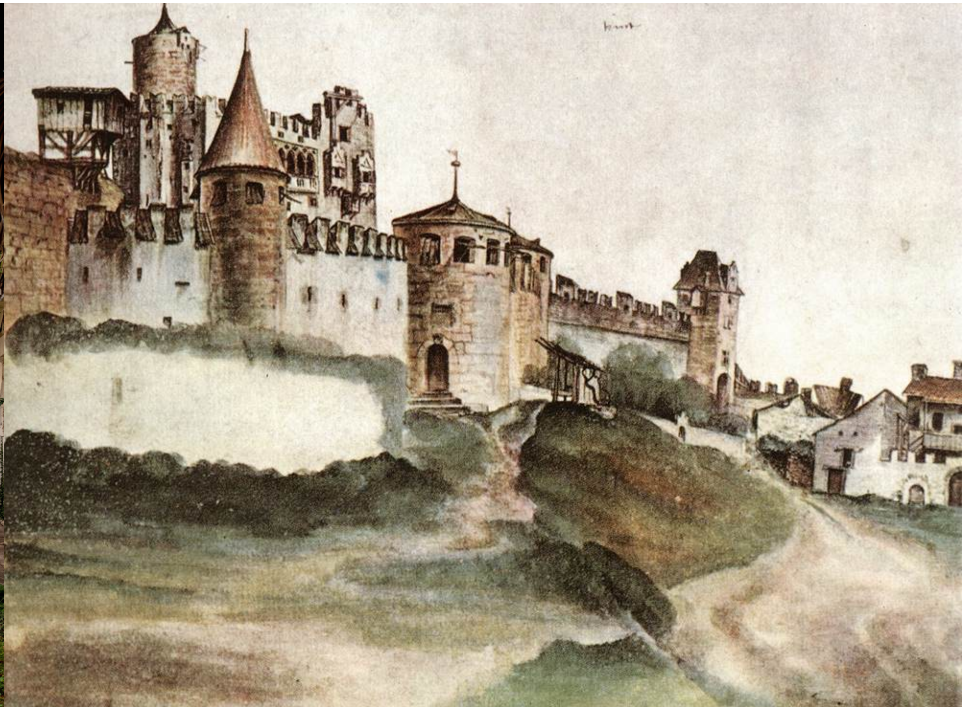
ECT* Workshop
The physics of strongly interacting matter: neutron stars, cold atomic gases and related systems



Anna Watts, Chris Pethick, Francesca Ferlaino, Achim Schwenk

Workshop logistics

ECT* code of conduct: Please abide by code of conduct

Exciting program with talks from astrophysics, nuclear physics, and cold atom physics. Keep broad communities in mind

Round of introductions: Name, Institution, Interests

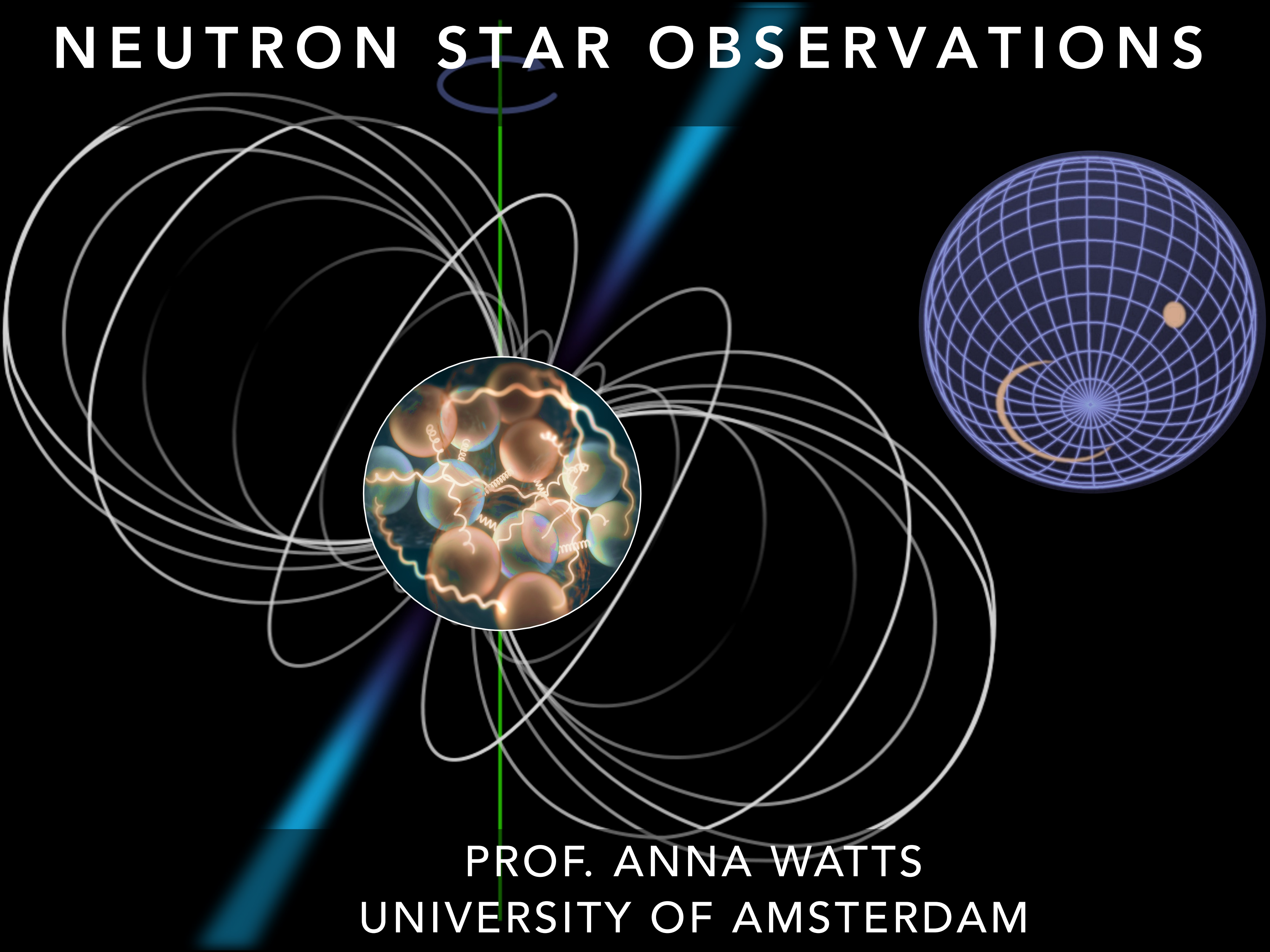
Ample time for discussions and questions

Coffee breaks and lunches in Villa, covered by ECT*
Social dinner on Wednesday, other dinners are self-organized

Please upload your slides to Indico (preferred), or send to Ines and me

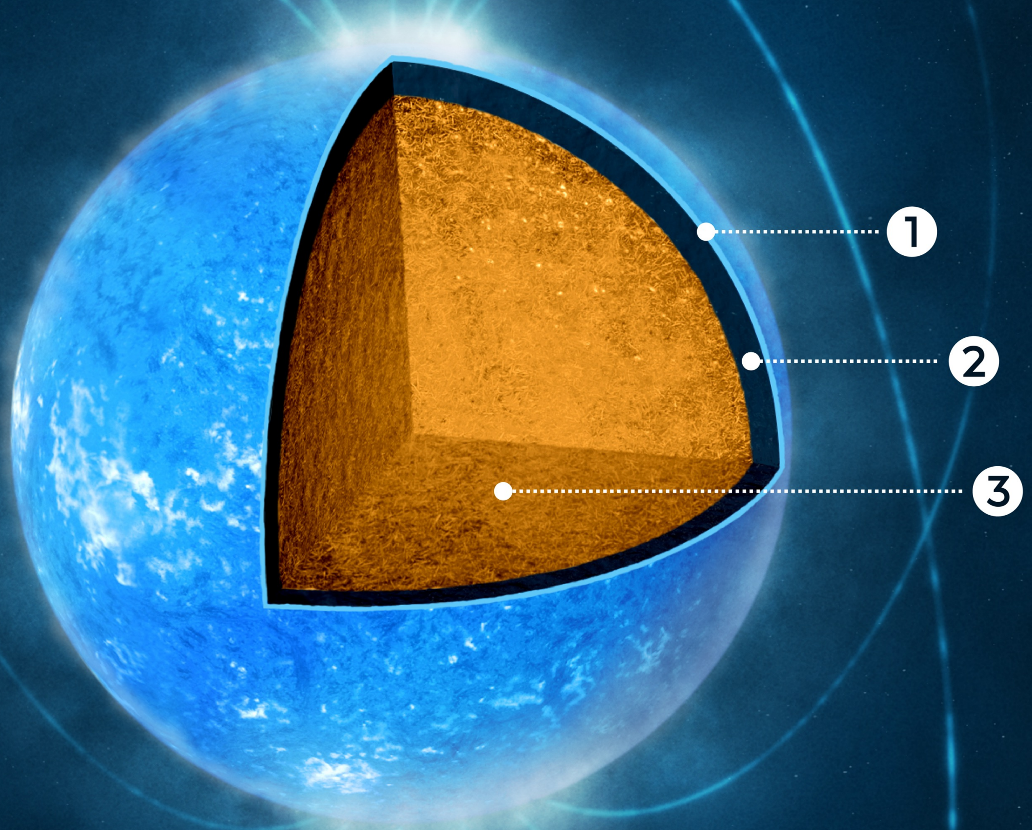
Any other logistics questions?

