The Nuclear Symmetry Energy:
new directions from new results?

W. Trautmann, GSI Helmholtzzentrum
64291 Darmstadt, Germany

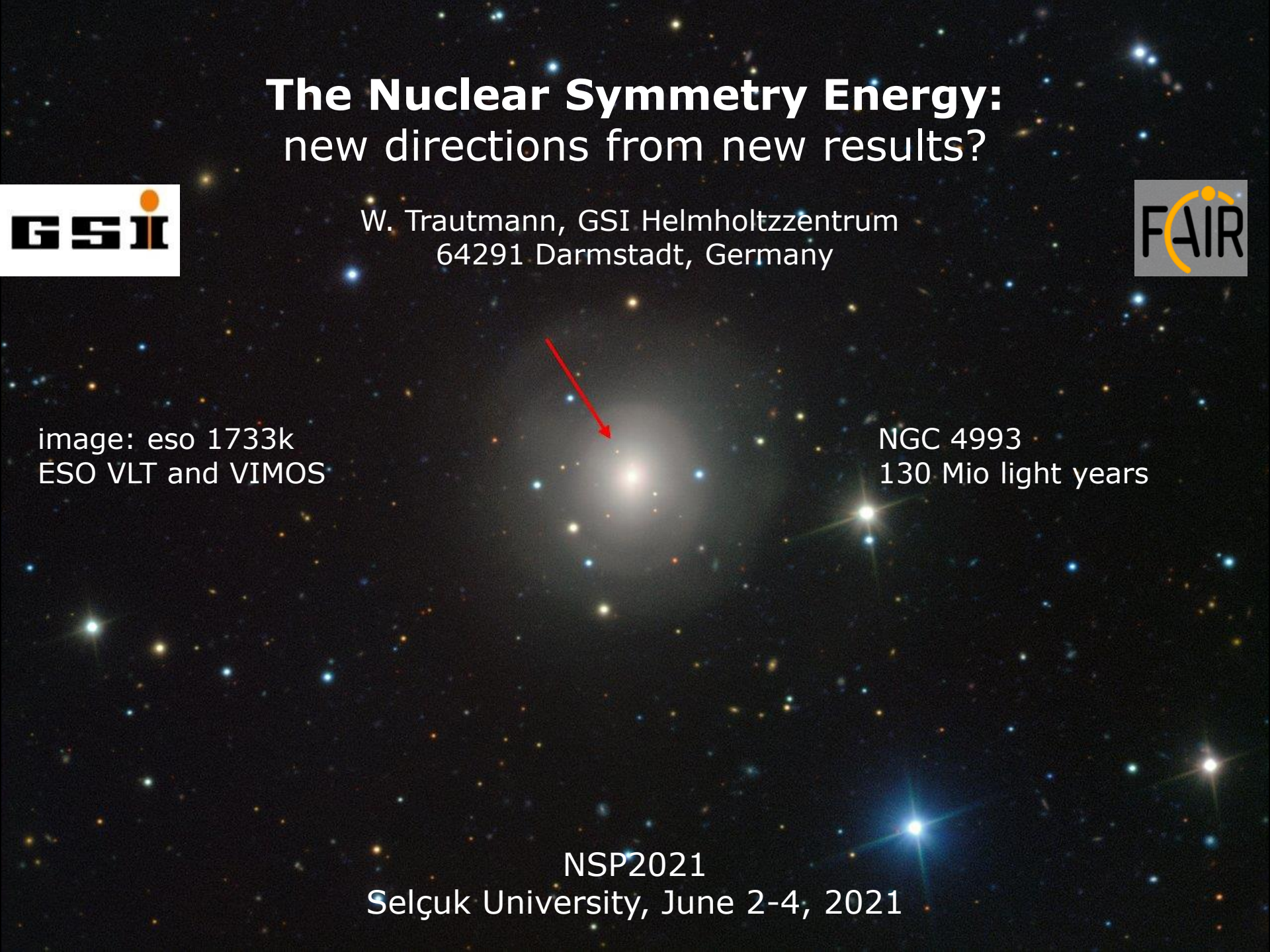


image: eso 1733k
ESO VLT and VIMOS

NGC 4993
130 Mio light years

NSP2021
Selçuk University, June 2-4, 2021

GW170817

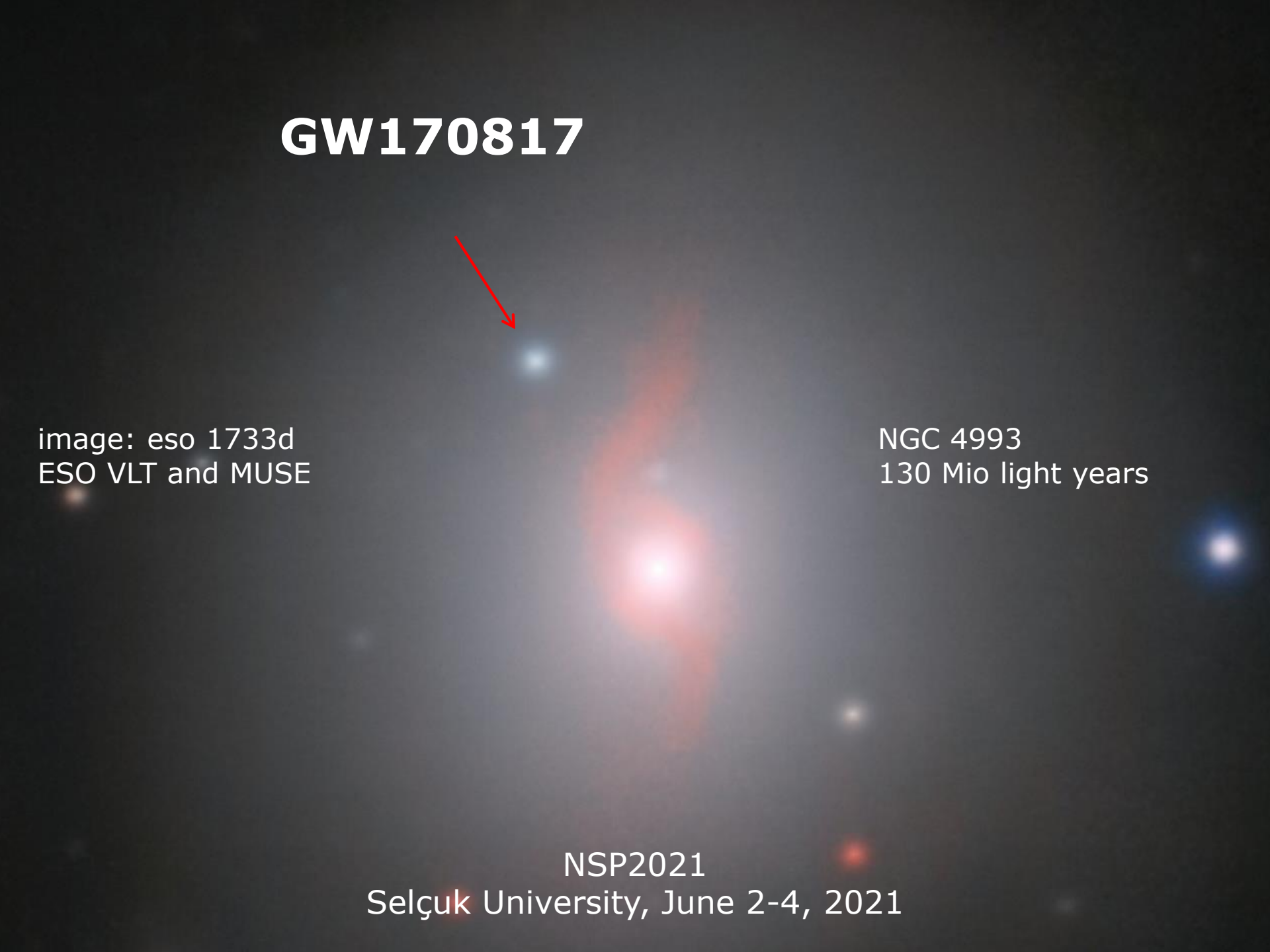


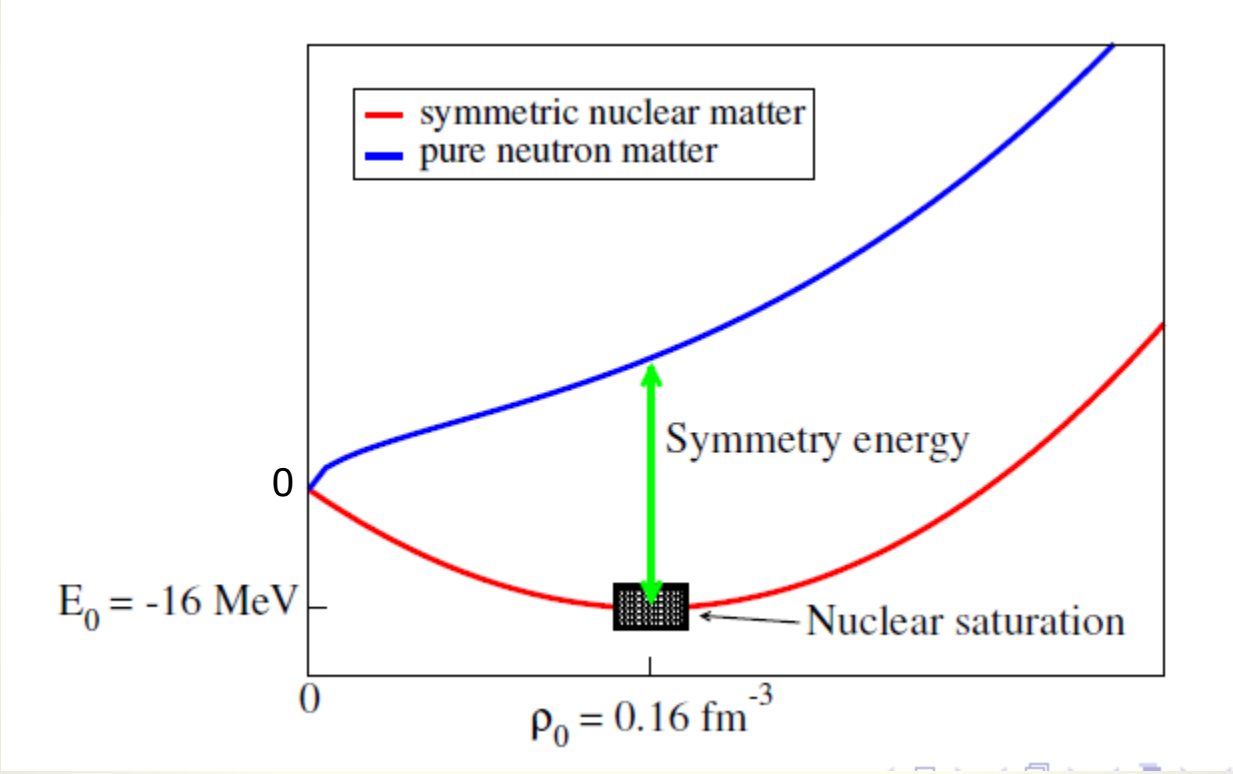
image: eso 1733d
ESO VLT and MUSE

NGC 4993
130 Mio light years

NSP2021
Selçuk University, June 2-4, 2021

Nuclear Equation of State (EoS)

