Kaon Condensation `a la Vector Manifestation in Dense Stellar System

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

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Part I

Introduction to Kaonic Physics

Dropping Kaon Mass in Dense Medium

Mass right around us

- Proton/Neutron Mass=938/940 MeV

Constituents: Quarks and gluons

- Proton= uud ; Neutron= udd

Sum of “current-quark” masses ≈ 10 MeV

Where do ~ 99% of the mass come from?

QCD Answer

- QCD on lattice explains the proton mass within ~ 10% .

" Energy stored in the motion of the (nearly) massless quarks and energy in massless gluons that connect them"

⇨ Proton mass ≈ 1 GeV

"Mass without mass"

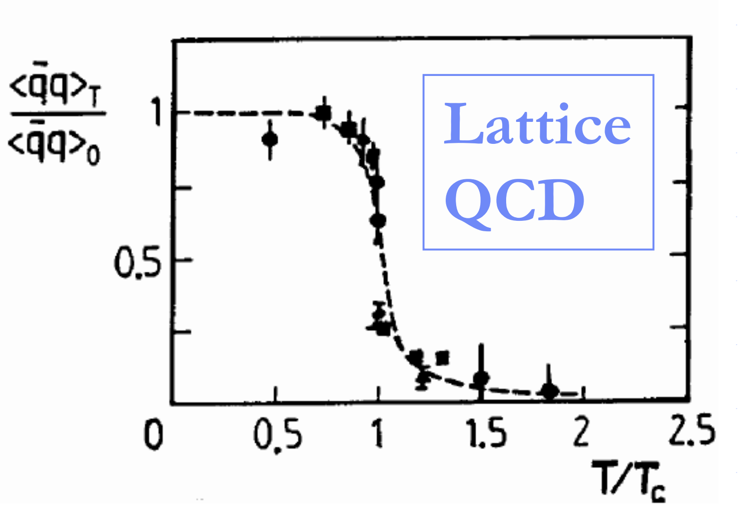
- Mass was generated by interactions of massless particles
- Technically, "chiral symmetry spontaneously broken (χSB)"

The Question

If the mass is generated by dynamical "dressing," can it be made to disappear by "undressing" in the laboratories (by heating or compressing) ?

Or can one dial the mass to zero?

Yes! through dialing the condensate to zero



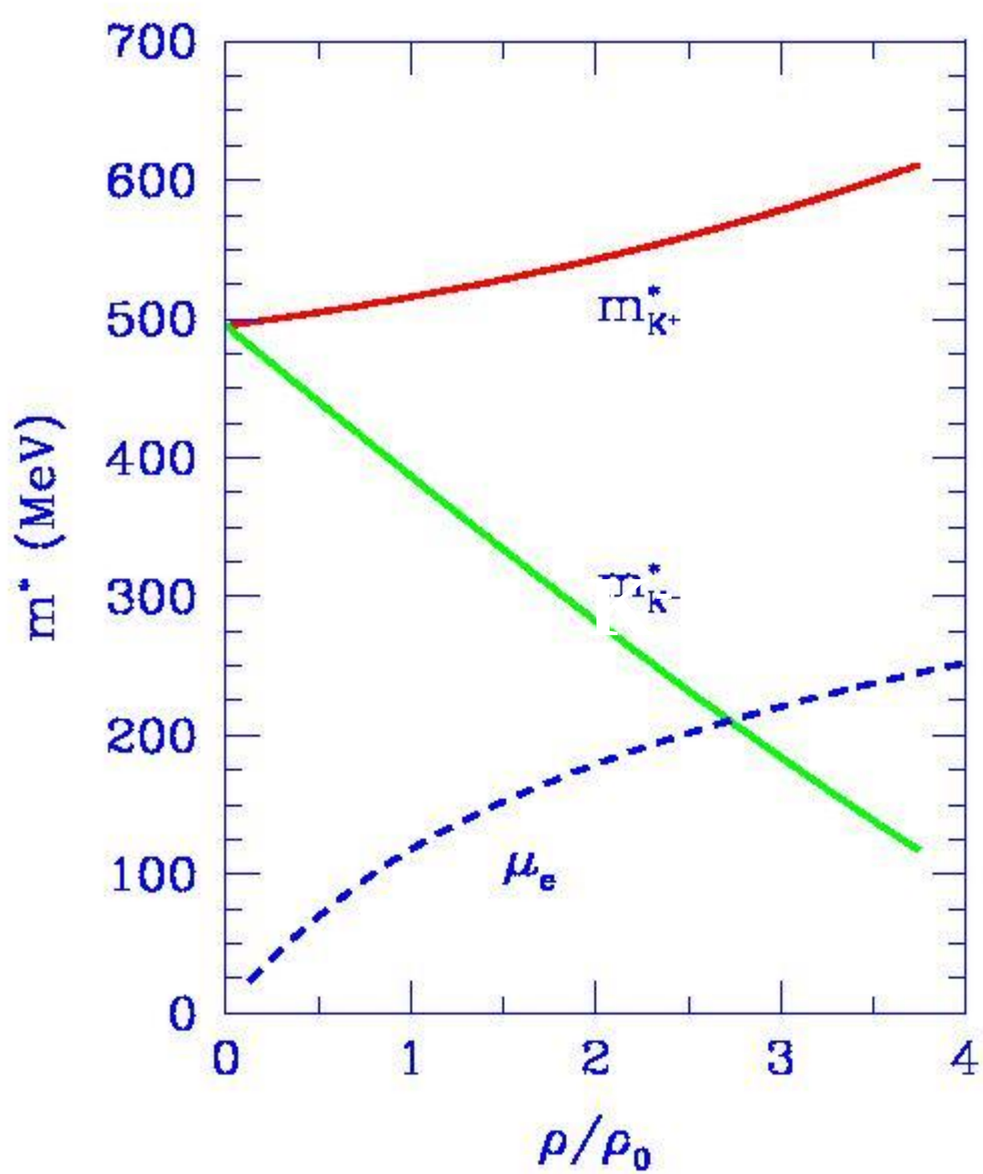
Kaons interactions with chiral symmetry

Interactions within up & down quarks (in K, p, n)

	scaler	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 Effective Mass (Chemical Potential)

