Nuclear Excited Studied by proton scattering With a High-Resolution Magnetic Spectrometer

Lecture IV

Equation of States
Neutron Stars

2306 1172 at https://menti.com

https://www.menti.com/al62qsgif5e7

Equation of State

Equation of State

Thermodynamics

only treats the equilibrium state

State variables: *n, p, V, T, S, U, …*

Equation of State (EoS):

An equation that holds among the state variables.

EoS depends on the material.

Example:

EoS of the ideal gas: $pV = nRT$

Nuclear Physics

The EoS of a matter made of nucleons is fundamental information for various applications:

e.g. a neutron star, supernova dynamics, heavy ion collision, ….

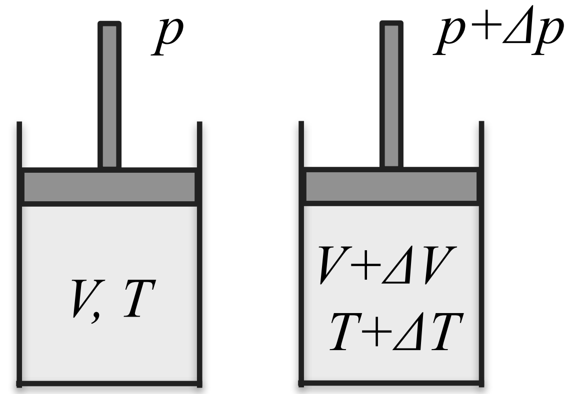
Study of EoS

Thermodynamics

Give a small change to the material

→ Observe the response

$$\kappa = -\frac{1}{V}\left(\frac{dV}{dp}\right)_S$$: adiabatic compressibility



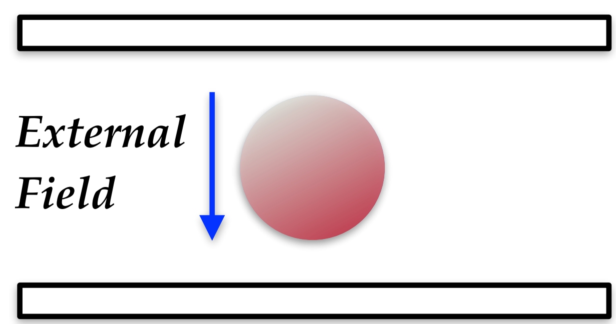
equilibrium

Nuclear Physics

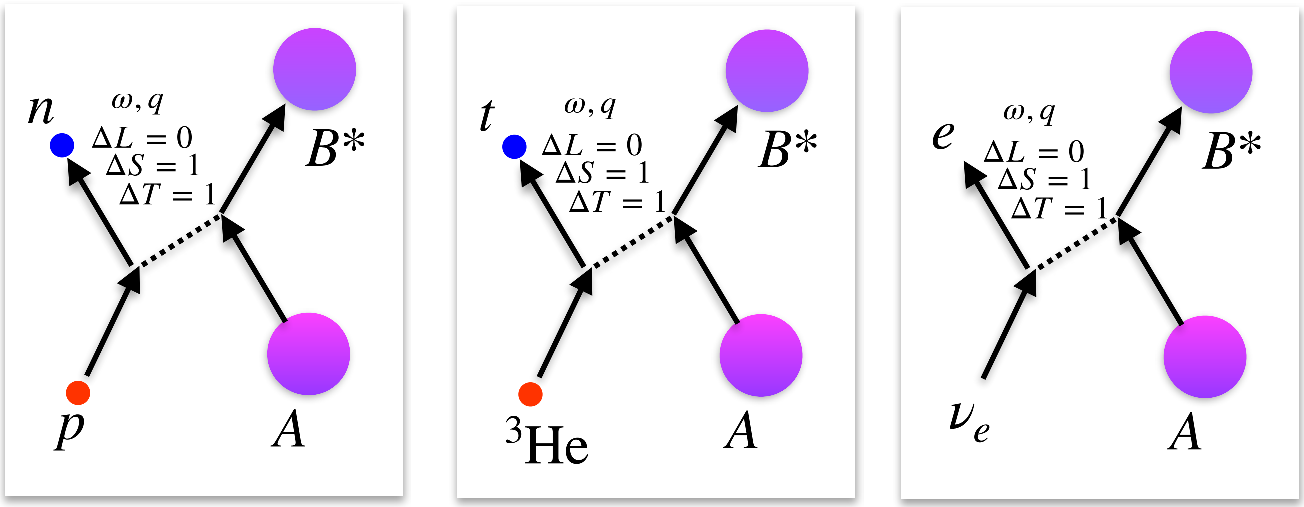
Give a small change by an external field

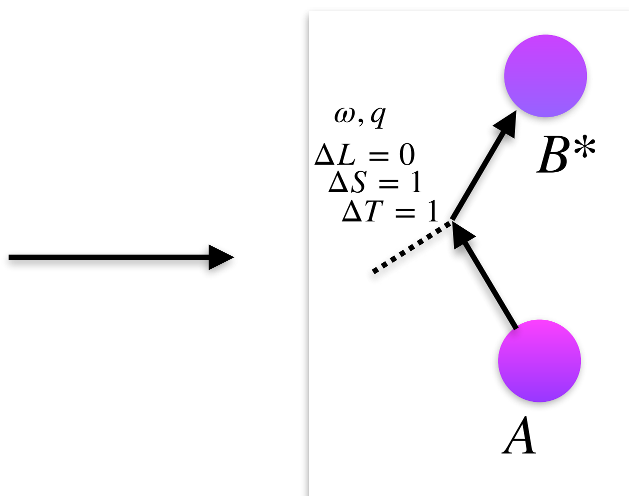
observe the response of the system

nuclear response



Nuclear Response





Response of a nucleus, *A*, to the external field:

$$\Delta L = 0, \Delta S = 1, \Delta T = 1$$

operator: $\boldsymbol{\sigma\tau}$

that depends on (ω, q)

Nuclear Matter

An ideal material, made of nucleons (protons and neutrons).

infinitely large and uniform

no surface effect nor shell effect ⟷ finite nuclei

Parameters:

ρ_n	: number density of neutrons	in *e.g.* particles/fm^3
ρ_p	: number density of protons	
E/A	: energy per nucleon	
T	: temperature (often neglected)	

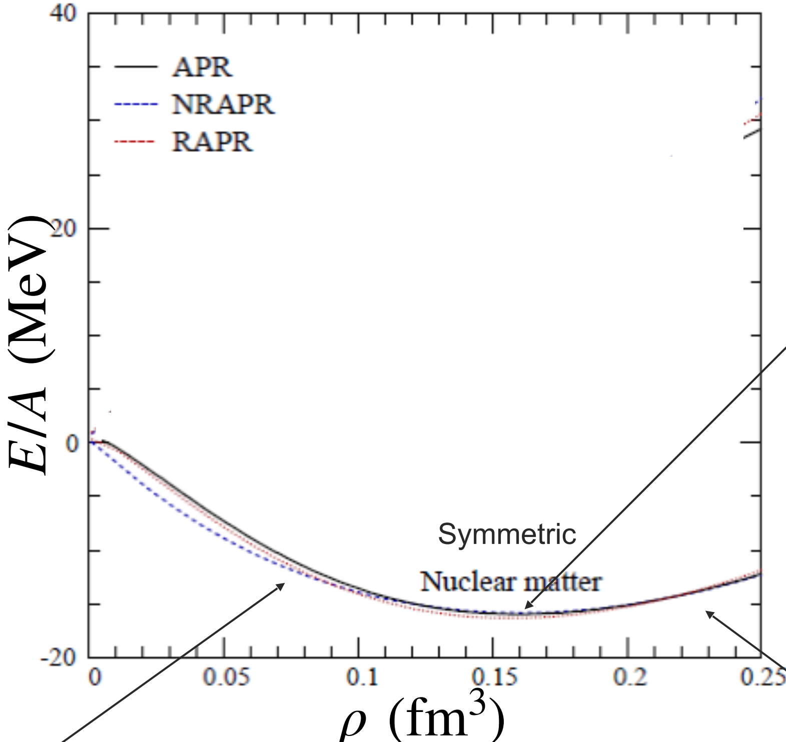
$\rho = \rho_n + \rho_p$: nucleon density

$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$: asymmetry parameter

$\delta = 0$: symmetric nuclear matter

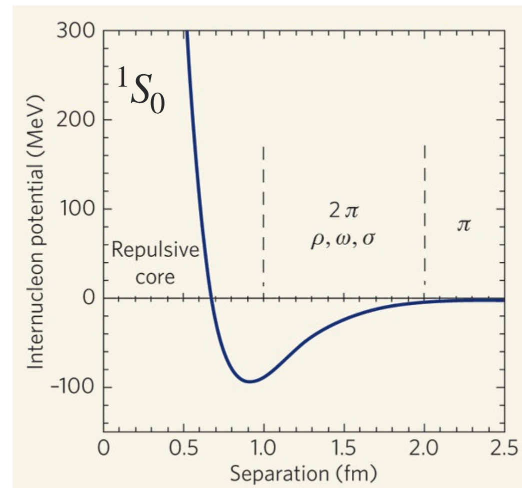
$\delta = 1$: pure neutron matter

Symmetric Nuclear Matter EoS



Saturation density: ρ_0 ~0.16 fm^{-3}

Nucleon-Nucleon Interaction



Energy increase at lower density:

Strong attraction by the tensor force

Energy increase at higher density:

1. density dependence of the tensor interaction
2. exchange interaction
3. repulsive core of the NN interaction、density dependence of the three-nucleon-force

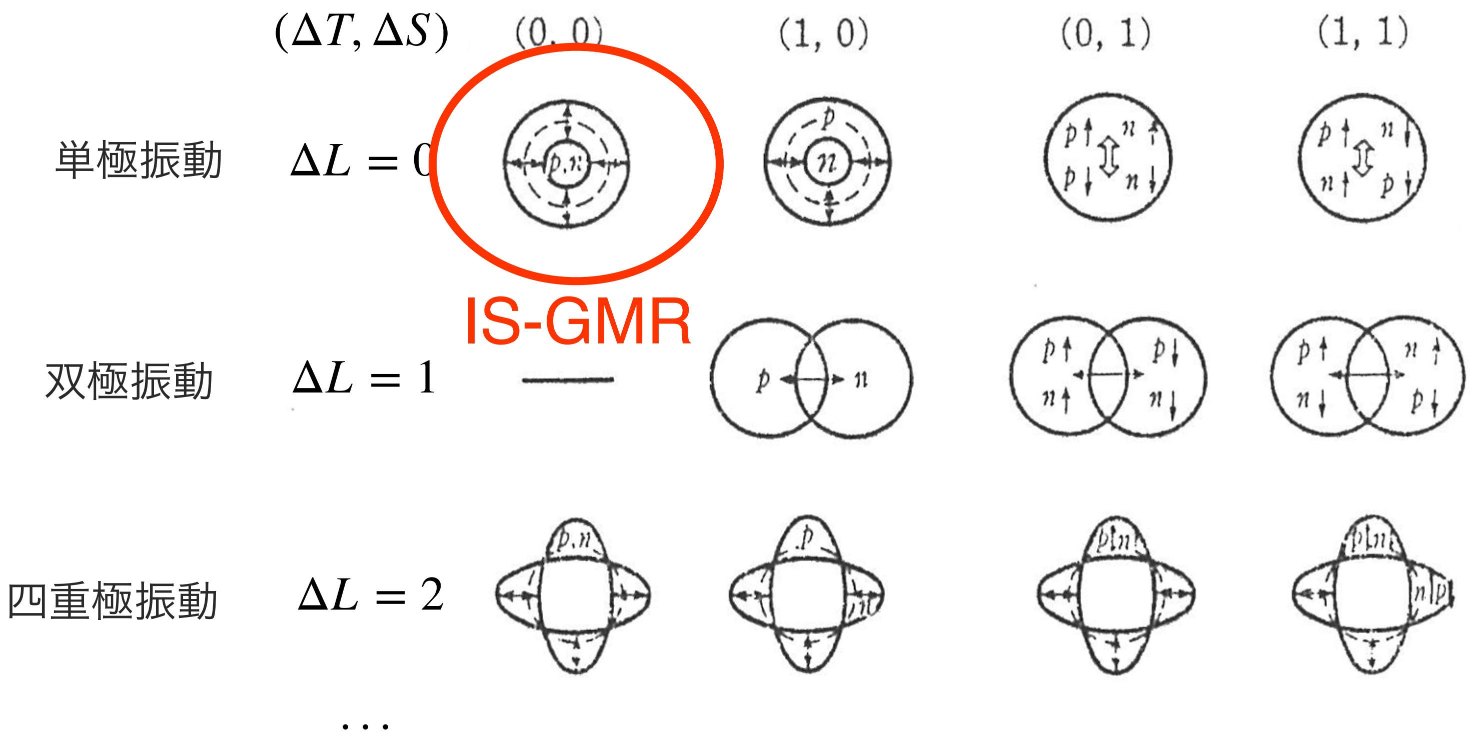
Equation of State incompressibility

Type of Giant Resonances

Giant Monopole Resonance (GMR)

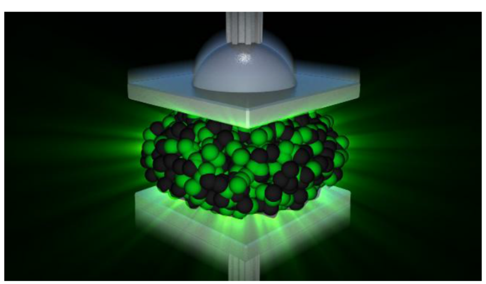
$r^2 Y_0$

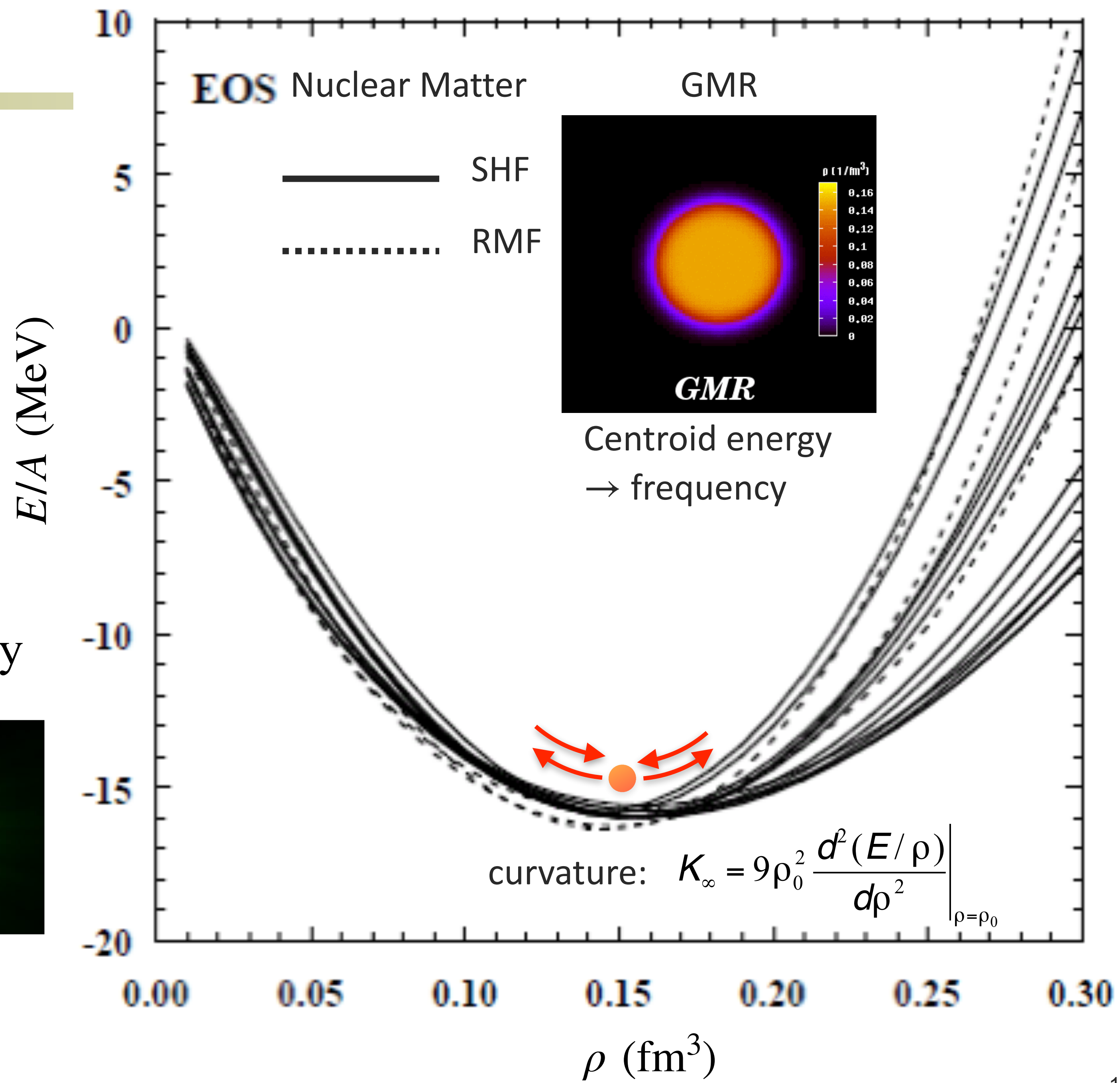
a higher harmonics



杉本・村岡「原子核構造学」

nuclear
incompressibility





(α,α') scattering

(α,α') reaction is selective for isoscalar ($\Delta T = 0$) $\Delta S = 0$ transitions

