Baikal@2013.7.16

Neutron Star Equations of State and Gravitational Waves

Chang-Hwan Lee @ PUSAN NATIONAL UNIVERSITY

Astro-Hadron Group in Pusan Nat'l Univ

- Problems related to NS
  - dense matter physics/ NS equation of states
  - formation and evolution of NS
  - GW from NS binaries

- LSC(LIGO Scientific Collaboration) members
  - Dr. Hee-Suk Cho
  - Y.M. Kim (NIMS)
  - M.G. Kim (1st year in Ph.D., pre-LSC member)

- Non-LSC members (2 students)
  - working on hadron physics (dense matter physics)
  - dense matter physics / NS equation of states

From NS Equation of States

- NS Equation of States
  - ✓ dense matter physics
  - ✓ kaon condensation
  - ✓ new approaches in hQCD
- Gravitational Waves
  - ✓ sources : neutron star binaries
  - ✓ GW waveform generation
  - ✓ GW data analysis

Today

To Gravitational Waves

Contents

- Motivations
- Open problems in NS mass observations
- Possibilities of `NS + high-mass NS/BH` binaries
- A new approach to NS Equation of state in hQCD

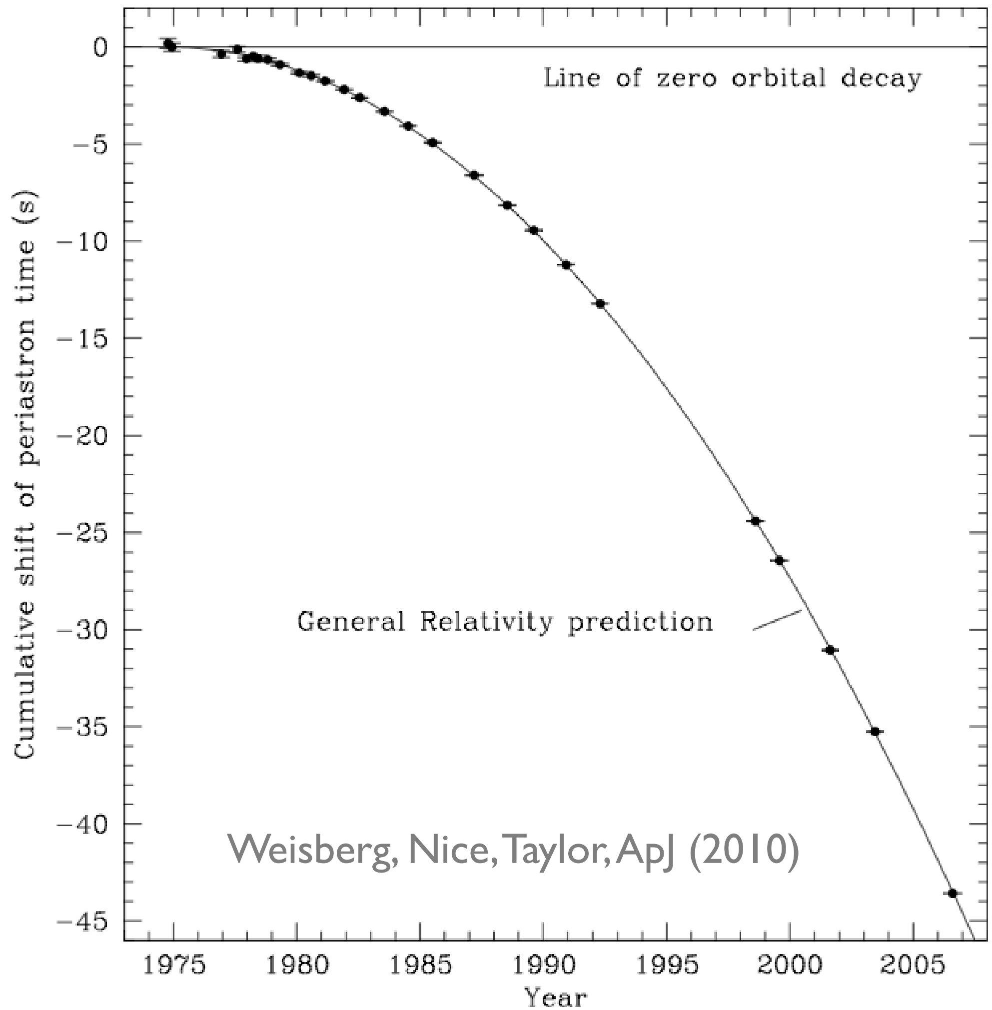
Gravitation Wave from Binary Neutron Star

B1913+16
Hulse & Taylor (1975)

Effect of Gravitational Wave Radiation

1993 Nobel Prize
Hulse & Taylor

Gravitational Wave Observatory



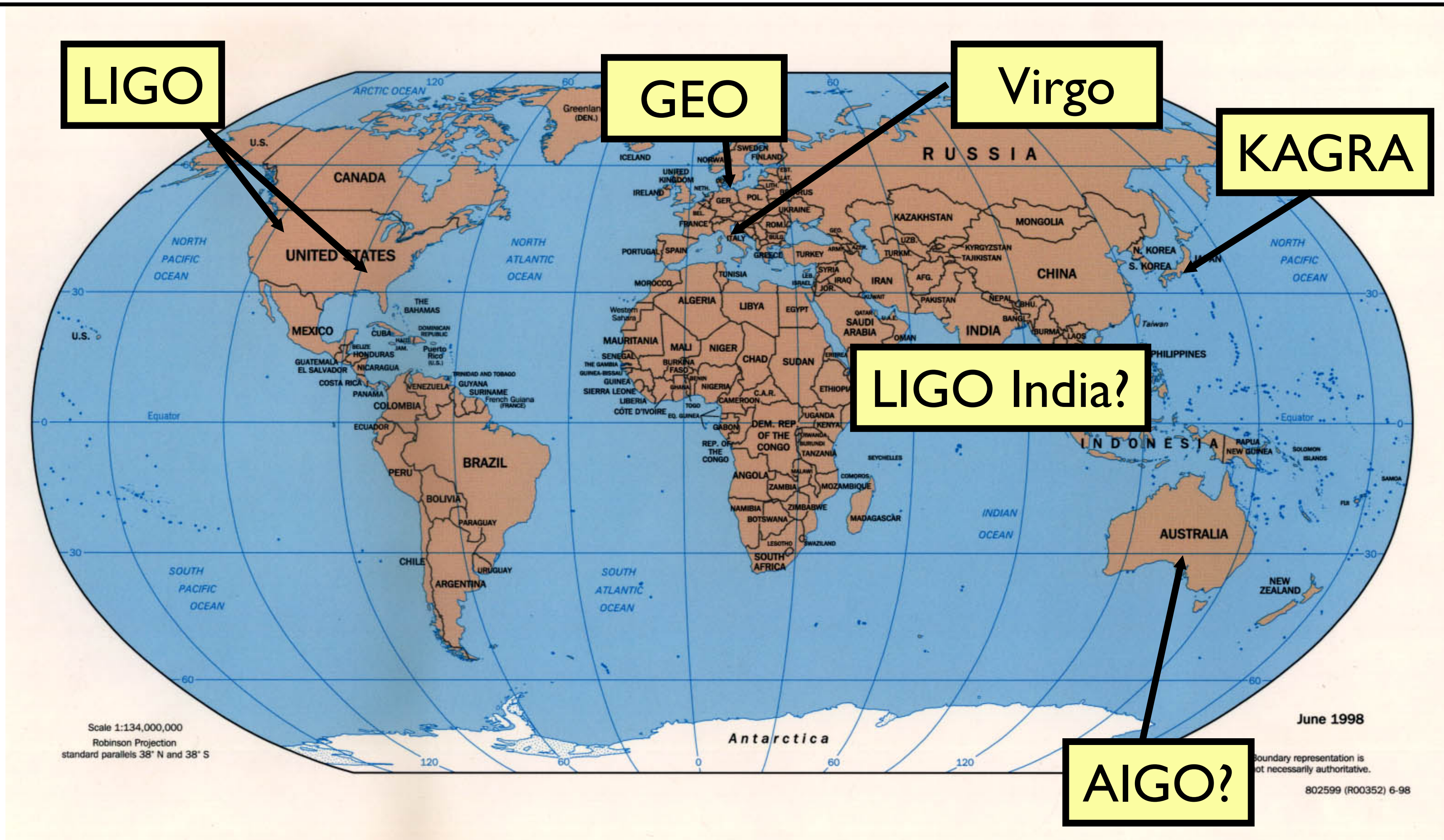
Weisberg, Nice, Taylor, ApJ (2010)

Neutron Stars

Cosmological Heavy Ion Collisions

Gravitational waves from NS-NS and NS-BH Binaries

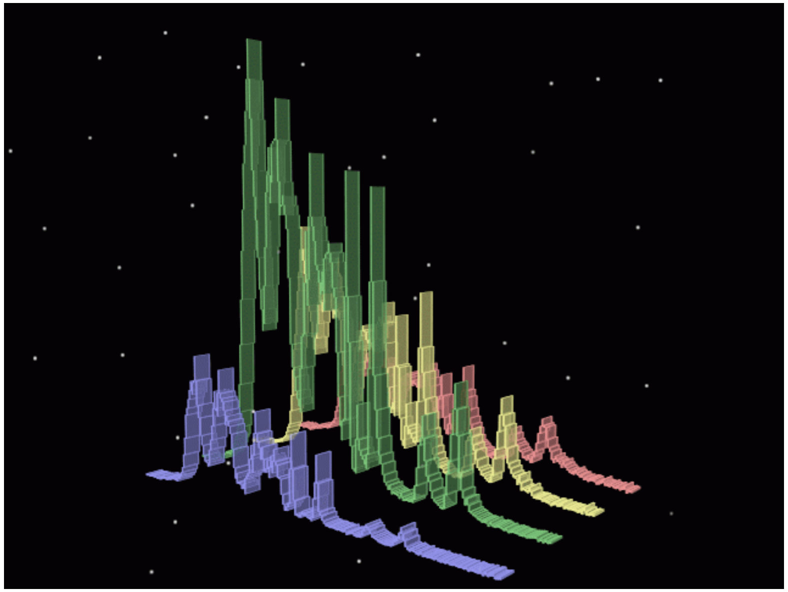
Network of Gravitational Wave Interferometers

