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Kaon Condensation in Neutron Stars & Related Issues

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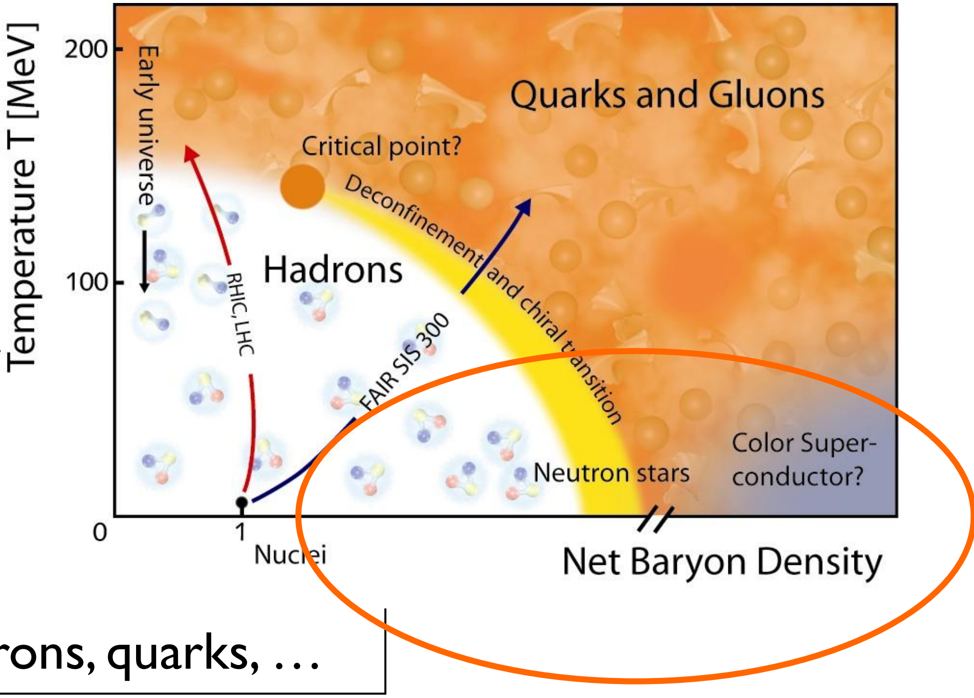
Contents

- Motivations : why Neutron Stars ?
- Kaon Condensation & Issues in Hadronic Physics
- Observations & Astrophysical Issues

Motivations 1: why Neutron Stars ?

Ultimate Testing place for physics of dense matter

- ✓ Chiral symmetry restoration
- ✓ Color superconductivity
- ✓ Color-flavor locking
- ✓ Quark-Gluon-Plasma ?
- ✓ AdS/QCD?



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

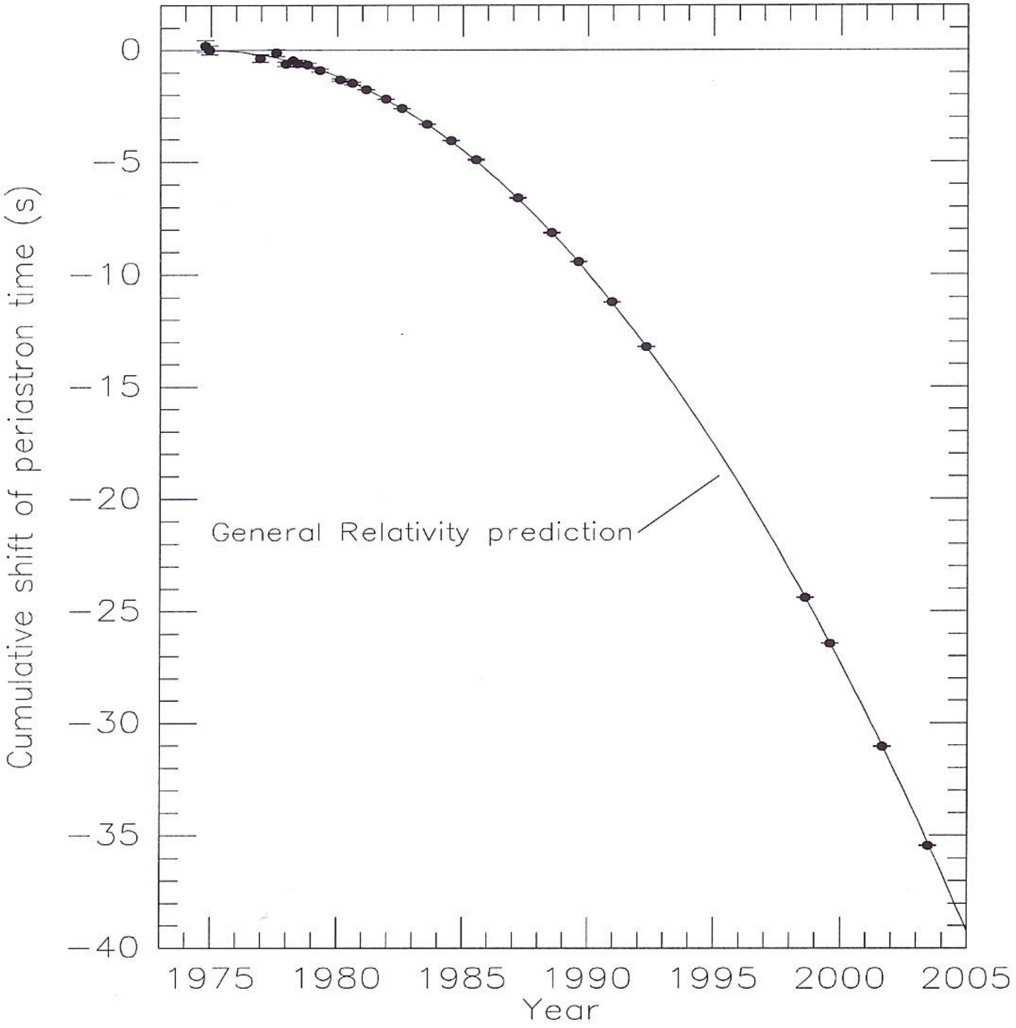
Gravitation Wave from Binary Neutron Star

