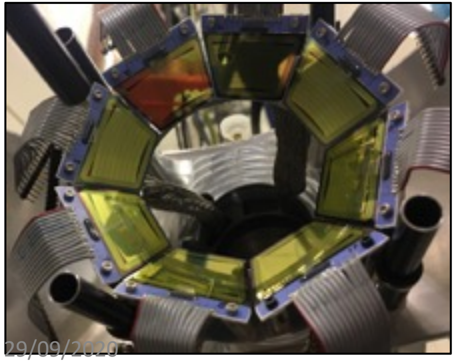


**SiRi:**
8x8 Si
ΔE-E particle
detectors
(≈6% of 4π)



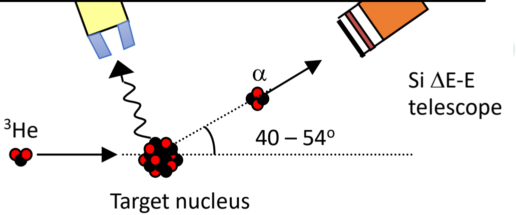
# Experiments at the Oslo Cyclotron Laboratory

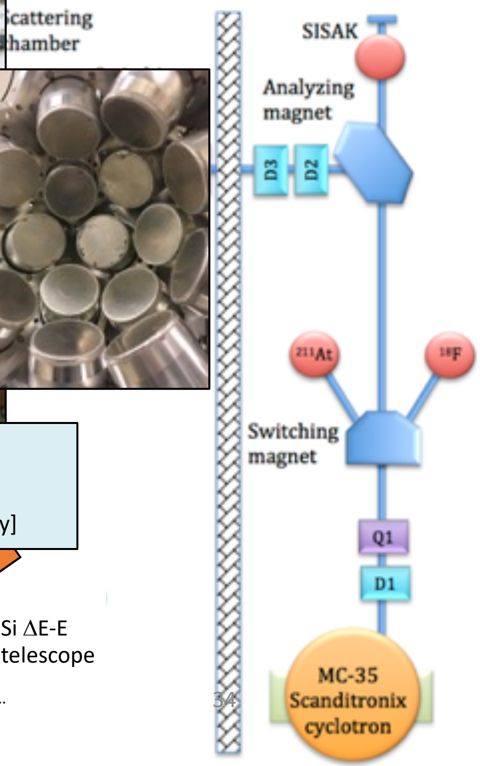
CACTUS:
26
collimated
NaI(Tl)
crystals,
5'' x 5''



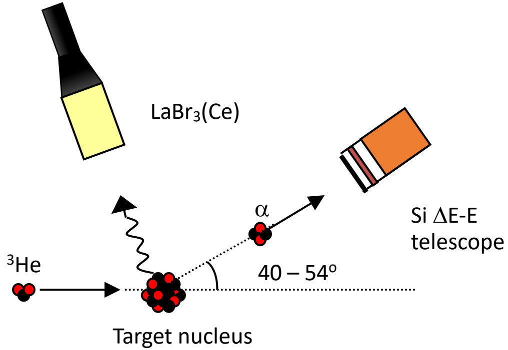
**SiRi:**
8x8 Si
ΔE-E particle
detectors
(≈6% of 4π)

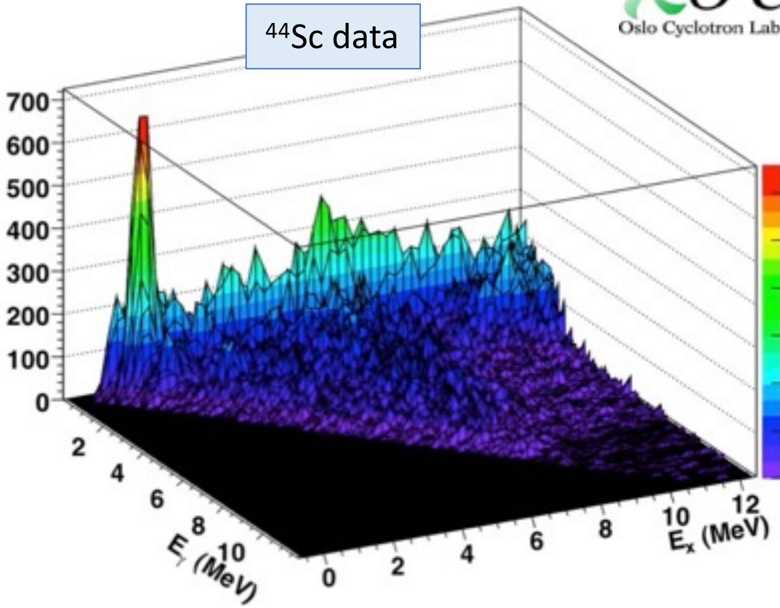
New γ-ray detector system **OSCAR**
(30 $LaBr_3$ 3.5'' x 8'' crystals)
[Funding from the Research Council of Norway]



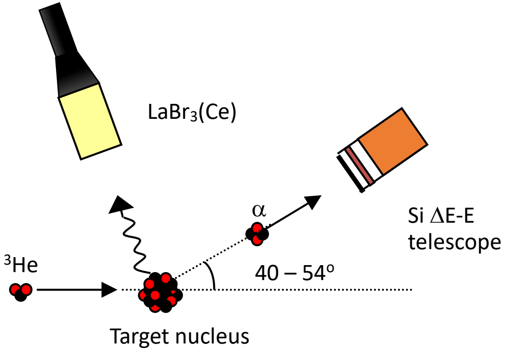
# The Oslo method in a 

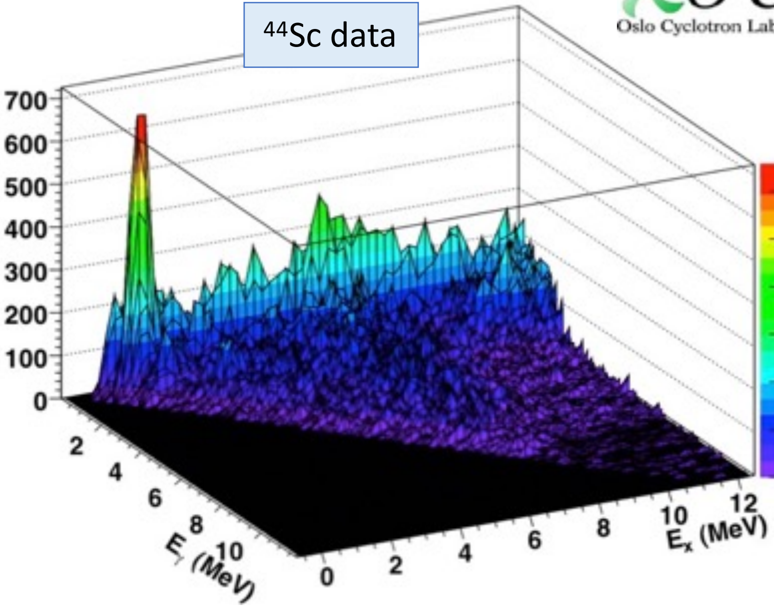



0. Get a hold of an (Eγ,Ex) matrix (~30-40 000 coincidences)
1. Correct for the γ-ray detector response [Guttormsen et al., NIM A 374, 371 (1996)]
2. Extract *distribution of* primary γs for each Ex [Guttormsen et al., NIM A 255, 518 (1987)]
3. Get level density and γ-strength from primary γ's [Schiller et al., NIM A 447, 498 (2000)]
4. Normalize & evaluate systematic errors [Schiller et al., NIM A 447, 498 (2000), Larsen *et al.*, PRC **83**, 034315 (2011)]

# The Oslo method in a 




0. Get a hold of an (Eγ,Ex) matrix (~30-40 000 coincidences)
1. Correct for the γ-ray detector response [Guttormsen et al., NIM A 374, 371 (1996)]
2. Extract *distribution of* prim
3. Get level density and γ-str
4. Normalize & evaluate syst

Larsen *et al.*, PRC **83**, 034315 (2011)]

Data and references:

**ocl.uio.no/compilation/**

Analysis codes and tools:

**github.com/oslocyclotronlab/oslo-method-software**

# Extraction of level density and γ-decay strength

**Ansatz:** primary γ matrix can be factorized into two independent functions (vectors)

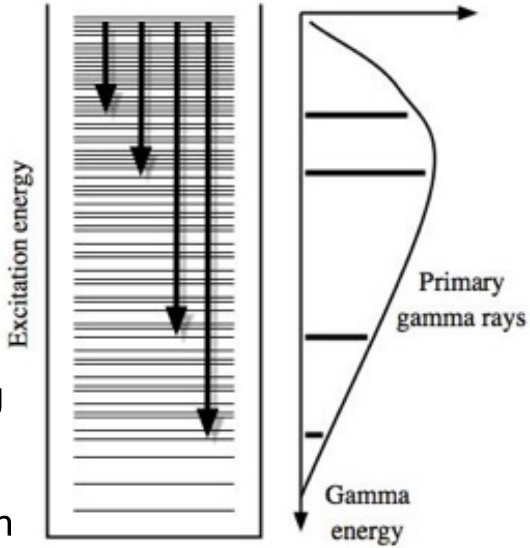
$$P(E_i, E_\gamma) \propto \rho(E_i - E_\gamma)\tau(E_\gamma)$$

