FAIR and strong interaction matter in the universe

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TECHNISCHE UNIVERSITÄT DARMSTADT

EMMI

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

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DFG

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European Research Council
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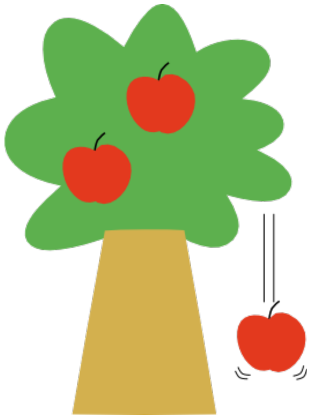
ERC AdG EUSTRONG

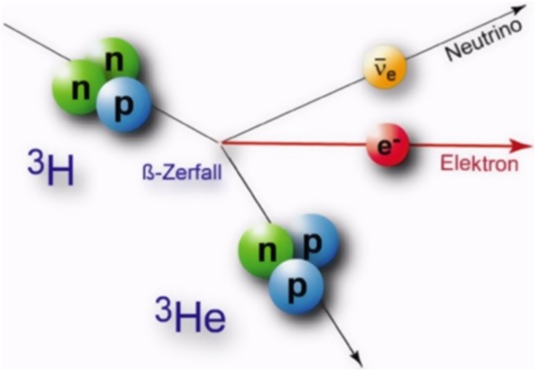
Bundesministerium für Bildung und Forschung

Fundamental interactions

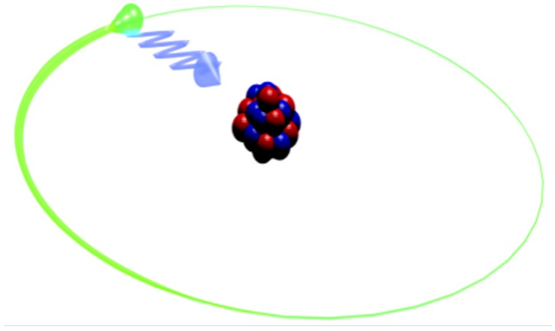
Gravity



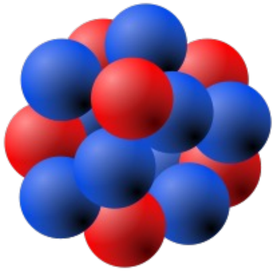
Weak interaction



Electrodynamics

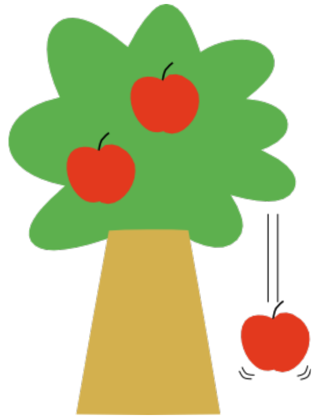


Strong interaction

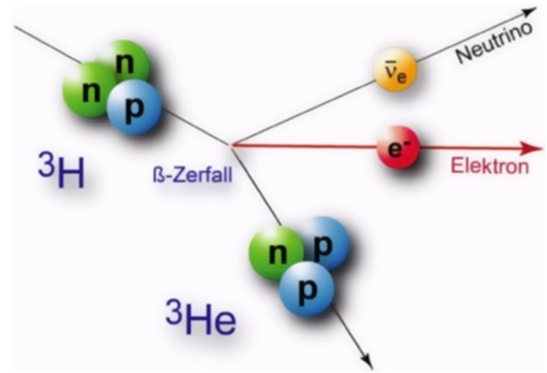


Fundamental interactions

Gravity



Weak interaction



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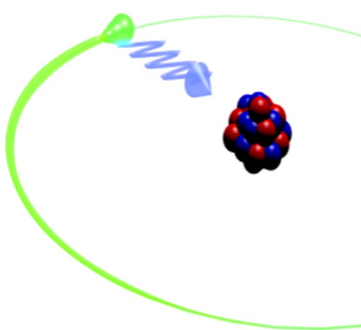
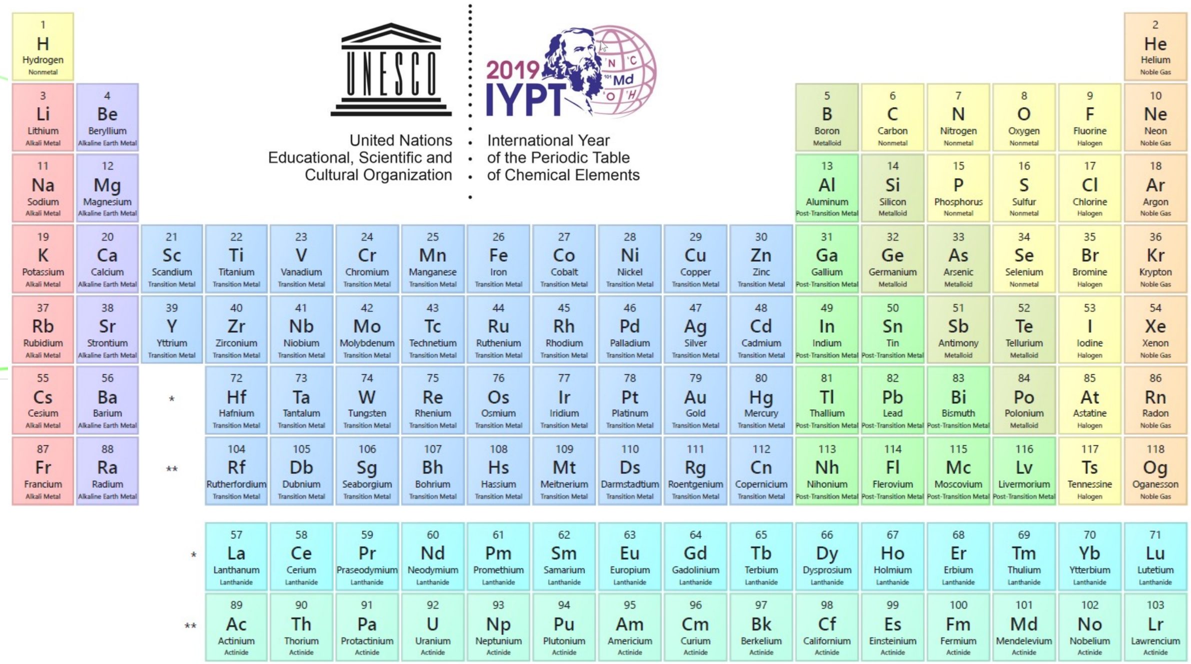


Periodic Table of Elements governed by electromagnetic interaction



Fundamental interactions

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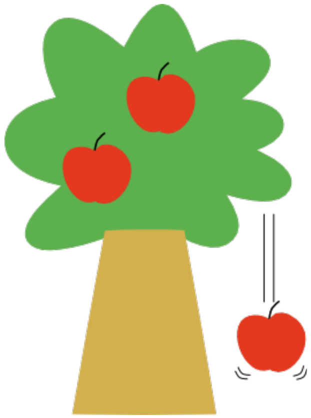

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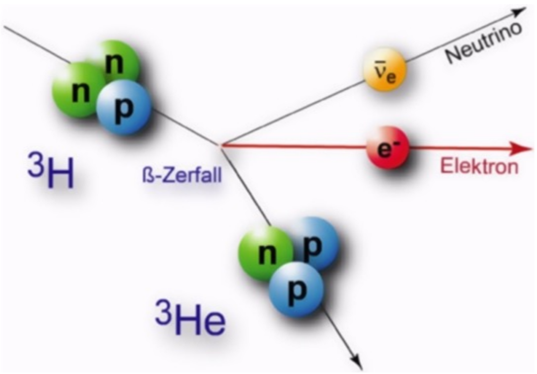

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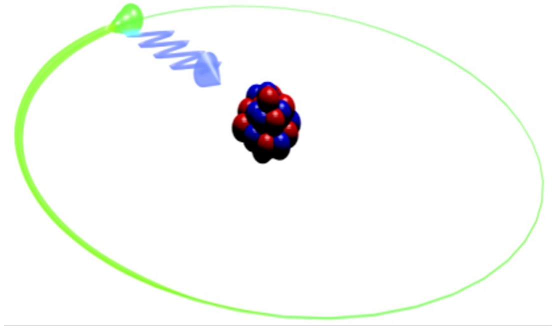
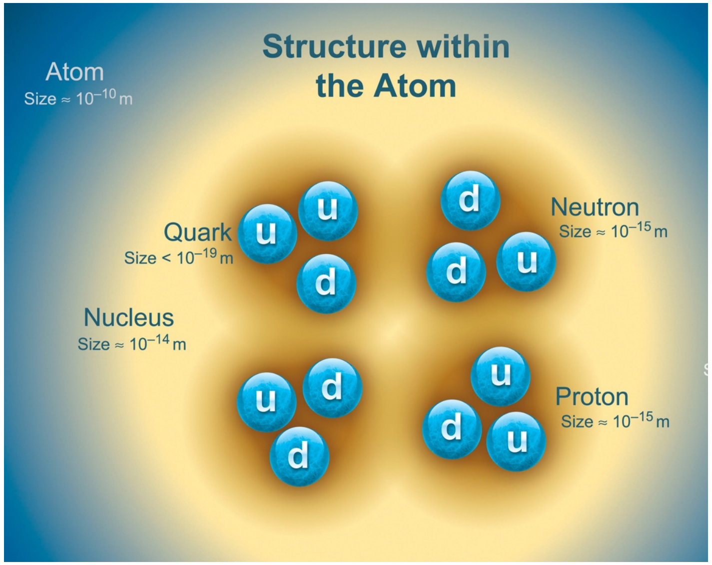


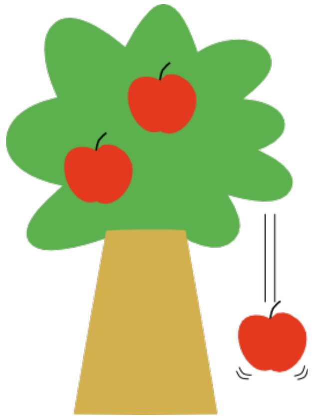
Strong interaction

Quantum chromodynamics (QCD)

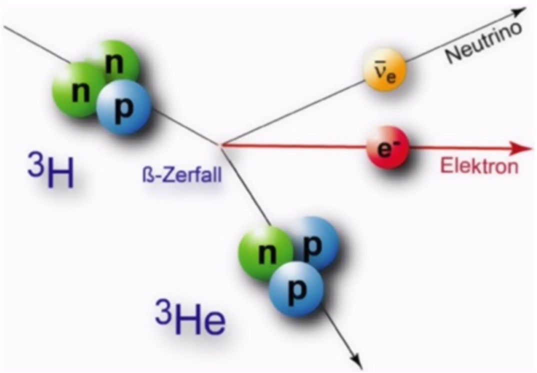


Fundamental interactions

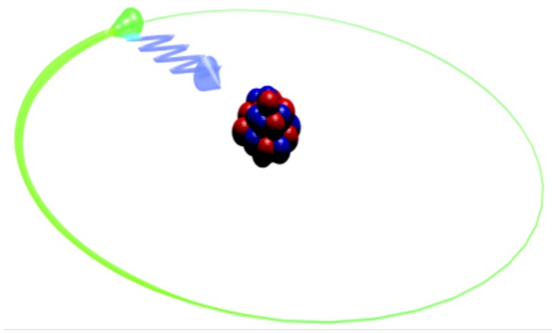
Gravity



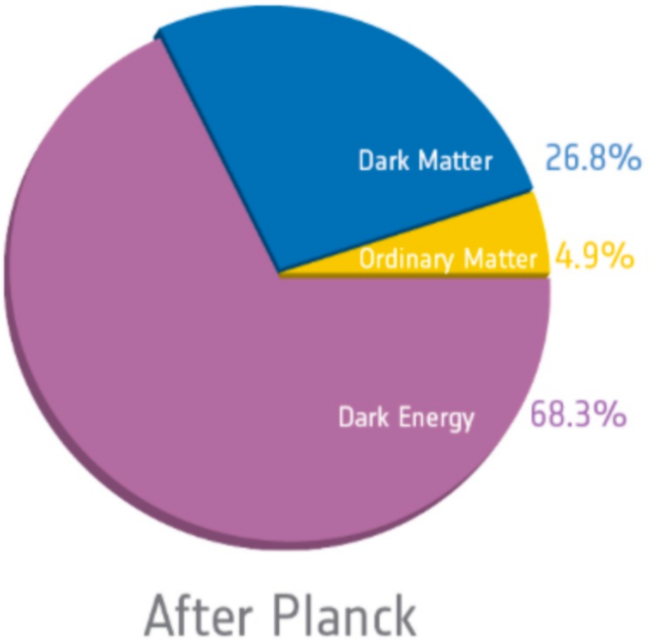
Weak interaction



Electrodynamics



Strong interaction in the universe



Nuclei bound by strong interactions

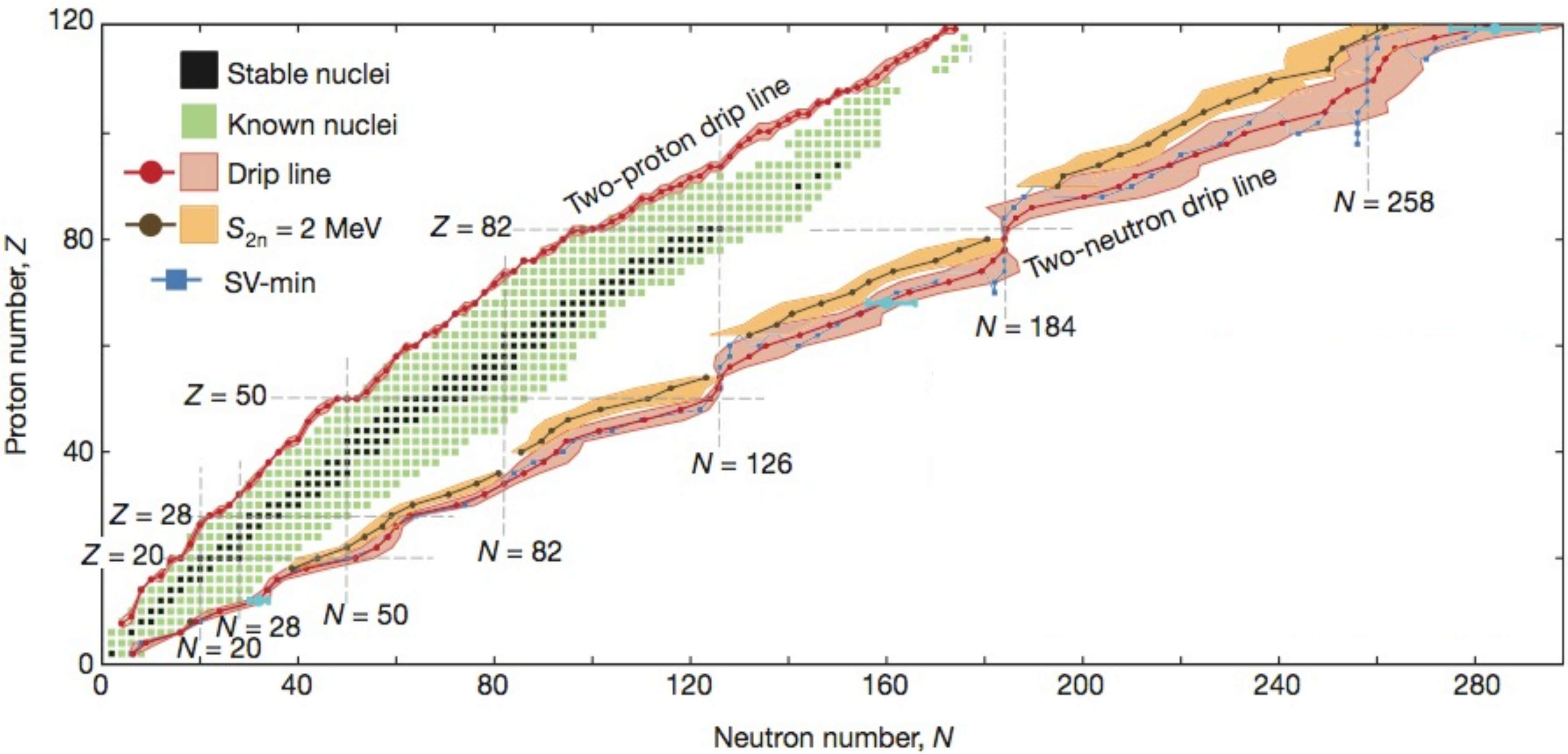
doi:10.1038/nature11188

The limits of the nuclear landscape

Jochen Erler[1,2], Noah Birge[1], Markus Kortelainen[1,2,3], Witold Nazarewicz[1,2,4], Erik Olsen[1,2], Alexander M. Perhac[1] & Mario Stoitsov[1,2]‡

~ 3000 nuclei discovered (288 stable), 118 elements

~ 4000±500 nuclei unknown, extreme neutron-rich



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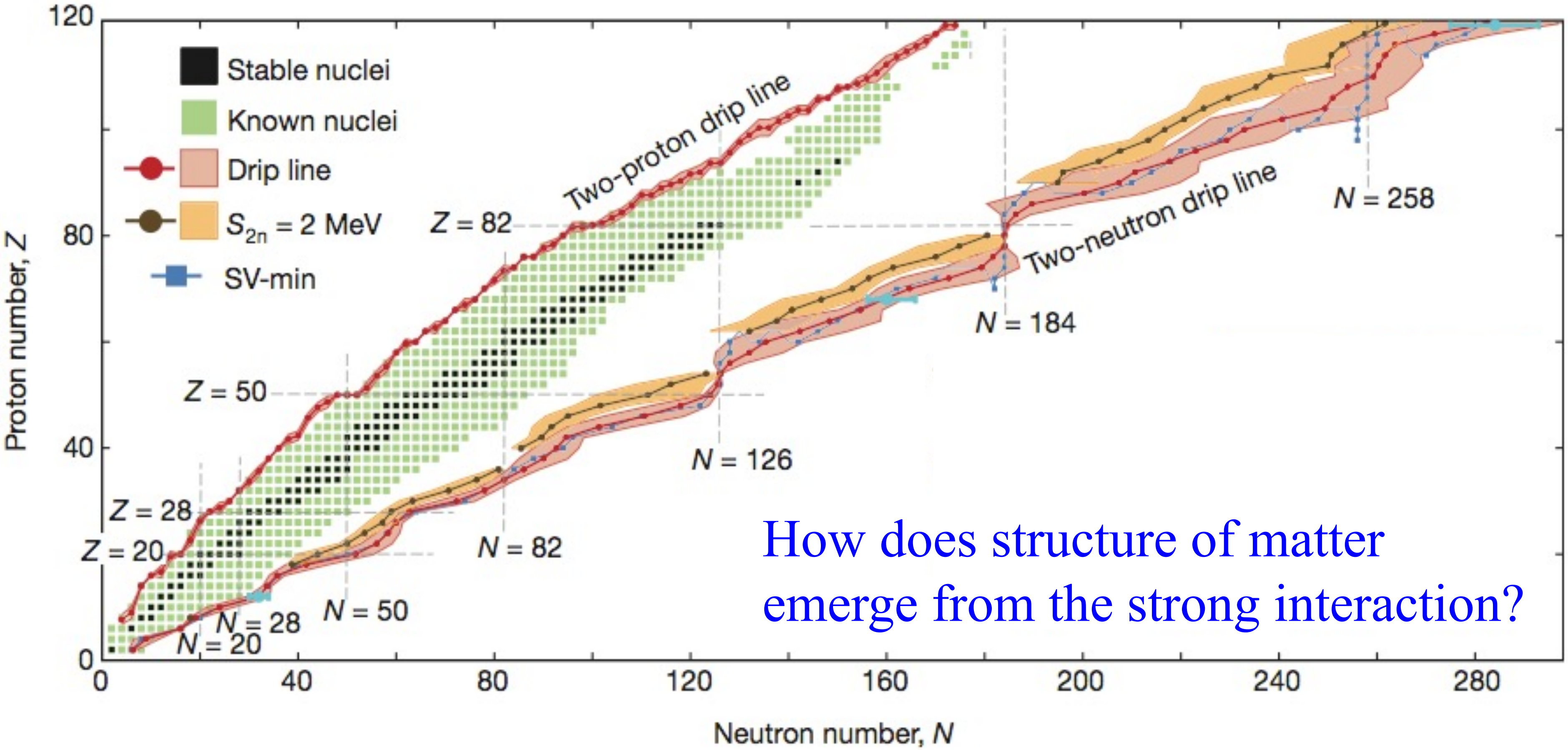

How does structure of matter emerge from the strong interaction?

