ECT*@2019.05.23

Neutron Star EoS Studies in Korea

for **RAON** New Rare Isotope Accelerator & **MMA** Multi-Messenger Astrophysics

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Chang-Hwan Lee / Pusan National University

As a member of ***BUD*** *Collaboration*

B*usan (****CHL, Myungkuk KIM****)*
U*lsan (Kyujin KWAK,* ***Young-Min KIM****)*
D*aegu (Chang Ho HYUN)*
Daejeon (Youngman KIM, IBS)
Montreal (Sangyong JEON, McGill)

Dense Matter Physics in Korea *my personal point of view*

Hadron Physics		*Astrophysics*
NS EoS with **Effective Field Theories** (with D.P.Min, **M.Rho** & G.E.Brown)	**1990s**	NS Binary as a source of GW (with **G.E.Brown**@Stony Brook)
	2003	**Korean Gravitational Wave Group** Nuclear physics + Astrophysics + Mathematics + Artificial Intelligence
Science-Business-Belt Project initiated by **D.P. Min**	**2006**	
RAON project was approved	**2009**	**KGWG** joined LIGO Scientific Collab.
Transport Studies history by YM Kim's talk application by MG Kim's talk		
	2017	**GW from NS-NS mergers** (Multi-messenger Astrophysics) Tidal deformability of NS
First run of RAON Symmetry Energy (later)	**2021**	

BUD Collaboration
for Astro-Hadron Physics

ECT* Workshops co-organized by Koreans & Europeans

Hadron Physics | *Astrophysics*

NS EoS with **Effective Field Theories** (with D.P.Min, **M.Rho** & G.E.Brown) — 1990s — NS Binary as

2003

Nuclear phys cs + Astrophysics + Mathema

Science-Business-Belt Project initiated by **D.P. Min** — 2006

RAON project was approved — 2009

Transport Studies history by YM Kim's talk application by MG Kim's talk — 2017 — (Multi-mes

Tidal deforn

First run of RAON Symmetry Energy (later) — 2021

BUD Collabora for Astro-Hadron

ECT* established in 1993

1994 Director: B. Mottelson

Organized by M. Rho & W. Weise
(my first visit to ECT* as a Ph.D. student)

2004 Director: W. Weise

Novel Approaches to the Nuclear Many-Body Problem: From Nuclei to Stellar Matter
Organisers: C-H. Lee (Co-ordinator) (*Pusan National Univ.*),
N. Kaiser (*TU Munich*),
A. Schwenk (*Ohio State Univ.*) [p. 36]

2015 Director: W. Weise

ECT*-APCTP Joint Workshop:
From Rare Isotopes to Neutron Stars
Francesca Gulminelli (LPC and University of Caen, France)
Chang-Hwan Lee (Pusan National University, Busan, Korea)
Yongseok Oh (Kyungpook National University, Daegu, Korea)
Jürgen Schaffner-Bielich (Goethe University Frankfurt, Germany)

Novel Approaches to Nuclear Many-Body Problem:

From Nuclei to Stellar Matter

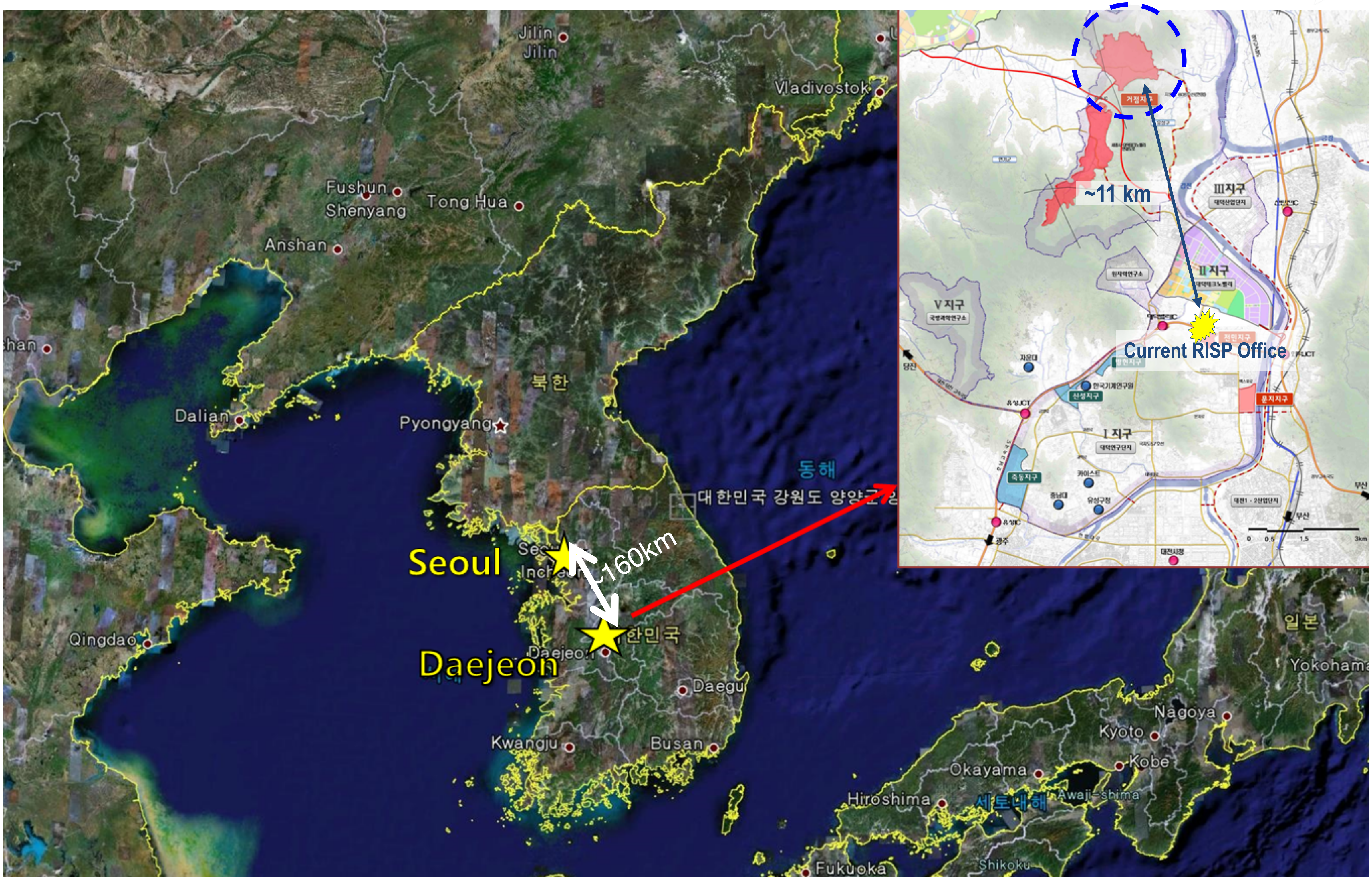
ECT*, Sep. 6-17, 2004

(organized by CH Lee, N Kaiser, A Schwenk)

Contents

- **Introduction of RAON** new rare isotope accelerator in Korea
  Rare isotope **A**ccelerator complex for **ON**-line experiments
- **NS EoS studies before RAON & GW detection**
- **NS EoS in the new era of multi-messenger astrophysics**
  - Direct measurement of NS mass from GW
  - Tidal Love number/deformability of NS from GW
- **Prospects**

RAON Site : Sindong in Daejeon



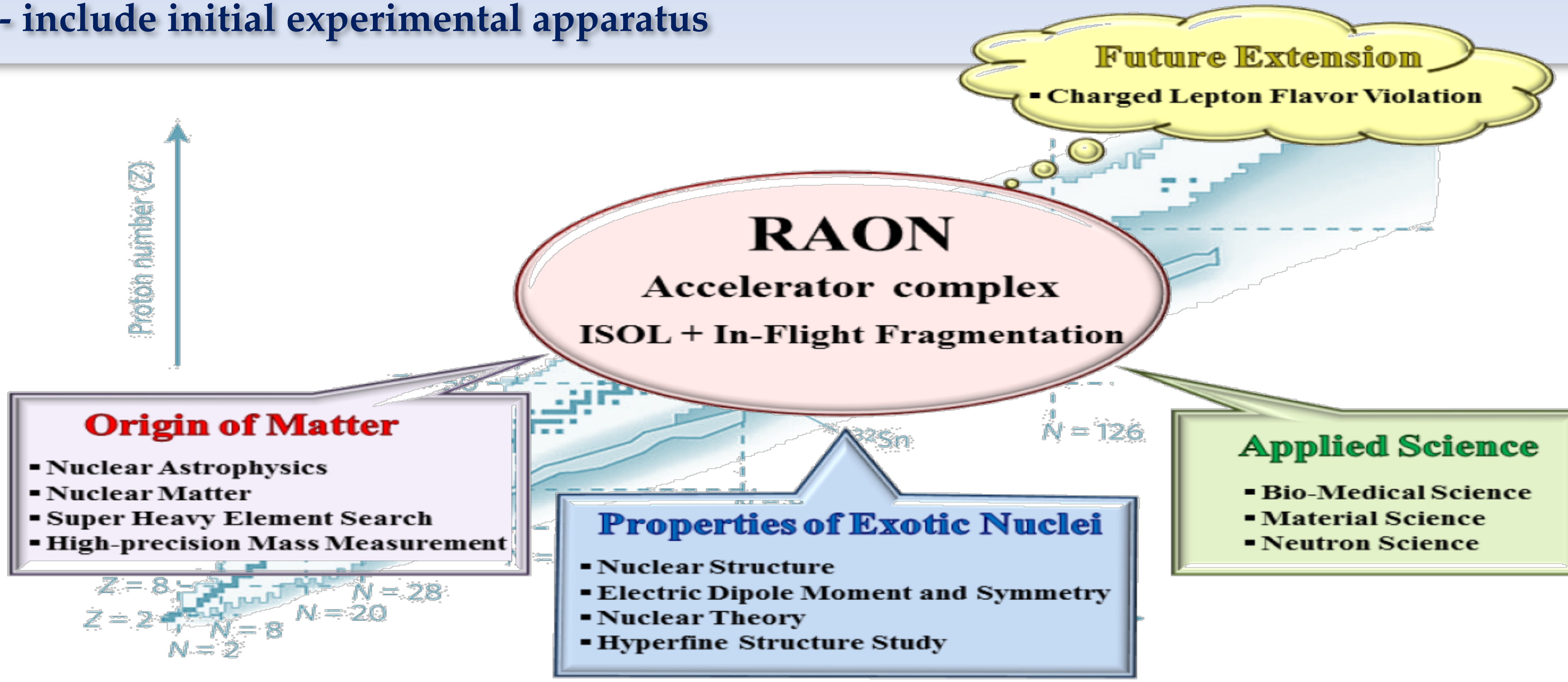
Courtesy of Youngman Kim (IBS)

Rare Isotope Science Project (RISP)

- Goal : To build a heavy ion accelerator complex RAON for rare isotope science researches in Korea
- Project period : 2011.12 - 2021.12
- Total Budget : ~$ 1.43 billion

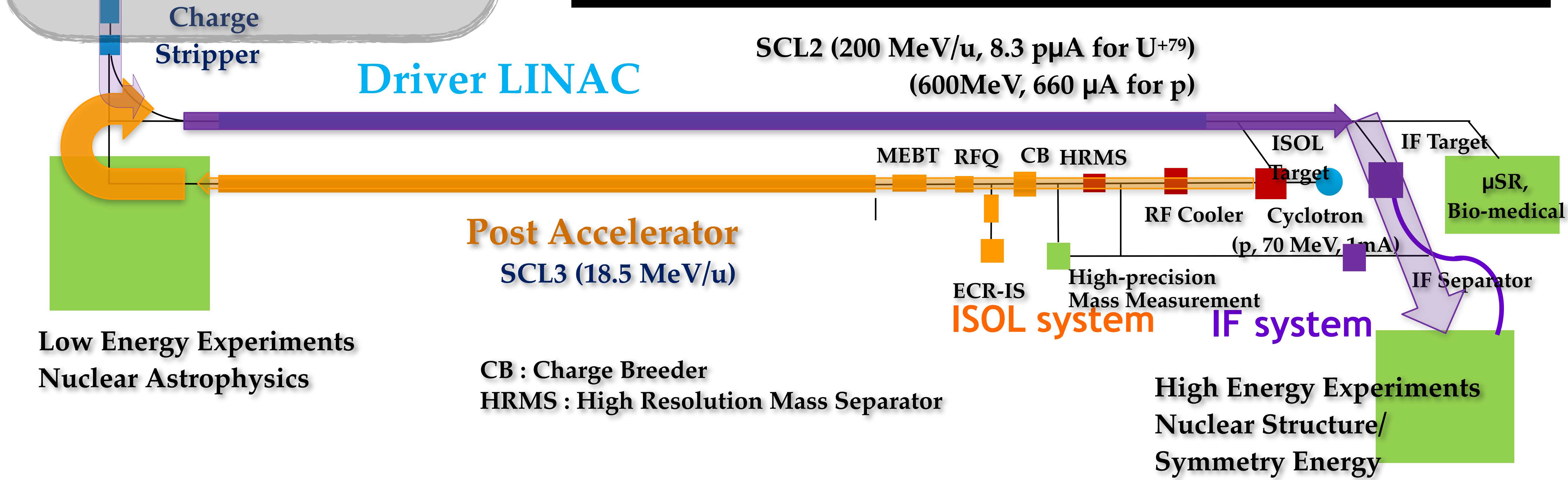
(Facilities ~ $ 0.46 bill., Bldgs & Utilities ~ $ 0.97 bill.)

- include initial experimental apparatus



RAON Concept

- High intensity RI beams by ISOL & IF
  - ISOL : direct fission of ^{238}U by 70MeV protons
  - IF : 200MeV/u, 8.3pμA of ^{238}U
- High quality neutron-rich RI beams
  - ^{132}Sn with up to ~250MeV/u, up to ~10^8 pps
- More exotic RI beams by ISOL+IF

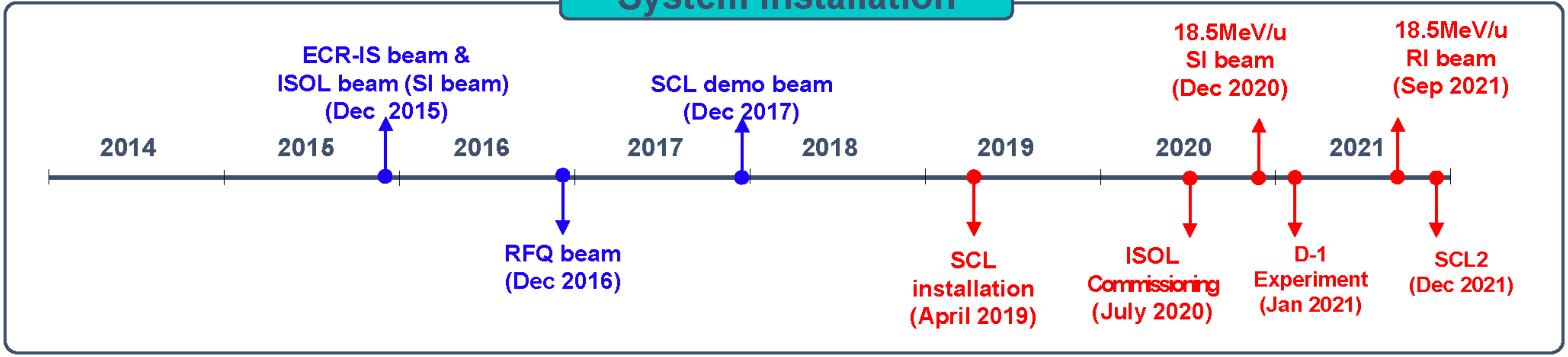


1. Overview

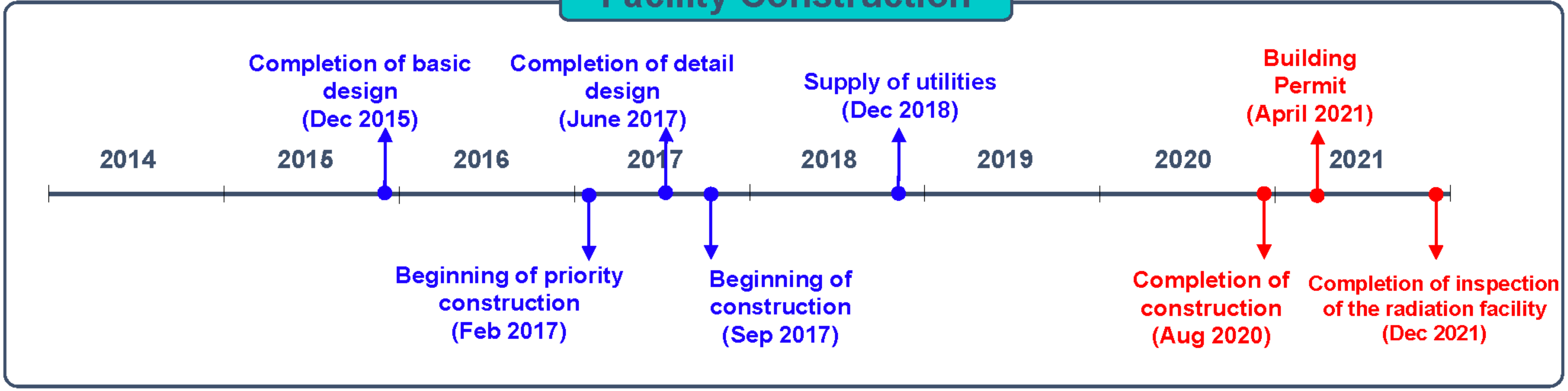
Project Milestone

(2018) SCL3 manufacturing, SCL2 Prototype → (2019) SCL3 Installation, SCL2 manufacturing → (2020) SCL3 Beam Commissioning/ Const. Completion → (2021) SCL3 Beam Commissioning/ Project Completion