NEUTRON STAR OBSERVATIONS



PROF. ANNA WATTS
UNIVERSITY OF AMSTERDAM

THE NEUTRON STAR INTERIOR



1 | OUTER CRUST

NUCLEI
ELECTRONS

2 | INNER CRUST

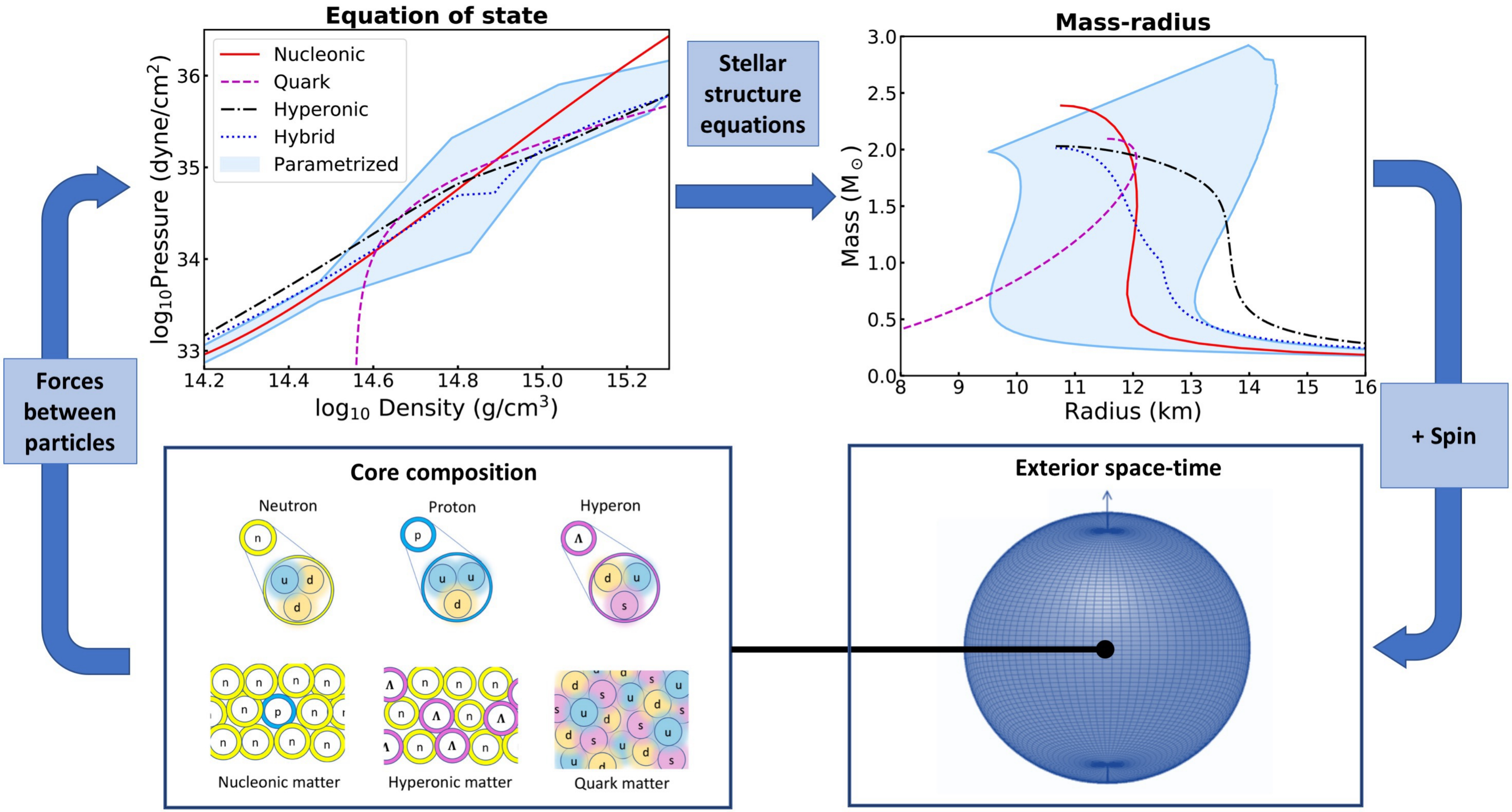
NUCLEI
ELECTRONS
SUPERFLUID NEUTRONS

3 | CORE

SUPERFLUID NEUTRONS
SUPERCONDUCTING PROTONS
HYPERONS?
DECONFINED QUARKS?
COLOR SUPERCONDUCTOR?

Figure: Watts et al. 2016

FROM NUCLEAR PHYSICS TO TELESCOPE



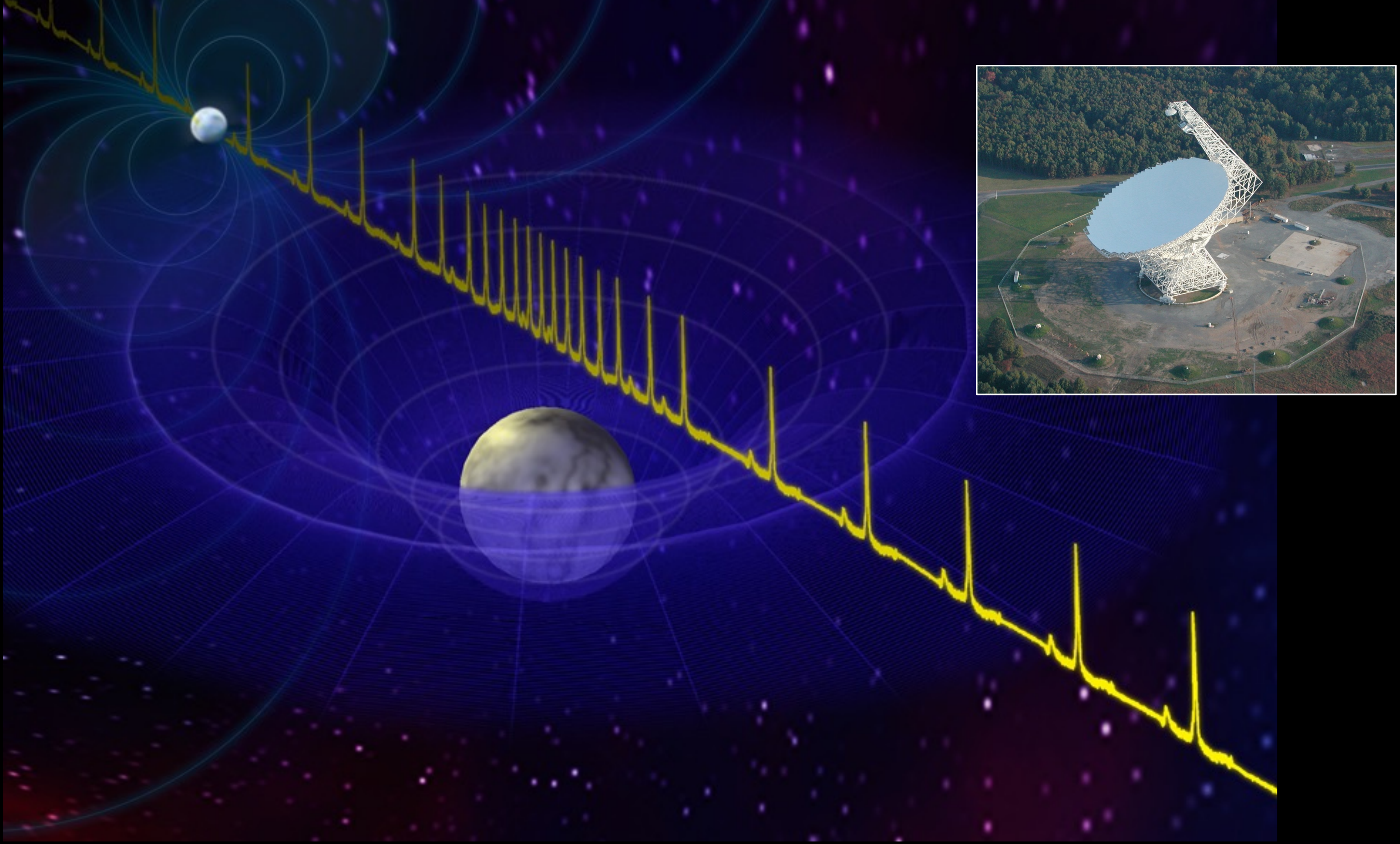
Stellar structure equations

+ Spin

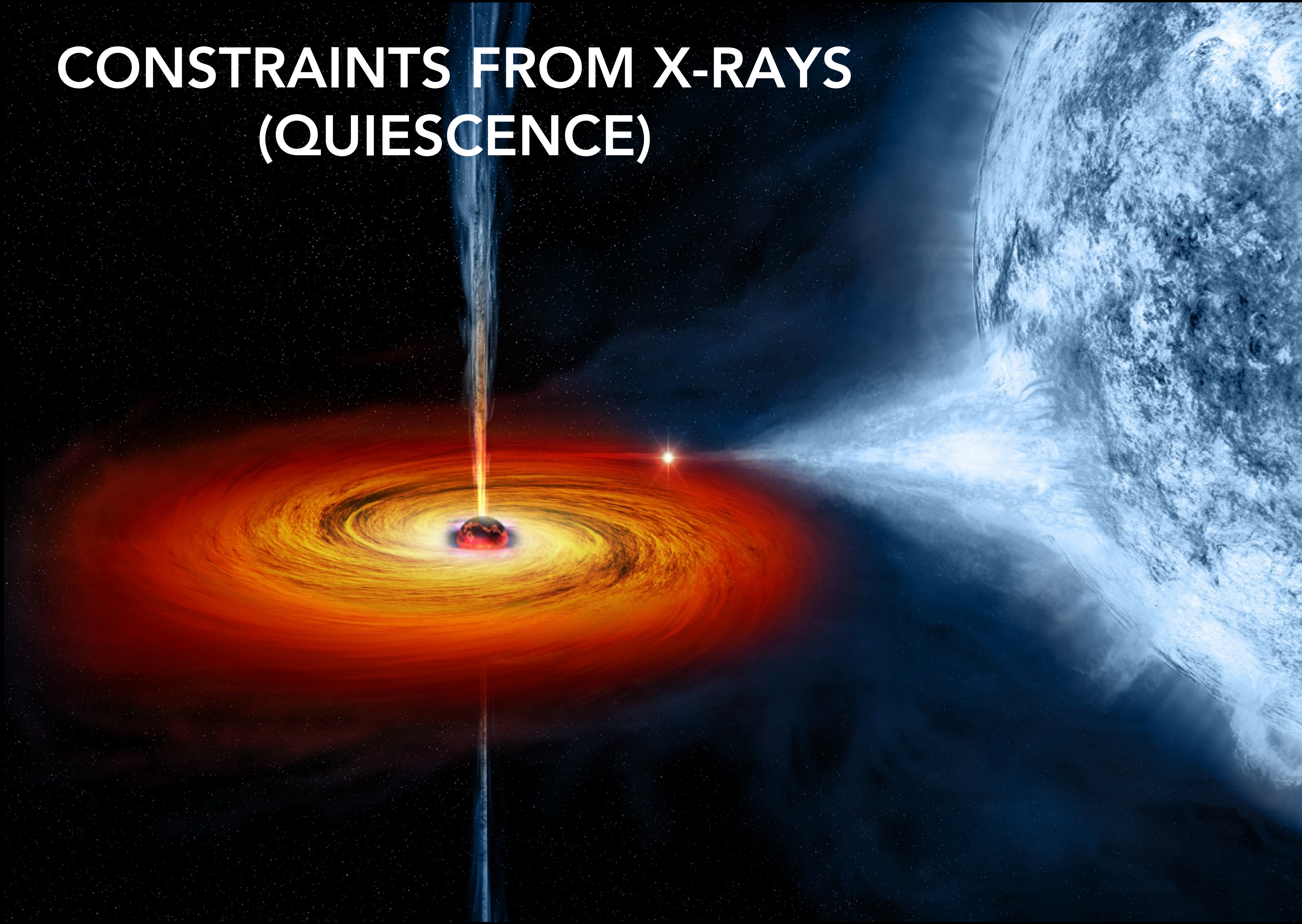
Forces between particles

Figure: Adapted from Ray et al. 2019

CONSTRAINTS FROM RADIO PULSAR TIMING



Masses, moments of inertia via relativistic effects.
But also glitches/timing noise (crust/superfluids)…..



CONSTRAINTS FROM X-RAYS (QUIESCENCE)

