ECT*@2019.10.17

NS EOS and tidal deformability with nuclear energy functionals

Chang-Hwan Lee / Pusan National University

Dense Nuclear & Stellar Matter Studies

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

BUD[2] *Collaboration*

***B**usan (**CHL**, Myungkuk KIM)*
***U**lsan (**Kyujin KWAK**, Young-Min KIM)*
***D**aegu (**Chang Ho HYUN**, …)*
***D**aejeon (**Youngman KIM**, …)*
*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.
New Transport DJBUU **Nuclear Structure DRHBc**	**2017**	**GW from NS-NS mergers** (Multi-messenger Astrophysics) Tidal deformability of NS
First run of RAON Symmetry Energy (later)	**2021**	

BUD² 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... + 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 deform...

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)

Works with G.E. Brown & H.A. Bethe

1999

The formation of high-mass black holes in low-mass X-ray binaries

G.E. Brown[a,1], C.-H. Lee[a,2], Hans A. Bethe[b,3]

2000

HYPERCRITICAL ADVECTION-DOMINATED ACCRETION FLOW

G. E. Brown and C.-H. Lee

Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794

and

H. A. Bethe

A theory of gamma-ray bursts

G.E. Brown[a], C.-H. Lee[a], R.A.M.J. Wijers[a], H.K. Lee[b], G. Israelian[c], H.A. Bethe[d]

Evolution of black holes in the galaxy

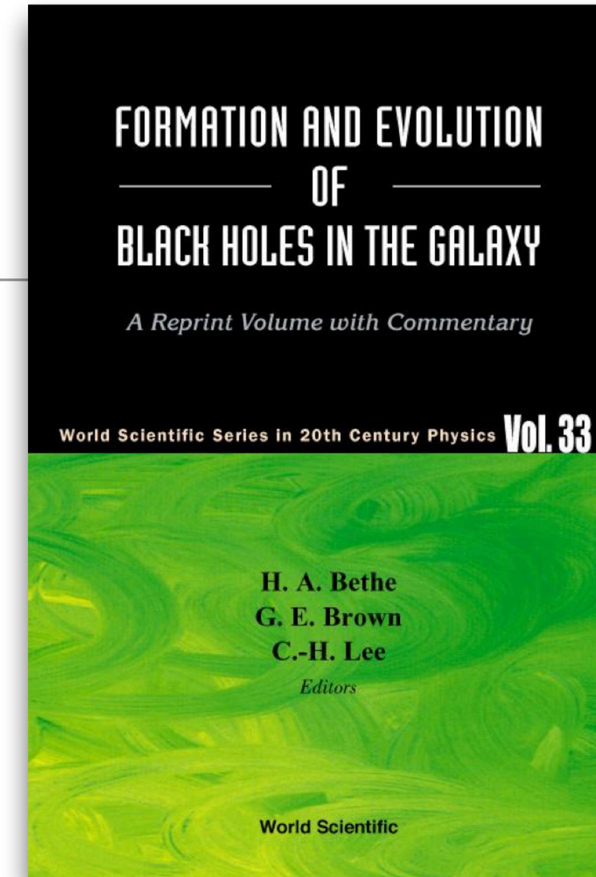
G.E. Brown[a,*], C.-H. Lee[a], R.A.M.J. Wijers[a], H.A. Bethe[b]

2001

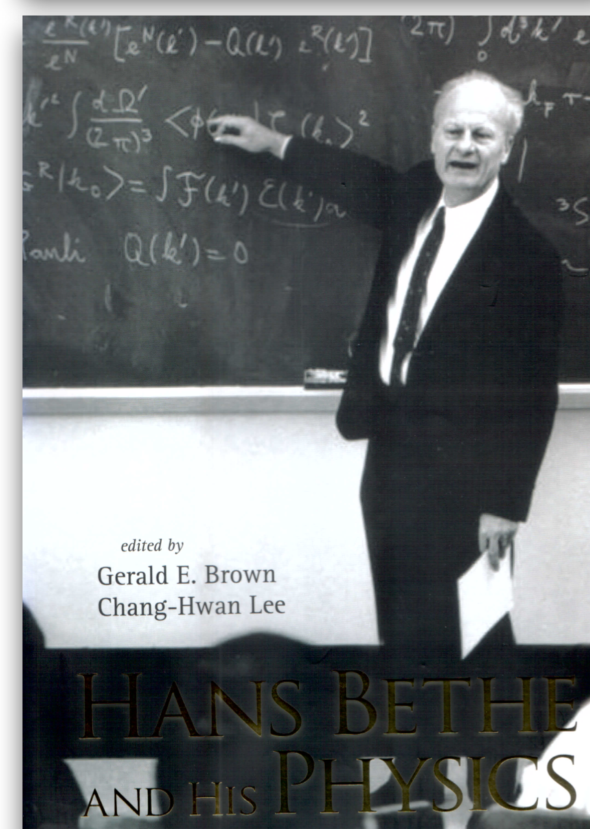
Formation of high mass X-ray black hole binaries

G.E. Brown[a], A. Heger[b], N. Langer[c], C.-H. Lee[a,d,*], S. Wellstein[e], H.A. Bethe[f]

2003



2006



Contents

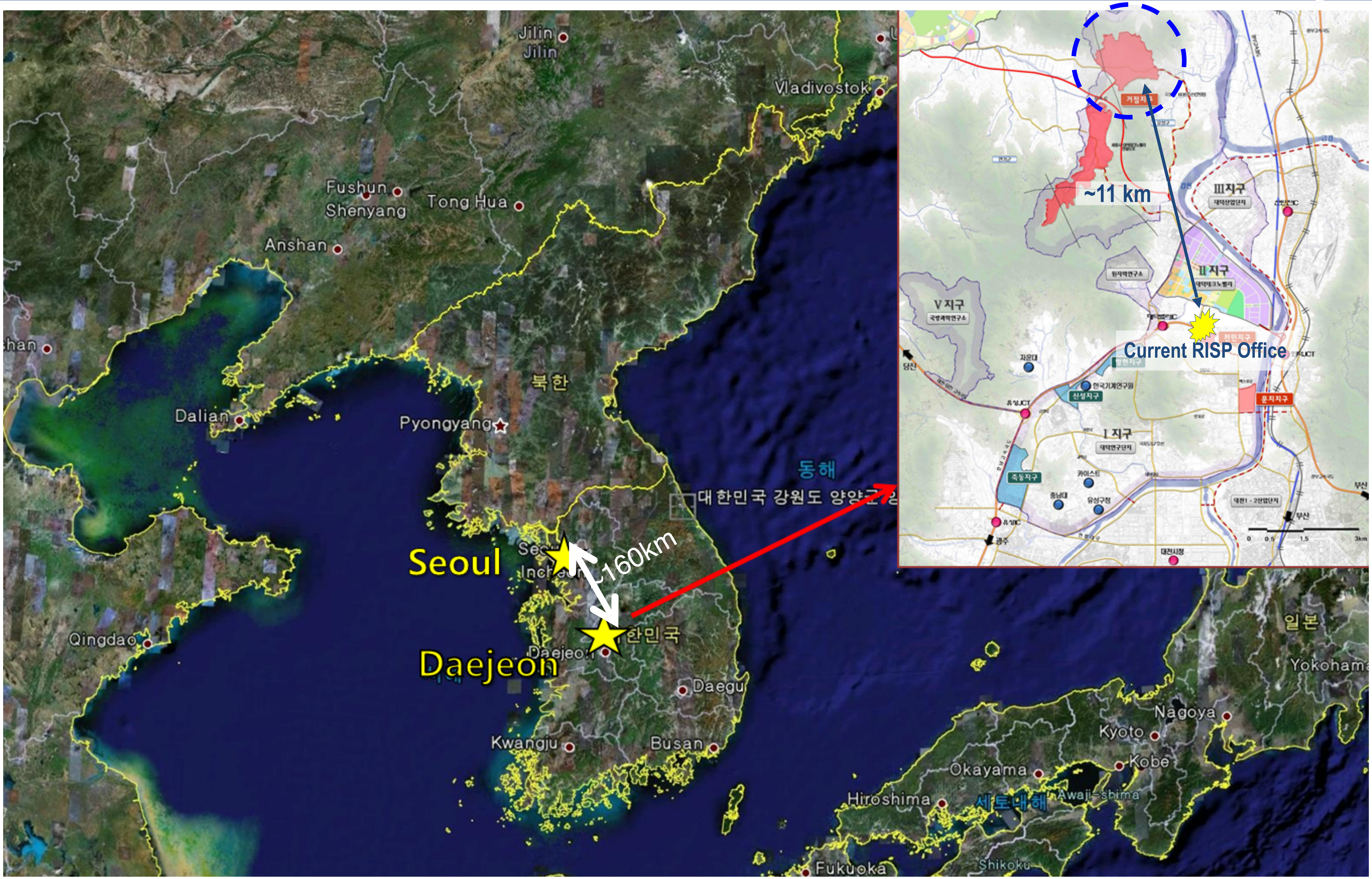
1. **Introduction of RAON**
   - new rare isotope accelerator in Korea
2. **Possible origin of high-mass neutron stars**
   - NS binary evolution (work done before GW detection)
3. **New development in BUD^2 Collaboration**
   - KIDS: new energy density functional
   - Application of KIDS to NS properties
4. **Prospects**

Laboratory probes of the nuclear matter EOS

RAON Rare isotope Accelerator complex for ON-line experiments

Courtesy of
Youngman Kim (IBS)
Seung-Woo Hong (RAON User Liaison Center, SKKU)

RAON Site : Sindong in Daejeon

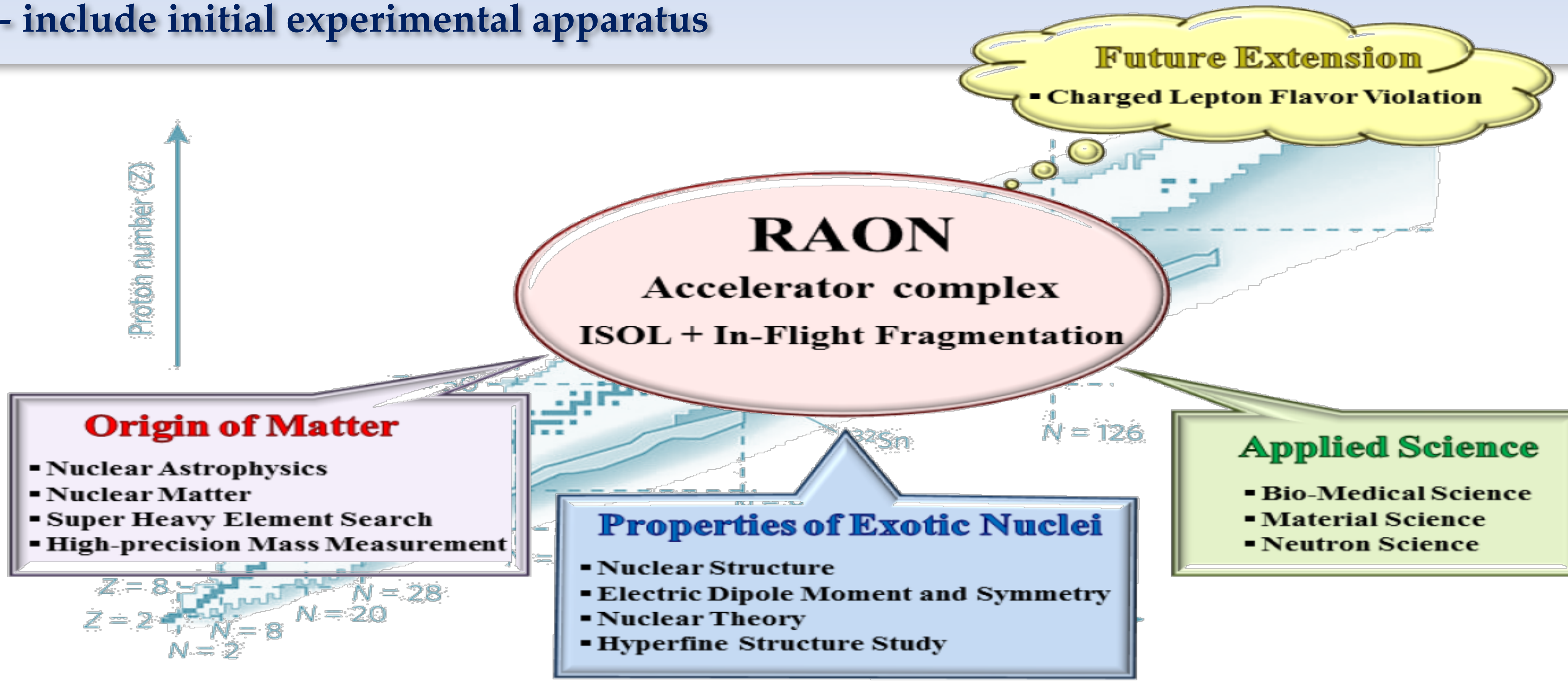


Rare Isotope Science Project (RISP)

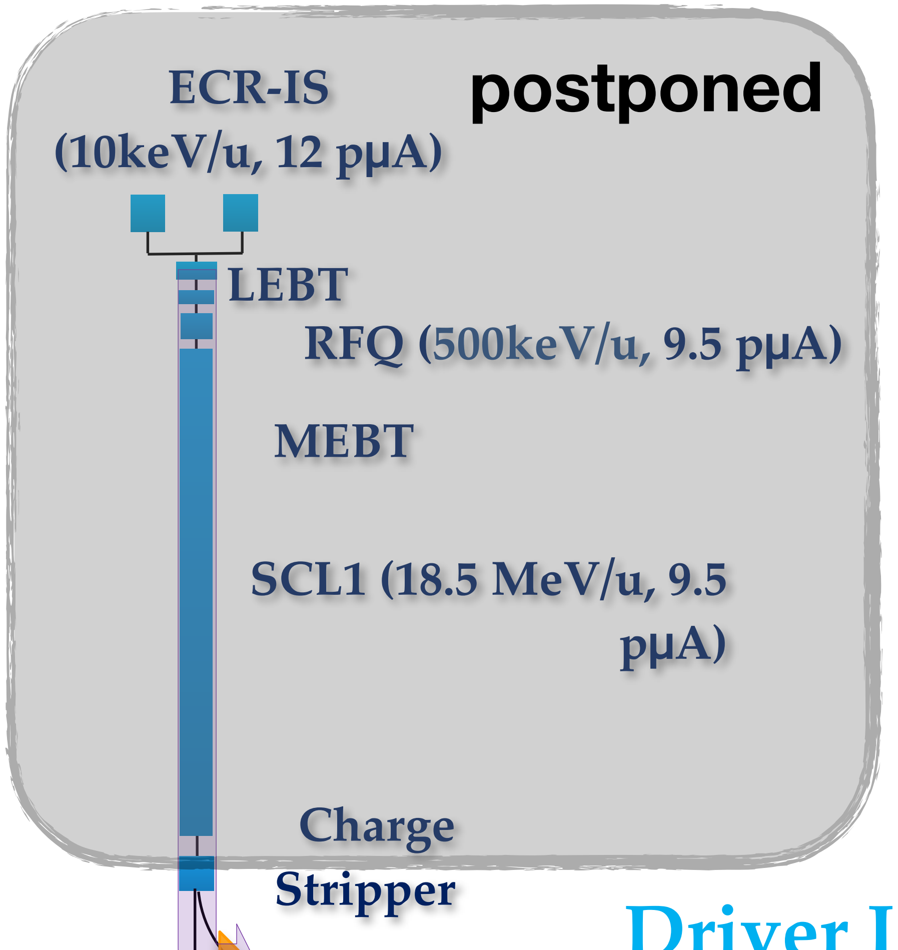
- Goal : To build a heavy ion accelerator complex RAON for rare isotope science researches in Korea
- Project period : 2011.12 - 2021.12
- Total Budget : ~$ 1.43 billion

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

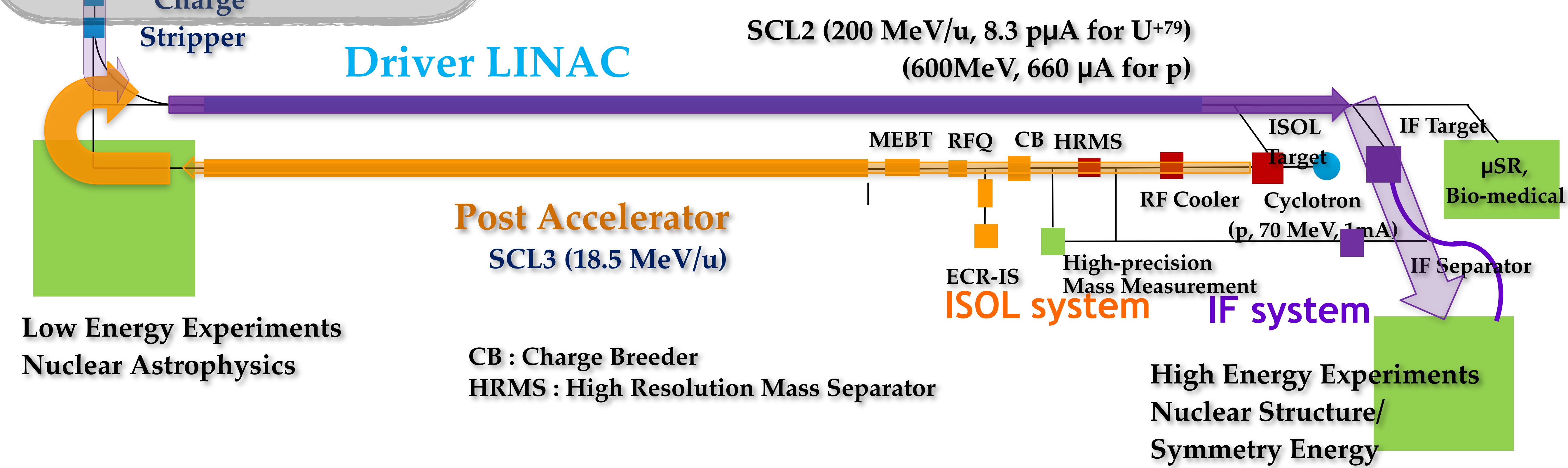
- include initial experimental apparatus



