HIM2010-12@yonsei.10.12.11

Neutron Star Binaries and Related Astrophysical Issues

Chang-Hwan Lee @ PUSAN NATIONAL UNIVERSITY

APCTP
Asia Pacific Center for Theoretical Physics

Q) Maximum Mass of Neutron Star ?

Nature 467, 1081 (Oct. 28, 2010)

PSR J1614-2230

(Millisecond Pulsas & White Dwarf Binary)

1.97 ± 0.04 Msun

(measurement based on Shapiro delay)

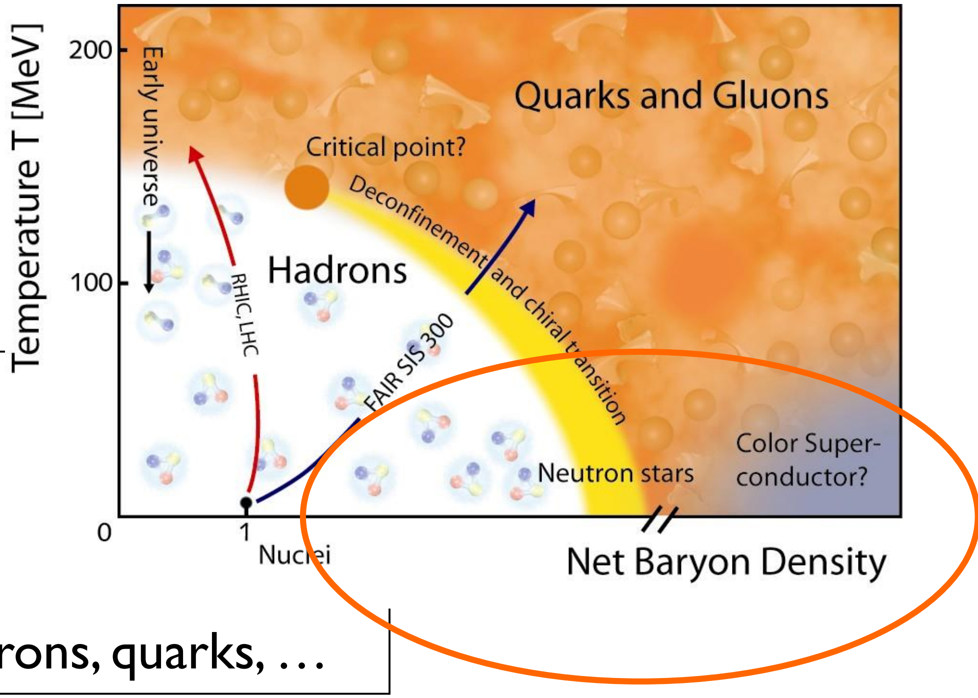
Contents

- Motivation
- Neutron Star Equation of States
- Maximum Neutron Star Mass (Observations)
- Other Astrophysical Issues
  - Formation & Evolution of NS Binaries
  - Gamma-ray Bursts
  - Gravitational Wave”

Motivations 1: why Neutron Stars ?

Ultimate Testing place for physics of dense matter

- ✓ Chiral symmetry restoration
- ✓ Color superconductivity
- ✓ Color-flavor locking
- ✓ Quark-Gluon-Plasma ?
- ✓ … … …



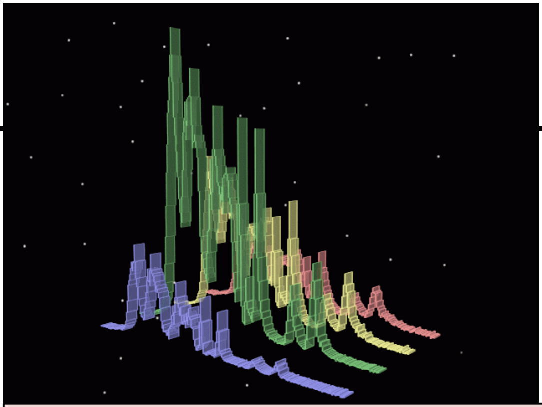
Neutron Stars
M = 1.5 solar mass
R < 15km
A = 10^57 nucleons
composed of p, n, e, hyperons, quarks, …

- Motivations 2: why Neutron Stars ?

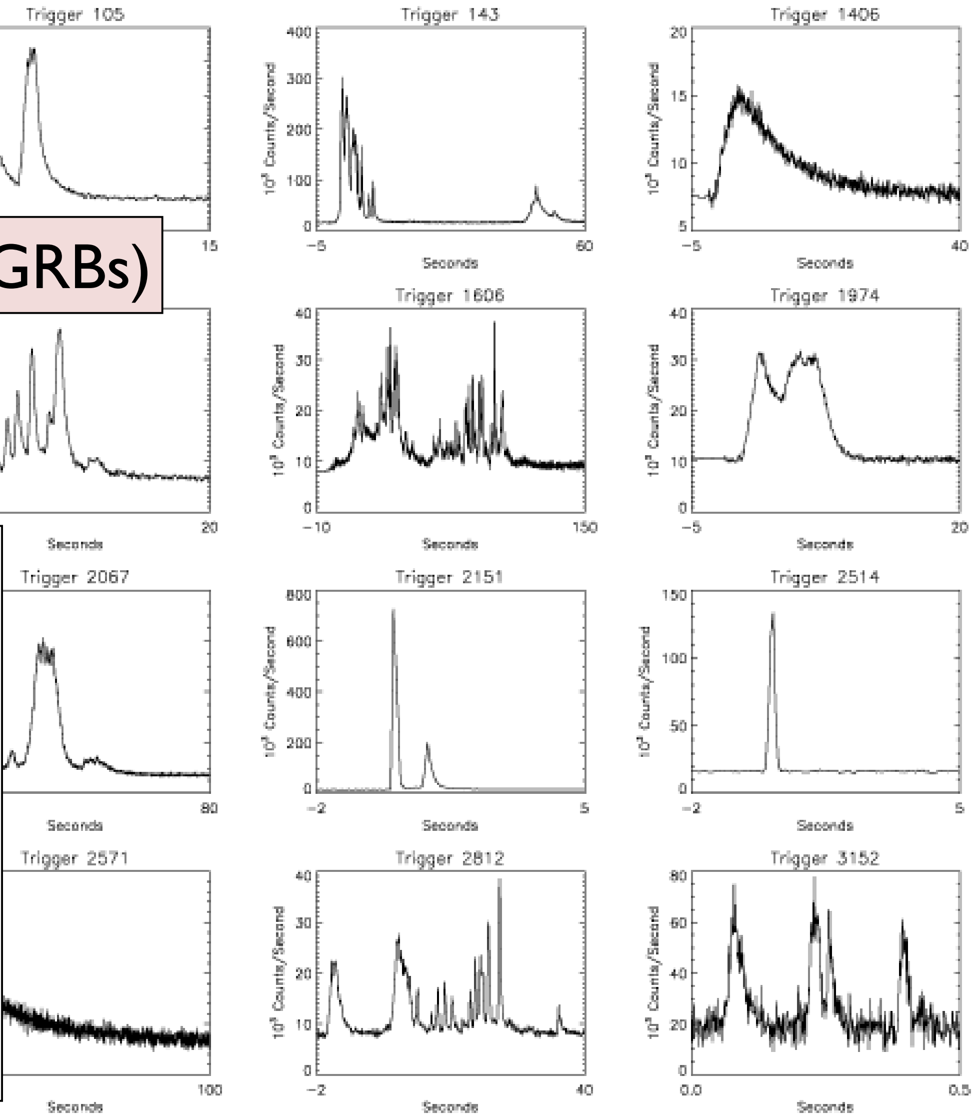
Cosmological Heavy Ion Collisions

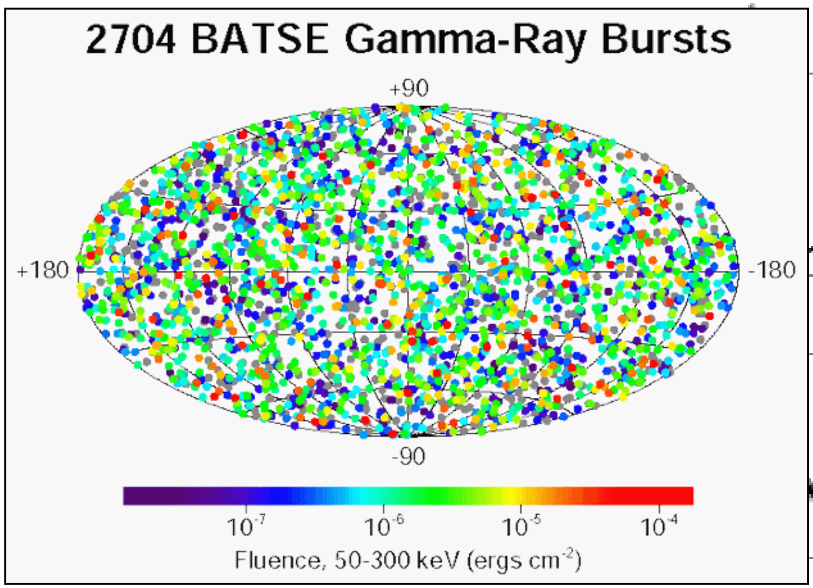
Gravitational waves from
NS-NS and NS-BH Binaries

Motivations 3: why Neutron Stars ?

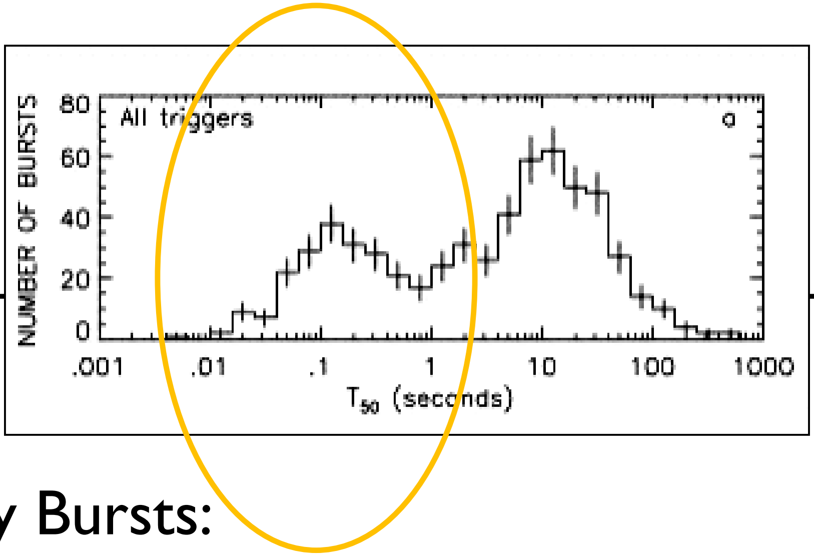


Origin of gamma-ray bursts (GRBs)





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

Motivations 4 : Possible Connection to Heavy Ion Collisions

- NS : higher density, low T, long lifetime

  HIC : high density, high T, very short lifetime

- main difficulties for NS : cannot design experiment

  one can design detectors only,

  then, wait !!!

