NUCLEAR STRUCTURE AND ASTROPHYSICS: SELECTED TOPICS (BORMIO 2025)

Michaela Thiel
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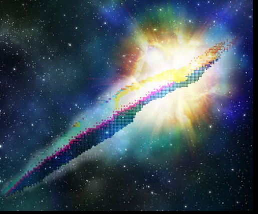


NUCLEAR STRUCTURE AND ASTROPHYSICS: SELECTED TOPICS

Monday 27th January 2025

09:10 Cecilia Chirenti „Astrophysical constraints on the **NEUTRON STAR EQUATION OF STATE** from **SHORT GAMMA-RAY BURSTS**“

Tuesday 28th January 2025

09:45 Ani Aprahamian „Were the **HEAVY ELEMENTS MADE IN NATURE**?“

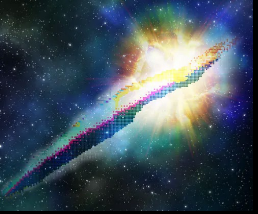
11:00 Adi Ashkenazi „The **NUCLEAR ASPECTS** of **NEUTRINO OSCILLATION** mesurements“

Wednesday 29th January 2025

17:00 James Lattimer „Recent developments in extracting the **EOS FROM OBSERVATIONS**“

Thursday 30th January 2025

09:00 Jacklyn Gates „Pursuing new **SUPERHEAVY ELEMENTS**“



NUCLEAR STRUCTURE AND ASTROPHYSICS: SELECTED TOPICS

NUCLEAR STRUCTURE:

① the basics

② ab initio nuclear models

③ neutrino oscillation measurements

④ superheavy nuclei

NUCLEAR ASTROPHYSICS:

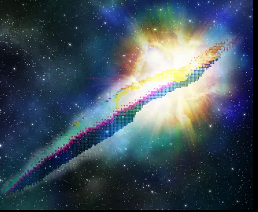
① introduction

② stars: nature‘s nuclear reactors

③ life and death of a star

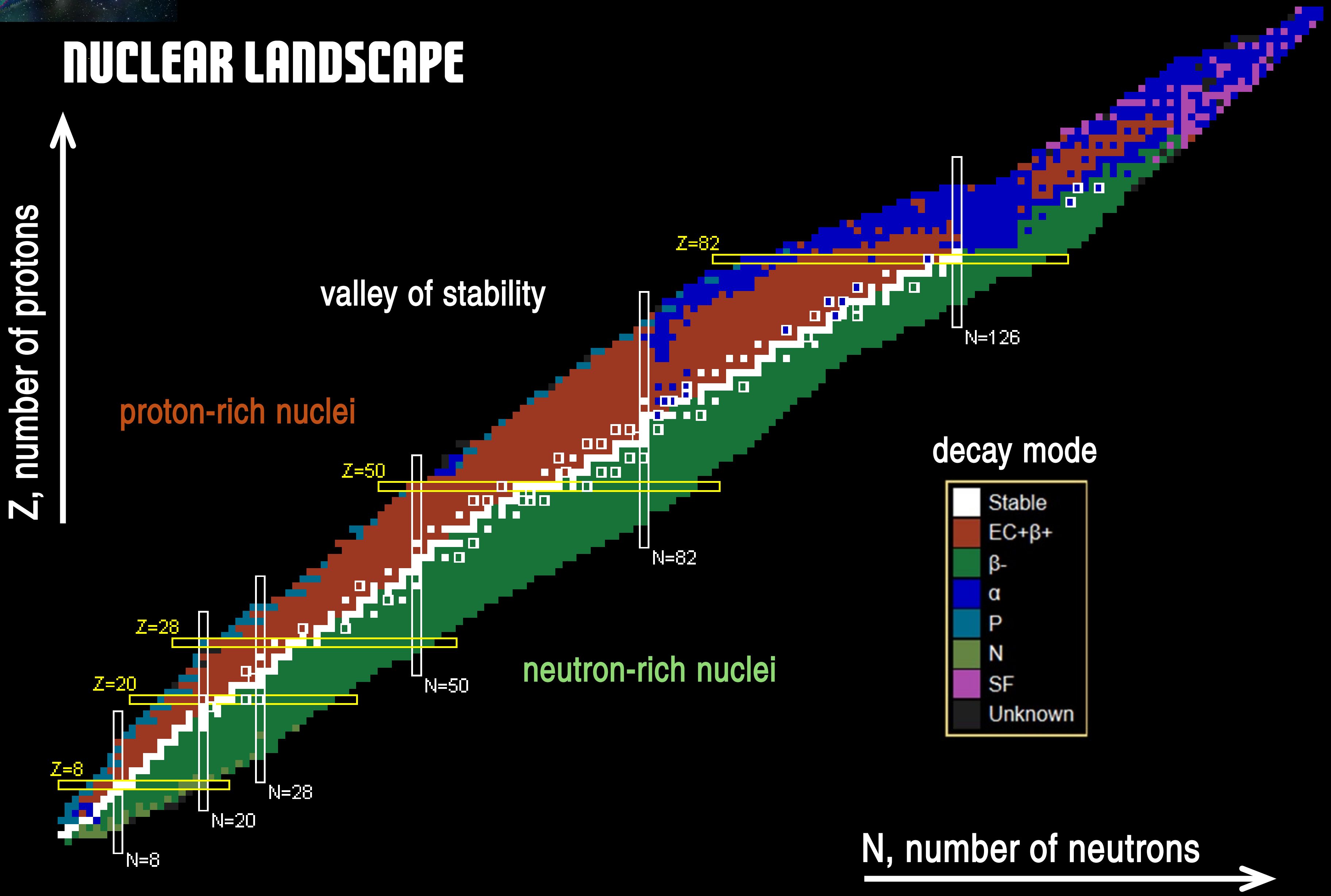
④ nuclear Equation of State

⑤ s, r, p, rp processes



NUCLEAR STRUCTURE: THE BASICS

NUCLEAR LANDSCAPE



≈ 300 STABLE NUCLEI

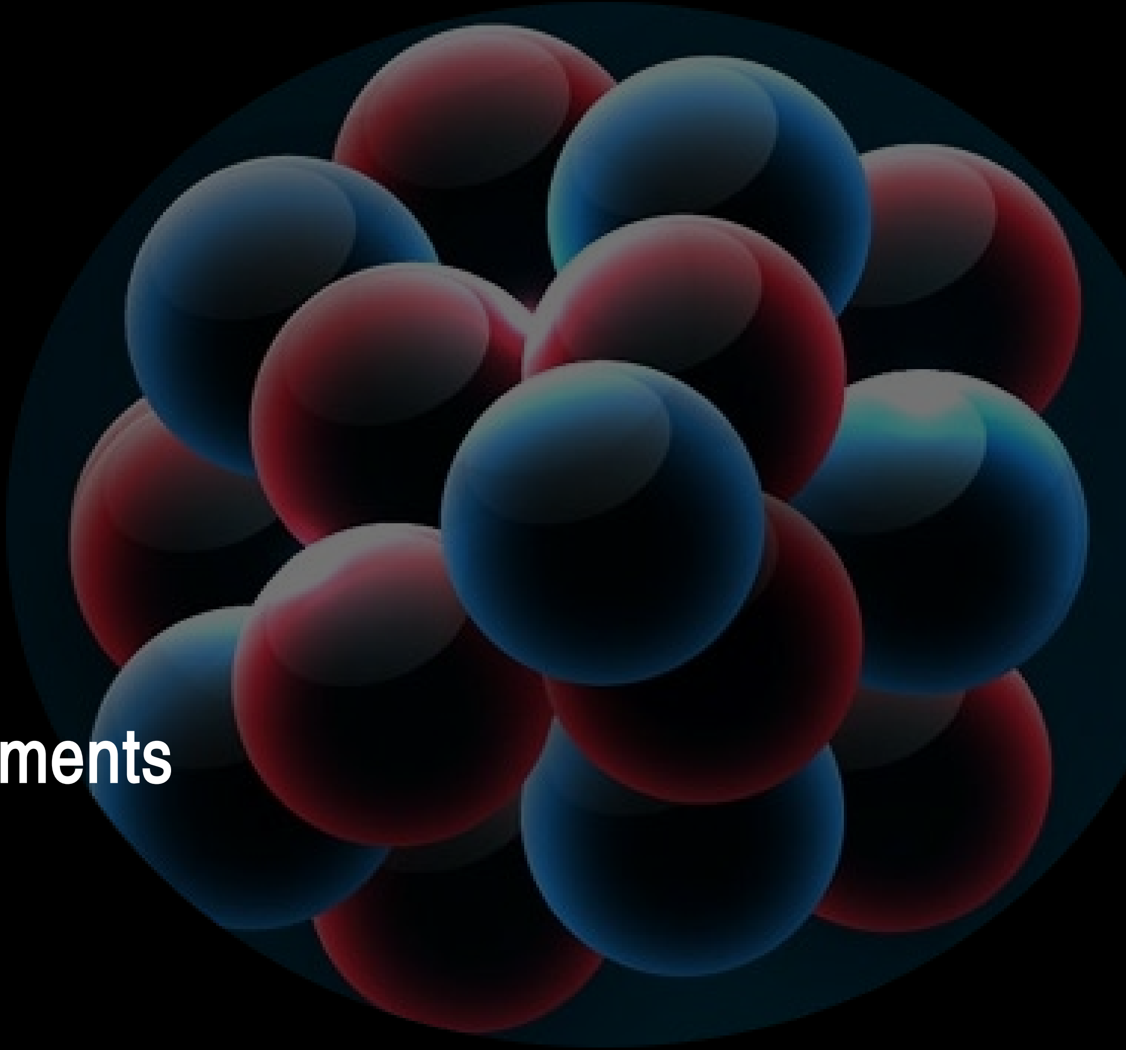
- $Z \cong N$ up to ^{40}Ca
- $N > Z$ for $A > 40$

≈ 3000 UNSTABLE NUCLEI

ISLAND OF STABILITY?

Nuclear Structure: The Basics

Static properties to describe a nucleus:

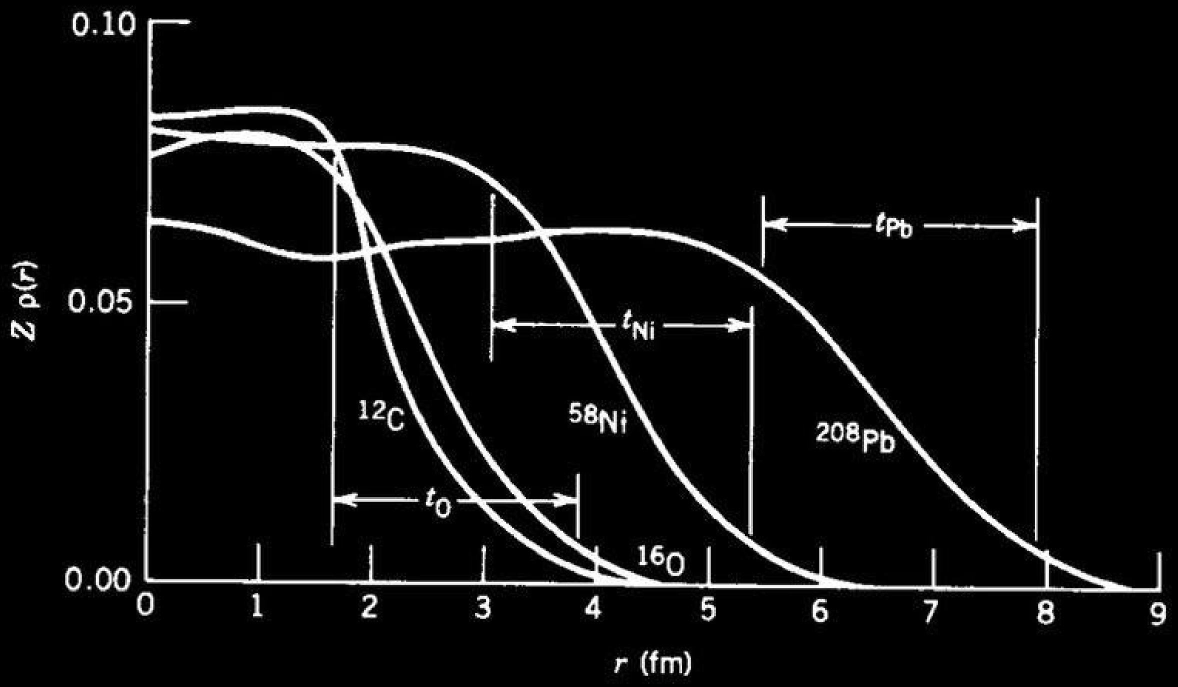


electric charge
radius
mass
binding energy
angular momentum
parity
magnetic dipole and electric quadrupole moments
energies of excited states

NUCLEAR STRUCTURE: THE BASICS

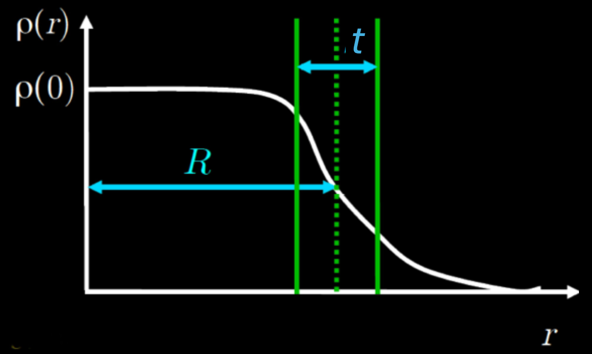
see Patrick Achenbach's talk on Tuesday

CHARGE DISTRIBUTIONS IN (STABLE) NUCLEI



well described by
FERMI PARAMETRISATION

$$\rho(r) = \frac{\rho(0)}{1+e^{(r-R)/t}}$$

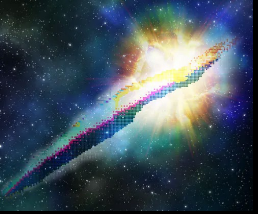


RADIUS R
↪ increases with A: $\mathbf{R} = \mathbf{r_0} \cdot \mathbf{A^{1/3}}$ $(r_0 \approx 1{,}2\text{fm})$

SURFACE WIDTH or **SKIN THICKNESS** t

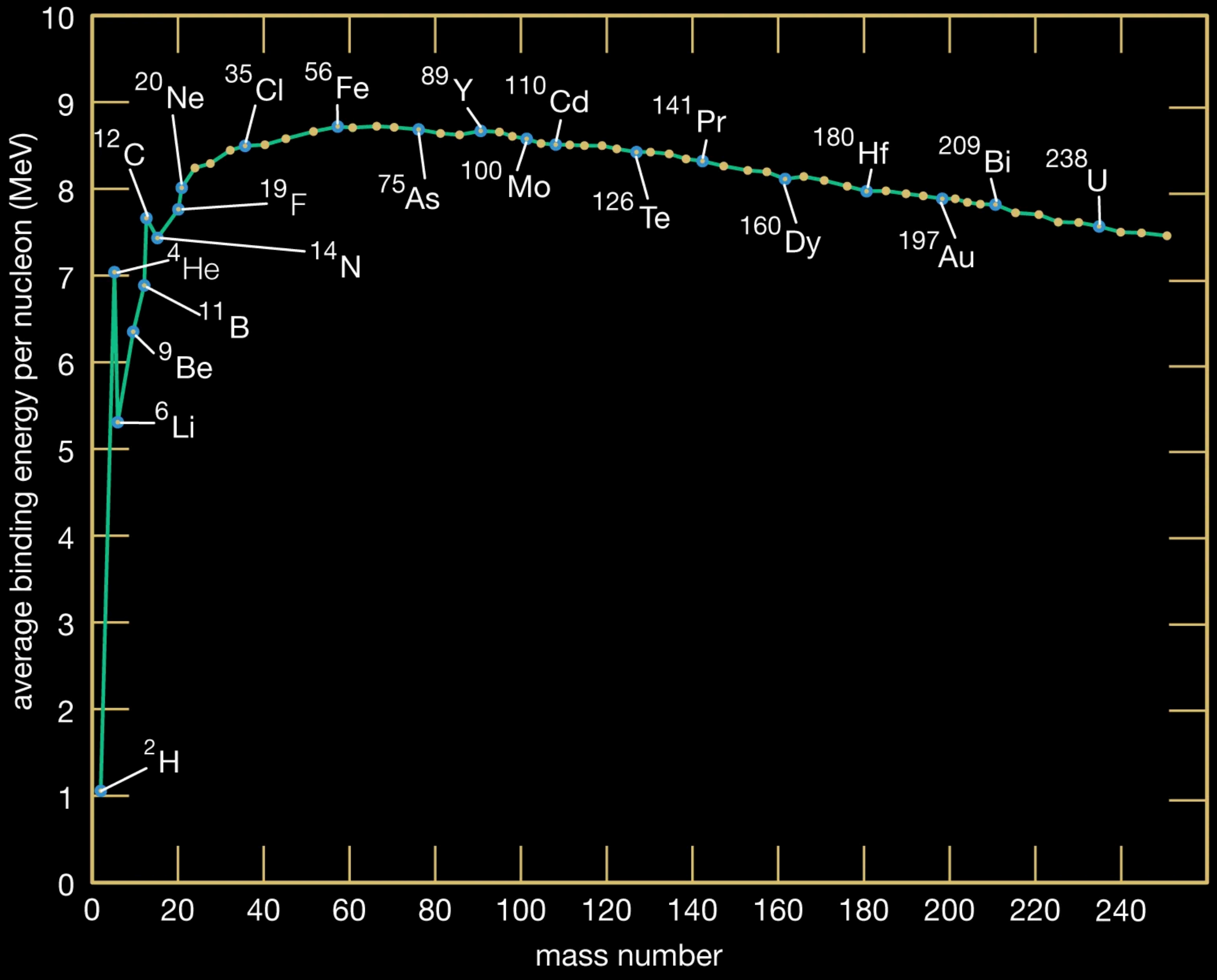
- const. density ρ_0 in the interior (saturation)
- same skin thickness t

→ (stable) nuclei look like **LIQUID DROPS** of radius $R \propto A^{1/3}$



NUCLEAR STRUCTURE: THE BASICS

BINDING ENERGY



BINDING ENERGY B:

energy required to split a nucleus into its constituents

$$\mathbf{m(Z,N) = \left(Zm_p + Nm_n\right) - B}$$

↪ gives information on

- forces between nucleons
- stability of nucleus
- energy released or required in nuclear decays or reactions

characterize binding energy with only a few general parameters

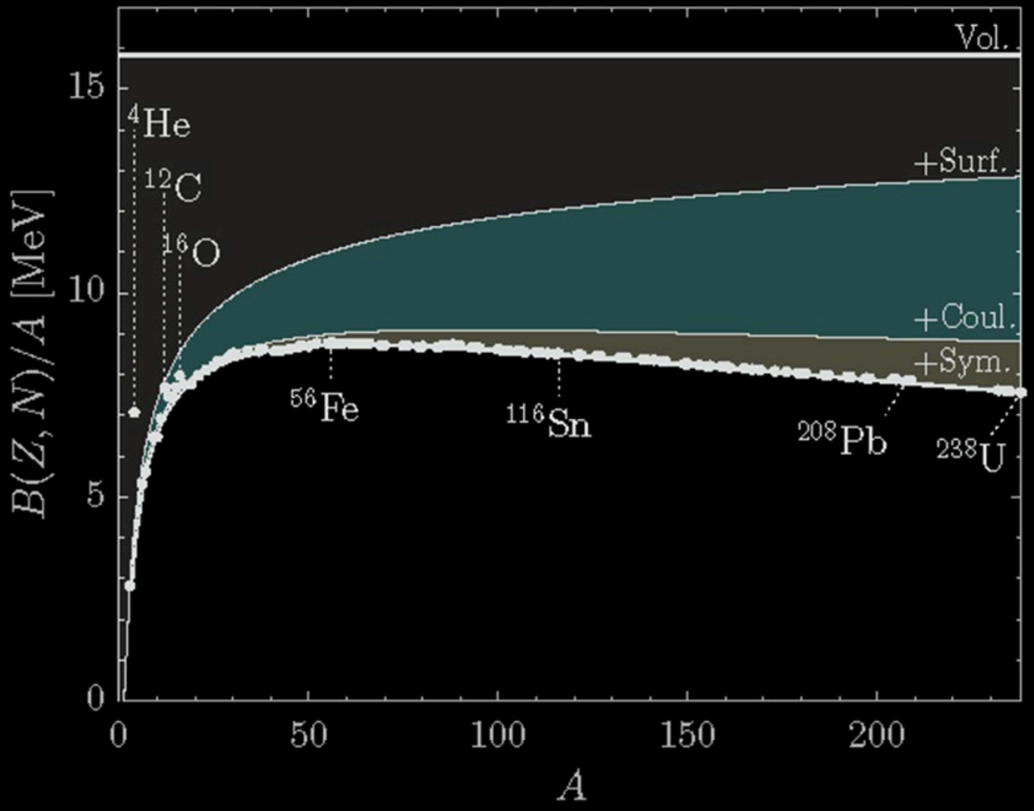
↪ **LIQUID DROP MODEL**

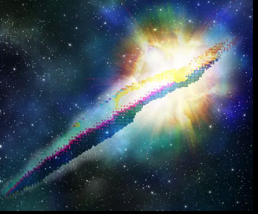
NUCLEAR STRUCTURE: THE BASICS

LIQUID DROP MODEL

Bethe-Weizsäcker semi-empirical mass formula:

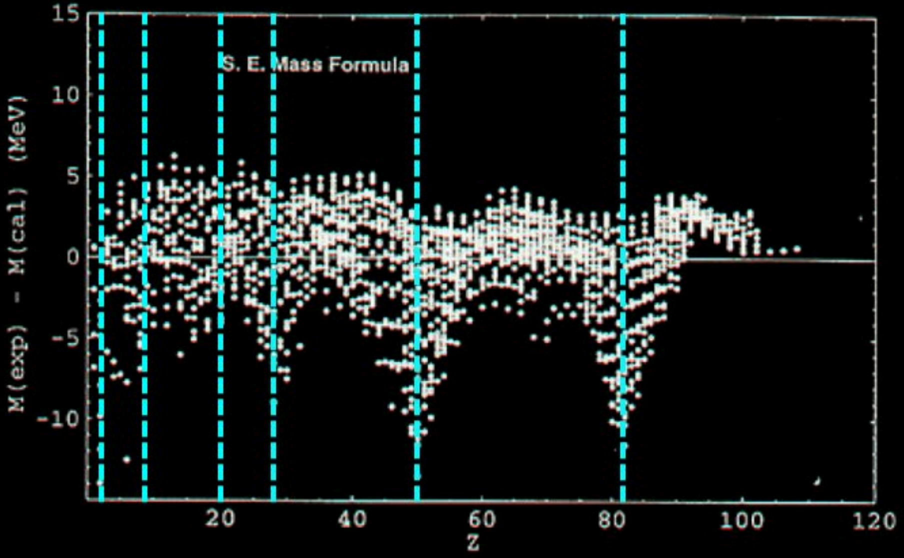
$$\mathbf{B(Z,N) = a_v \cdot A - a_s \cdot A^{2/3} - a_c \cdot \frac{Z(Z-1)}{A^{1/3}} - a_{sym} \cdot \frac{(A-2Z)^2}{A}}$$

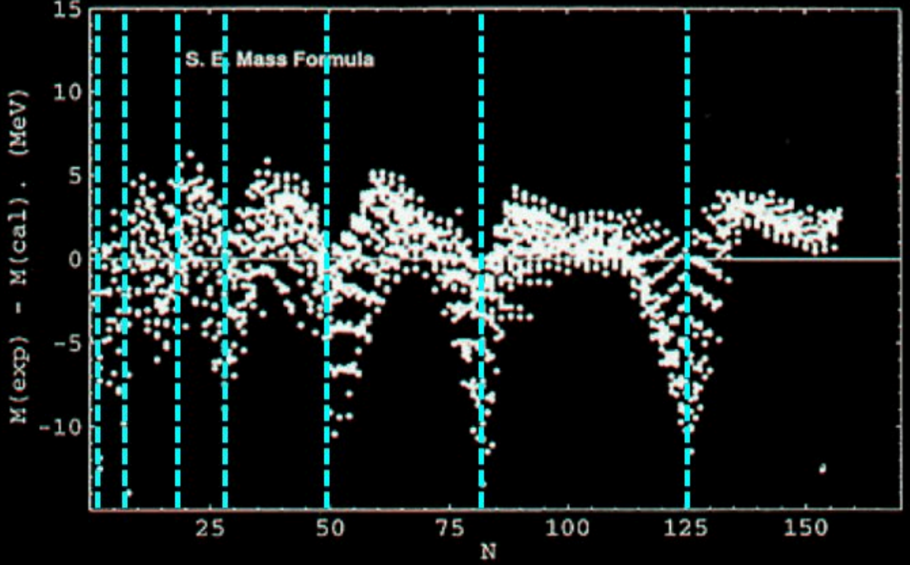




NUCLEAR STRUCTURE: THE BASICS

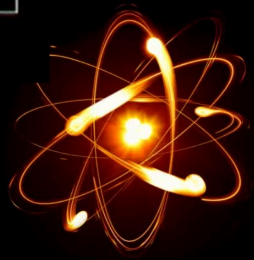
VARIATION FROM THE SEMI-EMPIRICAL MASS FORMULA





more bound systems at Z or N = 2, 8, 20, 28, 50, 82, 126,…

↪ **SHELL STRUCTURE** in nuclei as in atoms?