RAON Concept

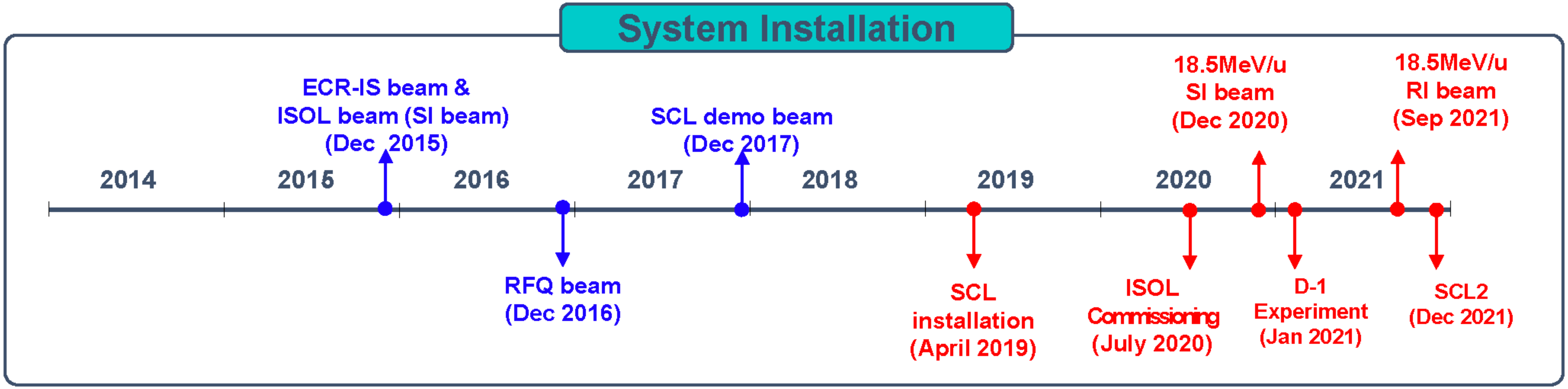


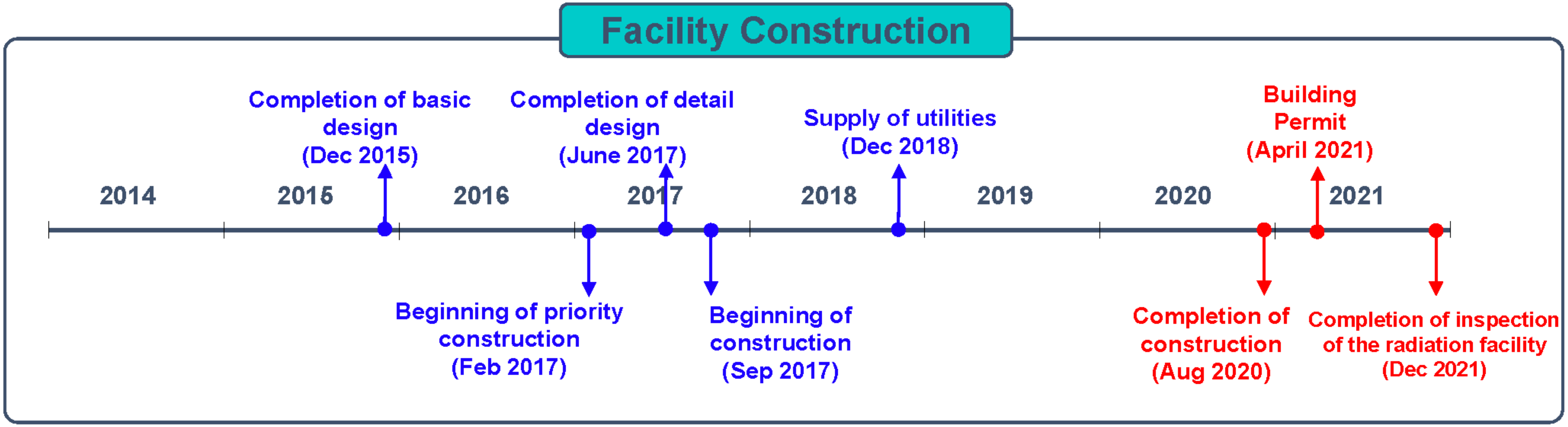
- ❑ High intensity RI beams by ISOL & IF
  - ISOL : direct fission of ^{238}U by 70MeV protons
  - IF : 200MeV/u, 8.3pμA of ^{238}U
- ❑ High quality neutron-rich RI beams
  - ^{132}Sn with up to ~250MeV/u, up to ~10^8 pps
- ❑ More exotic RI beams by ISOL+IF



Project Milestone

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






Sep. 2019
Area ~ 1M m²

Installation of the First Superconducting Cavites and Cryomodules
2019.9.26

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 ~)

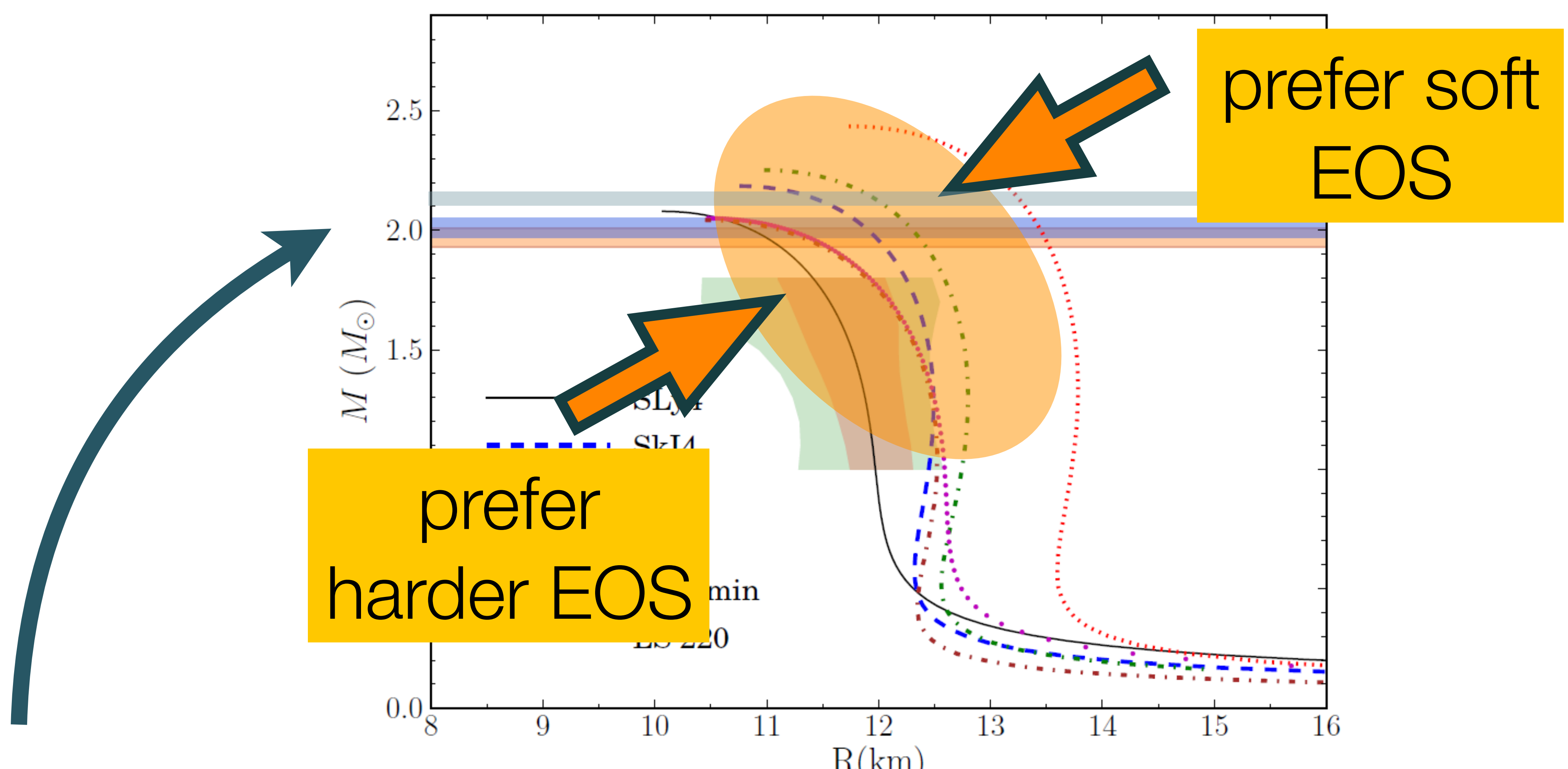
- Beam acceleration for ISOL → SCL3 → SCL2 → IF **(ISOL+IF)**
- Beam commissioning and experiments for IF, LAMPS, Neutron, bio-medical and muSR
- **Ramping-up to get the 400kW beams (more than 5 yrs)**
- Energy upgrade to 400MeV/u (requires budget)

Contents

Mass & radius of neutron star

Tidal deformability of NS from GW

Strangeness in NS



Neutron Star-White Dwarf Binaries

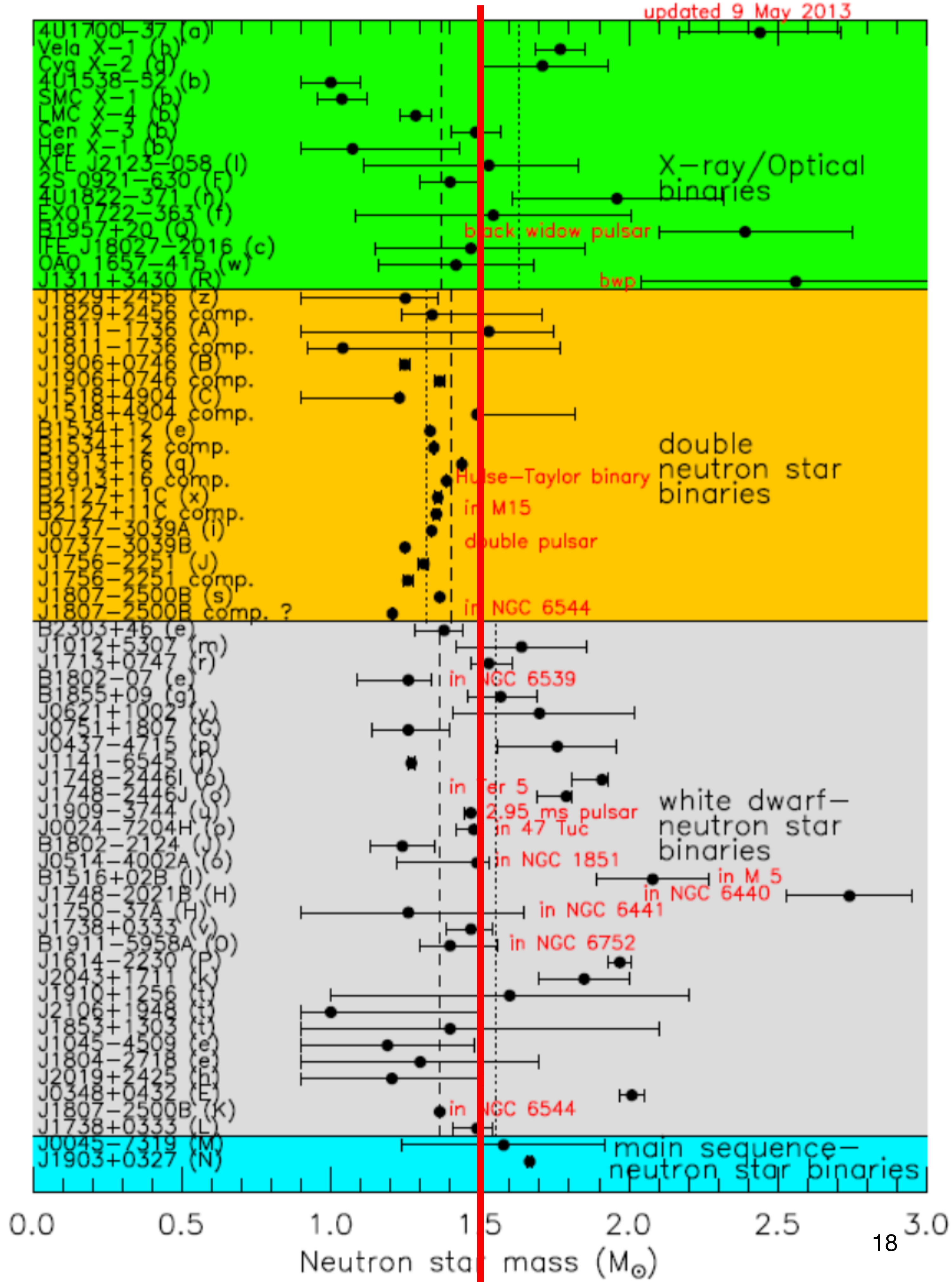
1.97 solar mass NS : Nature (2010)

2.01 solar mass NS : Science (2013)

2.14 solar mass NS : Nature Astronomy (2019)

All well measured NS masses in NS-NS binaries are less than 1.5 solar mass!

Why?



Prakash (2013)

Our open questions

2 $M_\odot$ NS has been observed in NS-WD binaries

- Why all well-measured NS masses in NS-NS binaries are less than 1.5 $M_\odot$?
- What is the maximum mass of neutrons stars?

Before the observation of high-mass neutron stars

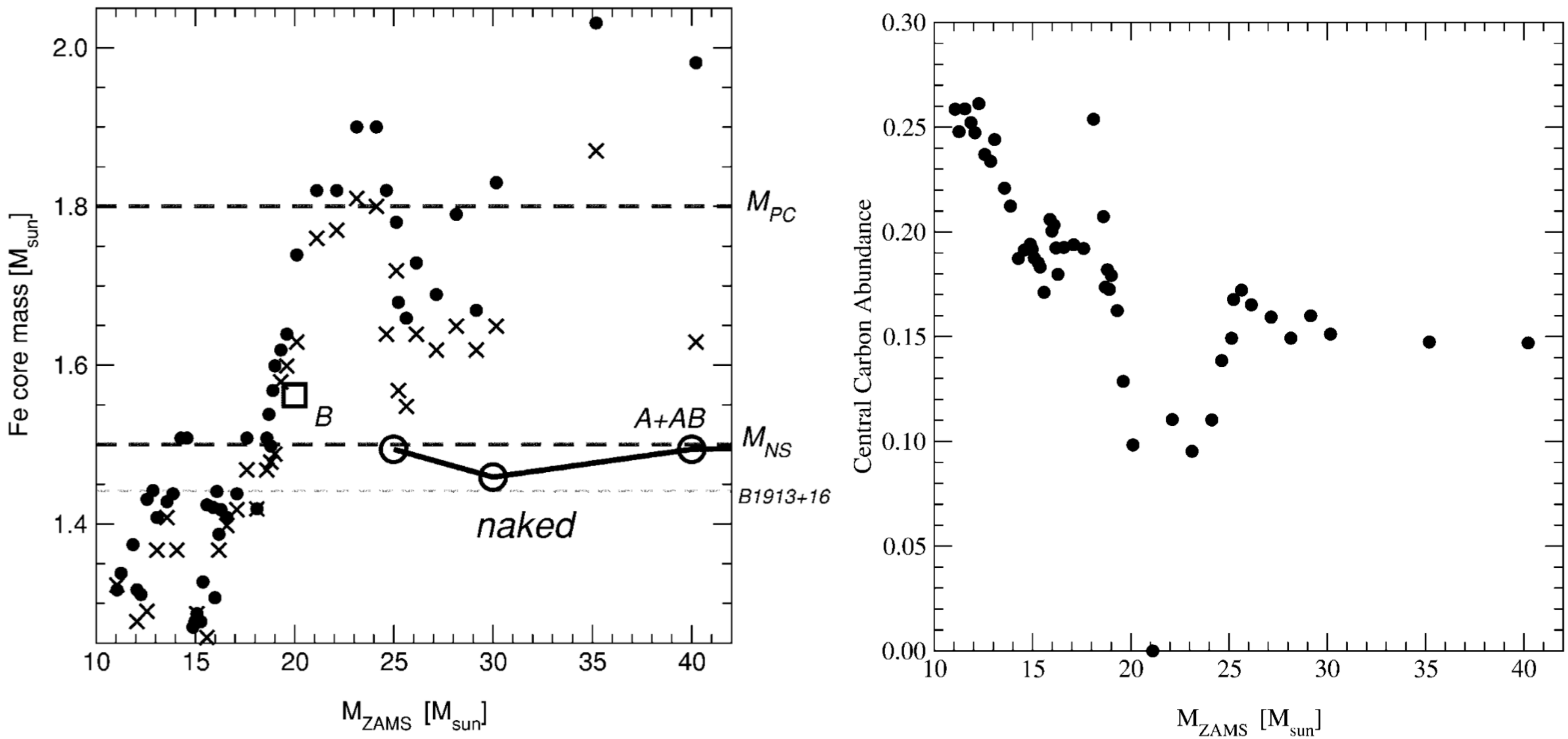
Lee, Park, Brown, ApJ 670 (2007) 741

We discussed the maximum mass of NS can be significantly higher than 1.5 $M_\odot$ as far as the evolution is concerned.