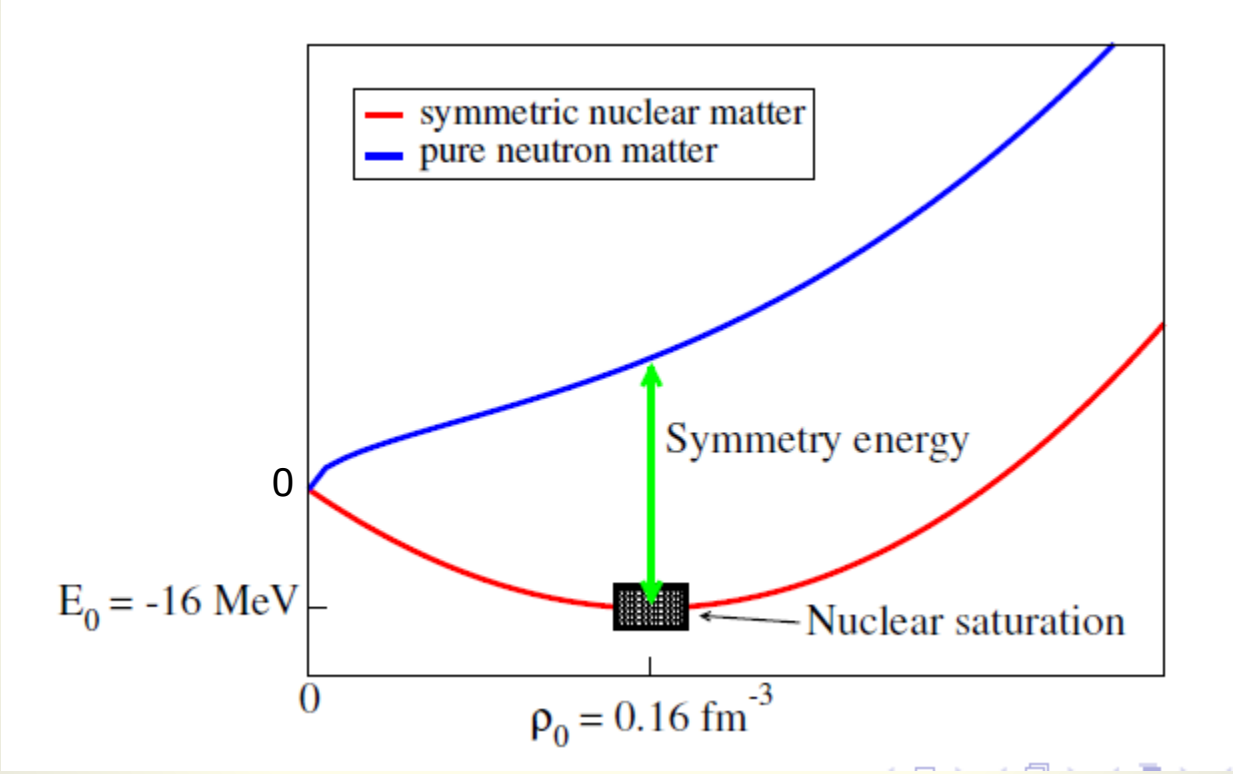
from a talk of Stefano Gandolfi



Nuclear Equation of State (EoS)

asymmetry $\delta = (\rho_n - \rho_p)/\rho$

from a talk of Stefano Gandolfi



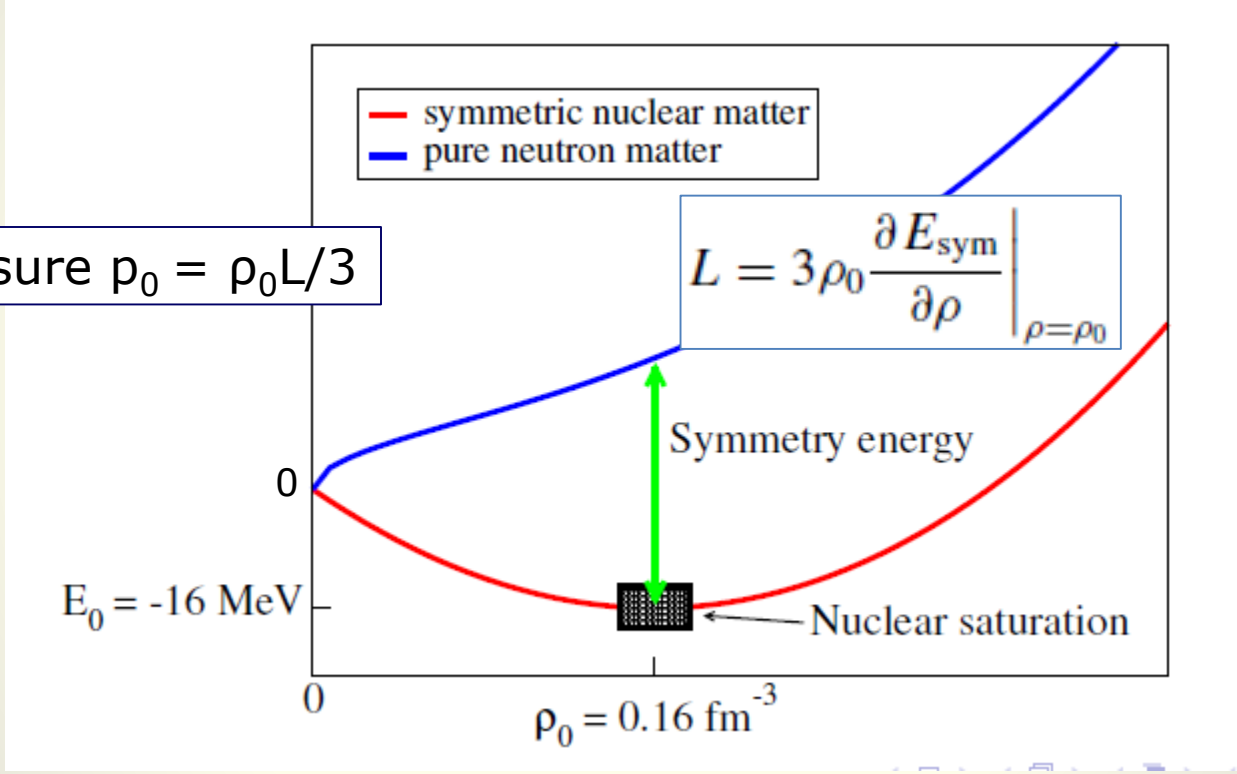
$$E_A(\rho,\delta) = E_A(\rho,0) + \mathbf{E_{sym}(\rho) \cdot \delta^2} + O(\delta^4)$$

Nuclear Equation of State (EoS)

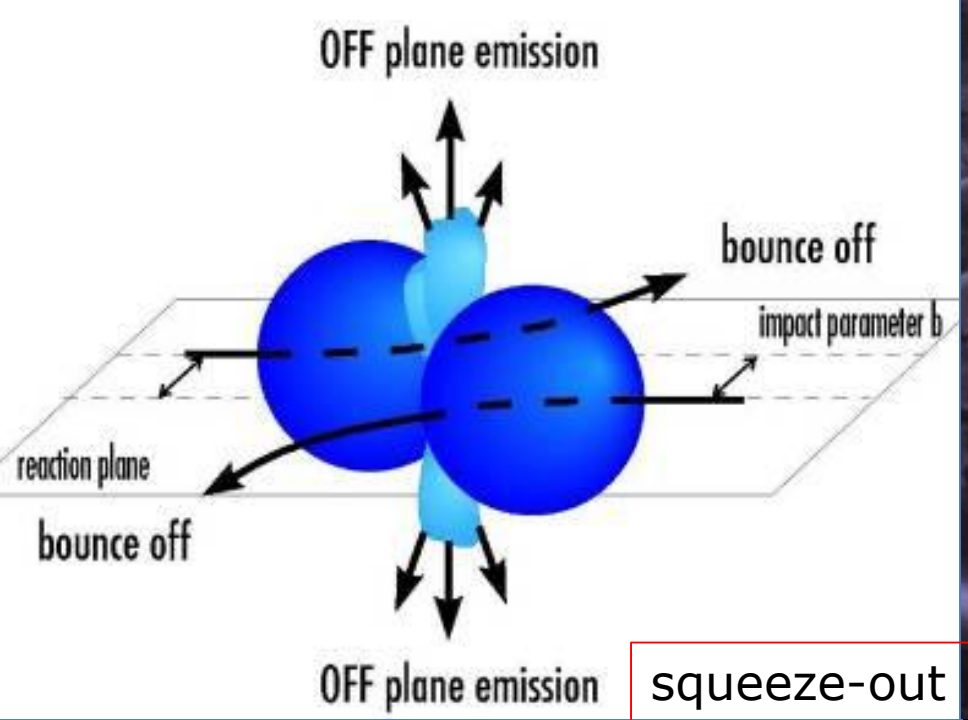
from a talk of Stefano Gandolfi

asymmetry $\delta = (\rho_n - \rho_p)/\rho$

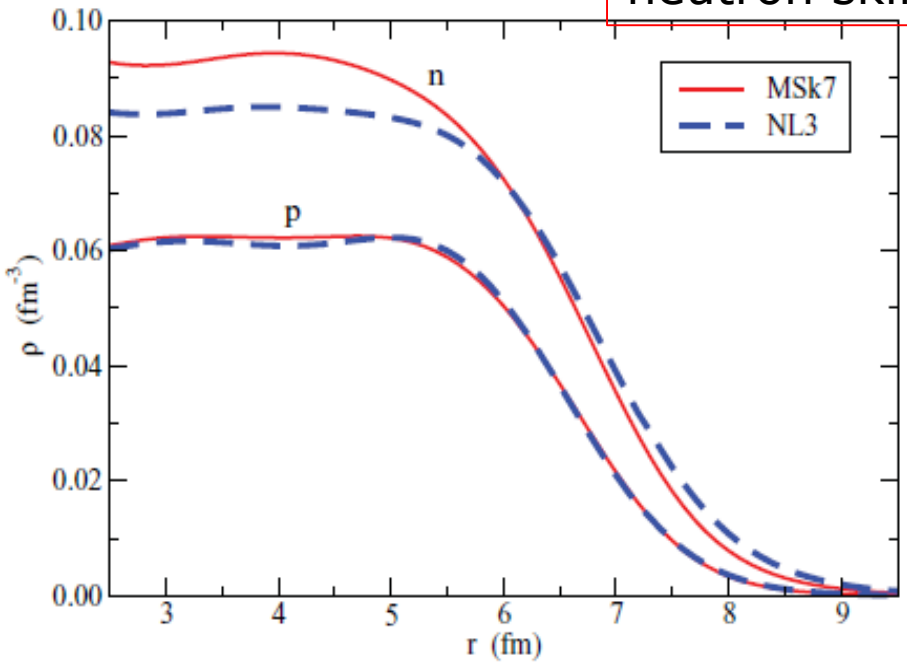
pressure $p_0 = \rho_0 L/3$

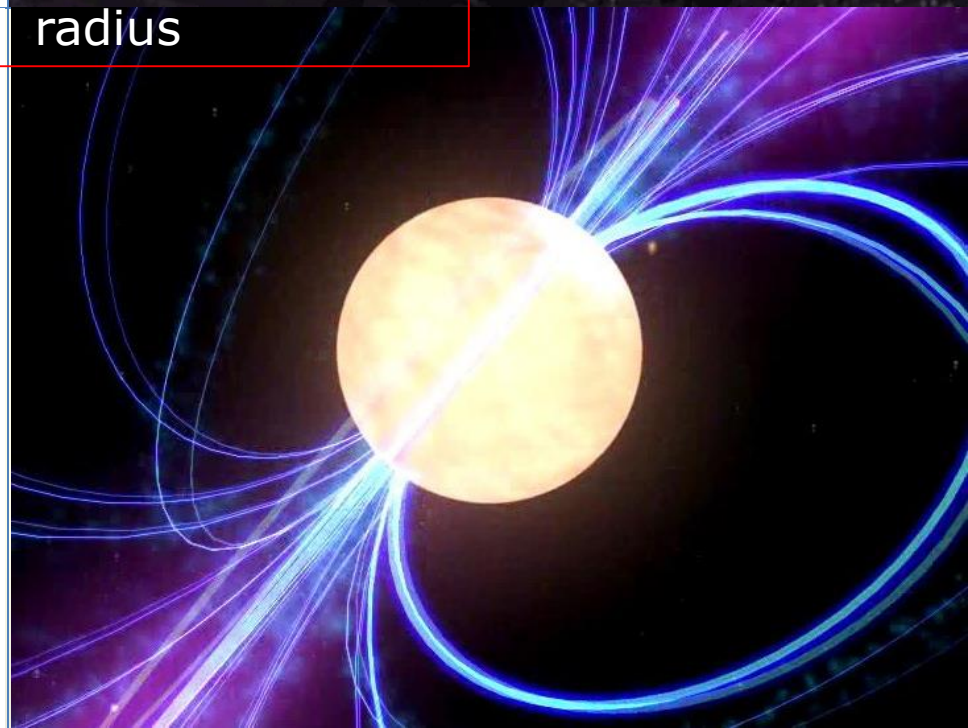


$$E_A(\rho,\delta) = E_A(\rho,0) + \mathbf{E_{sym}(\rho) \cdot \delta^2} + O(\delta^4)$$



squeeze-out tidal deformation
neutron skin radius

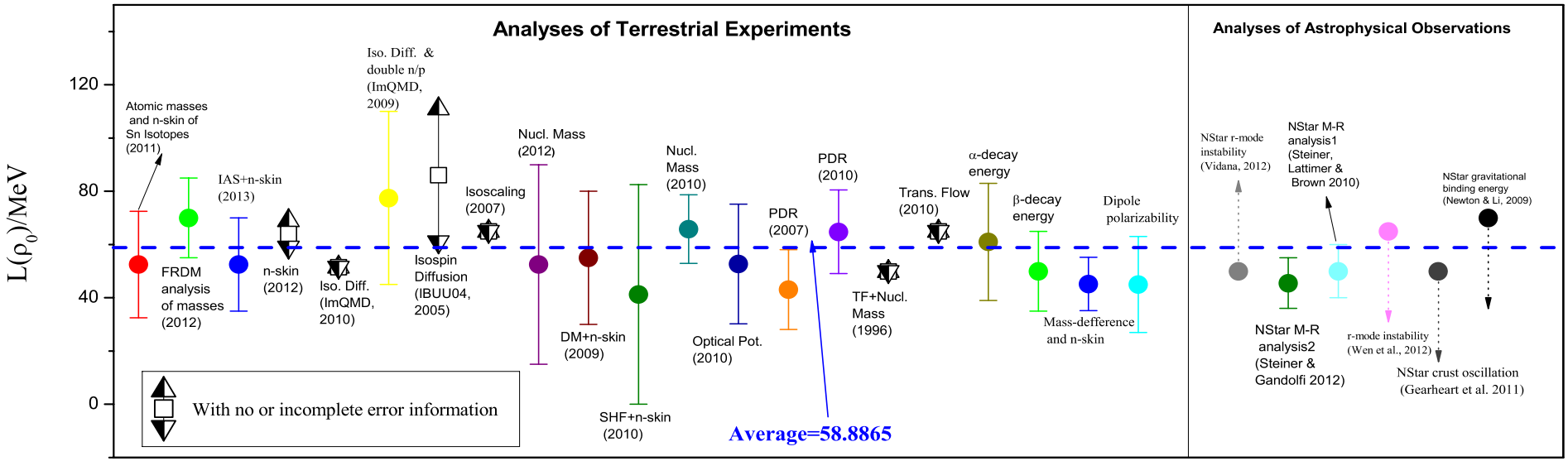




the world average in 2013: L = 58.8865 MeV

Li and Han, PLB 727 (2013)