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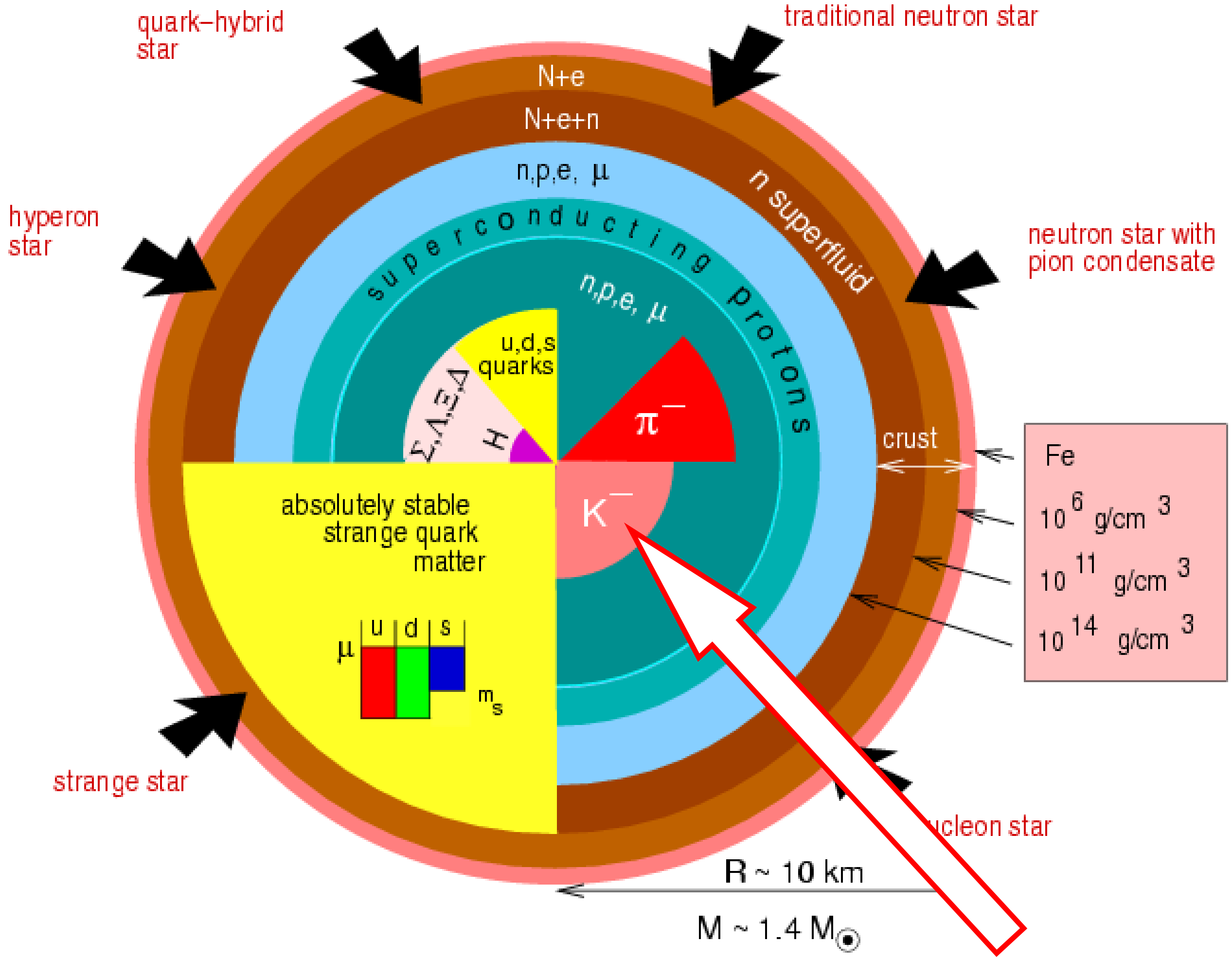
“Neutron/Strange/Quark” Star



A few remarks

- There are many equation of states (EoS) for NS
- In this talk, kaon condensation will be introduced as an example of "soft EoS".
- Astrophysical approaches in NS masses in are rather independent of the details of EoS as long as they are "soft".

Kaons interactions with chiral symmetry

Interactions with up & down quarks in p, n

	scalar	vector	total
K+ $(u\bar{s})$	attractive	repulsive	slightly repulsive
K- $(\bar{u}s)$	attractive	attractive	attractive

s-quark doesn't do much because it's different quark !

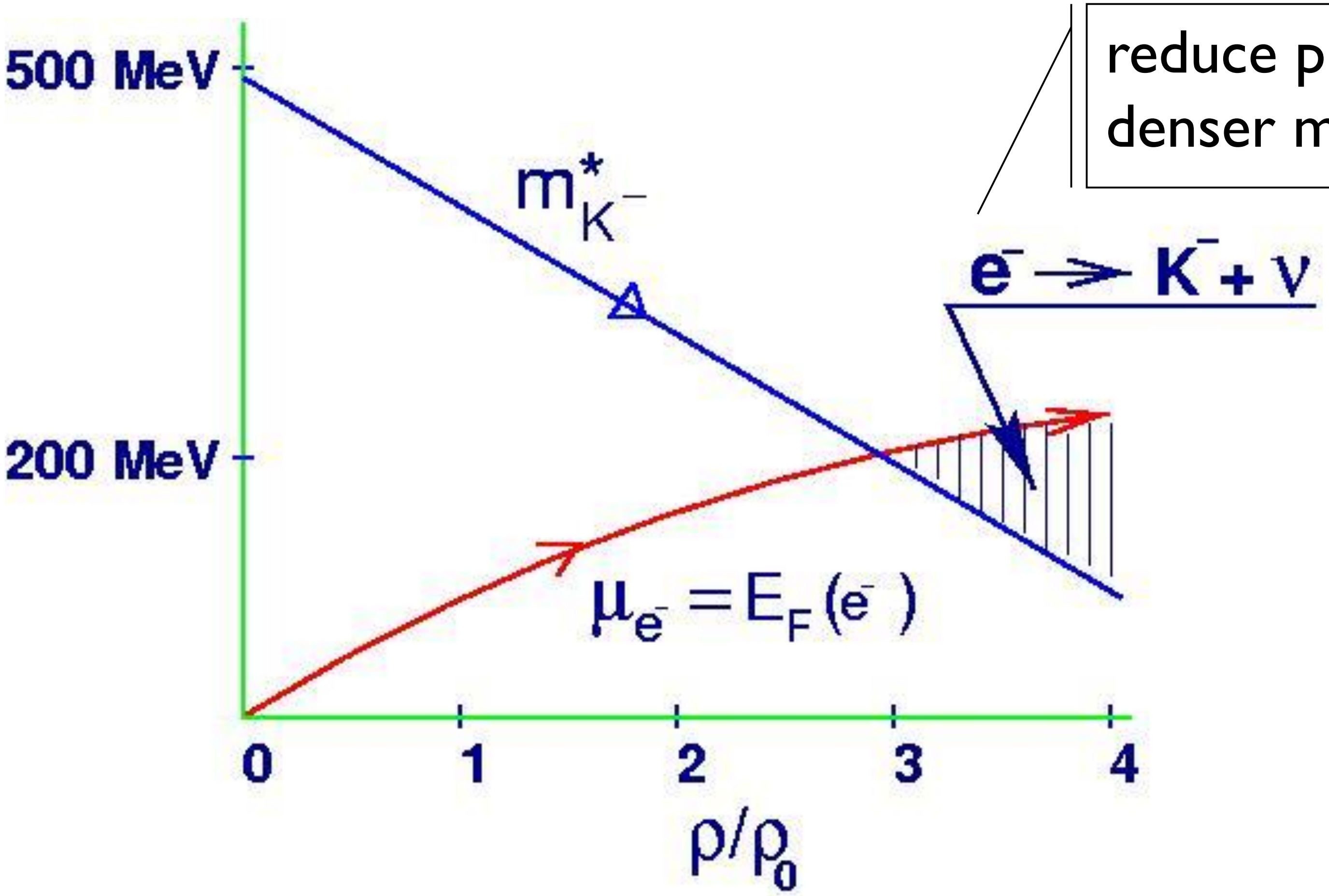
Kaon condensation in dense matter

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 !