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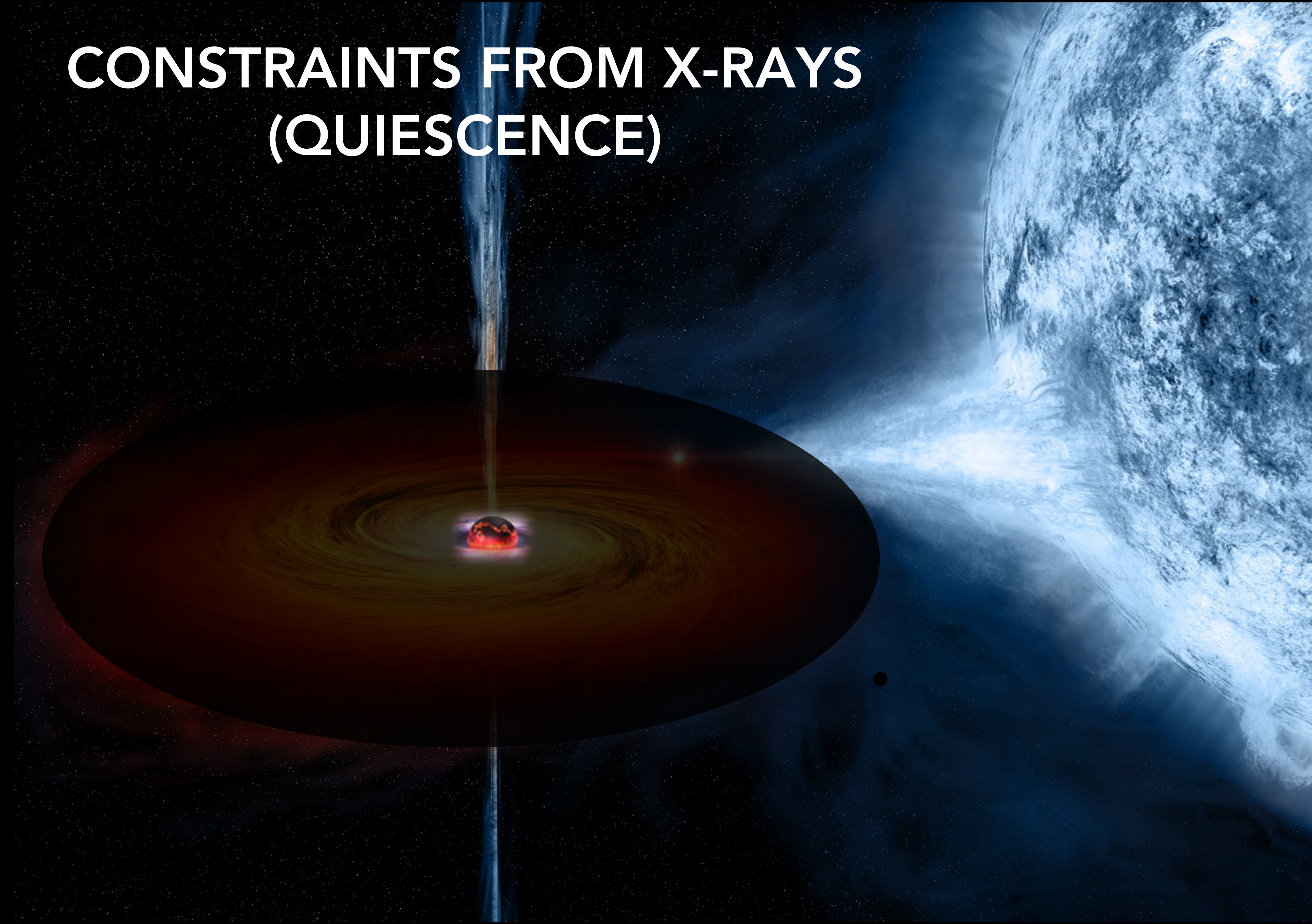
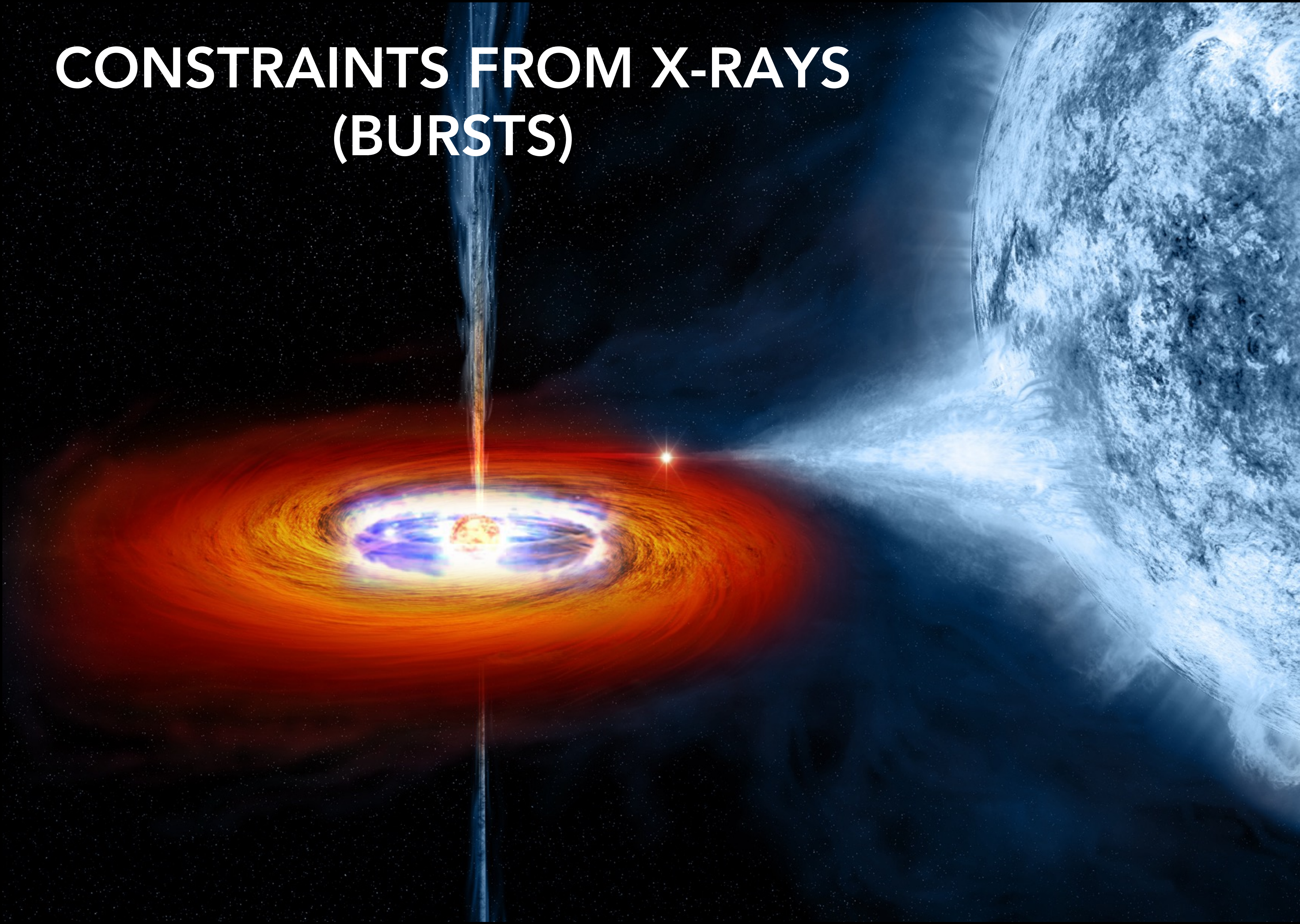
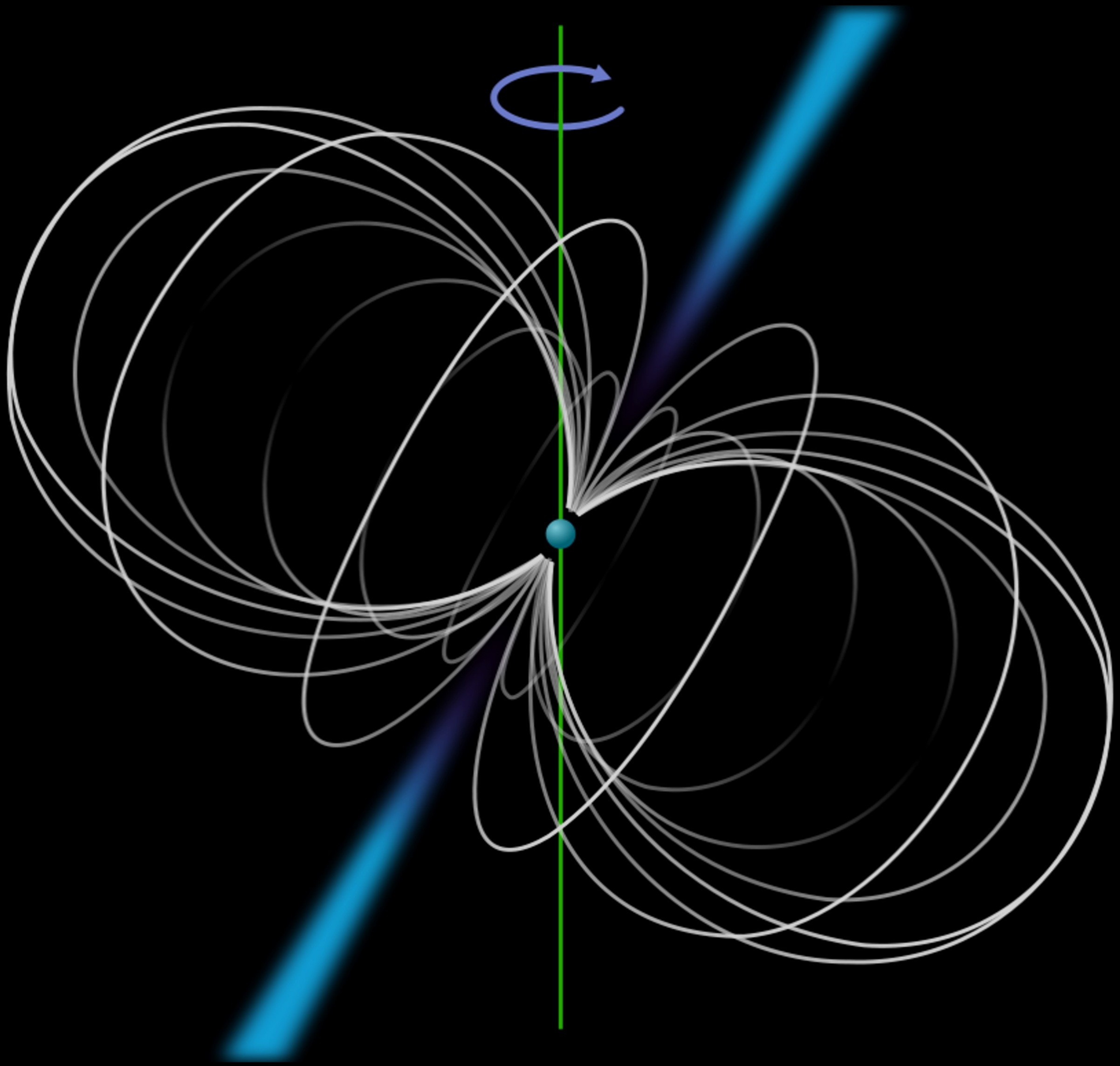


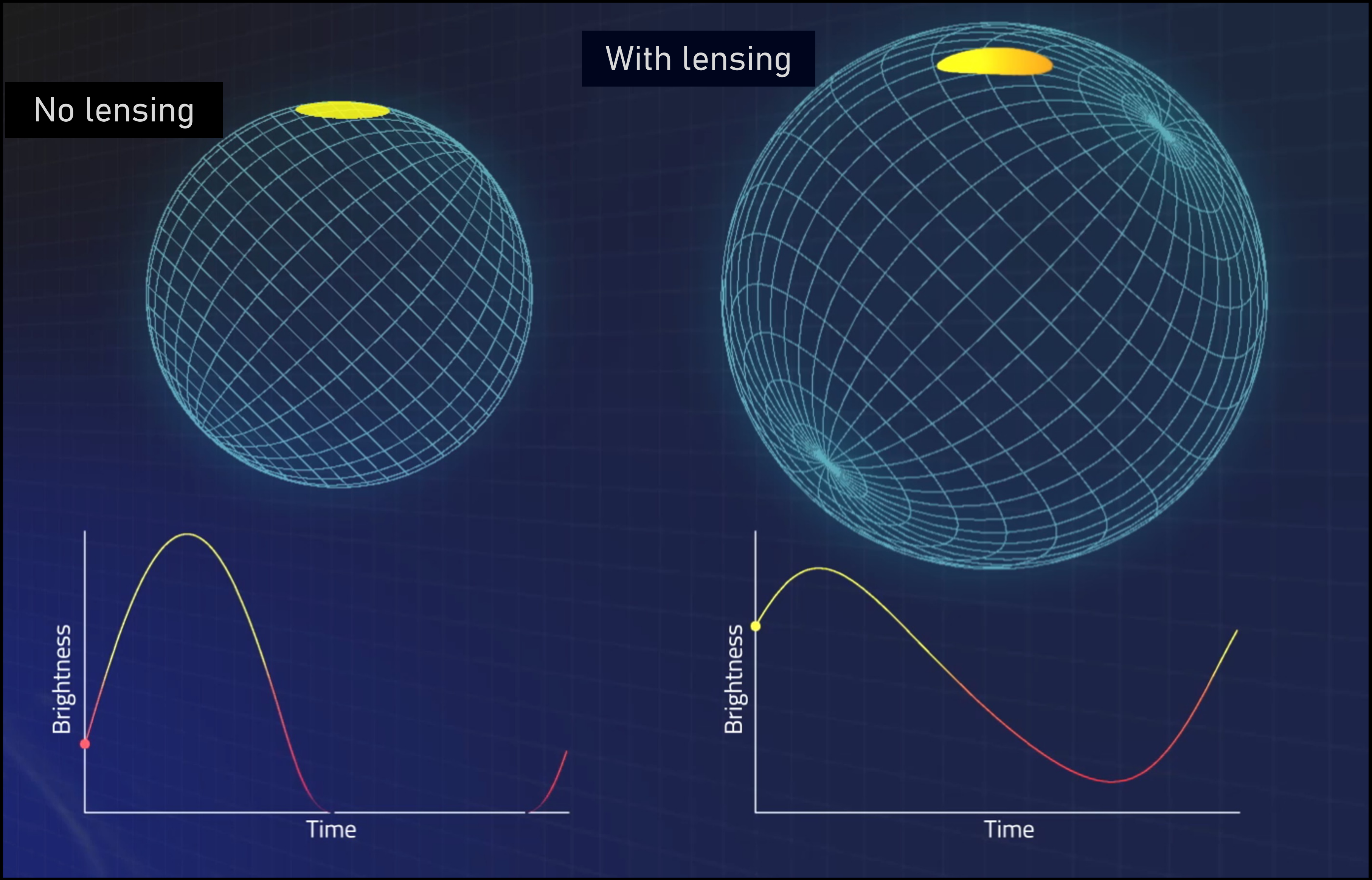
CONSTRAINTS FROM X-RAYS (BURSTS)