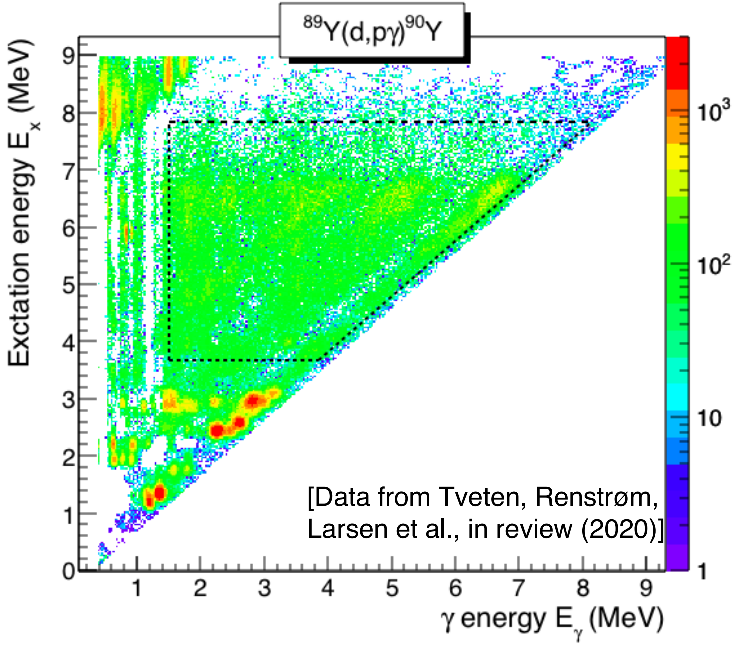
$$f(E_\gamma) = \tau(E_\gamma) / 2\pi E_\gamma^3$$

**Two important assumptions:**

1) The γ decay takes place a long time after the level is formed
2) The γ-decay strength varies *slowly* with $E_x$ (at high $E_x$ – high level density)

-> mild variant of the Brink hypothesis
[Brink, Doctoral thesis, Oxford (1955)]



# Surprise! The low-energy upbend

VOLUME 93, NUMBER 14 PHYSICAL REVIEW LETTERS week ending 1 OCTOBER 2004

## Large Enhancement of Radiative Strength for Soft Transitions in the Quasicontinuum

A. Voinov,[1,2,*] E. Algin,[3,4,5,6] U. Agvaanluvsan,[3,4] T. Belgya,[7] R. Chankova,[8] M. Guttormsen,[8] G. E. Mitchell,[4,5] J. Rekstad,[8] A. Schiller,[3,†] and S. Siem[8]

[1]*Frank Laboratory of Neutron Physics, Joint Institute of Nuclear Research, 141980 Dubna, Moscow region, Russia*
[2]*Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA*
[3]*Lawrence Livermore National Laboratory, L-414, 7000 East Avenue, Livermore, California 94551, USA*
[4]*North Carolina State University, Raleigh, North Carolina 27695, USA*
[5]*Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA*
[6]*Department of Physics, Osmangazi University, Meselik, Eskisehir, 26480 Turkey*
[7]*Institute of Isotope and Surface Chemistry, Chemical Research Centre HAS, P.O. Box 77, H-1525 Budapest, Hungary*
[8]*Department of Physics, University of Oslo, N-0316 Oslo, Norway*

(Received 26 April 2004; published 29 September 2004)

Radiative strength functions (RSFs) for the $^{56,57}$Fe nuclei below the separation energy are obtained from the $^{57}$Fe($^3$He, $\alpha\gamma$)$^{56}$Fe and $^{57}$Fe($^3$He, $^3$He$'\gamma$)$^{57}$Fe reactions, respectively. An enhancement of more than a factor of 10 over common theoretical models of the soft ($E_\gamma \lesssim 2$ MeV) RSF for transitions in the quasicontinuum (several MeV above the yrast line) is observed. Two-step cascade intensities with soft primary transitions from the $^{56}$Fe($n$, $2\gamma$)$^{57}$Fe reaction confirm the enhancement.

DOI: 10.1103/PhysRevLett.93.142504 PACS numbers: 25.40.Lw, 25.20.Lj, 25.55.Hp, 27.40.+z

# Surprise! The low-energy upbend

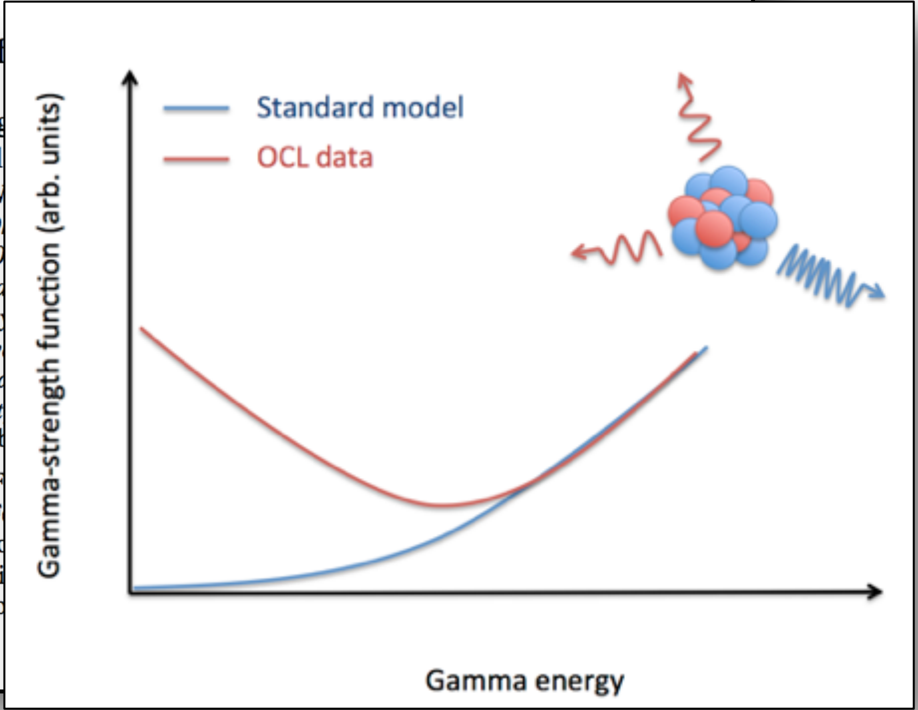
VOLUME 93, NUMBER 14 PHYSICAL REVIEW LETTERS week ending 1 OCTOBER 2004

**Large Enhancement of Radiative Strength f**

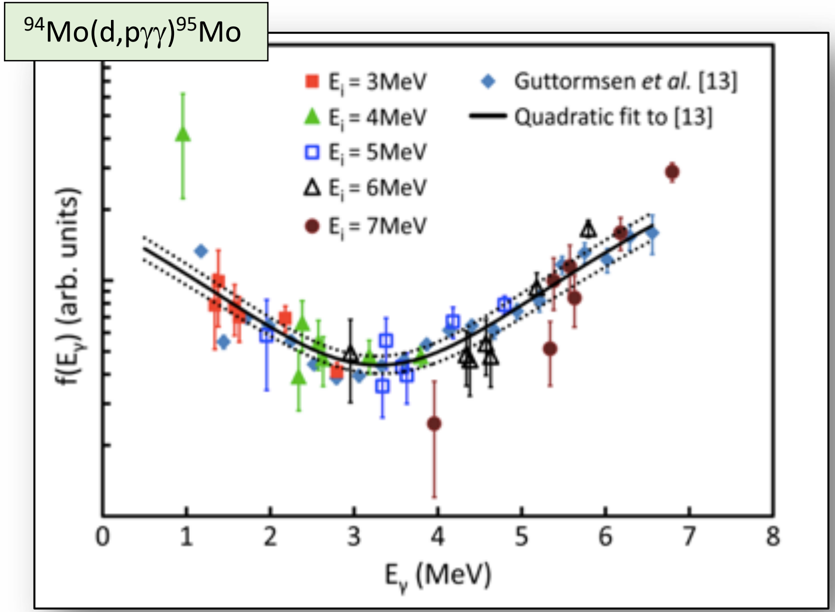
A. Voinov,[1,2,*] E. Algin,[3,4,5,6] U. Agvaanluvsan,[3,4] T. Belg
J. Rekstad,[8] A. Schil
[1]*Frank Laboratory of Neutron Physics, Joint Institute of N*
[2]*Department of Physics and Astronomy, O*
[3]*Lawrence Livermore National Laboratory, L-414, 70*
[4]*North Carolina State University, Ra*
[5]*Triangle Universities Nuclear Laborator*
[6]*Department of Physics, Osmangazi Univ*
[7]*Institute of Isotope and Surface Chemistry, Chemical Resea*
[8]*Department of Physics, Universit*
(Received 26 April 2004; pub

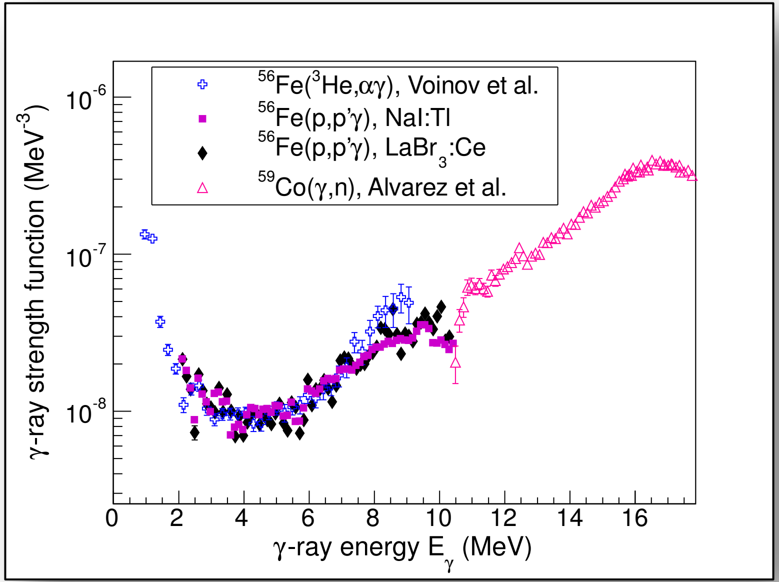
Radiative strength functions (RSFs) for the $^{56,57}$F
from the $^{57}$Fe($^3$He, $\alpha\gamma$)$^{56}$Fe and $^{57}$Fe($^3$He, $^3$He$'\gamma$)$^{57}$F
than a factor of 10 over common theoretical models c
quasicontinuum (several MeV above the yrast line) i
primary transitions from the $^{56}$Fe($n$, $2\gamma$)$^{57}$Fe reactio