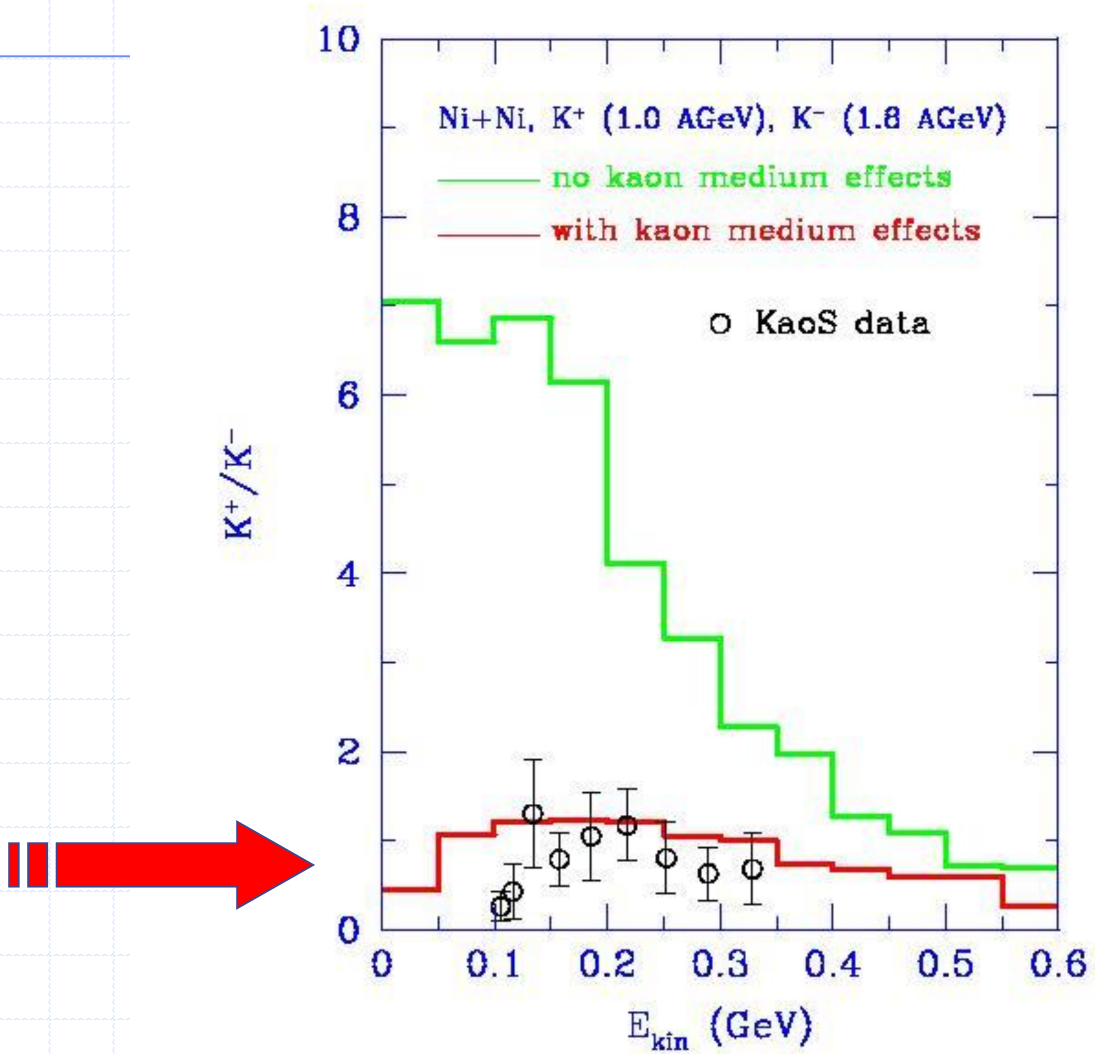


Mass drops

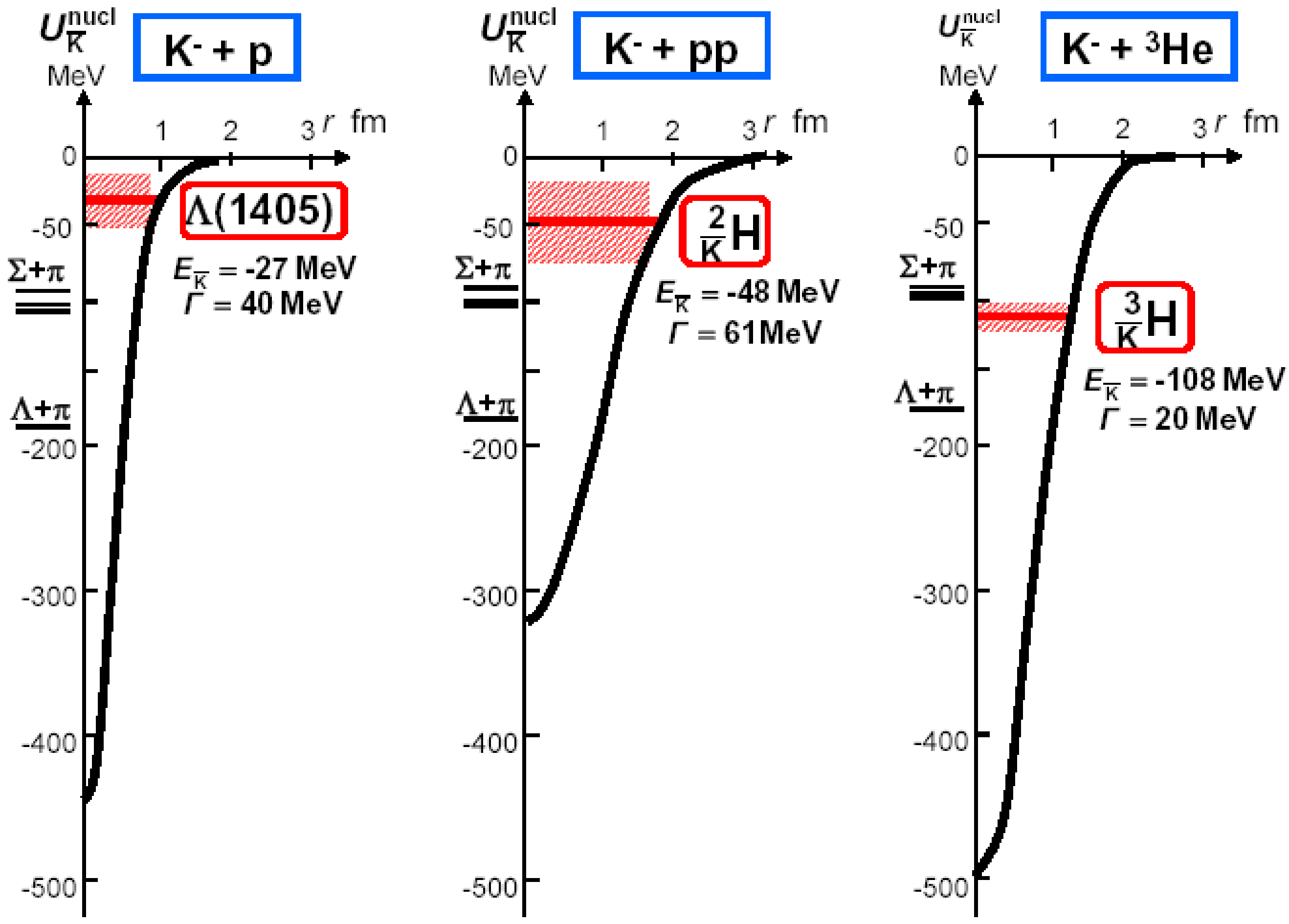
⇩

Easier to produce

Kaon Production in Heavy Ion Collision supports Dropping K⁻ mass !



Recent Developments: Kaonic Nuclear Bound States



Y. Akaishi & T. Yamazaki, Phys. Rev. C 65 (2002) 044005

Yamazaki et al.

PLB 597 (2004) 263

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Physics Letters B 597 (2004) 263–269

PHYSICS LETTERS B

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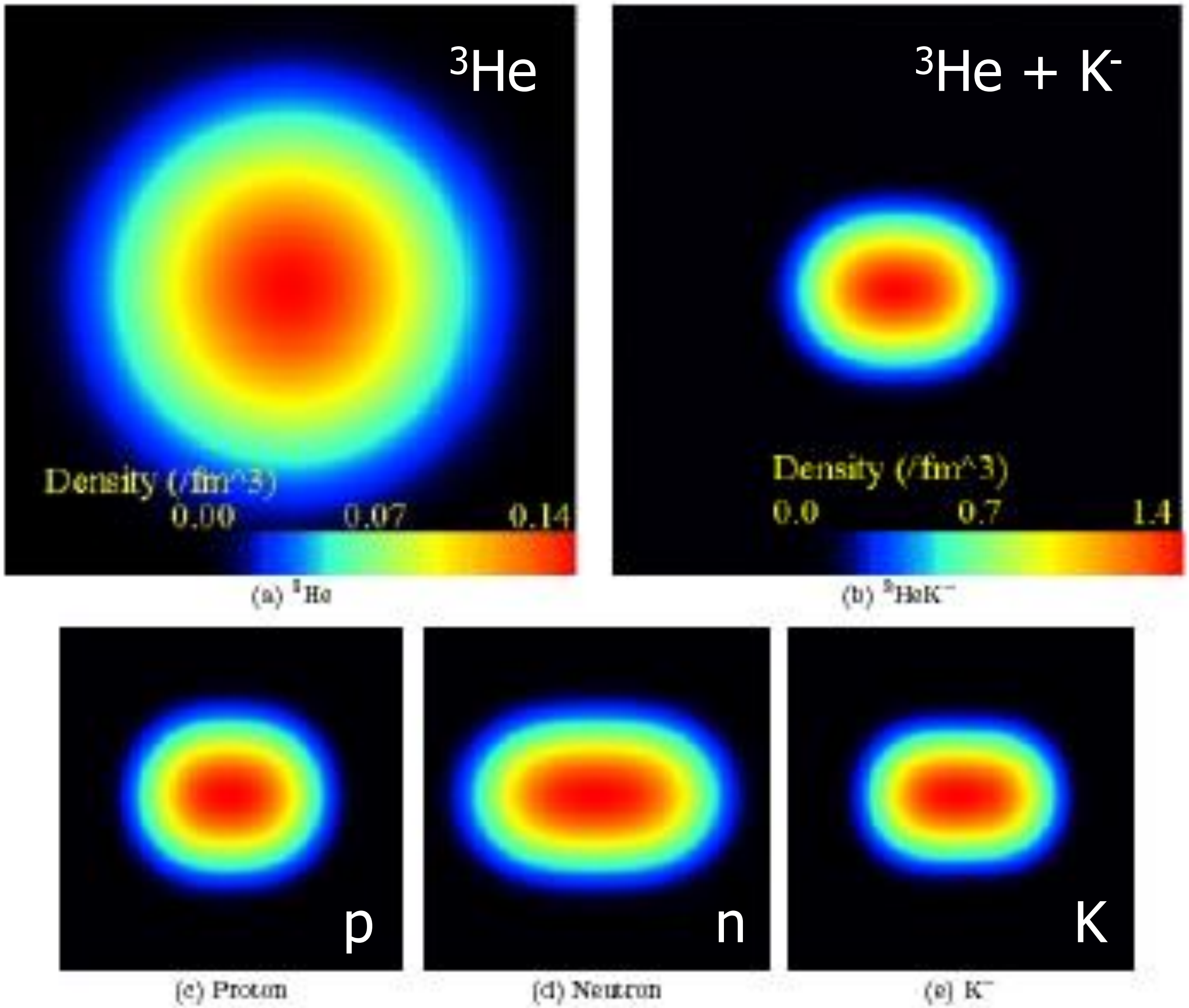
Discovery of a strange tribaryon $S^0(3115)$ in ^4He(stopped K^-, p) reaction

T. Suzuki [a], H. Bhang [b], G. Franklin [c], K. Gomikawa [a], R.S. Hayano [a], T. Hayashi [d,1], K. Ishikawa [d], S. Ishimoto [e], K. Itahashi [f], M. Iwasaki [f,d], T. Katayama [d], Y. Kondo [d], Y. Matsuda [f], T. Nakamura [d], S. Okada [d,2], H. Outa [e,2], B. Quinn [c], M. Sato [d], M. Shindo [a], H. So [b], P. Strasser [f,3], T. Sugimoto [d], K. Suzuki [a,4], S. Suzuki [e], D. Tomono [d], A.M. Vinodkumar [d], E. Widmann [a], T. Yamazaki [f], T. Yoneyama [d]

Total binding energy : 194 MeV from K^-ppn

Mass = 3117 MeV, width < 21 MeV

Kaonic Nuclei - Mini Strange Star



Dote et al.

FIG. 1: Calculated density contours of $ppnK^-$. Comparison between (a) usual ^3He and (b) $^3HeK^-$ is shown in the size of 7.5 by 7.5 fm. Individual contributions of (c) proton, (d) neutron and (e) K^- are given in the size of 4.5 by 4.5 fm.