ROTATION-POWERED PULSARS



PULSE PROFILE MODELING



Credit: Morsink/Moir/Arzoumanian/NASA-GSFC

NICER ON THE ISS

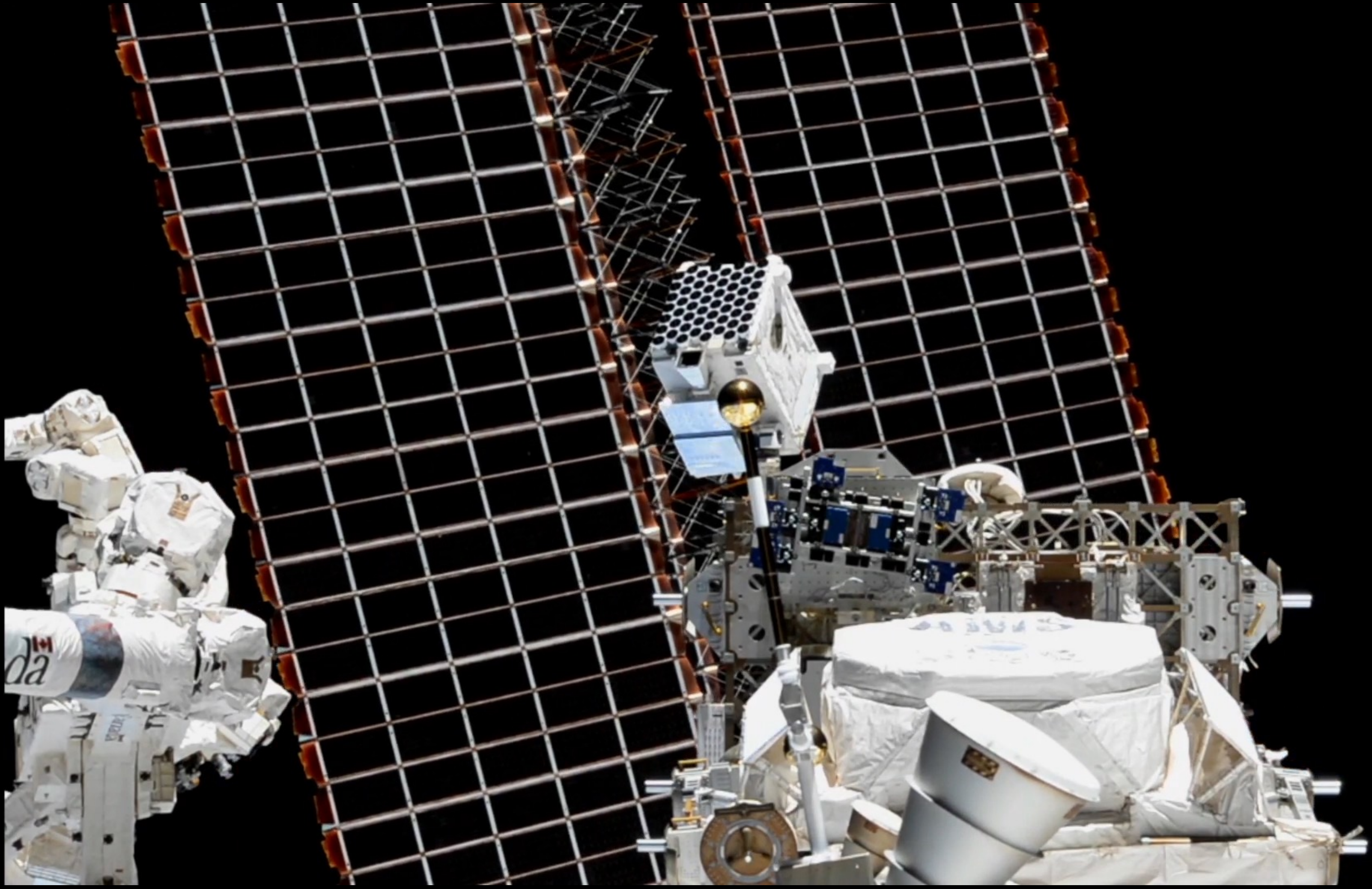
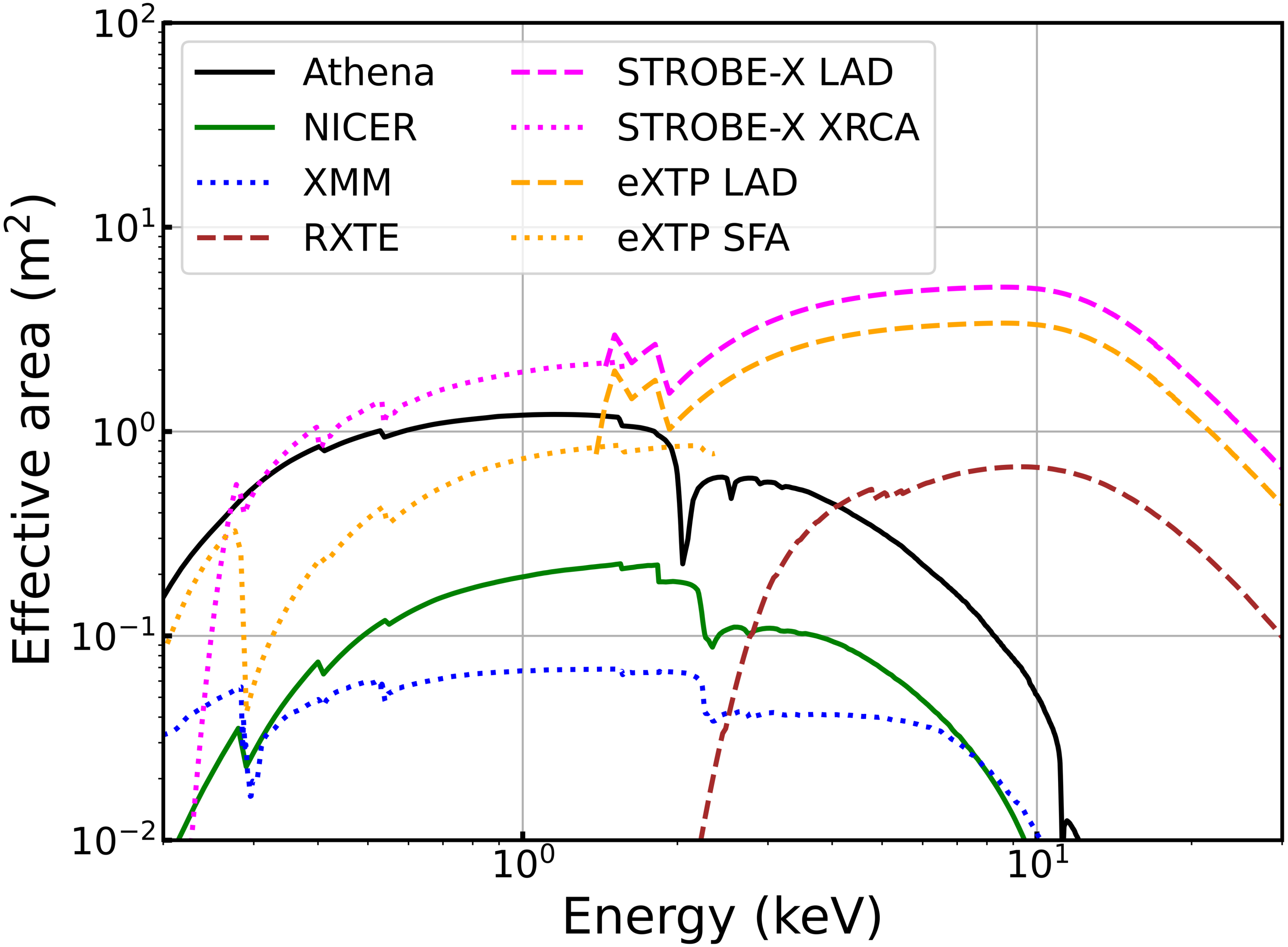