$(L=3p_0/\rho_0)$



observation of neutron stars

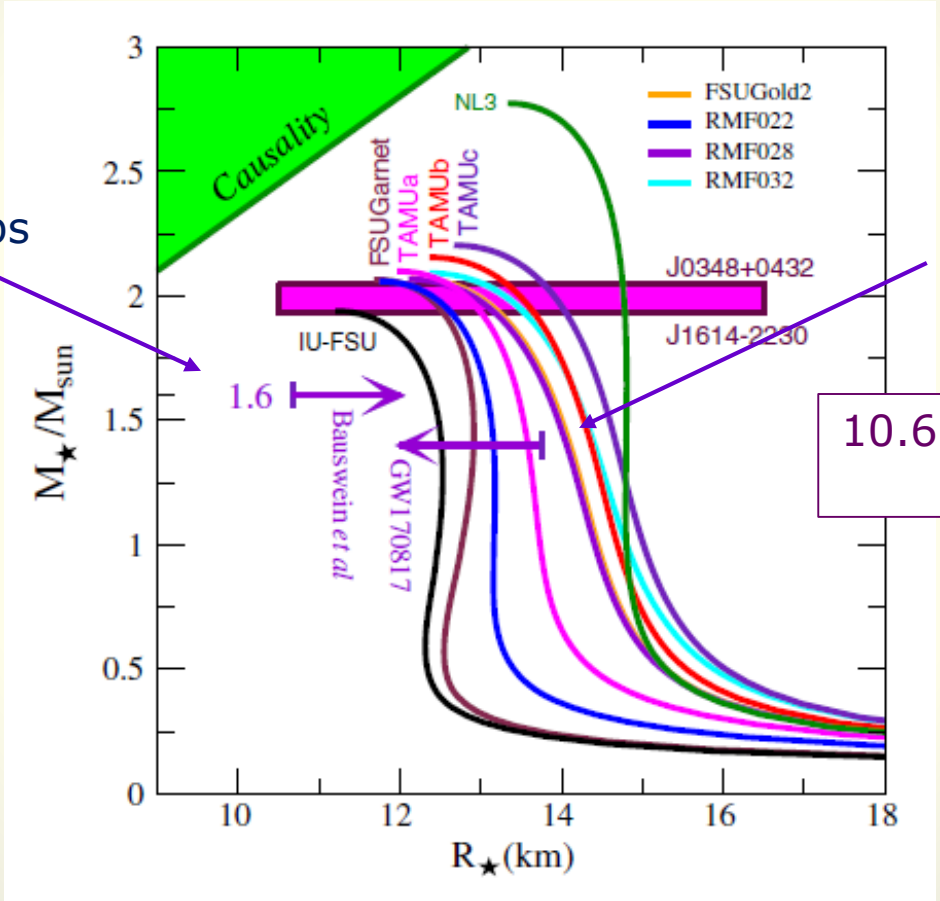
neutron skins
masses
collective excitations
isospin diffusion

crust oscillations
r-mode instabilities
mass-radius analysis

GW170817: pre- and post-merger dynamics

Bauswein et al.:
max mass +
no prompt collaps

ApJL 850 (2017)



Fattoyev et al.:
max mass +
tidal deformability

PRL 120 (2018)

10.6 km < R < 13.8 km

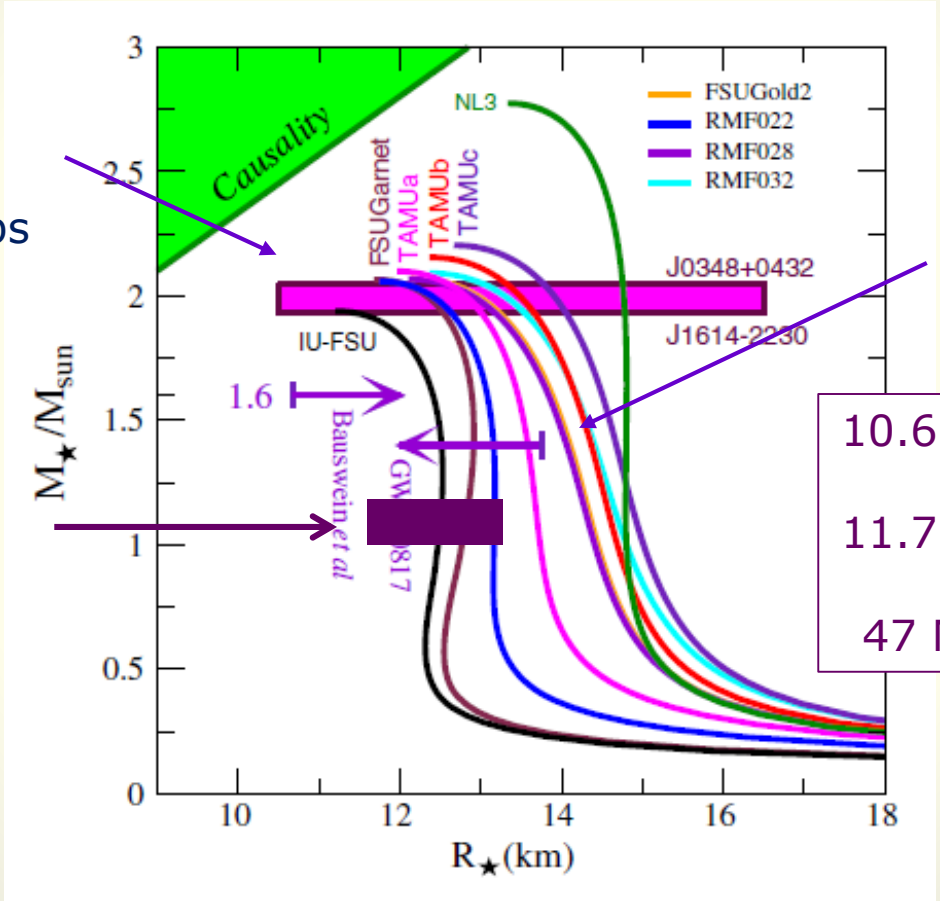
from: Fattoyev et al., PRL 120 (2018)

GW170817: pre- and post-merger dynamics

Bauswein et al.:
max mass +
no prompt collaps

ApJL 850 (2017)

refined analysis



Fattoyev et al.:
max mass +
tidal deformability

PRL 120 (2018)

10.6 km < R < 13.8 km

11.7 km < R < 13.3 km

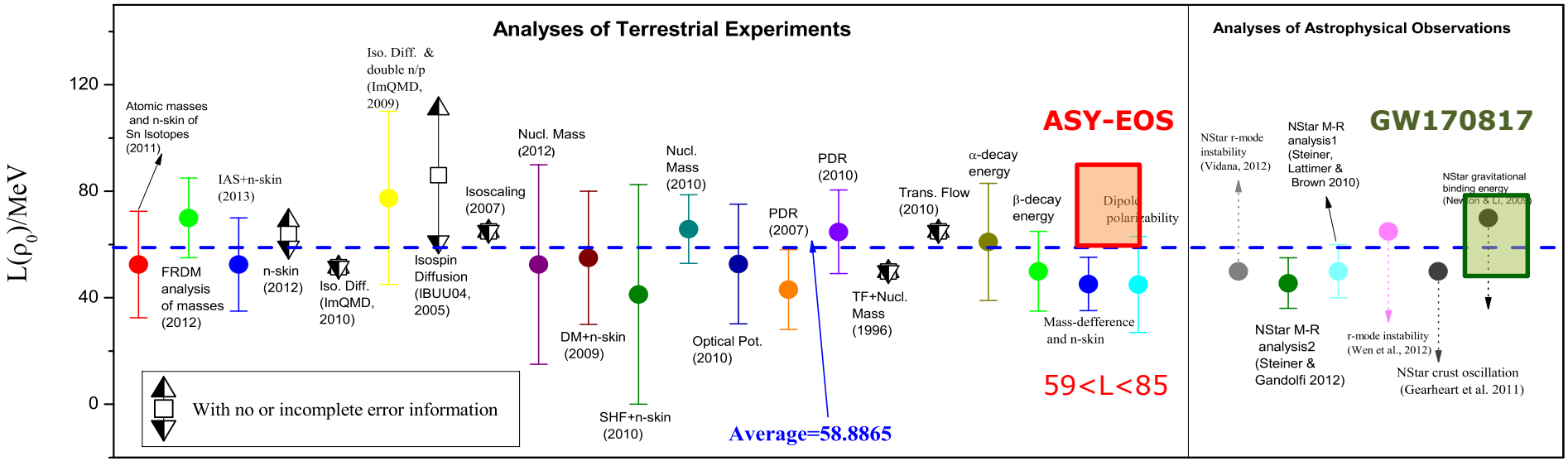
47 MeV < L < 78 MeV

from: Fattoyev et al., PRL 120 (2018)

the world average in 2013: L = 58.8865 MeV

Li and Han, PLB 727 (2013)