Nuclei bound by strong interactions

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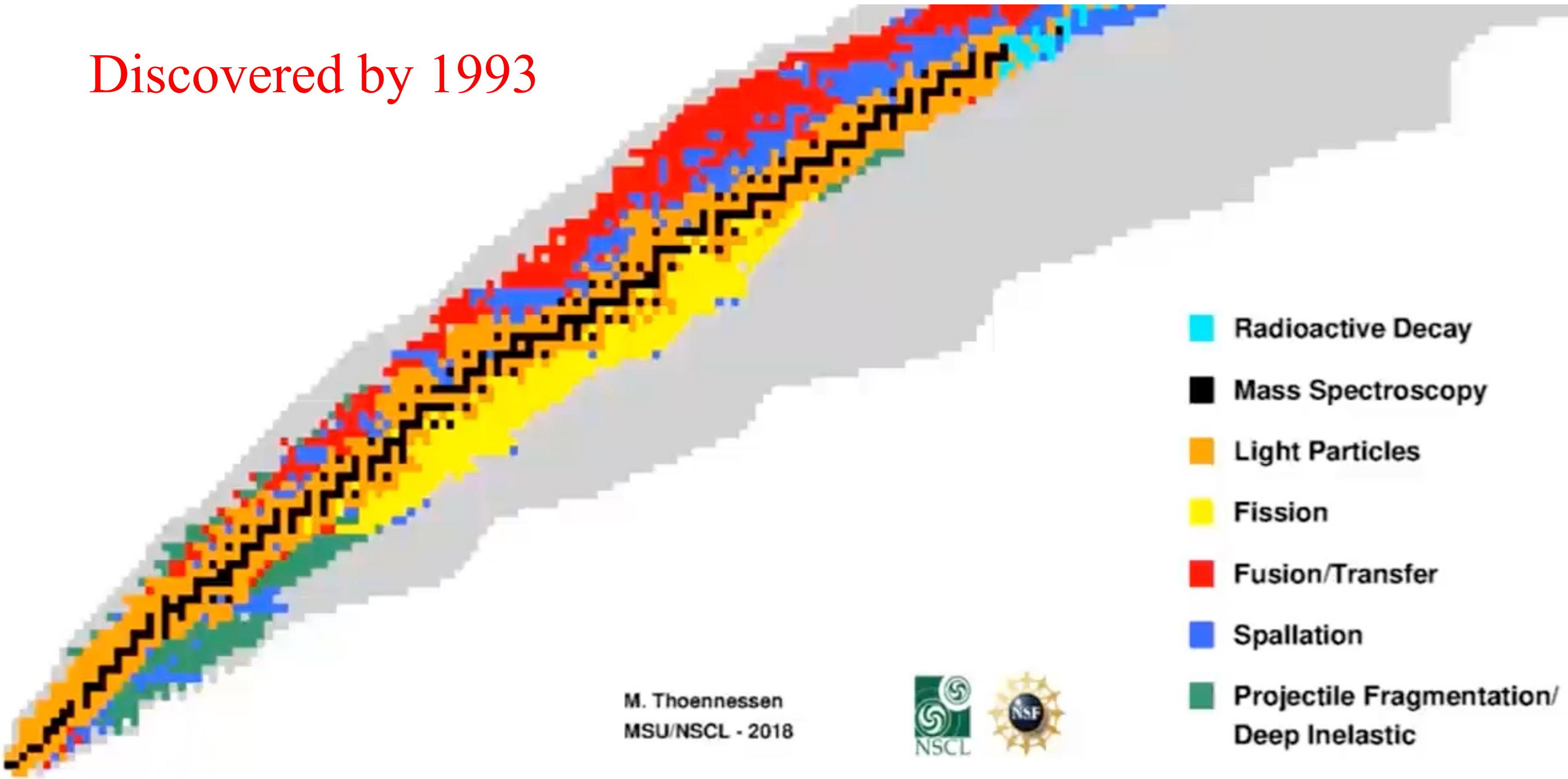
Discovered by 1993



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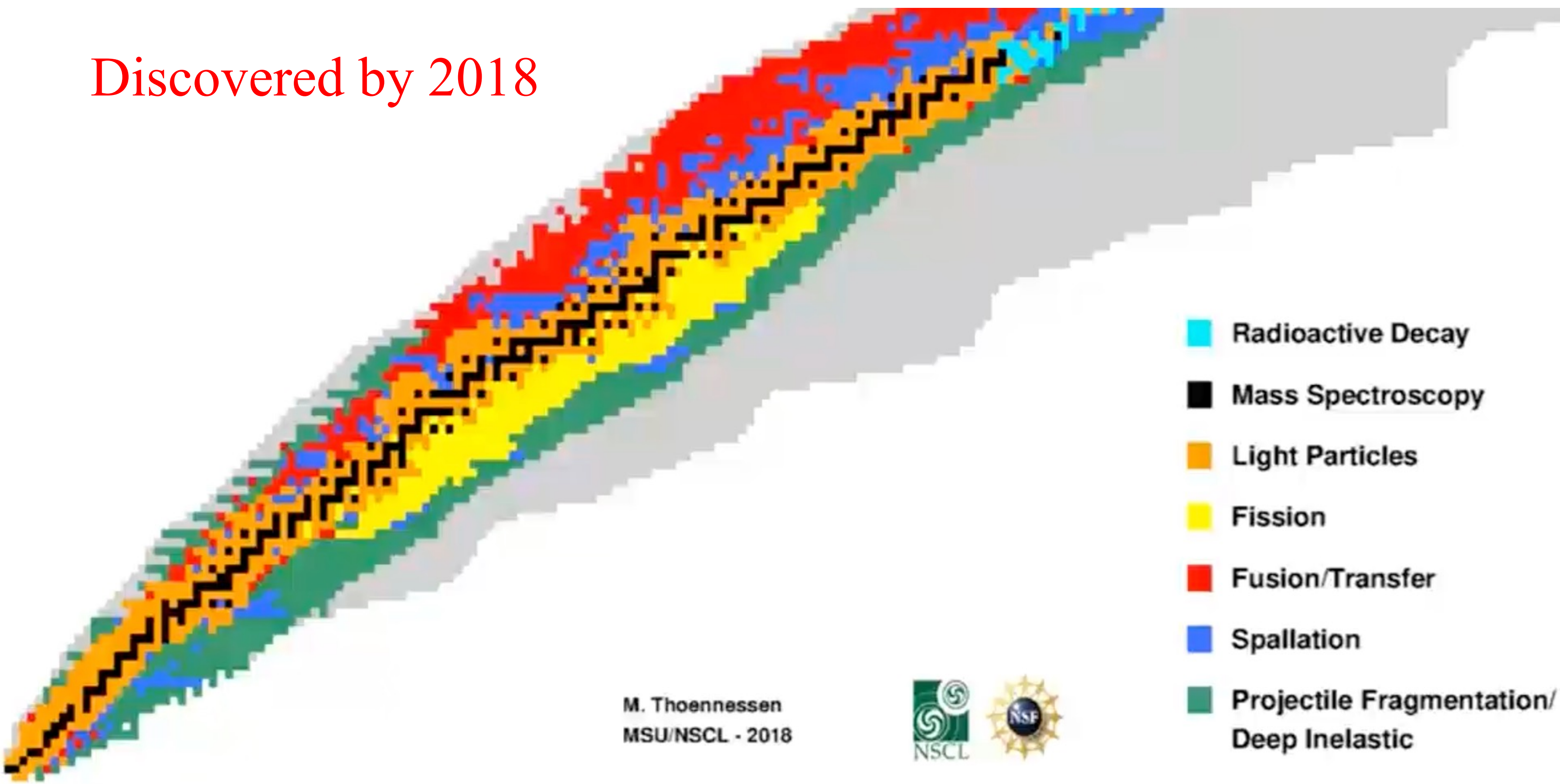
~ 4000 ± 500 nuclei unknown, extreme neutron-rich

Discovered by 2018



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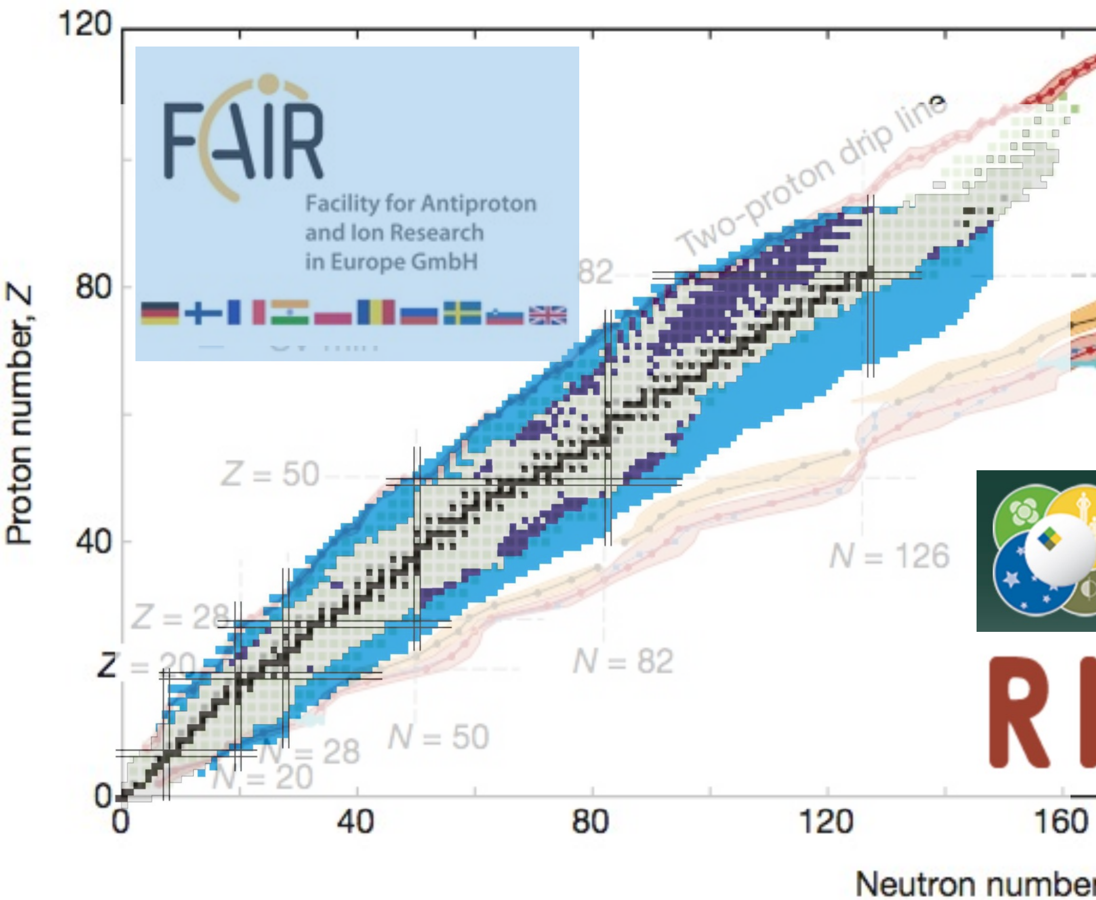

Facility for Rare Isotope Beams
at Michigan State University

RIBF

RIKEN NiSHiNA CENTER
RIKEN Nishina Center for Accelerator-Based Science

Nuclei bound by strong interactions

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The limits of the nuclear landscape

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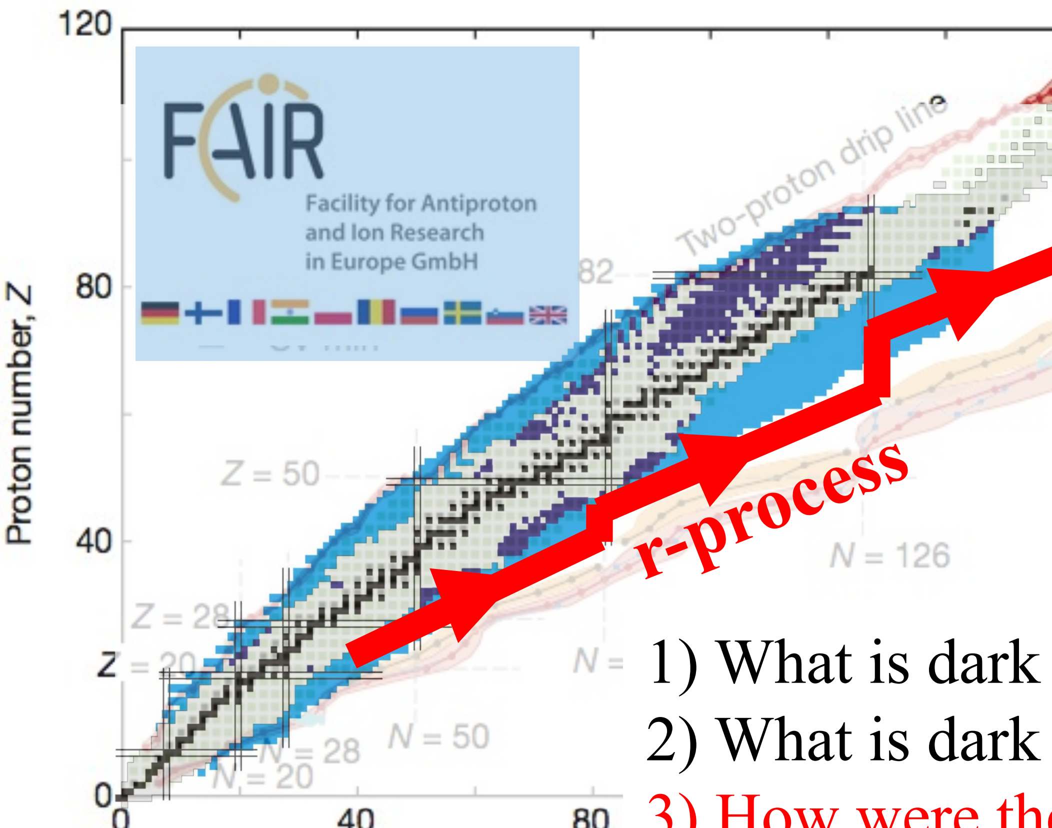
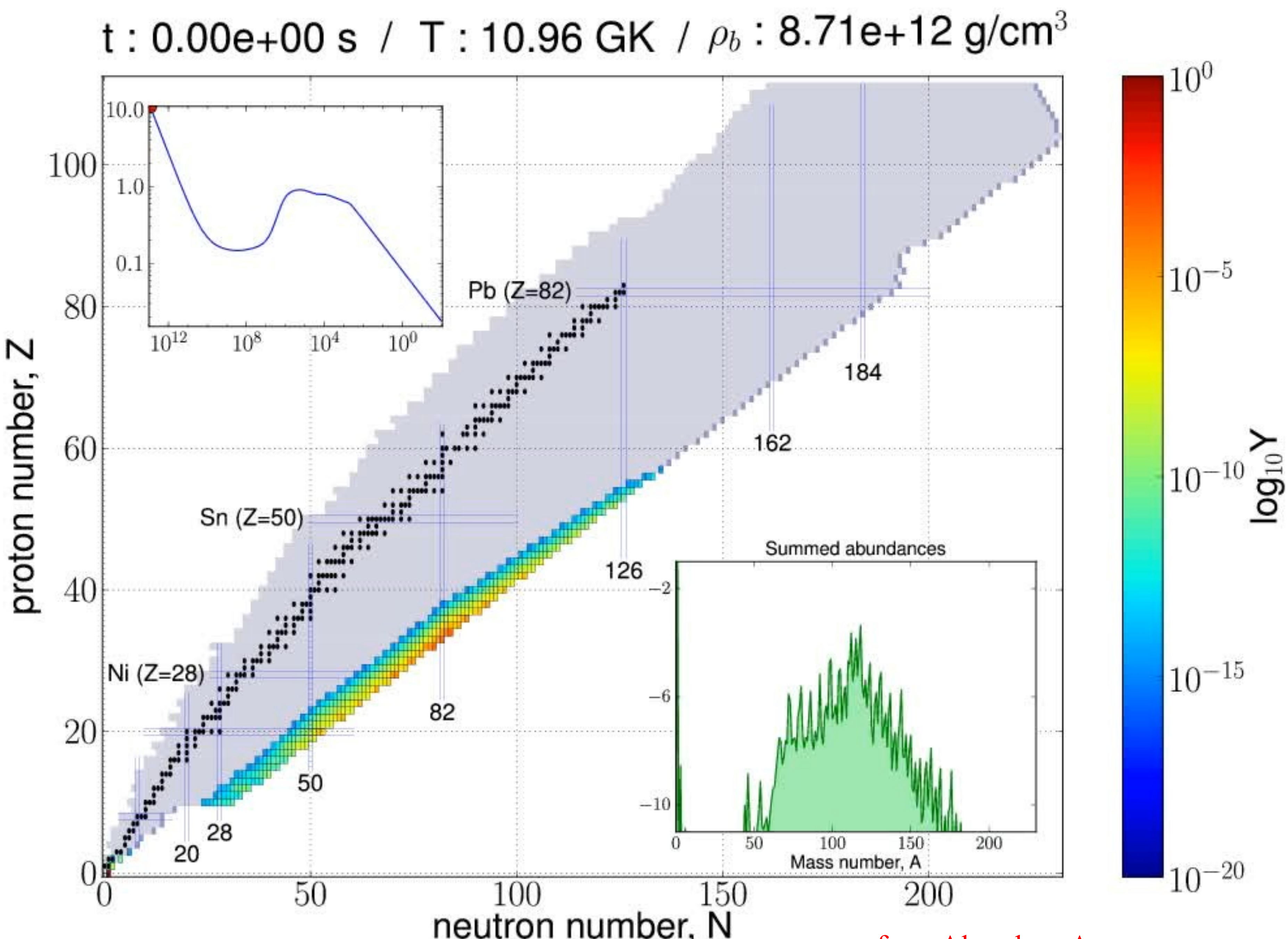
~ 3000 nuclei discovered (288 stable), 11

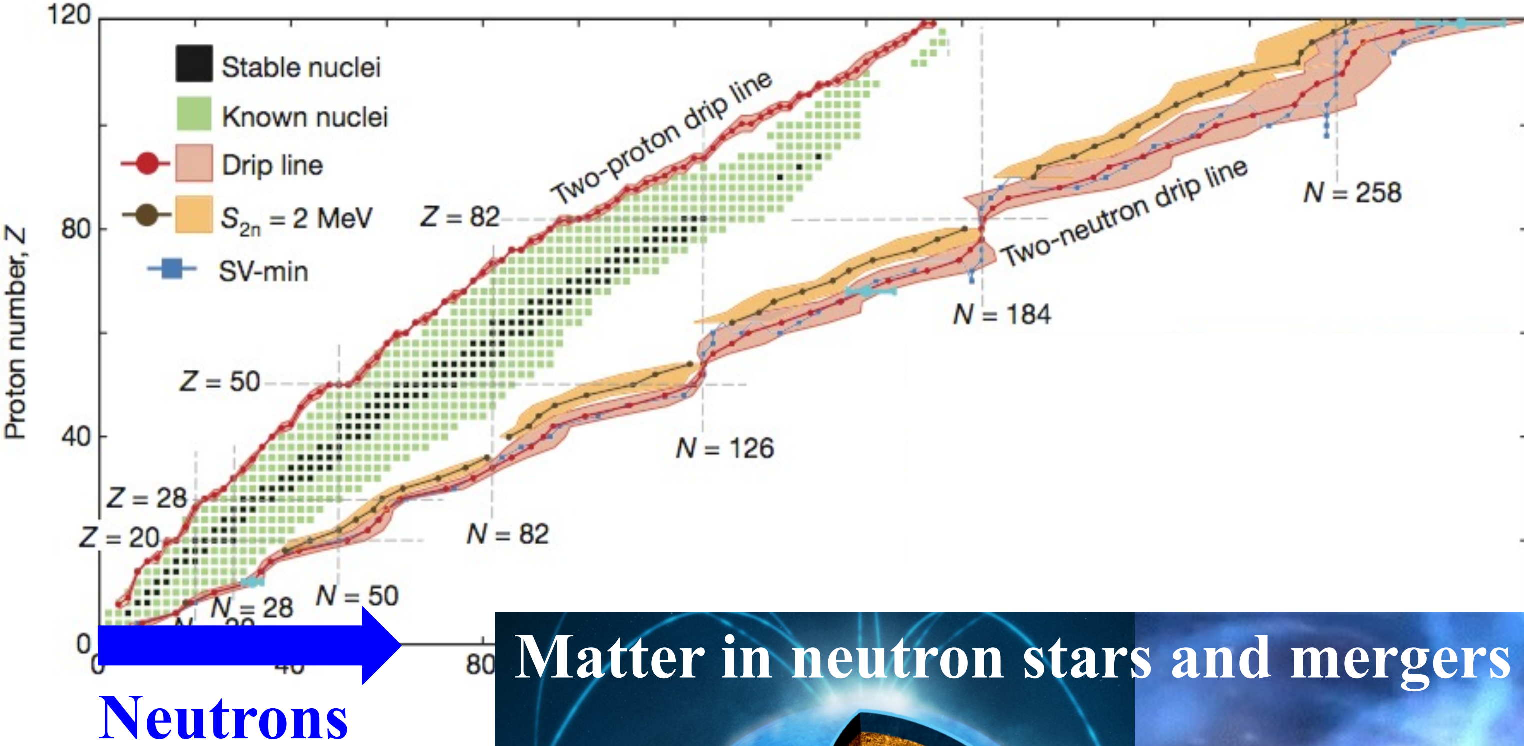
~ 4000±500 nuclei unknown, extreme n



1) What is dark matter?
2) What is dark energy?
3) How were the elements from iron to uranium made?



from Almudena Arcones



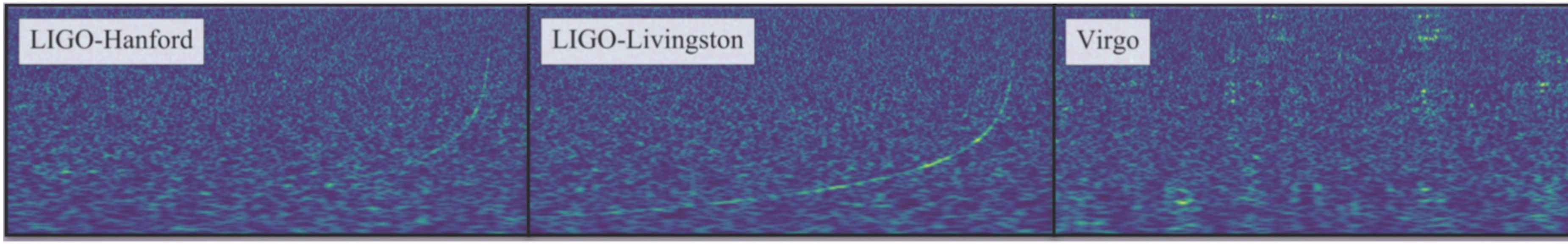
Matter in neutron stars and mergers

from Watts et al., RMP (2016)

