

# FAIR and strong interaction matter in the universe

Achim Schwenk



TECHNISCHE  
UNIVERSITÄT  
DARMSTADT



Fysikdagarna, Lund, June 16, 2022



European Research Council  
Established by the European Commission

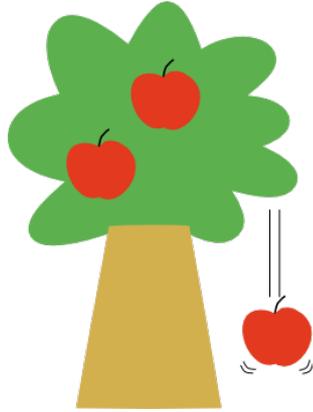
ERC AdG EUSTRONG



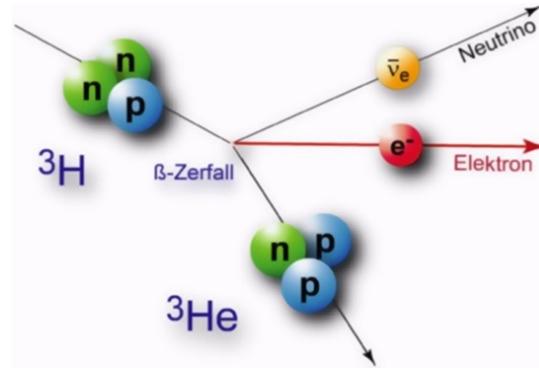
Bundesministerium  
für Bildung  
und Forschung

# Fundamental interactions

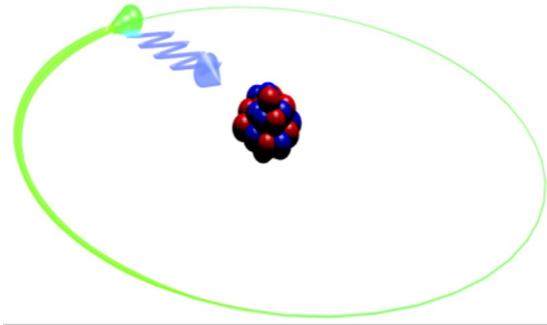
Gravity



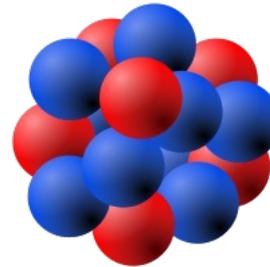
Weak interaction



Electrodynamics

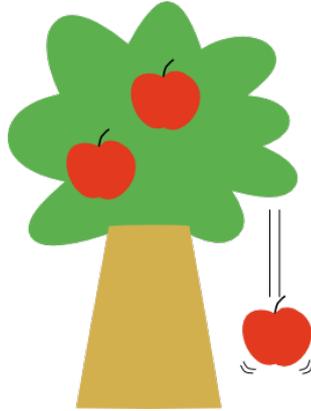


Strong interaction

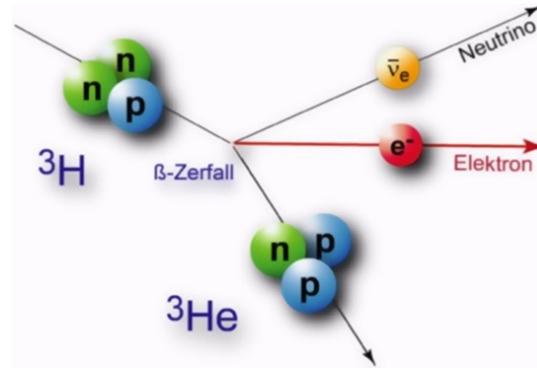


# Fundamental interactions

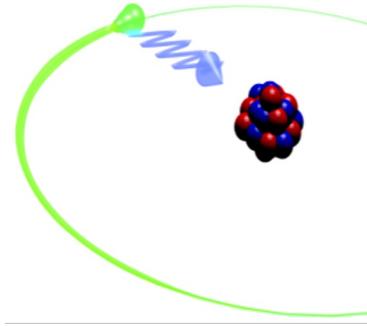
## Gravity



## Weak interaction



## Electrodynamics



## Periodic Table of Elements governed by electromagnetic interaction

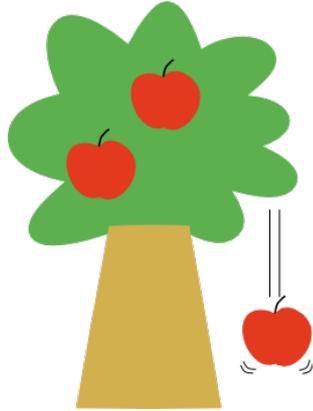



United Nations Educational, Scientific and Cultural Organization • International Year of the Periodic Table of Chemical Elements

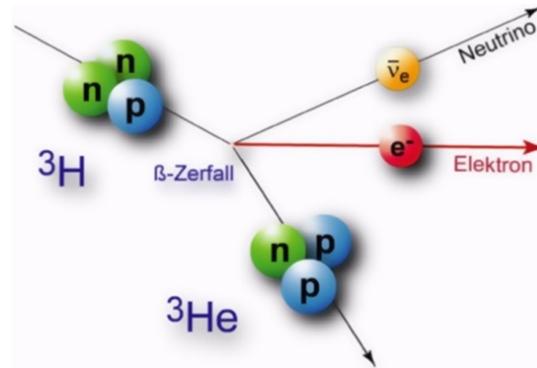
1 H Hydrogen Nonmetal																	2 He Helium Noble Gas
3 Li Lithium Alkali Metal	4 Be Beryllium Alkaline Earth Metal											5 B Boron Metalloid	6 C Carbon Nonmetal	7 N Nitrogen Nonmetal	8 O Oxygen Nonmetal	9 F Fluorine Halogen	10 Ne Neon Noble Gas
11 Na Sodium Alkali Metal	12 Mg Magnesium Alkaline 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

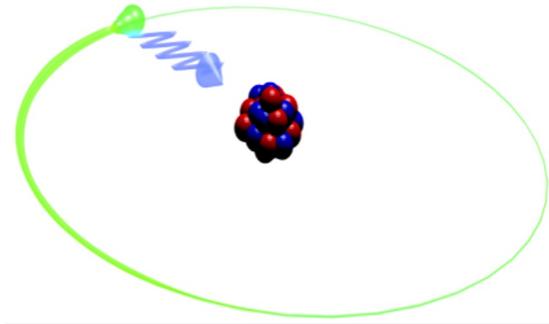
## Gravity



## Weak interaction

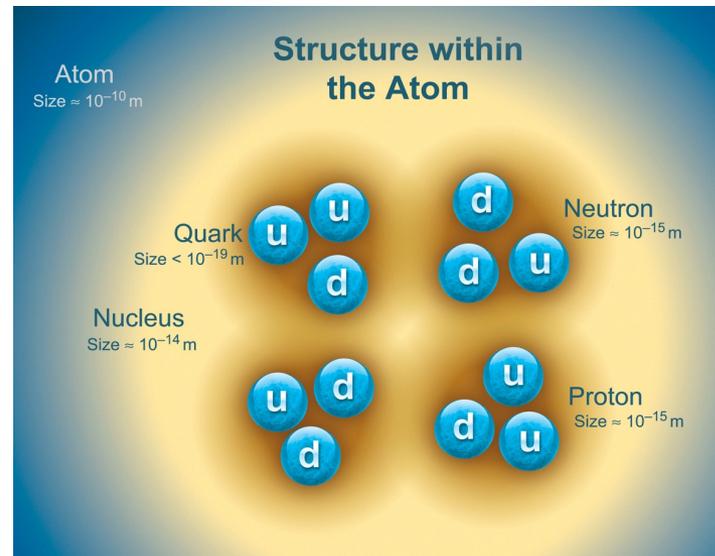


## Electrodynamics



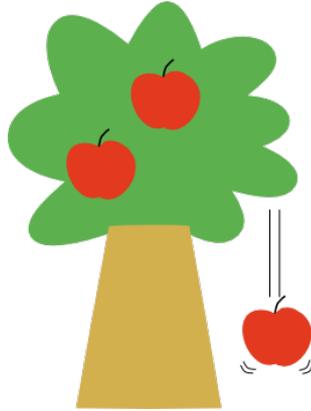
## Strong interaction

## Quantum chromodynamics (QCD)

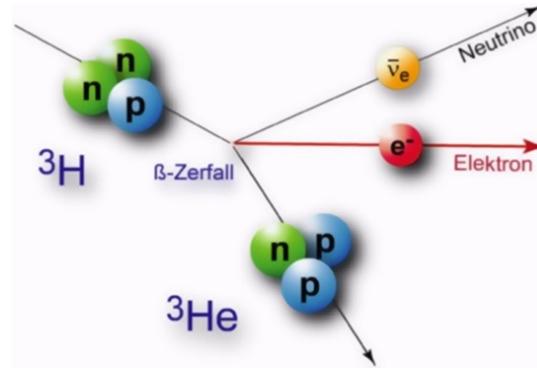


# Fundamental interactions

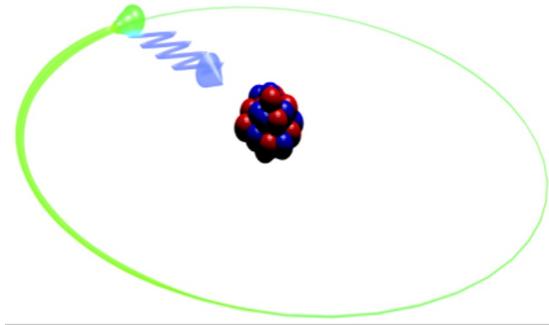
## Gravity



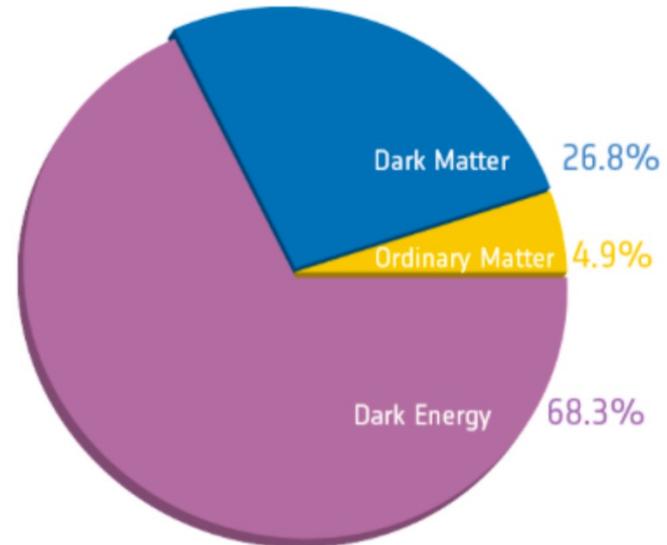
## Weak interaction



## Electrodynamics



## Strong interaction in the universe



After Planck

# Nuclei bound by strong interactions

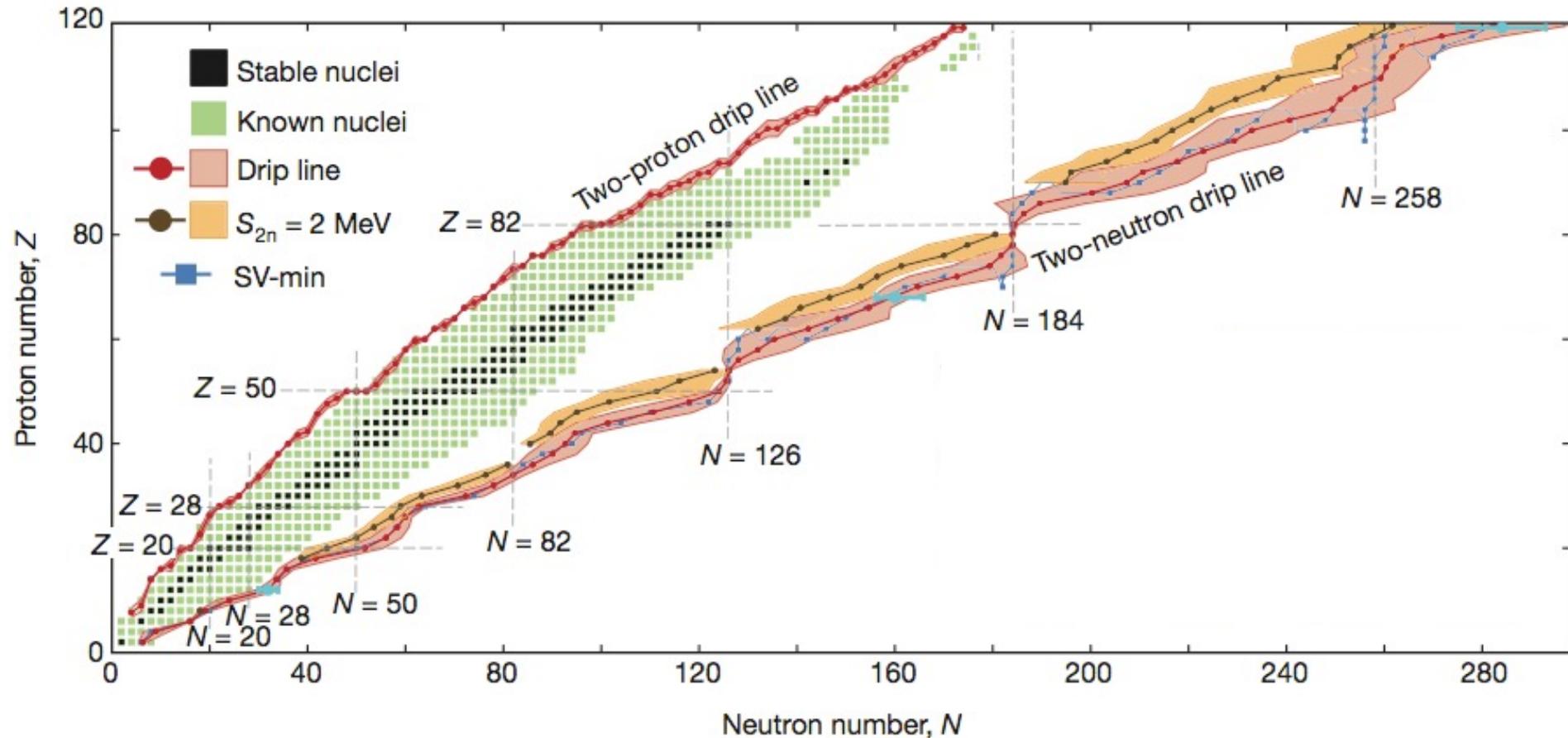
doi:10.1038/nature11188

## The limits of the nuclear landscape

Jochen Erler<sup>1,2</sup>, Noah Birge<sup>1</sup>, Markus Kortelainen<sup>1,2,3</sup>, Witold Nazarewicz<sup>1,2,4</sup>, Erik Olsen<sup>1,2</sup>, Alexander M. Perhac<sup>1</sup> & Mario Stoitsov<sup>1,2†</sup>

~ 3000 nuclei discovered (288 stable), 118 elements

~  $4000 \pm 500$  nuclei unknown, extreme neutron-rich



# Nuclei bound by strong interactions

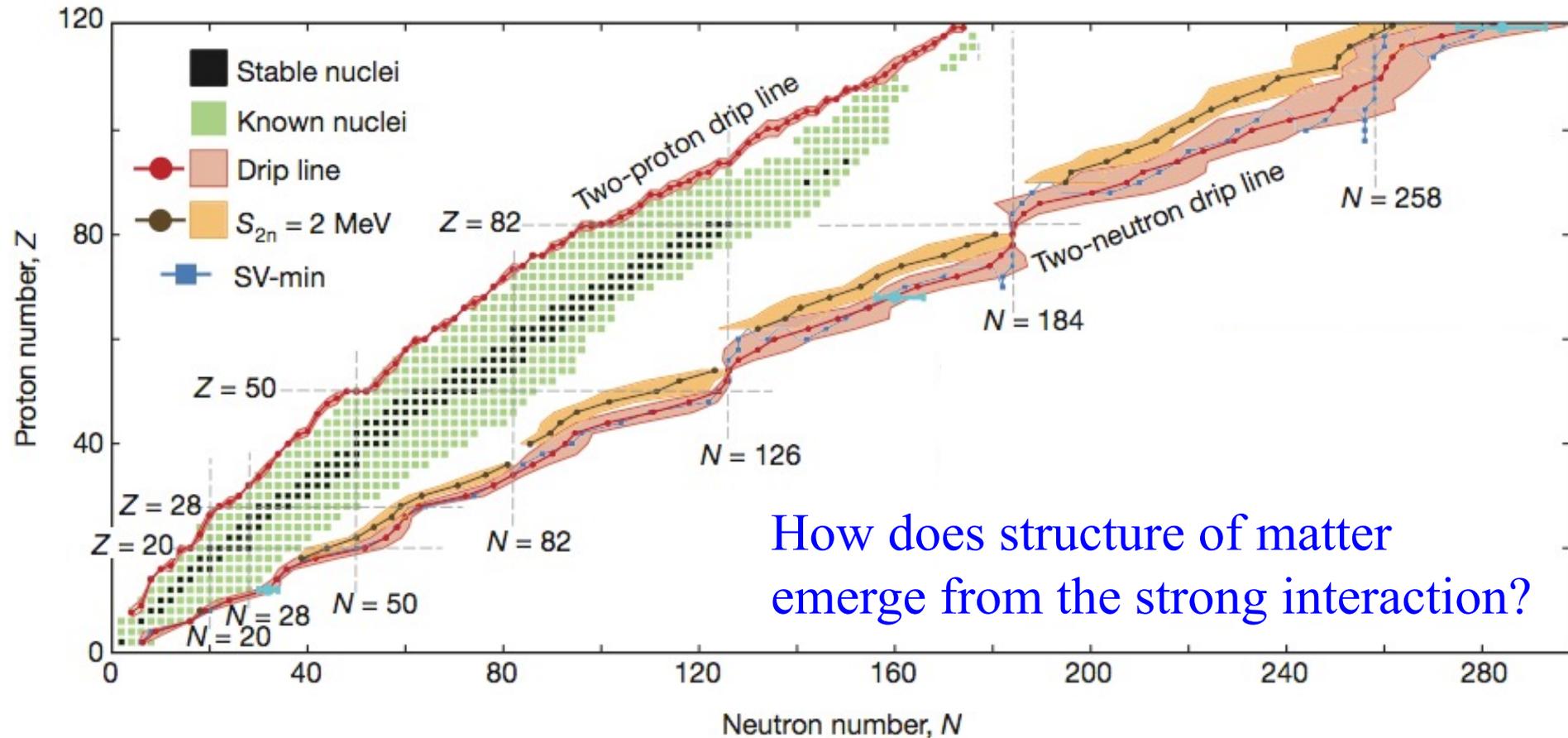
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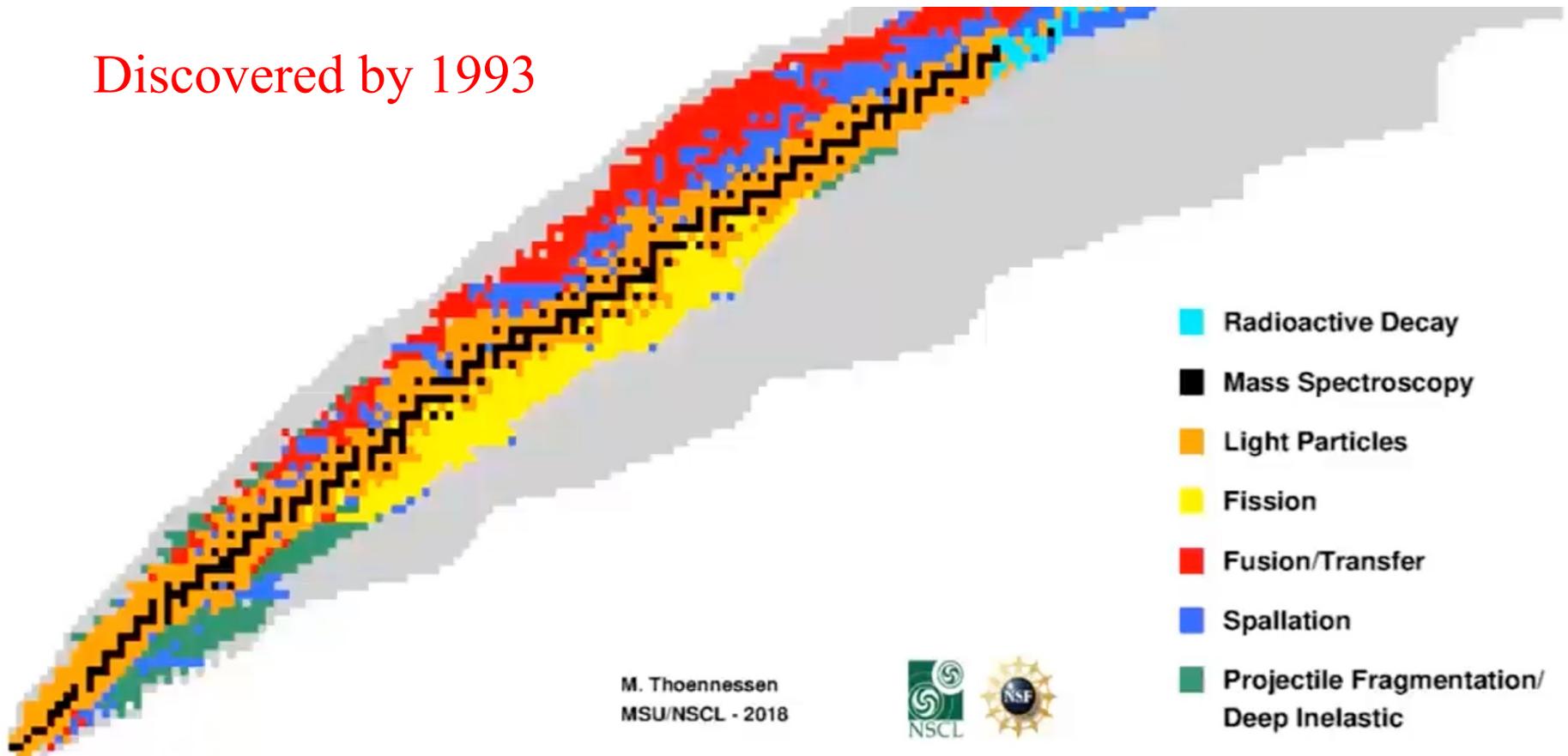
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~ 3000 nuclei discovered (288 stable), 118 elements