$$\Delta S = 0,\ \Delta T = 0$$

$$\alpha + A \rightarrow \alpha + A^*$$

α: $T = 0$, spin 0

A: $\vec{T}_i$, $\vec{J}_i$

α: $T = 0$, spin 0

A^*: $\vec{T}_f = \vec{T}_i$, $\vec{J}_f = \vec{J}_i + \Delta\vec{L}$

If the target g.s. has spin-parity of $J^\pi = 0^+$ and isospin T_0

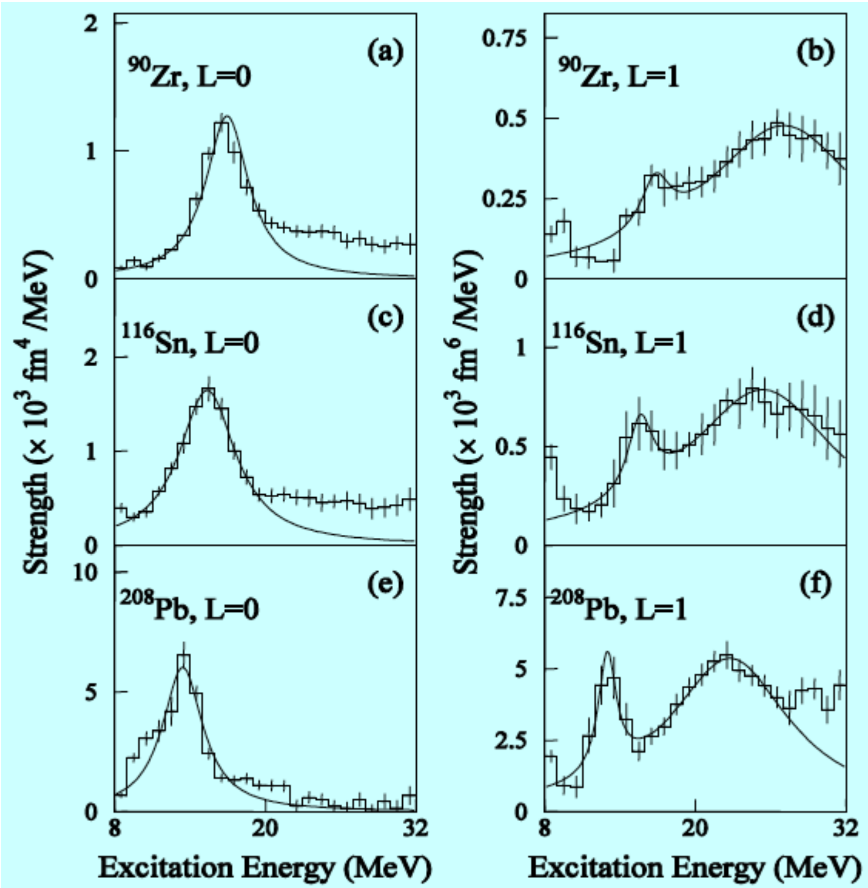
the excited state has

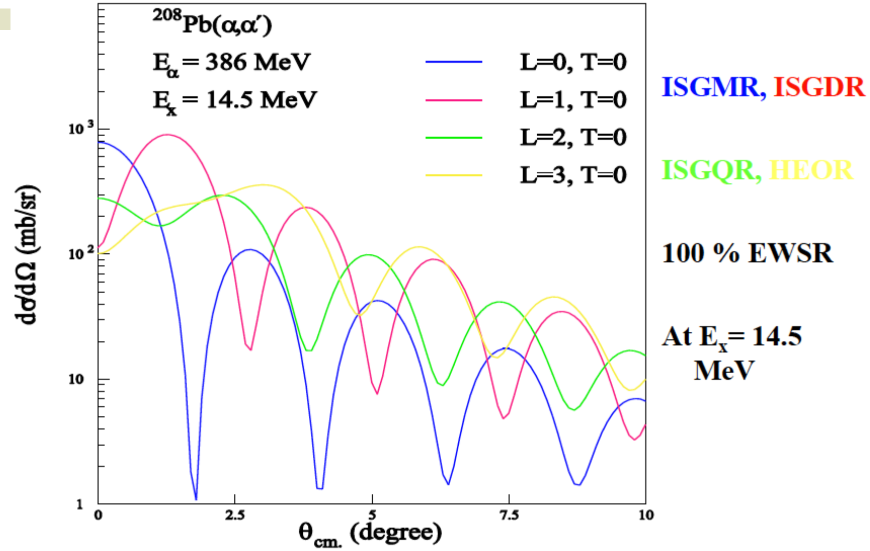
spin-parity of $J^\pi = 0^+$ and isospin T_0 for $\Delta L = 0$ ISGMR

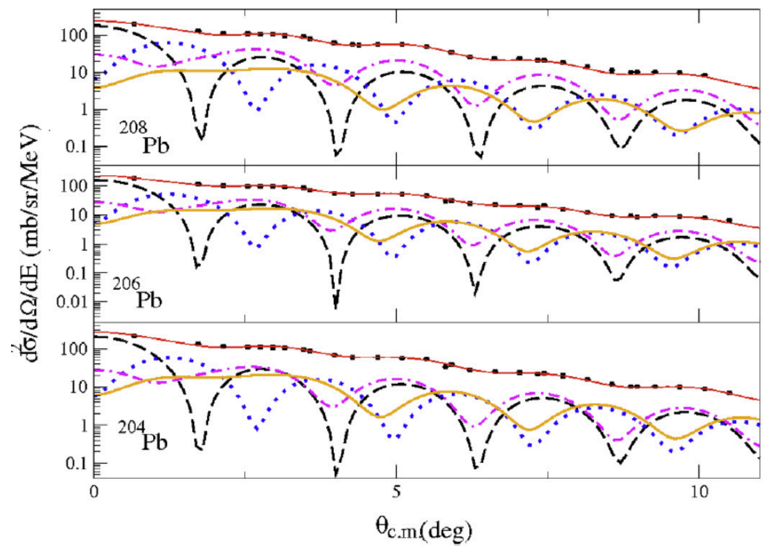
spin-parity of $J^\pi = 1^-$ and isospin T_0 for $\Delta L = 1$ ISGDR

spin-parity of $J^\pi = 2^+$ and isospin T_0 for $\Delta L = 2$ ISGQR

ISGMR ISGDR







at Ex = 13.5 MeV.

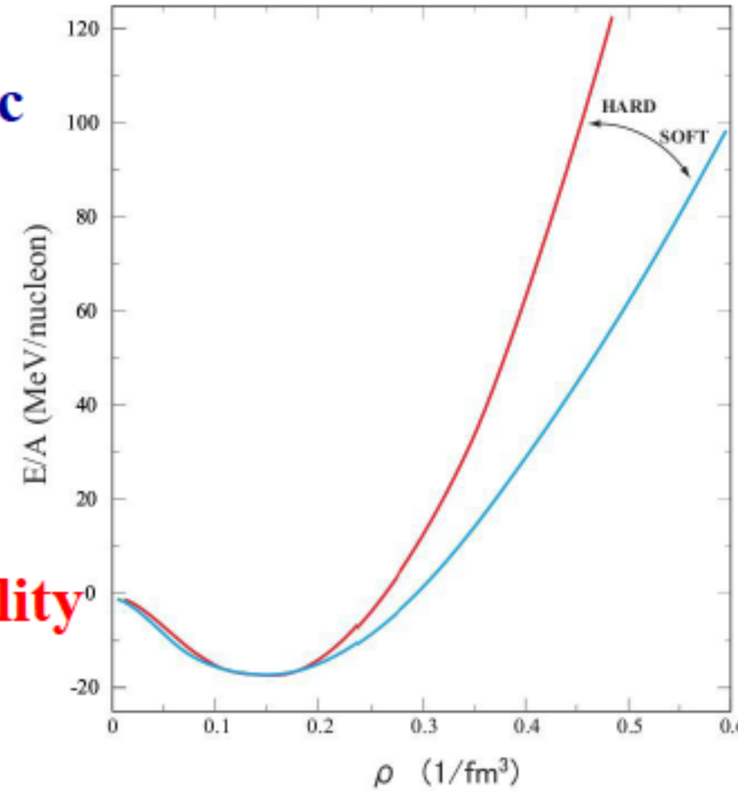
U. Gary and G. Colò, PPNP 101,55 (2018).

For the equation of state of symmetric nuclear matter at saturation nuclear density:

$$\left[\frac{d(E/A)}{d\rho}\right]_{\rho=\rho_0} = 0$$

and one can derive the incompressibility of nuclear matter:

$$K_{nm} = \left[9\rho^2 \frac{d^2(E/A)}{d\rho^2}\right]_{\rho=\rho_0}$$



E/A: **binding energy per nucleon**

ρ **: nuclear density**

ρ₀ **: nuclear density at saturation**

J.P. Blaizot, Phys. Rep. 64 (1980) 171

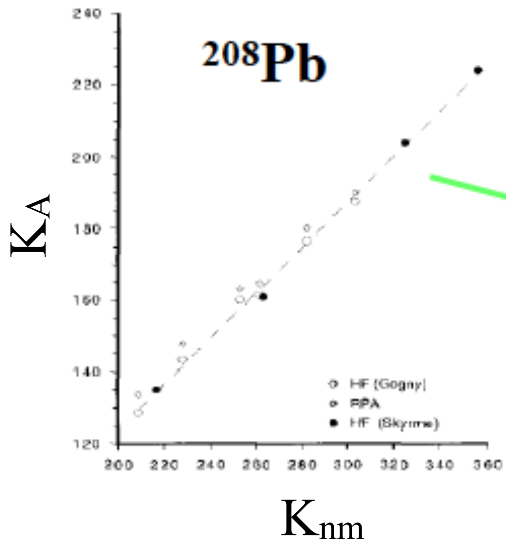
Courtesy of M.N. Harakeh

E/A: binding energy per nucleon

ρ : nuclear density

ρ_0 : nuclear density at saturation

K_A: incompressibility



K_A is obtained from excitation energy of ISGMR

$K_A = 0.64 K_{nm} - 3.5$

J.P. Blaizot, NPA591 (1995) 435

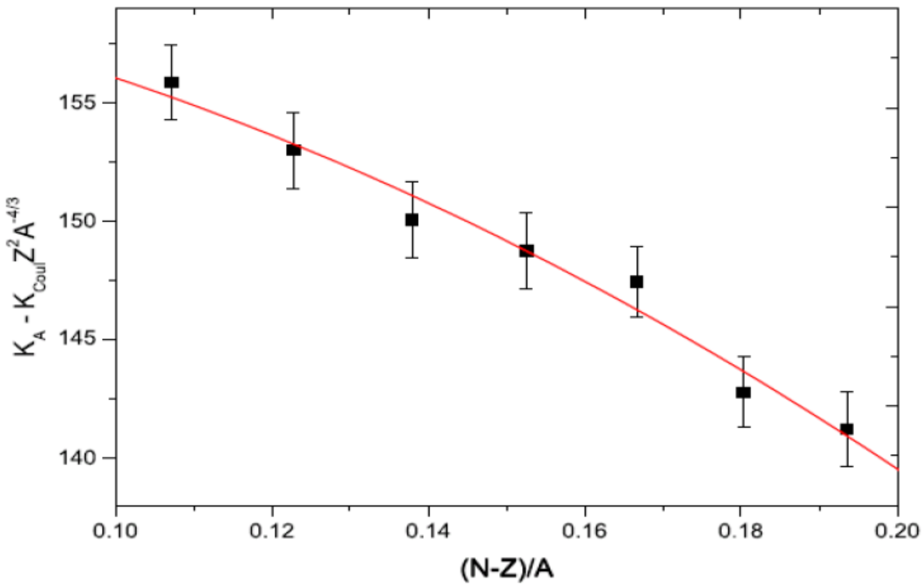
From GMR data on ^{208}Pb and ^{90}Zr,

$K_\infty = 240 \pm 10$ MeV

[See, *e.g.*, G. Colò *et al.*, Phys. Rev. C 70 (2004) 024307]

ISGDR energy is consistent.

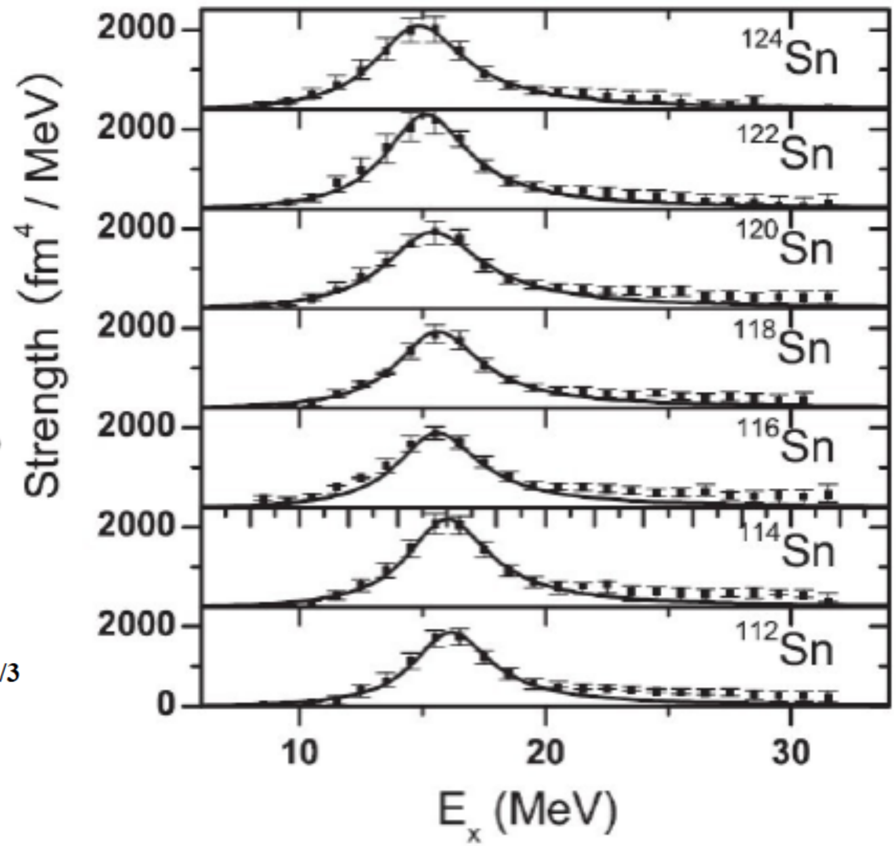
U. Garg and G. Colò, PPNP 101,55 (2018).



$$K_\tau = -\ 550 \pm 100\ \text{MeV}$$

$$K_A \sim K_{vol}(1 + cA^{-1/3}) + K_\tau((N - Z)/A)^2 + K_{Coul}Z^2A^{-4/3}$$

$$K_\tau^\infty = K_{\text{sym}} - 6L - \frac{Q_0}{K_\infty}L$$



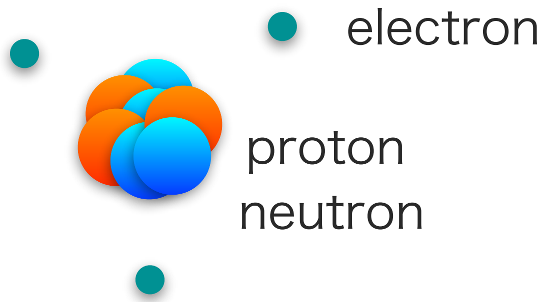
T. Li et al., PRC99, 162503(2007)

Softness of Sn and Cd nuclei is still unresolved

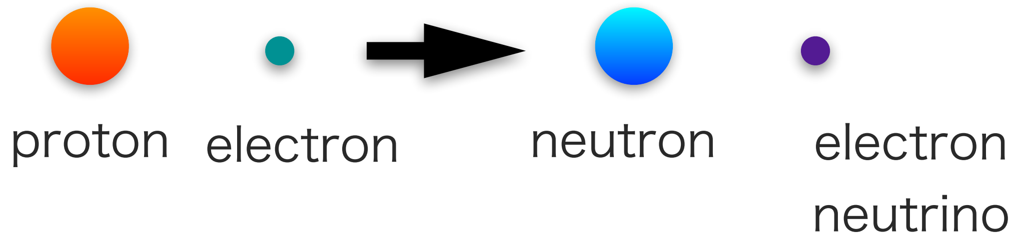
D. Patel et al., PLB**718**, 447 (2012)