New Astronomy 6 (2001) 457–470

Formation of high mass X-ray black hole binaries

G.E. Brown[a], A. Heger[b], N. Langer[c], C.-H. Lee[a,d,*], S. Wellstein[e], H.A. Bethe[f]



In close binaries (evolution without H envelope)

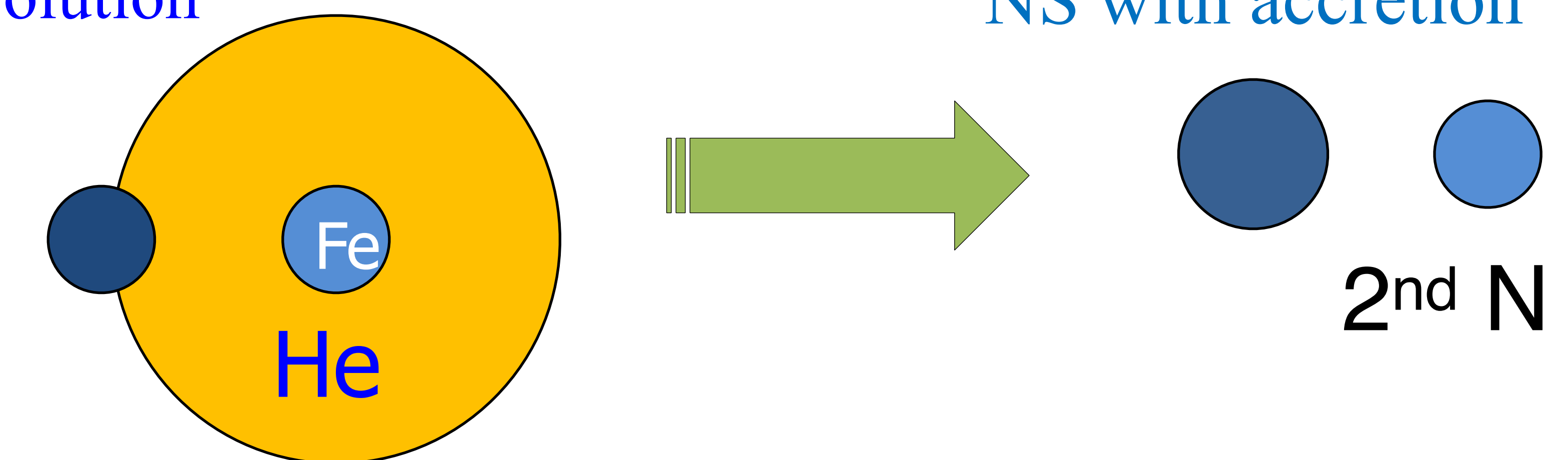
low Fe core mass ➡ NS mass = 1.3 - 1.5 solar mass

Fate of first born NS

Common envelope evolution

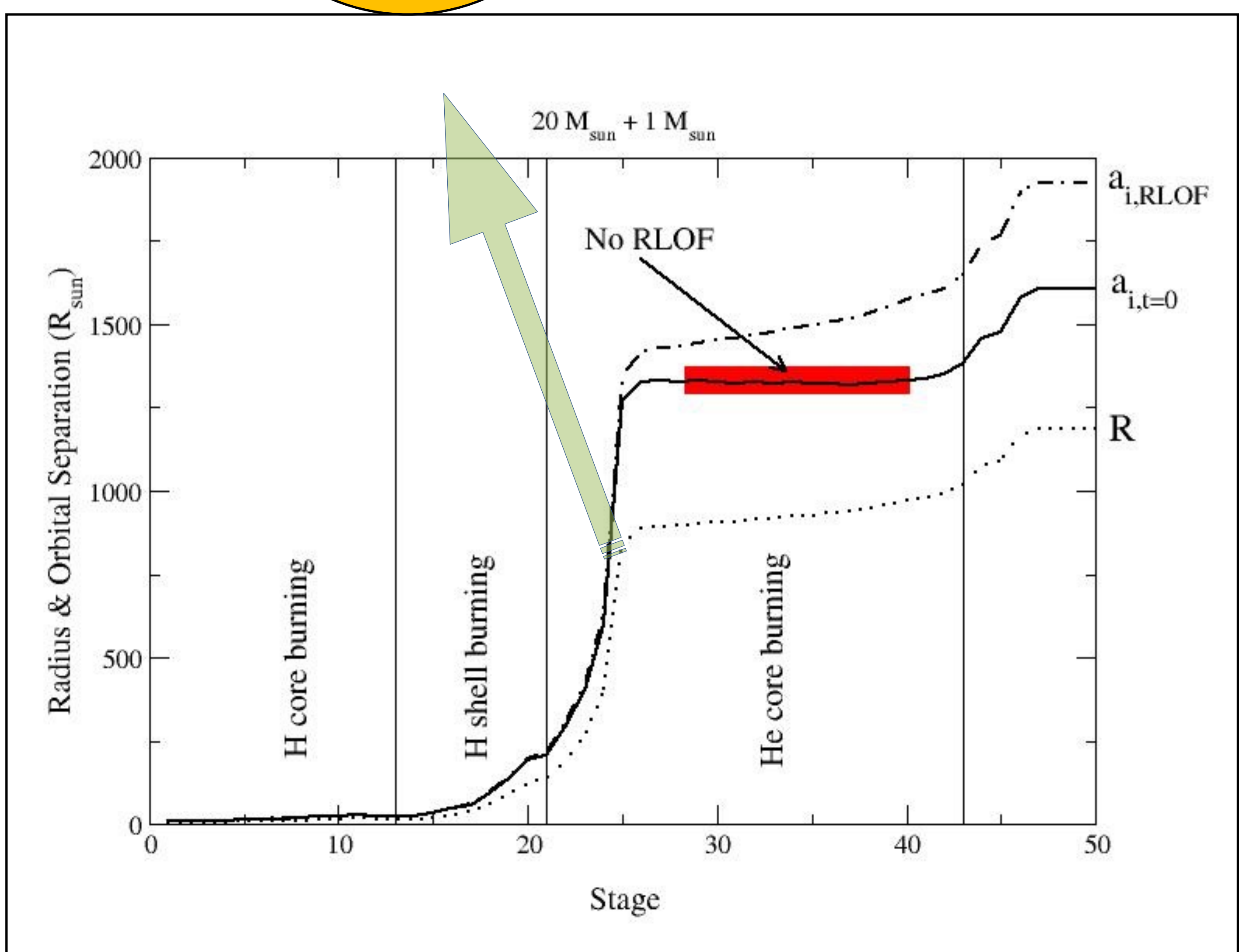
NS with accretion

1st-born NS



2nd NS/WD

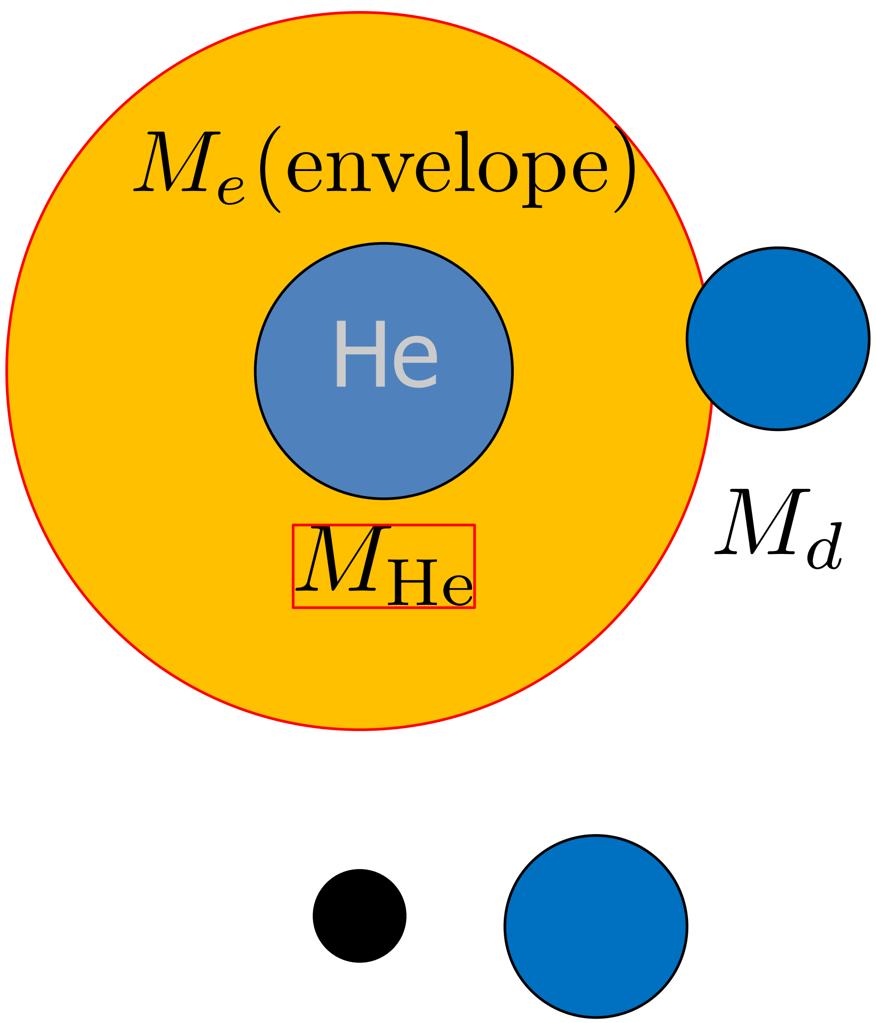
Evolution of Companion



Common envelope evolution

Gravitational self-energy of H envelope

Progenitors M_p



$$\frac{GM_pM_e}{\lambda R} = \frac{GM_pM_e}{\lambda r_L a_i} = \alpha_{\mathrm{ce}}\left(\frac{GM_{\mathrm{He}}M_d}{2a_f} - \frac{GM_pM_d}{2a_i}\right)$$

Change of binary orbital energy

Q) How to determine $\lambda\alpha_{\mathrm{ce}}$

What we have discovered in Soft X-ray transients (BH binary)

Formation and evolution of black hole X-ray transient systems

G.E. Brown[a], C.-H. Lee[a,b,*], T.M. Tauris[c]

New Astronomy 6 (2001) 331

$$\lambda\alpha_{ce} \approx 0.2 - 0.5$$

DISCOVERY OF A BLACK HOLE MASS-PERIOD CORRELATION IN SOFT X-RAY TRANSIENTS AND ITS IMPLICATION FOR GAMMA-RAY BURST AND HYPERNOVA MECHANISMS

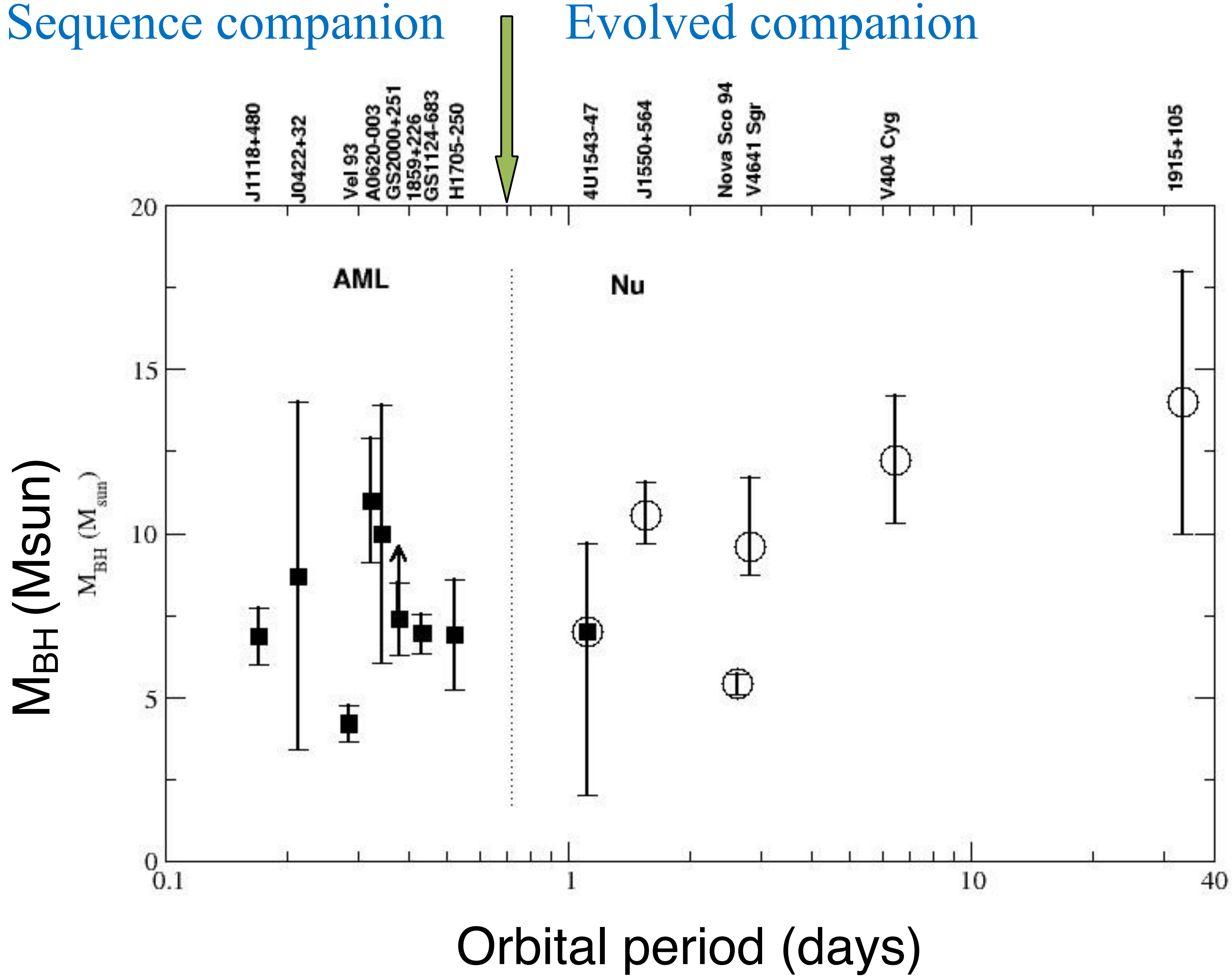
C.-H. Lee,[1,2,3] G. E. Brown,[3] and R. A. M. J. Wijers[3,4]