$(L=3p_0/\rho_0)$

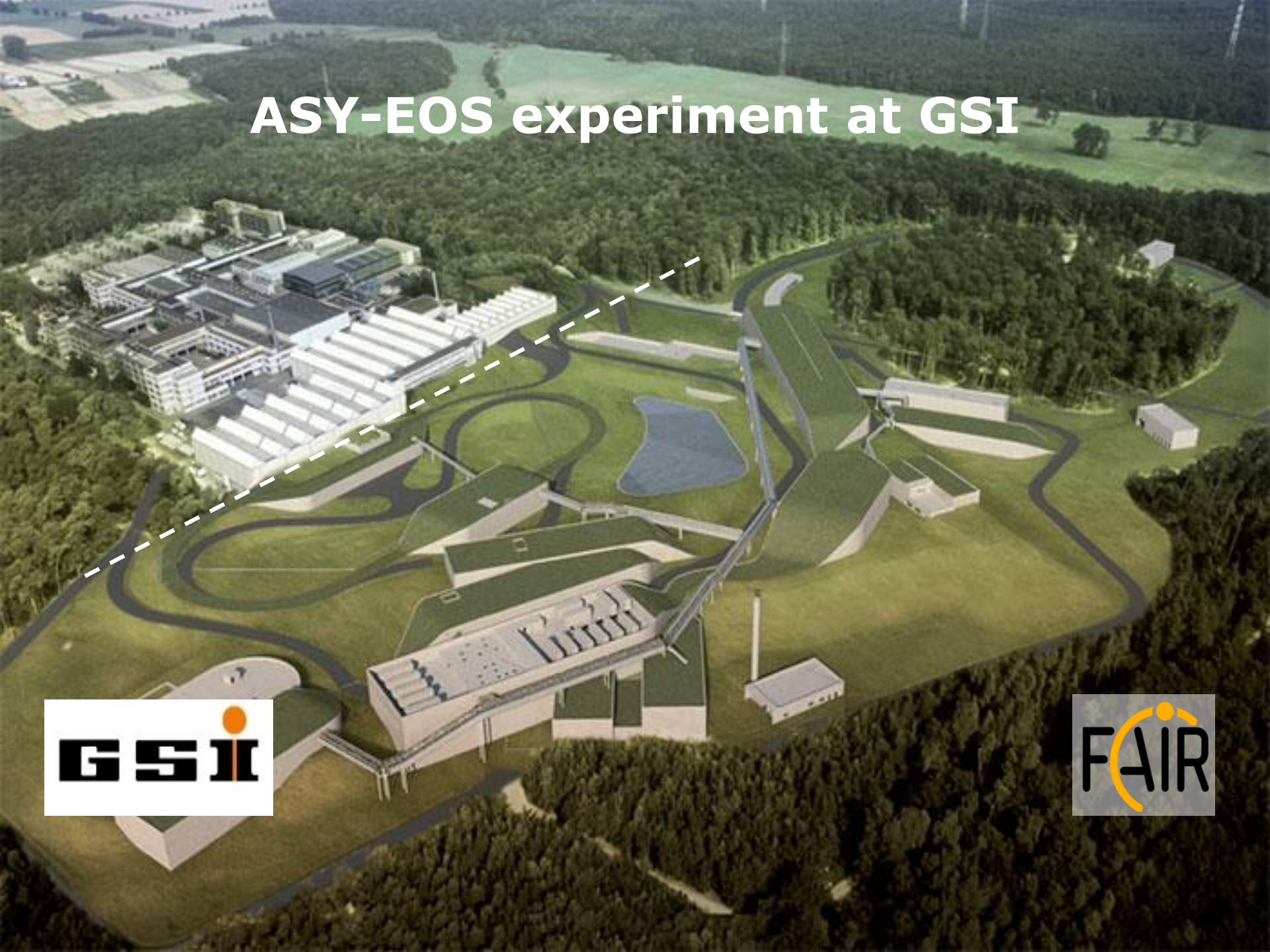


observation of neutron stars

neutron skins
masses
collective excitations
isospin diffusion

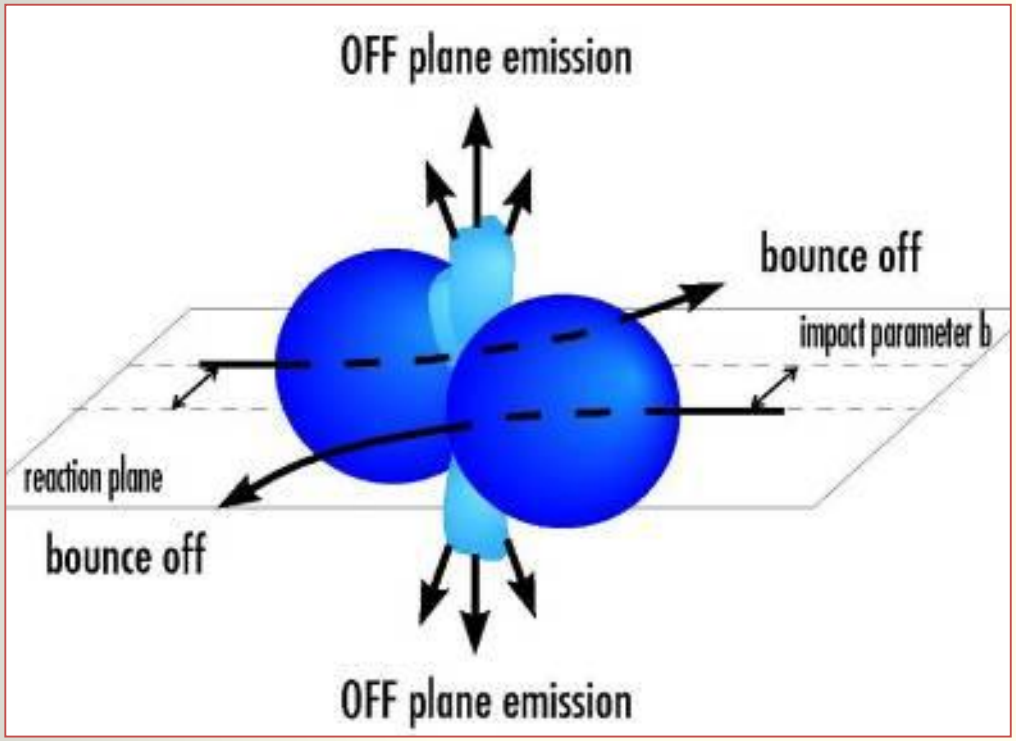
crust oscillations
r-mode instabilities
mass-radius analysis

ASY-EOS experiment at GSI



ASY-EOS: pressure gauge for neutron-star matter

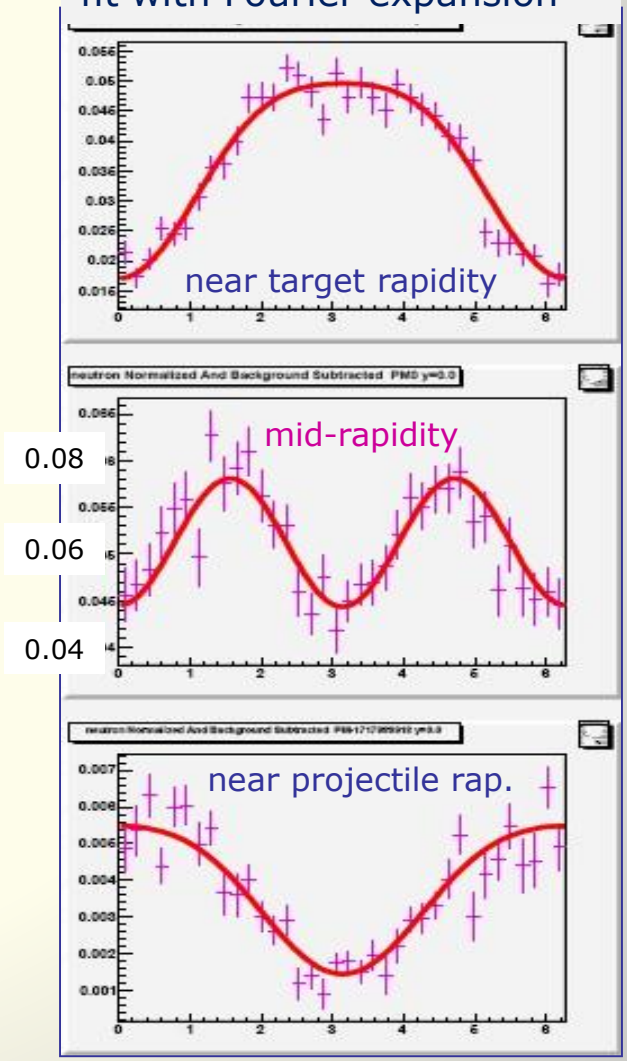
Buchwald/Frankfurt

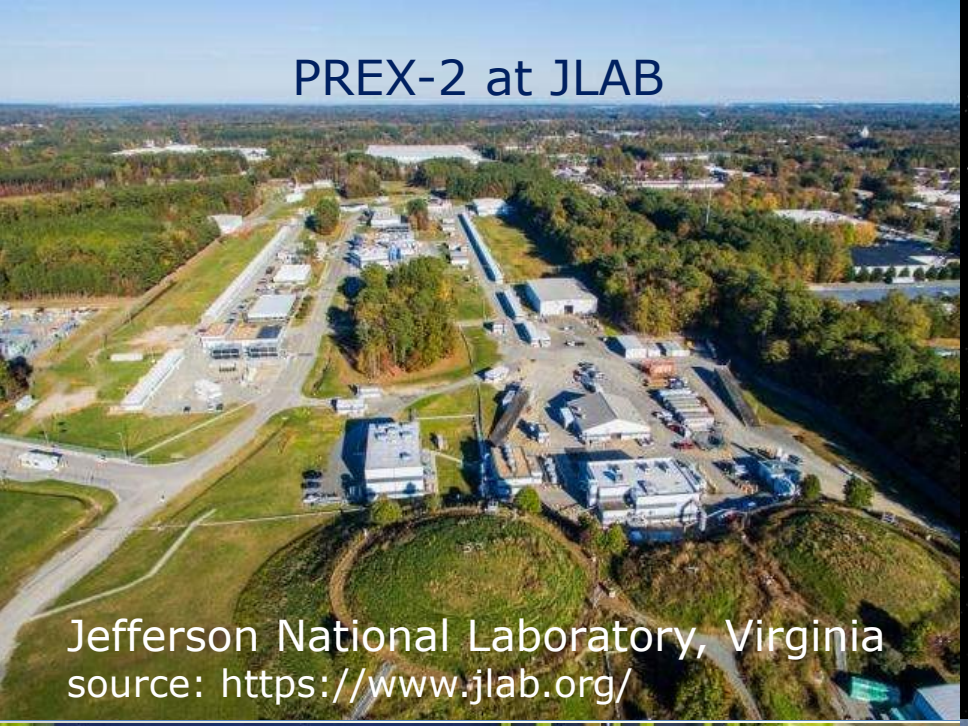


ASY-EOS experiment in 2011
^{197}Au + ^{197}Au @ 400 A MeV
Russotto et al., PRC 94 (2016)