System Installation



Facility Construction



Conventional Facilities


SCL2


SCL3


Low Energy A/B


ISOL


IF/ High Energy A


High Energy B


SCL3

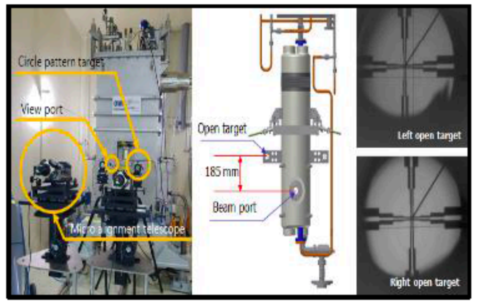

Bending Section


SCL3-gallery

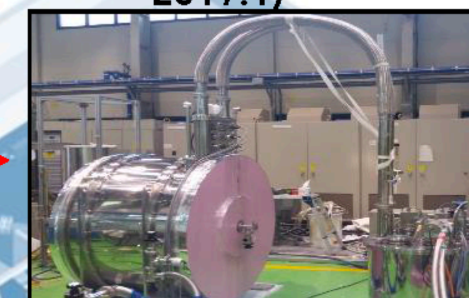
Accelerator Bd.

Major achievements

QWR cryomodule test complete
(2017.05)



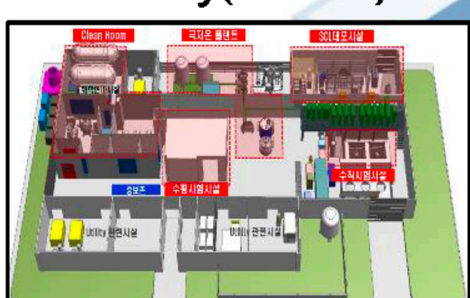
Achievement of low temperature test for LTS and HTS quadrupole prototype magnet (LTS 2016.1, HTS 2017.1)



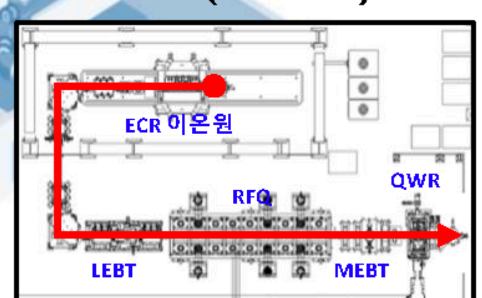
1st Oxygen Ion beam acceleration with RFQ(2016.12)

HWR cryomodule test complete
(2018.03)

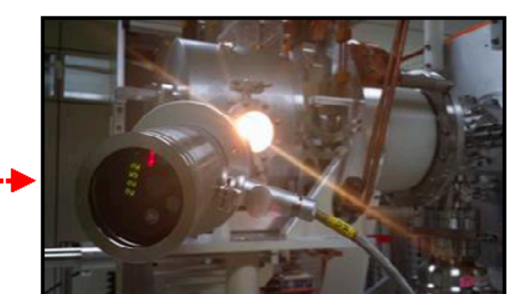
Superconducting RF Test facility(2016.06)



1st Oxygen Ion beam acceleration with QWR module, SCL Demo(2017.10)



High purity Sn beam extraction using RILIS (2015.12)



Summary & Outlook

▪ Accelerator

- Mass production for SCL3 is under way
- SCL2 is under pre-production phase
- **From April, 2019, installation for SCL will start from SCL3**.

▪ By the end of 2021, we will achieve

- **SI beams:** Stable ion beams (^{16}O, ^{40}Ar) from ECRIS → SCL3 → low E exp hall
- **RI beams:** RIBs extraction from ISOL → re-acceleration through SLC3 → low E exp hall
- Stable / RI beams will be delivered to low-E experimental hall
- **Early phase experiments are going to be performed using KOBRA**
  → RIBs production at KOBRA (A<~50, beam energy < 20 MeV/u) using SI beams from SCL3
- Beam commissioning starts for SCL2
- Installation and commissioning for IF, LAMPS, Neutron, bio-medical and muSR
  → Collaborative works with RUA (RAON Users Association) via RULC (RAON Users Liason Center)

▪ Post RISP (2021 ~)

- Beam acceleration for ISOL → SCL3 → SCL2 → IF **(ISOL+IF)**
- Beam commissioning and experiments for IF, LAMPS, Neutron, bio-medical and muSR
- **Ramping-up to get the 400kW beams (more than 5 yrs)**
- Energy upgrade to 400MeV/u (requires budget)

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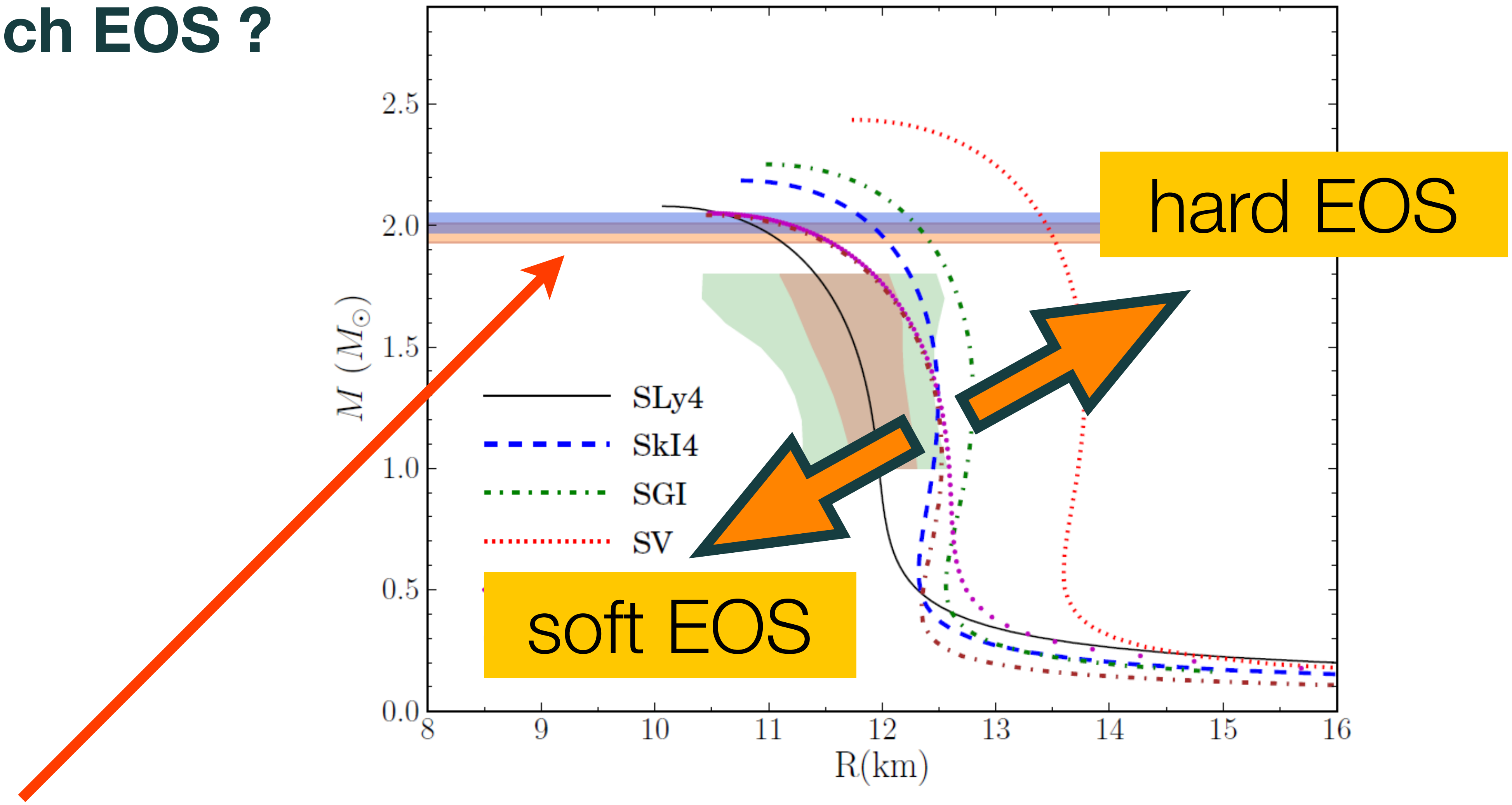
Mass & radius of neutron star

Q) Which EOS ?



Neutron Star-White Dwarf Binaries

1.97 solar mass NS : Nature 467 (2010) 1081

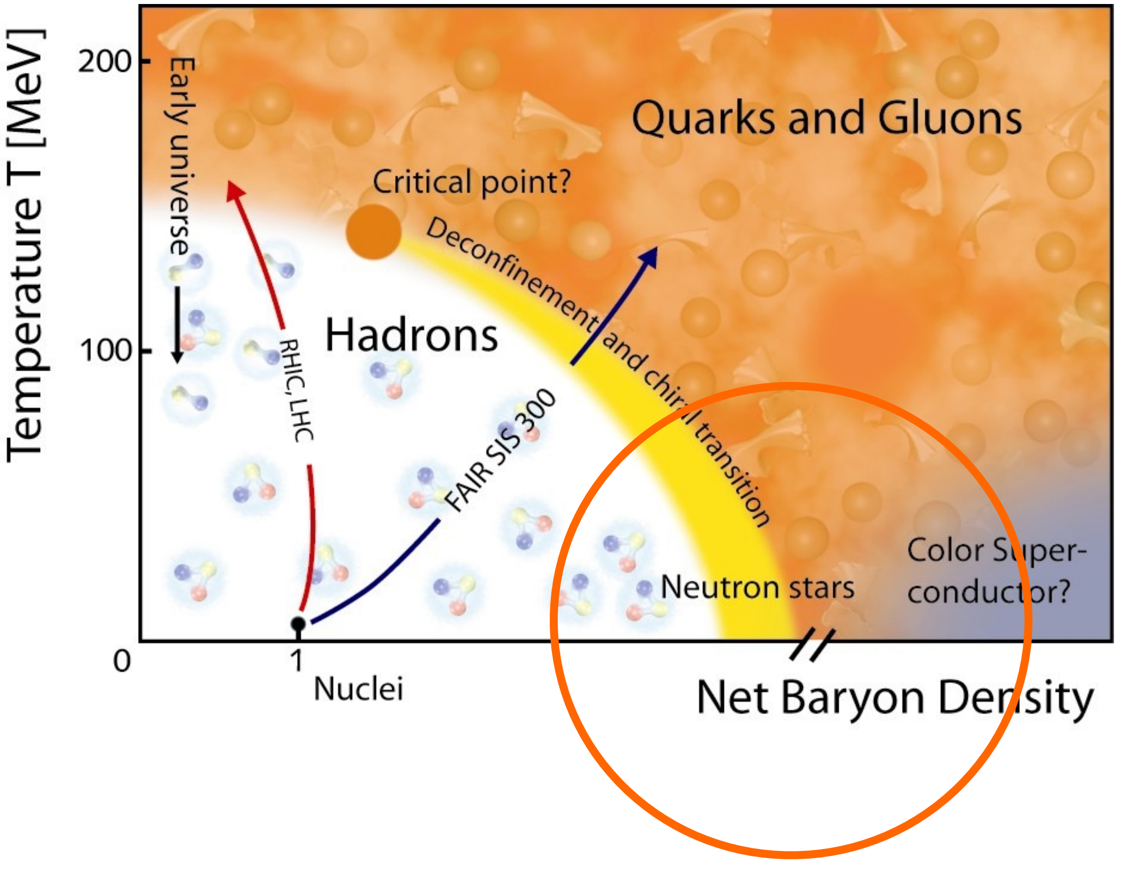
2.01 solar mass NS : Science 340 (2013) 6131

Contributions of **Mannque Rho** (Saclay, France)

Approaches based on fundamental symmetries

Ultimate testing place for physics of dense matter

- ✓ chiral symmetry restoration
- ✓ color superconductivity
- ✓ color-flavor locking
- ✓ (u,d,s) quark states
- ✓ AdS/QCD
- ✓ symmetry energy
- ✓ tensor forces
- ✓ 3-body forces
- ✓ … …



Contributions of **Mannque Rho** (Saclay, France)

selected (biased) references

From kaon–nuclear interactions to kaon condensation

G.E. Brown [a,1], Chang-Hwan Lee [b,2], Mannque Rho [c], Vesteinn Thorsson [d]

Nuclear Physics A567 (1994) 937–956
North-Holland

Physics Reports 391 (2004) 353–361

Nature of the chiral restoration transition in QCD

Gerald E. Brown[a,*], Loïc Grandchamp[a,b], Chang-Hwan Lee[c], Mannque Rho[d,e]

PRL **96,** 062303 (2006) PHYSICAL REVIEW LETTERS week ending 17 FEBRUARY 2006

Strangeness Condensation by Expanding about the Fixed Point of the Harada-Yamawaki Vector Manifestation

G. E. Brown,[1] Chang-Hwan Lee,[2,3] Hong-Jo Park,[2] and Mannque Rho[4,5]

arXiv:1804.00305

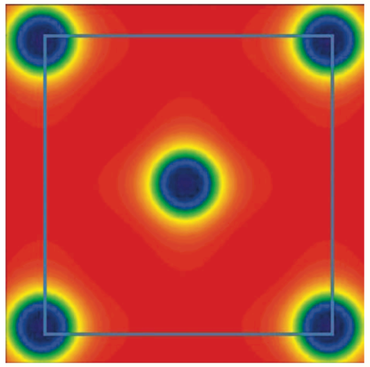
A pseudo-conformal equation of state in compact-star matter from topology change and hidden symmetries of QCD

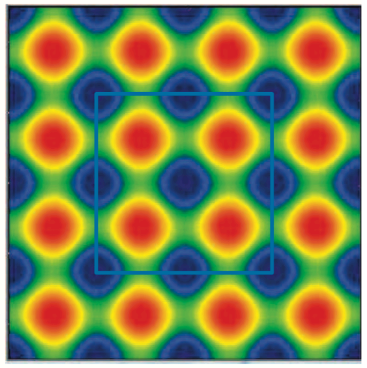
Yong-Liang Ma,[1] Hyun Kyu Lee,[2] Won-Gi Paeng,[3] and Mannque Rho[4]