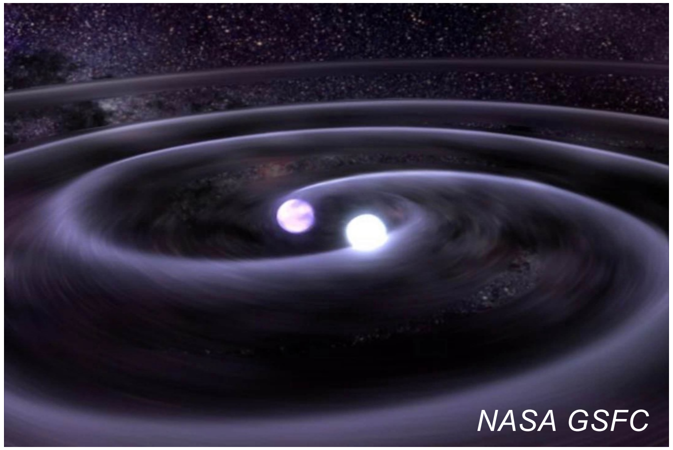
Image: NASA

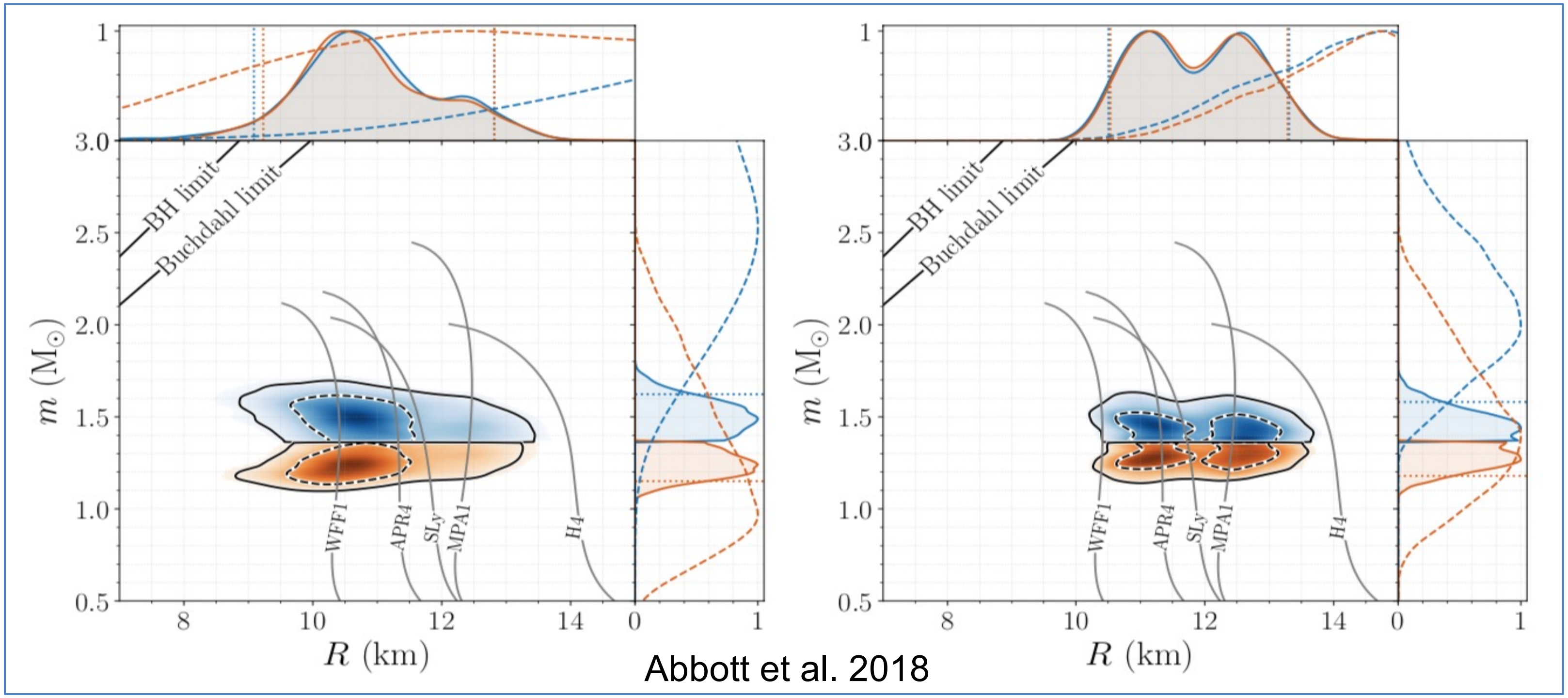
FUTURE X-RAY TELESCOPES



CONSTRAINTS FROM GRAVITATIONAL WAVES

- NS-NS and NS-BH mergers
- Tidal deformabilities
- “Mass gap” objects!
- Electromagnetic counterparts


NASA GSFC



Abbott et al. 2018

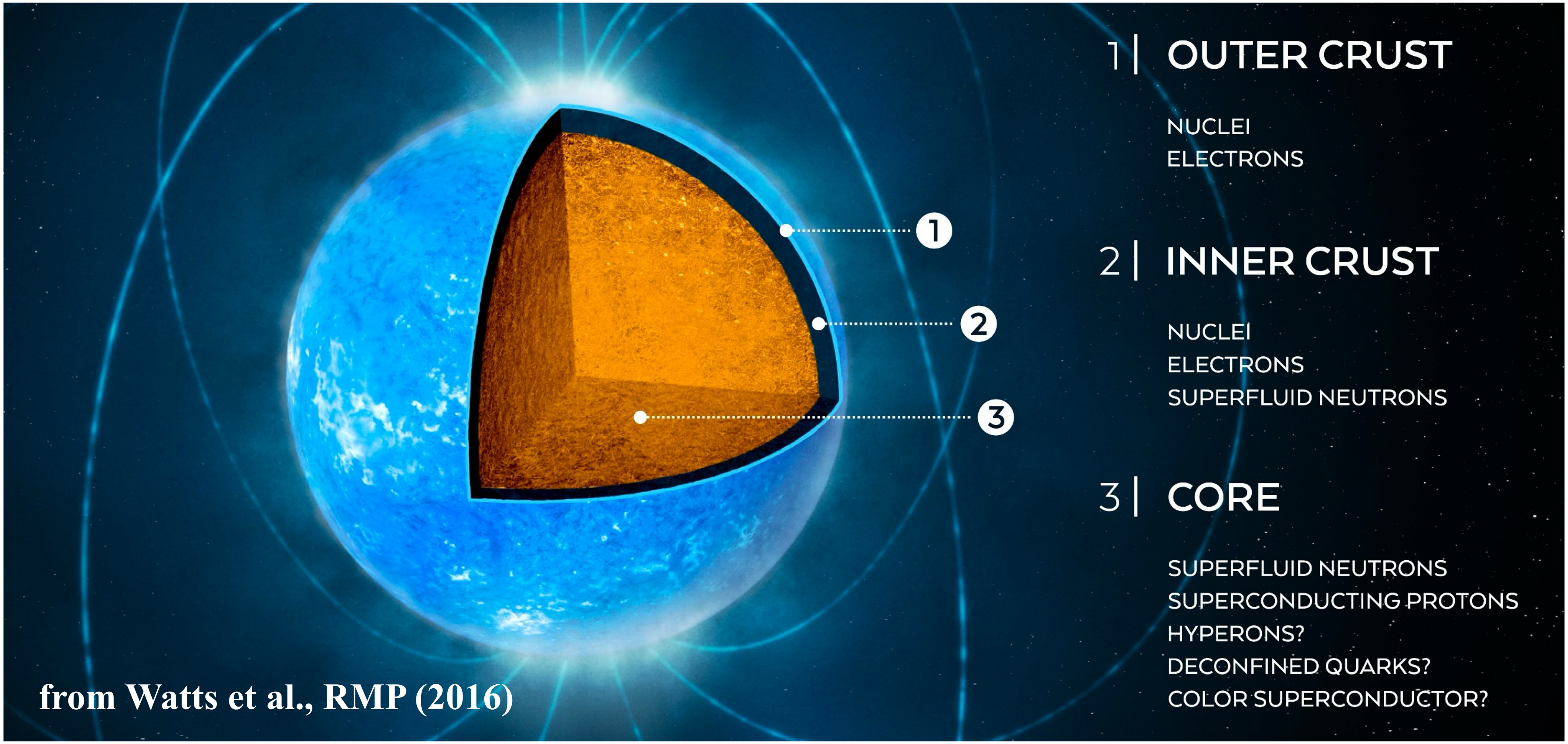
Extreme matter in neutron stars

cold dense matter up to ~ 10 n_0 with saturation density $n_0 = 0.16$ fm^{-3}

governed by strong interactions (QCD)

up to 1-2 n_0: nucleons (neutrons and protons) + electrons (and muons)

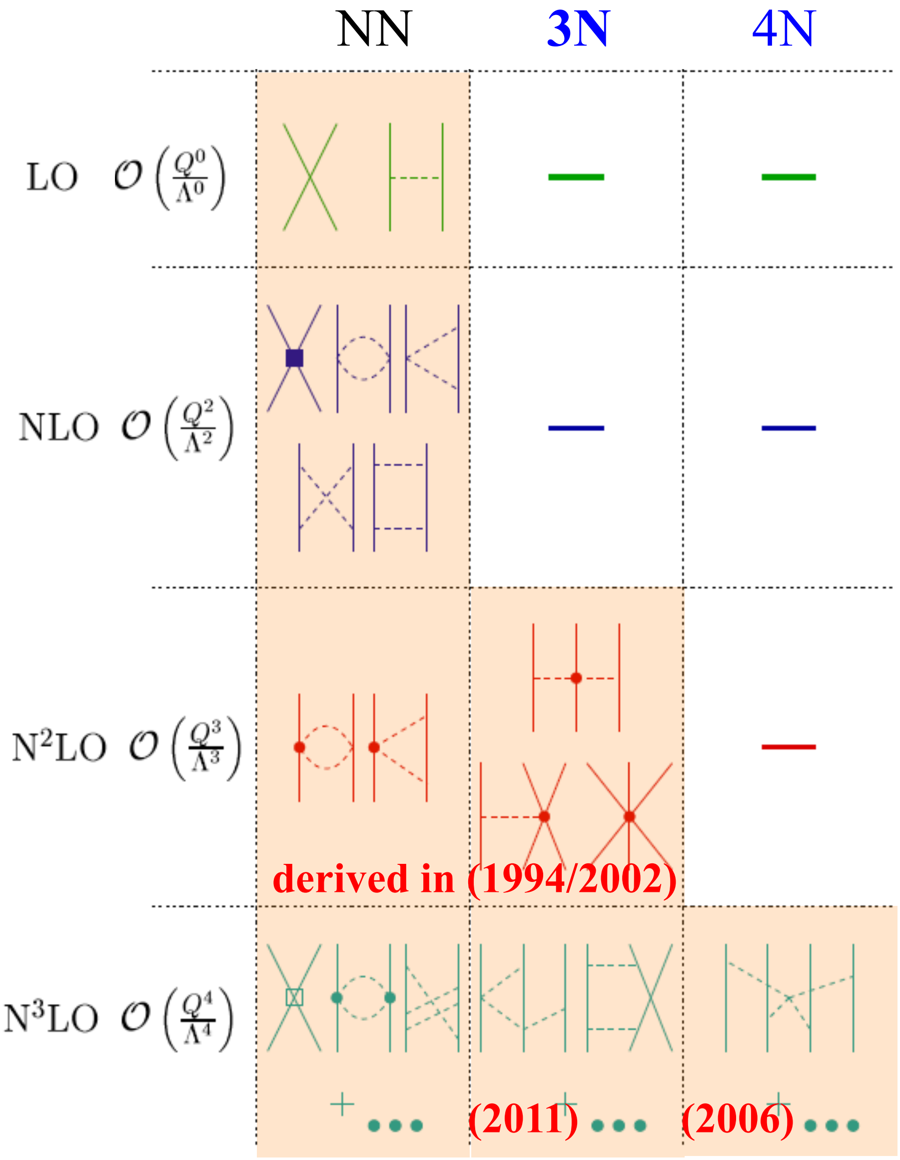
chiral effective field theory sets pressure of first few km to inside



from Watts et al., RMP (2016)

Chiral effective field theory for nuclear forces

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



based on symmetries of strong interaction (QCD)

long-range interactions governed by pion exchanges

powerful approach for many-body interactions

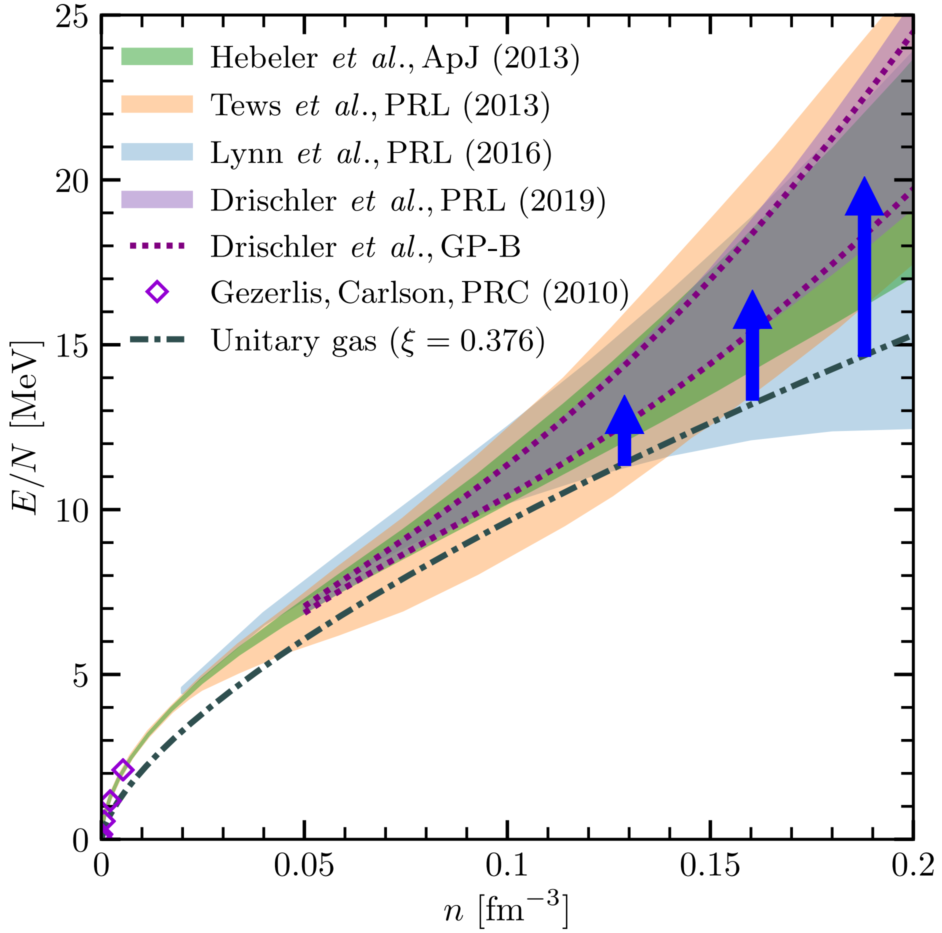
all 3- and 4-neutron forces predicted to N^3LO