CHL, G.E. Brown, R.A.M.J. Wijers, ApJ 575 (2002) 996

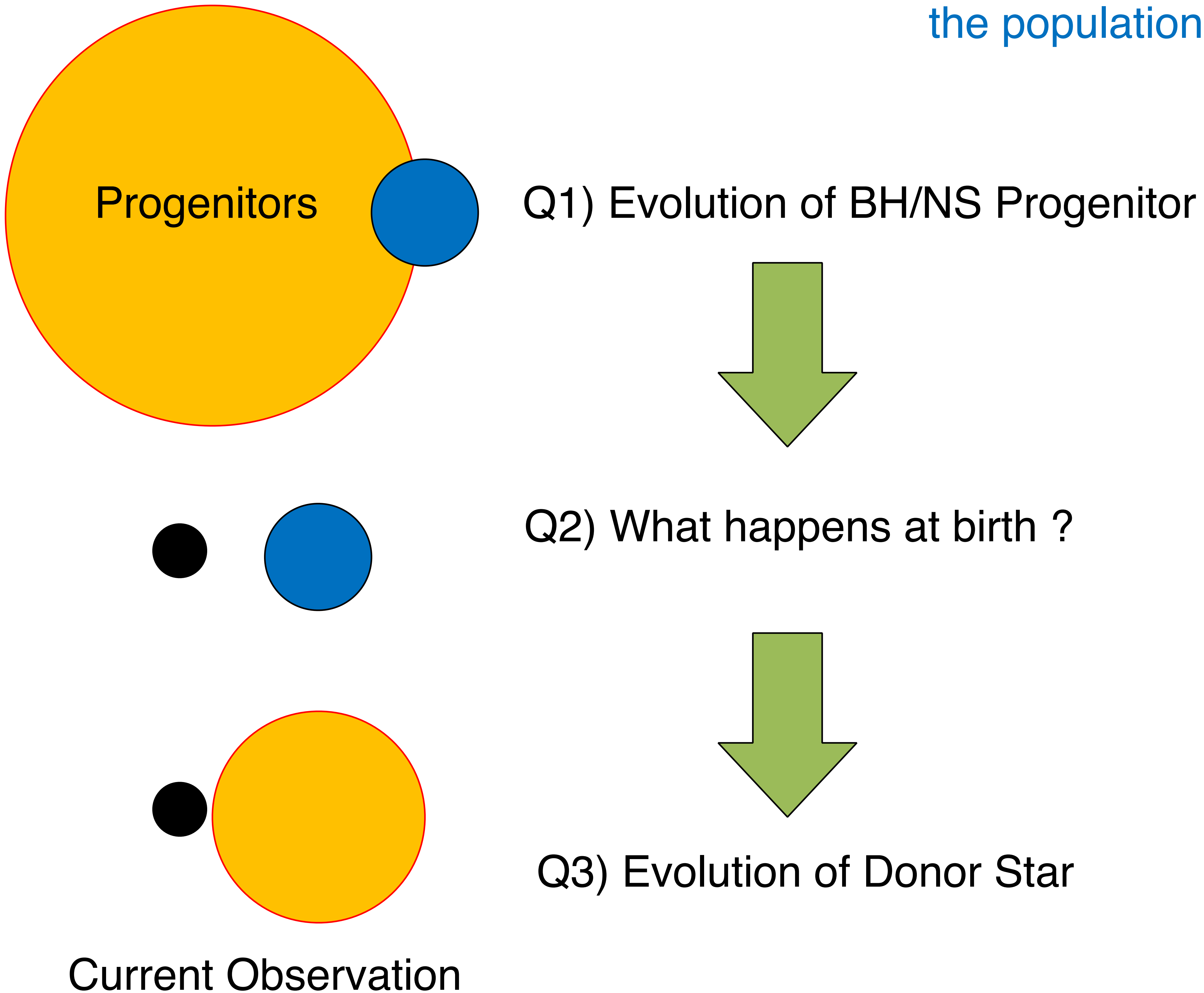
$$\boxed{\lambda\alpha_{ce} = 0.2}$$

BH Binaries / Soft X-ray Transients

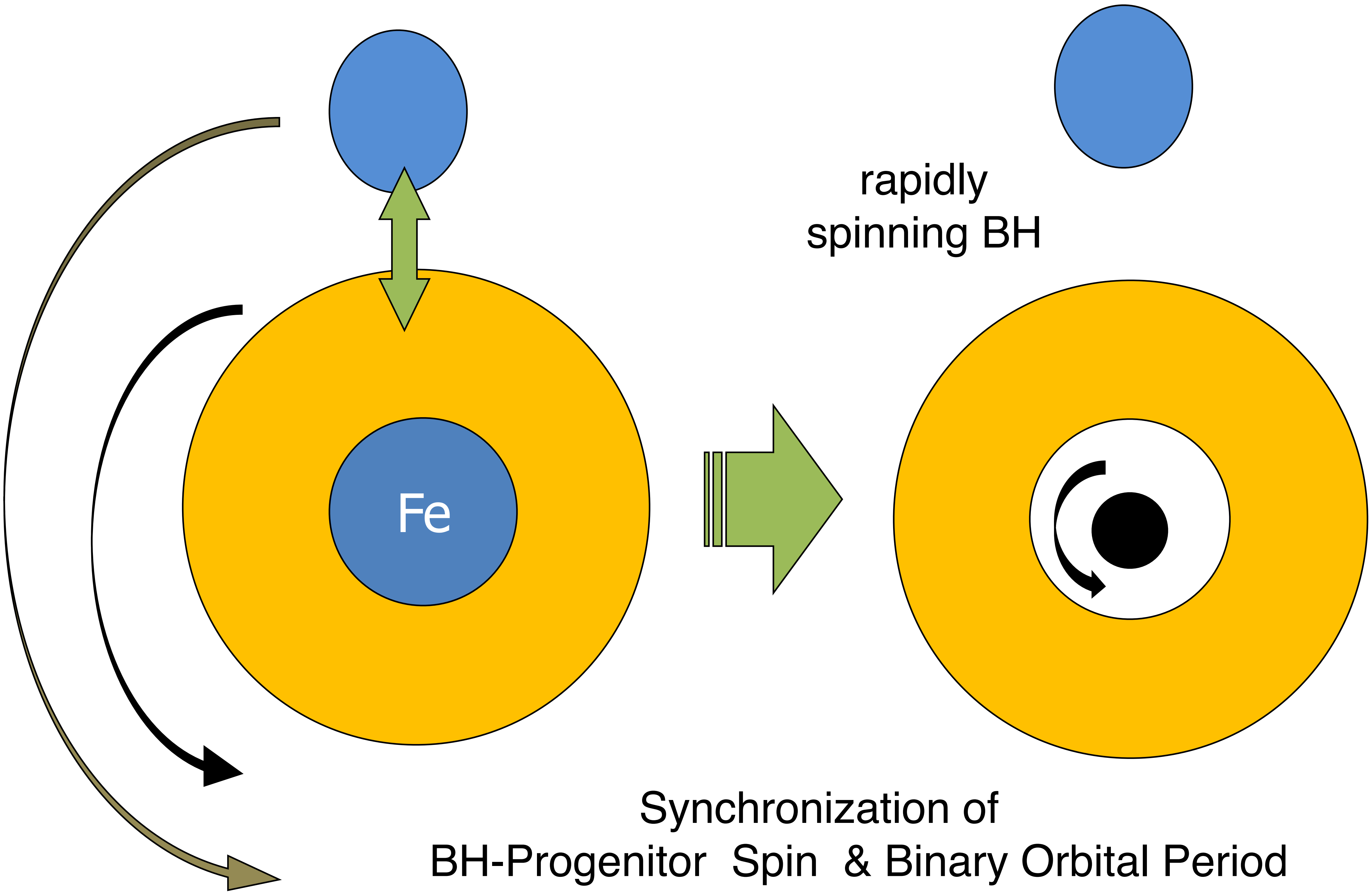
Main Sequence companion　Evolved companion



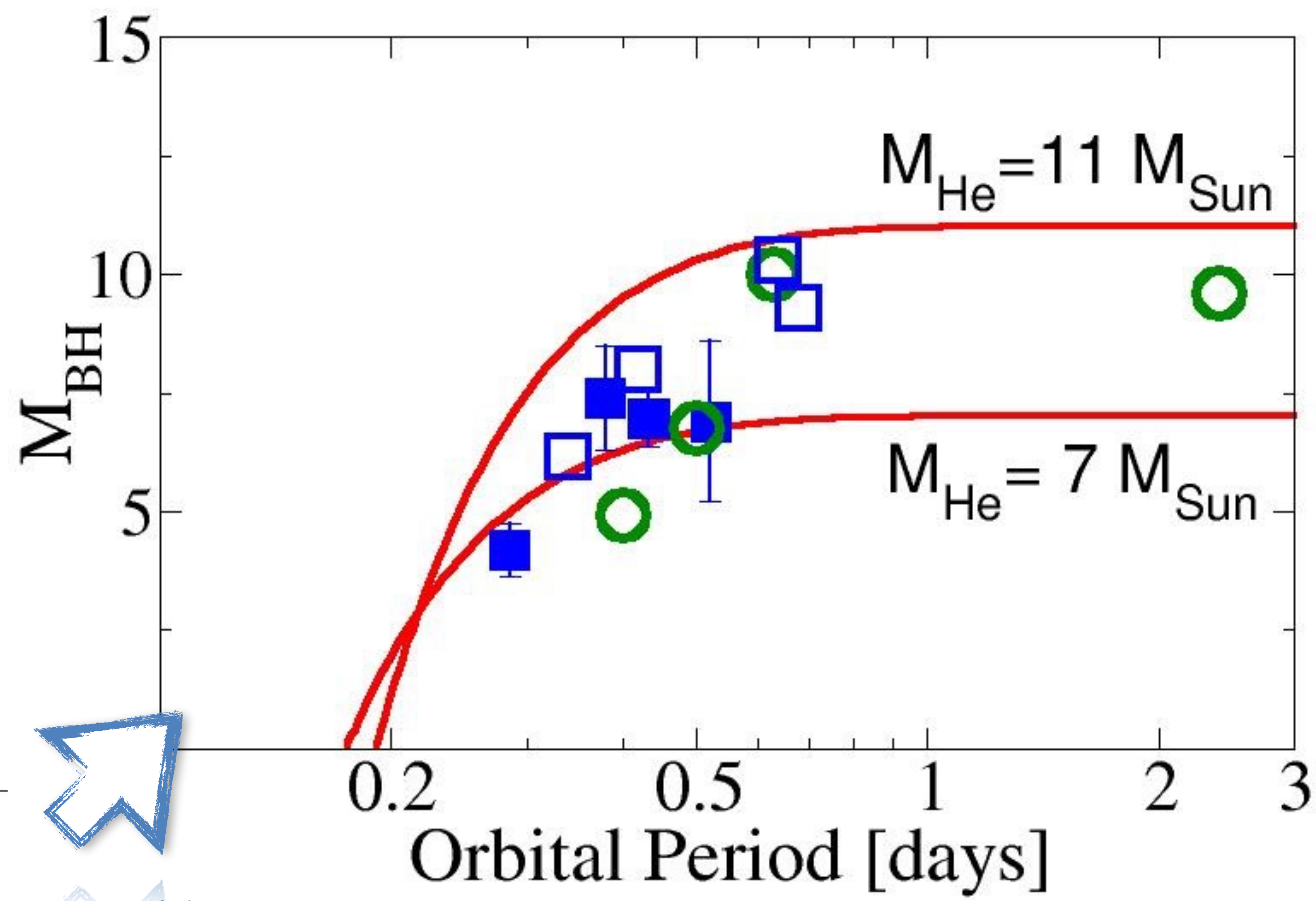
Q) How can we understand the population of SXTs ?

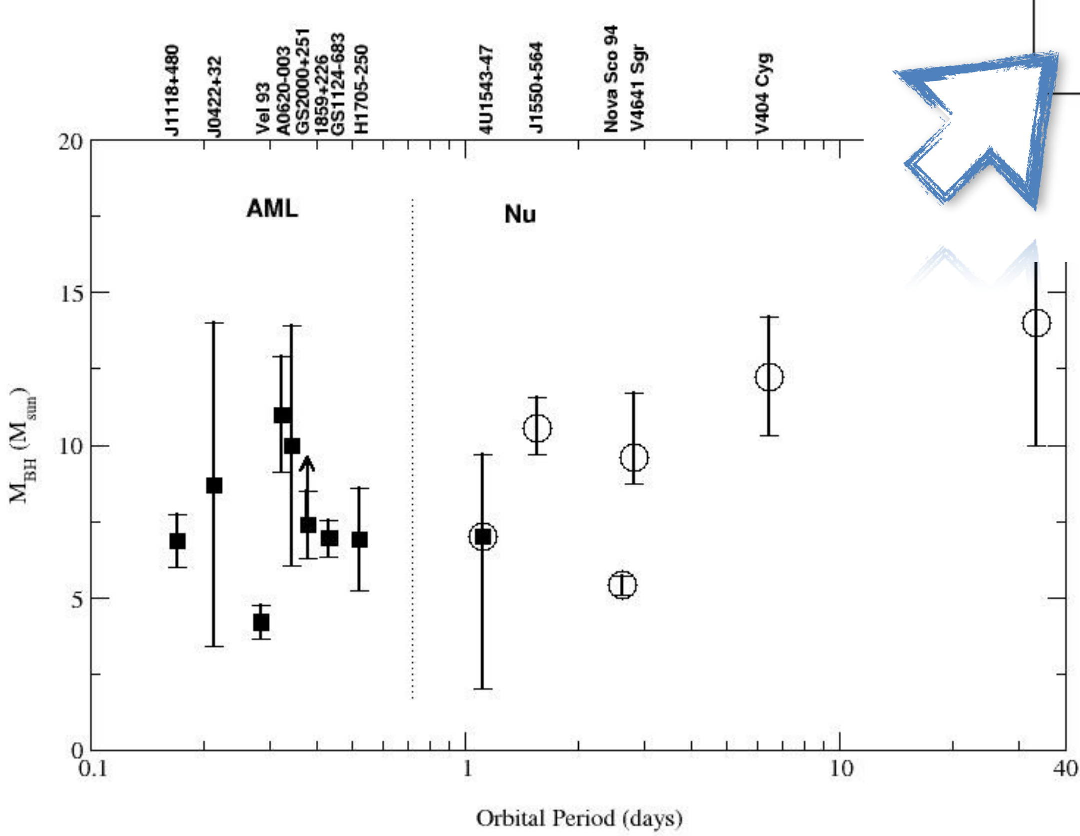


Tidal interaction just before BH formation



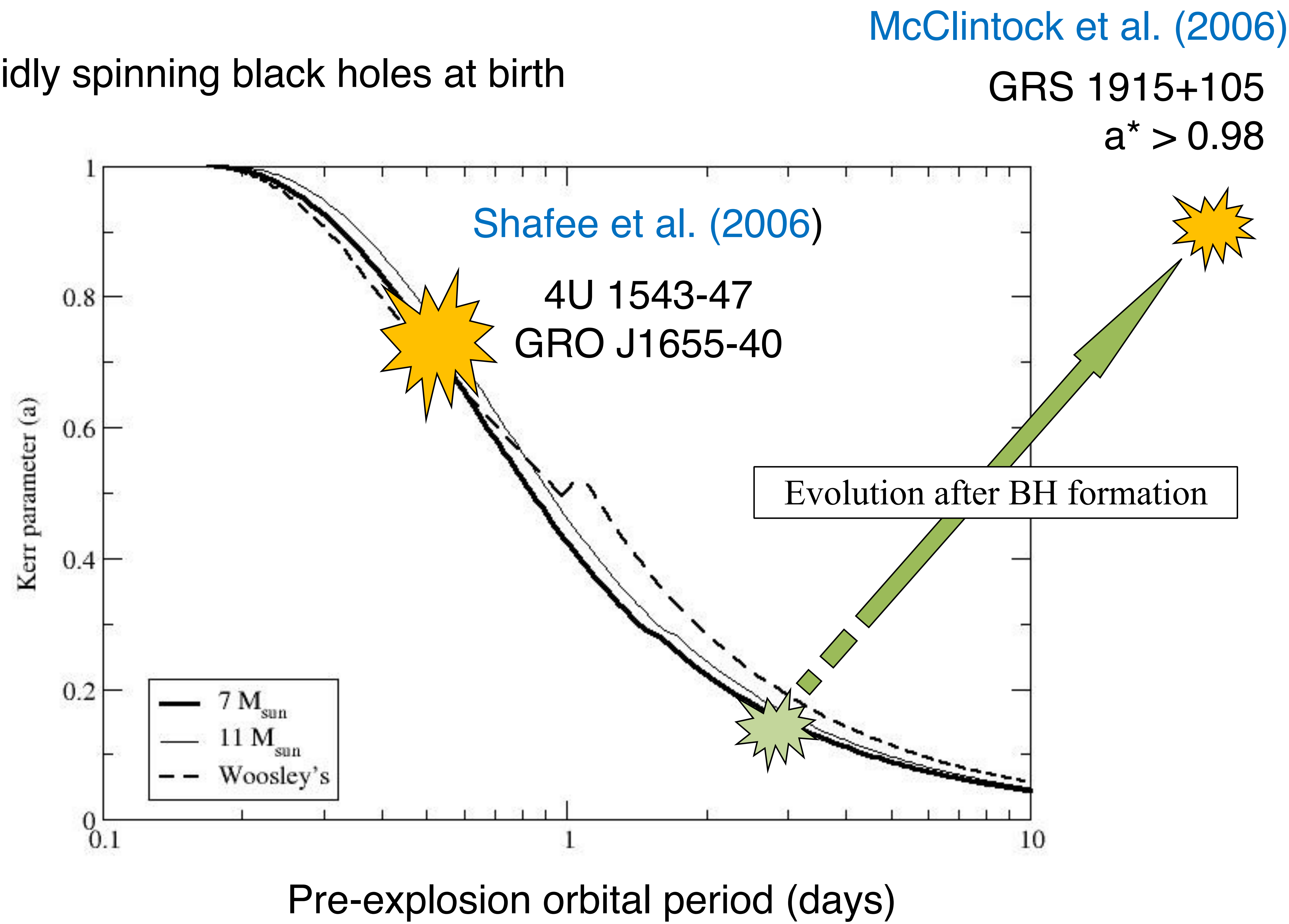
Reconstructed BH Binaries at the time of birth



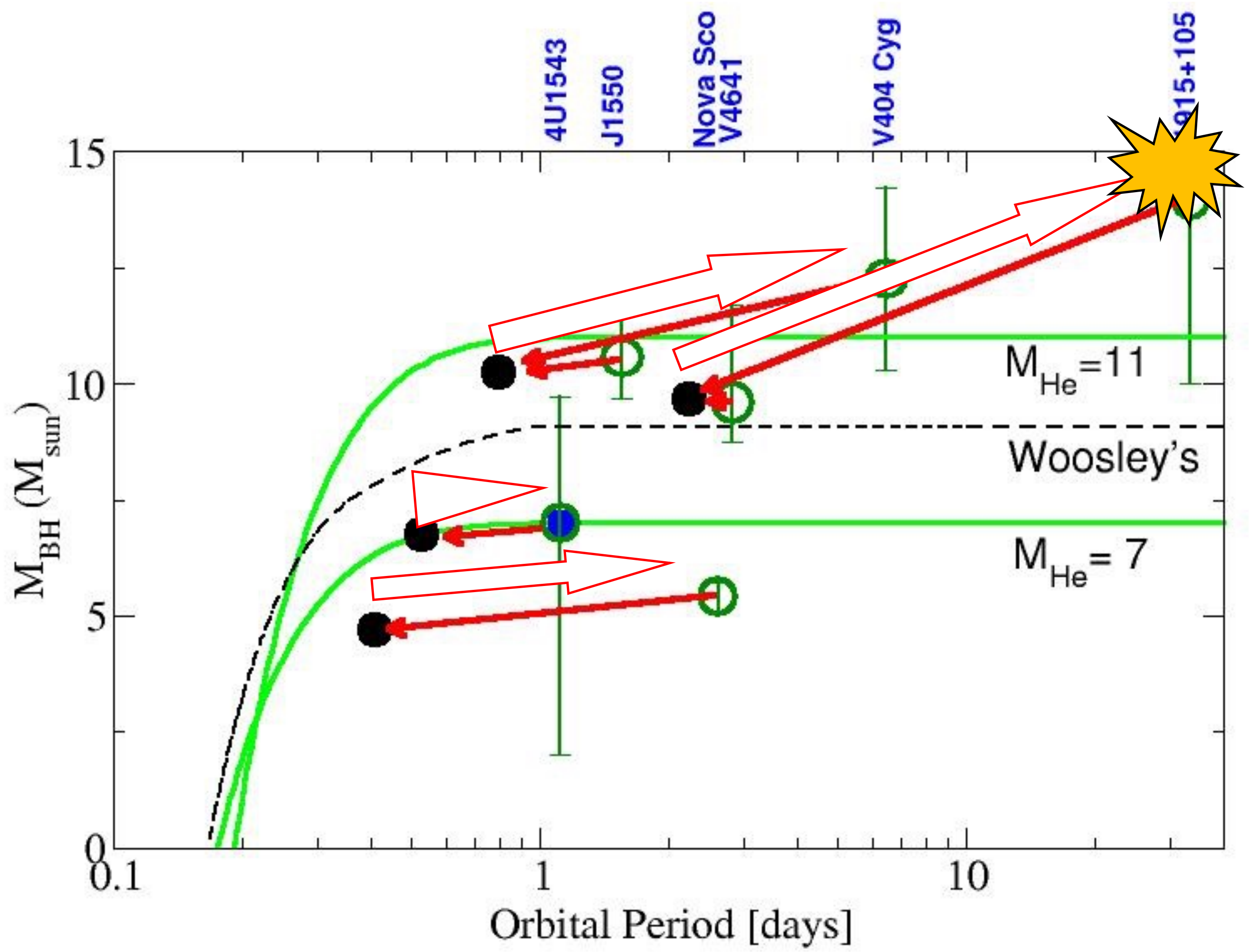


Current observation

Rapidly spinning black holes at birth



Evolution after BH formation



GRS 1915+105

spin-up due to accretion

Kerr parameters for stellar mass black holes and their consequences for GRBs and hypernovae
Moreno Mendez, Brown, Lee, Walter (ApJ 727:29, 2011)

What if we apply the same evolution to NS binaries

Lee, Park, Brown, ApJ 670,741(2007)
Lee, Cho, Nuclear Physics A 928 (2014) 296

Eddington limit / critical accretion rate

$$L_{\mathrm{Edd}} = \frac{4\pi c G M}{\kappa} \approx 1.3 \times 10^{38} \frac{M}{M_\odot} \mathrm{erg\ s^{-1}}$$

$$\kappa = \sigma_T N_A$$

Thomson scattering cross section σ_T

Avogadro's number N_A

$$L_{\mathrm{Edd}} = \eta \dot{M}_{\mathrm{Edd}} c^2$$

$$\dot{M}_{\mathrm{Edd}} = \frac{4\pi G M}{\kappa c \eta} \approx \frac{1}{\eta} 0.45 \times 10^{-8} \left(\frac{M}{M_\odot} \right) M_\odot\ \mathrm{yr^{-1}}$$

Super-critical accretion onto first born NS

- Eddington Accretion Rate : photon pressure balances the gravitation attraction
- If this limit holds, neutron star cannot be formed from the beginning (e.g. SN1987A; 10^8 Eddington Limit).
- Neutrinos can take the pressure out of the system allowing the supercritical accretion when accretion rate is bigger than 10^4 Eddington limit !
  (T > 1 MeV : Thermal neutrinos dominates !)

