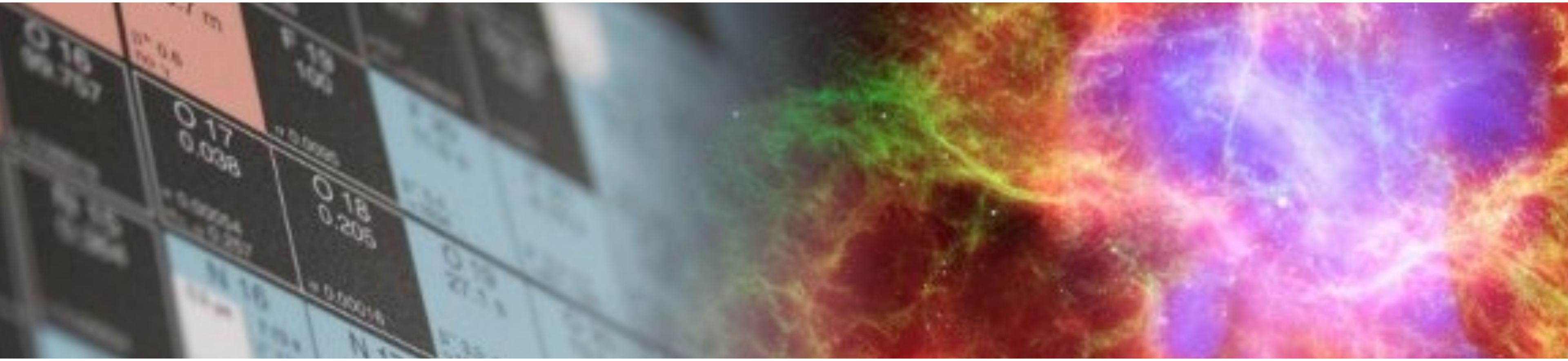
From nuclei to stars –
The strong interaction in the universe

Achim Schwenk

TECHNISCHE UNIVERSITÄT DARMSTADT

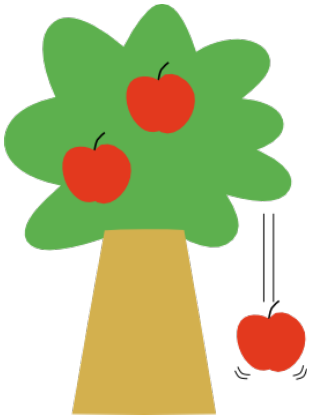


Mainz Physics Colloquium, Nov. 30, 2021

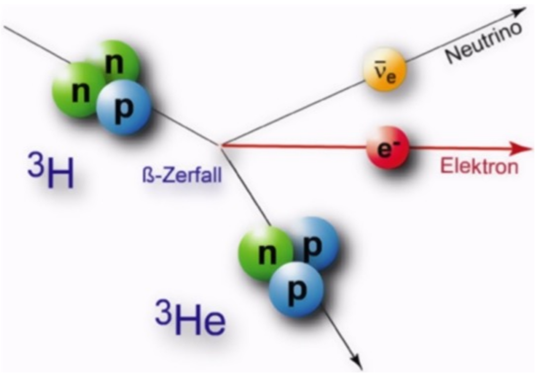
DFG
SFB 1245
erc
Bundesministerium für Bildung und Forschung
EMMI

Fundamental interactions

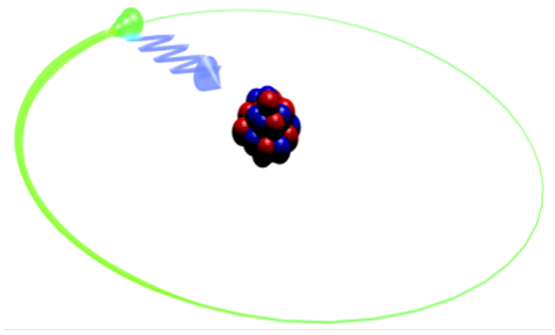
Gravity



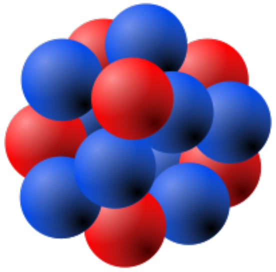
Weak interaction



Electrodynamics

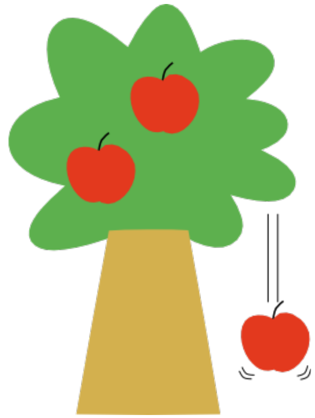


Strong interaction

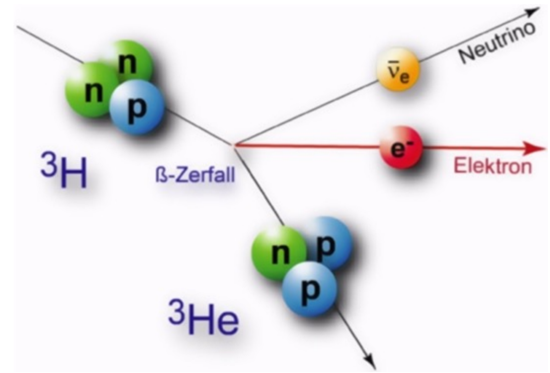


Fundamental interactions

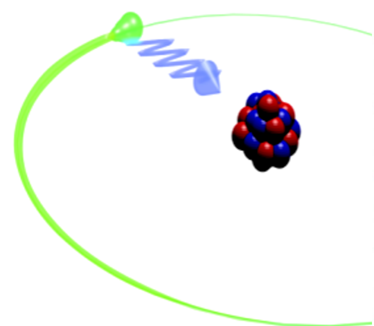
Gravity



Weak interaction



Electrodynamics



Periodic Table of Elements governed by electromagnetic interaction

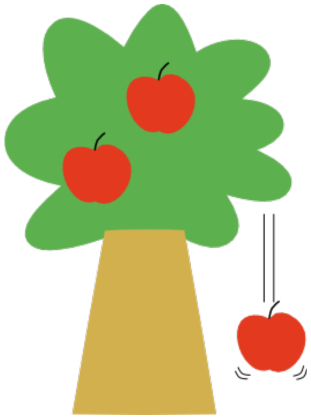
United Nations Educational, Scientific and Cultural Organization

2019 IYPT International Year of the Periodic Table of Chemical Elements

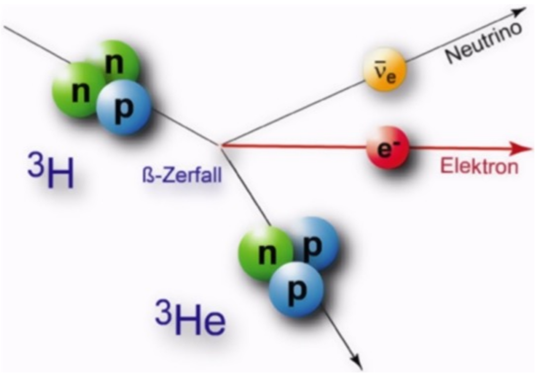
1 H Hydrogen Nonmetal																	2 He Helium Noble Gas
3 Li Lithium Alkali Metal	4 Be Beryllium Alkaline Earth Metal											5 B Boron Metalloid	6 C Carbon Nonmetal	7 N Nitrogen Nonmetal	8 O Oxygen Nonmetal	9 F Fluorine Halogen	10 Ne Neon Noble Gas
11 Na Sodium Alkali Metal	12 Mg Magnesium Alkaline Earth Metal											13 Al Aluminum Post-Transition Metal	14 Si Silicon Metalloid	15 P Phosphorus Nonmetal	16 S Sulfur Nonmetal	17 Cl Chlorine Halogen	18 Ar Argon Noble Gas
19 K Potassium Alkali Metal	20 Ca Calcium Alkaline Earth Metal	21 Sc Scandium Transition Metal	22 Ti Titanium Transition Metal	23 V Vanadium Transition Metal	24 Cr Chromium Transition Metal	25 Mn Manganese Transition Metal	26 Fe Iron Transition Metal	27 Co Cobalt Transition Metal	28 Ni Nickel Transition Metal	29 Cu Copper Transition Metal	30 Zn Zinc Transition Metal	31 Ga Gallium Post-Transition Metal	32 Ge Germanium Metalloid	33 As Arsenic Metalloid	34 Se Selenium Nonmetal	35 Br Bromine Halogen	36 Kr Krypton Noble Gas
37 Rb Rubidium Alkali Metal	38 Sr Strontium Alkaline Earth Metal	39 Y Yttrium Transition Metal	40 Zr Zirconium Transition Metal	41 Nb Niobium Transition Metal	42 Mo Molybdenum Transition Metal	43 Tc Technetium Transition Metal	44 Ru Ruthenium Transition Metal	45 Rh Rhodium Transition Metal	46 Pd Palladium Transition Metal	47 Ag Silver Transition Metal	48 Cd Cadmium Transition Metal	49 In Indium Post-Transition Metal	50 Sn Tin Post-Transition Metal	51 Sb Antimony Metalloid	52 Te Tellurium Metalloid	53 I Iodine Halogen	54 Xe Xenon Noble Gas
55 Cs Cesium Alkali Metal	56 Ba Barium Alkaline Earth Metal	*	72 Hf Hafnium Transition Metal	73 Ta Tantalum Transition Metal	74 W Tungsten Transition Metal	75 Re Rhenium Transition Metal	76 Os Osmium Transition Metal	77 Ir Iridium Transition Metal	78 Pt Platinum Transition Metal	79 Au Gold Transition Metal	80 Hg Mercury Transition Metal	81 Tl Thallium Post-Transition Metal	82 Pb Lead Post-Transition Metal	83 Bi Bismuth Post-Transition Metal	84 Po Polonium Metalloid	85 At Astatine Halogen	86 Rn Radon Noble Gas
87 Fr Francium Alkali Metal	88 Ra Radium Alkaline Earth Metal	**	104 Rf Rutherfordium Transition Metal	105 Db Dubnium Transition Metal	106 Sg Seaborgium Transition Metal	107 Bh Bohrium Transition Metal	108 Hs Hassium Transition Metal	109 Mt Meitnerium Transition Metal	110 Ds Darmstadtium Transition Metal	111 Rg Roentgenium Transition Metal	112 Cn Copernicium Transition Metal	113 Nh Nihonium Post-Transition Metal	114 Fl Flerovium Post-Transition Metal	115 Mc Moscovium Post-Transition Metal	116 Lv Livermorium Post-Transition Metal	117 Ts Tennessine Halogen	118 Og Oganesson Noble Gas
		*	57 La Lanthanum Lanthanide	58 Ce Cerium Lanthanide	59 Pr Praseodymium Lanthanide	60 Nd Neodymium Lanthanide	61 Pm Promethium Lanthanide	62 Sm Samarium Lanthanide	63 Eu Europium Lanthanide	64 Gd Gadolinium Lanthanide	65 Tb Terbium Lanthanide	66 Dy Dysprosium Lanthanide	67 Ho Holmium Lanthanide	68 Er Erbium Lanthanide	69 Tm Thulium Lanthanide	70 Yb Ytterbium Lanthanide	71 Lu Lutetium Lanthanide
		**	89 Ac Actinium Actinide	90 Th Thorium Actinide	91 Pa Protactinium Actinide	92 U Uranium Actinide	93 Np Neptunium Actinide	94 Pu Plutonium Actinide	95 Am Americium Actinide	96 Cm Curium Actinide	97 Bk Berkelium Actinide	98 Cf Californium Actinide	99 Es Einsteinium Actinide	100 Fm Fermium Actinide	101 Md Mendelevium Actinide	102 No Nobelium Actinide	103 Lr Lawrencium Actinide

Fundamental interactions

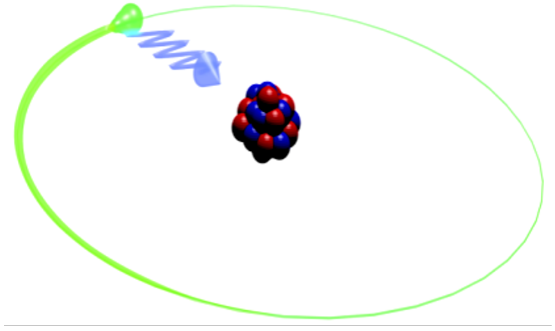
Gravity



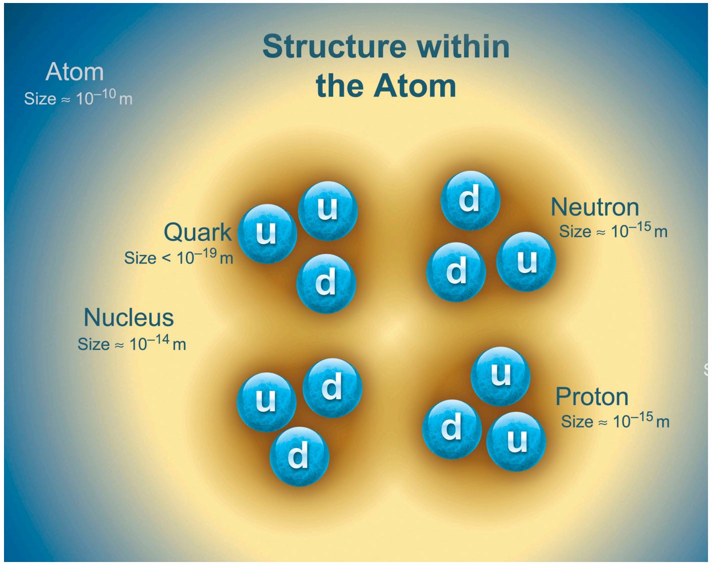
Weak interaction



Electrodynamics

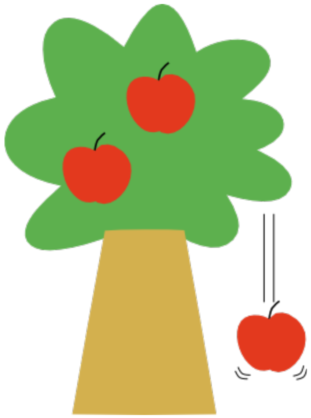


Strong interaction
Quantum chromodynamics (QCD)

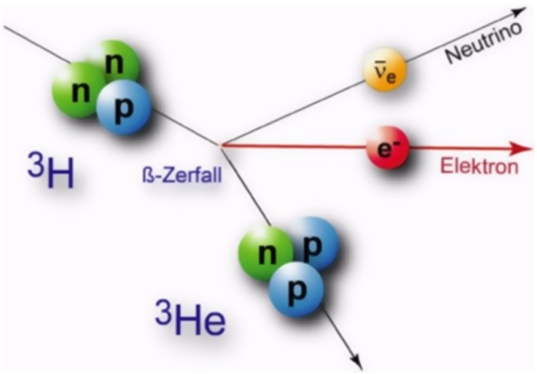


Fundamental interactions

Gravity



Weak interaction



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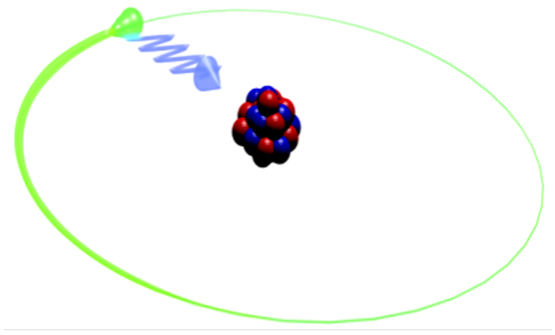
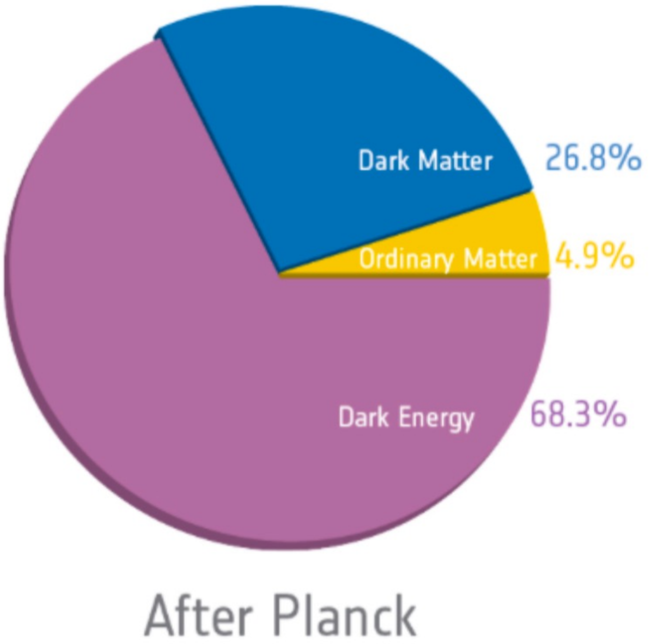


Strong interaction in the universe



Nuclei bound by strong interactions

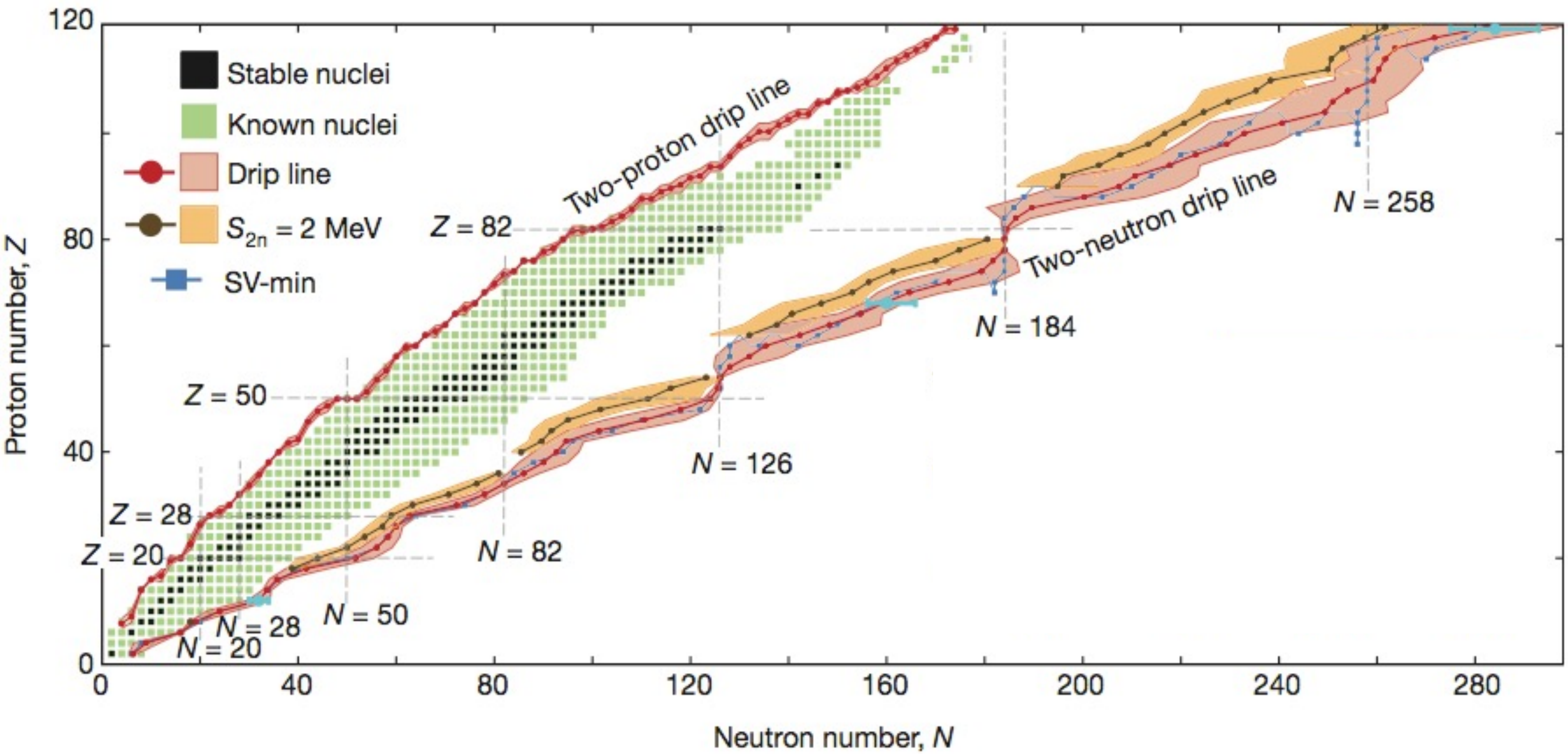
doi:10.1038/nature11188

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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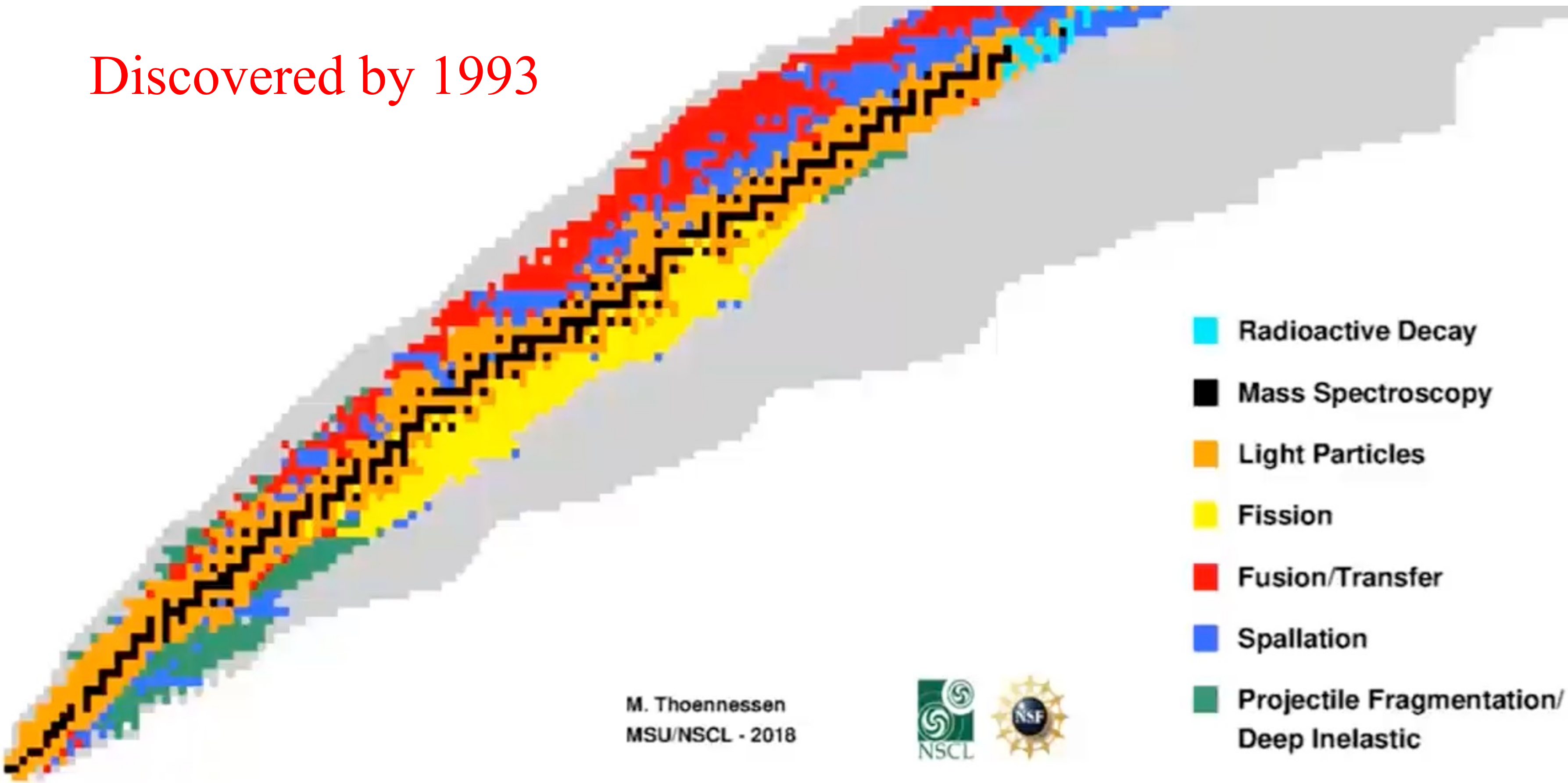
Discovered by 1993



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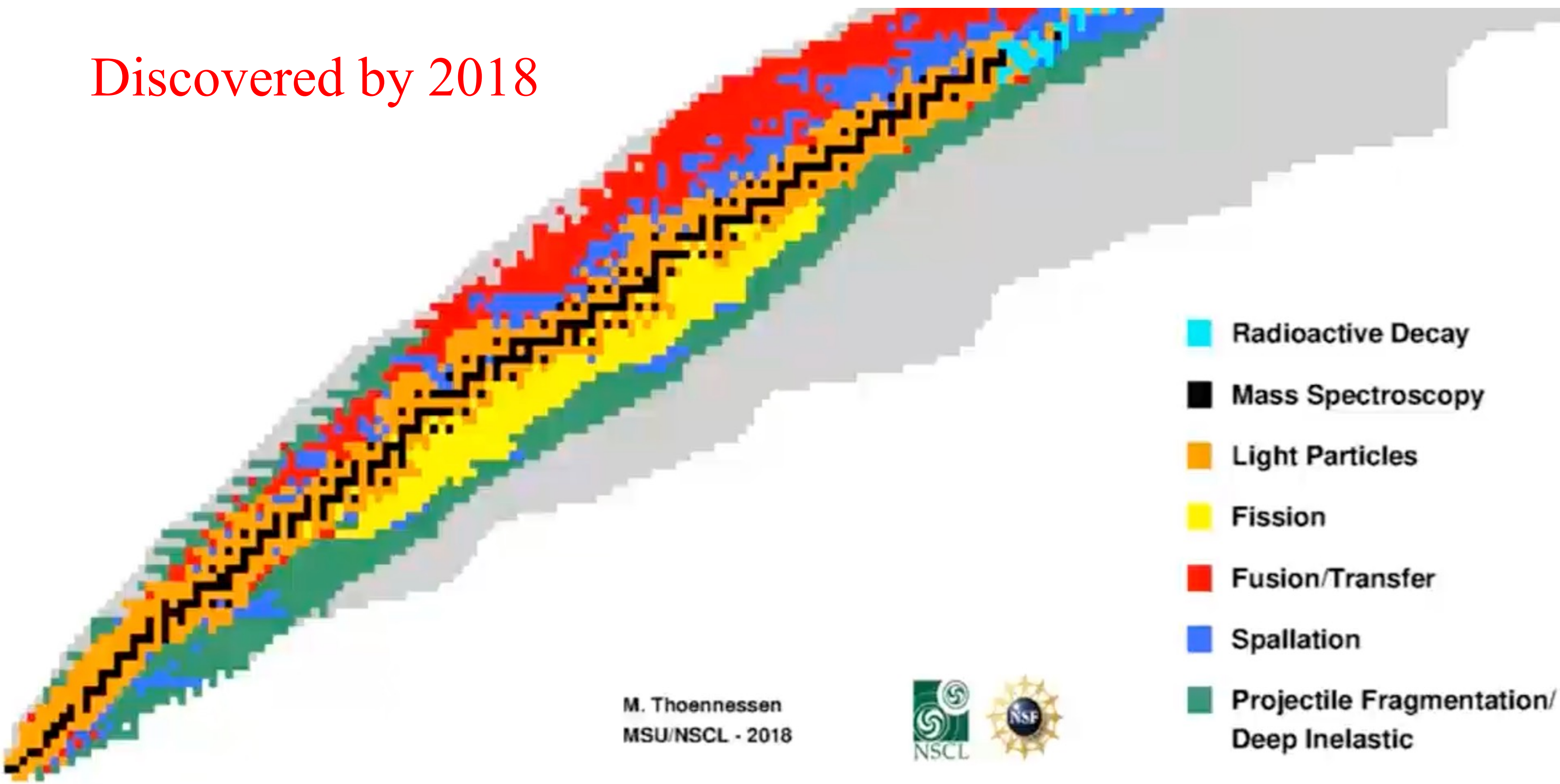