~ 4000  $\pm$  500 nuclei unknown, extreme neutron-rich

Discovered by 1993



# Nuclei bound by strong interactions

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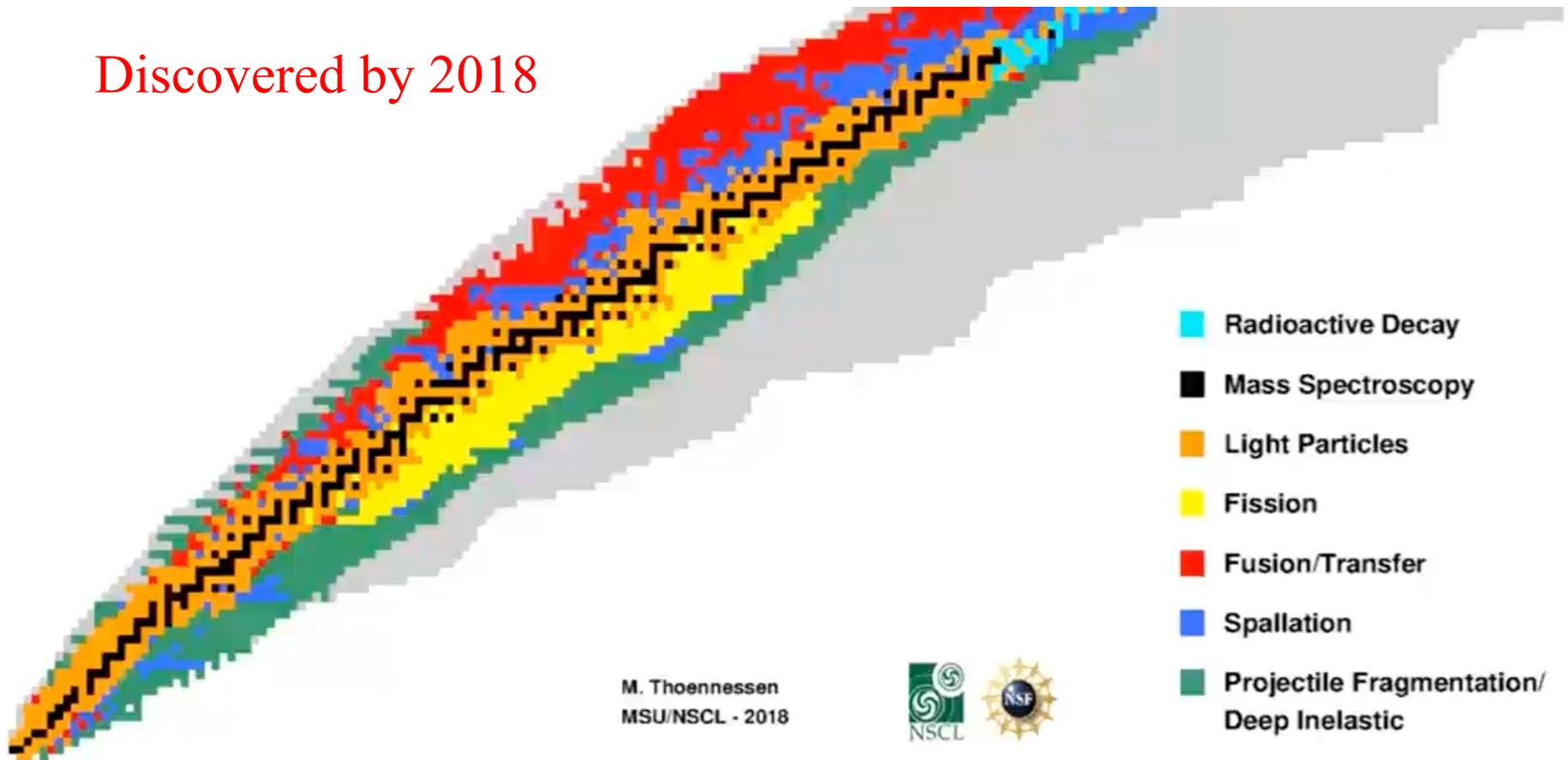
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~ 3000 nuclei discovered (288 stable), 118 elements

~ 4000  $\pm$  500 nuclei unknown, extreme neutron-rich

Discovered by 2018



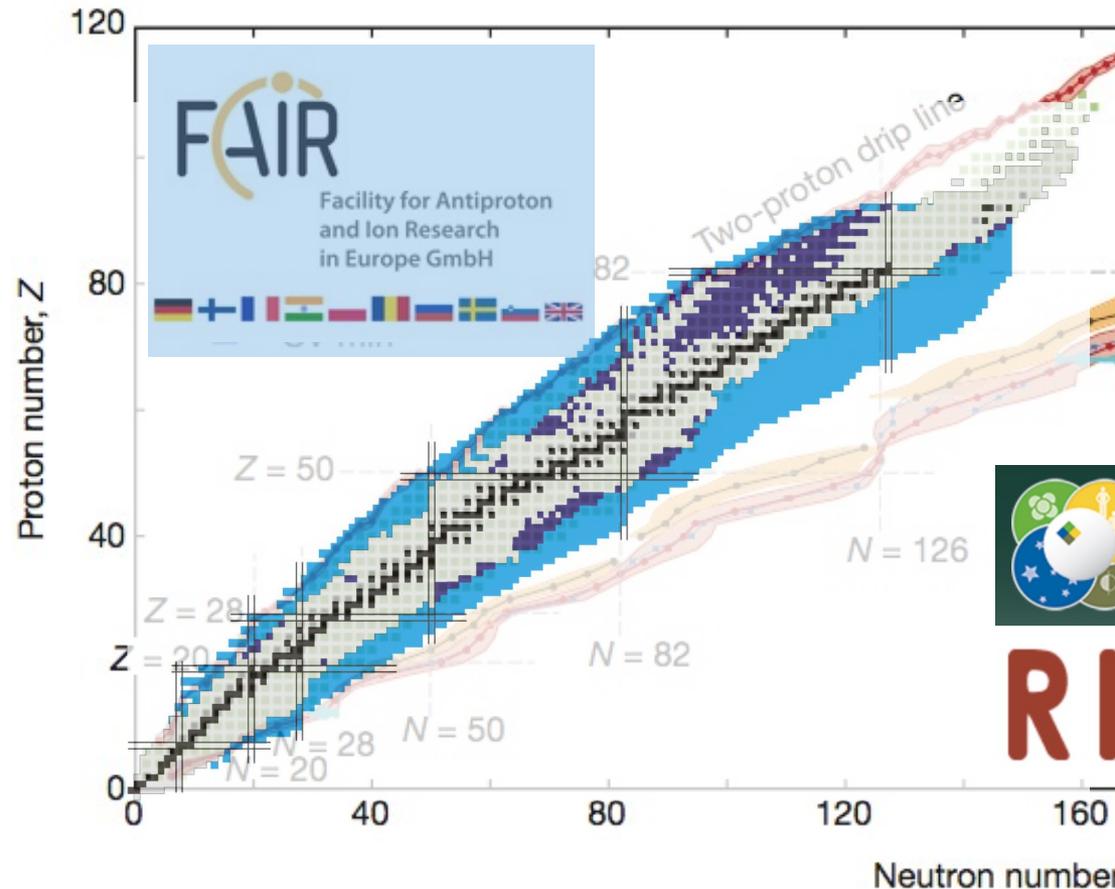
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- ~ 3000 nuclei discovered (288 stable), 118 elements
- ~ 4000 ± 500 nuclei unknown, extreme neutron-rich



RIBF



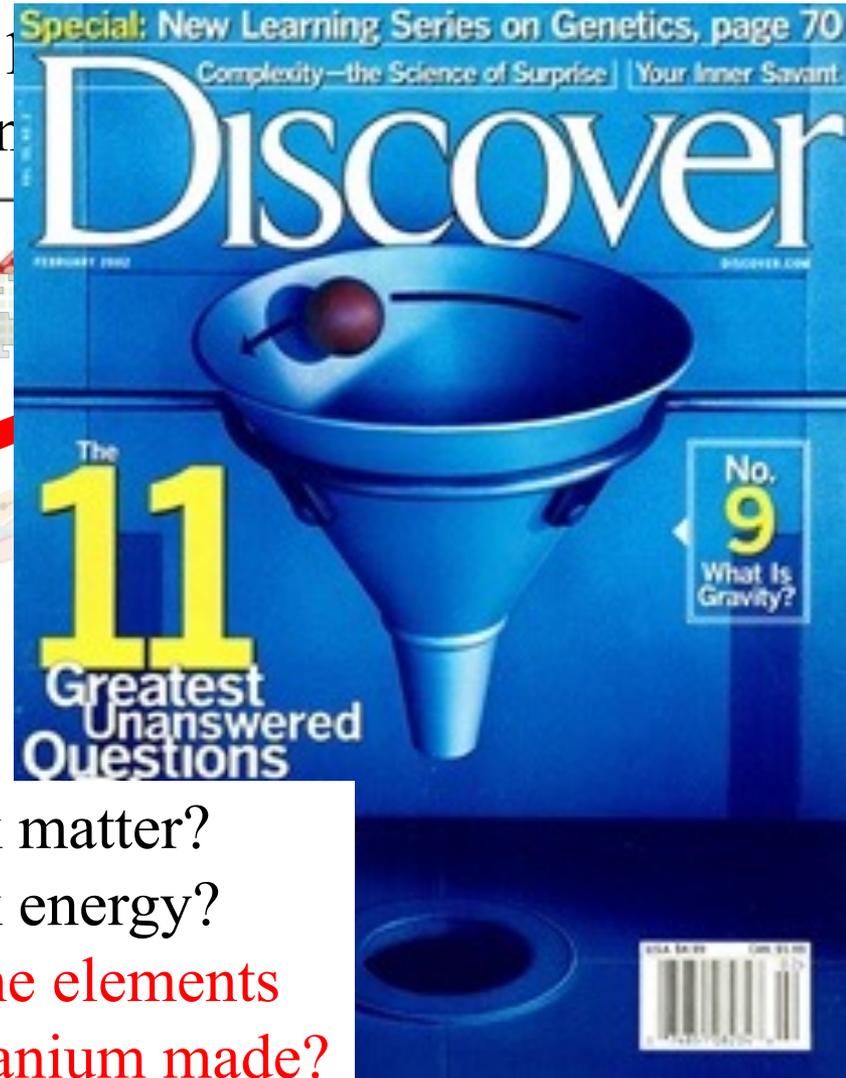
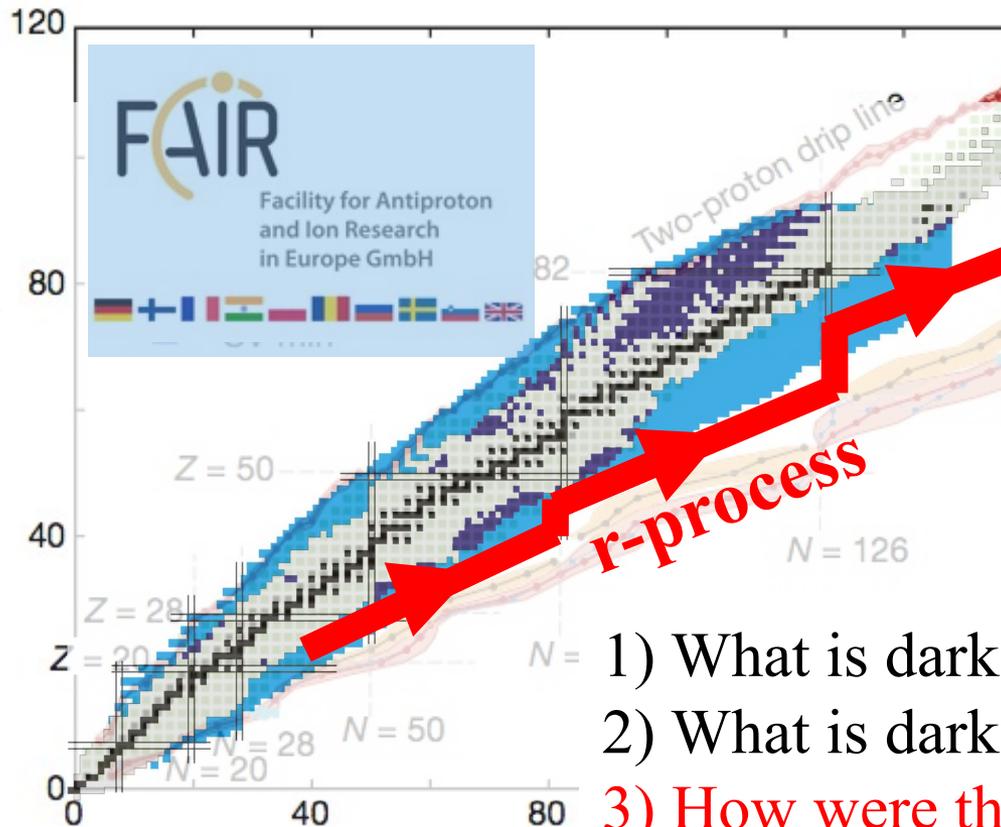
# Nuclei bound by strong interactions

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## The limits of the nuclear landscape

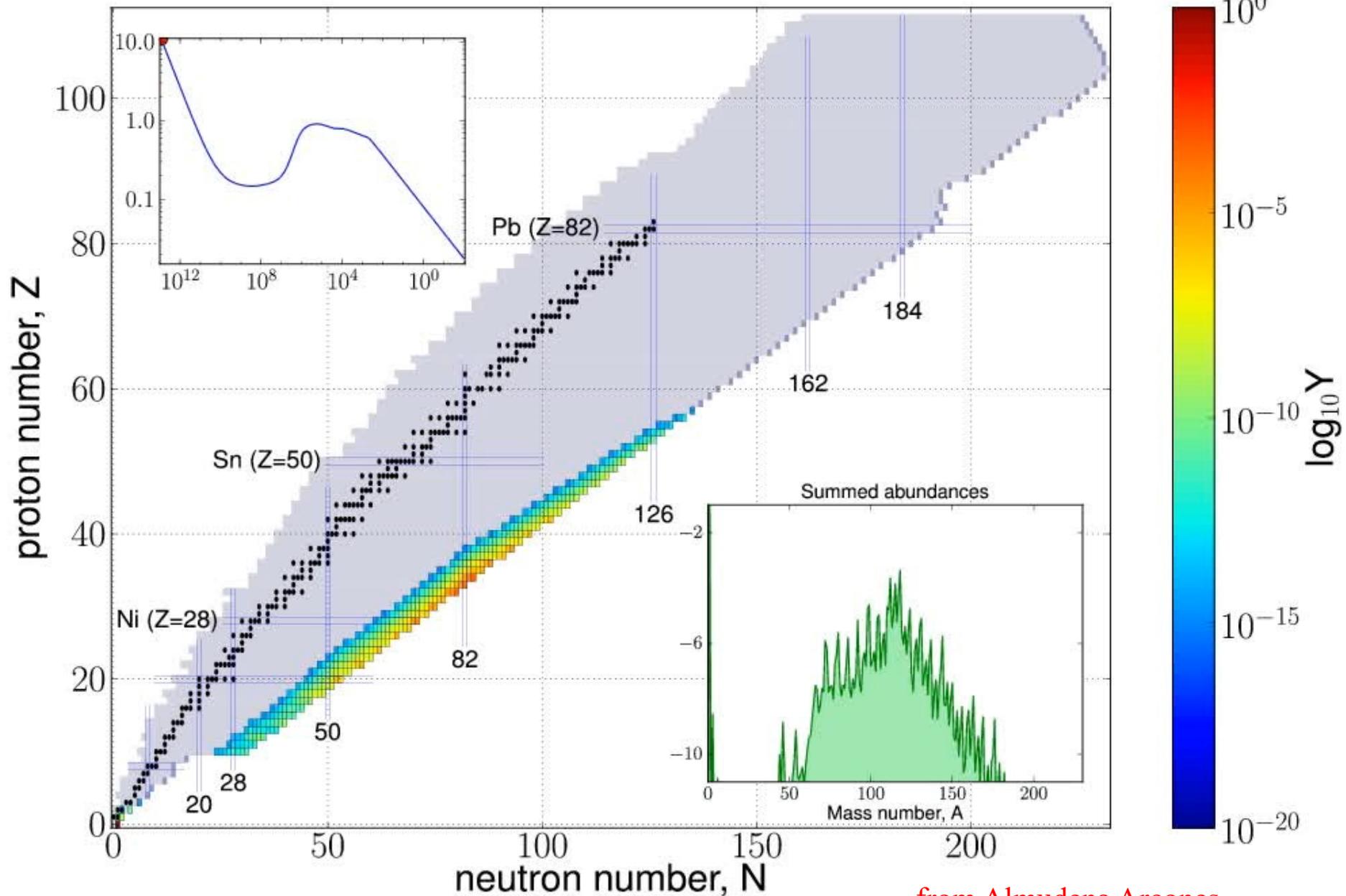
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~ 3000 nuclei discovered (288 stable), 1100 predicted  
~ 4000 ± 500 nuclei unknown, extreme r-process

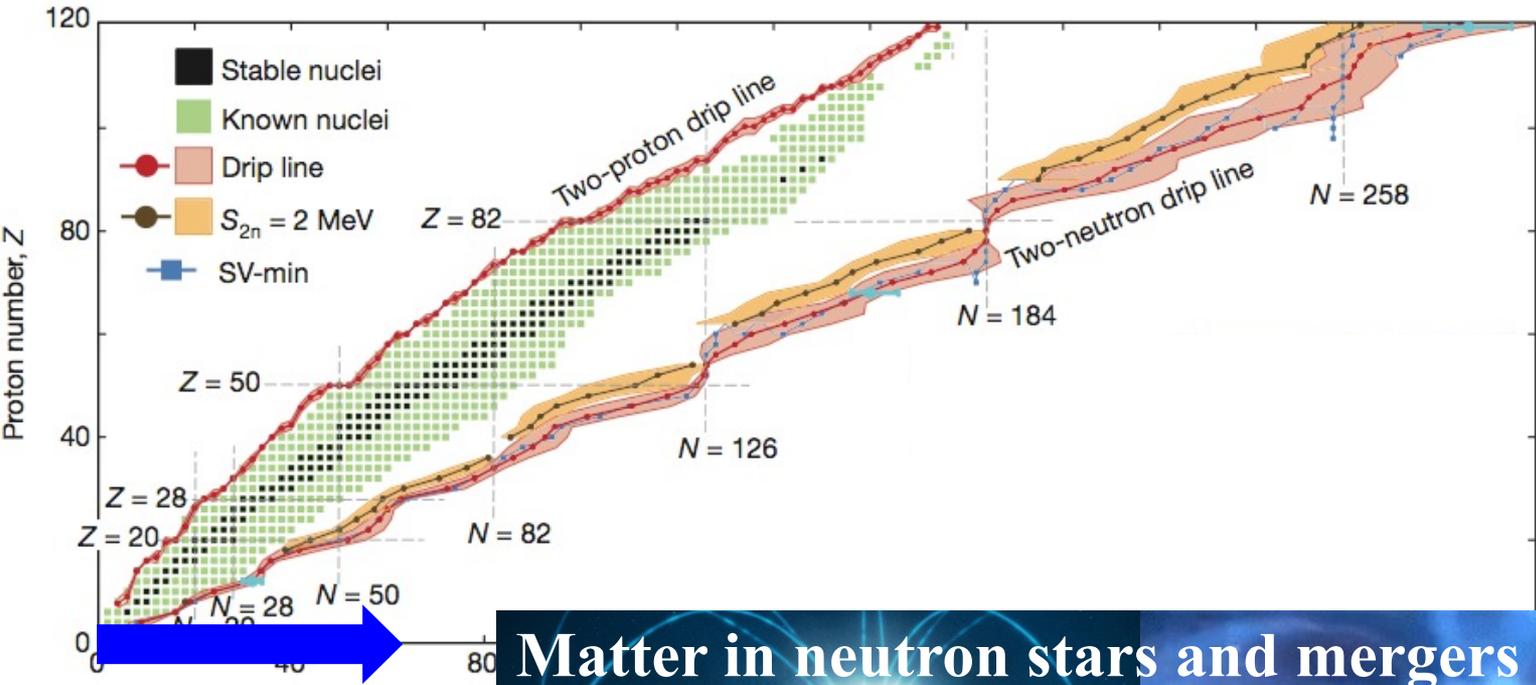


- 1) What is dark matter?
- 2) What is dark energy?
- 3) How were the elements from iron to uranium made?