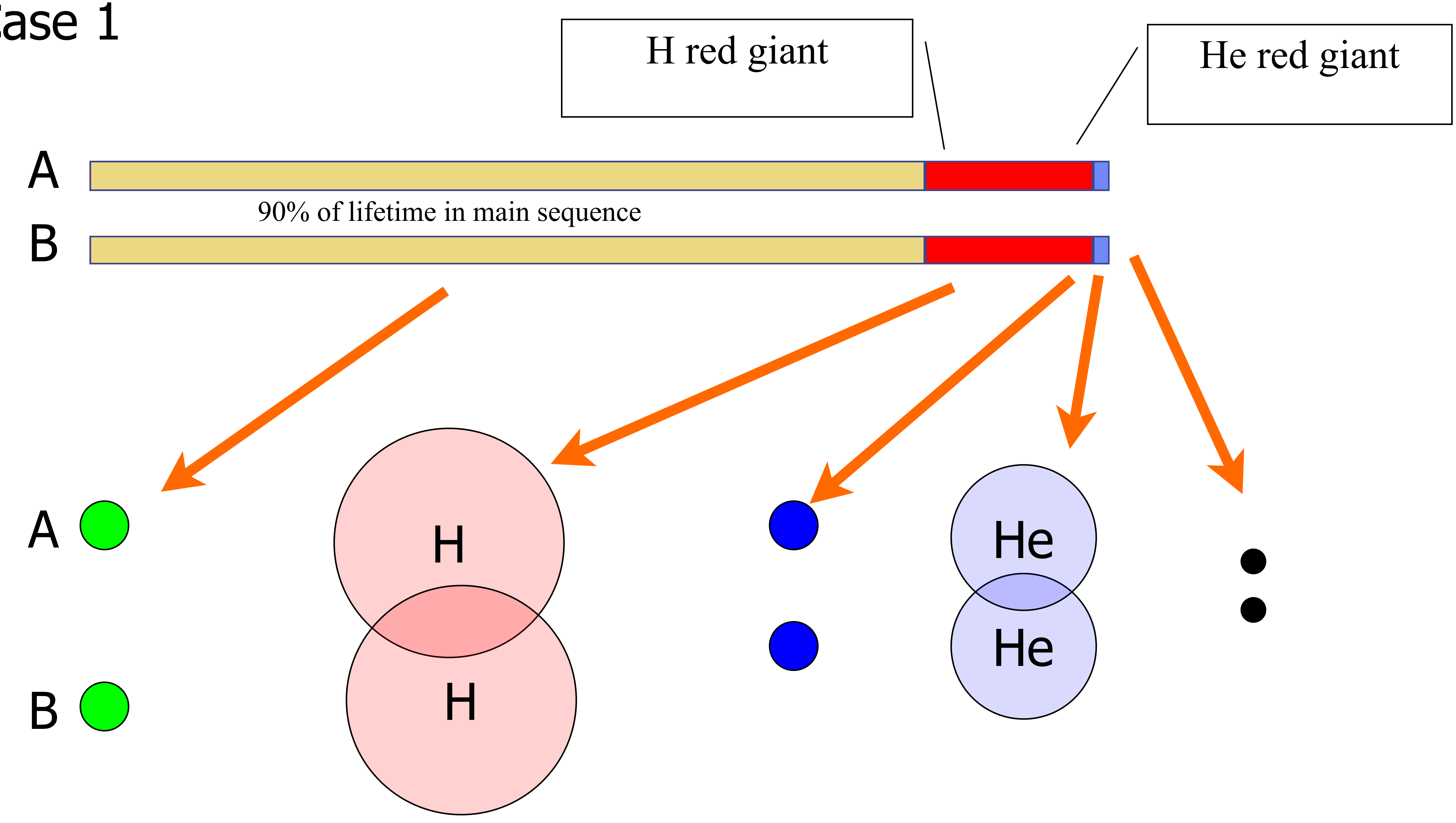
Q) What is the implications of supercritical accretion?

THE ASTROPHYSICAL JOURNAL, 541:918–923, 2000 October 1

HYPERCRITICAL ADVECTION-DOMINATED ACCRETION FLOW

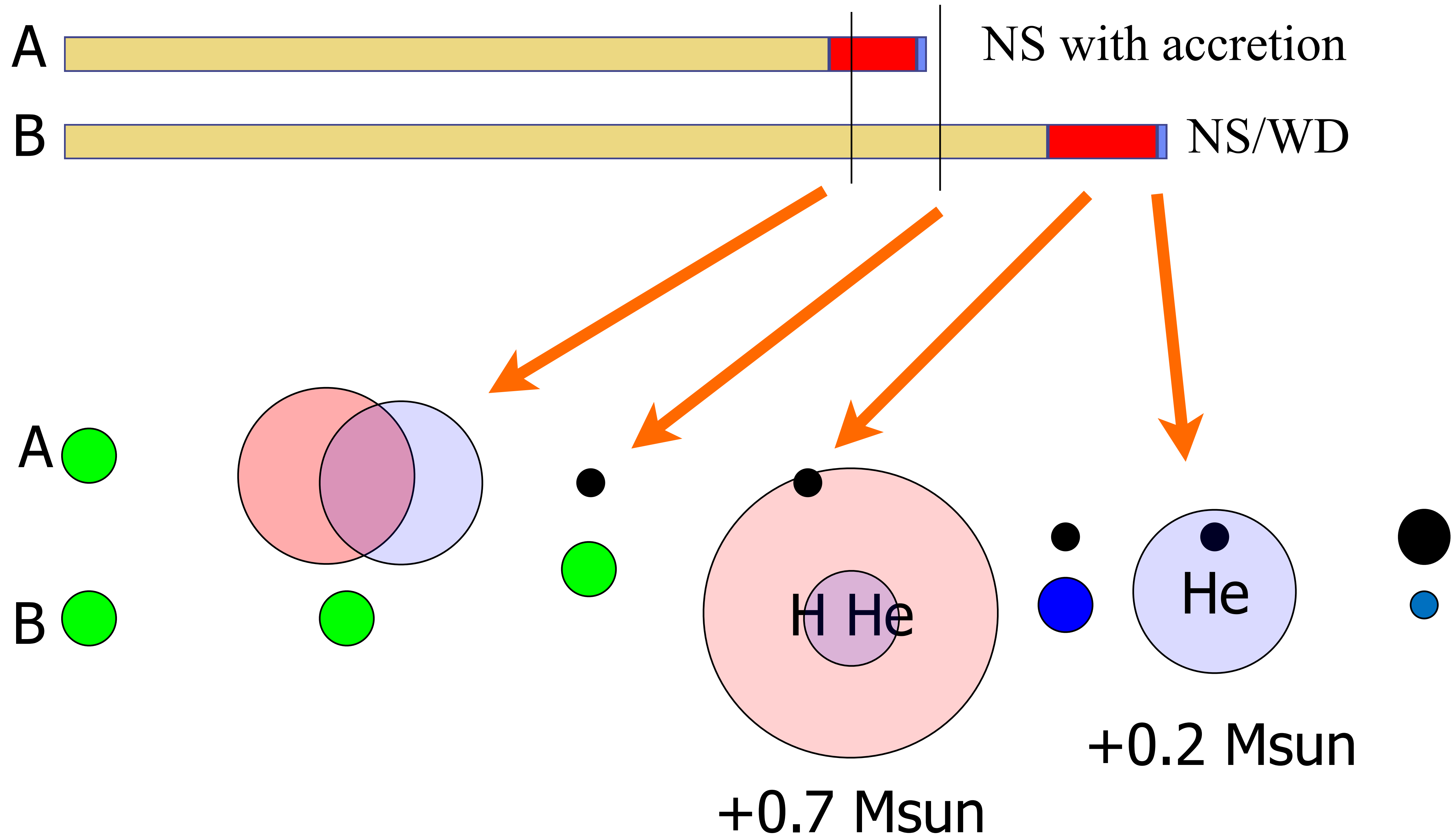
G. E. BROWN AND C.-H. LEE
Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794
AND
H. A. BETHE

Case 1



Formation of nearly equal mass NS-NS binary

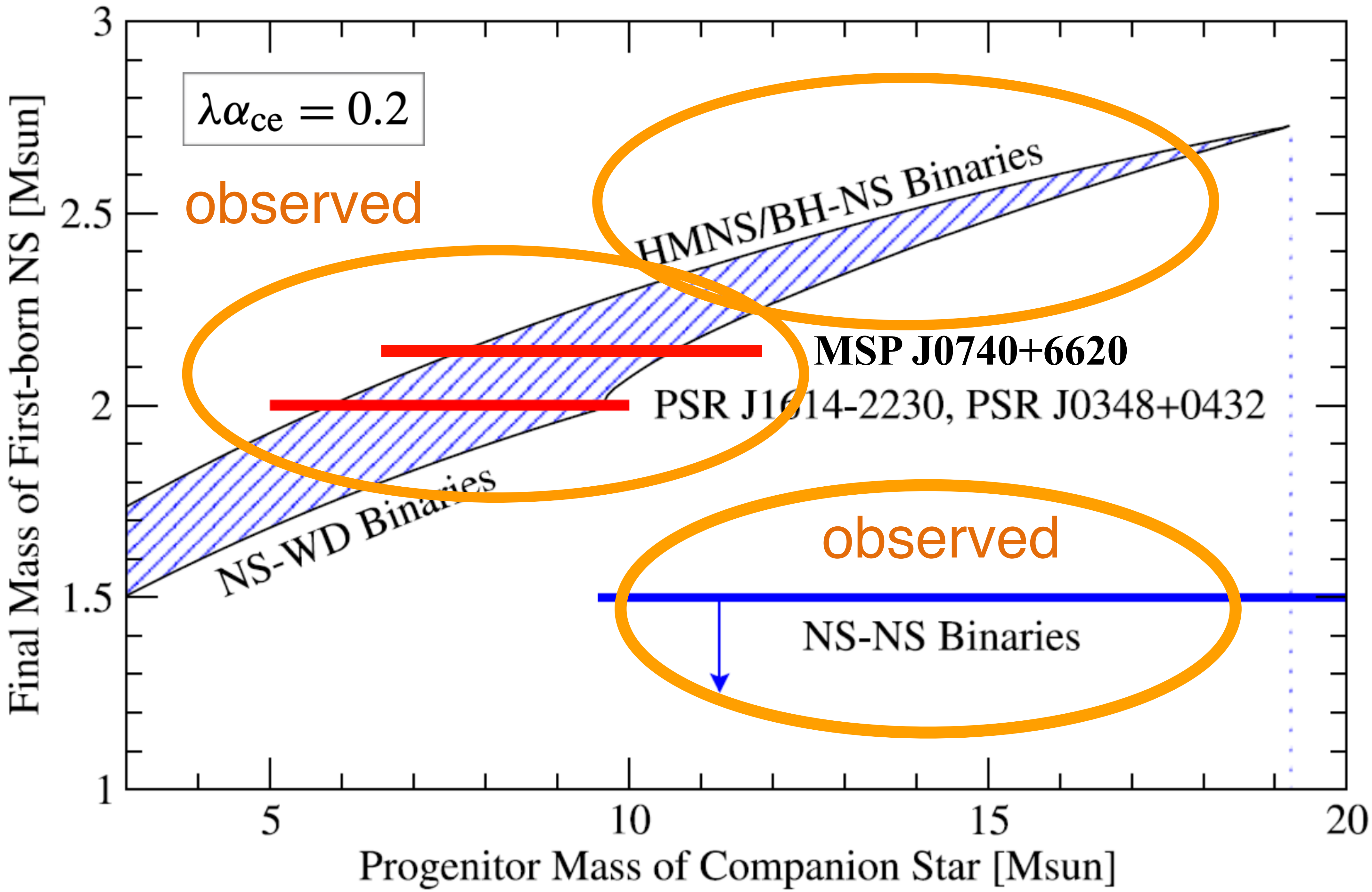
Case 2



Supercritical Accretion: First born NS can accrete up to 0.9 $M_{\odot}$

Final mass of first-born NS with supercritical accretion

C.-H. Lee, H.-S. Cho / Nuclear Physics A 928 (2014) 296–304



Contents

Courtesy of Chang Ho Hyun (Daegu)

KIDS Nuclear Energy Density Functional

- **KIDS**

Korea: **I**BS-**D**aegu-**S**ungkyunkwan

- **Collaboration**
  - **Model construction**

  P. Papakonstantinou, Y. Lim (IBS), C. H. Hyun (Daegu), T.-S. Park (Sungkyunkwan)

  - **Nuclear structures**

  H. Gil (Kyungpook) , E. In (Sungkyunkwan) P. Papakonstantinou, Y.-H. Song (IBS), C. H. Hyun, Y. Oh (Kyungpook)

  - **Heavy-ion collision**

  M. Kim (Pusan), H. Gil, Y. M. Kim (UNIST), P. Papakonstantinou, Y. Kim (IBS), C. H. Hyun, C.-H. Lee (Pusan), S. Jeon (McGill)

Related publication

Phys. Rev. C 97, 014312 (2018)

Phys. Rev. C 98, 065805 (2018)

Phys. Rev. C 99, 064319 (2019)

Phys, Rev. C 100, 014312 (2019)

Strategy

1. Expand energy density in powers of k_F/m_ρ.

2. Fix α_i to ρ_0=0.16fm^{-3}, E/A=16.0 MeV, K_0=240 MeV of symmetric nuclear matter (SNM).

3. Fit β_i to the APR EoS of pure neutron matter (PNM).

4. Consider 3, 4, and 5 terms for β_i while fixing α_i to 3 terms.

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

$$\rho = \rho_n + \rho_p$$

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

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

Expansion parameter k_F/m_ρ: less than 1 even at $\rho = 8\rho_0$.