Part II

Kaon Condensation
` a la Vector Manifestation

Why Strange Quarks in Neutron Stars ?

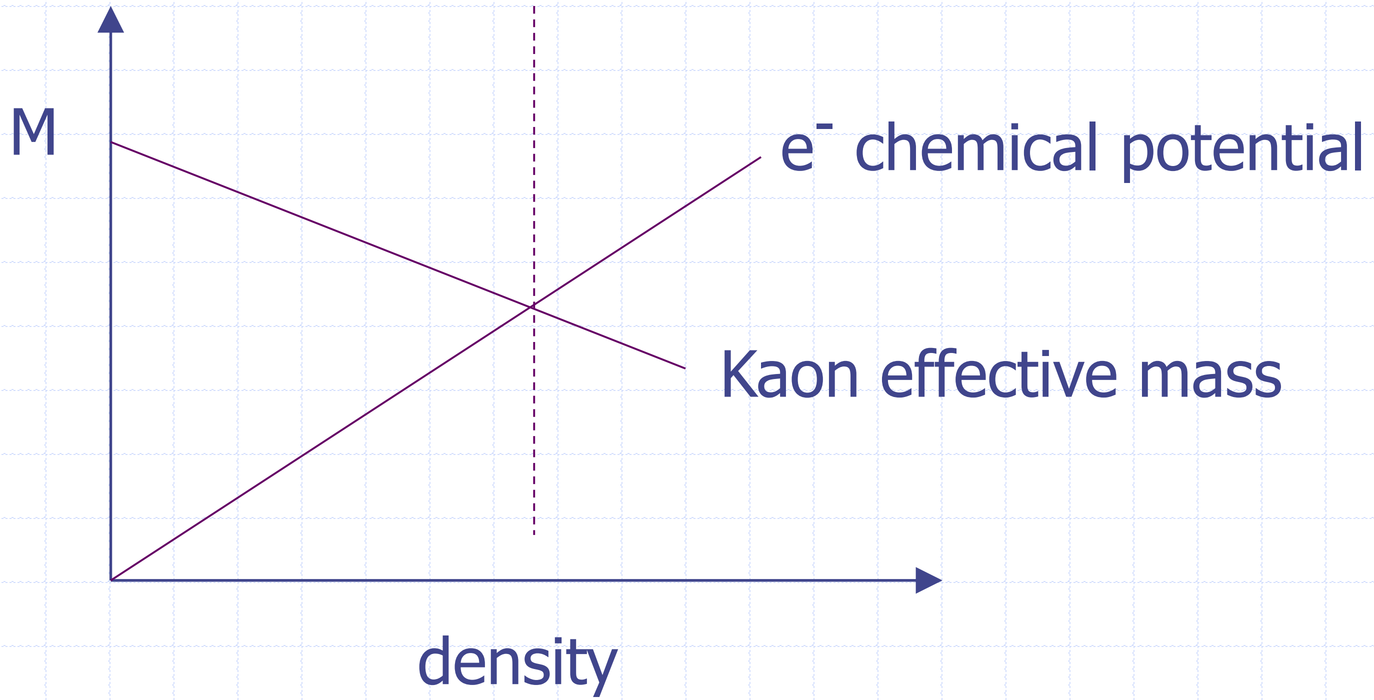
- proton, neutron: *u, d quarks*
- By introducing *strange quark*, we have one more degrees of freedom, energy of the system can be reduced!
- In what form ? *Kaon, Hyperons* … …

Kaon is the lighest particle with strange quark !