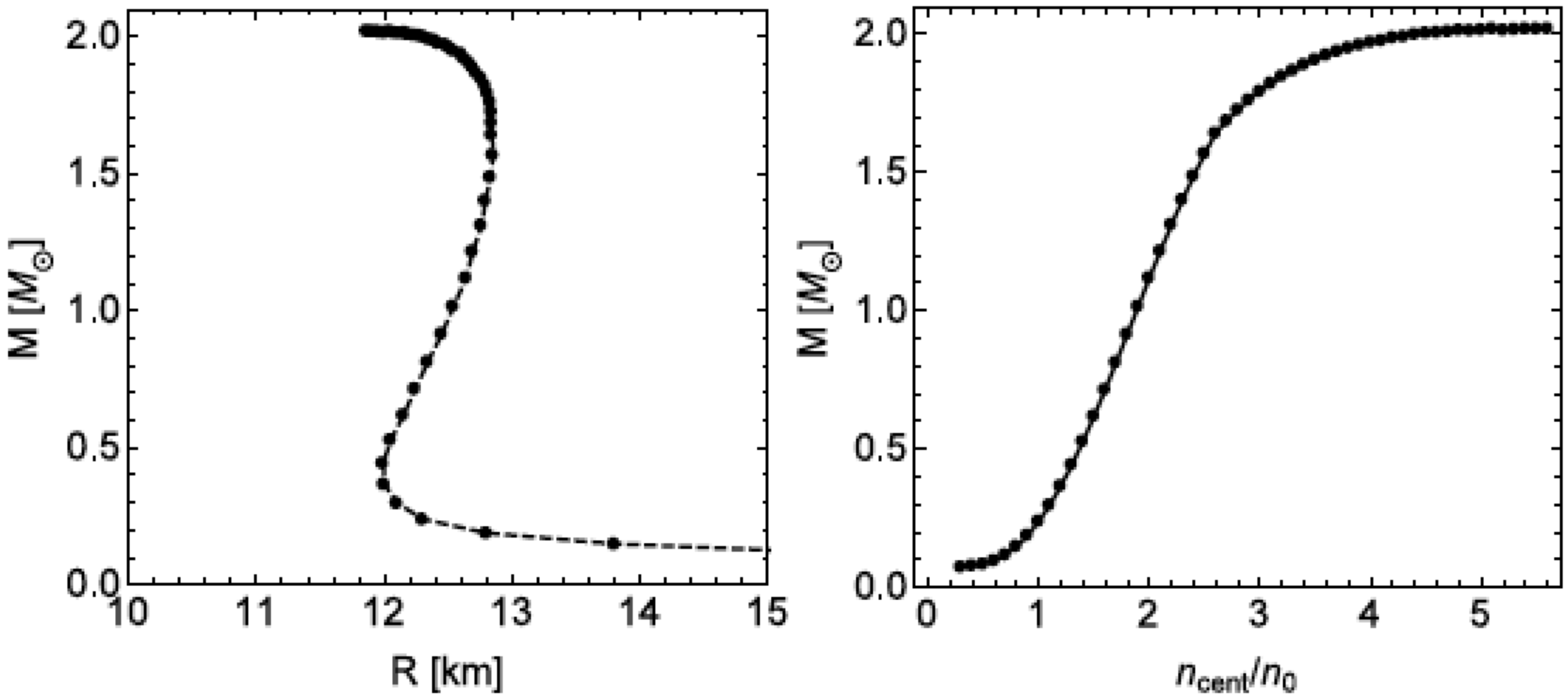
Contributions of **Mannque Rho** (Saclay, France)

most recent works

Transition from Skyrmion to Half-Skyrmion





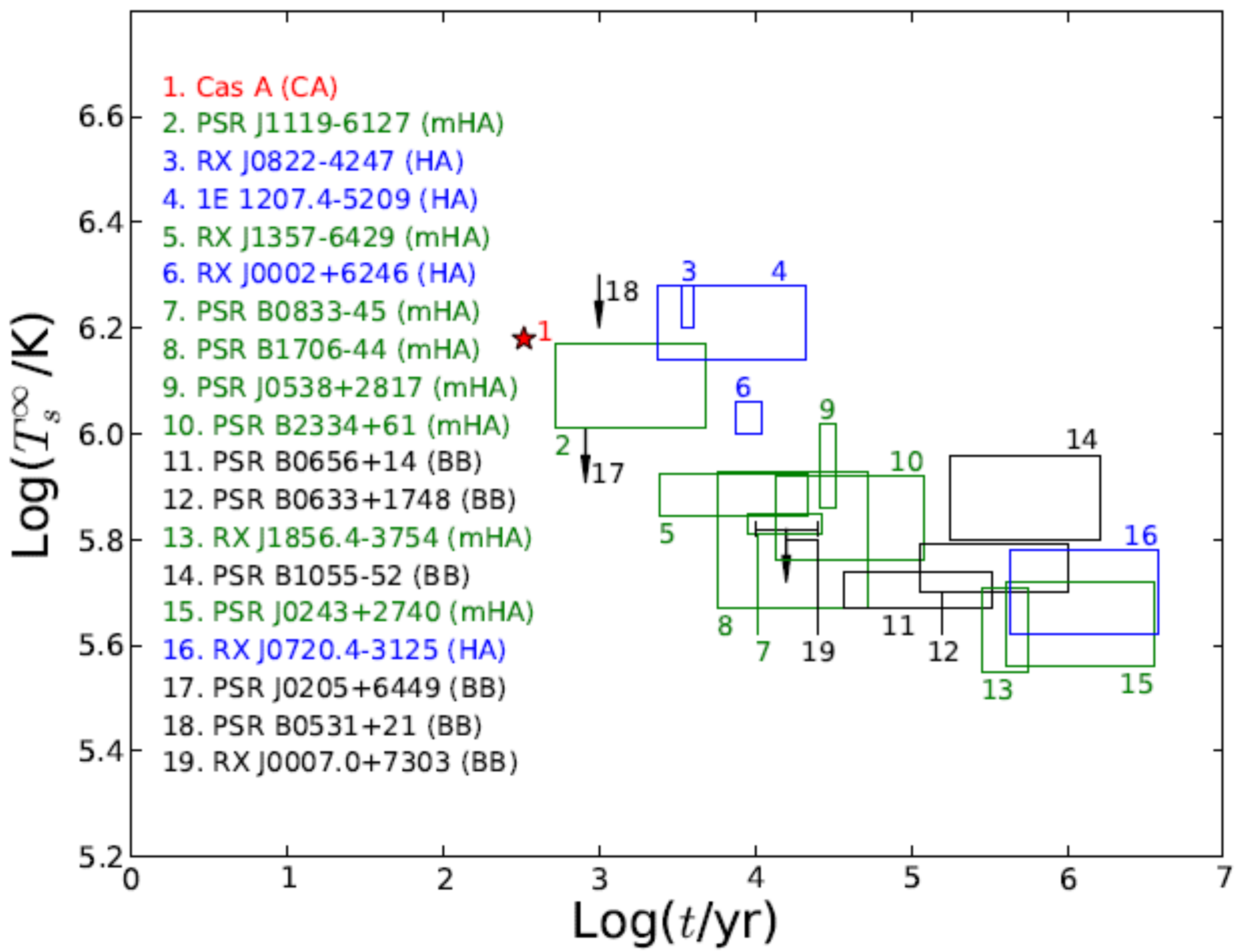


Y.-L. Ma & M. Rho, arXiv:1612.066000
Y.-L. Ma, H.K. Lee, W.-G. Paeng, M. Rho, arXiv:1804.00305

Recent Phenomenological Approaches

- NS Cooling at T~O(keV)
- Low-Mass X-ray binaries : NS masses & radii
- KIDS new DFT theory developed in Korea
  for finite nuclei and dense matter

Neutron Star Cooling



depends on

- particle fraction
- elements in the envelope
- nuclear superfluidity
- … …

Y.Lim, C H Hyun, CHL, IJMPE (2017)

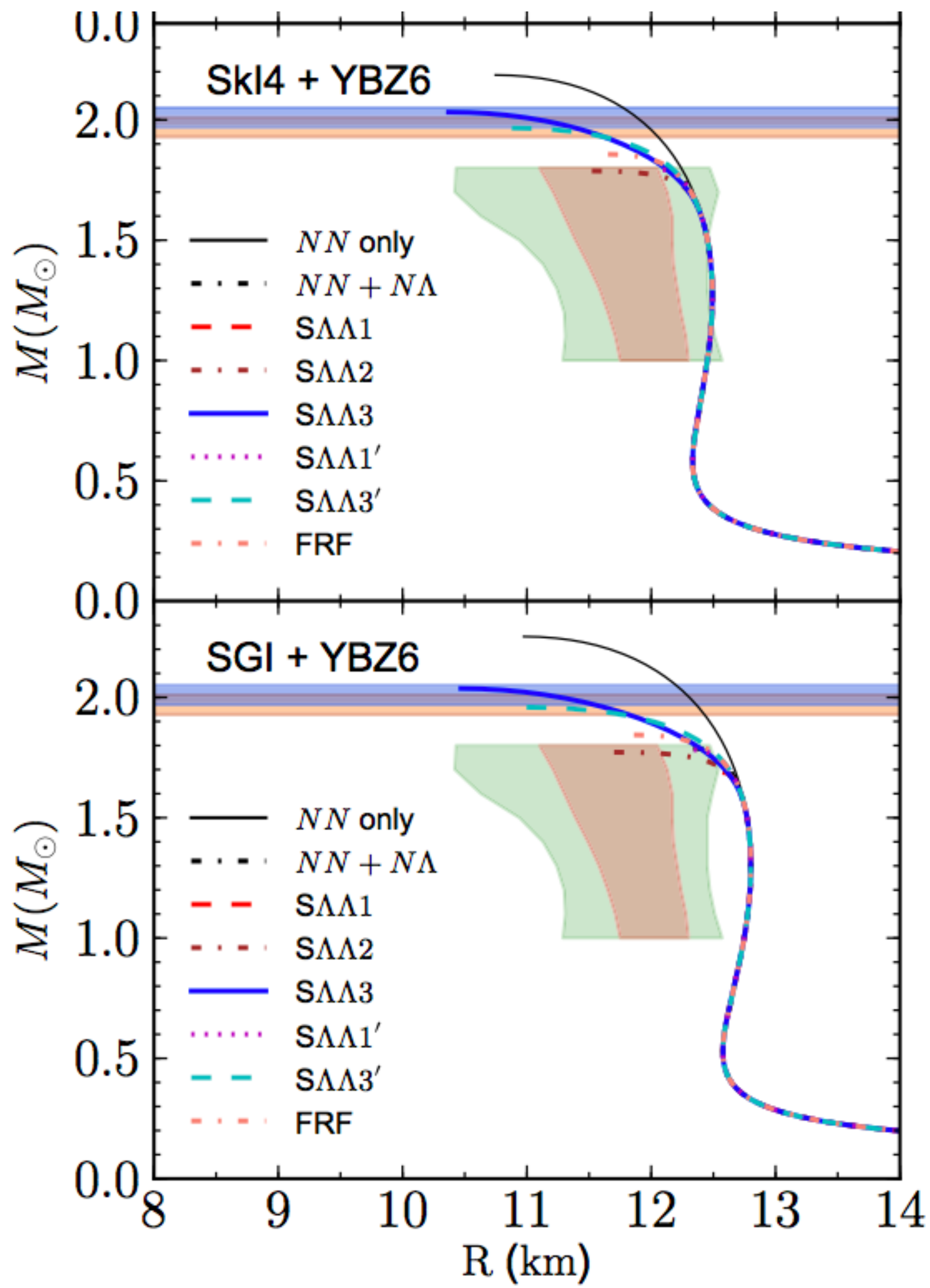
Cooling Mechanism

- **Photon emission** : mostly on the surface
- **Neutrino emission** : entire region, major energy loss

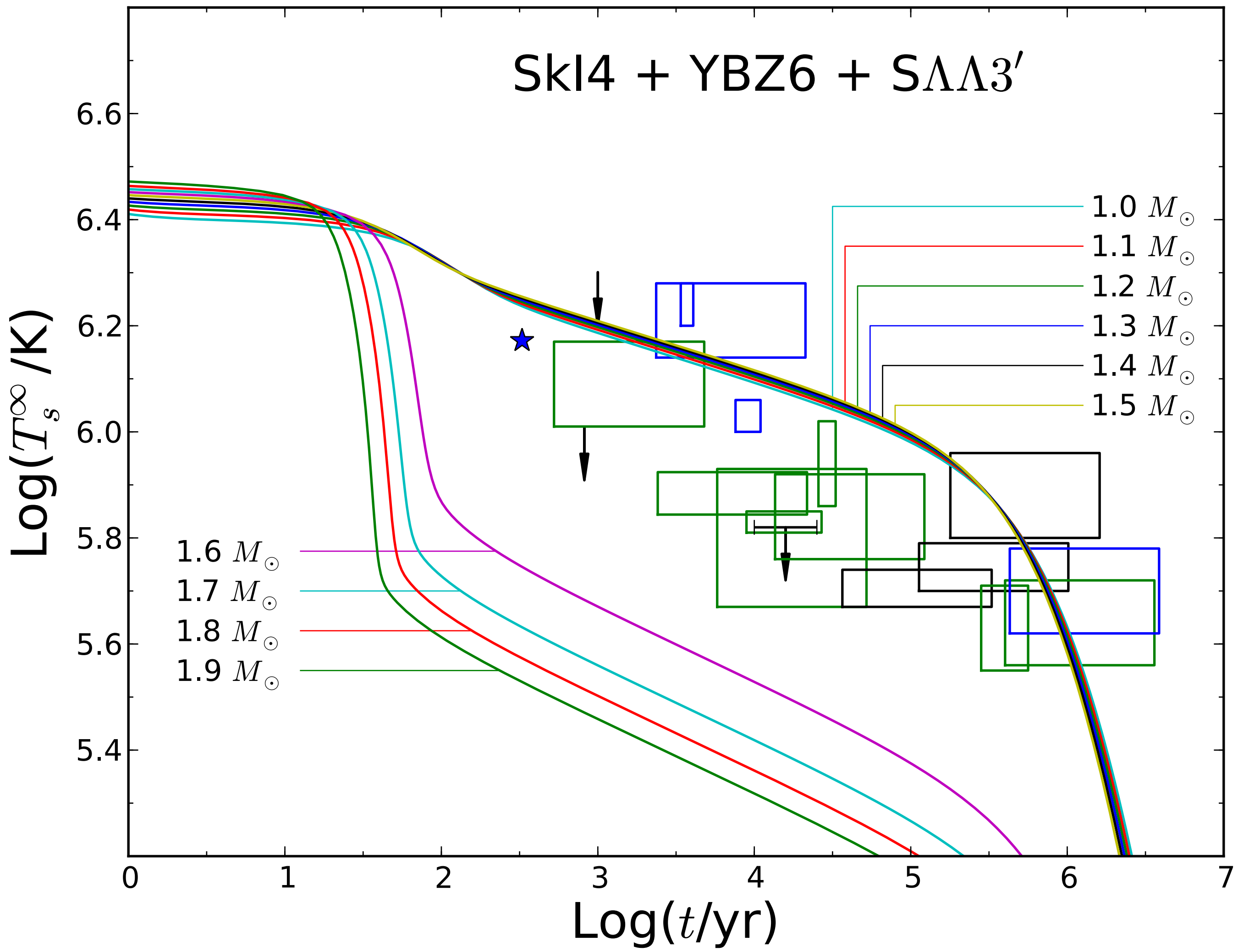
Name	Process	Emissivity[b] (erg cm^{-3} s^{-1})	
Modified Urca (neutron branch)	$n+n \rightarrow n+p+e^- + \bar{\nu}_e$ $n+p+e^- \rightarrow n+n+\nu_e$	$\sim 2\times 10^{21}\, \mathcal{R}\, T_9^8$	Slow
Modified Urca (proton branch)	$p+n \rightarrow p+p+e^- + \bar{\nu}_e$ $p+p+e^- \rightarrow p+n+\nu_e$	$\sim 10^{21}\, \mathcal{R}\, T_9^8$	Slow
Bremsstrahlung	$n+n \rightarrow n+n+\nu\bar{\nu}$ $n+p \rightarrow n+p+\nu\bar{\nu}$ $p+p \rightarrow p+p+\nu\bar{\nu}$	$\sim 10^{19}\, \mathcal{R}\, T_9^8$	Slow
Cooper pair formations	$n+n \rightarrow [nn]+\nu\bar{\nu}$ $p+p \rightarrow [pp]+\nu\bar{\nu}$	$\sim 5\times 10^{21}\, \mathcal{R}\, T_9^7$ $\sim 5\times 10^{19}\, \mathcal{R}\, T_9^7$	
Direct Urca	$n \rightarrow p+e^- + \bar{\nu}_e$ $p+e^- \rightarrow n+\nu_e$	$\sim 10^{27}\, \mathcal{R}\, T_9^6$	Fast
π^- condensate	$n+ < \pi^- > \rightarrow n+e^- + \bar{\nu}_e$	$\sim 10^{26}\, \mathcal{R}\, T_9^6$	Fast
K^- condensate	$n+ < K^- > \rightarrow n+e^- + \bar{\nu}_e$	$\sim 10^{25}\, \mathcal{R}\, T_9^6$	Fast