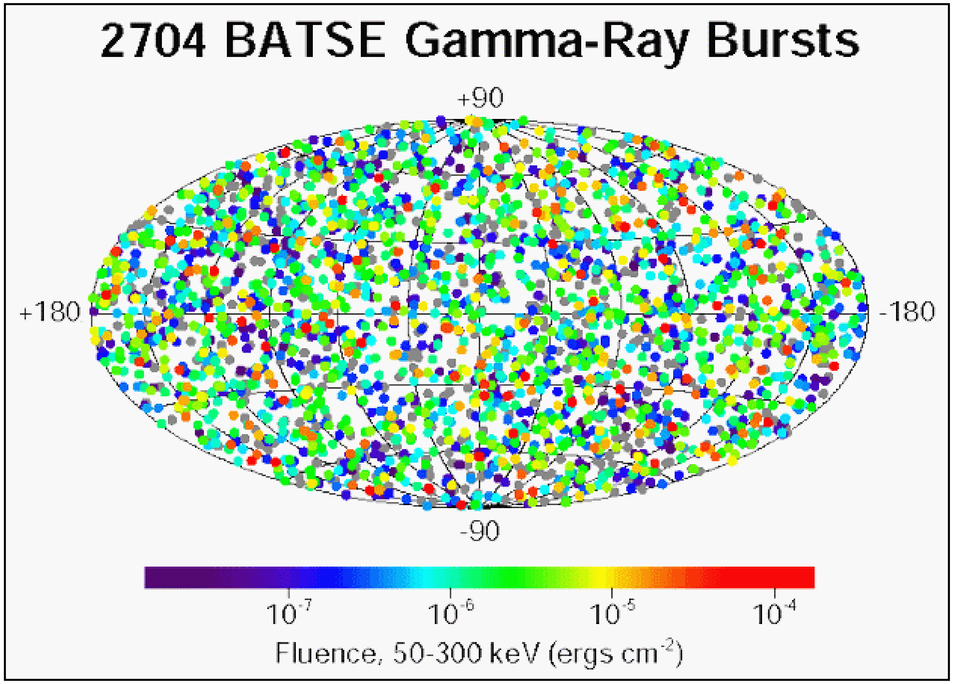


KGWG


THE KOREAN GRAVITATIONAL WAVE GROUP
Korean
Gravitational-Wave Group
Introduction
People
Research
Activities
Publications
News
CBC Wiki (Member Only)
Worldwide
Mega-Science
Projects
Gravitational-wave detection is a global project
of seeking a new window to the Universe.
This will open an era of gravitational wave astronomy.

Origin of gamma-ray bursts (GRBs)





T_{90}=milli sec – min

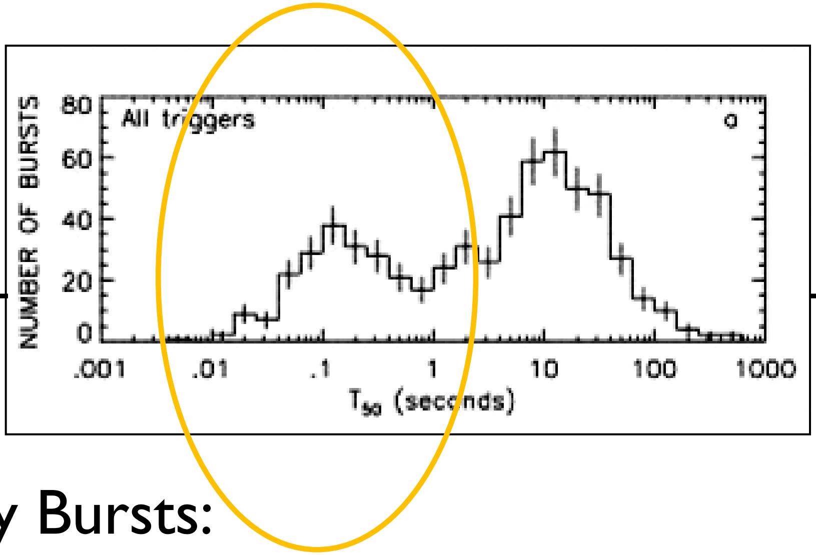
Brightest event in the Universe

1970s :Vela Satellite

1990s: CGRO, Beppo-SAX

2000s: HETE-II, Swift

Two groups of GRBs



- Long-duration Gamma-ray Bursts:

  => HMBH Binaries

- Short Hard Gamma-ray Bursts:

  Duration time < 2 sec

  => NS-NS, NS-BH Binaries

seen NS-NS binaries which will coalesce within Hubble time

PSR	P (ms)	P_b (hr)	e	Total Mass $M_\odot$	τ_c (Myr)	τ_{GW} (Myr)
J0737−3039A	22.70	2.45	0.088	2.58	210	87
J0737−3039B	2773	2.45	0.088	2.58	50	87
B1534+12	37.90	10.10	0.274	2.75	248	2690
J1756−2251	28.46	7.67	0.181	2.57	444	1690
B1913+16	59.03	7.75	0.617	2.83	108	310
B2127+11C	30.53	8.04	0.681	2.71	969	220
J1141−6545†	393.90	4.74	0.172	2.30	1.4	590

Globular Cluster : no binary evolution

White Dwarf companion

Can we see BH-NS binaries as pulsars if they exist ?

Pulsar life time : 1/B

Fresh pulsar : B ~ 10^{12} G

Recycled pulsar : B ~ 10^{8} G

~10^4 times longer lifetime

+ beaming effect

- NS(recycled)-NS(fresh)
  → first-born NS is recycled by accretion
  → NS(recycled) : longer pulsar life time
- BH-NS(fresh)
  → one can see only NS(fresh) : short life time

~10^4 bigger chance

GW sources with NS

- NS-NS – already seen
- NS-BH – no evidence yet
  - contribution to GW is still unknown

Q) what is the boundary between NS & BH ?
  - maximum mass of neutron stars

Contents

1.97 Msun NS discovered in a NS-White Dwarf Binary

LETTER

doi:10.1038/nature09466

A two-solar-mass neutron star measured using Shapiro delay

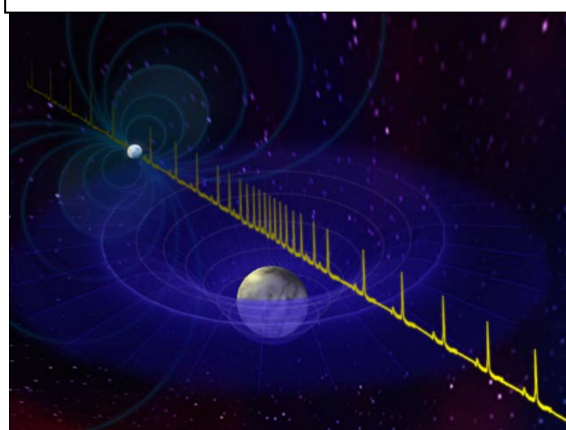
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

October 27, 2010

Contact:

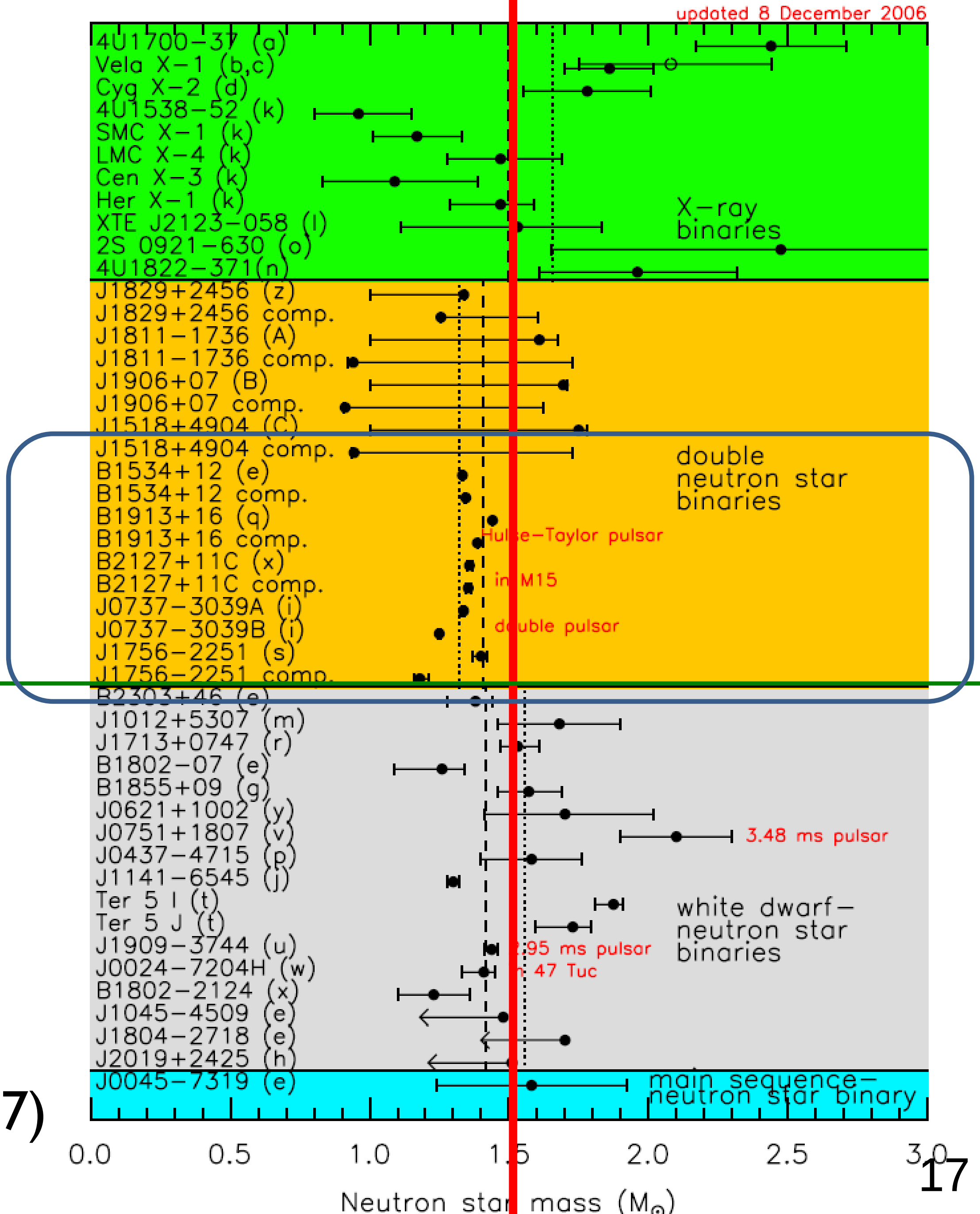
Dave Finley, Public Information
Socorro, NM
(575) 835-7302
dfinley@nrao.edu