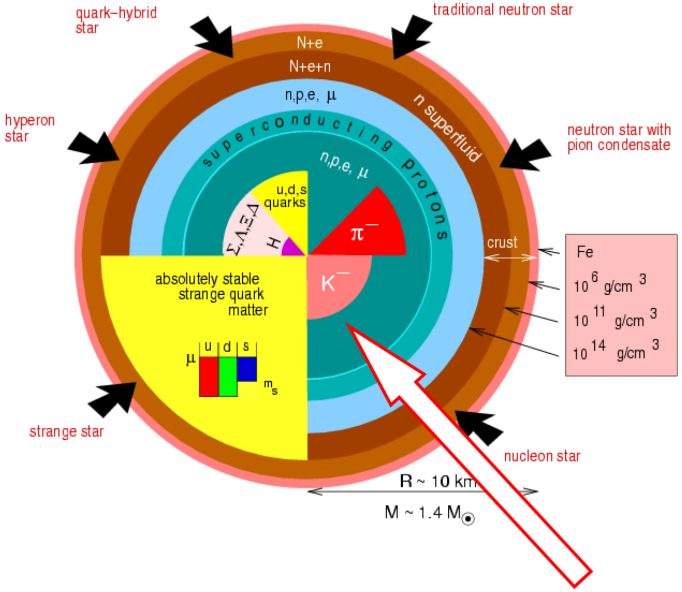
Kaon Condensation in Dense Matter

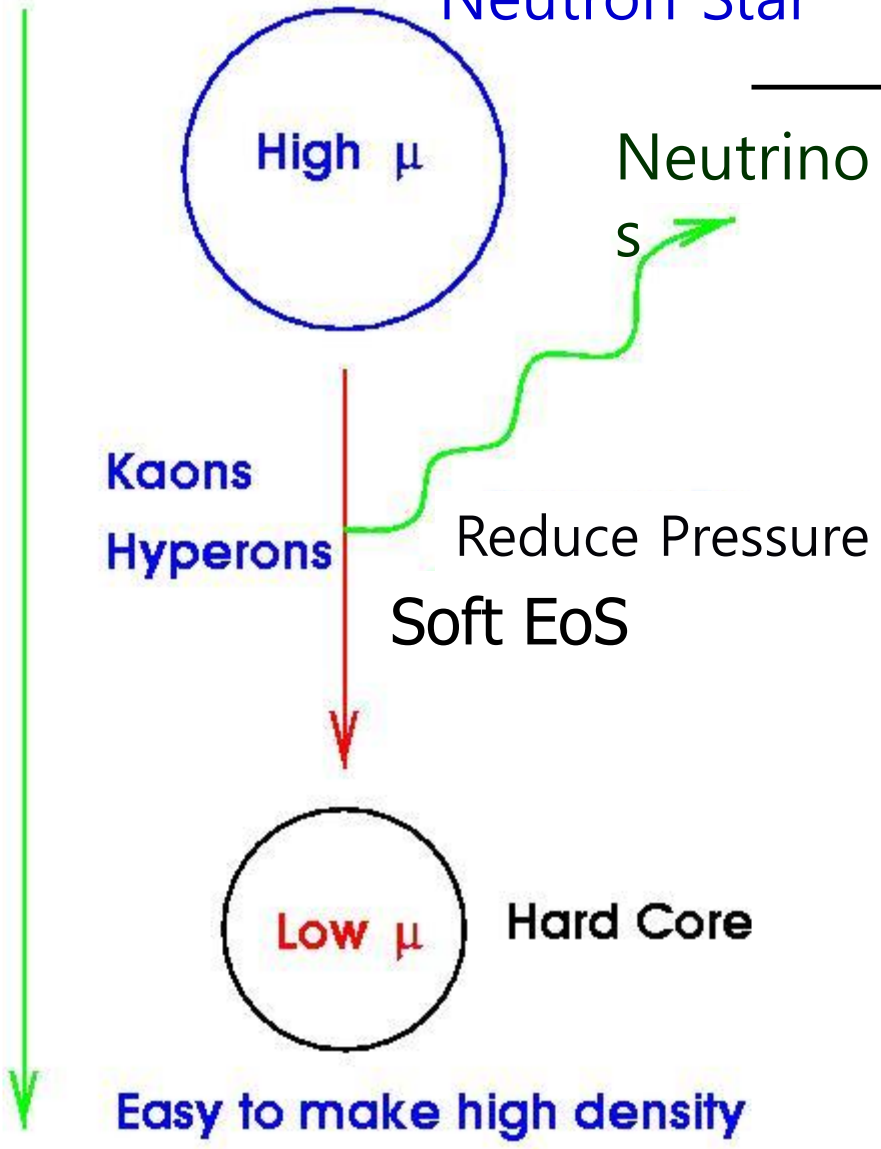


reduce pressure forming denser medium

ρ_0 = nuclear matter density

Astrophysical Implications





Neutron Star

High μ

Neutrinos

Kaons

Hyperons

Reduce Pressure

Soft EoS

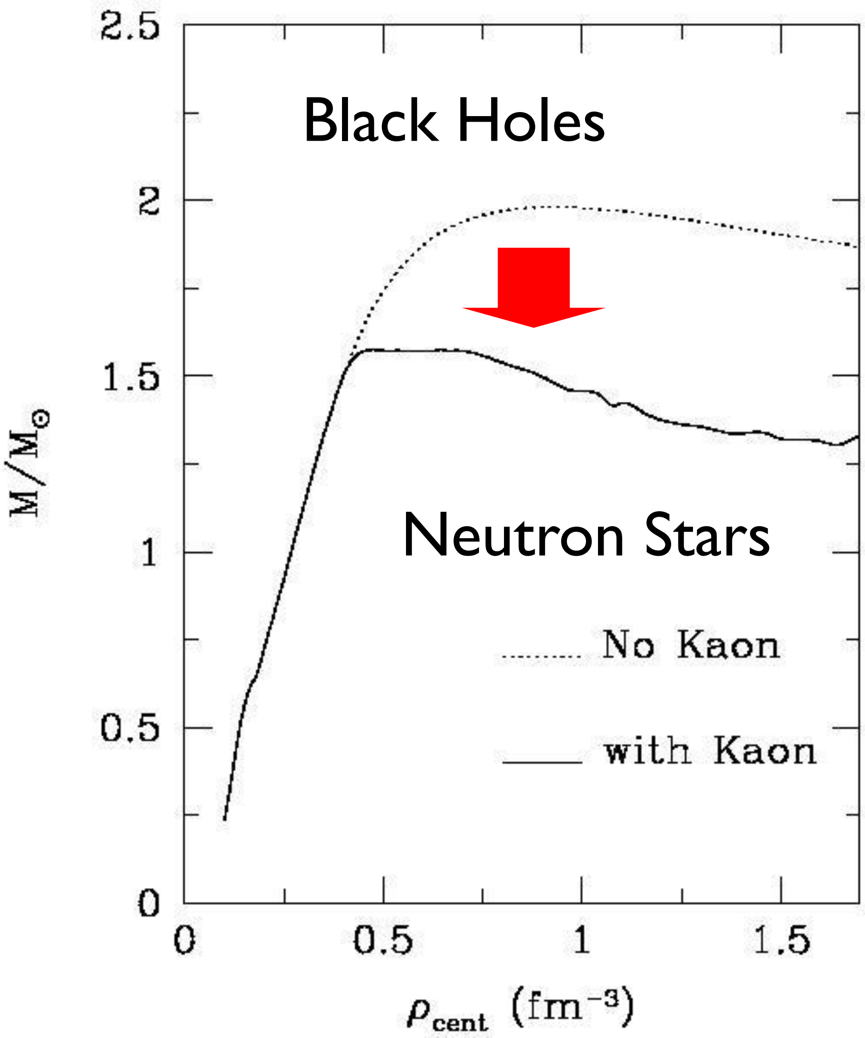
Low μ

Hard Core

Easy to make high density

Formation of low mass Black Hole

Soft equation of state (e.g., kaon condensation)



Q) What is the critical density for kaon condensation ?

1. Conventional approaches (bottom-up):
   from zero density to higher density
2. New approaches (top-down):
   from high density where symmetry is restored
   - e.g., vector manifestation fixed point
   - e.g., AdS/QCD

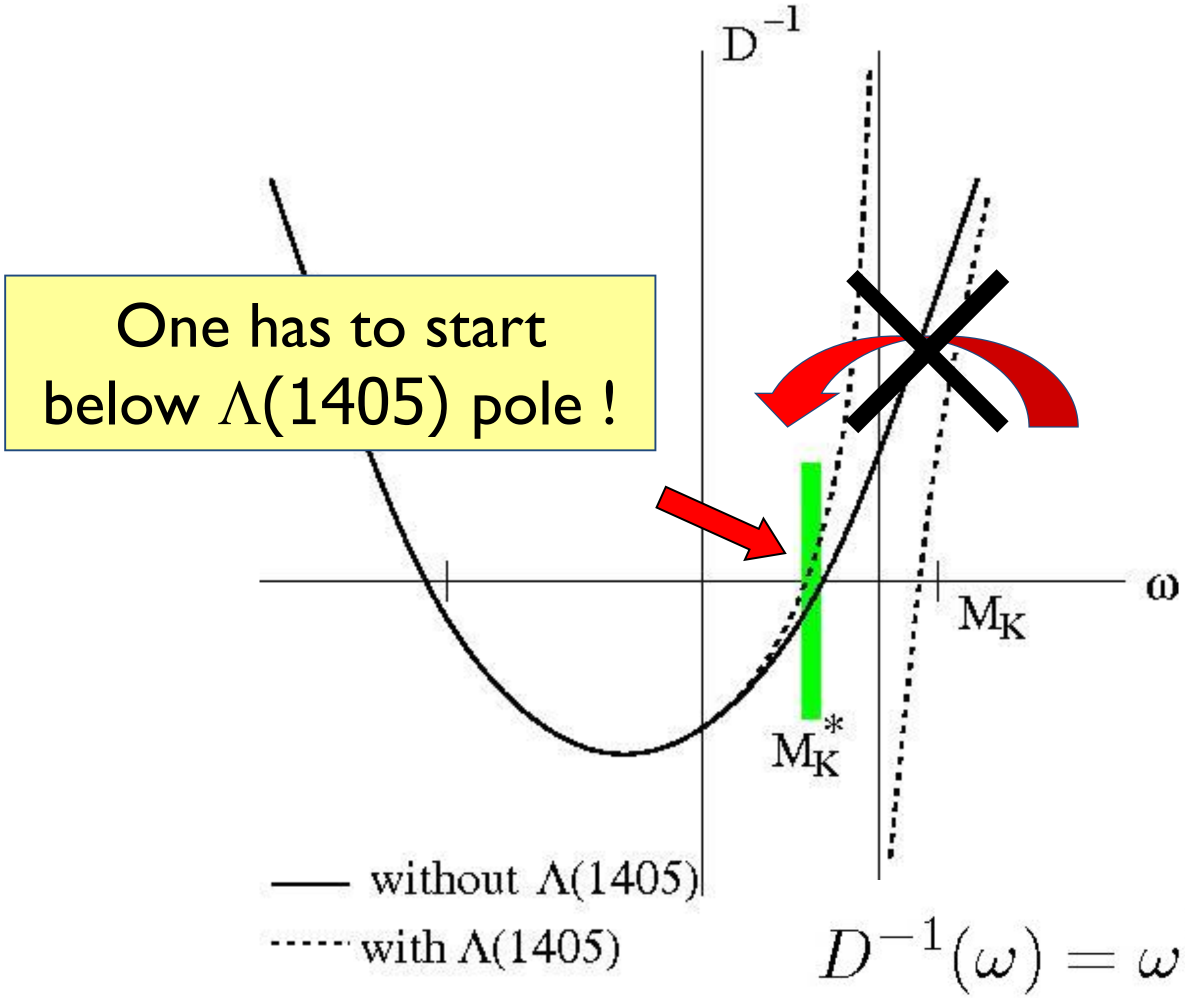
Problems in bottom-up approach

1. Problem in K^-p Scattering amplitude:
   experiment : - 0.67 + i 0.63 fm (repulsive)
   chiral symmetry : + (attractive !)

2. Problem of $\Lambda(1405)$
   pole position of $\Lambda(1405)$
   => only 30 MeV below KN threshold

Perturbation breaks down in bottom-up approach !

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



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

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

Essense of KN scattering & kaon condensation puzzle

$$\Pi(\omega) \simeq -\rho_p \mathcal{T}^{K^- p} - \rho_n \mathcal{T}^{K^- n}$$

$$\mathcal{T}^{K^- p} = \frac{1}{f^2}\left\{\omega + \Sigma_{KN}\left(1 - 0.37\frac{\omega^2}{M_K^2}\right) - g^2_{\Lambda(1405)}\left(\frac{\omega^2}{\omega + m_B - m_{\Lambda(1405)}}\right)\right\}$$

$$\mathcal{T}^{K^- n} = \frac{1}{f^2}\left\{\frac{\omega}{2} + \Sigma_{KN}\left(1 - 0.37\frac{\omega^2}{M_K^2}\right)\right\}$$

Near $\omega=M_K/2$, $\Lambda(1405)$ is irrelevant !

$$\Pi_{K^-}(\omega) \approx -\rho_p \mathcal{T}^{K^- p} - \rho_n \mathcal{T}^{K^- n} \approx -\frac{3}{2f^2}\rho\Sigma_{KN}.$$

$$\boxed{\Delta U_{K^-} \approx \frac{1}{2}\frac{\Pi_{K^-}}{M_K(1 + M_K/m_p)} \approx -135\text{MeV}\frac{\rho}{\rho_0}}$$

Wanted : New Top-down approaches

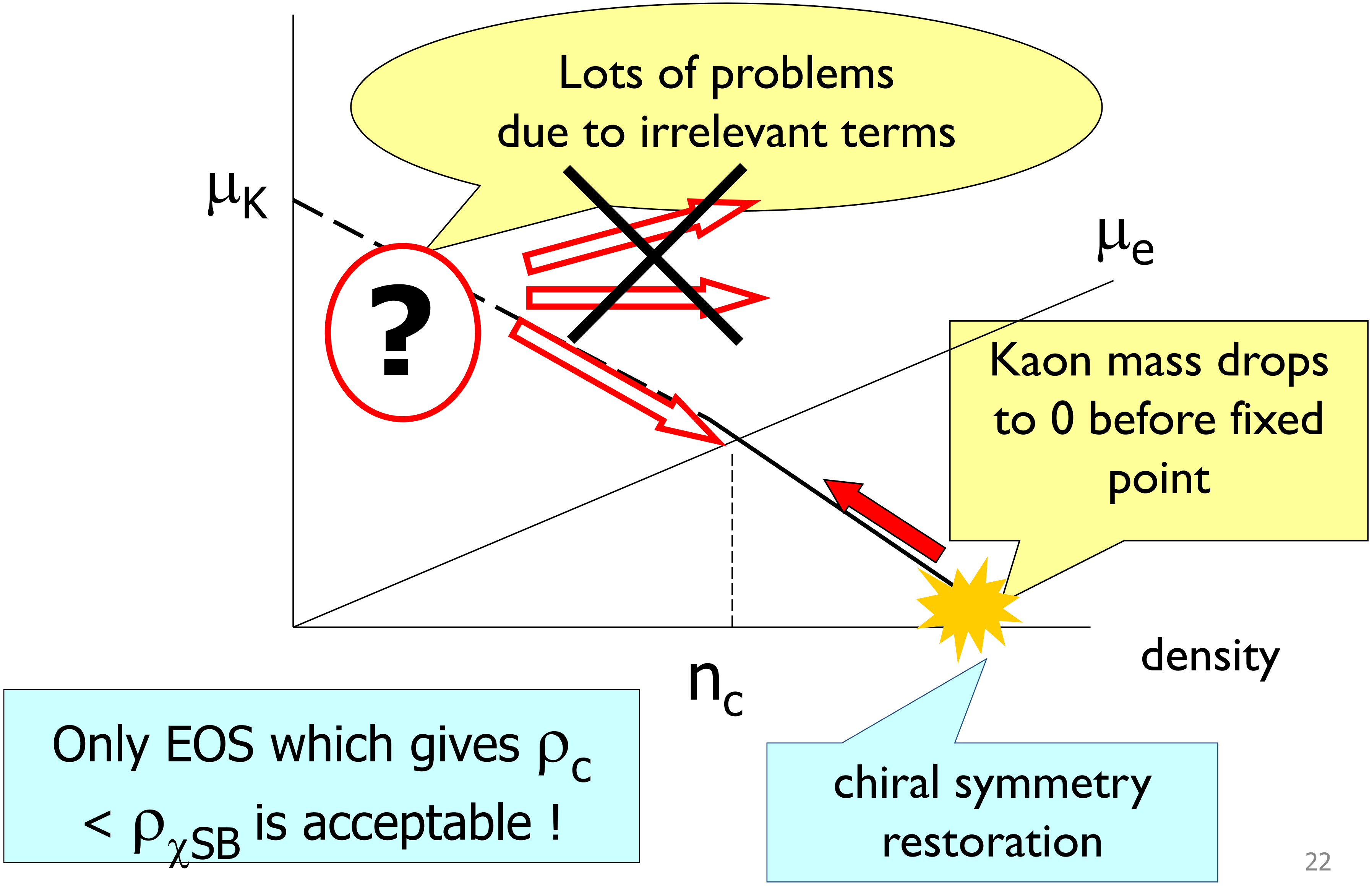
Q) Is there a proper way to treat kaon condensation which doesn't have problems with the irrelevant terms, e.g., $\Lambda(1405)$, etc, from the beginning ?