B1913+16
Hulse & Taylor (1975)

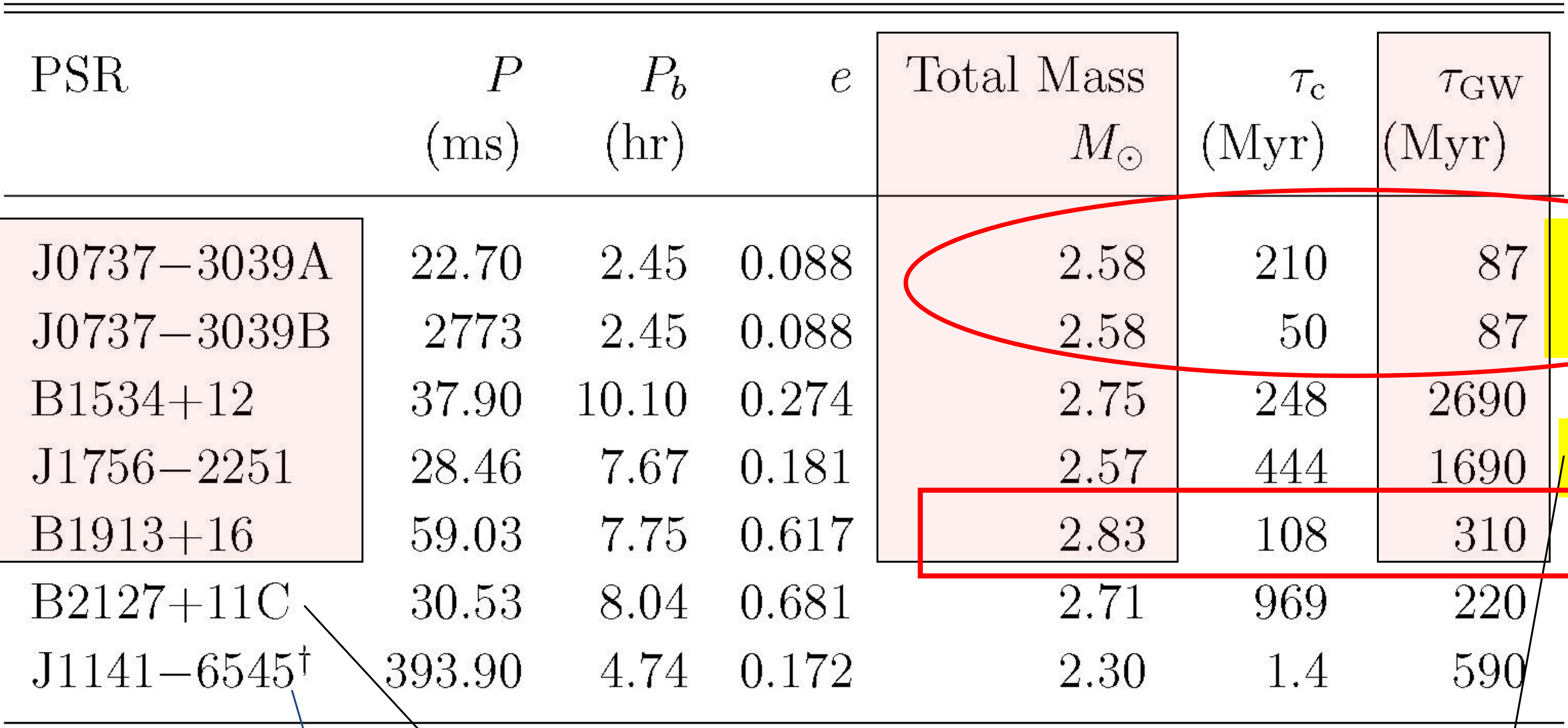
Effect of Gravitational Wave Radiation

1993 Nobel Prize
Hulse & Taylor

LIGO was based on the merger of DNS



NS (radio pulsar) which coalesce within Hubble time



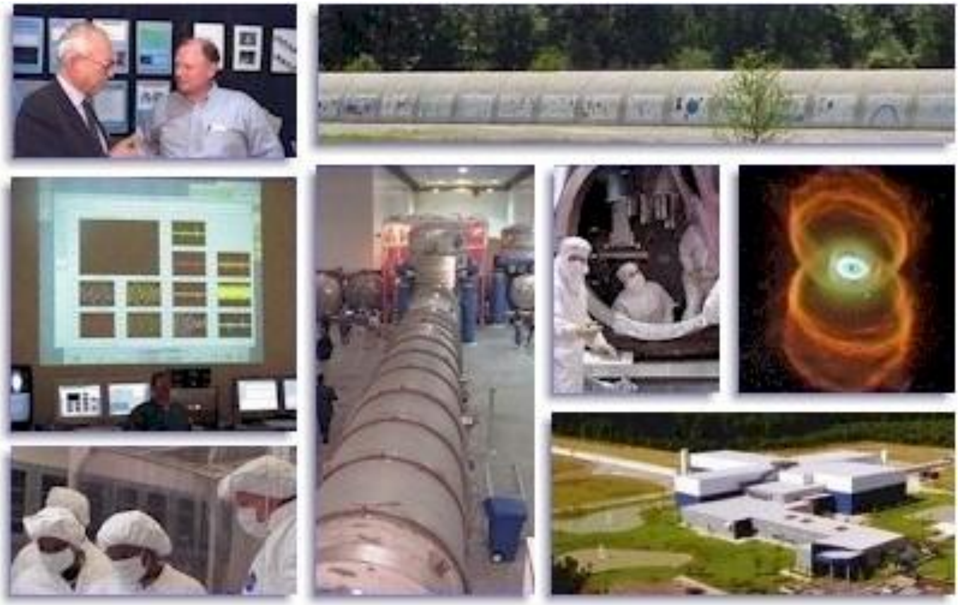
PSR	P (ms)	P_b (hr)	e	Total Mass $M_\odot$	τ_c (Myr)	τ_{GW} (Myr)	
J0737−3039A	22.70	2.45	0.088	2.58	210	87	(2003)
J0737−3039B	2773	2.45	0.088	2.58	50	87	(2004)
B1534+12	37.90	10.10	0.274	2.75	248	2690	(1990)
J1756−2251	28.46	7.67	0.181	2.57	444	1690	(2004)
B1913+16	59.03	7.75	0.617	2.83	108	310	(1975)
B2127+11C	30.53	8.04	0.681	2.71	969	220	(1990)
J1141−6545†	393.90	4.74	0.172	2.30	1.4	590	(2000)