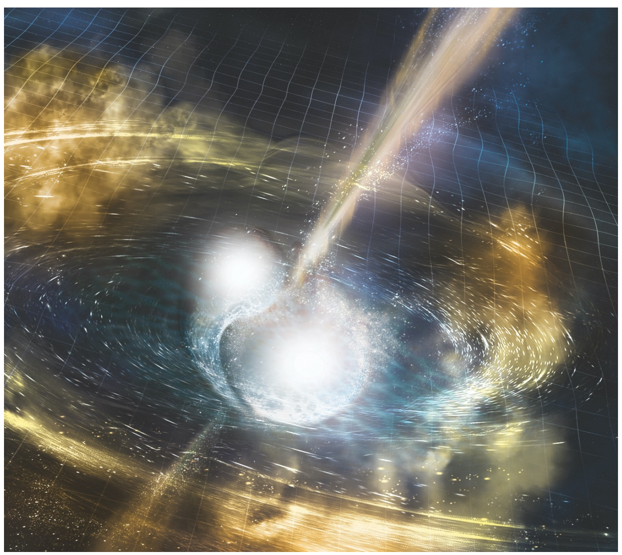
NASA/Goddard/LIGO/Virgo

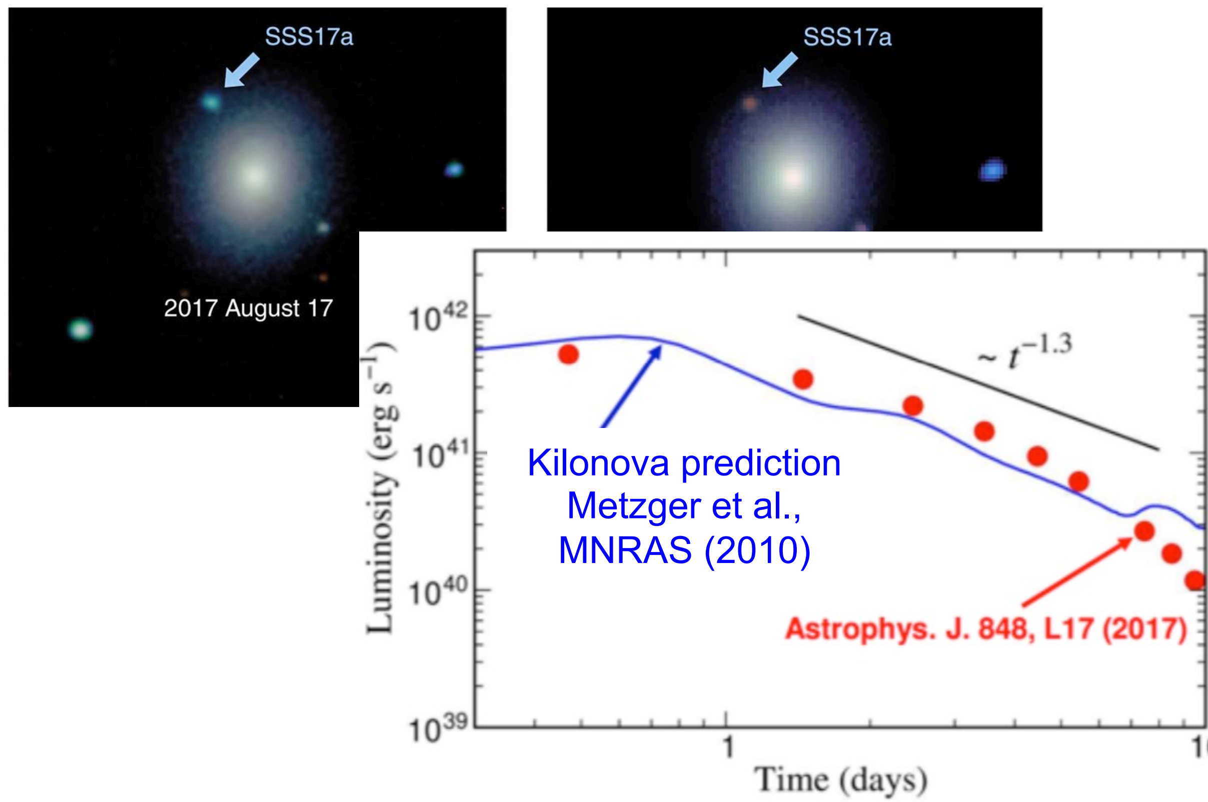
Multi-messenger era: neutron star merger GW170817

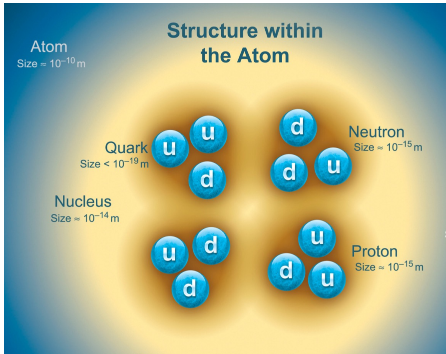
gravitational wave signal: provides constraints on neutron star radii

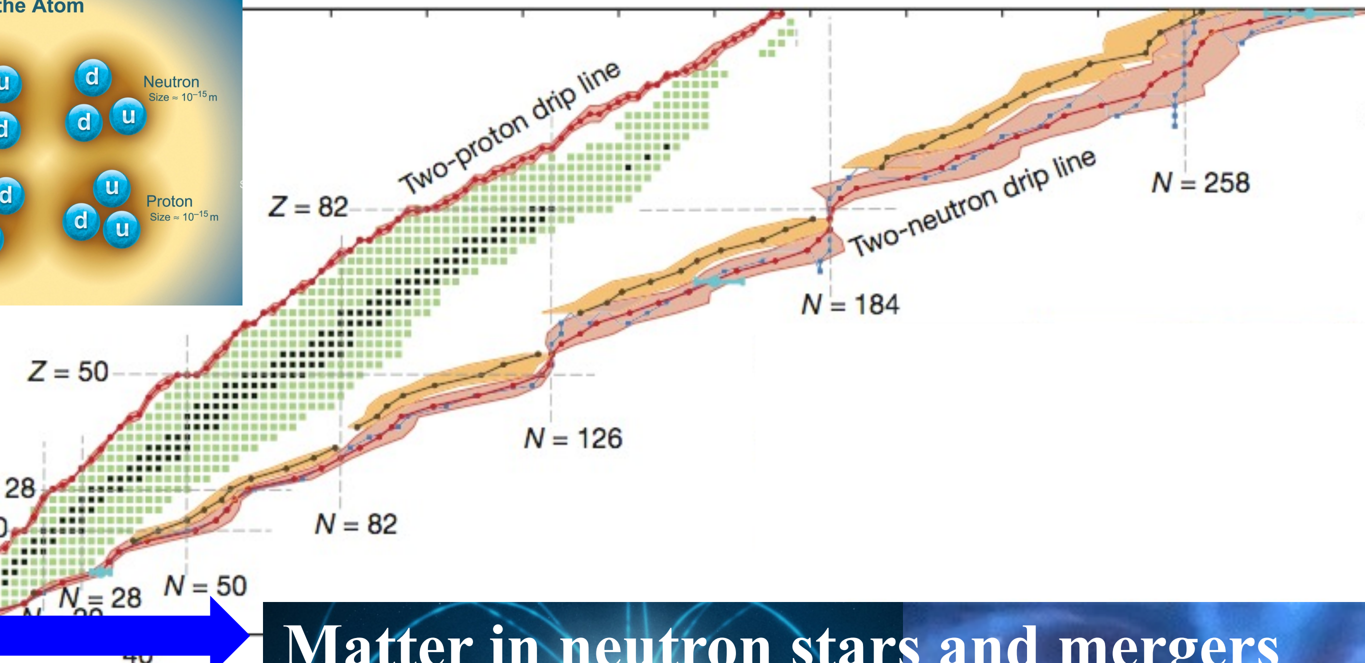


short gamma-ray burst + kilonova light curve: decay of r-process nuclei



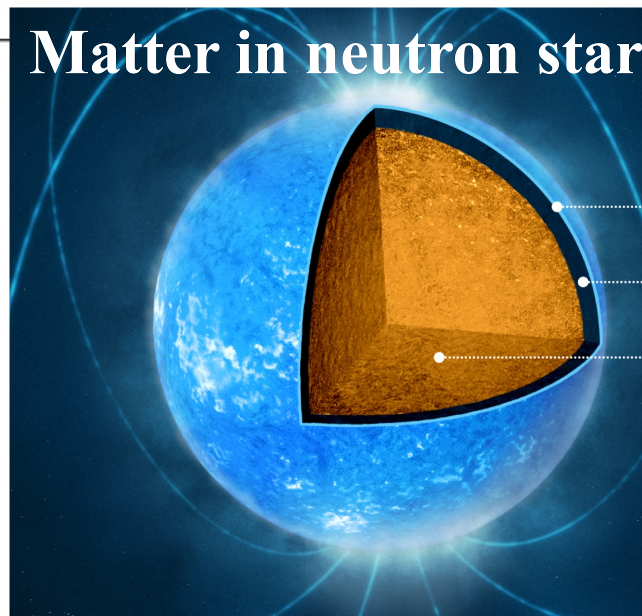






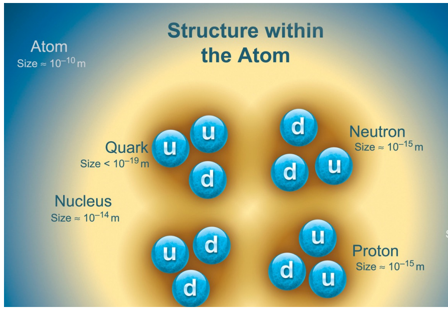
Neutrons

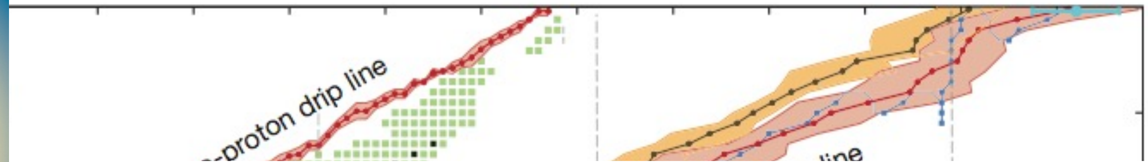
Matter in neutron stars and mergers



from Watts et al., RMP (2016)

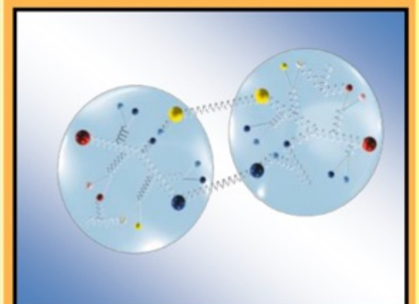
NASA/Goddard/LIGO/Virgo





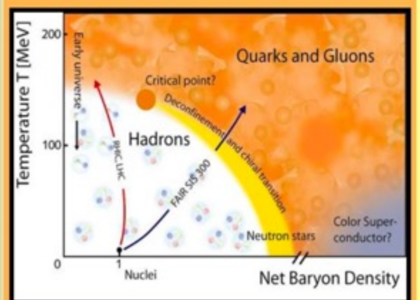
4 FAIR research pillars

PANDA



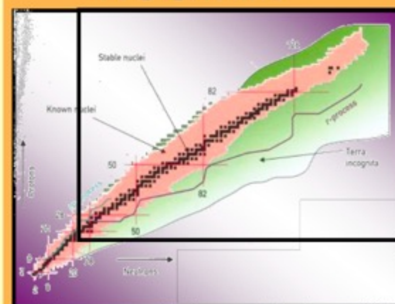
hadron structure and dynamics

C.B.M.



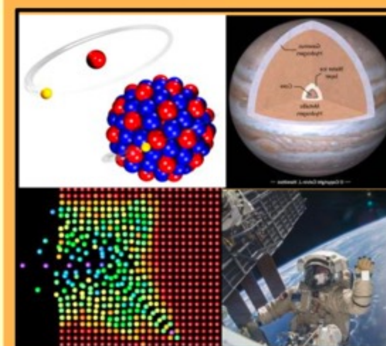
QCD phase structure and properties of QCD matter

NUSTAR

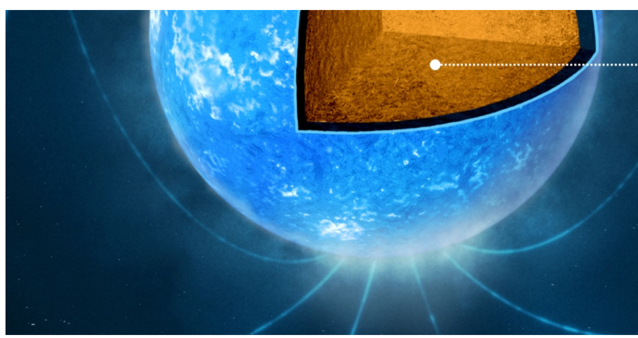


nuclear structure and nuclear astrophysics

APPA



atomic physics, plasma physics, materials science, biophysics

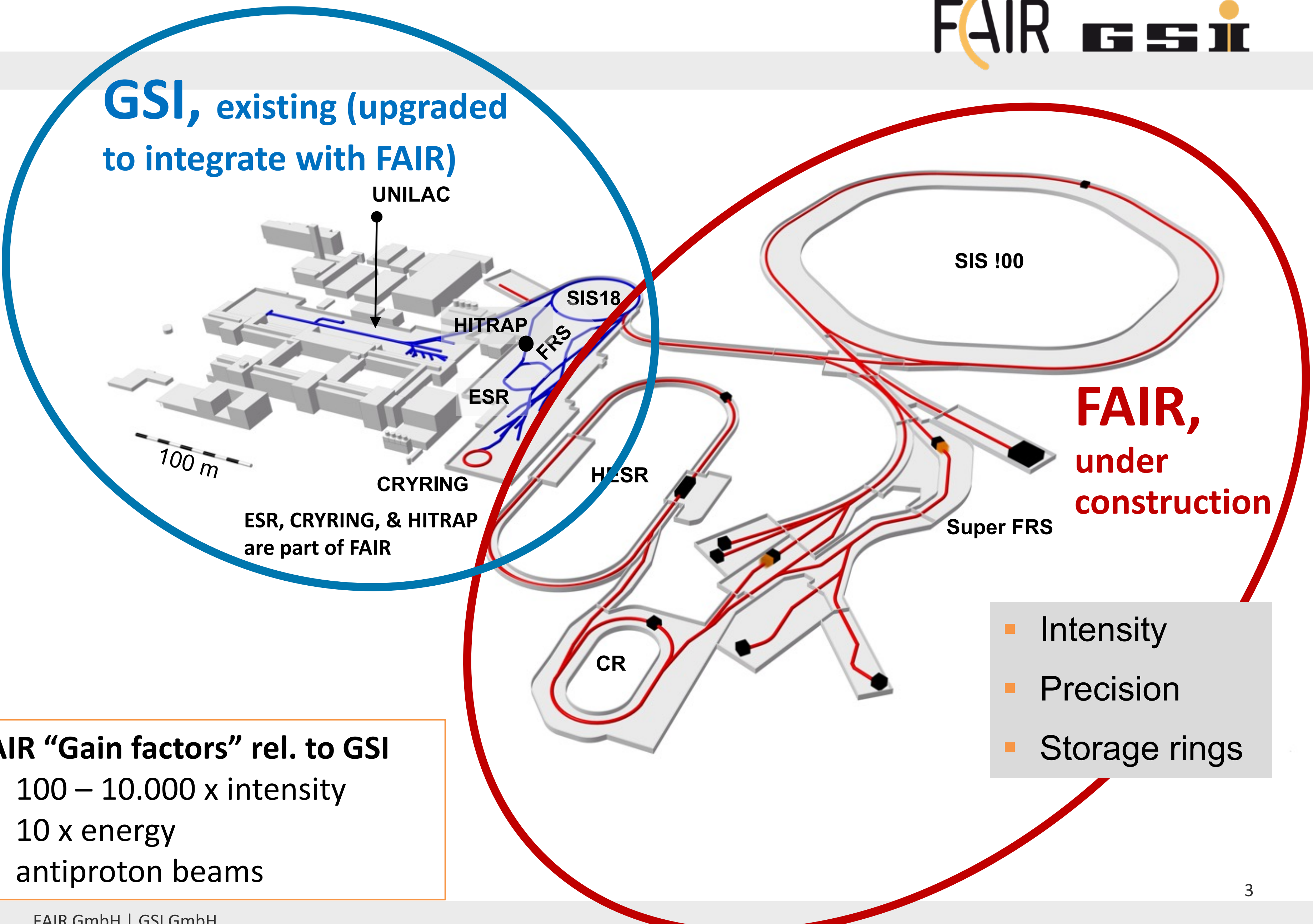


from Watts et al., RMP (2016)

NASA/Goddard/LIGO/Virgo

GSI and FAIR – The Facility

slides from Giubellino/Leifels @ 2021 KHuK meeting



- Intensity
- Precision
- Storage rings

FAIR “Gain factors” rel. to GSI

- 100 – 10.000 x intensity
- 10 x energy
- antiproton beams

2021 2022 2023 2024 2025 2026 2027 2028

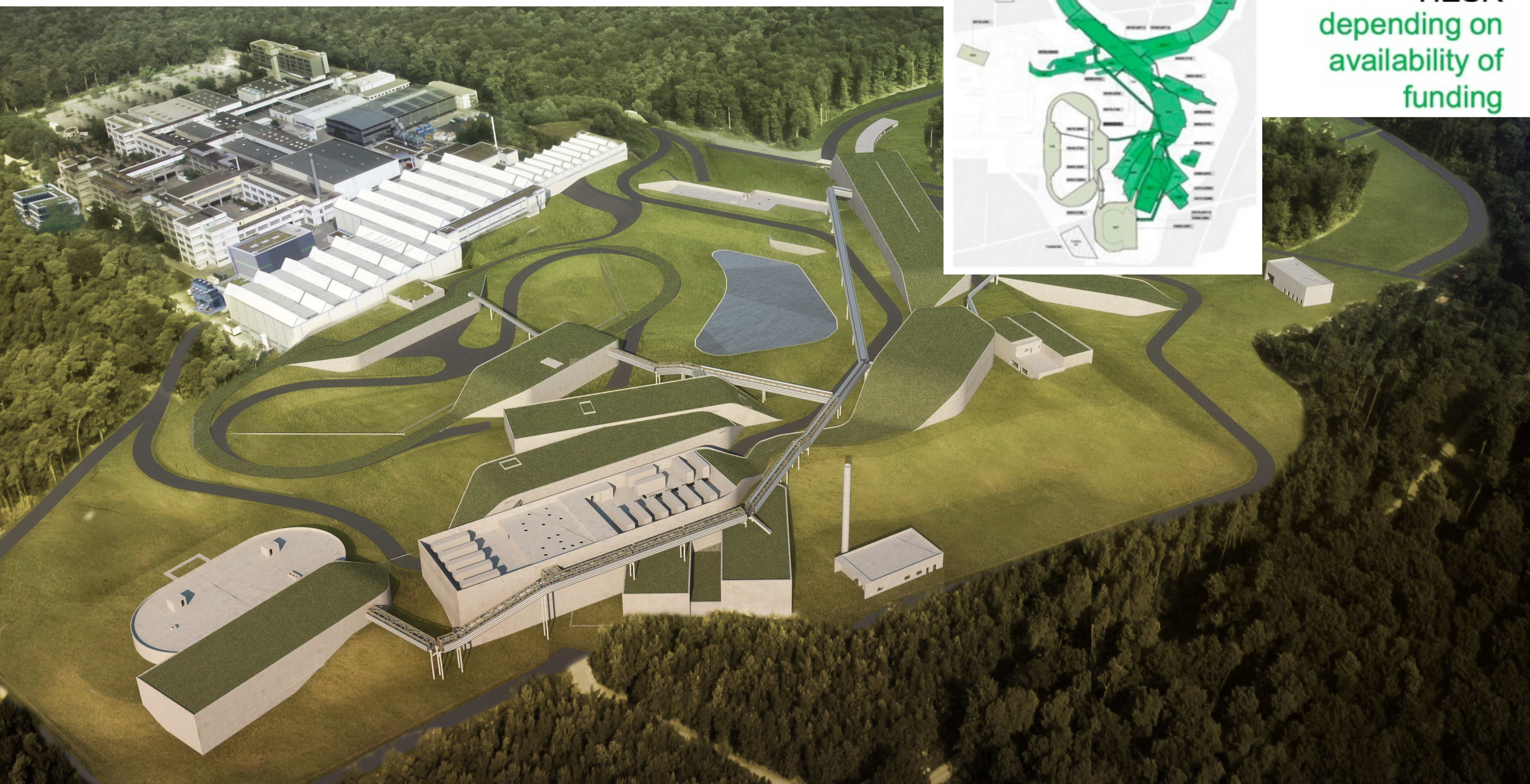
FAIR Phase-0 since 2019

FAIR Early Science SIS18 beam

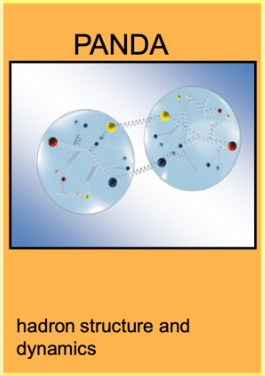
FAIR operation Intermediate objective

FAIR full operation MSV: p-linac, CR and HESR depending on availability of funding

Top priority for European Nuclear Physics Community

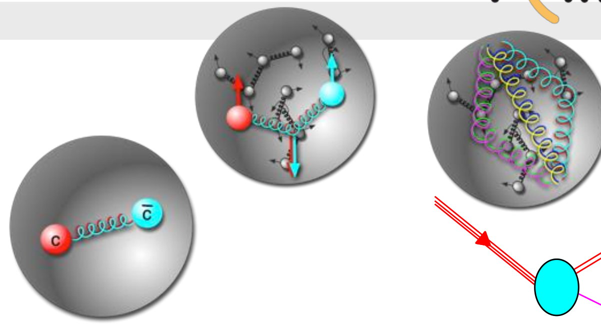


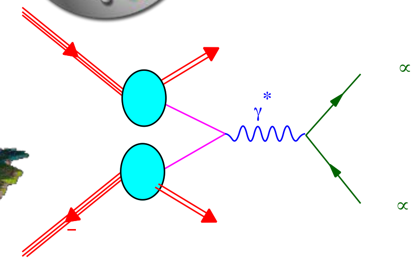

FAIR May 2022

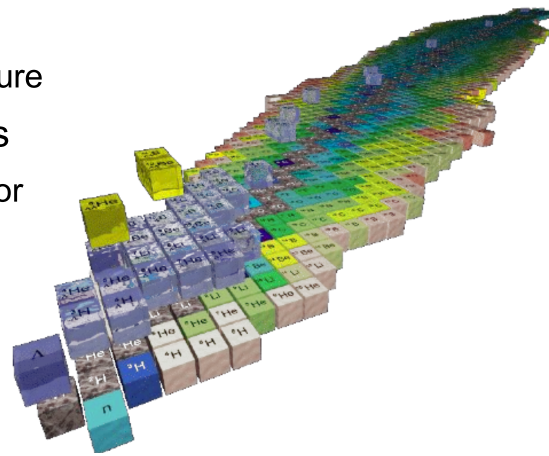


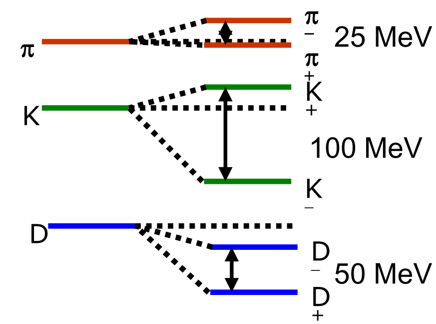
PANDA physics case

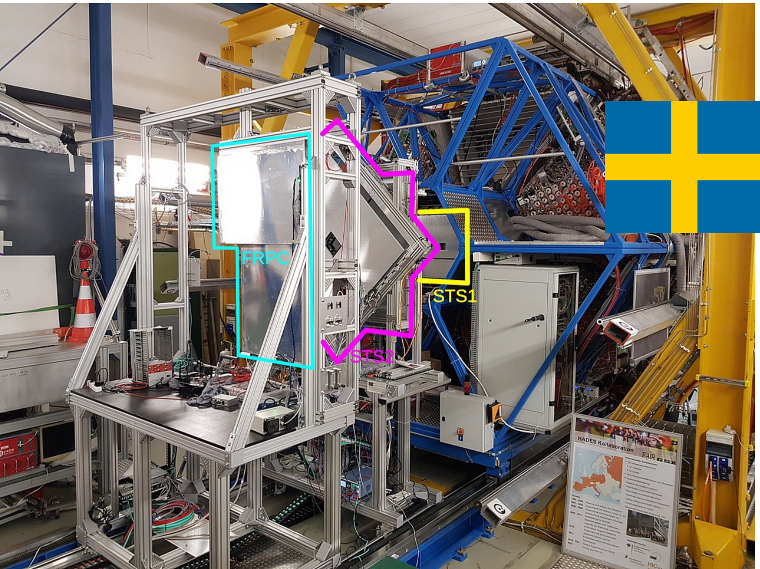
- Gluonic excitations
  - Hybrids, glueballs
- Charmonium states
  - Precision spectroscopy
- Time-like
  - Form factors, nucleon structure
- In medium mass modifications
  - Extension to the charm sector
- Extension of nuclear chart
  - Double hypernuclei
- And much more...