$t : 0.00e+00 \text{ s} / T : 10.96 \text{ GK} / \rho_b : 8.71e+12 \text{ g/cm}^3$



from Almudena Arcones

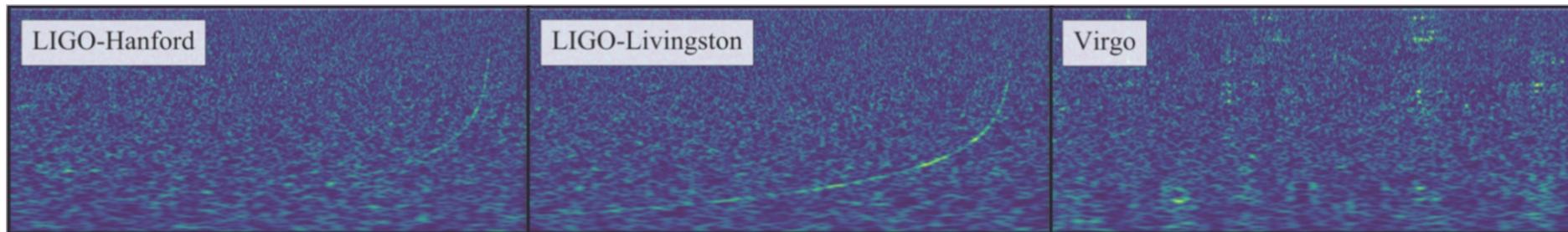


from Watts et al., RMP (2016)

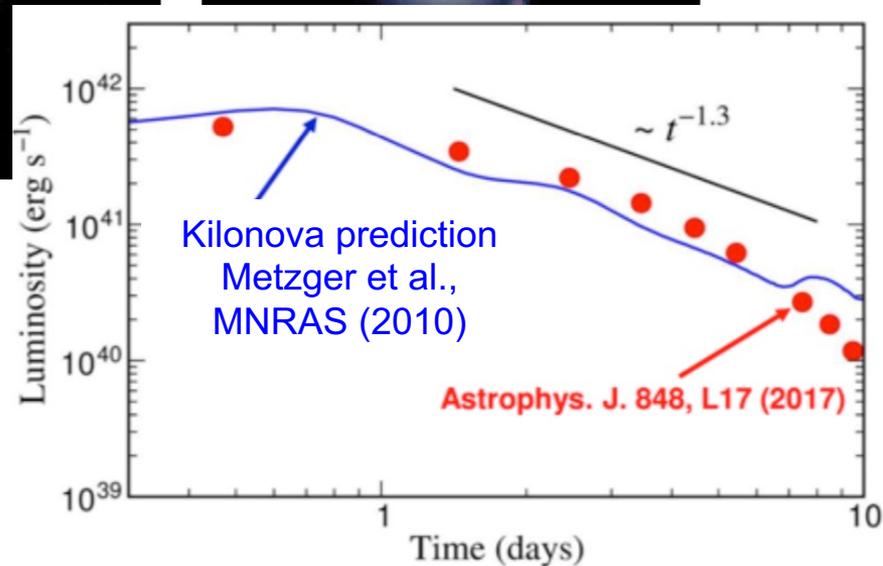
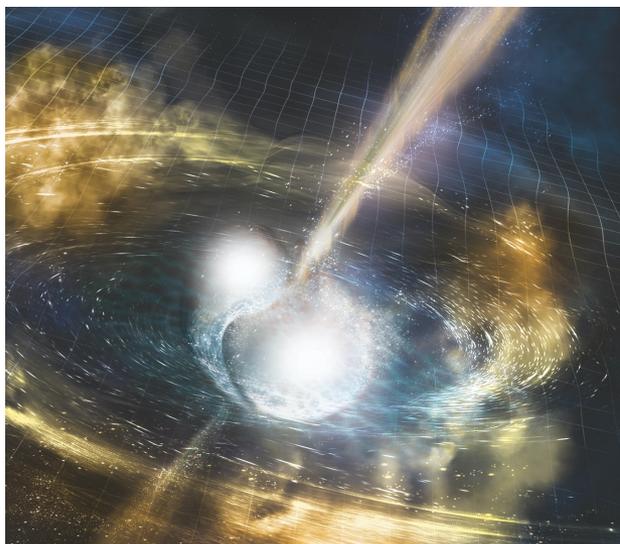
NASA/Goddard/LIGO/Virgo

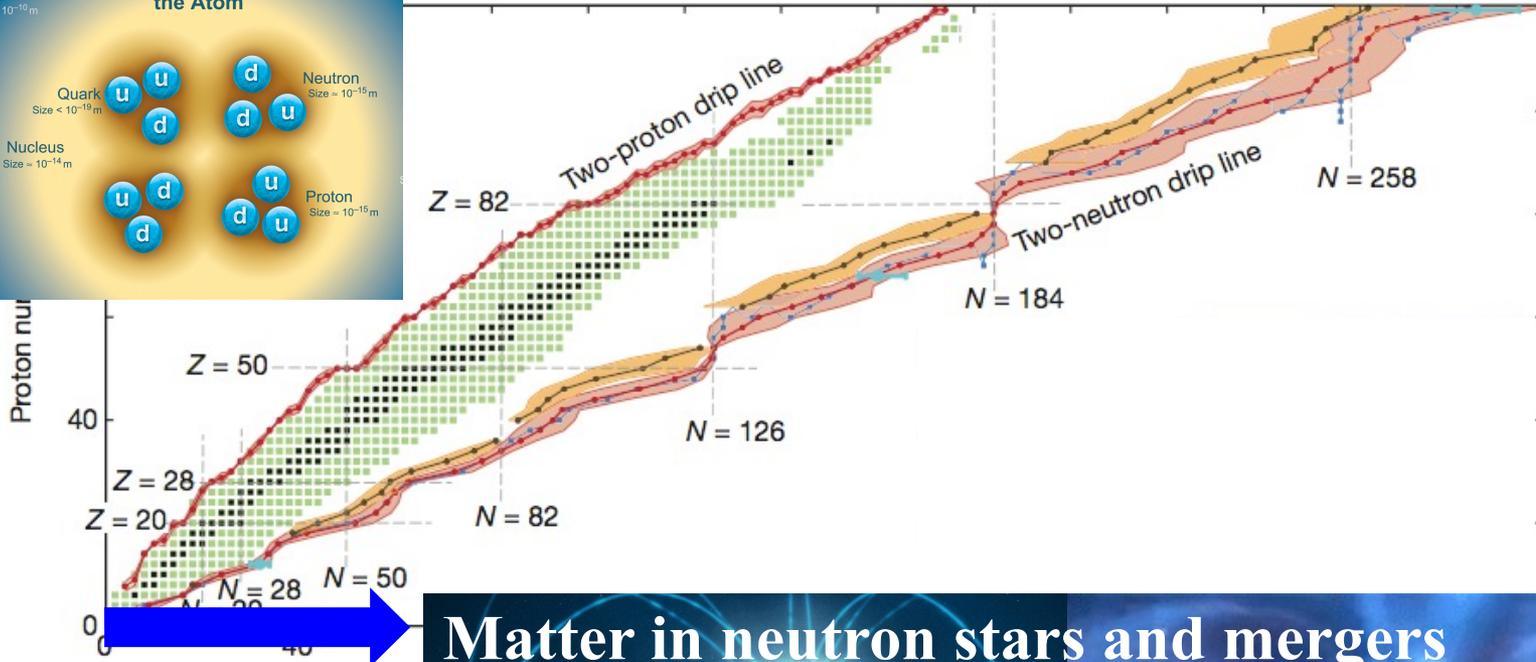
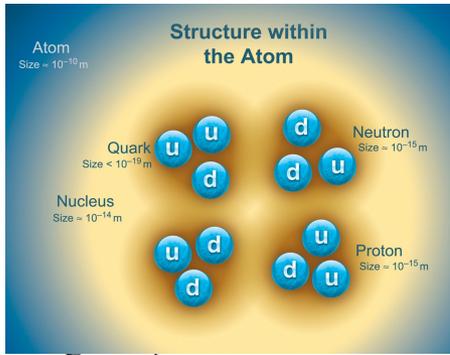
# Multi-messenger era: neutron star merger GW170817

gravitational wave signal: provides constraints on neutron star radii



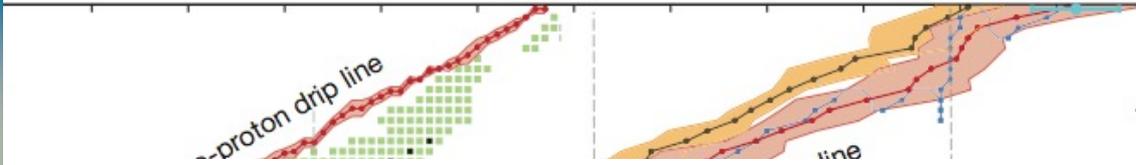
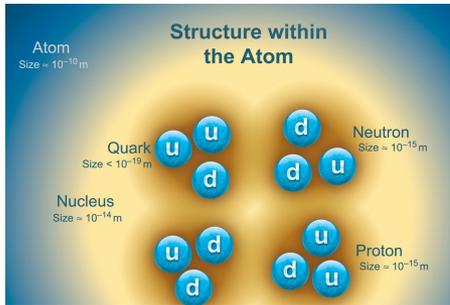
short gamma-ray burst + kilonova light curve: decay of r-process nuclei





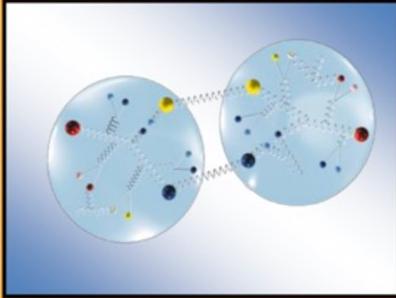
from Watts et al., RMP (2016)

NASA/Goddard/LIGO/Virgo



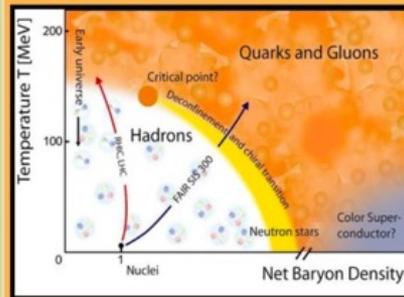
## 4 FAIR research pillars

### PANDA



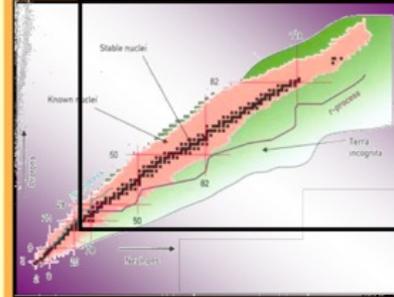
hadron structure and dynamics

### C.B.M.



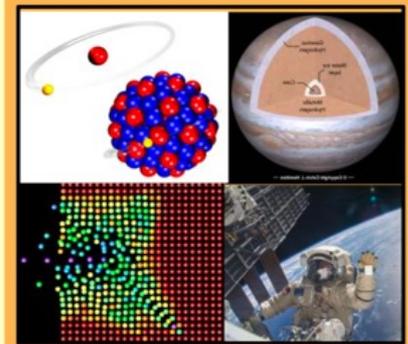
QCD phase structure and properties of QCD matter

### NUSTAR

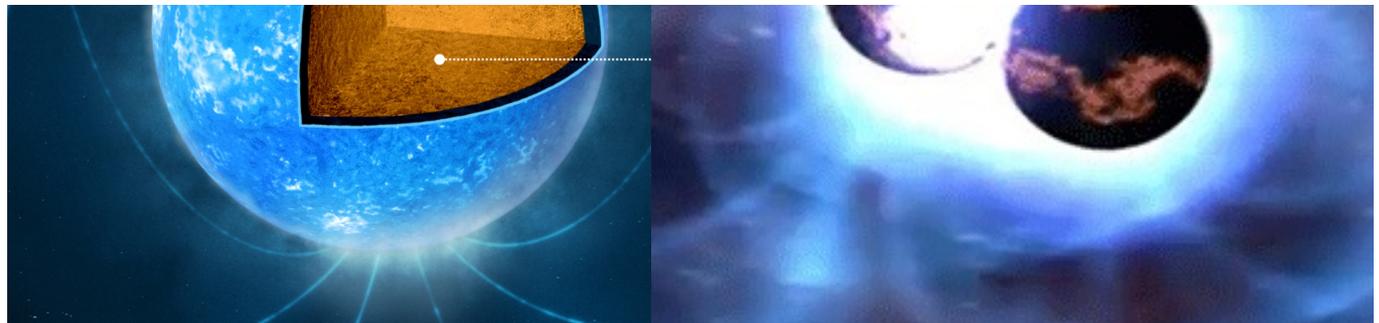


nuclear structure and nuclear astrophysics

### APPA



atomic physics, plasma physics, materials science, biophysics

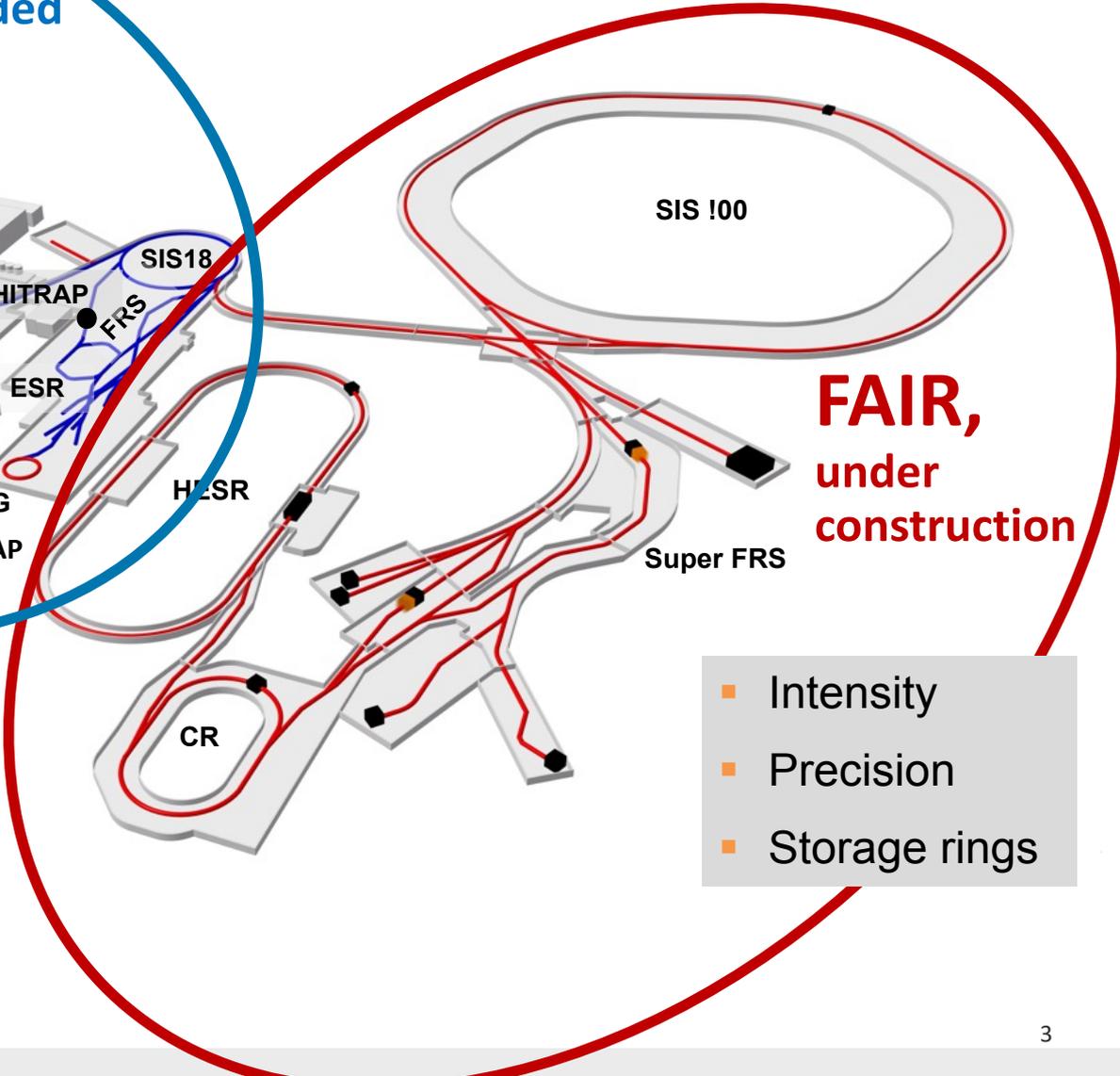
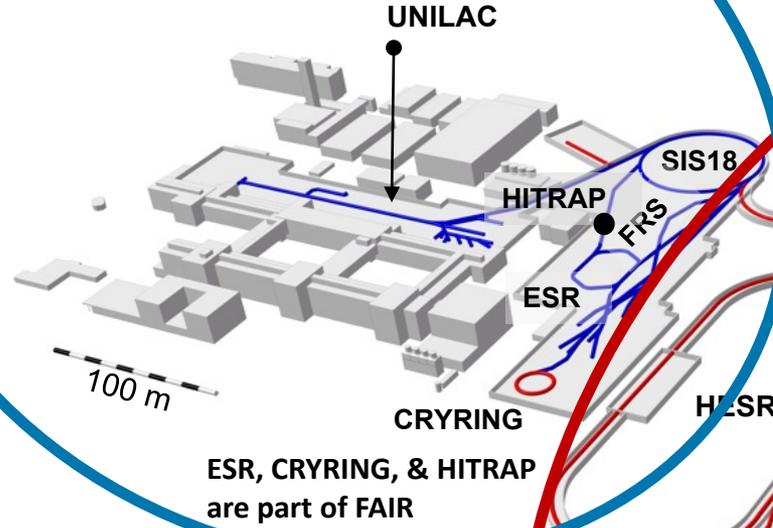


from Watts et al., RMP (2016)