Start from where the symmetry is fully restored !

- Kaon Condensation `a la HY Vector Manifestation
- AdS/QCD, etc.

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

Kaon condensation from RG fixed point (PRL 101, 091101 (2008))



Lots of problems
due to irrelevant terms

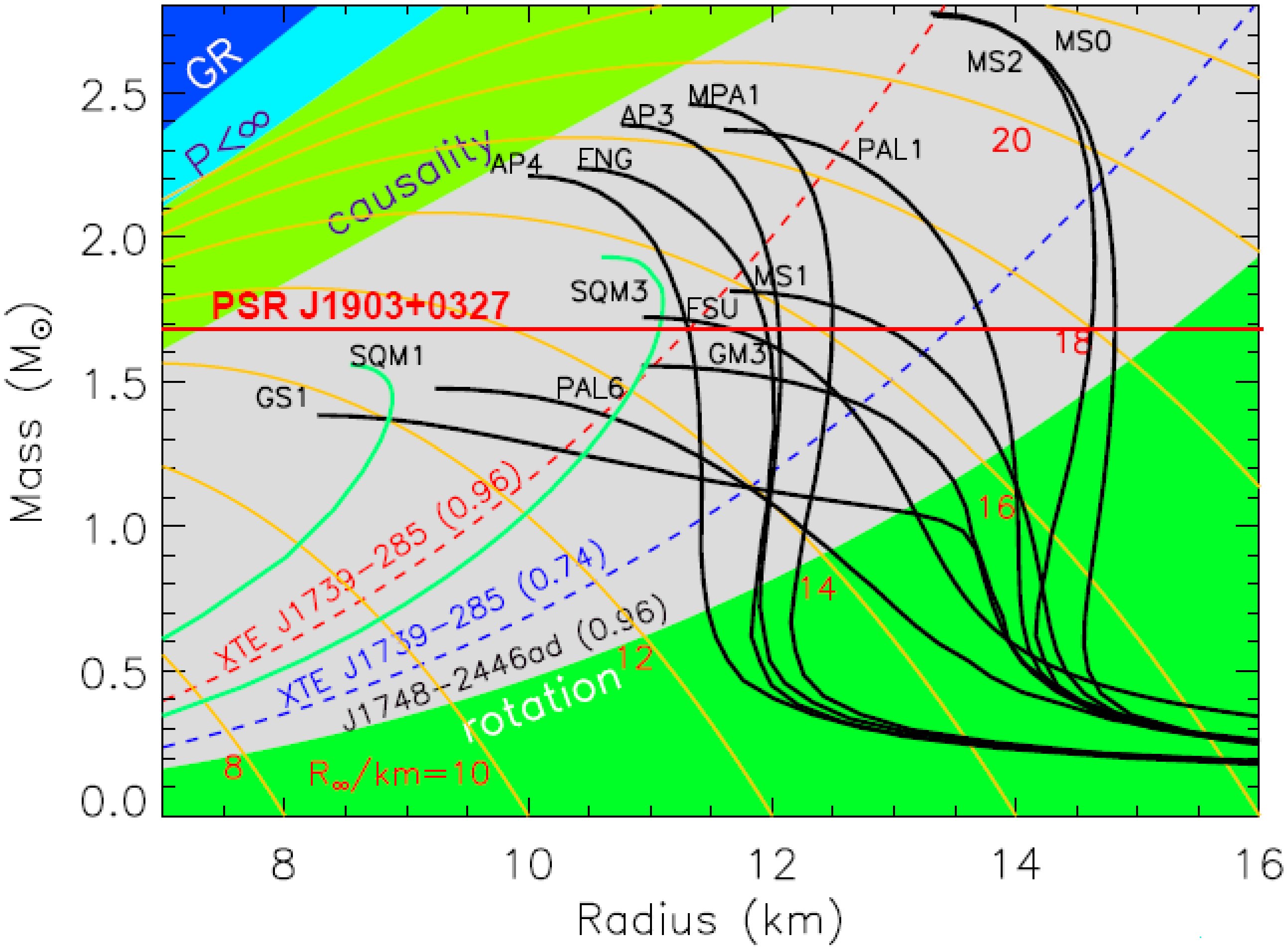
Kaon mass drops
to 0 before fixed
point

chiral symmetry
restoration

Only EOS which gives ρ_c
$< \rho_{\chi SB}$ is acceptable !

Open Question:

Given the theoretical uncertainties,
which one is the right one ?



arXiv:0907.3219v1

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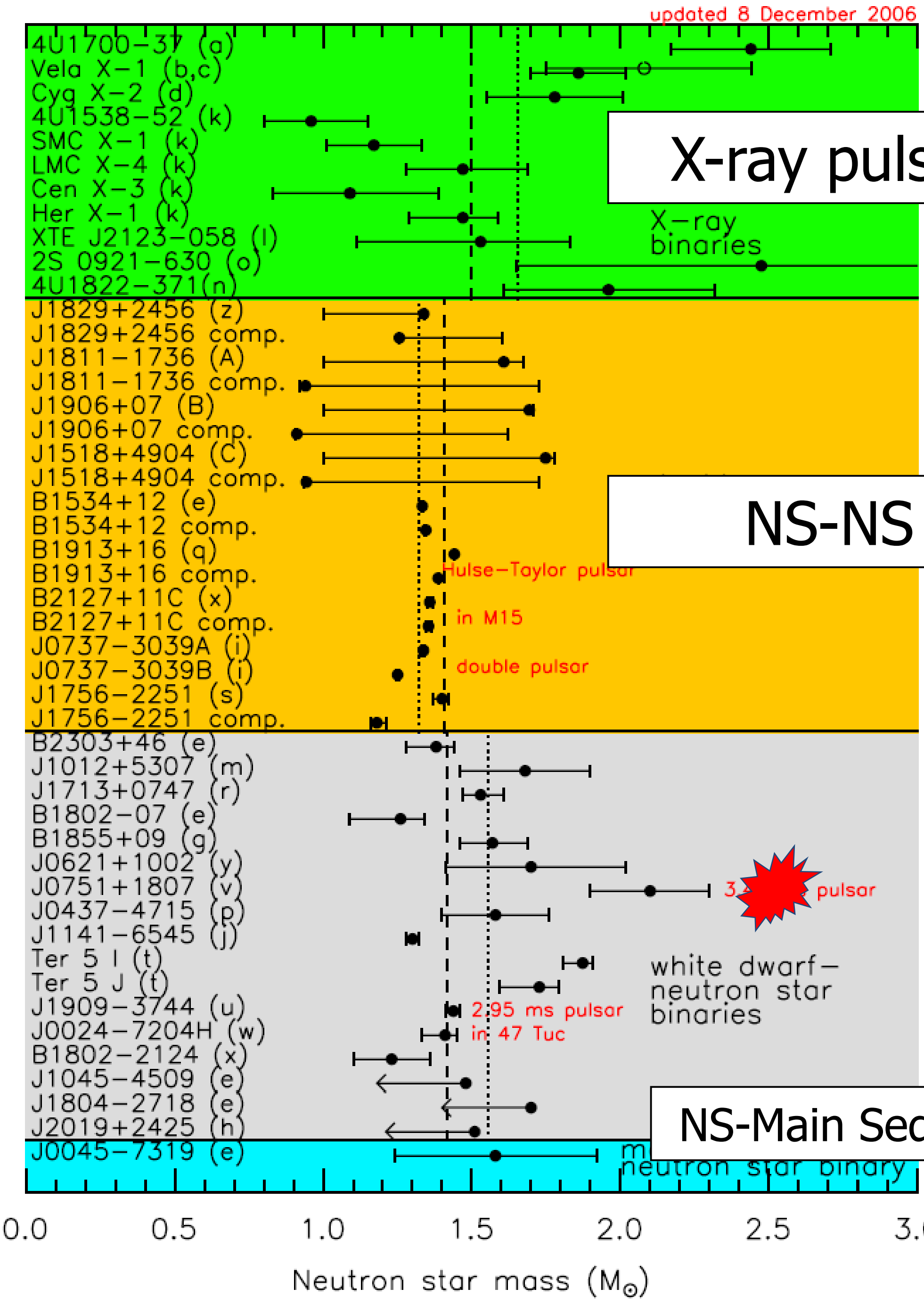
Q) Higher (than 1.5 Msun) neutron star masses ?

1. Radio pulsars(white dwarf companion)
   Nature 467, 1081 (2010) : J1614-2230 (1.97 Msun)
2. X-ray Binary
3. Millisecond Pulsar J1903+0327

Lattimer & Prakash (2007)

1. Neutron Stars with White Dwarf companions



X-ray pulsar

NS-NS

WD-NS Binary

NS-Main Sequence

Proven uncertainties in high-mass NS in NS-WD

Pulsar J0751+1807

2.1 ± 0.2 solar mass

Nice et al., ApJ 634 (2005) 1242.