Not important

Globular Cluster : no binary evolution

White Dwarf companion

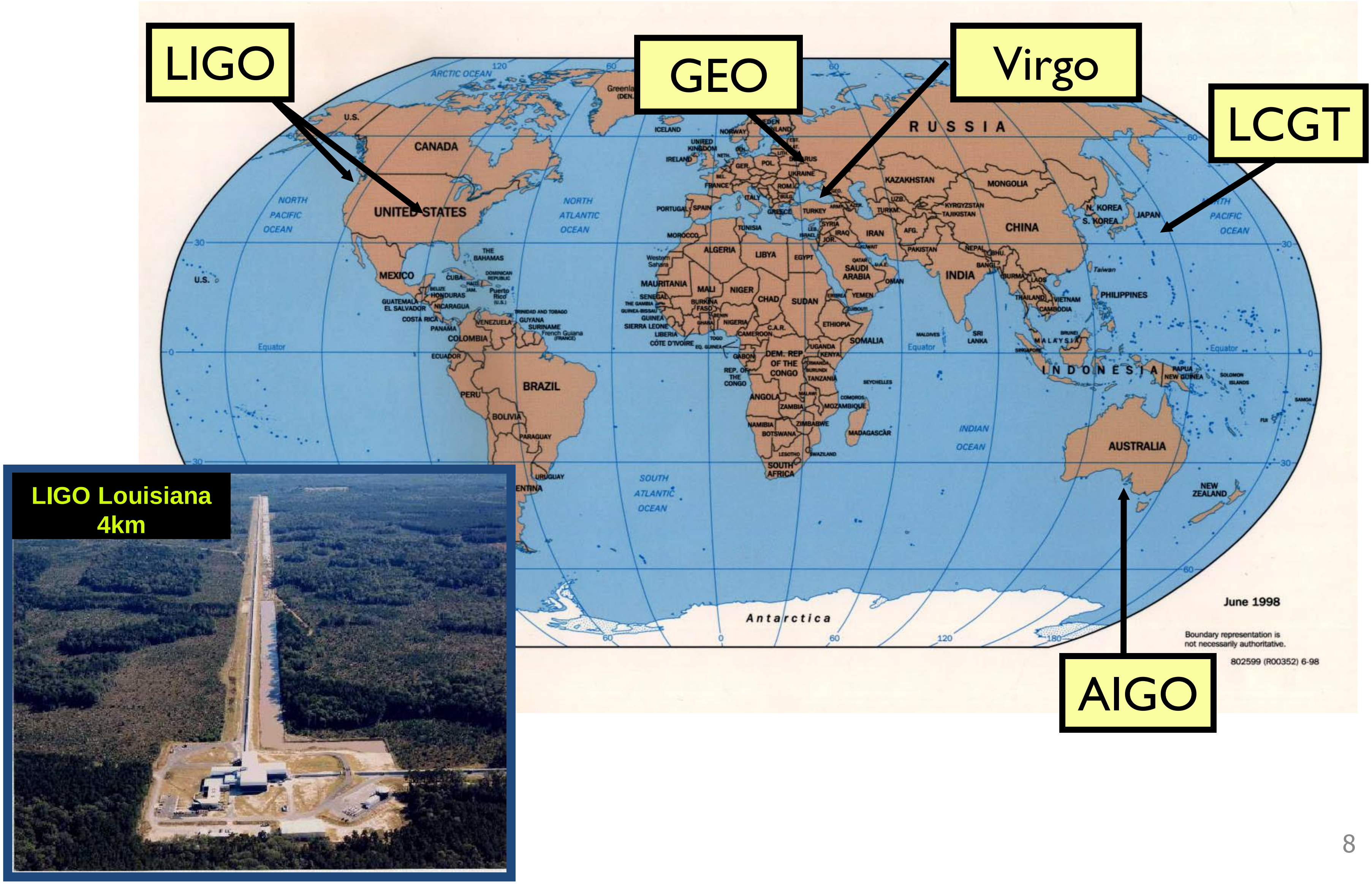
Laser Interferometer Gravitational Wave Observatory



LIGO I : in operation
(since 2004)

LIGO II: in progress
(2014 ?)