A Neutron Star

Conversion of material into neutrons → Supernova

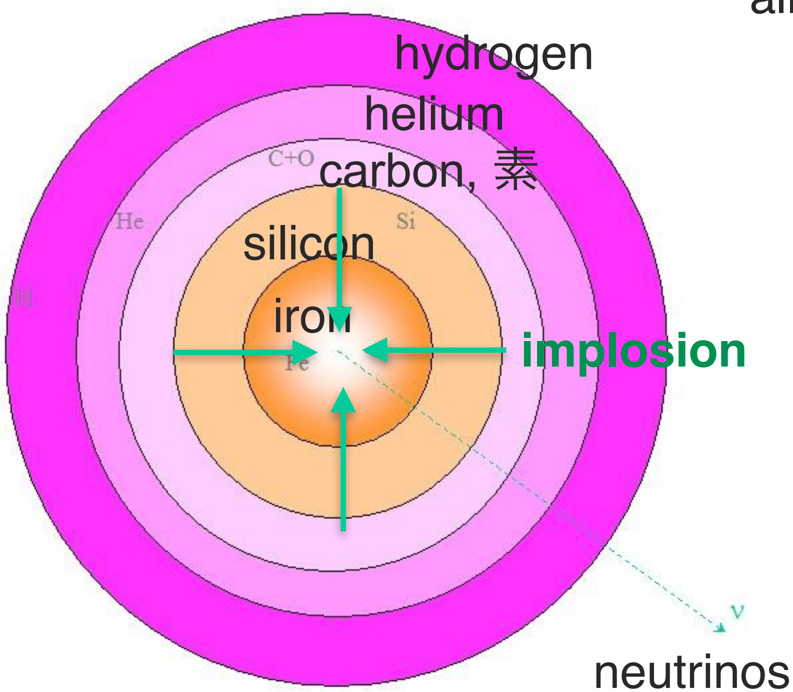


atom



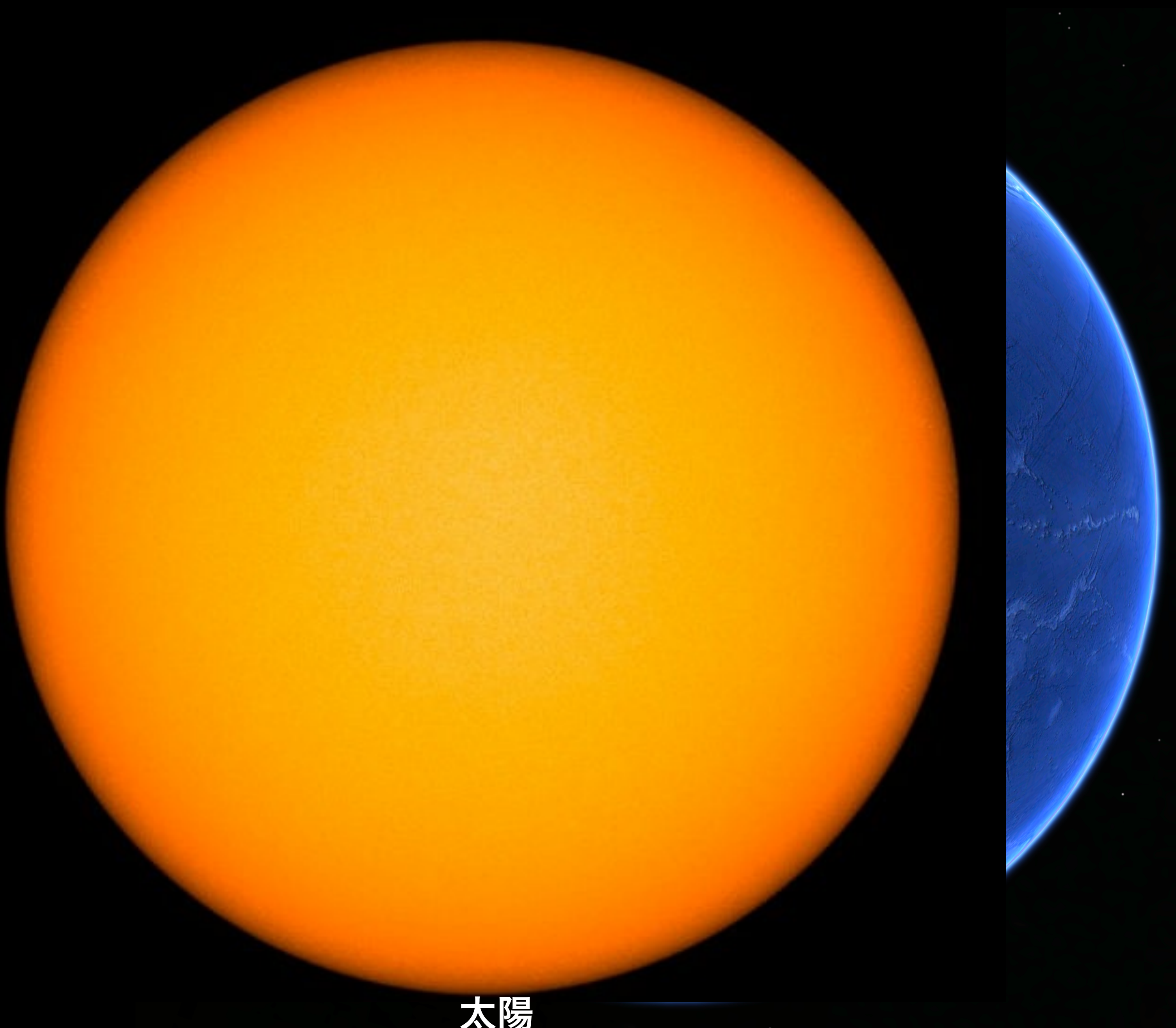
After burn-out of a (sufficiently heavy) star :

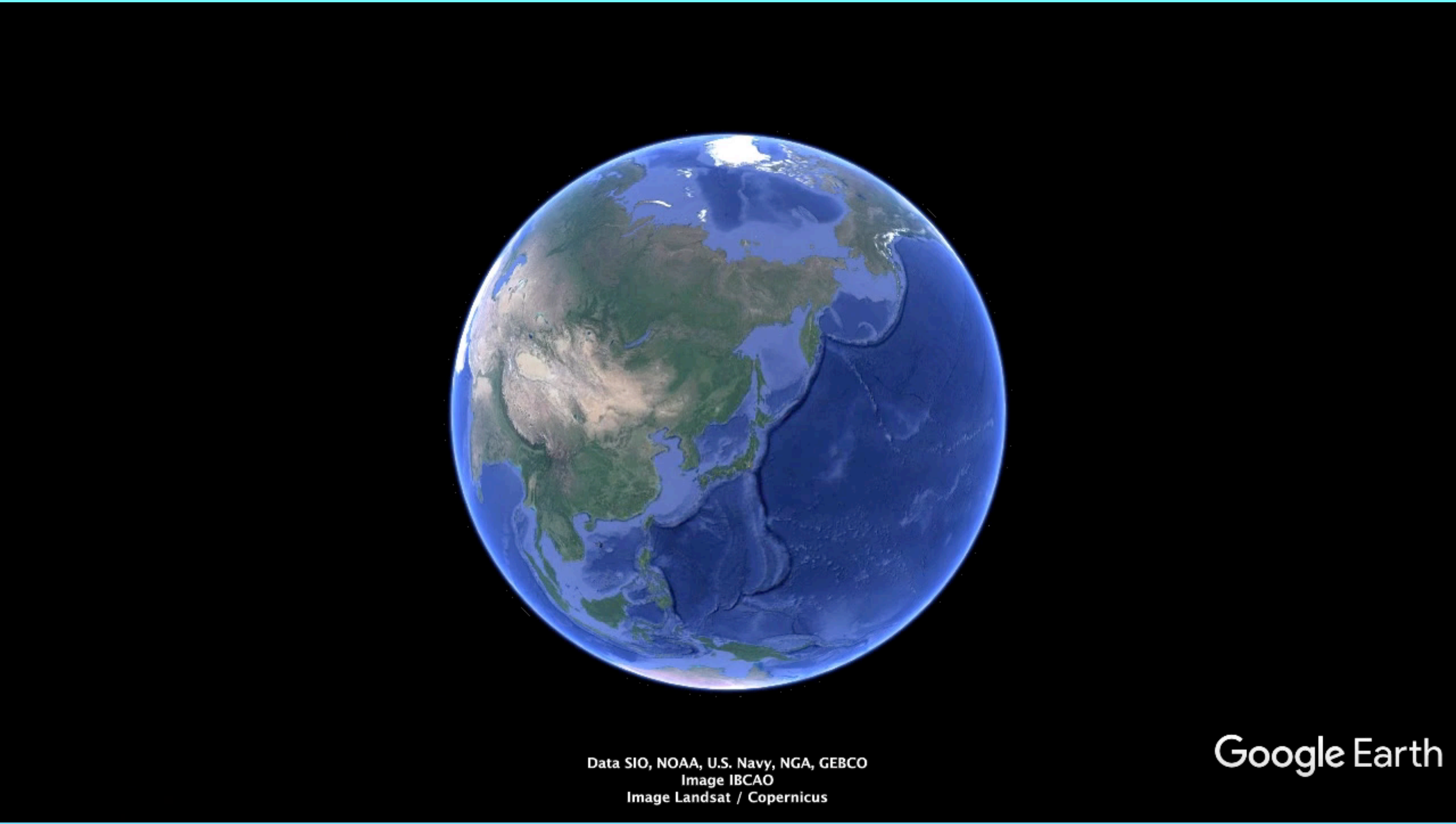
all the materials are converted into neutrons



Core-Collapse Supernova

supernova SN1987A


太陽


Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image IBCAO
Image Landsat / Copernicus
Google Earth

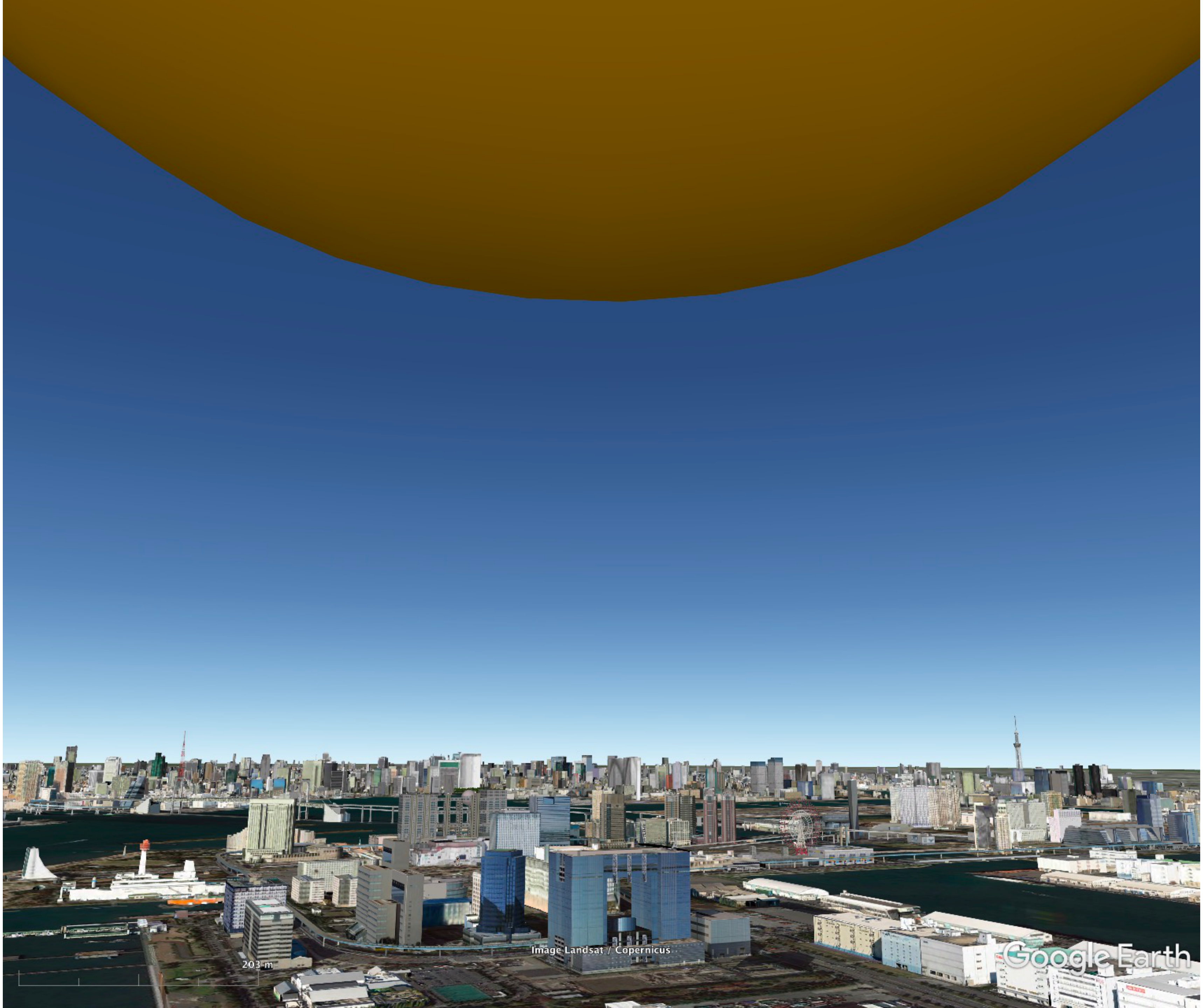
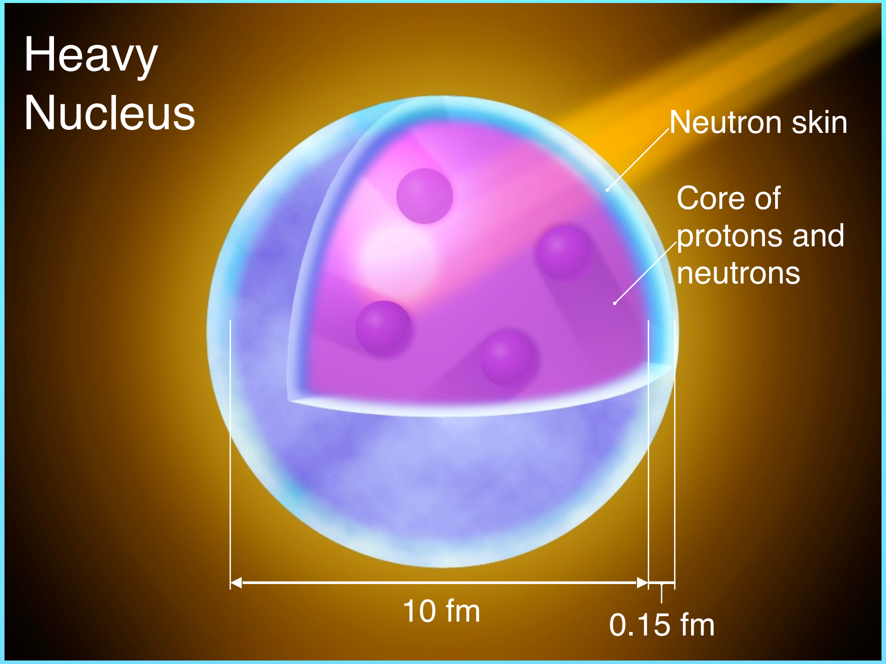
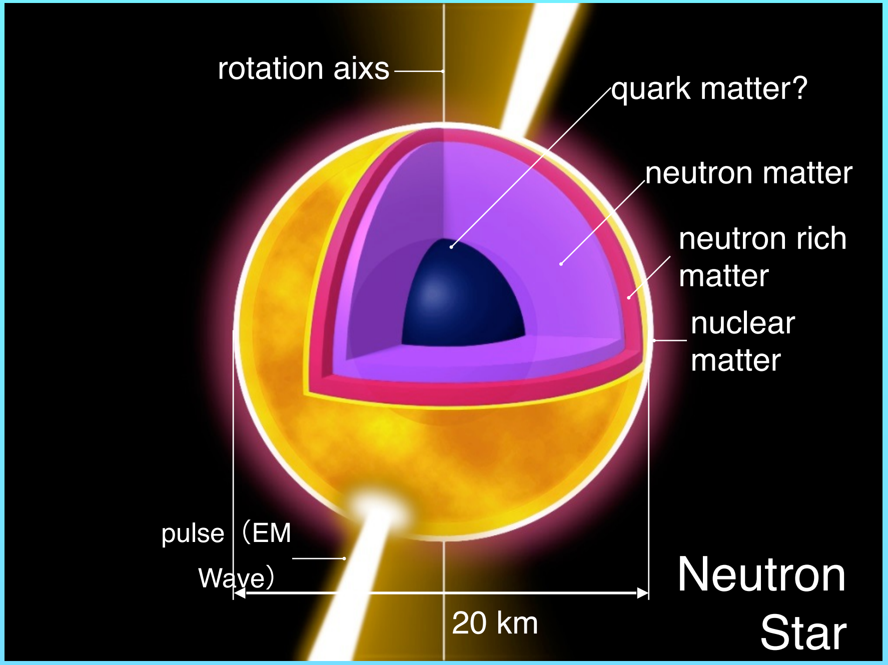


Image Landsat / Copernicus
203 m
Google Earth

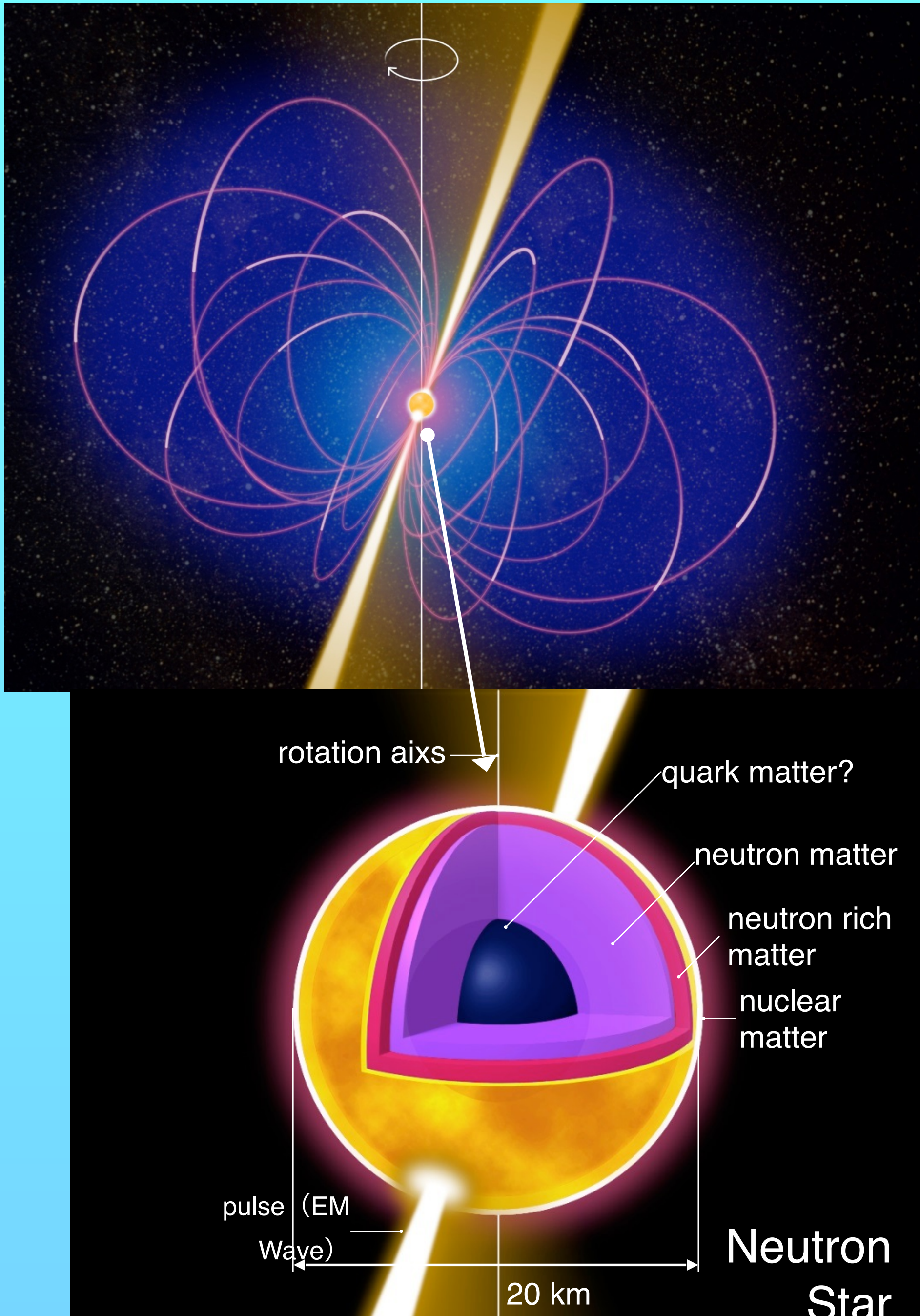
A neutron star is a “big” nucleus





factor of 10^{18}

Neutron Star



Radius; 12km

Mass: 1-2 solar mass

Density: 1 G ton/cm^3

Gravity: 0.6G higher on the earth

Time: 20% slower than on the earth

Temperature: 1 M K

Magnetic field: $10^4 \sim 10^{12}$ T

Rotation freq.: 0.01 ~ 1000 /sec

A neutron star is considered to be the origin of “pulsers” and “magneters”.