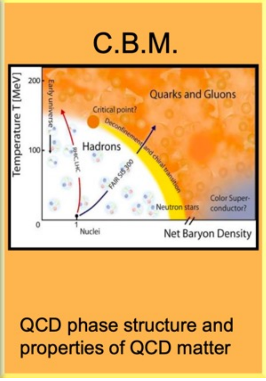






Strong involvement from Sweden (Lund, KTH, U Stockholm, Uppsala)

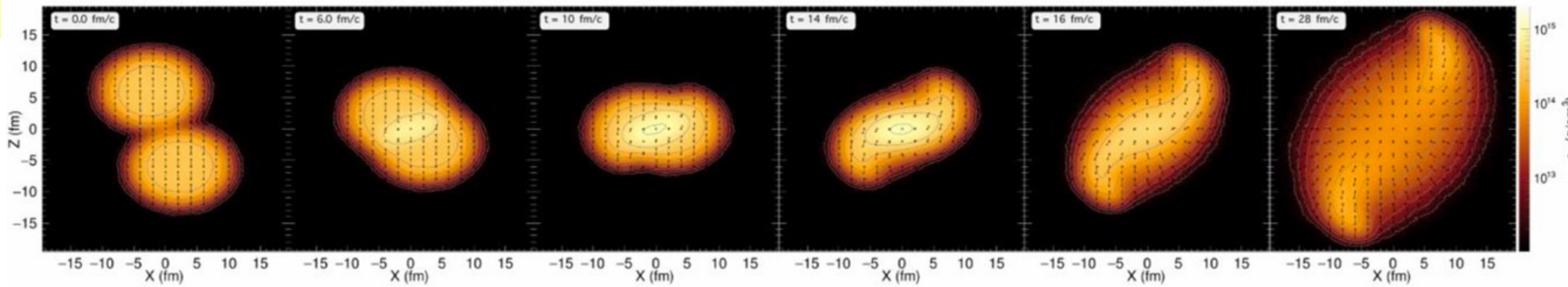
Production and decay of hyperons in HADES using PANDA technology:
4 week physics run in March 2022

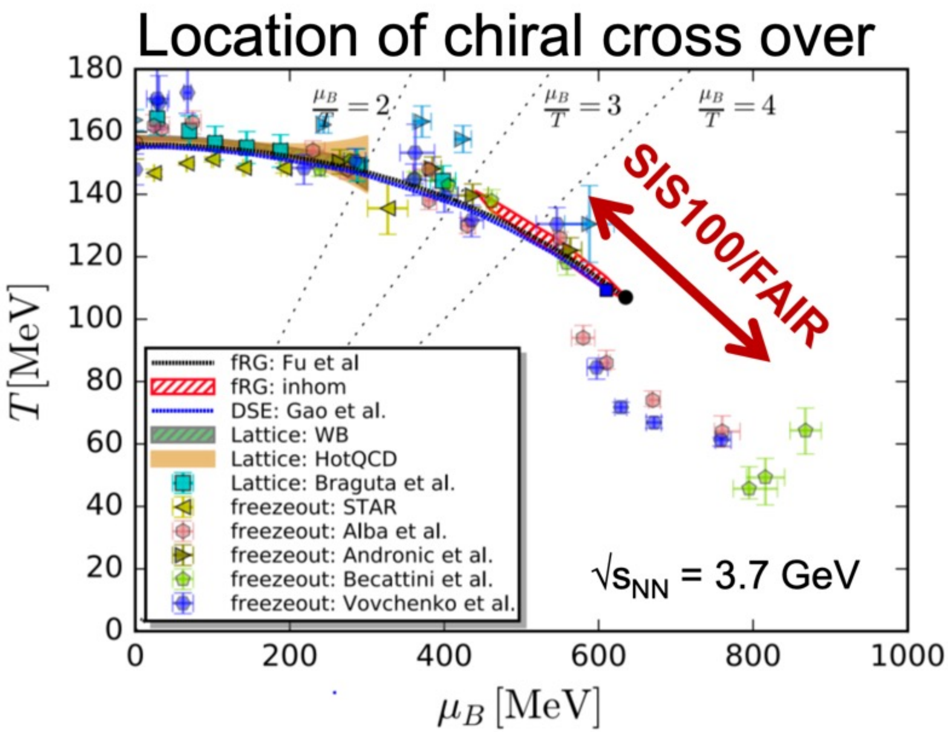


Compressed Baryonic Matter

heavy-ion collisions to create matter at high baryon densities

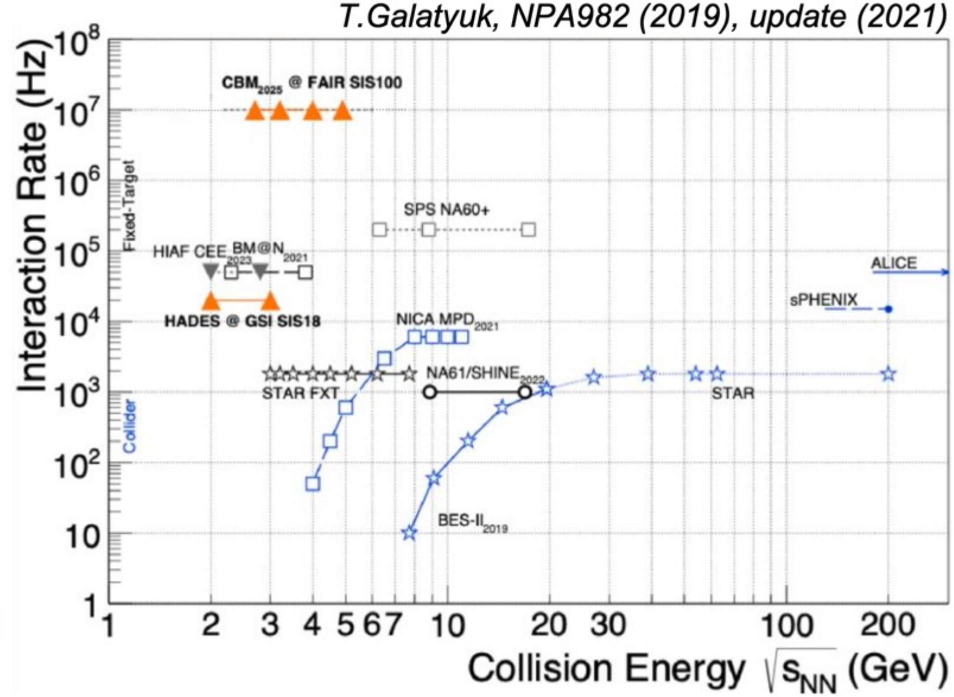
explore QCD phase diagram and properties of dense matter

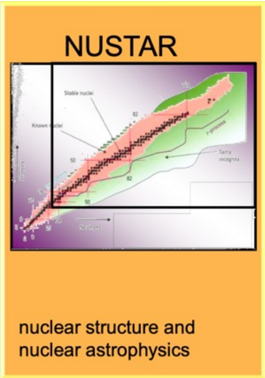




CBM Collaboration, EPJA 53 3 (2017) 60

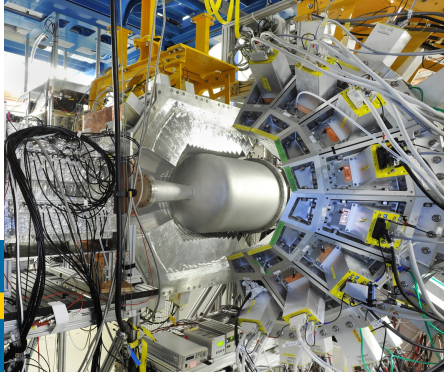
T.Galatyuk, NPA982 (2019), update (2021)





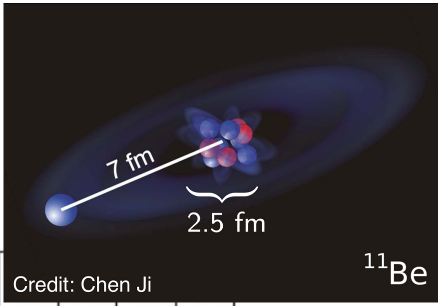
NUSTAR: reactions and halo nuclei

Strong involvement from Sweden in NUSTAR
(Chalmers, Lund, KTH, U Stockholm)

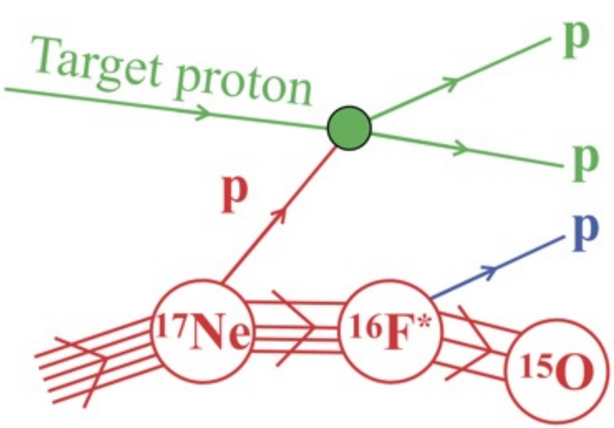


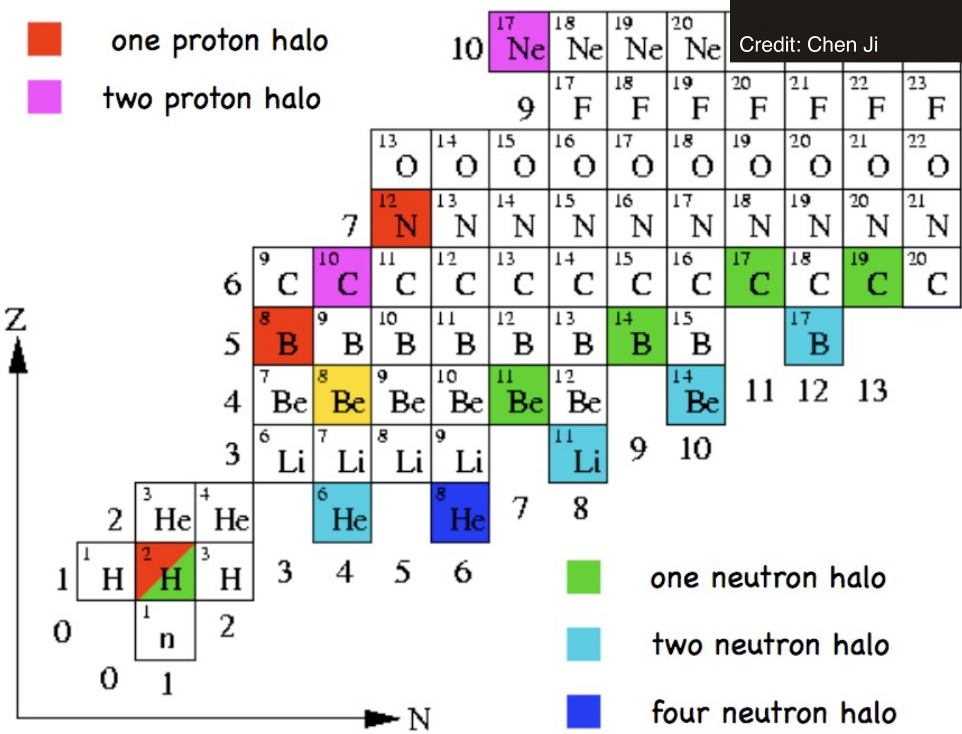
R3B with CALIFA

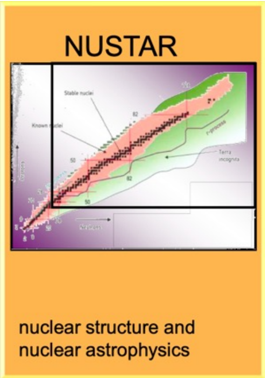
2n halos: ^{11}Li=^{9}Li+n+n,… in light nuclei
only known examples of Borromean states in nature



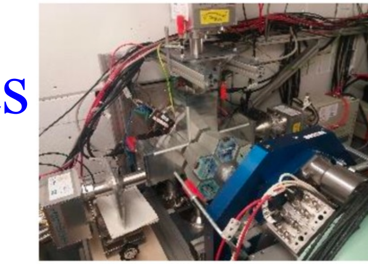
unveiling **two-proton halo-nucleus ^{17}Ne** using
proton knock-out reactions
Lehr et al., PLB (2022) (Chalmers)





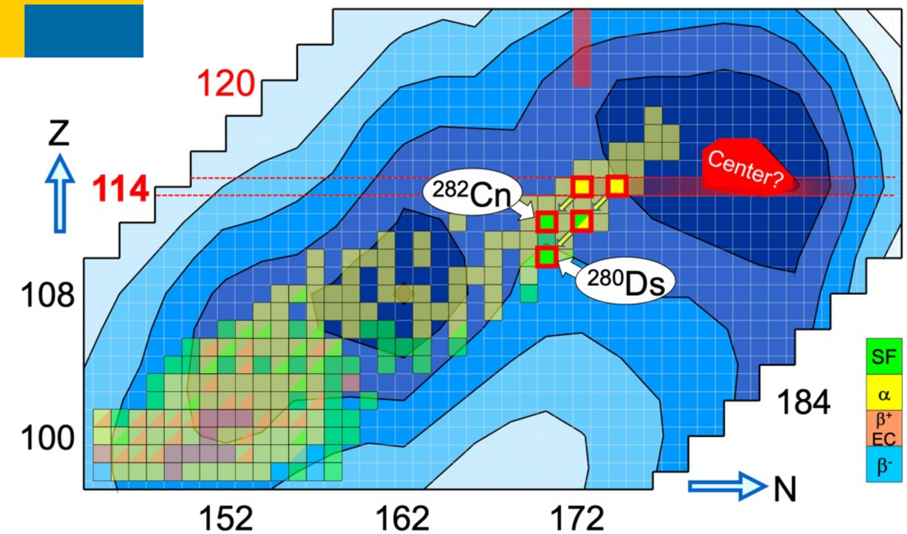


NUSTAR: heavy and superheavy elements


TASISpec+

high-resolution α-photon nuclear spectroscopy
of superheavy decay chains:
island of stability not at Z=114 Såmark-Roth et al., PRL (2021) (LUND)

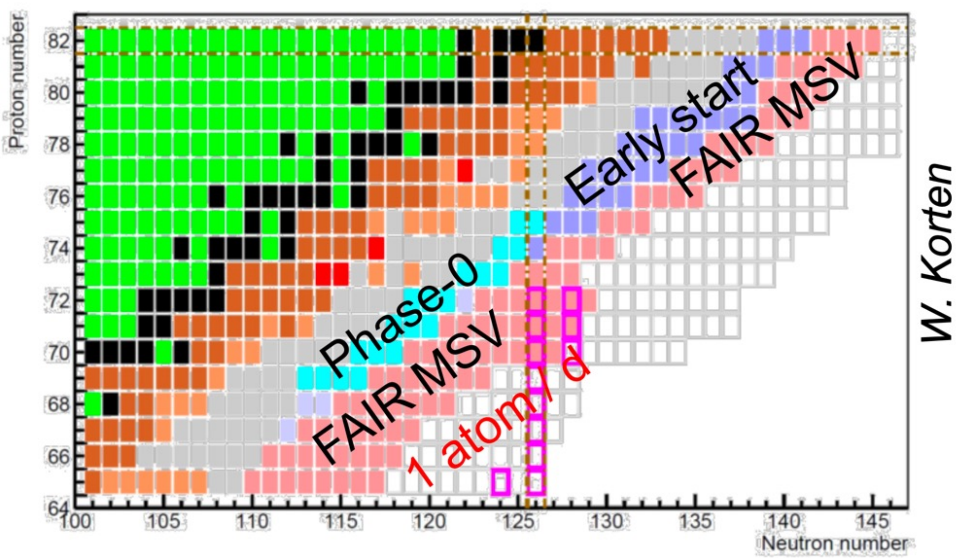
Chart of superheavy nuclei



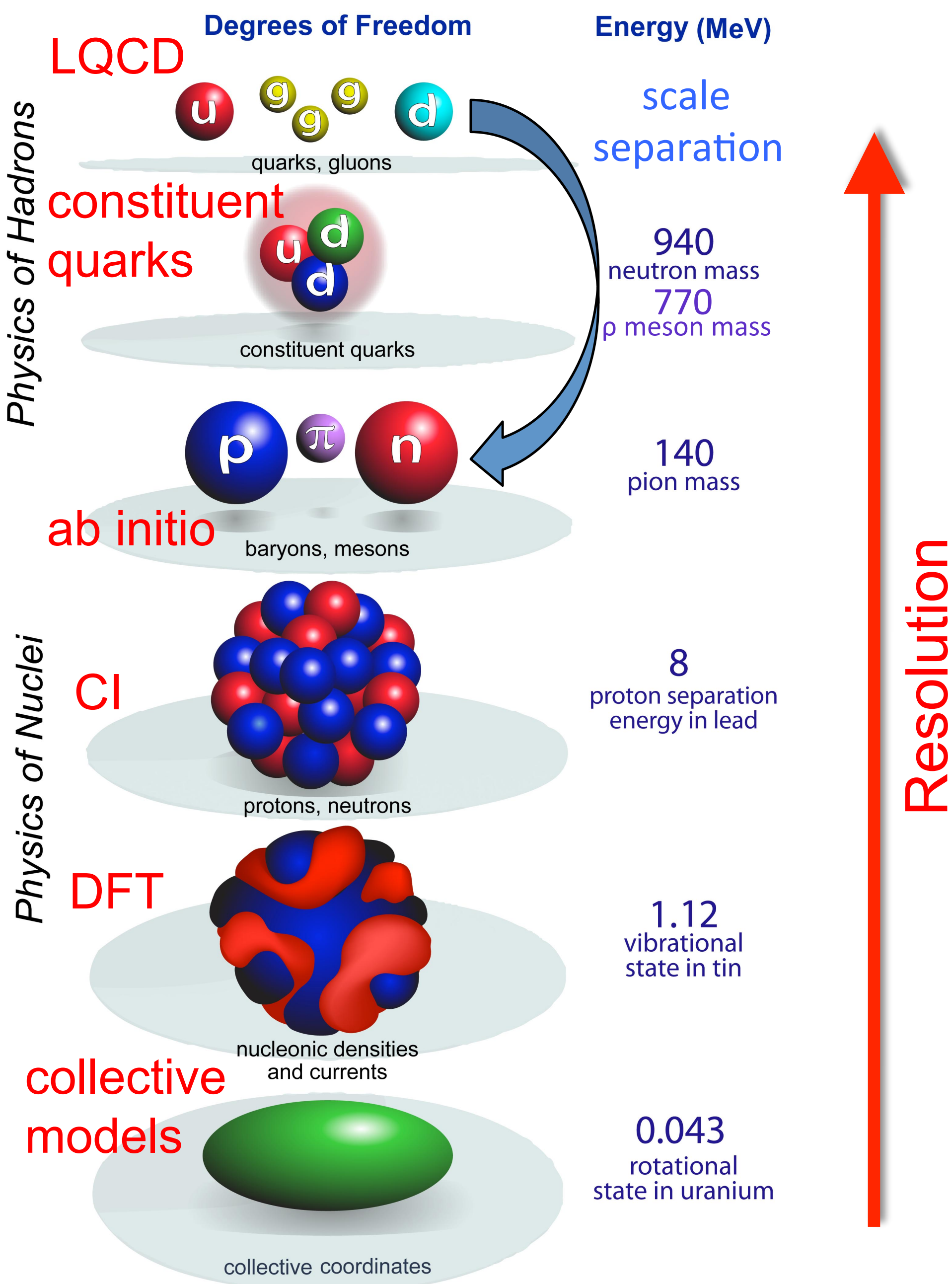
Calculated shell stabilization energy (Sobiczewski *et al.*)
Colored boxes: known nuclei

Future FAIR: heavy + neutron-rich

- towards the r-process waiting points at the **N=126 shell closure**



Hierarchy of degrees of freedom



Emergent phenomena:

Protons and neutrons from QCD

Nuclear forces

Nuclear structure

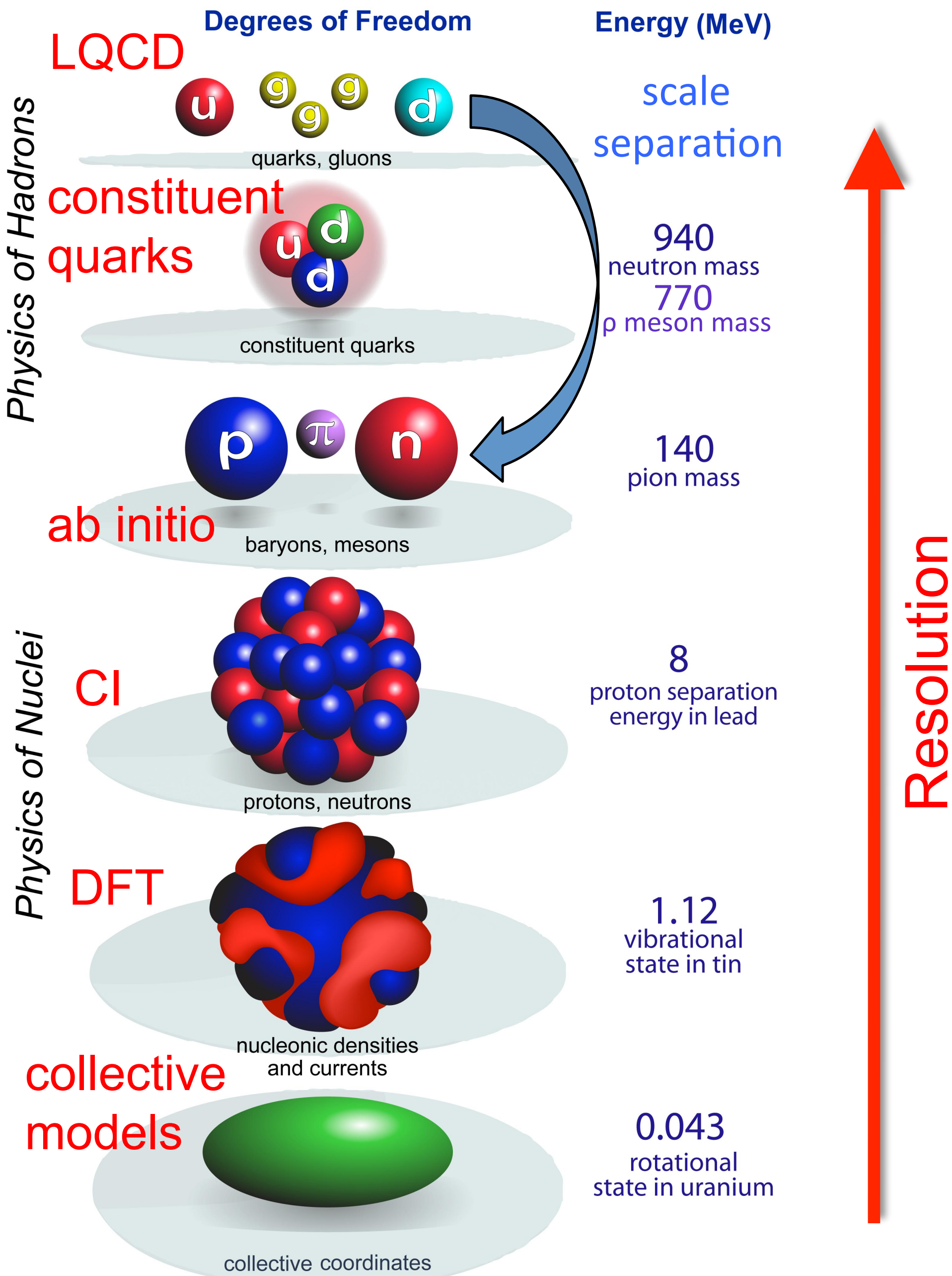
Large scattering length (universal) physics

…

Can we describe these phenomena quantitatively with theoretical uncertainties?