Result1: validity of systematic expansion

* Naturalness: Order of coefficients $10^{-1} \sim 10^{1}$

* Dimensionless coefficients

$$\mathcal{E}_i(\rho,\delta) = c_i(\delta)\rho^{1+i/3} = \left[\left(\frac{\nu}{6\pi^2}\right)^{1+i/3} c_i(\delta) m_\rho^{2+i}\right] m_\rho \left(\frac{k_F}{m_\rho}\right)^{3+i}$$

$$c_i^{dim}(\delta) = \left(\frac{\nu}{6\pi^2}\right)^{1+i/3} c_i(\delta) m_\rho^{2+i}$$

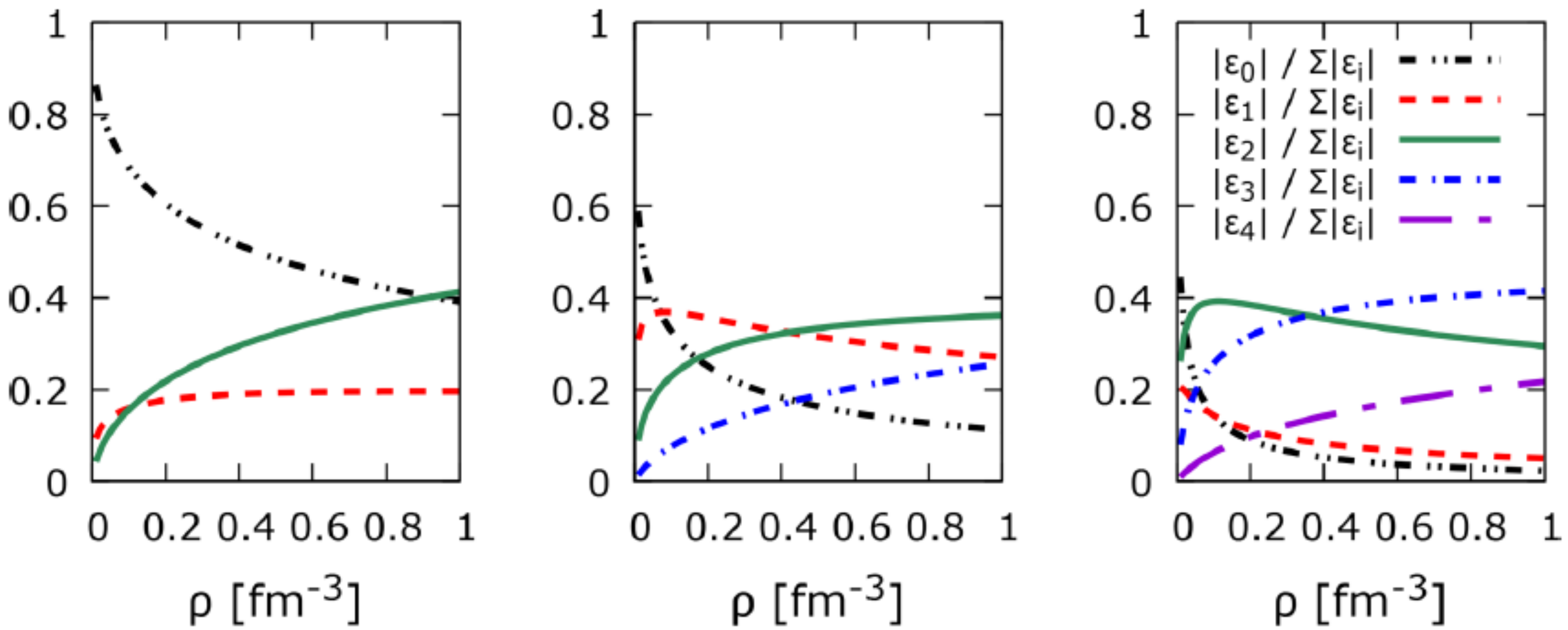
	c_0^{dim}	c_1^{dim}	c_2^{dim}	c_3^{dim}
δ=0	-3.6	6.6	0.6	
δ=1	-1.1	3.4	-5.9	3.3

Result2: Convergence

Ratio of magnitude of individual interaction term divided by their sum

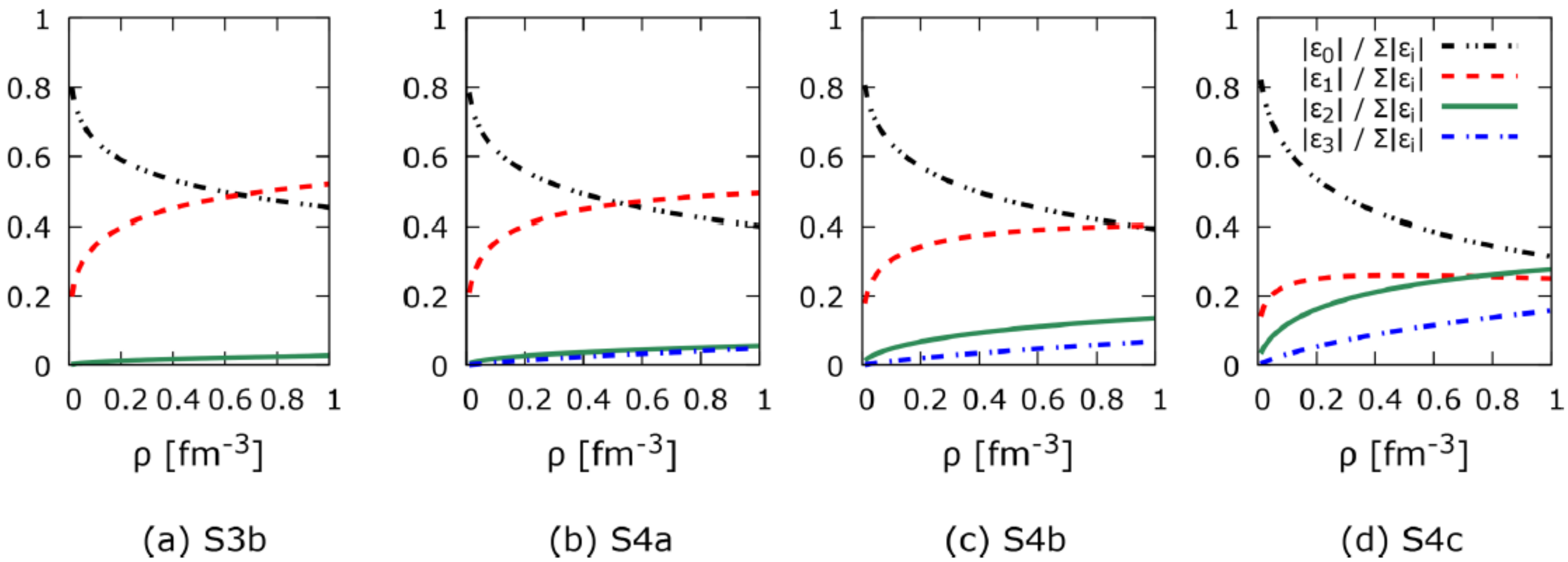
Pure Neutron Matter

$$\mathcal{E}_i(\rho,\delta) = c_i(\delta)\rho^{1+i/3}$$



(a) P3 (b) P4 (c) P5

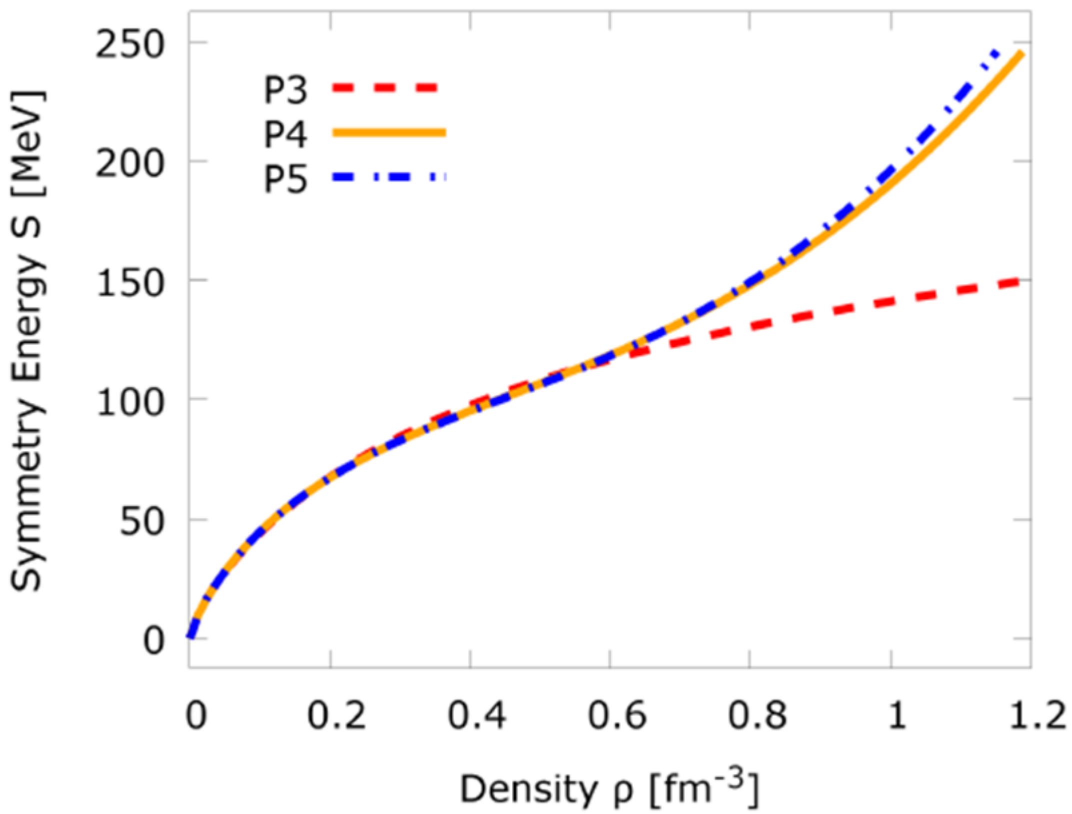
Symmetric Nuclear Matter



* Hierarchy ($|\varepsilon_0|>|\varepsilon_1|>|\varepsilon_2|>\ldots$) is valid at low densities.

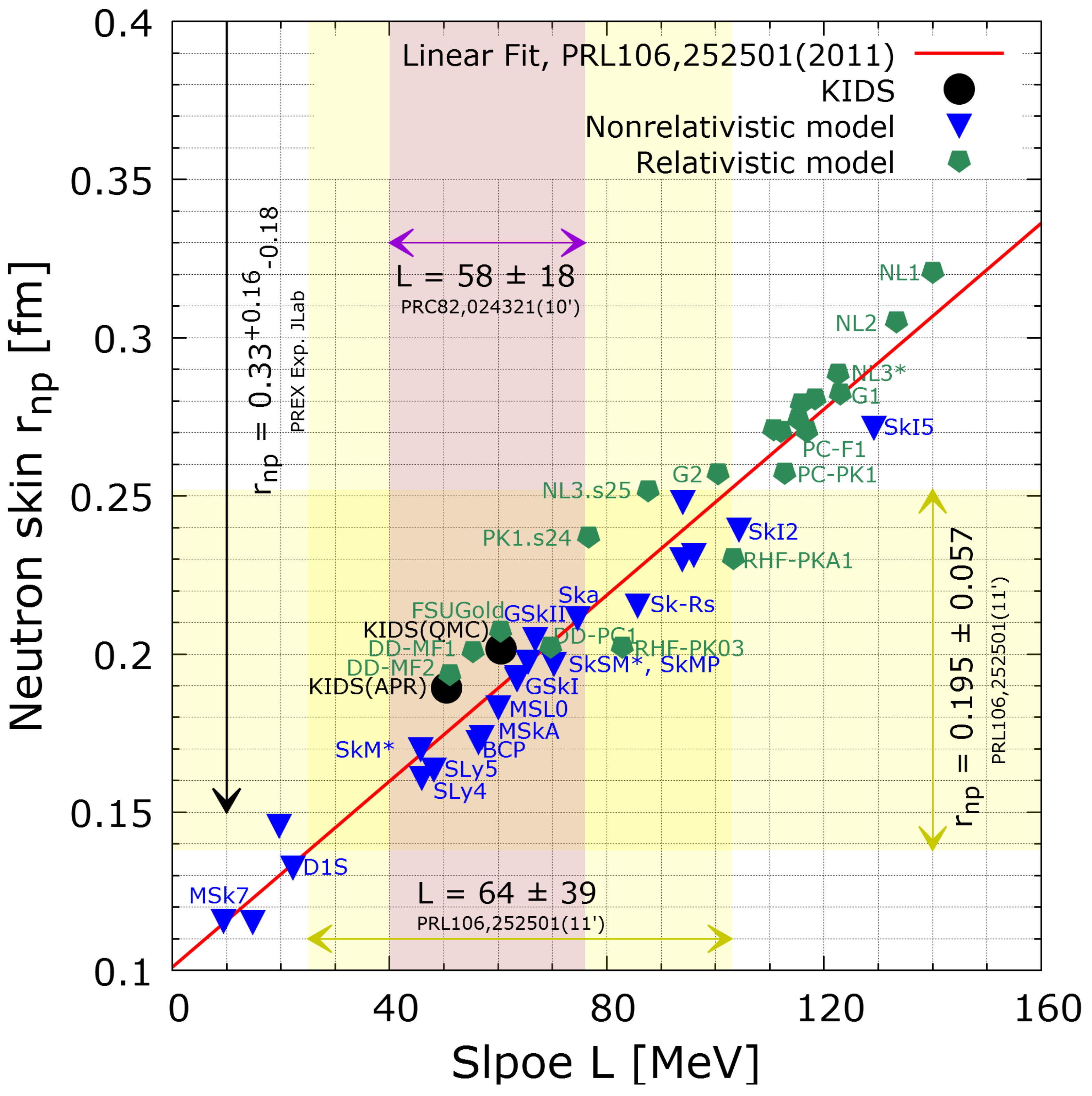
* However, hierarchy is better for SNM.

Result3: Symmetry Energy



- No difference up to $\rho \sim 0.6$ fm^{-3} ($\sim 4\rho_0$): Higher order terms ($\rho^{6/3}$, $\rho^{7/3}$) are negligible.
- Marginal difference between P4 and P5 up to $\rho \sim 1.2$ fm^{-3} ($\sim 8\rho_0$): Four terms are sufficient for neutron stars.

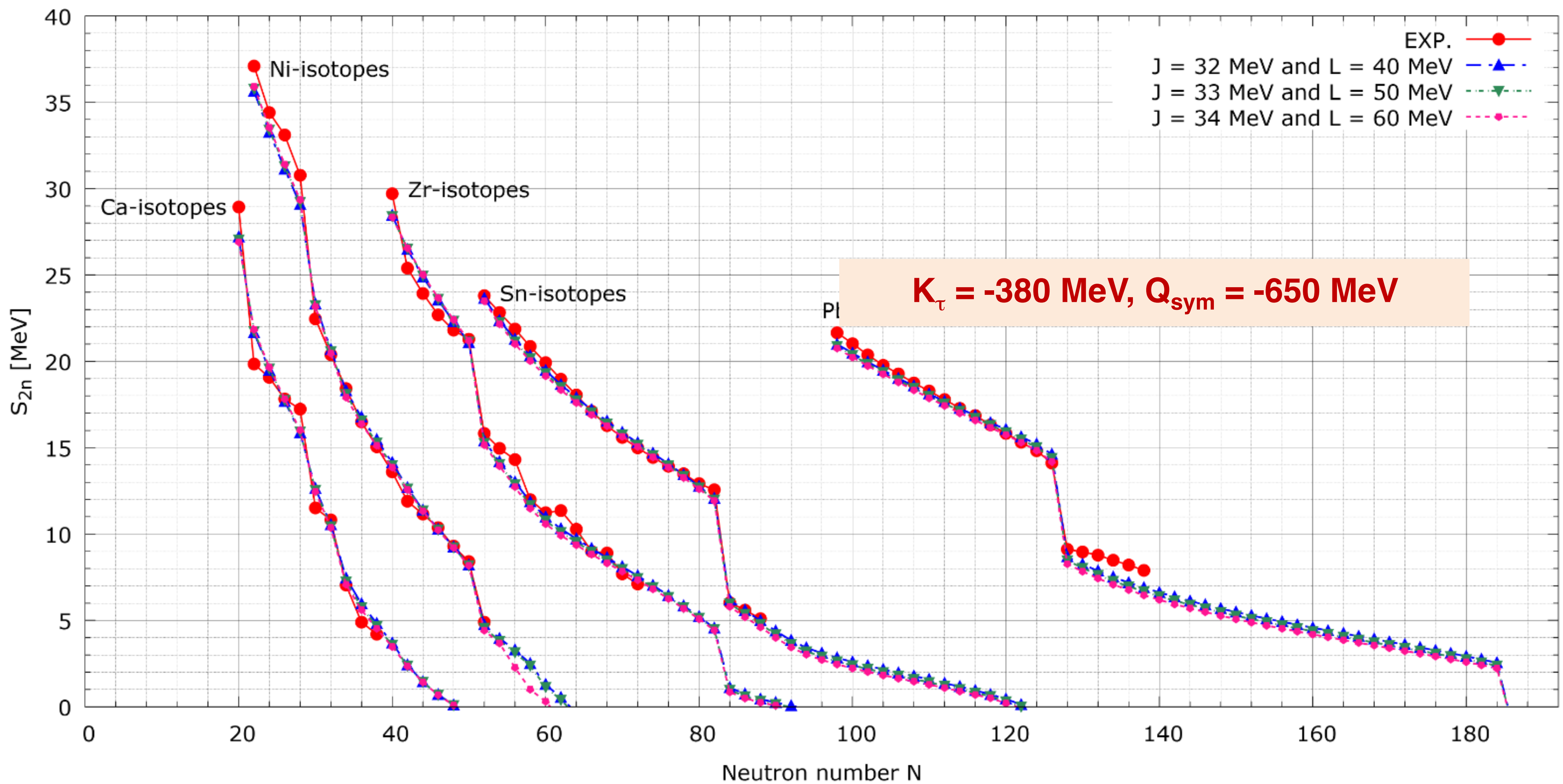
Correlation between neutron skin thickness r_{np} and slope parameter L of ^{208}Pb



In the KIDS model, J, L, K_{sym}, … can be chosen arbitrary, so one can check the correlation more systematically.

$$S(\rho) = J + L\,x + \frac{1}{2}K_{\rm sym}\,x^2 + \mathcal{O}(x^3) \qquad K_\tau \equiv K_{\rm sym} - 6L - \frac{Q_0}{K_0}L. \qquad x \equiv (\rho - \rho_0)/3\rho_0$$