Equation of State
Symmetry Energy

Nuclear Equation of State (EOS)
at zero temperature

Nuclear EOS neglecting Coulomb

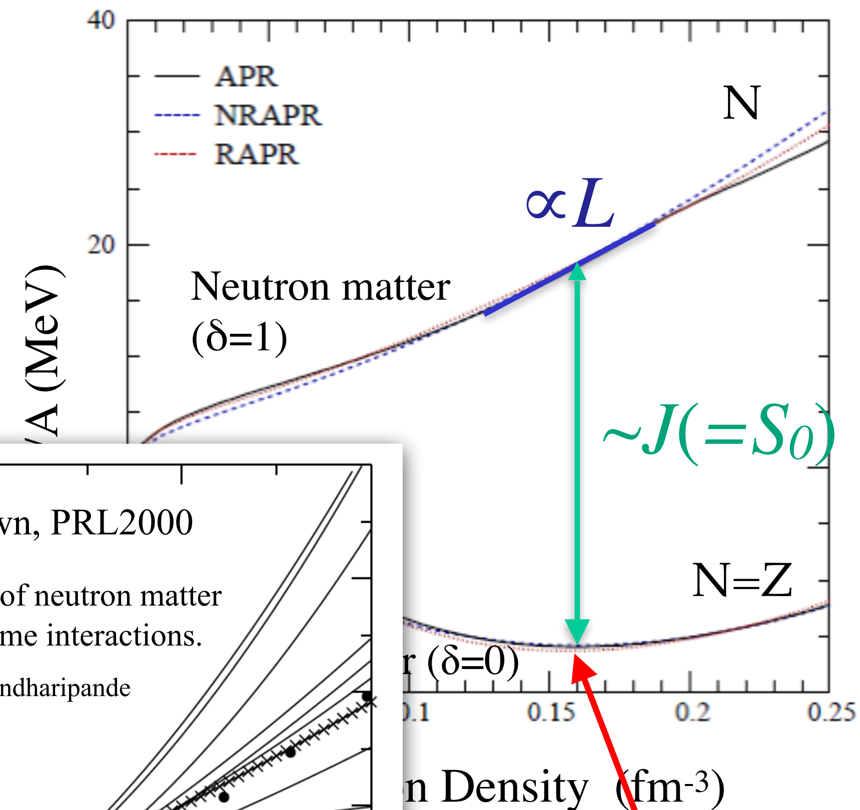
$$\frac{E}{A}(\rho,\delta)=\frac{E}{A}(\rho,0)+S(\rho)\delta^2+\cdots$$

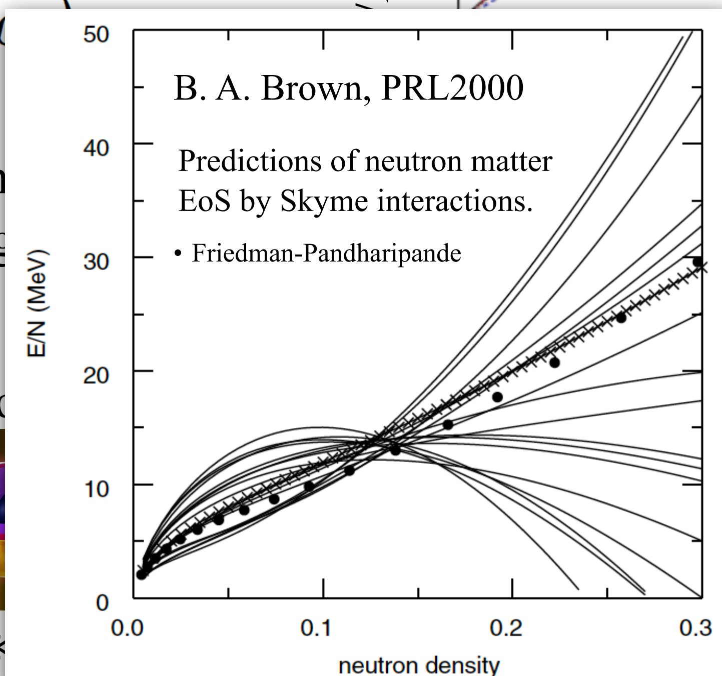
$$\delta\equiv\frac{\rho_n-\rho_p}{\rho_n+\rho_p}$$ Asymmetry parameter

Symmetry energy

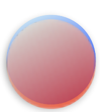
$$S(\rho)=J+\frac{L}{3\rho_0}(\rho-\rho\ldots$$

⇔ difference between *p-n* ch…
how the system energy chang…
are replaced by the neutrons…



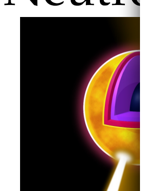


Nucleus



$Z \lesssim N$

Neutr…



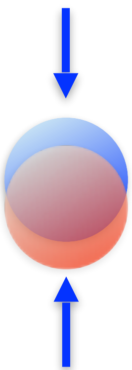
Z≪

Static Electric Dipole Polarizability (α_D)

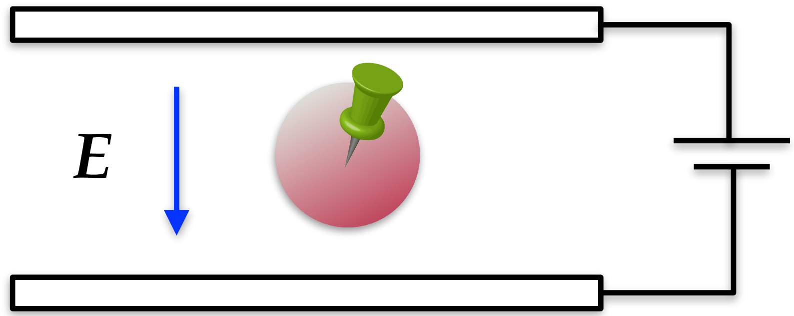
Electric dipole moment

$$p = \alpha_D \times E$$

α_D**: electric dipole polarizability**



The **restoring force** originates from the **symmetry energy.**



nucleus

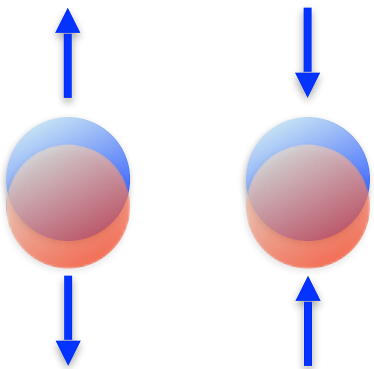
in a static electric field

with fixing the c.m. position

Electric dipole polarizability (EDP) is sensitive to the symmetry energy below the nuclear saturation density.

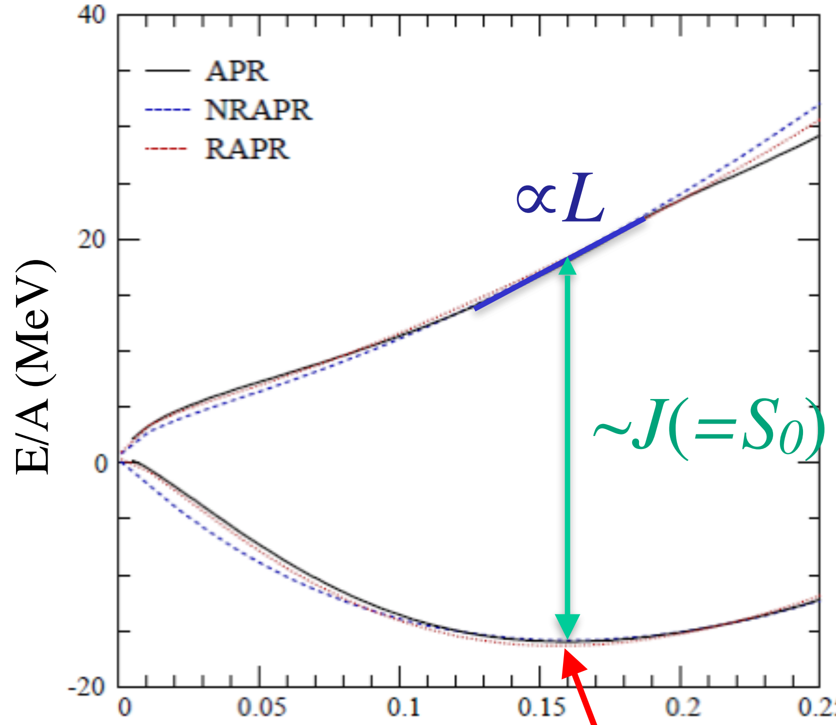
Symmetry Energy (J and L parameters)
Keys to Understand the Neutron Matter Equation of State (EOS)

Electric Force Symmetry Energy



α_D is determined by the balance between the two.

Nuclear Equation of State



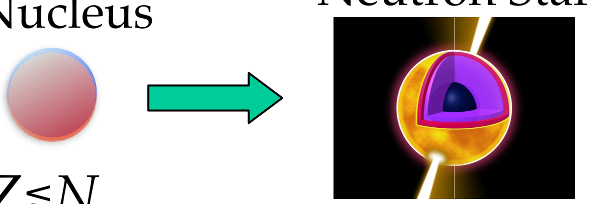
neutron matter

symmetric nuclear matter (N=Z)

Nucleon Density (fm^{-3})

Saturation Density ρ_0

Nucleus Neutron Star

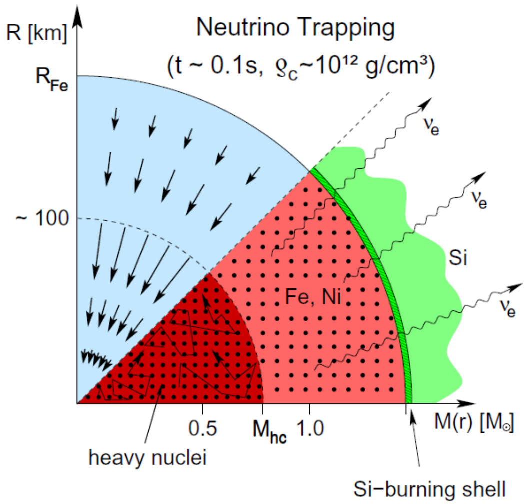


$Z \lesssim N$ $Z \ll N$

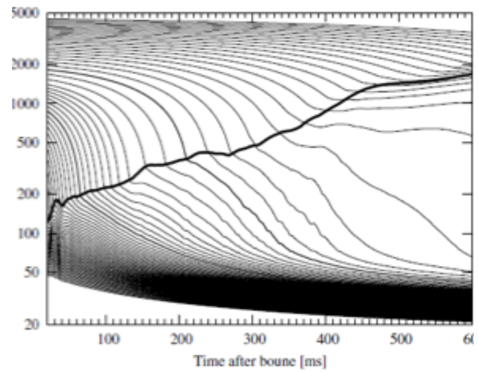
Symmetry Energy of the Nuclear EOS

is fundamental information for stellar processes

Core-collapse supernova

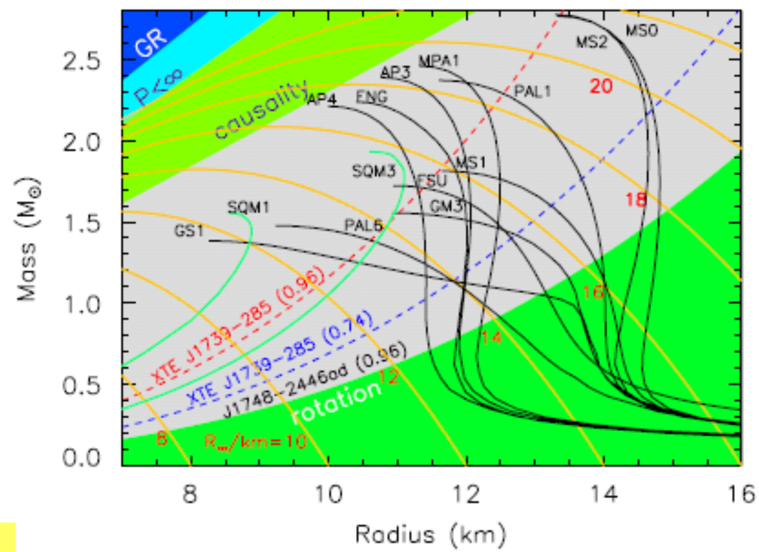


Langanke and Martinez-Pinedo



Y. Suwa et al., ApJ764, 99 (2013).

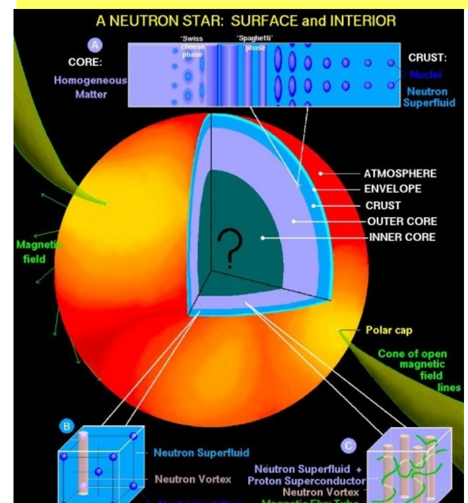
Neutron star mass vs radius



Lattimer et al., Phys. Rep. 442, 109(2007)

Nucleosynthesis

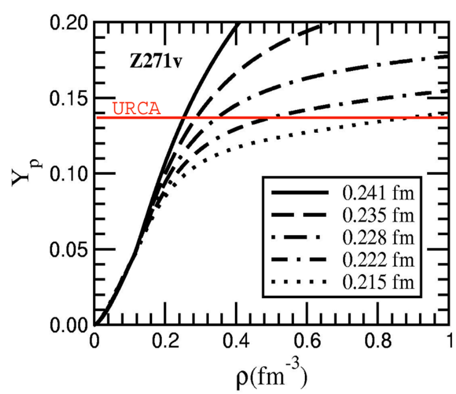
Neutron star structure



Neutron Star Merger Gravitational Wave

https://www.youtube.com/watch?v=IZhNWh_lFuI

Neutron star cooling



Lattimer and Prakash, Science 304, 536 (2004).

http://www.astro.umd.edu/~miller/nstar.html

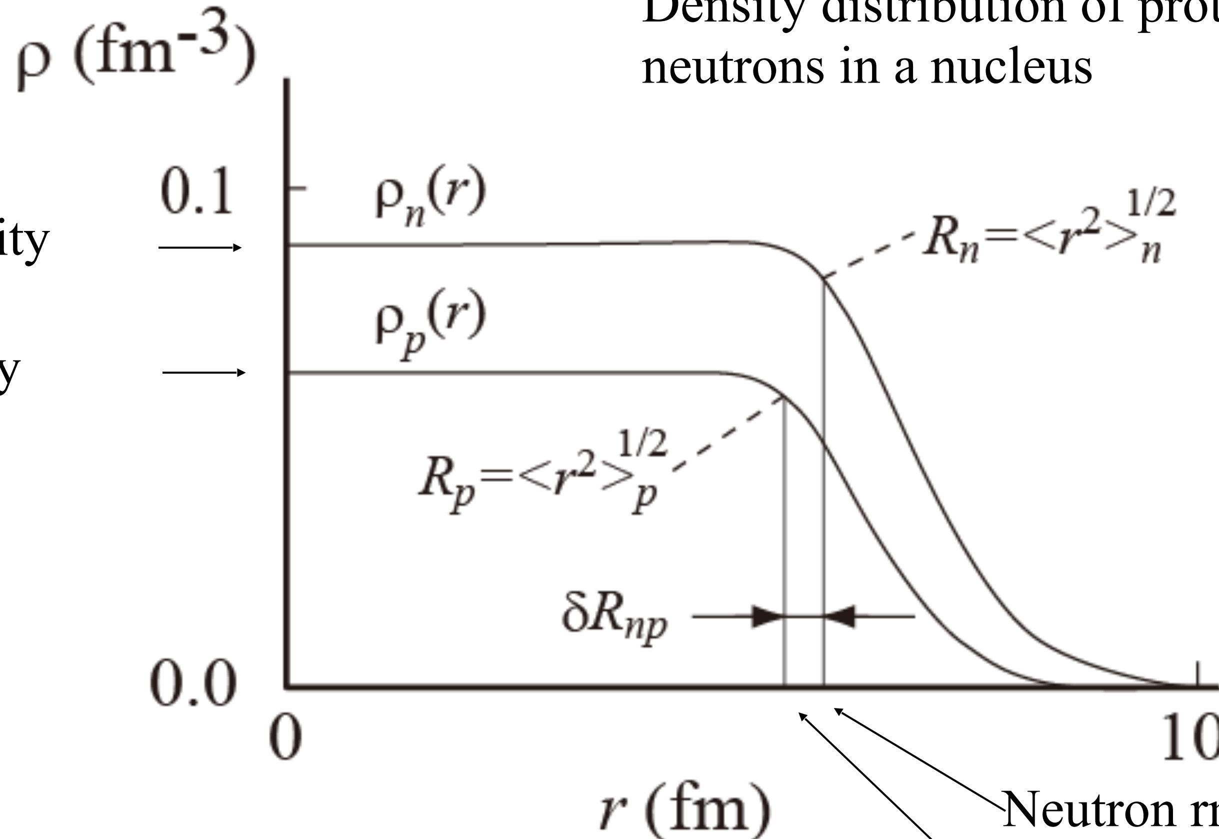
Neutron Skin and Density Dependence of the Symmetry Energy