Astronomers Discover Most Massive Neutron Star Yet Known



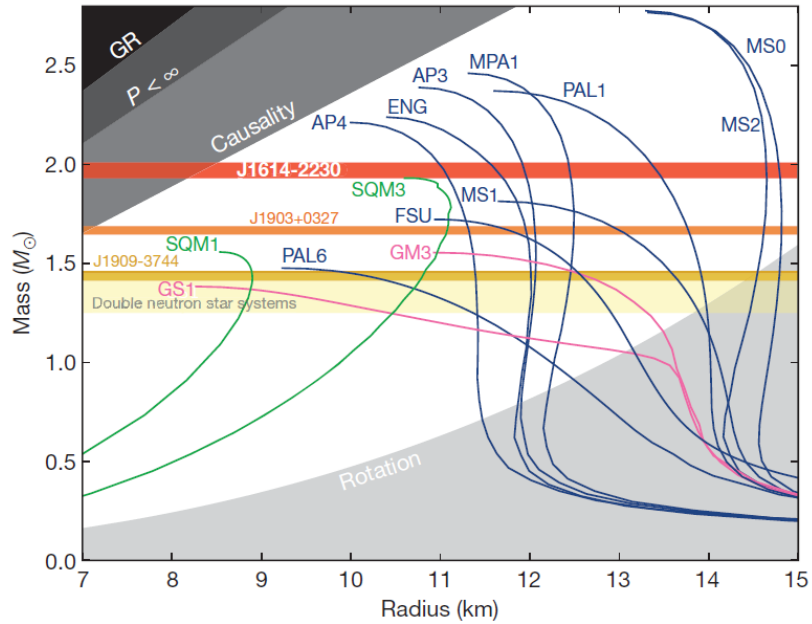
http://www.nrao.edu/pr/2010/bigns/

All well measured NS masses in NS-NS binaries are < 1.5 Msun



Lattimer & Prakash (2007)

Wanted



Nature 467, 1081

- 1.97 Msun NS was observed in a NS-WD binary
- Why all well-measured NS masses in NS-NS binaries are less than 1.5 Msun?
- NS mass may/should depend on the evolution process.

arXiv:0907.3219v1

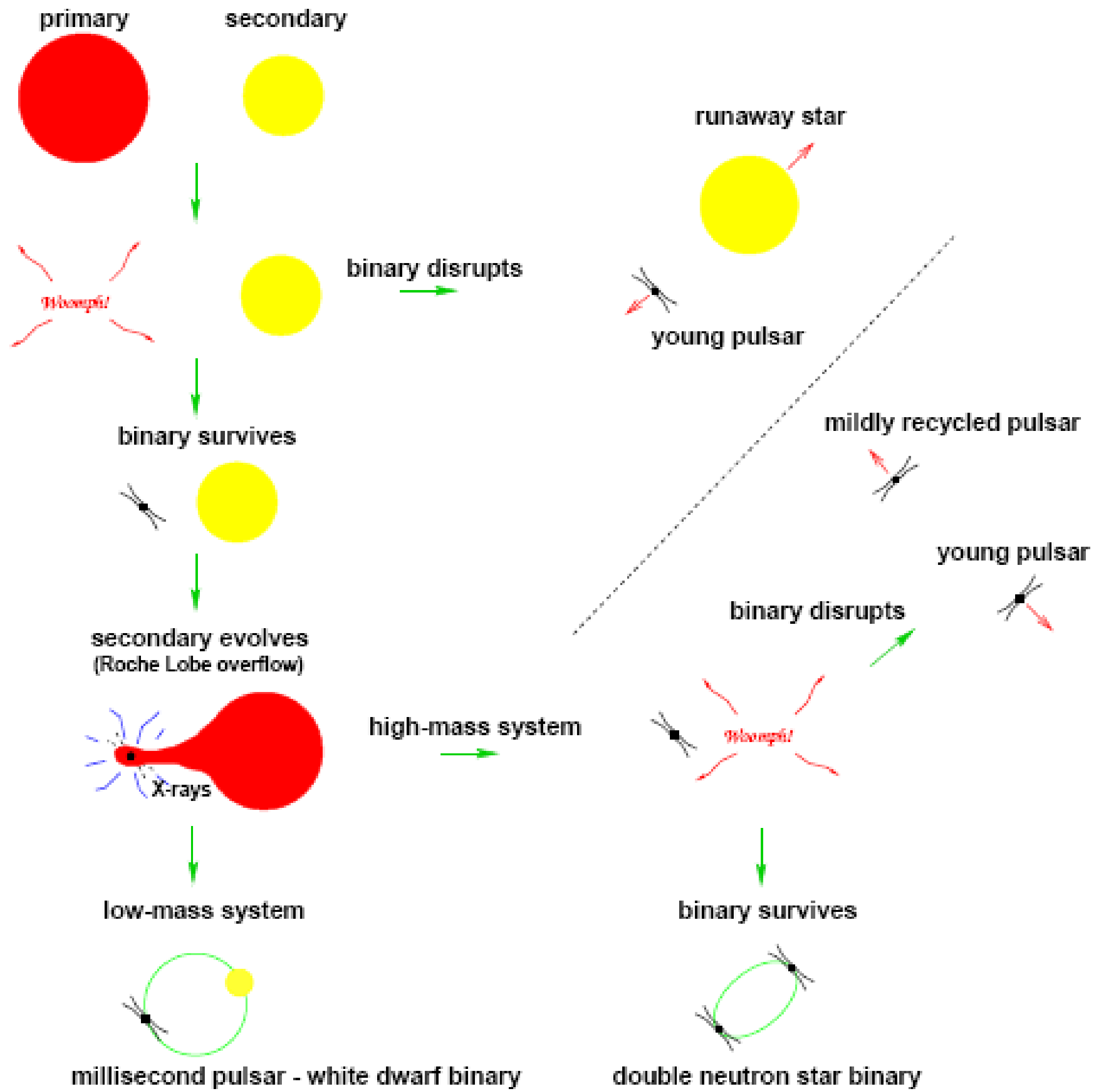


FIGURE 1. Formation of millisecond pulsars. From Lorimer (2008).

Accretion process is essential in understanding NS binaries

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Eddington Luminosity & Eddington Limit

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

$$\kappa = \sigma_T N_A$$

Thomson scattering cross section σ_T

Avogadro's number N_A

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

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

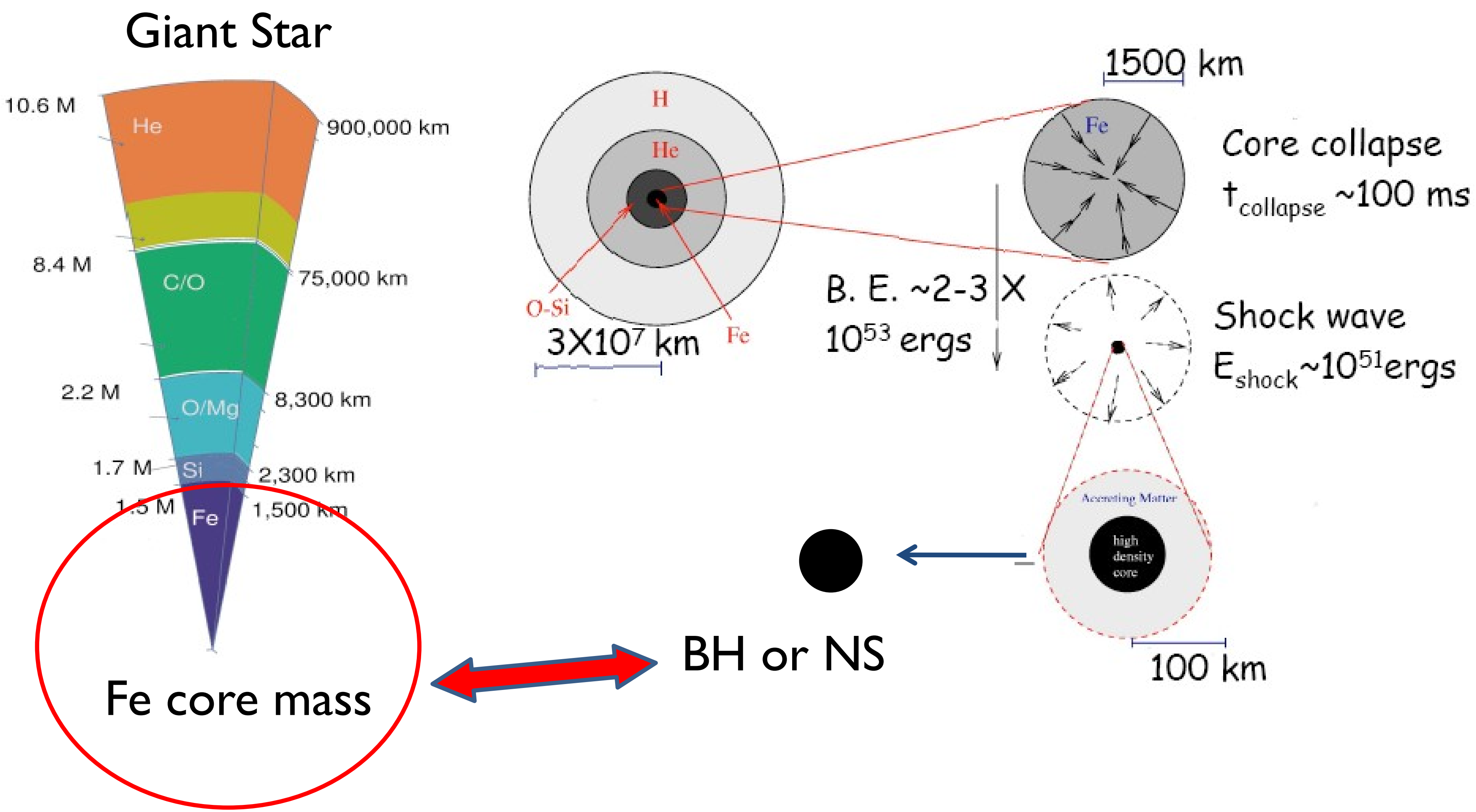
[Lee,Park,Brown,ApJ 670,741(2007)]