NASA/Goddard/LIGO/Virgo



**GSI, existing (upgraded to integrate with FAIR)**



**FAIR, under construction**

- 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

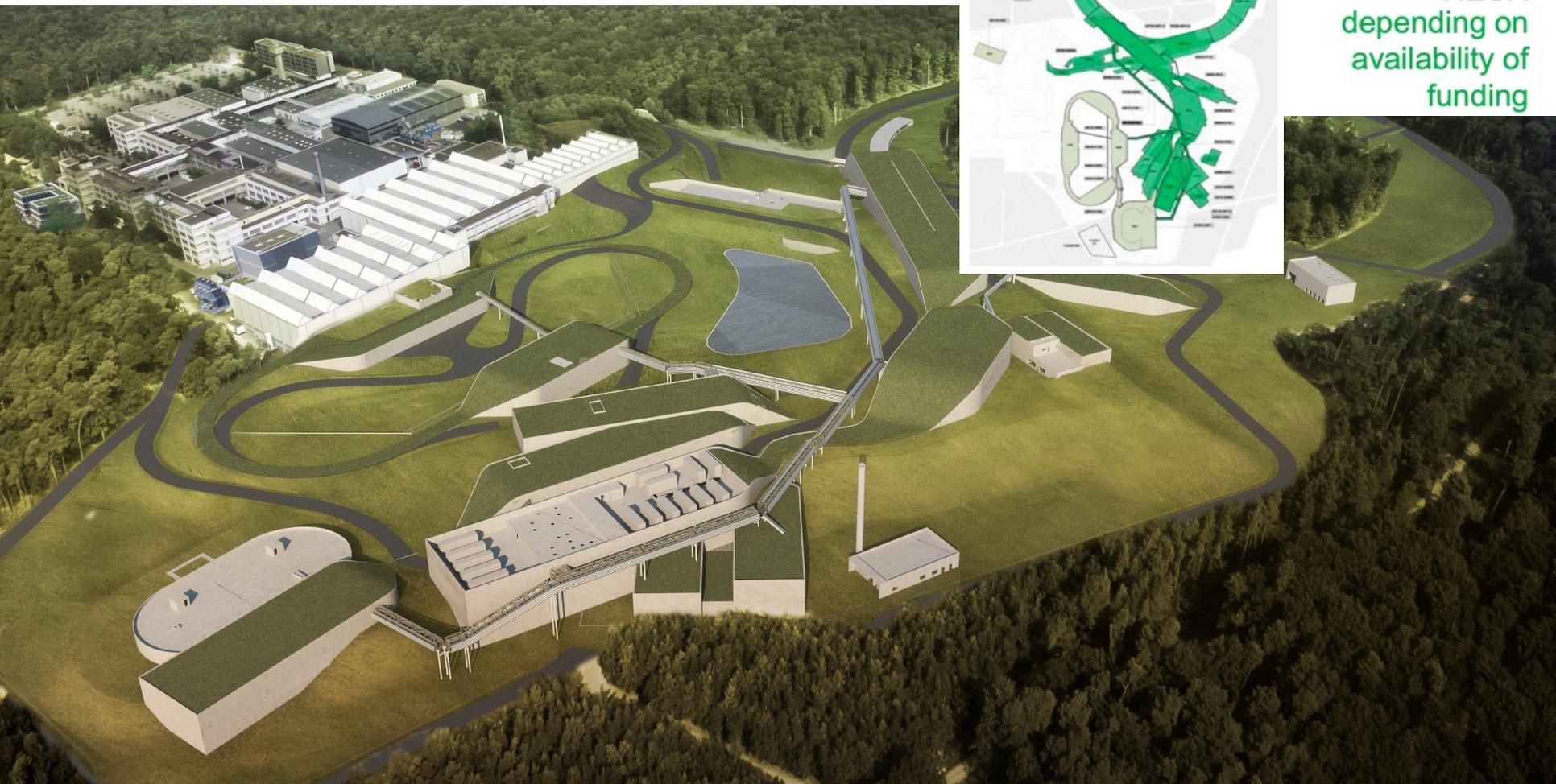
FAIR Phase-0  
since 2019

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

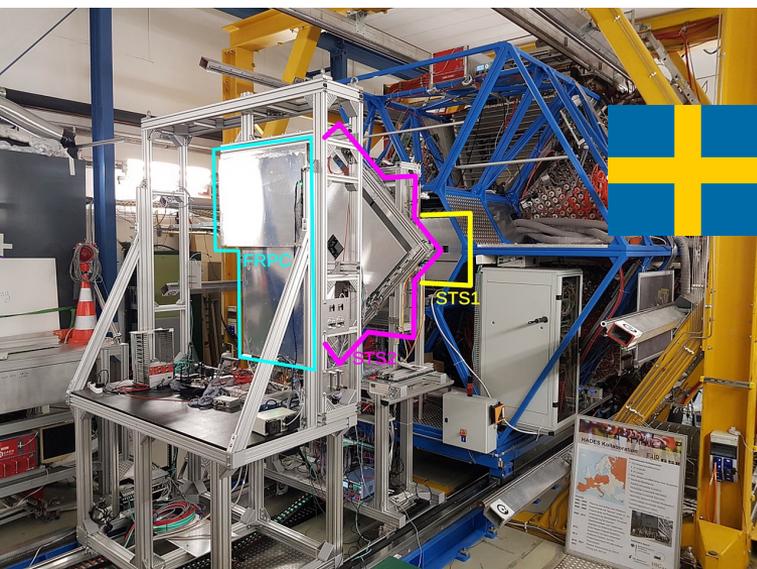
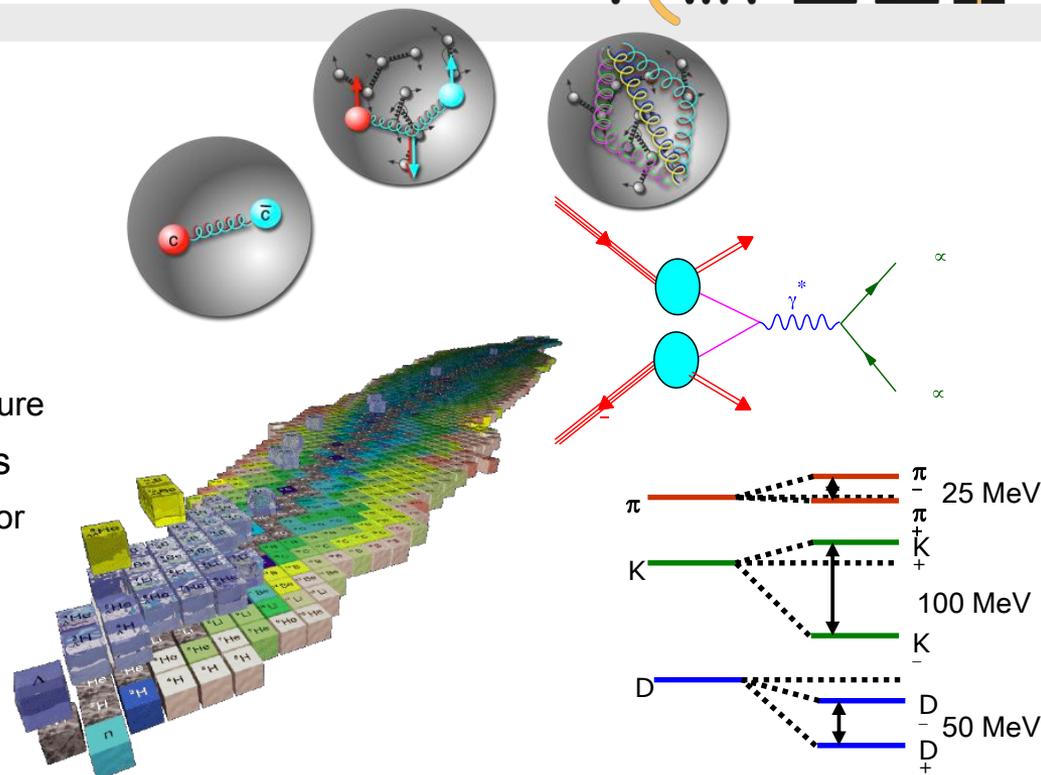


FAIR May 2022



# 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...

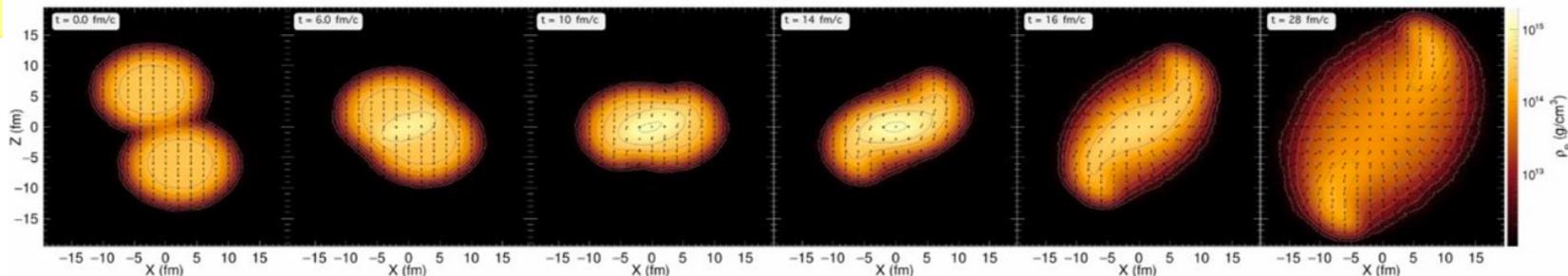
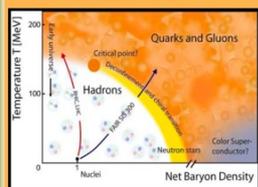


Strong involvement from Sweden  
(Lund, KTH, U Stockholm, Uppsala)

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

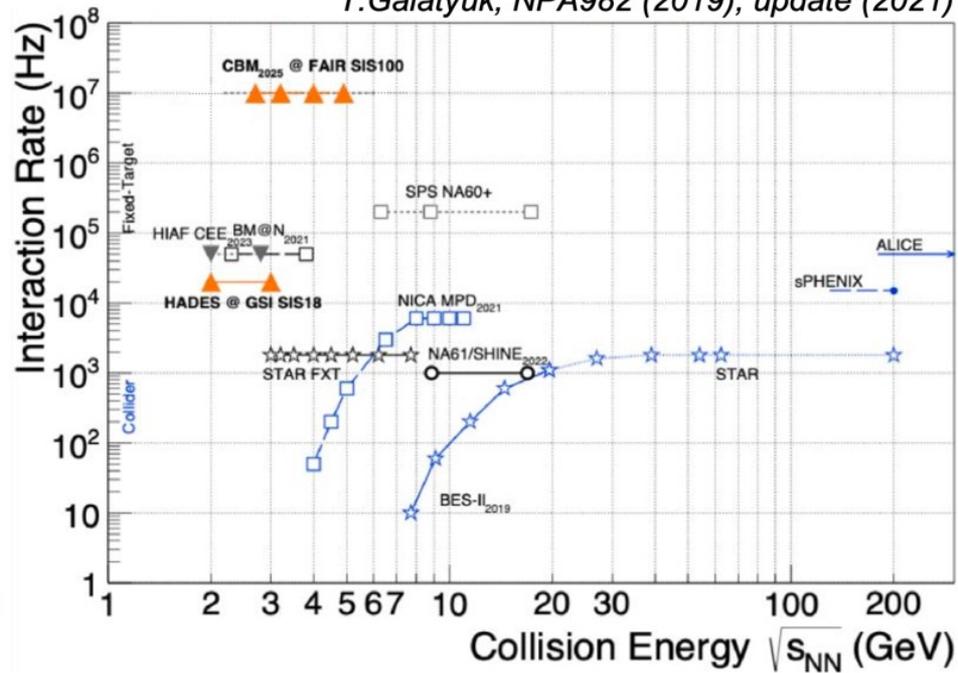
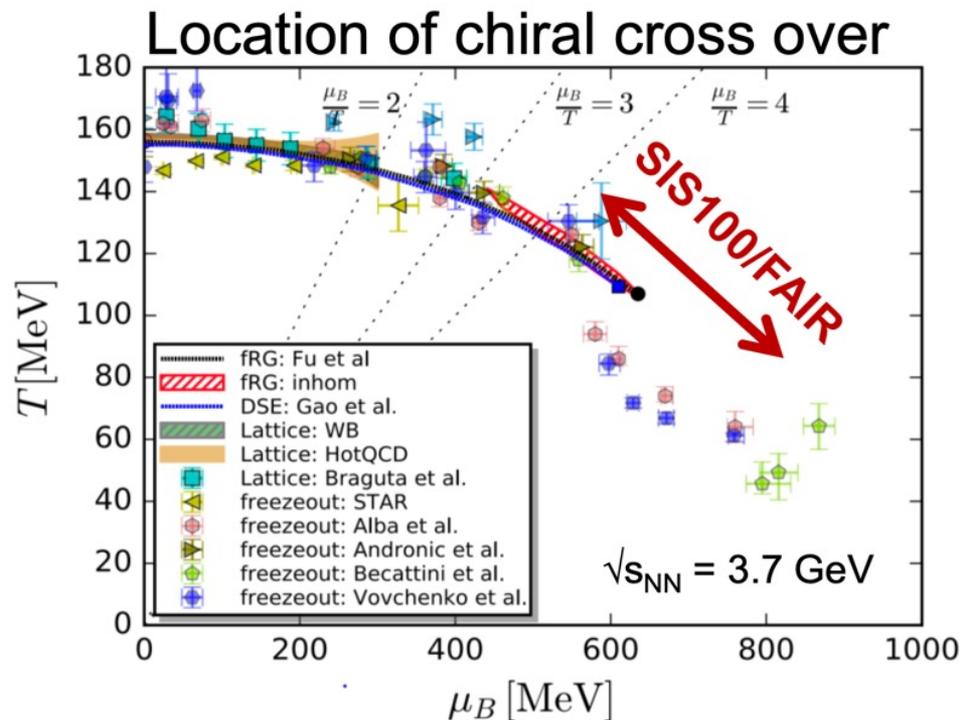
# Compressed Baryonic Matter

heavy-ion collisions to create matter at high baryon densities  
explore QCD phase diagram and properties of dense matter



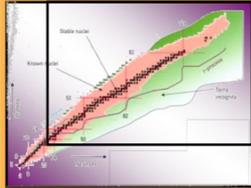
CBM Collaboration, EPJA 53 3 (2017) 60

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





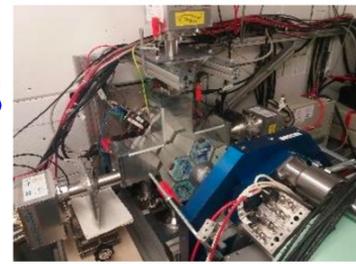
NUSTAR



nuclear structure and nuclear astrophysics

# NUSTAR: heavy and superheavy elements

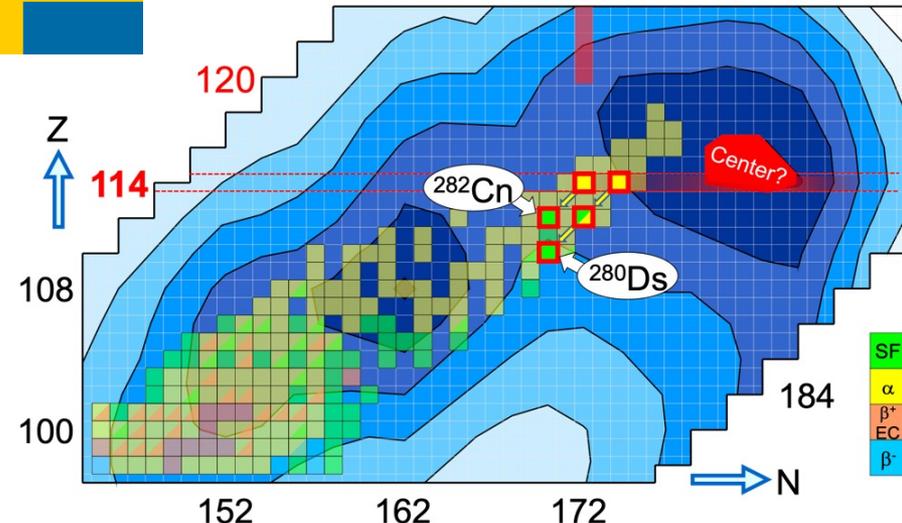
high-resolution  $\alpha$ -photon nuclear spectroscopy  
 of superheavy decay chains:  
 island of stability not at  $Z=114$  *Såmark-Roth et al., PRL (2021) (LUND)*



TASISpec+



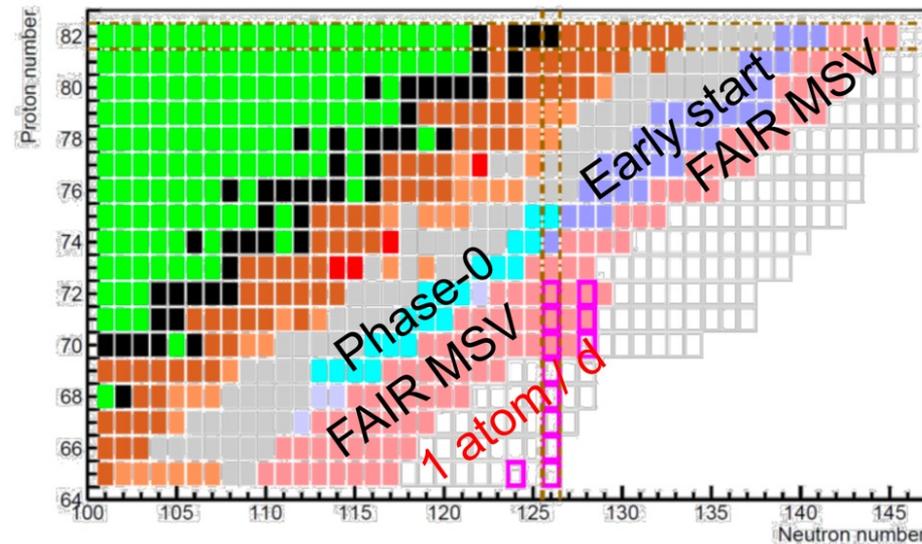
Chart of superheavy nuclei



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

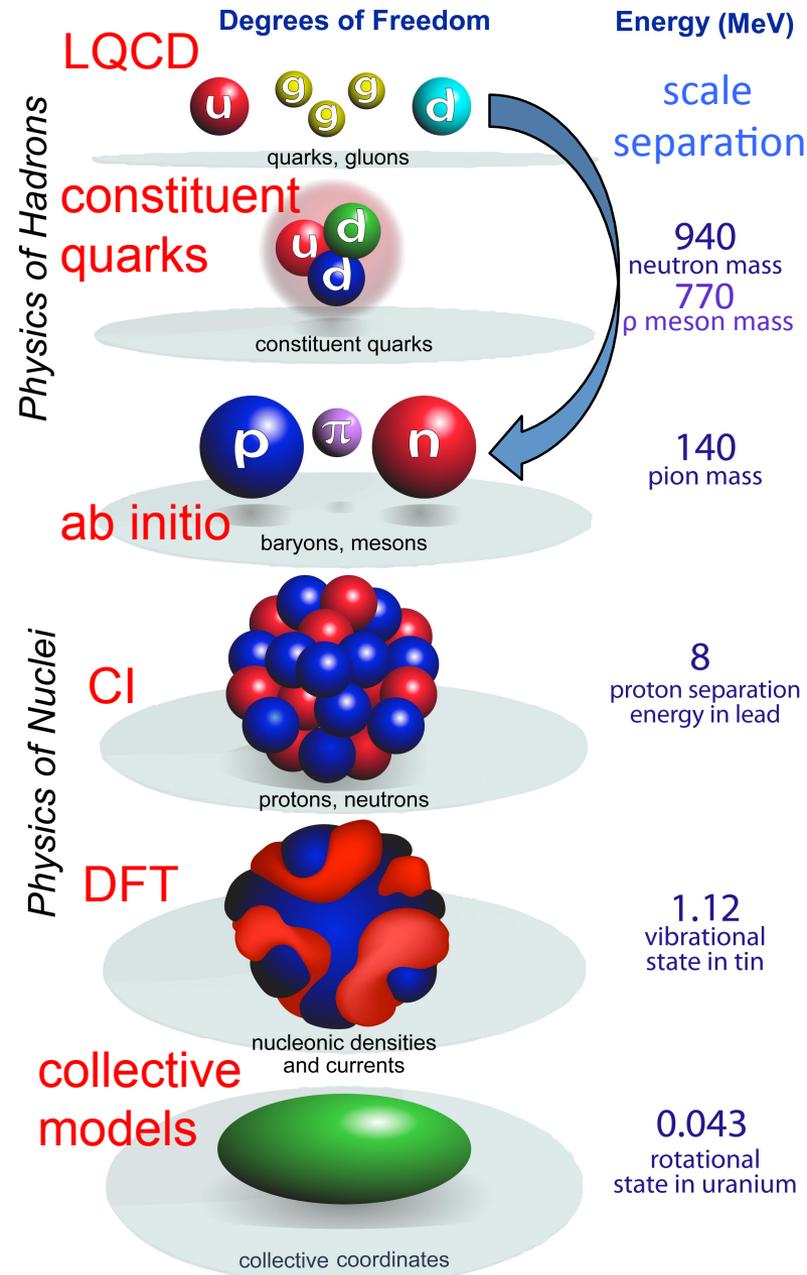
## Future FAIR: heavy + neutron-rich

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



W. Korten

# Hierarchy of degrees of freedom



## Emergent phenomena:

Protons and neutrons from QCD

Nuclear forces

Nuclear structure

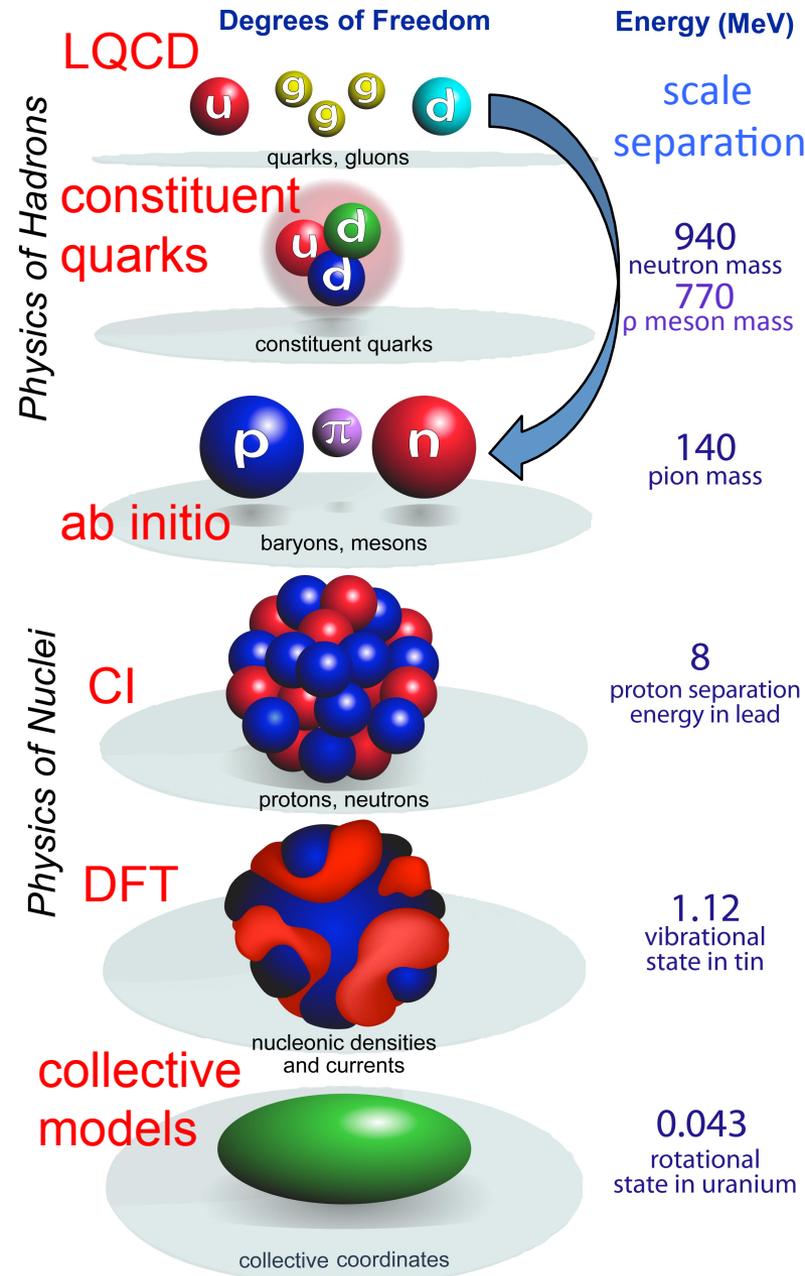
Large scattering length  
(universal) physics

...