Density distribution of protons and neutrons in a nucleus

^{208}Pb

Neutron density

Proton density

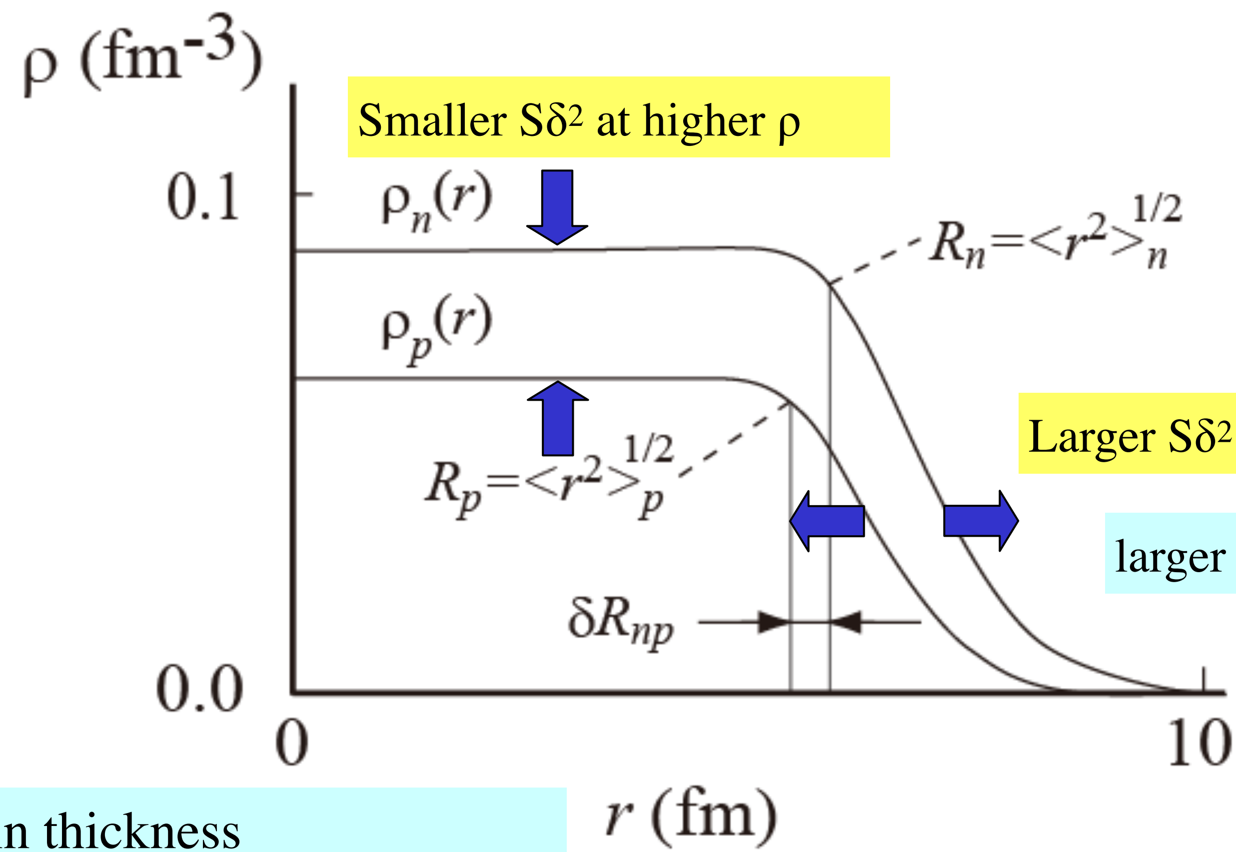


Neutron rms radius

Proton rms radius

Neutron Skin and Density Dependence of the Symmetry Energy

For larger *L*:



Larger $S\delta^2$ at lower ρ

larger neutron skin

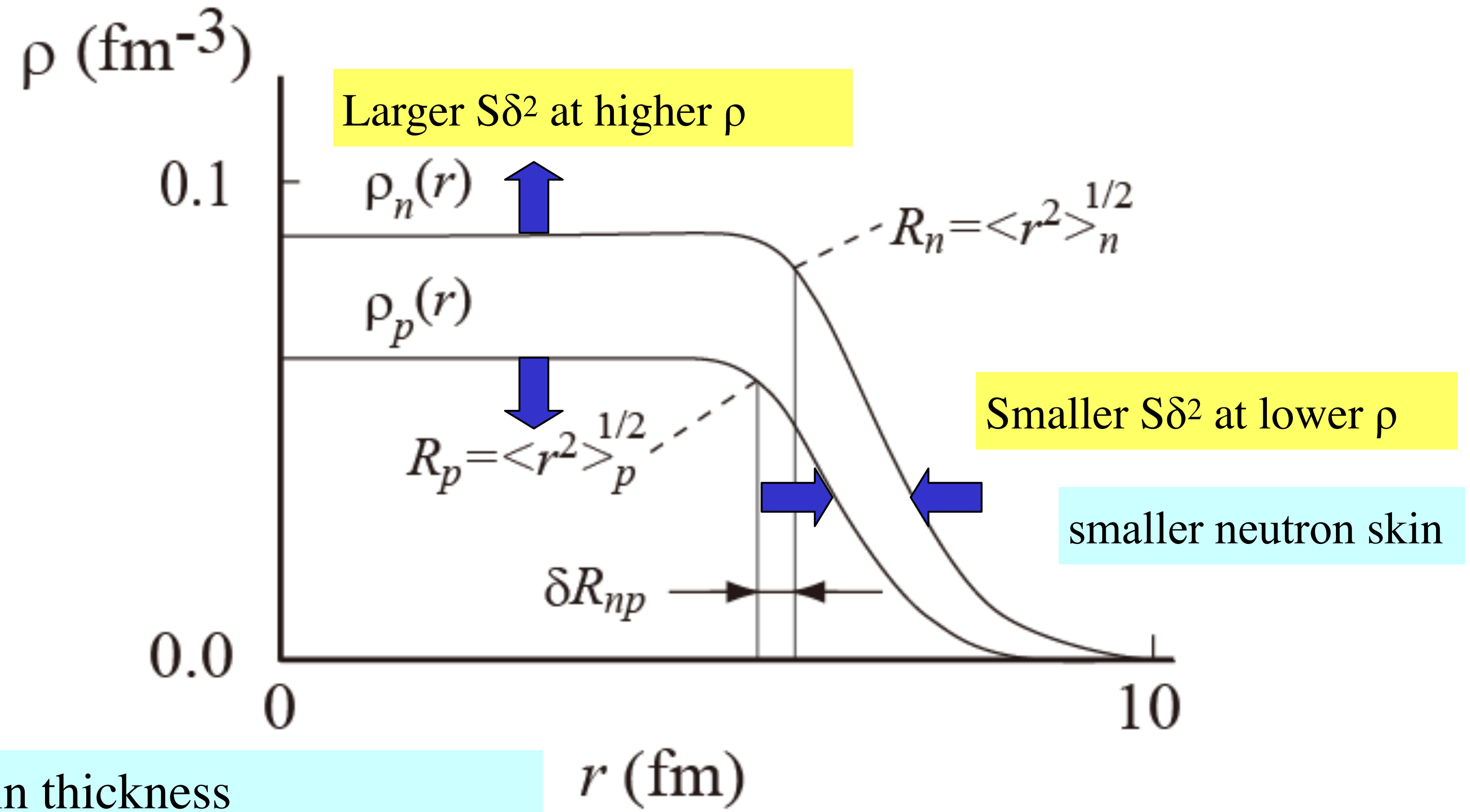
Neutron skin thickness

↕

Density dependence of the symmetry energy ← Energy minimum (equilibrium)

Neutron Skin and Density Dependence of the Symmetry Energy

For smaller *L*:



Neutron skin thickness

↕

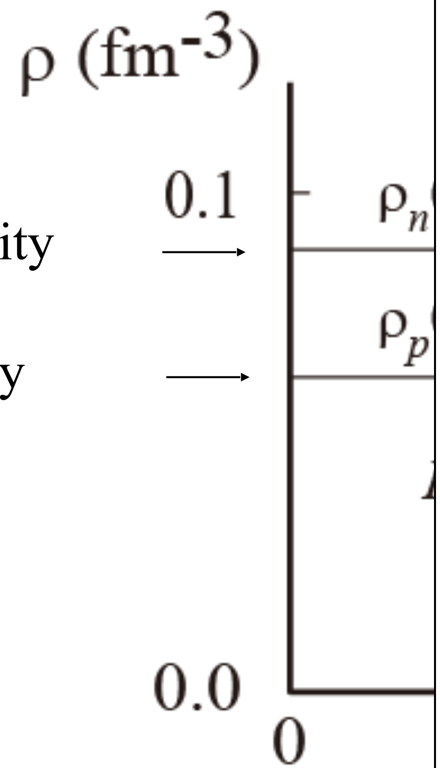
Density dependence of the symmetry energy ← Energy minimum (equilibrium)

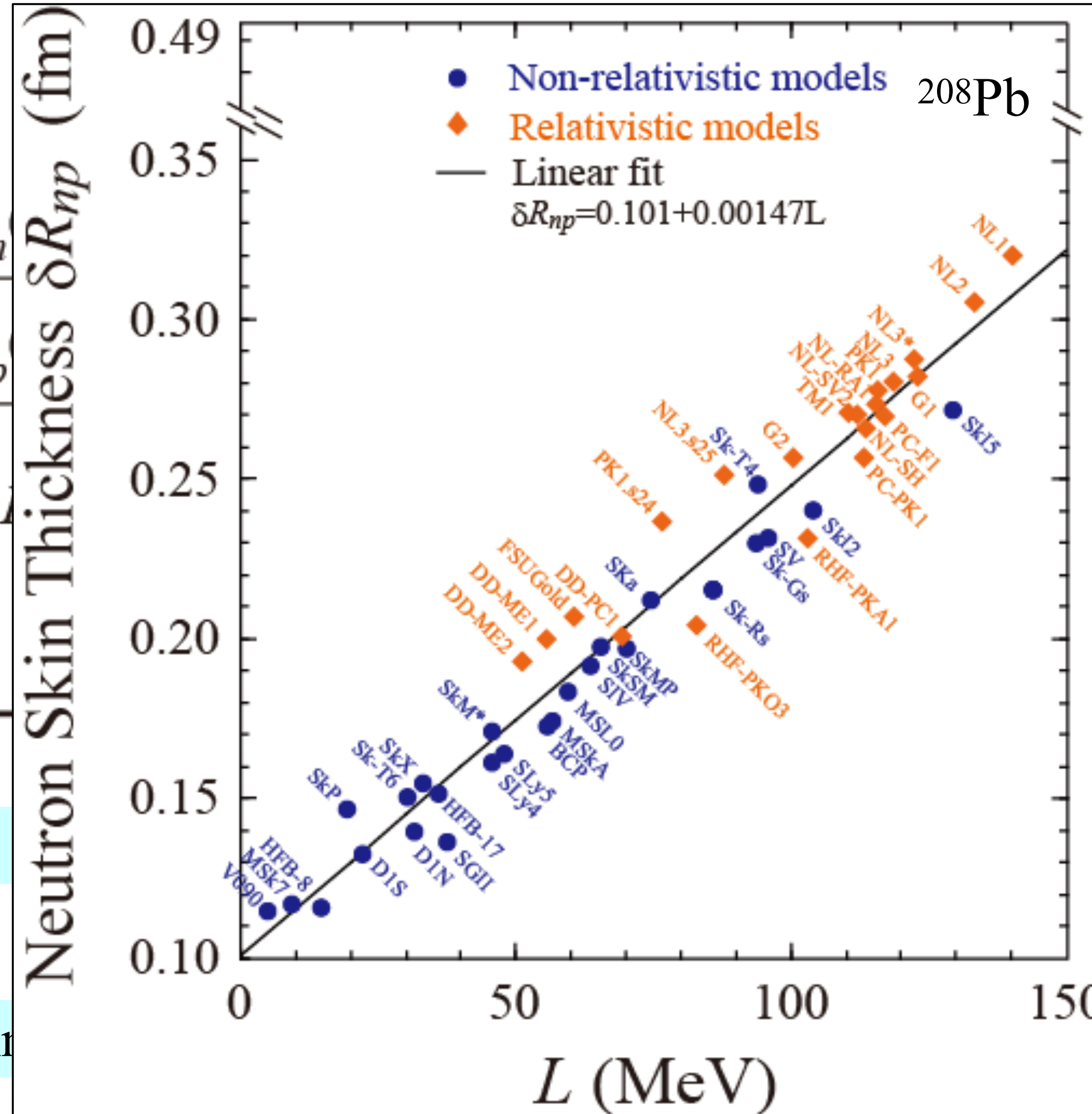
Neutron Skin and Density Dependence of the Symmetry Energy