Supercritical Accretion onto first-born NS

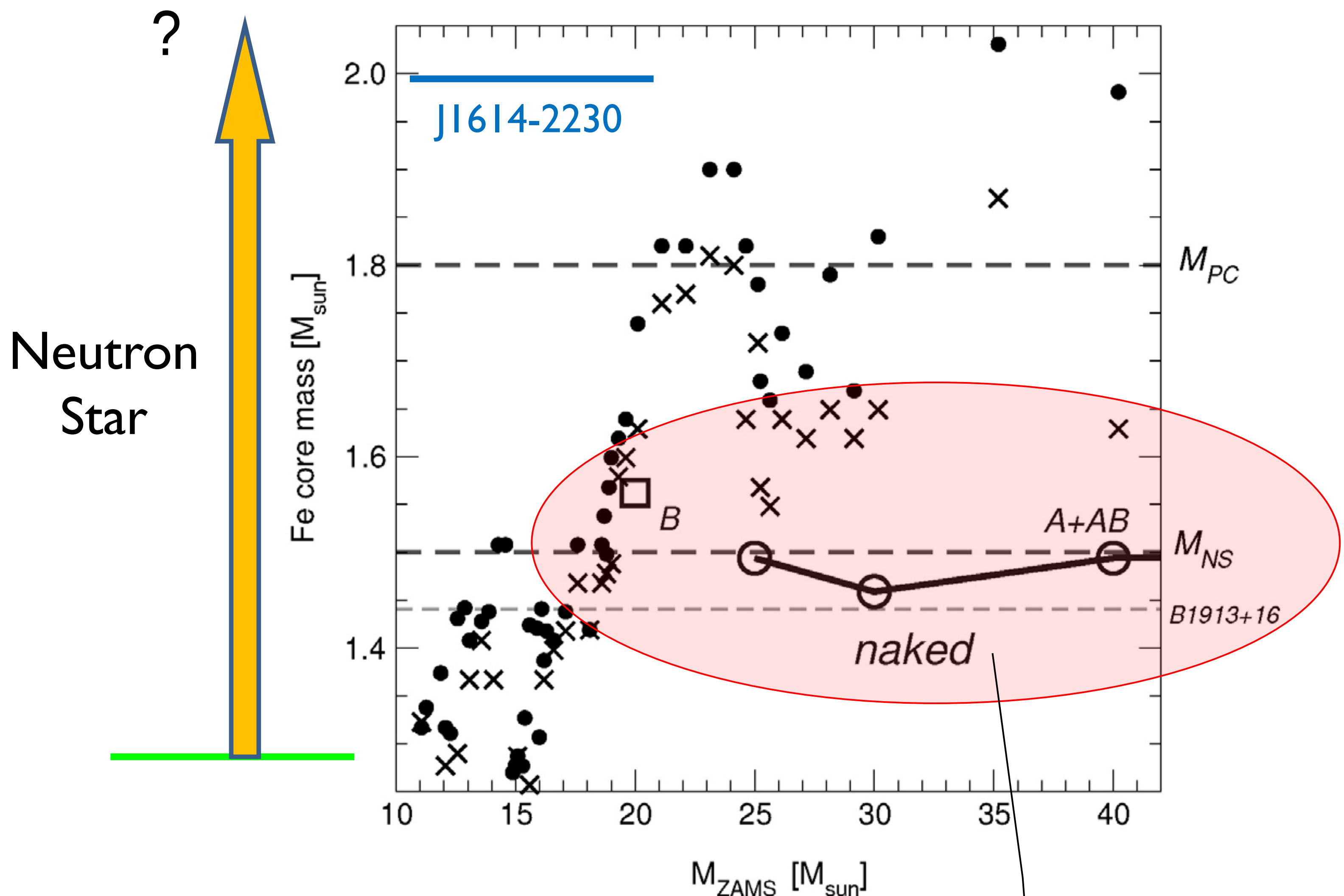
- Eddington Accretion Rate : photon pressure balances the gravitation attraction
- If this limit holds, neutron star cannot be formed from the beginning (e.g. SN1987A; 10^8 Eddington Limit).
- Neutrinos can take the pressure out of the system allowing the supercritical accretion when accretion rate is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

Q) What is the implications of supercritical accretion ?

One has to understand formation of BH/NS



Fe core mass before collapse (Brown et al. New Aston. 6,457)



□ & ○ : evolution without H envelope

Fresh NS mass from Fe core collapse

In close binaries (evolution without H envelope)

low Fe core mass ⇨ NS mass = 1.3 - 1.5 Msun

This value is independent of NS equation of state.

Q) What is the fate of primary (first-born) NS in binaries ?

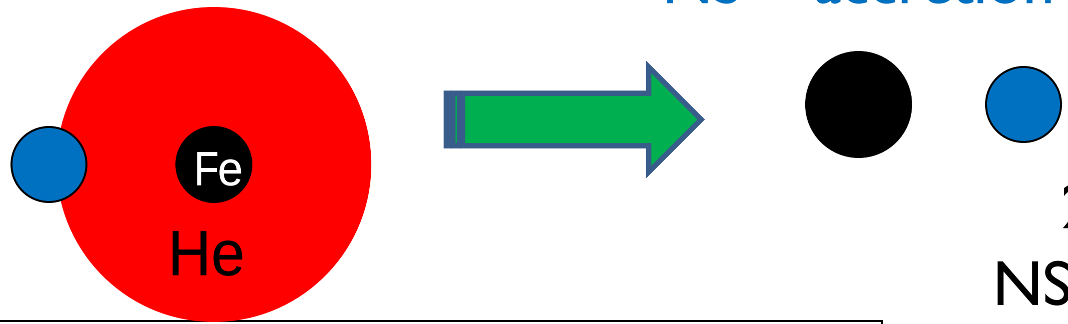
Note: Accurate mass estimates of NS come from binaries