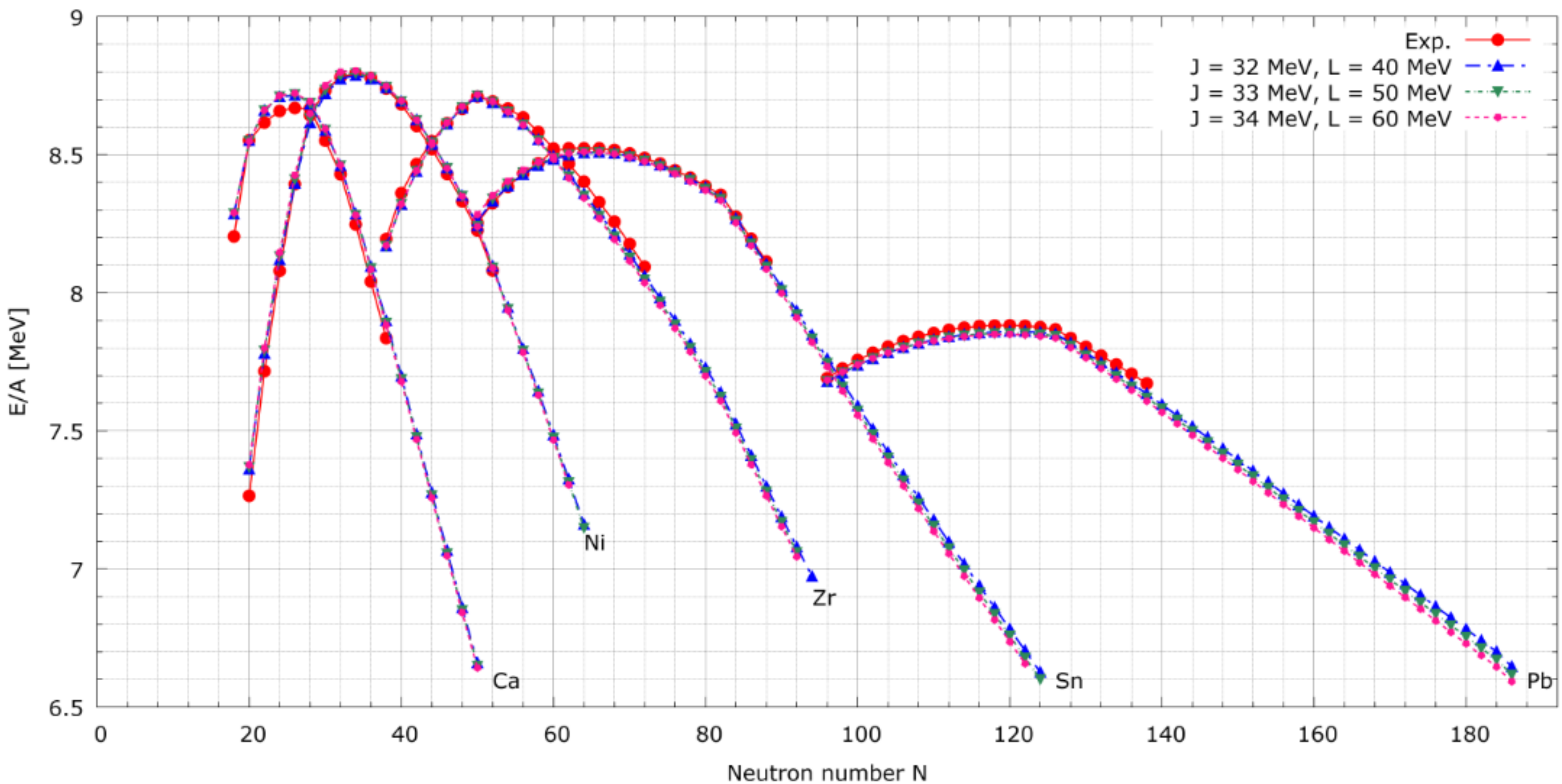
S_{2n} two-neutron separation energy S_{2n}



For a given K_τ One find (J, L) combinations that can reproduce experimental S_{2n}

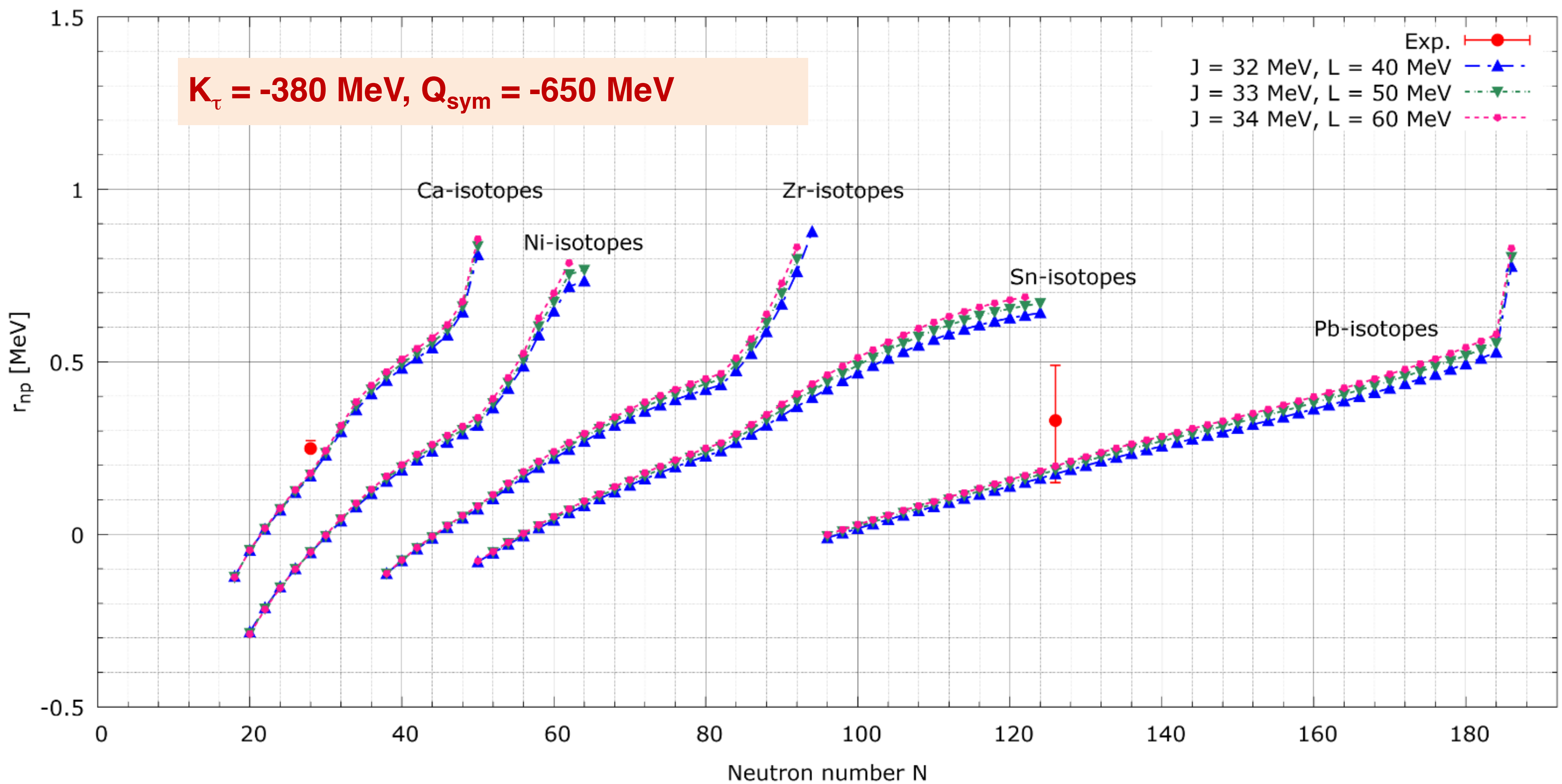
Binding energy per nucleon

K_τ = -380 MeV, Q_{sym} = -650 MeV



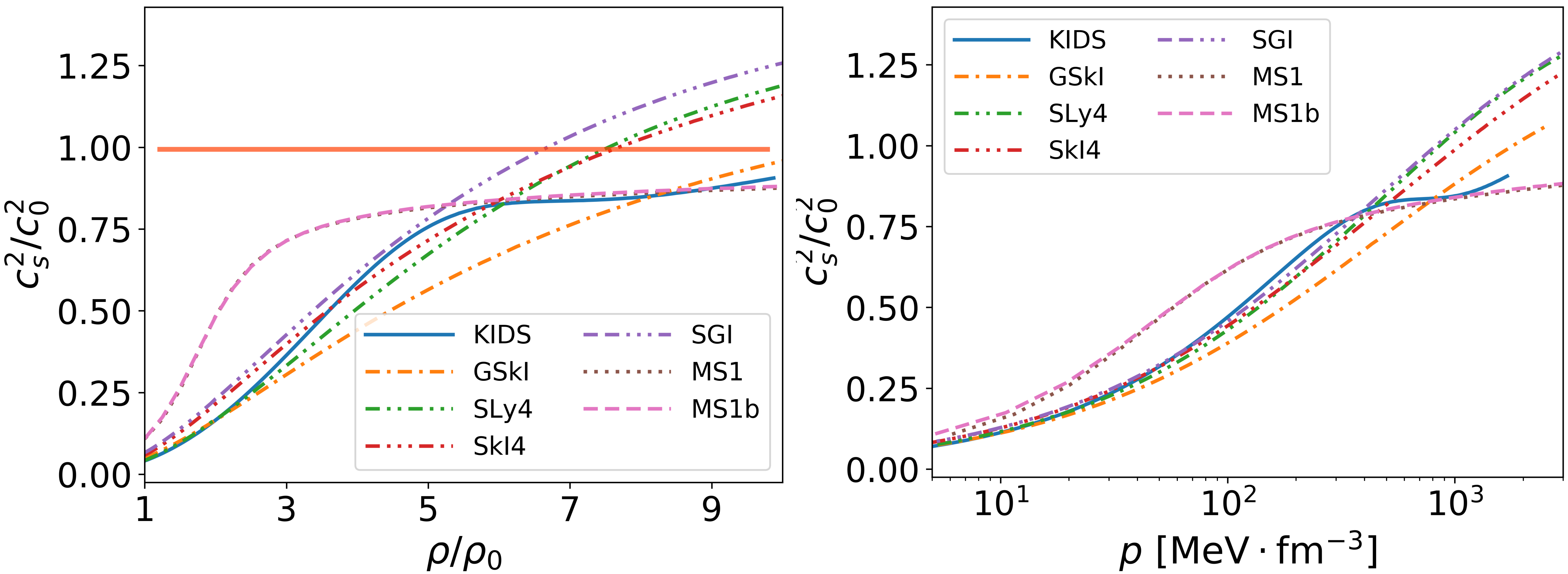
r_{np}

neutron skin thickness r_{np}



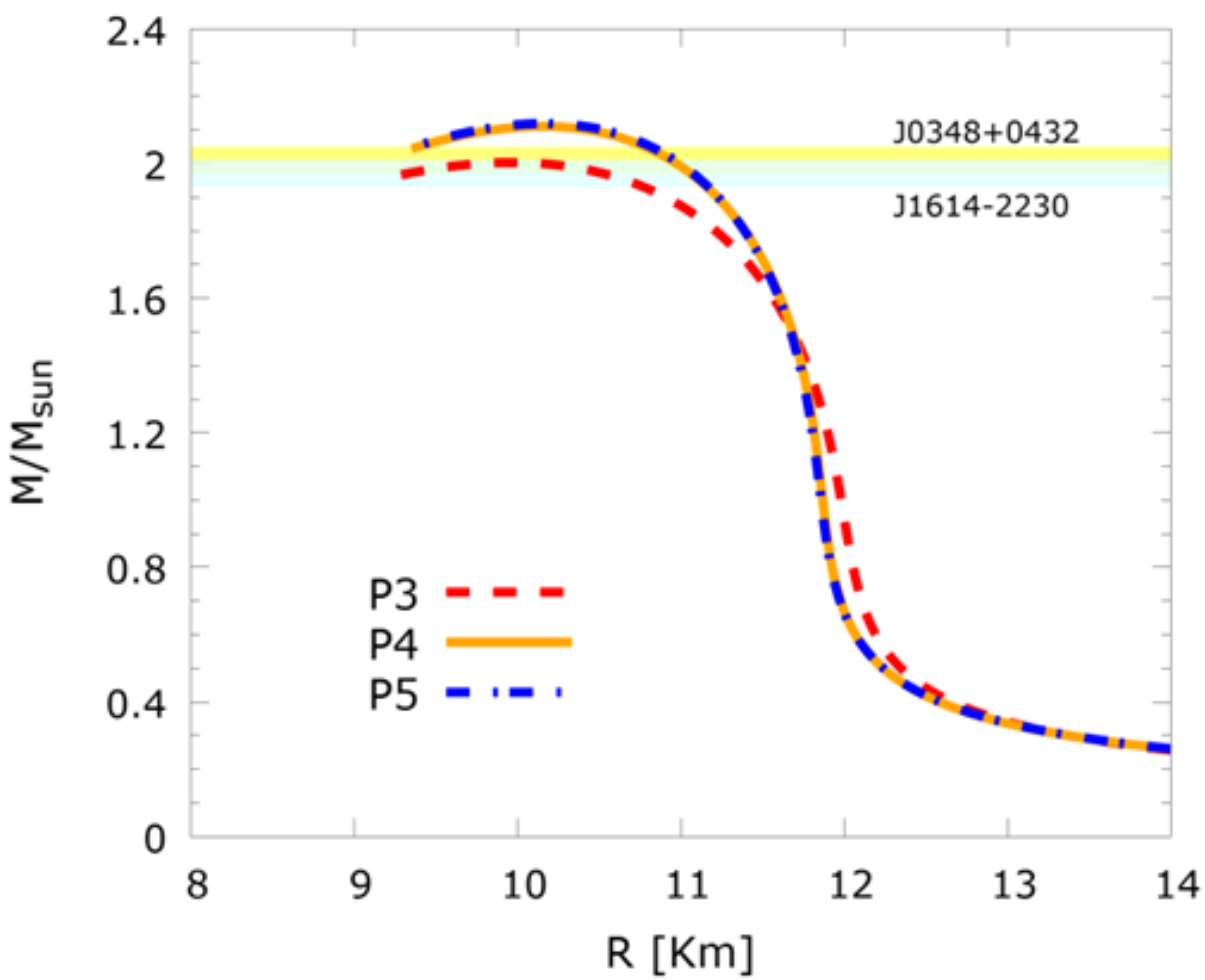
- **J and L can be correlated strongly via S_{2n} of neutron-rich nuclei.**
- **Measurement of r_{np}, S_{2n} and neutron drip line can provide more stringent constraints and correlations of J, L and K_{sym}.**