Tews et al., PRL (2013)

Weinberg (1990,91), van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Meißner,…

Chiral effective field theory calculations of neutron matter

good agreement up to saturation density for neutron matter



comparison from Huth et al., PRC (2021)

slope determines pressure of neutron matter

comparison to unitary Fermi gas

— · — · — · — · — · — · —

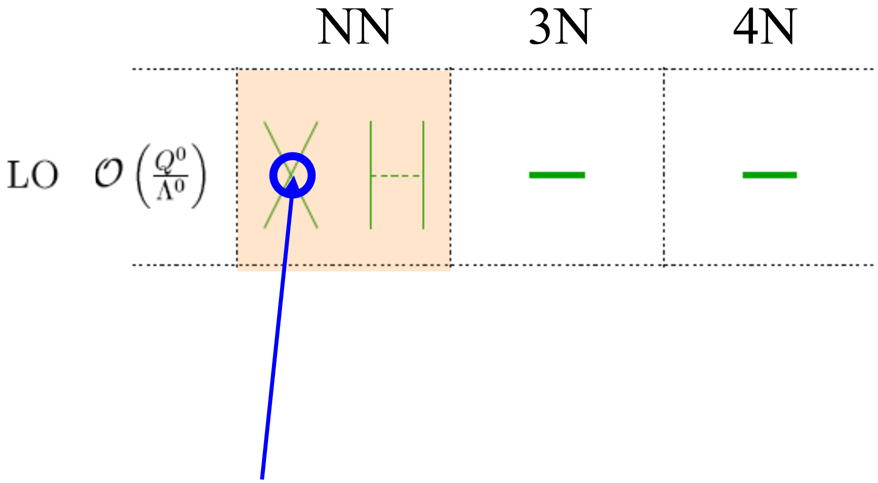
measured with cold atoms

behavior very similar to 0.1 fm^{-3} because neutrons have large scattering length a_s = -18.5 fm

stronger increase towards higher densities (EOS becomes stiffer) due to repulsive 3N forces

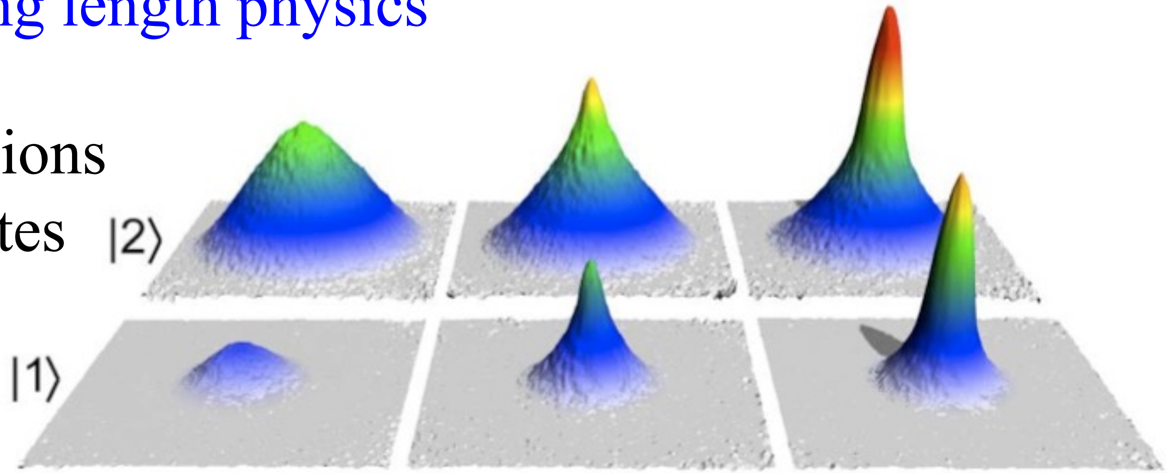
Chiral effective field theory for nuclear forces

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



large scattering length physics

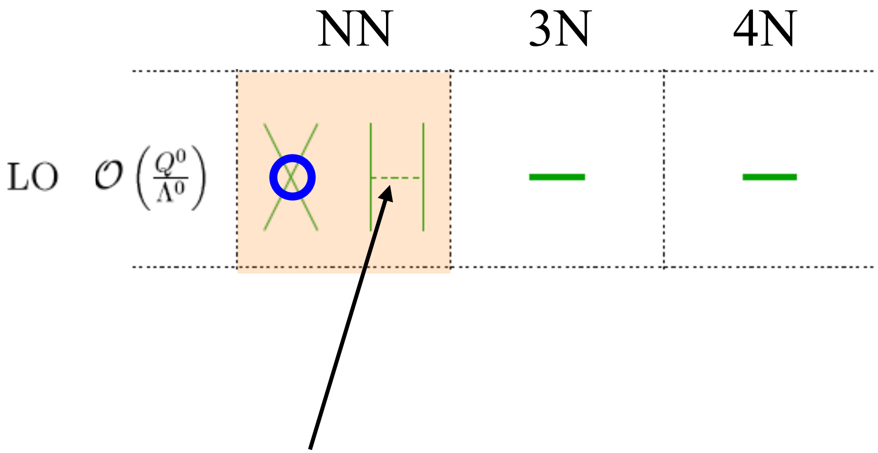
cold fermions
2 spin states
large a_s



neutrons with same density, temperature and spin polarization
have the same properties

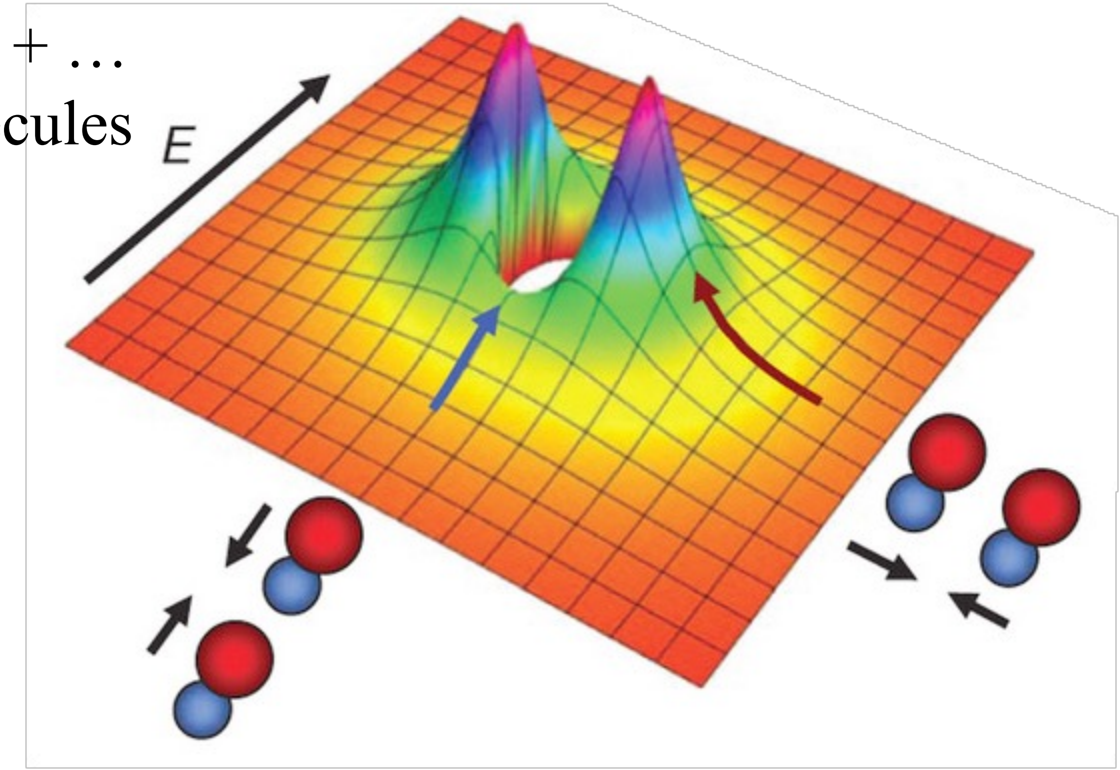
Chiral effective field theory for nuclear forces

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



pion tensor/dipole interactions + …

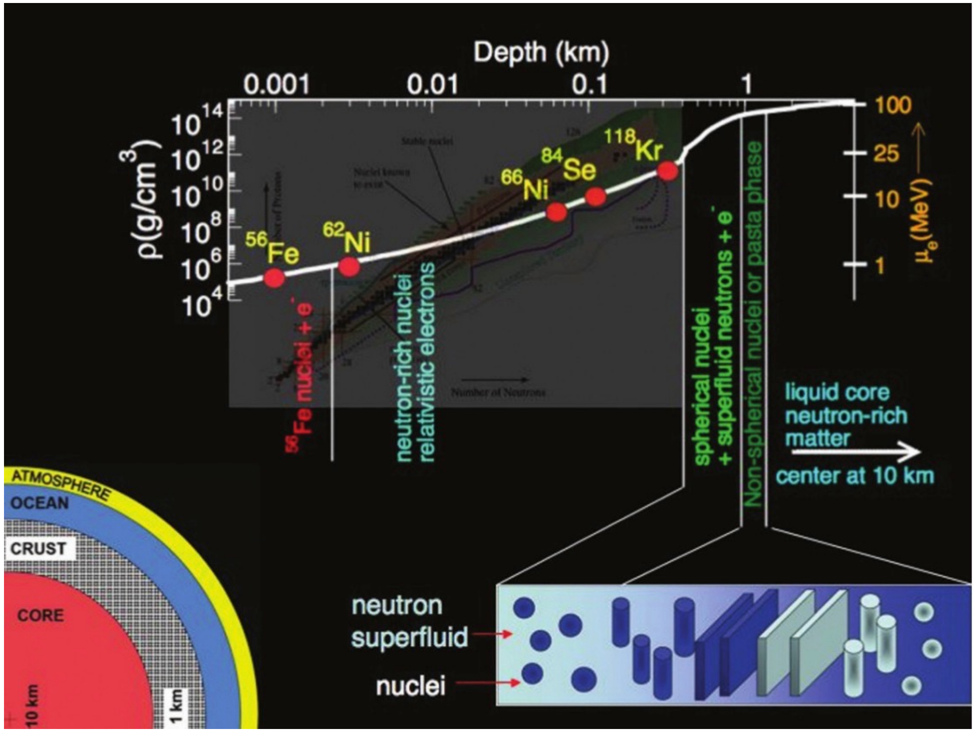
→ compare to cold polar molecules

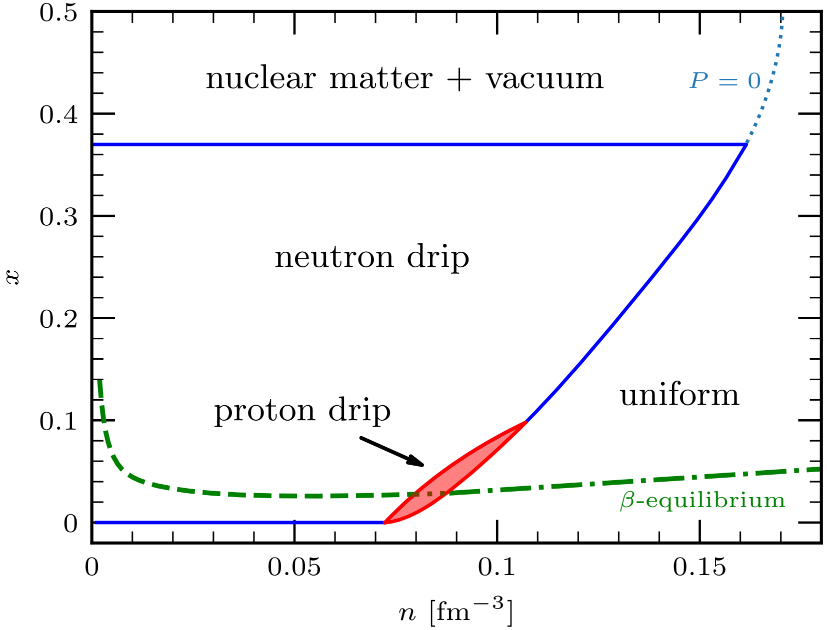


Neutron star matter has low concentration of protons

~ 5% proton fraction in denser neutron matter

below ~ 0.5 n_0 possible pasta phases: clusters/structures of high density surrounded by neutron (and proton) gas: neutron (proton) drip