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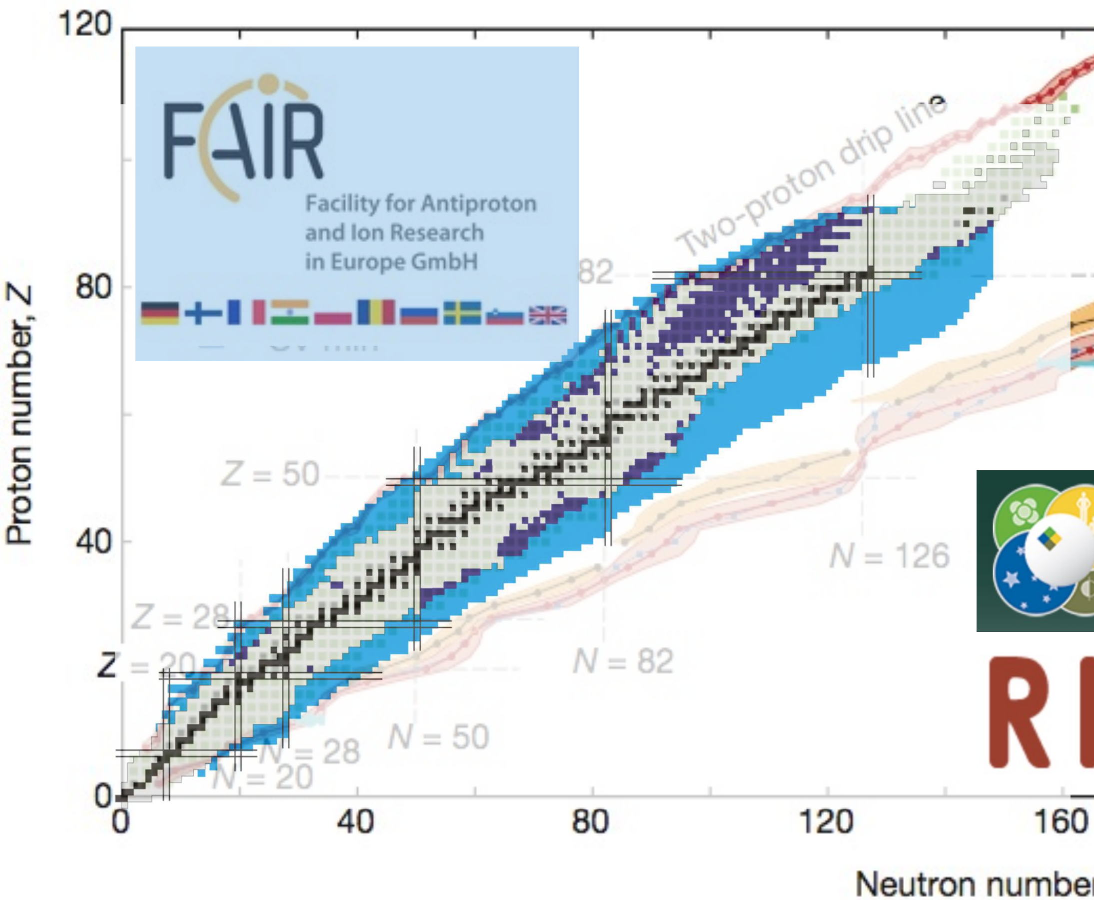

FAIR
Facility for Antiproton and Ion Research in Europe GmbH

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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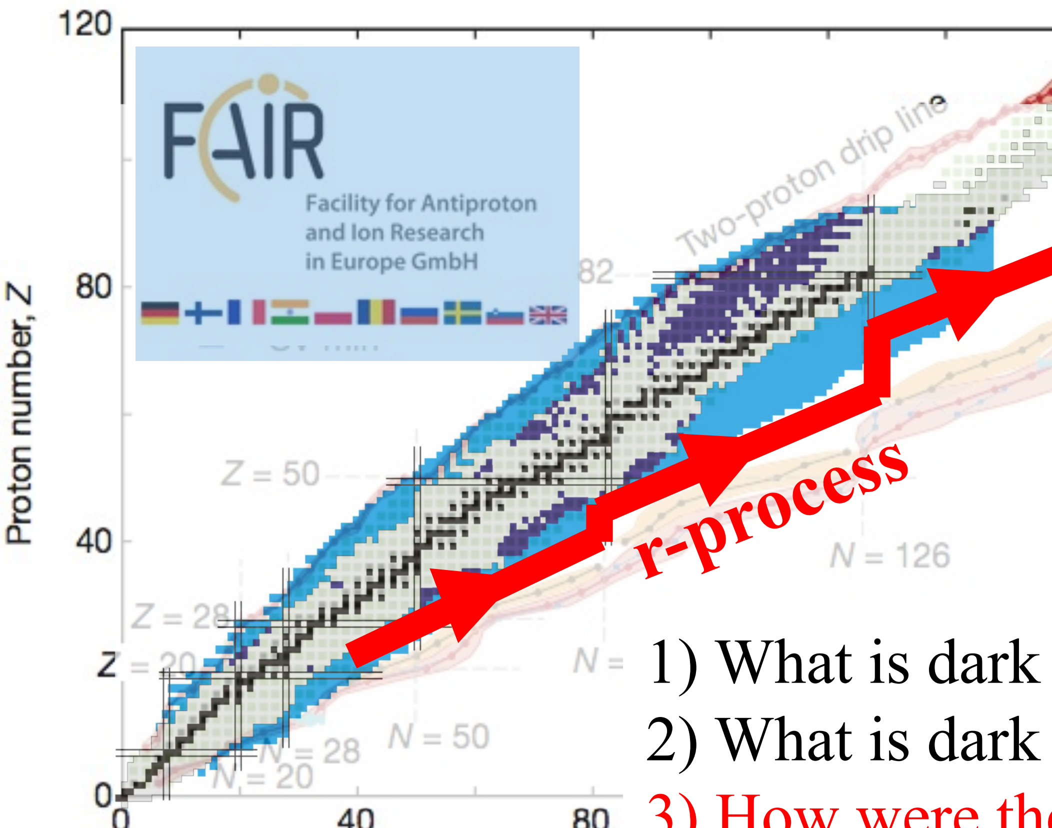
~ 3000 nuclei discovered (288 stable), 11

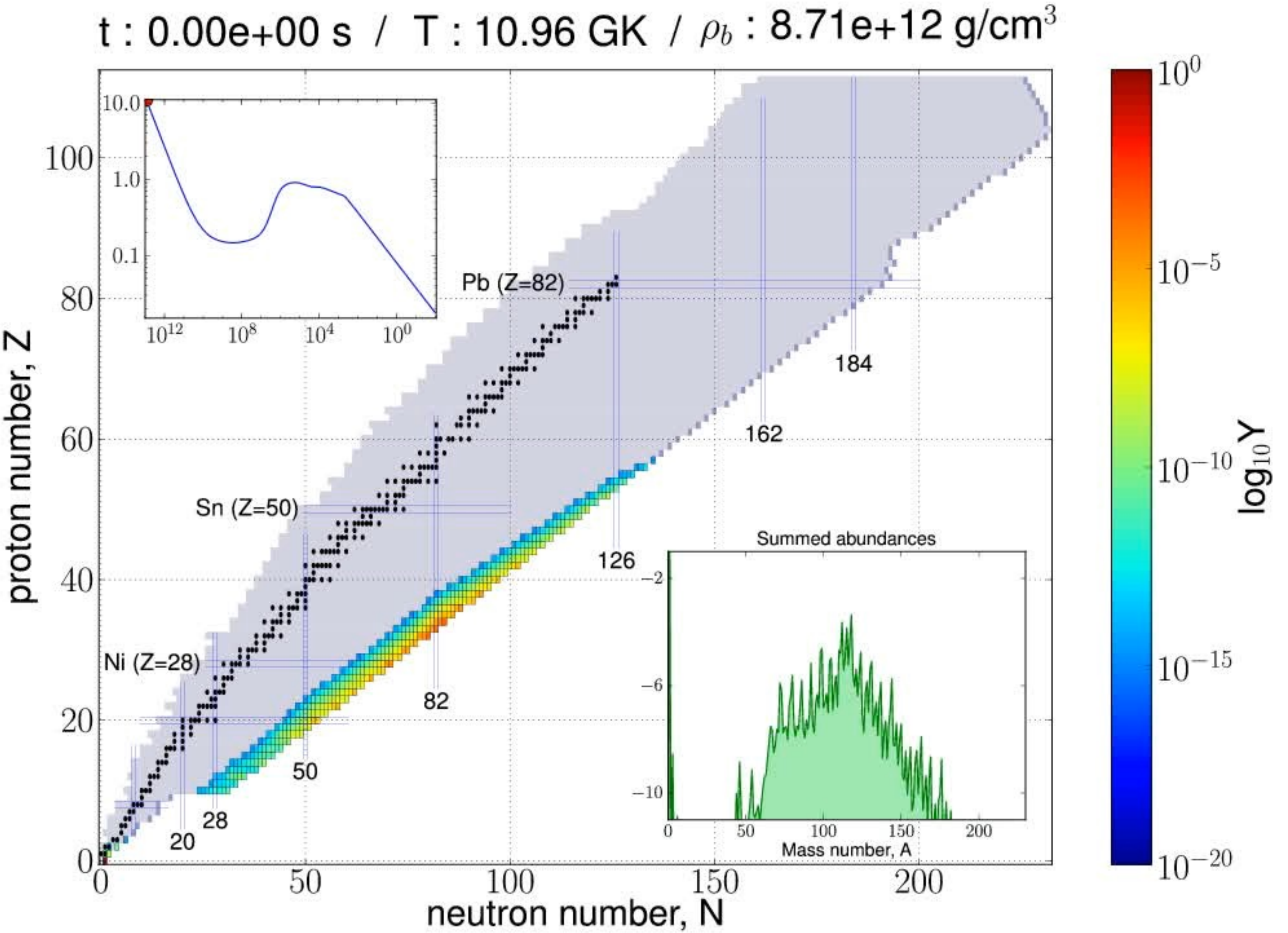
~ 4000±500 nuclei unknown, extreme n



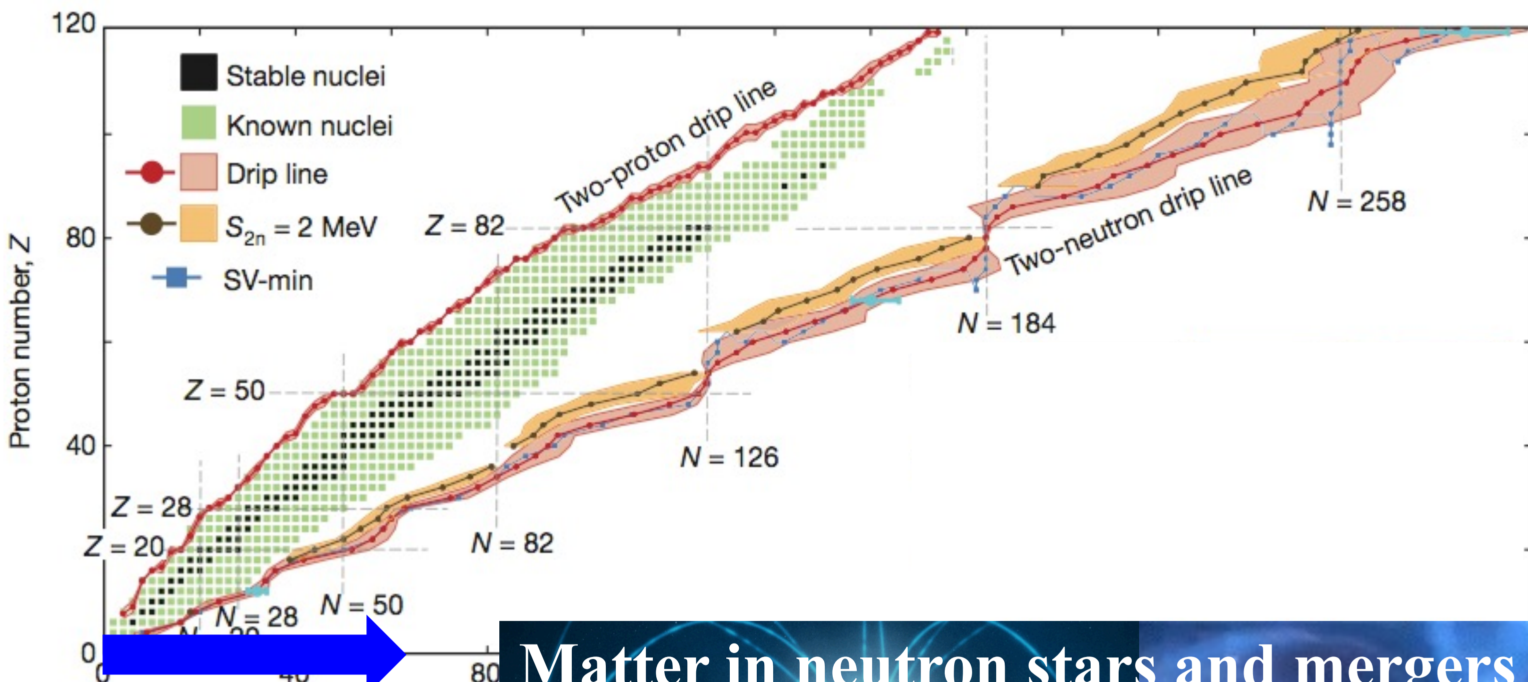
1) What is dark matter?

2) What is dark energy?

3) How were the elements from iron to uranium made?

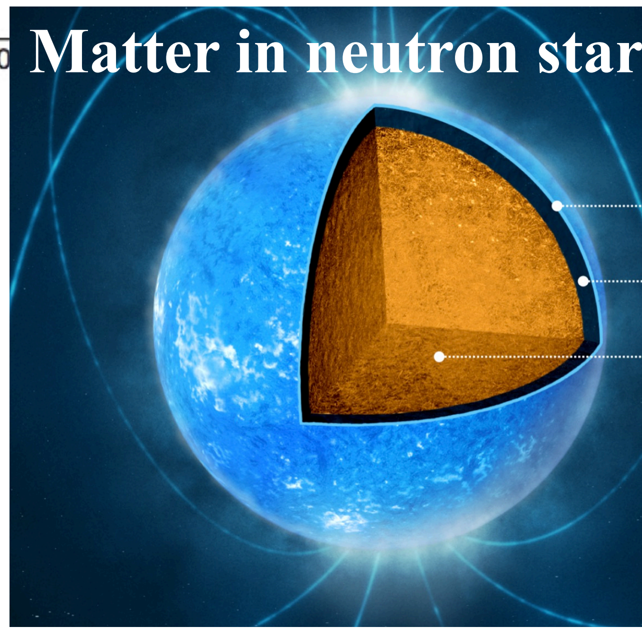


t : 0.00e+00 s / T : 10.96 GK / ρ_b : 8.71e+12 g/cm^3
proton number, Z
neutron number, N
Pb (Z=82)
Sn (Z=50)
Ni (Z=28)
20
28
50
82
126
162
184
Summed abundances
Mass number, A
$\log_{10}$Y



Neutrons

Matter in neutron stars and mergers

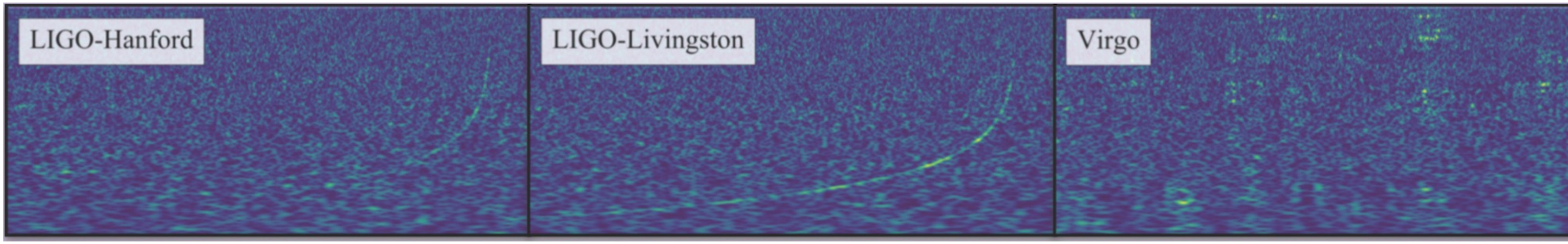


from Watts et al., RMP (2016)

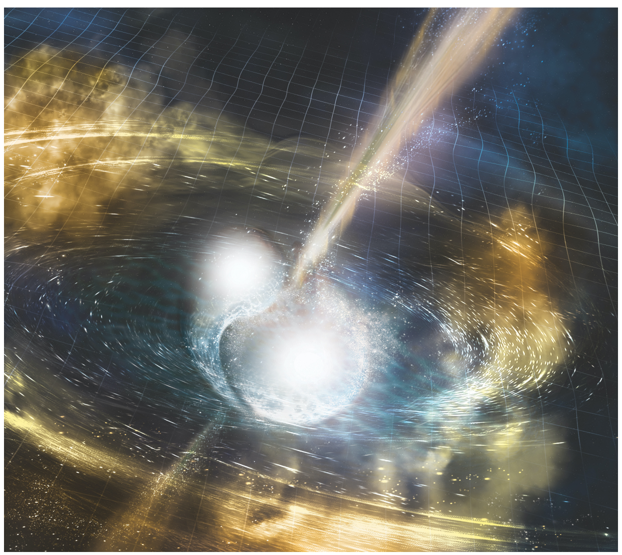
NASA/Goddard/LIGO/Virgo

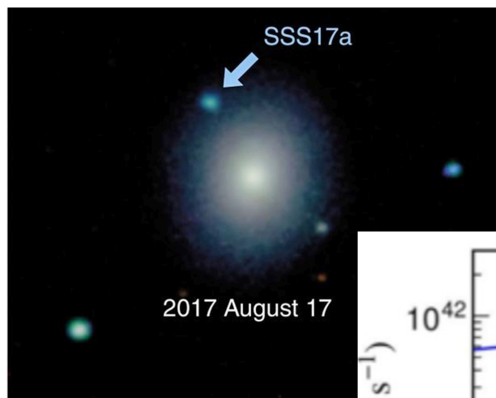
Multi-messenger era: neutron star merger GW170817

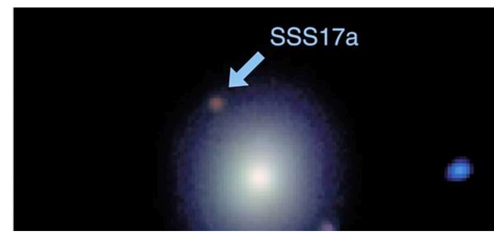
gravitational wave signal: provides contraints on neutron star radii

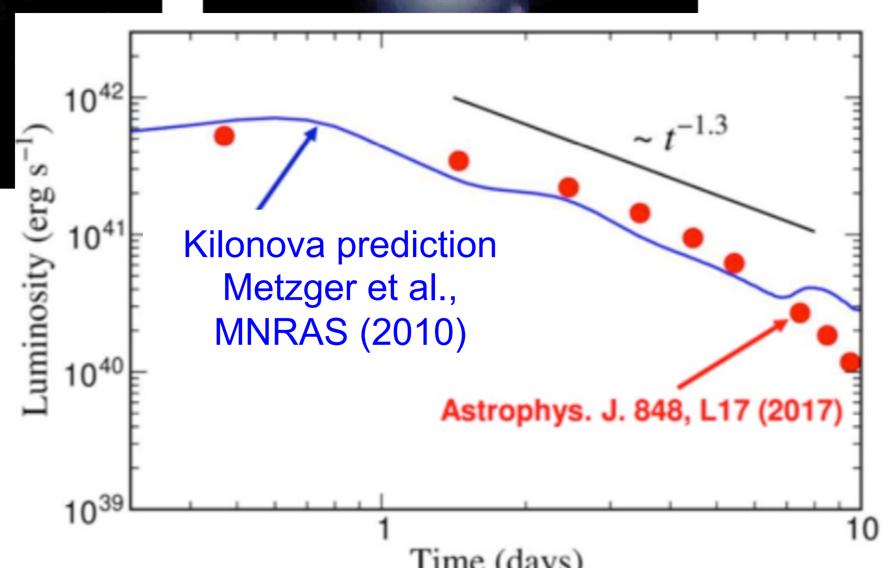


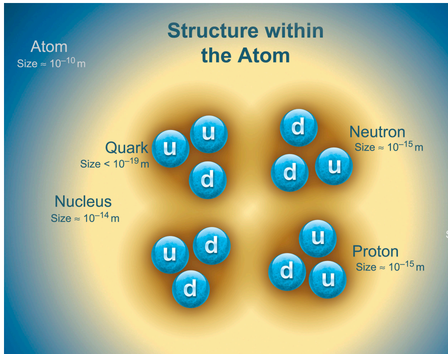
short gamma-ray burst + kilonova light curve: decay of r-process nuclei

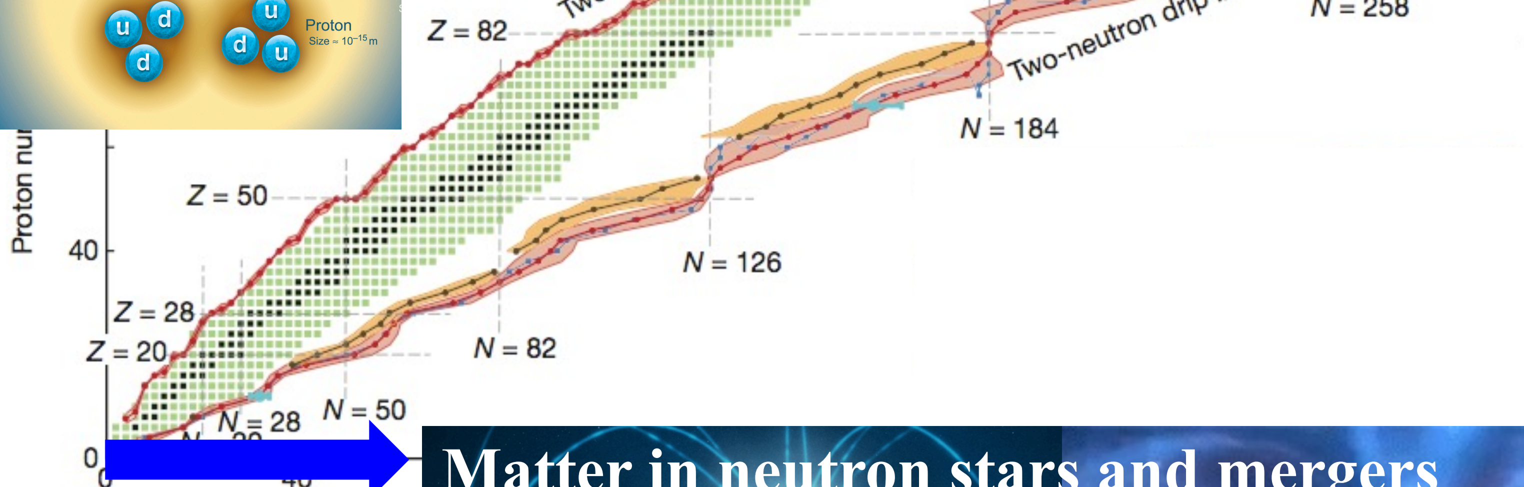






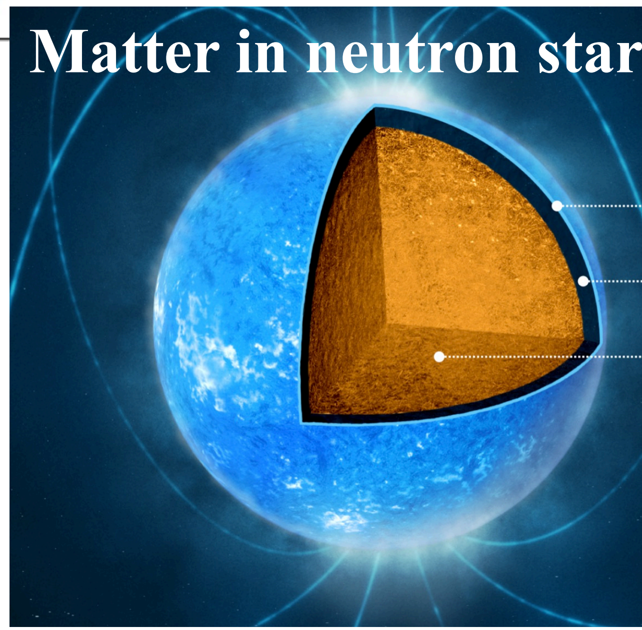






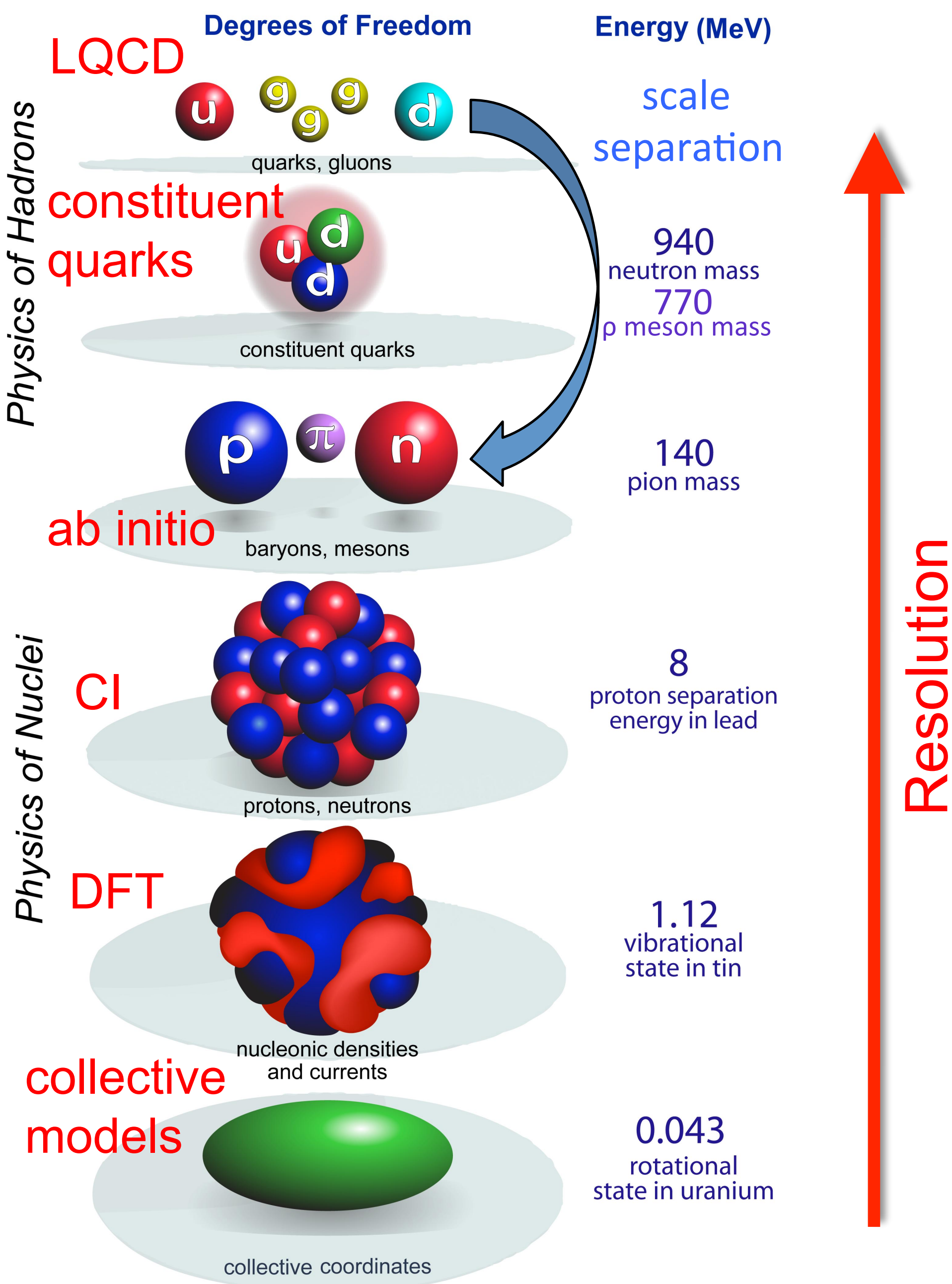
Neutrons

Matter in neutron stars and mergers



from Watts et al., RMP (2016) NASA/Goddard/LIGO/Virgo

Hierarchy of degrees of freedom



Emergent phenomena:

Protons and neutrons from QCD

Nuclear forces

Nuclear saturation,
shell structure, and clusters

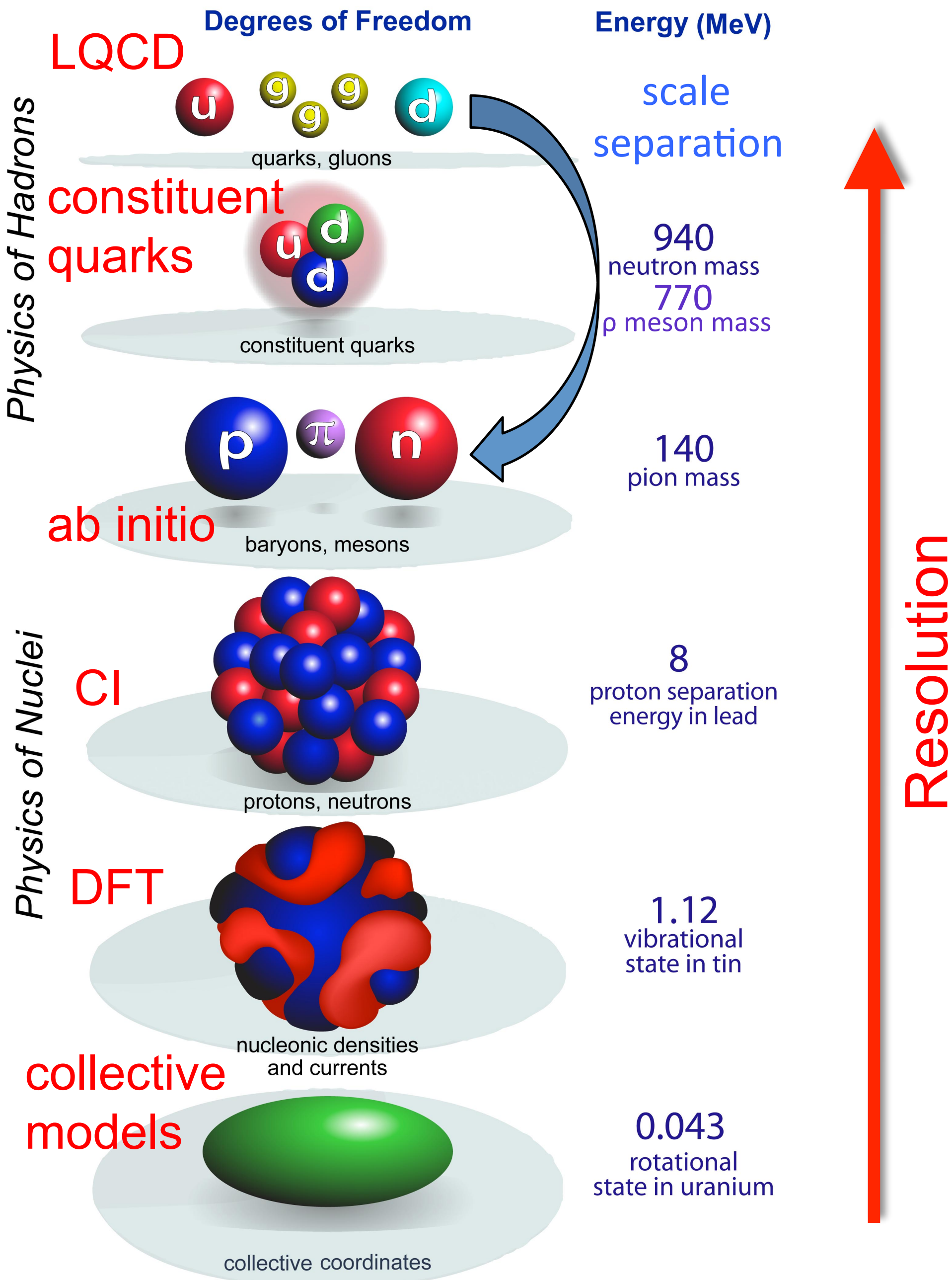
Large scattering length
(universal) physics

…

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)

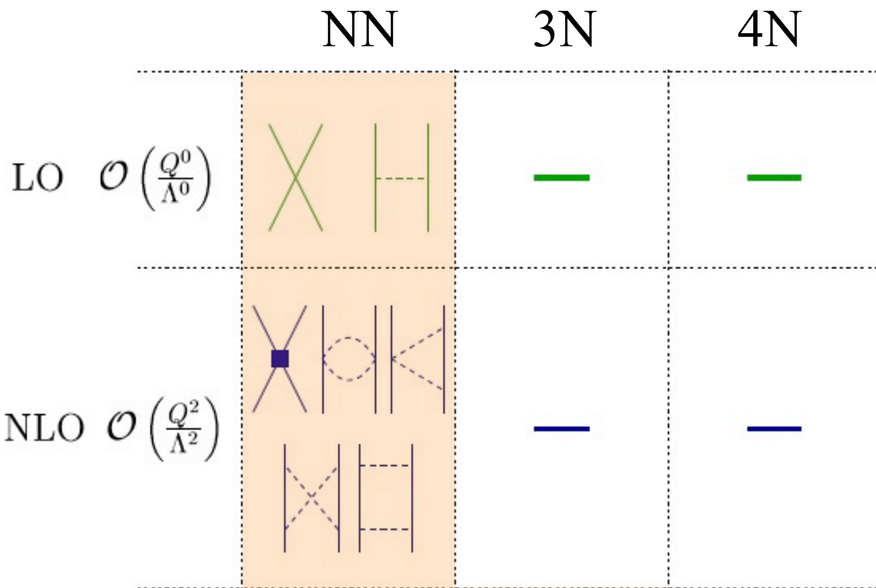
EFT for heavy nuclei: collective degrees of freedom

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 $(Q/\Lambda)^n$



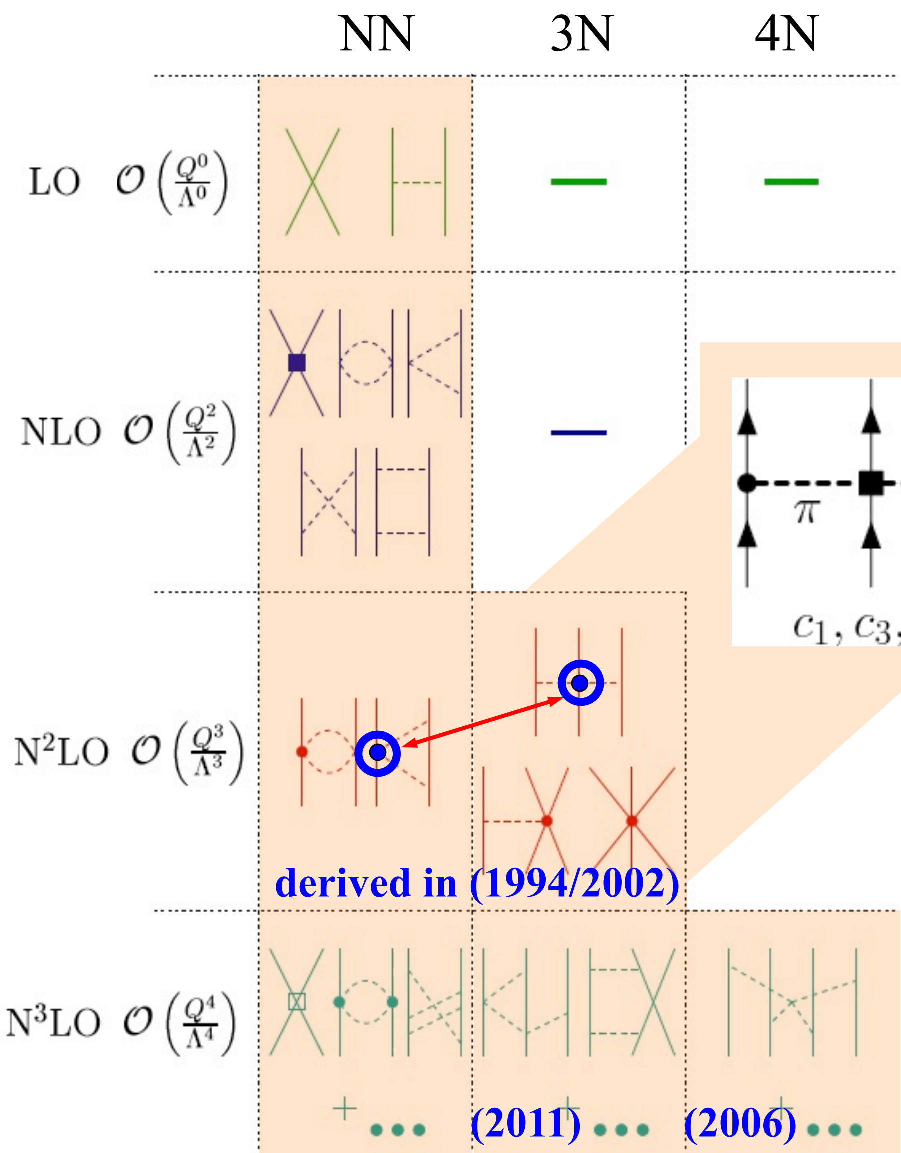
based on symmetries of strong interaction (QCD)

long-range interactions governed by pion exchanges (phonons of QCD)

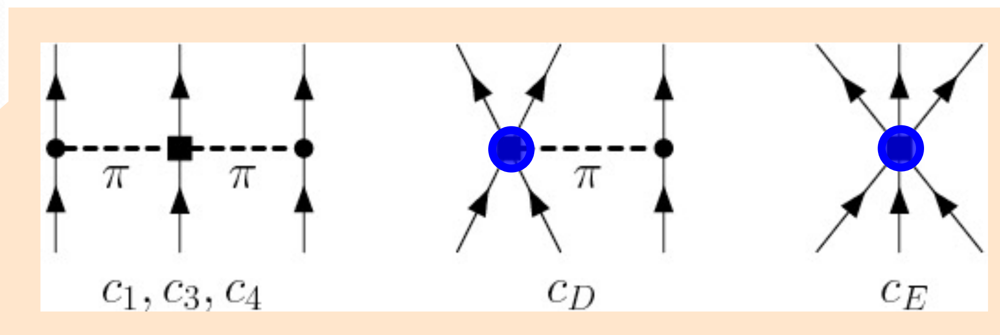
Weinberg (1990,91)

Chiral effective field theory for nuclear forces

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



powerful approach for
many-body interactions



only 2 new couplings at N^2LO

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

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

Chiral effective field theory for nuclear forces

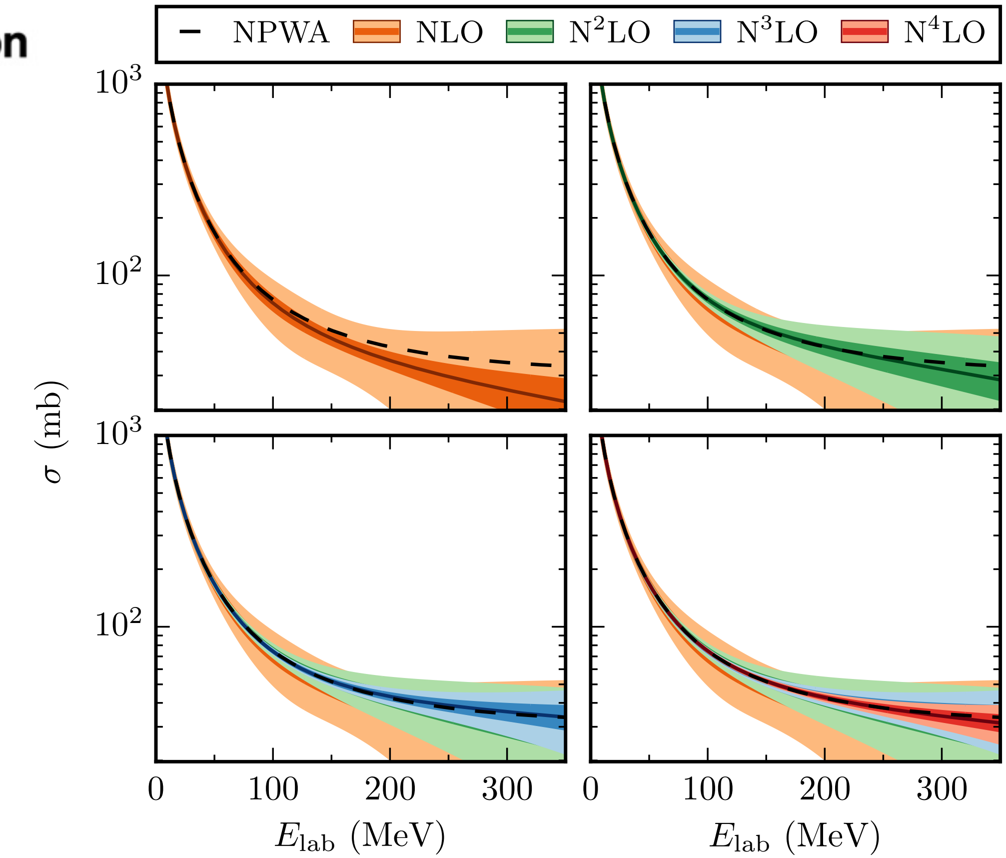
Systematic expansion (power counting) in low momenta $(Q/\Lambda)^n$

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

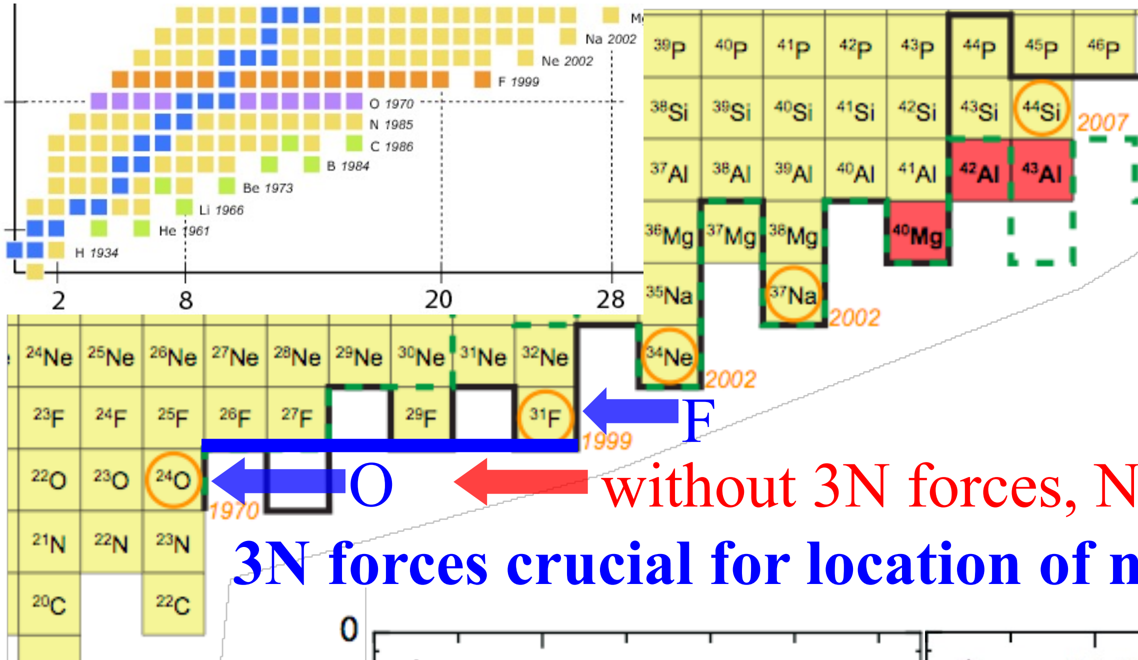
R J Furnstahl[1], D R Phillips[2] and S Wesolowski[1]

Bayesian uncertainty estimates and model checking



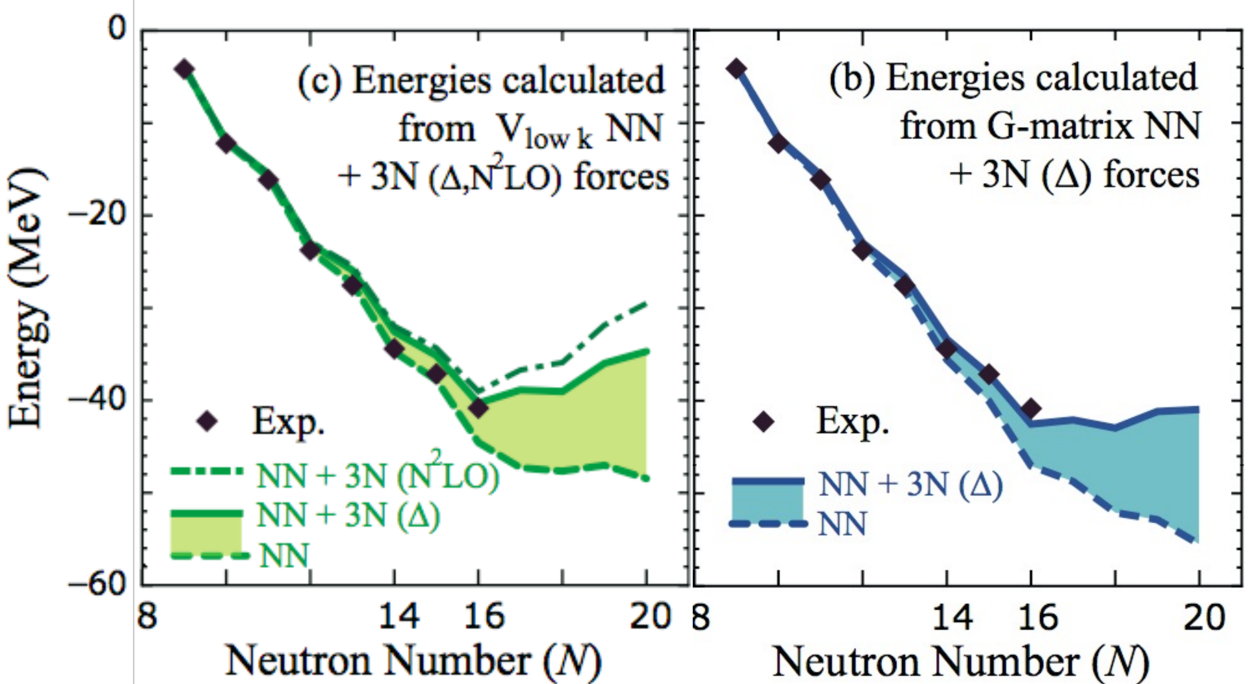
Furnstahl, Phillips, Klos, Wesolowski, Melendez (2015-)

The oxygen anomaly Otsuka et al., PRL (2010)



without 3N forces, NN interactions too attractive

3N forces crucial for location of neutron dripline



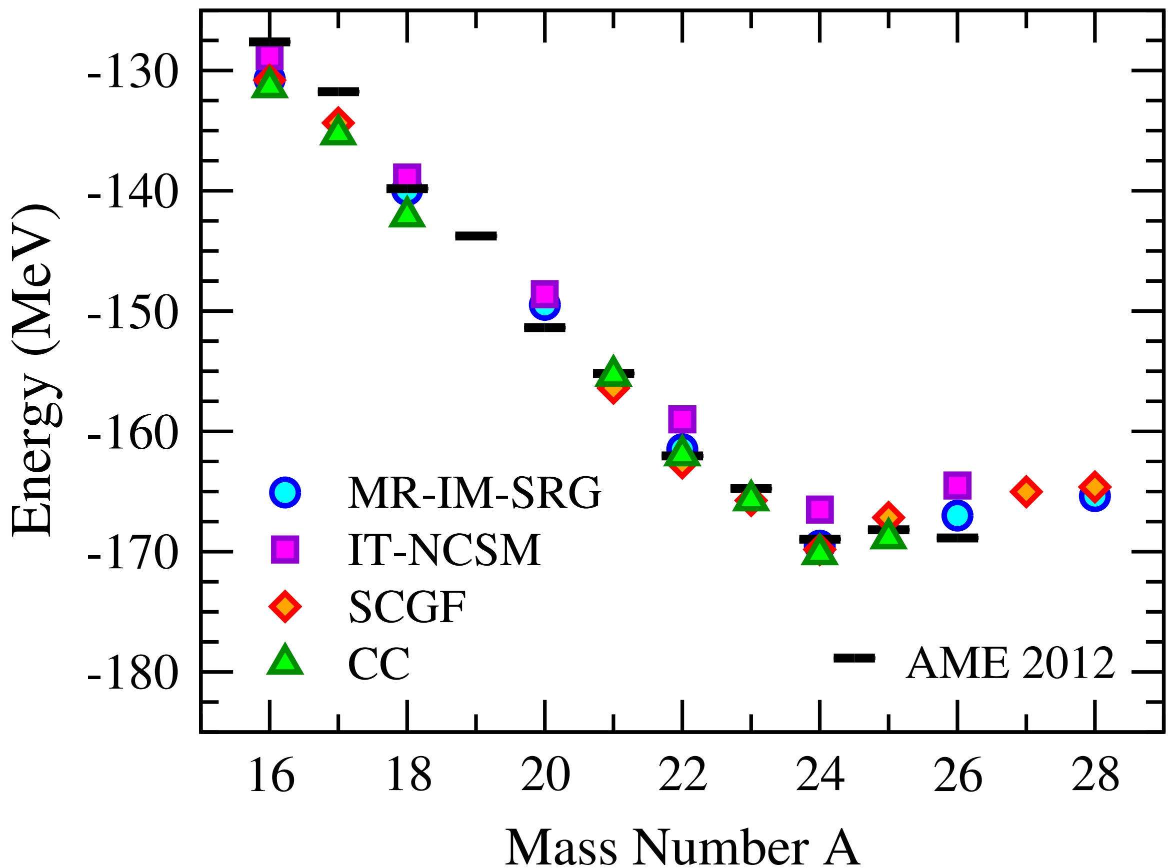
Ab initio calculations of neutron-rich oxygen isotopes

based on same NN+3N interactions with different many-body methods

CC theory/CCEI
Hagen et al., PRL (2012),
Jansen et al., PRL (2014)

Multi-Reference
In-Medium SRG
and IT-NCSM
Hergert et al., PRL (2013)

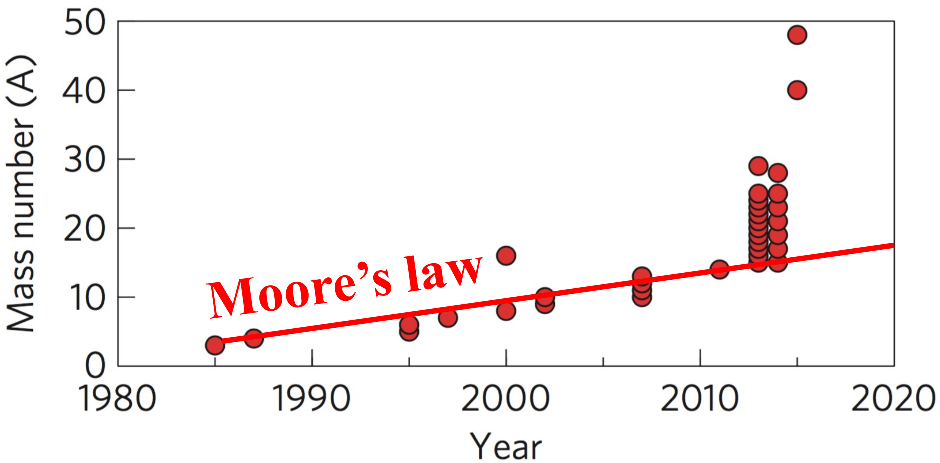
Self-Consistent
Green's Functions
Cipollone et al., PRL (2013)



Many-body calculations of medium-mass nuclei have smaller uncertainty compared to uncertainties in nuclear forces

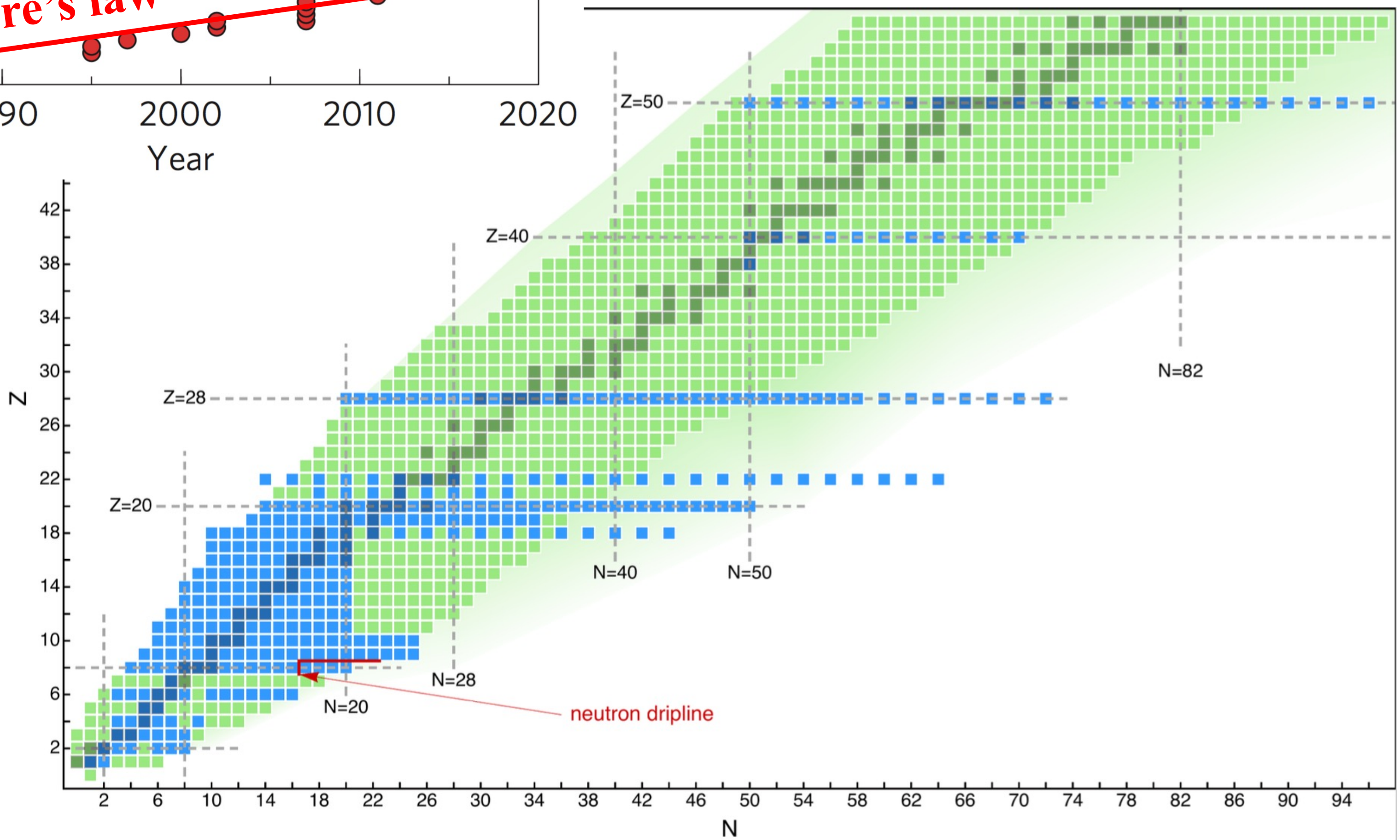
Ab initio calculations of nuclei

great progress in last 5 years to access nuclei up to A ~ 50



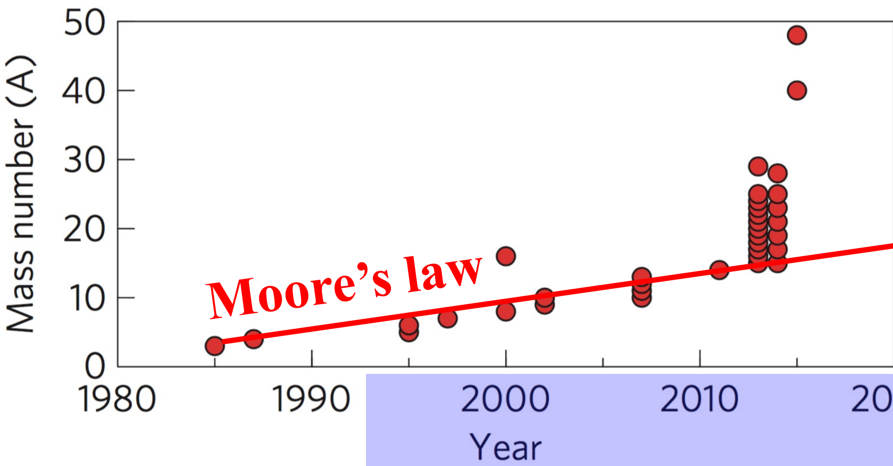
from Hagen et al., Nature Phys. (2016)