DOI: 10.1103/PhysRevLett.93.142504



# What do we know about the upbend from exp.?



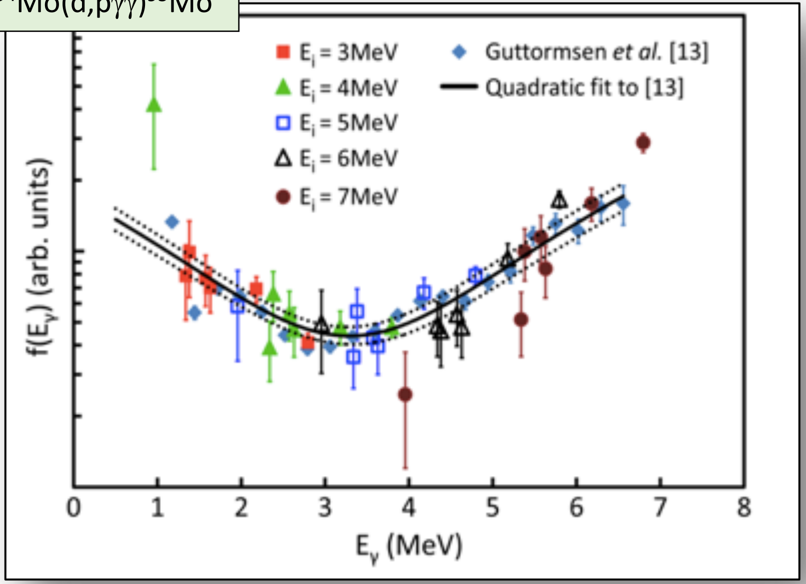




**Confirmed** with an independent technique using (d,pγγ) coincidences
[M. Wiedeking et al., PRL **108**, 162503 (2012)]

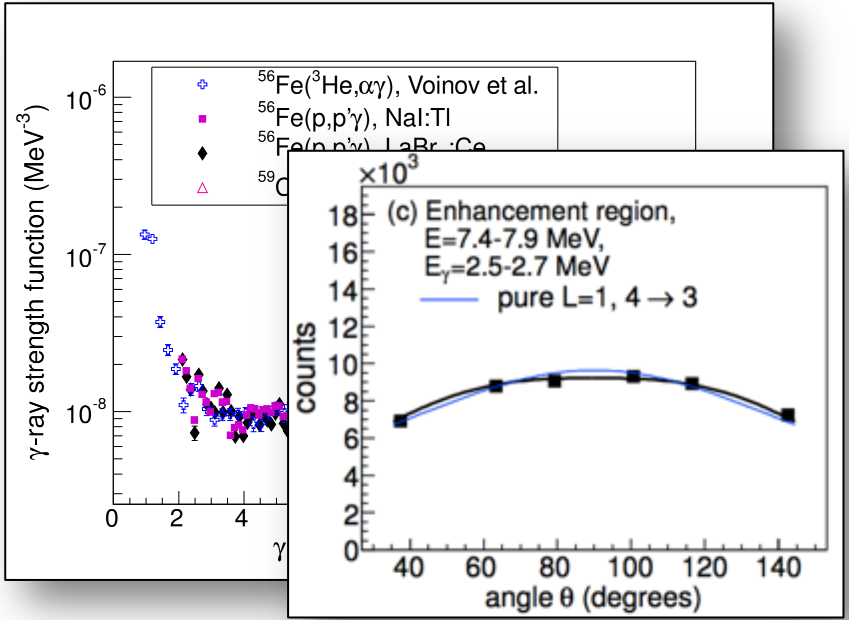
CACTUS + 6 3.5'' x 8'' $LaBr_3$(Ce) from HECTOR+
Dominated by **dipole transitions**
[A.C. Larsen et al., PRL **111**, 242504 (2013)]

# What do we know about the upbend from exp.?

$^{94}Mo(d,p\gamma\gamma)^{95}Mo$



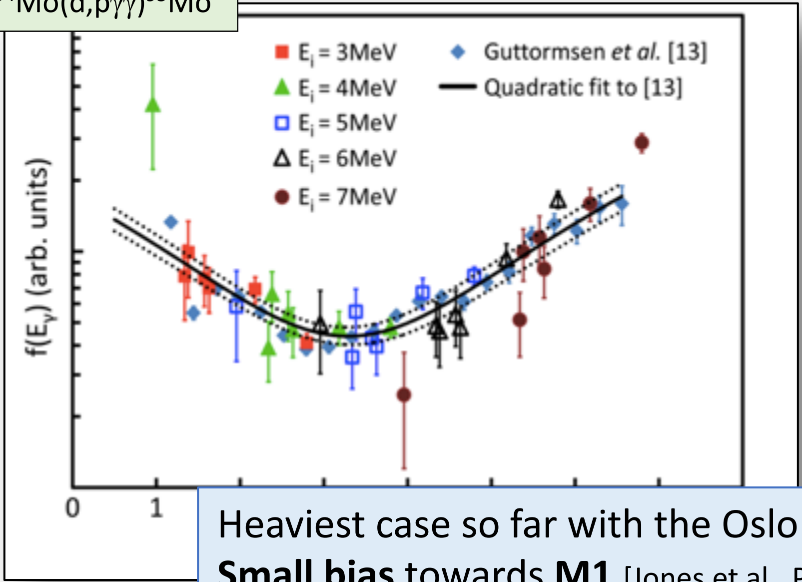

**Confirmed** with an independent technique using (d,p$\gamma\gamma$) coincidences
[M. Wiedeking et al., PRL **108**, 162503 (2012)]

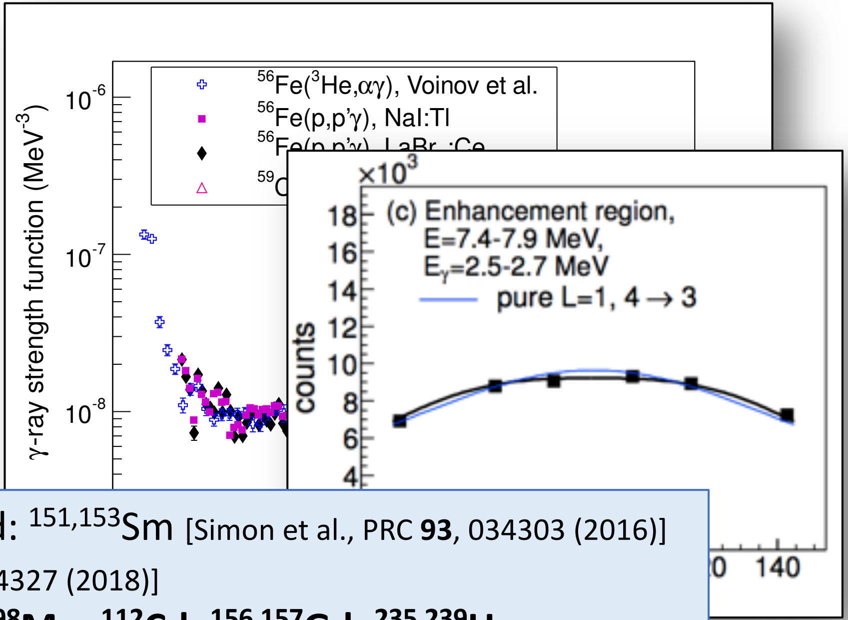



CACTUS + 6 3.5'' x 8'' $LaBr_3(Ce)$ from HECTOR+
Dominated by **dipole transitions**
[A.C. Larsen et al., PRL **111**, 242504 (2013)]

# What do we know about the upbend from exp.?

$^{94}Mo(d,p\gamma\gamma)^{95}Mo$




Heaviest case so far with the Oslo method: $^{151,153}Sm$ [Simon et al., PRC **93**, 034303 (2016)]