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)

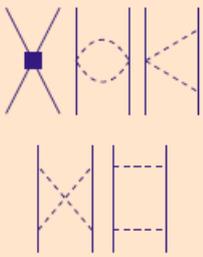
EFT for heavy nuclei: collective degrees of freedom

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  $(Q/\Lambda_b)^n$

		NN	3N	4N	
LO	$\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$				based on symmetries of strong interaction (QCD)
NLO	$\mathcal{O}\left(\frac{Q^2}{\Lambda^2}\right)$				long-range interactions governed by pion exchanges



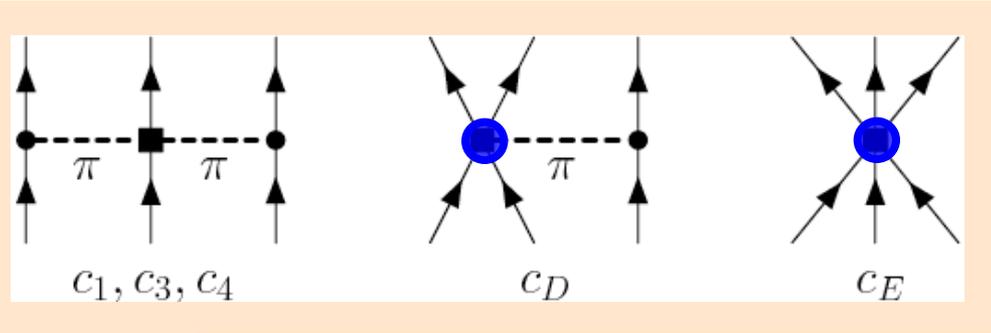
Weinberg (1990,91)

# Chiral effective field theory for nuclear forces

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

	NN	3N	4N
LO $\mathcal{O}\left(\frac{Q^0}{\Lambda^0}\right)$			
NLO $\mathcal{O}\left(\frac{Q^2}{\Lambda^2}\right)$			
N <sup>2</sup> LO $\mathcal{O}\left(\frac{Q^3}{\Lambda^3}\right)$			
N <sup>3</sup> LO $\mathcal{O}\left(\frac{Q^4}{\Lambda^4}\right)$			

powerful approach for many-body interactions



only 2 new couplings at N<sup>2</sup>LO

all 3- and 4-neutron forces predicted to N<sup>3</sup>LO

derived in (1994/2002)

+ ... (2011) ... (2006) ...

# 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

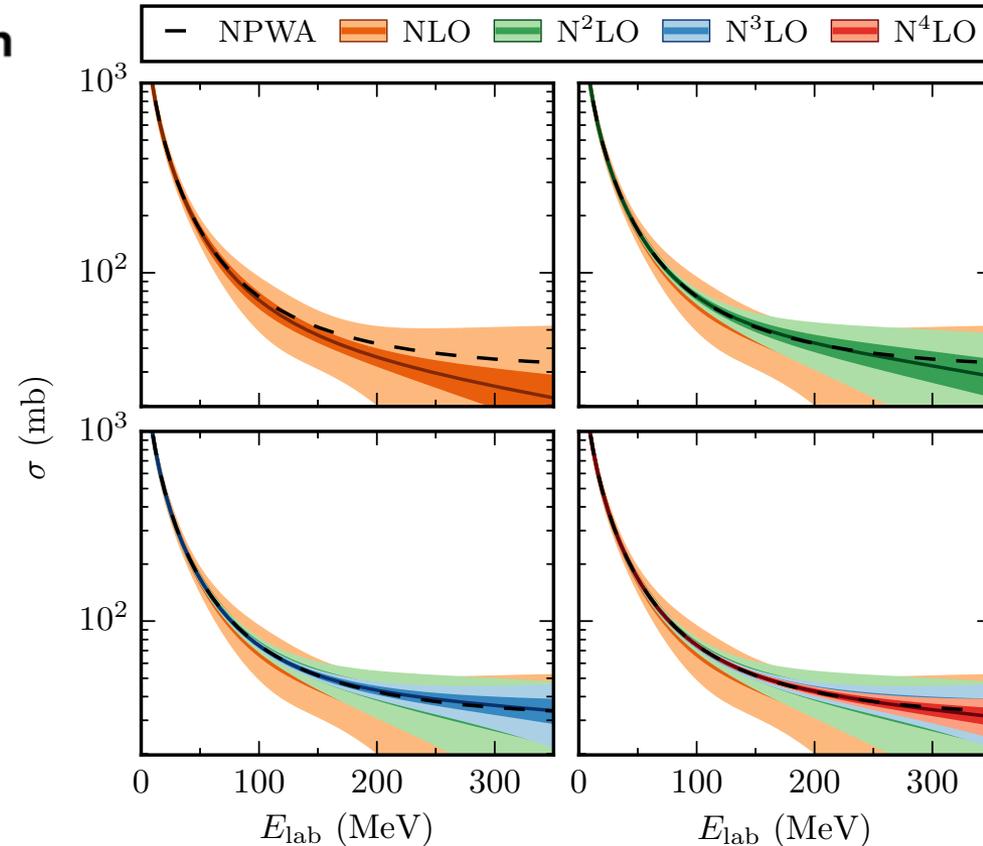
J. Phys. G: Nucl. Part. Phys. **42** (2015) 034028 (20pp)

doi:10.1088/0954-3899/42/3/034028

## A recipe for EFT uncertainty quantification in nuclear physics

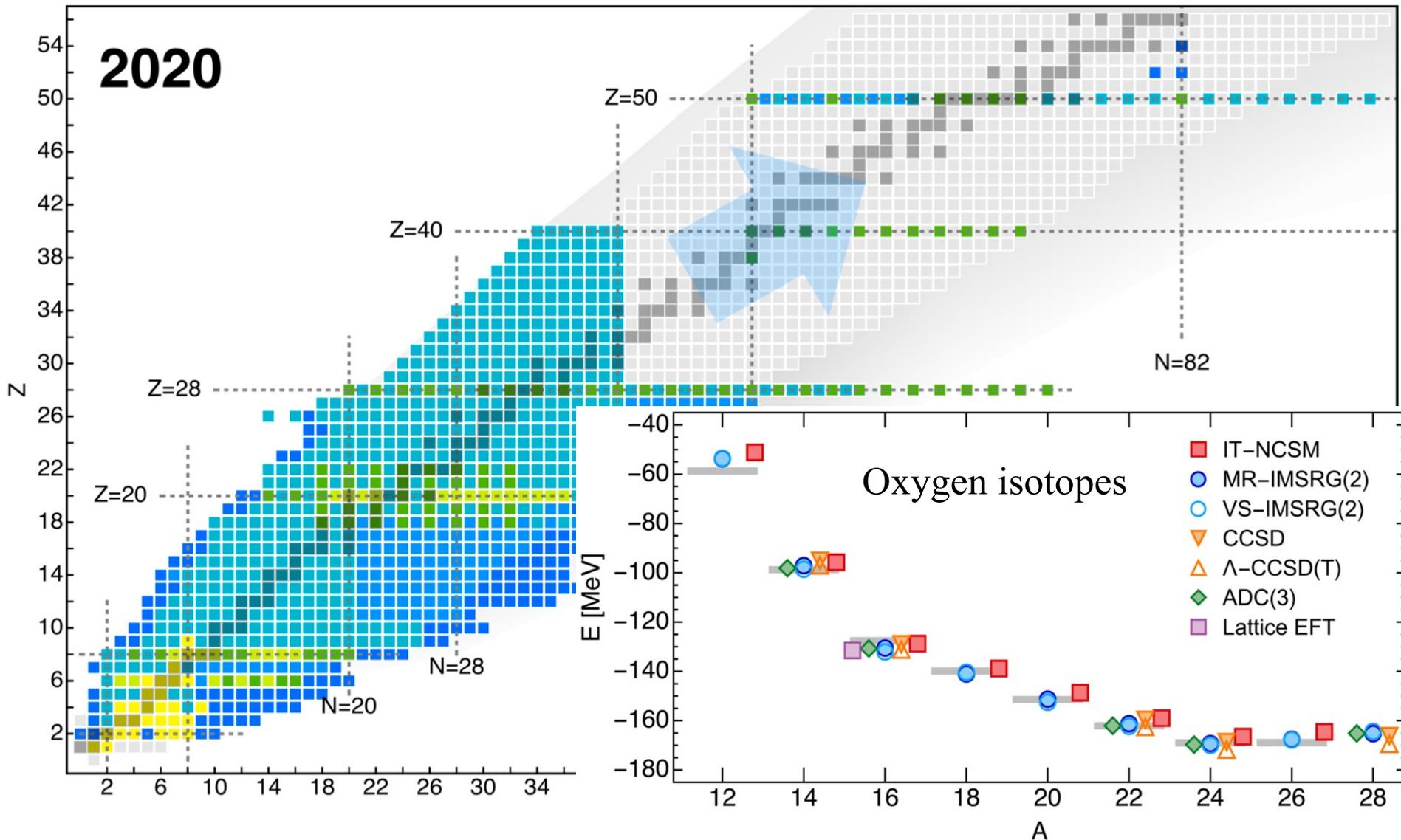
R J Furnstahl<sup>1</sup>, D R Phillips<sup>2</sup> and S Wesolowski<sup>1</sup>

## Bayesian uncertainty estimates and model checking



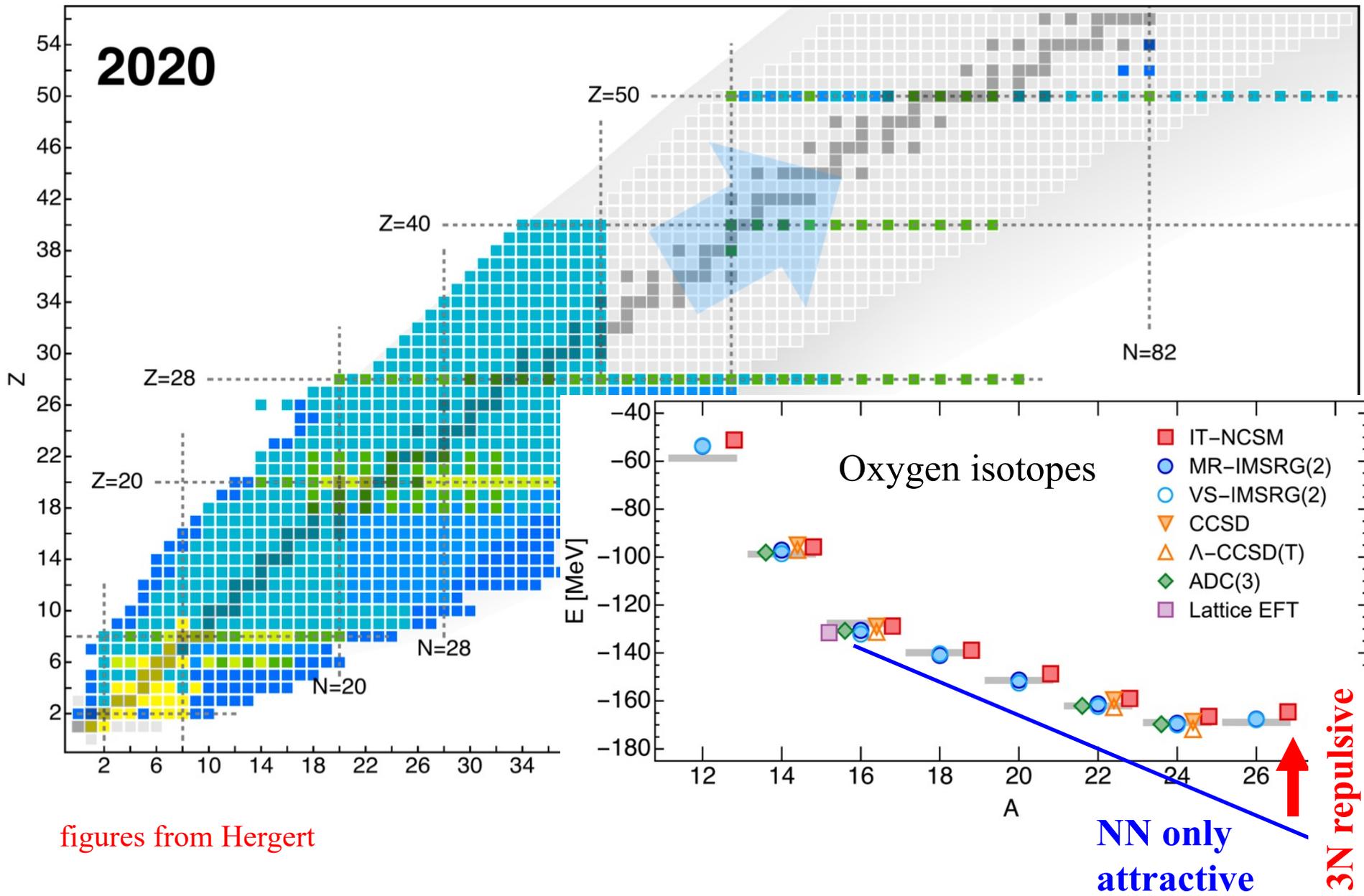
Furnstahl, Phillips, Klos, Wesolowski, Melendez (2015-)