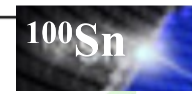
from Hergert et al., Phys. Rep. (2016)

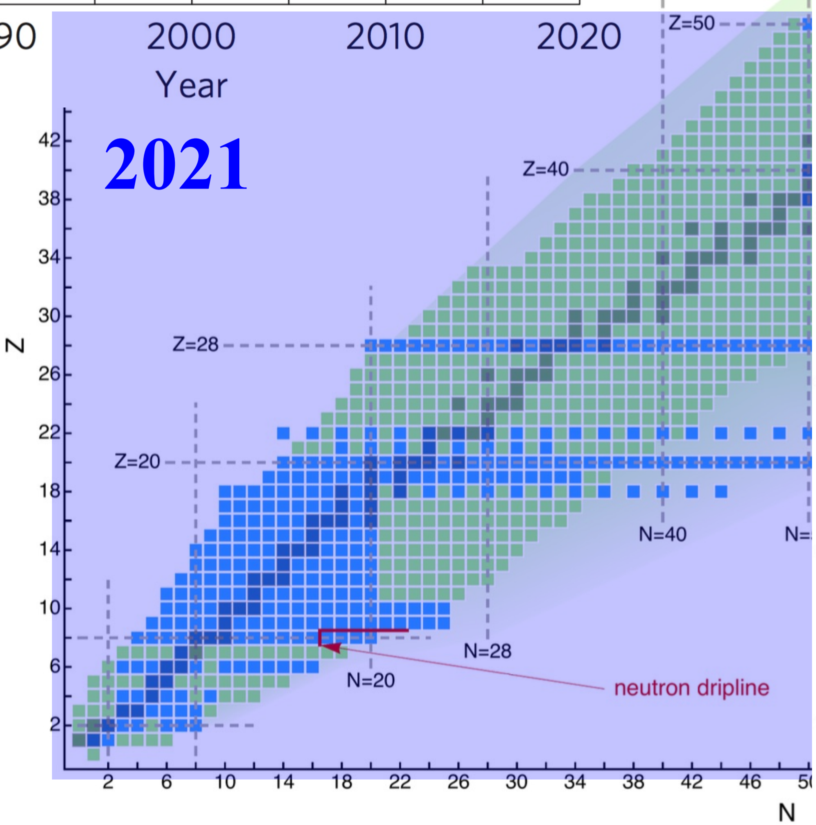


Ab initio calculations

great progress in last 5 years to access nucle





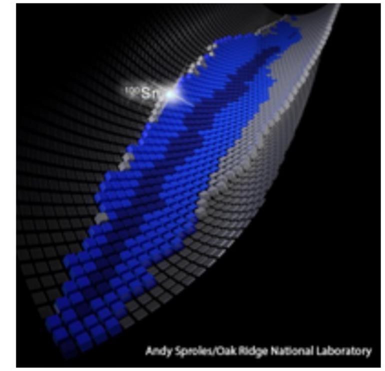


Editors' Suggestion

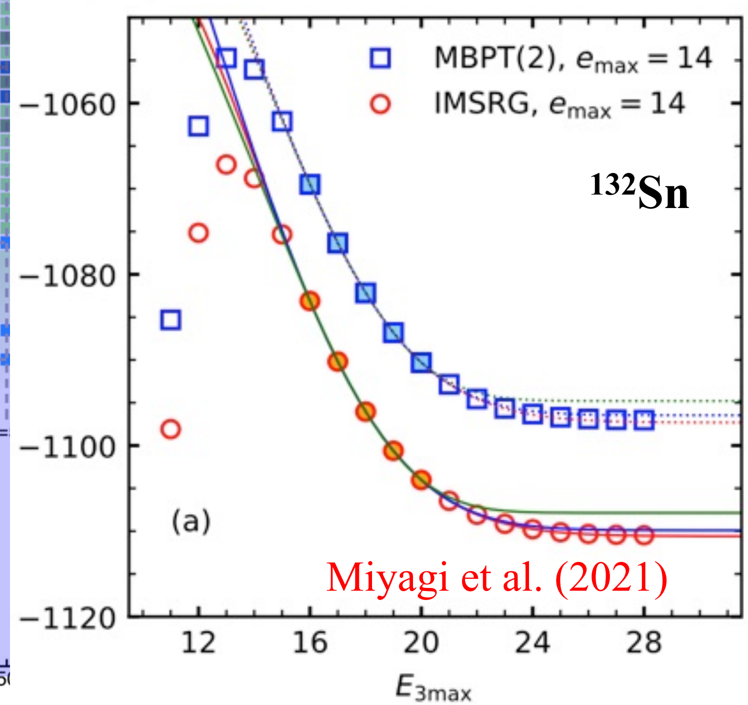
Structure of the Lightest Tin Isotopes

T. D. Morris, J. Simonis, S. R. Stroberg, C. Stumpf, G. Hagen, J. D. Holt, G. R. Jansen, T. Papenbrock, R. Roth, and A. Schwenk

Phys. Rev. Lett. **120**, 152503 (2018) – Published 12 April 2018



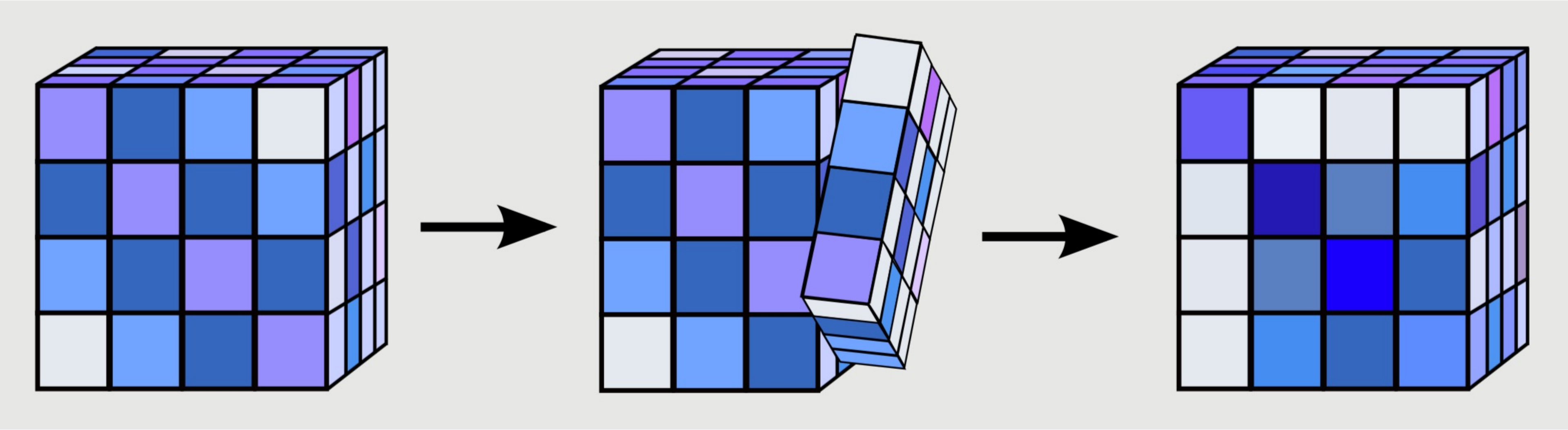
Ab-inito calculations of ^{100}Sn with $N = Z = 50$ predict it to be doubly magic.



In-medium similarity renormalization group

Tsukiyama, Bogner, AS, PRL (2011), Hergert et al., Phys. Rep. (2016)

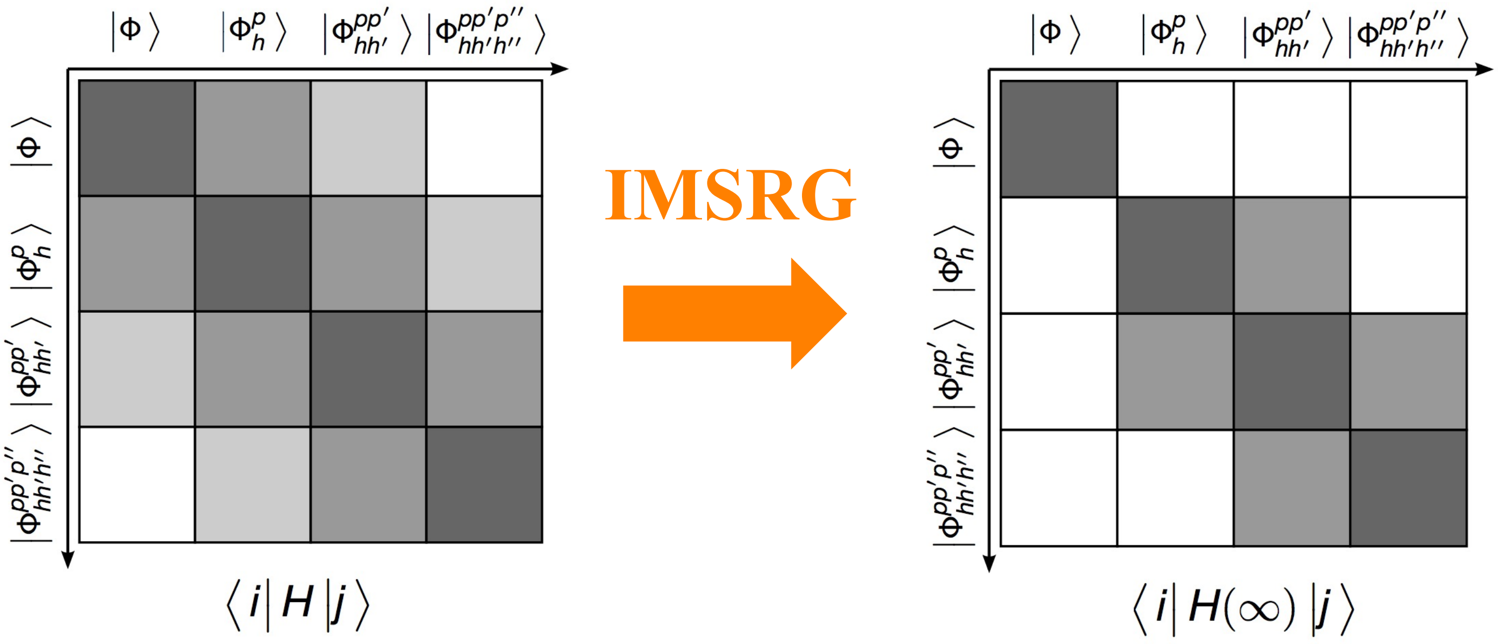
continuous transformation to block-diagonal form (→ decoupling)



In-medium similarity renormalization group

Tsukiyama, Bogner, AS, PRL (2011), Hergert et al., Phys. Rep. (2016)

flow equations to decouple higher-lying particle-hole states



s = 0

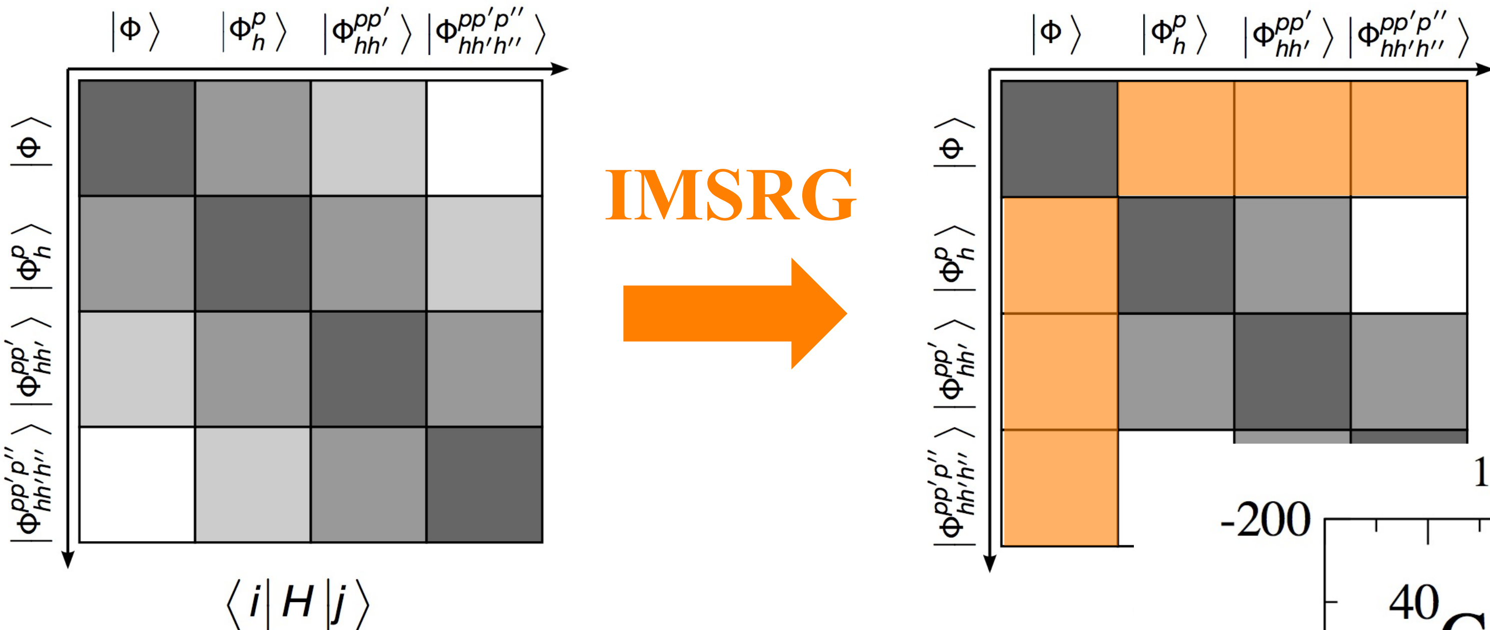
s = ∞

$$H(s) = U(s)H(0)U^\dagger(s)$$

In-medium similarity renormalization group

Tsukiyama, Bogner, AS, PRL (2011), Hergert et al., Phys. Rep. (2016)

flow equations to decouple higher-lying particle-hole states

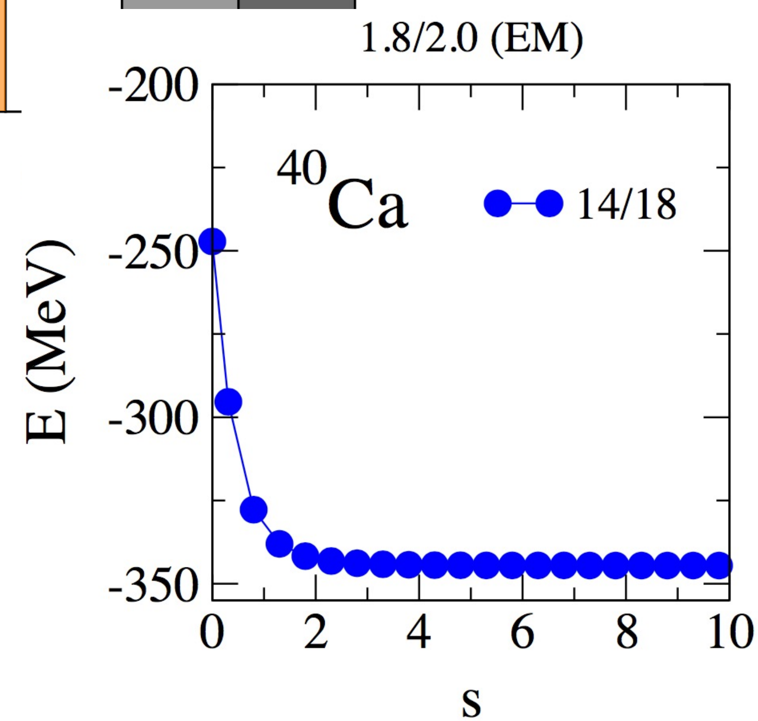


s = 0

$$H(s) = U(s)H(0)U^\dagger(s)$$

$$\frac{d}{ds}H(s) = [\eta(s), H(s)]$$

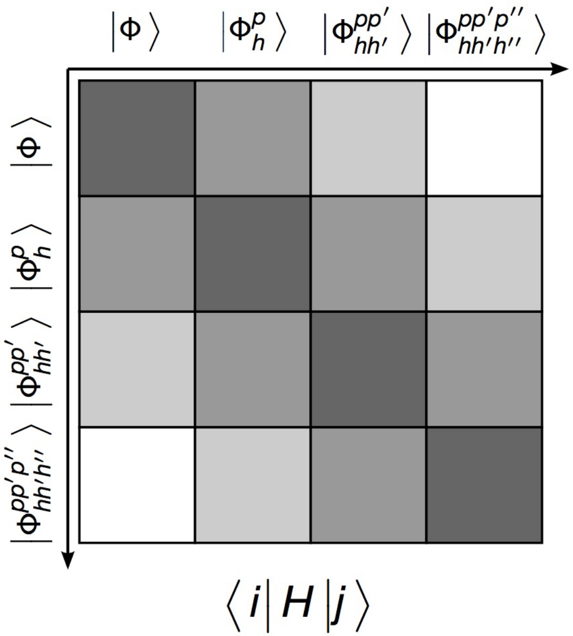
with generator $\eta = [H^d(s), H^{od}(s)]$



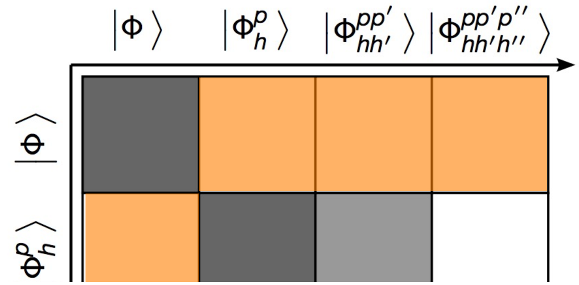
In-medium similarity renormalization group

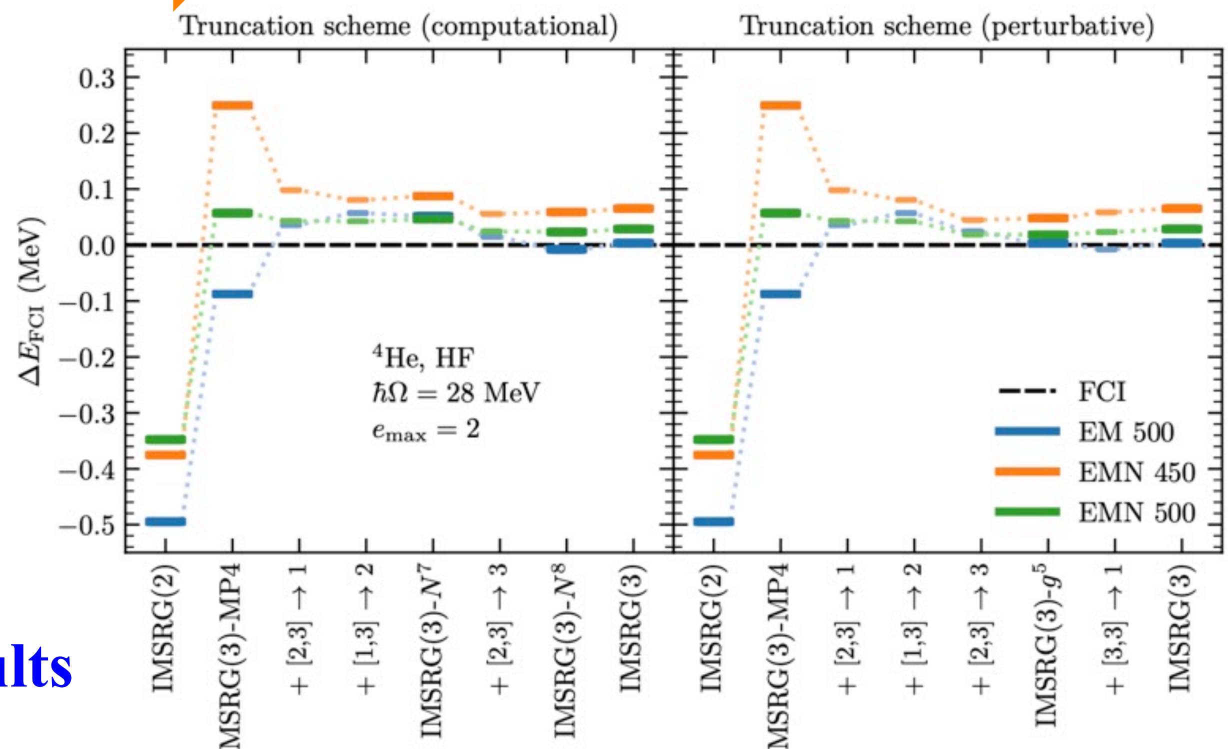
Tsukiyama, Bogner, AS, PRL (2011), Hergert et al., Phys. Rep. (2016)

flow equations to decouple higher-lying particle-hole states



IMSRG





First IMSRG(3) results

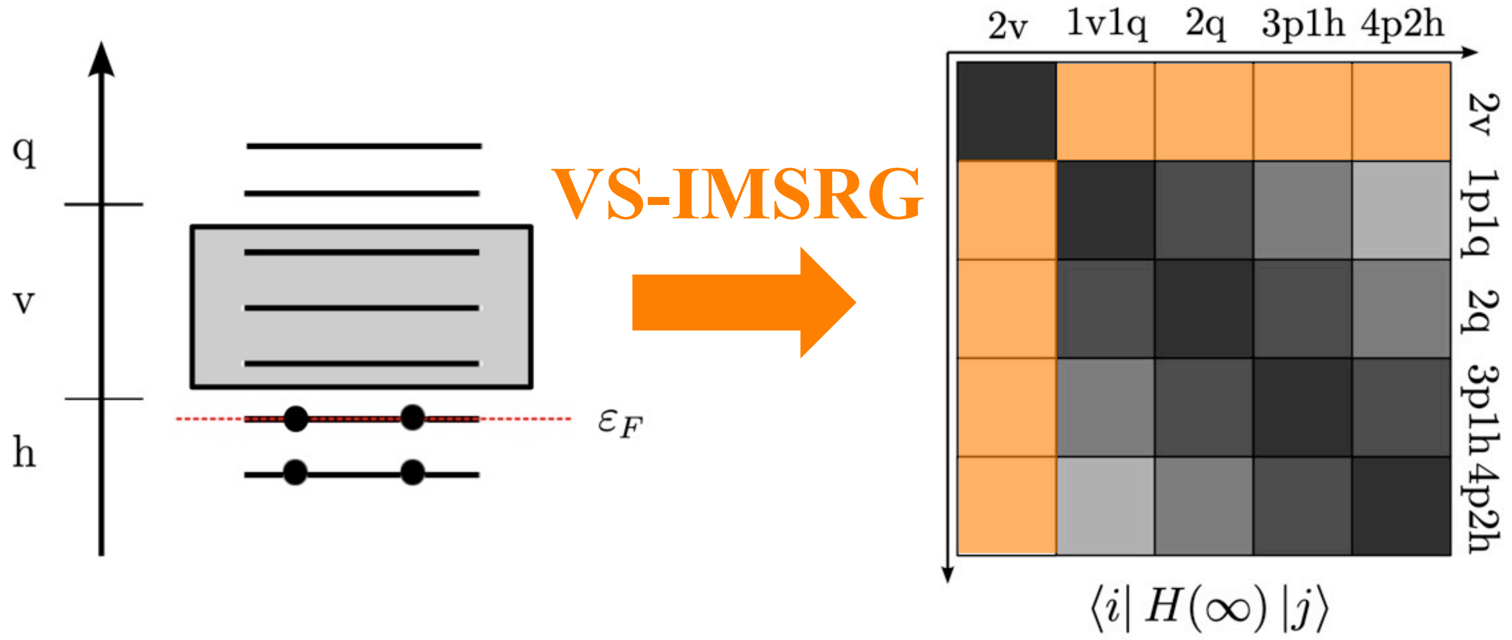
Heinz et al. (2021)

Valence space IMSRG

Tsukiyama et al. (2012); Bogner et al., PRL (2014); Stroberg et al., PRL (2016), PRL (2018)

decouple valence space of few particles

followed by exact diagonalization in valence space



Valence space IMSRG

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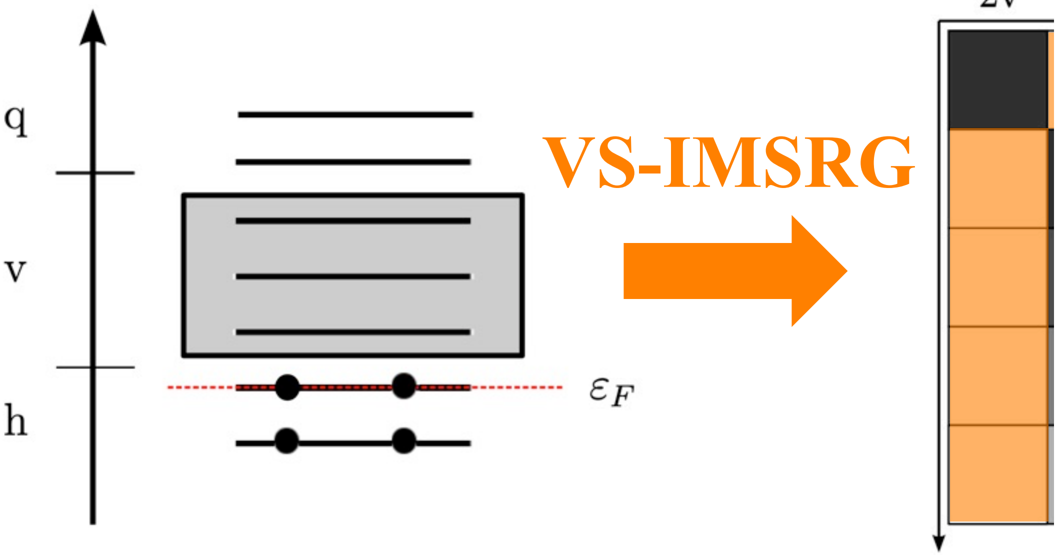
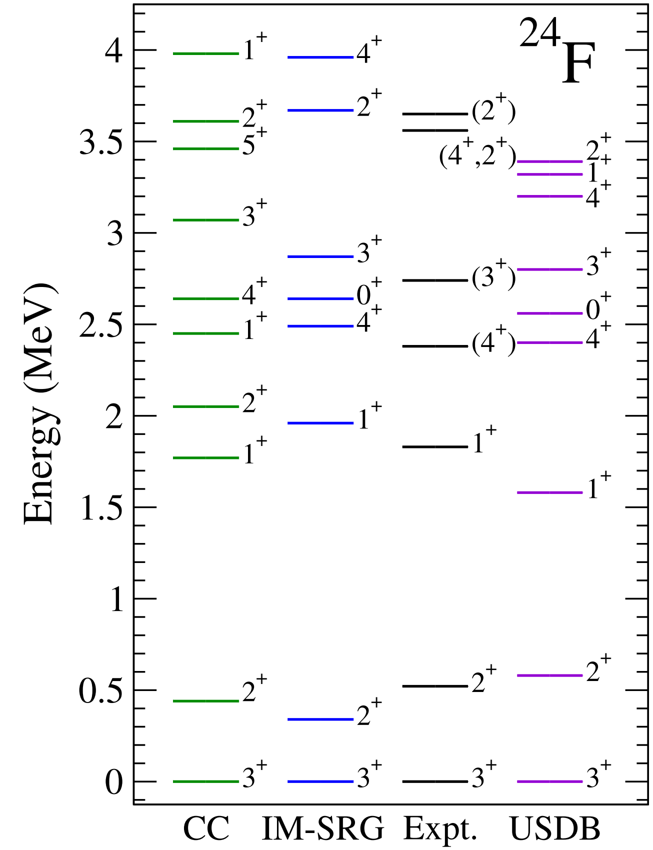