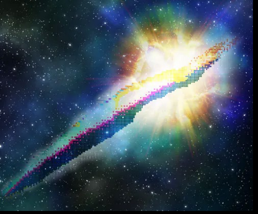


MAGIC NUMBERS

2 8 20 28 50 82 126

^{4}He ^{16}O ^{40}Ca ^{58}Ni ^{120}Sn ^{208}Pb

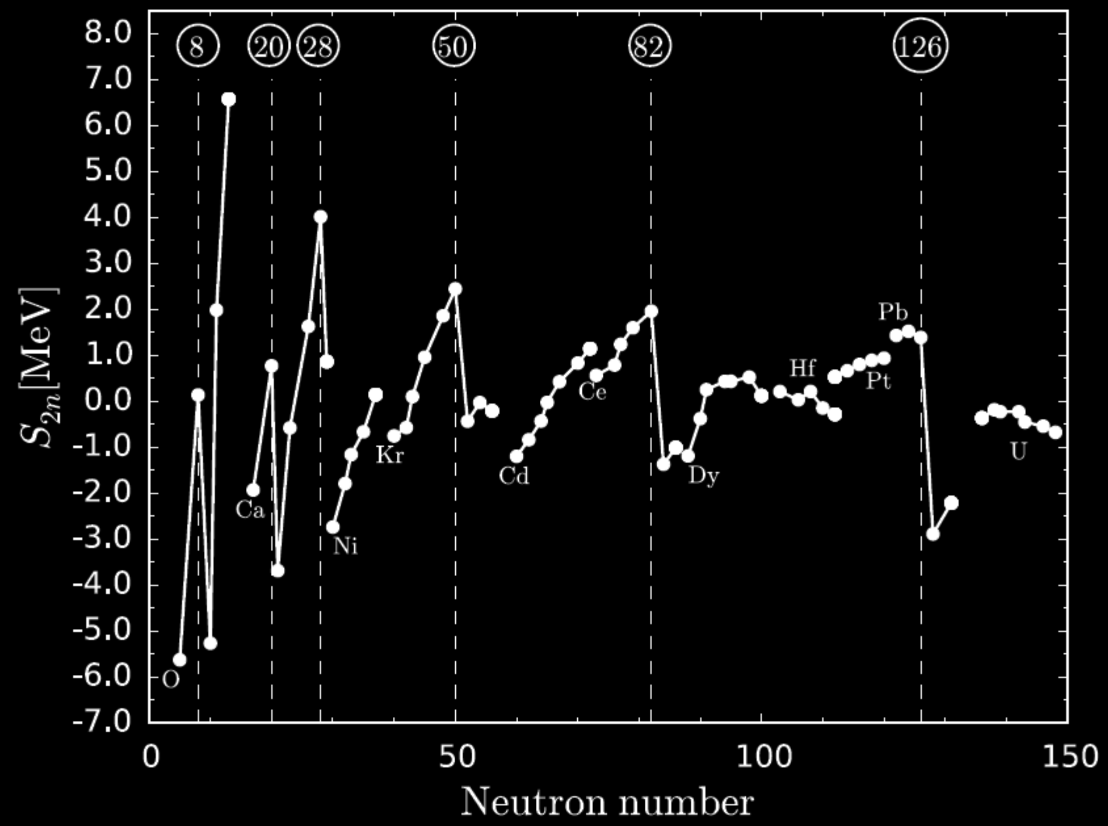
^{4}He ^{16}O ^{40}Ca ^{48}Ca ^{132}Sn ^{208}Pb



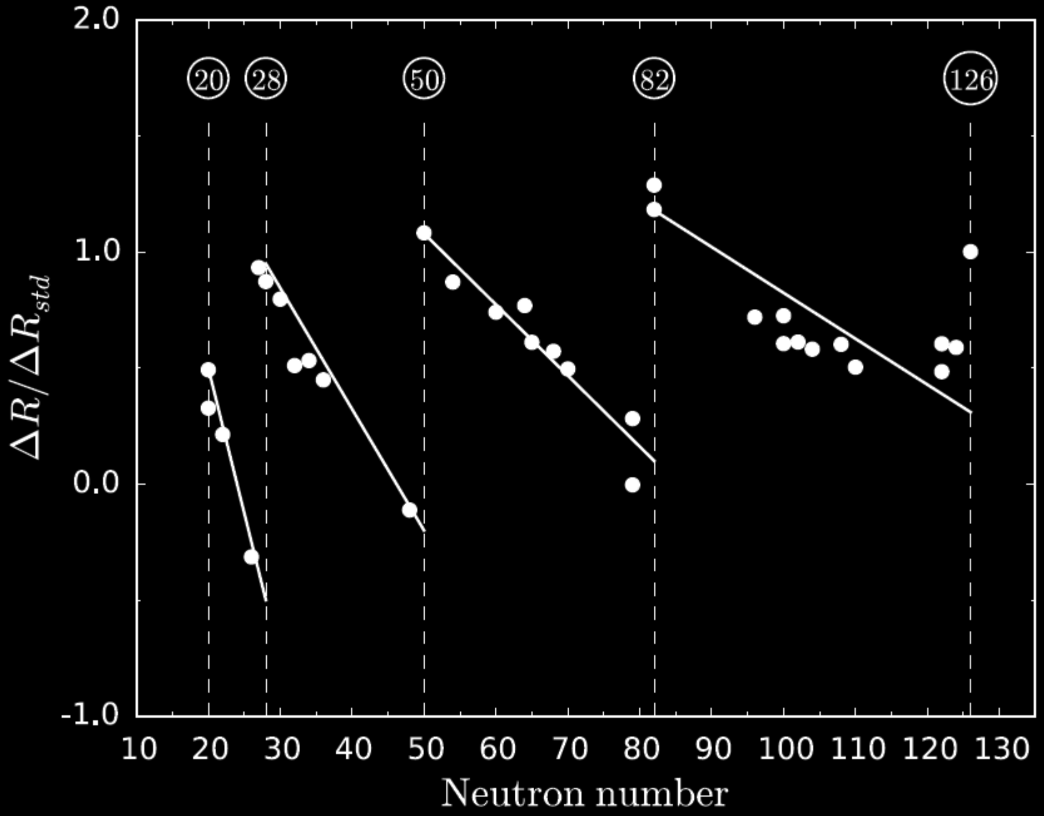
NUCLEAR STRUCTURE: THE BASICS

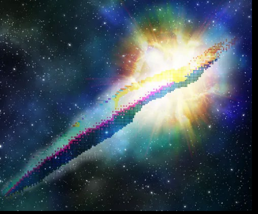
EXPERIMENTAL EVIDANCE FOR SHELL STRUCTURE IN NUCLEI

two-neutron separation energy



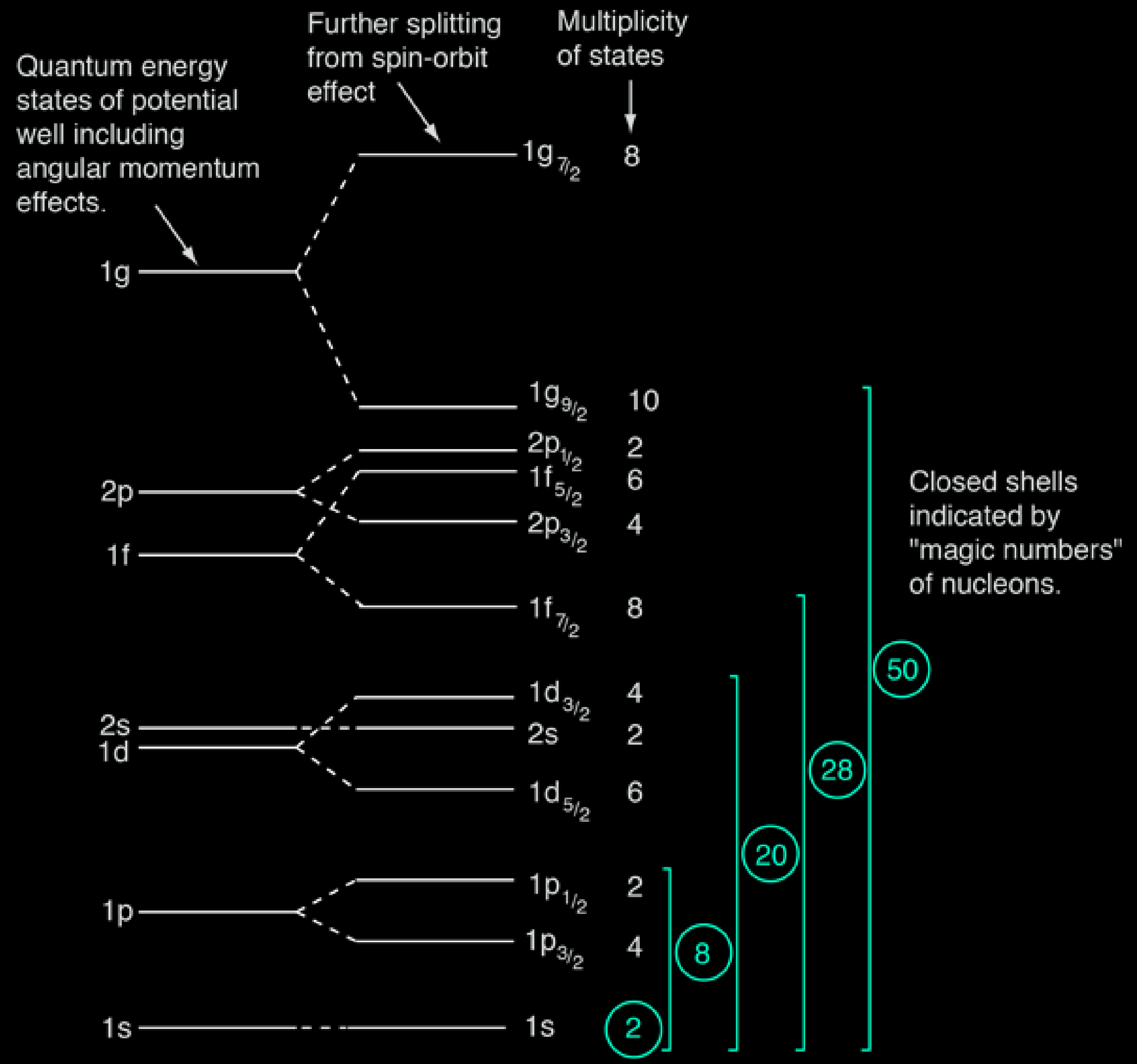
nuclear-charge radii





NUCLEAR STRUCTURE: THE BASICS

NUCLEAR SHELL MODEL



developed in 1949
by Maria Göppert-Mayer and Hans Jensen

at leading order nucleons are seen as:

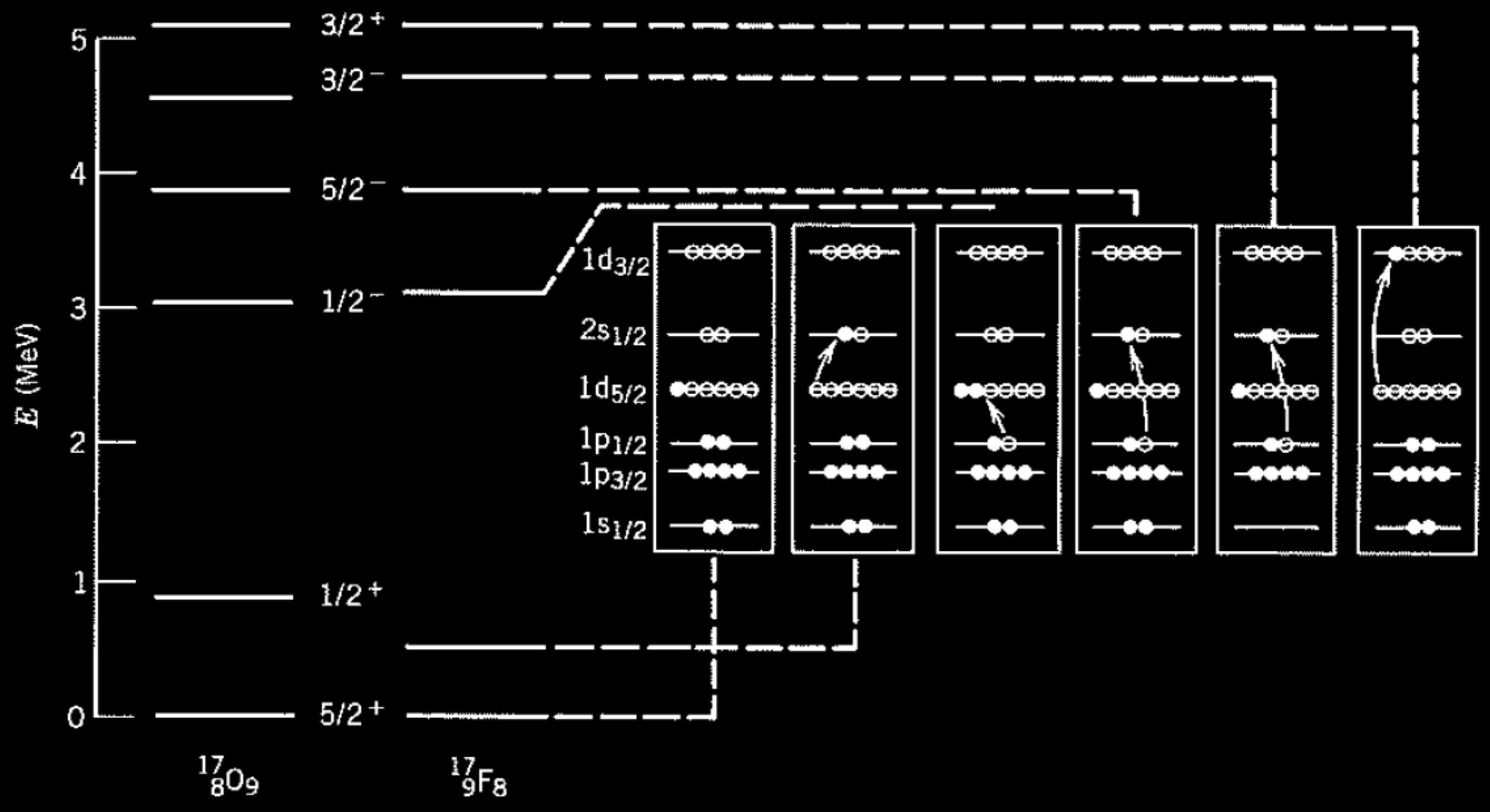
- **INDEPENDENT** particles
- evolving in a **MEAN FIELD**
- which generates orbitals
  grouped in **SHELLS** separated by energy gaps
- closed shells ⇔ **MAGIC NUMBERS**

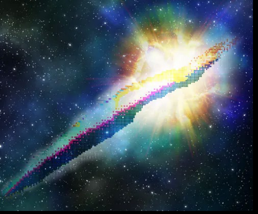
↪ **SPIN-ORBIT COUPLING** is crucial
to get the right ordering of shells

Nuclear Structure: The Basics

Nuclear Shell Model

explains **SPIN** and **PARITY** of the ground state of many nuclei and some of the **EXCITED LEVELS** e.g. ^{17}O and ^{17}F:



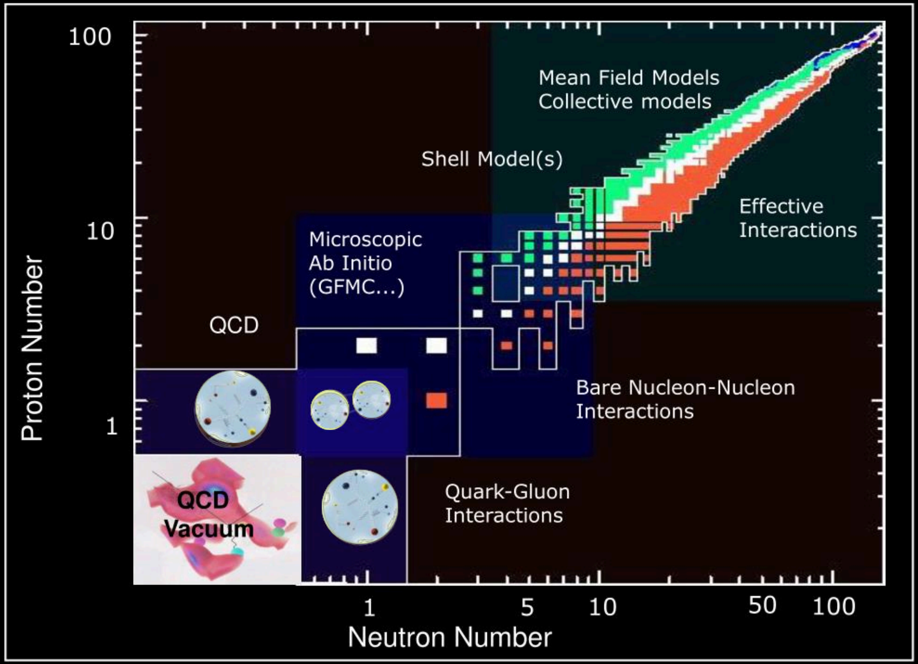


NUCLEAR STRUCTURE: THE BASICS

NUCLEAR MODELS

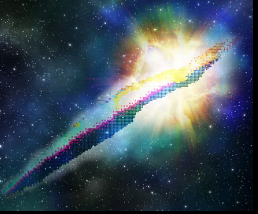
up to here: potential assumed based on empirical facts

can we build **AB INITIO** models (i.e. based on first principles)?
↪ nucleons as building blocks
↪ realistic NN-interaction



AB INITIO METHODS: description of nuclei starting from the bare NN & 3N interactions.
NUCLEAR SHELL MODEL: nuclear average potential + (residual) interaction between nucleons.

MEAN-FIELD METHODS: nuclear average potential with global parametrisation (+ correlations).
PHENOMENOLOGICAL MODELS: specific nuclei or properties with local parametrisation.



Nuclear structure: ab initio nuclear models

Many-body Hamiltonian

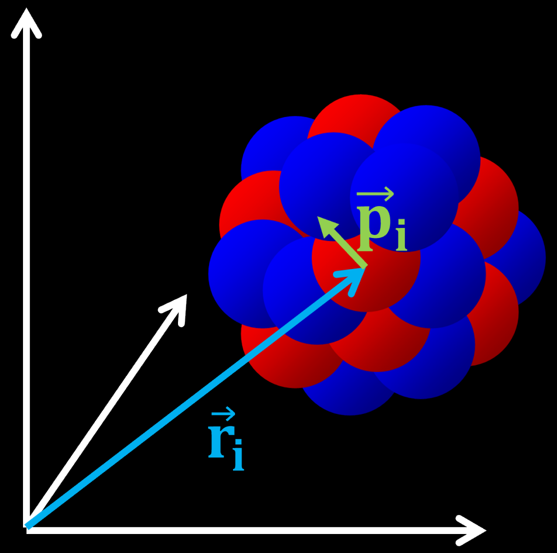
nuclear structure calculations: A nucleons (Z protons and N neutrons)

relative motion described by the A-body Hamiltonian:

$$H = \sum_{i=1}^{A} \frac{p_i^2}{2m} + \sum_{i<j}^{A} V(\vec{r}_i, \vec{r}_j) + \cdots$$

→ solve the A-body Schrödinger equation

$$H\Psi(\vec{r}_1, \vec{r}_2, \dots, \vec{r}_A) = E\Psi(\vec{r}_1, \vec{r}_2, \dots, \vec{r}_A)$$



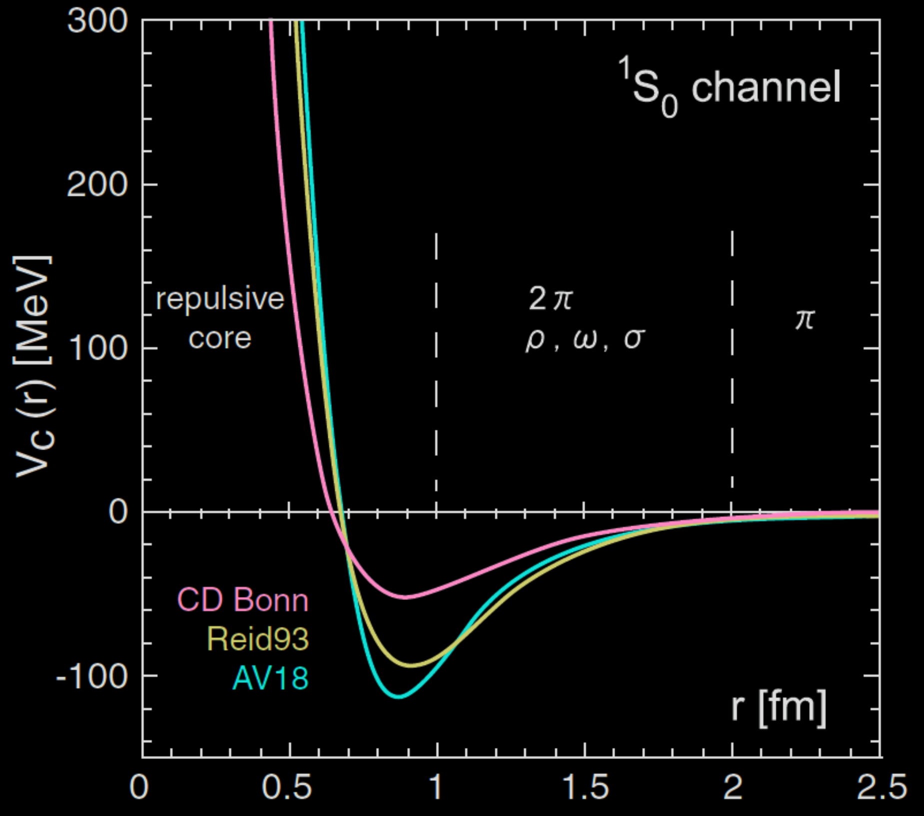
NUCLEAR STRUCTURE: AB INITIO NUCLEAR MODELS

REALISTIC NN-INTERACTIONS

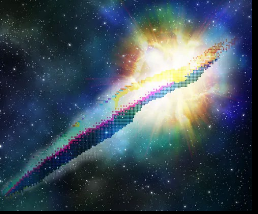
construct NN-potentials
based on neutron and proton scattering data
and properties of light nuclei

⟺ **PHENOMENOLOGICAL POTENTIALS** fitted on NN-observables:

- d binding energy,
- NN-phaseshifts

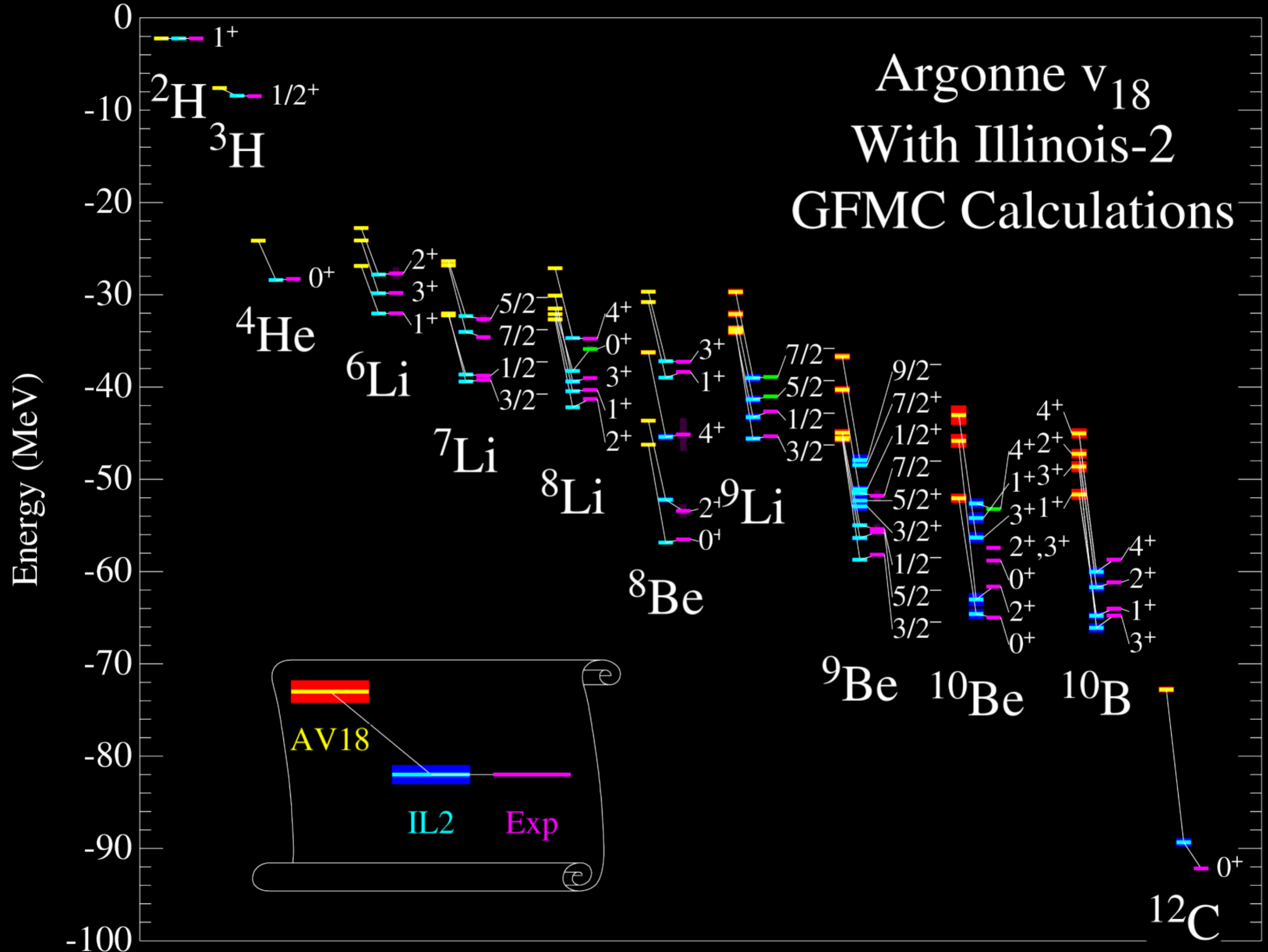


N. Ishii et al., PRL 99, 022001 (2007)



NUCLEAR STRUCTURE: AB INITIO NUCLEAR MODELS

ENERGY LEVELS OF LIGHT NUCLEI: EXPERIMENT VS THEORETICAL CALCULATION

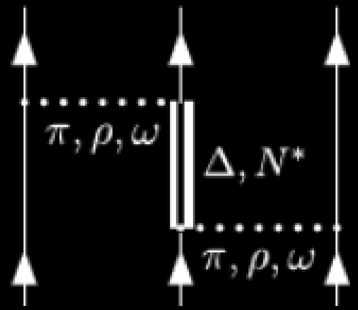


Carlson, Pieper, Wiringa et al.

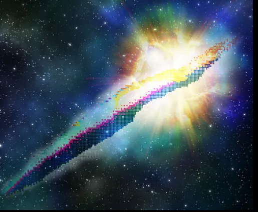
V_{NN} underbinds the nucleus
↪ need **THREE-BODY FORCES**

$$H = \sum_{i=1}^{A} T_i + \sum_{j>i=1}^{A} V_{ij} + \sum_{k>j>i=1}^{A} V_{ijk} + \cdots$$

three-body forces account for intermediate excitation of nucleons



↪ can be derived from **EFFECTIVE FIELD THEORY**



NUCLEAR STRUCTURE: AB INITIO NUCLEAR MODELS

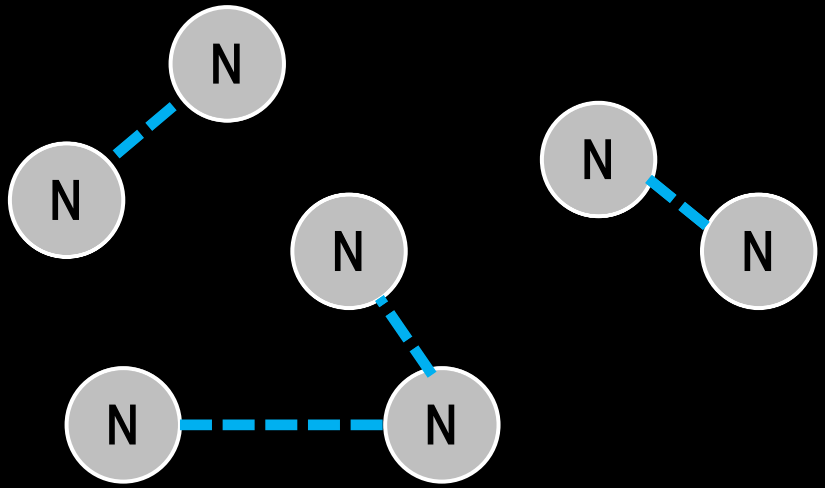
EFFECTIVE FIELD THEORY (EFT)

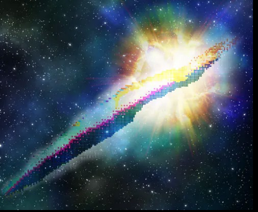
is an effective quantum field theory based on QCD symmetries
with resolution scale Λ that selects appropriate degrees of freedom

$\hookrightarrow$ hierarchy of EFTs that describe the strong interaction across multiple scales

$\hookrightarrow$ scale separation simplifies description of physical processes

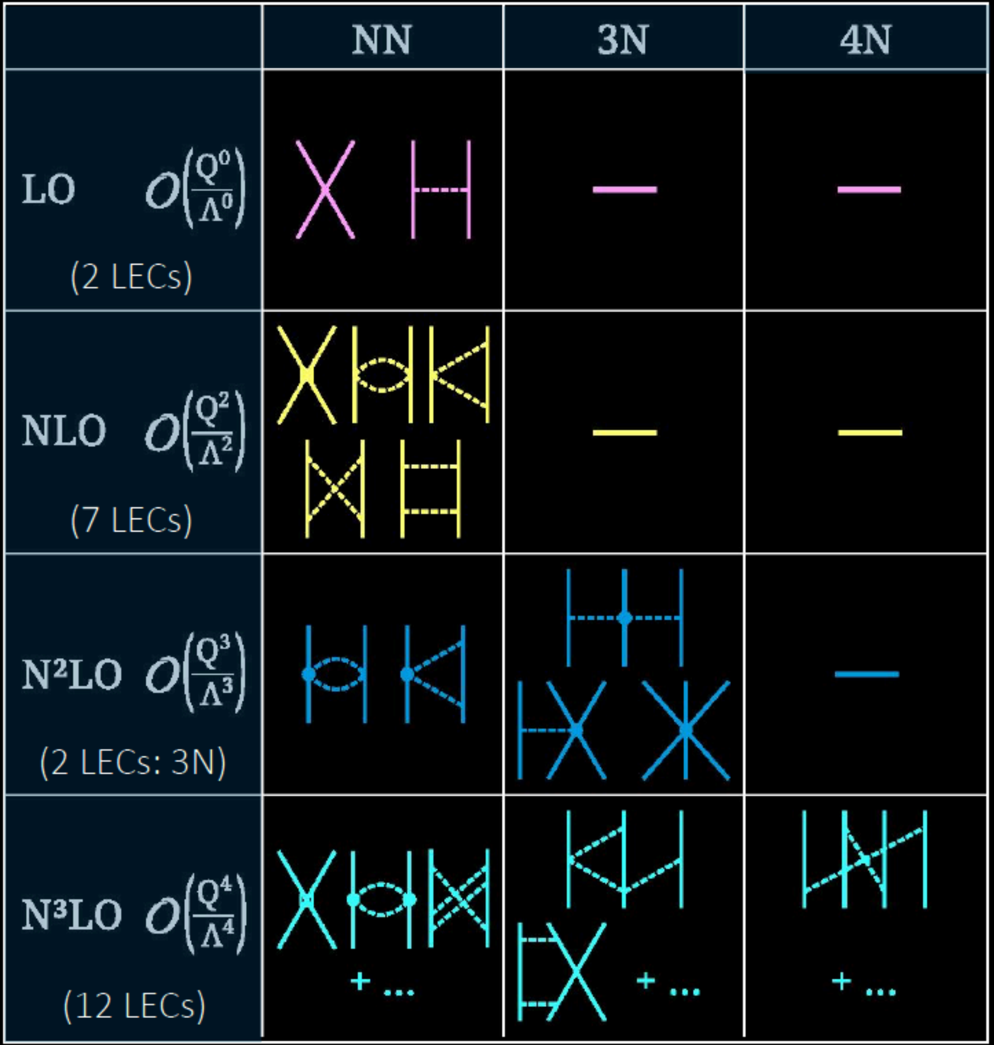
$\hookrightarrow$ relevant degrees of freedom in nuclear physics: **NUCLEONS AND MESONS** $\Leftrightarrow$ **CHIRAL EFT**