Keller et al., arXiv:2401.13461

structure / dynamics of neutron star crust and related cold atom physics

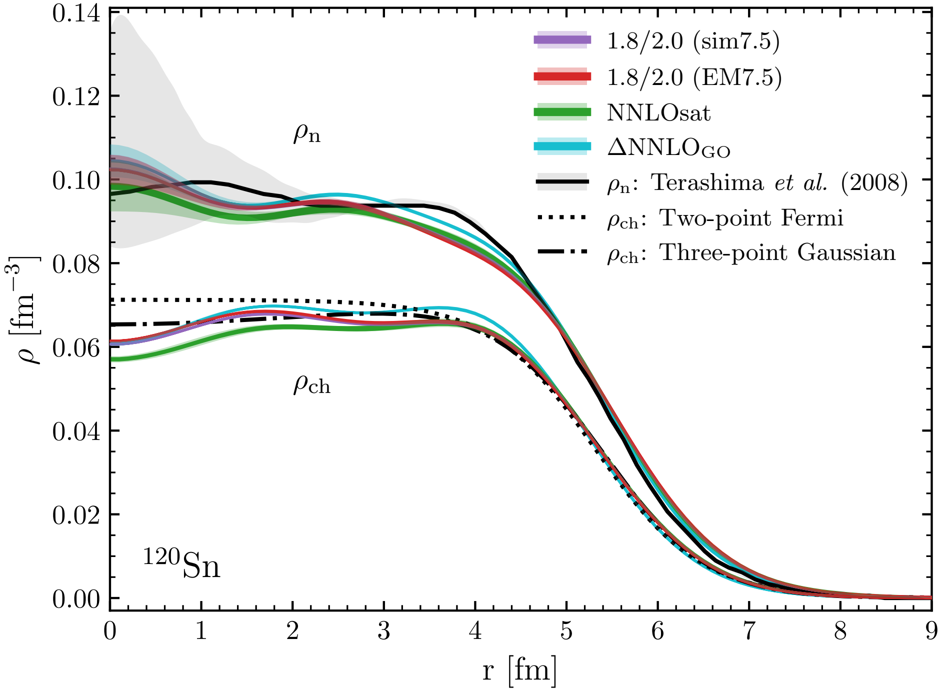
Constraints from nuclear experiments

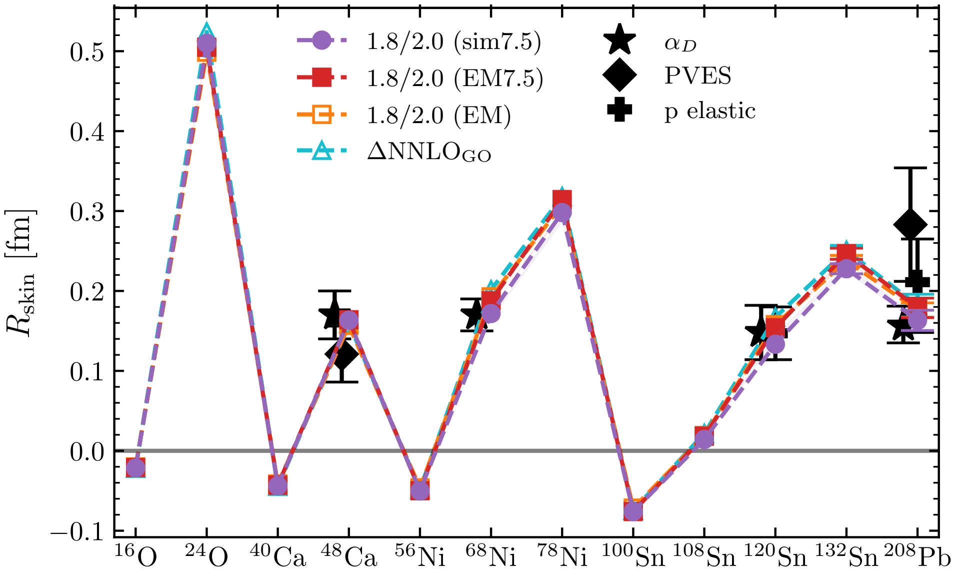
neutron skin = $R_n - R_p$
probes neutron matter pressure,
large pressure ~ larger skin

different experiments sensitive
to neutron skin, provides
constraints on matter around n_0

neutron skins tightly predicted
in chiral EFT calculations

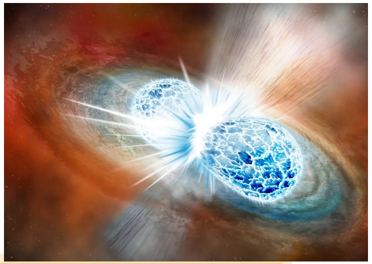
Arthius et al., arXiv:2401.06675,
Novario et al., PRL (2023)

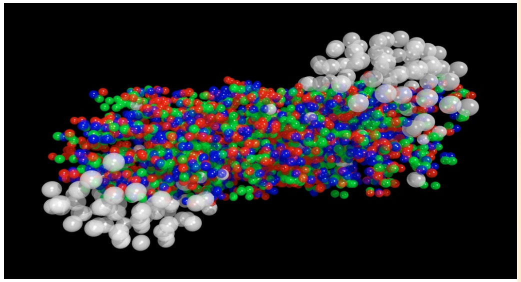


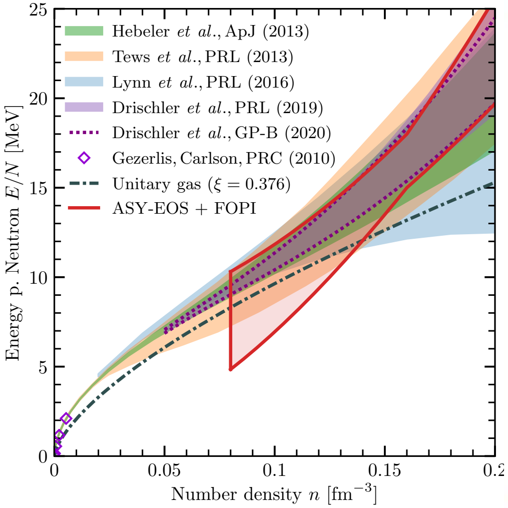


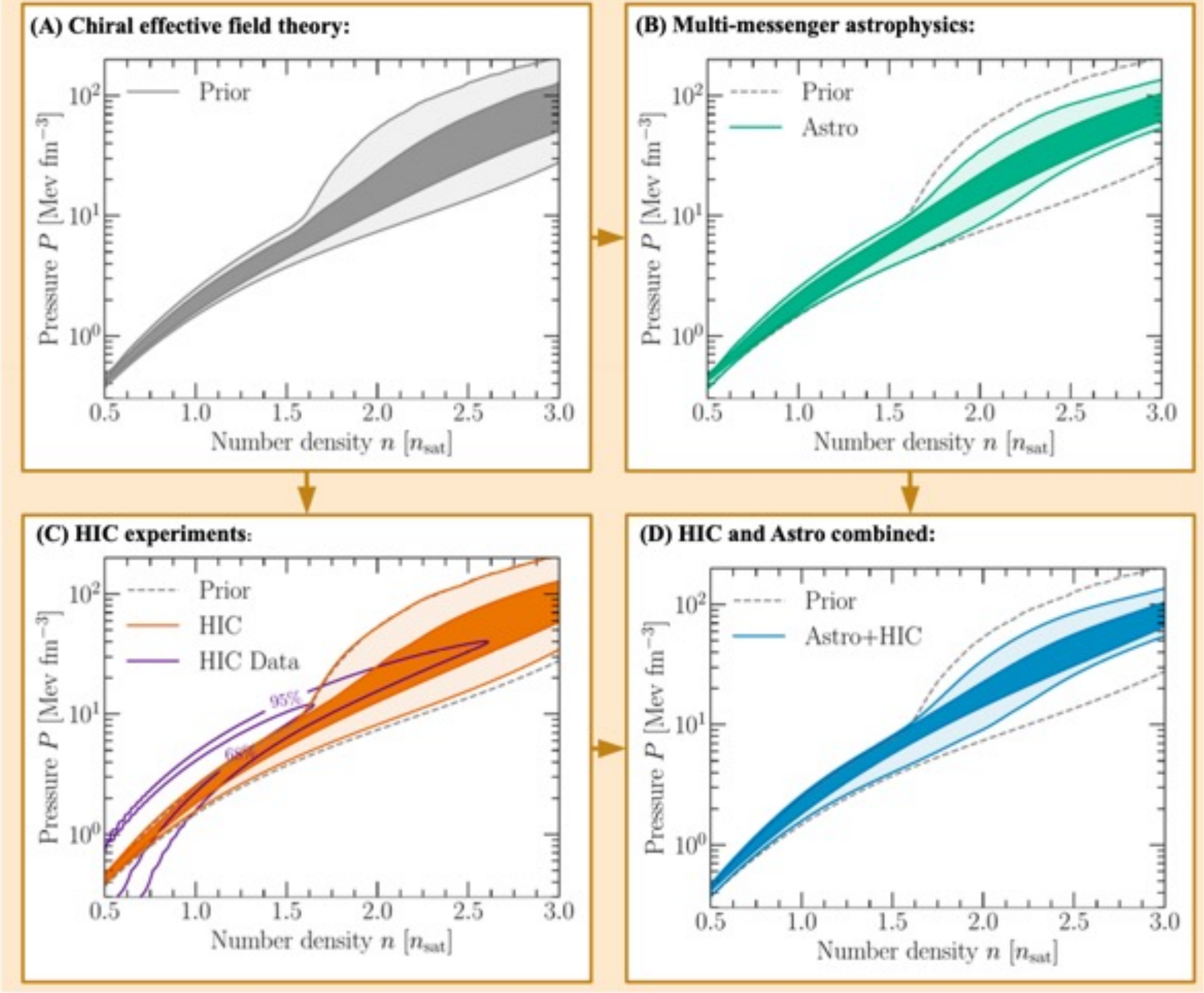
Equation of state constraints at intermediate densities

information from astrophysics and heavy-ion collisions









Huth, Pang et al., Nature (2022)