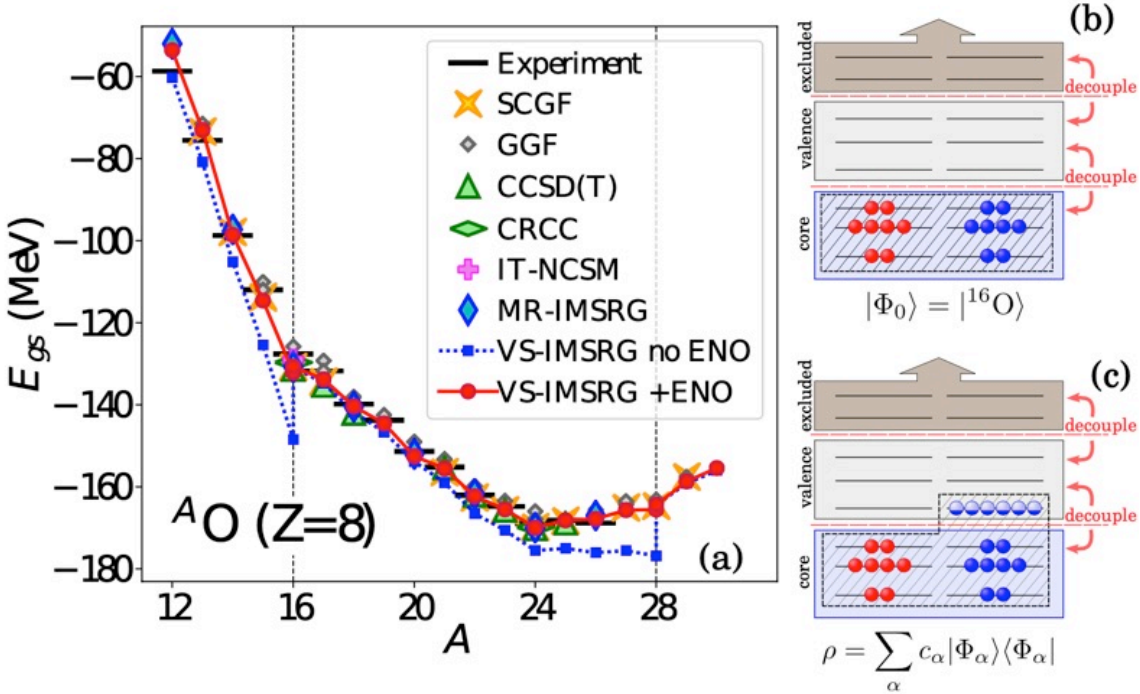


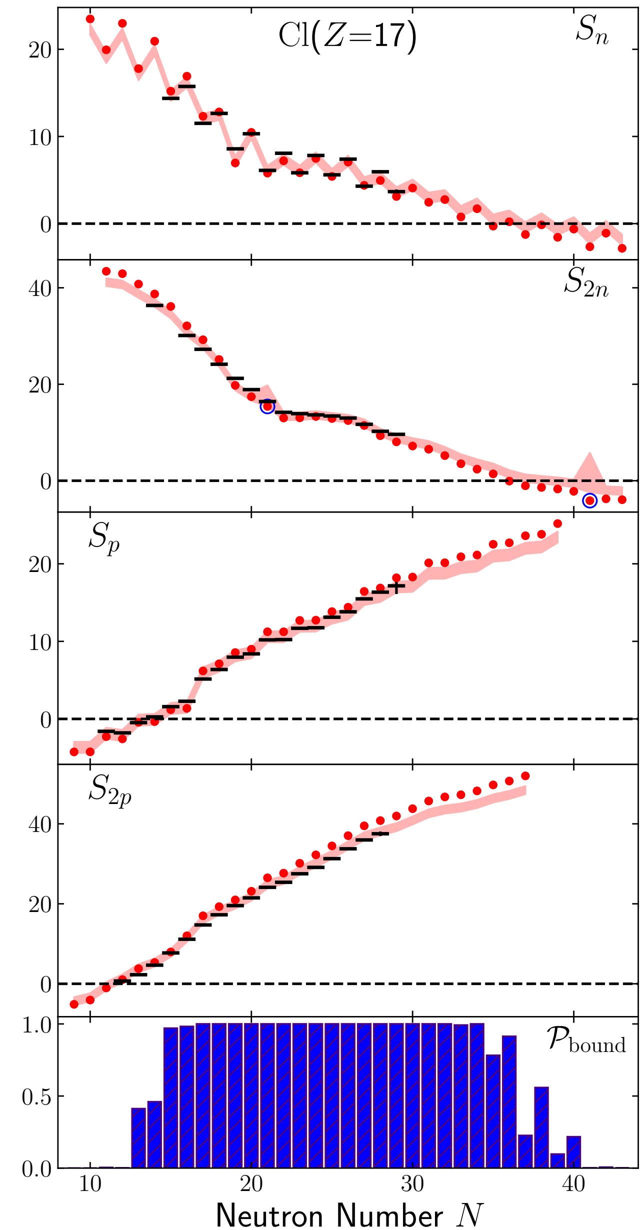
Cáceres et al., PRC (2015)

Valence space IMSRG

with ensemble normal ordering to move along isotopic chains

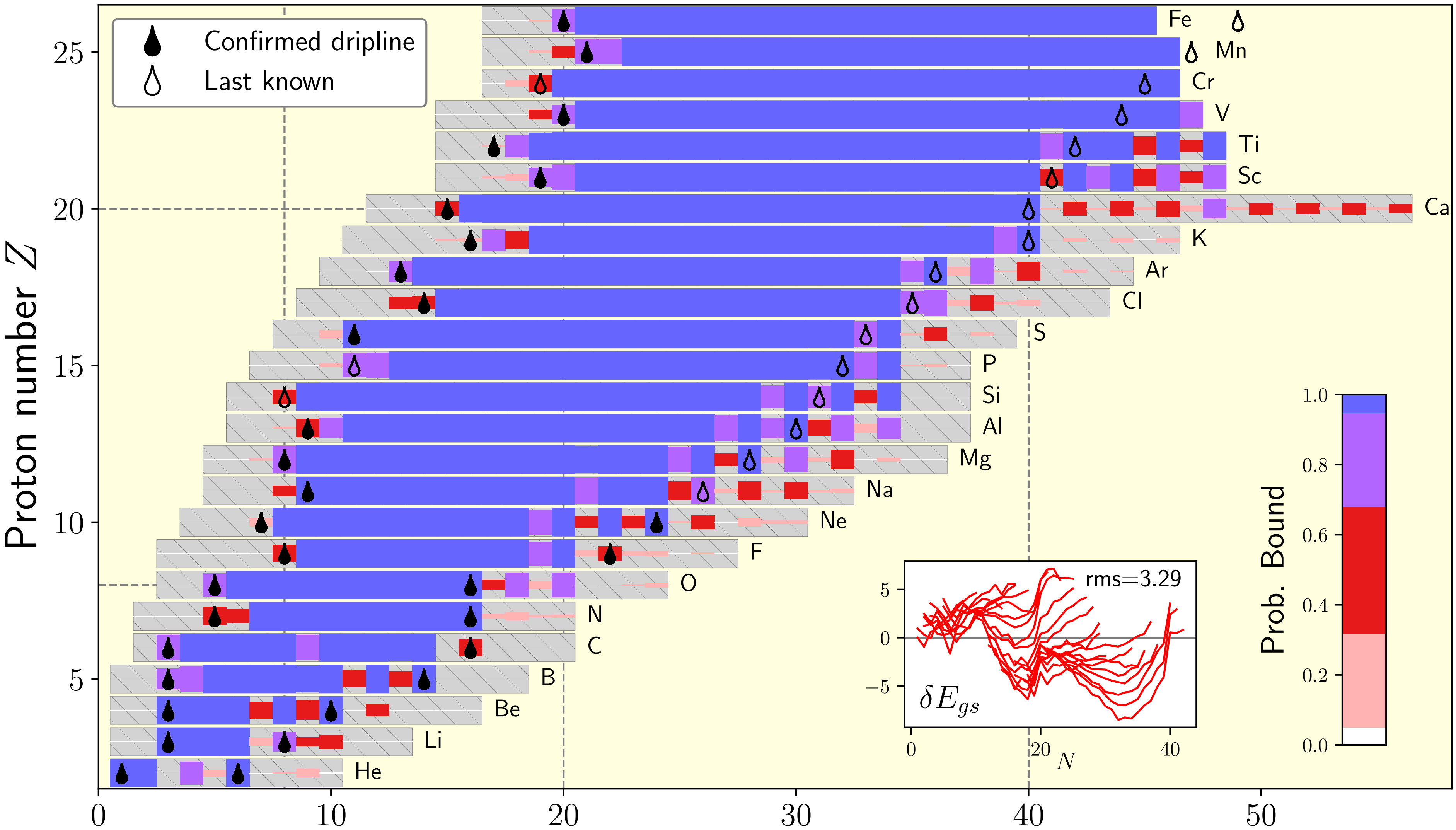
Stroberg et al., PRL (2016), PRL (2018), PRL (2021)





enables access to all open-shell nuclei!

Nuclear landscape based on a chiral NN+3N interaction

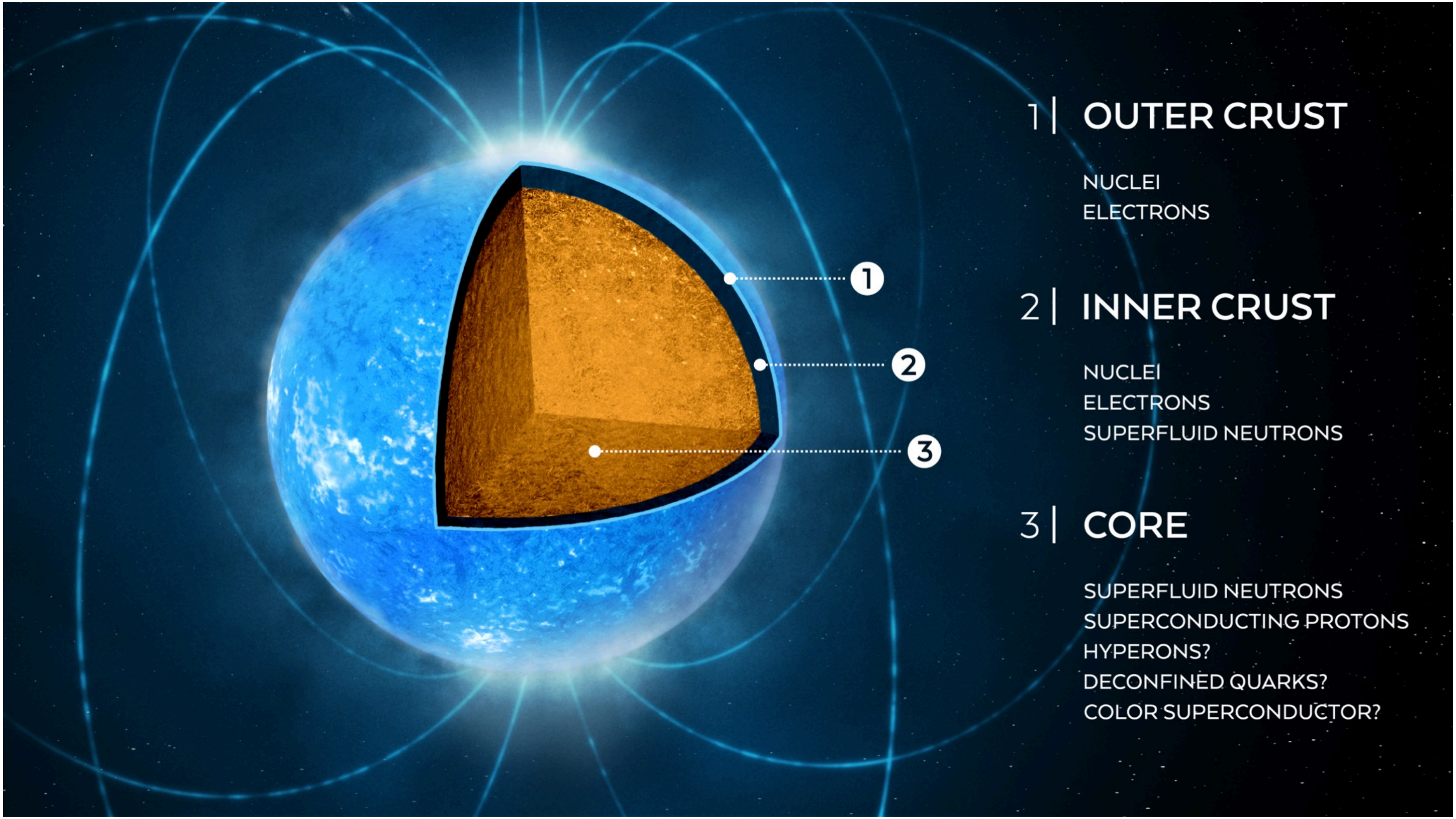


Stroberg, Holt, AS, Simonis, PRL (2021)

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

Extreme matter in neutron stars

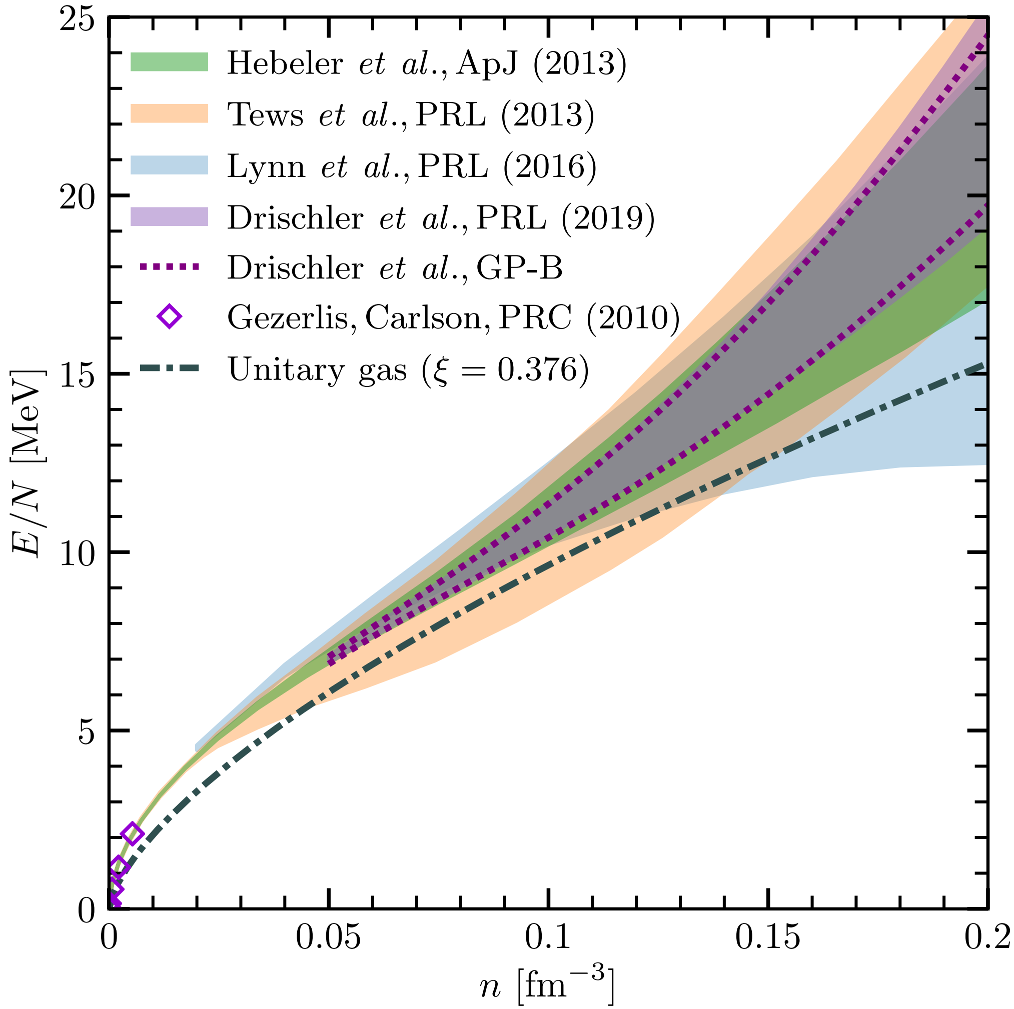
governed by the same strong interactions



Watts et al., RMP (2016)

Chiral EFT calculations of neutron matter

good agreement up to saturation density for neutron matter
nonlocal/local int. and different calcs. (MBPT, QMC, SCGF, CC)

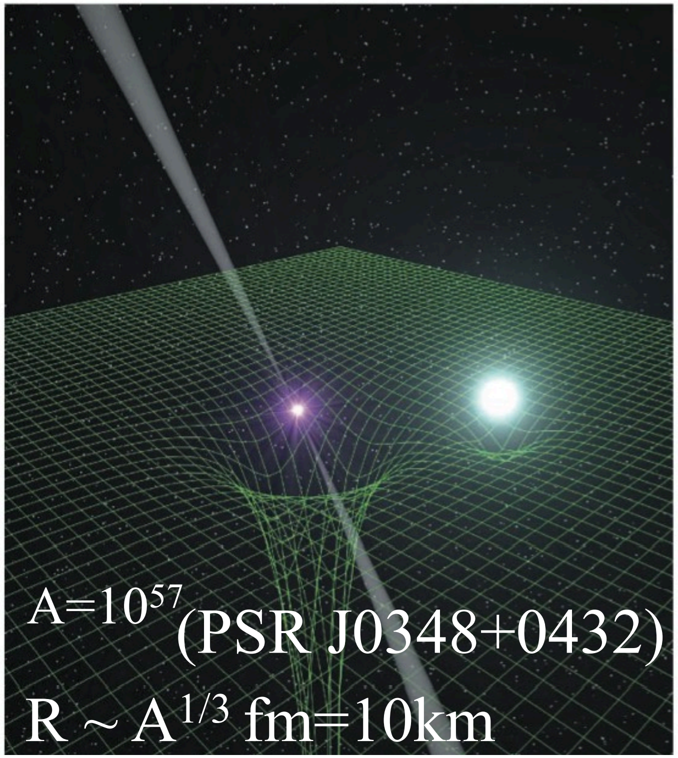


slope determines pressure of neutron matter

from Huth, Wellenhofer, AS (2020)

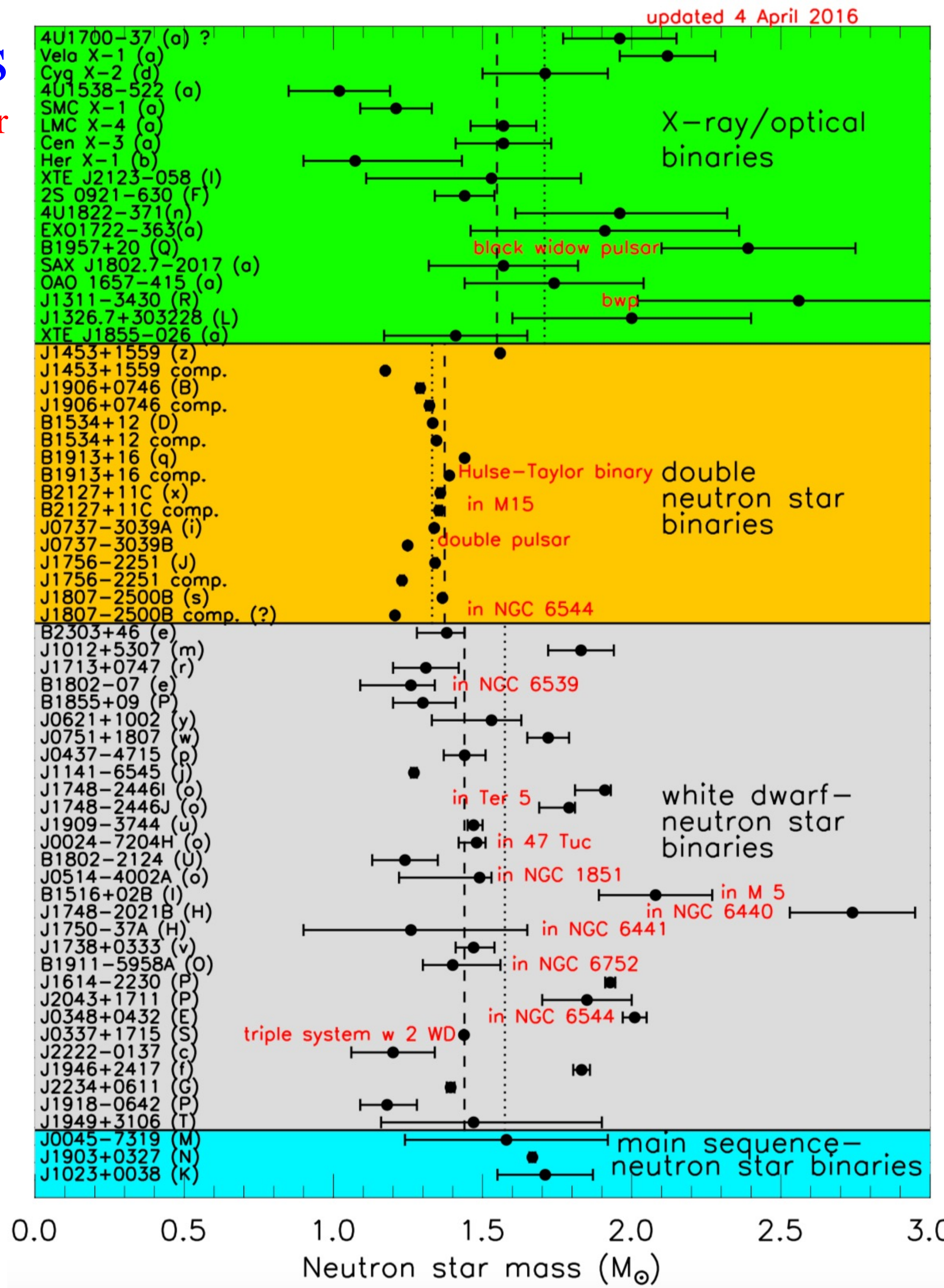
Neutron star masses

from Jim Lattimer



three 2 M_{sun} neutron stars obs.

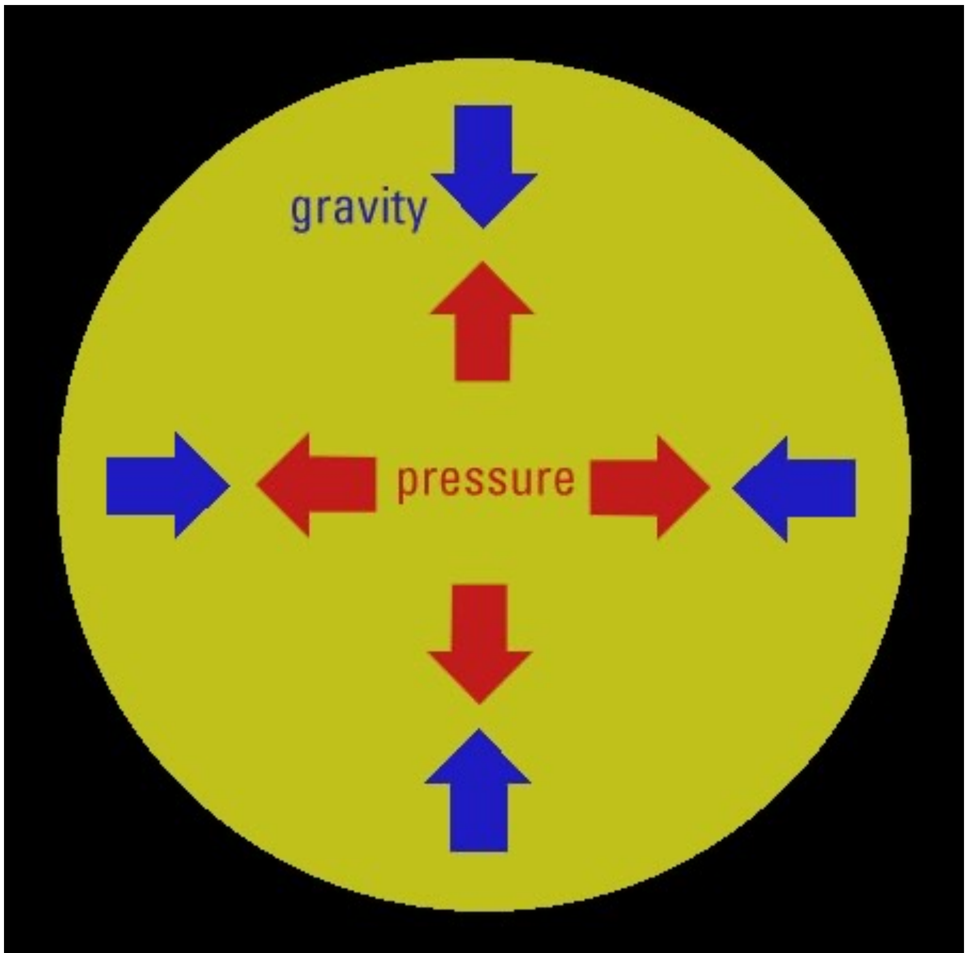
Demorest et al, Nature (2010),
Antoniadis et al., Science (2013),
2.08±0.07 M_{sun} Fonseca et al. (2021)



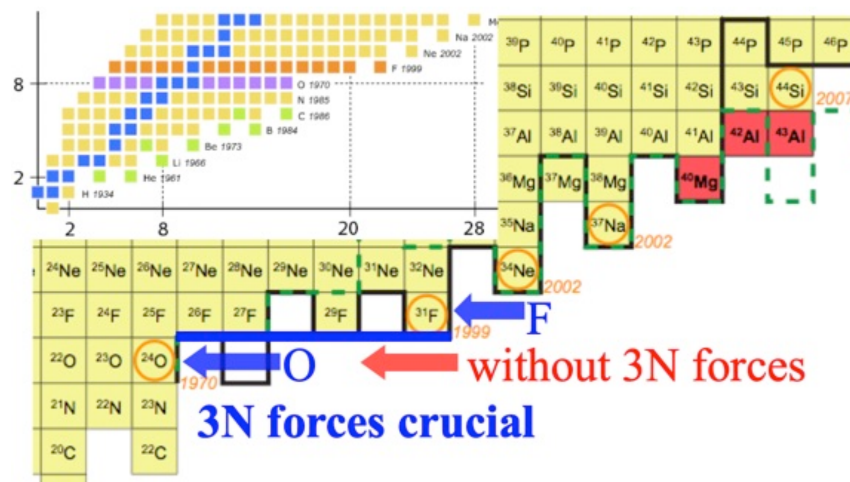
Why are stars stable?