Hyperons in Skyrme force models

IJMPE 12, 1550100 (2015)



NS Cooling with hyperons

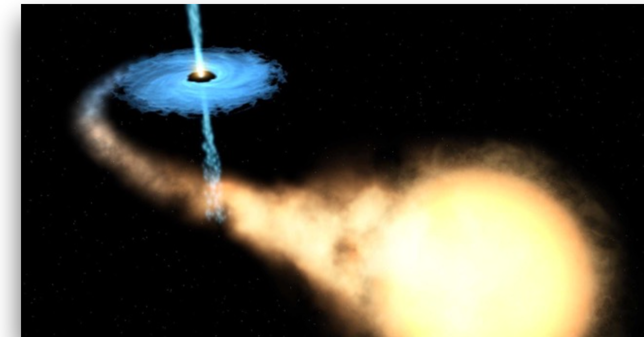


NS mass : 1.0 – 2.0 $M_\odot$

- abrupt drop: ingnition of direct URCA
- stiffer EoS allows early direct Urca
- no calculated-curve can explain middle-age data
- **require real fine-tuning**

with Yeunhwan Lim, Chang Ho Hyun, IJMPE (2017)

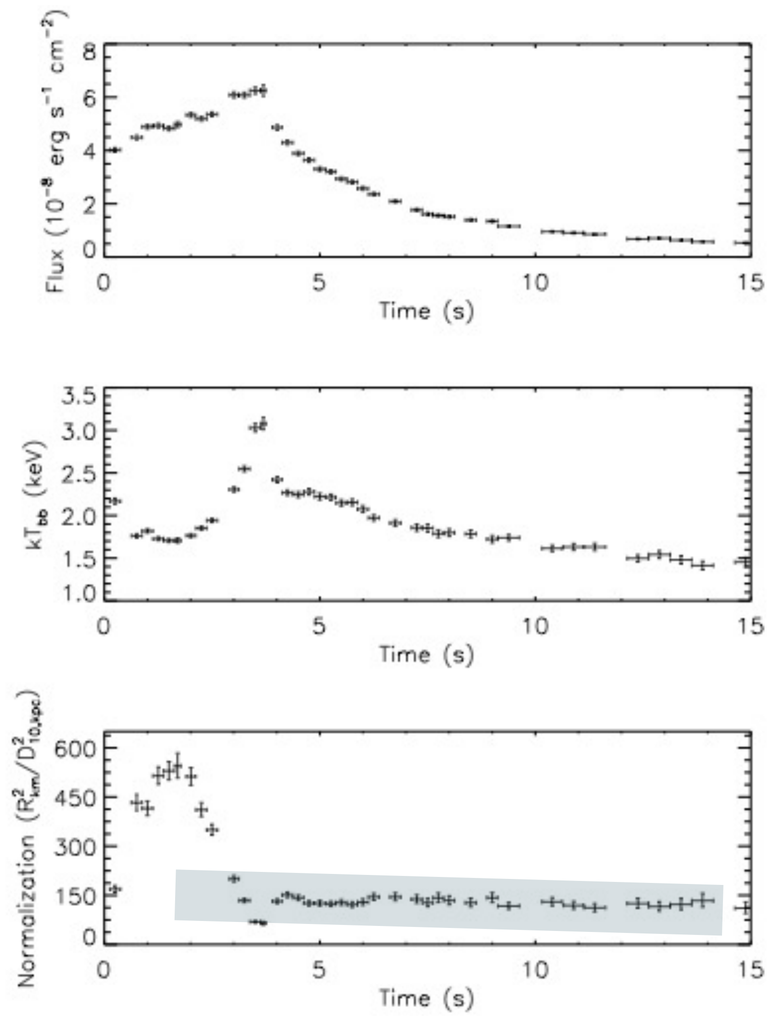
M & R from **LMXB** Low-Mass X-ray Binary

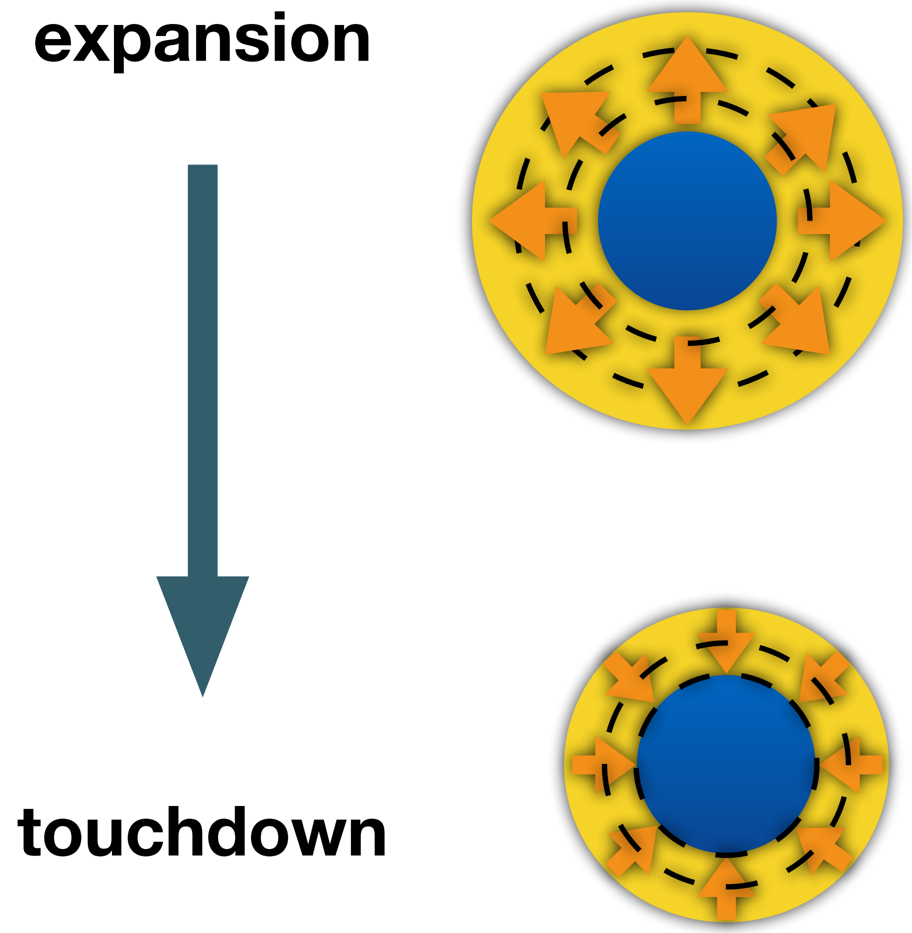


flux

temperature

radius





$$F_{\mathrm{TD},\infty} = \frac{GMc}{\kappa D^2}\left(1 - \frac{2GM}{Rc^2}\right)^{1/2},$$

$$A \equiv \frac{F_\infty}{\sigma T^4_{\mathrm{bb},\infty}} = f_c^{-4}\frac{R^2}{D^2}\left(1 - \frac{2GM}{Rc^2}\right)^{-1}$$

Ozel et al. 2009

Observations & most probable masses & radii of sources

TABLE 1
OBSERVATIONAL VALUES FOR FOUR PRE XRBS USED IN THIS WORK

	EXO 1745–248	4U 1608–522	4U 1820–30	4U 1746–37
D (kpc)	6.3 ± 0.6	5.8± 2.0 [a]	8.2± 0.7	11.05± 0.85
A ($km^2\,kpc^{-2}$)	1.17± 0.13	3.246± 0.024	0.9198± 0.0186	0.109± 0.044
$F_{TD,\infty}$ (10^{-8} erg $cm^{-2}\,s^{-1}$)	6.25± 0.2	15.41± 0.65	5.39± 0.12	0.269± 0.057

TABLE 3
MOST PROBABLE MASS AND RADIUS ESTIMATED VIA MONTE CARLO SIMULATIONS WITH FIXED HYDROGEN MASS FRACTION (X)

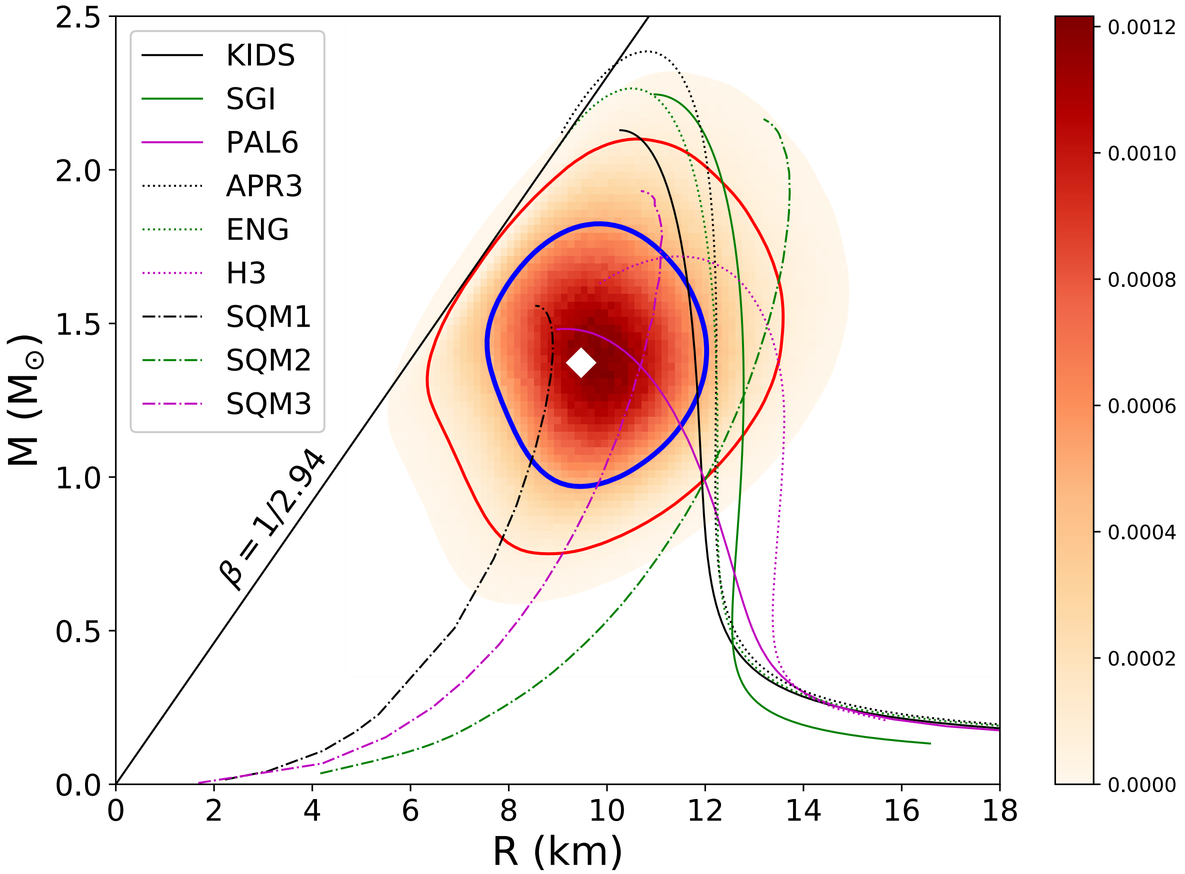
	Mass ($M_\odot$)			Radius (km)		
Object	X = 0.1	X = 0.3	X = 0.7	X = 0.1	X = 0.3	X = 0.7
EXO 1745–248	1.24±0.018	1.43±0.020	1.57±0.032	10.38±0.084	9.58±0.1208	8.29±0.171
4U 1608–522	1.37±0.040	1.60±0.031	1.92±0.018	11.62±0.600	11.36±0.385	9.77±0.1611
4U 1820–30	1.80±0.023	1.91±0.022	–	11.67±0.115	10.16±0.100	–
4U 1746–37 [a]	0.15±0.003	0.18±0.003	0.24±0.005	6.26±0.118	6.05±0.085	5.99±0.125
4U 1746–37 [b]	0.23±0.009	0.27±0.014	0.35±0.015	7.54±0.152	7.50±0.133	7.28±0.209

OBSERVATIONAL CONSTRAINT ON MASS AND RADIUS OF NEUTRON STAR IN LOW-MASS X-RAY BINARY BY OPACITY MEASUREMENT

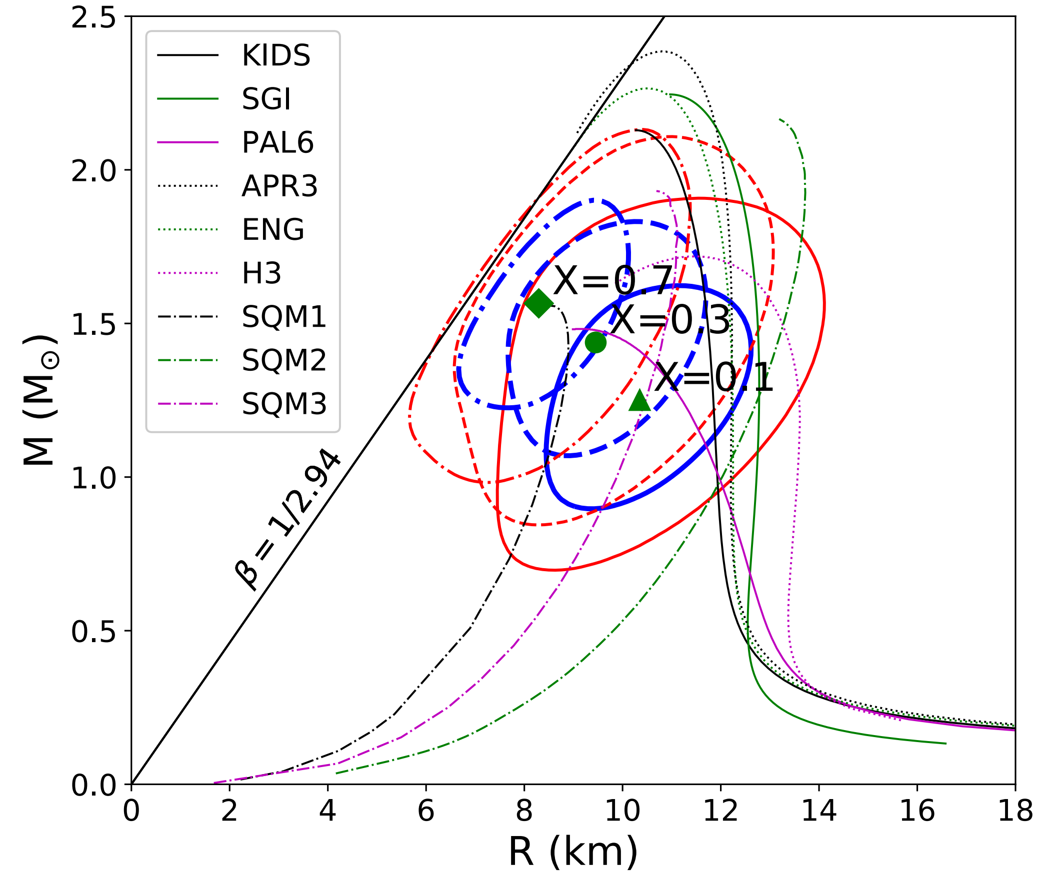
MYUNGKUK KIM,[1] YOUNG-MIN KIM,[2] KWANG HYUN SUNG,[2] CHANG-HWAN LEE[1], AND KYUJIN KWAK[2]

EXO 1745-248 previous work and new work

Uniform distribution of hydrogen fraction



Fixed value of hydrogen fraction



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MYUNGKUK KIM,[1] YOUNG-MIN KIM,[2] KWANG HYUN SUNG,[2] CHANG-HWAN LEE[1], AND KYUJIN KWAK[2]

KIDS nuclear energy density functional

PRC 97, 014312 (2018)

- **Motivation**

Construct models for nuclear structures on a basis with systematic expansion scheme.