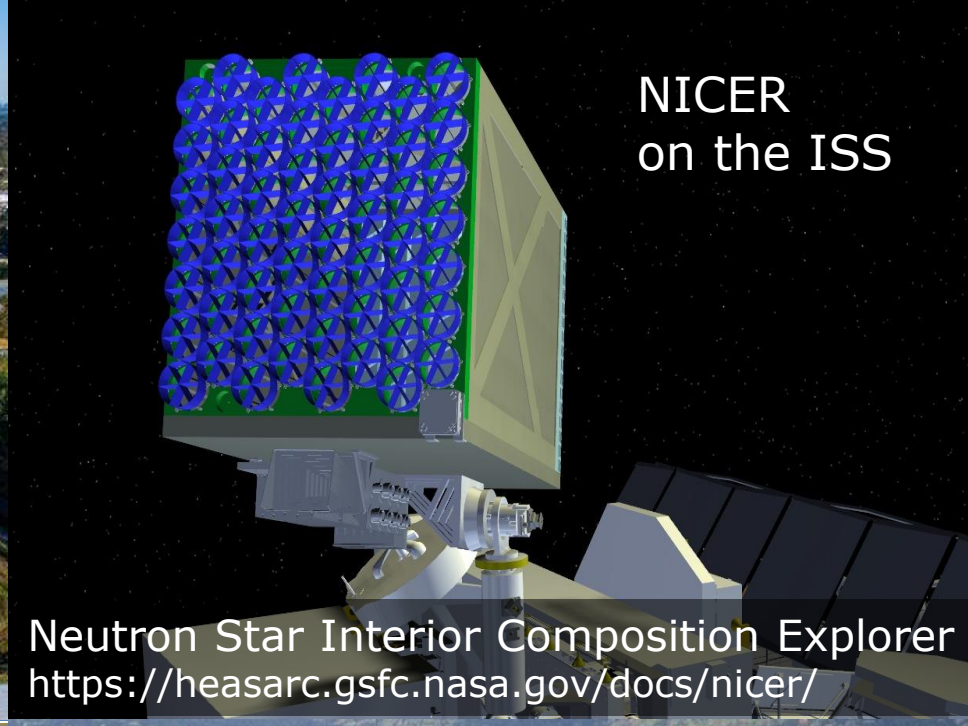
L=72±13 MeV

neutrons (FOPI-LAND)
fit with Fourier expansion

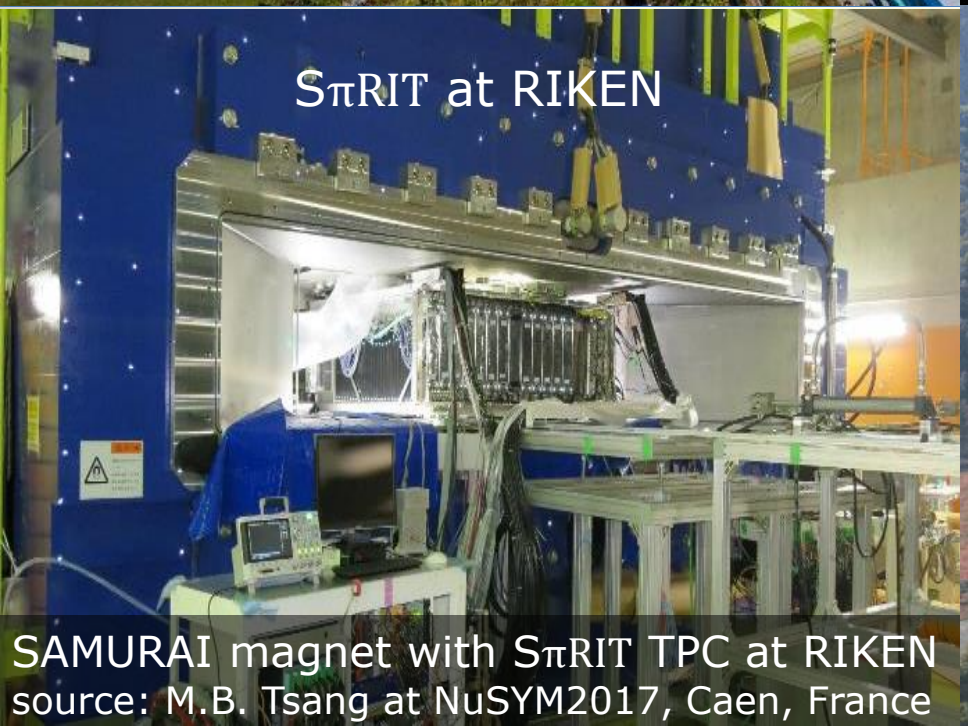




Jefferson National Laboratory, Virginia
source: https://www.jlab.org/



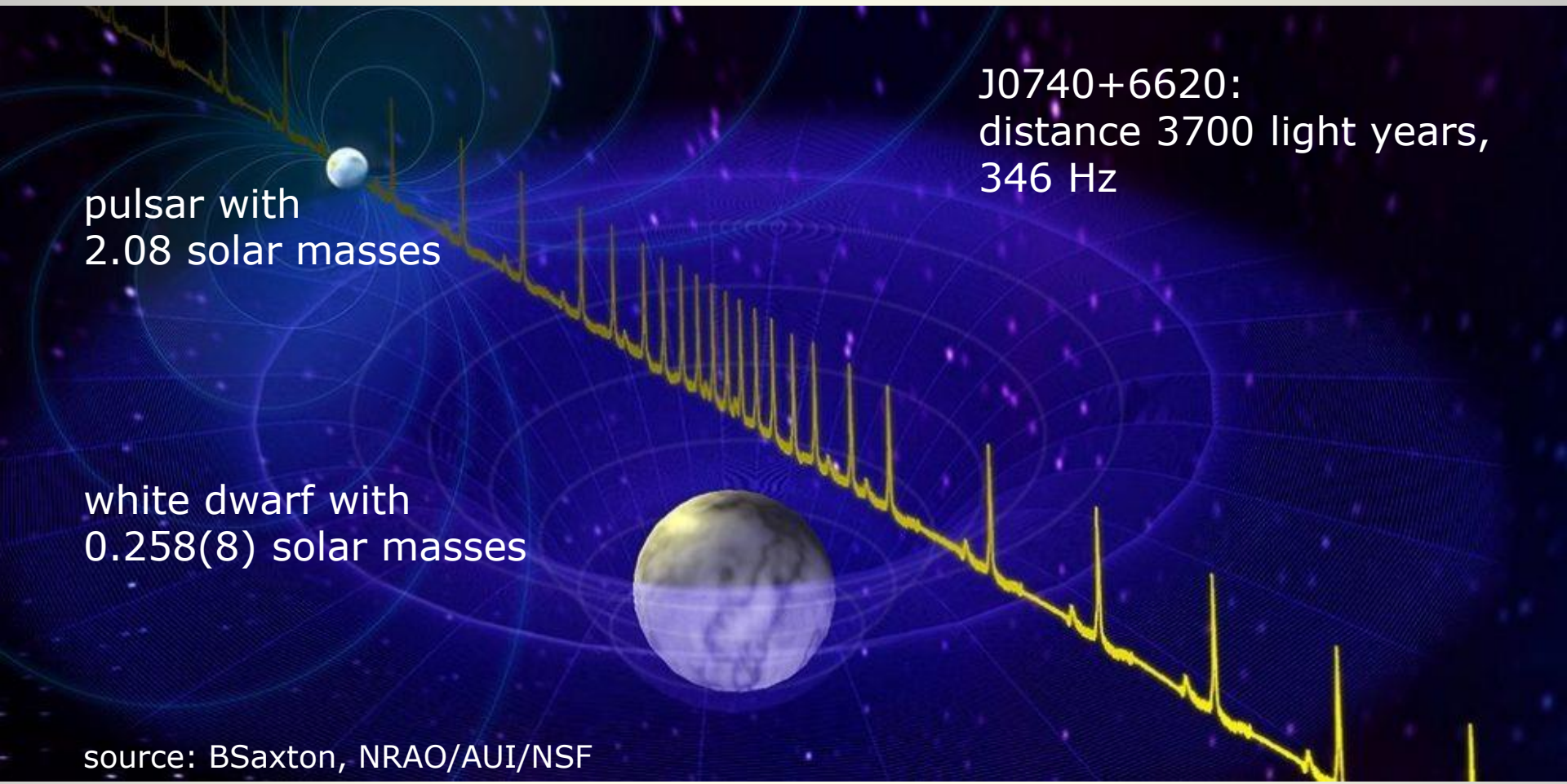
Neutron Star Interior Composition Explorer
https://heasarc.gsfc.nasa.gov/docs/nicer/



SAMURAI magnet with SπRIT TPC at RIKEN
source: M.B. Tsang at NuSYM2017, Caen, France

Alleghenny mountains, Virginia
source: NRAO/AUI, CC BY 3.0

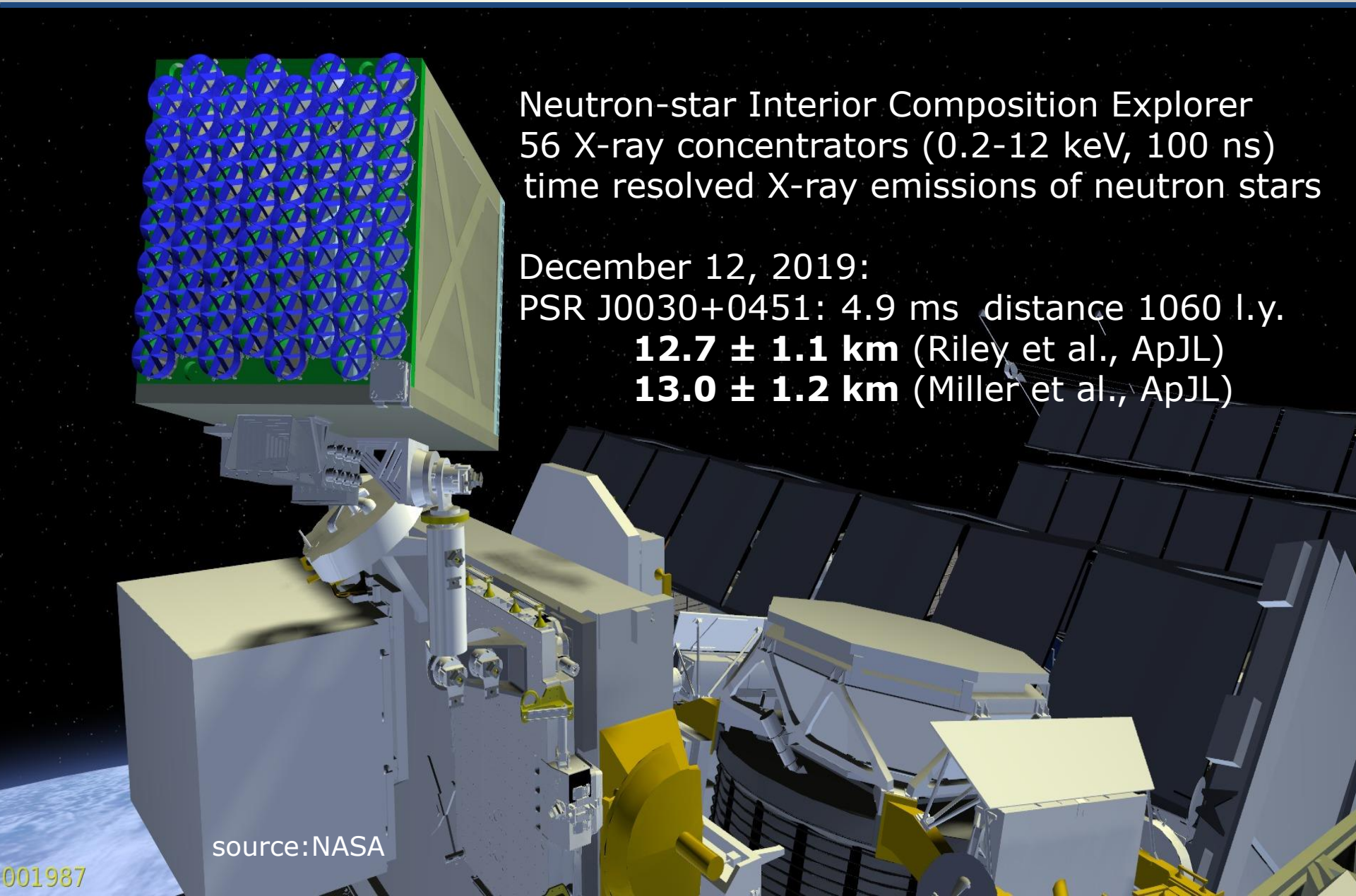
Shapiro time delay



pulsar mass 2.08 ± 0.07 solar masses (68% credibility)
pulsar spin 346.5319964608338(3) Hz

Cromartie+, Nat. Astron., 4, 72; Fonseca+, arXiv:2104.00880

NICER on the ISS



Neutron-star Interior Composition Explorer
56 X-ray concentrators (0.2-12 keV, 100 ns)
time resolved X-ray emissions of neutron stars

December 12, 2019:
PSR J0030+0451: 4.9 ms distance 1060 l.y.
12.7 ± 1.1 km (Riley et al., ApJL)
13.0 ± 1.2 km (Miller et al., ApJL)

Science Measurements

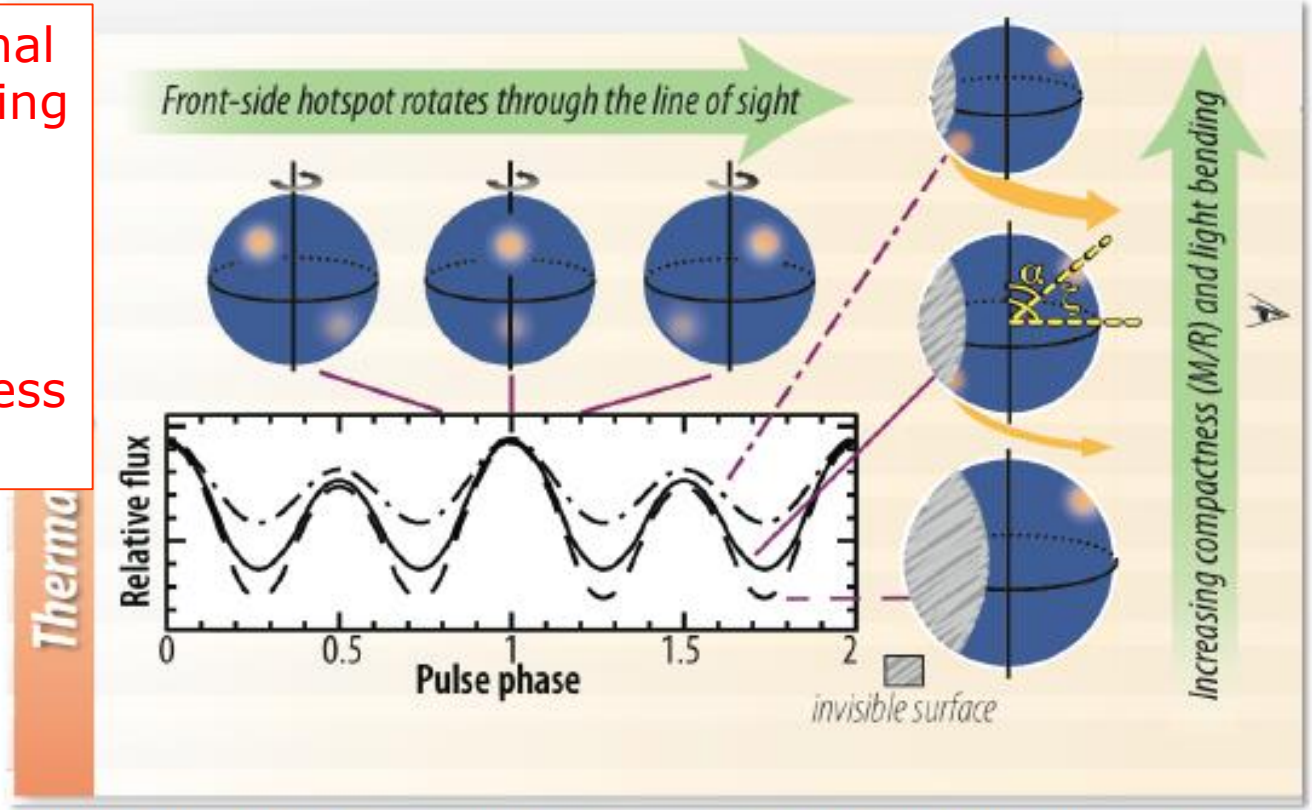
NICER

Reveal stellar structure through lightcurve modeling, long-term timing, and pulsation searches

gravitational light bending

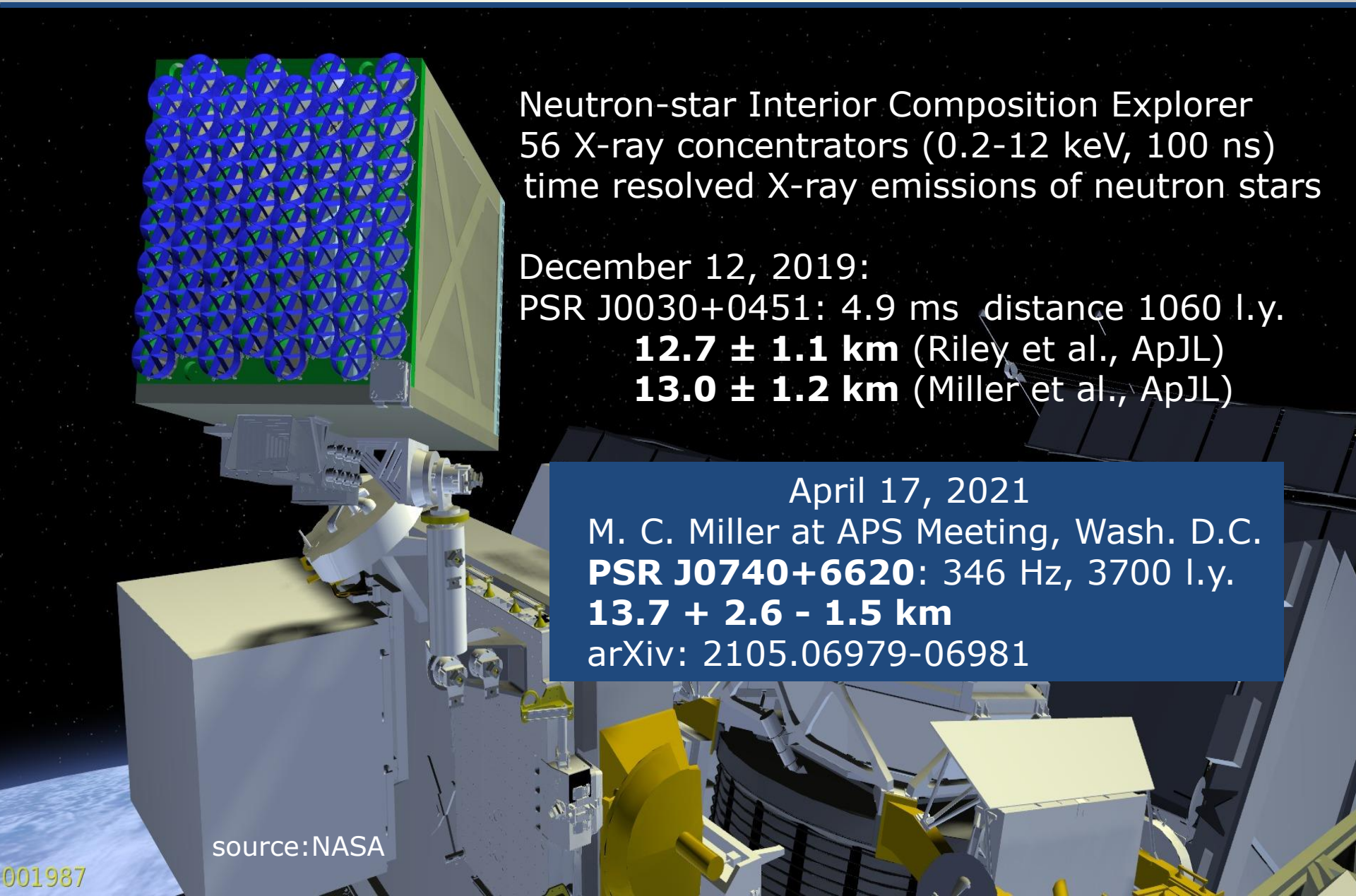
lightcurve modeling

compactness M/R



Lightcurve modeling constrains the compactness (*M/R*) and viewing geometry of a non-accreting millisecond pulsar through the depth of modulation and harmonic content of emission from rotating hot-spots, thanks to gravitational light-bending…