due to their mass, stars would undergo gravitational collapse

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

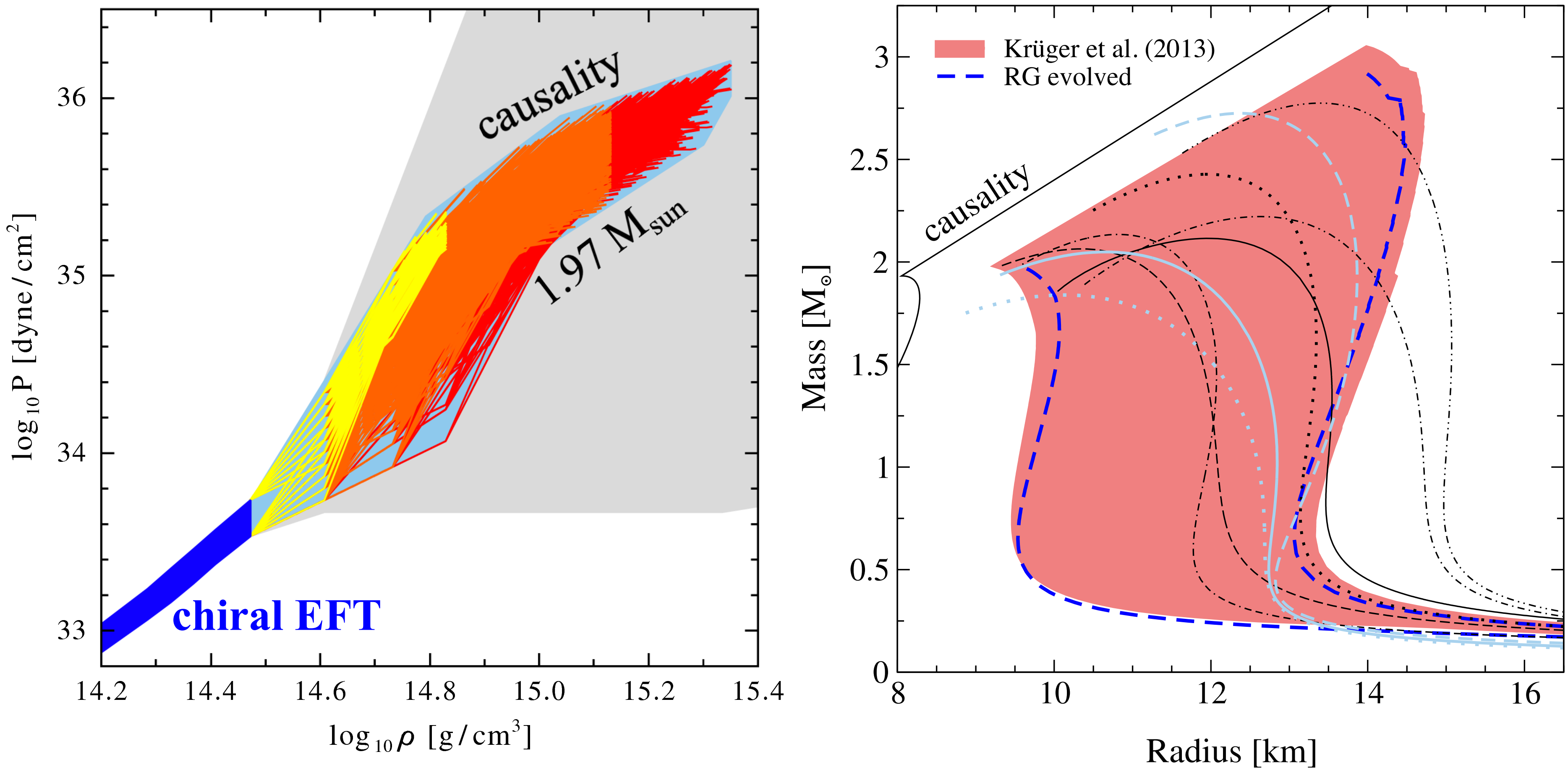


For neutrons:
pressure of Fermi gas
plus strong interactions



Impact on neutron stars Hebeler et al., 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 ρ_0 modest central densities

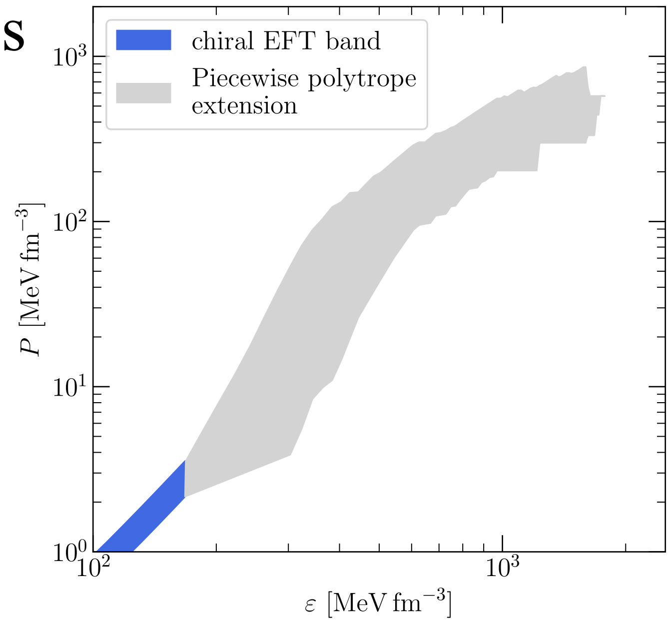
speed of sound needs to exceed ~0.65c to get 2 M_{sun} stars Greif et al., ApJ (2020)

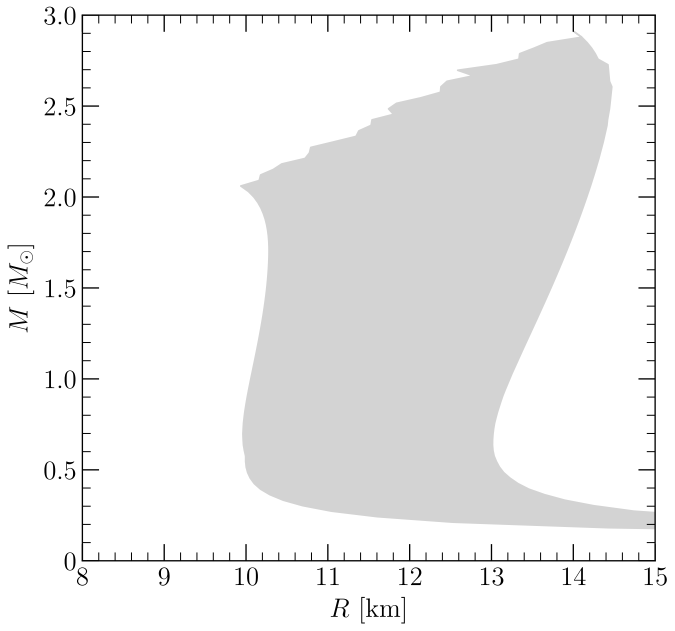
Neutron star EOS: chiral EFT plus general extensions

piecweise polytropes

Hebeler et al., ApJ (2013)

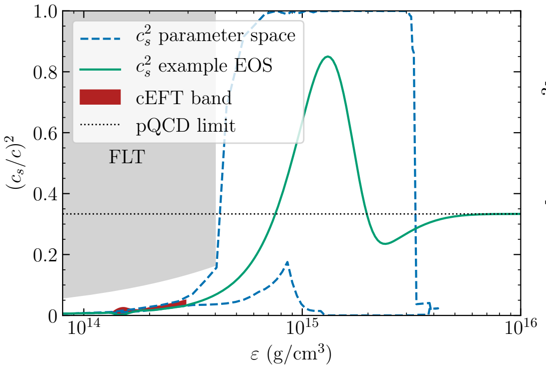
constrained to support 2 M_{sun}

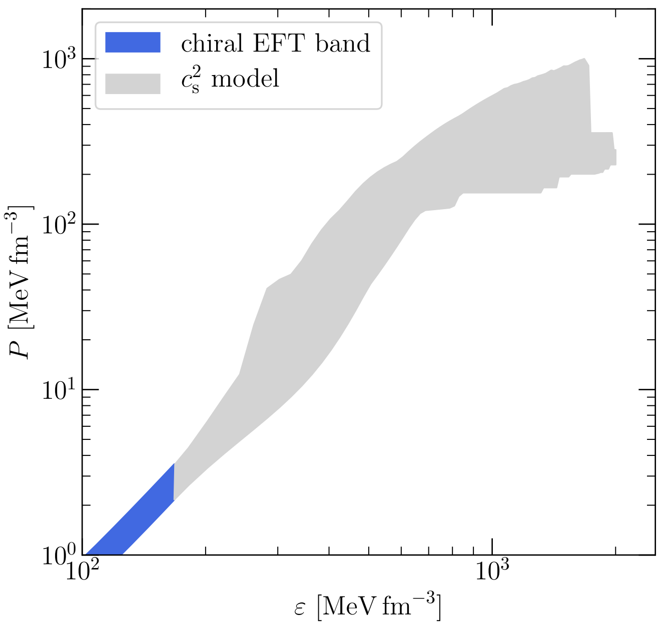


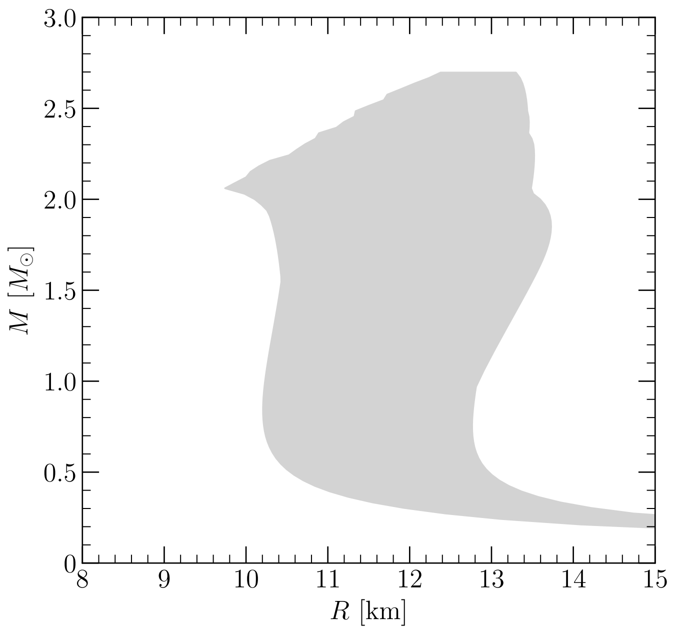


c_s model

Greif et al., MNRAS (2019)





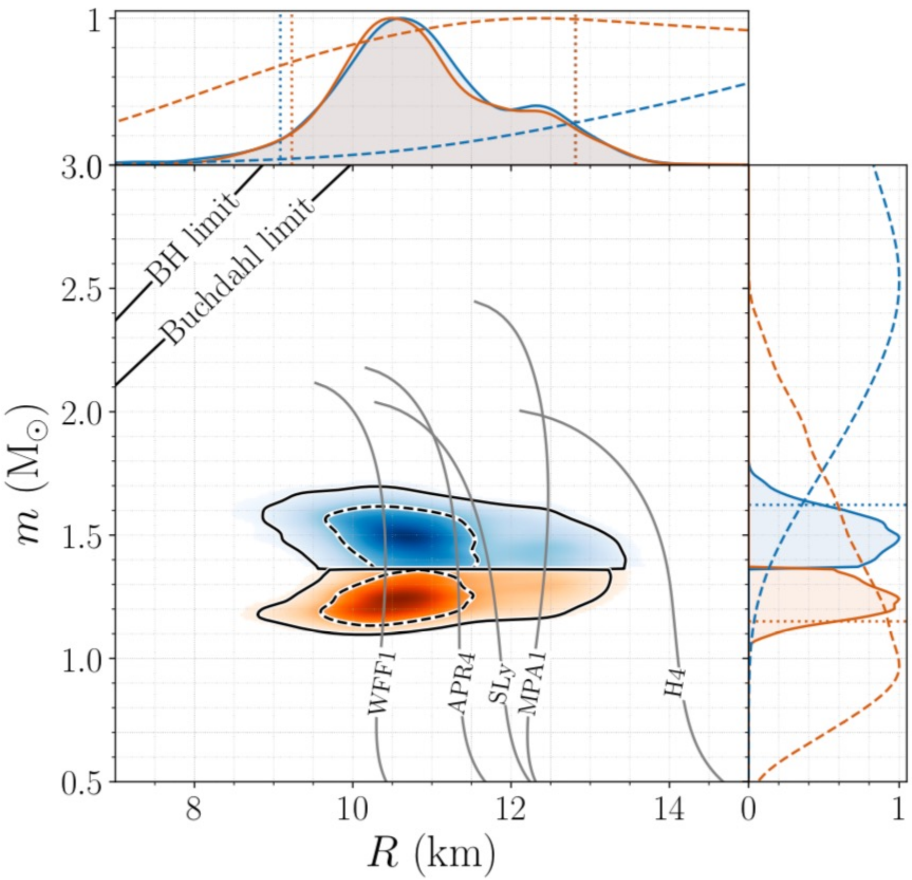


Neutron star radius from GW170817

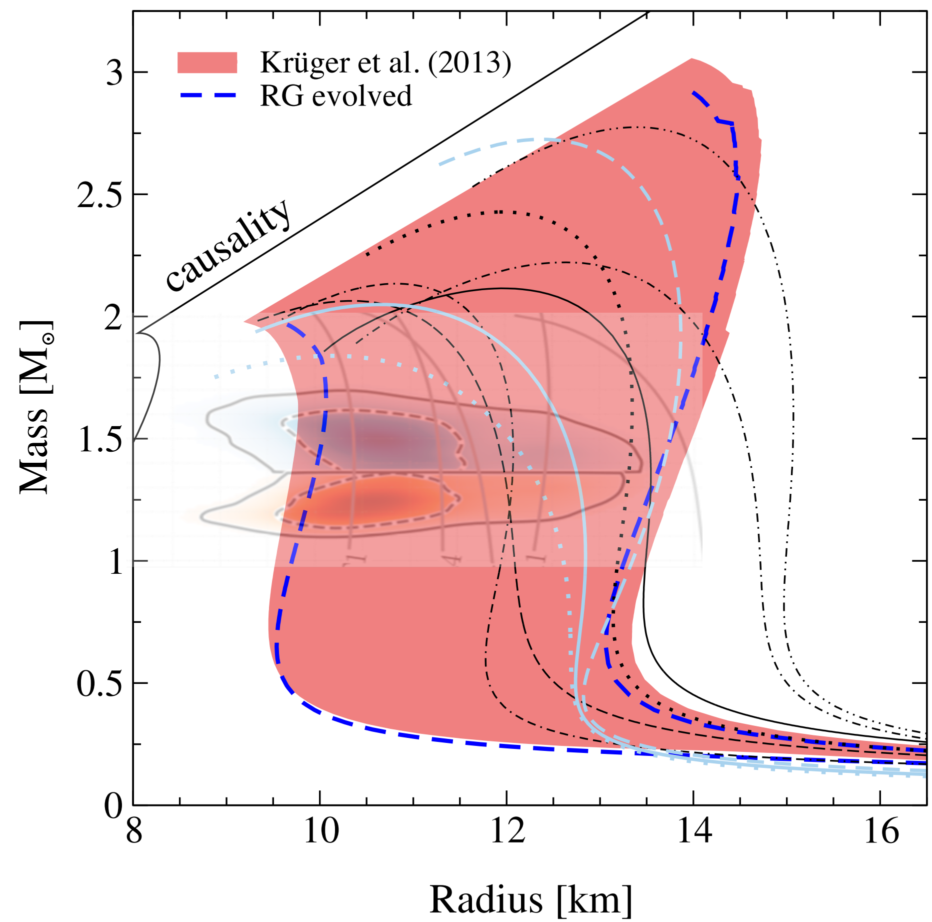
chiral EFT + general EOS extrapolation: 9.7 - 13.9 km for M=1.4 M_{sun}

GW170817: Measurements of neutron star radii and equation of state

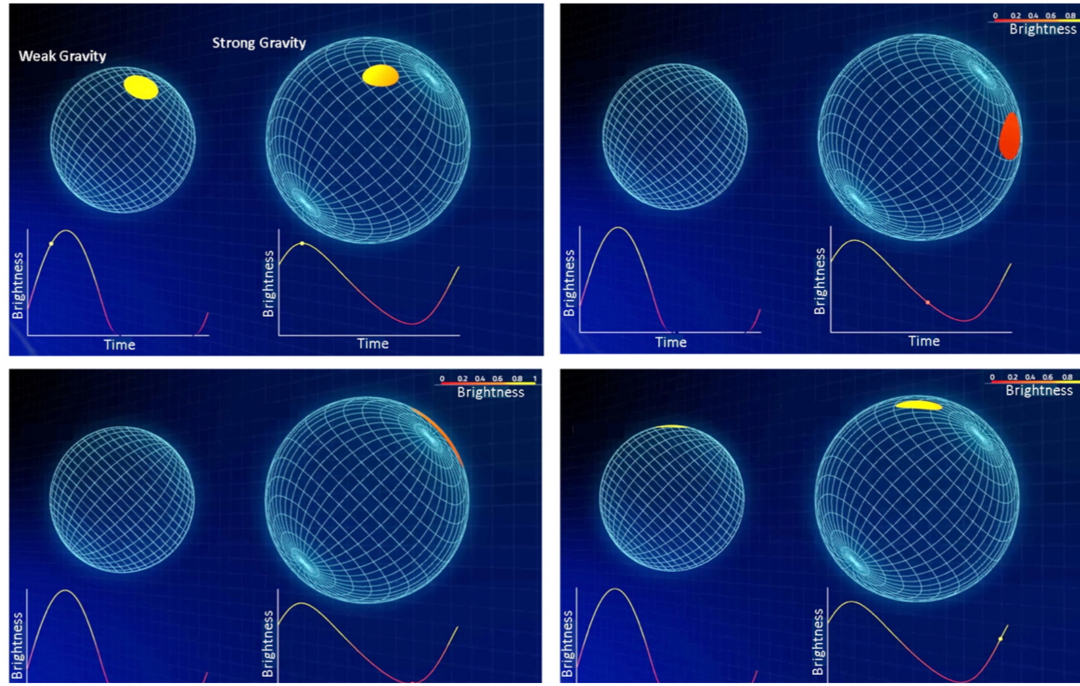
The LIGO Scientific Collaboration and The Virgo Collaboration
(compiled 30 May 2018)



excellent agreement with GW170817 from LIGO/Virgo



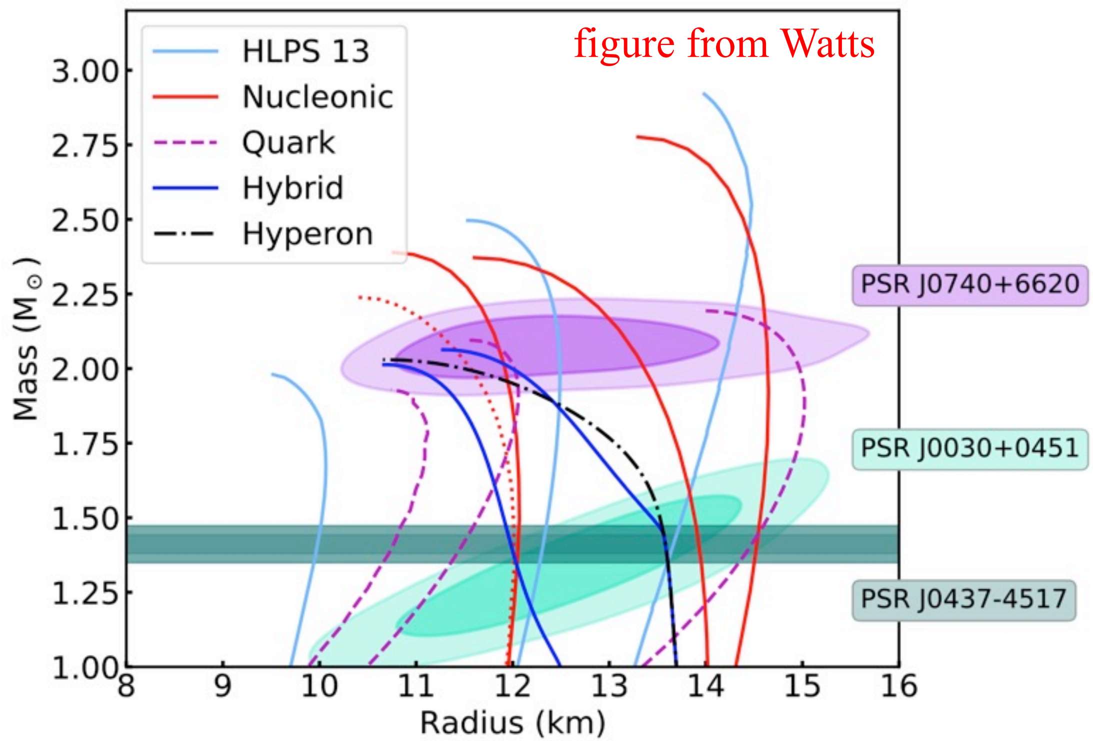
NICER results



Neutron star radius from pulse profile modeling

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

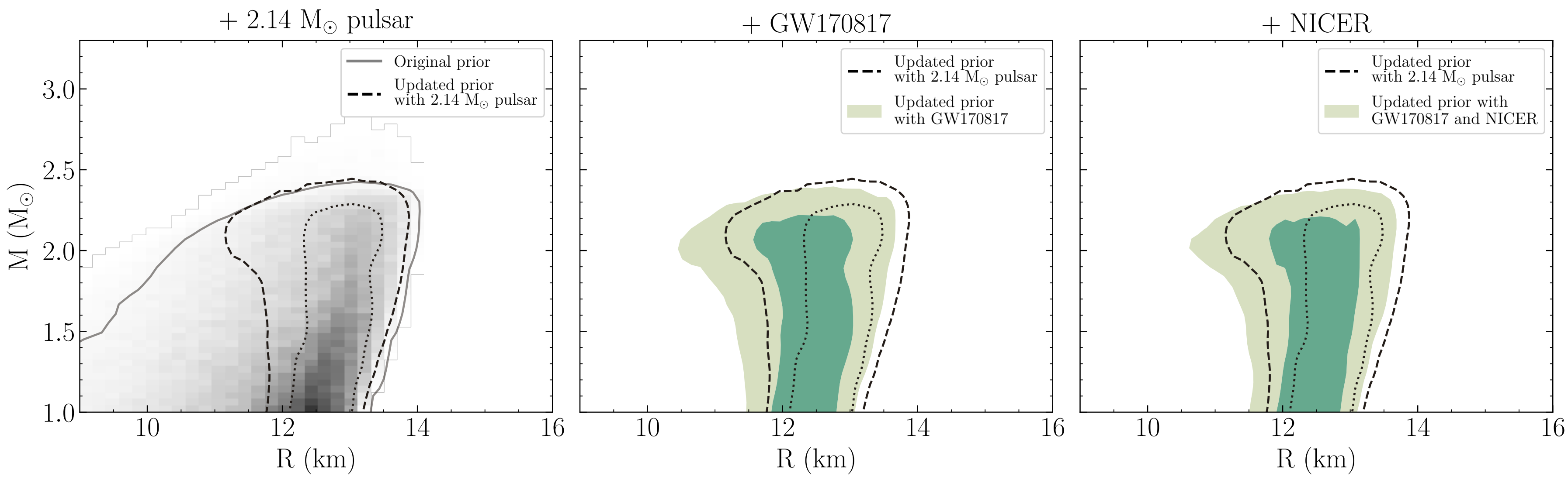
similar results from Illinois-Maryland analysis
Miller et al., ApJL (2019), (2021)



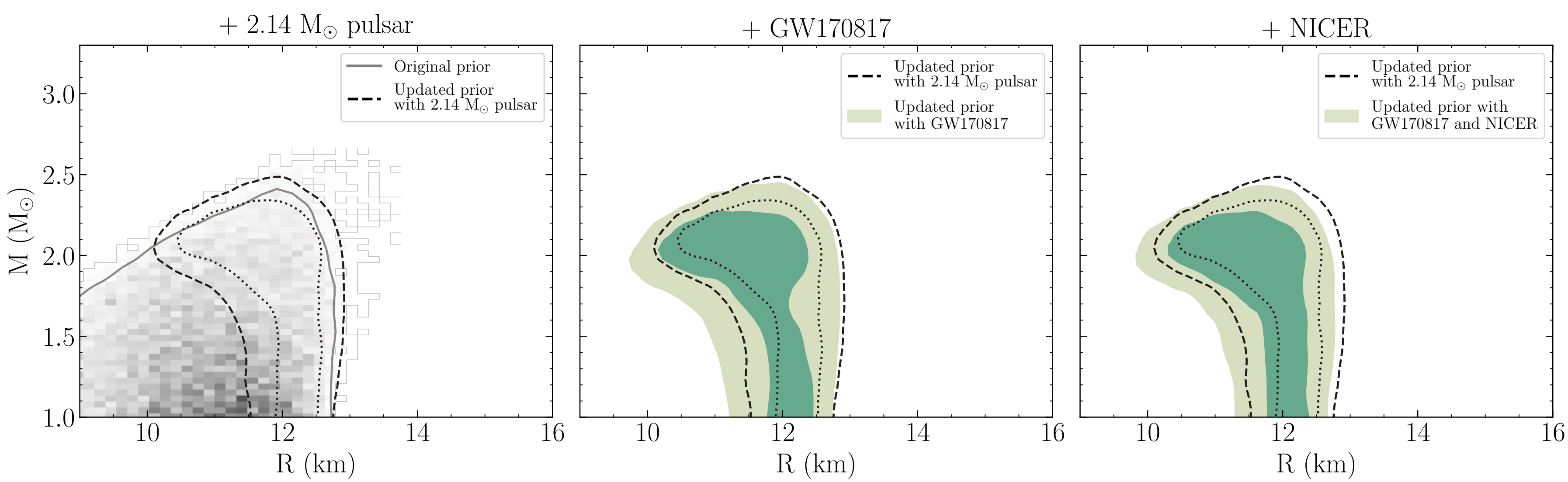
Combined LIGO/Virgo and NICER constraints (J0030 only)