Can we connect each level in the tower back to QCD?

Hierarchy of degrees of freedom



Tower of effective field theories

Chiral EFT: nucleons, pions

Pionless EFT: nucleons only (low-energy few-body) or nucleons + clusters (halo EFT)

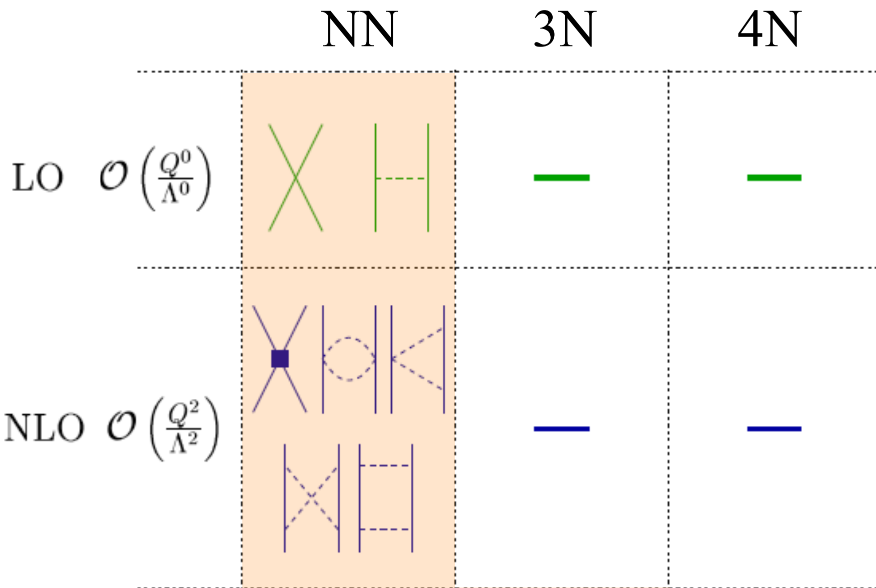
EFT for heavy nuclei: collective degrees of freedom

EFT at Fermi surface: Fermi liquid theory, superconductivity

EFT for nuclear DFT? densities as degrees of freedom

Chiral effective field theory for nuclear forces

Systematic expansion (power counting) in low momenta $(Q/\Lambda_b)^n$



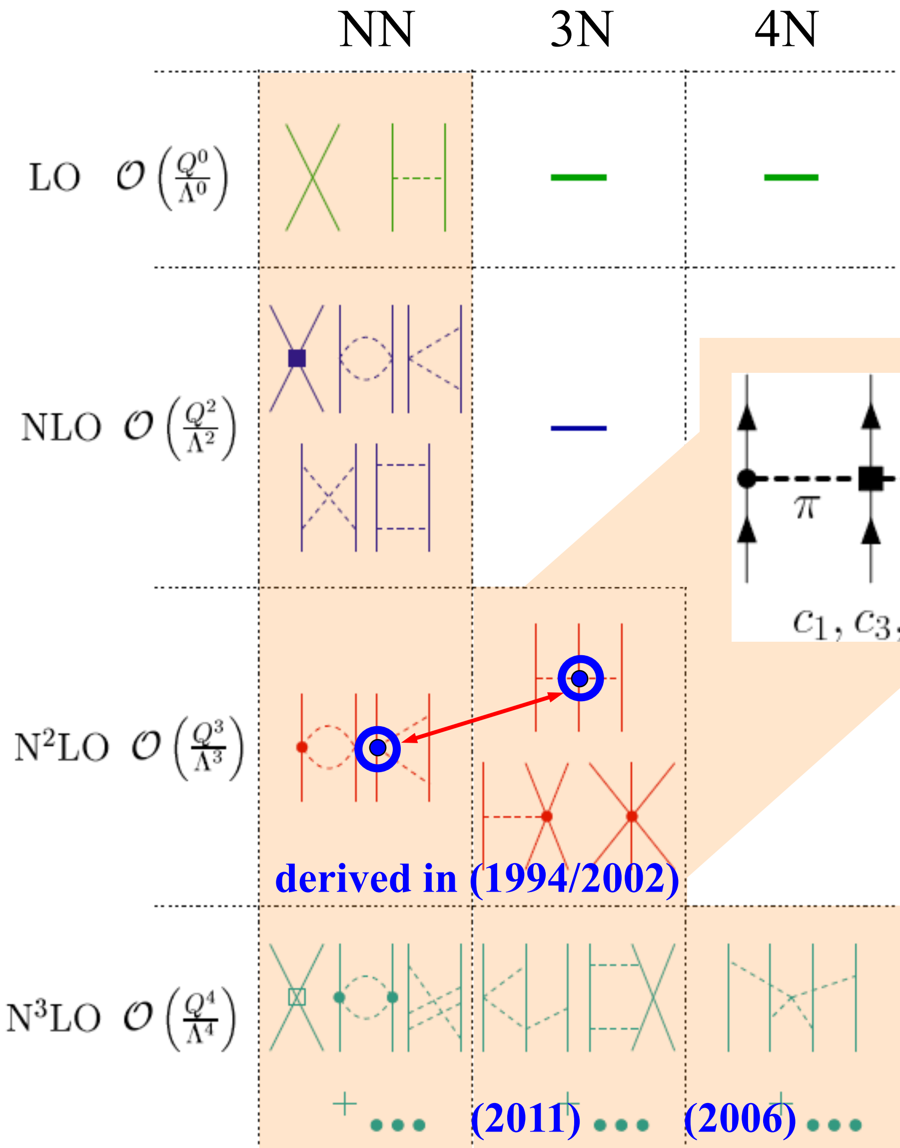
based on symmetries of strong interaction (QCD)

long-range interactions governed by pion exchanges

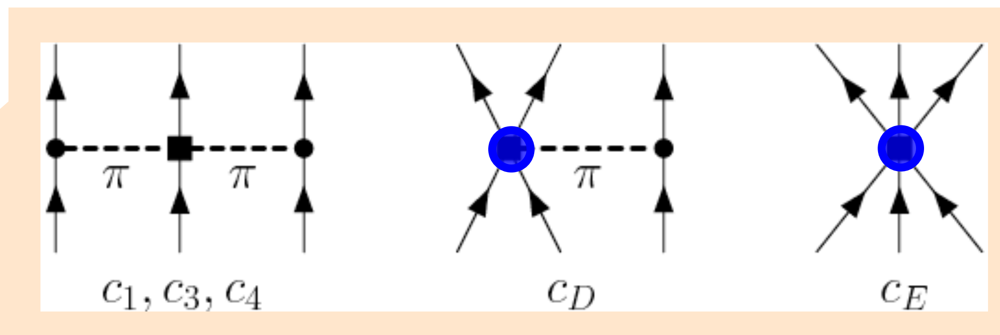
Weinberg (1990,91)

Chiral effective field theory for nuclear forces

Systematic expansion (power counting) in low momenta $(Q/\Lambda_b)^n$



powerful approach for
many-body interactions



only 2 new couplings at N^{2}LO

all 3- and 4-neutron forces
predicted to N^{3}LO

Weinberg, van Kolck (1992-1994), Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Meissner,…

Chiral effective field theory for nuclear forces

Systematic expansion (power counting) in low momenta $(Q/\Lambda_b)^n$

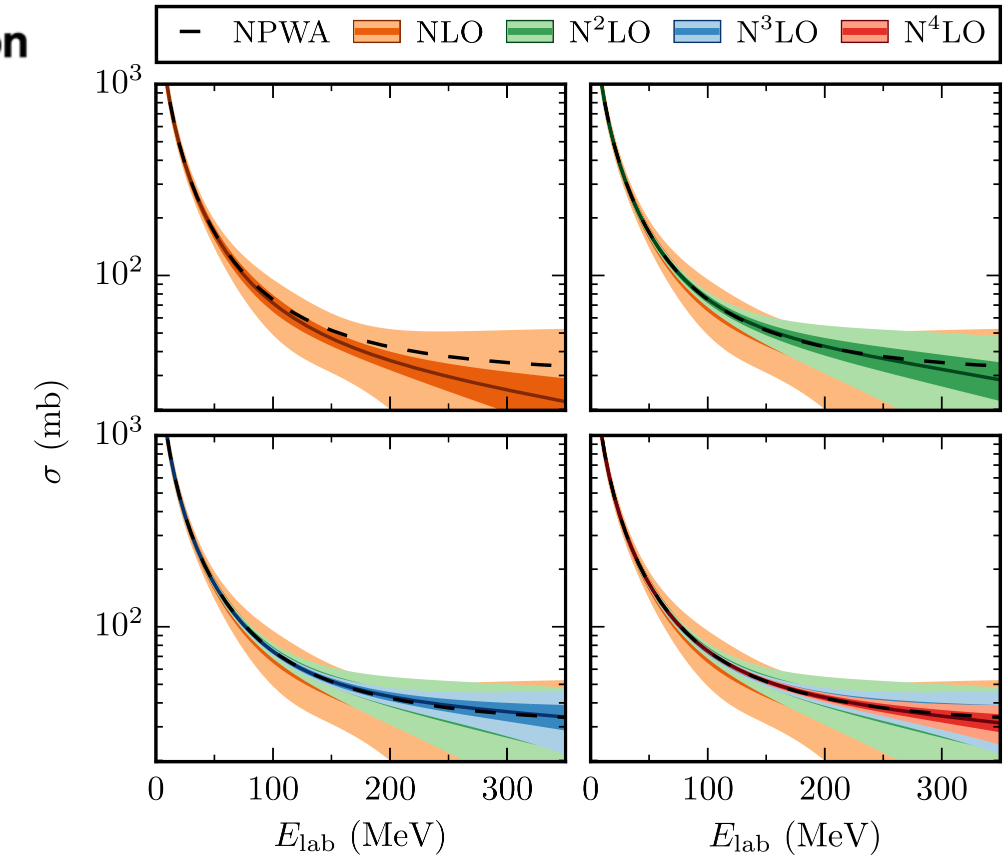
IOP Publishing   Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **42** (2015) 034028 (20pp)   doi:10.1088/0954-3899/42/3/034028

A recipe for EFT uncertainty quantification in nuclear physics

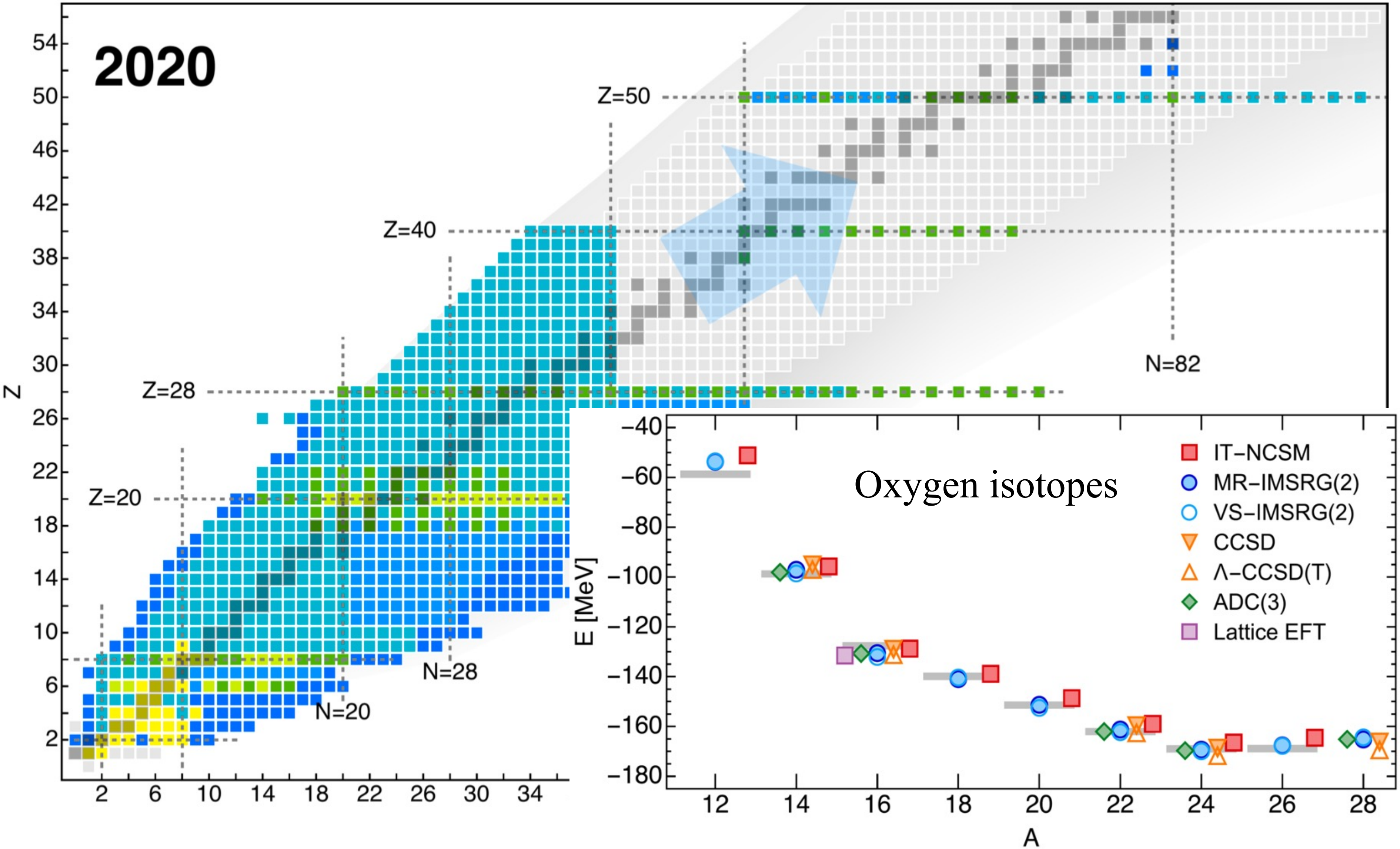
R J Furnstahl[1], D R Phillips[2] and S Wesolowski[1]

Bayesian uncertainty estimates and model checking



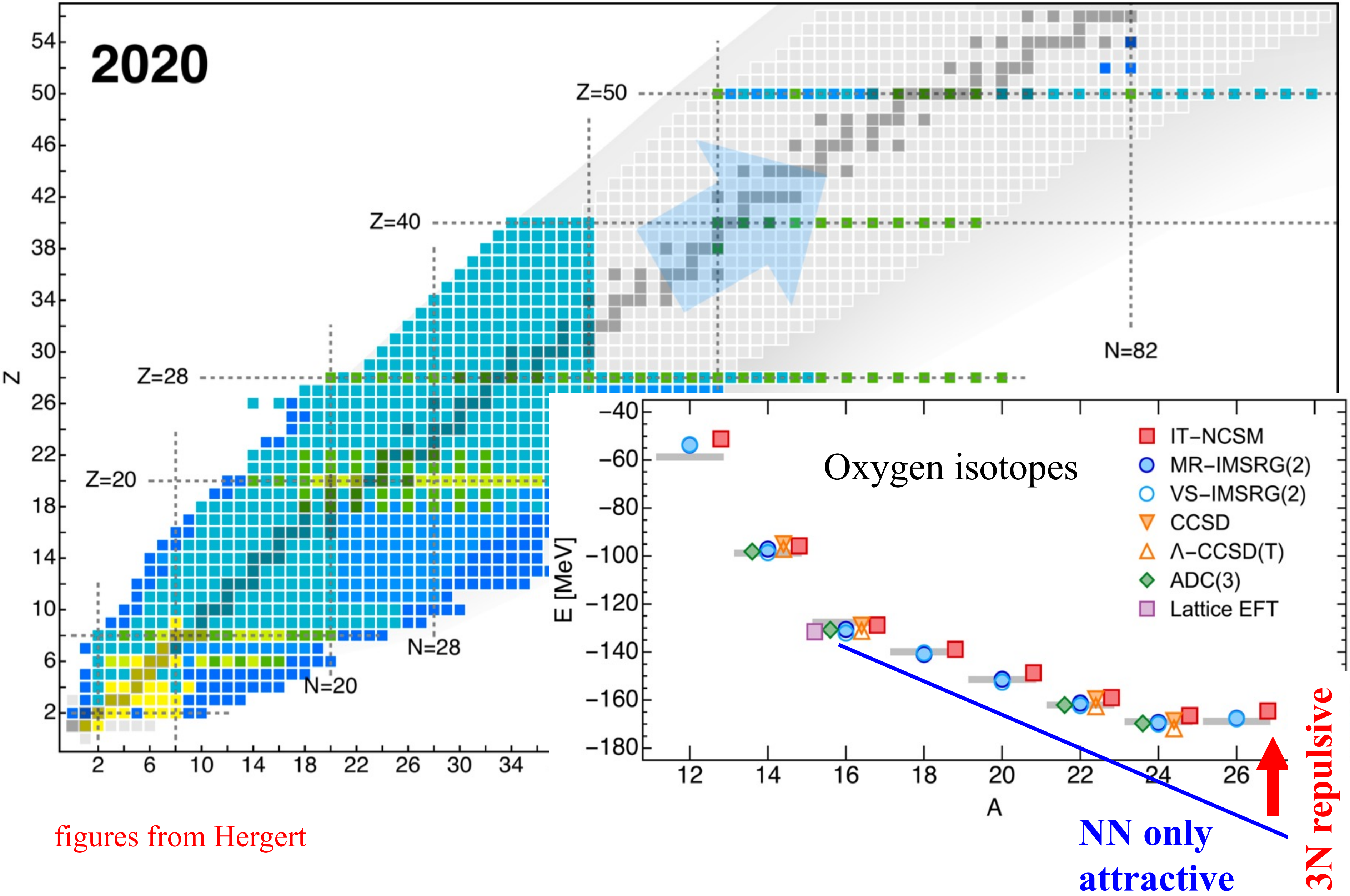
Furnstahl, Phillips, Klos, Wesolowski, Melendez (2015-)