NICER on the ISS



Neutron-star Interior Composition Explorer
56 X-ray concentrators (0.2-12 keV, 100 ns)
time resolved X-ray emissions of neutron stars

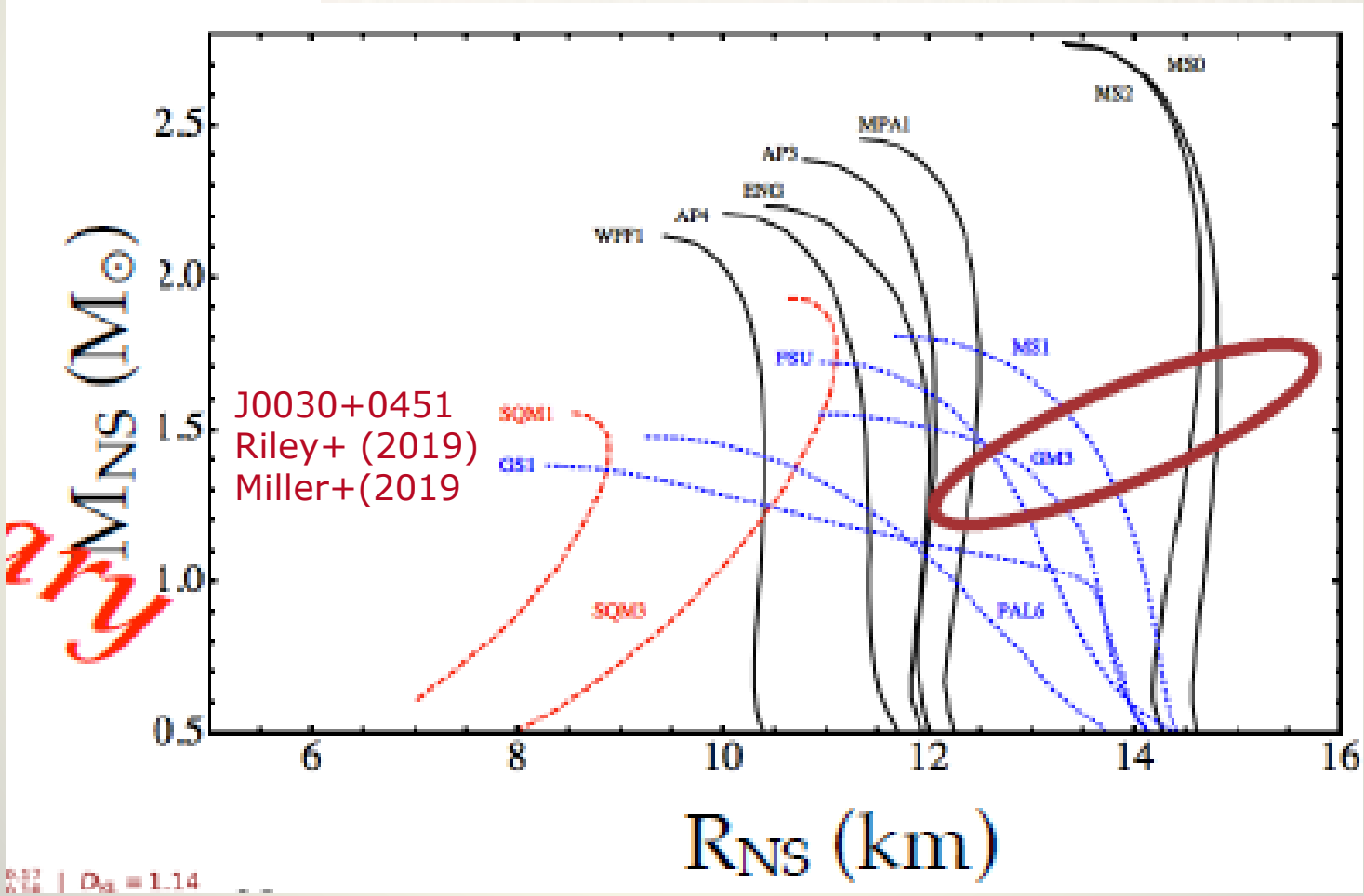
December 12, 2019:
PSR J0030+0451: 4.9 ms distance 1060 l.y.
12.7 ± 1.1 km (Riley et al., ApJL)
13.0 ± 1.2 km (Miller et al., ApJL)

April 17, 2021
M. C. Miller at APS Meeting, Wash. D.C.
PSR J0740+6620: 346 Hz, 3700 l.y.
13.7 + 2.6 - 1.5 km
arXiv: 2105.06979-06981

source:NASA

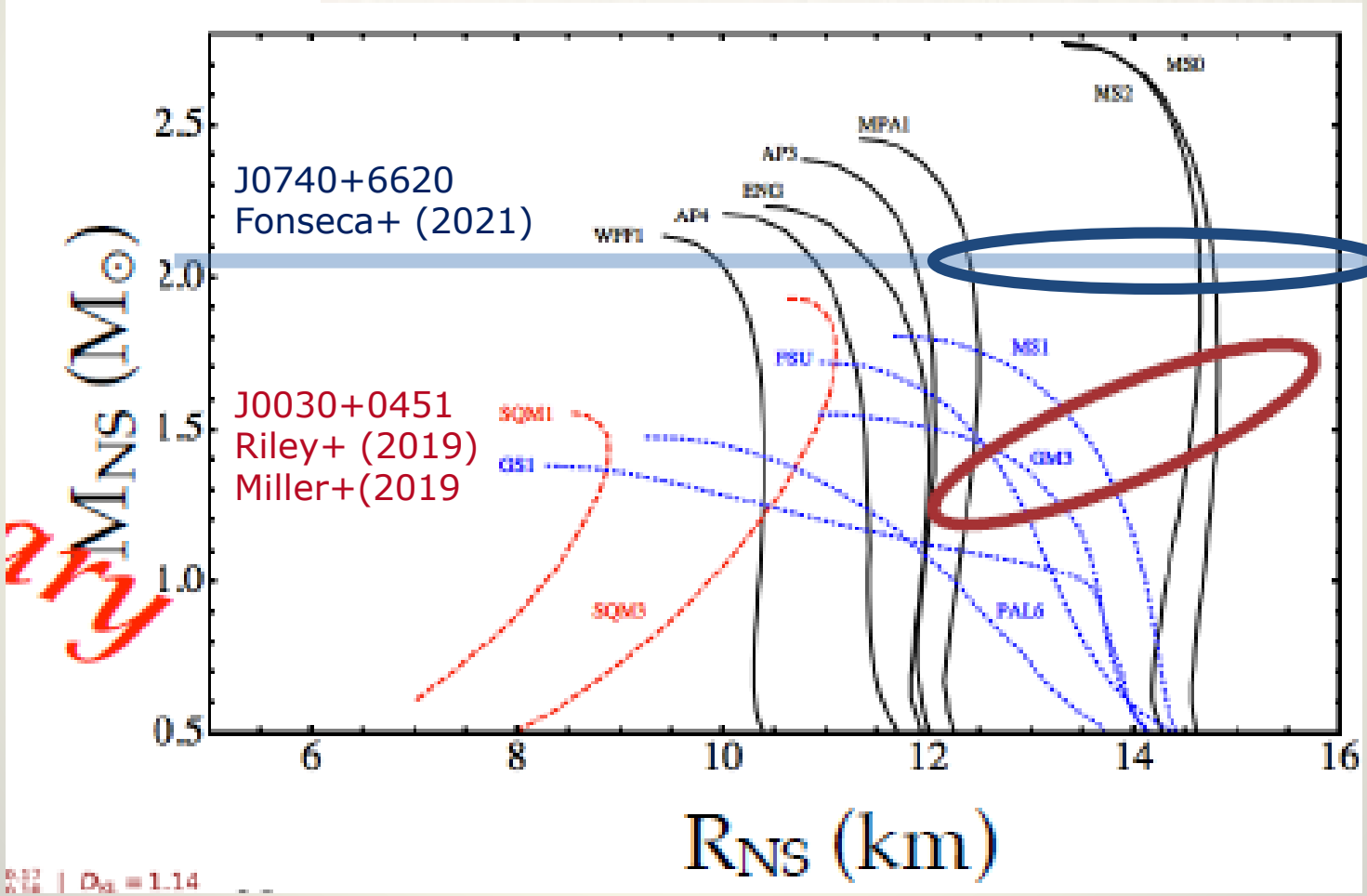
Preliminary results for dual-temperature two polar caps model.

Sebastien Guillot, talk at NuSYM 2019, Da Nang, Vietnam



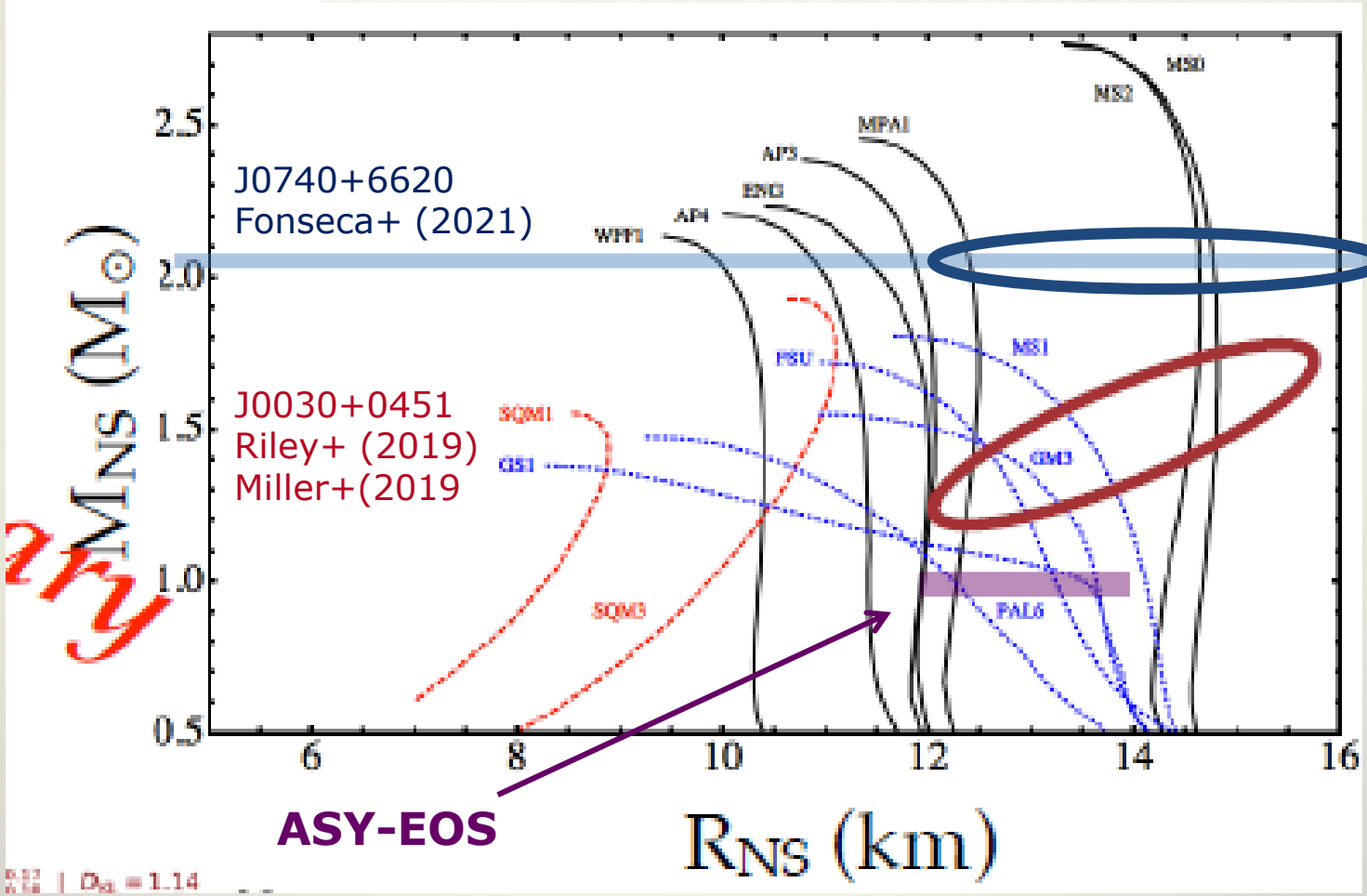
Preliminary results for dual-temperature two polar caps model.