$$\mathscr{E}(\rho,\delta) = \mathscr{T}(\rho,\delta) + \sum_{i=0}^{N-1} c_i(\delta)\rho^{1+i/3},$$

$$c_i(\delta) = \alpha_i + \beta_i \delta^2$$

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

- **Fitting**
  - α_i : ρ_0 = 0.16 fm^{-3}, BE = 16.0 MeV, K_0 = 240 MeV,

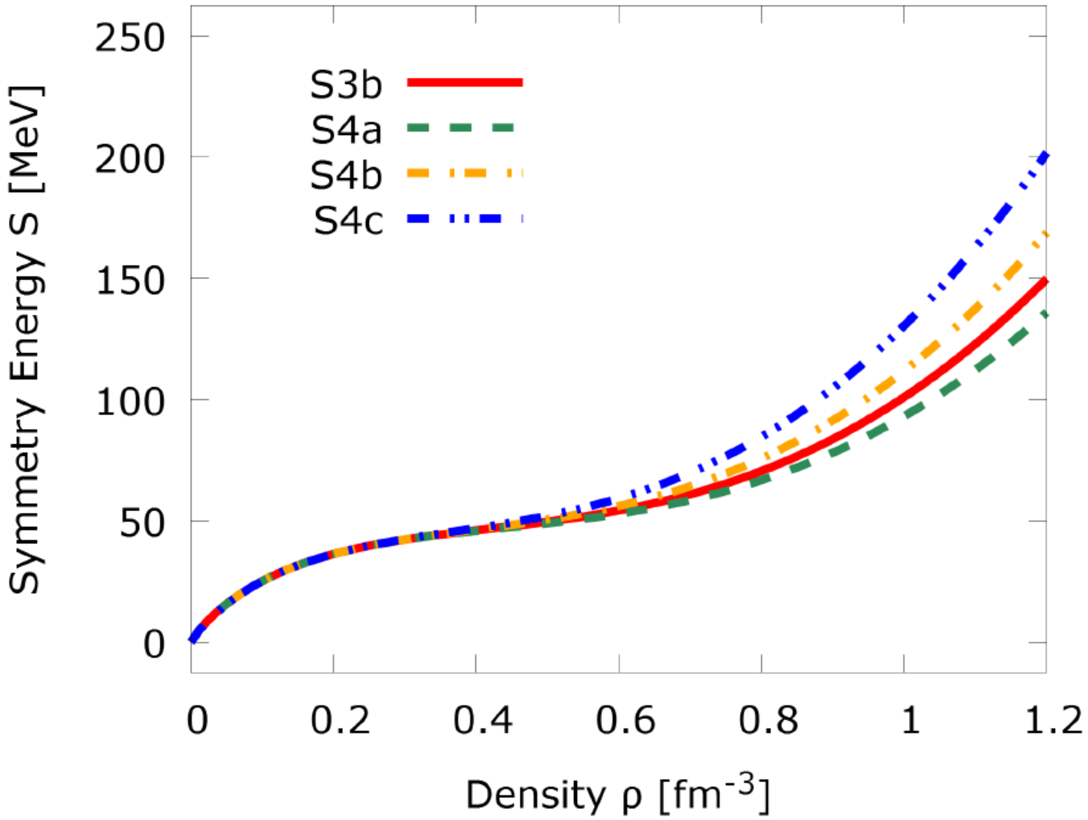
    Q_0 = -360, -390, -420 MeV (skewness)
  - β_i : pure neutron matter EoS of APR, QMC and etc
  - Parameters for closed-shell magic nuclei
    - E/A, R_c of ^{40}Ca, ^{48}Ca, and ^{208}Pb (only 6)
    - Specific values of isoscalar and isovector effective masses m^*_s and m^*_v

- **Result1 : Convergence in nuclear matter** (arXiv:1903.04123)

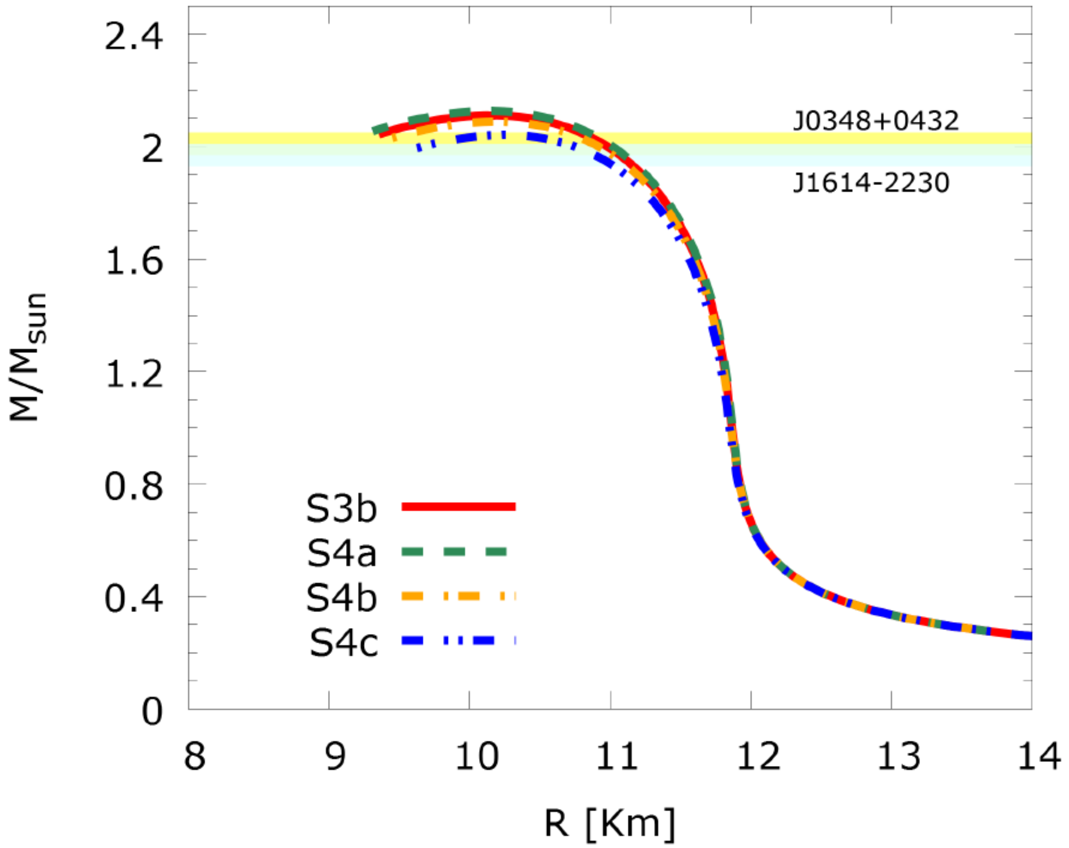
  - S*m*P4: change symmetric part, and fix the number in asym. part to unto i=4.

    m: (4a, 4b, 4c) = Q_0: (-360, -390, -420) MeV

* Symmetry energy



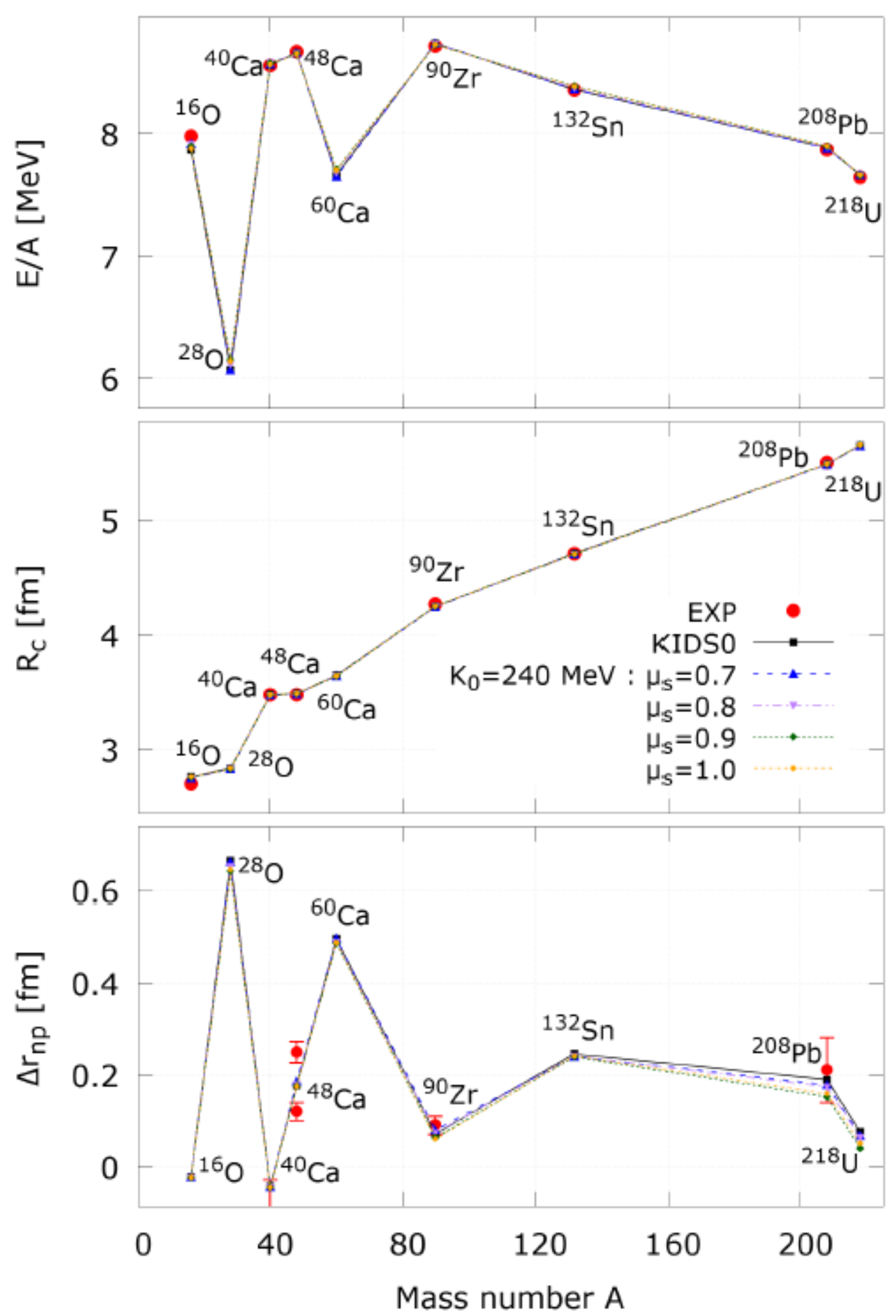
* Neutron star mass-radius



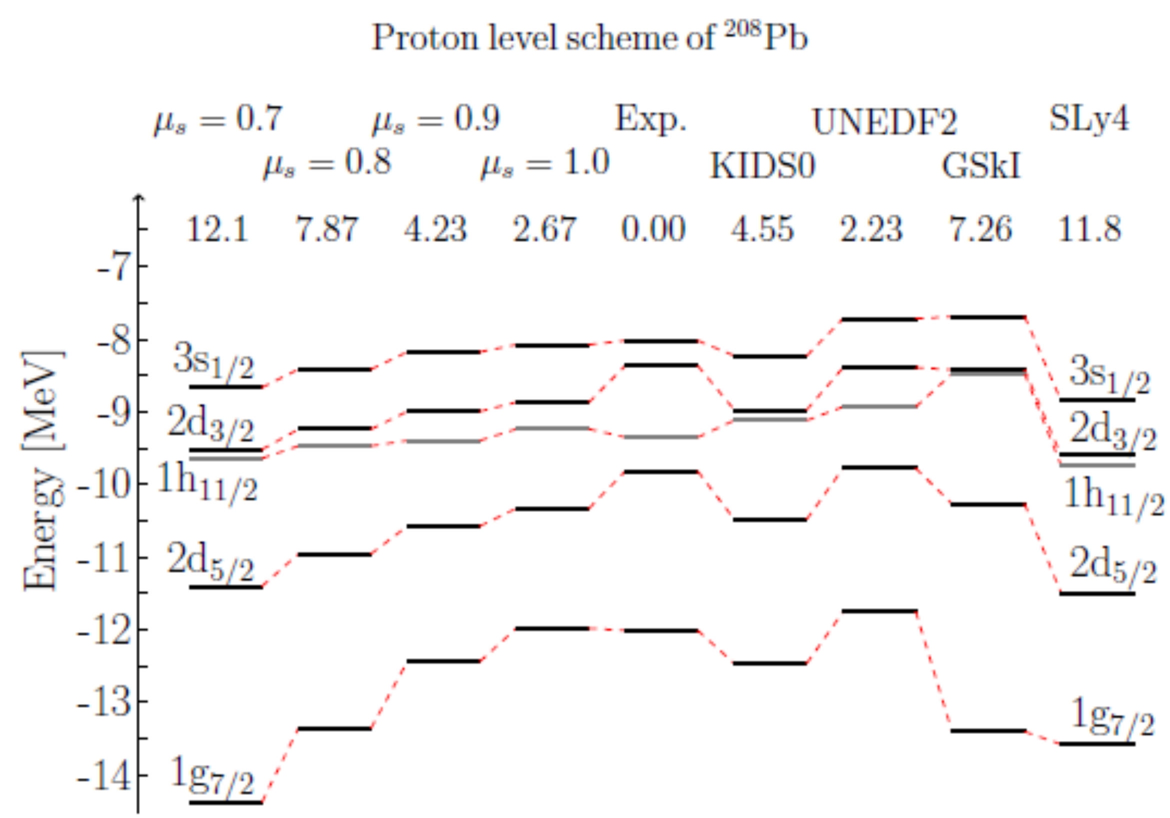
• Result2 : Dependence on the effective mass (arXiv:1805.11321)

$\mu_s = m^*_s / m$ (m: free nucleon mass)

* Bulk properties



* Single particle levels of ^{208}Pb



KIDS nuclear energy density functional

- **Works in progress**
  - Neutron drip line of Ca, Ni, Sn.
  - Heavy-ion collision with DJBUU
  - δ^4 contribution in the symmetry energy
  - Iso-scalar and iso-vector multipole resonances

- **Works in the future**
  - Tensor force
  - Deformation
  - Mass table
  - Super-heavy elements
  - Application to nuclear reactions

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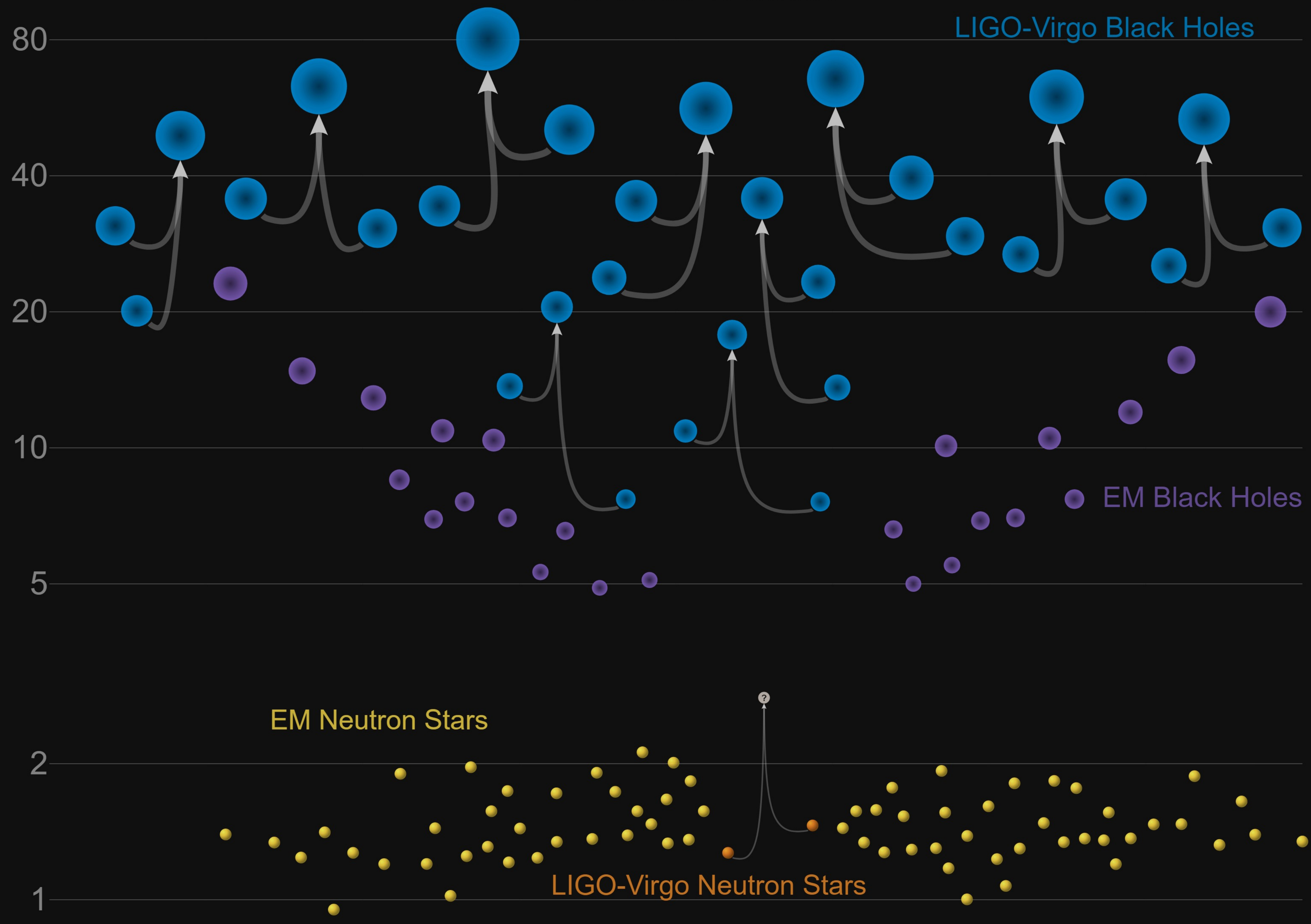
Masses in the Stellar Graveyard

in Solar Masses



LIGO-Virgo | Frank Elavsky | Northwestern

Dec 2019

PRL 119, 161101 (2017)
Selected for a Viewpoint in Physics
PHYSICAL REVIEW LETTERS
week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