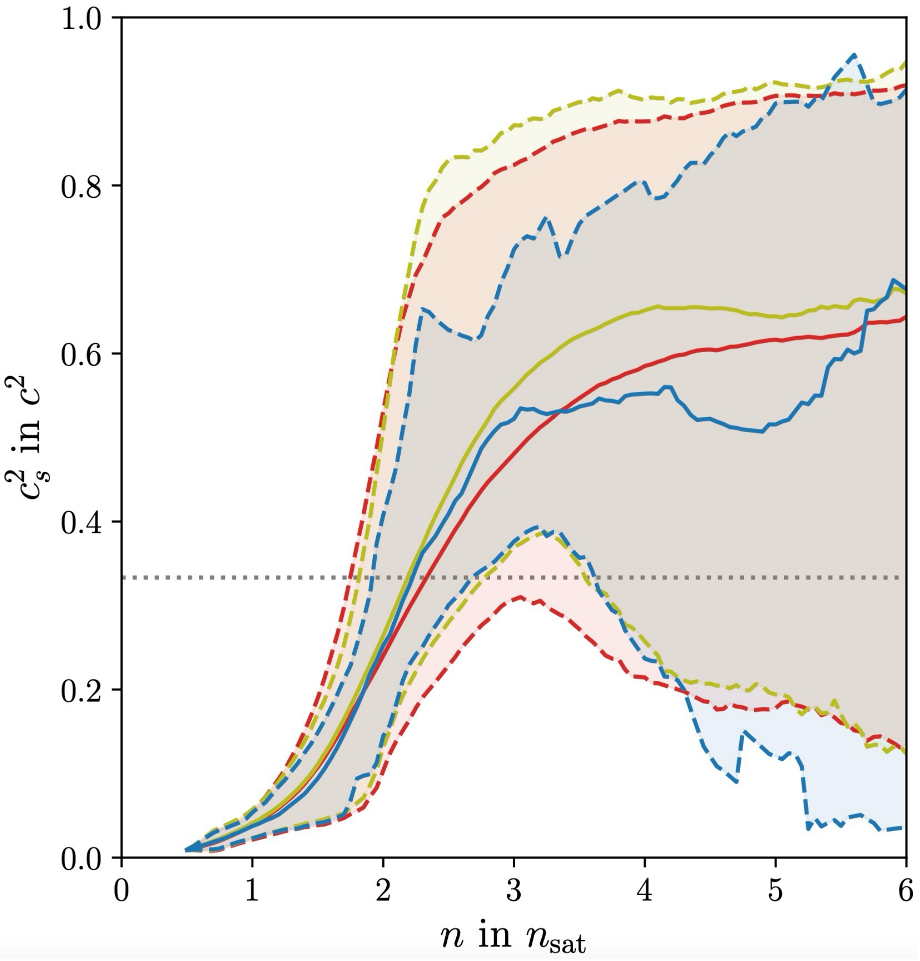
Supernuclear densities: high speed of sound

What is physical origin of high speed of sound reached in neutron stars?

How can we better pin down the equation of state at supernuclear densities?

Constraints from perturbative QCD calculations
Annala, Gorda, Kurkela, Vuorinen et al.

Information on relevant degrees of freedom?

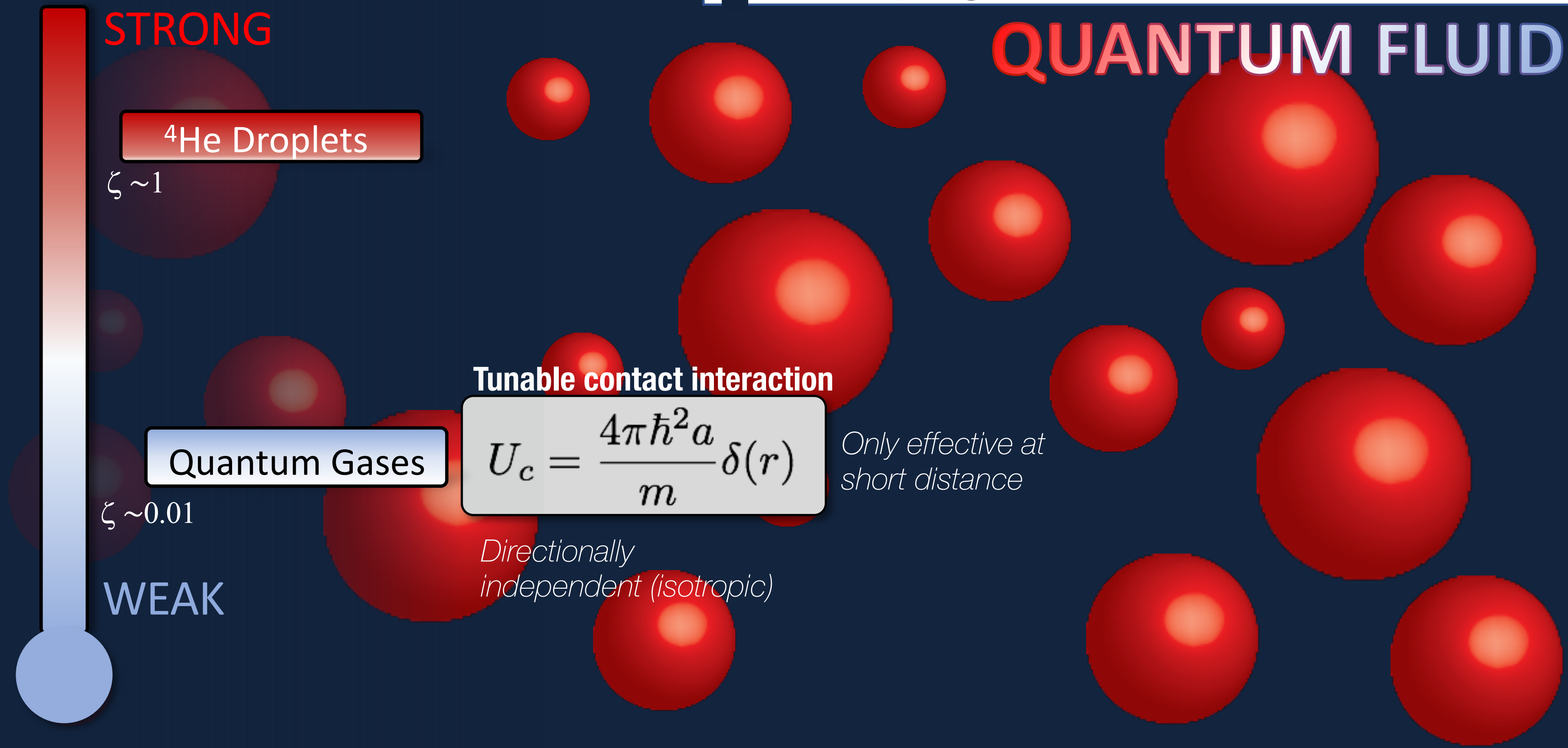


Koehn et al., arXiv:2402.04172

Why Many-Body Quantum systems are keeping us so busy and fascinated?

QUANTUM FLUID

$$\zeta = \frac{\text{Range of Interaction}}{\text{Mean interp. Distance}} = \frac{a}{d}$$



Tunable contact interaction

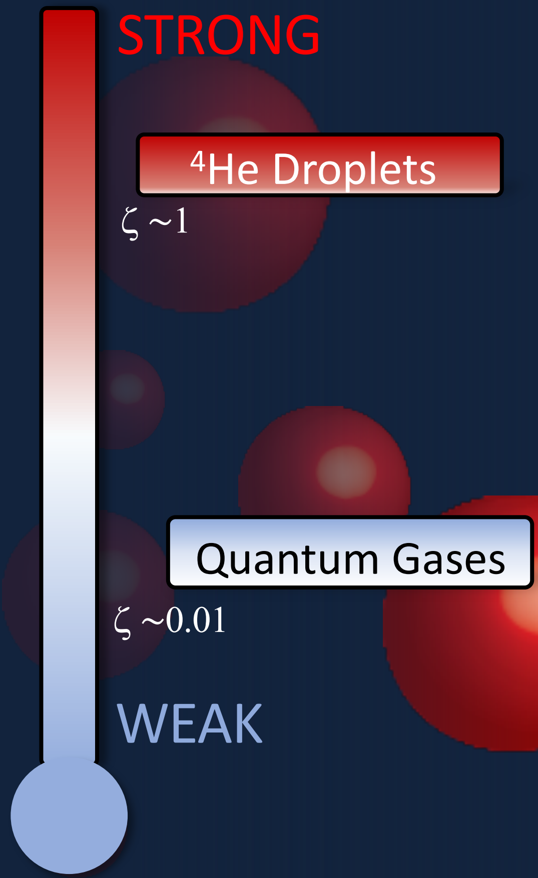
$$U_c = \frac{4\pi\hbar^2 a}{m}\delta(r)$$

Only effective at short distance

Directionally independent (isotropic)

Why Many-Body Quantum systems are keeping us so busy and fascinated?

$$\zeta = \frac{\text{Range of Interaction}}{\text{Mean interp. Distance}} = \frac{a}{d}$$



STRONG

^{4}He Droplets

$\zeta \sim 1$

Quantum Gases

$\zeta \sim 0.01$

WEAK

QUANTUM FLUID

Quantum gas (dilute)

Interparticle spacing $d = n^{-1/3}$

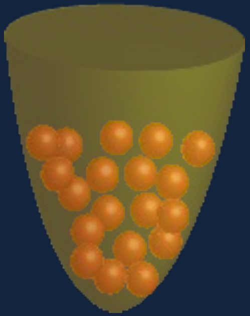
Density $n_{th} = 10^{14}\ cm^{-3}$

De Broglie wavelength λ_{dB} = 1000 nm

Ultracold quantum gases

A Macroscopic ensemble 10^5 neutral atoms (bosons/fermions) in gas phase, confined into a trap made of light

Temperature/statistics



Ultracold

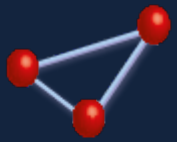
$\lambda_{\mathrm{dB}} \sim \mathrm{d}$

$n\lambda_{\mathrm{dB}}^{3} \gtrsim 2.6$

Bosons or Fermions

Interactions

Two-body scattering



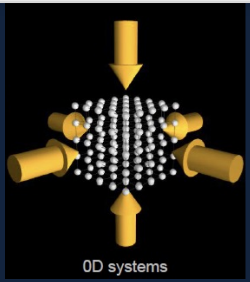
Composite objects

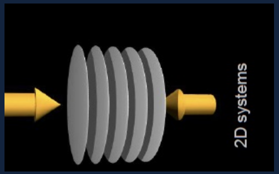
Internal degree of freedoms

“spin-up” “spin-down”

Control of the internal energy levels (Zeeman, hyperfine, …)

Dimentionality





Ultracold quantum gases = Quantum Fluid

Model systems for different phenomena in the field of solid-states, helium superfluid, neutron stars.

Modulated superfluids

How to extend concepts of superfluidity to quantum phases breaking translational symmetry?

ELENA POLI - Rotating dipolar gases: supersolids, vortices and glitches

SANDRO STRINGARI - Propagation of sound in density modulated superfluids

Ultracold quantum gases = Quantum Fluid

Model systems for different phenomena in the field of solid-states, helium superfluid, neutron stars.

Modulated superfluids

New Exotic Phases

Mapping to exotic phenomena ?

MACIEJ GALKA - Realisation of a Laughlin state of two rapidly rotating fermions

ELINOR KATH - Curved and Expanding Spacetimes in a Bose-Einstein Condensate

Ultracold quantum gases = Quantum Fluid

Transport/Dynamics

Modulated superfluids

New Exotic Phases

CHRISTOPH EIGEN - Few- and many-body physics with box-trapped 39K Bose gases

THOMAS SCHAEFER - Transport Properties of Ultracold Gases and Dense Matter

Workshop goals

- Survey observational data on masses, radii, tidal deformability and moment of inertia, understand all aspects in the modeling processes
- Improve our understanding of matter with low proton concentrations in neutron stars at around nuclear density
- Determine whether or not pasta phases are stable
- Understand dynamics of pasta phases in neutron stars and supersolid phases in cold Fermi gases
- Better pin down the equation of state at supranuclear densities
- Understand physical origin of maximum in sound velocity at high densities deduced from observations of neutron stars
- Explore constraints from nuclear experiments in the laboratory
- Explore possible cold gas experiments that could illuminate unresolved issues