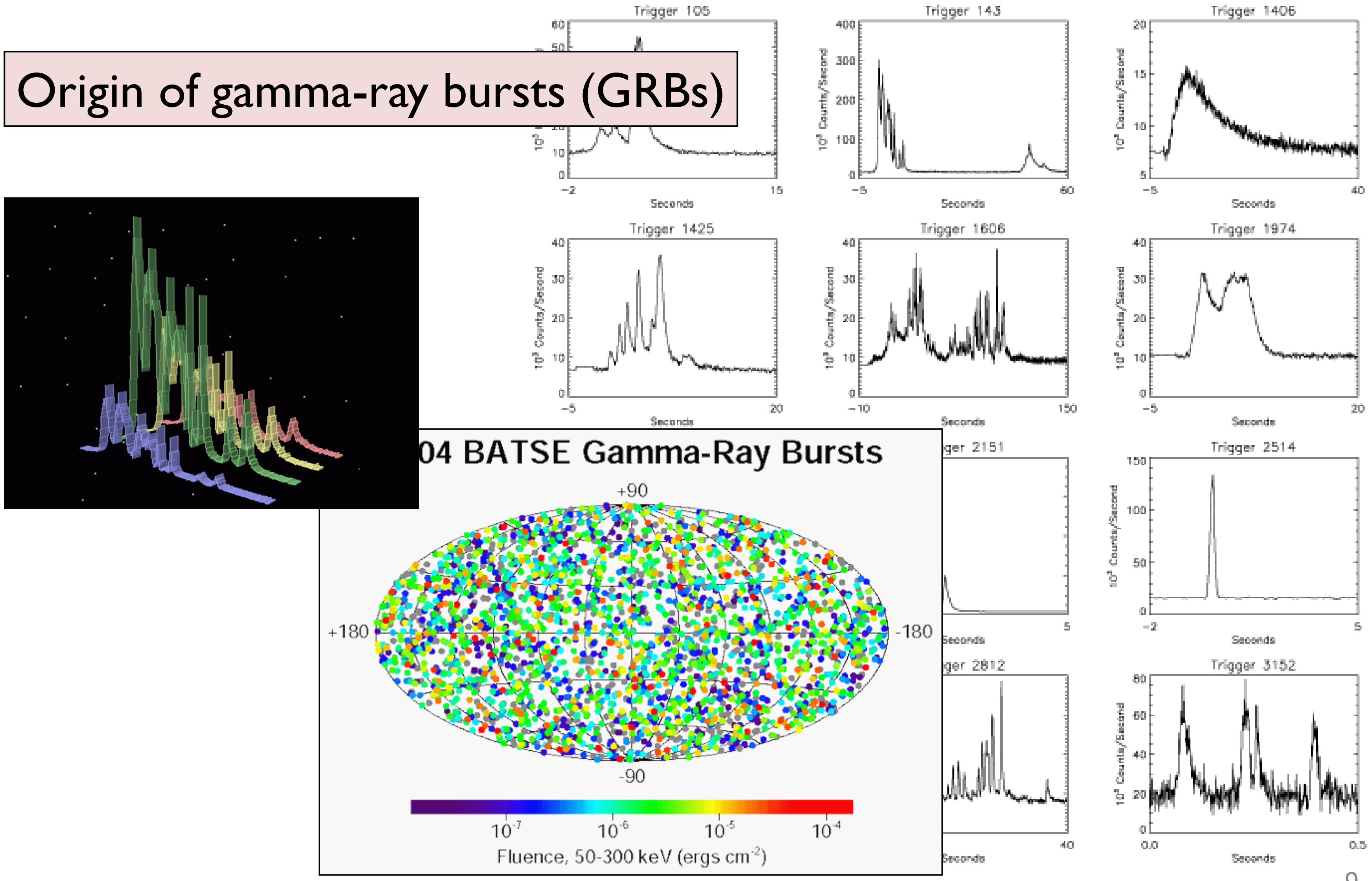
Network of Interferometers



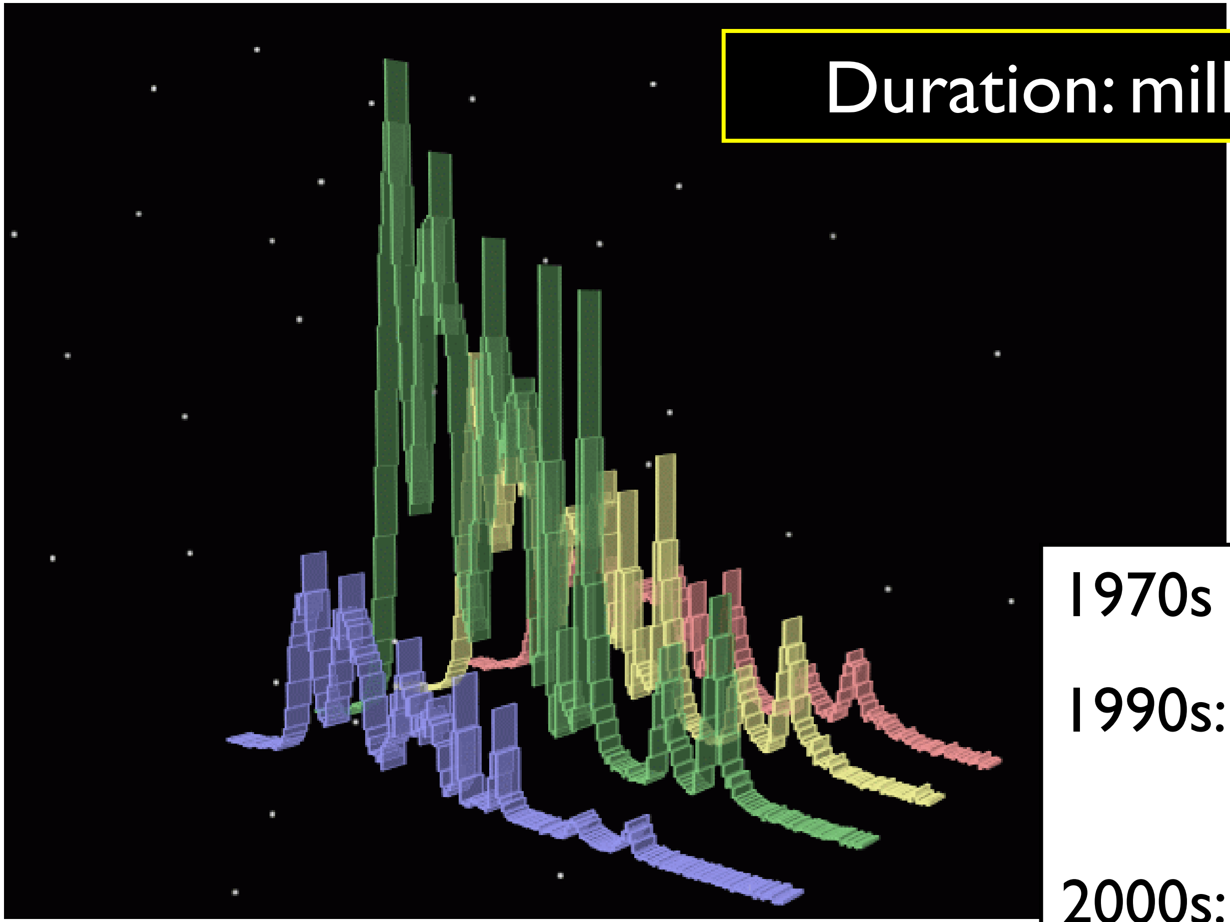
LIGO Louisiana 4km

Motivations 3: why Neutron Stars ?