Final fate of first-born NS

Accretion

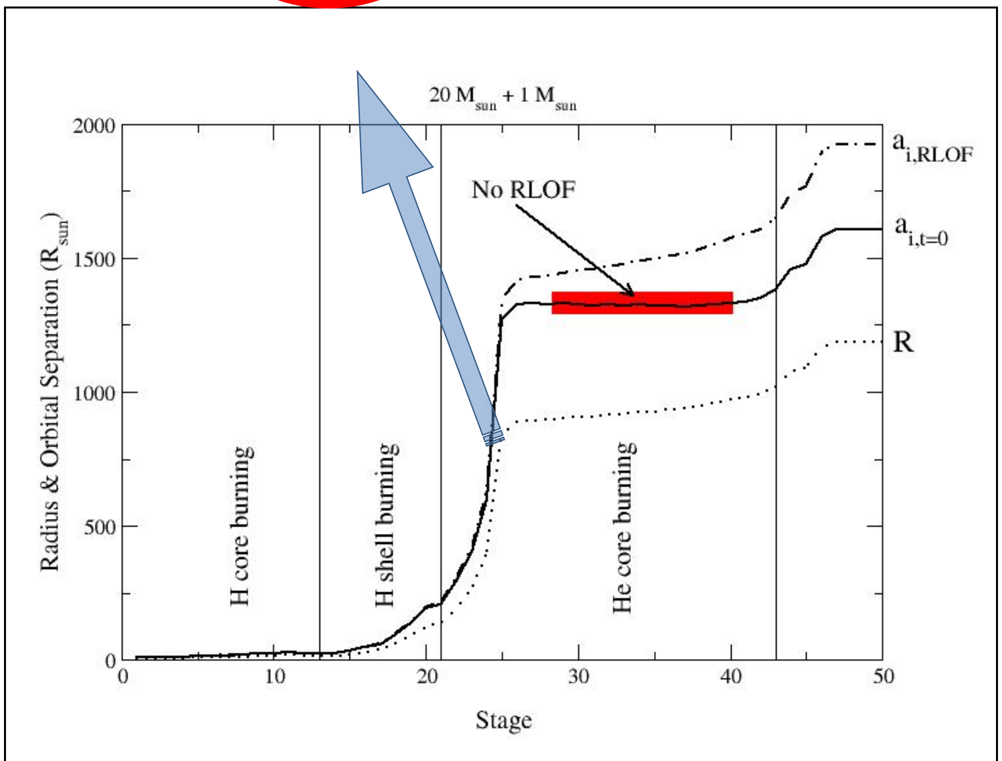
NS + accretion

1st-born NS

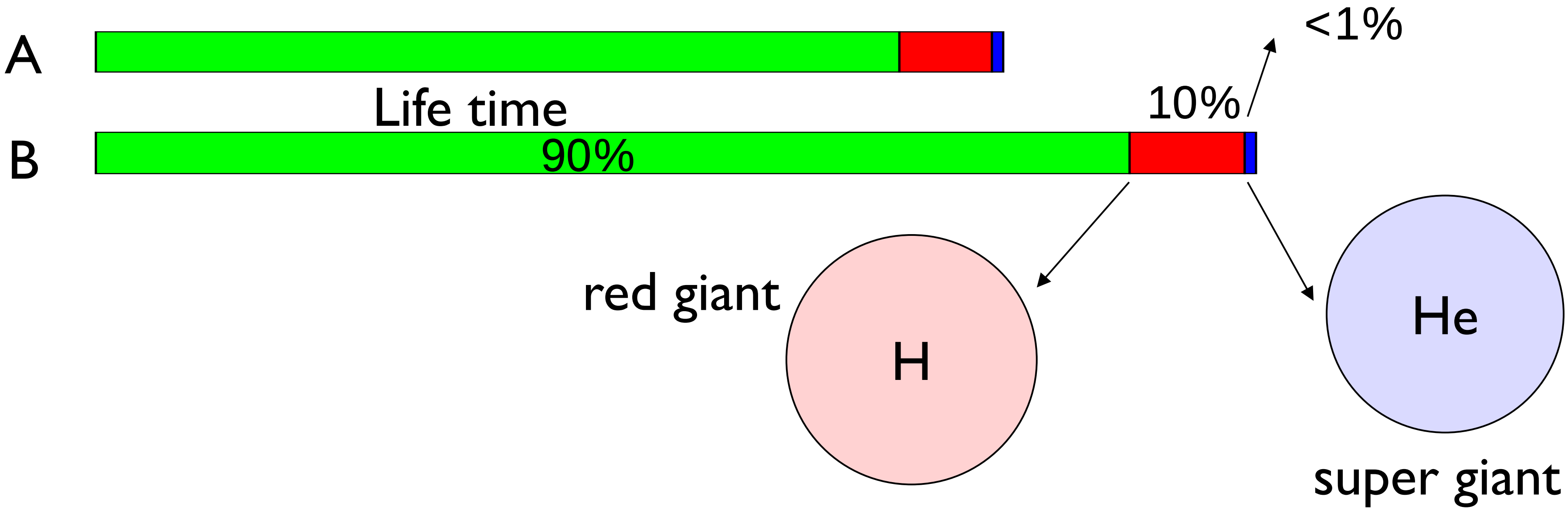


2nd NS/WD

Evolution of Companion



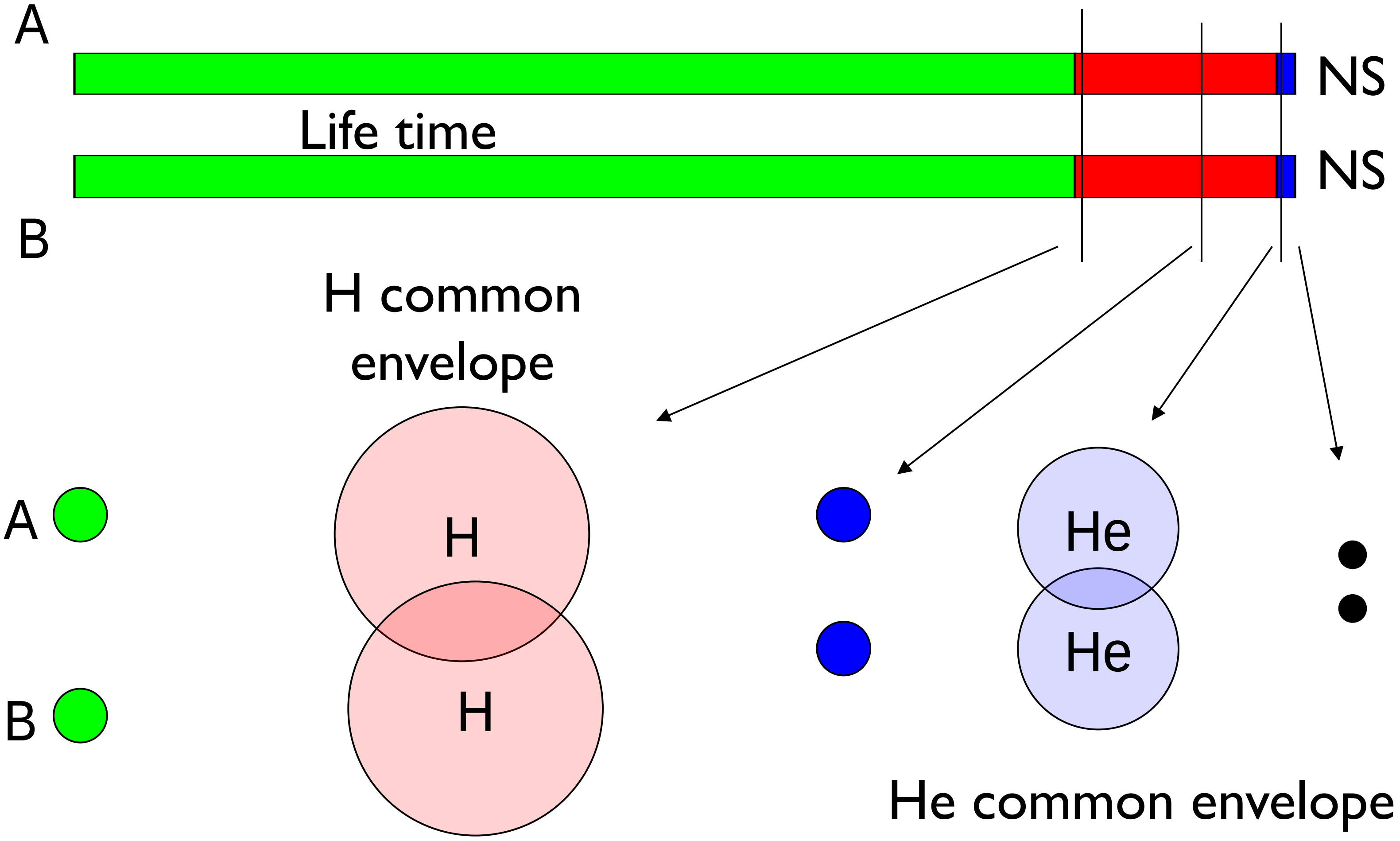
Evolution of binary stars



Original ZAMS(Zero Age Main Sequence) Stars

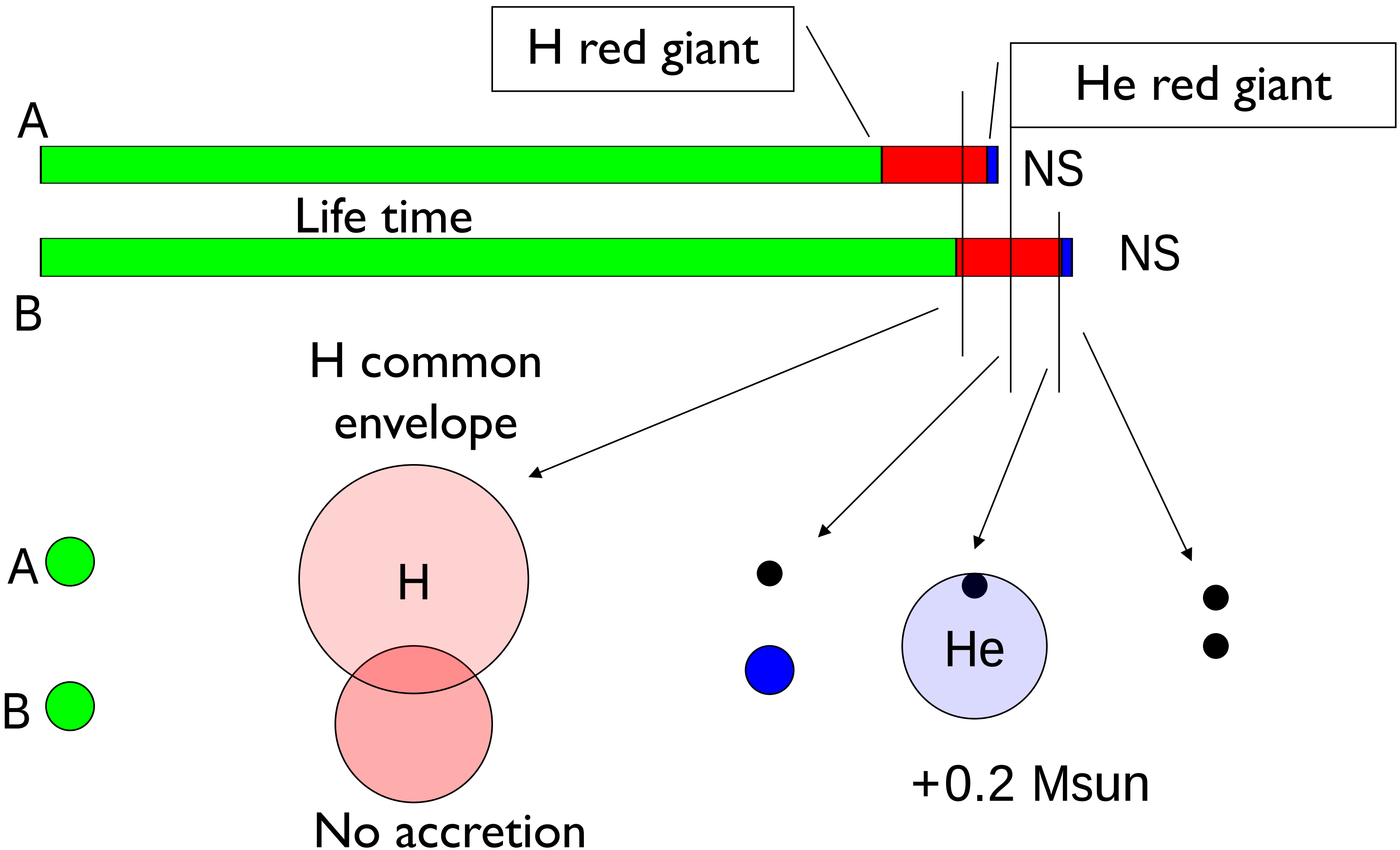
- Probability = $1/M^{2.5}$
- Life Time = $1/M^{2.5}$
- $\Delta M=4\%$,
  $\Delta T_{life}=(1 - 1/1.04^{2.5})= 10\%$,
  $\Delta P=10\%$ (population probability)