Nice, talk@40 Years of Pulsar, McGill,
Aug 12-17, 2007

$1.26^{+0.14}_{-0.12}$ solar mass

difficulties in Bayesian analysis for WD mass

Recent measurement by **Shapiro delay**

Nature 467, 1081 (Oct. 28, 2010)

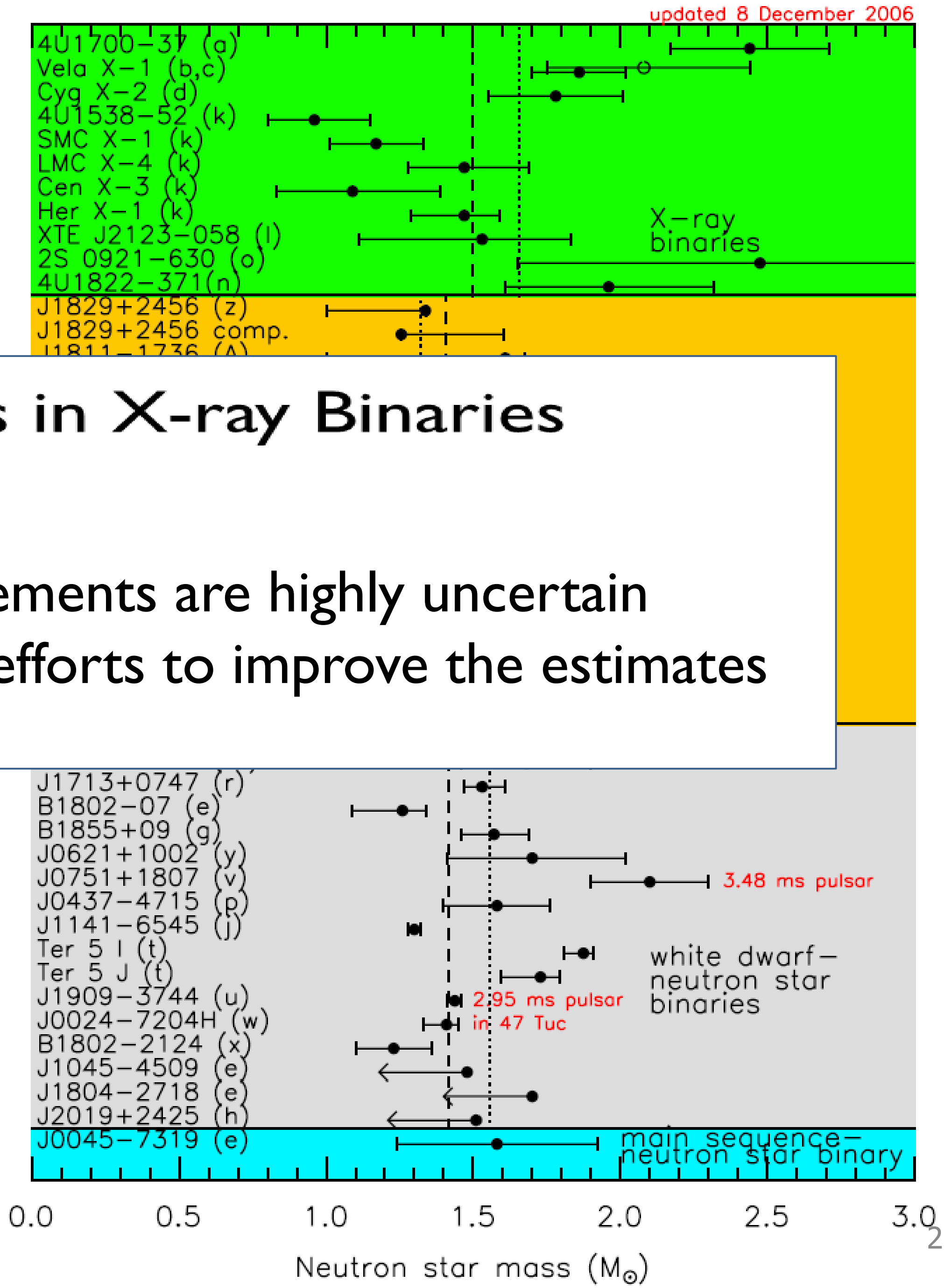
PSR J1614-2230

(Millisecond Pulsas & White Dwarf Binary)

1.97 ± 0.04 Msun

(measurement based on Shapiro delay)

X-ray Pulsars



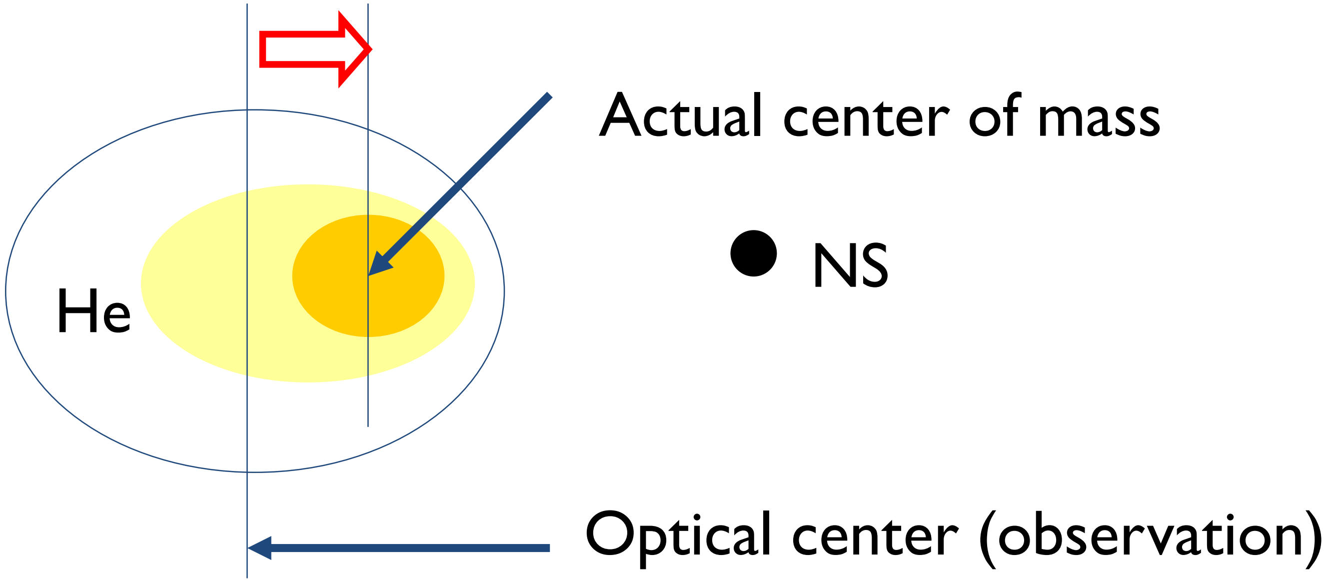
2. Neutron Stars in X-ray Binaries

- Mass measurements are highly uncertain
- Many recent efforts to improve the estimates

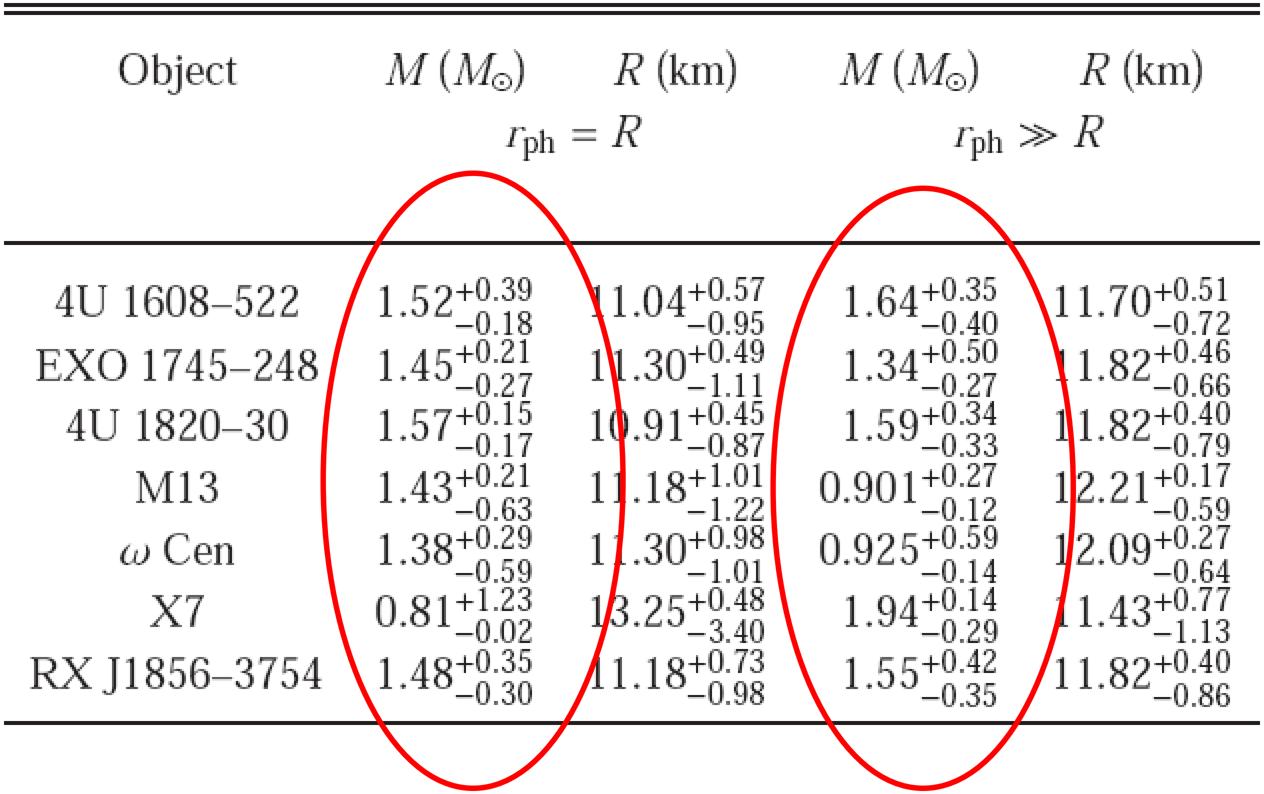
Lattimer & Prakash (2007)

Q) X-ray Binary [Vela X-1] > 2 Msun ?

"The best estimate of the mass of Vela X-1 is 1.86 M_{sun}. Unfortunately, no firm constraints on the equation of state are possible since systematic deviations in the radial-velocity curve ***do not allow us to exclude a mass around 1.4 M_{sun}*** as found for other neutron stars." [Barziv et al. 2001]