Great progress in ab initio calculations of nuclei



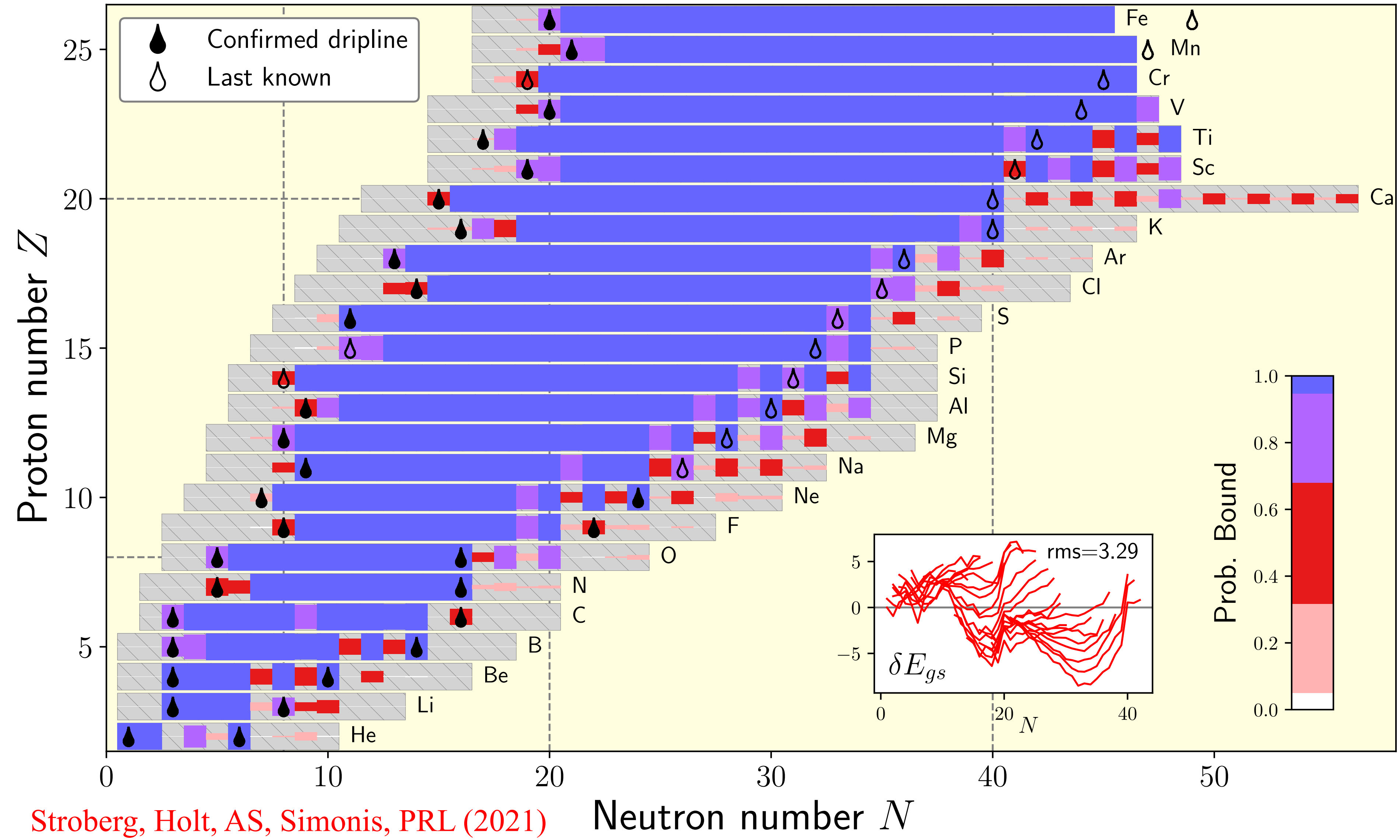
figures from Hergert

Great progress in ab initio calculations of nuclei



figures from Hergert

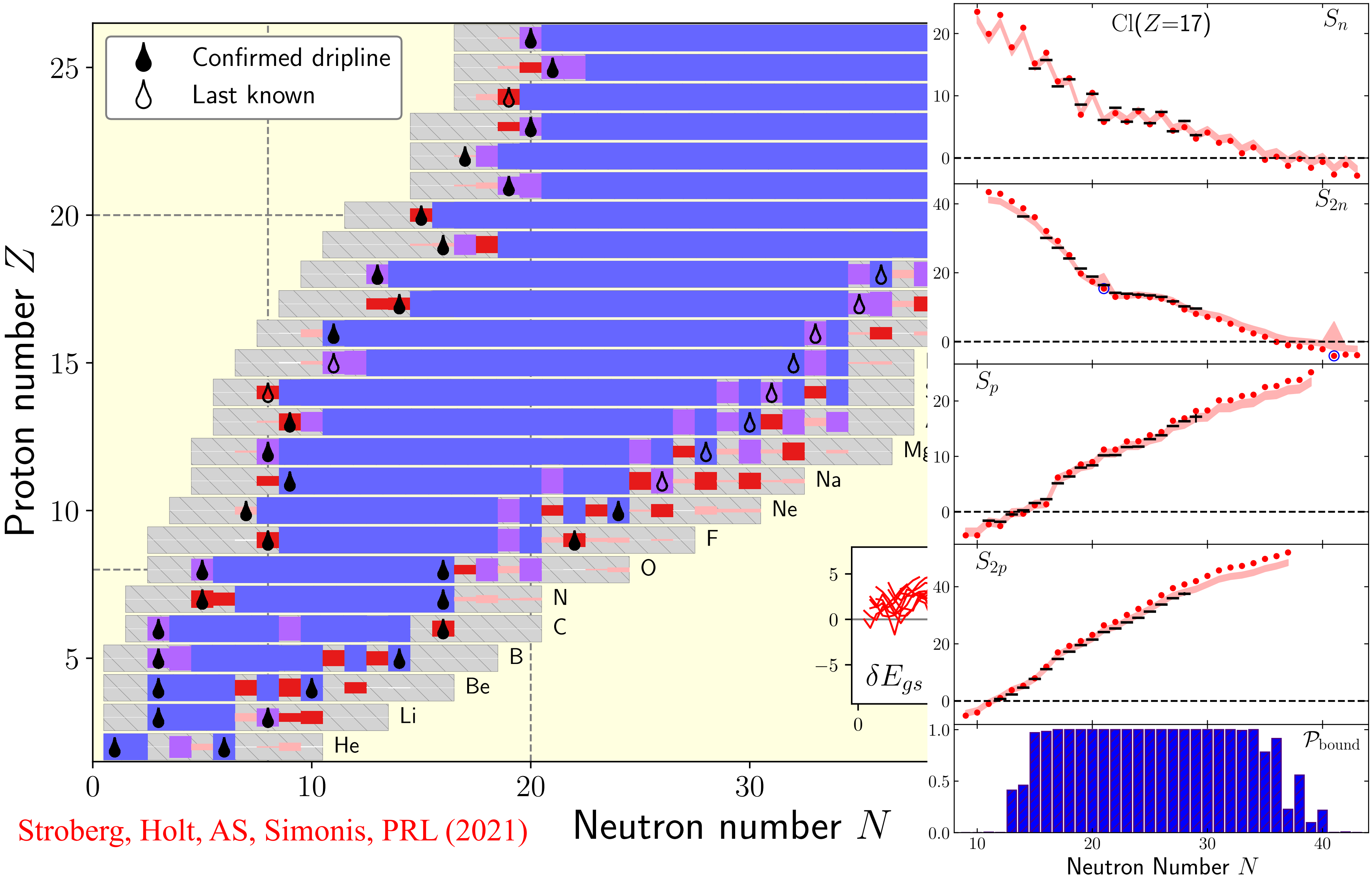
Nuclear landscape based on a chiral NN+3N interaction



Stroberg, Holt, AS, Simonis, PRL (2021)

ab initio is advancing to global theories, limitations due to input NN+3N

Nuclear landscape based on a chiral NN+3N interaction



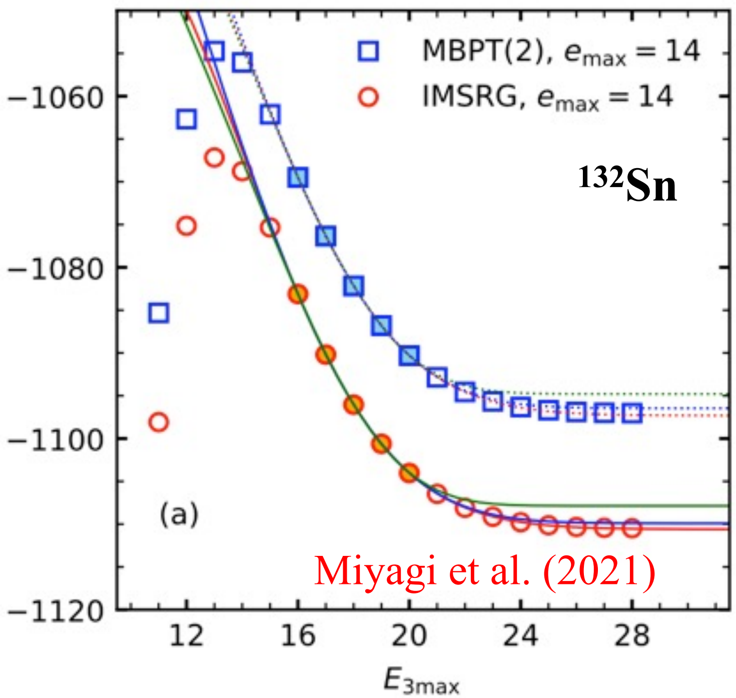
Stroberg, Holt, AS, Simonis, PRL (2021)

ab initio is advancing to global theories, limitations due to input NN+3N

First ab initio calculations of ^{208}Pb

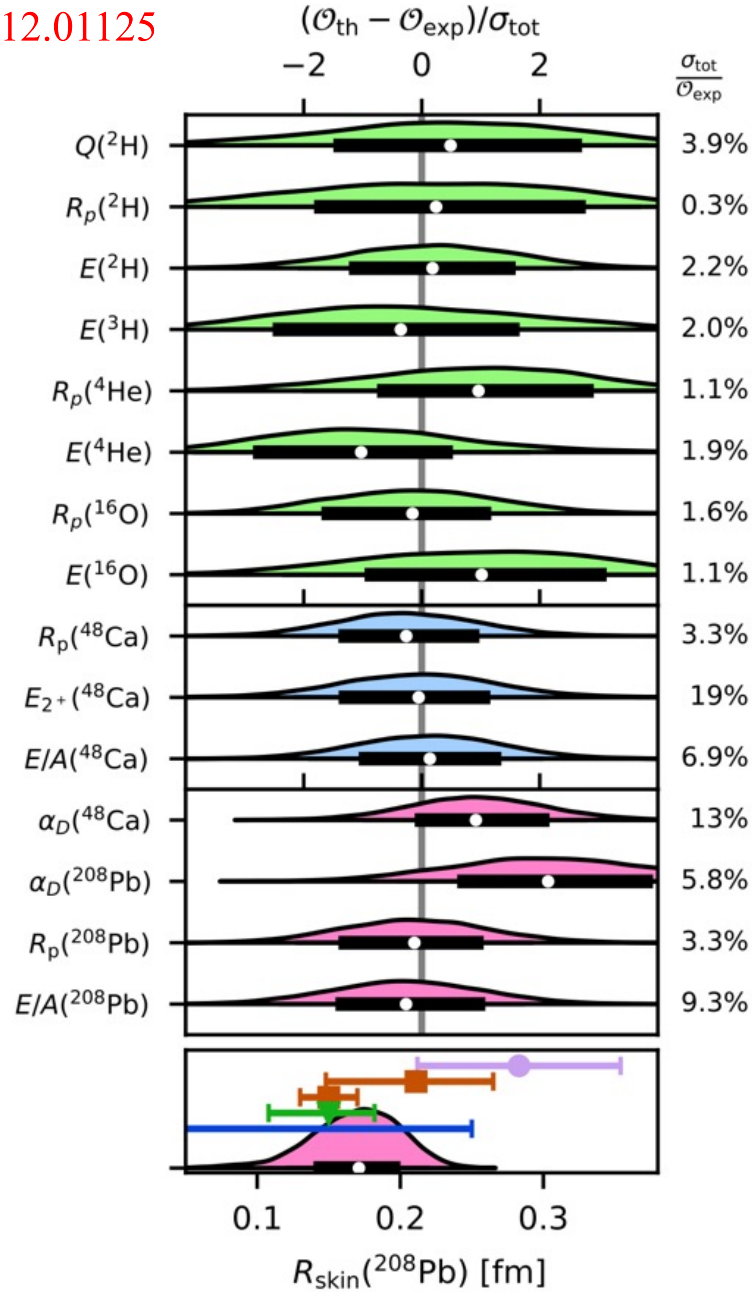
Hu, Jiang, Miyagi et al. [Chalmers, ORNL, TRIUMF], arXiv:2112.01125

enabled by 3N advances



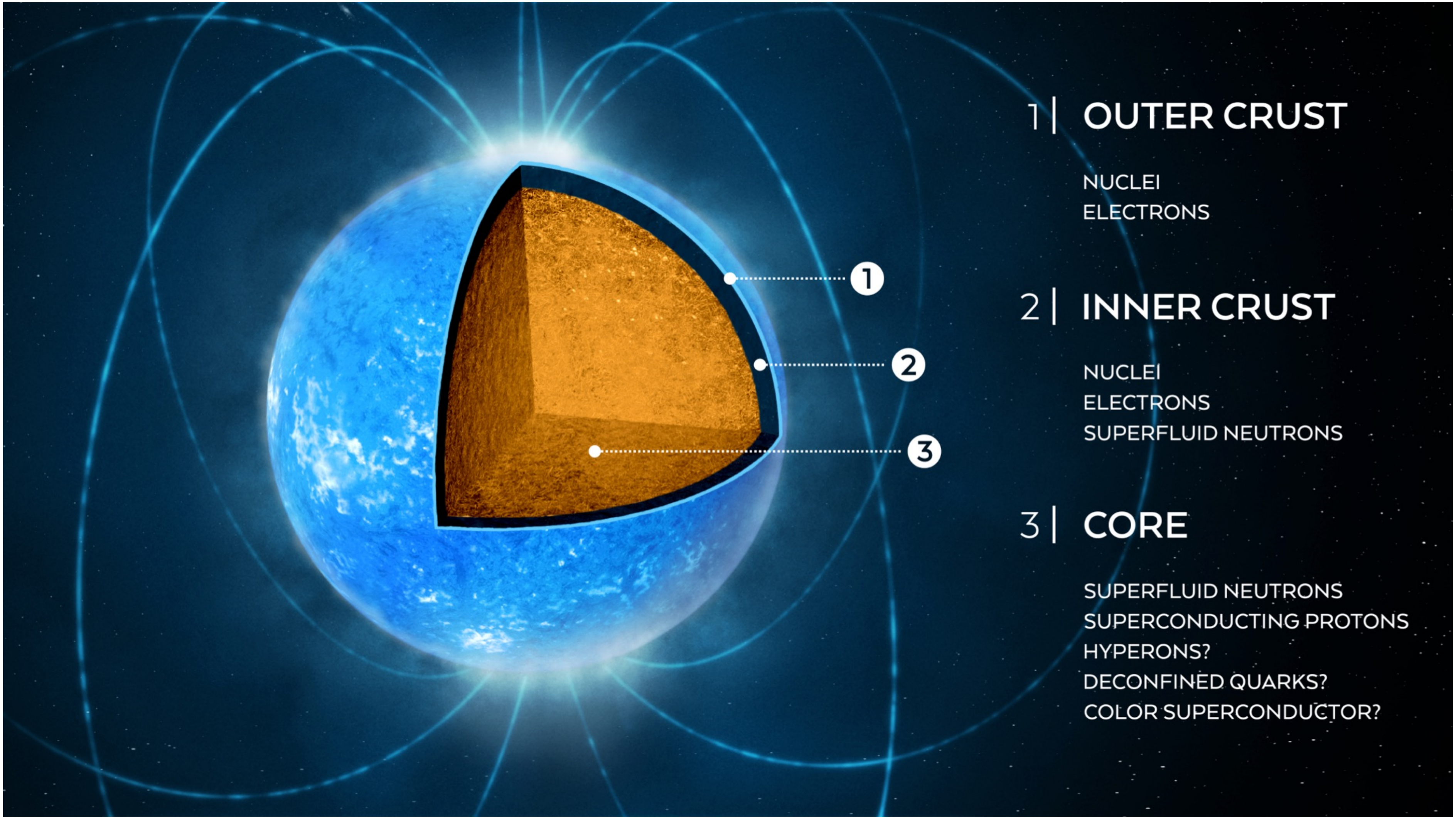
statistical methods via history matching
to explore uncertainties in NN+3N

predicted **neutron skin of ^{208}Pb**
agrees with most experiments!



Extreme matter in neutron stars

governed by the same strong interactions

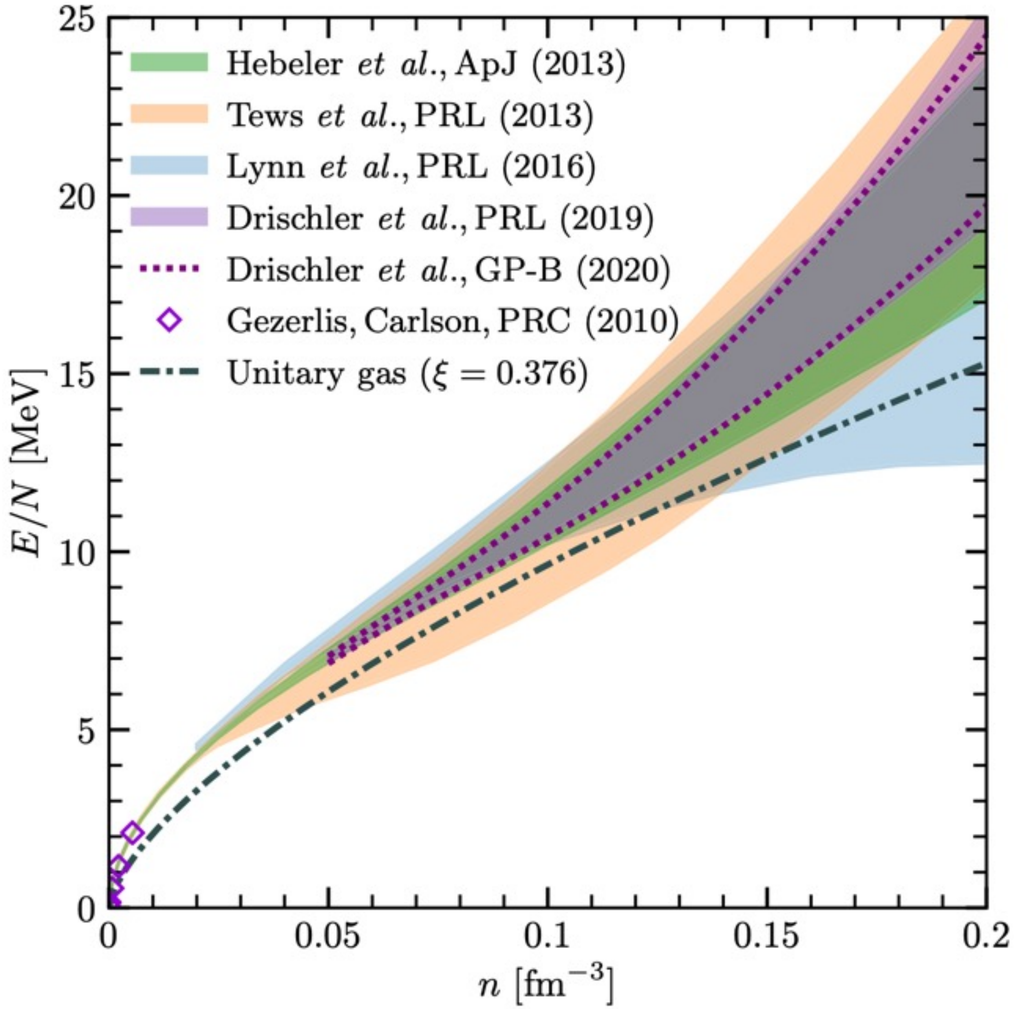


Watts et al., RMP (2016)

Chiral EFT calculations of neutron matter

good agreement up to saturation density for neutron matter

different NN+3N interactions and different many-body methods

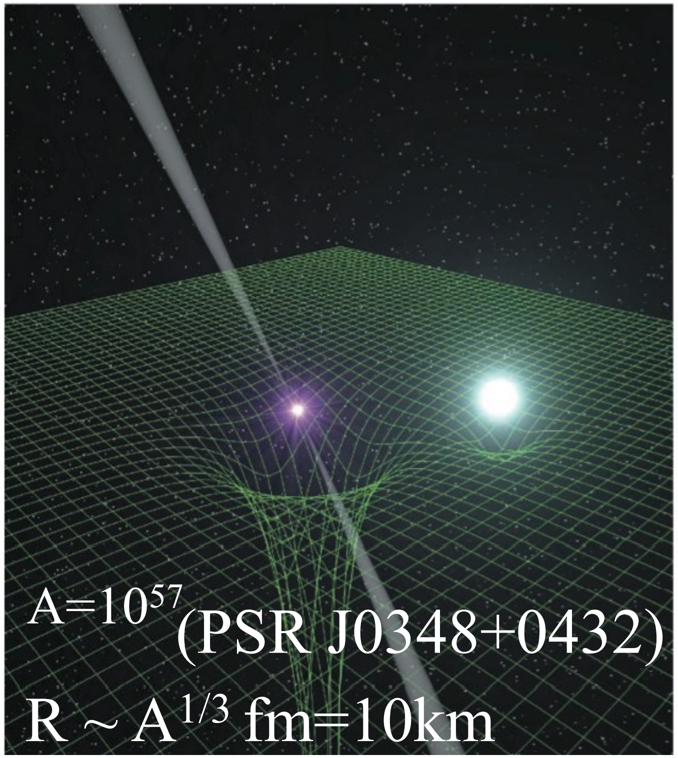


slope determines pressure of neutron matter

from Huth, Wellenhofer, AS, PRC (2020)

Neutron star masses

from Jim Lattimer

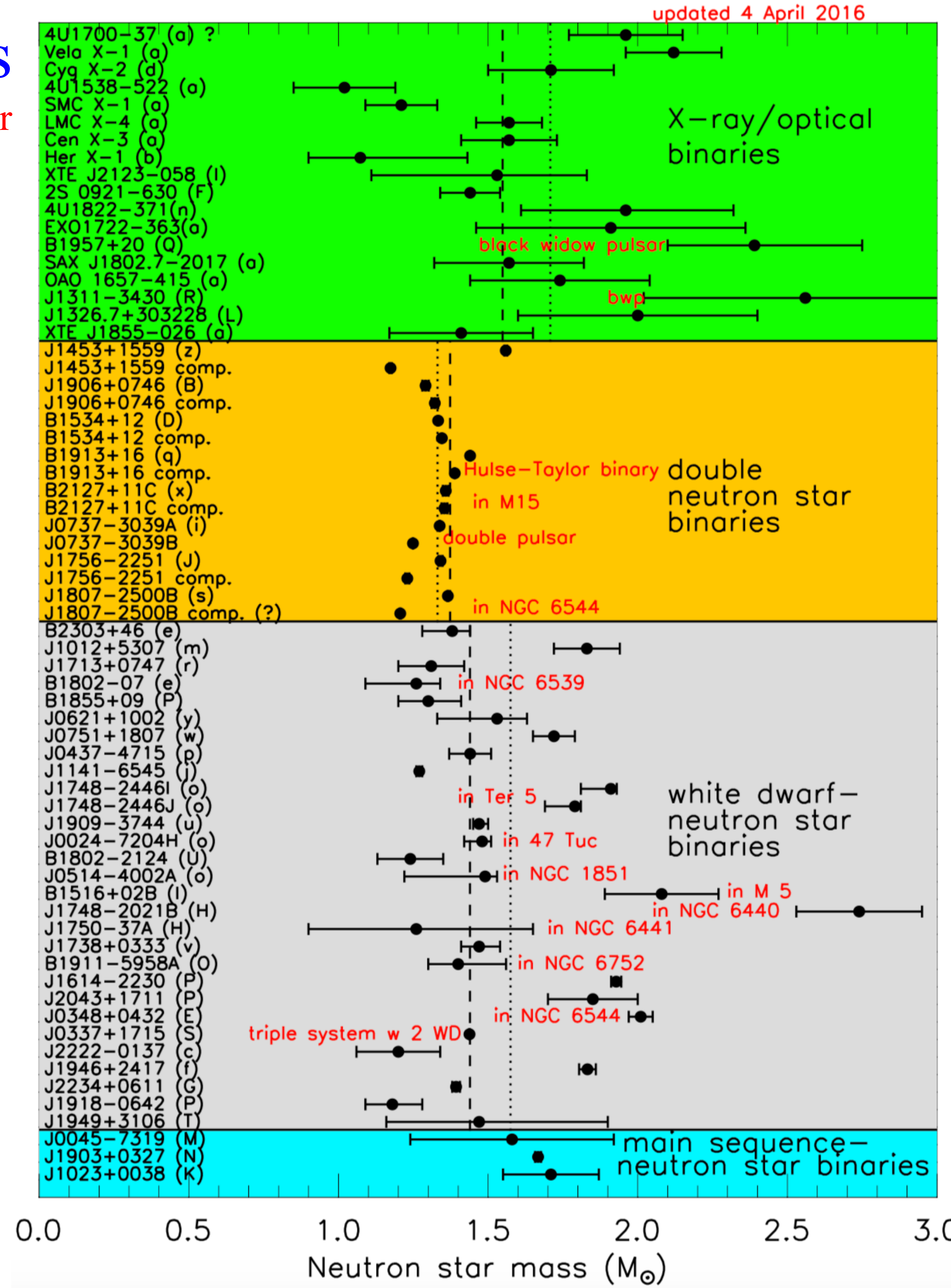


three 2 M_{sun} neutron stars obs.