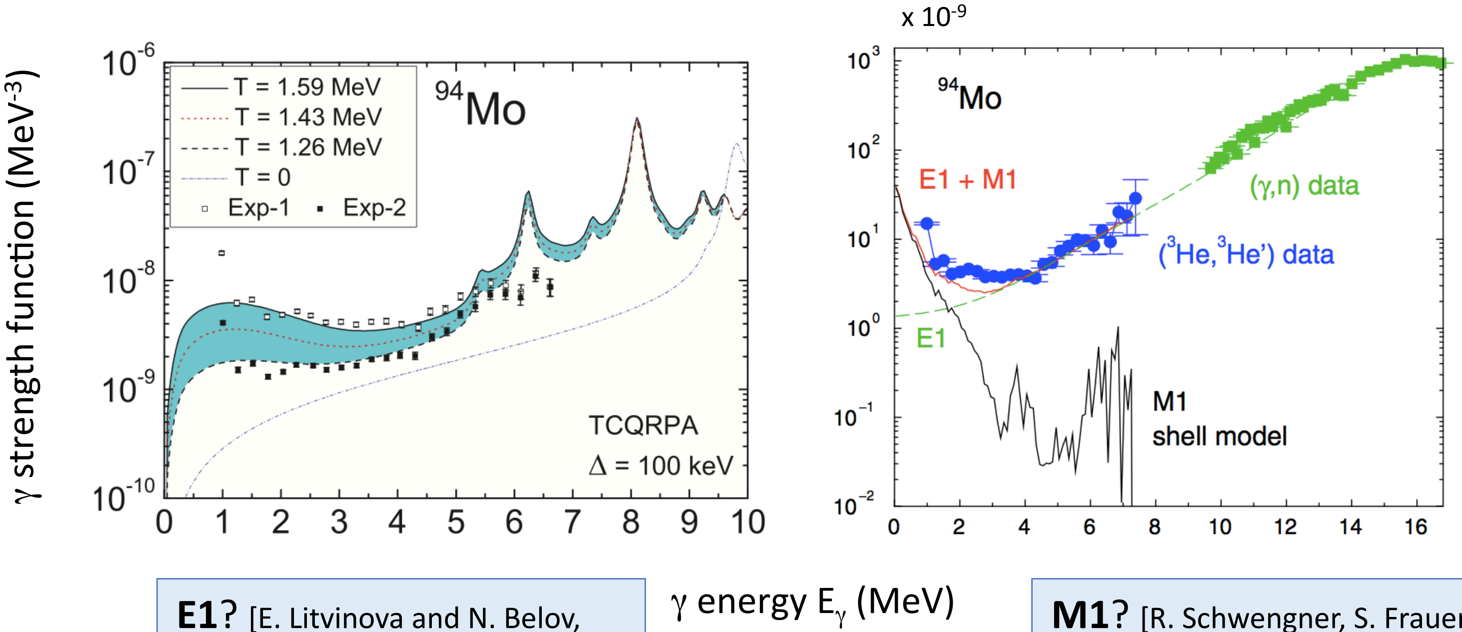
**Small bias** towards **M1** [Jones et al., PRC **97**, 024327 (2018)]

**M1** consistent with **all DANCE spectra: $^{96,98}Mo$, $^{112}Cd$, $^{156,157}Gd$, $^{235,239}U$**
[Krticka et al., PRC **99**, 044308 (2019)]

**Confirmed**
using (d,pγγ) coincidences
[M. Wiedeking et al., PRL **108**, 162503 (2012)]

Dominated by **dipole transitions**
[A.C. Larsen et al., PRL **111**, 242504 (2013)]

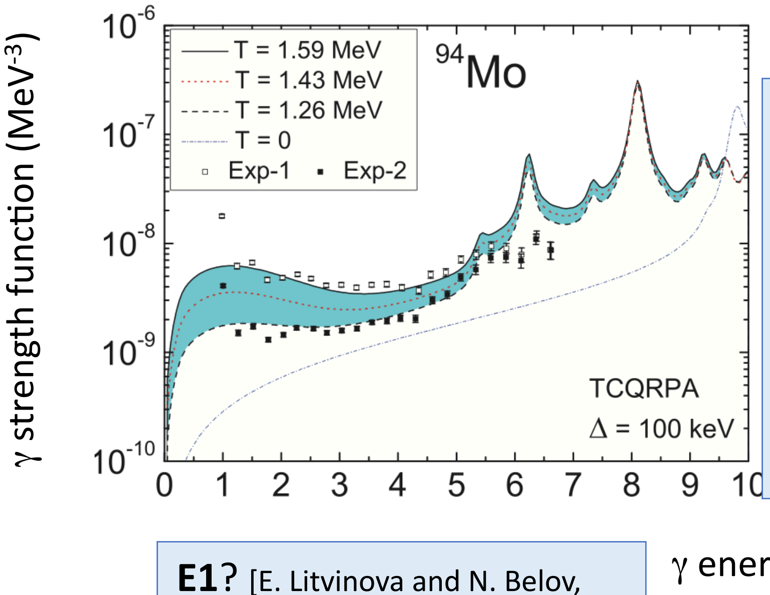
# What does theory tell us?

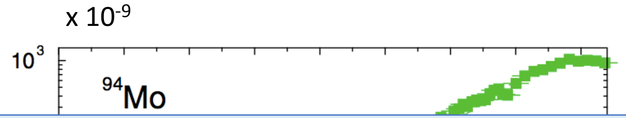



**E1**? [E. Litvinova and N. Belov, PRC **88**, 031302(R) (2013)]
Thermal-continuum quasiparticle random-phase approximation

**M1**? [R. Schwengner, S. Frauendorf, and A. C. Larsen, PRL **111**, 232504 (2013)]
Configuration interaction shell model

# What does theory tell us?



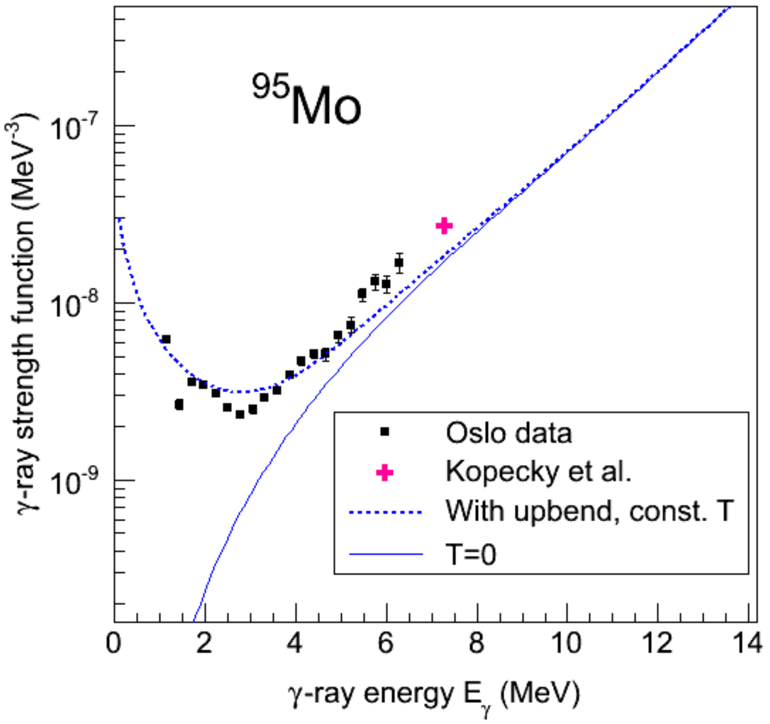

**More M1 within the shell model:**

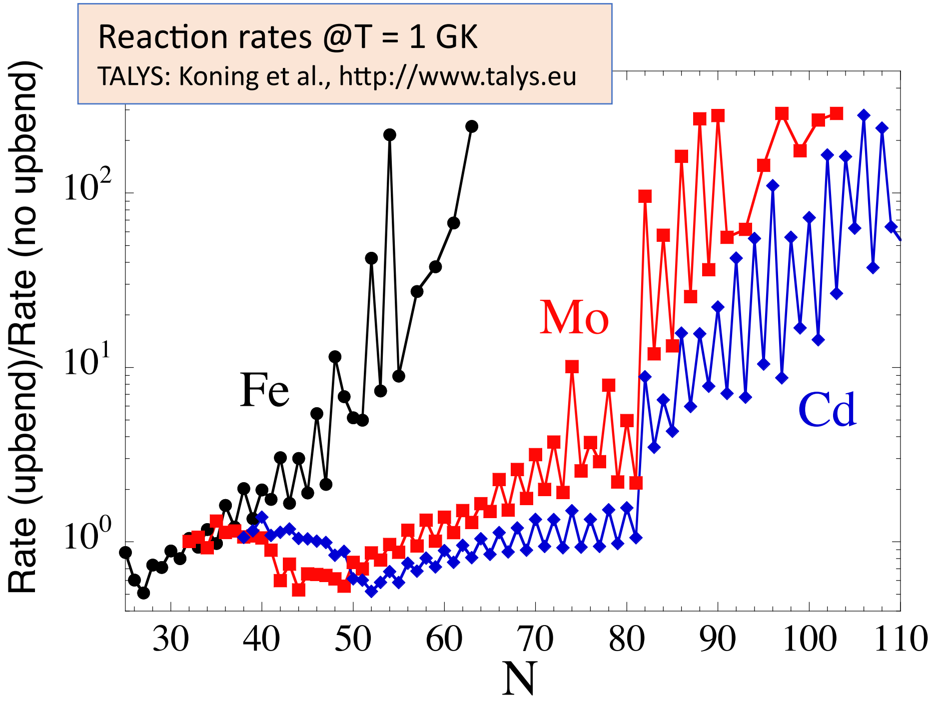
- B. Alex Brown and A.C. Larsen, PRL **113**, 252502 (2014)
- R. Schwengner, S. Frauendorf, B. Alex Brown, PRL **118**, 092502 (2017)
- K. Sieja, PRL **119**, 052502 (2017)
- S. Karampagia, B. A. Brown, and V. Zelevinsky, PRC **95**, 024322 (2017)
- A.C. Larsen, J.E. Midtbø et al., PRC **97**, 054329 (2018)
- S. Goriely et al., PRC **98**, 014327 (2018)
- J.E. Midtbø et al., PRC **98**,064321 (2018)
- K. Sieja, PRC **98**, 064312 (2018)
- F. Naqvi et al., PRC **99**, 054331 (2019)