Case 1 : $\Delta T < 1\%$



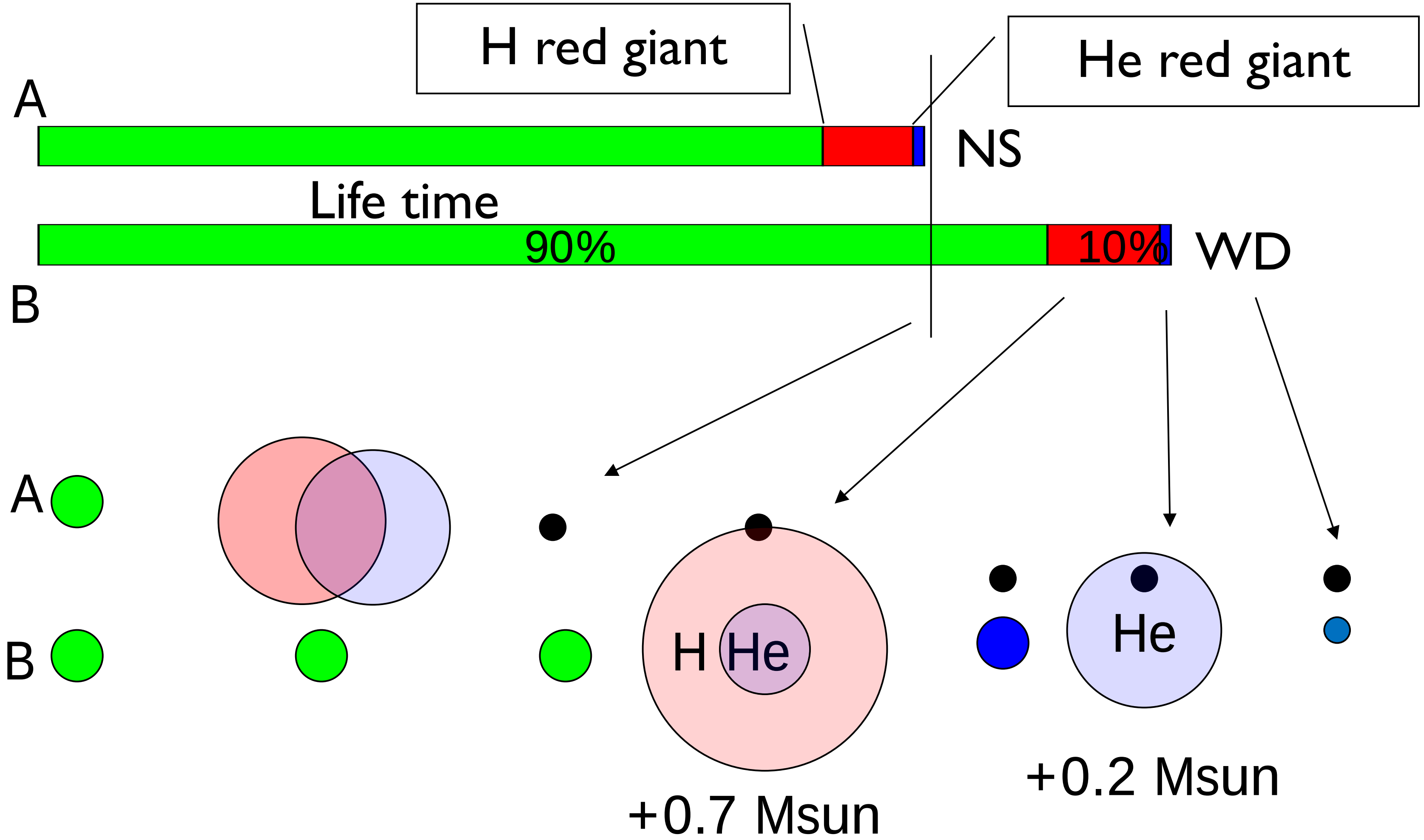
No accretion : nearly equal mass NS-NS binary!

Case 2 : 1% < ΔT < 10%



First born NS should accrete only < 0.2 $M_\odot$!

Case 3 : ΔT > 10%



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

How mass & orbit change during the evolution?

A few efficiencies (not calculable from first principles)

$$\dot{E}_{\rm acc} = \frac{1}{2} c_d \frac{G(M_{\rm NS} + M_{\rm giant})}{a} \dot{M}_{\rm NS}$$

$$-\dot{E}_{\rm orb} = \frac{1}{2} \frac{GM_{\rm giant}}{a} \dot{M}_{\rm NS} + \frac{1}{2} \frac{GM_{\rm NS}}{a} \dot{M}_{\rm giant} - \frac{1}{2} \frac{GM_{\rm NS} M_{\rm giant}}{a^2} \dot{a}$$

$$\dot{E}_{\rm acc} = -\dot{E}_{\rm orb}$$

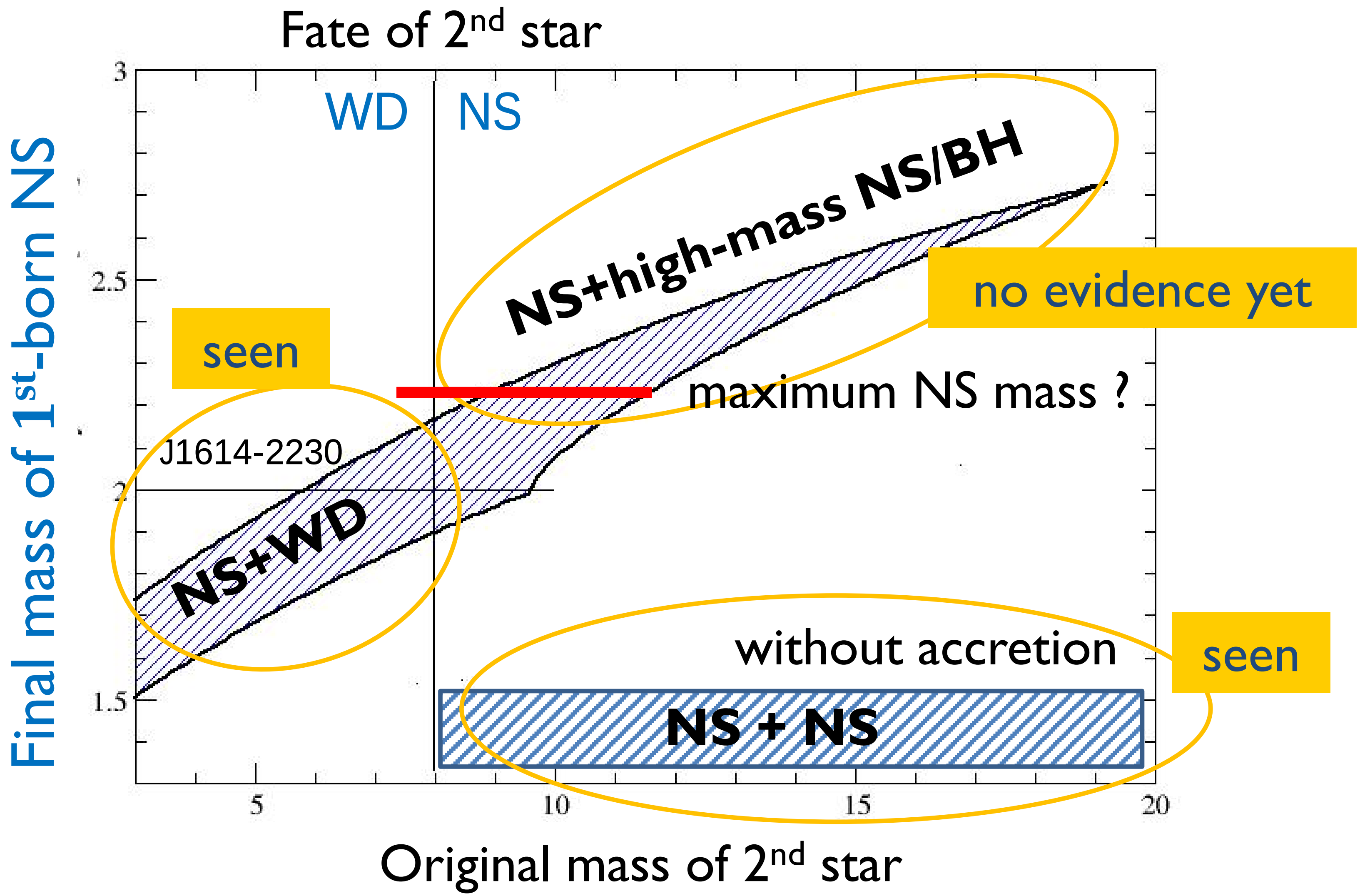
$$\alpha_{\rm ce} \frac{dE_{\rm orb}}{dM_{\rm giant}} = -\frac{dE_{\rm bind}}{dM_c}$$

$$E_{\rm bind} = -\frac{1}{\lambda} \frac{GM_{\rm giant}(M_{\rm giant} - M_{\rm giant,core})}{a}$$

c_d=6, $\alpha_{ce}\lambda$=0.2
are consistent with
SXT(Soft X-ray Transient)
Lee,Brown,Wijers,ApJ(2002)

Belczynski et al., ApJ, 572, 407

Final mass of first-born NS with supercritical accretion



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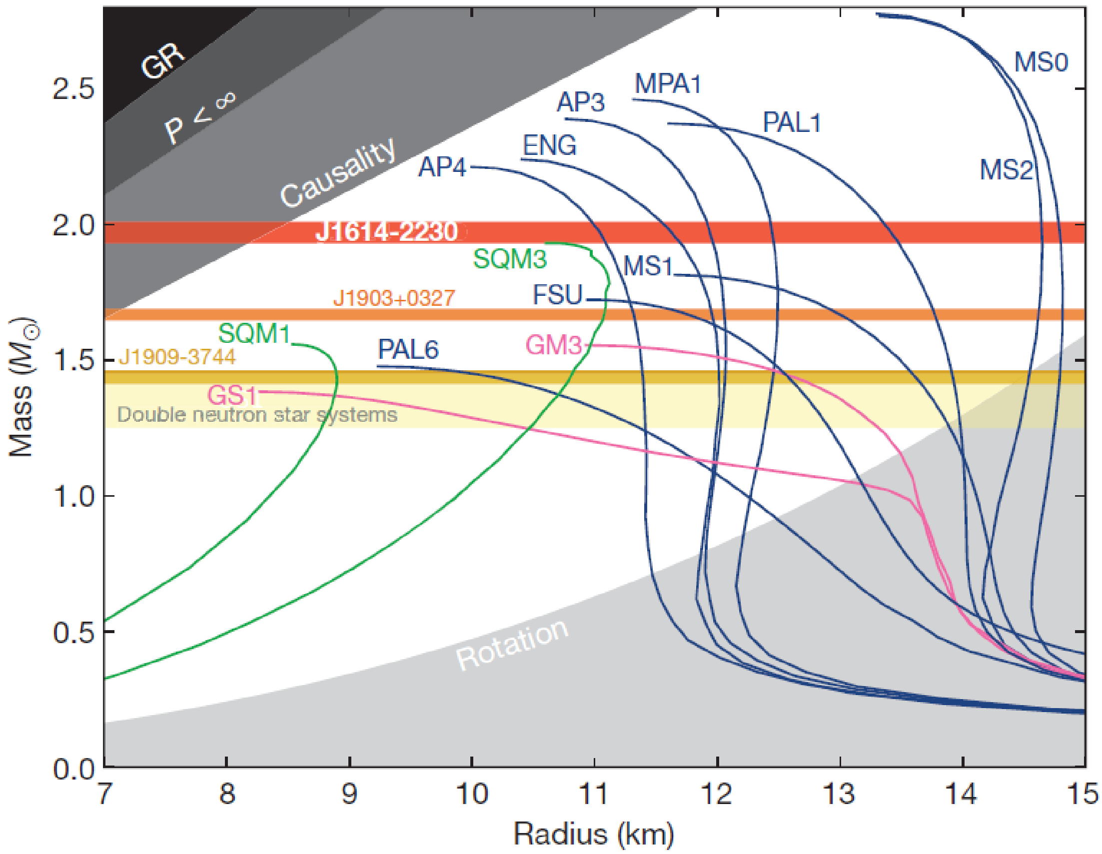
Which one is right EOS ?