Origin of gamma-ray bursts (GRBs)



Gamma-ray bursts (GRBs)

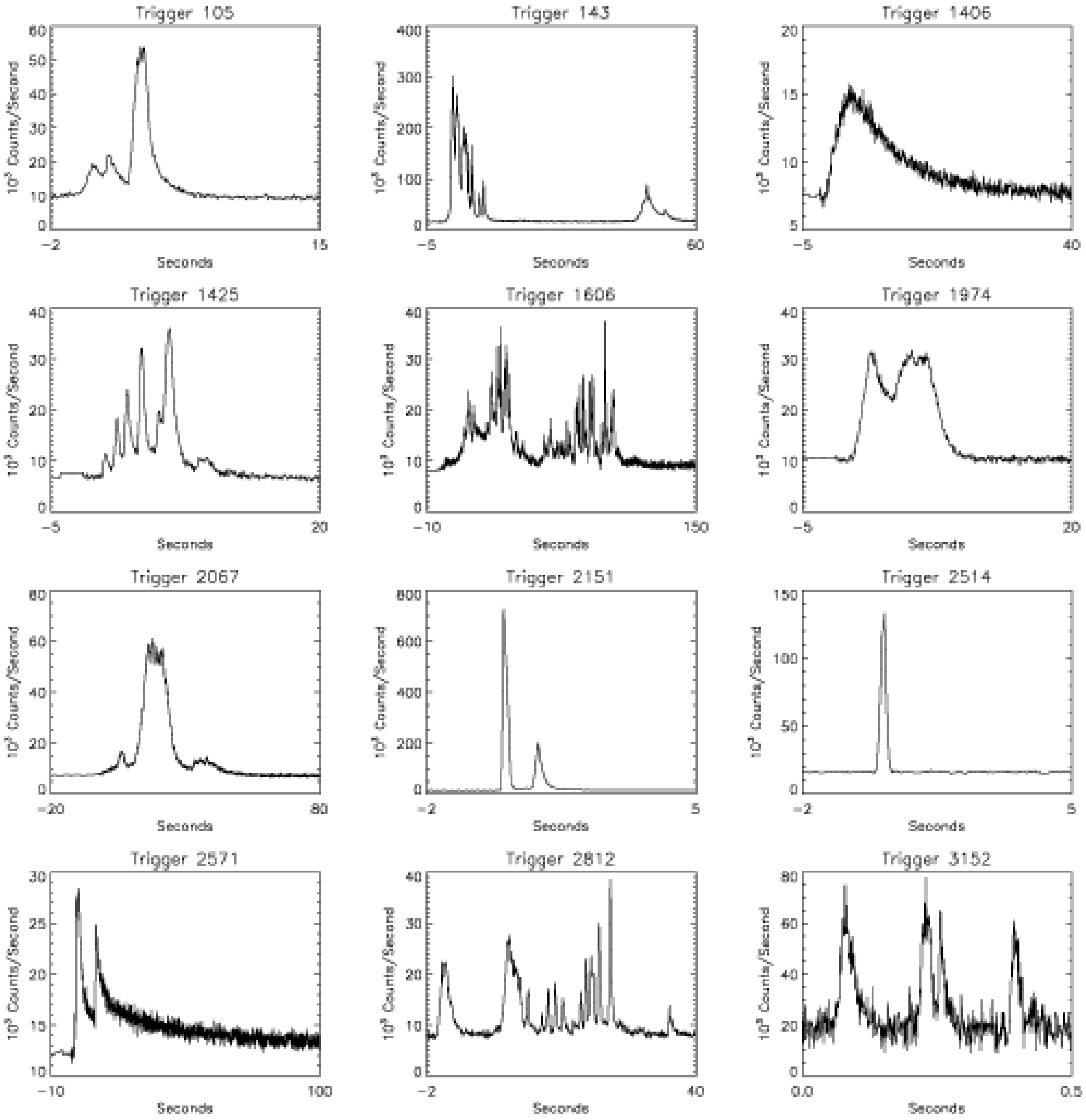


Duration: milli sec - min

1970s : Vela Satellite

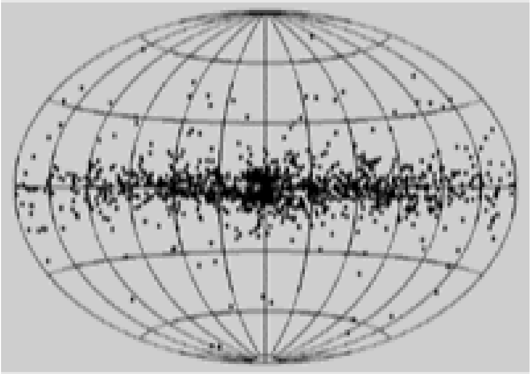
1990s: CGRO,
Beppo-SAX

2000s: HETE-II, Swift

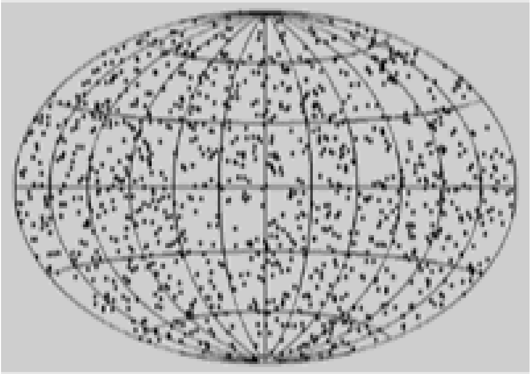

Trigger 105
Trigger 143
Trigger 1406
Trigger 1425
Trigger 1606
Trigger 1974
Trigger 2067
Trigger 2151
Trigger 2514
Trigger 2571
Trigger 2812
Trigger 3152
10³ Counts/Second
Seconds
−2
15
−5
60
−5
40
−5
20
−10
150
−5
20
−20
80
−2
5
−2
5
−10
100
−2
40
0.0
0.5

Galactic or Extra-Galactic ?