**E1**? [E. Litvinova and N. Belov, PRC **88**, 031302(R) (2013)]
Thermal-continuum quasiparticle random-phase approximation

**M1**? [R. Schwengner, S. Frauendorf, and A. C. Larsen, PRL **111**, 232504 (2013)]
Configuration interaction shell model

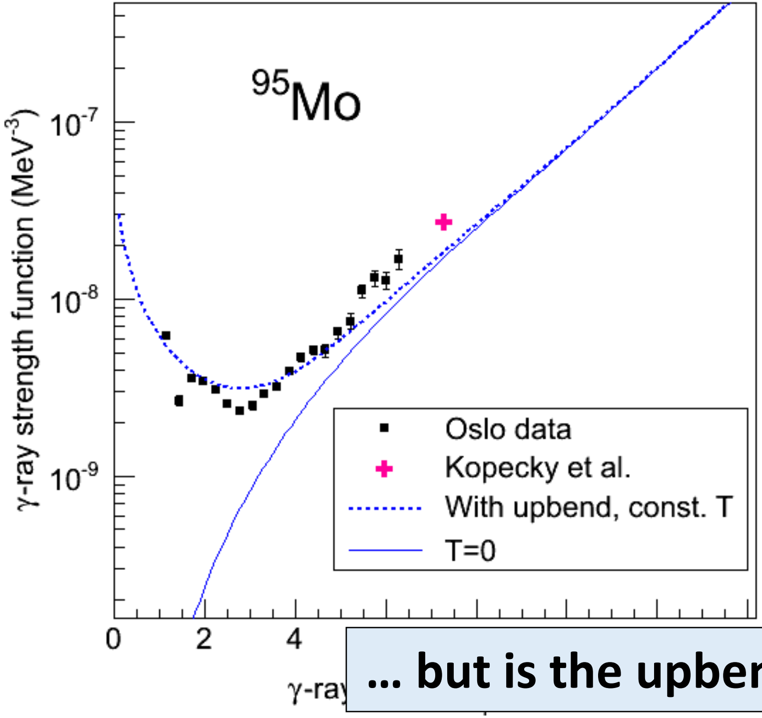
# Impact on r-process (n,γ) reaction rates?

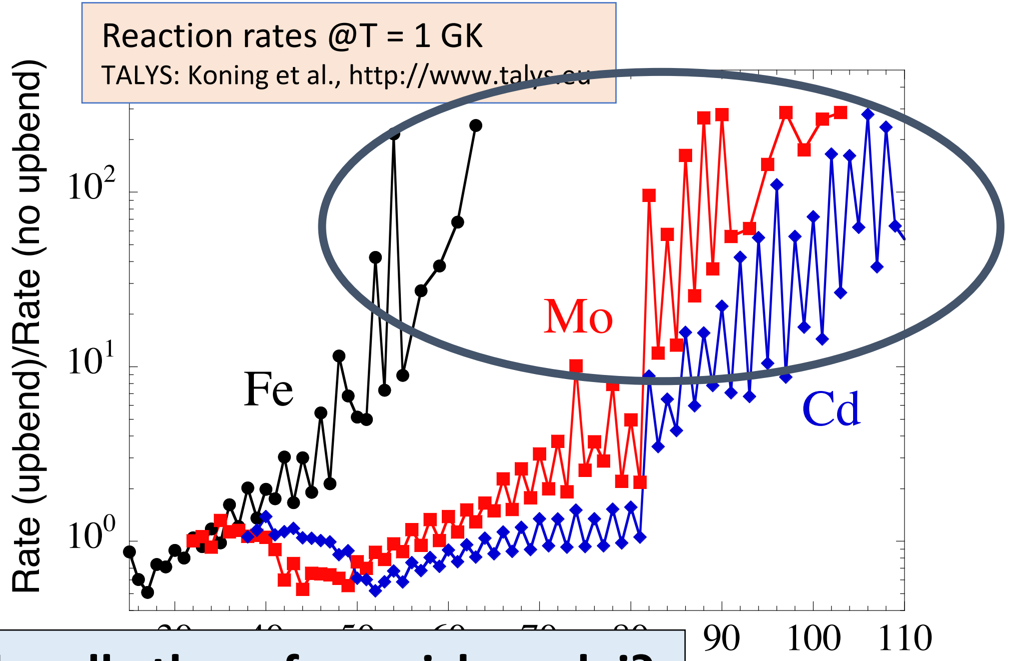



[A.C. Larsen and S. Goriely, Phys. Rev. C **82**, 014318 (2010)]

# Impact on r-process (n,γ) reaction rates?




**… but is the upbend really there for n-rich nuclei?**

[A.C. Larsen and S. Goriely, Phys. Rev. C **82**, 014318 (2010)]

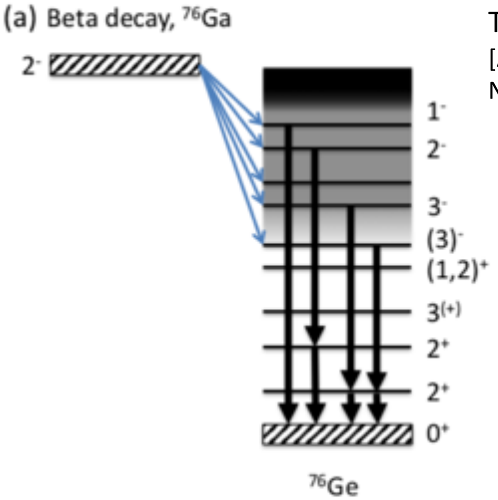
# The beta-Oslo method

Special thanks to
**Artemis Spyrou,**
**Sean Liddick,**
**Magne Guttormsen**

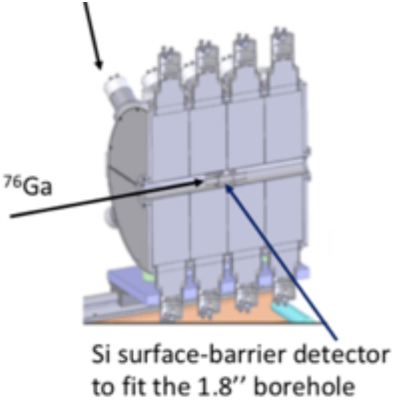
**Recipe:**

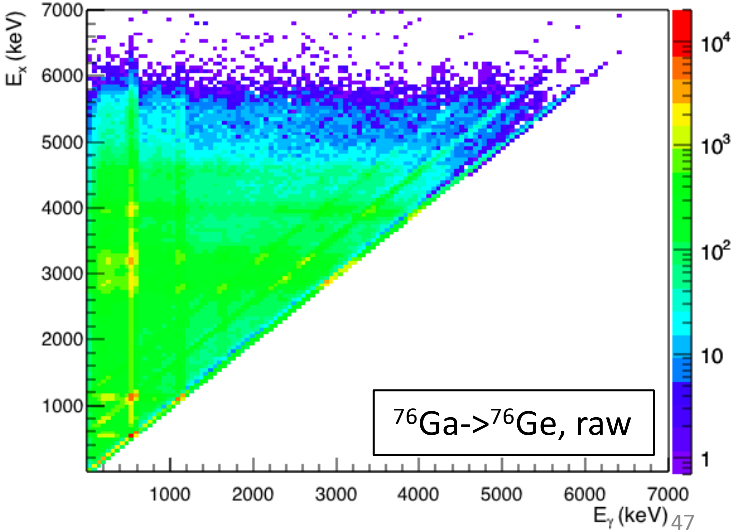
1) Implant a neutron-rich nucleus inside a *segmented* total-absorption spectrometer (preferably with $Q_\beta \approx S_n$)
2) Measure $\beta^-$ in coincidence with *all* $\gamma$ rays from the daughter nucleus
3) Apply Oslo method to the $(E_x, E_\gamma)$ matrix to extract level density & $\gamma$- strength

**Segments give individual γ rays, the sum of all gives $E_x$**



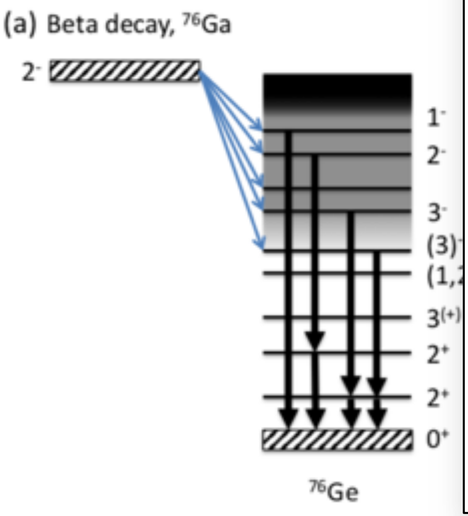

The SuN detector @ NSCL/MSU
[A. Simon, S.J. Quinn, A. Spyrou et al., NIM A 703, 16 (2013)]



# The beta-Oslo method

Special thanks to
**Artemis Spyrou,**
**Sean Liddick,**
**Magne Guttormsen**




**Recipe:**


PRL **113,** 232502 (2014) PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2014


**Novel technique for Constraining *r*-Process $(n, \gamma)$ Reaction Rates**


A. Spyrou,[1,2,3,*] S. N. Liddick,[1,4,†] A. C. Larsen,[5,‡] M. Guttormsen,[5] K. Cooper,[1,4] A. C. Dombos,[1,2,3] D. J. Morrissey,[1,4] F. Naqvi,[1] G. Perdikakis,[6,1,3] S. J. Quinn,[1,7,3] T. Renstrøm,[5] J. A. Rodriguez,[1] A. Simon,[1,8] C. S. Sumithrarachchi,[1] and R. G. T. Zegers[1,7,3]