refer talks by
M.G. Cheon (Tue) & H.K. Lee (Thu)

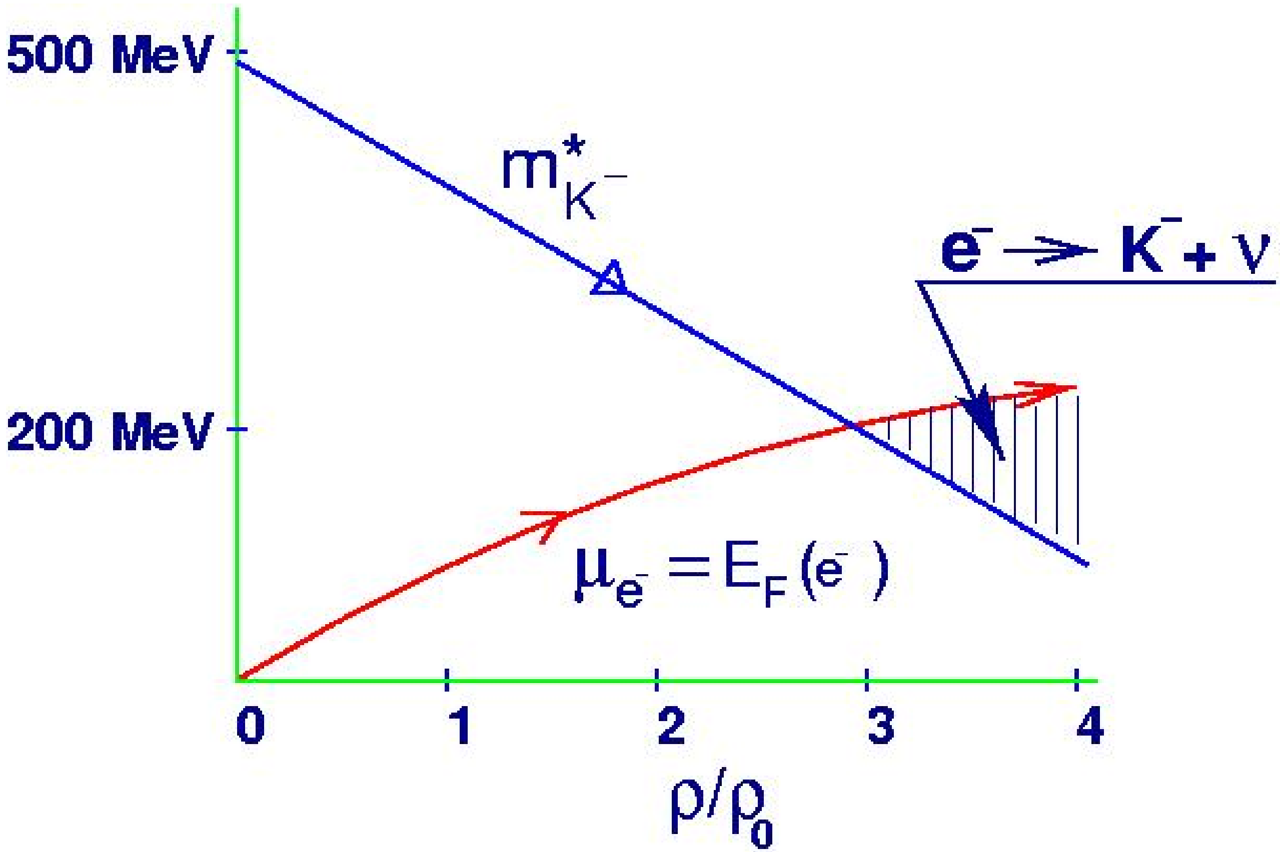
Nature 467, 1081

Why strange quarks in neutron stars ?

- ✓ proton, neutron: u, d quarks
- ✓ By introducing strange quark
  - we have one more degrees of freedom
  - energy of the system can be reduced!
- ✓ In what form ?
  kaon, hyperons … …

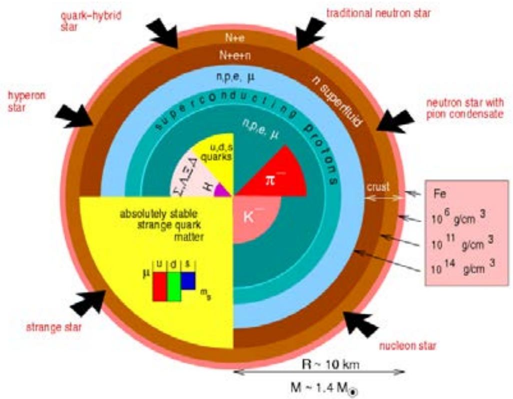
Kaon is the lighest particle with strange quark !

Kaon Condensation in Dense Matter



ρ_0 = nuclear matter density

Astrophysical Implications



Neutron Star

High μ

Neutrinos

Kaons

Hyperons

Reduce Pressure

Soft EoS

Low μ

Hard Core

Easy to make high density

Formation of low mass Black Hole

Two different approaches for kaon condensation

- ✓ Conventional approach :
  - from zero density to higher density
- ✓ Top-down approaches :
  - from high density where chiral symmetry is restored to lower density
  - possibilities in recent hQCD

Problems in conventional approaches

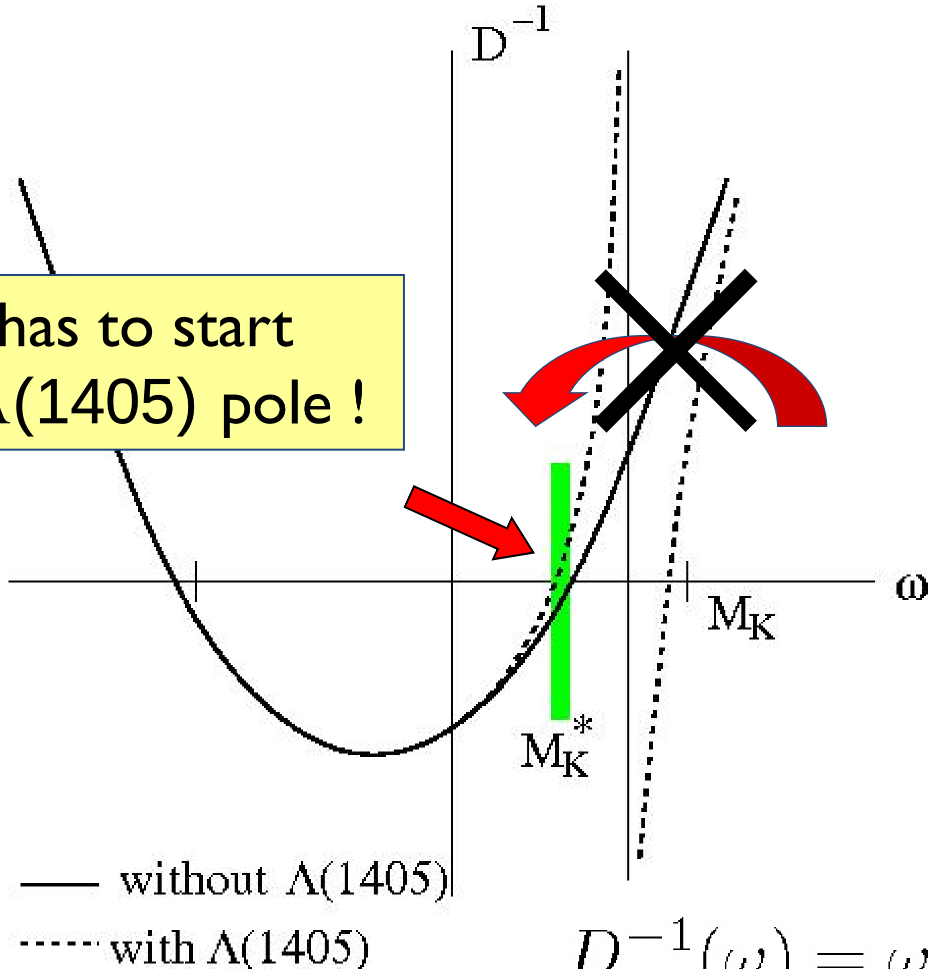
- ✓ Problem in $K^{-}p$ Scattering amplitude:
  experiment : - 0.65 + i 0.81 fm (repulsive)
  chiral symmetry : + (attractive !)

- ✓ Problem of $\Lambda(1405)$
  pole position of $\Lambda(1405)$
  → only 30 MeV below KN threshold

Perturbation breaks down in conventional approach !

Far below $\Lambda(1405)$ pole, $\Lambda(1405)$ is irrelevant !

One has to start below $\Lambda(1405)$ pole !