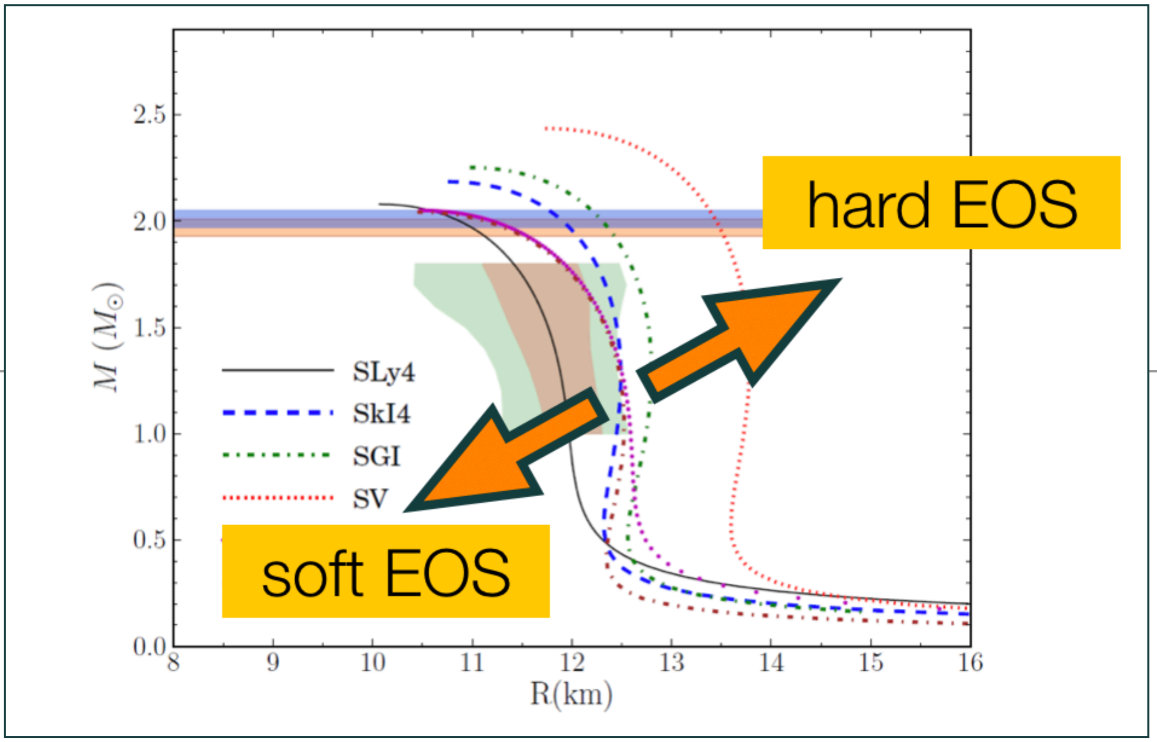
	Low-spin priors ($\|\chi\| \leq 0.05$)	High-spin priors ($\|\chi\| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

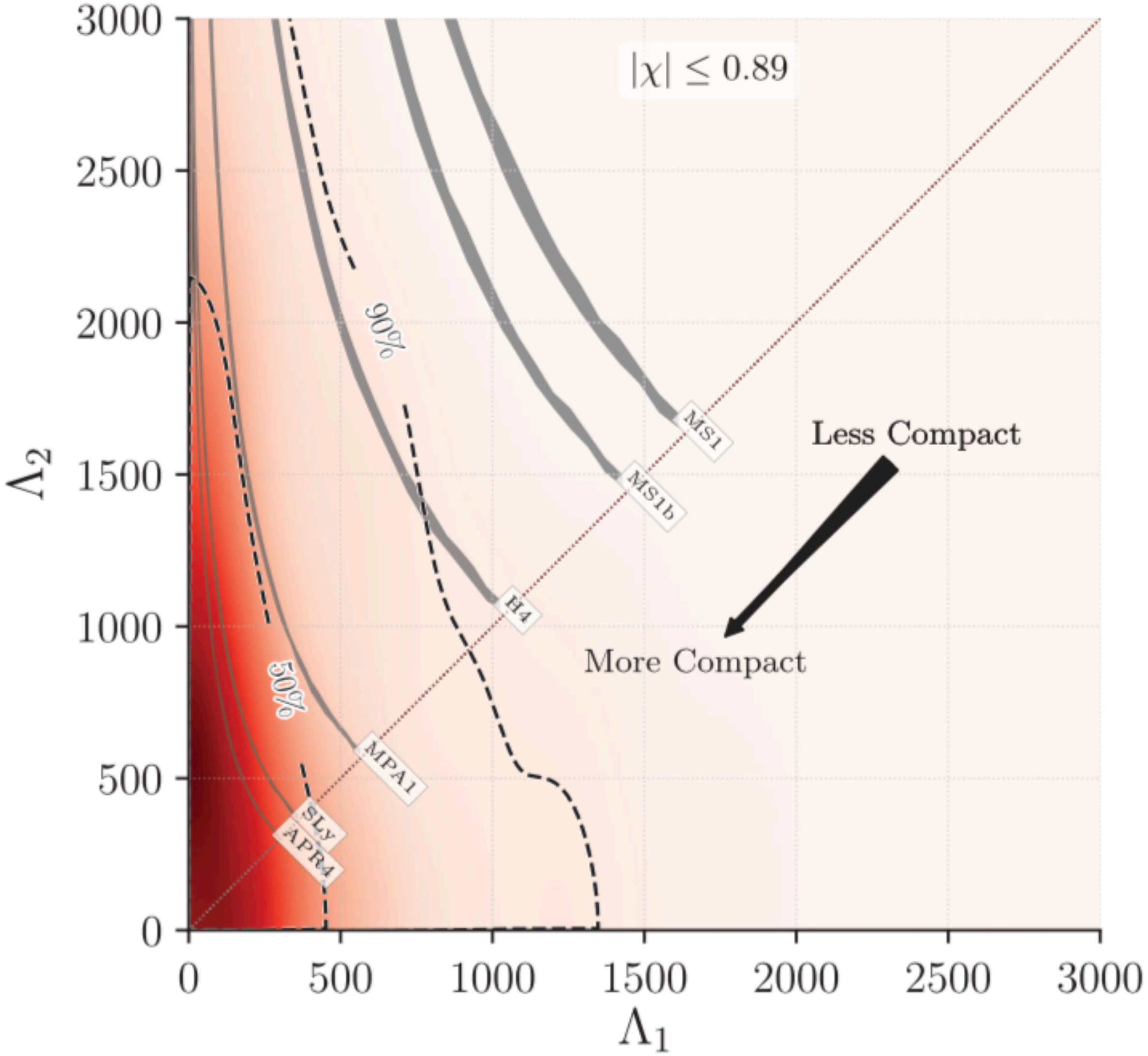
d = 40 Mpc

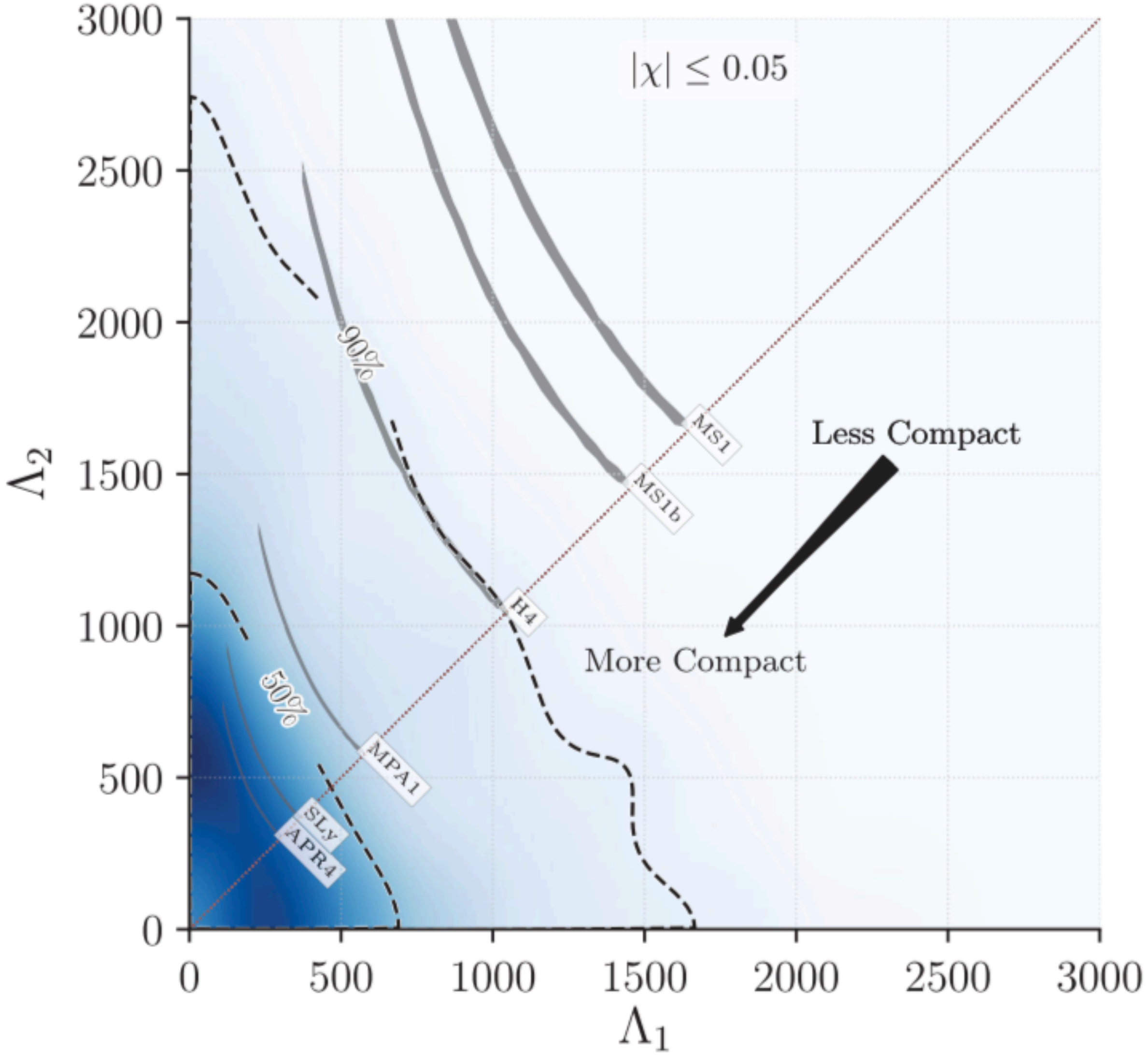
Lambda < 800

GW170817
Information of Neutron Star Structure
has been revealed by Gravitational Waves

perfer lower Λ (soft EOS)







A new constraints by GW obs. (1)

Spectral expansion of adiabatic index [Lindblom et al.]

$$\epsilon(p) = \sum_k \epsilon_k \Phi_k(p).$$

$$\Gamma(p) = \frac{\epsilon + p}{p} \frac{dp}{d\epsilon}$$

$$\frac{d\epsilon(p)}{dp} = \frac{\epsilon(p) + p}{p\,\Gamma(p)}$$

$$\Gamma(p) = \exp\left[\sum_k \gamma_k \Phi_k(p)\right]$$

$$\Gamma(x) = \exp\left(\sum_k \gamma_k\, x^k\right)$$

$$\epsilon(p) = \frac{\epsilon_0}{\mu(p)} + \frac{1}{\mu(p)} \int_{p_0}^{p} \frac{\mu(p')}{\Gamma(p')} dp'$$