[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*
[5]*Department of Physics, University of Oslo, NO-0316 Oslo, Norway*
[6]*Central Michigan University, Mount Pleasant, Michigan, 48859, USA*
[7]*Department of Physics & Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[8]*Department of Physics and The Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA*



(Received 25 August 2014; published 2 December 2014)



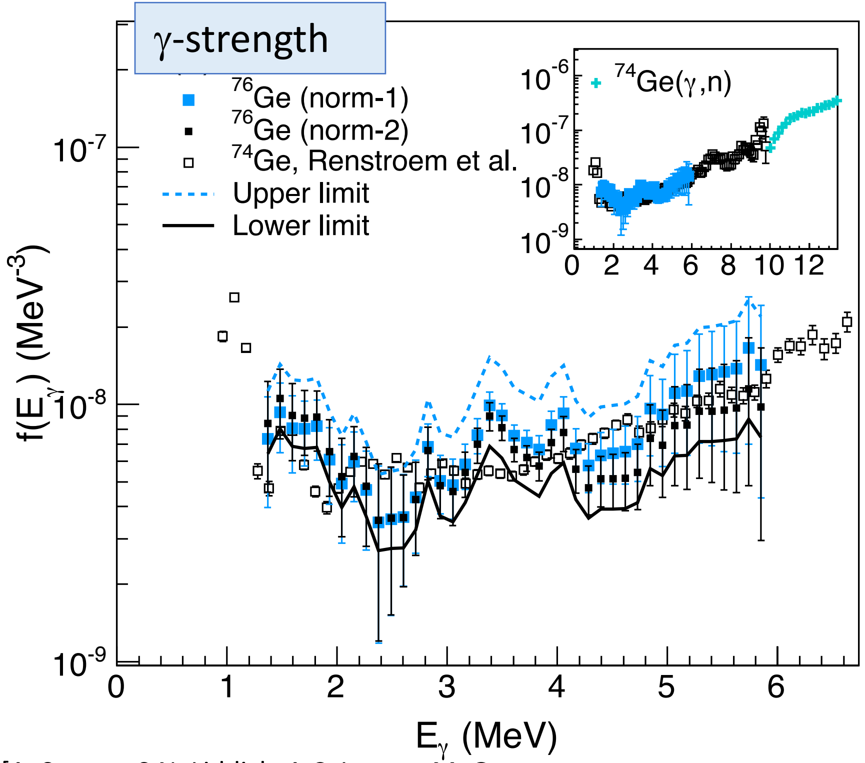
A novel technique has been developed, which will open exciting new opportunities for studying the very neutron-rich nuclei involved in the *r* process. As a proof of principle, the $\gamma$ spectra from the $\beta$ decay of $^{76}$Ga have been measured with the SuN detector at the National Superconducting Cyclotron Laboratory. The nuclear level density and $\gamma$-ray strength function are extracted and used as input to Hauser-Feshbach calculations. The present technique is shown to strongly constrain the $^{75}$Ge$(n,\gamma)^{76}$Ge cross section and reaction rate.

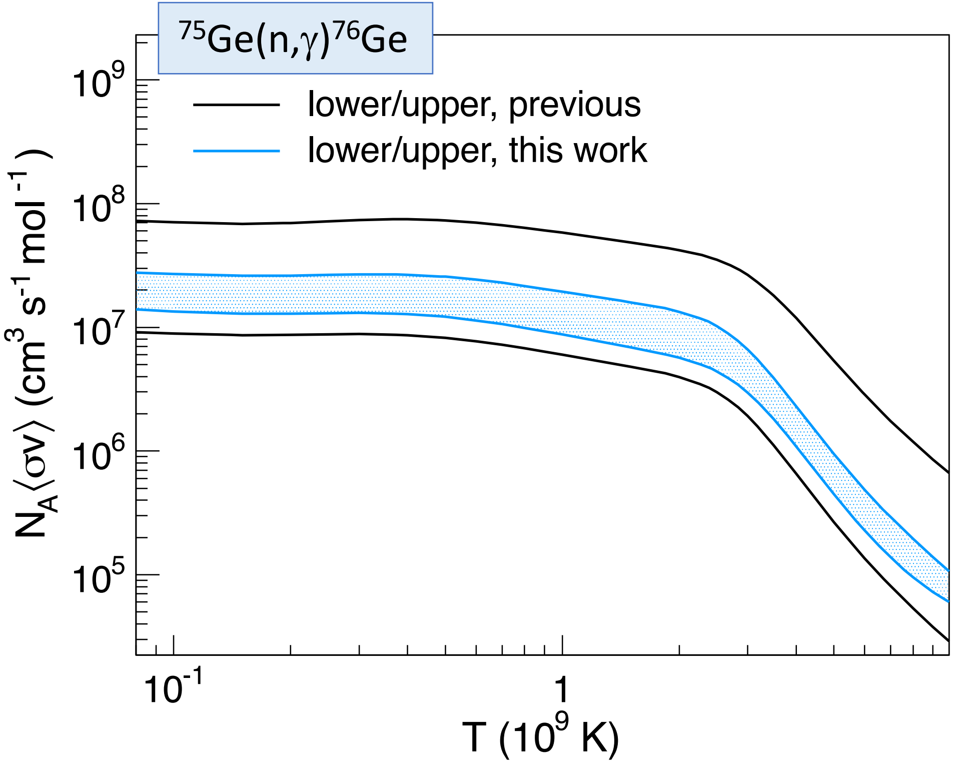


DOI: 10.1103/PhysRevLett.113.232502 PACS numbers: 26.30.Hj, 21.10.Ma, 27.50.+e


$E_\gamma$ (keV)

# The beta-Oslo method: $^{76}$Ge results



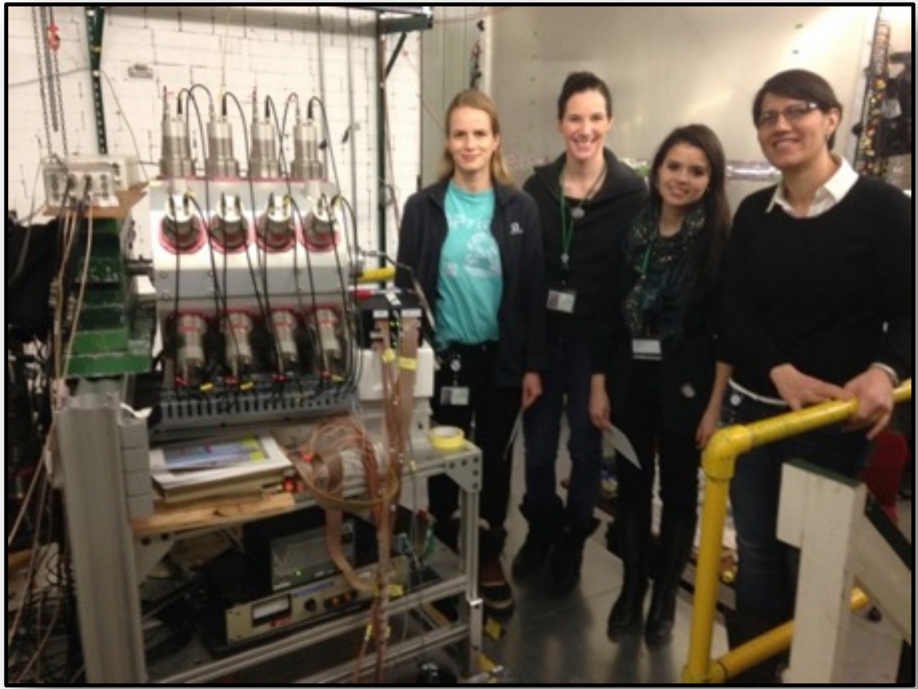




[A. Spyrou, S.N. Liddick, A.C. Larsen, M. Guttormsen et al., PRL **113**, 232502 (2014)]

# The beta-Oslo method: $^{70}Co \rightarrow {}^{70}Ni$

Discretionary beam time @ NSCL/MSU, Feb 2015; $^{70}Co$ beta-decaying into $^{70}Ni$

$^{86}Kr$ primary beam, 140 MeV/nucleon
$^{70}Co$ implanted on DSSD detector in SuN



$^{70}Co$ g.s. $T_{1/2}$: 105 ms, $I^{\pi} = 6^-$, $Q_{\beta}$ = 12.3 MeV
$S_n$ of $^{70}Ni$: 7.3 MeV
Initial spins, $^{70}Ni$: $5^-, 6^-, 7^-$

[S.N. Liddick A. Spyrou, B.P. Crider, F. Naqvi, A.C. Larsen, M. Guttormsen et al., PRL **116**, 242502 (2016)]

# The beta-Oslo method: $^{70}$Co → $^{70}$Ni

Discretionary beam time @ NSCL/MSU, Feb 2015; $^{70}$Co beta-decaying into $^{70}$Ni

86

70

$^{70}$C

$S_n$

Ini

[S

N

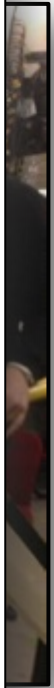
PRL 116, 242502 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