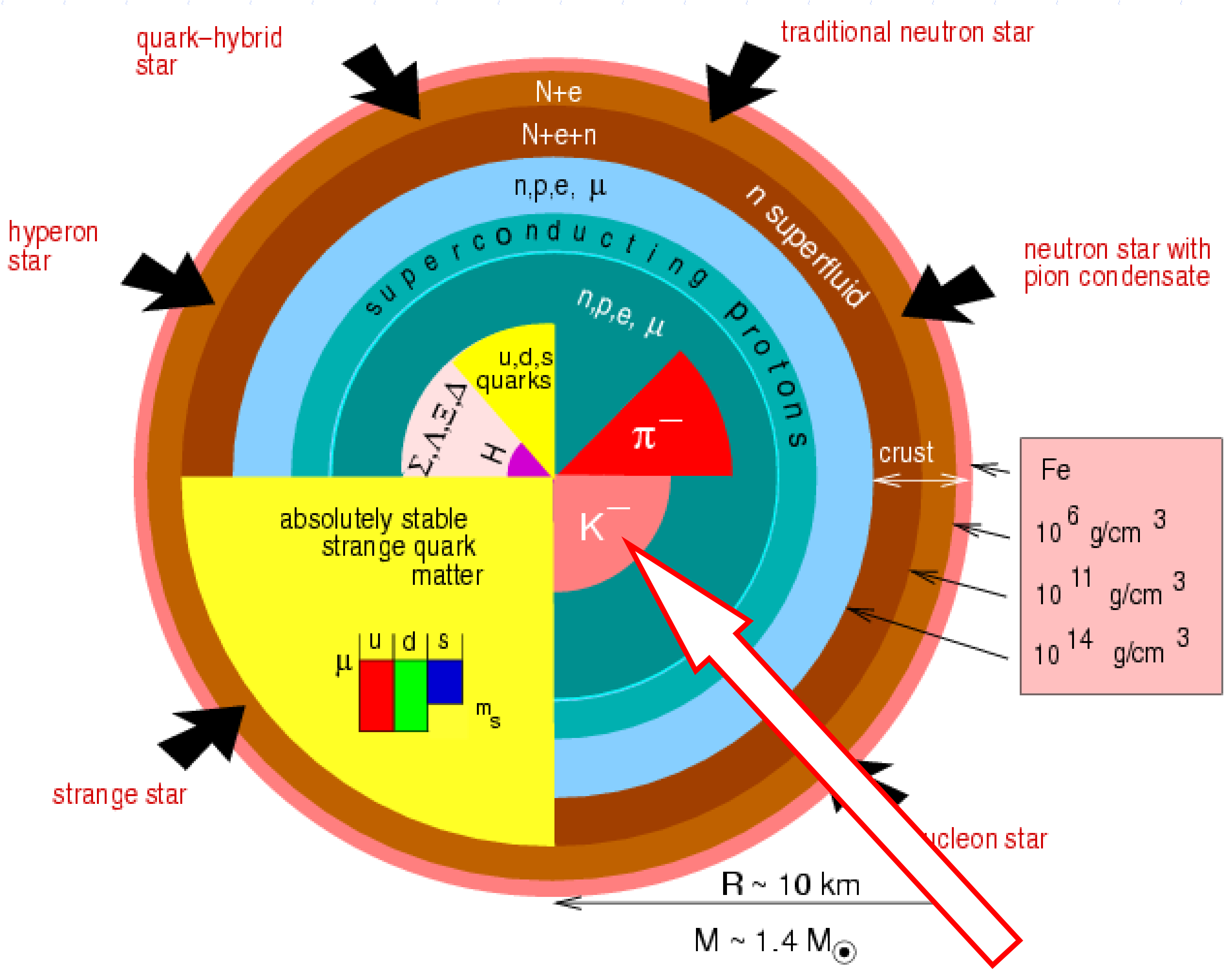
Kaon Condensation

reduce pressure
forming denser medium

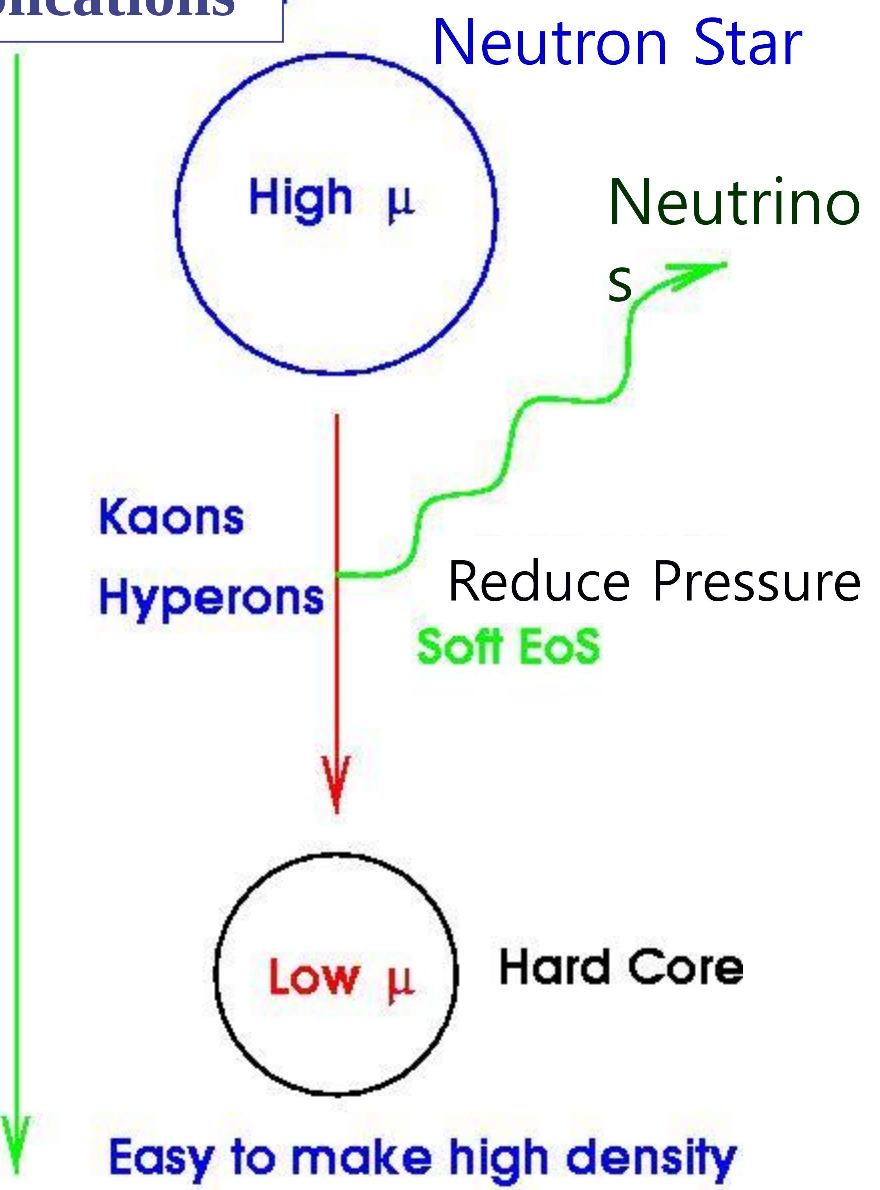
$p + e^- \rightarrow p + K^-$



“Neutron/Strange/Quark” Star

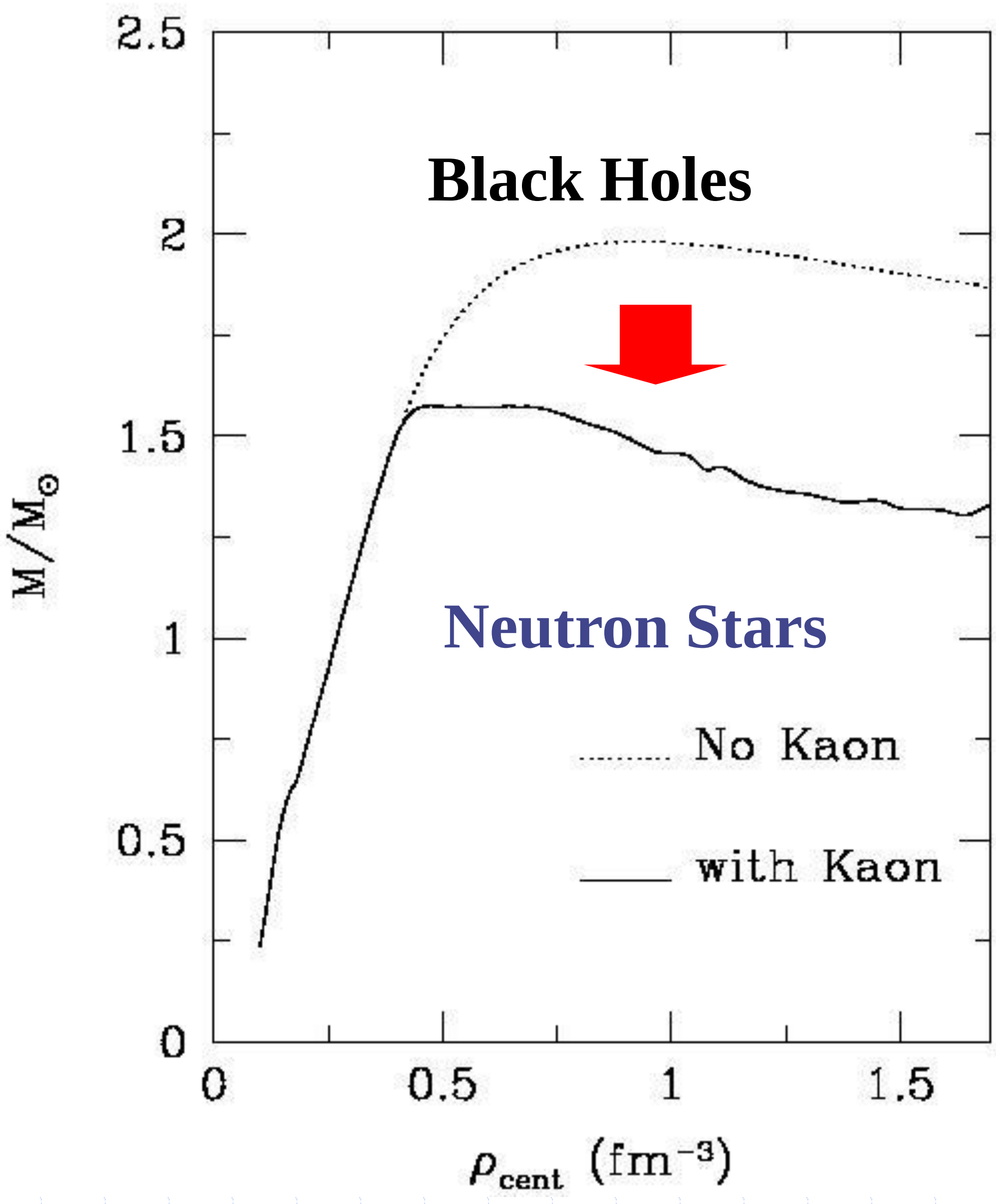


Astrophysical Implications



Formation of low mass Black Hole

Maximum Mass of NS



Q) What is the critical density for kaon condensation ?

1. Conventional approach (bottom-up):
   from zero density to higher density
2. New approach (top-down):
   from VM fixed point to lower density

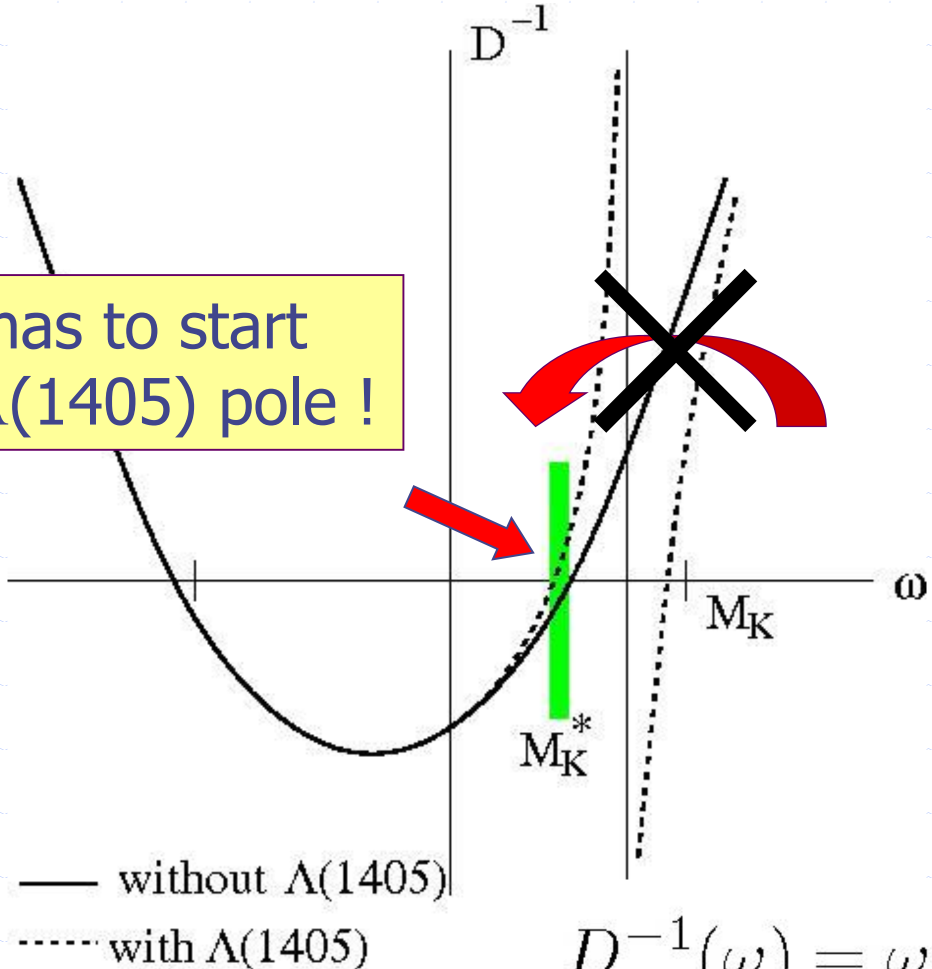
Problems in bottom-up approach

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 !



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

New Top-down approach

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 ?