X. Roca-Maza *et al.*, PRL**106**, 252501 (2011)

Neutron density

Proton density

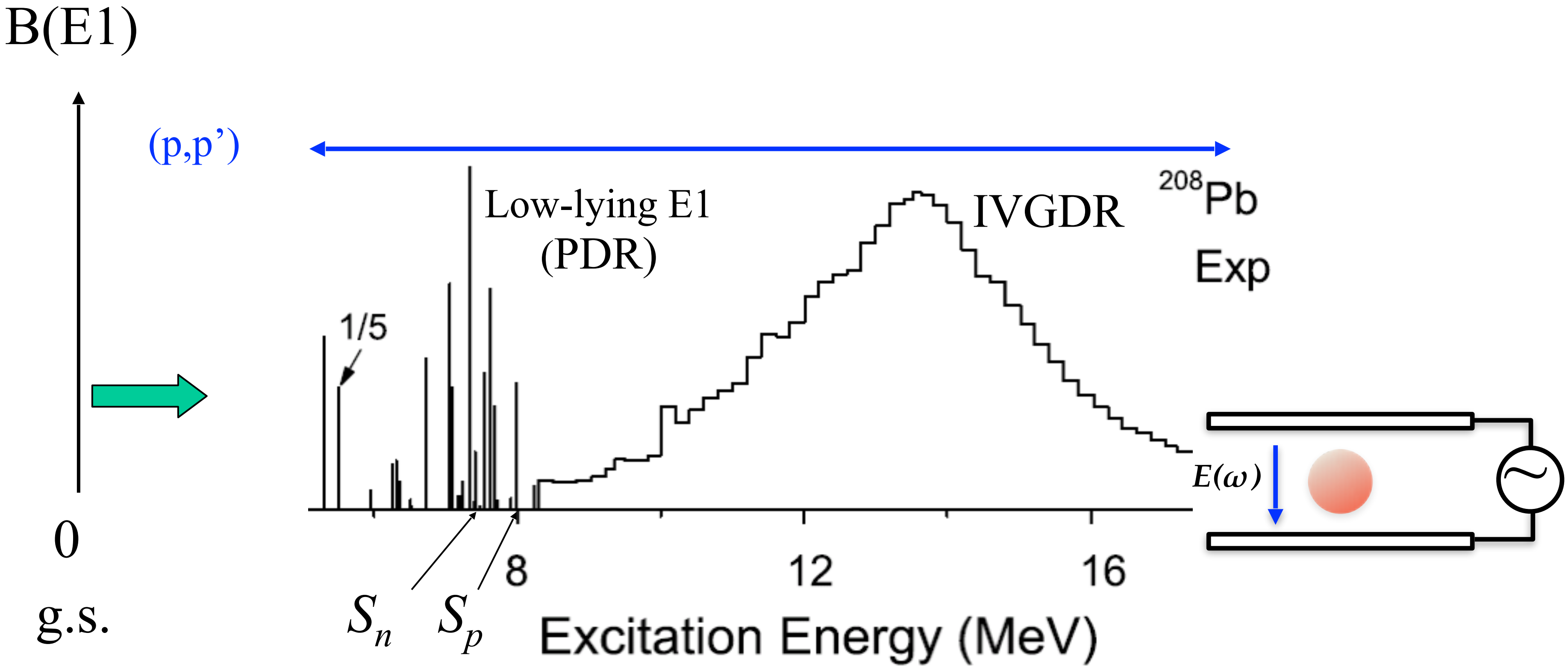




Neutron skin thickness

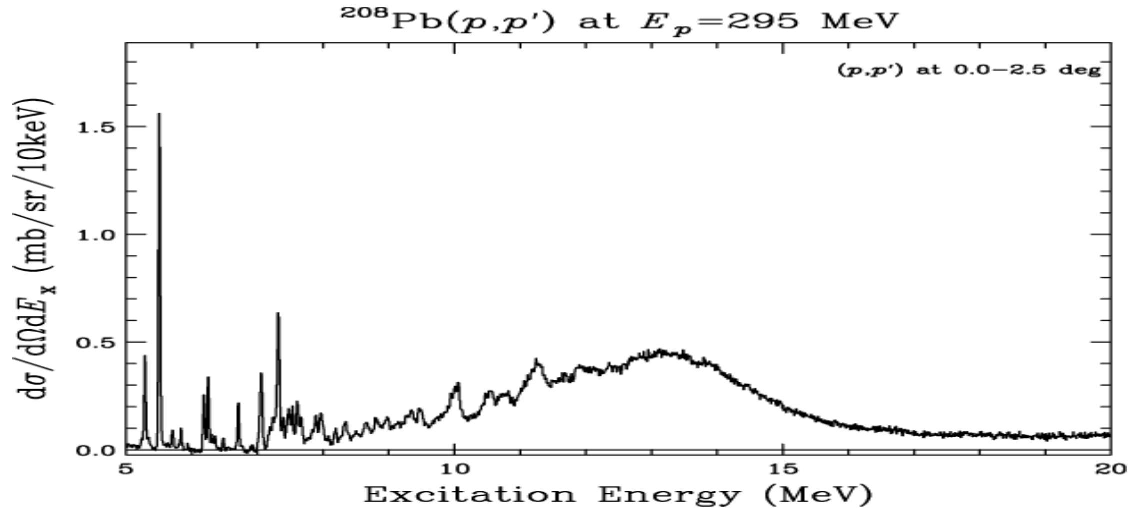
Density dependence of the sym

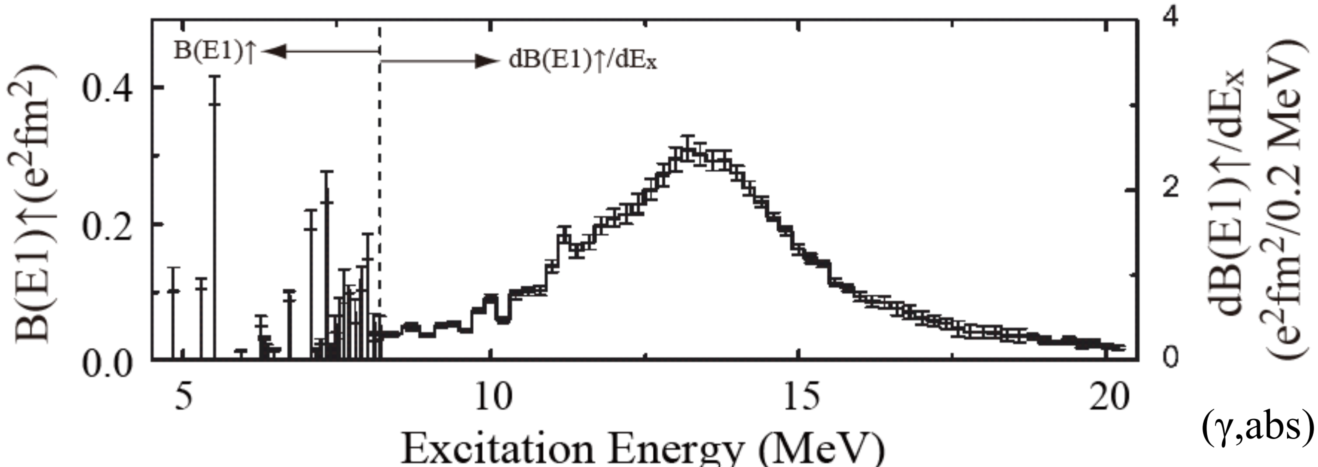
Probing the E1 Response by Proton Scattering



- Single shot measurement across S_n in $E_x = 5\text{-}22$ MeV.
- Uniform detection efficiency (80-90%) and solid angle
- High energy resolution (20-30 keV)
- Polarized beam, polarization detection → extraction of E1
- Isotopically enriched target with a few mg/cm^2 thickness

Electric Dipole Polarizability: ^{208}Pb, ^{120}Sn

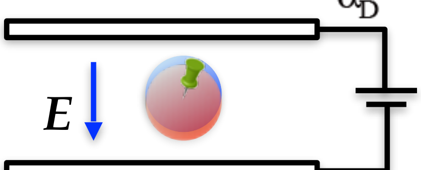




(γ,abs) at Mainz

E_x	0	10	20	130 MeV
α_D	2.7	16.2		1.2 fm³

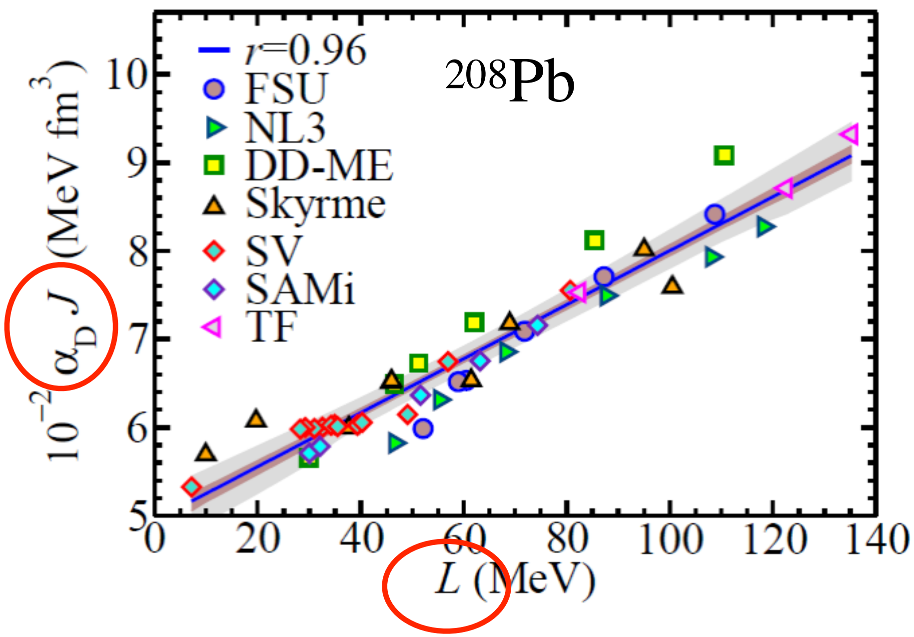
total 20.1±0.6 fm³



$$\alpha_D = \frac{8\pi}{9} \int \frac{dB(E1)}{\omega}$$

AT et al., PRL107, 062502(2011)

Electric Dipole Polarizability (α_D) in the correlation of J and L



X. Roca-Maza *et al*., PRC**88**, 024316(2013)

Correlations observed in various interaction sets in the framework of EDF.

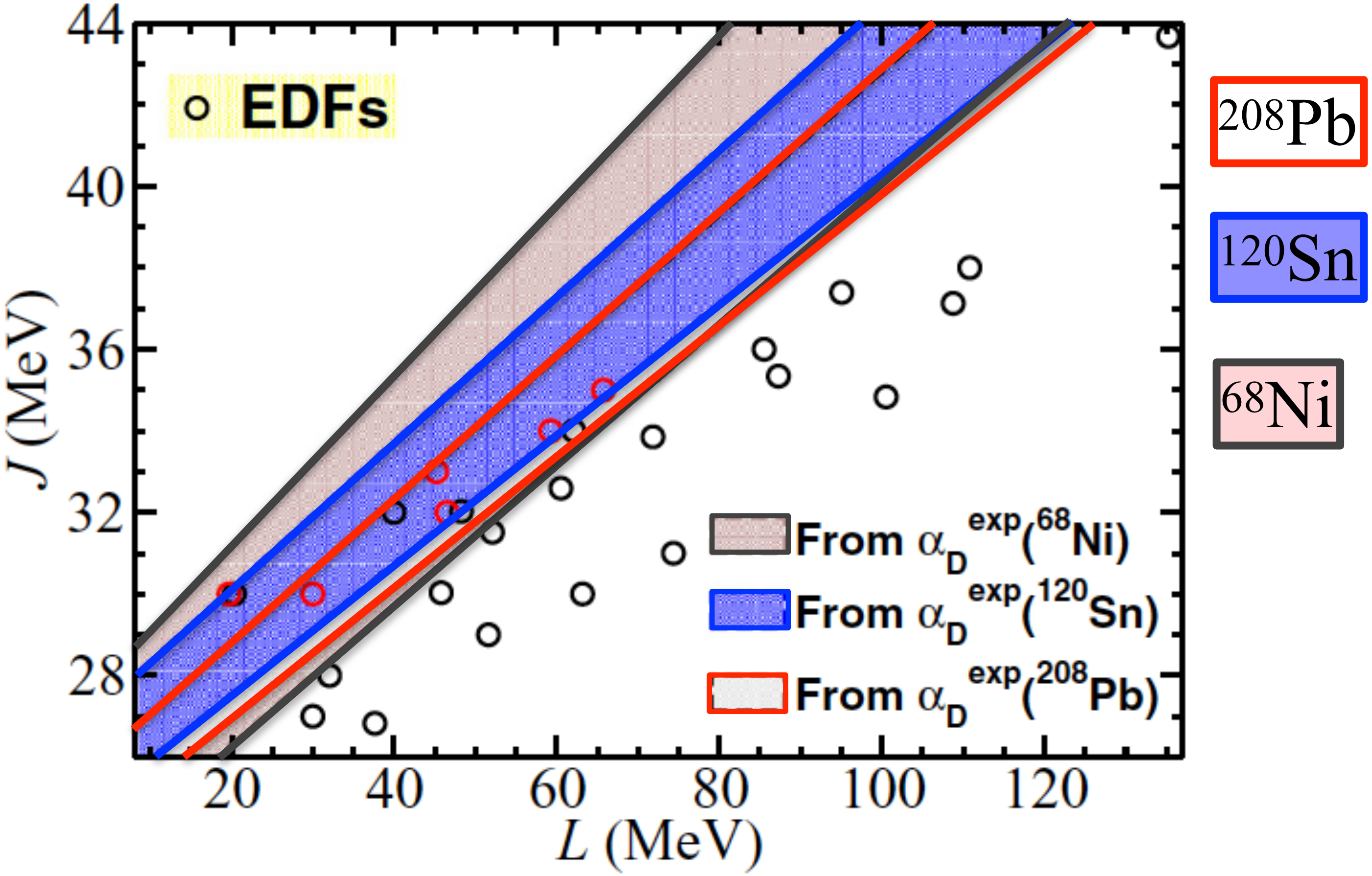
$$\alpha_D^{DM} \approx \frac{\pi e^2}{54} \frac{A\langle r^2 \rangle}{J} \left[1 + \frac{5}{3} \frac{L}{J} \epsilon_A \right]$$

insights from the droplet model

Precise determination of α_D of ^{208}Pb gives a constraint band in the *J*-*L* plane.

Constraints on J-L from the EDP data

X. Roca-Maza et al., PRC92, 064304(2015)

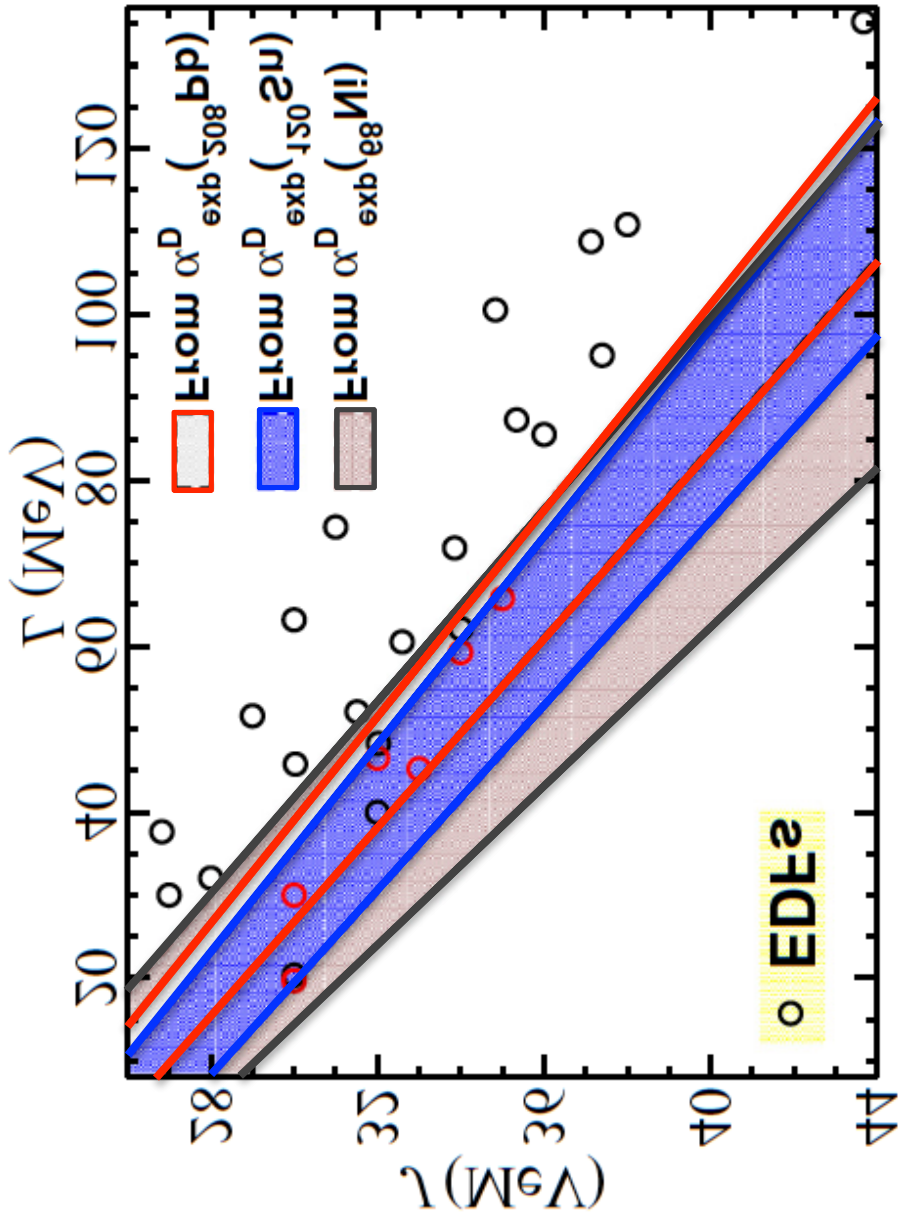


RCNP ^{208}Pb: AT *et al*., PRL**107**, 062502 (2011).

RCNP ^{120}Sn: T. Hashimoto *et al*., PRC**92**, 031305(R)(2015).

GSI ^{68}Ni: D.M. Rossi *et al*., PRL**111**, 242503 (2013).

Constraints on *J*-*L* from the EDP data



X. Roca-Maza et al., PRC92, 064304(2015)

^{208}Pb

^{120}Sn

^{68}Ni

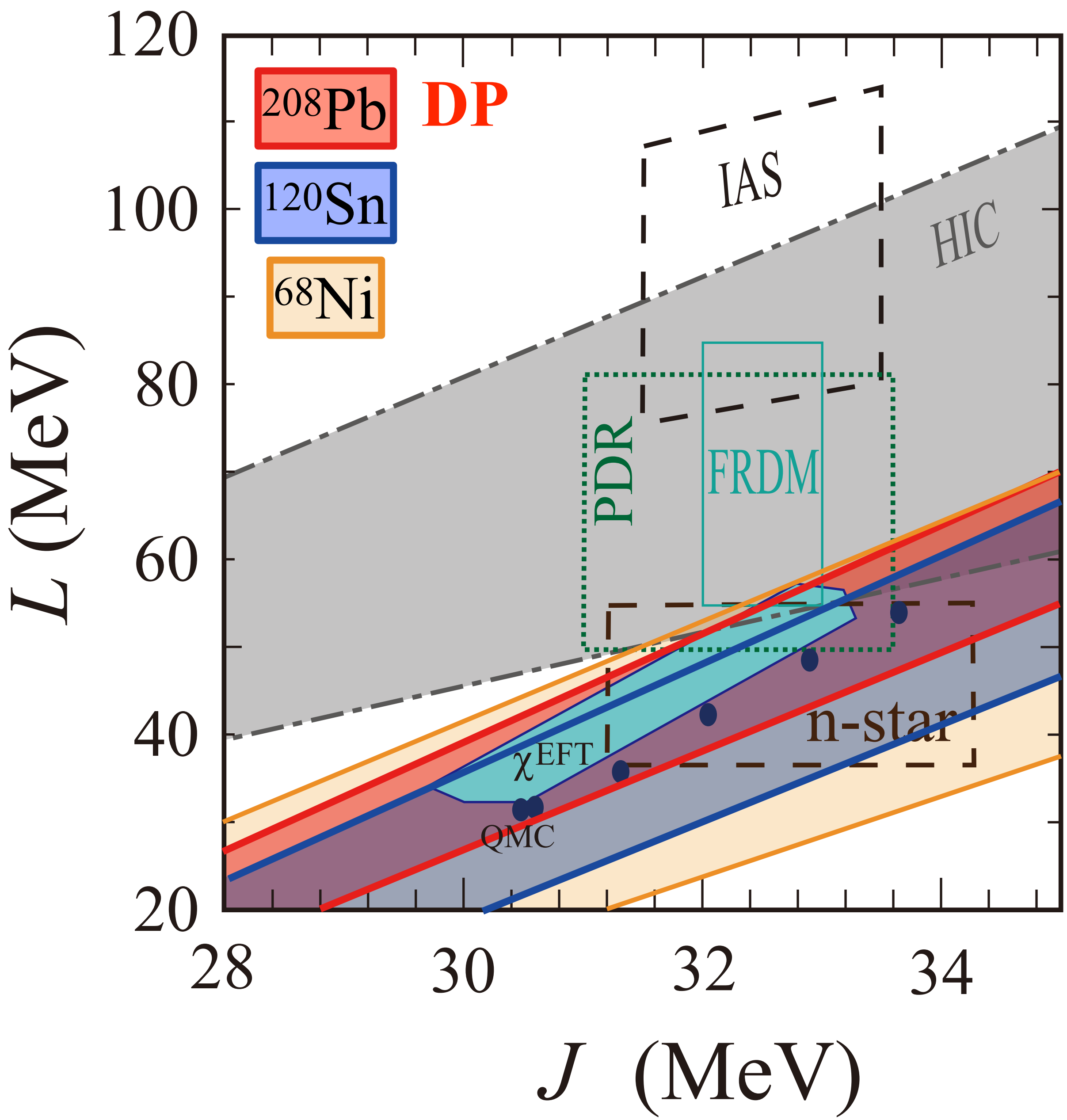
RCNP ^{208}Pb: AT *et al*., PRL**107**, 062502 (2011).