Steiner, Lattimer, Brown, arXiv:1005.0811

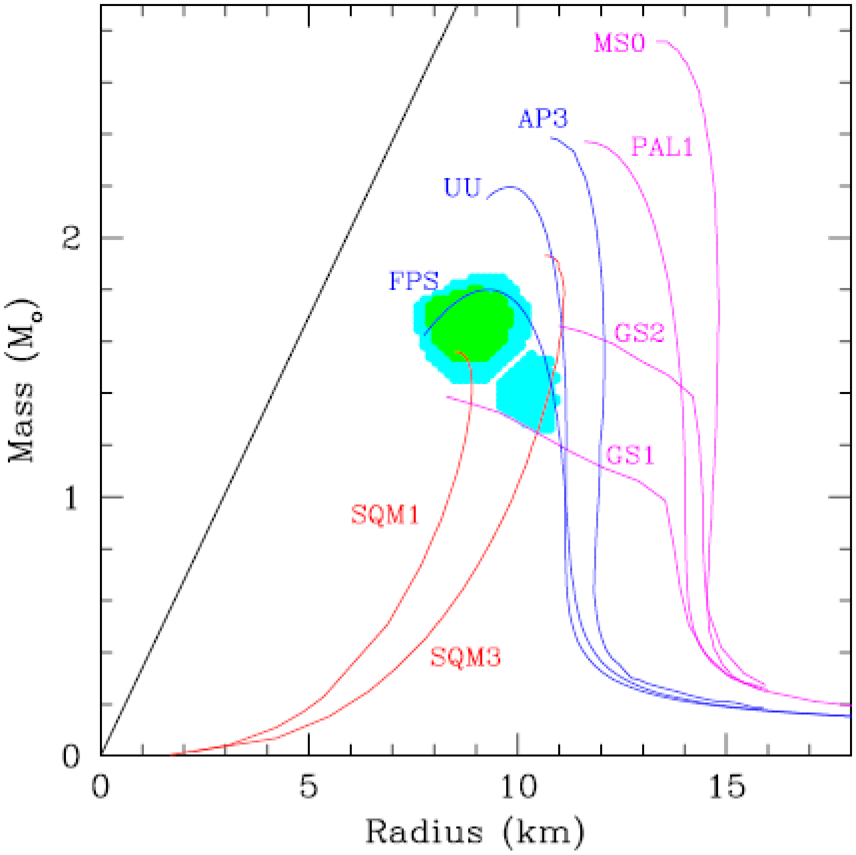


Object	$M\ (M_\odot)$	R (km)	$M\ (M_\odot)$	R (km)
	$r_{\rm ph} = R$		$r_{\rm ph} \gg R$	
4U 1608–522	$1.52^{+0.39}_{-0.18}$	$11.04^{+0.57}_{-0.95}$	$1.64^{+0.35}_{-0.40}$	$11.70^{+0.51}_{-0.72}$
EXO 1745–248	$1.45^{+0.21}_{-0.27}$	$11.30^{+0.49}_{-1.11}$	$1.34^{+0.50}_{-0.27}$	$11.82^{+0.46}_{-0.66}$
4U 1820–30	$1.57^{+0.15}_{-0.17}$	$10.91^{+0.45}_{-0.87}$	$1.59^{+0.34}_{-0.33}$	$11.82^{+0.40}_{-0.79}$
M13	$1.43^{+0.21}_{-0.63}$	$11.18^{+1.01}_{-1.22}$	$0.901^{+0.27}_{-0.12}$	$12.21^{+0.17}_{-0.59}$
ω Cen	$1.38^{+0.29}_{-0.59}$	$11.30^{+0.98}_{-1.01}$	$0.925^{+0.59}_{-0.14}$	$12.09^{+0.27}_{-0.64}$
X7	$0.81^{+1.23}_{-0.02}$	$13.25^{+0.48}_{-3.40}$	$1.94^{+0.14}_{-0.29}$	$11.43^{+0.77}_{-1.13}$
RX J1856–3754	$1.48^{+0.35}_{-0.30}$	$11.18^{+0.73}_{-0.98}$	$1.55^{+0.42}_{-0.35}$	$11.82^{+0.40}_{-0.86}$

$r_{\rm ph}$= radius of photosphere

The Mass and Radius of the Neutron Star in EXO 1745−248

Feryal Özel[1], Tolga Güver and Dimitrios Psaltis[1]



arXiv:1810.1521

tightly constrained pairs of values

$M = 1.7\ M_\odot$ and $R = 9$ km.

$M = 1.4\ M_\odot$ and $R = 11$ km

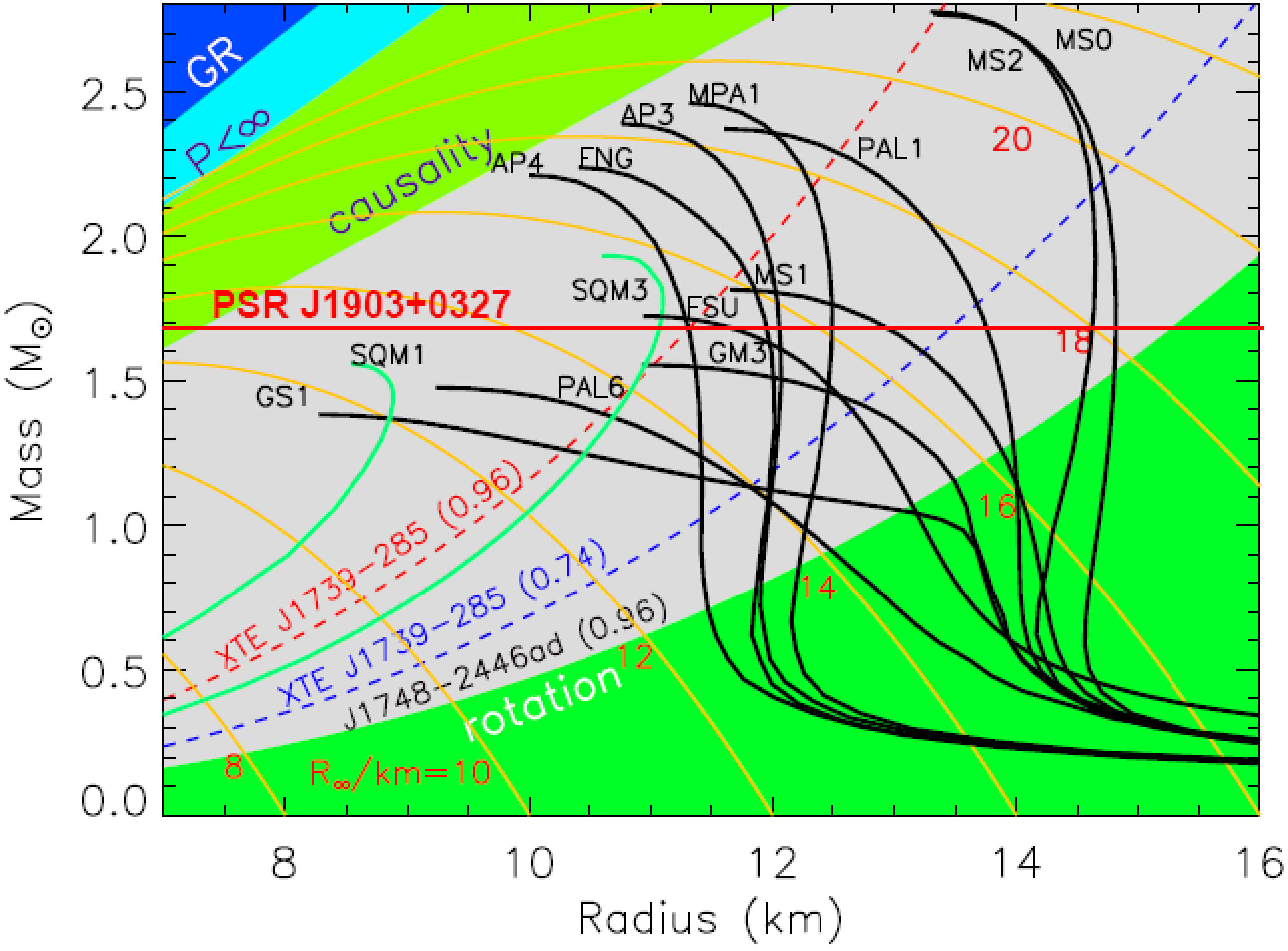
2 sigma error

3. Millisecond Pulsar J1903+0327

D.J. Champion et al., Science 320, 1309 (2008)

- orbital period : P=95.1741 days
- Spin period : P=2.14991 ms (recycled pulsar)
- Highly eccentricity : e=0.43668
- Mass estimate = 1.74(4) Msun
- Observations of NS-MS(main sequence) binary requires different evolution process

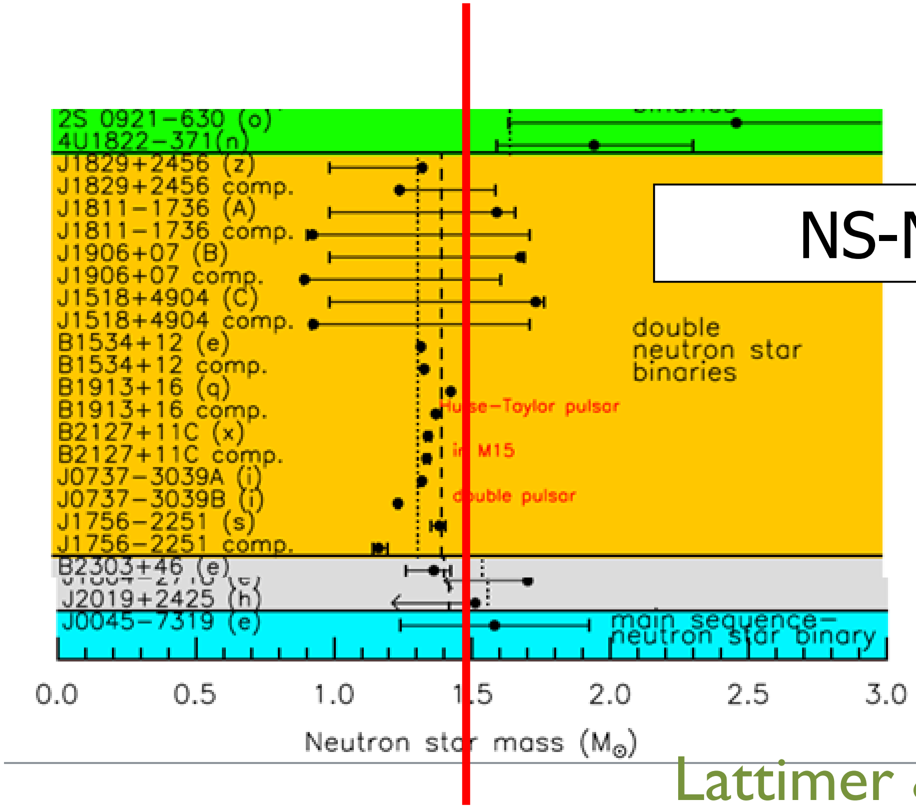
arXiv:0907.3219v1



If this limit is firm, maximum neutron star mass should be at least 1.7 Msun

Q) IF maximum NS mass is confirmed to be 1.7 Msun

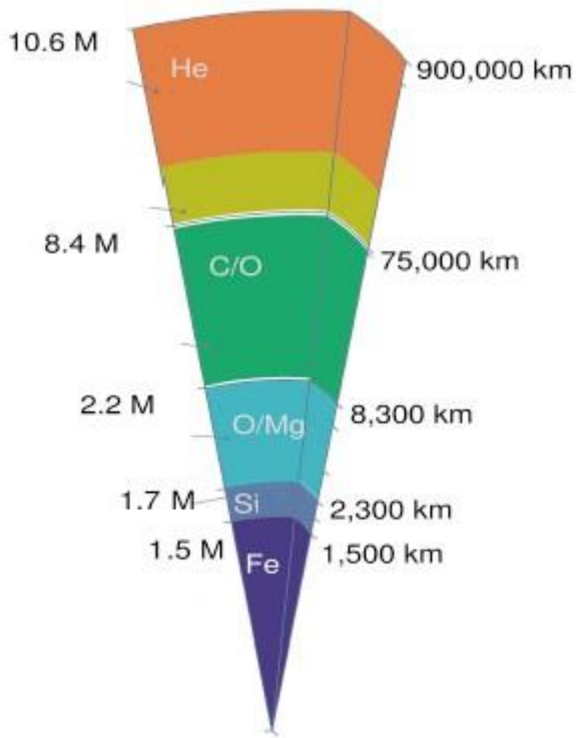
- Why all well-measured NS masses in NS-NS binaries are < 1.5 Msun ?
- Maybe, new-born NS mass is constrained by the stellar evolution, independently of maximum mass of NSs.