Kaon Condensation `a la Vector Manifestation

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

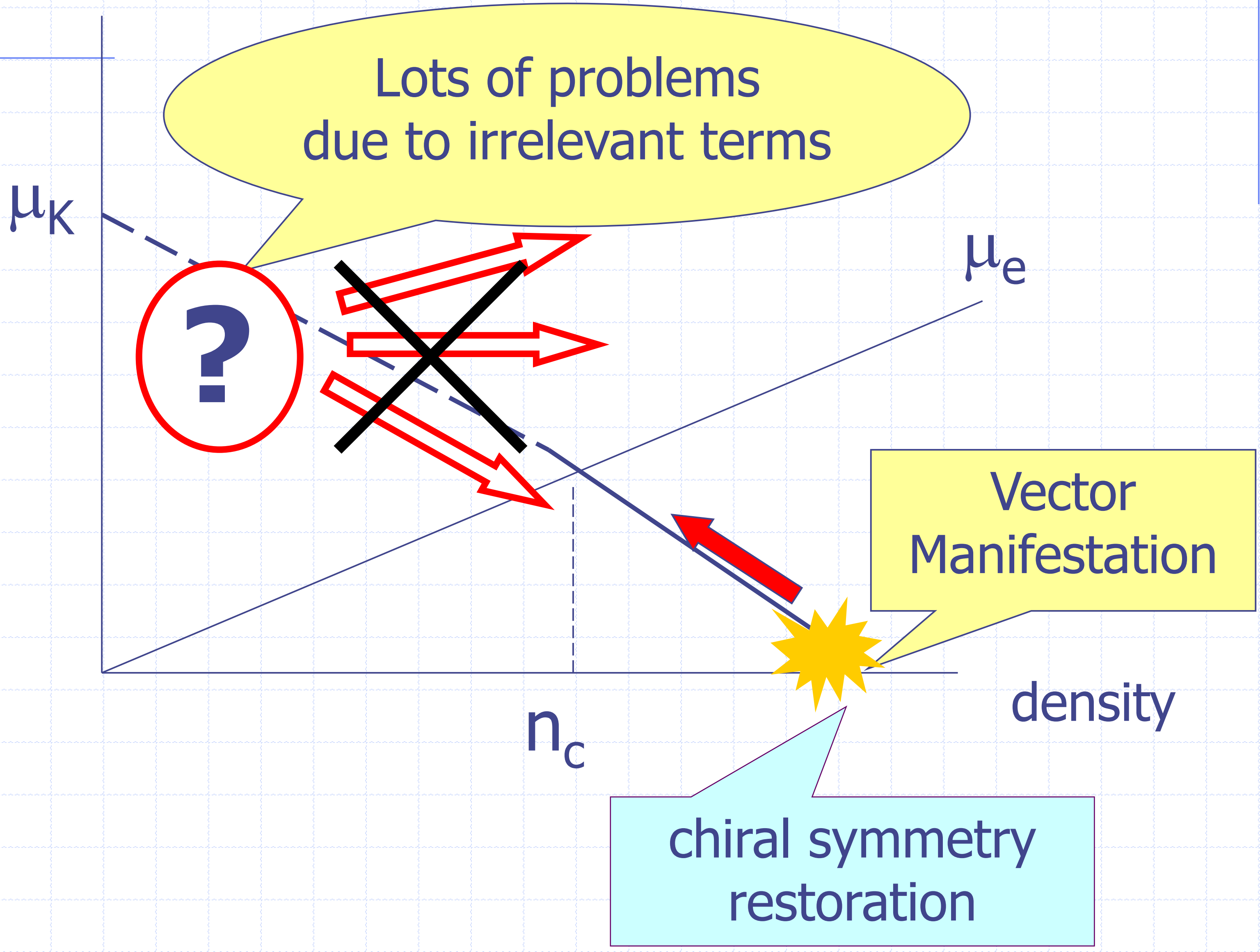
Vector Manifestation (up & down quarks)

Harada & Yamawaki

- When chiral symmetry (exactly) restored, $<\underline{q}q>=0$.
- Scale invariance should apply.
- Only stable RG (Renormalization Group) fixed point is physically meaningful.
- At this point, rho-mass goes to zero, etc.

Q) Can this give some constraints on the uncertainties in the analysis based on conventional approach ?

Kaon condensation from fixed point



Weinberg-Tomozawa term:

- most relevant from the point of view of RGE `a la VM.
- ω, ρ exchange between kaon & nucleon.

$$V_N(\omega) = -3V_{K^-}(\omega)\ .$$

$$V_{K^-}(\omega) = -\frac{3}{8F_\pi^2}n \simeq -57\ \mathrm{MeV}\ \frac{n}{n_0}$$

$|V_N(\omega)|$ = 171 MeV at n_0 is well below experimental 270 MeV

$$F_\pi \to f_\pi^\star \approx 0.8 F_\pi$$

Deeply bound pionic atoms [Suzuki et al.]

$$\frac{g^{\star 2}}{m_\rho^{\star 2}} = \frac{1}{a^\star F_\pi^{\star 2}} \approx \frac{1}{a^\star}\left(\frac{1}{0.8 F_\pi}\right)^2$$

$$a \equiv (F_\sigma / F_\pi)^2$$

$$m_\rho^2 = 2 F_\pi^2 g^2$$

fixed point of VM ➡ a*=1 (Harada et al.)

$$\frac{[g^{\star 2}/m_\rho^{\star 2}]_{\text{fixed point}}}{[g^2/m_\rho{}^2]_{\text{zero density}}} = \frac{[a F_\pi^2]_{\text{zero density}}}{[a^\star F_\pi^{\star 2}]_{\text{fixed point}}} \simeq \frac{2}{0.8^2} \simeq 3.1.$$

Enhancement at fixed point due to BR & VM

Critical density of chiral symmetry restoration

$$N_{ChiralSR} = 4\ n_0$$

ρ–mass drops to zero around 4 n_0

Brown/Rho [PR 396 (2004) 1]

Kaon potential at critical density without BR & VM

$$V_{K^-} = -\frac{1}{aF_\pi^2}\left(\frac{x_n}{2}+x_p\right)n_c = -129\ \mathrm{MeV}$$

10% p, n_c=3.1 n_0

Kaon potential at fixed point (4n_0) with BR + VM

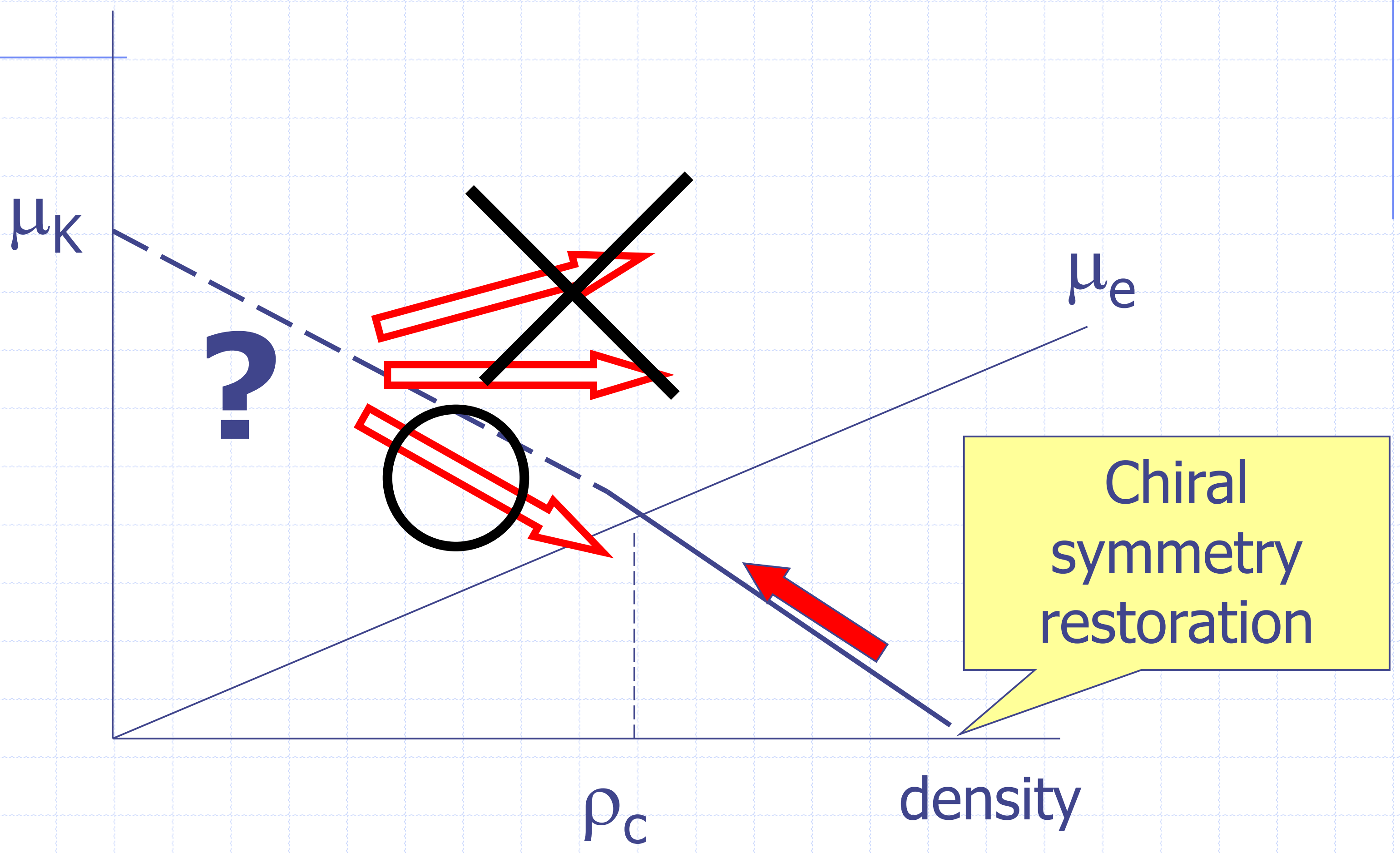
$$V_{K^-} \approx -\frac{4}{3.1}\times 3.1 \times 129\ \mathrm{MeV} = -516\ \mathrm{MeV} \lesssim -m_{K^-}$$

BR scaling & HM-VM

Enough attraction to bring kaon effective mass to zero at VM fixed point !