## Experimental Neutron Capture Rate Constraint Far from Stability

S. N. Liddick,[1,2] A. Spyrou,[1,3,4] B. P. Crider,[1] F. Naqvi,[1] A. C. Larsen,[5] M. Guttormsen,[5] M. Mumpower,[6,7] R. Surman,[6] G. Perdikakis,[8,1,4] D. L. Bleuel,[9] A. Couture,[10] L. Crespo Campo,[5] A. C. Dombos,[1,3,4] R. Lewis,[1,2] S. Mosby,[10] S. Nikas,[8,4] C. J. Prokop,[1,2] T. Renstrom,[5] B. Rubio,[11] S. Siem,[5] and S. J. Quinn[1,3,4]

[1]*National Superconducting Cyclotron Laboratory (NSCL), Michigan State University, East Lansing, Michigan 48824, USA*
[2]*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA*
[5]*Department of Physics, University of Oslo, N-0316 Oslo, Norway*
[6]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[7]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87544, USA*
[8]*Central Michigan University, Mount Pleasant, Michigan 48859, USA*
[9]*Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, California 94550-9234, USA*
[10]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[11]*IFIC, CSIC-Universidad de Valencia, 46071 Valencia, Spain*

(Received 5 January 2016; published 16 June 2016)



# The beta-Oslo method: $^{70}Co \rightarrow {}^{70}Ni$

Discretionary beam time @ NSCL/MSU, Feb 2015;$^{70}$Co beta-decaying into $^{70}$Ni

86

70

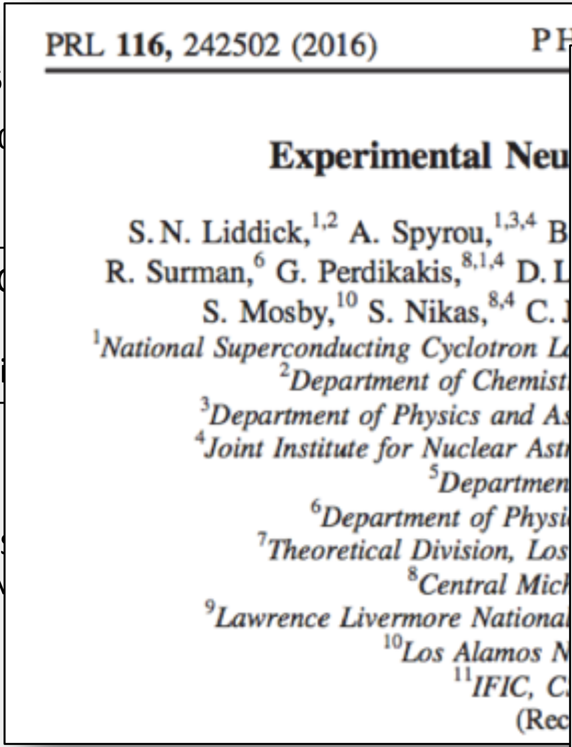
70

$S_n$

Ini

[S

N

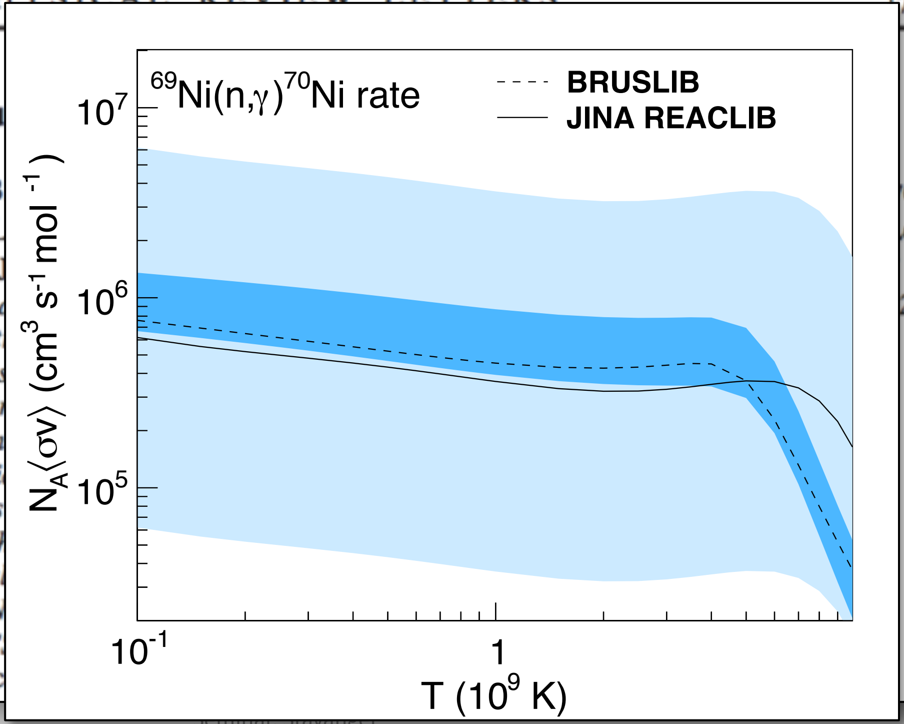


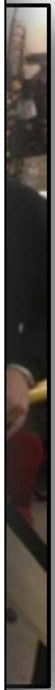
PRL 116, 242502 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

**Experimental Neu**

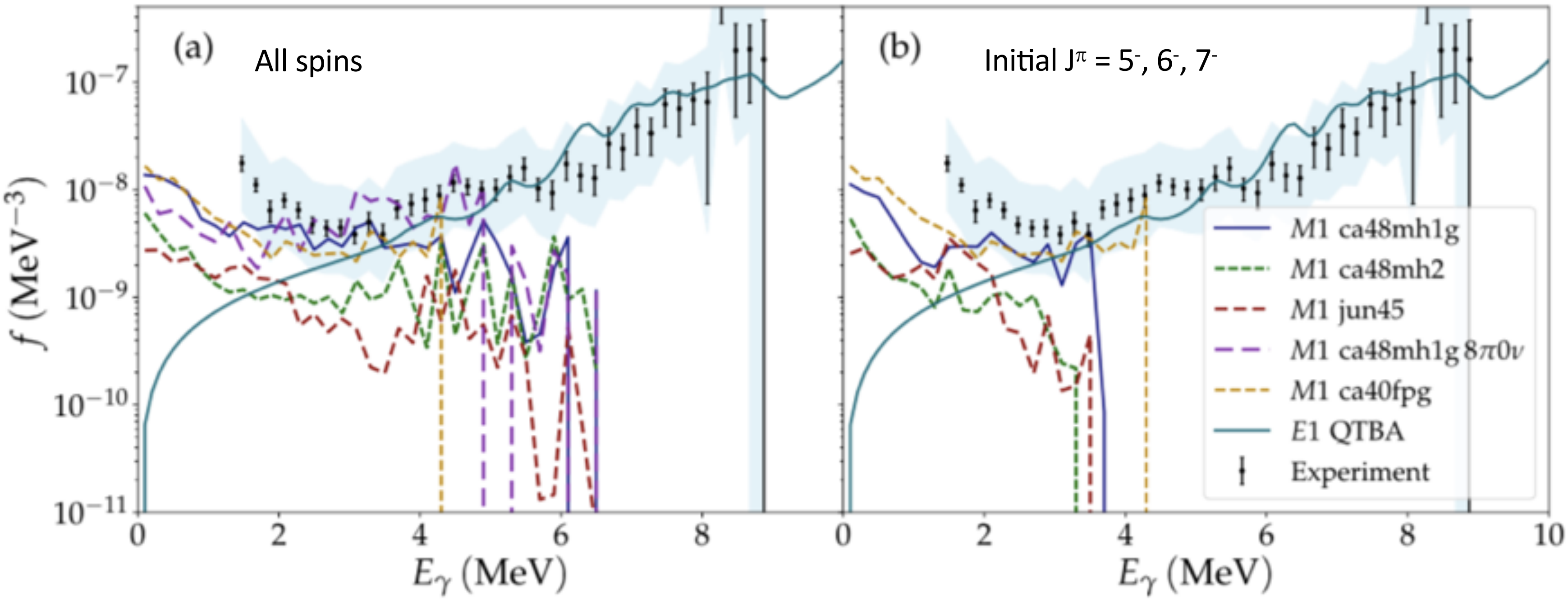
S. N. Liddick,[1,2] A. Spyrou,[1,3,4] B... ...er,[6,7]
R. Surman,[6] G. Perdikakis,[8,1,4] D. L... ...ewis,[1,2]
S. Mosby,[10] S. Nikas,[8,4] C. J...

[1]*National Superconducting Cyclotron La... ...24, USA*
[2]*Department of Chemist...*
[3]*Department of Physics and As...*
[4]*Joint Institute for Nuclear Astr...*
[5]*Departmen...*
[6]*Department of Physi...*
[7]*Theoretical Division, Los...*
[8]*Central Mich...*
[9]*Lawrence Livermore National...*
[10]*Los Alamos N...*
[11]*IFIC, C...*
(Rec...