$$\mu(p) = \exp\left[-\int_{p_0}^{p} \frac{dp'}{p'\,\Gamma(p')}\right]$$

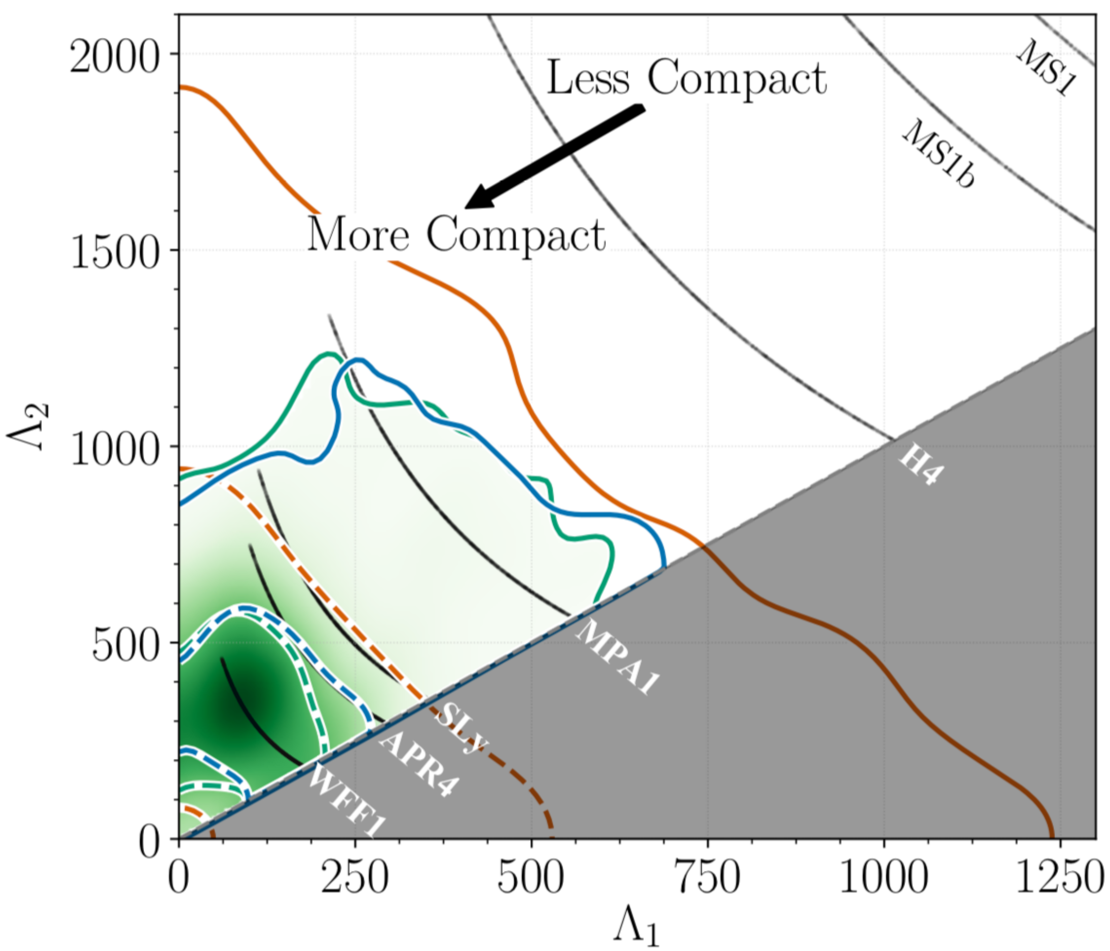
piecewise polytropic EoS

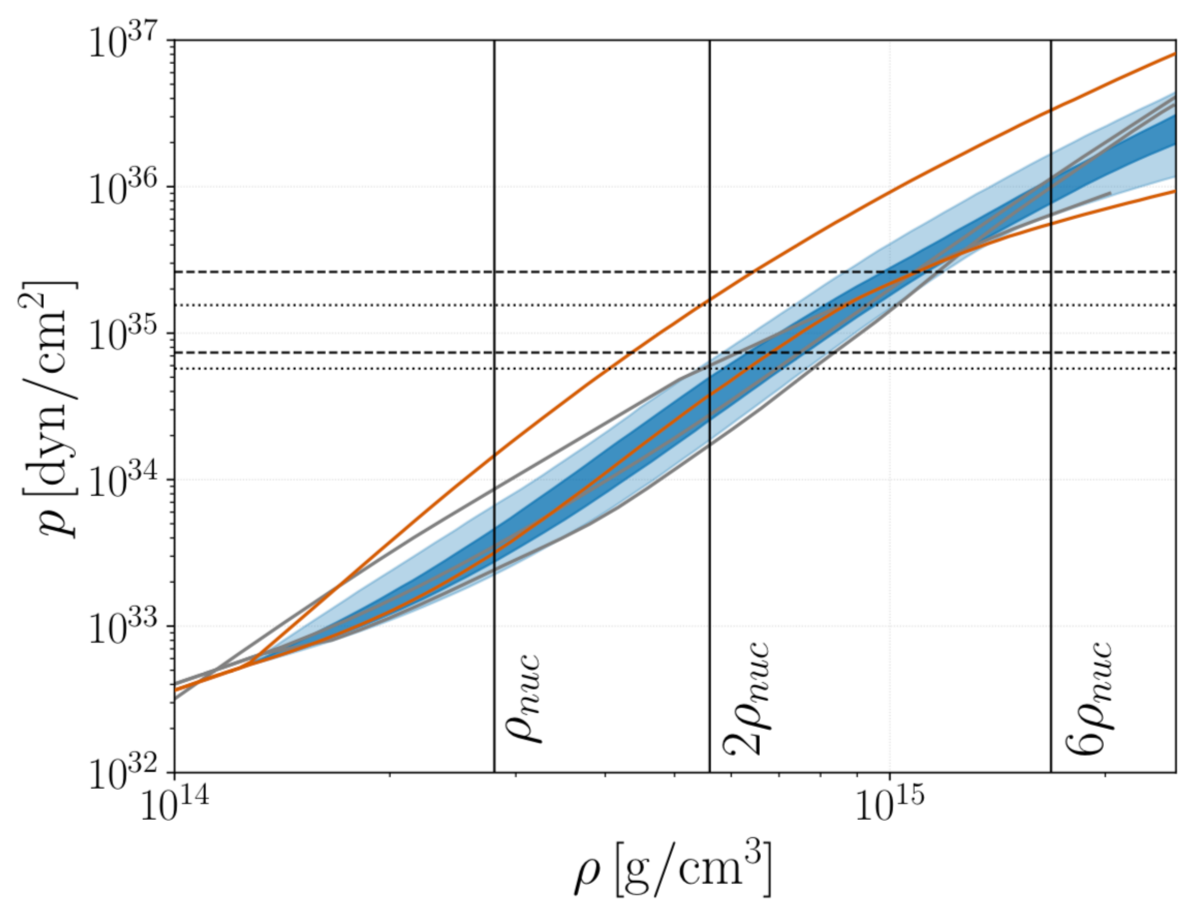
$$p(\rho) = K_i \rho^{\Gamma_i}$$

A new constraints by GW obs. (1)

$\Lambda(1.4M_\odot)=190^{+390}_{-120}$

$P(2\,\rho_{nuc}) = 3.5^{+2.7}_{-1.7} \times 10^{34}$ dyne/cm^2
$P(6\,\rho_{nuc}) = 9.0^{+7.9}_{-2.6} \times 10^{35}$ dyne/cm^2





$\rho_{nuc} = 2.8 \times 10^{14}$ g/cm^3

Abbott et al. (LSC and Virgo), PRL 121, 161101 (2018)

A new constraints by GW obs. (2)

Universal (Eos-insensitive) relations

Yagi & Yunes, PR 681, 1 (2017)

I-Love-Q relation, …

- Moment of inertia (I)
- Tital Love number (Love)
- Quardupole moment (Q)

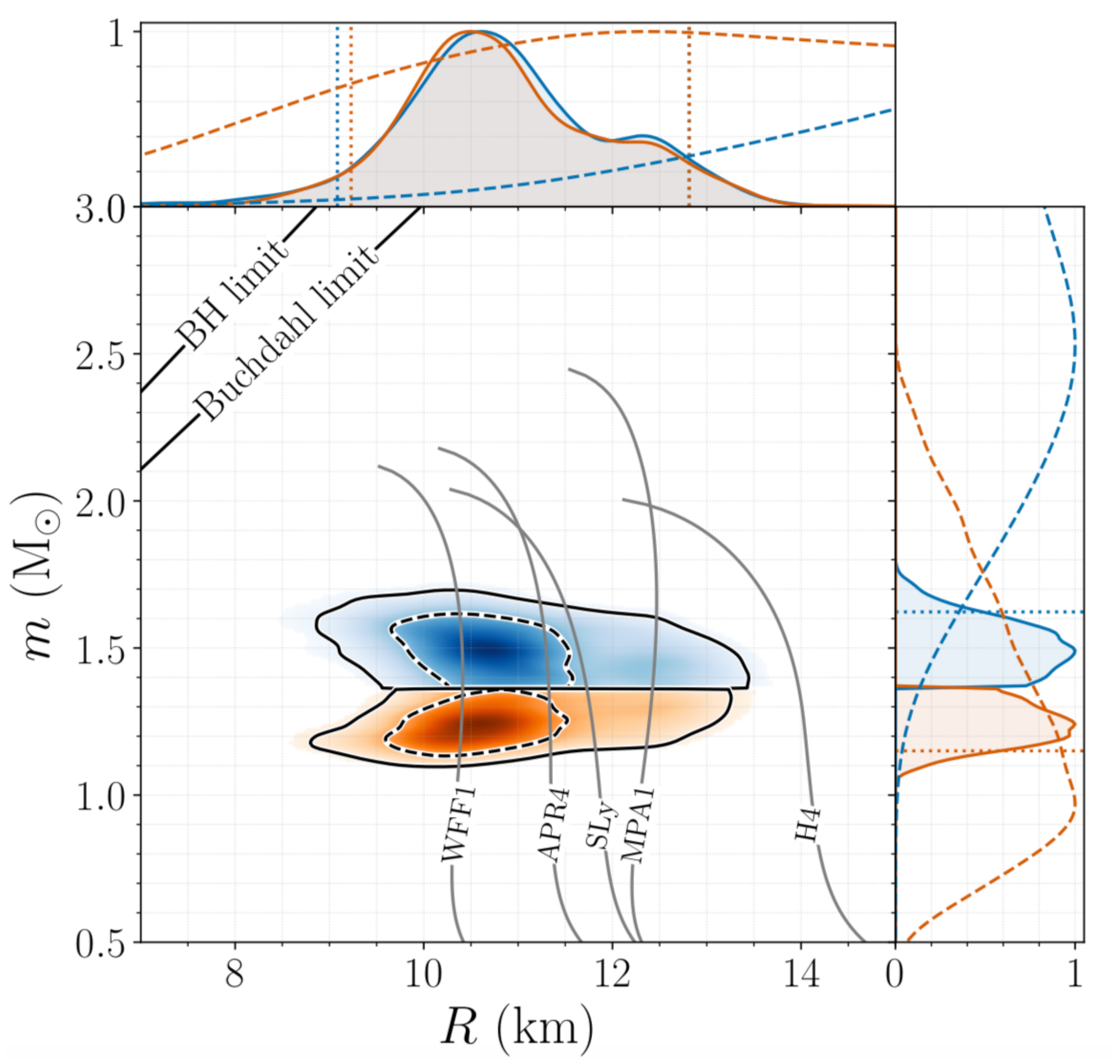
Applications

- X-ray observations
- Gravitational-wave measurements
- Gravitational & astrophysical test of GR

A new constraints by GW obs. (2)

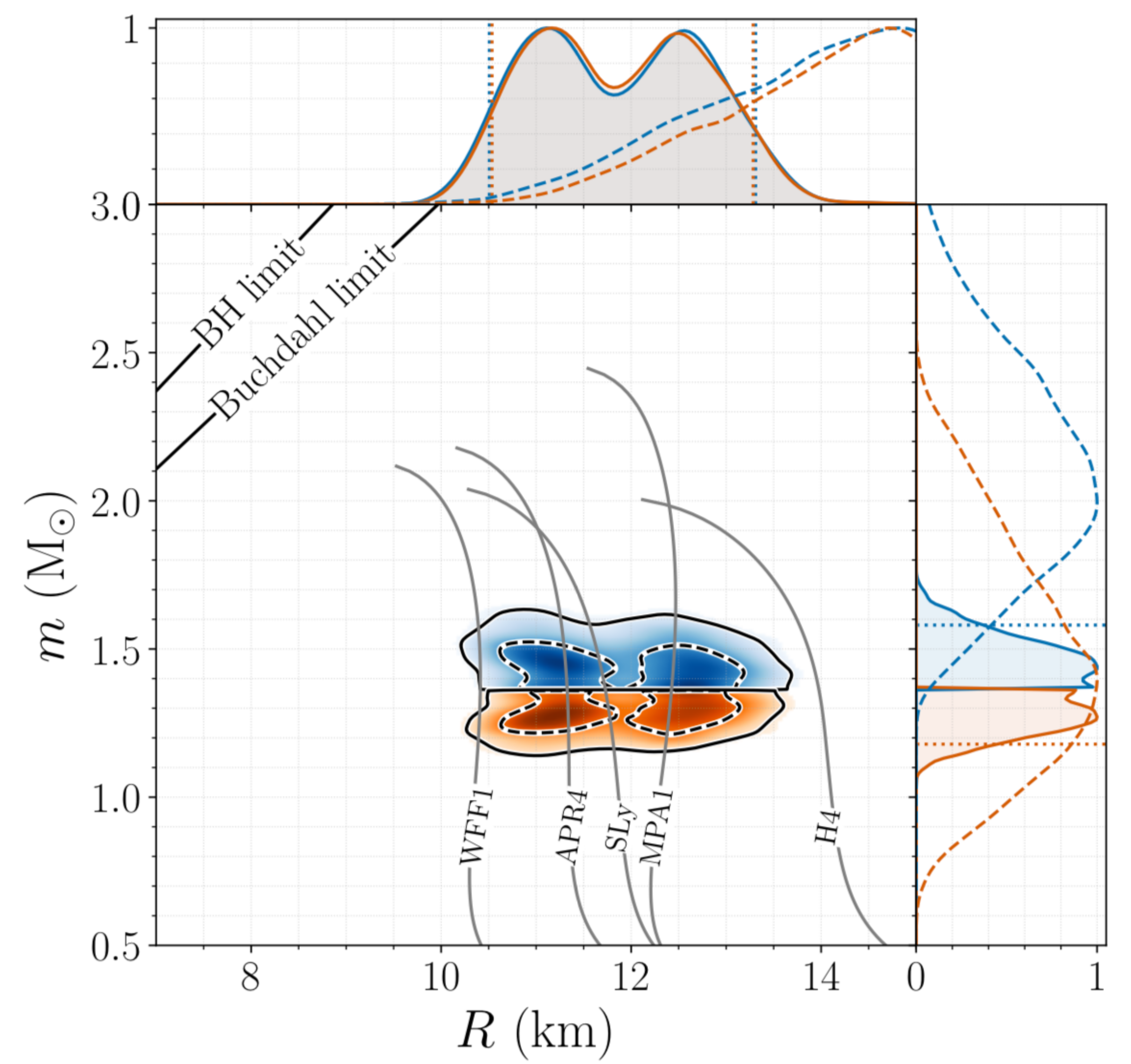
EoS insensitive relations (Yagi&Yunes,PR2017)

R_1=10.8 $^{+2.0}_{-1.7}$ km
R_2=10.7 $^{+2.1}_{-1.5}$ km



Parametrized EoS: M_{max} >= 1.97 $M_\odot$

R_1=11.9 $^{+1.4}_{-1.4}$ km
R_2=11.9 $^{+1.4}_{-1.4}$ km



Abbott et al. (LSC and Virgo), PRL 121, 161101 (2018)

What we have done in Korea

PHYSICAL REVIEW C **98**, 065805 (2018)

Tidal deformability of neutron stars with realistic nuclear energy density functionals

Young-Min Kim,[1] Yeunhwan Lim,[2] Kyujin Kwak,[1] Chang Ho Hyun,[3] and Chang-Hwan Lee[4]
[1]*School of Natural Science, Ulsan National Institute of Science and Technology (UNIST), Ulsan 44919, Korea*
[2]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
[3]*Department of Physics Education, Daegu University, Gyeongsan 38453, Korea*
[4]*Department of Physics, Pusan National University, Busan 46241, Korea*

(Received 1 May 2018; revised manuscript received 14 August 2018; published 26 December 2018)

Nuclear Physics + Astrophysics

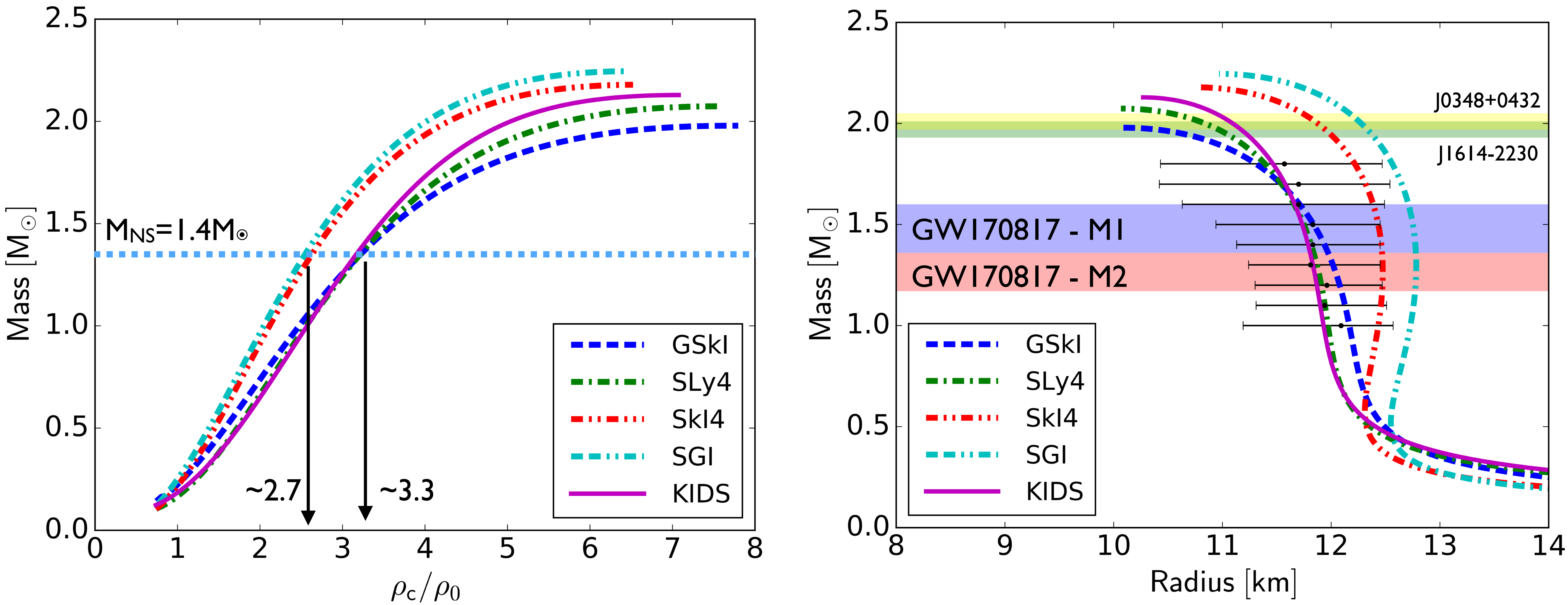
Constraints on Nuclear EoS

- Nuclear data: hundreds of models (Skyrme force, RMF, …)
- Neutron star maximum mass
  1.97 ± 0.04 M⊙ [Nature 467, 1081 (2010)]
  2.01 ± 0.04 M⊙ [Science 340, 448 (2013)]
- 11 experimental/empirical data for nuclear matter around saturation density [Phys.Rev. C 85, 035201 (2012)]