NUCLEAR STRUCTURE: AB INITIO NUCLEAR MODELS

CHIRAL EFFECTIVE FIELD THEORY (χEFT)



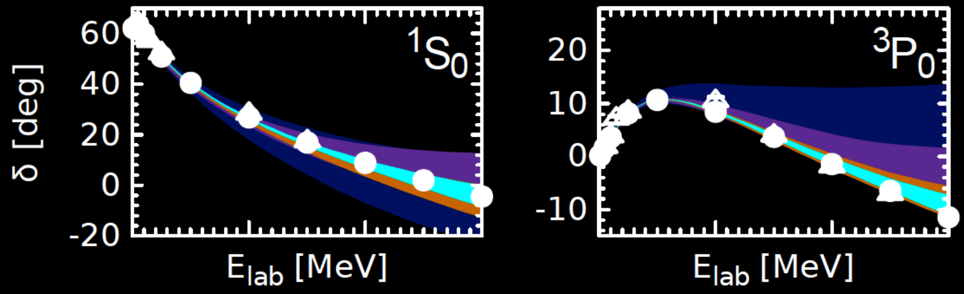
systematic expansion of nuclear forces in Q/ Λ

natural hierarchy of nuclear forces

power counting scheme results in systematic expansion
↪ enables **UNCERTAINTY ESTIMATES**

low energy constants (LEC) unknown
↪ fit to NN data (NN scattering)
↪ fit to 3N data (binding energies, radii)

np scattering phase shifts

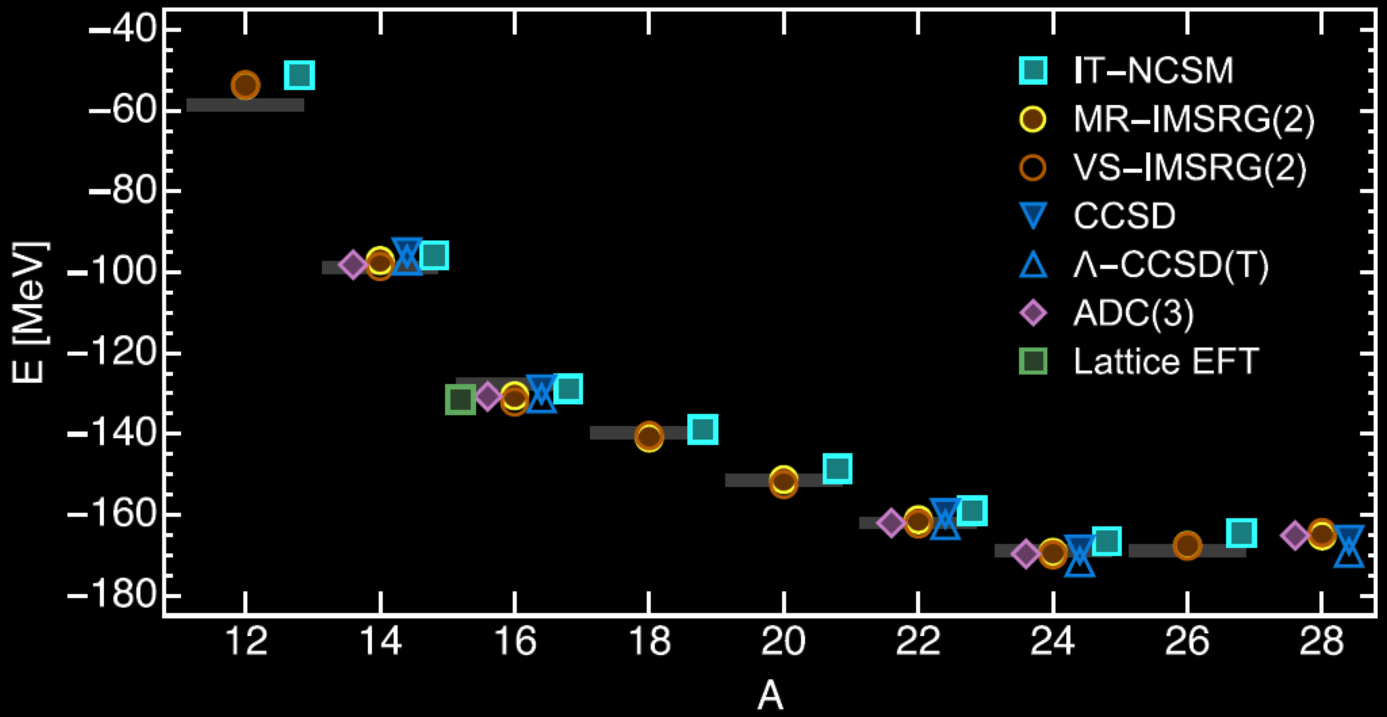


E. Epelbaum et al., PRL 115 (2015) 122301

NUCLEAR STRUCTURE: AB INITIO NUCLEAR MODELS

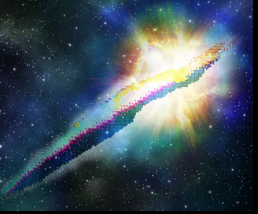
OXYGEN ISOTOPIC CHAIN

H. Hergert, Front. Phys. 8 (2020) 379



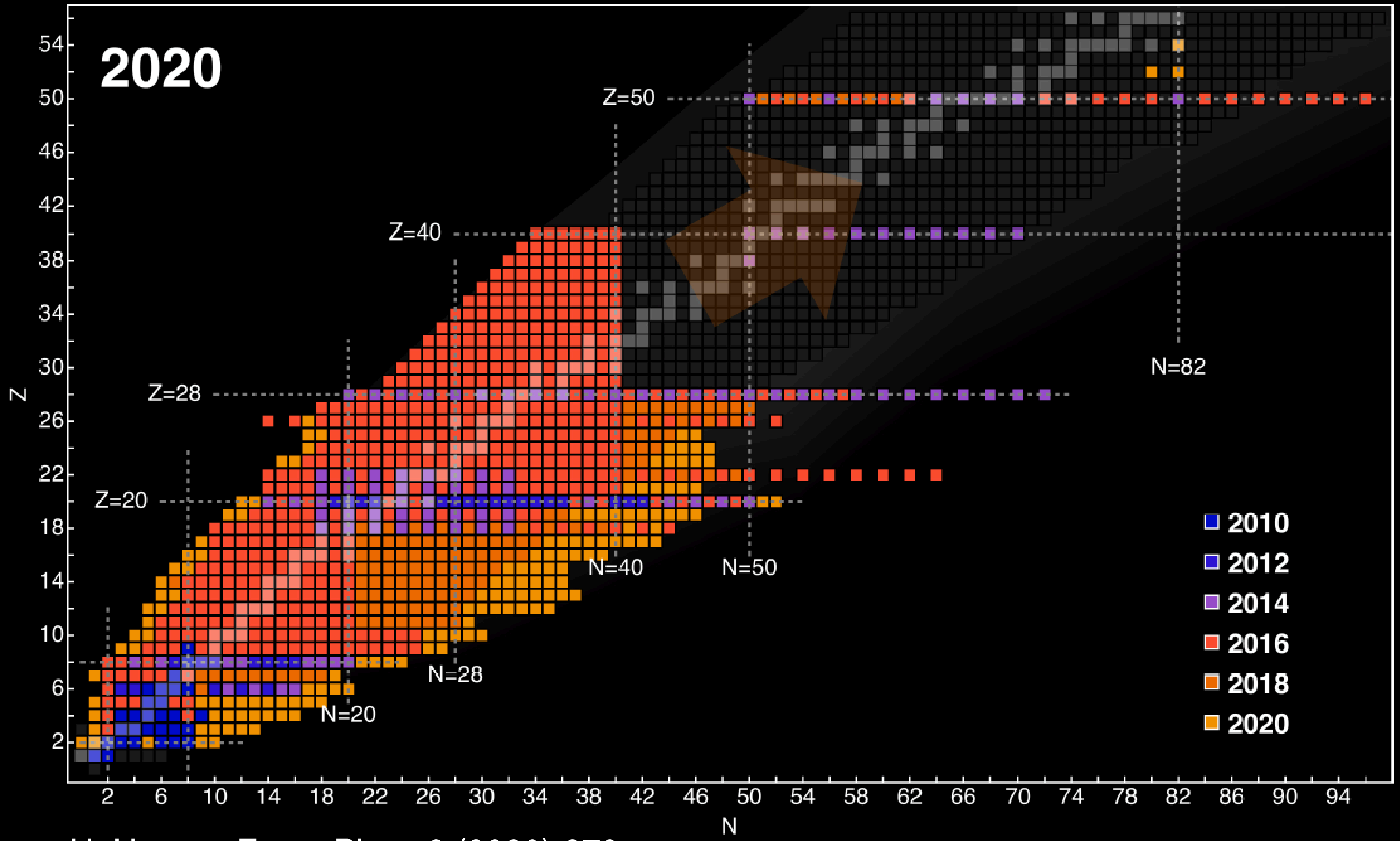
ground state energies obtained from different ab initio methods are in good agreement
- with each other
- with experiment

all theoretical approaches require 3N forces to reproduce the dripline at ^{24}O

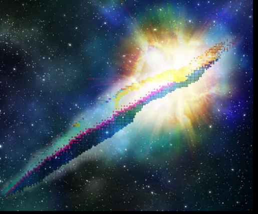


NUCLEAR STRUCTURE: AB INITIO NUCLEAR MODELS

PROGRESS IN AB INITIO NUCLEAR STRUCTURE CALCUATIONS



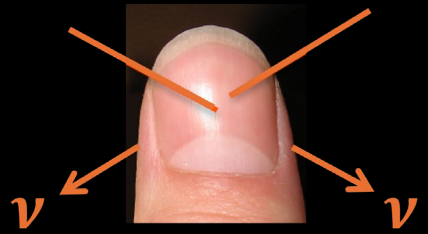
H. Hergert Front. Phys. 8 (2020) 379



NUCLEAR STRUCTURE: NEUTRINO OSCILLATION MEASUREMENTS

NEUTRINOS

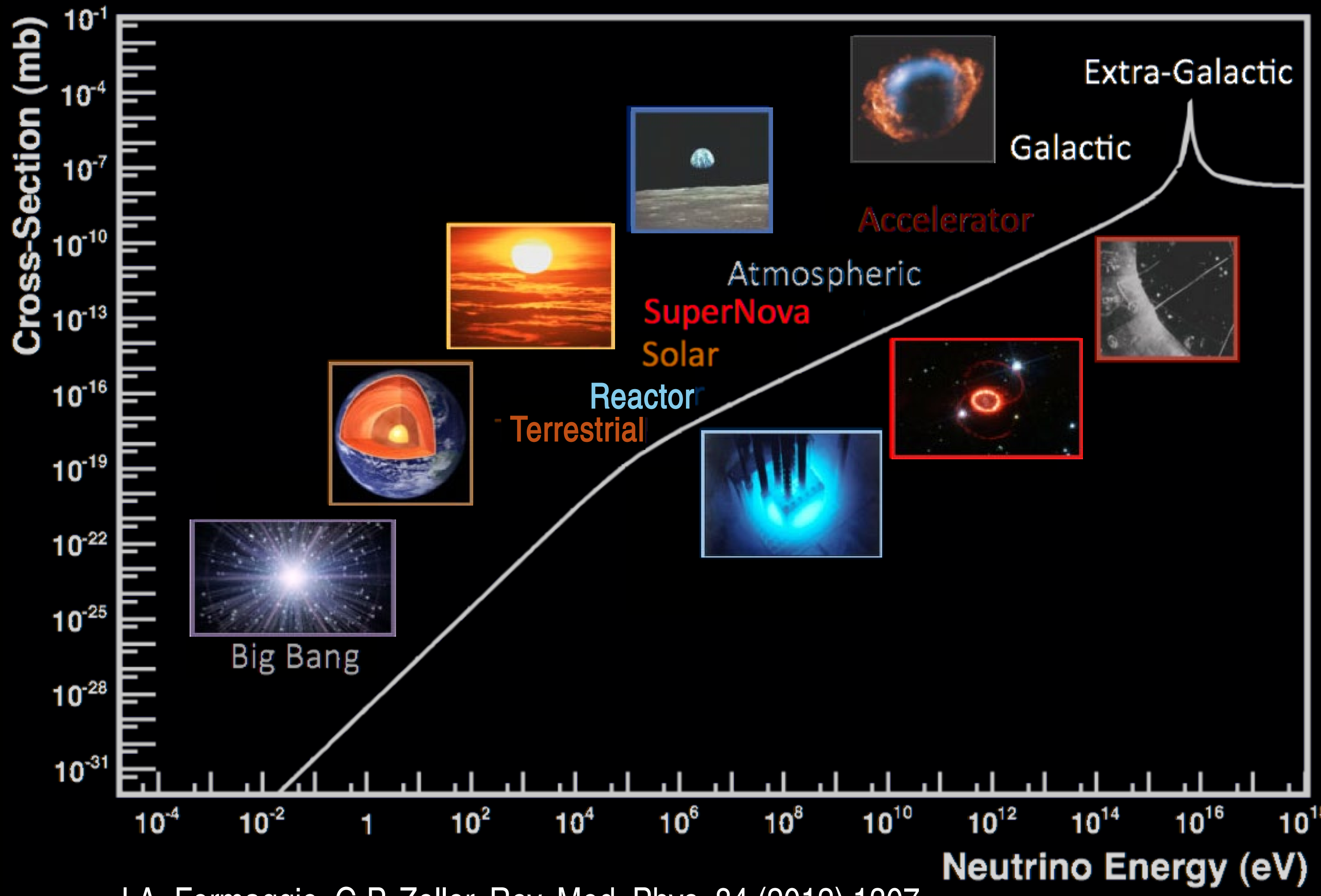
- have no charge
- are everywhere
  ↪ 10^{12} neutrinos pass through every cm^2 every second



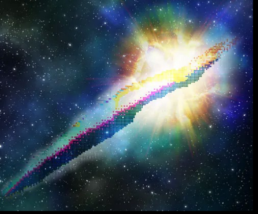
NUCLEAR STRUCTURE: NEUTRINO OSCILLATION MEASUREMENTS

NEUTRINOS

- have no charge
- are everywhere
  ↪ **WHERE DO THEY COME FROM?**



J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84 (2012) 1307



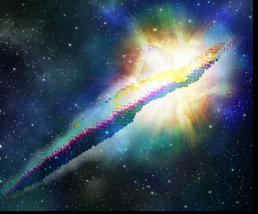
NUCLEAR STRUCTURE: NEUTRINO OSCILLATION MEASUREMENTS

NEUTRINOS

- have no charge
- are everywhere
  ↪ 10^{12} neutrinos pass through every cm^2 every second
- are very weakly interacting
  ↪ would need 10 light-years of lead to stop a 1MeV neutrino
- come in three flavours

ν_e ν_μ ν_τ

- have very small masses

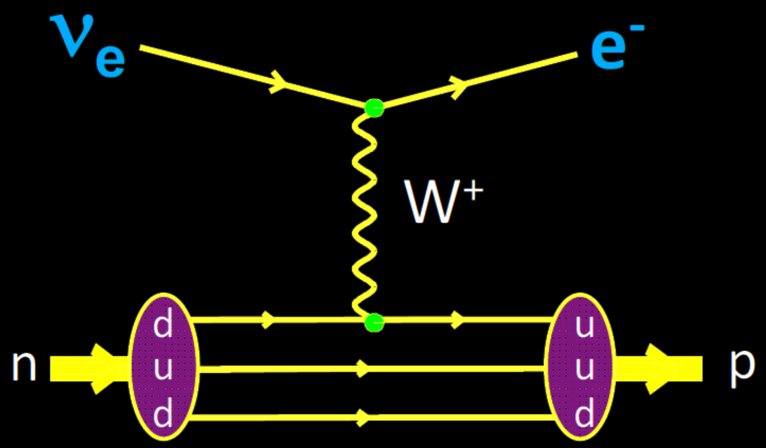


NUCLEAR STRUCTURE: NEUTRINO OSCILLATION MEASUREMENTS

HOW TO DETECT NEUTRINOS?

↪ via their weak interactions!

$$\nu_e + \mathbf{n} \to \mathbf{p} + \mathbf{e}^-$$

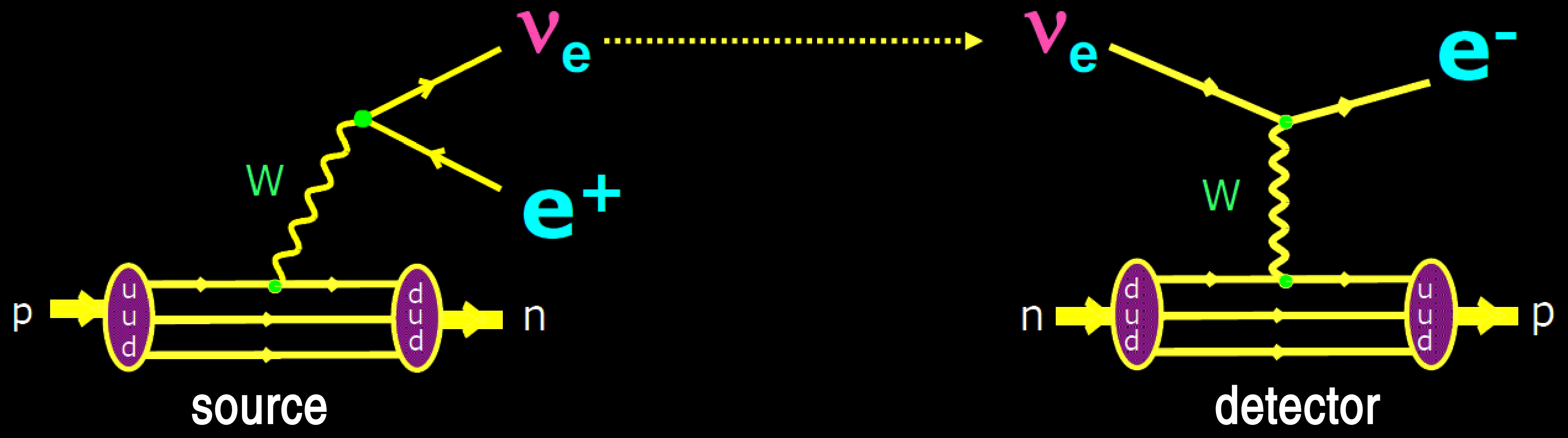


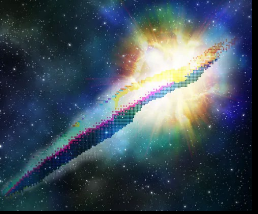
NUCLEAR STRUCTURE: NEUTRINO OSCILLATION MEASUREMENTS

HOW TO DETECT NEUTRINOS?

↪ via their weak interactions!

$$\nu_e + \mathbf{n} \rightarrow \mathbf{p} + \mathbf{e}^-$$

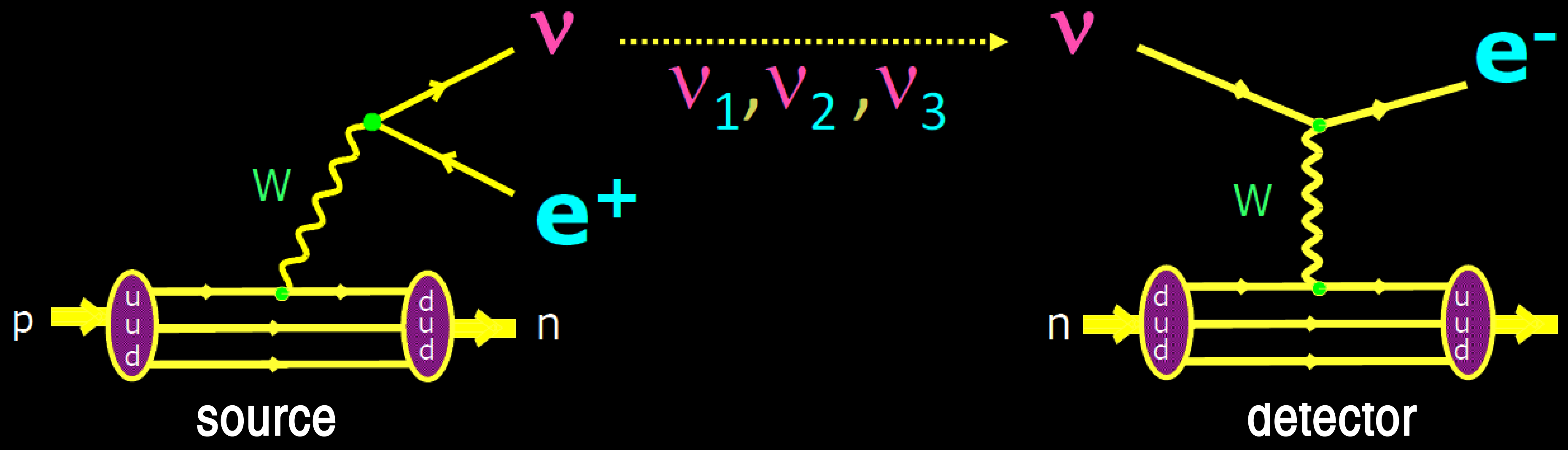




NUCLEAR STRUCTURE: NEUTRINO OSCILLATION MEASUREMENTS

HOW TO DETECT NEUTRINOS?

↪ via their weak interactions!

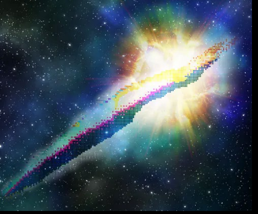


- **FLAVOUR EIGENSTATES:** ν_e, ν_μ, ν_τ
  ↪ Eigenstates of the weak Hamiltonian
- **MASS EIGENSTATES:** ν_1, ν_2, ν_3
  ↪ Eigenstates of the Hamiltonian describing a free neutrino

NEUTRINO MIXING

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i$$

with $\alpha = e, \mu, \tau$

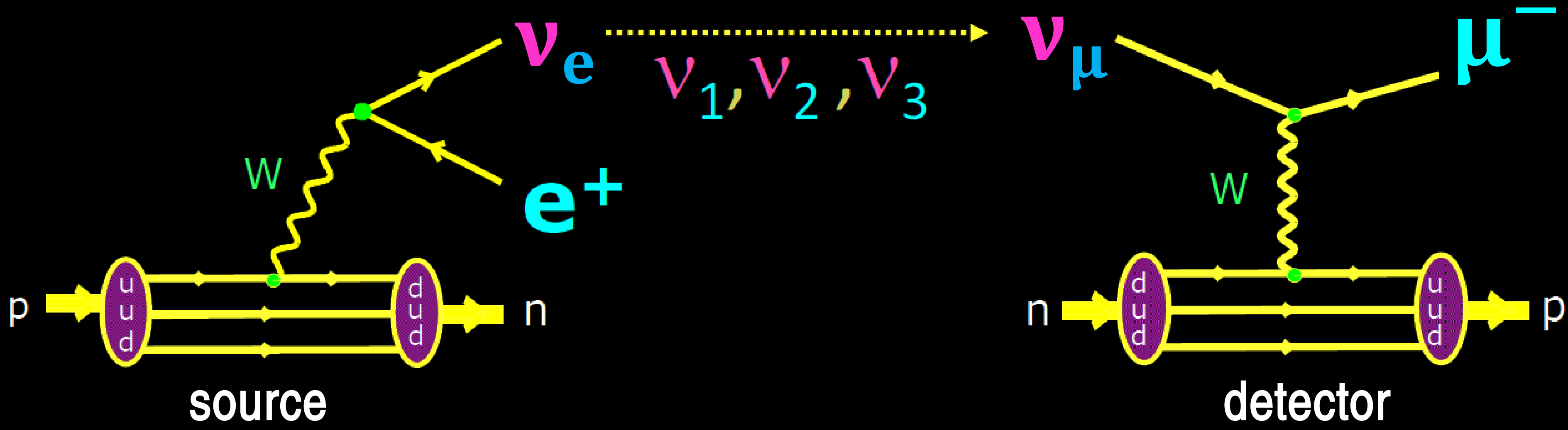


NUCLEAR STRUCTURE: NEUTRINO OSCILLATION MEASUREMENTS

HOW TO DETECT NEUTRINOS?