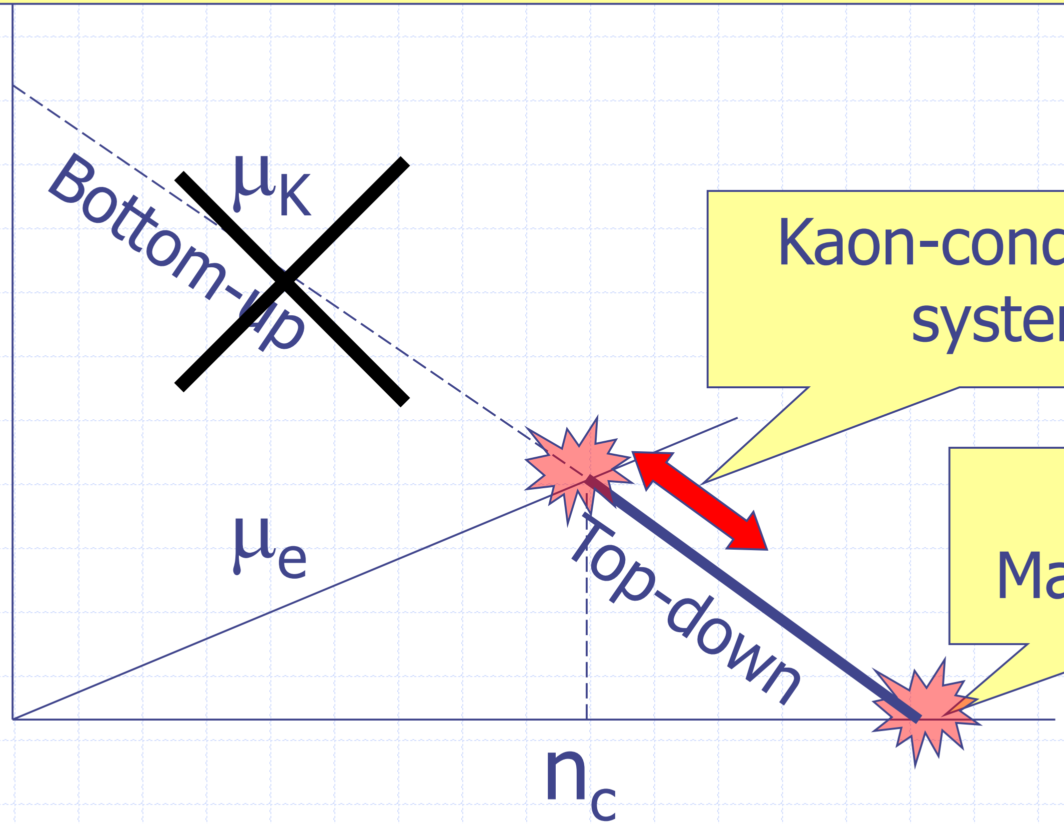
At fixed point, kaon effective mass goes to zero !

Kaon condensation from fixed point



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

All the arguments against kaon condensation (which is based on bottom-up approach) is irrelevant at densities near VM fixed point !



Kaon condensation comes in before chiral symmetry restoration (in u-, d-quark sector)

Part III

Observations and Prospects

Smoking Gun for kaon condensation

- SN 1987A
- Radio Pulsars
- Double Neutron Star Binaries
- Short-Hard Gamma-ray Bursts

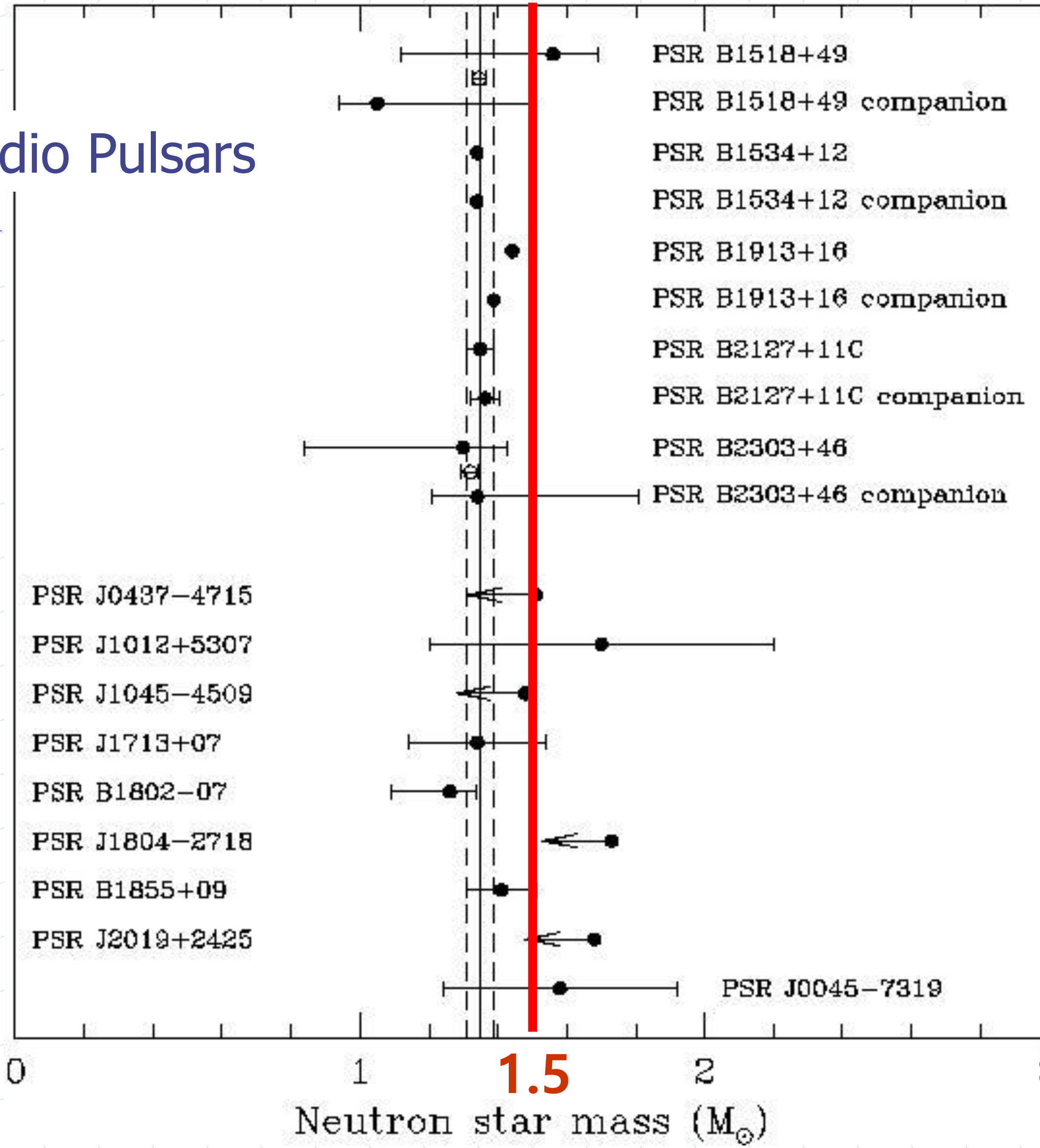
Speculations

- Isolated Single Neutron Stars
- X-ray Binary [Vela X-1]
- Radio pulsar in J0751+1807 (white dwarf companion)

SN 1987A

- Formation of 1.5 Msun NS : theoretically confirmed by neutrino detection.
- Progenitor 16 Msun O-star, 1.5 Msun Fe core.
- No evidence of NS, yet. (e.g., no Pulsar signal, lower total luminosity by an order of magnitude)
- NS went into Small Mass Black Hole (after cooling & accretion) !!

Masses of Radio Pulsars



Double Neutron Stars (NS-NS binary) are all consistent with kaon condensation

J0737-3039: 1.337 M_{sun} & 1.290 M_{sun}

"Most recent observation of binary neutron star is also consistent with the limit suggested by kaon condensation." [nature, 2003]

PSR J1756-2251: 1.4 M_{sun} & 1.2 M_{sun}

astro-ph/0411796

Short-Hard Gamma-ray Burst : Colliding NS binaries

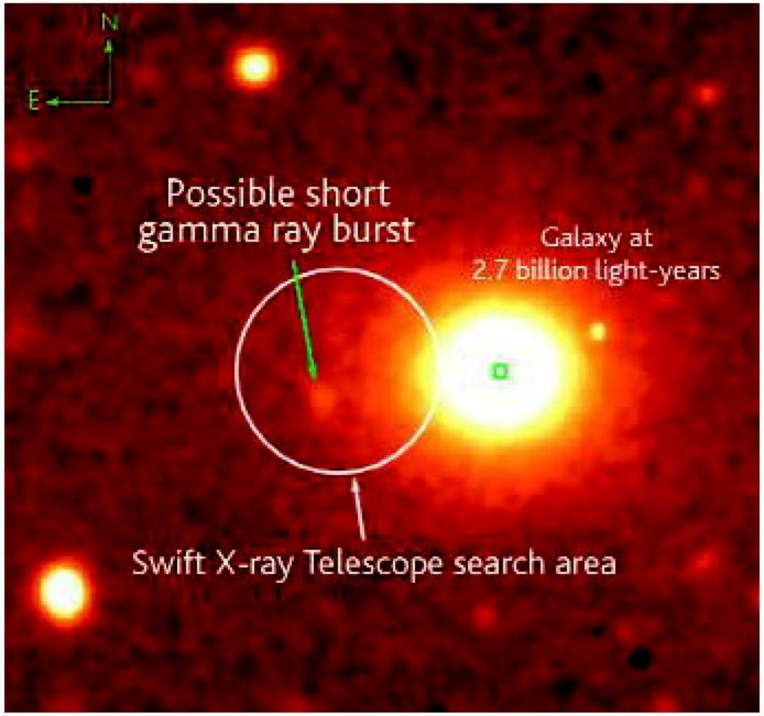
GAMMA RAY ASTRONOMY

Signs Point to Neutron-Star Crash

Astronomers think they have witnessed their first colossal crash of two neutron stars, an event that has tantalized theorists for decades.