# Great progress in ab initio calculations of nuclei

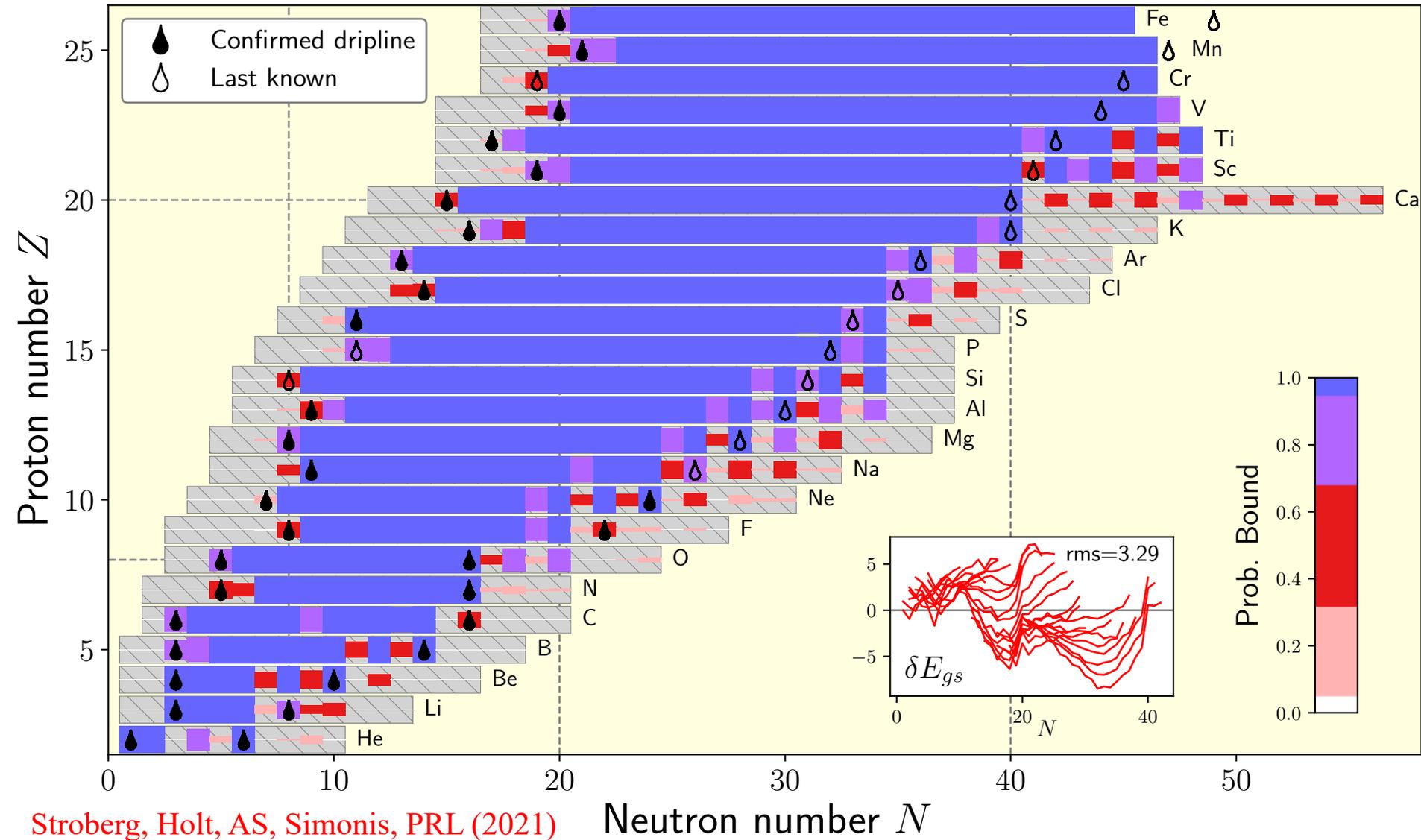


figures from Hergert

# Great progress in ab initio calculations of nuclei

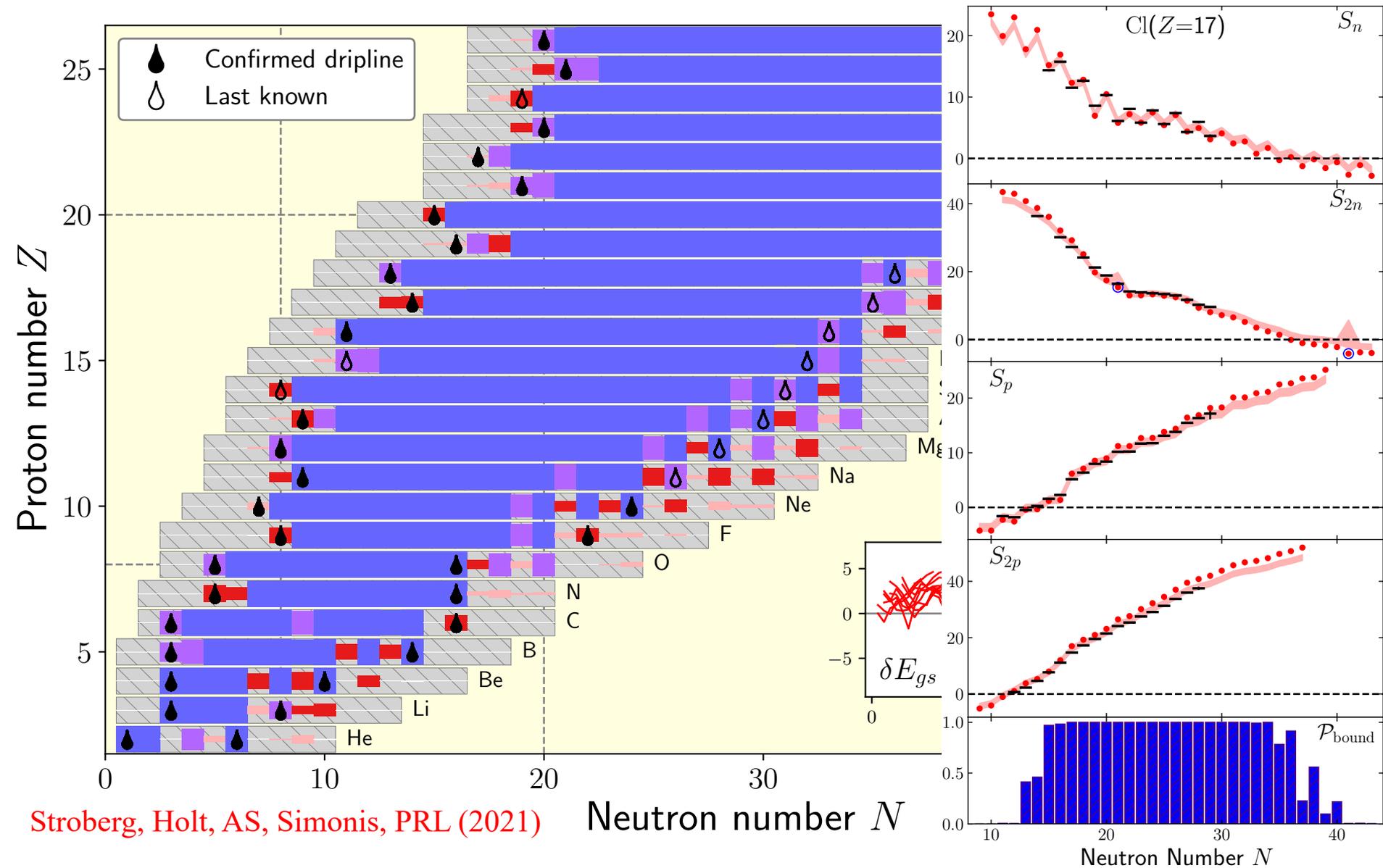


# Nuclear landscape based on a chiral NN+3N interaction



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

# Nuclear landscape based on a chiral NN+3N interaction

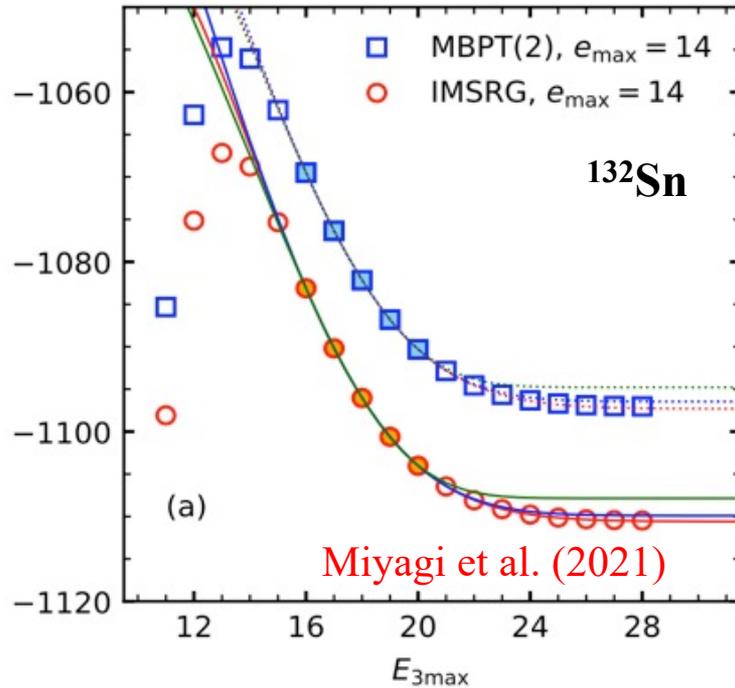


ab initio is advancing to global theories, limitations due to input NN+3N

# First ab initio calculations of $^{208}\text{Pb}$

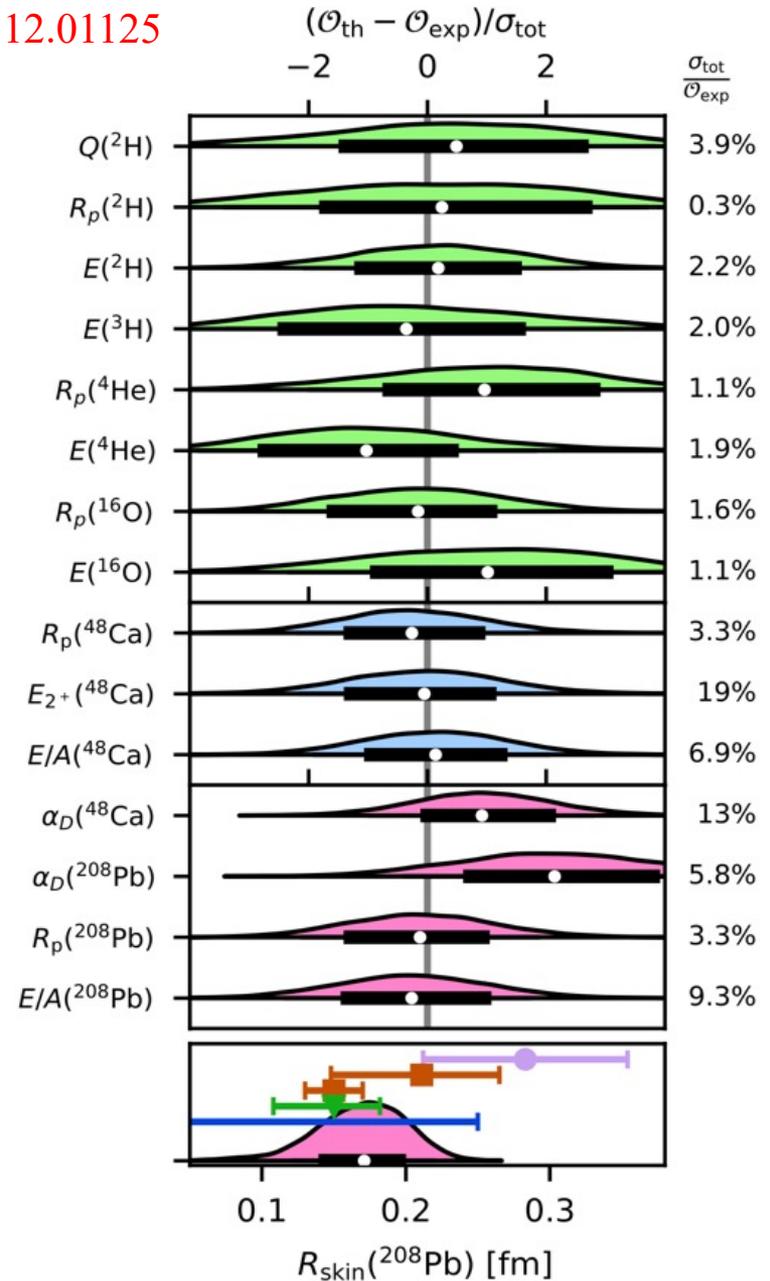
Hu, Jiang, Miyagi et al. [Chalmers, ORNL, TRIUMF], arXiv:2112.01125

enabled by 3N advances



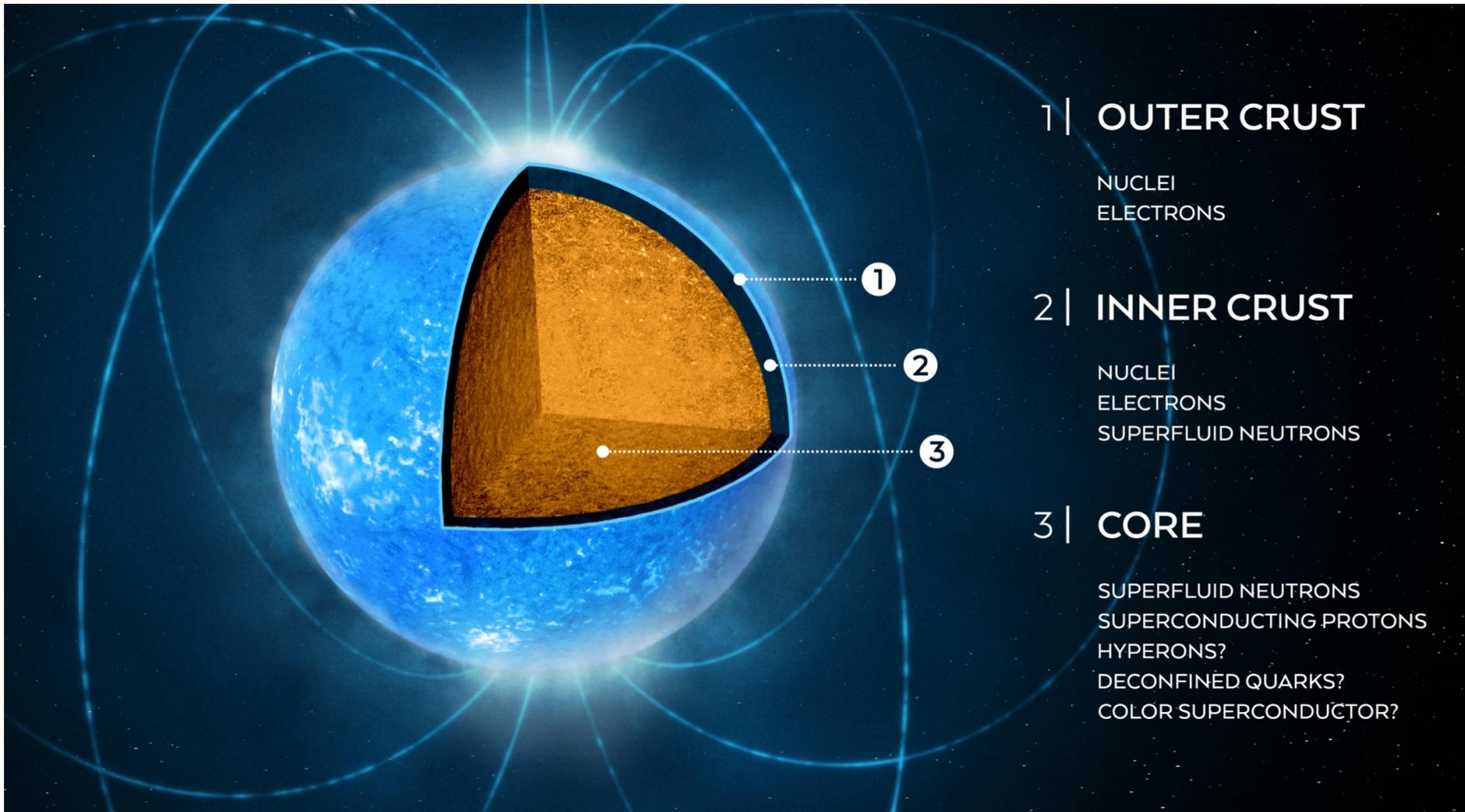
statistical methods via history matching  
to explore uncertainties in NN+3N

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



# Extreme matter in neutron stars

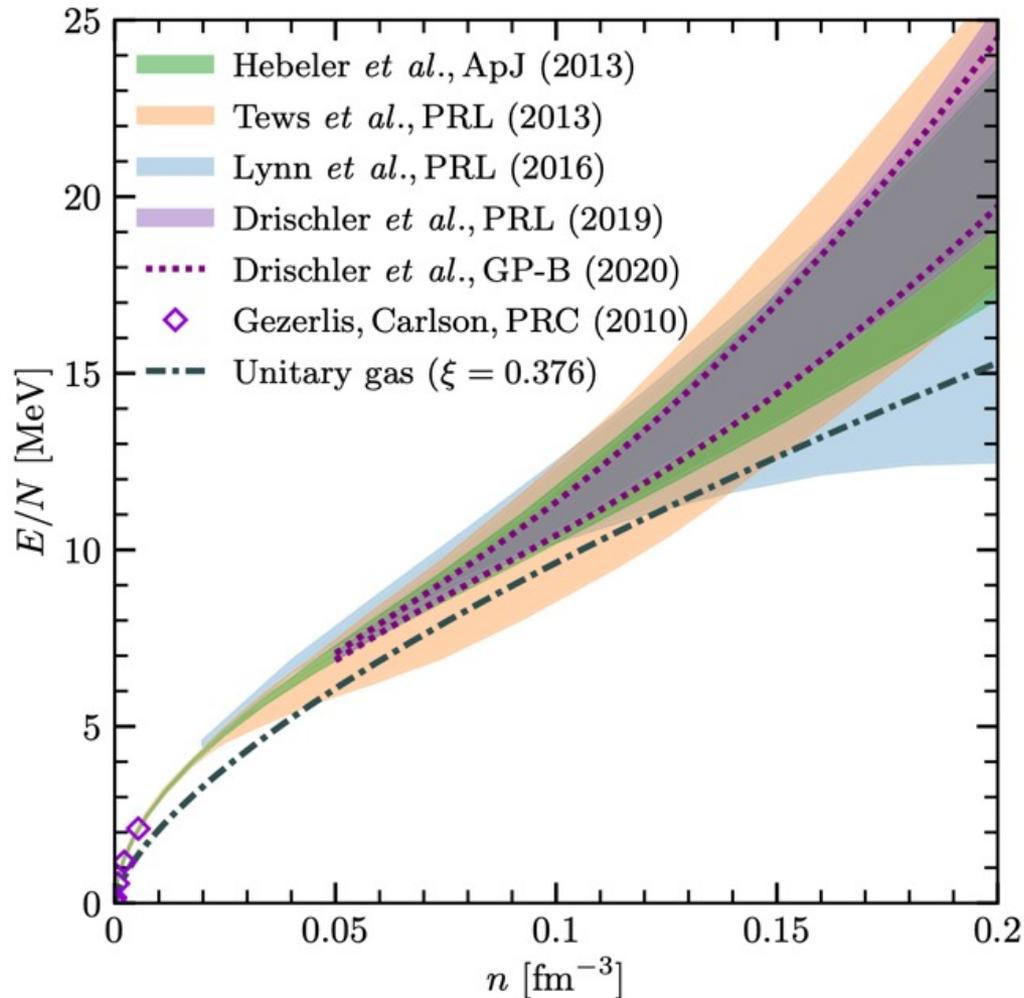
governed by the same strong interactions



# Chiral EFT calculations of neutron matter

good agreement up to saturation density for neutron matter

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

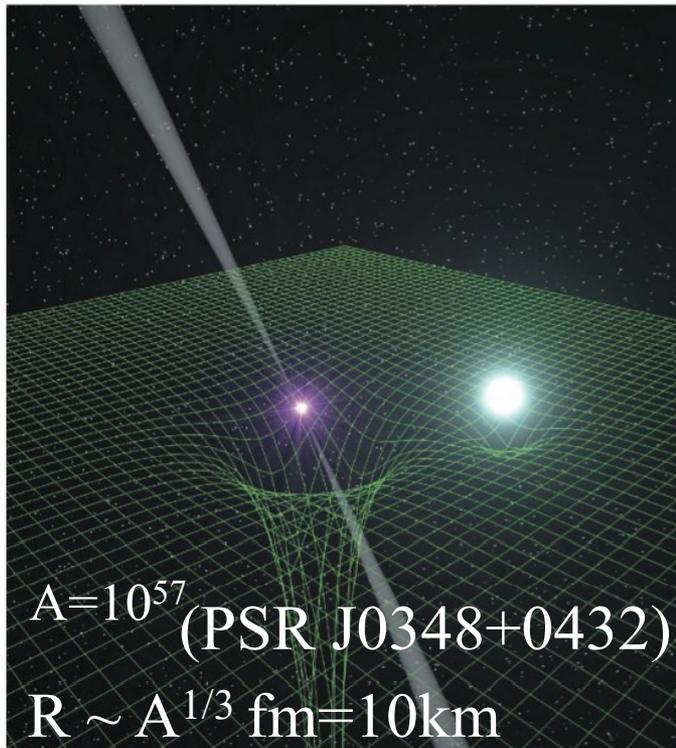


slope determines  
pressure of  
neutron matter

from Huth, Wellenhofer, AS, PRC (2020)

# Neutron star masses

from Jim Lattimer

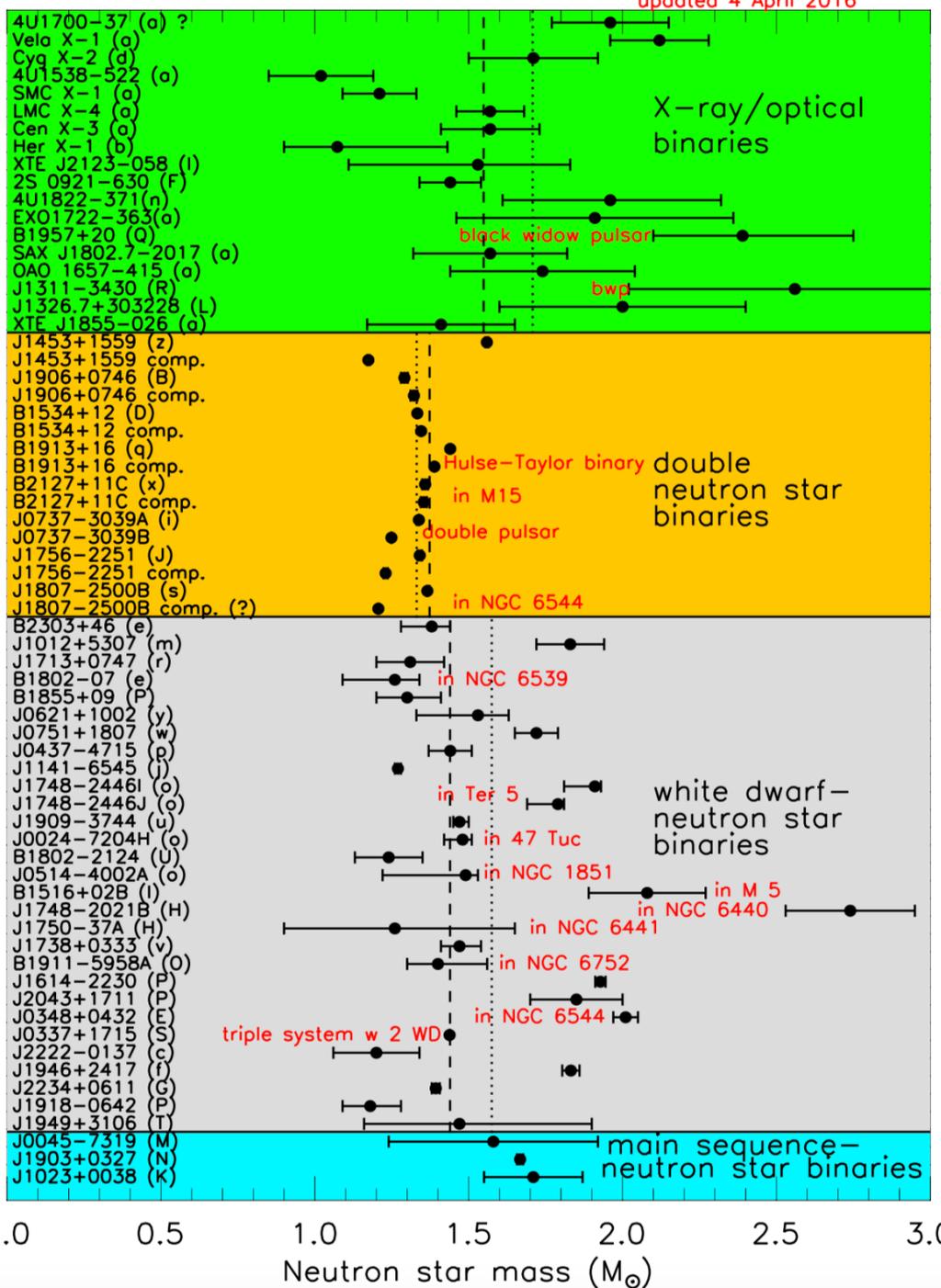


three  $2 M_{\text{sun}}$  neutron stars obs.