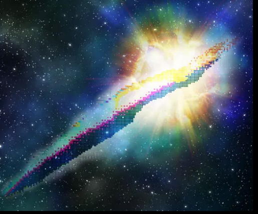
↪ via their weak interactions!

$$\nu_\mu + n \rightarrow p + \mu^-$$



- **NEUTRINO OSCILLATIONS** (start with two flavours)
  ↪ **each flavour (e, μ) is a superposition of different masses (1,2)**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



NUCLEAR STRUCTURE: NEUTRINO OSCILLATION MEASUREMENTS

ACCELERATOR-BASED OSCILLATION EXPERIMENTS

↪ neutrino oscillation probability

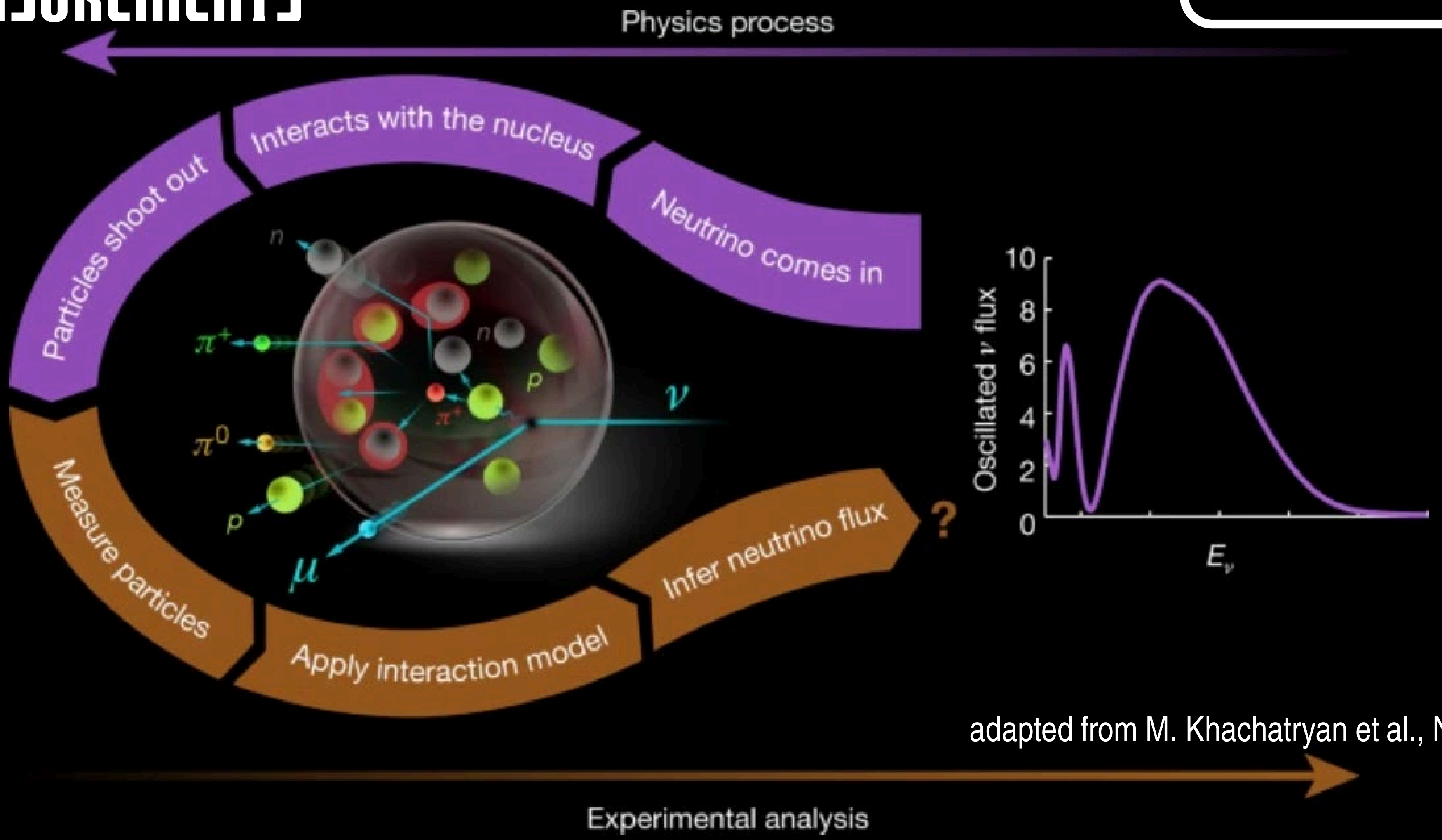
$$P_{\nu_\mu \to \nu_e}(E, L) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

E: neutrino energy
L: propagation distance
θ: neutrino mixing angle
$\Delta m^2 = m_{\nu_1}^2 - m_{\nu_2}^2$

↪ to extract oscillation parameters the neutrino energy has to be reconstructed in every neutrino-nucleus scattering event

NUCLEAR STRUCTURE: NEUTRINO OSCILLATION MEASUREMENTS

see Adi Ashkenazi's talk on Tuesday



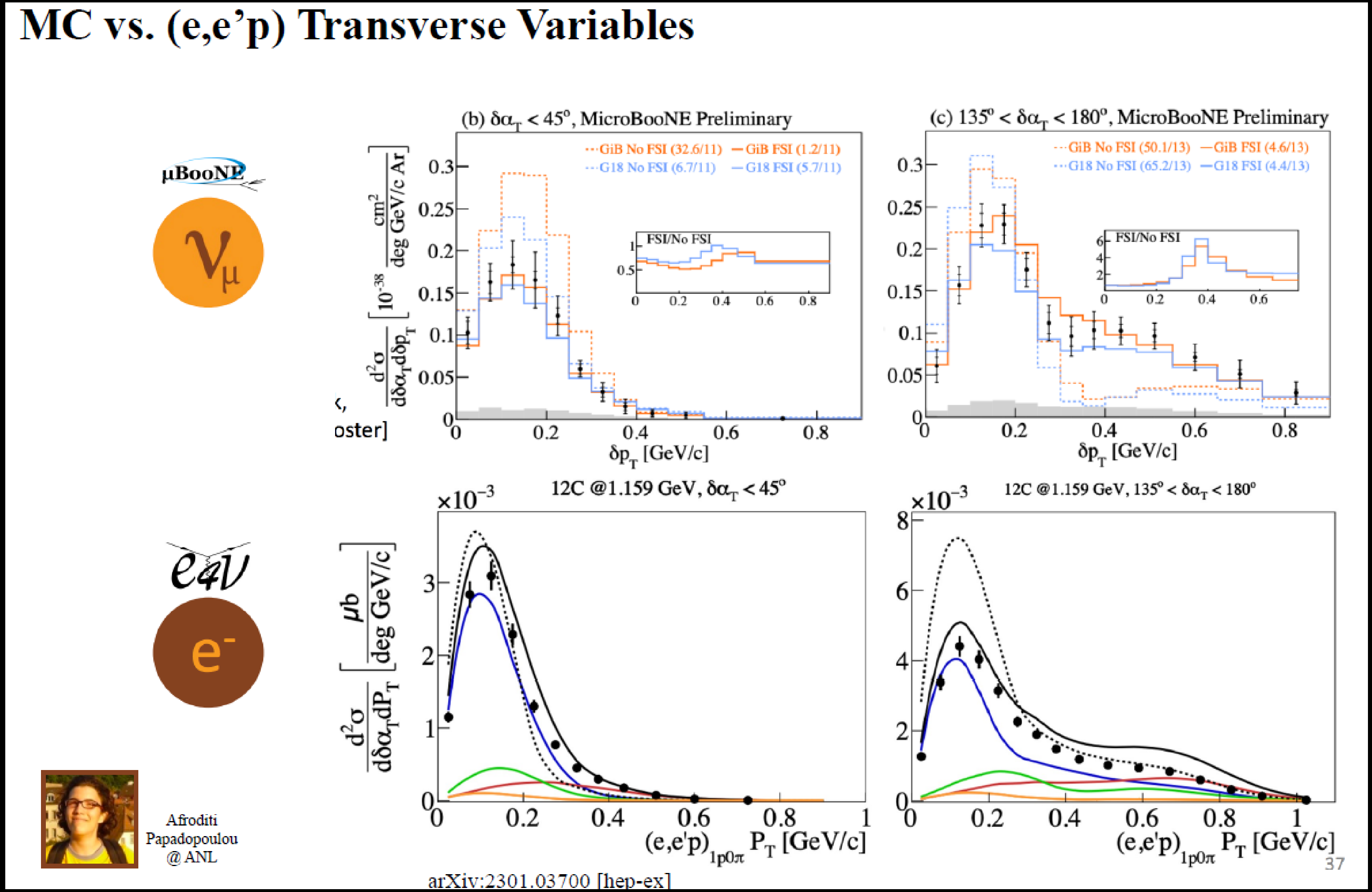
adapted from M. Khachatryan et al., Nature 599 (2021) 7886

reliable **NUCLEAR THEORIES NEEDED** for interpretation of ν data

↪ precise description of $\nu - \mathrm{N}$ interaction needed!

NUCLEAR STRUCTURE: NEUTRINO OSCILLATION MEASUREMENTS

see Adi Ashkenazi's talk on Tuesday



IDEA: use electron scattering

↪ constrain model uncertainties

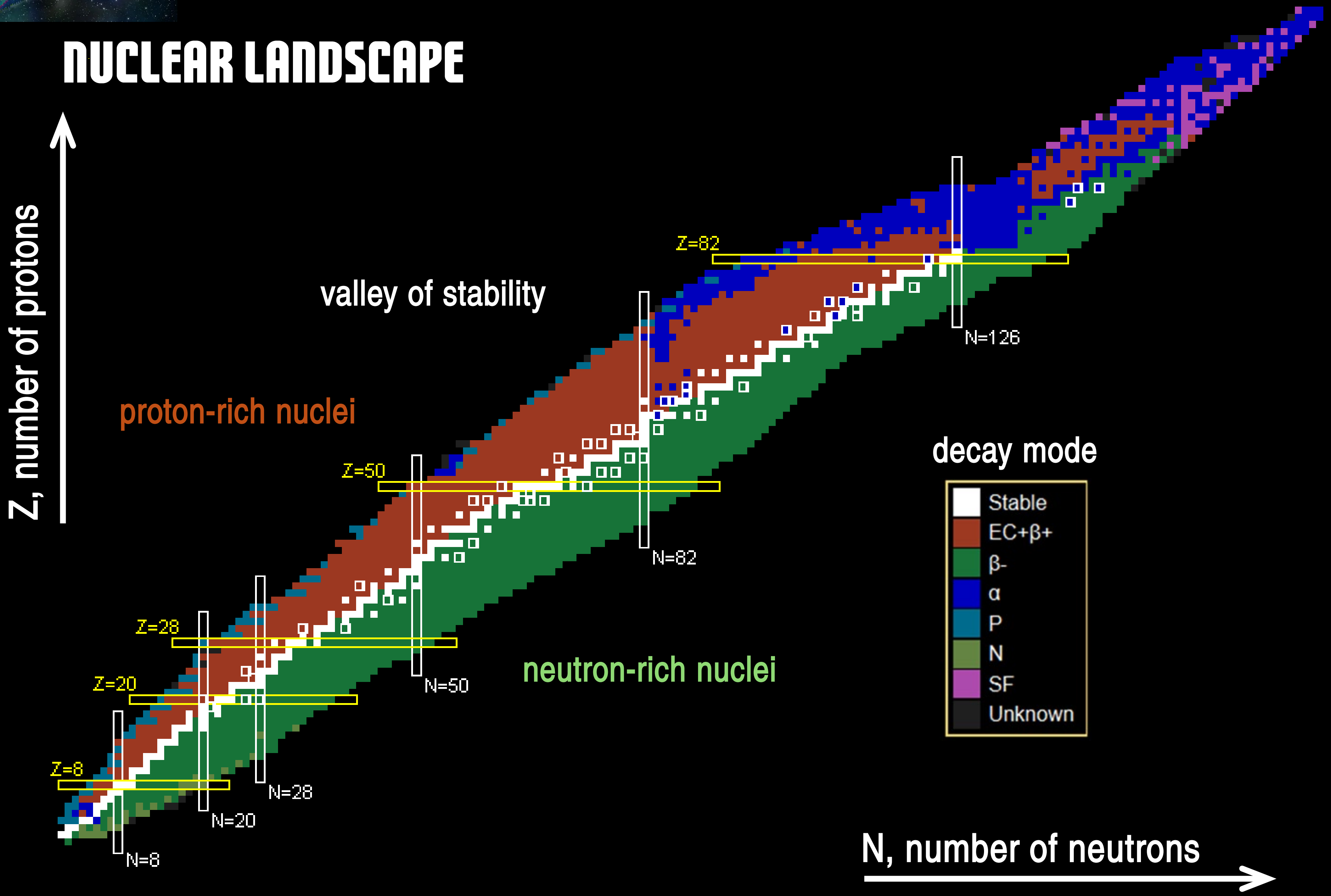
↪ test energy reconstruction methods

GOAL:

leverage e-N and ν-N scattering data to constrain exiting models and improve simulation environment

NUCLEAR STRUCTURE

NUCLEAR LANDSCAPE



≈ 300 STABLE NUCLEI

- $Z \cong N$ up to ^{40}Ca
- $N > Z$ for A>40

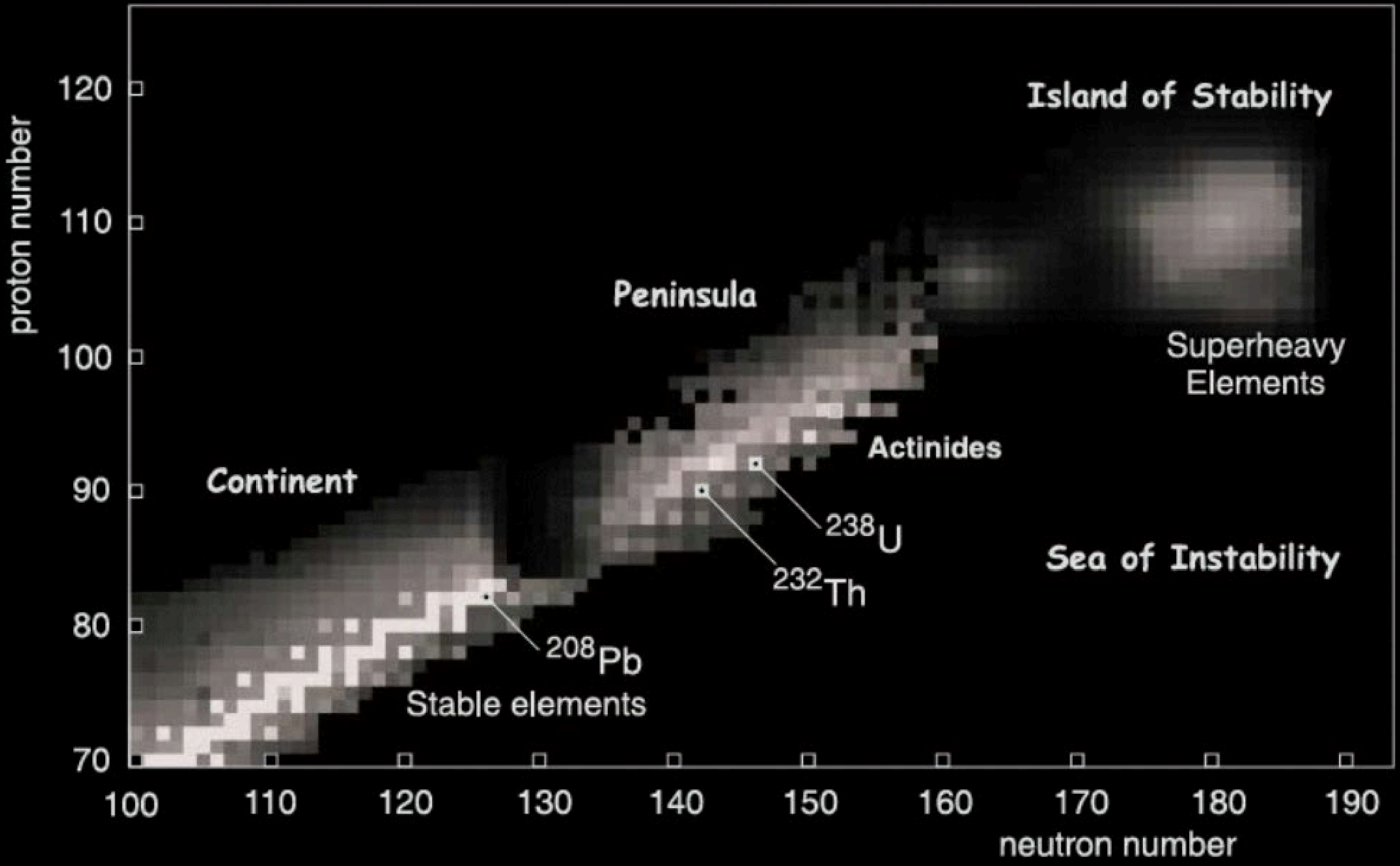
≈ 3000 UNSTABLE NUCLEI

ISLAND OF STABILITY?

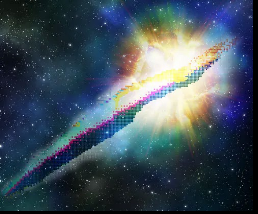
NUCLEAR STRUCTURE: SUPERHEAVY NUCLEI

does the stability end with Uranium OR is there an **ISLAND OF STABILITY**?

is there a new magic number for Z ~ 114-126?



Y. Oganessian, Rad. Act. 99 (2011) 429



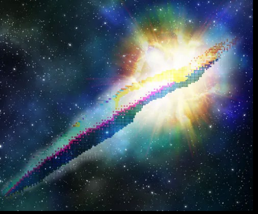
NUCLEAR STRUCTURE: SUPERHEAVY NUCLEI

nuclei with Z>103 already predicted in the late 1960s
based on theoretical models extending the nuclear shell model

nuclear shell effects provide increased binding energy
↪ stabilize superheavy elements (SHE) against spontaneous fission

ISLAND OF STABILITY

region of superheavy nuclei
near spherical proton and neutron shell closures at $Z = 114$ and $N = 184$



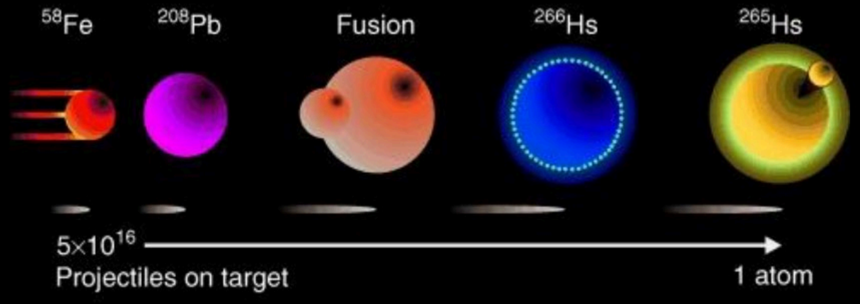
NUCLEAR STRUCTURE: SUPERHEAVY NUCLEI

SYNTHESIS OF SUPERHEAVY ELEMENTS

cold fusion reactions

^{208}Pb or ^{209}Bi + massive projectile ($A \geq 50$) → high Z + (1-2n)

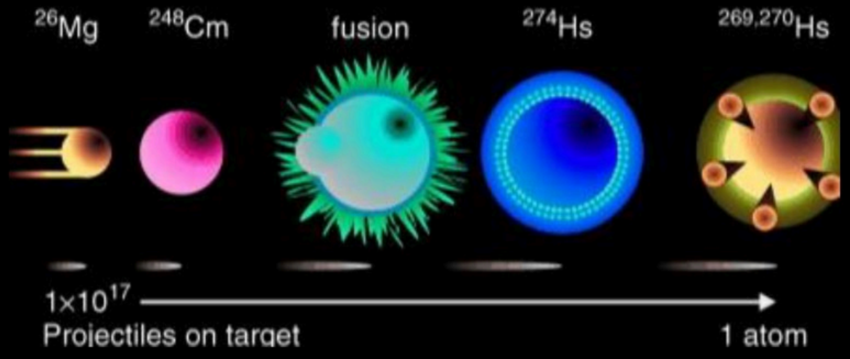
successfully applied to synthesis
elements Z=107-112



hot fusion reactions

^{48}Ca on actinide target → SHE + (4-5n)

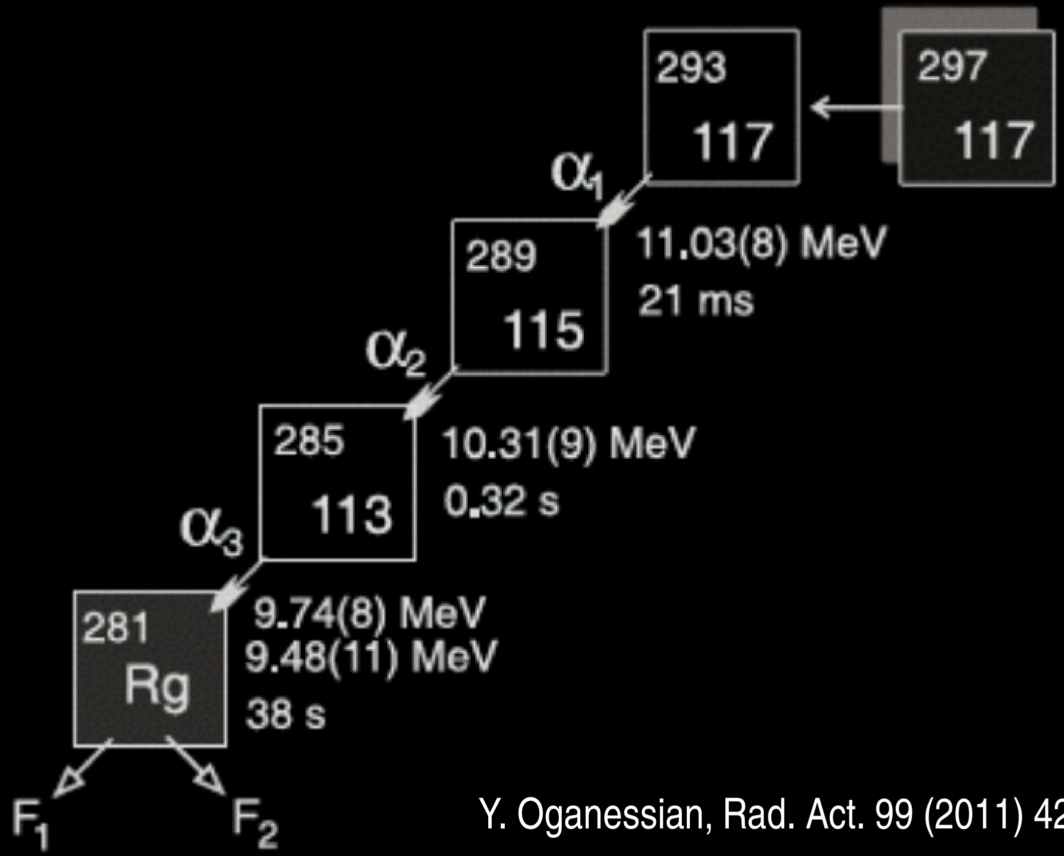
used for synthesis of elements Z=114-118



presently 118 elements known up to **OGANESSON** (Og)

Identification of superheavy elements

↪ α-decay will occur until spontaneous fission occurs
↪ observation of sequential α-decays



Y. Oganessian, Rad. Act. 99 (2011) 429

NUCLEAR STRUCTURE: SUPERHEAVY NUCLEI

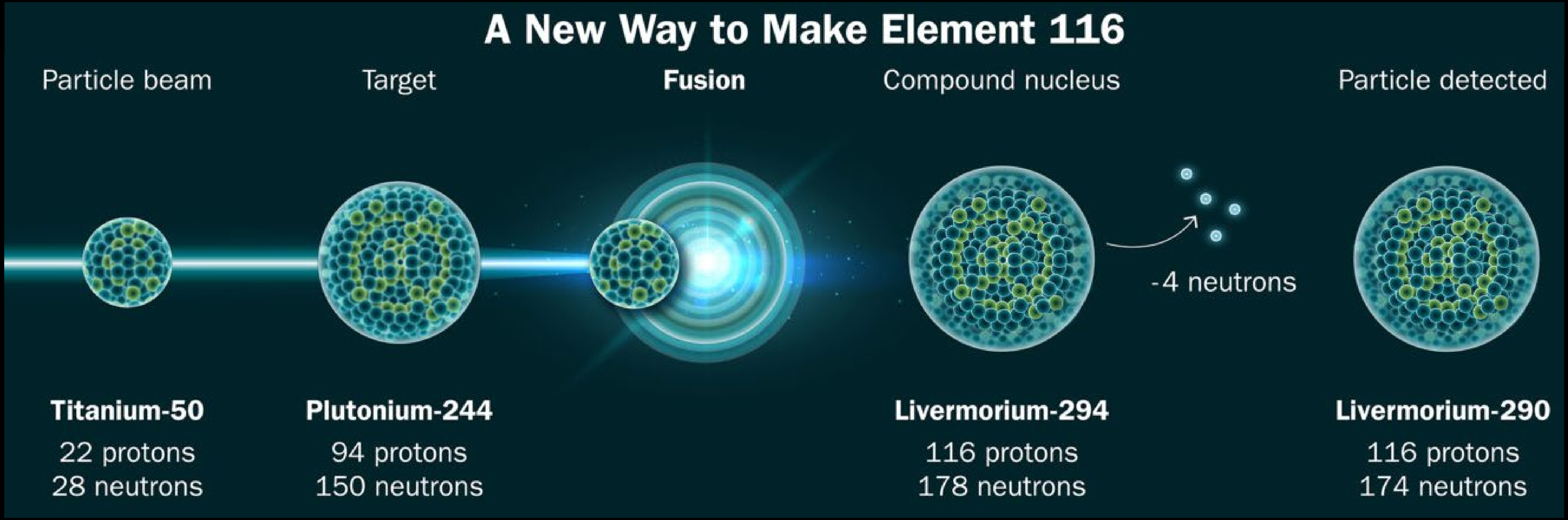
see Jacklyn Gates' talk on Thursday

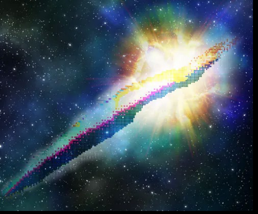
ON THE WAY TO PRODUCE ELEMENT 120

elements Z=114-118 were all produced using ^{48}Ca beams on actinide targets

↪ heaviest possible target: californium → 98 protons

↪ heavier beams needed





NUCLEAR STRUCTURE: SUPERHEAVY NUCLEI

see Ani Aprahamian's talk on Tuesday

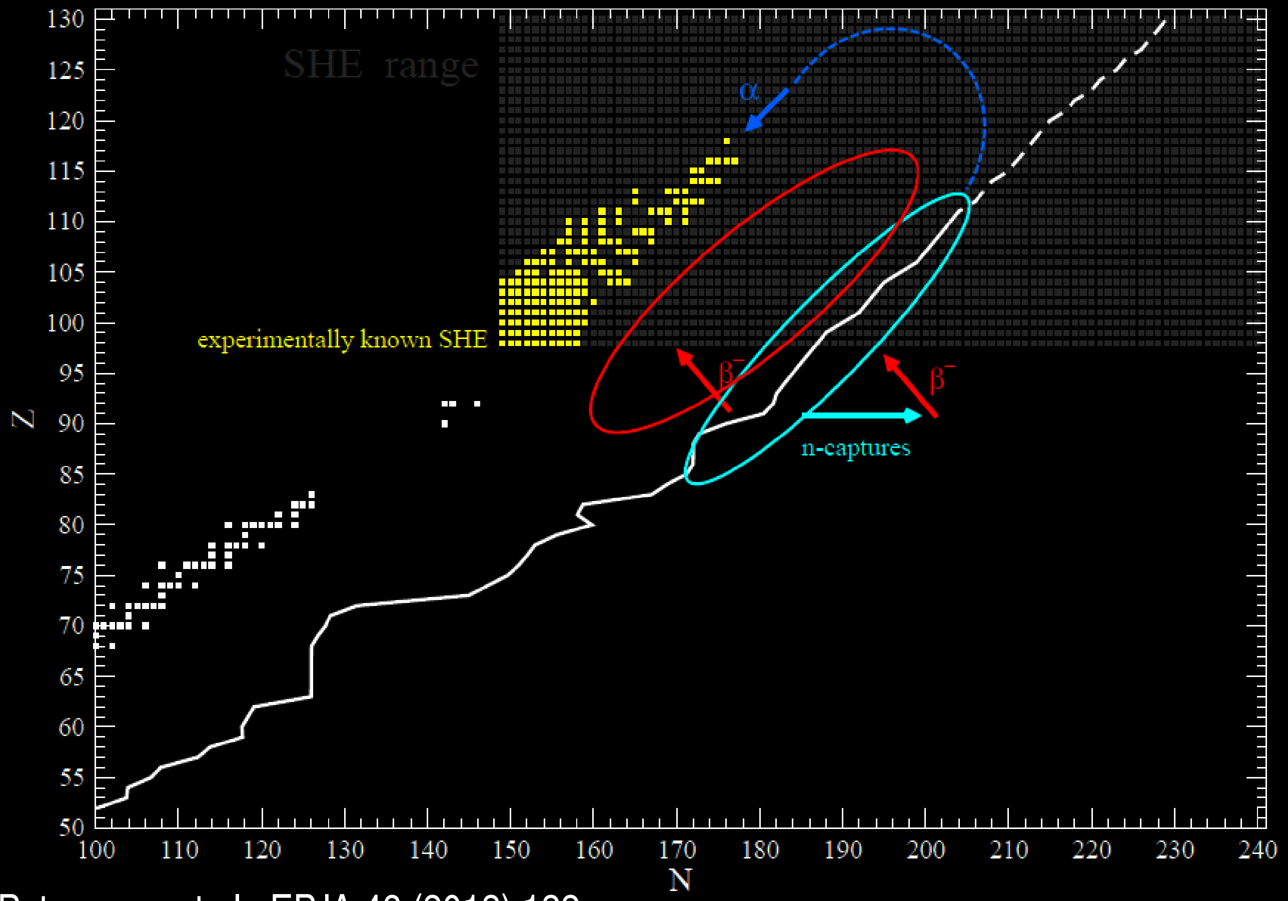
CAN SUPERHEAVY ELEMENTS BE PRODUCED IN NATURE?

possible site: astrophysical rapid neutron capture process

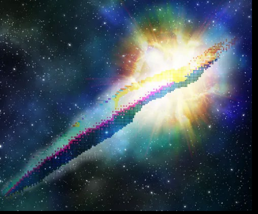
↪ surpassing area of fission dominance

↪ subsequent beta-decays of higher charge number nuclei ends with finite abundance in valley of beta-stability

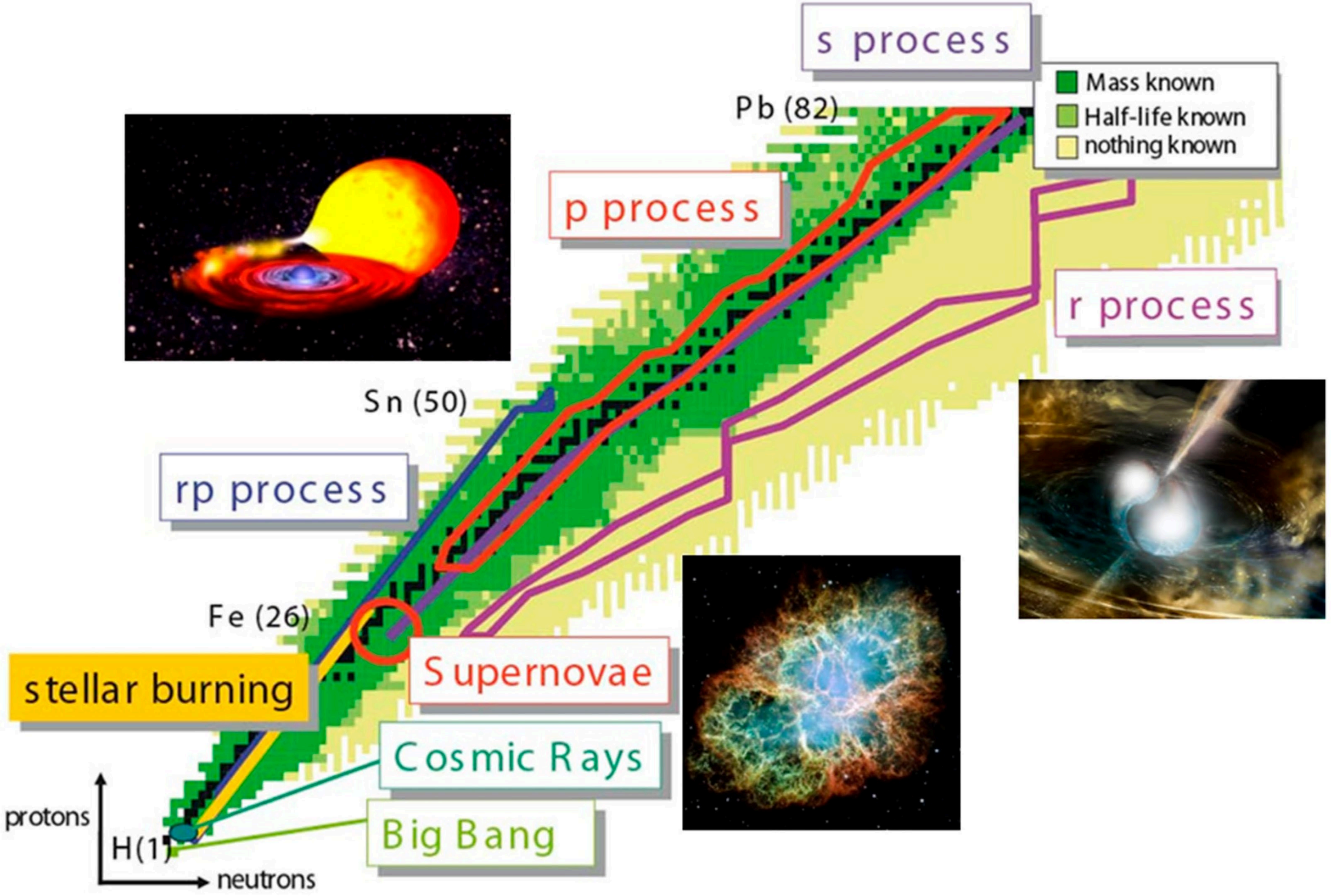
↪ alpha-decay chains towards the island of superheavy nuclei



I. Petermann et al., EPJA 48 (2012) 122



NUCLEAR ASTROPHYSICS



THE BIG QUESTIONS

- creation of heavy elements?
- nuclear engines for the life and death of stars?
- EoS of neutron-rich matter?