speed of sound



Result4: Neutron Star

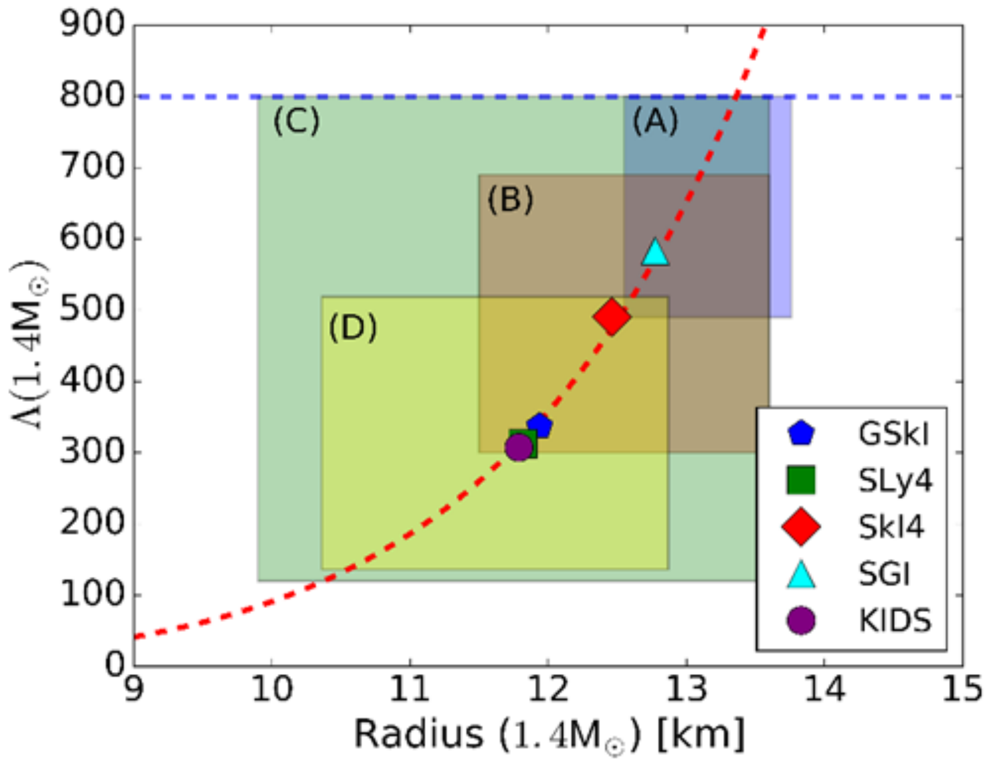
Mass-Radius Relation



Tidal Deformability

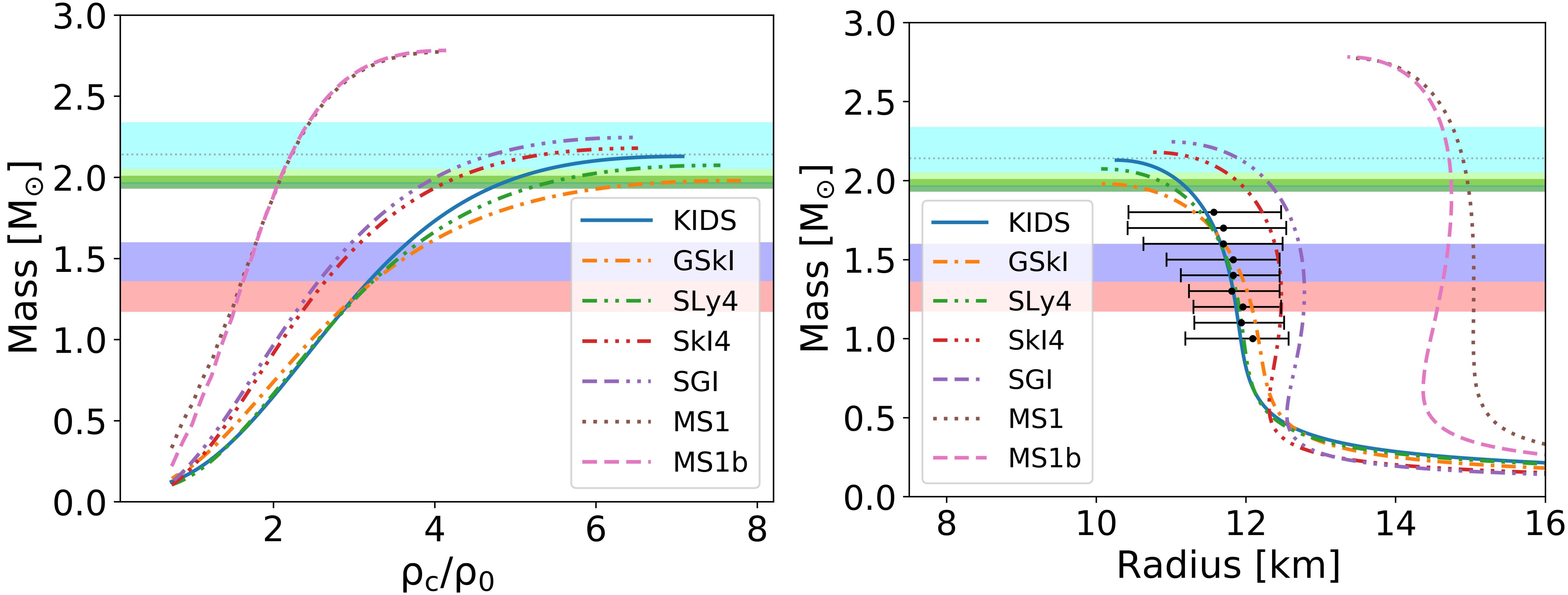
	P3	P4	P5
$\Lambda_{1.4}$	316	304	289

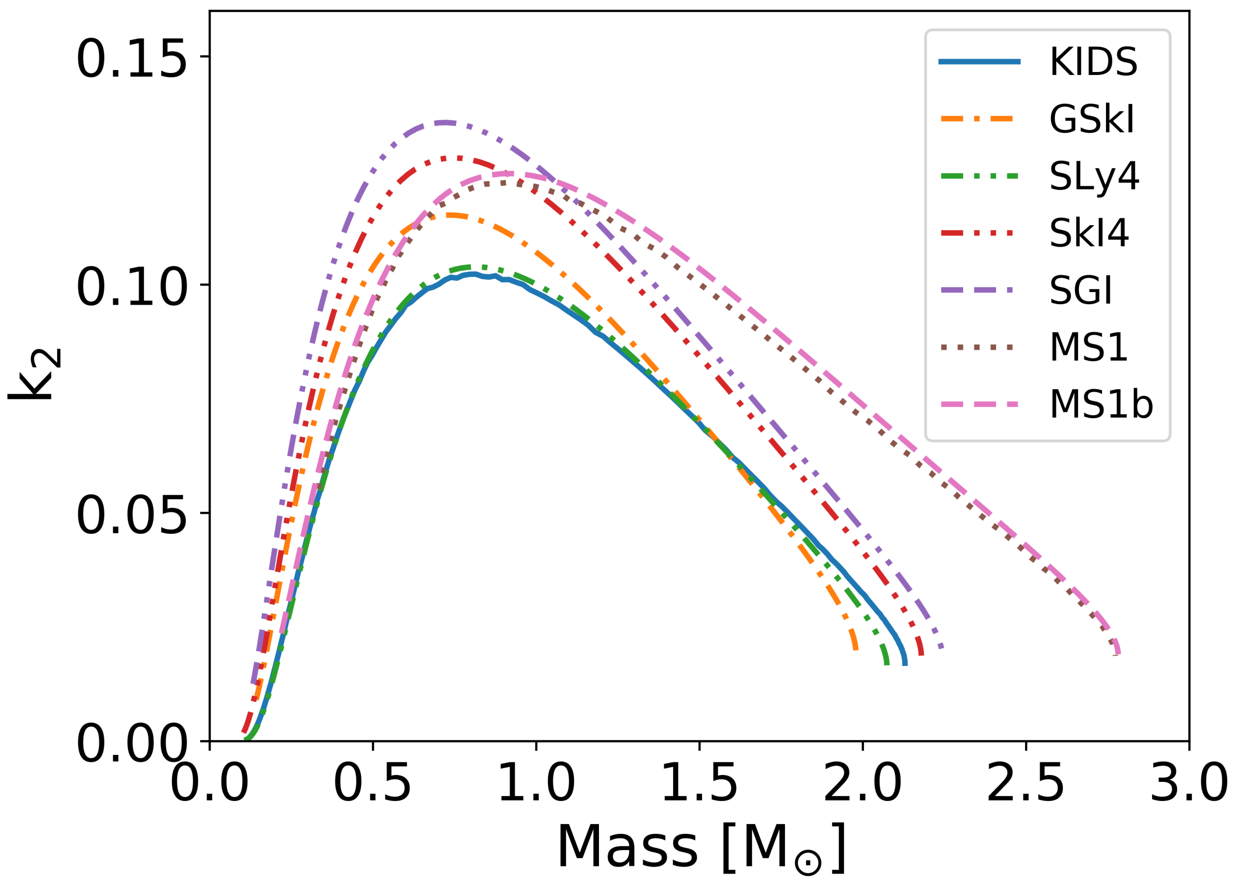
arXiv:180511581v1: 70 <$\Lambda_{1.4}$< 580

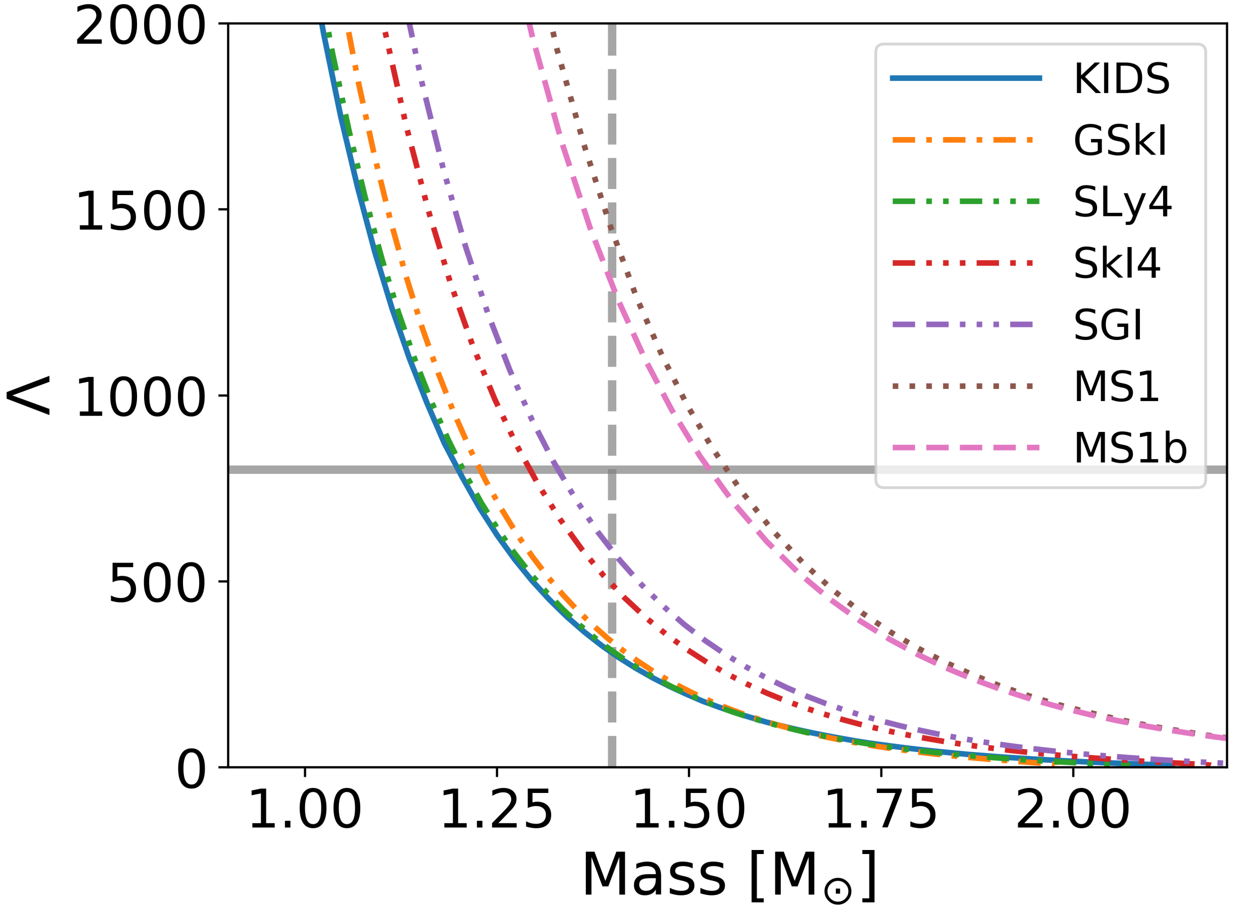


Red dot curve: $\Lambda \propto R^{7.5}$ by E. Annala et al., PRL120(2018)

Neutron star properties




0.15
0.10
0.05
0.00
k2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Mass [M⊙]
KIDS
GSkI
SLy4
SkI4
SGI
MS1
MS1b


2000
1500
1000
500
0
Λ
1.00
1.25
1.50
1.75
2.00
Mass [M⊙]
KIDS
GSkI
SLy4
SkI4
SGI
MS1
MS1b

Contents

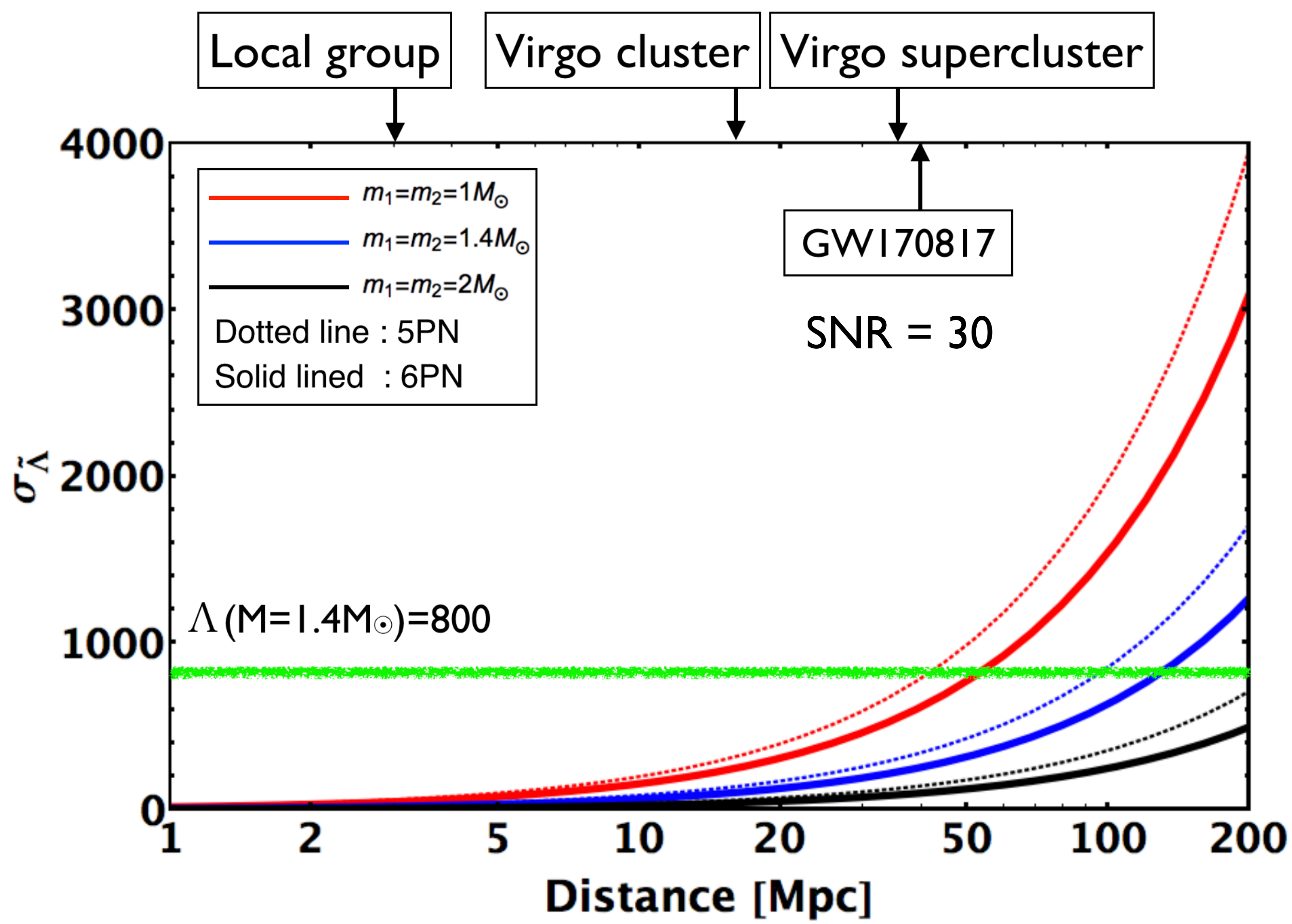
1. **Introduction of RAON**
   - new rare isotope accelerator in Korea
2. **Possible origin of high-mass neutron stars**
   - NS binary evolution
3. **New development in BUD^2 Collaboration**
   - KIDS: new energy density functional
   - Application of KIDS to NS properties
4. **Prospects**

With RAON & MMA Observation

- We developed a new effective model **KIDS**
- We also developed a new transport code **DJBUU**
- With new results from RAON, NICER, and Multi-messenger (GW & EM) observations, we will be able to have better understanding on the physics of dense matter and NS properties.

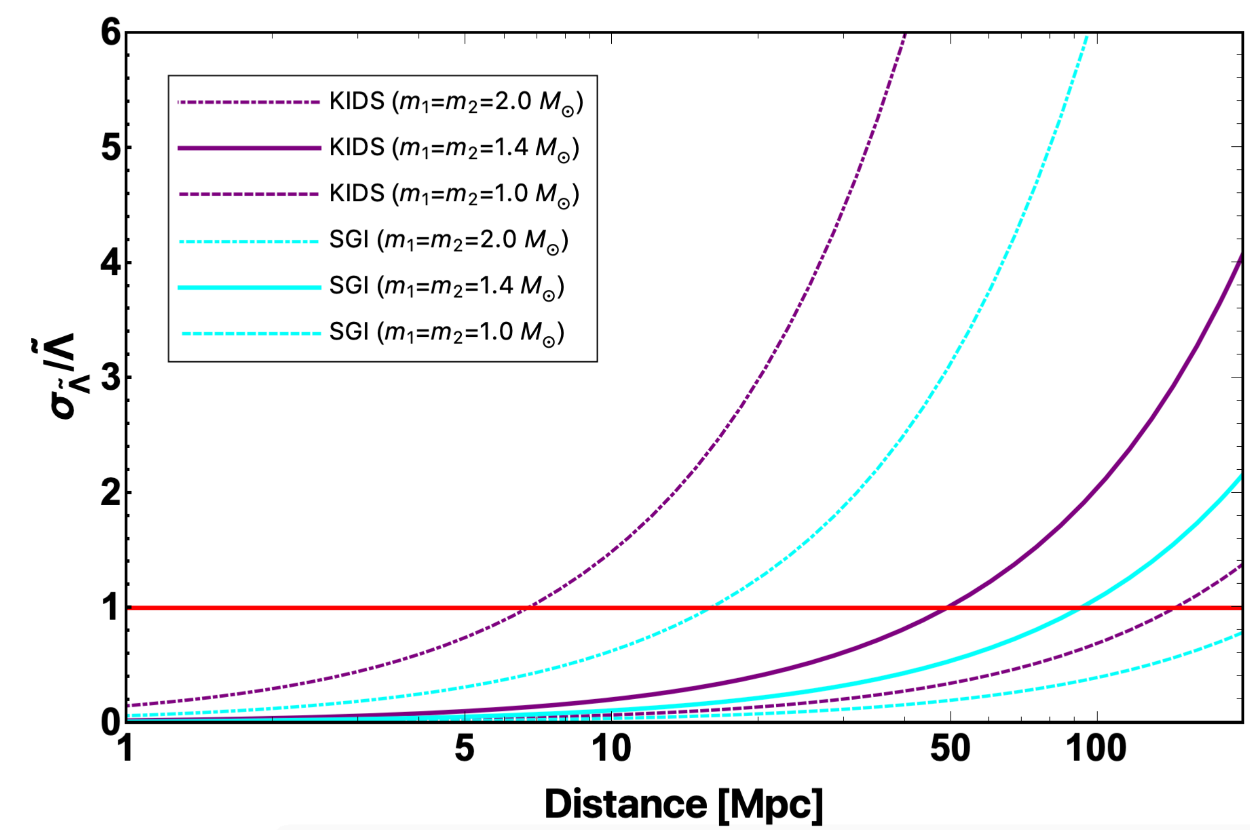
- BUD^2-McGill Collaboration
  DJBUU (*DaeJeon Boltzmann-Uehling-Uhlenbeck)*
  ** DaeJeon is city name in Korea where RAON will be built
  ** S. Jeon (McGill) ** developed MARTINI for RHIC/LHC

Measurement error vs. source distance



For one detector with optimal condition

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



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)

Binary interactions are always interesting

Thanks