Shortly after midnight EDT on 9 May, a NASA satellite detected a sharp flare of energy, apparently from the fringes of a distant galaxy. The news from Swift, launched in November 2004, was quickly disseminated to ground-based astronomers, triggering hours of intense research. As *Science* went to press, exhausted observers verified that their early observations look a lot like a neutron-star merger. "Prudence would say that we need a strong confirmation, but we're very excited by it," says astronomer Joshua Bloom of the University of California, Berkeley.

Colliding neutron stars would help explain a puzzling variety of the titanic explosions called gamma ray bursts (GRBs). Astronomers are

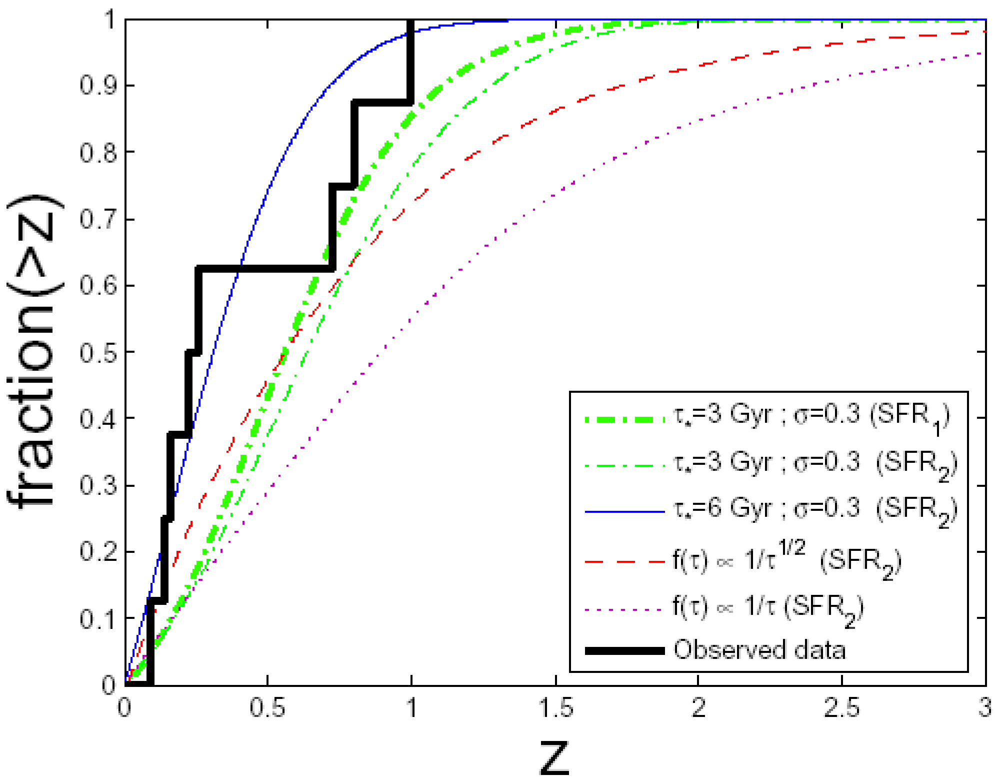


Neutron-star cataclysm? A faint patch of light (green arrow) may mark the spot where two neutron stars collided.

Science 308 (2005) 939

Short-Hard Gamma-ray Bursts (SHBs)

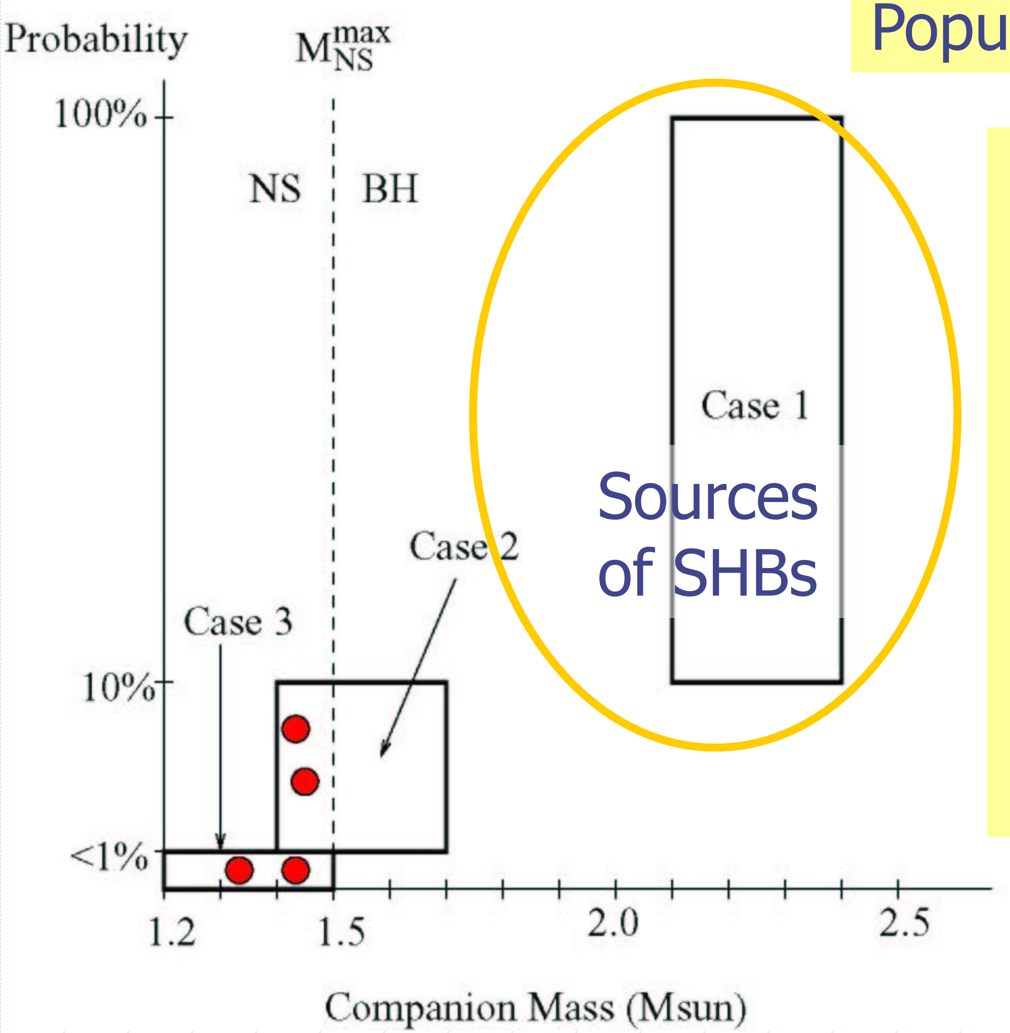
- Observed NS-NS binaries are inconsistent with SHBs
- *Invisible* old (> 6 Gyr) NS binaries are responsible for short-hard gamma-ray bursts (SHBs)



Nakar et al. a-p/0511254

What are the *invisible* old NS binaries ?

Our *invisible* NS-BH binaries are consistent with SHBs !



Population of NS Binary

- NS binaries with heavier companion should be more dominant.
- But, we see only NS binaries with companion mass < 1.5 Msun.
- Heavier ones went into BH.

Lee, Brown, a-p/0510380

Speculations

- Isolated Single Neutron Stars
- X-ray Binary [Vela X-1]
- Radio pulsar in J0751+1807 (white dwarf companion)

Q) Is kaon condensation still alive ?

Isolated Single Neutron Stars

J. Drake, 2003

Isolated NS Candidates

Source	PSPC (counts s^{-1})	T_{bb} (eV)	N_H (10^{20} cm^{-2})	log f_x/f_v	Period (s)	Optical Excess?	References
RBS 1223	0.29	118	~1	~5	5.16	Yes	9,14,16
RBS 1556	0.88	100	<1	~5	...	Yes	9,10,17
RBS 1774	0.11	92	4.6	$\gtrsim 3$	...	...	2,9,11,12,13
RX J0720	1.69	79	1.3	5.3	8.37	Yes	6,7,8
RX J0806	0.38	78	2.5	>3.4	11.37	...	11,15
RX J1856	3.64	57	2	4.9	...	Yes	2,3,4,5
RX J0420	0.11	57	1.7	>3.3	22.7	...	12

Is RX J1856.5-3754 a Quark Star?

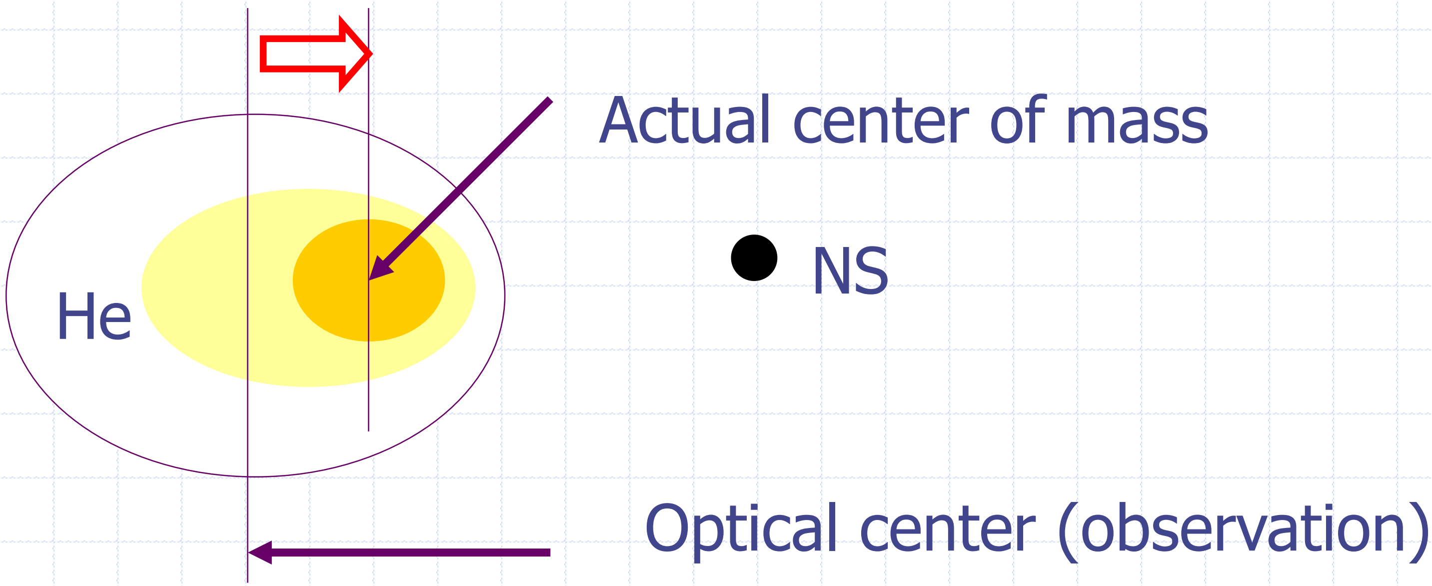
- Single temperature black body radiation cannot explain both X-ray & optical luminosity, etc.
- Until we can better understand the surface character, interpretation is open
- So, NS with kaon condensation is still open possibility !