⇓

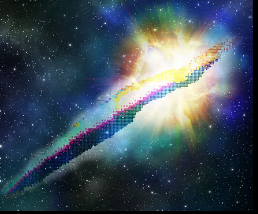
① introduction

② stars: nature‘s nuclear reactors

③ life and death of a star

④ nuclear Equation of State

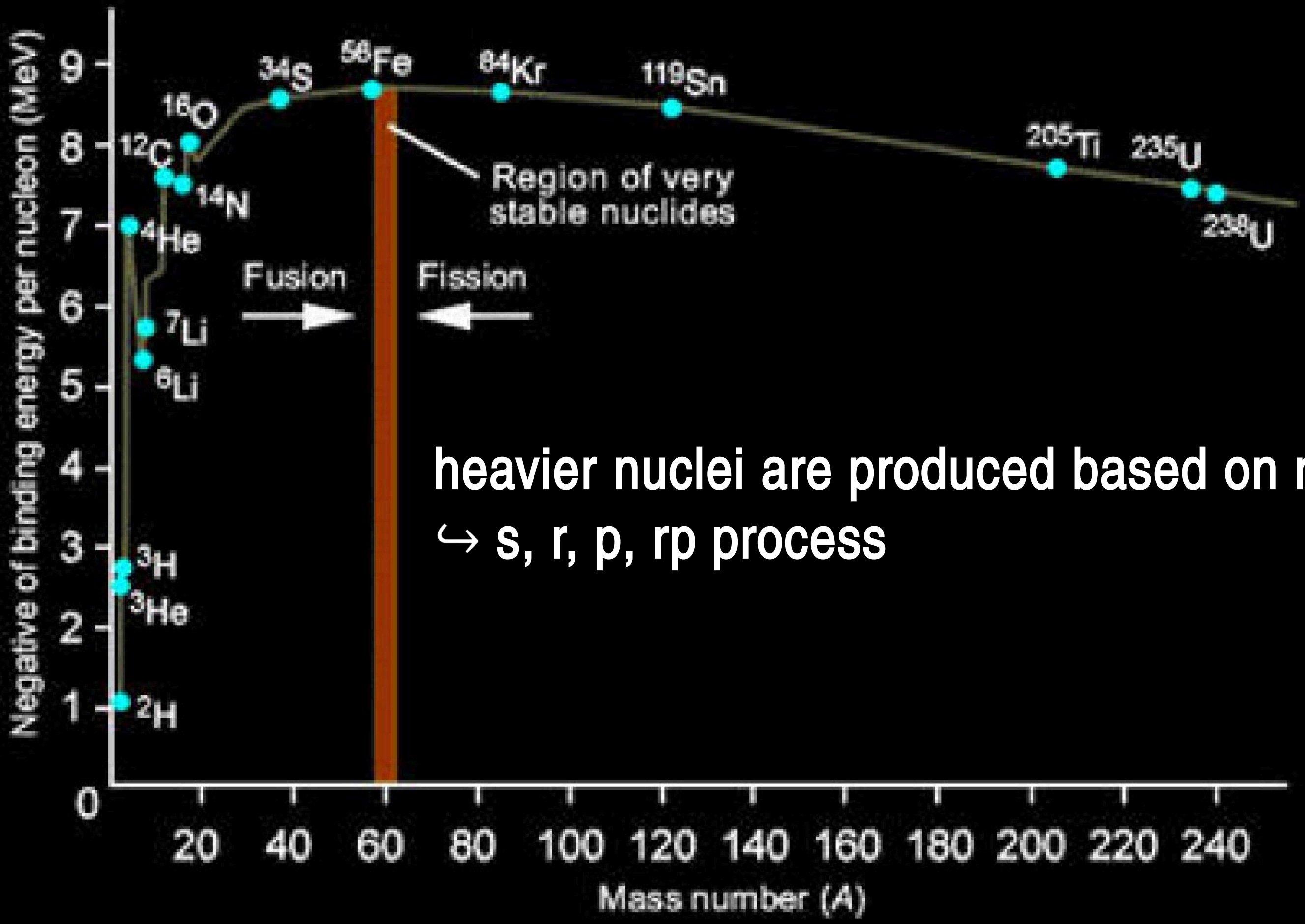
⑤ s, r, p, rp processes



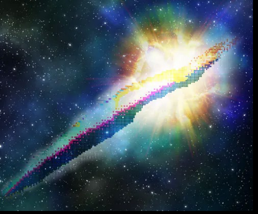
NUCLEAR ASTROPHYSICS: INTRODUCTION

NUCLEOSYNTHESIS IN A NUTSHELL

by fusion of light elements
the Fe-Ni region can be reached

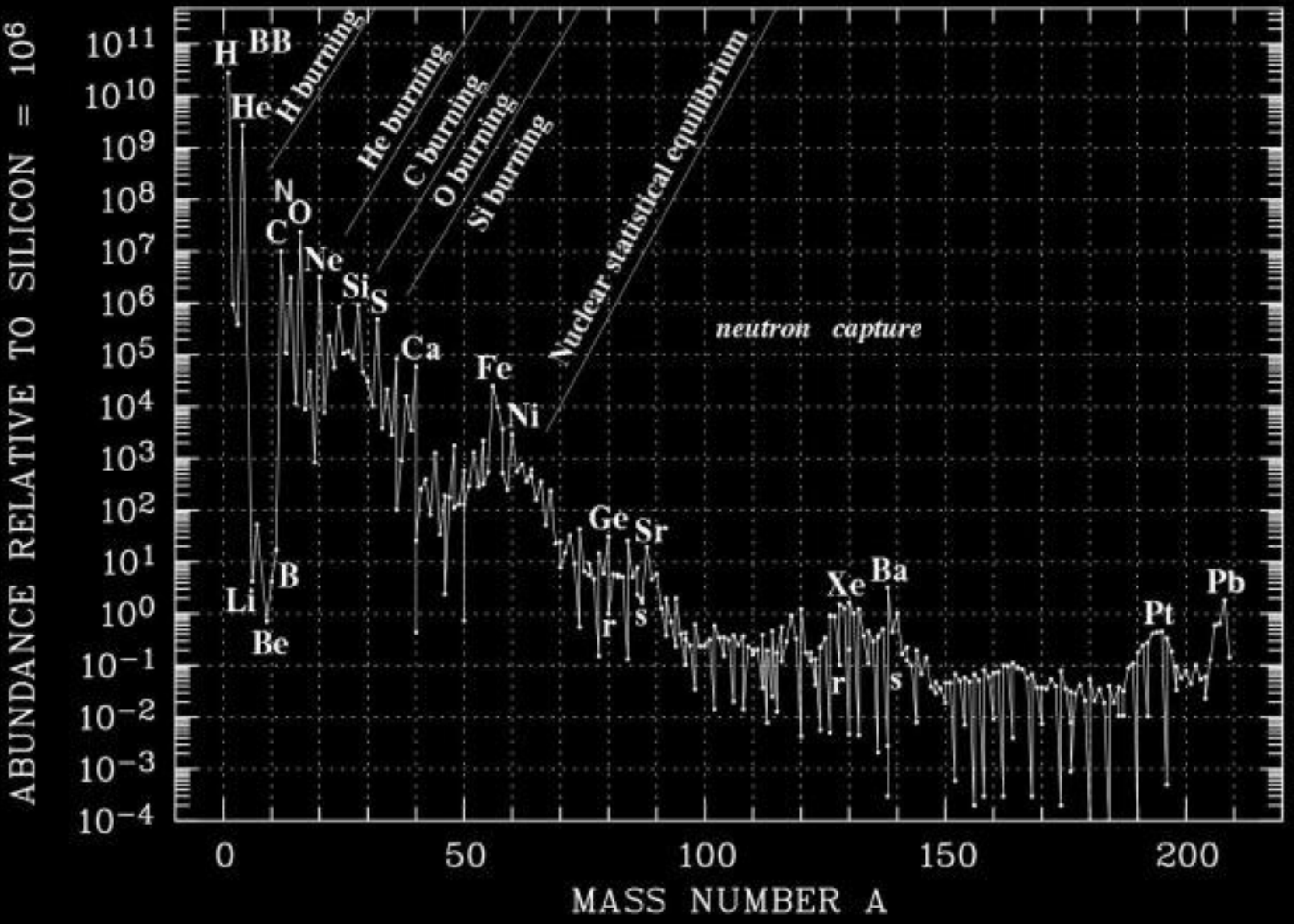


heavier nuclei are produced based on n or p capture processes
↪ s, r, p, rp process



NUCLEAR ASTROPHYSICS: INTRODUCTION

ABUNDANCES OF ELEMENTS



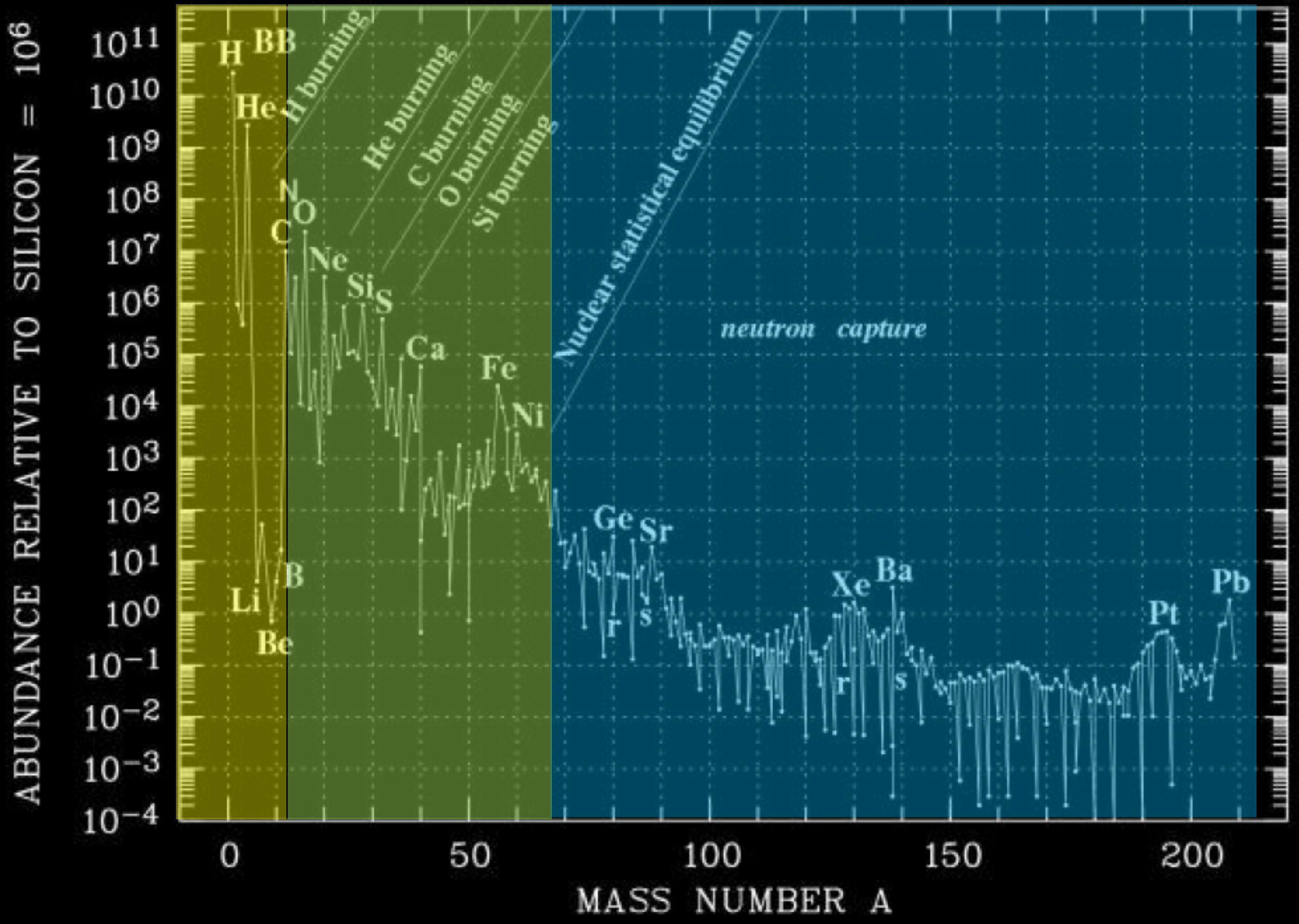
did you notice…

- odd-even staggering of abundances?
- larger alpha-nuclei abundance?
- broad peak around Fe?

(→ that is nuclear physics!)

NUCLEAR ASTROPHYSICS: INTRODUCTION

ABUNDANCES OF ELEMENTS



formation of elements:

big bang nucleosynthesis

fusion in stars, explosive burning:

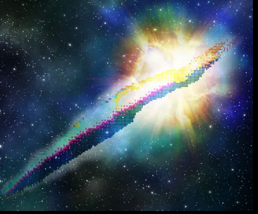
H → He

He → C, O

C, O → Si

Si → Fe group

s, r, p, rp process



NUCLEAR ASTROPHYSICS: STARS – NATURE'S NUCLEAR REACTORS

HYDROGEN BURNING: PP CHAIN

$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu_e$

$^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma$

69% | 31%

ppI (69%):

$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,{}^{1}H$

31%:

$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

99,7% | 0,3%

ppII (99,7%):

$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$

$^{7}Li + {}^{1}H \rightarrow 2\,{}^{4}He$

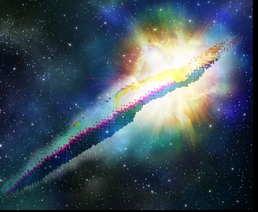
ppIII (0,3%):

$^{7}Be + {}^{1}H \rightarrow {}^{8}B + \gamma$

$^{8}B \rightarrow {}^{8}Be + e^{+} + \nu_e$

$^{8}Be \rightarrow 2\,{}^{4}He$

summary: $4p \rightarrow {}^{4}_{2}He + 2e^{+} + 2\nu_e + 25MeV$



NUCLEAR ASTROPHYSICS: STARS – NATURE'S NUCLEAR REACTORS

HYDROGEN BURNING: CNO CYCLE

if the star constains C, N or O, they can be used as catalyst to synthesize ^{4}He from 4p

CNO C – cycle:

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

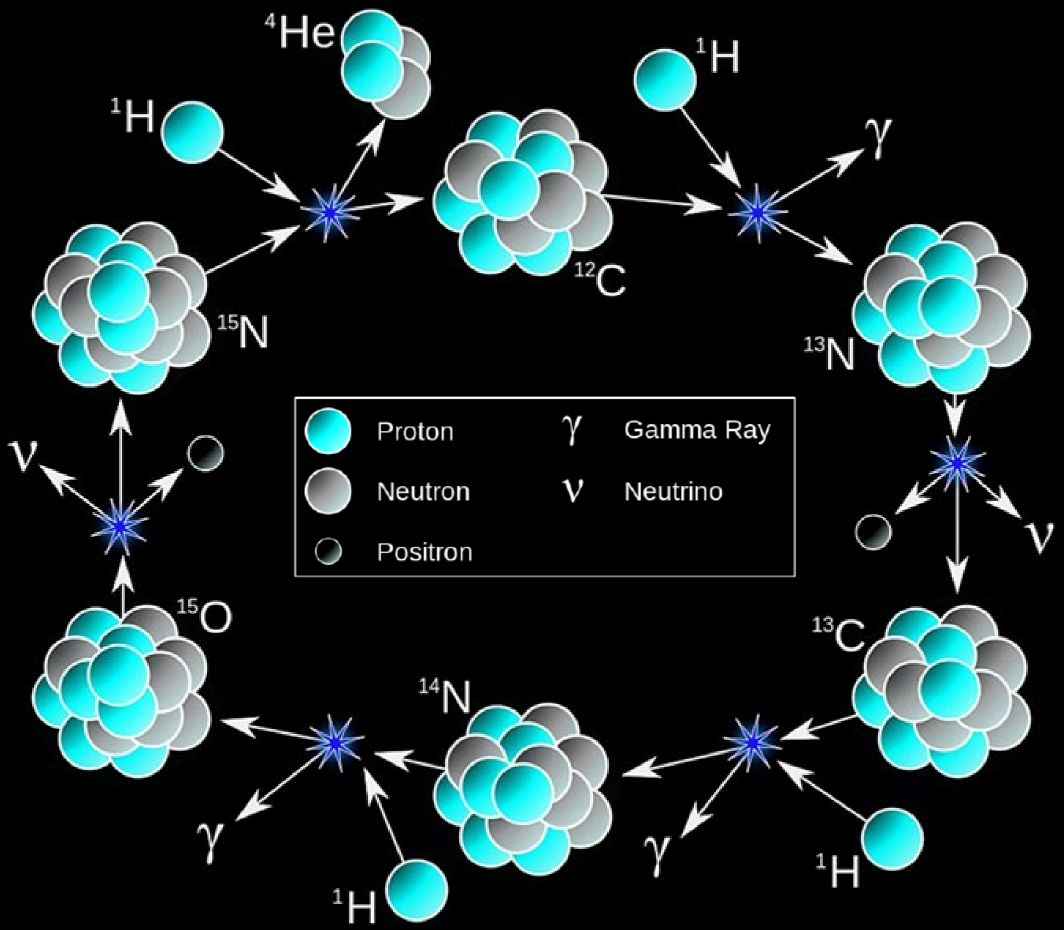
$$^{13}N \rightarrow {^{13}}C + e^+ + \nu_e$$

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

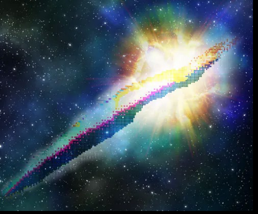
$$^{14}N + {^1}H \rightarrow {^{15}}O + \gamma$$

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

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



summary: $(^{12}\mathrm{C}) + 4p \rightarrow (^{12}\mathrm{C}) + {}^4_2\mathrm{He} + 2e^+ + 2\nu_e + 26.73\mathrm{MeV}$



REACTION RATE

we consider the radiative capture reaction: $1 + 2 \rightarrow 3 + \gamma$
the **REACTION RATE** is the number of reactions occuring per unit time and volume

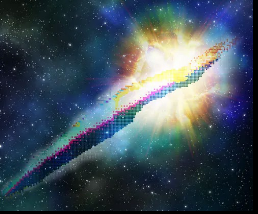
$$r = N_1 N_2 \sigma v$$

the velocity v is distributed according to Maxwell-Boltzmann

$$\phi(v) \propto e^{-E/kT}$$

$$\Rightarrow \langle \sigma v \rangle = 4\pi \int \phi(v) \sigma(v) v^3 dv$$

$$\propto \int e^{-E/kT} \sigma(E) E dE$$

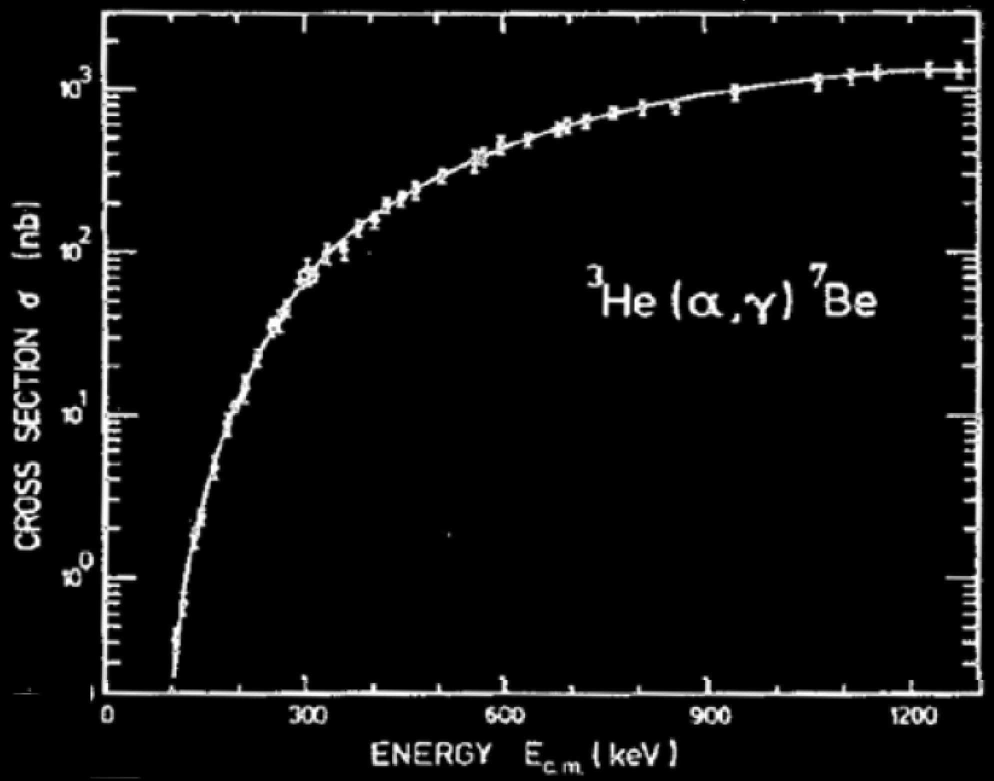


NUCLEAR ASTROPHYSICS: STARS – NATURE'S NUCLEAR REACTORS

σ(E) AT LOW ENERGY

due to **COULOMB BARRIER** σ plummets at low E
because reaction takes place only through **TUNNELING**

^{3}He + α $\rightarrow$ ^{7}Be + γ



ASTROPHYSICAL S FACTOR: THE NUCLEAR PHYSICS NUGGETS OF $\langle\sigma v\rangle$

often it is useful to remove the energy dependence from the cross section

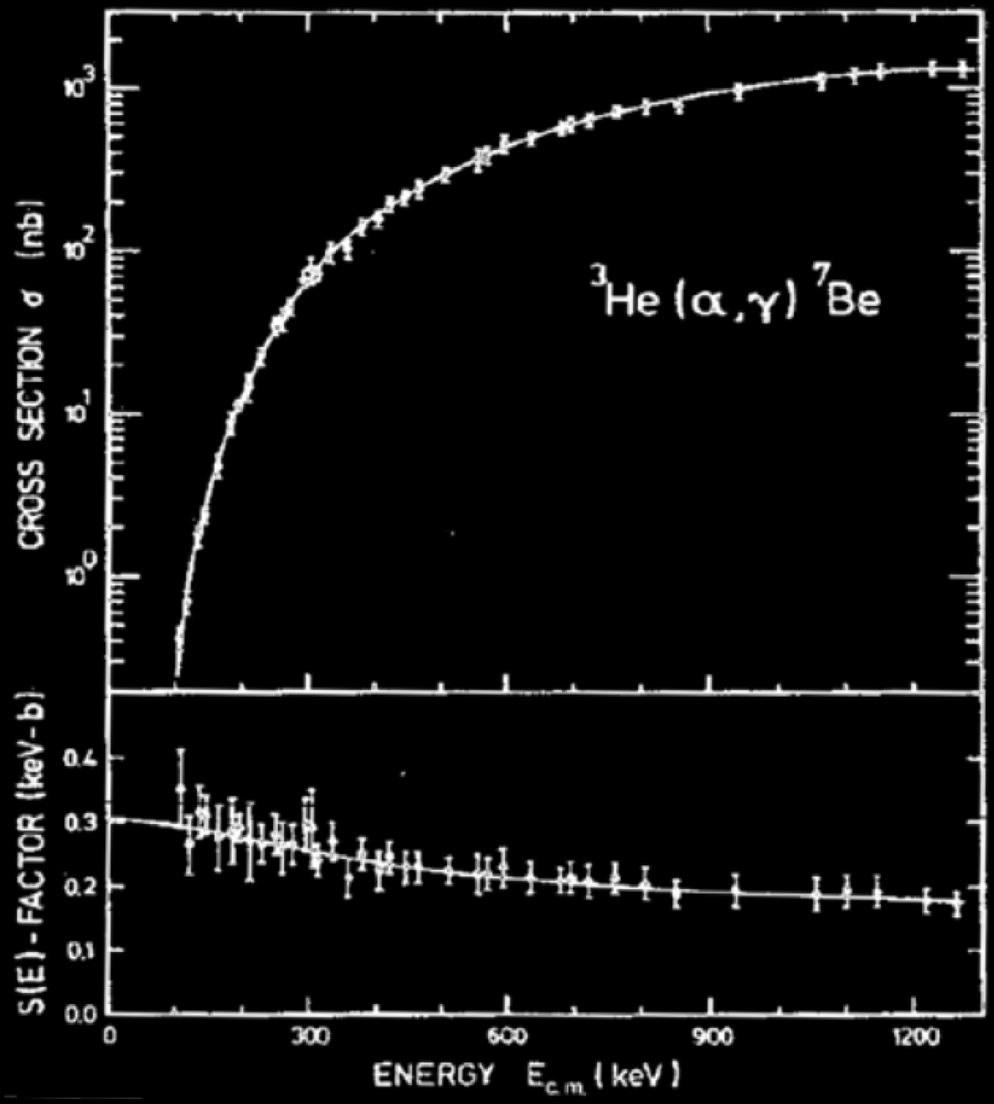
the rapid drop explained by the Gamow factor $\mathbf{e^{-2\pi\eta}}$