Demorest et al, Nature (2010),

Antoniadis et al., Science (2013),

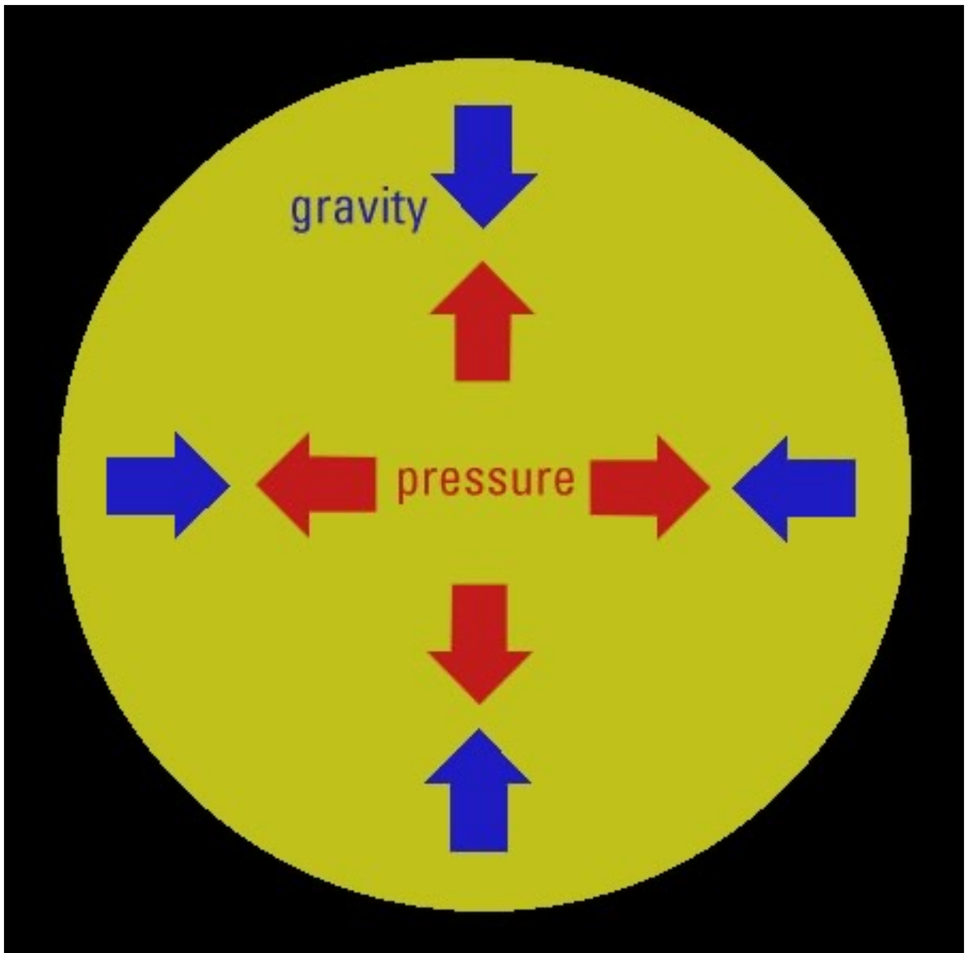
2.08±0.07 M_{sun} Fonseca et al. (2021)



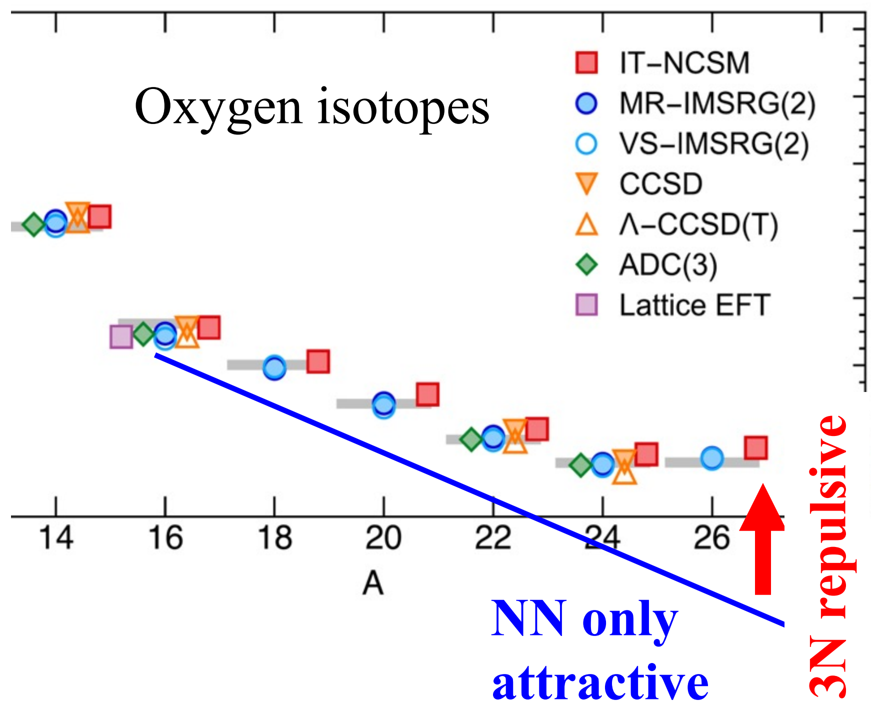
Why are neutron stars stable?

due to their mass, stars would undergo gravitational collapse

stabilized by the pressure of matter they consist of:
equation of state → hydrostatic equilibrium

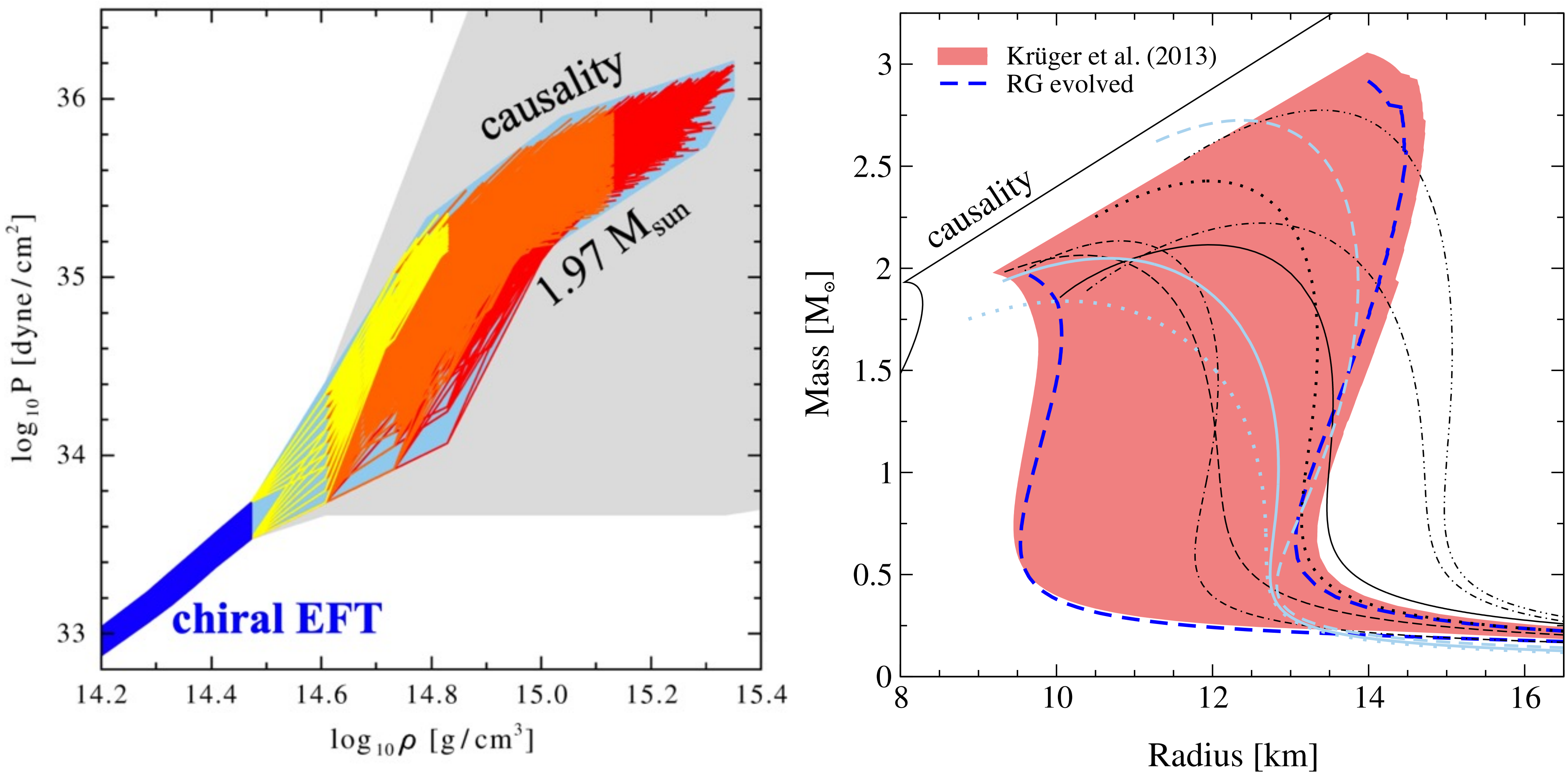


For neutrons:
pressure of Fermi gas
plus strong interactions



Impact on neutron stars Hebeler, Lattimer, Pethick, AS, PRL (2010), ApJ (2013)

constrain high-density EOS by causality, require to support 2 M_{sun} star



predicts neutron star radius: 9.7 - 13.9 km for M=1.4 M_{sun}

1.8 - 4.4 n_0 modest central densities

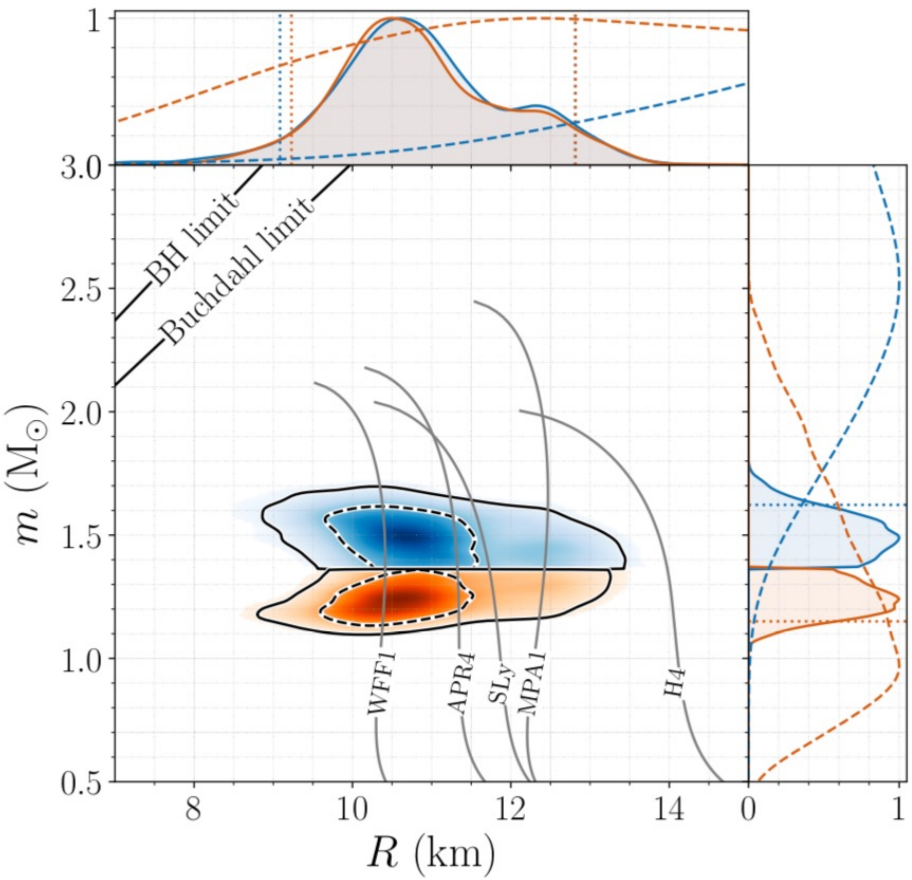
speed of sound needs to exceed 1/3 c^2 to get 2 M_{sun} stars Greif et al., ApJ (2020)

Neutron star radius from GW170817

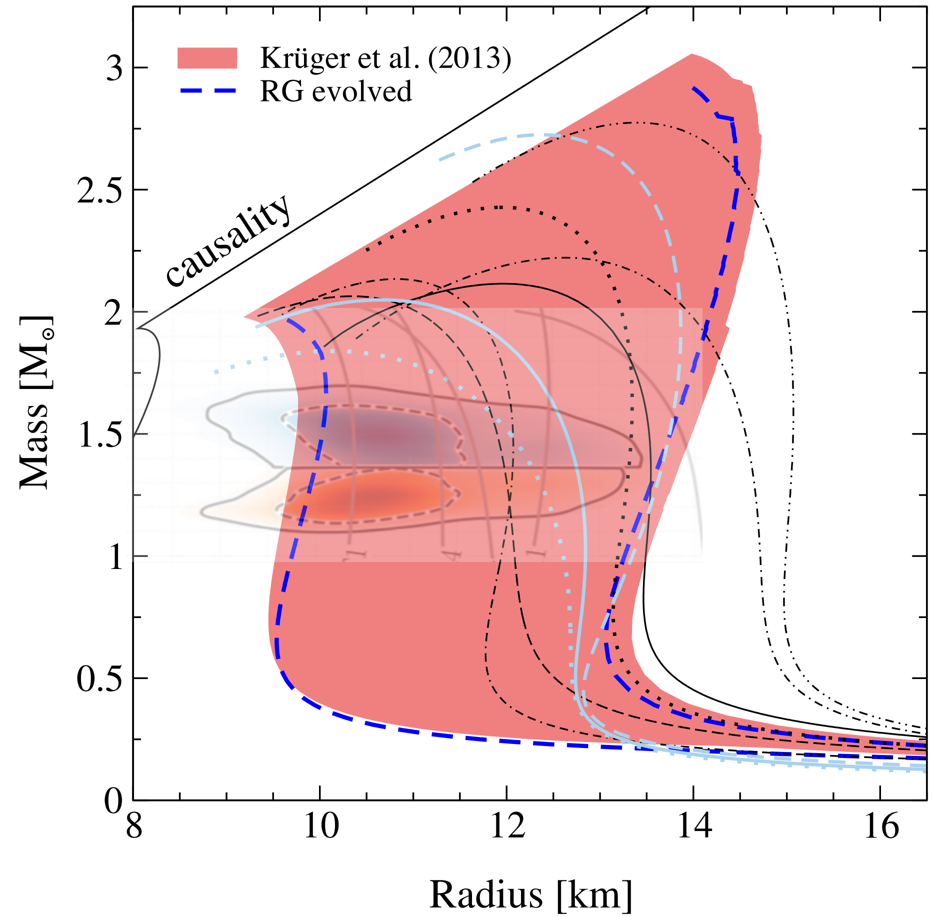
chiral EFT + general EOS extrapolation: 9.7 - 13.9 km for M=1.4 M_{sun}

GW170817: Measurements of neutron star radii and equation of state

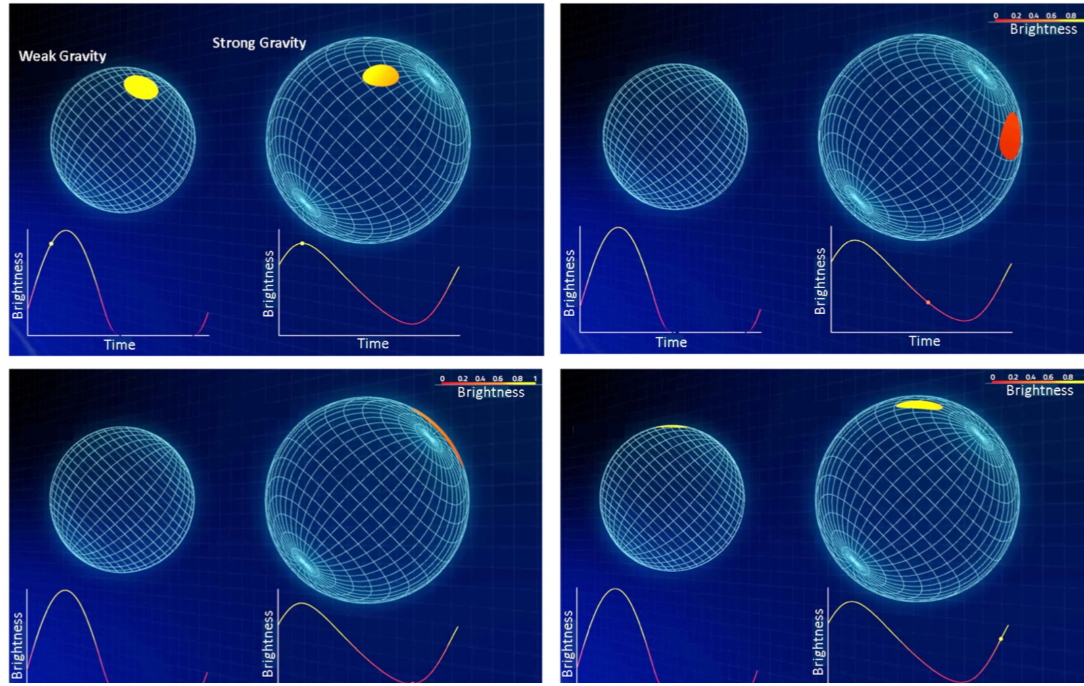
The LIGO Scientific Collaboration and The Virgo Collaboration
(compiled 30 May 2018)



excellent agreement with GW170817 from LIGO/Virgo



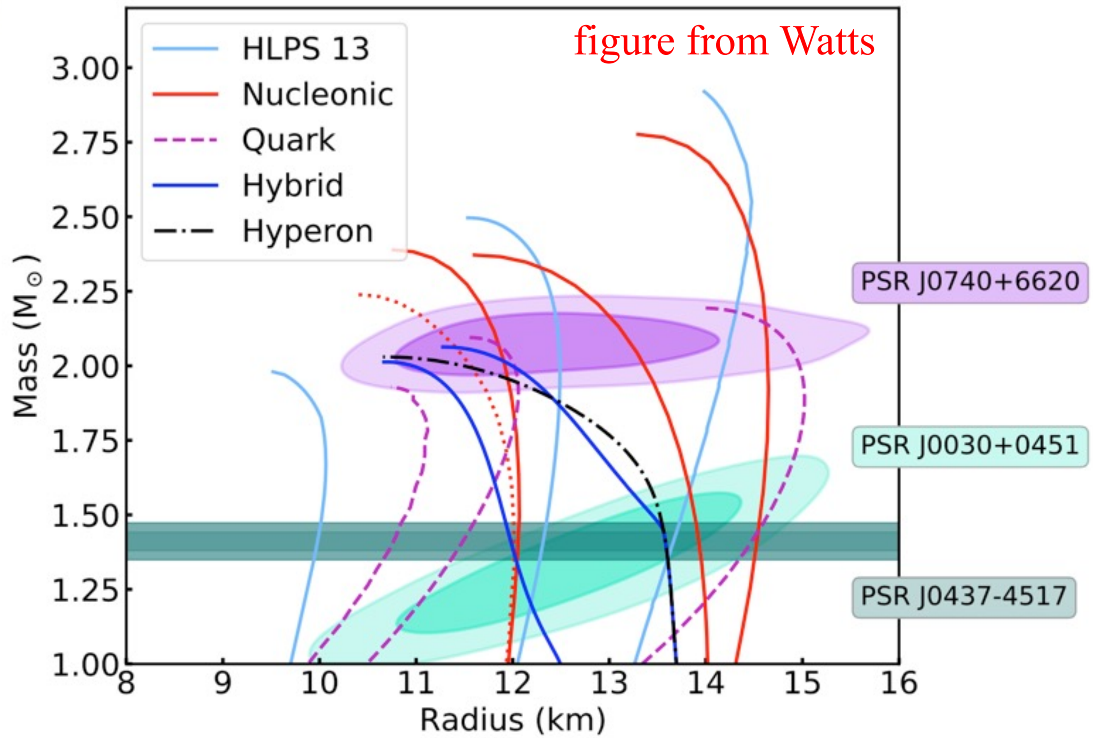
NICER results



Neutron star radius from pulse profile modeling

J0030 and J0740
here: Amsterdam analysis
Riley et al., ApJL (2019), (2021)