RCNP ^{120}Sn: T. Hashimoto *et al*., PRC**92**, 031305(R)(2015).

GSI ^{68}Ni: D.M. Rossi *et al*., PRL**111**, 242503 (2013).

These α_D data give essentially one constraint on the symmetry energy in the *J*-*L* plane.

Constraints on J and L



Tsang PRC2012

HIC: Heavy Ion Collision Analysis
Tsang PRL2009

IAS: Isobaric Analog State Energy
Danielewicz&Lee NPA2009

PDR: Pygmy Dipole Resonance in
^{132}Sn, ^{68}Ni, Carbone PRC2010

FRDM: Finite Range Droplet Model
Moller PRL2012

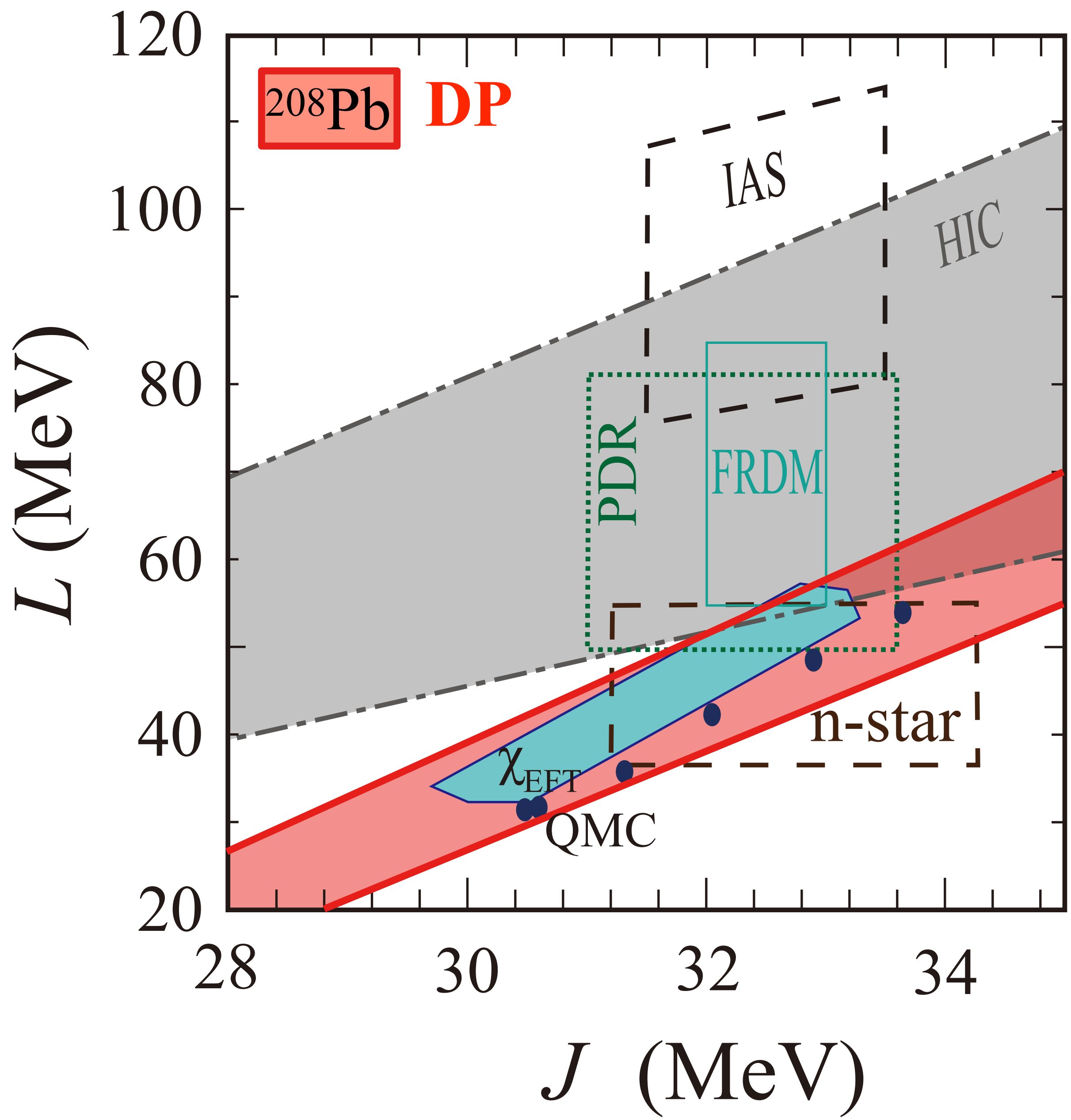
n-star: Quiescent Low-Mass X-ray
Binaries, Stainer PRL2012

χEFT: Chiral Effective Field Theory,
Tews PRL2013

QMC: Quantum Monte-Carlo Calc.
Gandolfi, EPJA50, 10(2014).

DP: Dipole Polarizability
^{208}Pb AT PRL2011
^{120}Sn Hashimoto PRC2015
^{68}Ni Rossi PRL2013

Constraints on J and L



Tsang PRC2012

HIC: Heavy Ion Collision Analysis
Tsang PRL2009

IAS: Isobaric Analog State Energy
Danielewicz&Lee NPA2009

PDR: Pygmy Dipole Resonance in
^{132}Sn, ^{68}Ni, Carbone PRC2010

FRDM: Finite Range Droplet Model
Moller PRL2012

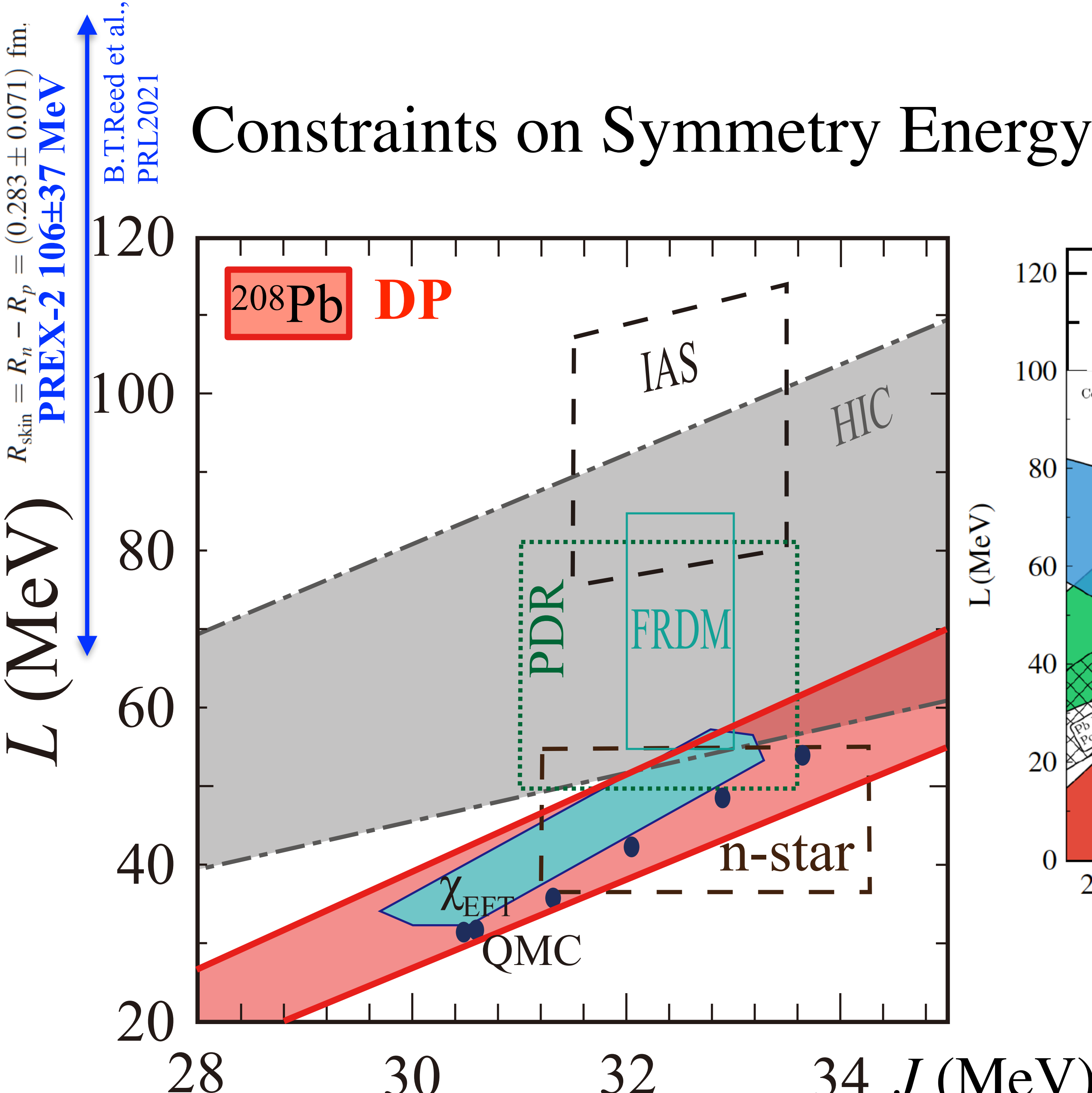
n-star: Quiescent Low-Mass X-ray
Binaries, Stainer PRL2012

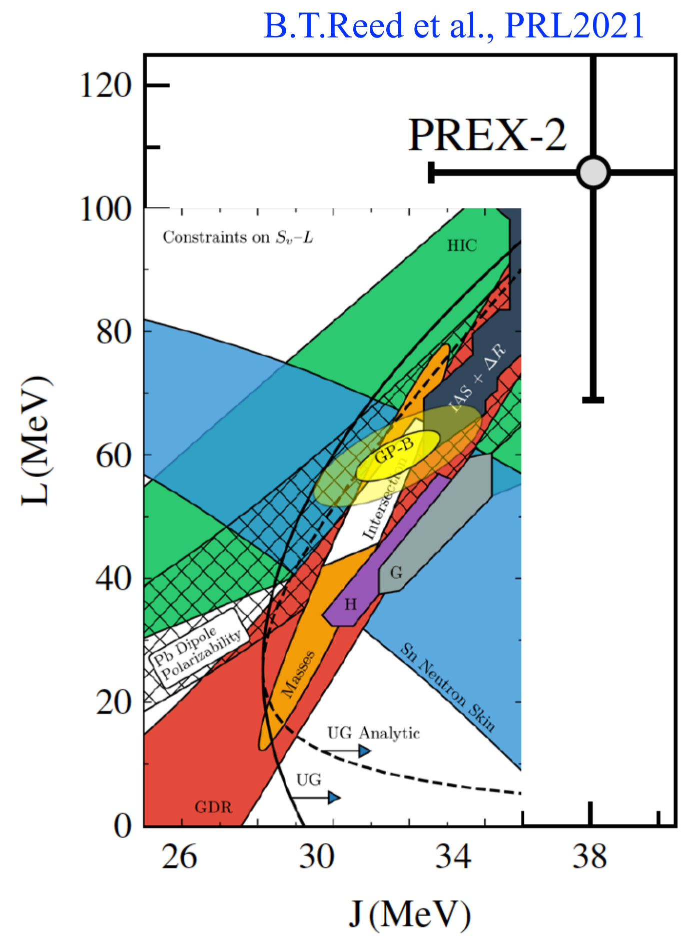
χ_{EFT}: Chiral Effective Field Theory,
Tews PRL2013

QMC: Quantum Monte-Carlo Calc.
Gandolfi, EPJA50, 10(2014).

DP: Dipole Polarizability
^{208}Pb AT PRL2011

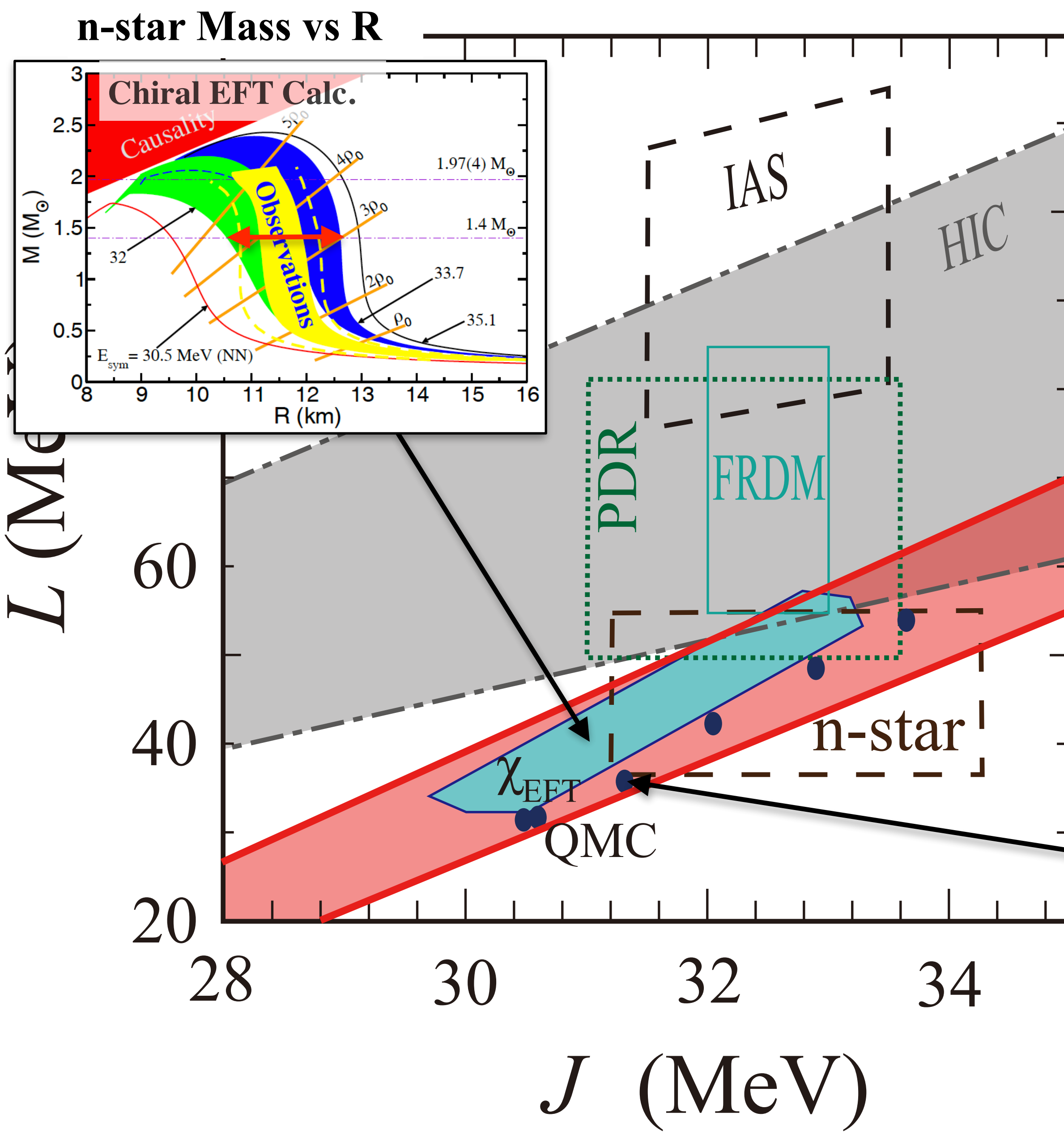
Constraints on Symmetry Energy (J and L)





DP: Dipole Polarizability
^{208}Pb AT PRL2011

Constraints on Symmetry Energy (J and L)