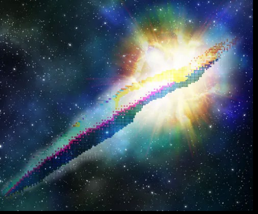
with the Sommerfeld parameter

$$\eta = \frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 \hbar v}$$

$$\Rightarrow \boldsymbol{\sigma(E)} = \frac{\mathbf{S(E)e^{-2\pi\eta}}}{\mathbf{E}}$$

the astrophysical S factor varies smoothly with E





NUCLEAR ASTROPHYSICS: STARS – NATURE'S NUCLEAR REACTORS

GAMOW PEAK

$$\langle\sigma v\rangle \propto \int e^{-E/kT}\sigma(E)E\,dE$$

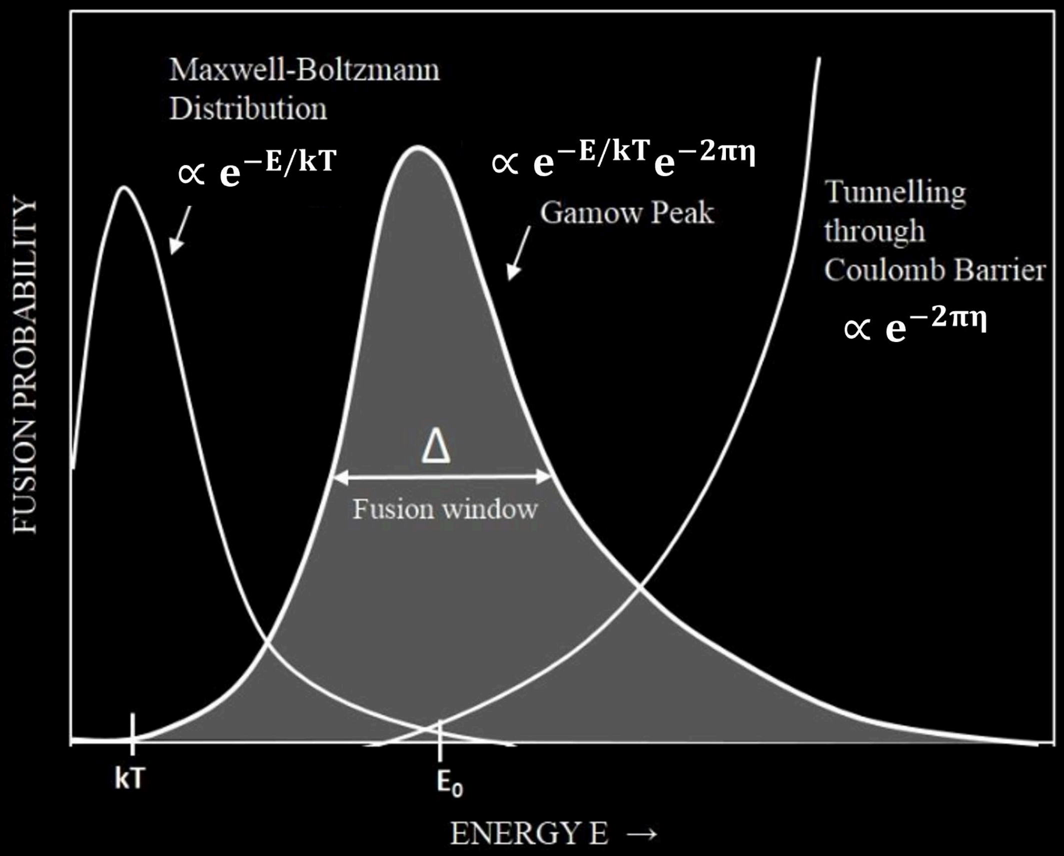
$$= \int e^{-E/kT}\,e^{-2\pi\eta}S(E)dE$$

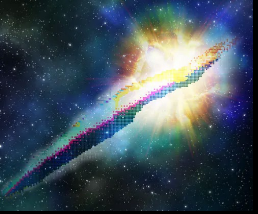
↪ S (i.e. σ) must be known
only in the Gamow peak:

$$g(E) = e^{-E/kT}e^{-2\pi\eta}$$

light nuclei fuse at lower temperature
(compared to heavier ones)

↪ **DIFFERENT STAGES** of nuclear burning in stars





NUCLEAR ASTROPHYSICS: STARS – NATURE'S NUCLEAR REACTORS

HELIUM BURNING

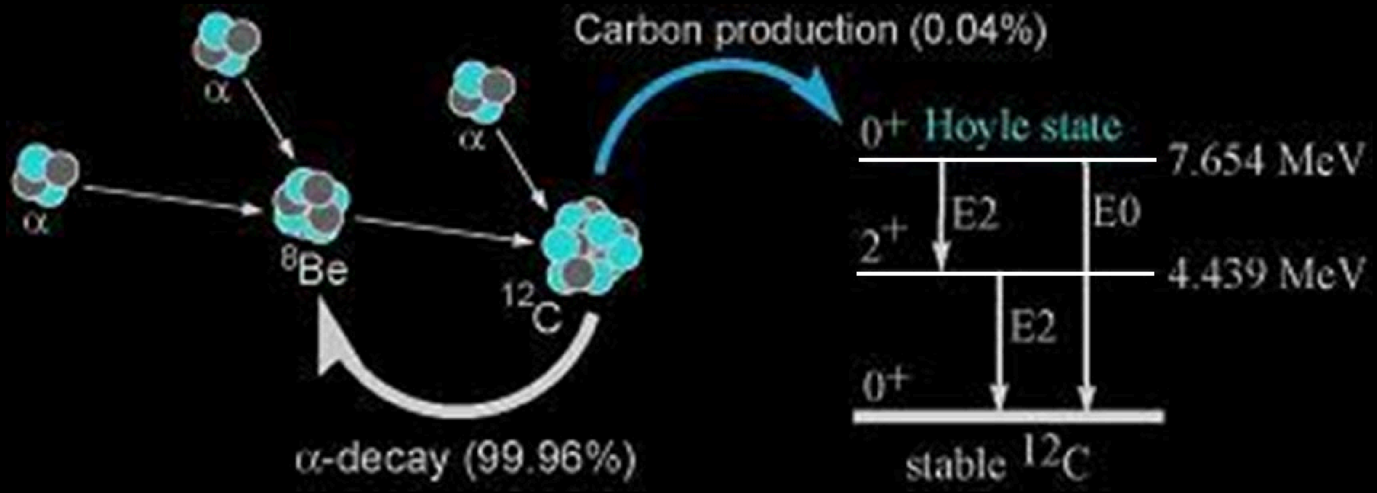
when enough ^4He has built up AND if temperature and pressure are high enough
↪ He fusion starts

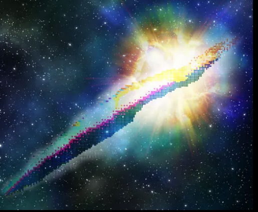
the obvious reaction would be $^4He + {}^4He$
BUT there are **NO STABLE NUCLEI WITH A=8**

this A=8 gap is bridged by the **TRIPLE-α PROCESS:**

$^4He + {}^4He \rightleftharpoons {}^8Be$

$^8Be + {}^4He \rightleftharpoons {}^{12}C^* \rightarrow {}^{12}C + \gamma$





NUCLEAR ASTROPHYSICS: STARS – NATURE'S NUCLEAR REACTORS

SUBSEQUENT STAGES

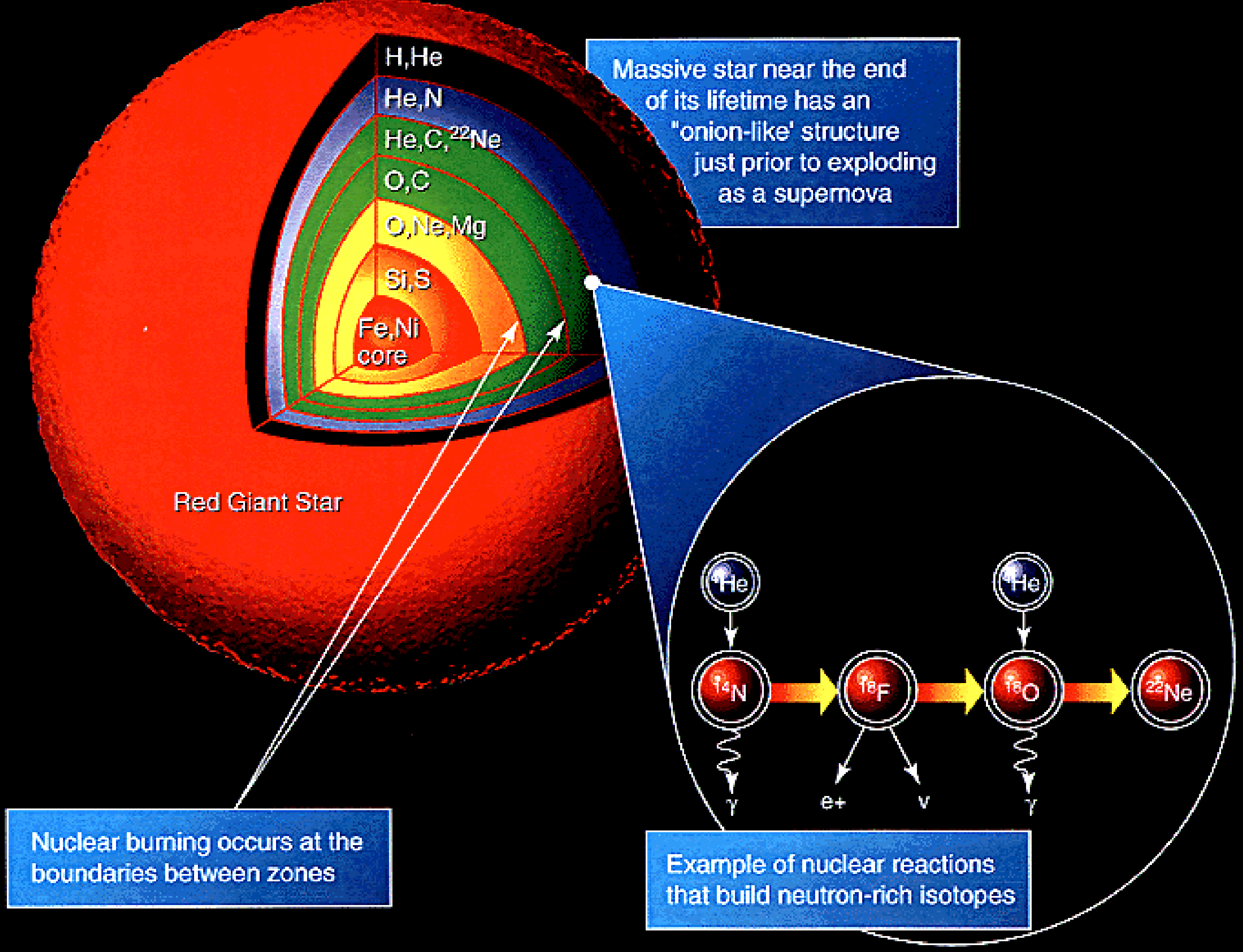
$^{12}C + {}^{4}He \rightarrow {}^{16}O + \gamma$

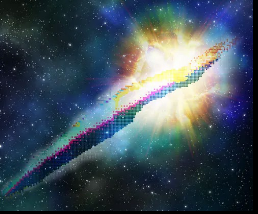
$^{16}O + {}^{4}He \rightarrow {}^{20}Ne + \gamma$

$^{12}C + {}^{12}C \rightarrow$
$^{23}Na + p$
$^{20}Ne + {}^{4}He$
$^{23}Mg + n$
$^{24}Mg + g$
$^{8}Be + {}^{16}O$

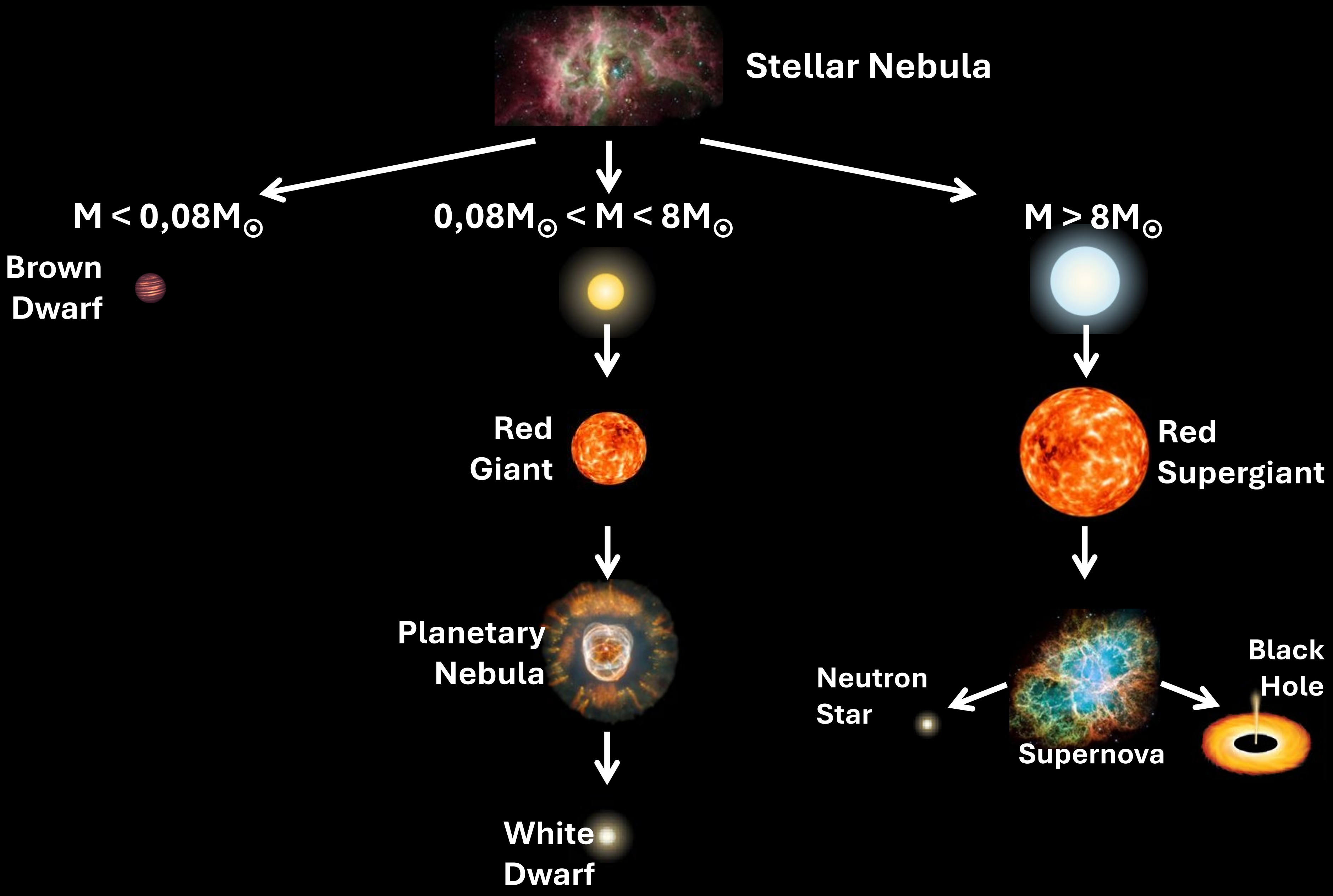
+ more advanced burning stages

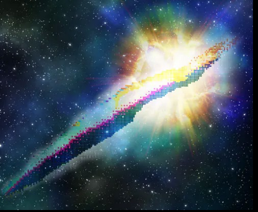
→ **ONION-LIKE STRUCTURE OF THE STAR**





NUCLEAR ASTROPHYSICS: LIFE AND DEATH OF A STAR





NUCLEAR ASTROPHYSICS: LIFE AND DEATH OF A STAR

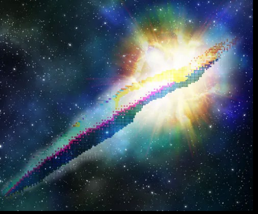
MEDIUM MASS STARS ($M \leq 8M_{\odot}$)

burning helium in their cores,
but cannot get hot enough to ignite carbon
↪ end with C-O core

H outer layer is expelled
↪ **PLANETARY NEBULA**

NGC 6543,
Cat‘s Eye Nebula

nuclear reactions stop and the remaining core cools down
↪ **WHITE DWARF** ($\mathbf{M} \sim \mathbf{M}_{\odot}$ and $\mathbf{R} \sim \mathbf{R}_{\oplus}$)
where gravity is compensated by the pressure of the electrons, which form a Fermi gas



NUCLEAR ASTROPHYSICS: LIFE AND DEATH OF A STAR

MASSIVE STARS ($M > 8M_{\odot}$)

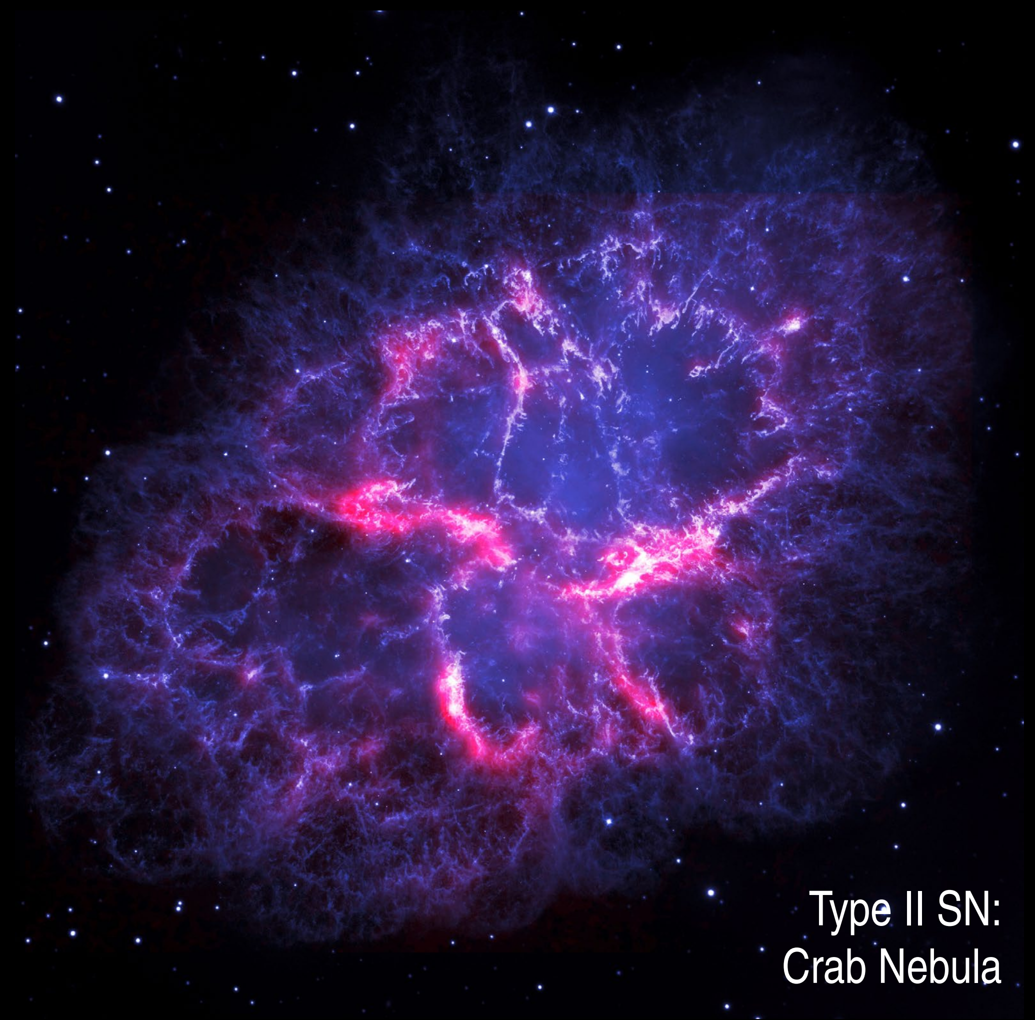
once Fe is produced, the stellar core collapses

- photodisintegration
- electron capture by the nuclei: $p + e^- \rightarrow n + \nu_e$
- neutron degeneracy sets in

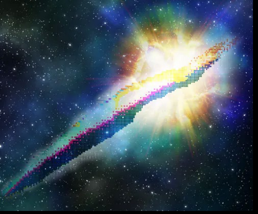
↪ **NEUTRON STAR** ($\mathrm{M} \sim \mathrm{M}_{\odot}$ and R ~10km; $\rho \sim \rho_0$)

↪ black hole ($\mathrm{M} \sim$ several $\mathrm{M}_{\odot}$)

outer layers expelled
↪ **CORE-COLLAPSE SUPERNOVA** (type II)



Type II SN:
Crab Nebula



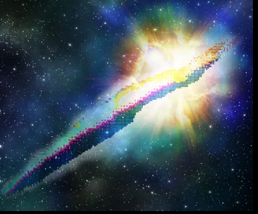
NUCLEAR ASTROPHYSICS: LIFE AND DEATH OF A STAR

What is a neutron star (NS)?

- for **ASTRONOMERS** NS are very **LITTLE STARS** “visible” as radio pulsars or sources of X- and γ-rays
- for **PARTICLE PHYSICISTS** NS are **NEUTRINO SOURCES** (mainly when they are born) and probably the only places in the Universe where deconfined quark matter may be abundant
- for **COSMOLOGISTS** NS are “almost” **BLACK HOLES**
- for **NUCLEAR PHYSICISTS** NS are the **BIGGEST NEUTRON-RICH NUCLEI** of the Universe

↪ NS are **EXCELLENT OBSERVATORIES** to test fundamental properties of matter under extreme conditions

↪ NS offer an interesting **INTERPLAY BETWEEN NUCLEAR PROCESSES AND ASTROPHYSICAL OBSERVABLES**



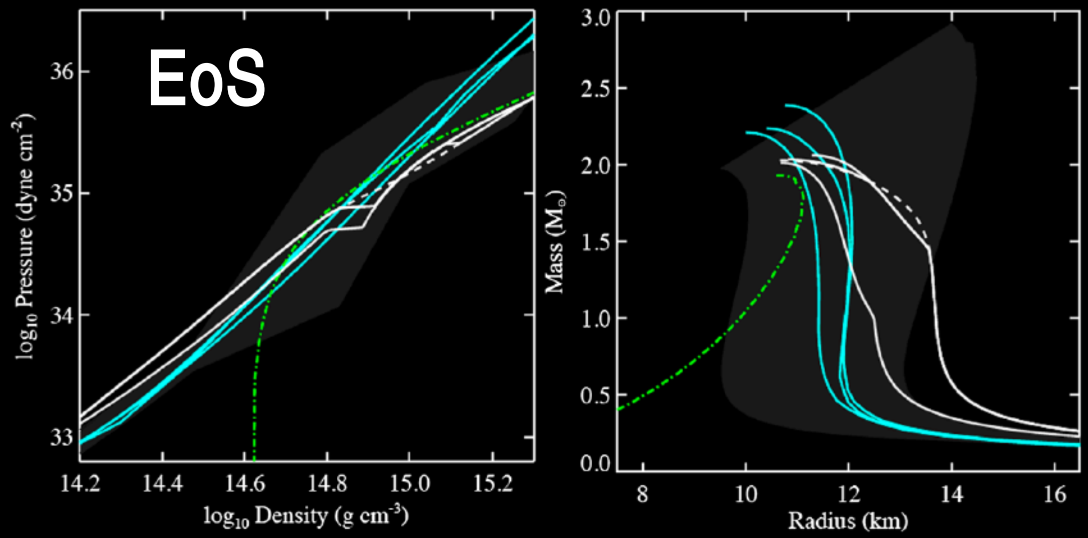
NUCLEAR ASTROPHYSICS: NUCLEAR EQUATION OF STATE

- neutron stars are bound by gravity NOT by the strong force
- neutron stars satisfy the **TOLMAN-OPPENHEIMER-VOLKOFF** (TOV) equation

$$\frac{dM}{dr} = 4\pi r^2 \varepsilon(r)$$

$$\frac{dP}{dr} = -G\frac{\varepsilon(r)M(r)}{r^2}\left[1+\frac{P(r)}{\varepsilon(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

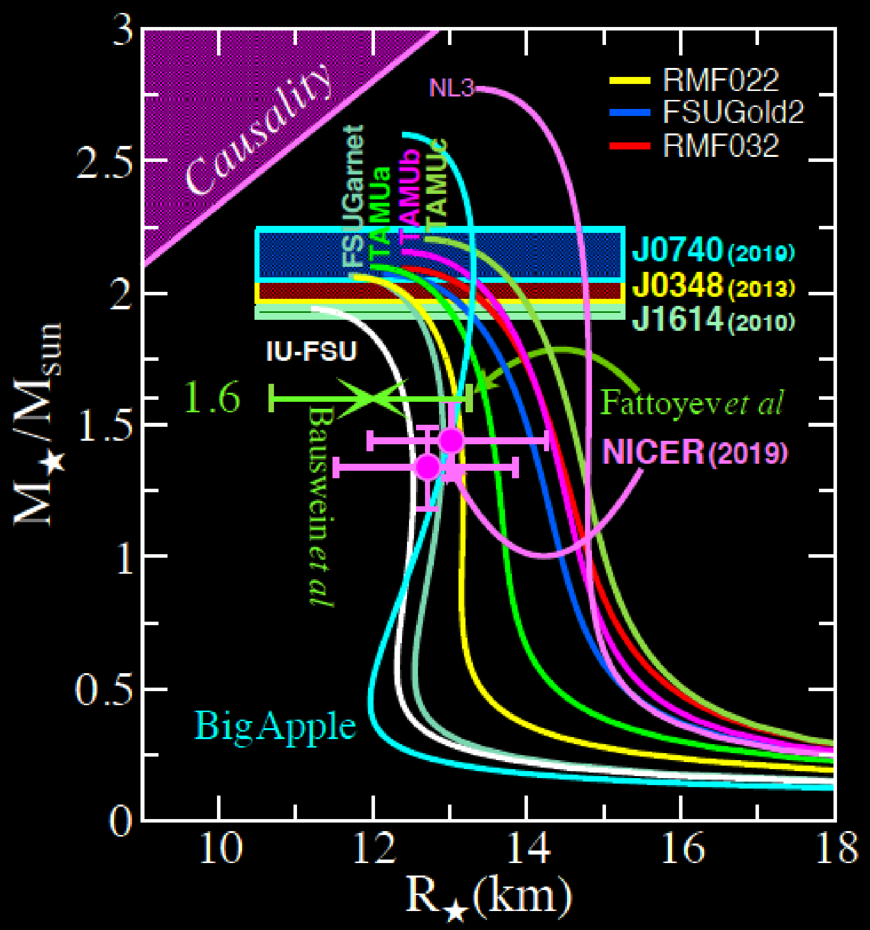
only physics that the TOV equation is sensitive to: **EQUATION OF STATE** (EoS) $\rightarrow P = P(\varepsilon)$



Mass-Radius relation is "unique" to the underlying EoS

NUCLEAR ASTROPHYSICS: NUCLEAR EQUATION OF STATE

MASS-RADIUS RELATION



the radius R of a neutron star with mass M cannot be arbitrarily small!