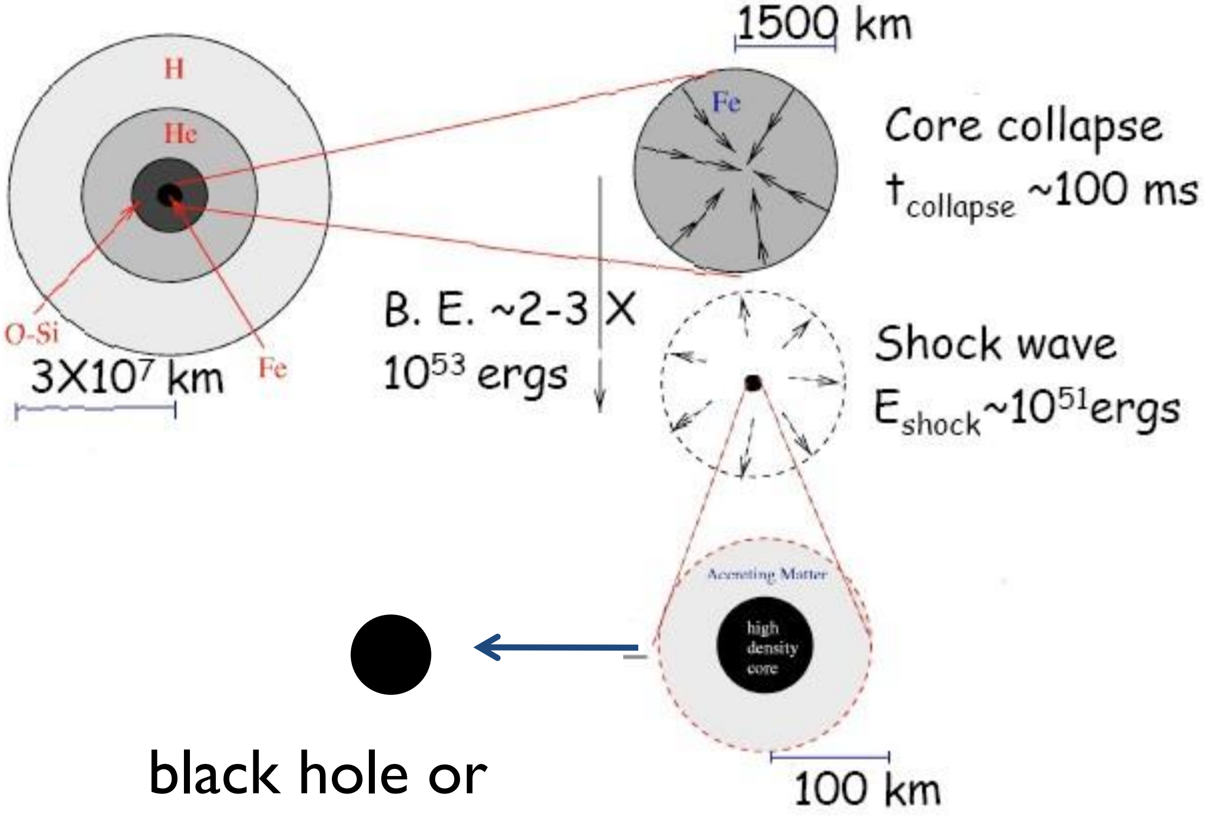
NS-NS

Lattimer & Prakash (2007)

One has to understand formation of black hole/neutron star

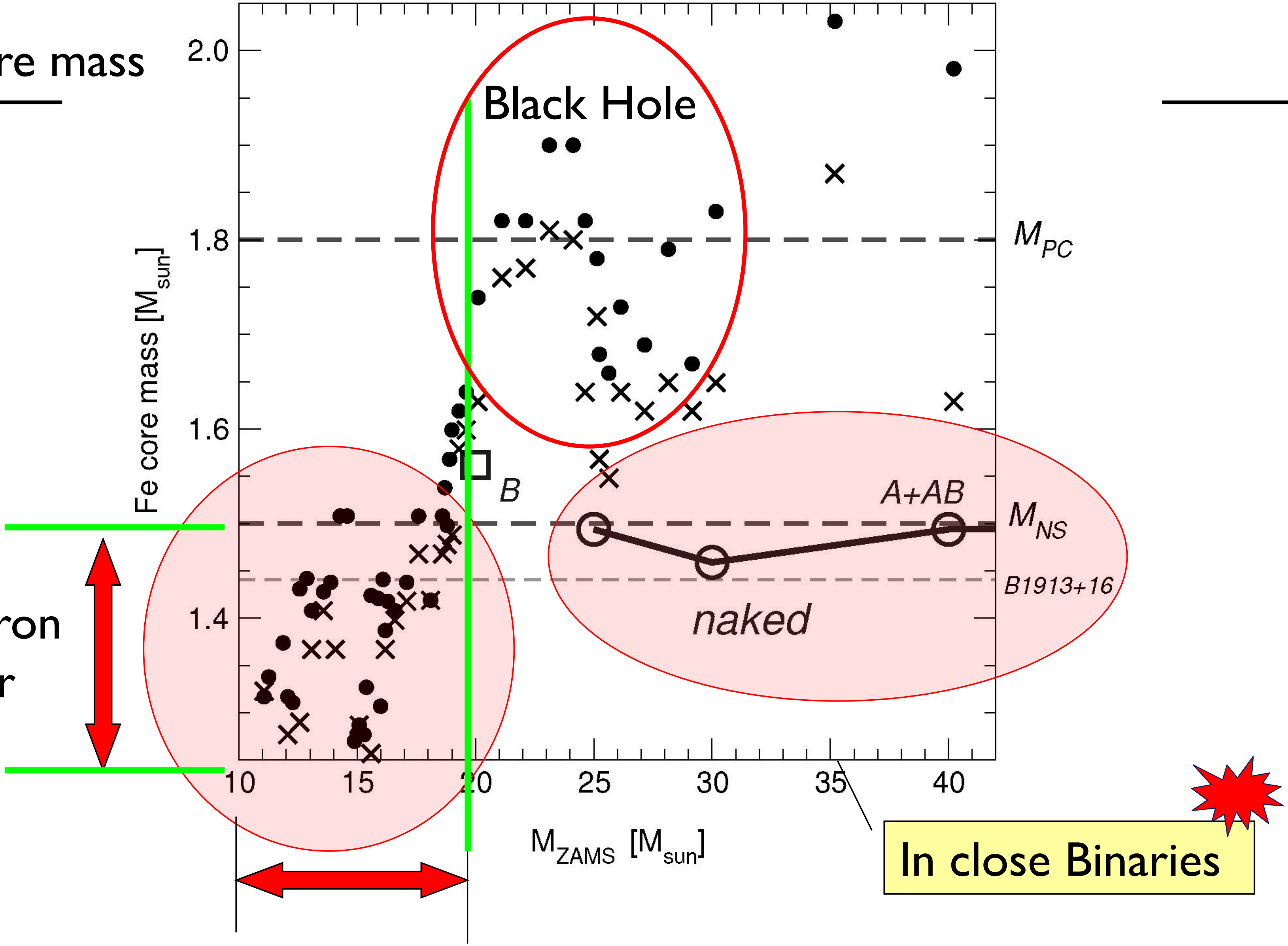


Giant Star



black hole or
neutron star

Fe core mass


Black Hole

Neutron Star

In close Binaries

Fresh NS mass from Fe core collapse

Both in single & close binaries

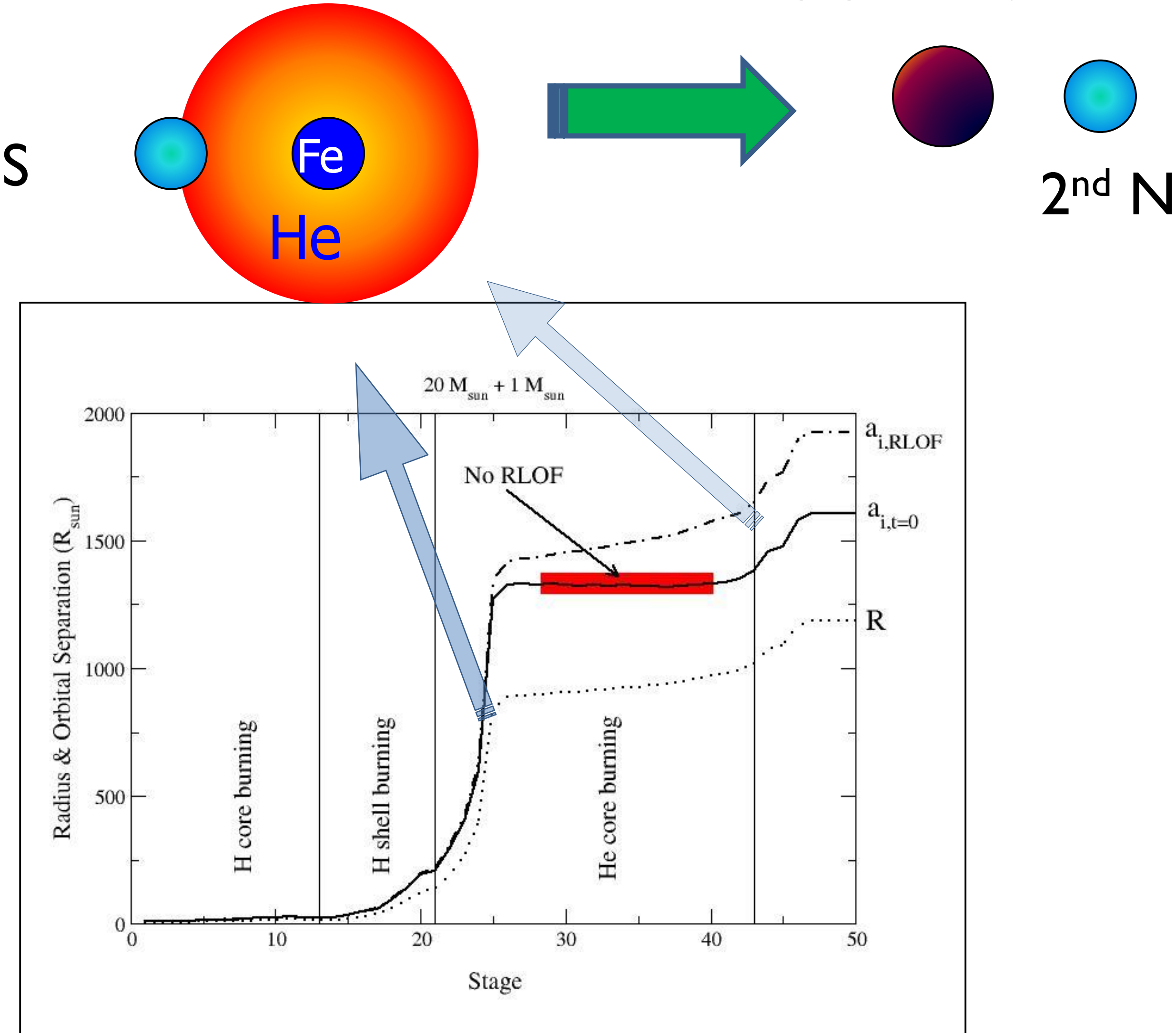
Fe core mass → NS mass = 1.3 - 1.5 Msun

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

Question) Final fate of first-born NS ?



Accretion

NS or BH ?