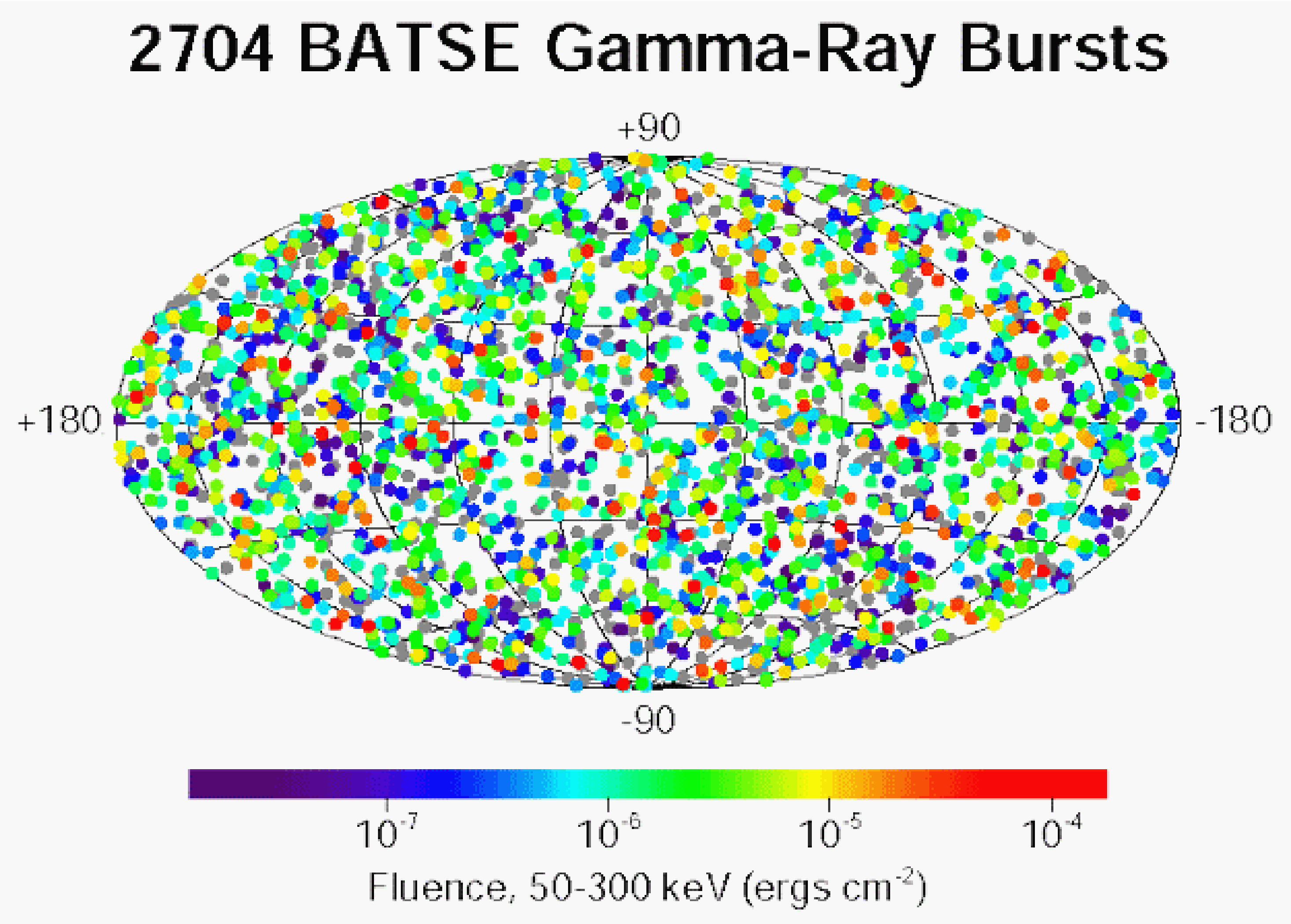
Distribution of Gamma-Ray Bursts on the Sky