↪ **GENERAL RELATIVITY**: a NS is not a black hole

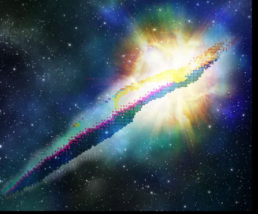
$$\hookrightarrow R > \frac{2GM}{c^2}$$

↪ **FINITE PRESSURE**: NS matter cannot be arbitrarily compressed

$$\hookrightarrow R > \frac{9}{4}\frac{GM}{c^2}$$

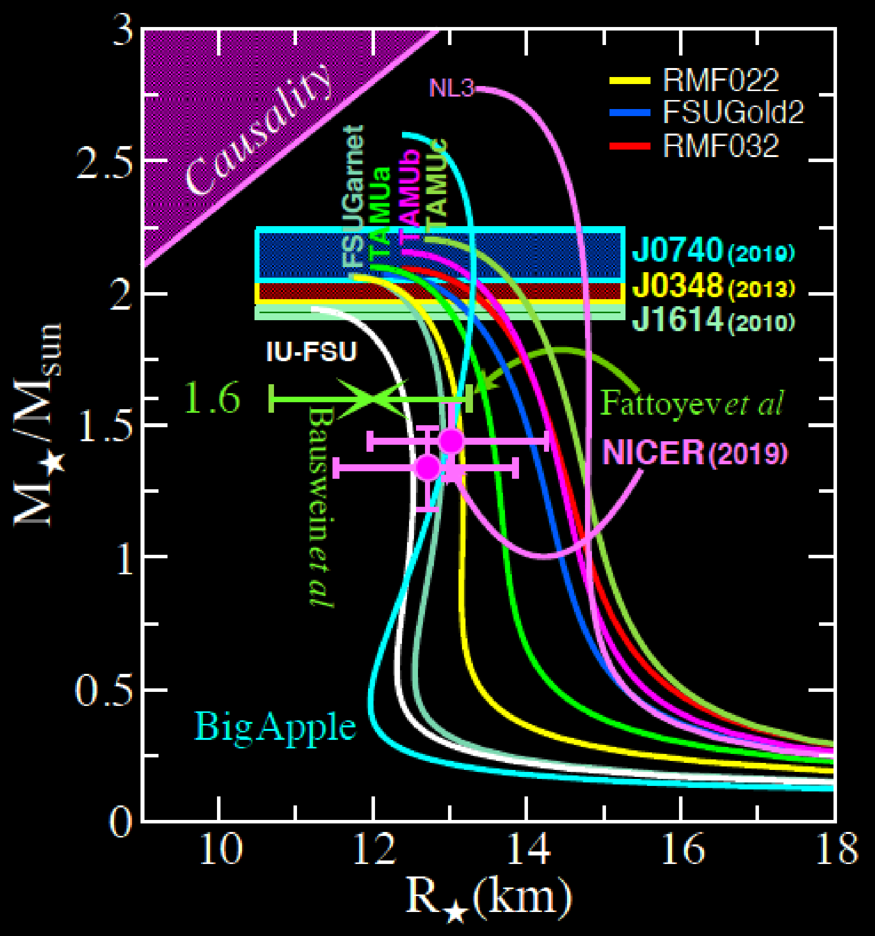
↪ **CAUSALITY**: speed of sound must be smaller than c

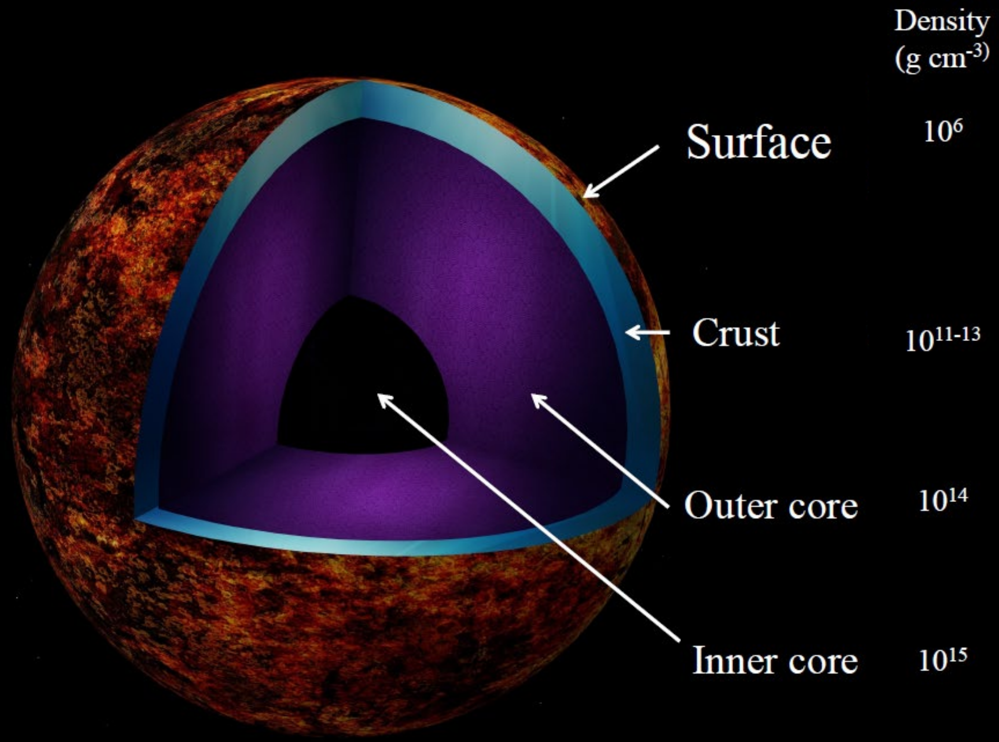
$$\hookrightarrow R > 2.9\frac{GM}{c^2}$$



NUCLEAR ASTROPHYSICS: NUCLEAR EQUATION OF STATE

MASS-RADIUS RELATION



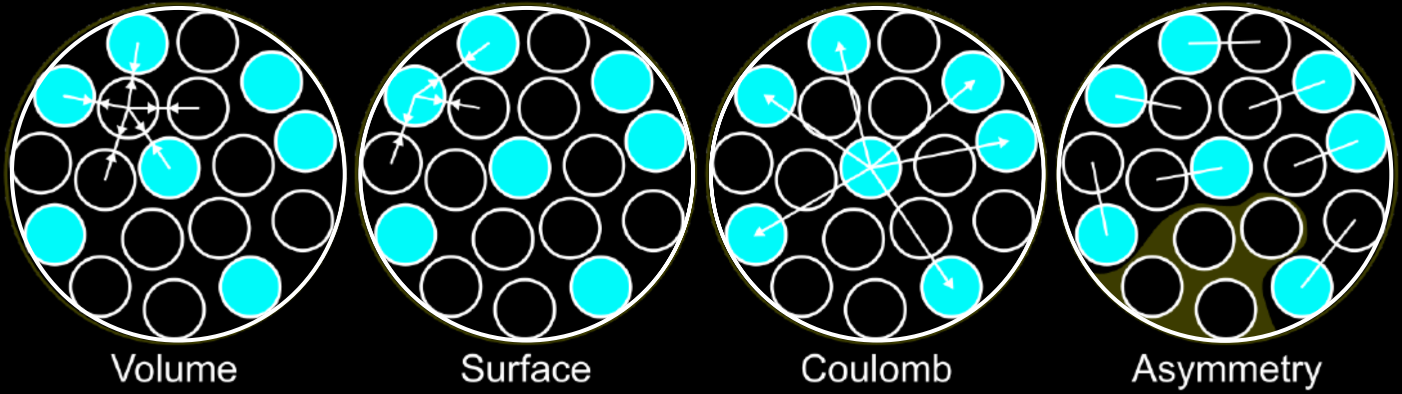


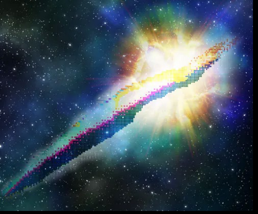
- ○ EoS must span about 10 orders of magnitude in baryon density
- ○ increase from $0.7 \rightarrow 2M_{\odot}$ must be explained by nuclear physics

NUCLEAR ASTROPHYSICS: NUCLEAR EQUATION OF STATE

Bethe-Weizsäcker: incompressible quantum liquid drop binding energy

$$\mathbf{B(Z,N) = a_v \cdot A - a_s \cdot A^{2/3} - a_c \cdot \frac{Z(Z-1)}{A^{1/3}} - a_{sym} \cdot \frac{(A-2Z)^2}{A}}$$





NUCLEAR ASTROPHYSICS: NUCLEAR EQUATION OF STATE

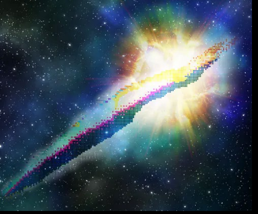
Bethe-Weizsäcker: incompressible quantum liquid drop binding energy

$$B(Z,N) = a_v \cdot A - a_s \cdot A^{2/3} - a_c \cdot \frac{Z(Z-1)}{A^{1/3}} - a_{sym} \cdot \frac{(A-2Z)^2}{A}$$

in the limit where volume V and $A \to \infty$ but $\frac{A}{V} = \rho_0 = \text{const.}$

$$\varepsilon(\alpha) \equiv -\frac{B(Z,N)}{A} = -a_V + J\alpha^2 \qquad \text{with } \alpha = (\rho_n - \rho_p)/(\rho_n + \rho_p)$$

incompressible $\rightarrow$ fails to reproduce response to density fluctuations

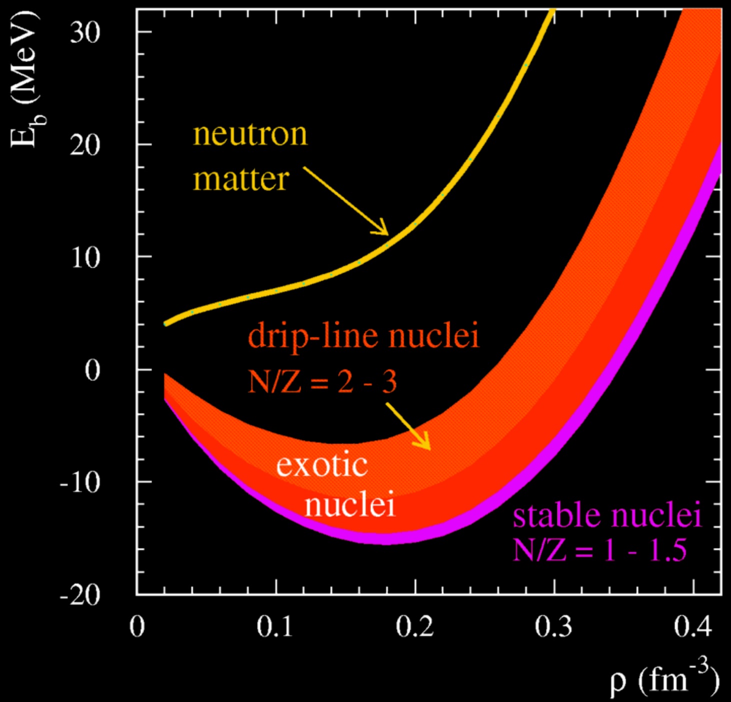


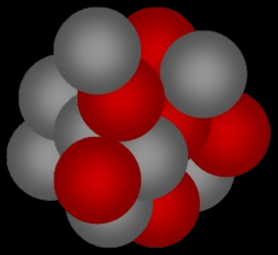
NUCLEAR ASTROPHYSICS: NUCLEAR EQUATION OF STATE

$$\varepsilon(\alpha) \equiv -\frac{B(Z,N)}{A} = -a_V + J\alpha^2$$ with $\alpha = (\rho_n - \rho_p)/(\rho_n + \rho_p)$

↪ Equation of State of asymmetric matter

$$\varepsilon(\rho,\alpha) = \varepsilon(\rho,\alpha=0) + S(\rho)\alpha^2 + \mathcal{O}(\alpha^4)$$ where $S(\rho)$ is the **SYMMETRY ENERGY**

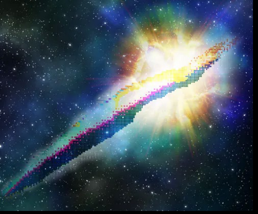


 vs. 

18 orders of magnitude smaller

55 orders of magnitude lighter

SAME Equation of State



NUCLEAR ASTROPHYSICS: NUCLEAR EOS

see James Lattimer's talk on Wednesday

SYMMETRY ENERGY

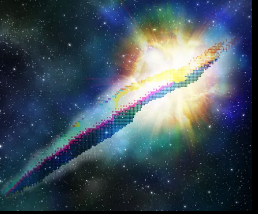
$S(\rho)$ characterisis the increase in energy from $N = Z$

Taylor expanded around $\rho = \rho_0$:

$$\mathrm{S}(\rho) = \mathrm{J} + \frac{\mathrm{L}}{3}\left(\frac{\rho - \rho_0}{\rho_0}\right) + \frac{1}{18}\mathrm{K}_{\mathrm{sym}}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2 + \cdots$$

the symmetry energy can be constrained from

- laboratory measurements → **NEUTRON SKIN THICKNESS**
- astrophysical observations → **MASS AND RADII OF NEUTRON STARS**
- nuclear structure calculations



NUCLEAR ASTROPHYSICS: NUCLEAR EOS

see James Lattimer's talk on Wednesday

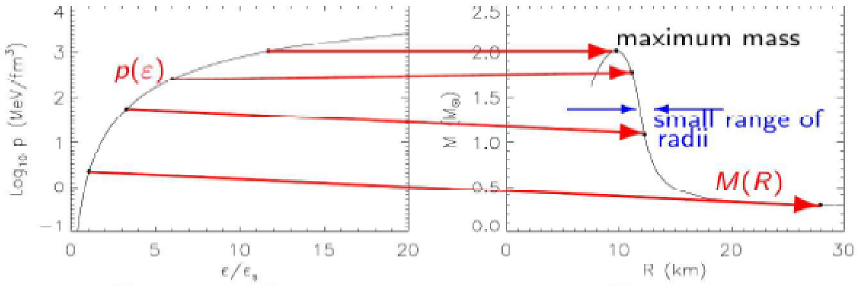
An Analytic Inversion of TOV Equations

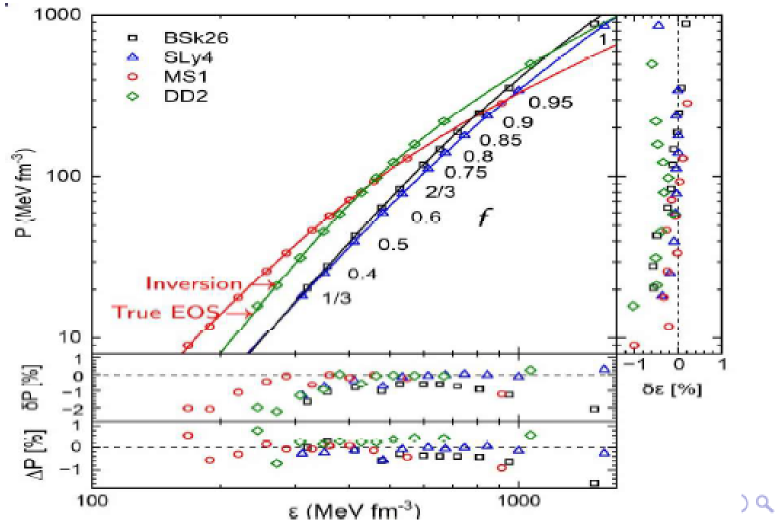
The TOV equations determine the neutron star M-R curve from the equation of state (EOS), i.e., the pressure-energy density (P-$\mathcal{E}$) relation. M-R observations can be converted to EOS information by inverting the TOV equations. We discovered a simple analytic inversion method using (M, R) values for fractional maximum mass points that gives the central P-$\mathcal{E}$ of those stars to better than 0.5%.

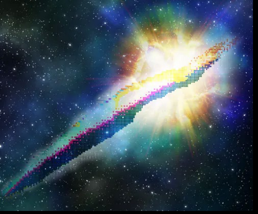
Tolman-Oppenheimer-Volkov equations

$$\frac{dp}{dr} = -\frac{G}{c^4}\frac{(mc^2 + 4\pi pr^3)(\varepsilon + p)}{r(r - 2Gm/c^2)}$$

$$\frac{dm}{dr} = 4\pi\frac{\varepsilon}{c^2}r^2$$

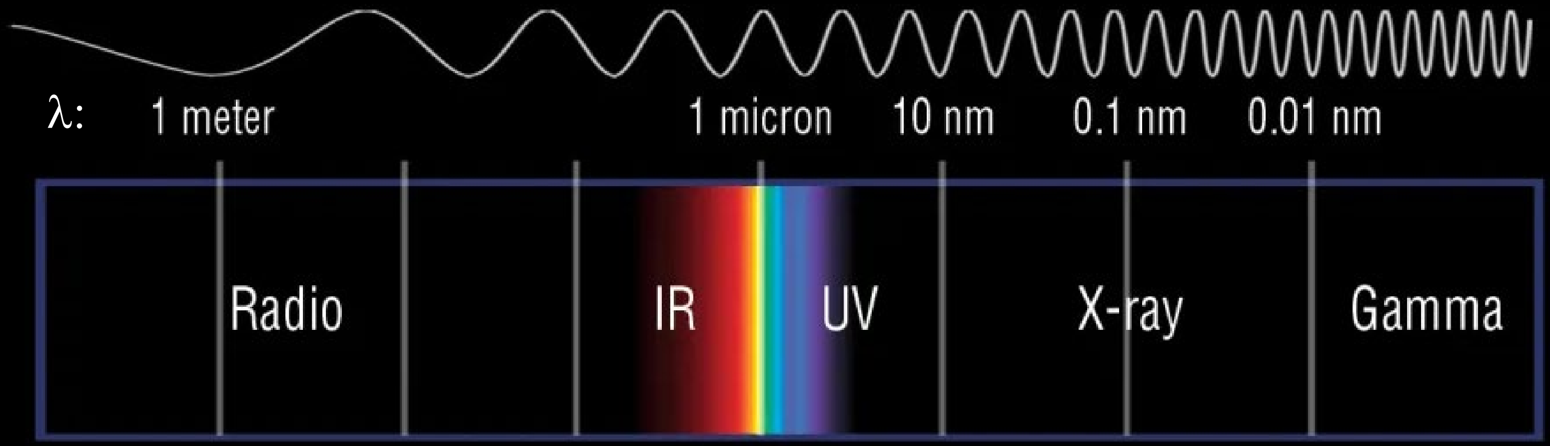




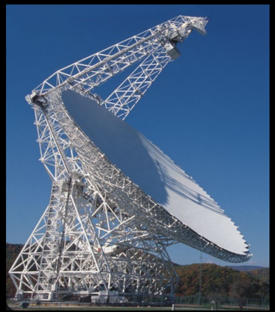


NUCLEAR ASTROPHYSICS: EOS AND NEUTRON STARS

observation of neutron stars



radio



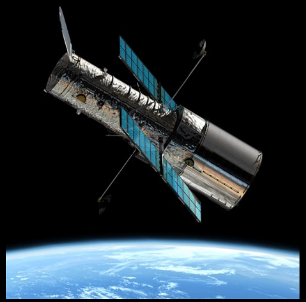
Green Bank

MeerKAT

IR and optical

VLT

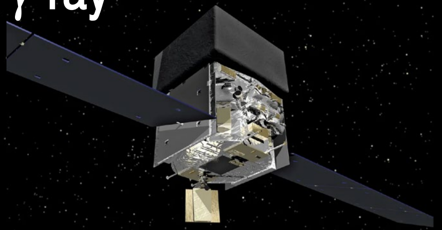
optical and UV



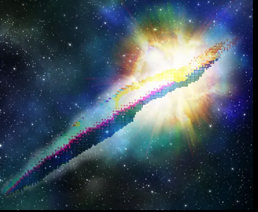
HST (Hubble)

X-ray and γ-ray

Chandra

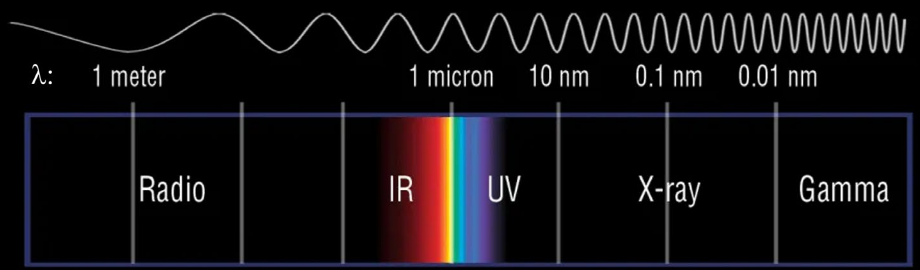


Fermi



NUCLEAR ASTROPHYSICS: EOS AND NEUTRON STARS

observation of neutron stars



radio

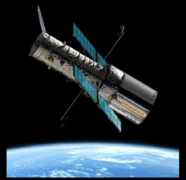
Green Bank

MeerKAT

IR and optical

VLT

optical and UV



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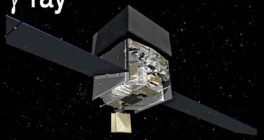
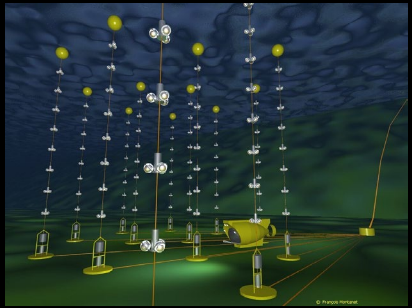


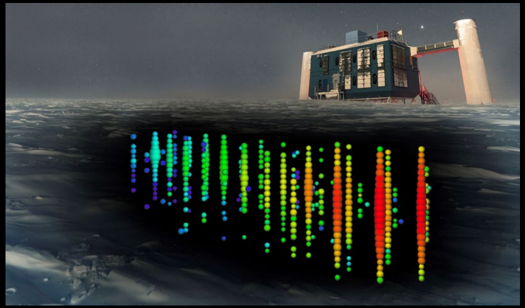
Fermi

gravitational waves

neutrinos



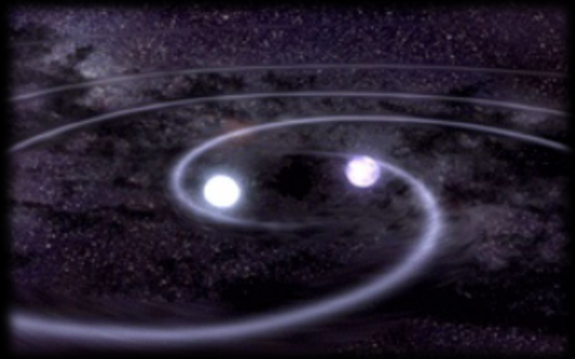
ANTARES

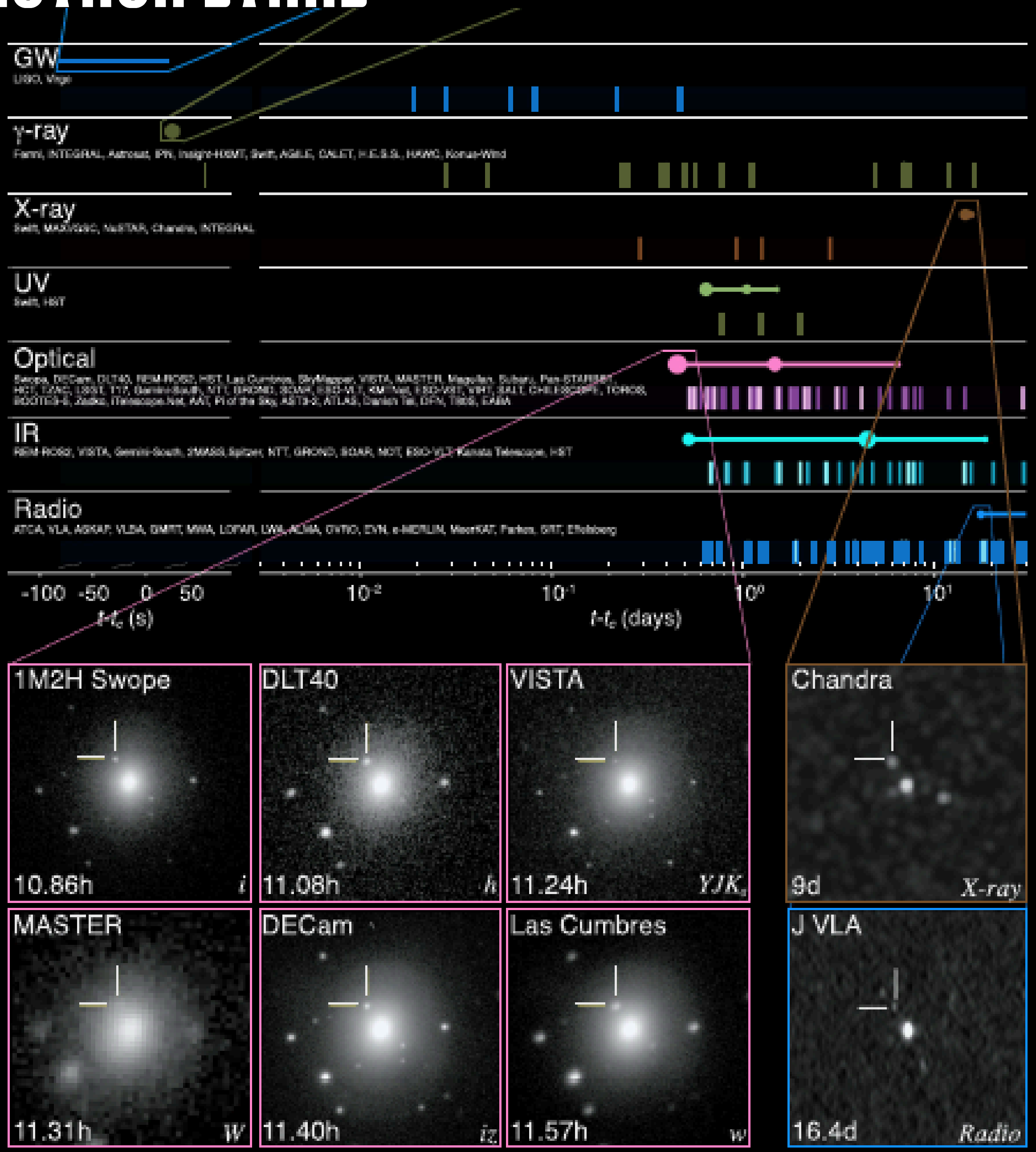


IceCube

NUCLEAR ASTROPHYSICS: EOS AND NEUTRON STARS

NEUTRON STAR MERGER GW170817





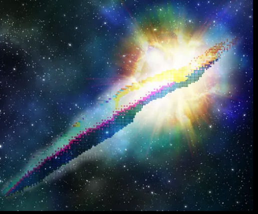
gravitational wave signal

+

γ- and X-ray, UV, optical, IR, and radio signals

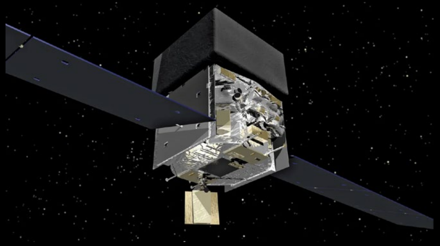
⇒ **MULTI-MESSENGER ASTRONOMY**

B.P. Abbott et al., ApJL 848 (2017) L12

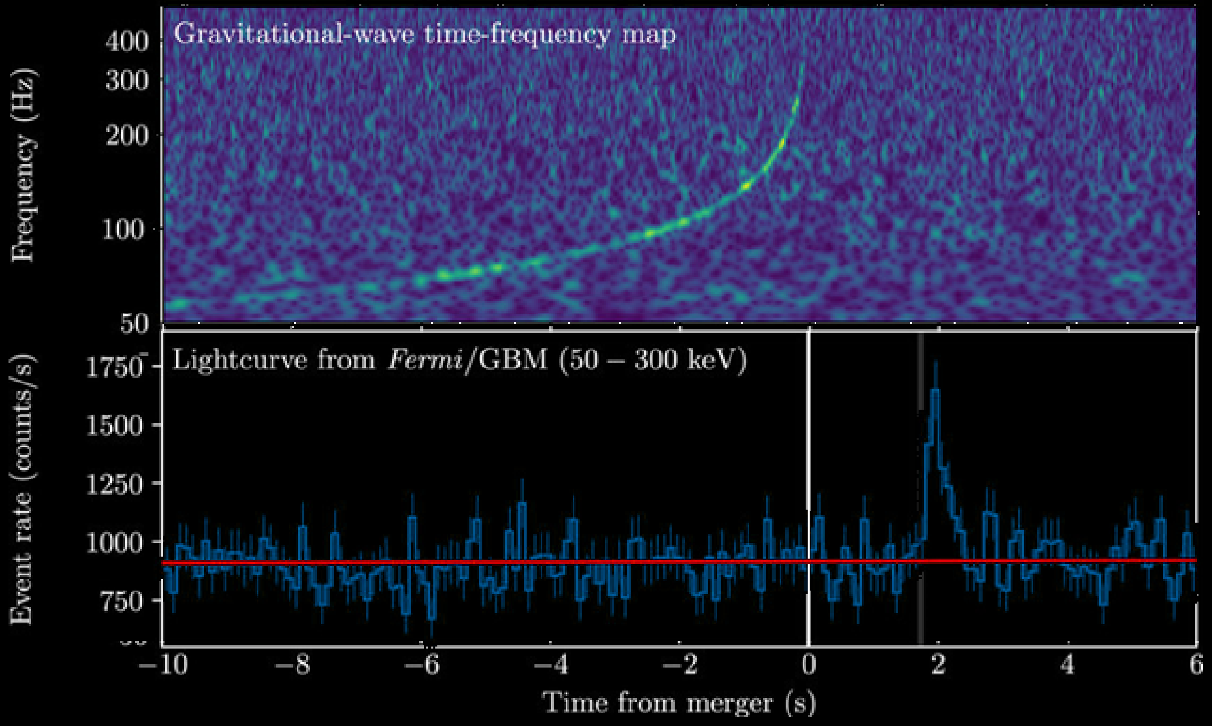


NUCLEAR ASTROPHYSICS: EOS AND NEUTRON STARS

NEUTRON STAR MERGER GW170817



Fermi



B.P. Abbott et al., PRL 119 (2017) 161101

GRAVITATIONAL WAVE (GW)

GAMMA RAY BURST (GRB)

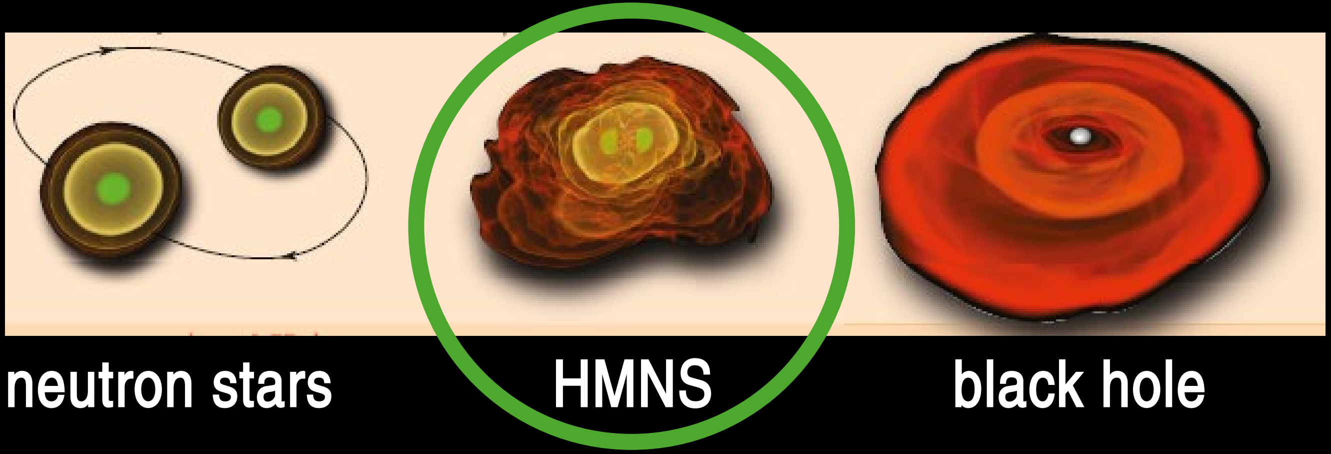
⇓

What powers the GRBs?