1st-born NS

2nd NS

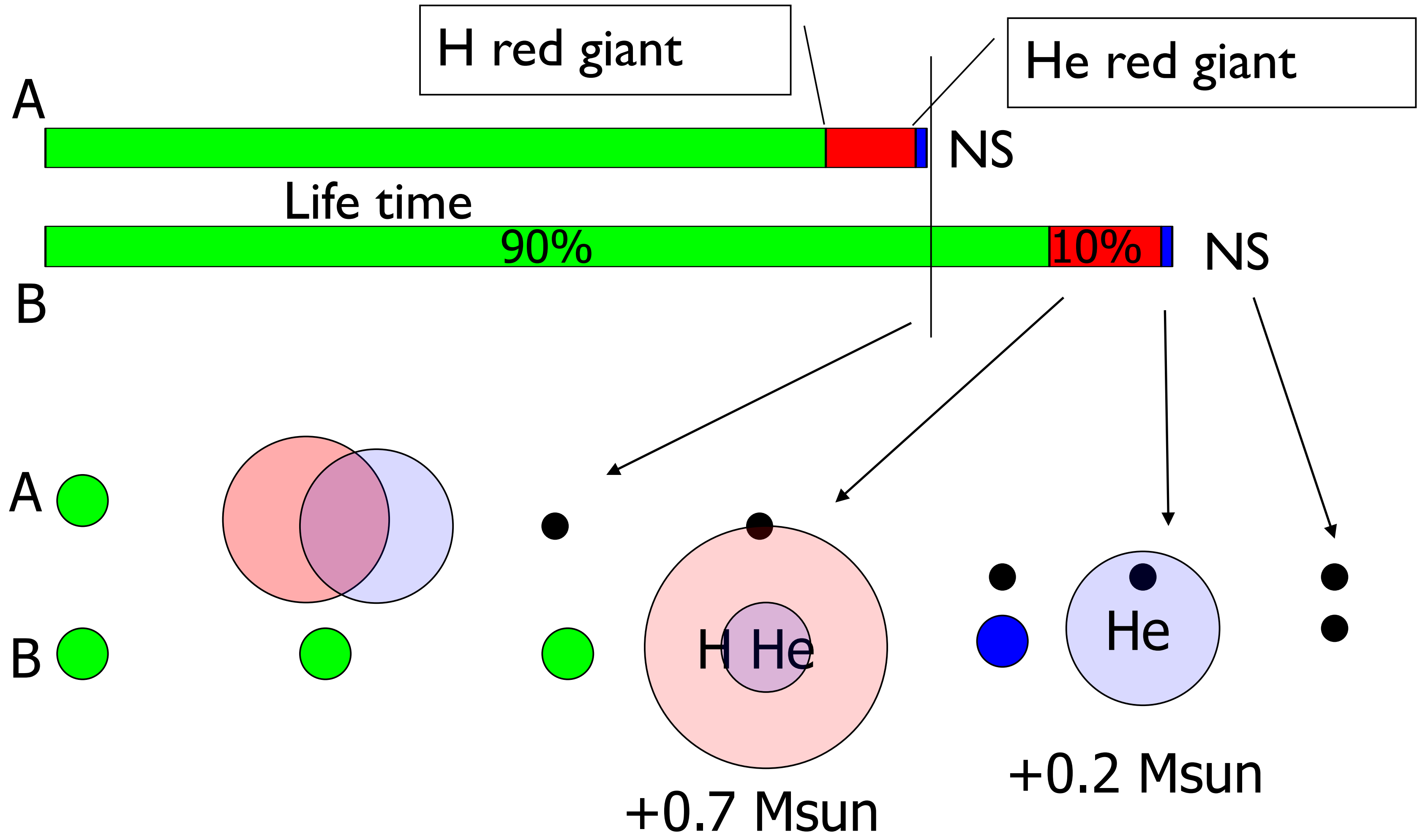
NS Progenitor Evolution

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 !)

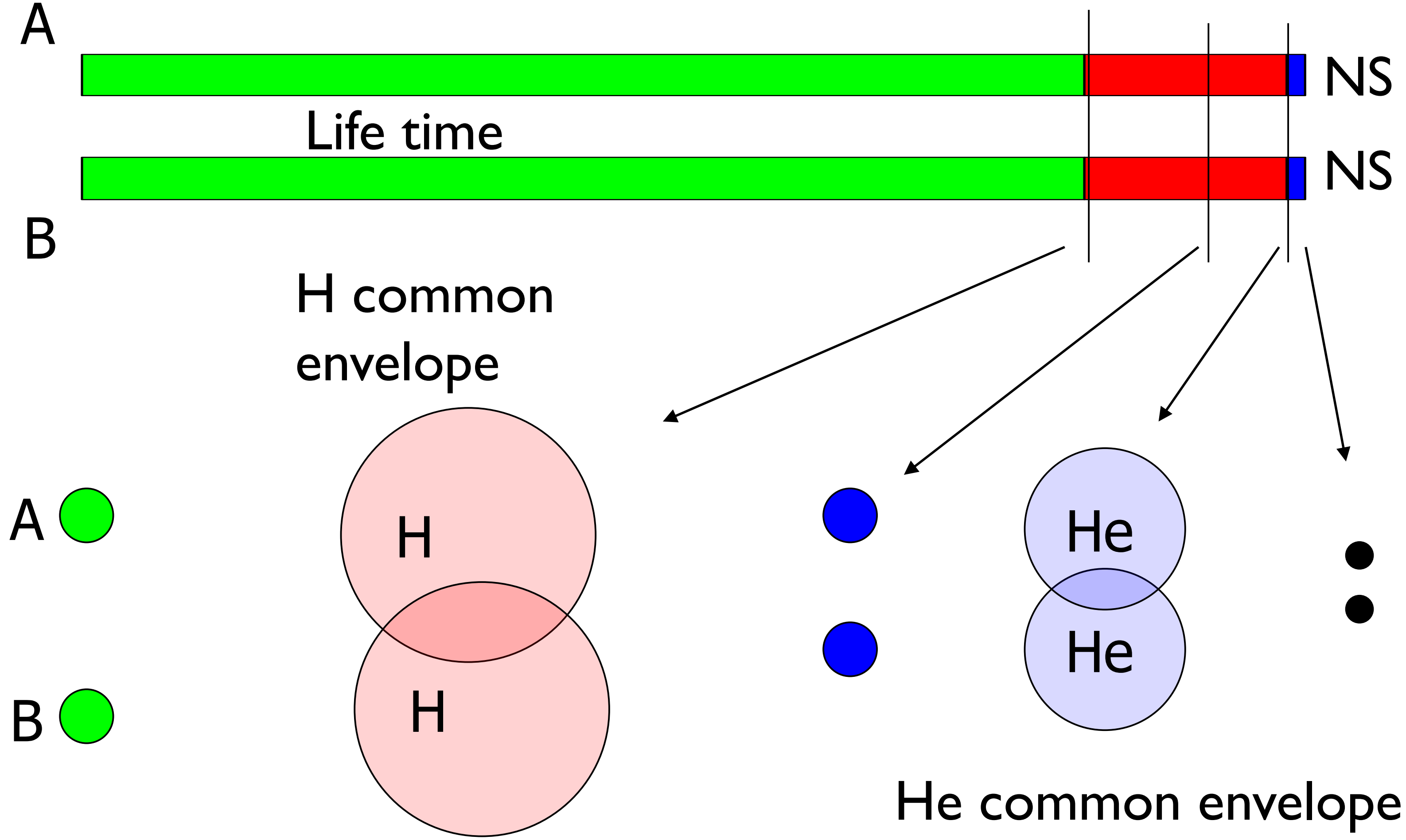
Q) What is the implications of supercritical accretion ?

Case 1 : $\Delta T > 10\%$



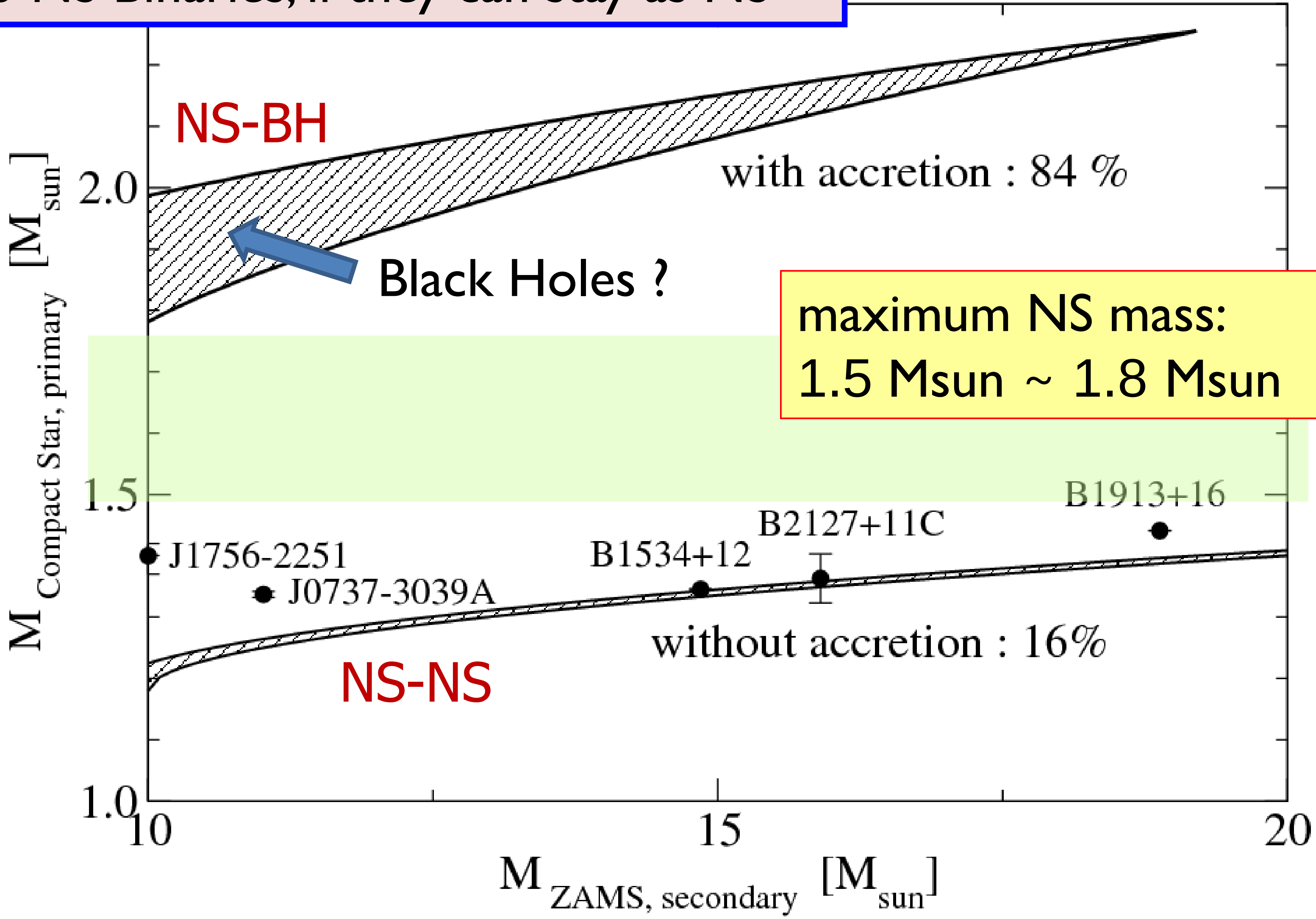
Supercritical Accretion:
First born NS should accrete 0.9 $M_\odot$!

Case 2 : $\Delta T < 1\%$



No accretion : nearly equal masses !

y-axis: final mass of first-born NS in NS-NS Binaries, if they can stay as NS



NS-BH

Black Holes ?

NS-NS

maximum NS mass:
1.5 Msun ~ 1.8 Msun

Lee et al., ApJ 670, 741 (2007)

Consequences of Supercritical Accretion

- Maximum NS mass can be any value within 1.5~1.8 Msun as far as supercritical accretion is concerned

- ***unseen*** "NS+LMBH" are 5 times more dominant than ***seen*** "NS+NS" system.
- "NS+LMBH" system may increase LIGO detection rate by factor of about 10.
- Possibilities of investigating NS inner structure via Gravitational Waves & Short-hard GRBs

Open Question ?

Are these different approaches consistent with each other ?

- Neutron Star Equation of States :
  Both in bottom-up & top-down approaches
- Neutron Star Observations (Radio, X-ray, Optical, …)
- Formation & Evolution Neutron Star Binaries
- Gravitational Waves from Colliding Neutron Stars
- Soft-Hard Gamma-ray Bursts from Colliding Neutron Stars
- ***Properties of Dense Matter from Heavy Ion Collisions***
- … …

Many Thanks