Sebastien Guillot, talk at NuSYM 2019, Da Nang, Vietnam



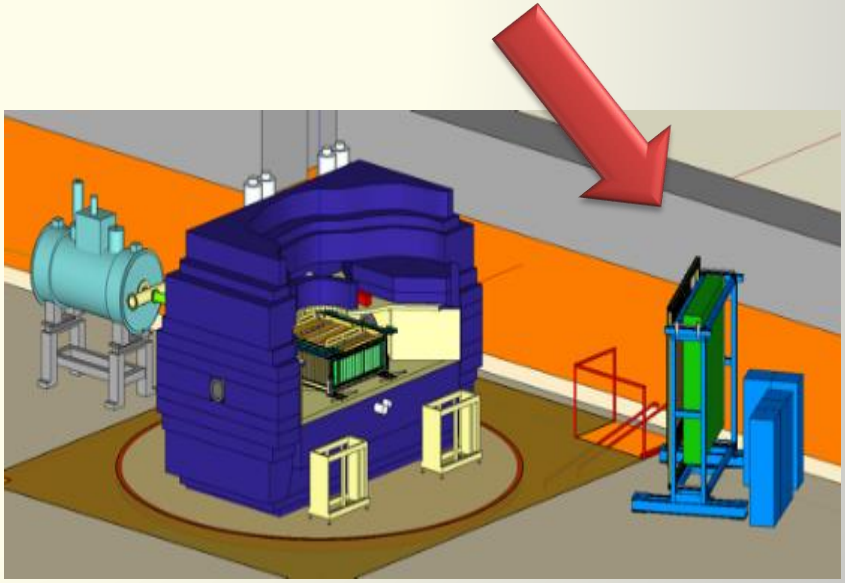
Preliminary results for dual-temperature two polar caps model.

Sebastien Guillot, talk at NuSYM 2019, Da Nang, Vietnam



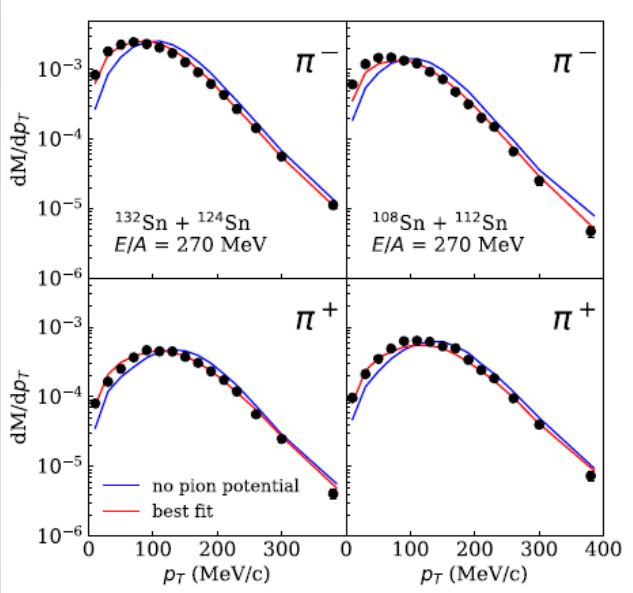
SπRIT experiment at RIKEN

- SπRIT TPC installed inside the SAMURAI magnet.
- NeuLAND is placed at 8.8 m from the target



source: M.B. Tsang at NuSYM2017, Caen, France

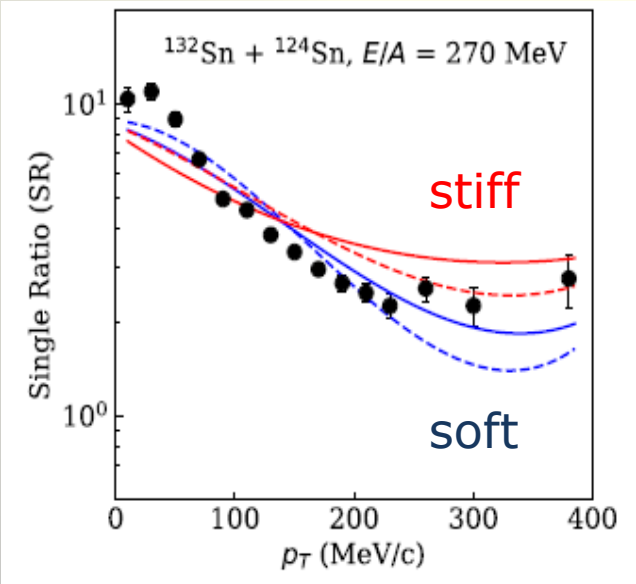
symmetry energy from pion spectral ratio



radioactive beams ^{108}Sn, ^{132}Sn

pion production probes n/p ratio in compressed zone

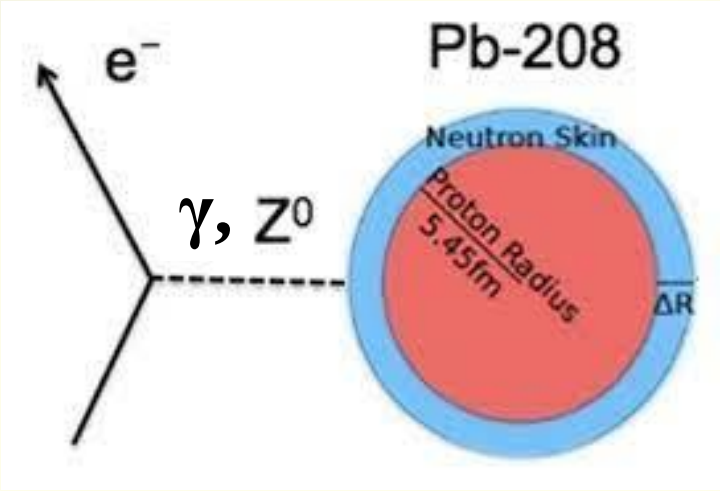
pion spectra reproduced with QMD transport model (Dan Cozma)



final result **42 < L < 117 MeV**

spectral π^-/π^+ ratios at large p_t

neutron skin from PREX-2



Jlab

polarized e^-
17 μA
E = 953 MeV

weak interaction **probes neutron distribution**
the weak charge of the proton is small (≈ 0.06)

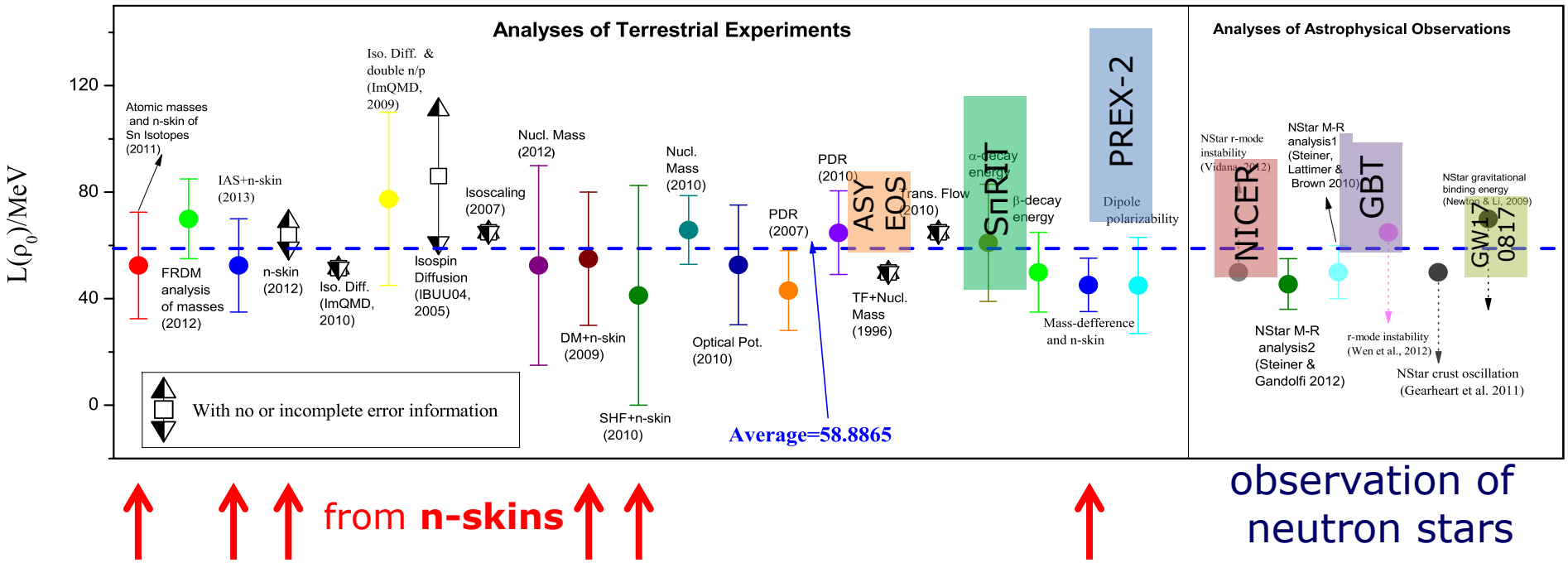
asymmetry ≈ 0.5 10^{-6}

neutron skin in ^{208}Pb $\Delta \mathbf{r_{np}}$ **= 0.28 ± 0.07 fm**

corresponds to **69 < L < 143 MeV**

Adhikari+, Phys. Rev. Lett. 126, 172502 (2021)

the world average in 2013: L = 58.8865 MeV



from **n-skins**

observation of neutron stars

6 very recent observations: <L> = 72 ± 8 MeV (2021)

responses to PREX-2: Δr_{np} = 0.28 ± 0.07 fm

Yue+ arXiv:2102.05267: 0.22 fm ≤ Δr_{np} ≤ 0.27 fm

arguing with nuclear structure and reactions and with astro results

Essick+ arXiv:2102.10074: Δr_{np} = 0.19 ± 0.03 fm

combining PREX-2 with astro and EFT results

Reed+ PRL 126, 172503 (2021)

discuss consequences

earlier data:

Rossi+ PRL 111 (2013) 0.15 ± 0.03 fm

Tamii+ EPJA 50 (2014) 0.165 ± 0.026 fm

pygmy dipole resonance and dipole polarizability

Aumann+ PRL 119 (2017) proposed project

measure neutron removal Xsection at high energy

expect $\Delta L \approx 10$ MeV and $\Delta(\Delta r_{np}) \leq 0.015$ fm

FAIR construction site

seen from the visitors‘ platform

ASY-EOS Collaboration

spokespersons: P. Russotto (Catania)
R.C. Lemmon (Daresbury)