NUCLEAR ASTROPHYSICS: EOS AND NEUTRON STARS

see Cecilia Chirenti's talk on Monday

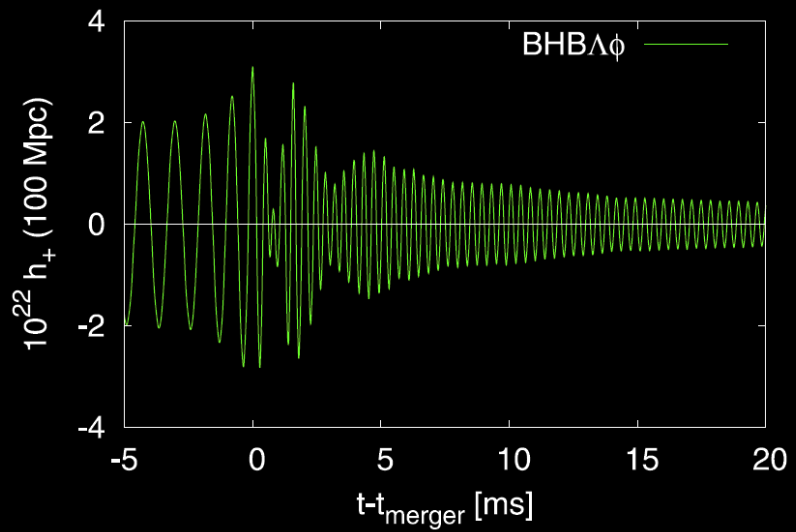
HYPERMASSIVE NEUTRON STAR (HMNS)

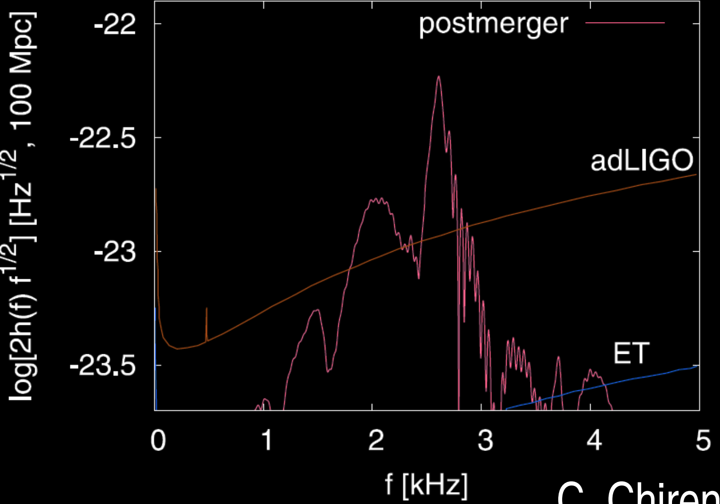


neutron stars HMNS black hole

- lives for $< 1s$
- spins fast
- emits kHz GWs
  ↪ too high for current GW detectors

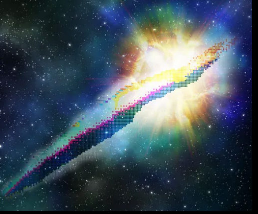
⇓





HMNS oscillations could result in a measurable **MODULATION OF THE GRB**
↪ quasiperiodic oscillations (QPO)

C. Chirenti et al., Astrophys. J. Lett. 884 (2019) 1



NUCLEAR ASTROPHYSICS: EOS AND NEUTRON STARS

see Cecilia Chirenti's talk on Monday

CONSTRAIN MASS-RADIUS RELATION

from oscillation modes obtain constraints on

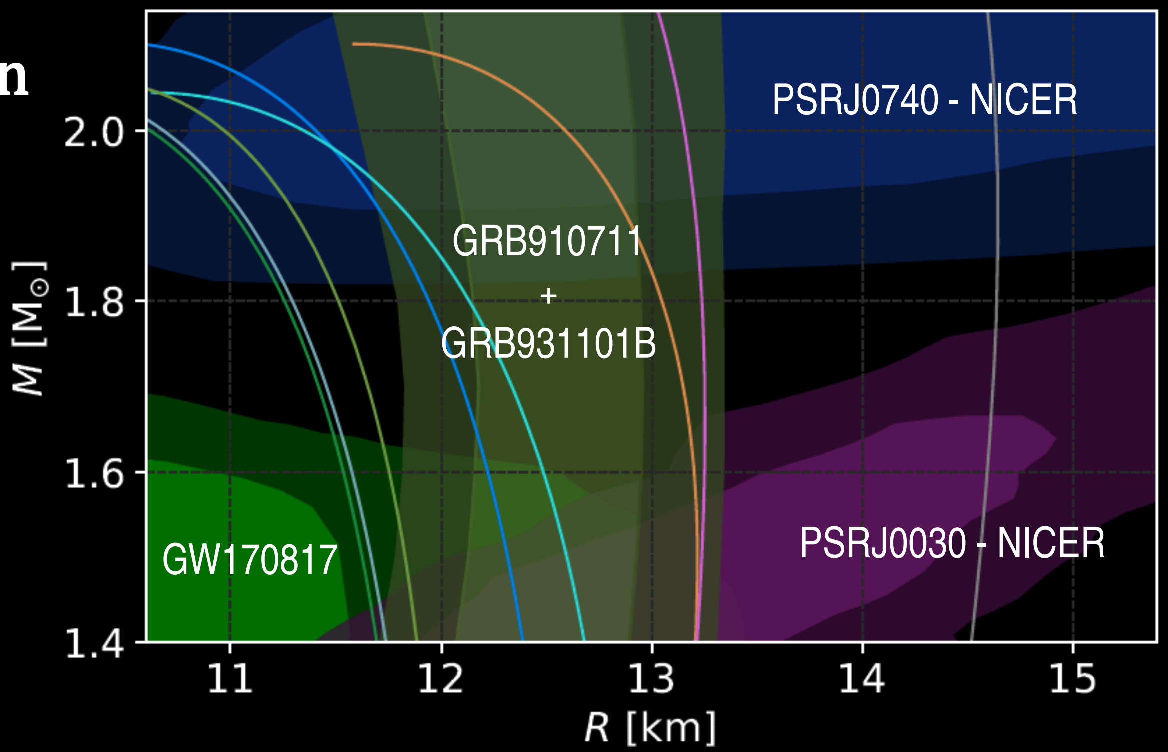
- chirp mass:

$$\mathcal{M} = \frac{(M_1 M_2)^{\frac{3}{5}}}{(M_1 + M_2)^{\frac{1}{5}}}$$

- binary tidal deformability

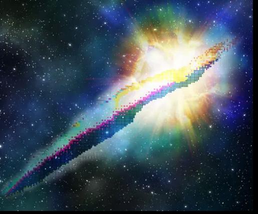
$$\tilde{\Lambda} = \frac{16}{13}\left(\frac{(M_1 + M_2) M_1^4 \tilde{\Lambda}_1}{(M_1 + M_2)^5} + (1 \leftrightarrow 2)\right)$$

$$\Rightarrow R_M(\tilde{\Lambda}, \mathcal{M}) = \alpha \left(\frac{\mathcal{M}}{1 M_\odot}\right) \left(\frac{\tilde{\Lambda}}{800}\right)^{\frac{1}{\beta}}$$



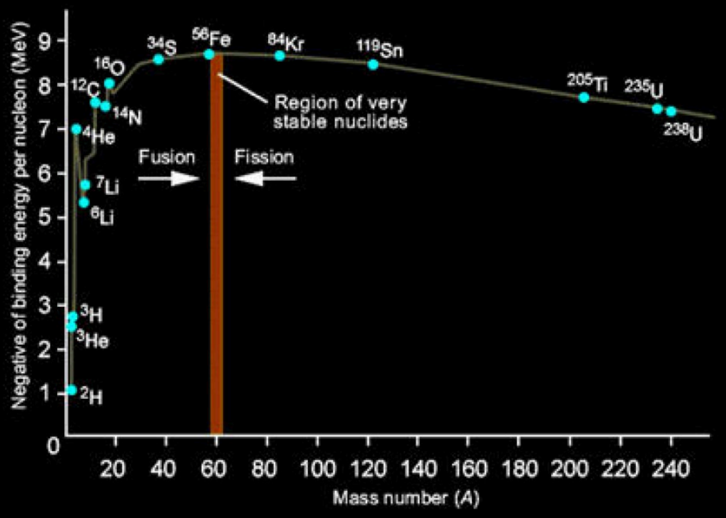
adapted from V. Guedes et al., arXiv: 2408.16534

$\Rightarrow$ **INFORMATION ABOUT EOS OBTAINED FROM GRB**

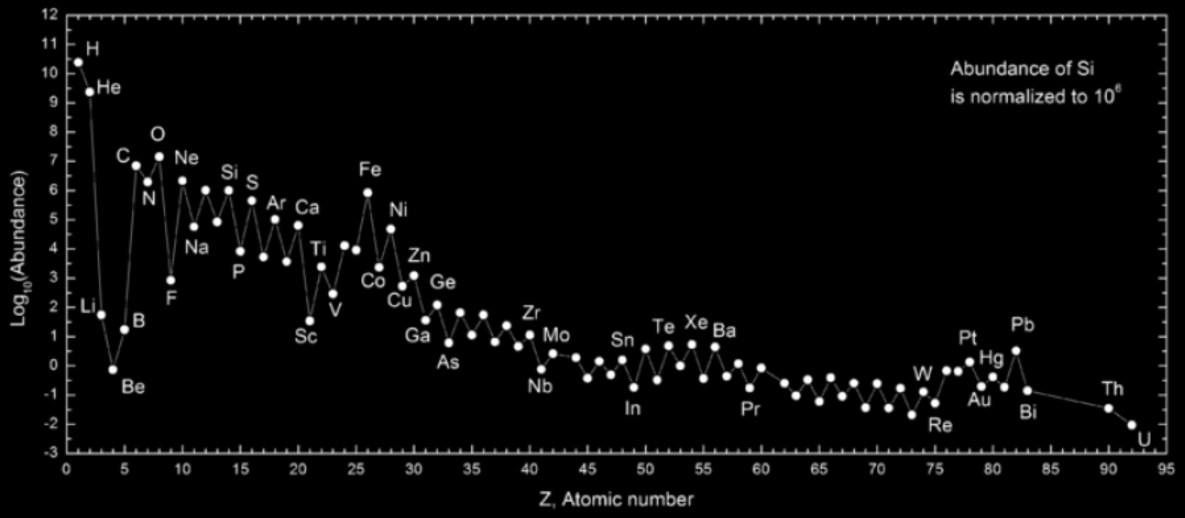


NUCLEAR ASTROPHYSICS: S, R, P, RP PROCESSES

HOW DO WE GET HEAVIER ELEMENTS?



- increasing Coulomb barrier suppresses fusion
- once Fe synthesised no further fusion

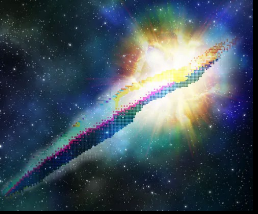


to explain formation of heavier elements

Burbidge, Burbidge and Hoyle (B^2FH) suggest in 1957

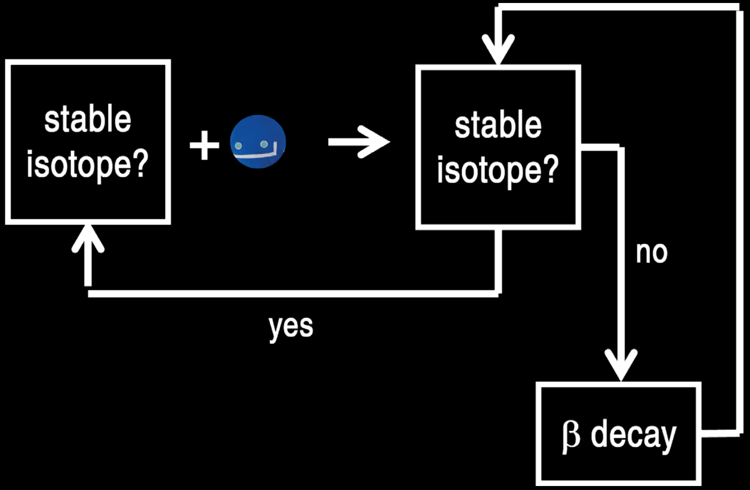
SUCCESSIVE CAPTURES OF NEUTRONS BY SEED NUCLEI

↪ s and r processes



NUCLEAR ASTROPHYSICS: S, R, P, RP PROCESSES

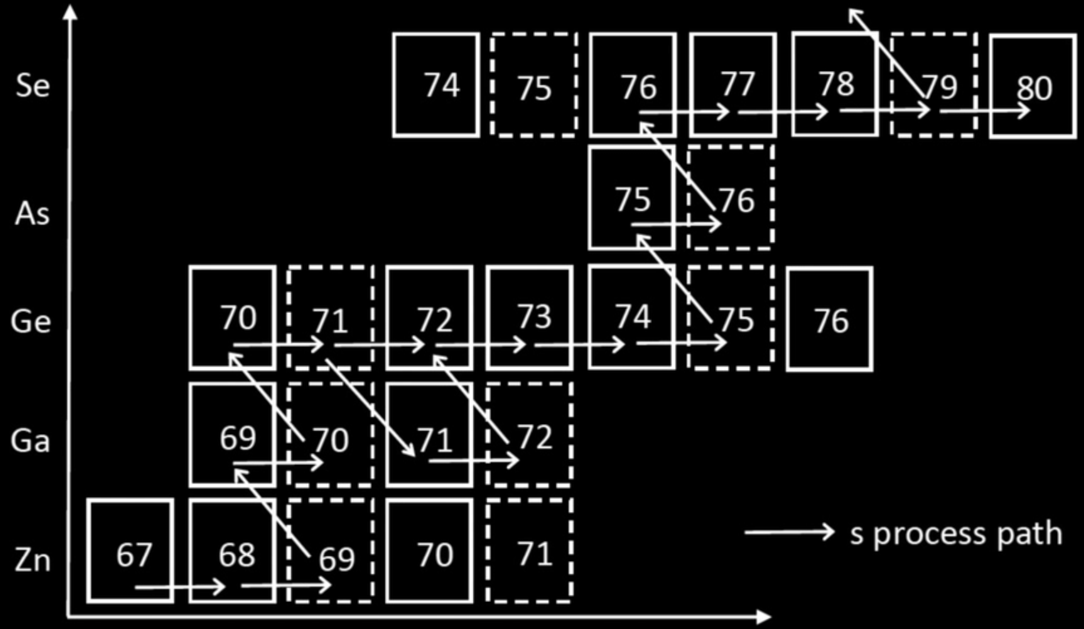
S PROCESS



the s process is a **SLOW** process of neutron capture by stable nuclei

↪ slow means slower than β deacy

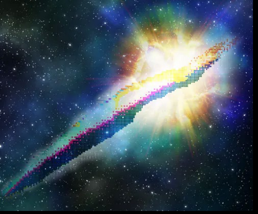
↪ requires small neutron flux
e.g. He burning stage of AGB stars



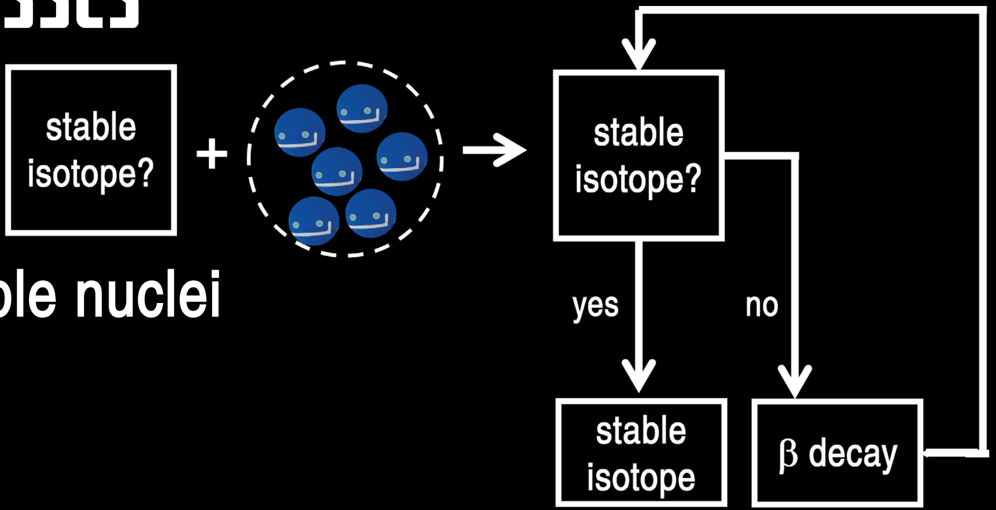
synthesis elements close to valley of stability

↪ does not explain

- isotopes away from stability
- heavy elements (U, Th, ...)



NUCLEAR ASTROPHYSICS: S, R, P, RP PROCESSES



R PROCESS

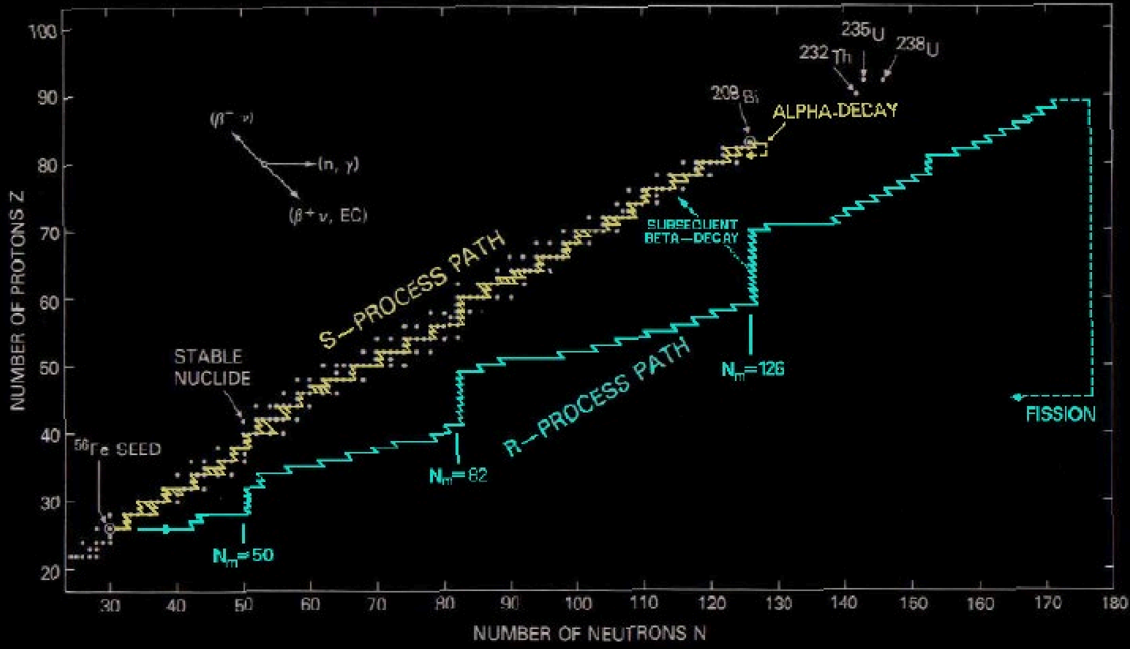
the r process is a **RAPID** process of neutron capture by stable nuclei

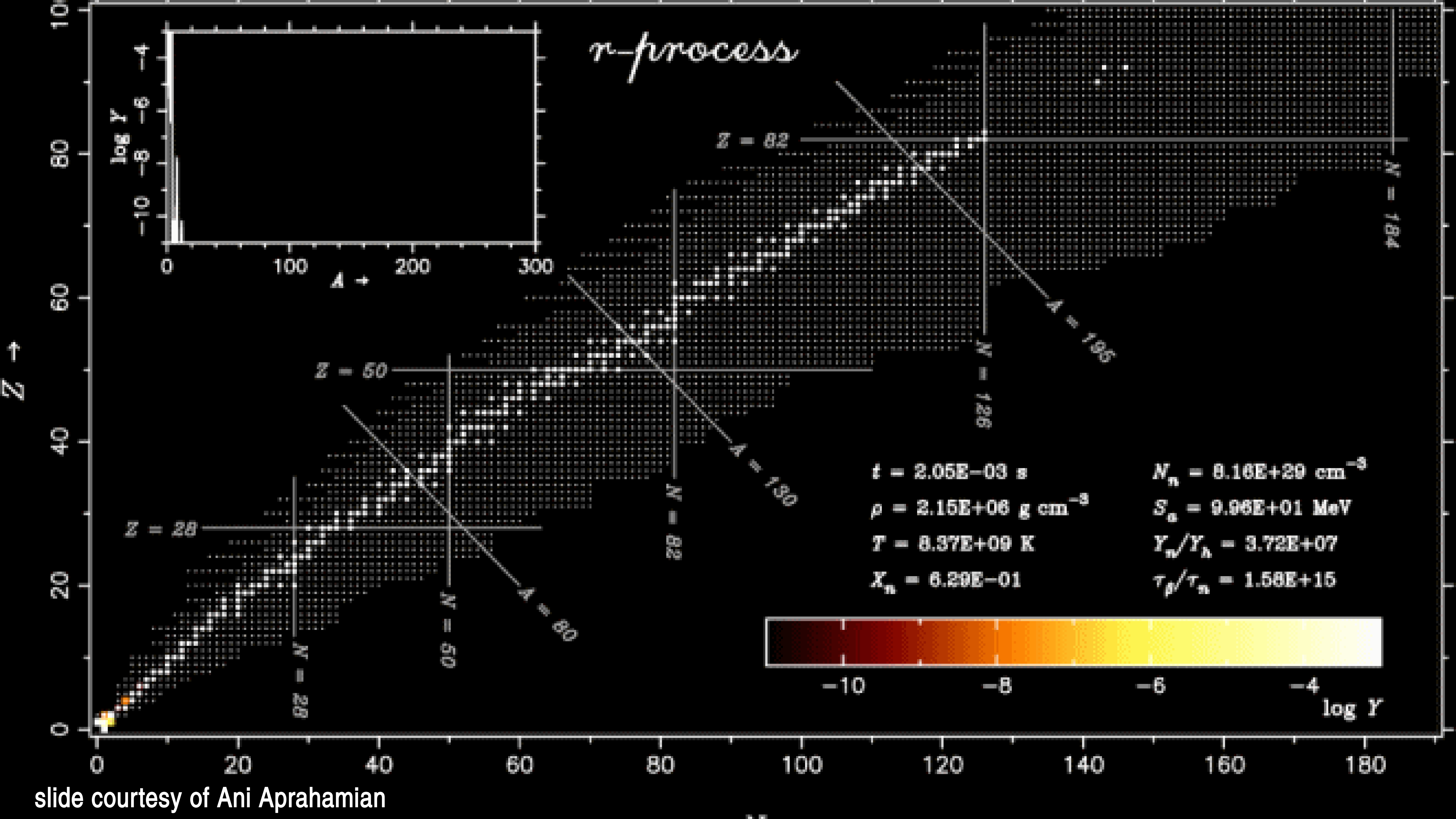
↪ rapid means faster than β deacy

↪ requires high neutron flux
e.g. core-collapse supernovae, neutron star mergers

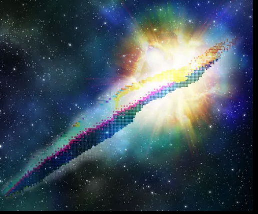
synthesis elements far away from valley of stability
↪ superheavy elements too?

see Ani Aprahamian's talk on Tuesday





slide courtesy of Ani Aprahamian



NUCLEAR ASTROPHYSICS: S, R, P, RP PROCESSES

P AND RP PROCESSES

s and r processes synthesis only neutron-rich nuclei

how to explain the presence of p-rich nuclei?

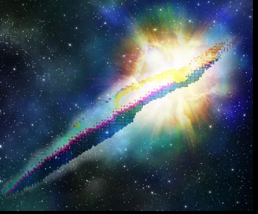
↪ p and rp processes are similar processes with **SUCCESSIVE PROTON CAPTURES**

P PROCESS:

slow capture of protons

synthesis proton-rich nuclei close to valley of stability

possible site: supernova



Nuclear Astrophysics: s, r, p, rp processes

rp processes

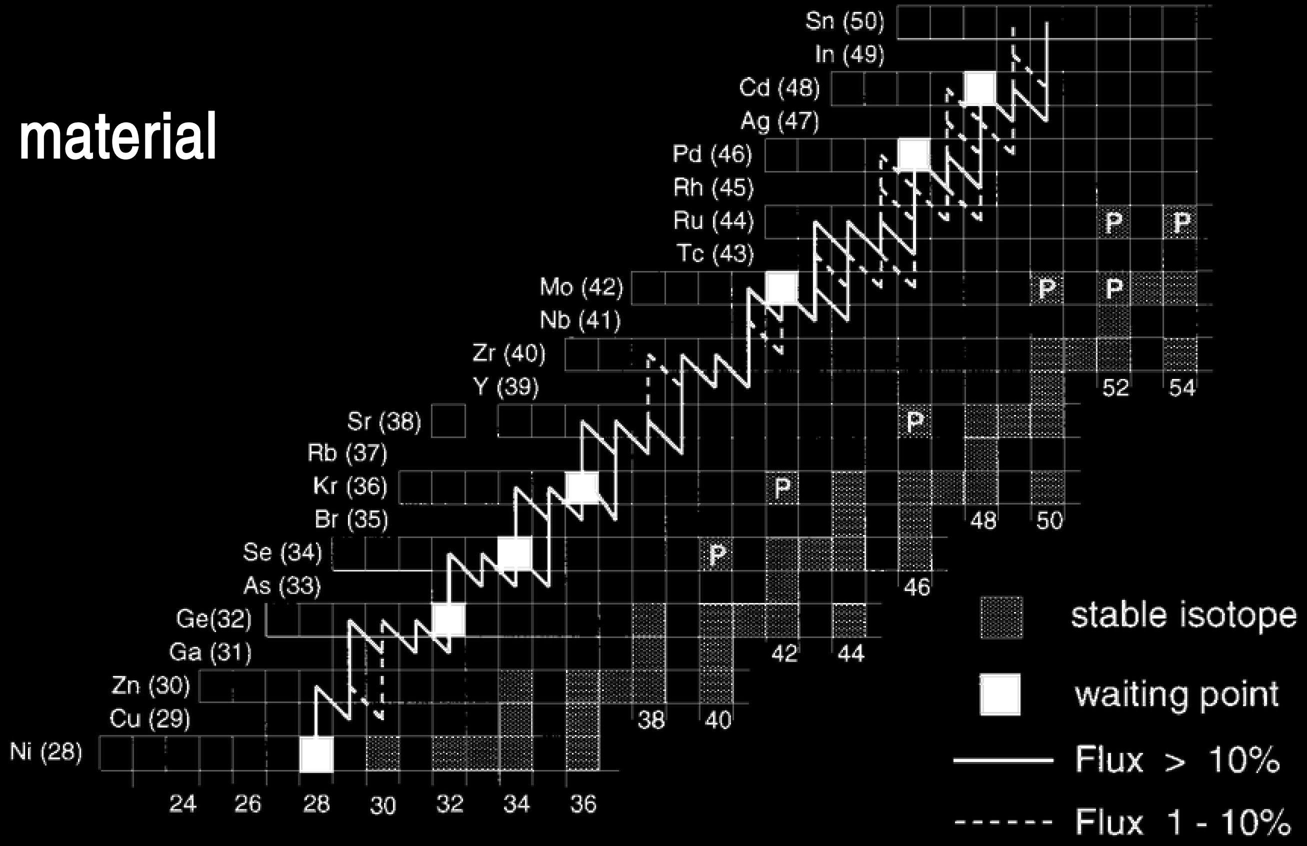
rapid proton-capture reactions synthesis elements away from valley of stability

possible sites:

- X-ray burst

↪ accretion by neutron star of H- and He-rich material from companion star

- supernova type Ia



SUMMARY

nuclei are synthesised in stellar environments during various processes

- pp chain, CNO cycles, He burning
- s and r processes (n capture)
- p and rp processes (p capture)

stable nuclei can be qualitatively described by liquid-drop and shell model

nowadays ab initio nuclear structure models from first principles

↪ **FUTURE CHALLENGES AND OPPOTUNITIES**
in nuclear structure and astrophysics
studying stable, exotic and superheavy nuclei