Raaijmakers et al., ApJL (2020)

piecewise polytrope extension



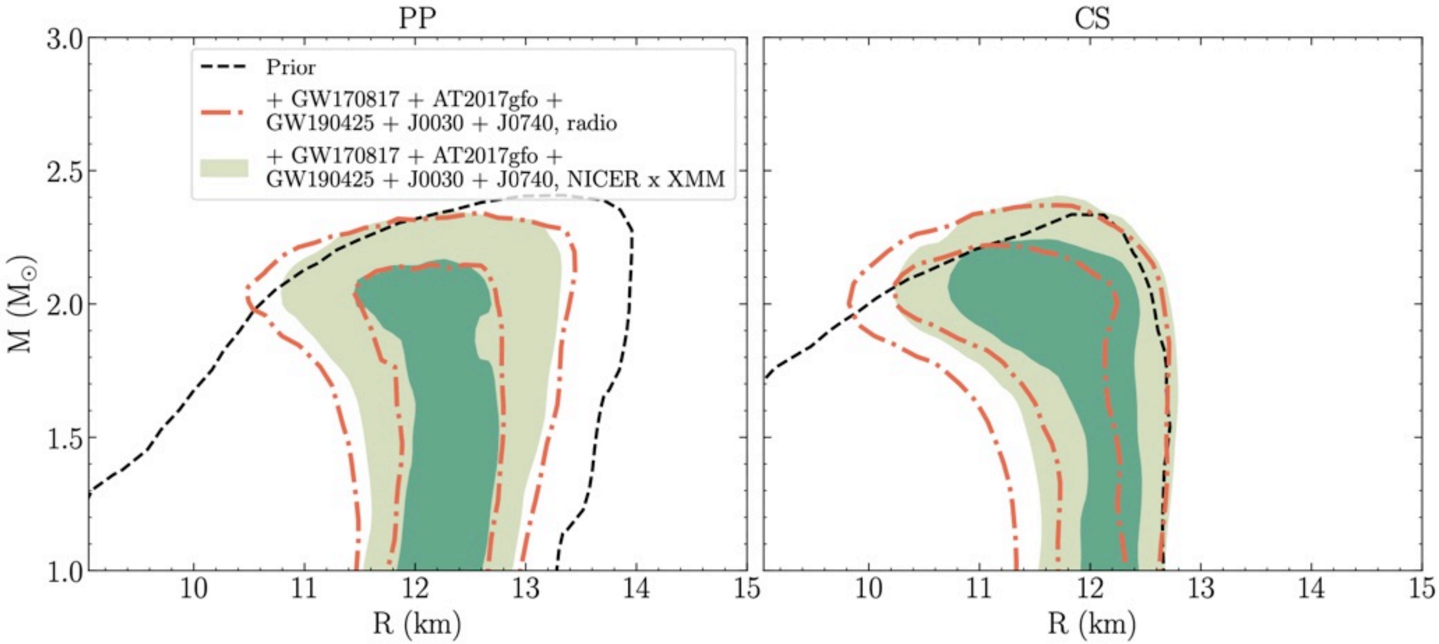
speed of sound model



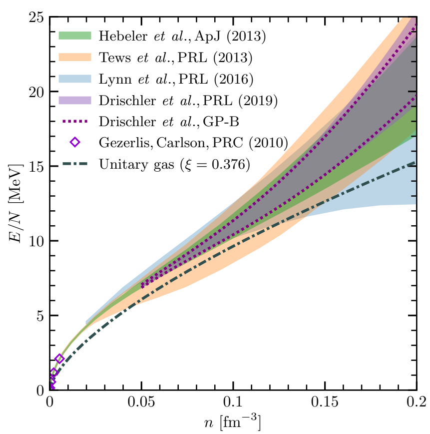
Combined merger and NICER constraints

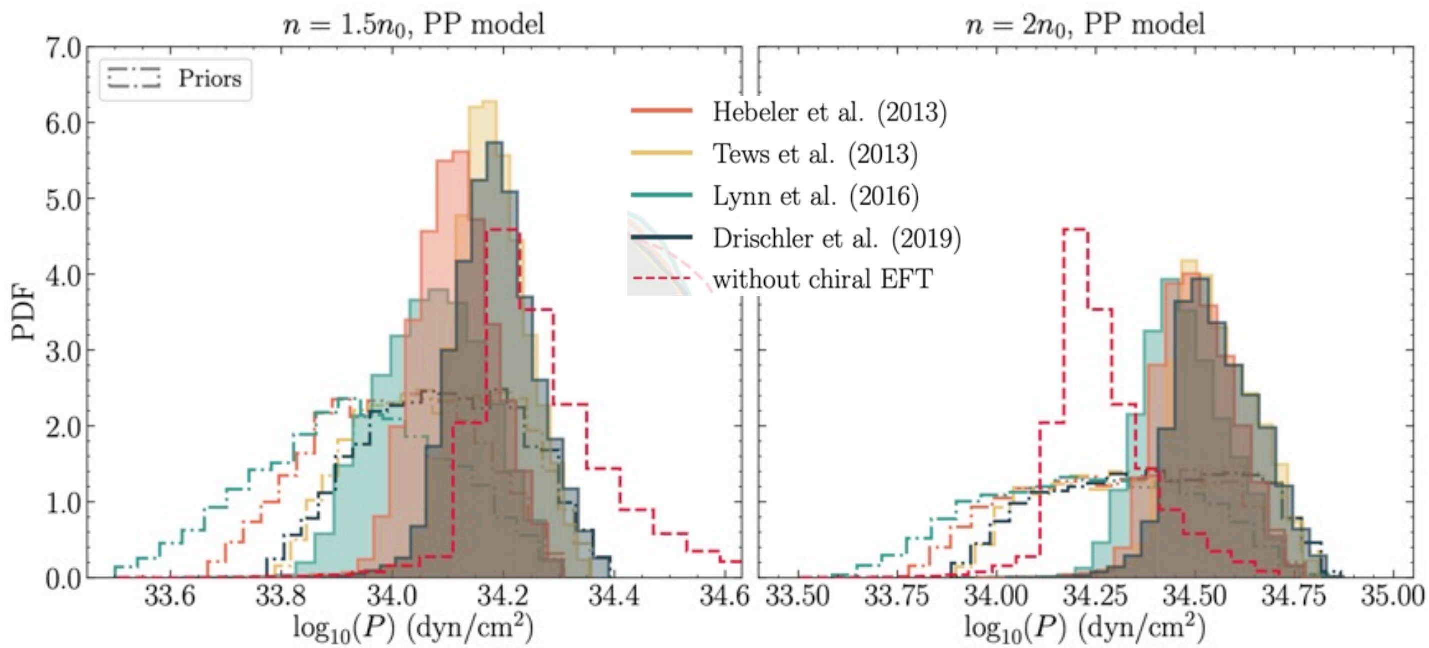
Raaijmakers et al., ApJL (2020), (2021)

for mass-radius



equation of state at 1.5 and 2 n_0



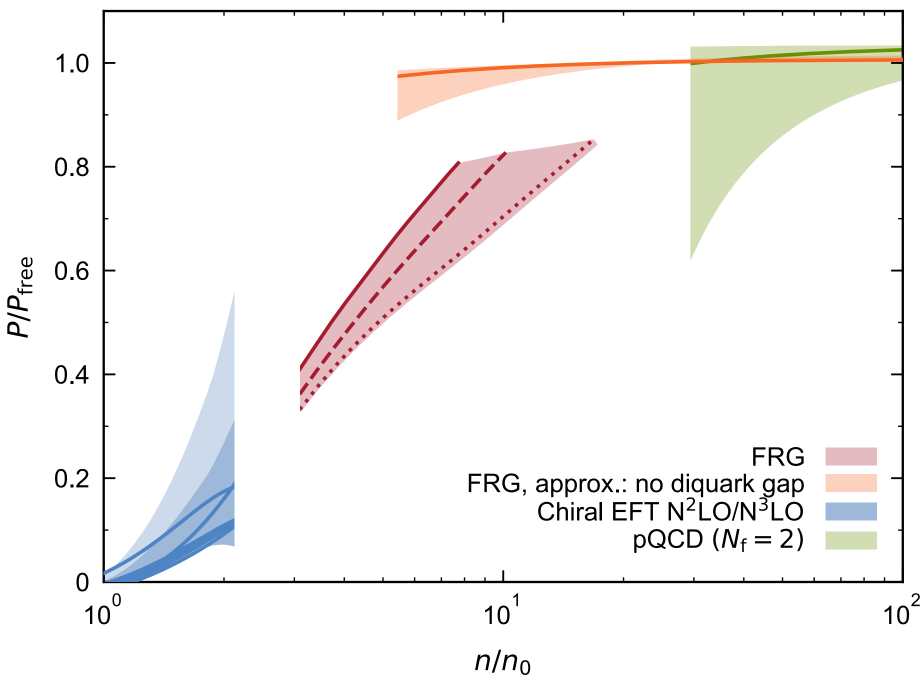


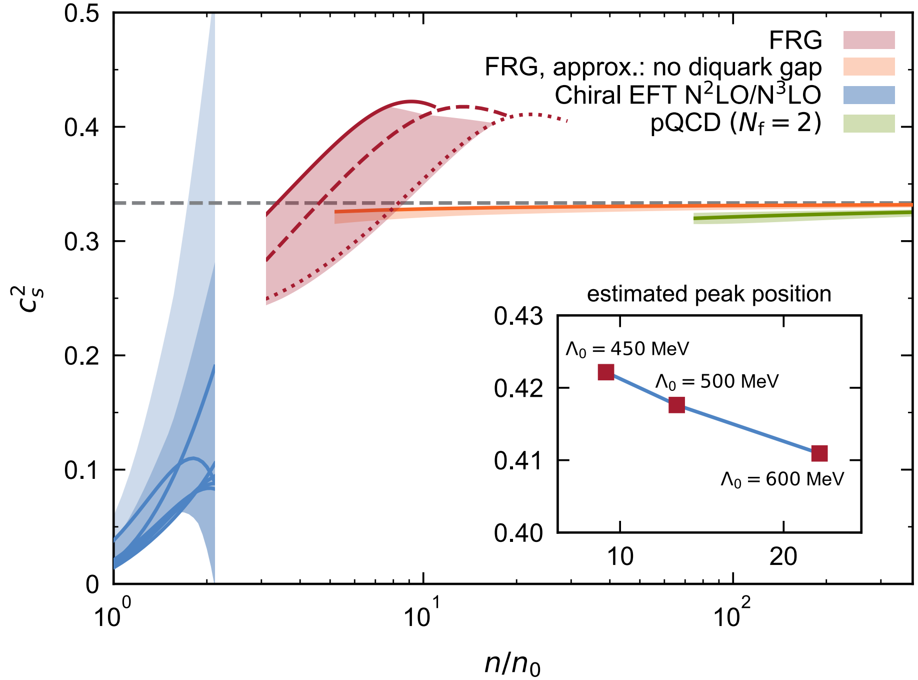
Functional RG: From QCD to intermediate densities

based on QCD at high densities

symmetric matter (m_u=m_d, no s quark, no electroweak interactions)

Leonhardt, Pospiech, Schallmo, Braun et al., PRL (2020)



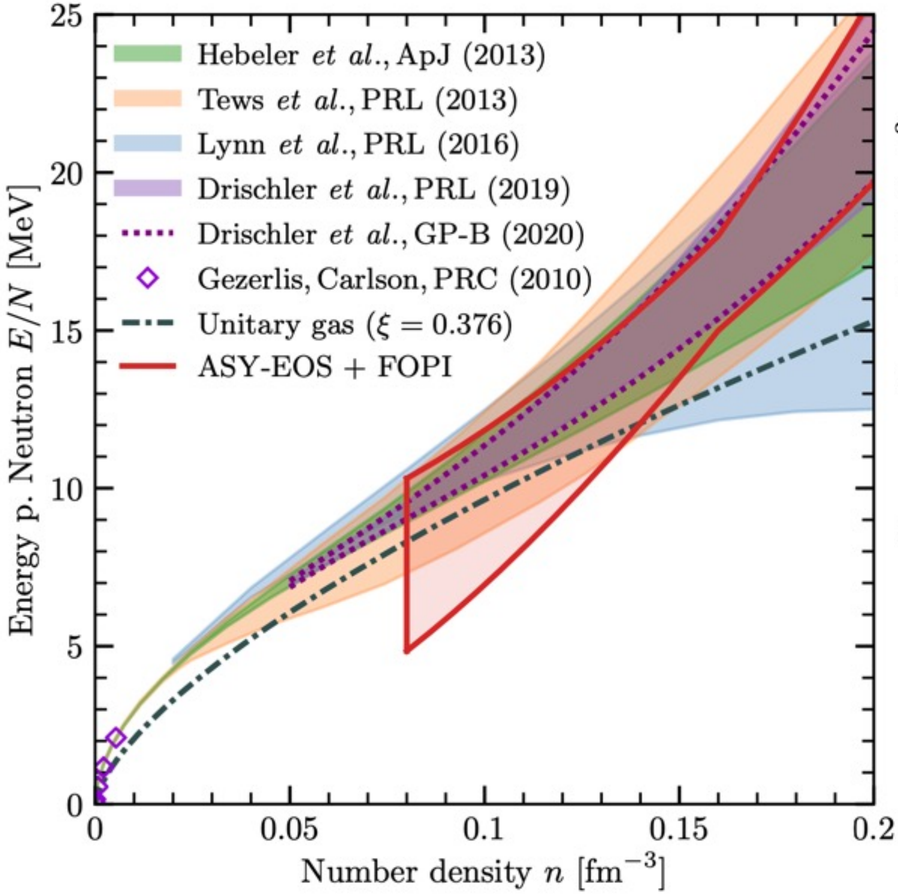


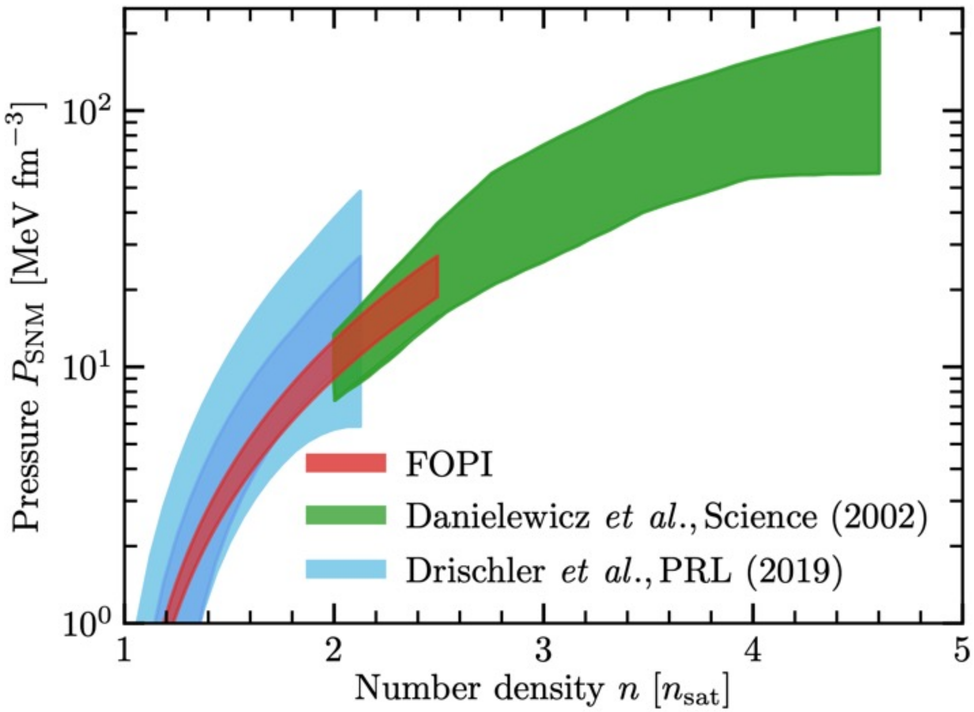
promising consistency between chiral EFT and FRG and pQCD

diquark correlations crucial for intermediate densities and high speed of sound

Constraints from heavy-ion collisions Huth, Pang et al., arXiv:2107.06229

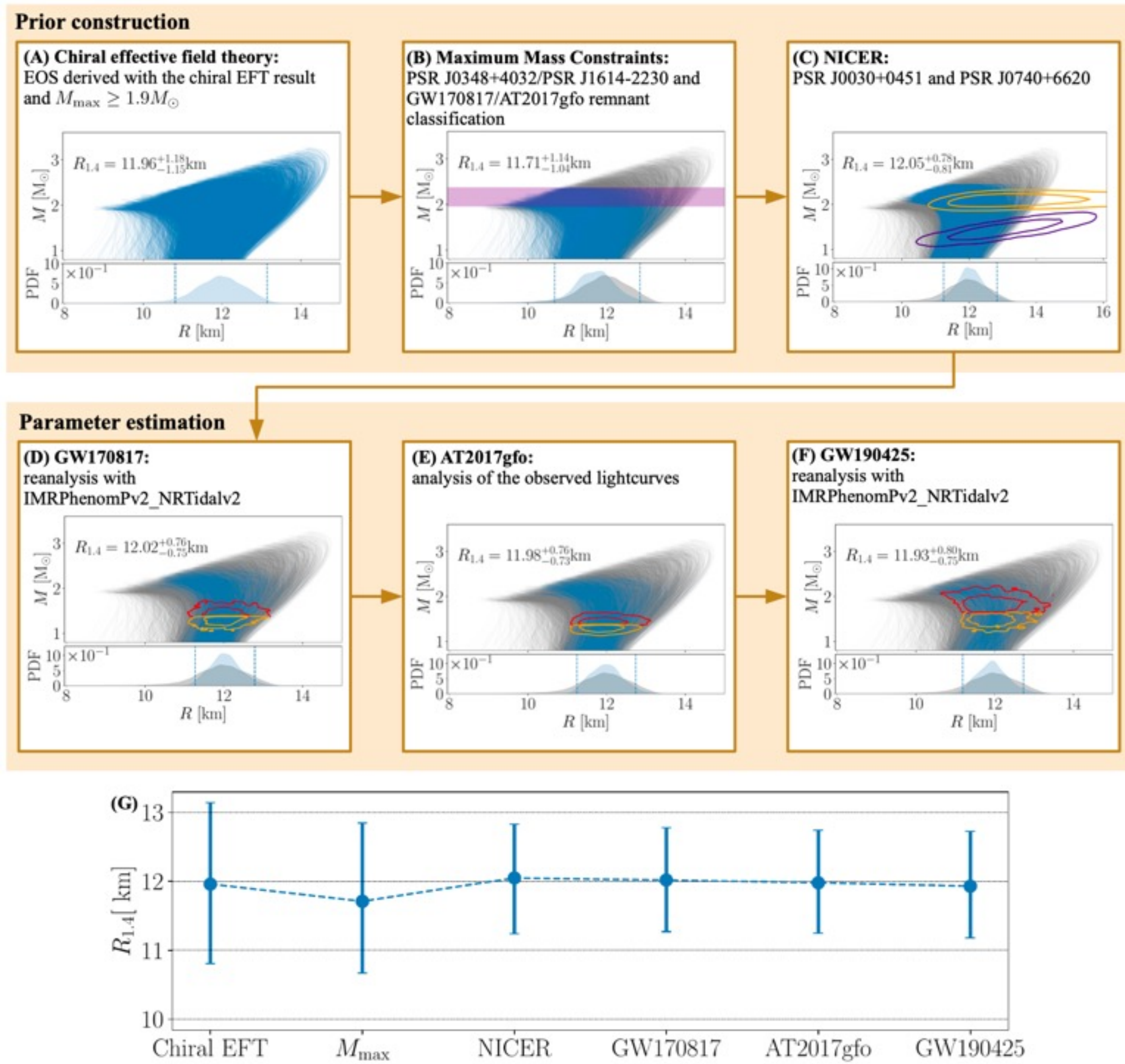
include in addition to chiral EFT: constraints from ASY-EOS and FOPI for neutron and symmetric matter with different functionals





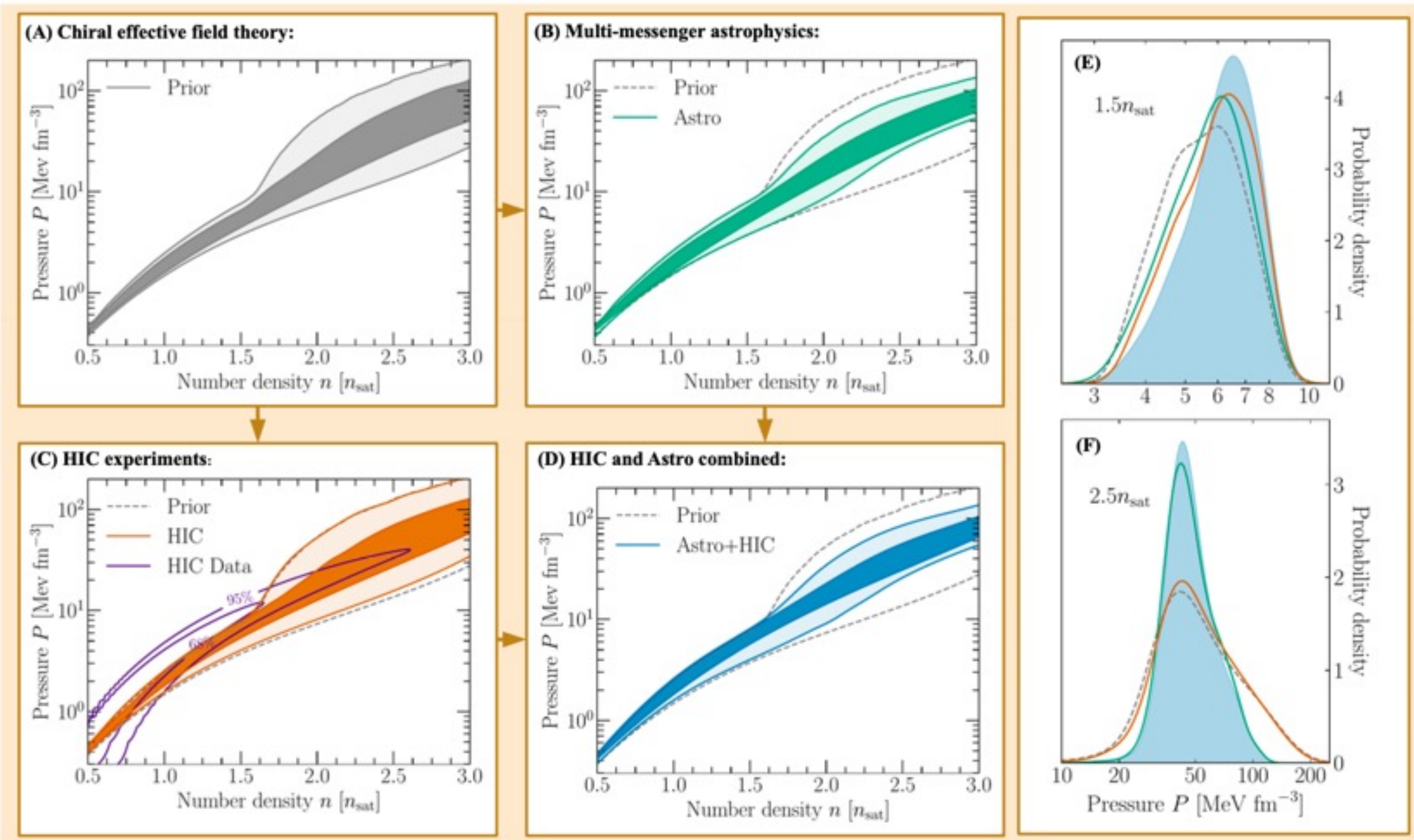
Constraints from heavy-ion collisions Huth, Pang et al., arXiv:2107.06229

Bayesian multi-messenger framework using EOS draws based on chiral EFT (QMC results) with c_s extension



Constraints from heavy-ion collisions Huth, Pang et al., arXiv:2107.06229

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



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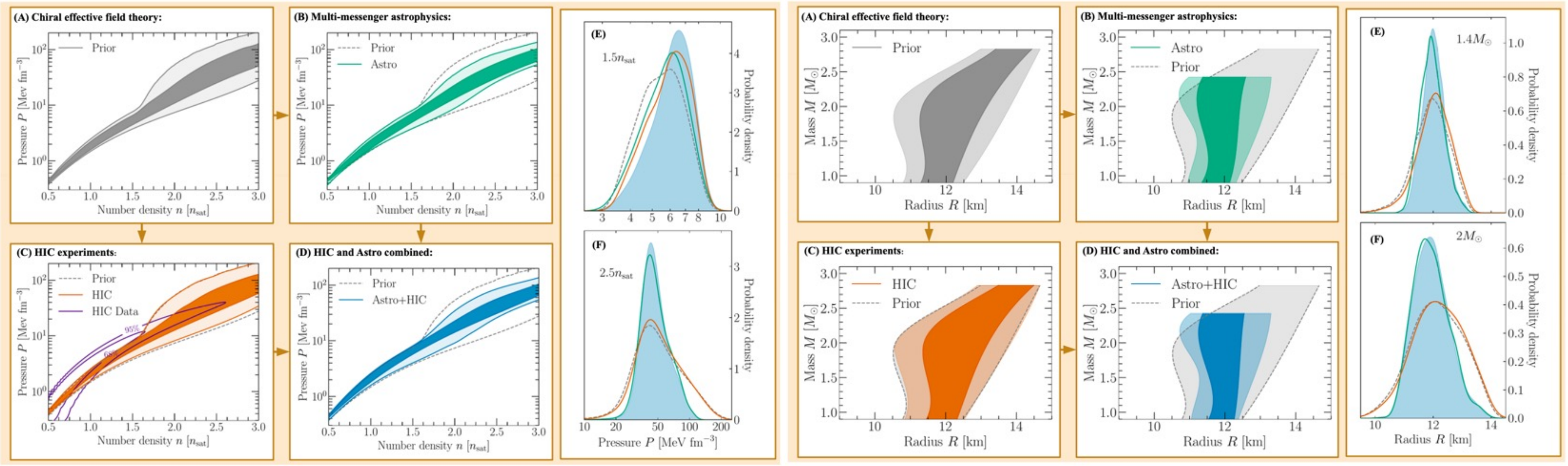


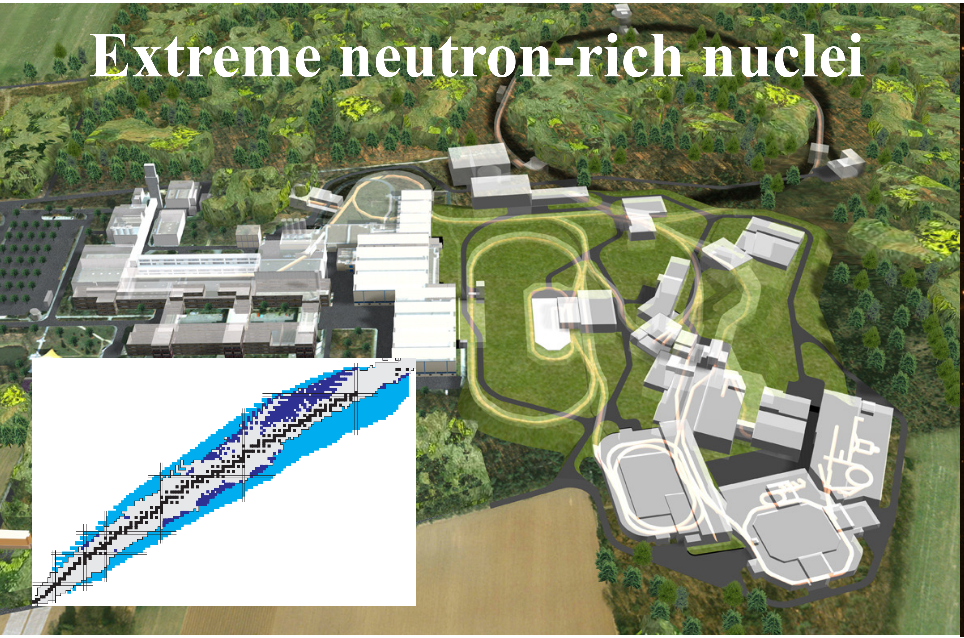
	Prior	Astro only	HIC only	Astro + HIC
$P_{1.5n_{\rm sat}}$	$5.59^{+2.04}_{-1.97}$	$5.84^{+1.95}_{-2.26}$	$6.06^{+1.85}_{-2.04}$	$6.25^{+1.90}_{-2.26}$
$R_{1.4}$	$11.96^{+1.18}_{-1.15}$	$11.93^{+0.80}_{-0.75}$	$12.06^{+1.13}_{-1.18}$	$12.01^{+0.78}_{-0.77}$

more HIC information for intermediate densities very interesting!