P. Russotto, PRC 94, 034608 (2016)
93 authors from 14 countries

HUZHOU UNIVERSITY

TECHNISCHE UNIVERSITÄT DARMSTADT

RIKEN

GSI

UNIVERSITY OF LIVERPOOL

INFN Istituto Nazionale di Fisica Nucleare

IN2P3

NSCL

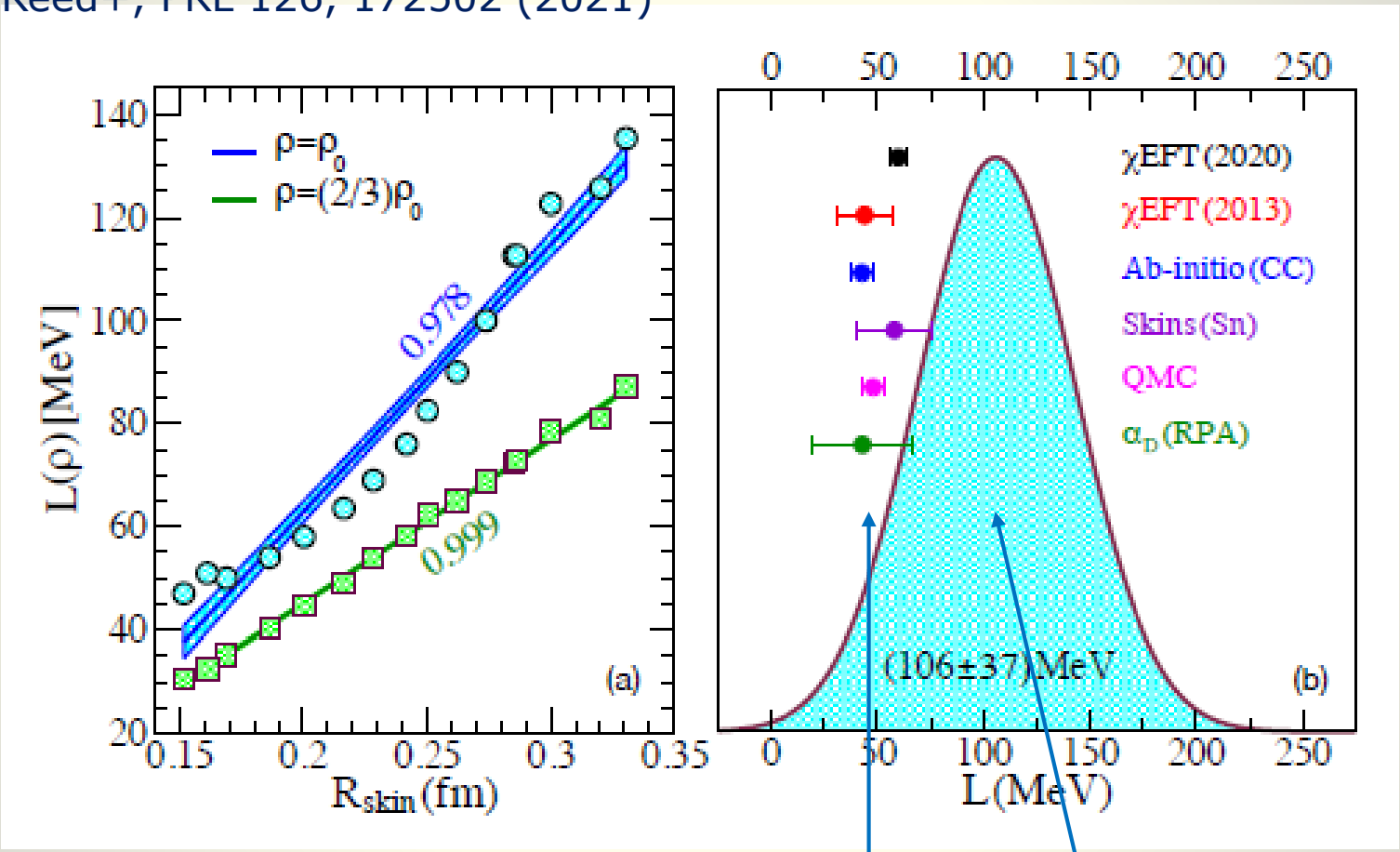
ATM

KACST

GANIL

responses to PREX-2: Δr_{np} = 0.28 ± 0.07 fm

Reed+, PRL 126, 172502 (2021)



correlations L(ρ) vs Δr_{np}

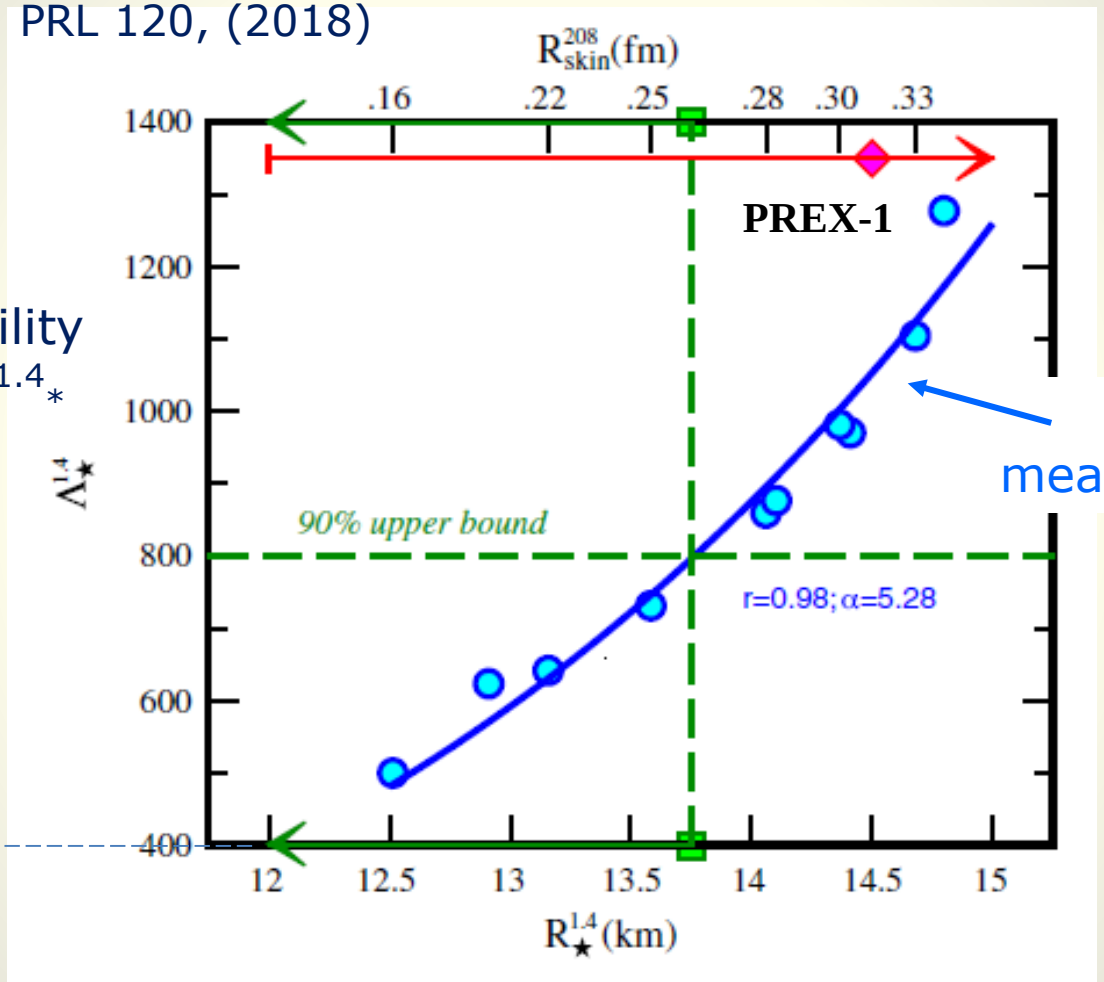
theory

PREX-2

tight correlations

from Fattoyev+, PRL 120, (2018)

tidal polarizability parameter $\Lambda^{1.4}_*$



10 relativistic mean-field models

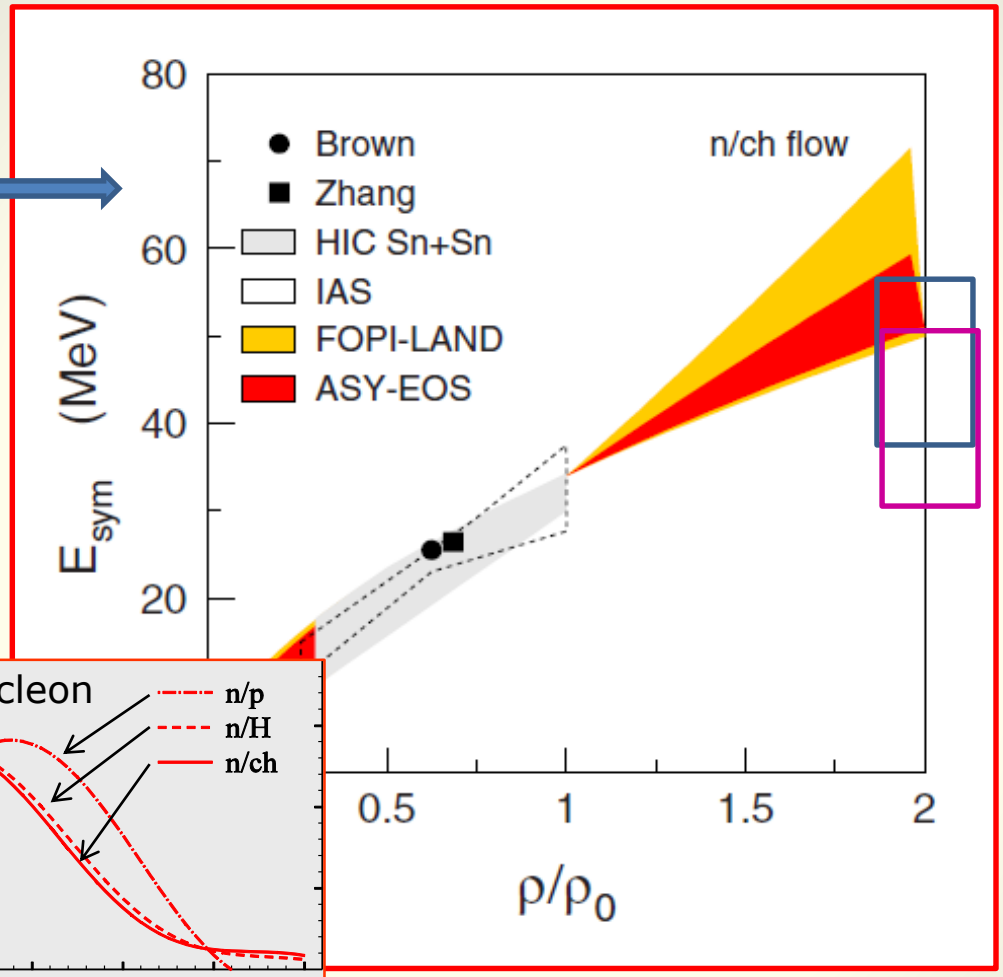
GW170817

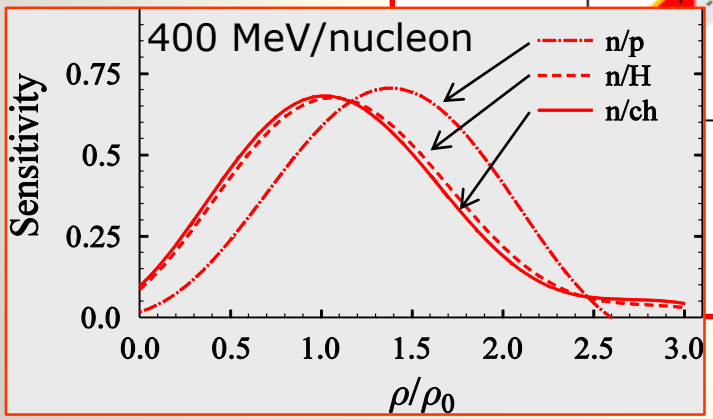
10.6

$\Lambda^{1.4}_*$ vs neutron skin (^{208}Pb) vs radius $R_{1.4}$ vs pressure (PNM ρ_0) vs L

ASY-EOS: neutron vs charged-particle elliptic flow ratios

compiled by
Horowitz et al.,
JPhysG (2014)





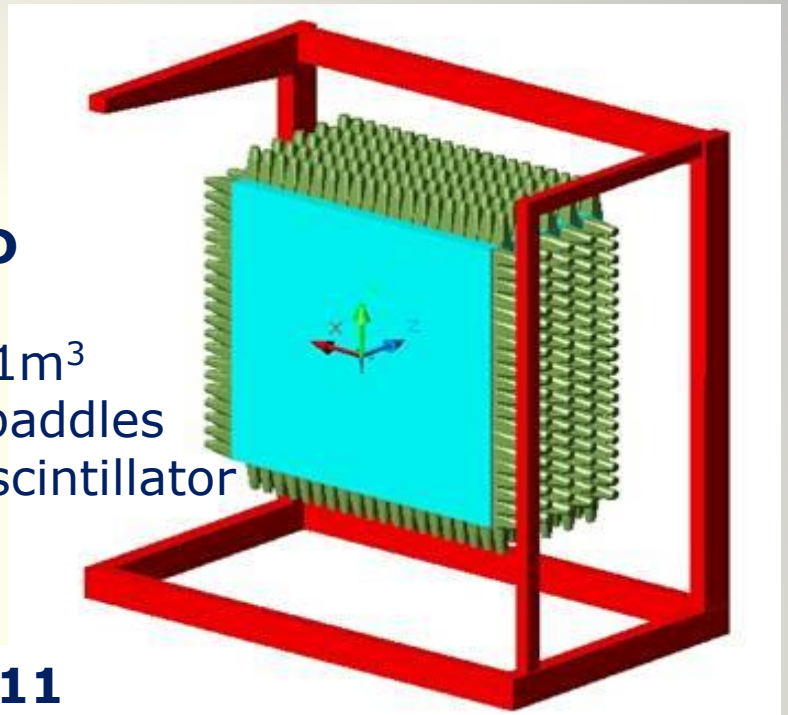
density probed by the elliptic flow ratio
in Au+Au at 400 MeV/nucleon

neutron star
X-ray observations
Zhang & Li
EPJA 55:39 (2019)
E_{sym} $(2\rho_0)$ =
47 ± 10 MeV

Bayesian analysis
GW170817 and
radii of QLMXB
Xie & Li
arXiv:1907.10741
R = 10.8 – 11.9 km
E_{sym} $(2\rho_0)$ =
39+12−8 MeV

LAND

2x2x1m^3
200 paddles
iron/scintillator



ASY-EOS in 2011
Au+Au @ 400 AMeV