$$D^{-1}(\omega) = \omega^2 - M_K^2 - \Pi(\omega)$$

Wanted : New Top-down approaches

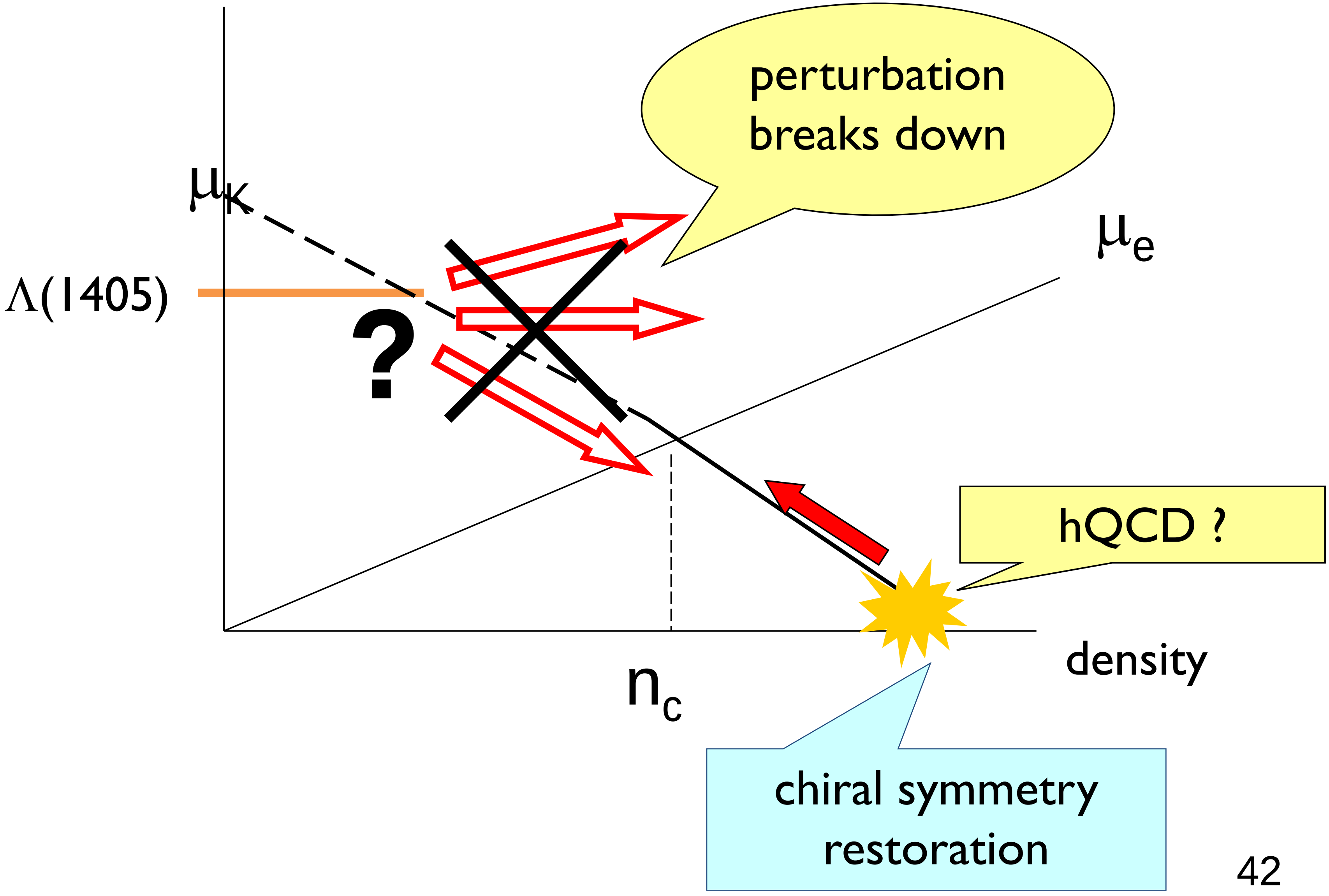
Q) Is there a proper way to treat strangeness in dense matter without problem of the irrelevant terms, e.g., $\Lambda(1405)$, from the beginning ?

Start from where the symmetry is fully restored !

- AdS/QCD, etc.

All irrelevant terms are out in the analysis from the beginning !

Goal: Strangeness in hQCD



Holographic QCD

refer talk by Bumhoon Lee (Fri)

- Bottom-up approach :
  start from QCD and attempt to guess
  its 5d holographic dual, AdS/CFT dictionaries
  → hard-wall model, soft-wall model, …

- Top-down approach :
  start from string theory, set brane configuration with DBI action, reproduce QCD-like theory
  → D3/D7, D4/D6, Sakai-Sugimoto …

Top-down in hQCD : one example

JHEP10 (2011) 111

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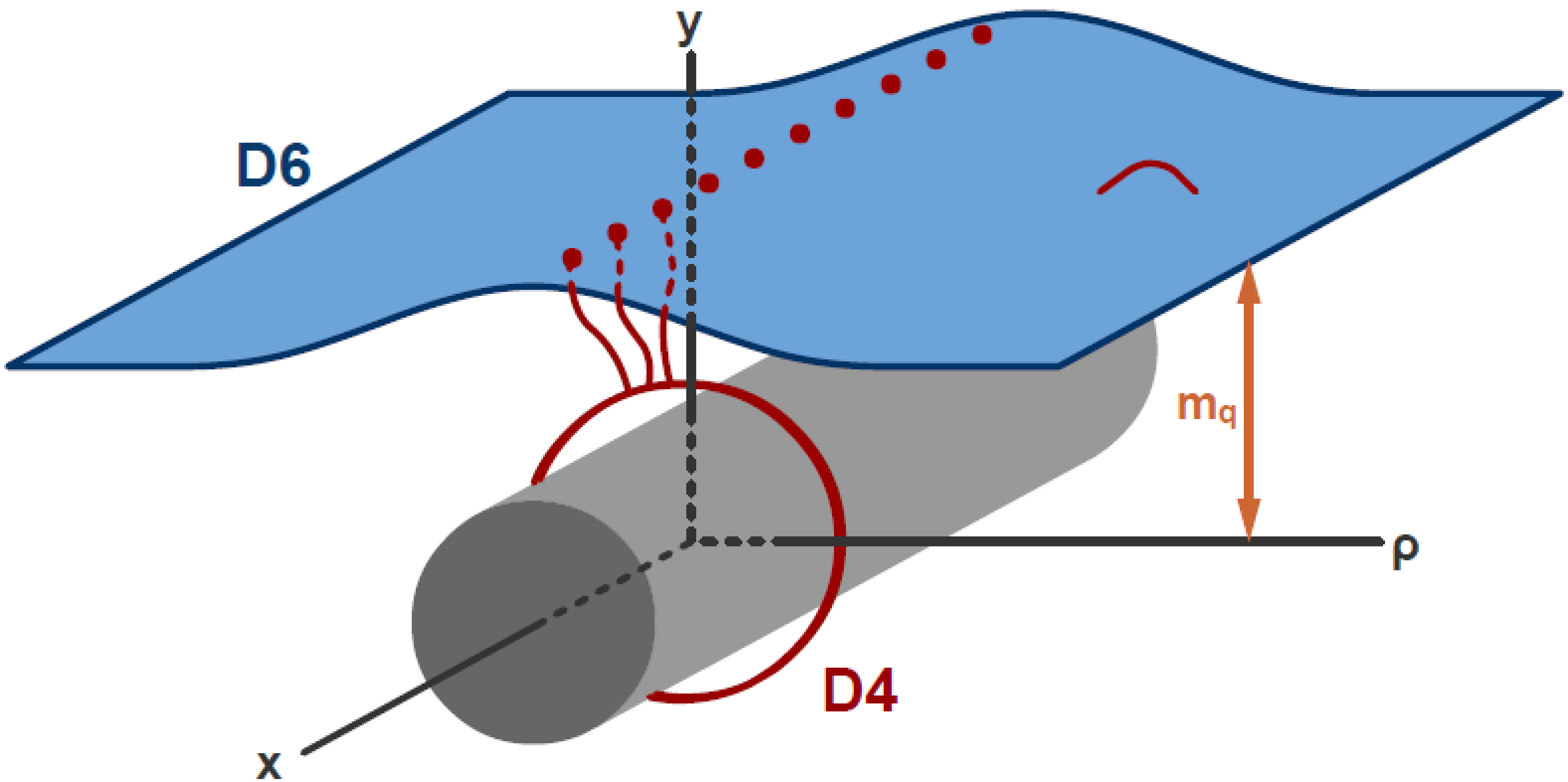
Holographic equations of state and astrophysical compact objects

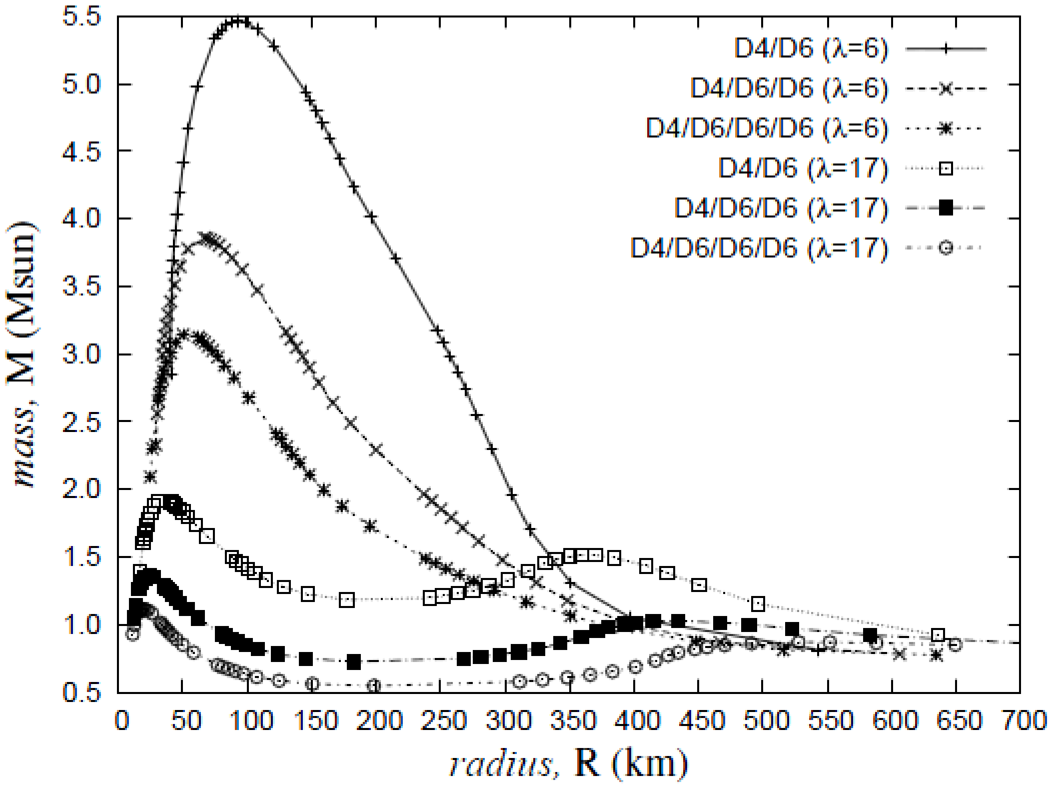
Youngman Kim,[a,b] Chang-Hwan Lee,[c] Ik Jae Shin[a] and Mew-Bing Wan[a]

Related works by S.-J. Sin et al. JHEP 03(2010)074, 04(2008)010, 06(2011)011

- add compact D4 branes ⇒ Baryon



Mass-radius relation



Far from realistic : what is the problem ?

hQCD: What is still missing ?

- proper attraction is missing
  in large Nc limit & large t'Hooft coupling limit
- mass of scalar field is bigger than that of vector field
- strangeness in hQD

more details of hQCD itself
→ talk by Bumhoon Lee (Fri)

Prospect

- possibilities of different class of NS binaries
  → typical NS + high-mass NS/BH (> 2 solar mass)
  → could be hidden GW sources

- new approaches to NS EoS in hQCD
  → still far from realistic
  → how to put strangeness

Many Thanks