Demorest et al, Nature (2010),

Antoniadis et al., Science (2013),

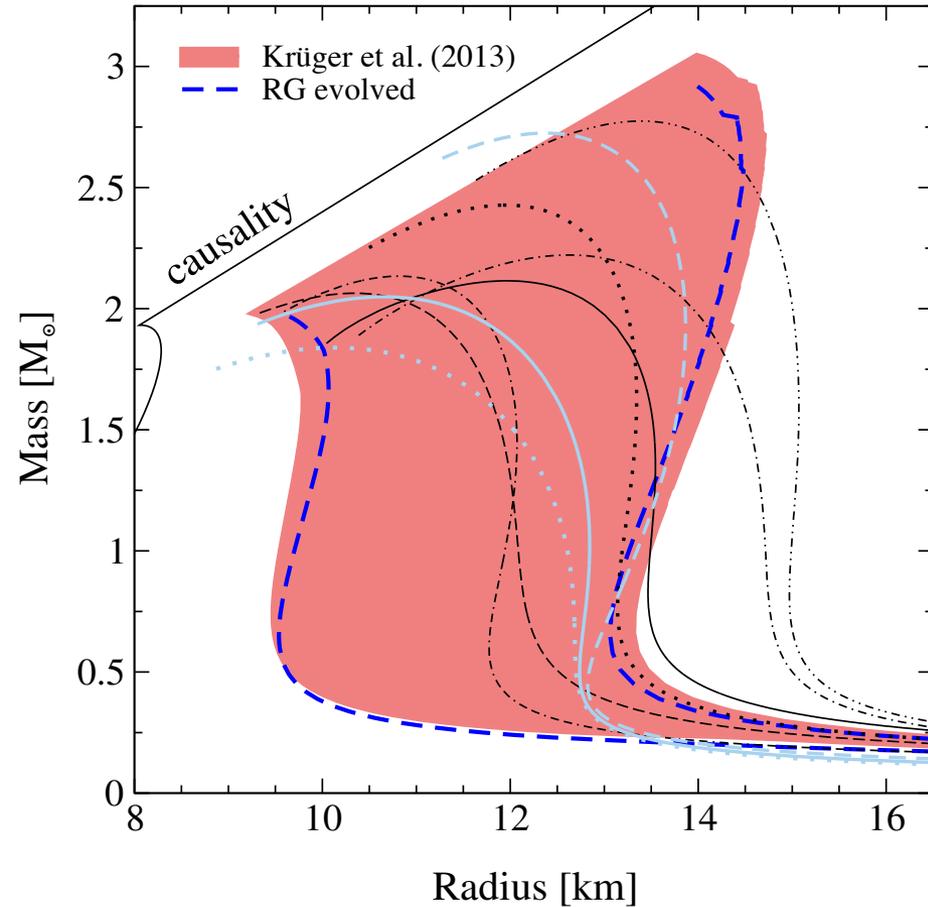
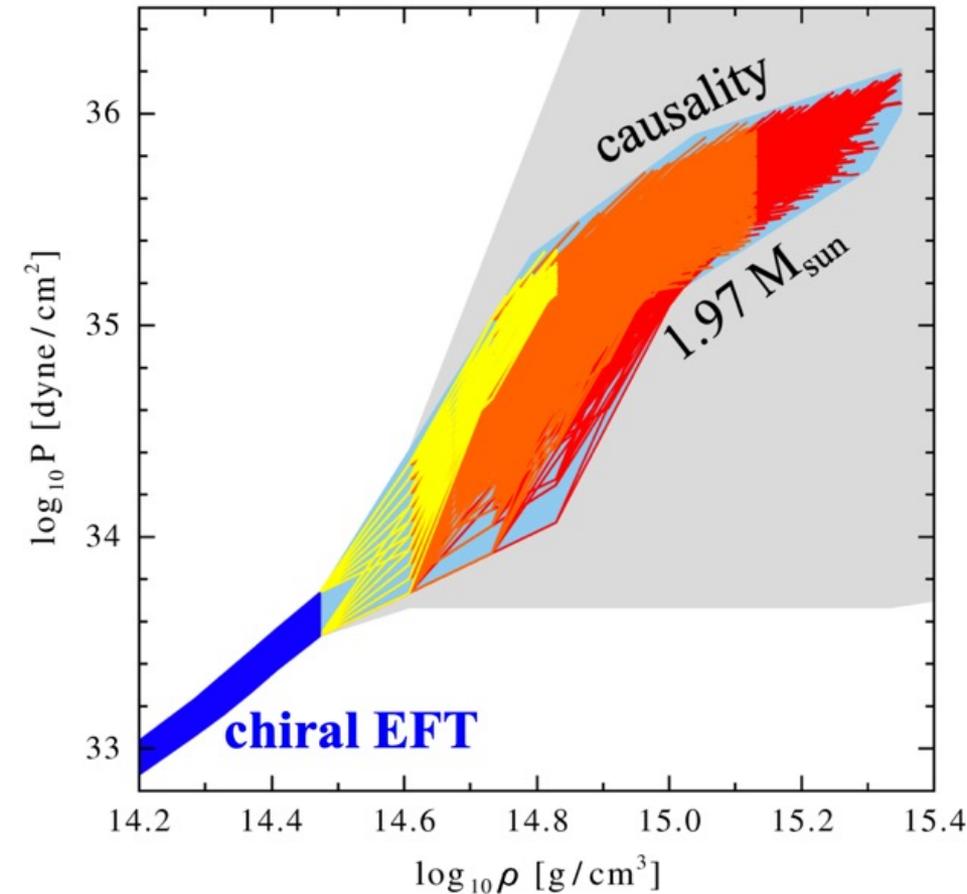
$2.08 \pm 0.07 M_{\text{sun}}$  Fonseca et al. (2021)





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

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



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

1.8 - 4.4  $n_0$  modest central densities

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

# Neutron star radius from GW170817

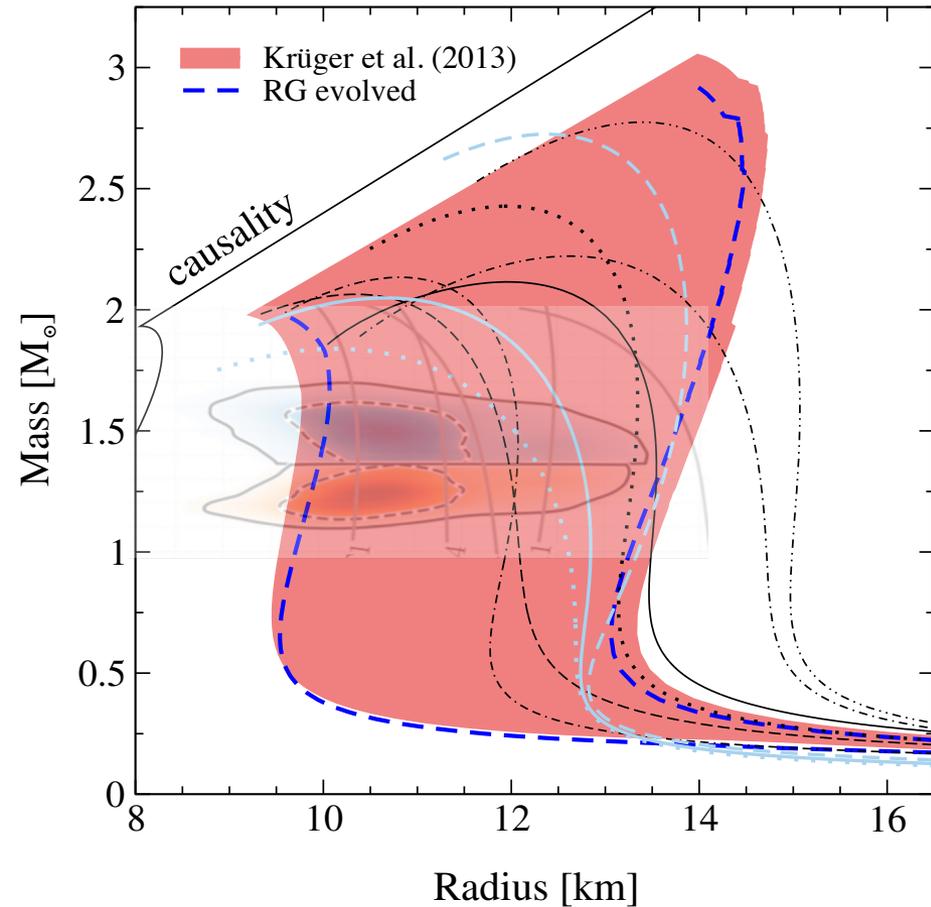
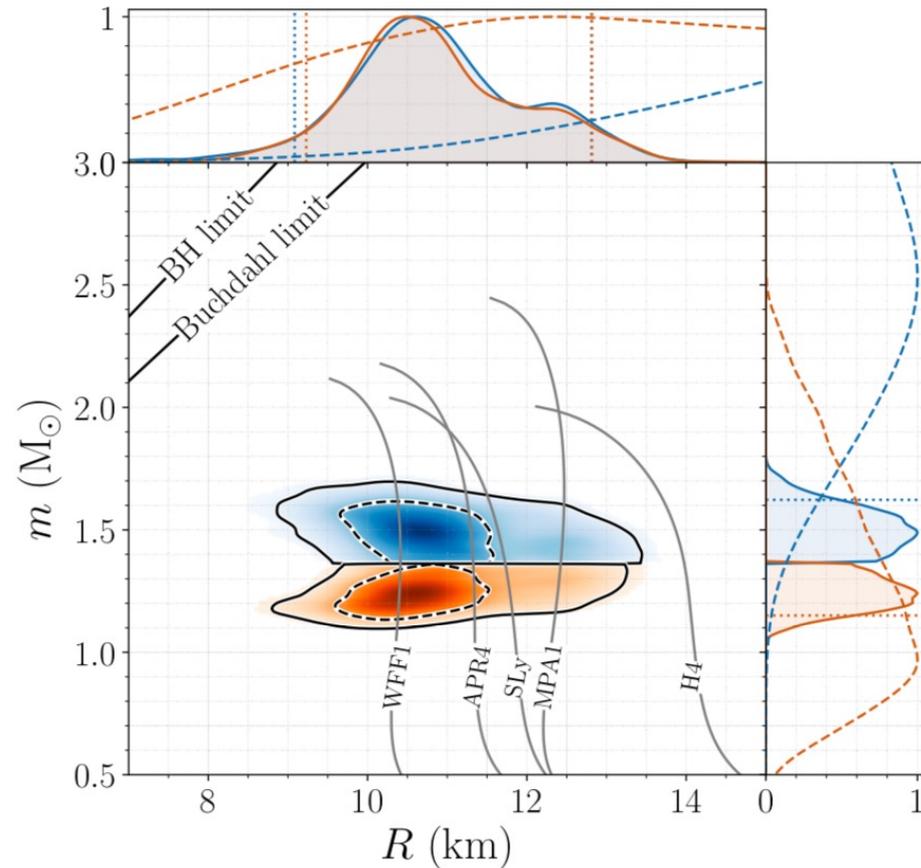
chiral EFT + general EOS extrapolation: 9.7 - 13.9 km for  $M=1.4 M_{\text{sun}}$

GW170817: Measurements of neutron star radii and equation of state

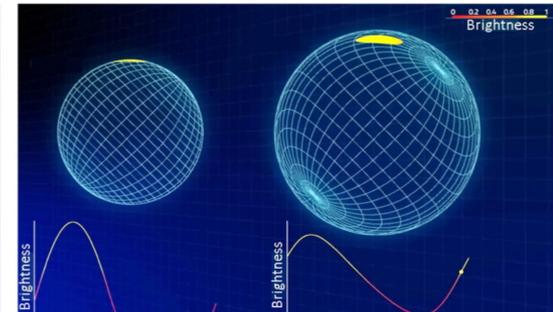
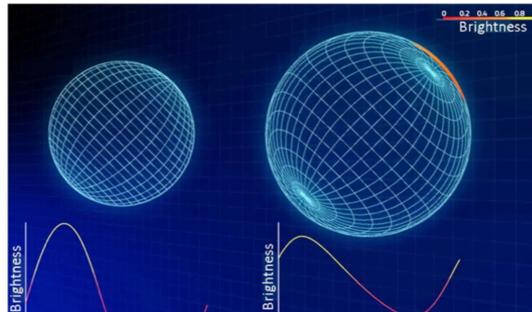
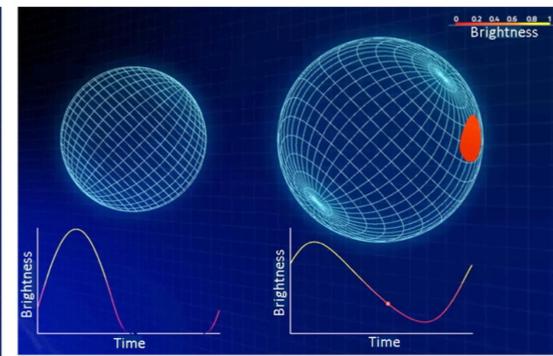
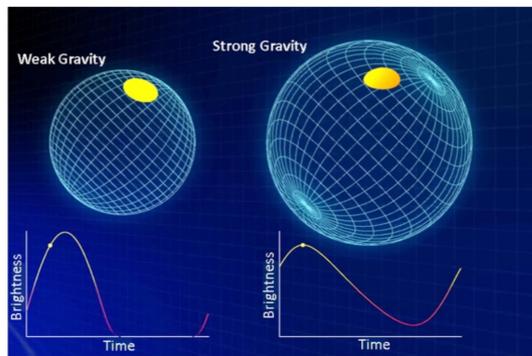
excellent agreement with

GW170817 from LIGO/Virgo

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



# NICER results



Neutron star radius from  
pulse profile modeling

J0030 and J0740

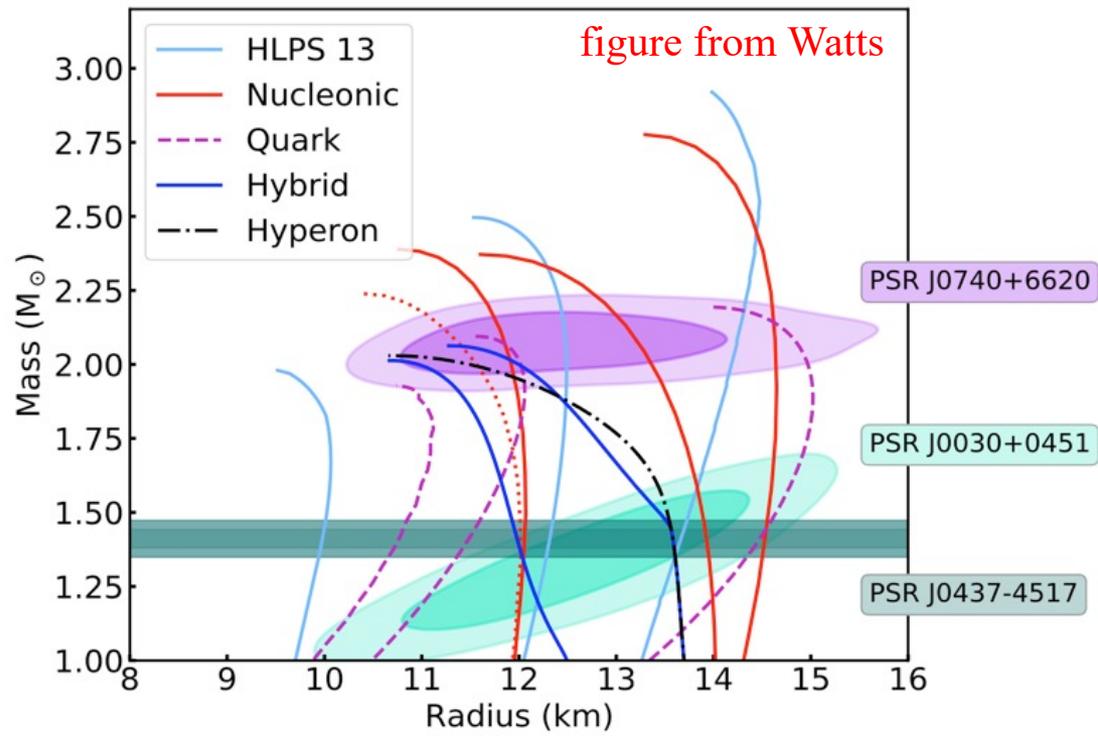
here: Amsterdam analysis

Riley et al., *ApJL* (2019), (2021)

similar results from

Illinois-Maryland analysis

Miller et al., *ApJL* (2019), (2021)

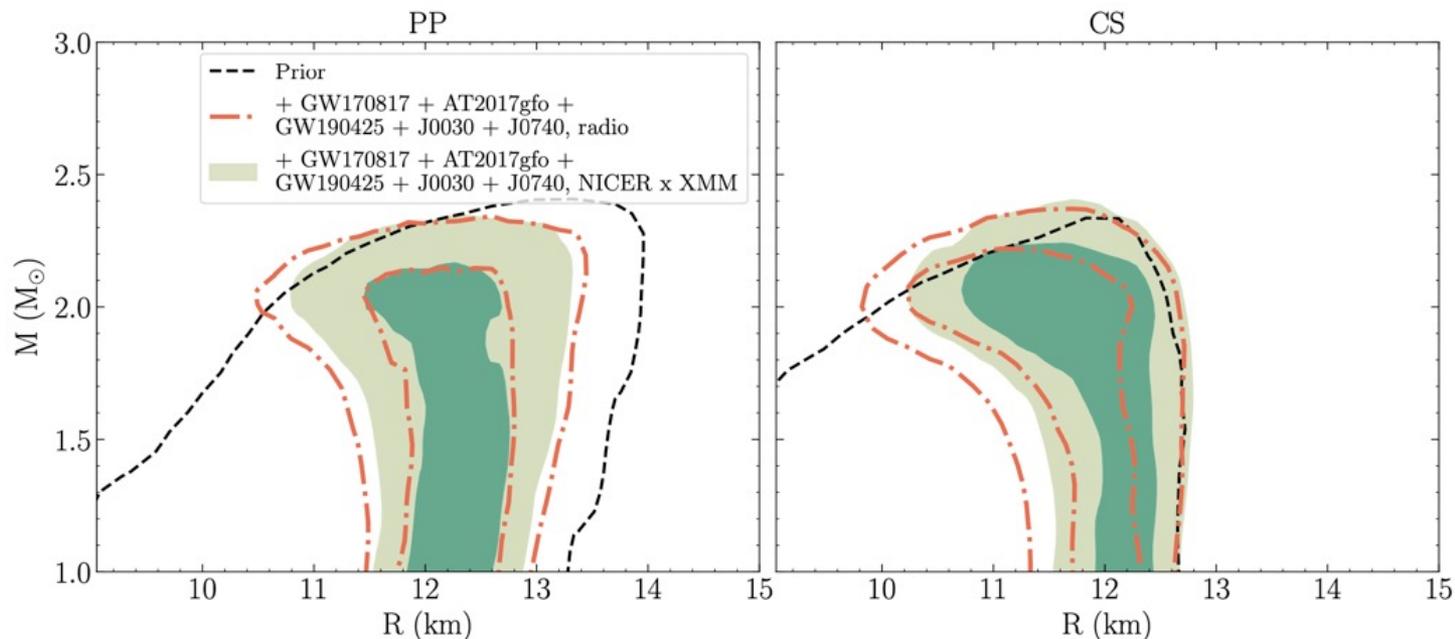


# Combined merger and NICER constraints

Raaijmakers et al.,  
ApJL (2020), (2021)  
for mass-radius

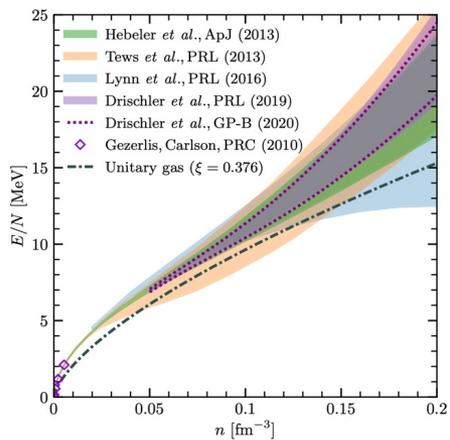
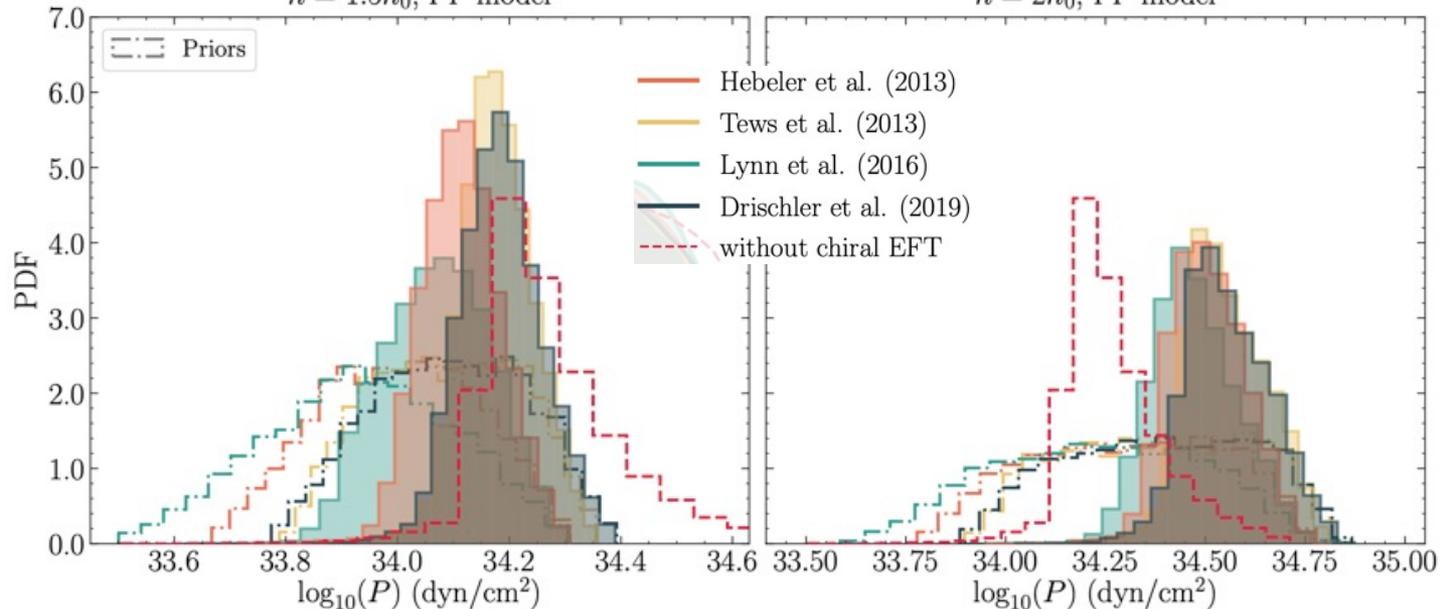
equation of state  
at  $1.5$  and  $2 n_0$