BH

X-ray Binaries			
4U1700−37	$2.44^{+0.27}_{-0.27}$	Vela X-1	$1.86^{+0.16}_{-0.16}$
Cyg X-1	$1.78^{+0.23}_{-0.23}$	4U1538−52	$0.96^{+0.19}_{-0.16}$
SMC X-1	$1.17^{+0.16}_{-0.16}$, 1.05 ± 0.09	XTE J2123−058	$1.53^{+0.30}_{-0.42}$
LMC X-4	$1.47^{+0.22}_{-0.19}$, 1.31 ± 0.14	Her X-1	$1.47^{+0.12}_{-0.18}$
Cen X-3	$1.09^{+0.30}_{-0.26}$, 1.24 ± 0.24	2A 1822−371	> 0.73
Neutron Star - Neutron Star Binaries			
1518+49	$1.56^{+0.13}_{-0.44}$	1518+49 companion	$1.05^{+0.45}_{-0.11}$
1534+12	$1.3332^{+0.0010}_{-0.0010}$	1534+12 companion	$1.3452^{+0.0010}_{-0.0010}$
1913+16	$1.4408^{+0.0003}_{-0.0003}$	1913+16 companion	$1.3873^{+0.0003}_{-0.0003}$
2127+11C	$1.349^{+0.040}_{-0.040}$	2127+11C companion	$1.363^{+0.040}_{-0.040}$
J0737−3039A	$1.337^{+0.005}_{-0.005}$	J0737−3039B	$1.250^{+0.005}_{-0.005}$
J1756−2251	$1.40^{+0.02}_{-0.03}$	J1756−2251 companion	$1.18^{+0.03}_{-0.02}$
Neutron Star - White Dwarf Binaries			
B2303+46	$1.38^{+0.06}_{-0.10}$	J1012+5307	$1.68^{+0.22}_{-0.22}$
J1713+0747	$1.54^{+0.007}_{-0.008}$	B1802−07	$1.26^{+0.08}_{-0.17}$
B1855+09	$1.57^{+0.12}_{-0.11}$	J0621+1002	$1.70^{+0.32}_{-0.29}$
J0751+1807	$2.20^{+0.20}_{-0.20}$	J0437−4715	$1.58^{+0.18}_{-0.18}$
J1141−6545	$1.30^{+0.02}_{-0.02}$	J1045−4509	< 1.48
J1804−2718	< 1.70	J2019+2425	< 1.51
Neutron Star - Main Sequence Binaries			
J0045−7319	$1.58^{+0.34}_{-0.34}$		

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]



Q) Radio pulsar in J0751+1807 [Nice et al. 2005]
≈ 2.1 Msun (with white dwarf companion)

White dwarf mass is not a direct measurement, but was determined by Baysian analysis.

Difficulty in Baysian analysis:
data is non-Gaussian, one has to consider the different weighting factors

Still, kaon-condensation is open possibility !

Current Status

All well-controlled observations
are consistent with kaon condensation.

Those observations with higher NS mass
cannot rule out the kaon condensation.

Prospects for LIGO

Gravitational Waves from Binary Mergers

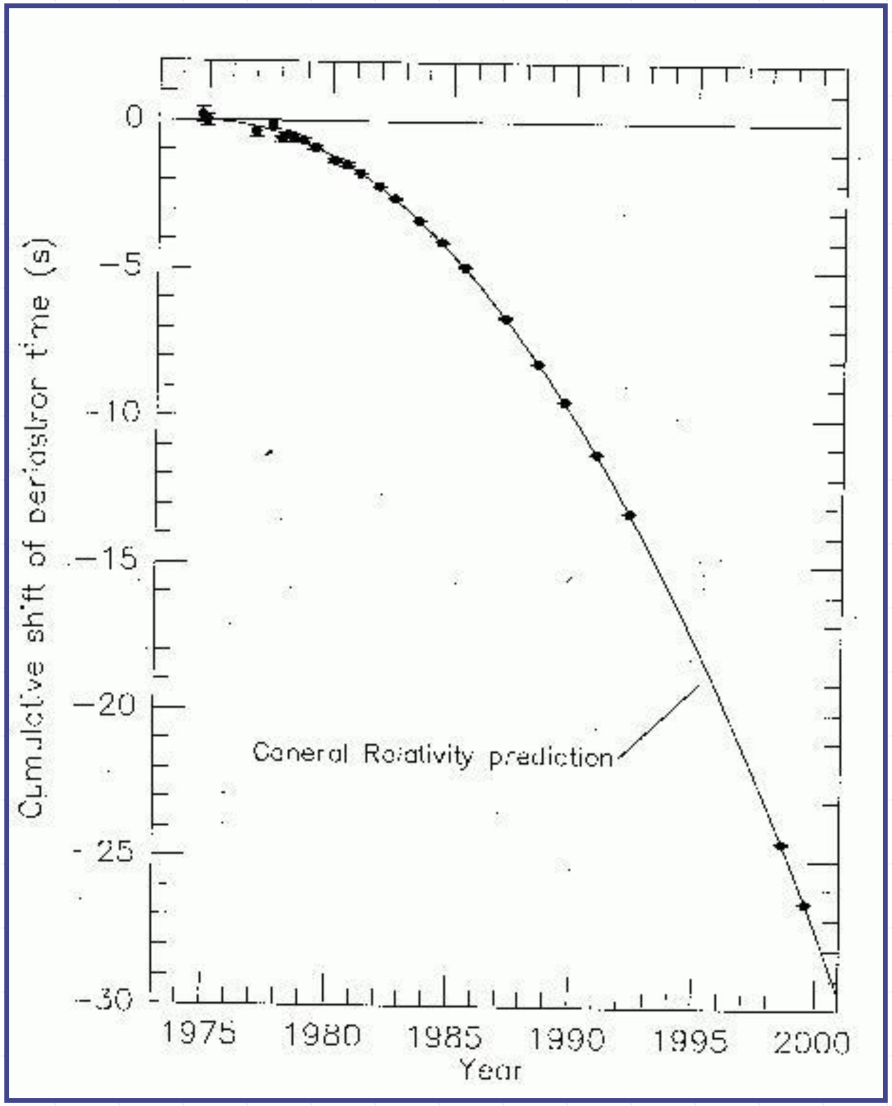
Gravitational Wave from Binary Neutron Star

B1913+16
Hulse & Taylor (1975)

Effect of Gravitational Wave Radiation

1993 Nobel Prize
Hulse & Taylor

LIGO was based on mergers of DNs



Laser Interferometer Gravitational Wave Observatory

LIGO I : in operation (since 2004)

LIGO II: in progress (2010 ?)

Kaon-Condensation vs Gravitation Wave Detector

NS + BH Binaries as GW source

Kaon condensation

- ***unseen*** "NS+BH" are 10 times more dominant than ***seen*** "NS+NS" system.
- "NS+BH" system may increase LIGO detection rate by factor of 20.

Predicted LIGO Detection Rates (yr^{-1}).

Binary Type	Initial LIGO	Advanced LIGO	Chirp Masses ($M_\odot$)
NS-NS†	0.0348	187	1.0 - 1.3
BH-NS††	0.696	3740	1.3 - 2.7
BH-BH**	0.58	2450	~ 6
Total	1.31	6377	

$$R_{\rm eff} = R_0 \left(\frac{M_{\rm chirp}}{M_\odot}\right)^{5/6}, \quad M_{\rm chirp} = \mu^{3/5} M_{\rm tot}^{2/5}$$

R_0=17 Mpc (initial LIGO), 280 Mpc (advanced LIGO)

Discussions

- VM: EOS with $\rho_{c(\textbf{kaon cond})} < \rho_{\chi SB}$ is acceptable.
- Kaon condensation in neutron stars is still open possibility after various recent observations.
- Invisible NS-BH binaries are consistent with SHBs & increase the LIGO detection rate by 20.

Conclusion

Why all these different approaches are
so consistent with each other ?

Kaon Condensation in χPT, Brown-Rho Scaling
Harada-Yamawaki Vector Manifestation, Kaon Production in KaoS, Kaonic Nuclei, SN1987A, Radio Pulsars,
Population of Double NS-binaries, Soft-Hard Gamma-ray Bursts,
Gravitation Wave Observations, …

Because nature prefers kaon condensation !
whether you like it or not

Thank you!