Tsang PRC2012

HIC: Heavy Ion Collision Analysis
Tsang PRL2009

IAS: Isobaric Analog State Energy
Danielewicz&Lee NPA2009

PDR: Pygmy Dipole Resonance in
^{132}Sn, ^{68}Ni, Carbone PRC2010

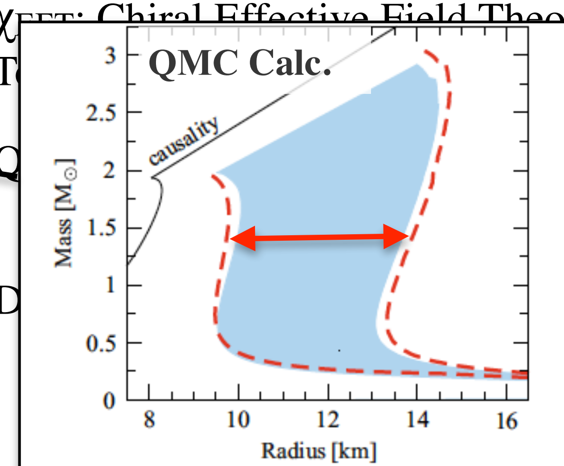
FRDM: Finite Range Droplet Model
Moller PRL2012

n-star: Quiescent Low-Mass X-ray
Binaries, Stainer PRL2012

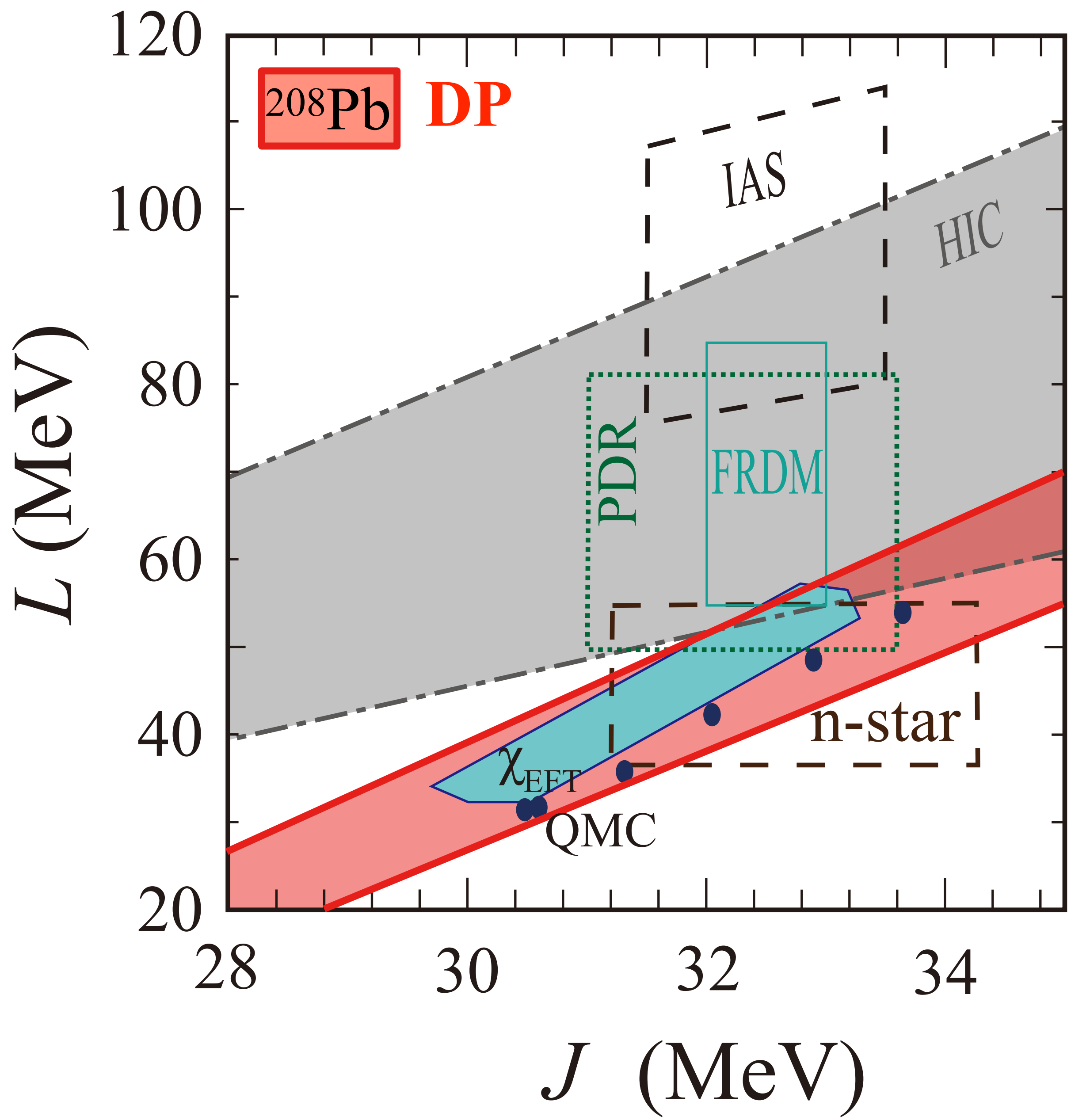
χ_{EFT}: Chiral Effective Field Theory,
T

Q c.

D



Constraints on Symmetry Energy (J and L)



Tsang PRC2012

HIC: Heavy Ion Collision Analysis
Tsang PRL2009

IAS: Isobaric Analog State Energy
Danielewicz&Lee NPA2009

PDR: Pygmy Dipole Resonance in
^{132}Sn, ^{68}Ni, Carbone PRC2010

FRDM: Finite Range Droplet Model
Moller PRL2012

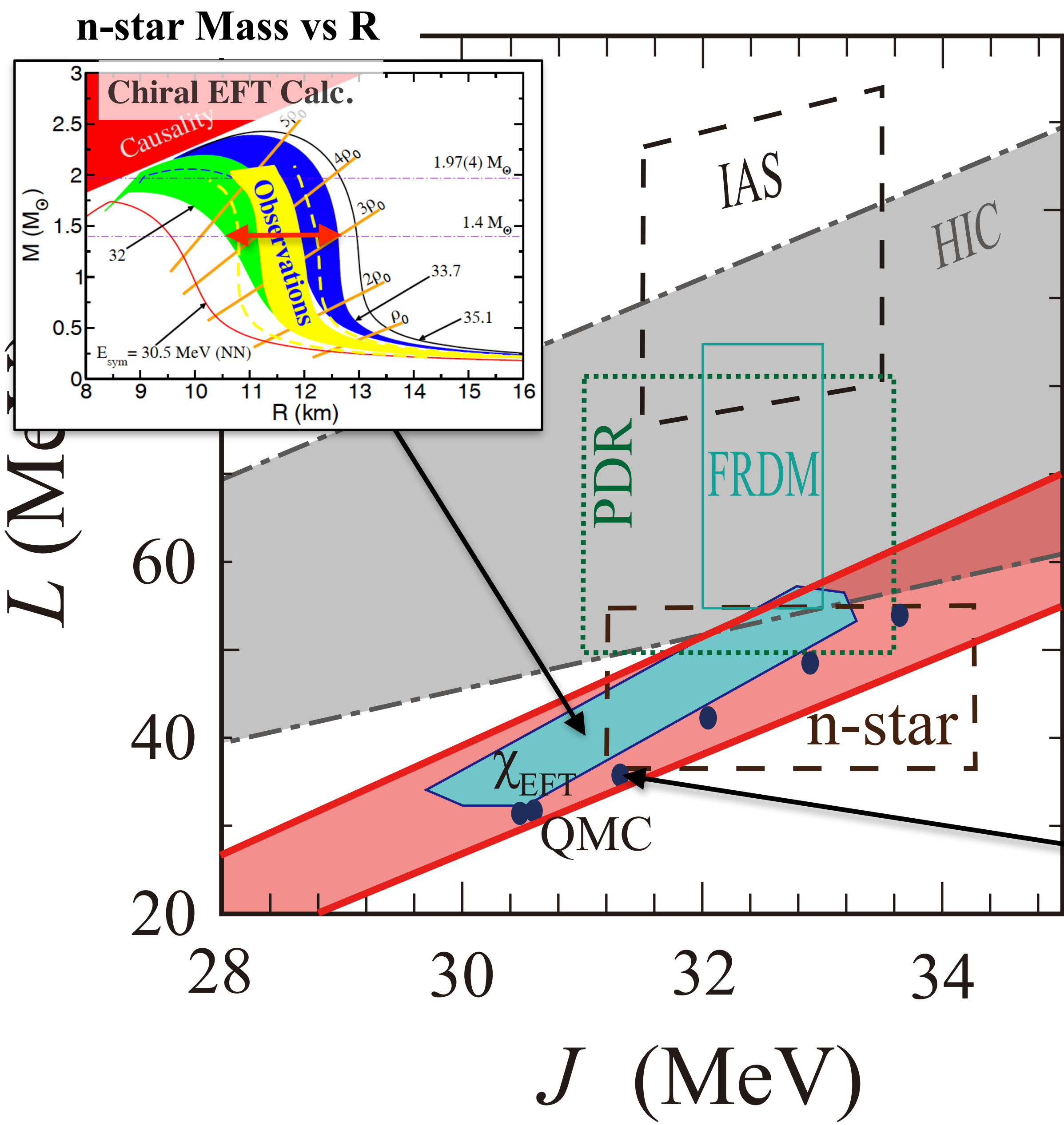
n-star: Quiescent Low-Mass X-ray
Binaries, Stainer PRL2012

χ_{EFT}: Chiral Effective Field Theory,
Tews PRL2013

QMC: Quantum Monte-Carlo Calc.
Gandolfi, EPJA50, 10(2014).

DP: Dipole Polarizability
^{208}Pb AT PRL2011

Constraints on Symmetry Energy (*J* and *L*)



Tsang PRC2012

HIC: Heavy Ion Collision Analysis
Tsang PRL2009

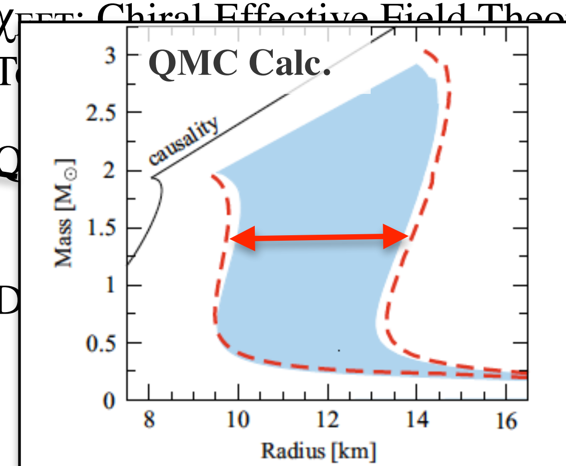
IAS: Isobaric Analog State Energy
Danielewicz&Lee NPA2009

PDR: Pygmy Dipole Resonance in
^{132}Sn, ^{68}Ni, Carbone PRC2010

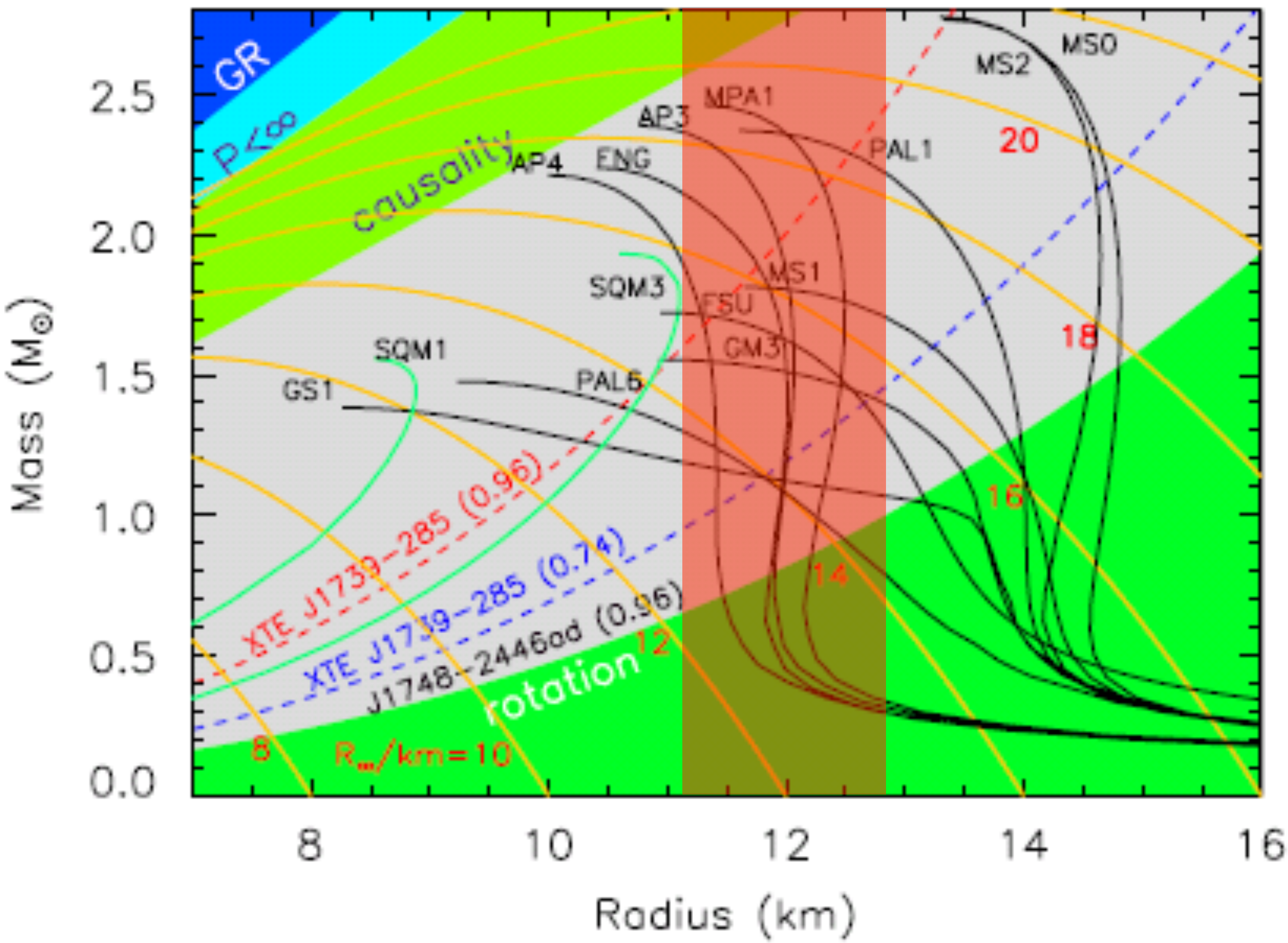
FRDM: Finite Range Droplet Model
Moller PRL2012

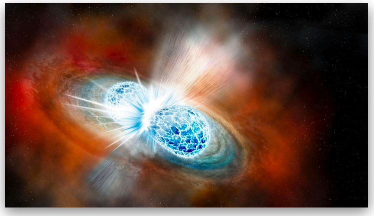
n-star: Quiescent Low-Mass X-ray
Binaries, Stainer PRL2012

χ_{EFT}: Chiral Effective Field Theory,



Neutron Star Mass-Radius Relation

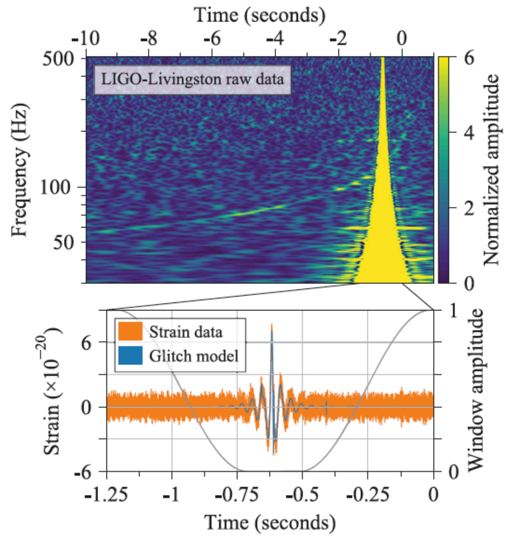


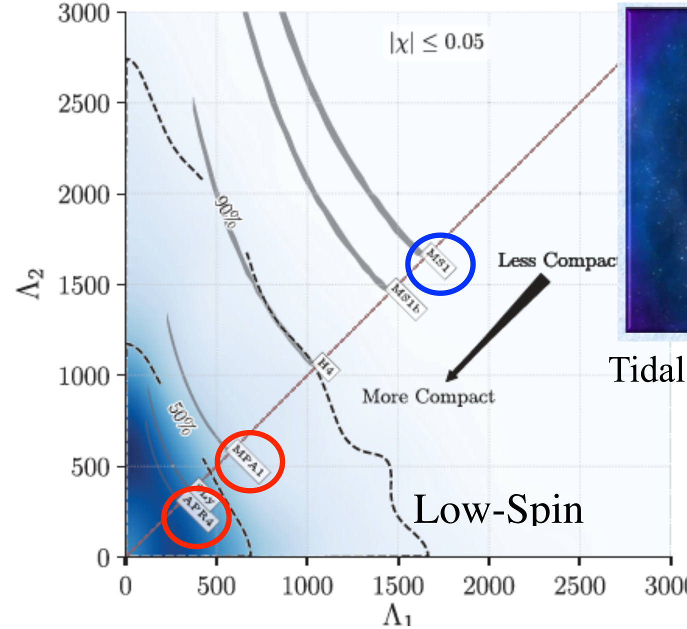


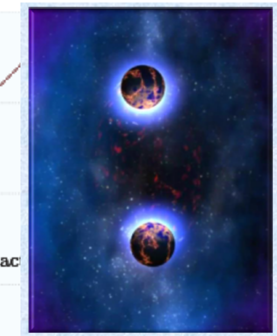
Neutron Star Merger GW170817

GW170817, PRL119, 161101(2017)

LIGO







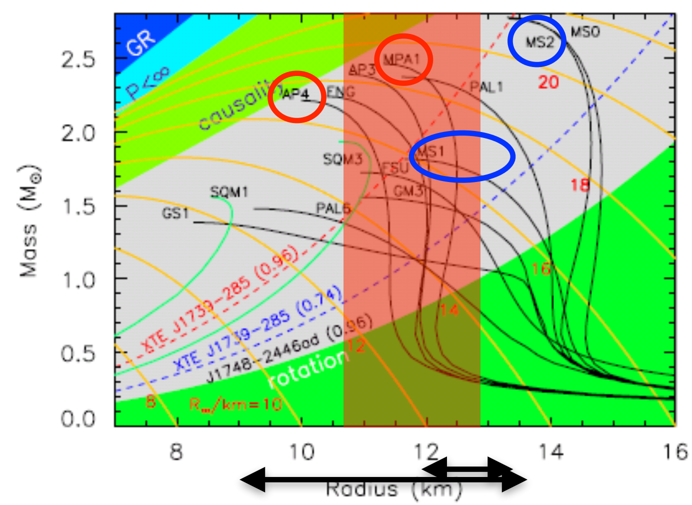
Tidal Deformation

12.00 < $R^{1.4}$ < 13.45 km

E.R. Most et al., PRL120, 261103(2018)

9.0 < $R^{1.4}$ < 13.6 km

I. Tews et al.,



N-star merger GW analysis is giving constraints on the nuclear EOS that are consistent with the study of atomic nuclei.

Further constrains are anticipated both from nuclear physics experiments and from gravitational wave observations.