astro prefers  
higher pressures



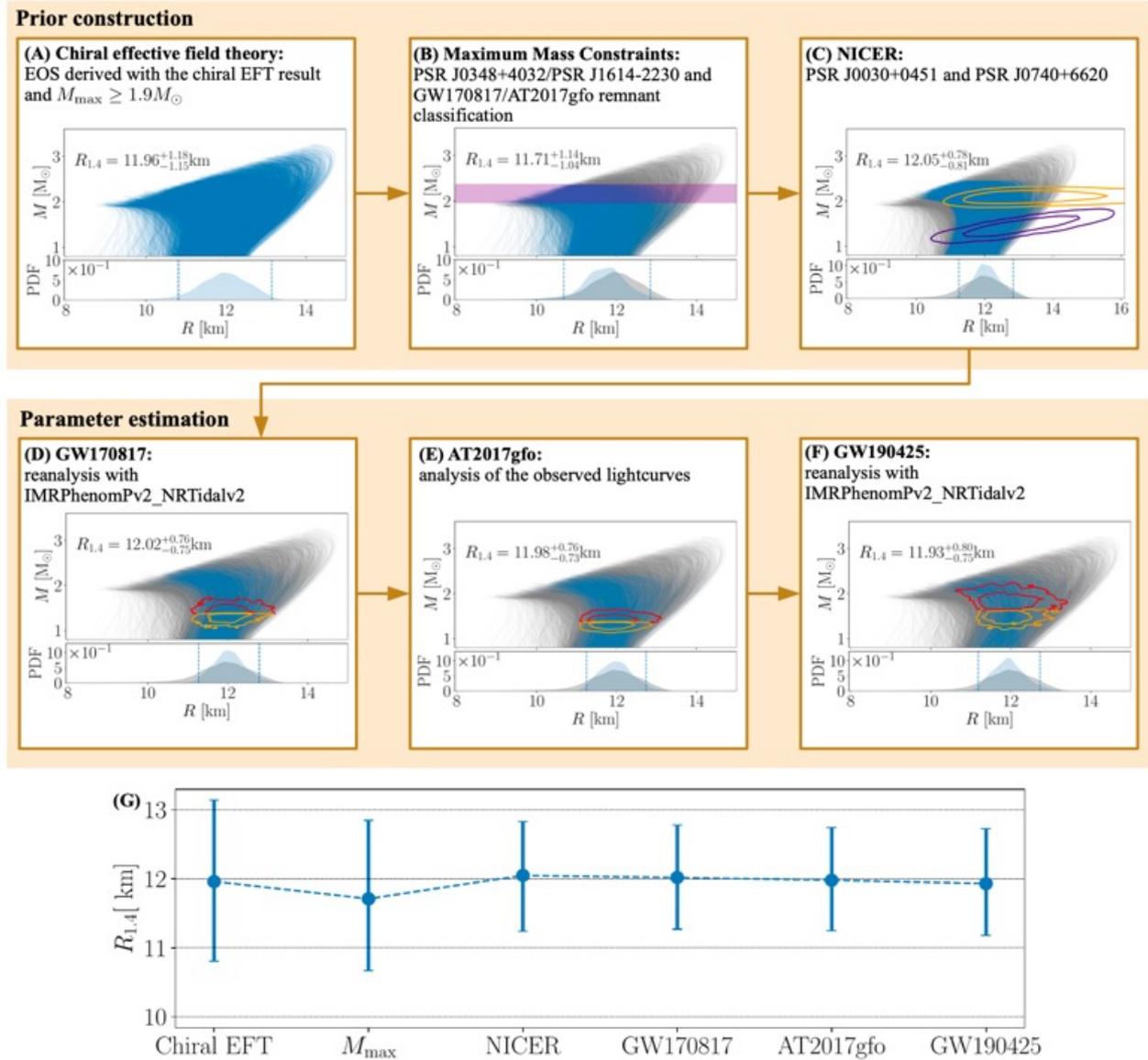
$n = 1.5n_0$ , PP model

$n = 2n_0$ , PP model



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

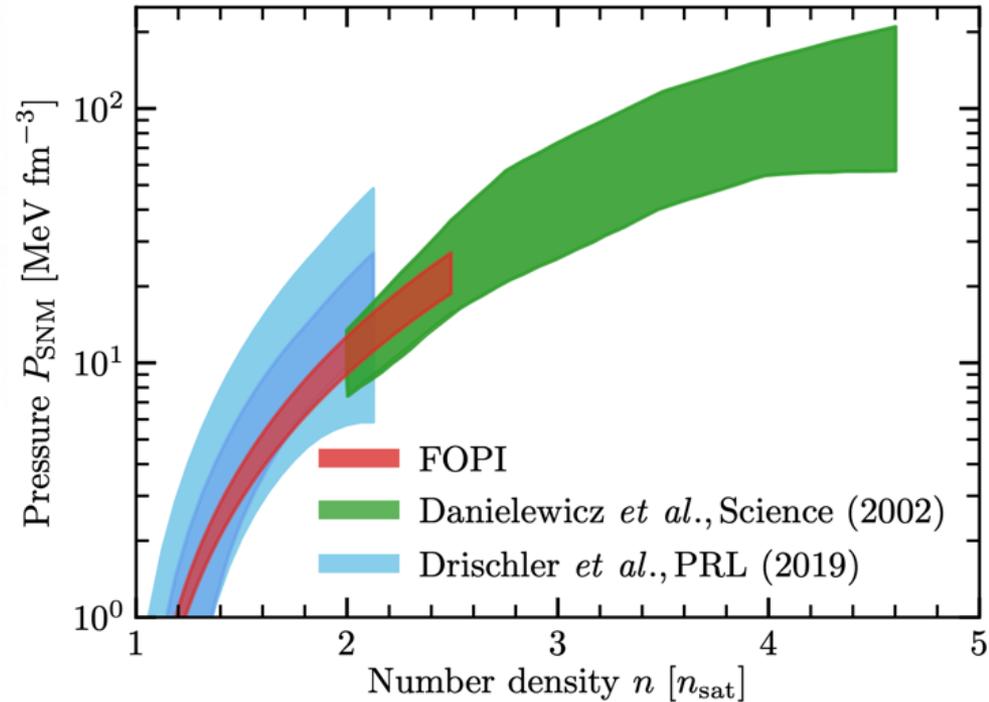
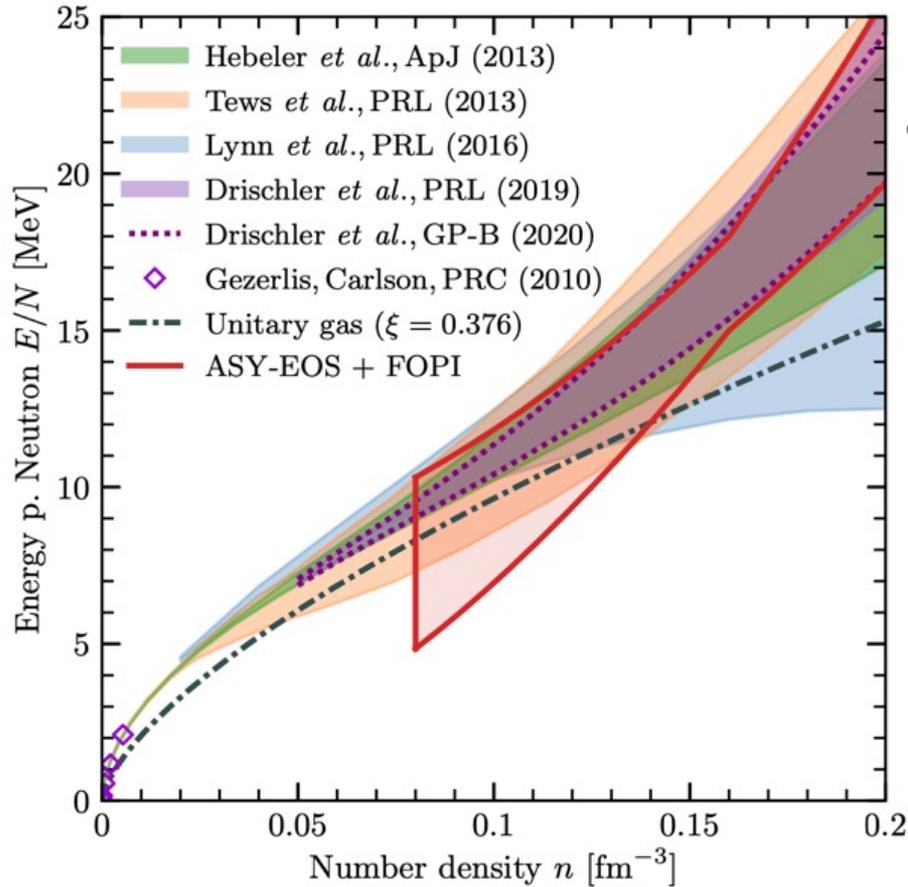
Bayesian multi-messenger framework using EOS draws based on chiral EFT



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

include constraints from heavy-ion collision experiments

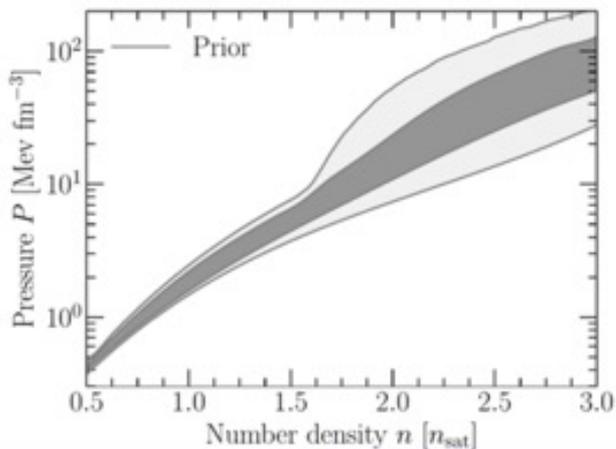
**ASY-EOS and FOPI at GSI** for neutron and symmetric matter



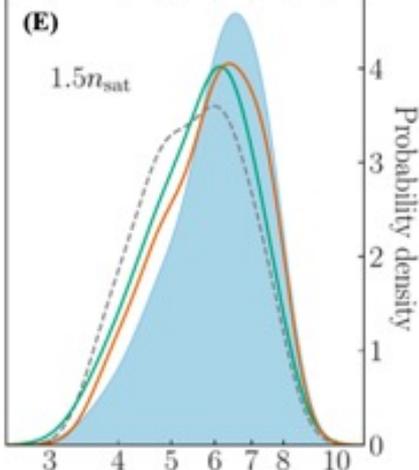
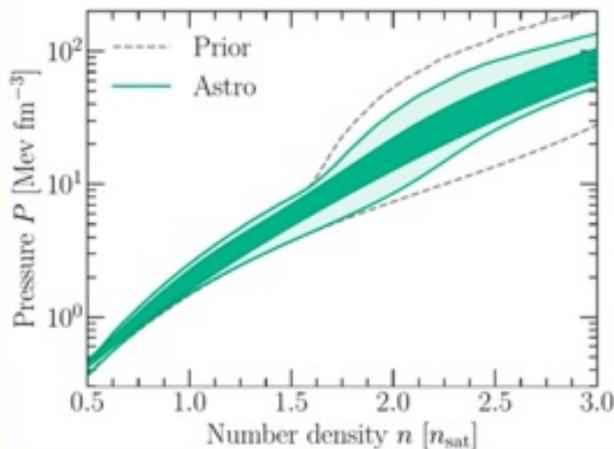
# Constraints from heavy-ion collisions Huth, Pang et al., Nature (2022)

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

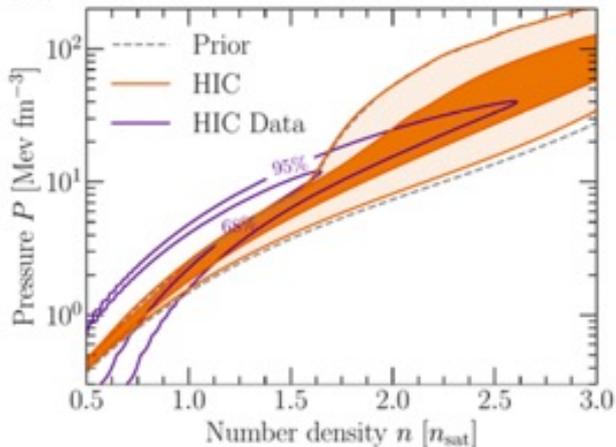
(A) Chiral effective field theory:



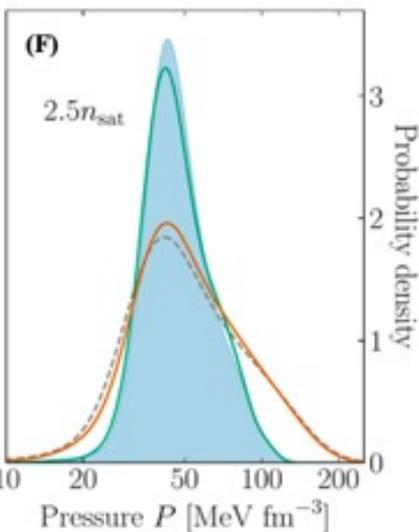
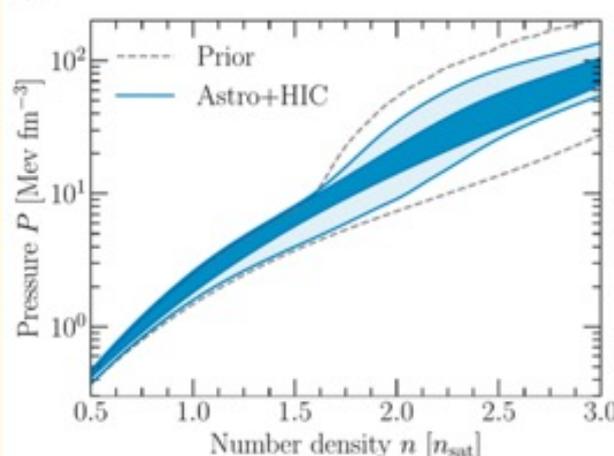
(B) Multi-messenger astrophysics:



(C) HIC experiments:



(D) HIC and Astro combined:



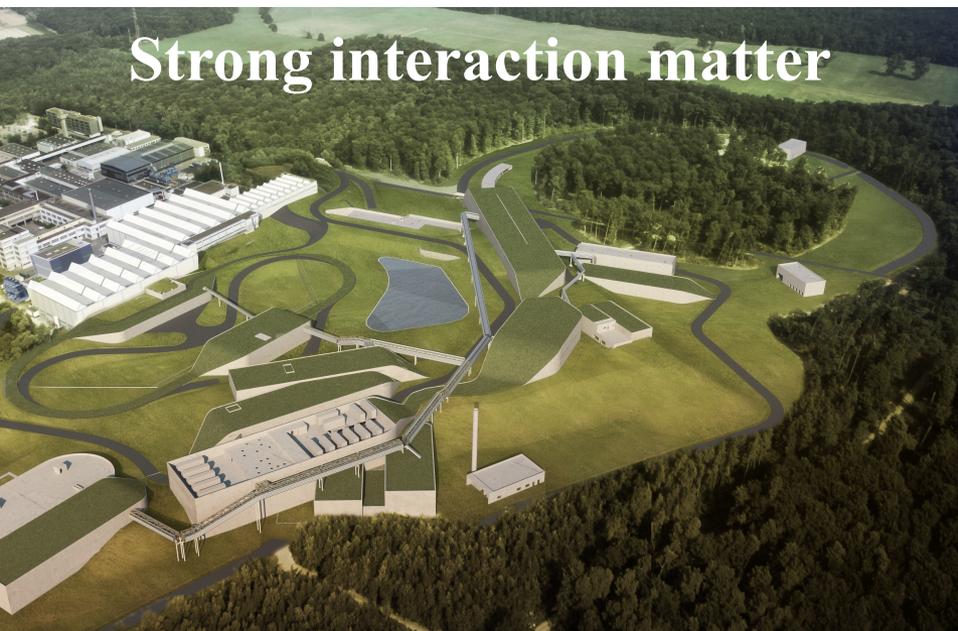
# Exciting era in strong interaction physics

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

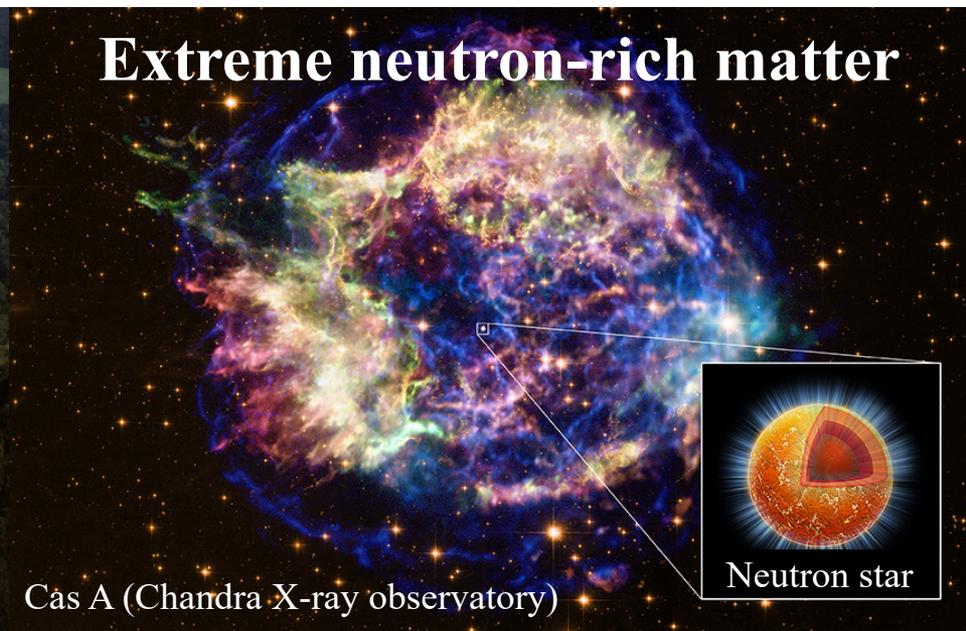
New experimental frontiers

New observations in astrophysics

**Strong interaction matter**



**Extreme neutron-rich matter**



**Thanks to our group  
and collaborators!**