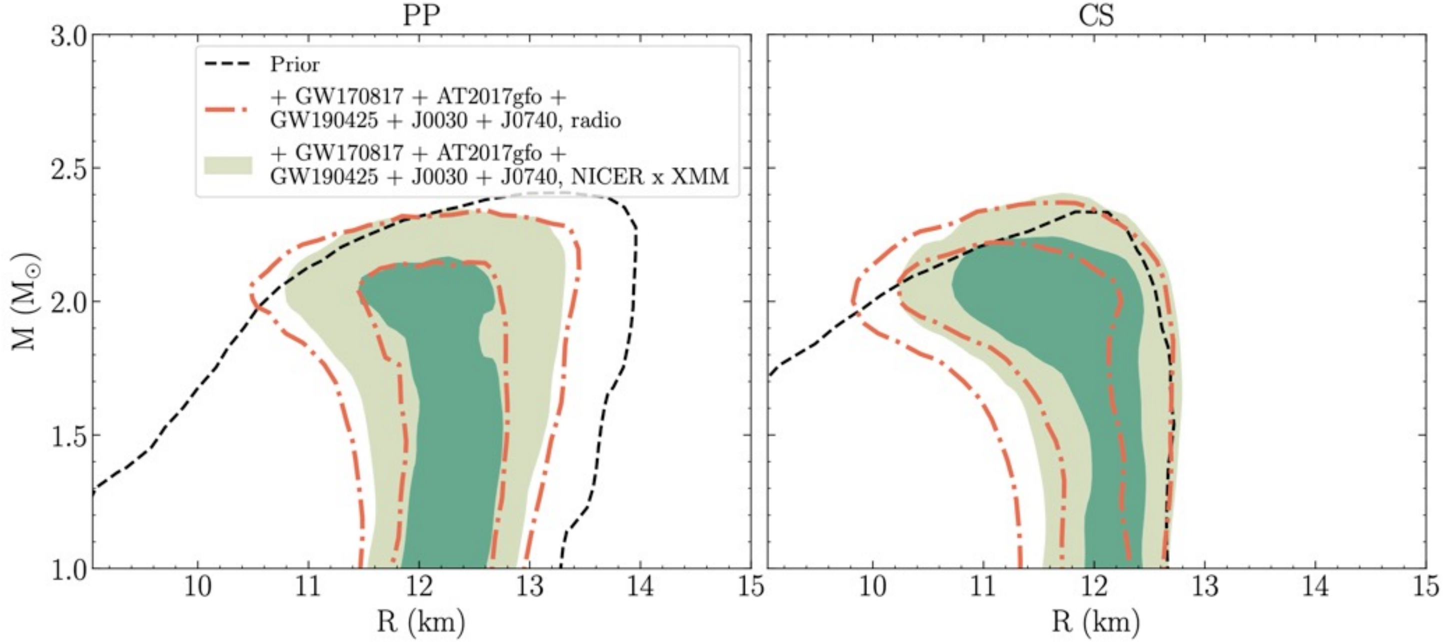
similar results from Illinois-Maryland analysis
Miller et al., ApJL (2019), (2021)



Combined merger and NICER constraints

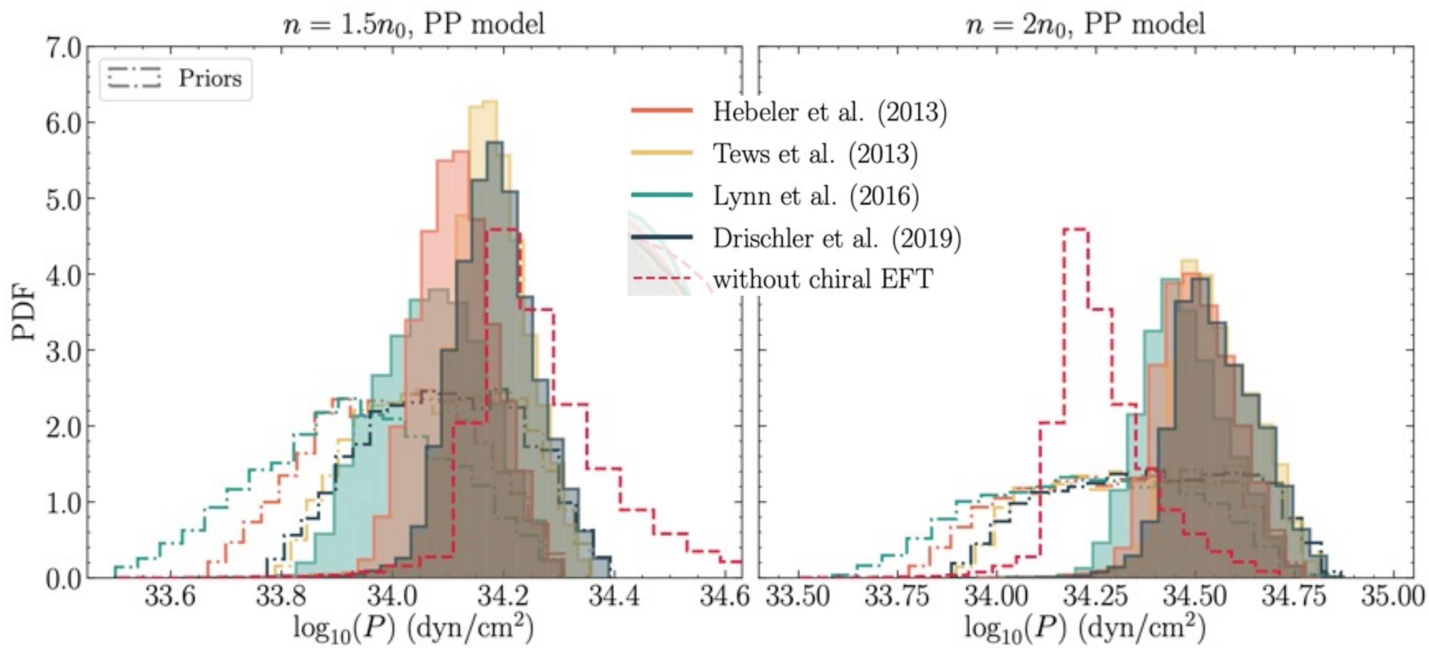
Raaijmakers et al., ApJL (2020), (2021)

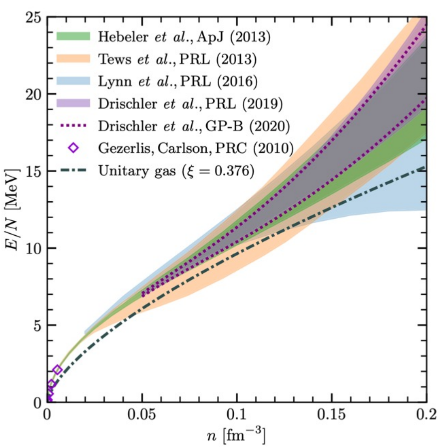
for mass-radius



equation of state at 1.5 and 2 n_0

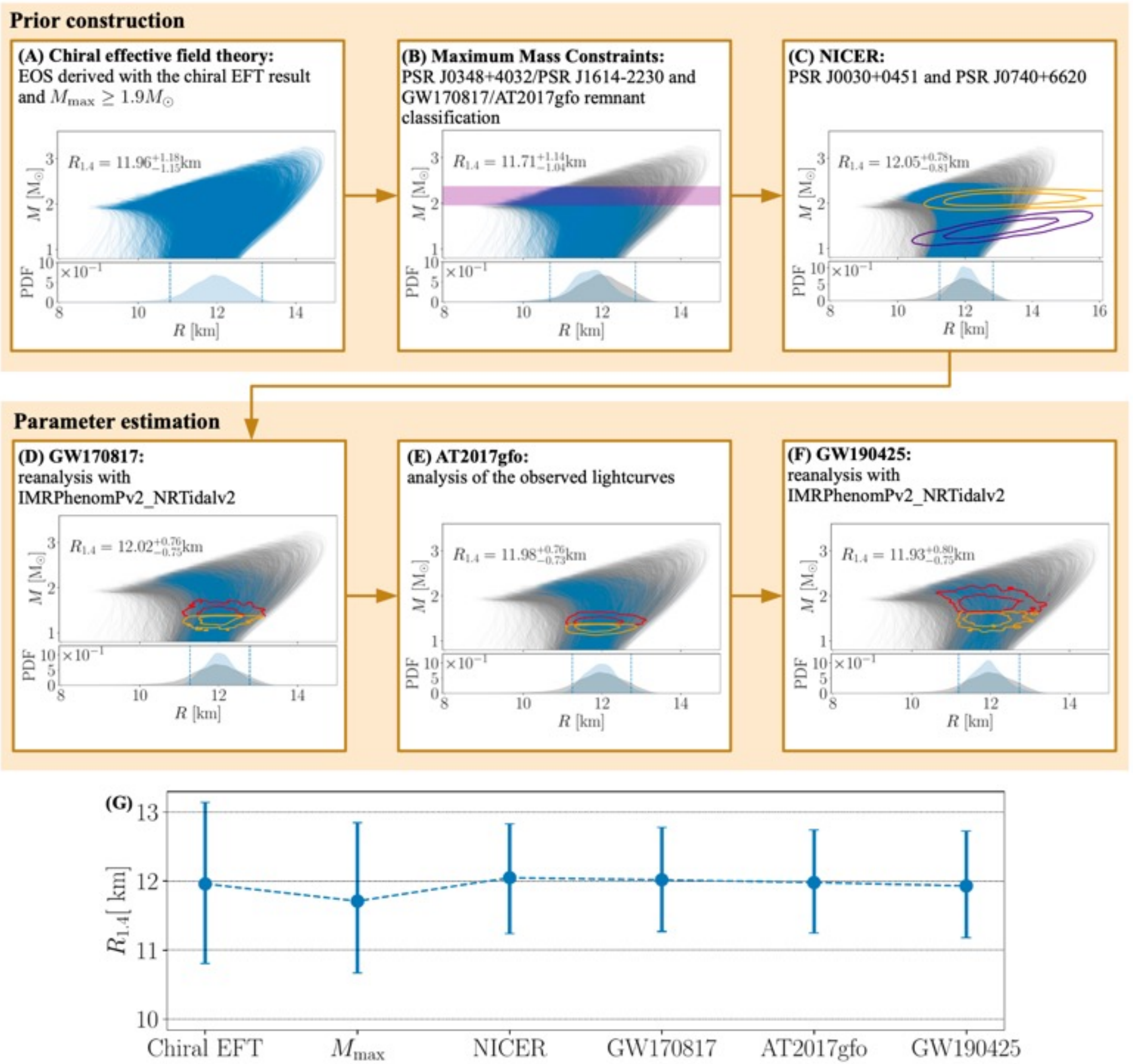
astro prefers higher pressures





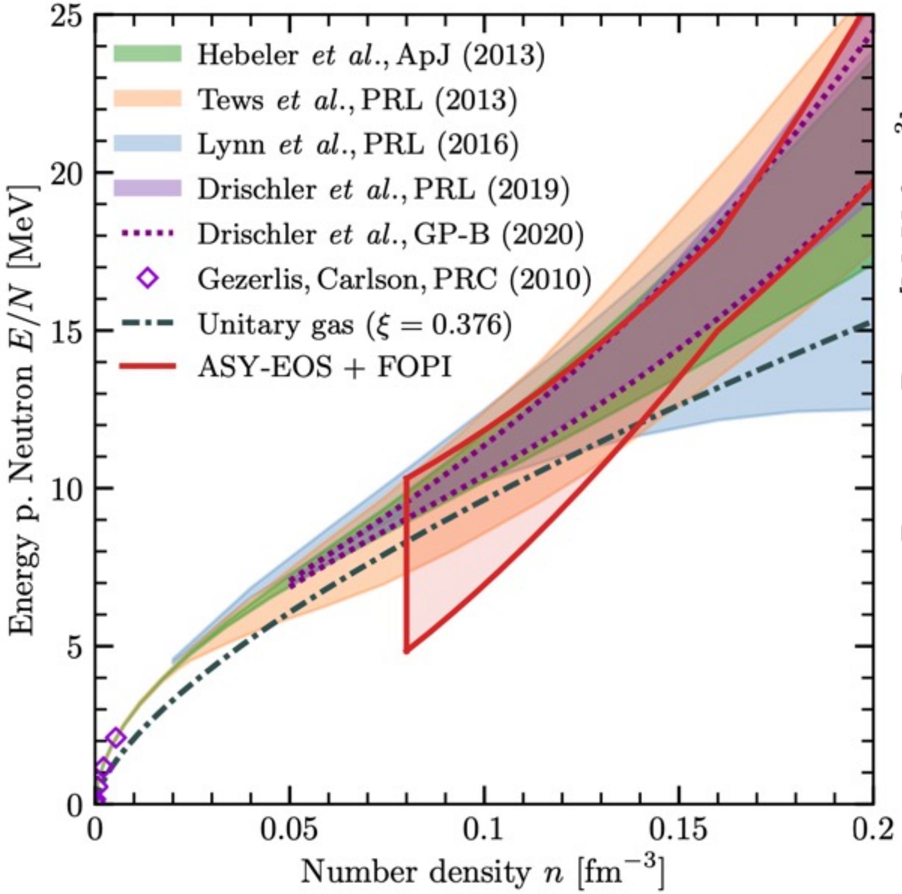
Constraints from heavy-ion collisions Huth, Pang et al., Nature (2022)

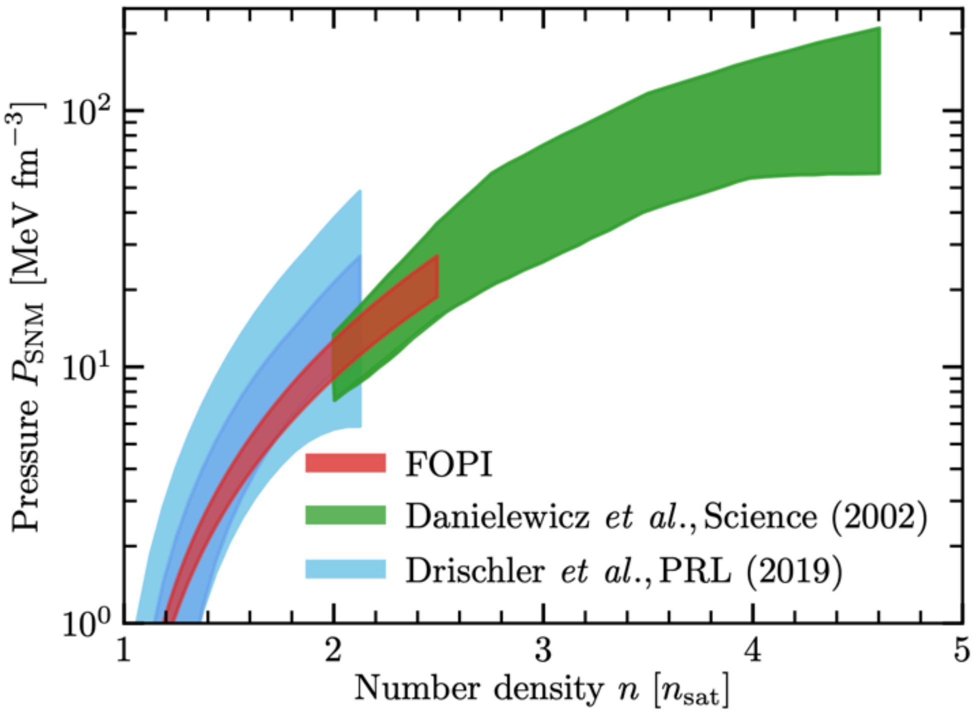
Bayesian multi-messenger framework using EOS draws based on chiral EFT



Constraints from heavy-ion collisions Huth, Pang et al., Nature (2022)

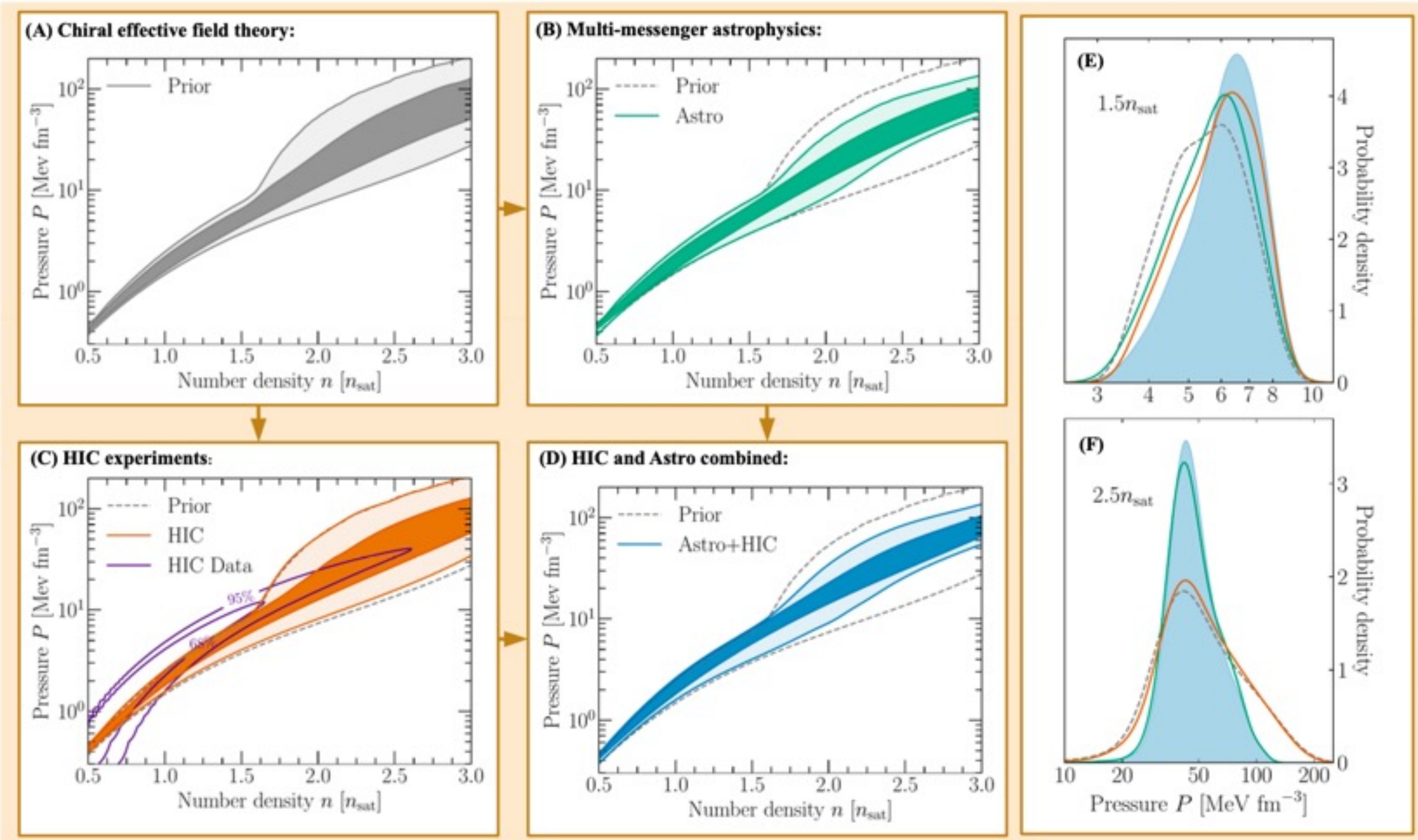
include constraints from heavy-ion collision experiments
ASY-EOS and FOPI at GSI for neutron and symmetric matter





Constraints from heavy-ion collisions Huth, Pang et al., Nature (2022)

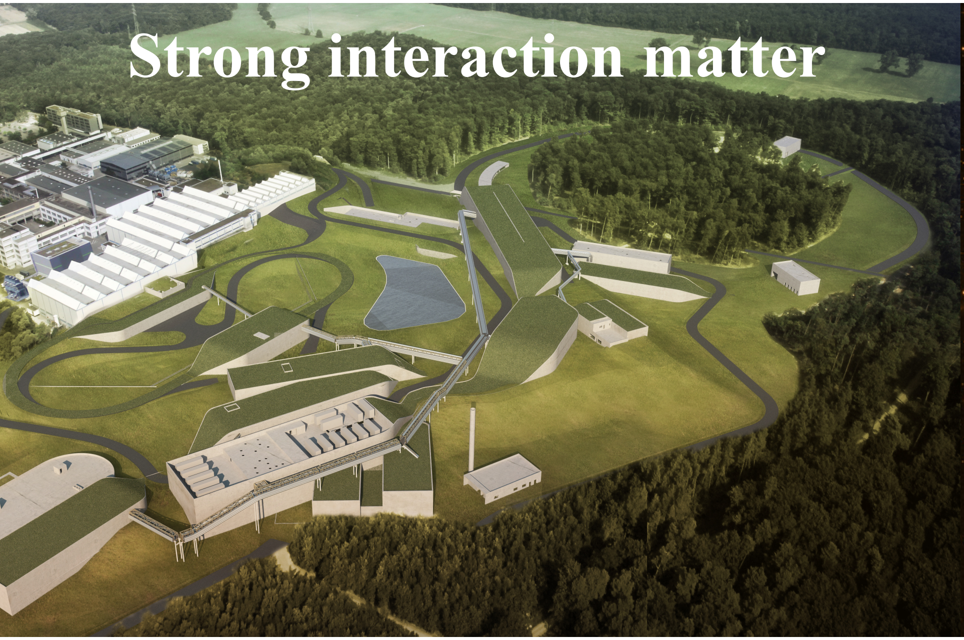
inclusion of HIC constraints prefers higher pressures, similar to NICER, overall remarkable consistency with chiral EFT and astro constraints

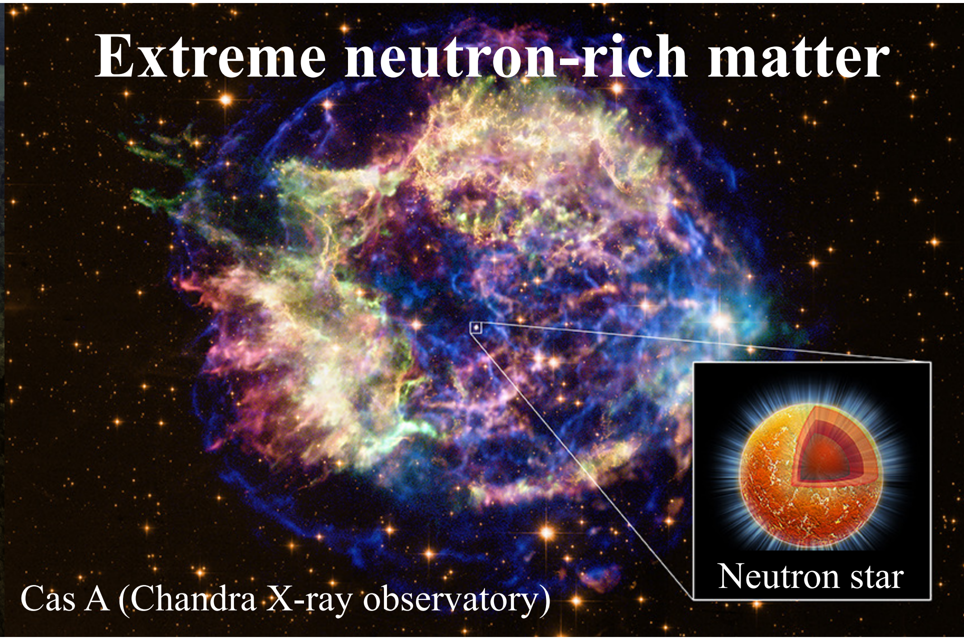


Exciting era in strong interaction physics

Effective field theory of strong interaction + powerful many-body theory

New experimental frontiers New observations in astrophysics





Thanks to our group and collaborators!