Constraint	Quantity	Eq.	Density Region	Range of constraint exp/emp	Range of constraint from CSkP	Ref.
SM1	K_o	(7),(15)	ρ_o (fm^{-3})	200 – 260 MeV	202.0 – 240.3 MeV	[64]
SM2	$K' = -Q_o$	(8),(16)	ρ_o (fm^{-3})	200 – 1200 MeV	362.5 – 425.6 MeV	[65]
SM3	$P(\rho)$	(6)	$2 < \frac{\rho}{\rho_o} < 3$	Band Region	see Fig. 1	[78]
SM4	$P(\rho)$	(6)	$1.2 < \frac{\rho}{\rho_o} < 2.2$	Band Region	see Fig. 2	[80]
PNM1	$\frac{E_{PNM}}{E^o_{PNM}}$	(31)	$0.014 < \frac{\rho}{\rho_o} < 0.106$	Band Region	see Fig. 3	[39, 40]
PNM2	$P(\rho)$	(6)	$2 < \frac{\rho}{\rho_o} < 3$	Band Region	see Fig. 5	[78]
MIX1	J	(9)	ρ_o (fm^{-3})	30 – 35 MeV	30.0 – 35.5 MeV	[44]
MIX2	L	(10)	ρ_o (fm^{-3})	40 – 76 MeV	48.6 – 67.1 MeV	[101]
MIX3	$K_{\tau,v}$	(21)	ρ_o (fm^{-3})	-760 – -372 MeV	-407.1 – -360.1 MeV	[107]
MIX4	$\frac{S(\rho_o/2)}{J}$	-	ρ_o (fm^{-3})	0.57 – 0.86	0.61 – 0.67	[110]
MIX5	$\frac{3P_{PNM}}{L\rho_o}$	(41)	ρ_o (fm^{-3})	0.90 – 1.10	1.02 – 1.10	[112]

Mass-Radius relations

Kim et al., arxiv:1805.00219

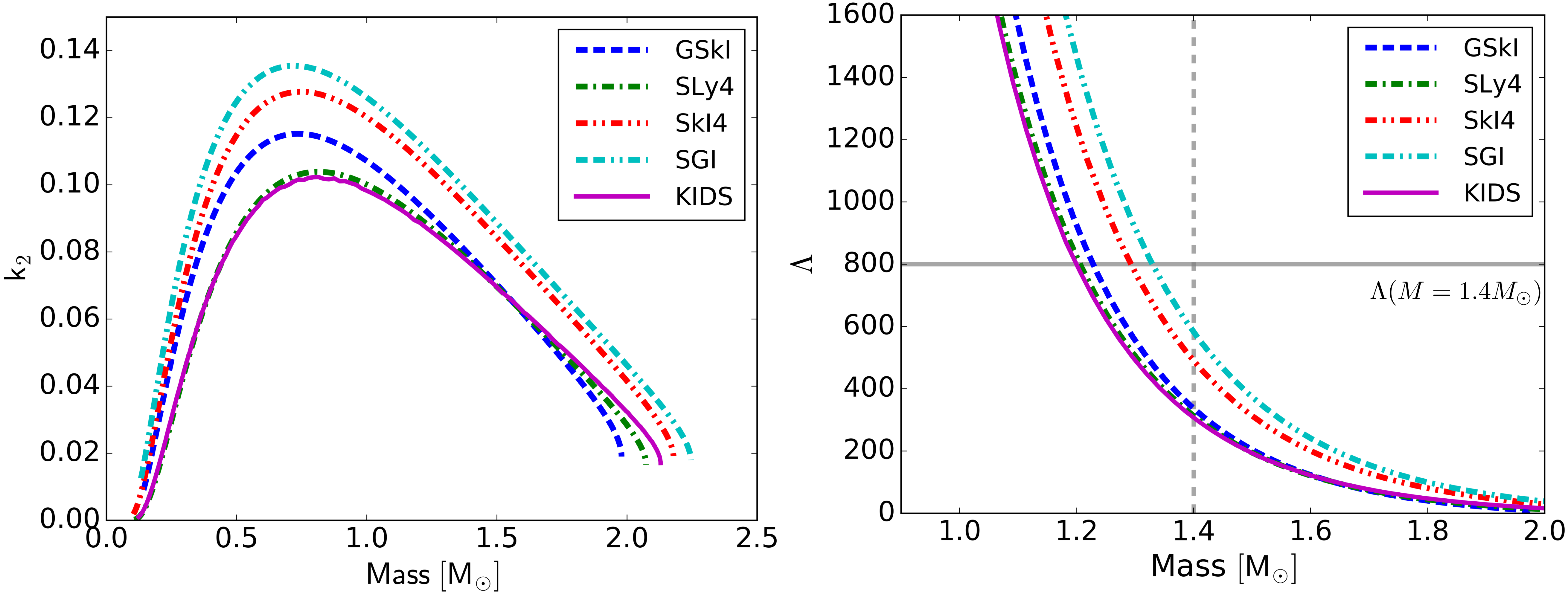


GW170817

- Mchirp = 1.188 $M_\odot$
- low spin prior : M1 = 1.36 ~ 1.60 $M_\odot$, M2 = 1.17 ~ 1.36 $M_\odot$
- high spin prior : M1 = 1.36 ~ 2.26 $M_\odot$, M2 = 0.86 ~ 1.36 $M_\odot$

Tidal deformability of a NS

Kim et al., arxiv:1805.00219



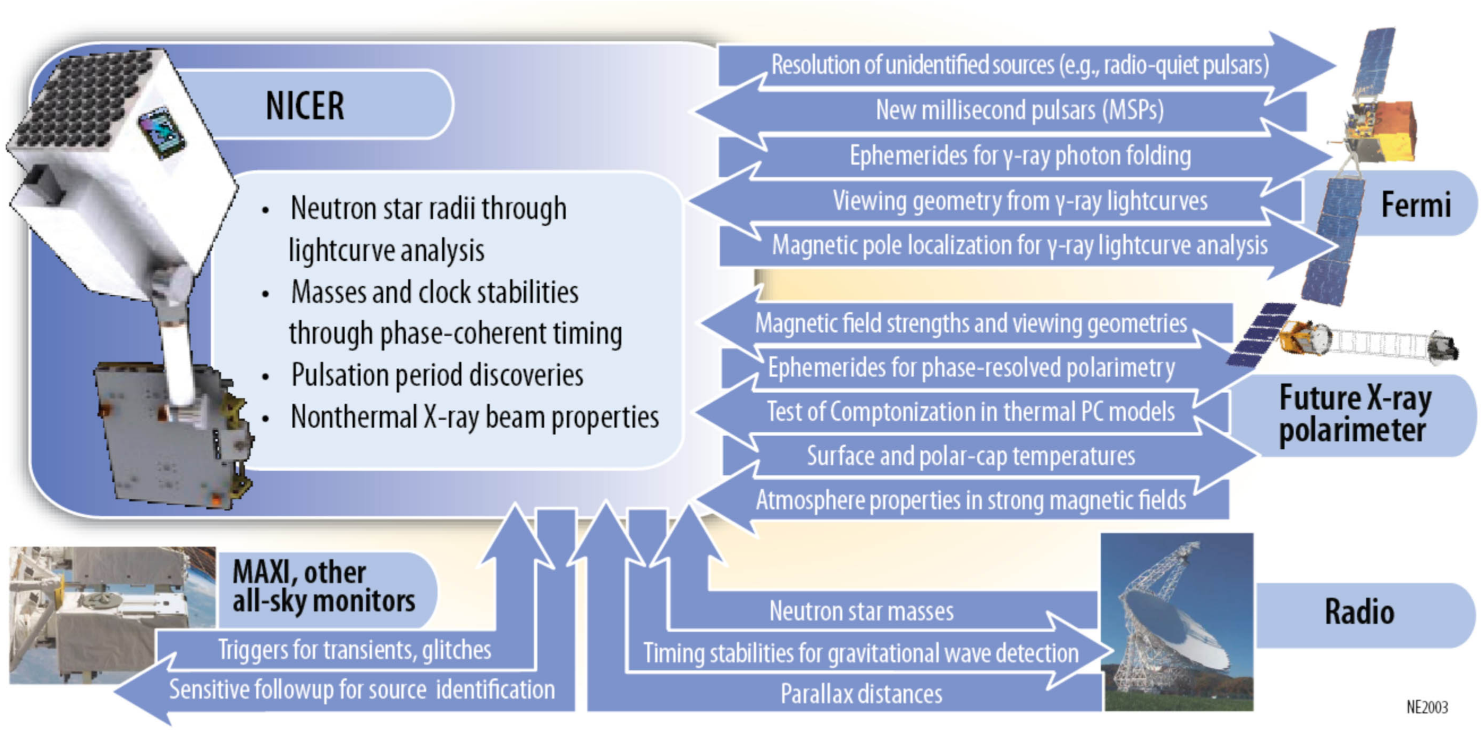
$$\Lambda = G\left(\frac{c^2}{Gm}\right)^5 \times \frac{2}{3}\frac{R^5}{G}k_2 = \frac{2}{3}\left(\frac{Rc^2}{Gm}\right)^5 k_2 \approx 9495\left(\frac{R_{10\mathrm{km}}}{m_{M_\odot}}\right)^5 k_2$$

Contents

- **Introduction of RAON** (new rare isotope accelerator in Korea)
- **NS EoS studies before RAON & GW detection**
- **NS EoS in the new era of multi-messenger astrophysics**
  - Direct measurement of NS mass from GW
  - Tidal Love number/deformability of NS from GW
- **Prospects**

NICER Neutron star Interior Composition ExploreR

- **launch**: June 2017, SpaceX
- **platform**: ISS ELC (ExPRESS Logistics Carrier)
- **instrument**: X-ray (0.2-12 keV)
- **objective**
  - ***structure***: neutron star radii to 5%, cooling timescales
  - ***dynamics***: stability of pulsars as clocks, properties of outbursts, oscillations, and precession
  - ***energetics***: intrinsic radiation patterns, spectra, and luminosities



Prospects of the Observing Runs

"Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA",
arXiv:1304.0670v4, LIGO-P1200087-v45, Living Rev. Relativity, 21, 3 (2018)

Epoch		2015 – 2016	2016 – 2017	2018 – 2019	2020+	2024+
Planned run duration		4 months	9 months	12 months	(per year)	(per year)
Expected burst range/Mpc	LIGO	40 – 60	60 – 75	75 – 90	105	105
	Virgo	—	20 – 40	40 – 50	40 – 70	80
	KAGRA	—	—	—	—	100
Expected BNS range/Mpc	LIGO	40 – 80	80 – 120	120 – 170	190	190
	Virgo	—	20 – 65	65 – 85	65 – 115	125
	KAGRA	—	—	—	—	140
Achieved BNS range/Mpc	LIGO	60 – 80	60 – 100	—	—	—
	Virgo	—	25 – 30	—	—	—
	KAGRA					
Estimated BNS detections		0.05 – 1	0.2 – 4.5	1 – 50	4 – 80	11 – 180
Actual BNS detections		0	1	—	—	—
90% CR % within	5 deg^2	< 1	1 – 5	1 – 4	3 – 7	23 – 30
	20 deg^2	< 1	7 – 14	12 – 21	14 – 22	65 – 73
	median/deg^2	460 – 530	230 – 320	120 – 180	110 – 180	9 – 12
Searched area % within	5 deg^2	4 – 6	15 – 21	20 – 26	23 – 29	62 – 67
	20 deg^2	14 – 17	33 – 41	42 – 50	44 – 52	87 – 90

We expect to observe more BNS and/or NS-BH

Slide by YMKim

Prospect

- **NICER** for Low-mass X-ray Binaries
  - Formation & Evolution of Neutron Star Binaries
  - NS radii within 5%
- **GW** from NS mergers
  - April 25, 2019 : NS-NS merger candidate (500 Mly, 153 Mpc)
  - April 26, 2019 : NS-BH merger candidate (1.2 Gly, 368 Mpc)
  - … …
- **RAON**
  - Effective Models for Nuclei
  - Symmetry Energy
  - Transport Studies : DJBUU (DaeJeon BUU) - next two talks

Measurement error vs. source distance

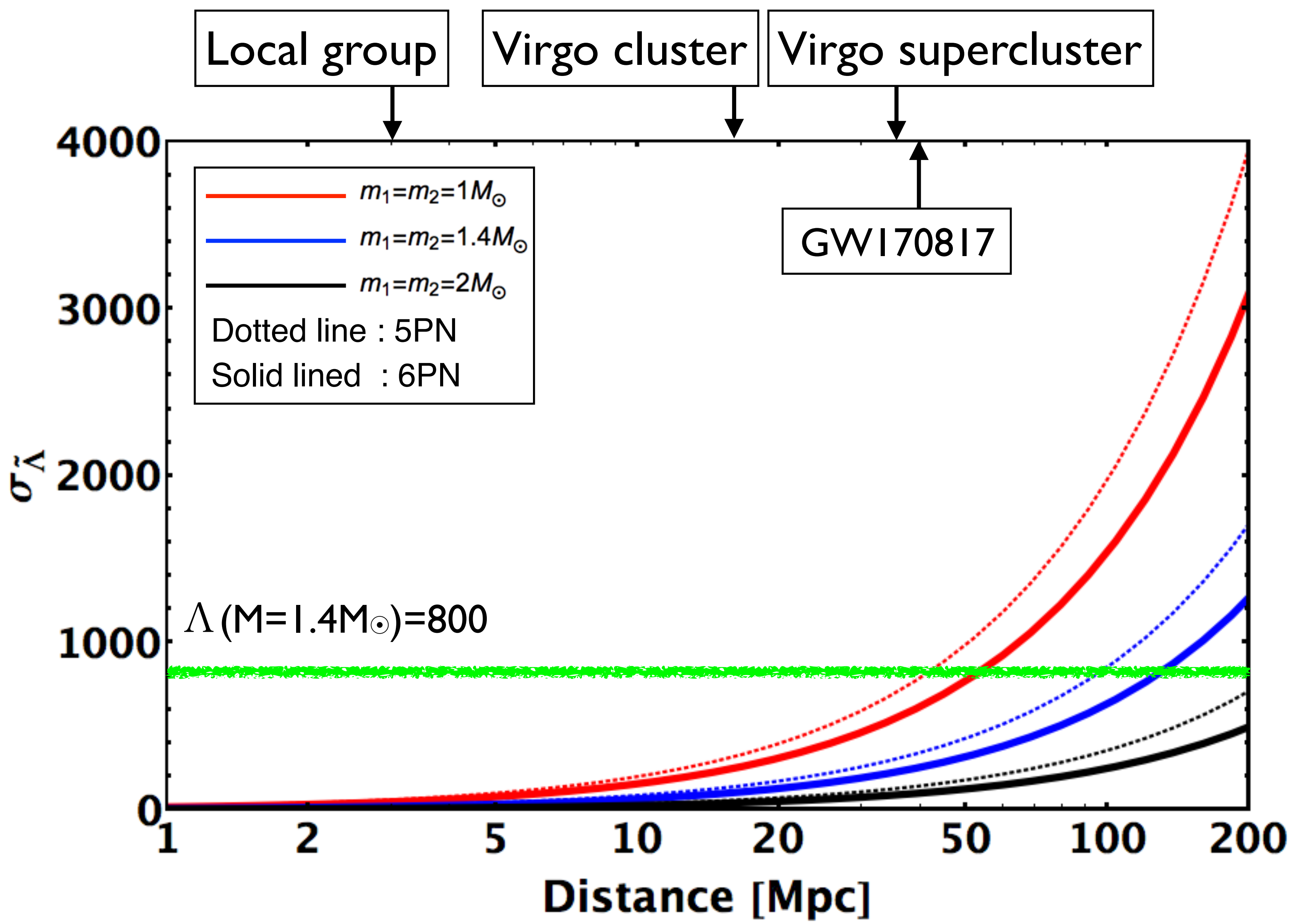


Fig. 1: Tidal deformability measurement error vs distance to the source. distances to galaxy clusters and GW20170817 distance are marked.

Y.B. Choi, H. S. Cho, C.-H. Lee

QCS2019 Busan, Korea

Asian Triangle Meeting

- QCS2014 Beijing, China
- QCS2017 Kyoto, Japan

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qcs2019.busan@gmail.com

https://www.apctp.org/plan.php/qcs2019