# The beta-Oslo method: $^{70}$Ni results

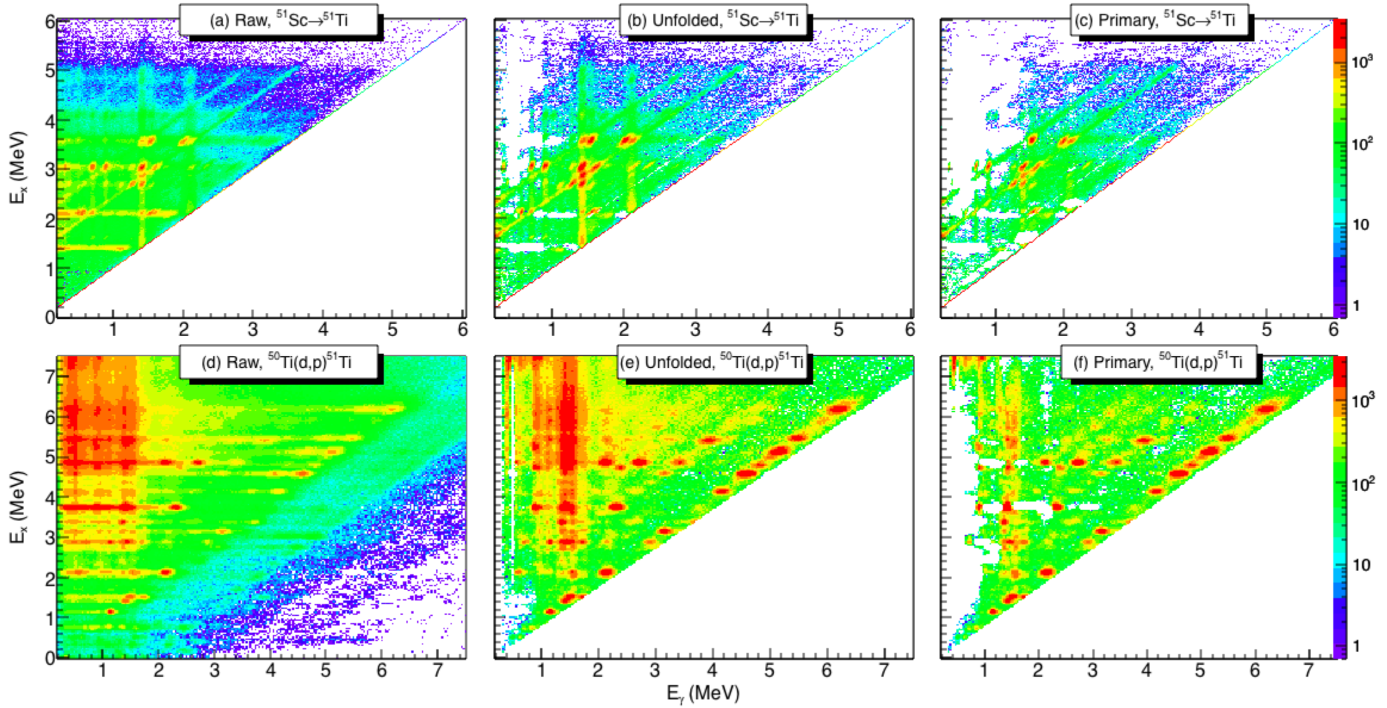



Improved data analysis: deconvolution of the $E_x$ axis as well [M. Guttormsen et al., in preparation]

[Larsen, Midtbø, Guttormsen, Renstrøm, Liddick, Spyrou et al., PRC **97**, 054329 (2018)]

# The beta-Oslo *and* Oslo method: $^{51}$Ti

Discretionary beam time @ NSCL/MSU, February 2015; $^{51}$Sc beta-decaying into $^{51}$Ti
Q-value, beta-decay: 6.503 MeV; $S_n$ = 6.372 MeV. Also: $^{50}$Ti(d,p$\gamma$)$^{51}$Ti @ OCL.

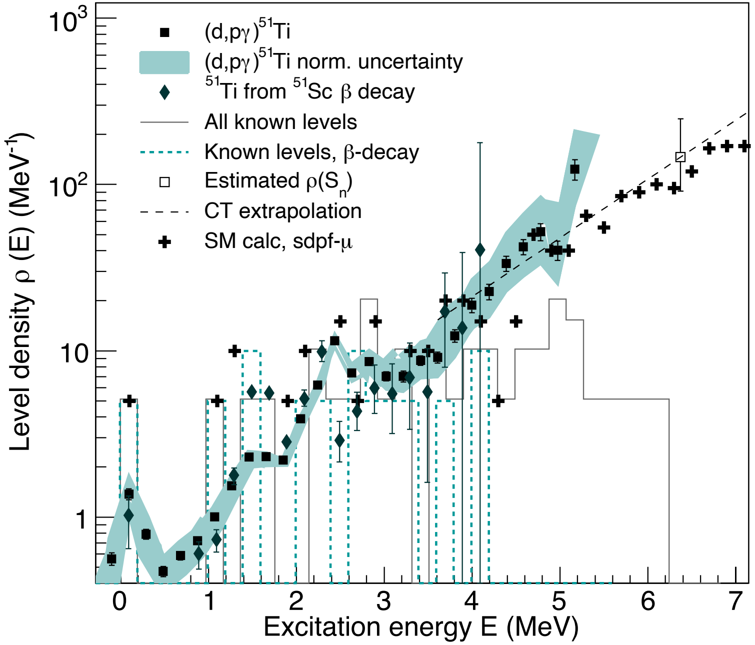


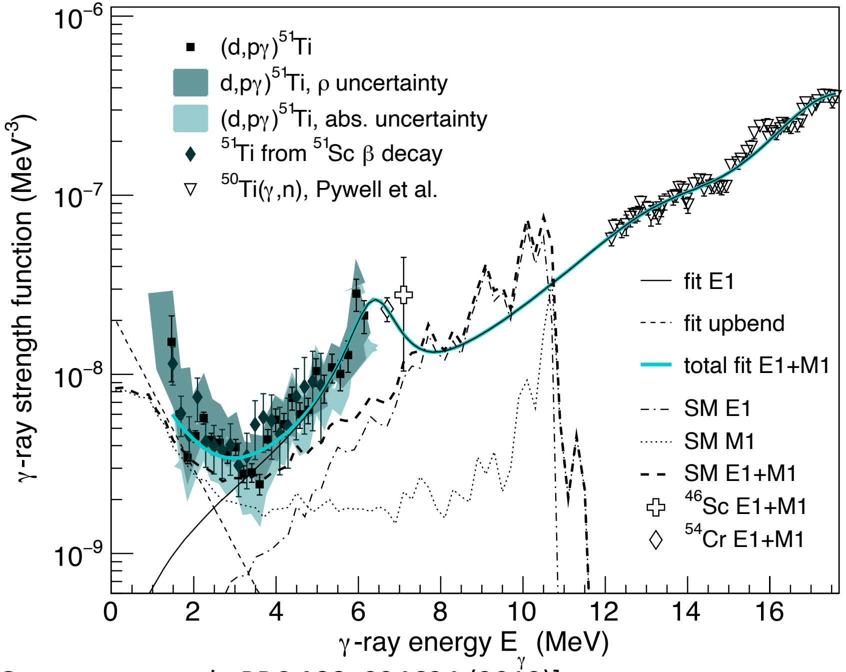

[S.N. Liddick, A.C. Larsen, M. Guttormsen et al., PRC **100**, 024624 (2019)]

# The beta-Oslo *and* Oslo method: $^{51}$Ti

## Almost the same spin range of final levels

Shell-model calculations by Jørgen E. Midtbø using KSHELL (Shimizu, https://arxiv.org/abs/1310.5431)

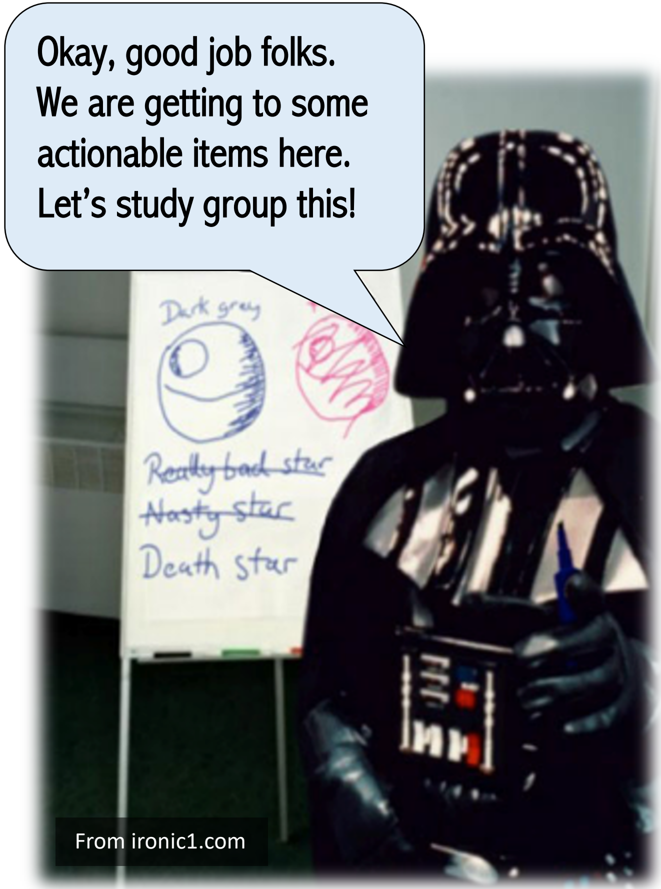



[S.N. Liddick, A.C. Larsen, M. Guttormsen et al., PRC **100**, 024624 (2019)]

# Summary & future work

The Oslo method and beta-Oslo method can provide experimental constraints on (n,$\gamma$) rates for moderately to neutron-rich nuclei needed for r-process nucleosynthesis calculations




**In the (near & not so near) future:**

(i) Extend the beta-Oslo method to more n-rich nuclei

(ii) Further improve Fully Bayesian Unfolding implemented by Vala Maria Valsdottir using the approach of Georgios Choudalakis (https://arxiv.org/abs/1201.4612)

(iii) Explore machine learning for unfolding of complex detector response

(iv) Improve theoretical predictions

…

**Many thanks for listening** 😀