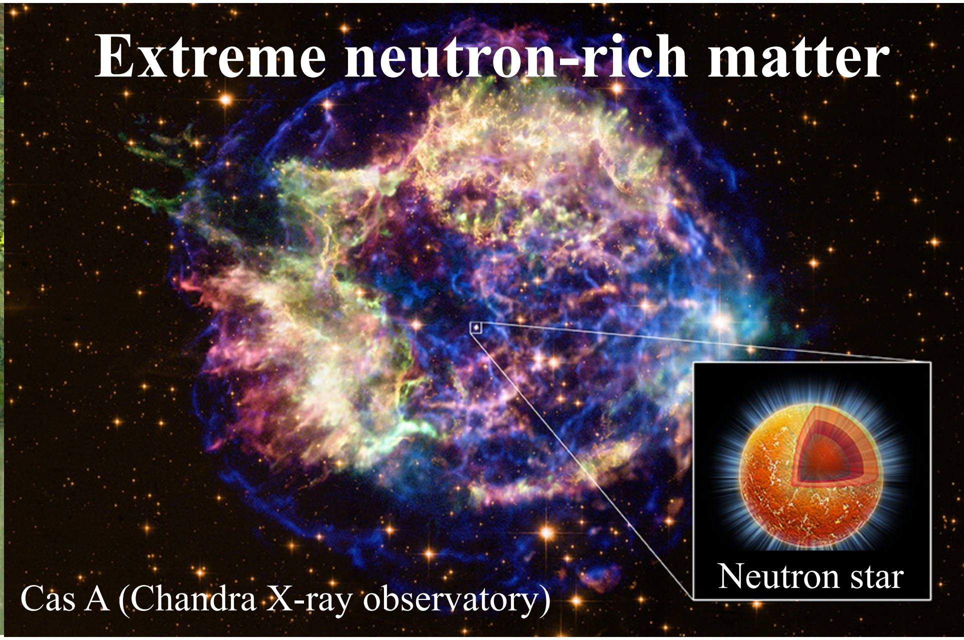
Exciting era in nuclear physics

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

New experimental frontier



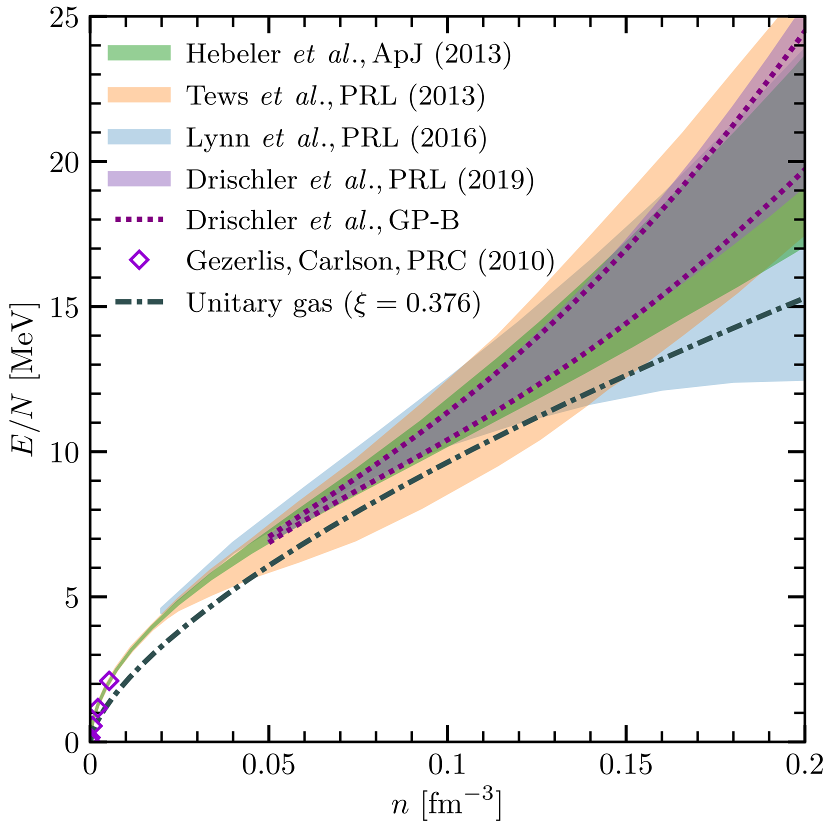
New observations in astrophysics



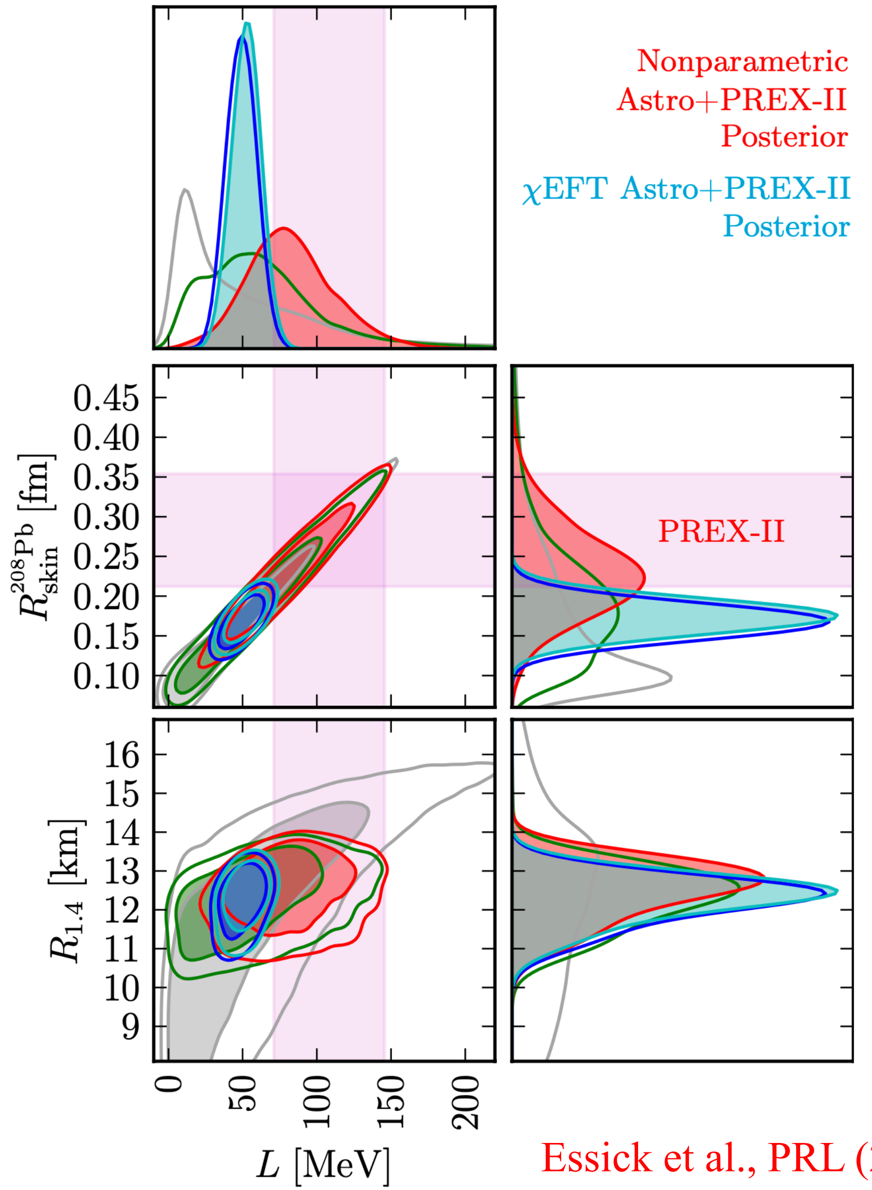
Thanks to our group and collaborators!

Chiral EFT calculations of neutron matter

slope (L parameter) determines pressure of neutron matter

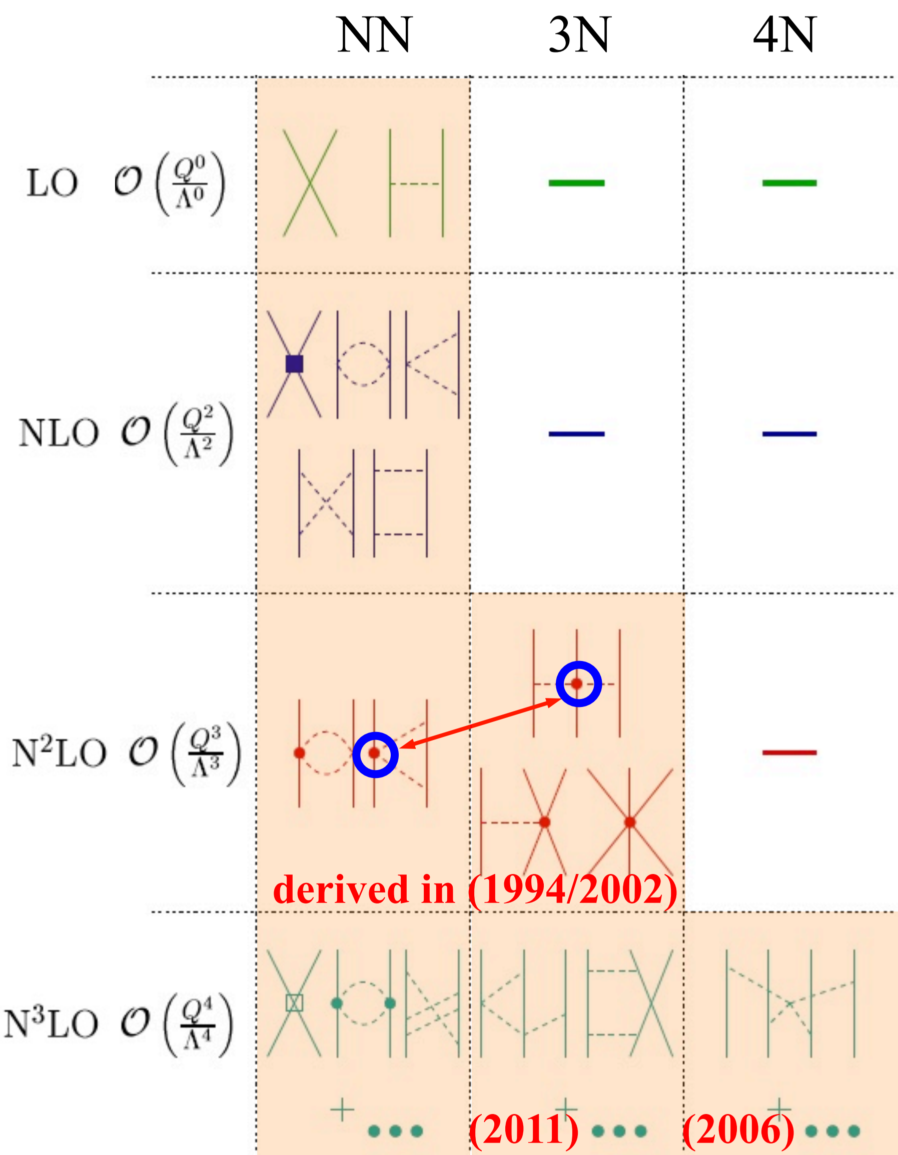


from Huth, Wellenhofer, AS (2020)



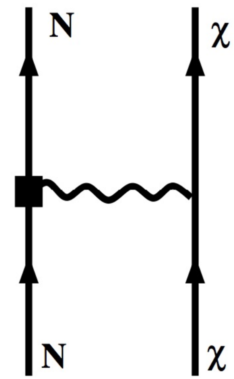
Essick et al., PRL (2021)

Chiral EFT for coupling to **electroweak interactions**

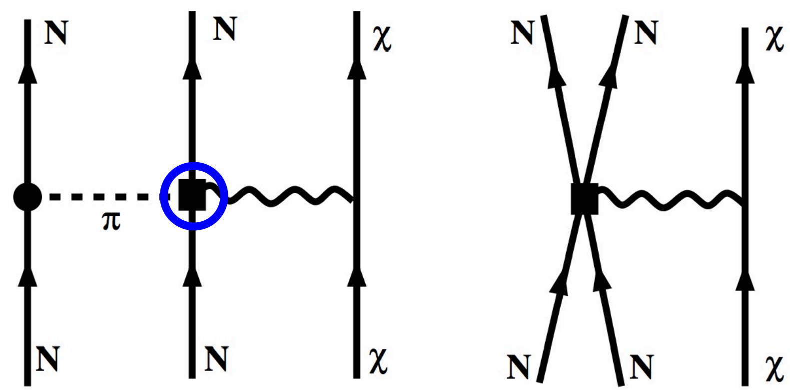


axial-vector currents (beta decays)

one-body currents at Q^0 and Q^2



+ two-body currents at Q^3



same couplings in forces and currents!

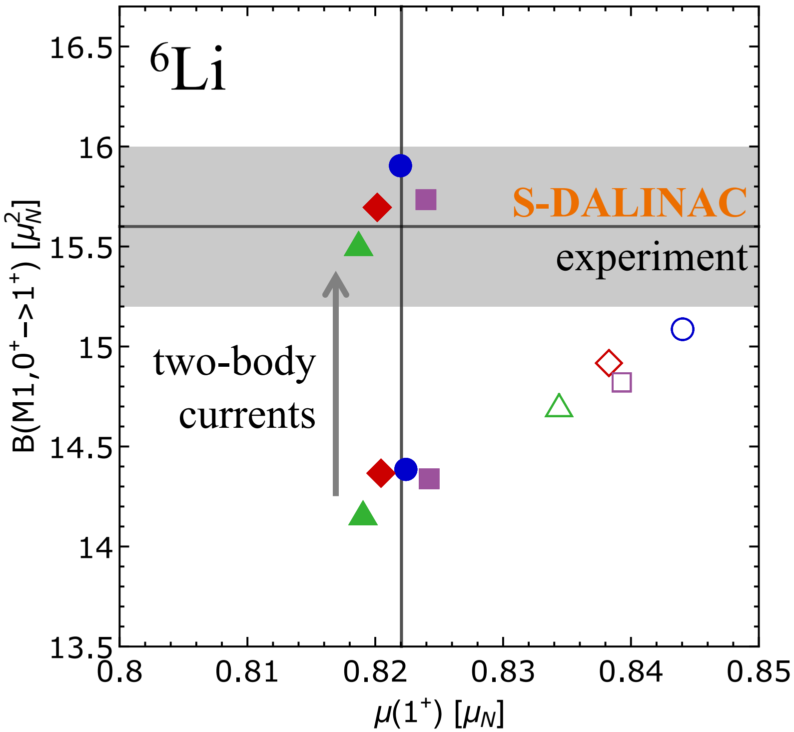
Chiral EFT for coupling to **electroweak interactions**

consistent electroweak one- and two-body currents

magnetic properties of light nuclei

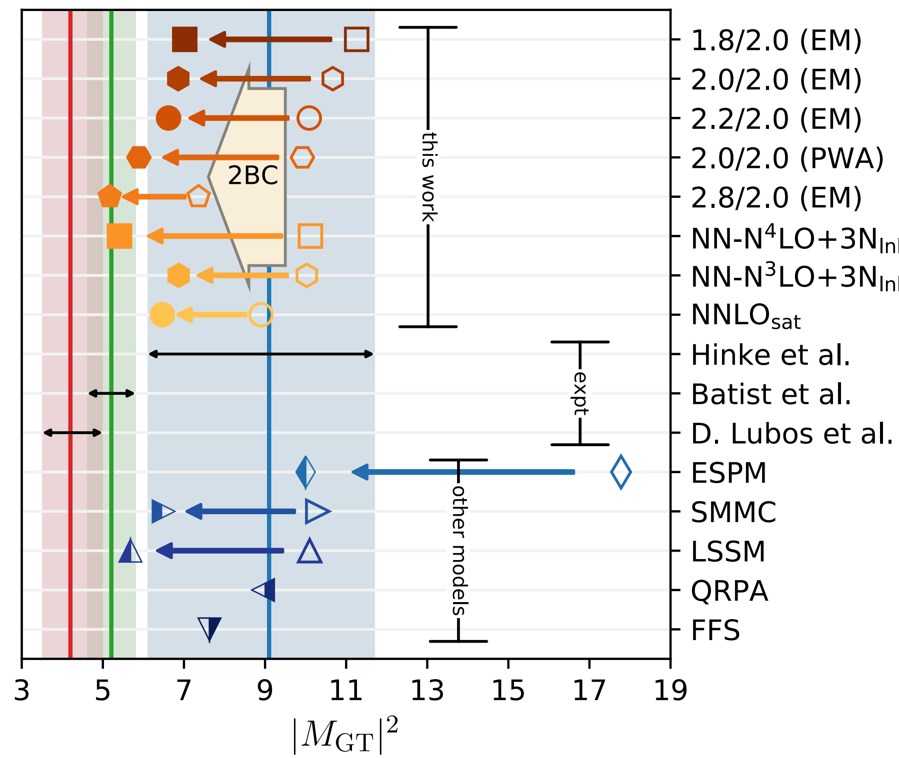
Pastore et al. (2012-)

B(M1) of ^{6}Li Gayer et al., PRL (2021)



Gamow-Teller beta decay of ^{100}Sn

Gysbers et al., Nature Phys. (2019)

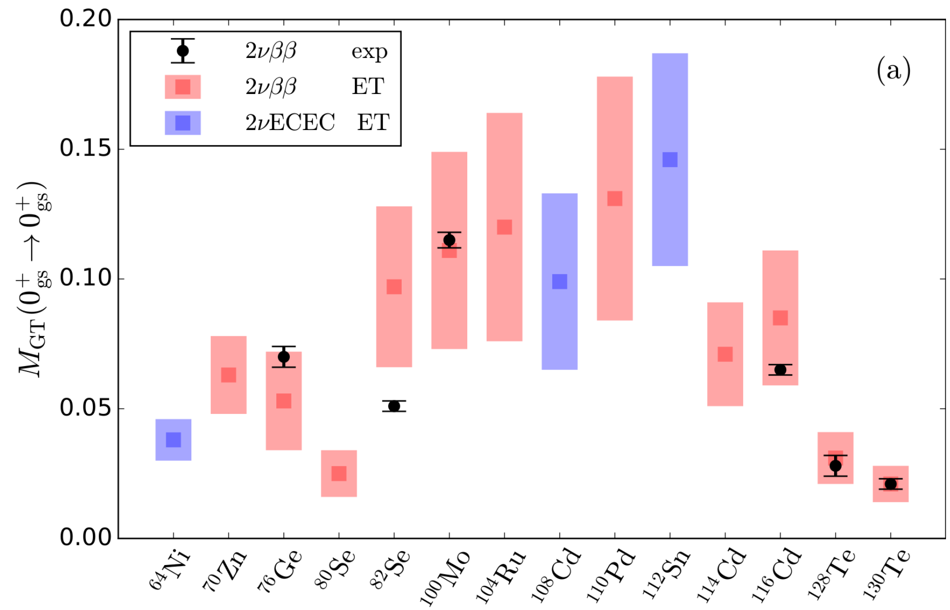


two-body currents (2BC) key for quenching puzzle of beta decays

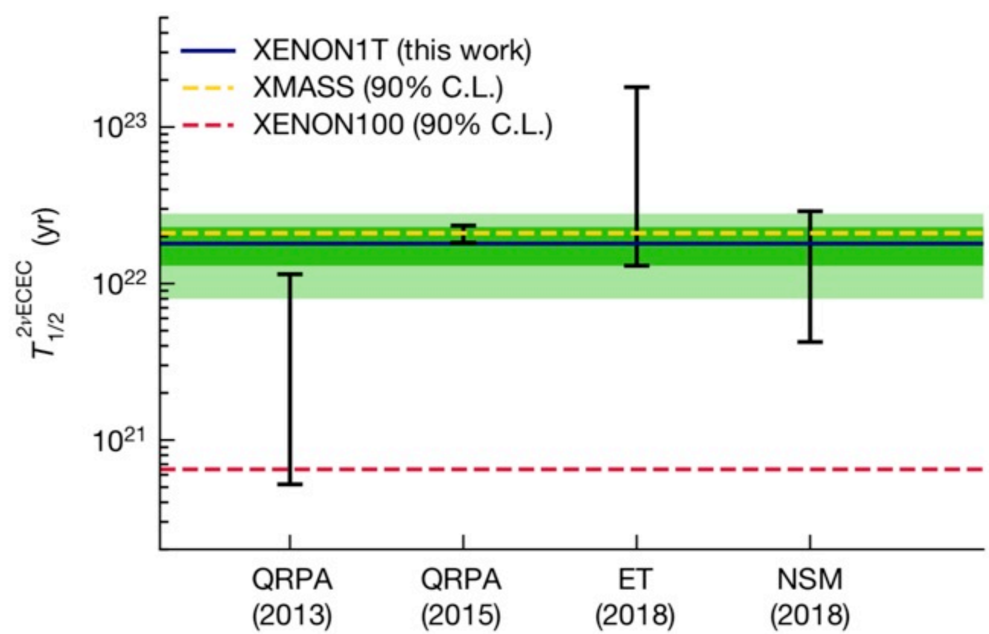
Effective theory for heavy nuclei

near spherical nuclei based on core + phonons + particles/holes as degrees of freedom

Gamow-Teller transitions for single and double-beta decay at LO
Coello Perez et al., PRC (2018)

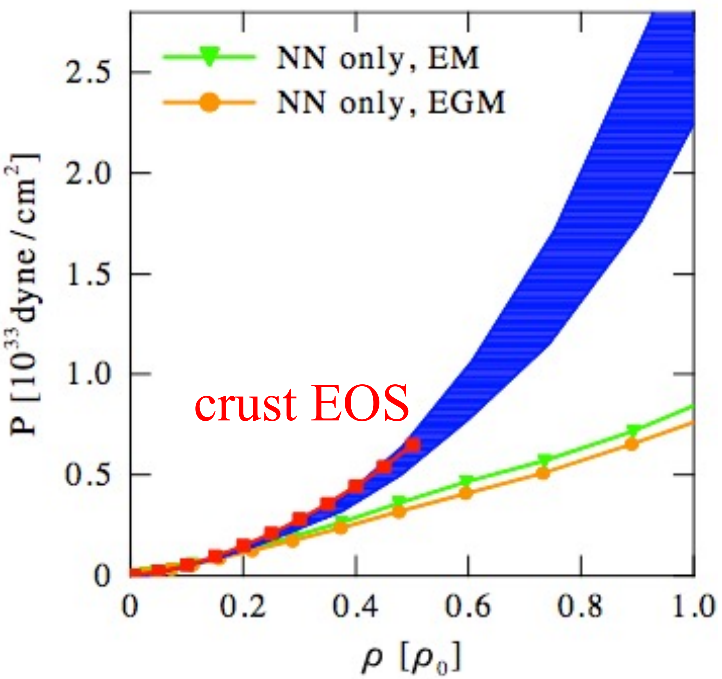


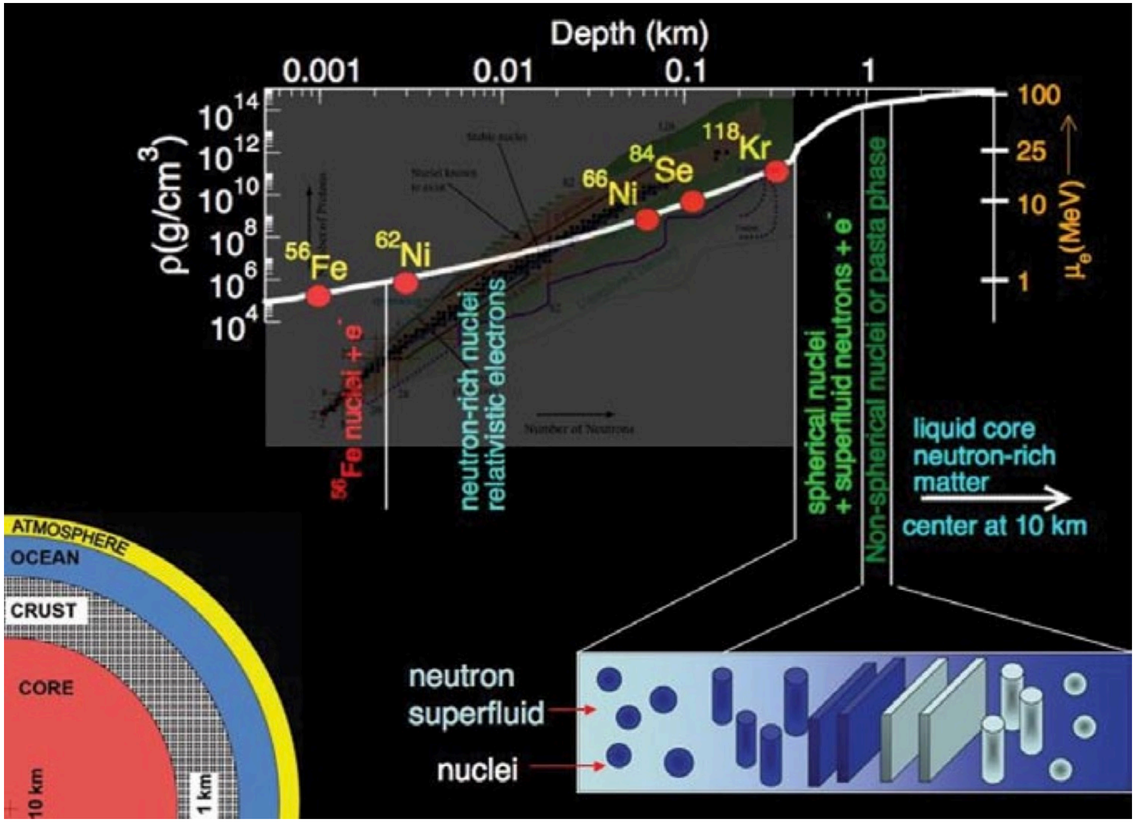
prediction (ET and shell model) for double electron capture on ^{124}Xe Coello Perez et al., PLB (2019)
first observed by XENON collaboration Aprile et al. Nature (2019)



Impact on neutron stars Hebeler et al., PRL (2010), ApJ (2013)

Equation of state/pressure for neutron-star matter (includes small $Y_{e,p}$)

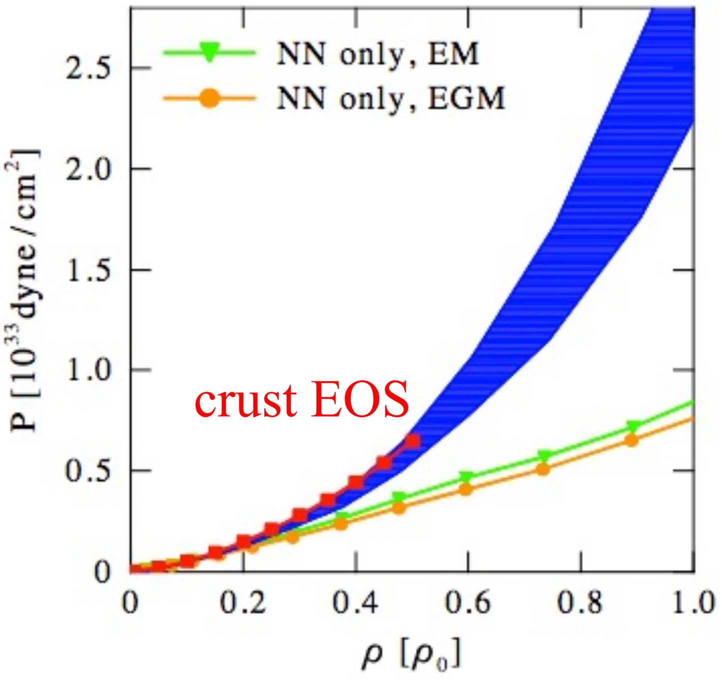


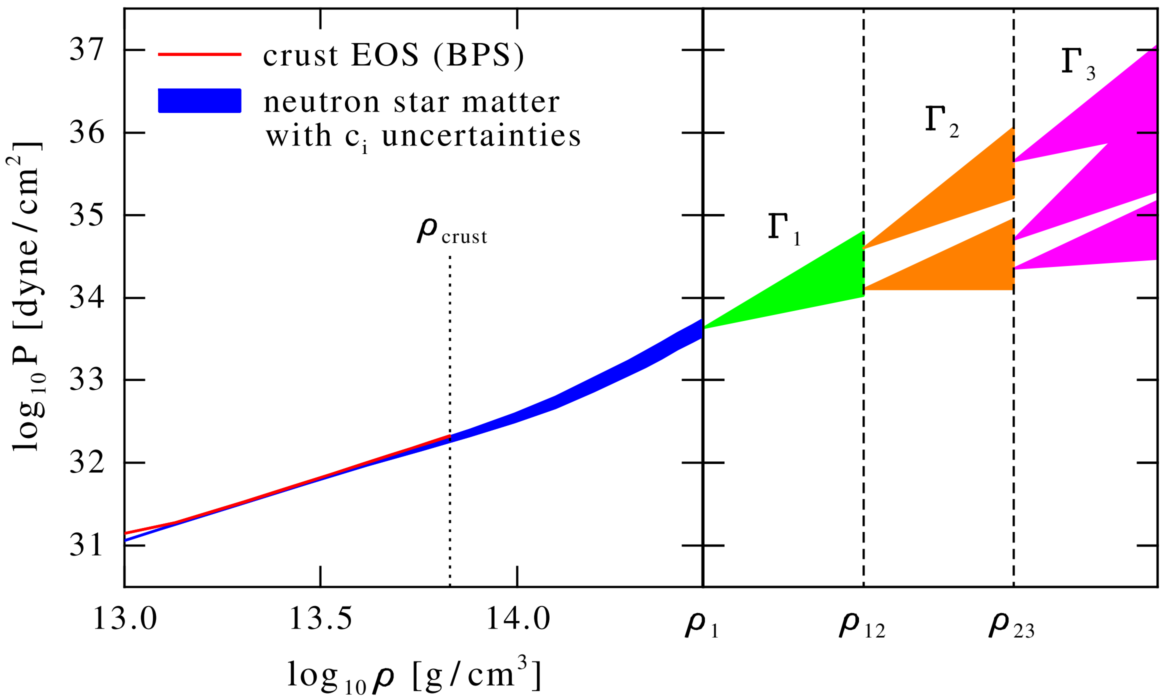


pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

Impact on neutron stars Hebeler et al., PRL (2010), ApJ (2013)

Equation of state/pressure for neutron-star matter (includes small $Y_{e,p}$)





pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included

extend uncertainty band to higher densities using piecewise polytropes allow for soft regions

EOS constraints from GW170817

piecweise polytropes
Hebeler et al., ApJ (2013)
c_s model
Greif et al., MNRAS (2019)
constrained to
support 2 M_{sun}

LIGO/Virgo
PRX (2019)
chirp mass,
mass ratio,
binary tidal
deformability

very consistent
with nucl. physics
+ NS masses
Greif et al.