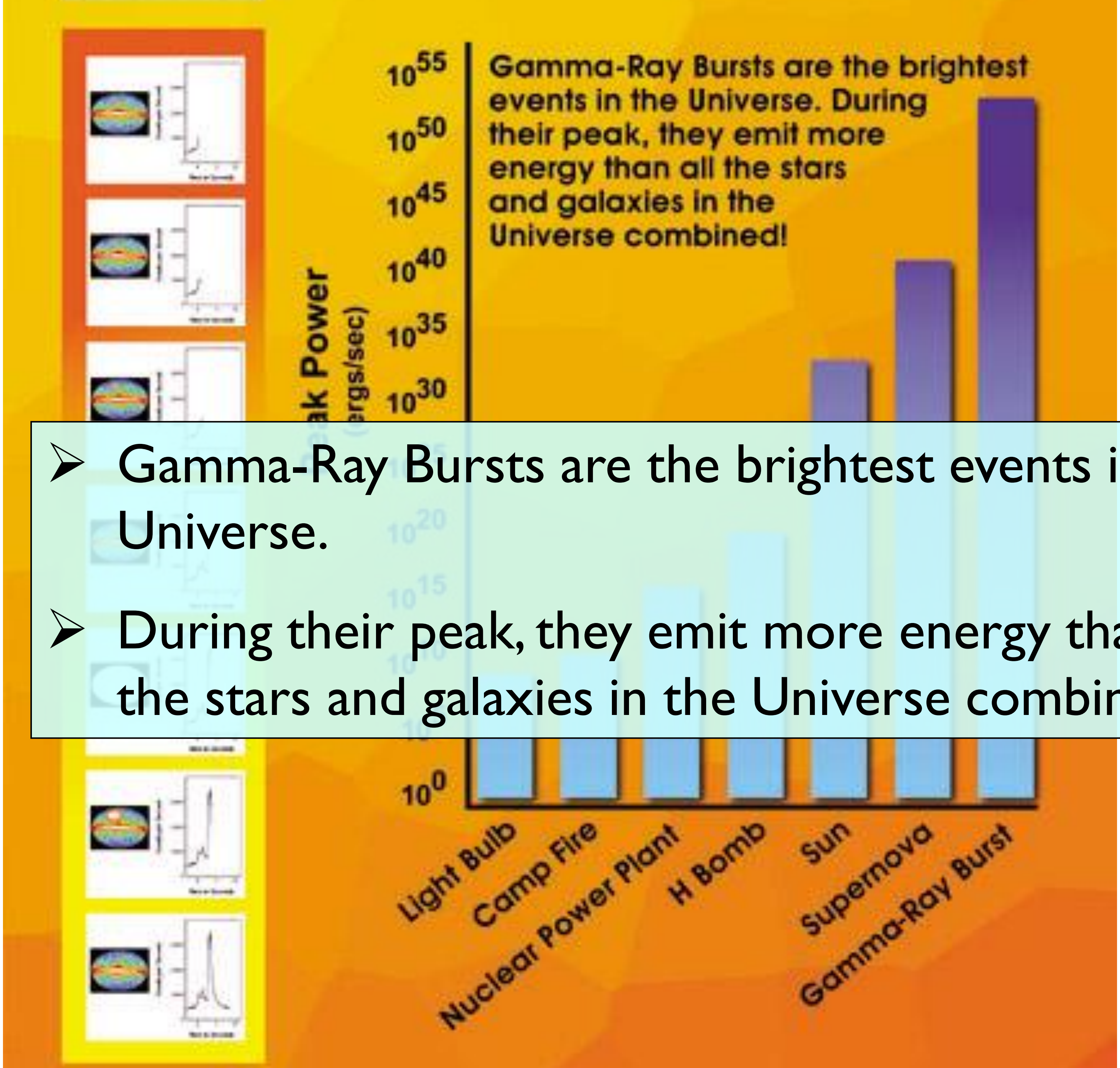


Expected



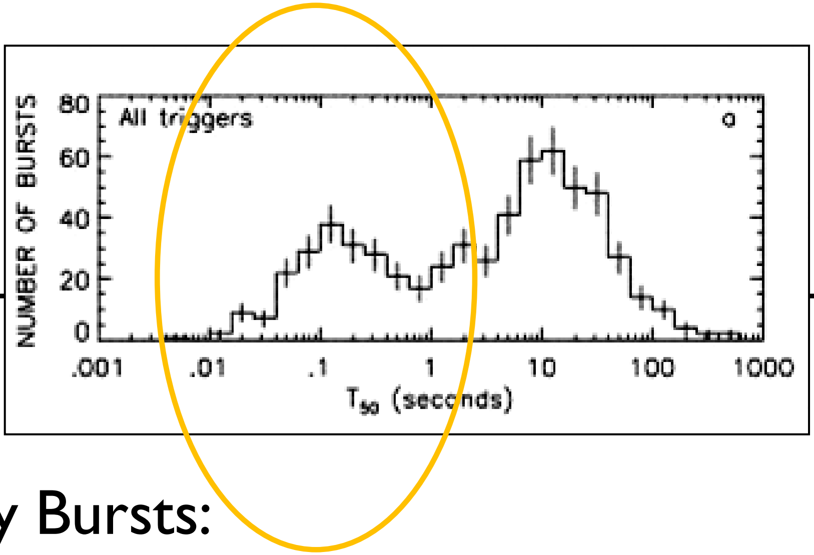
Observed


2704 BATSE Gamma-Ray Bursts
+90
+180
-180
-90
10^{-7}
10^{-6}
10^{-5}
10^{-4}
Fluence, 50-300 keV (ergs cm^{-2})



- ➢ Gamma-Ray Bursts are the brightest events in the Universe.
- ➢ During their peak, they emit more energy than all the stars and galaxies in the Universe combined !

Two groups of GRBs



- Long-duration Gamma-ray Bursts:

  => HMBH Binaries

- Short Hard Gamma-ray Bursts:

  Duration time < 2 sec

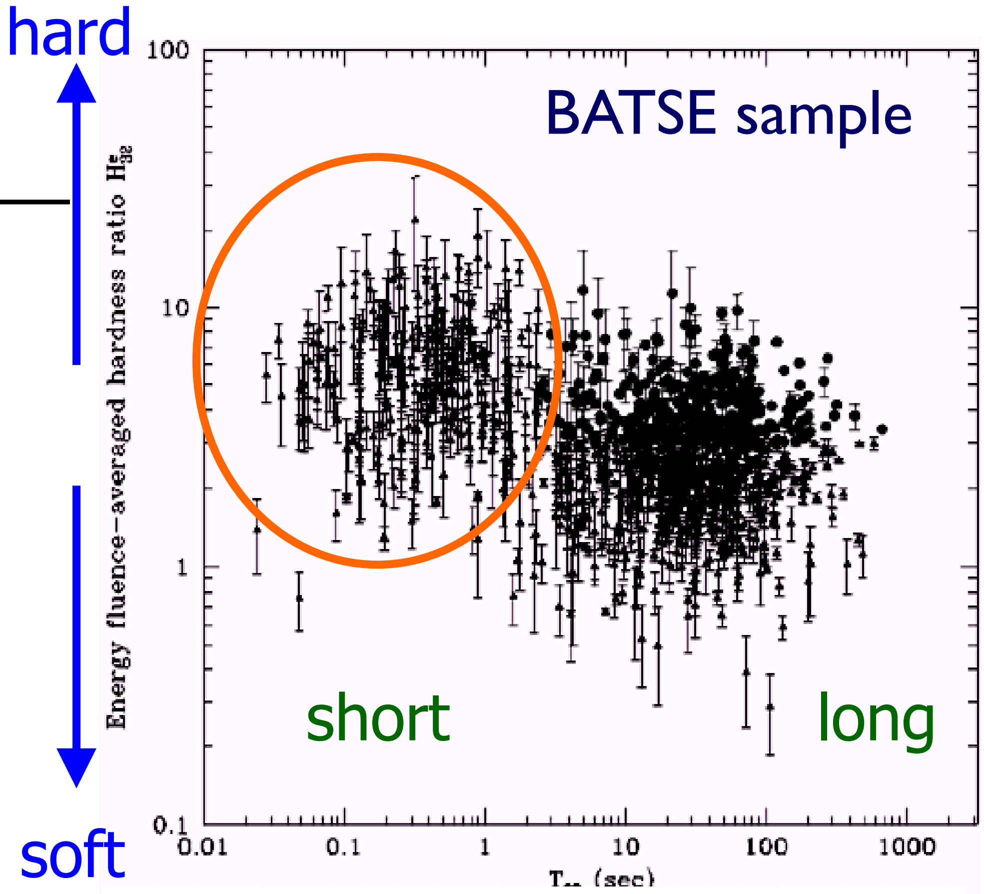
  => NS-NS, NS-BH Binaries

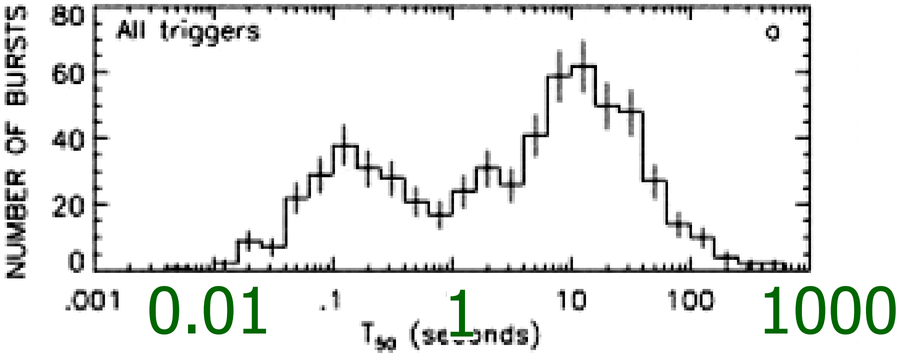
Short-hard GRBs

No optical counterpart (?)

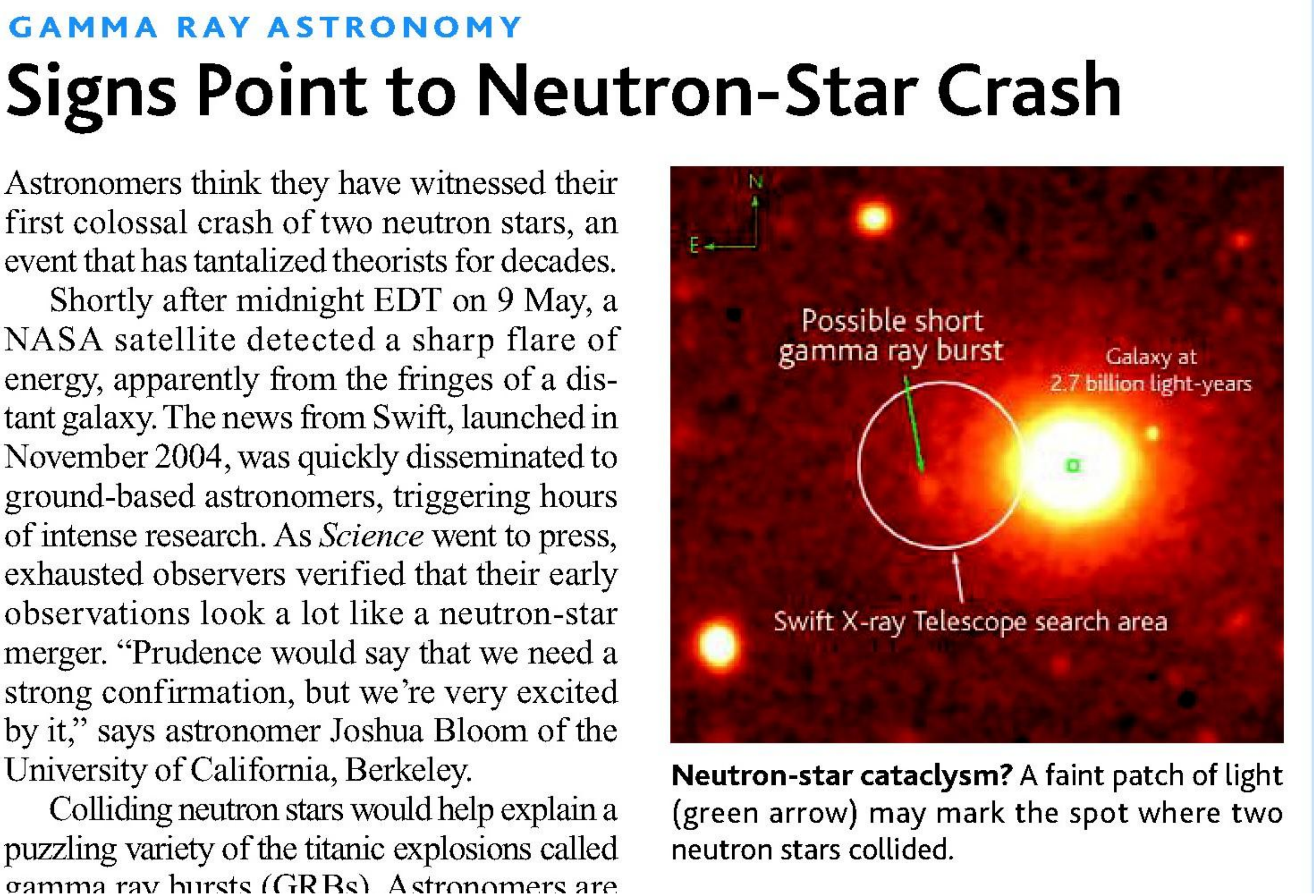
Origin

- Neutron star merger?
- Magnetar flare?
- Supernova?





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

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 !!!

Summary of Motivations

- ✓ Ultimate Testing place for physics of dense matter.
- ✓ Sources for gravitational wave detector; LIGO.
  - testing place of dynamical general relativity
- ✓ Sources for gamma ray bursts
- ✓ Possible connection to Heavy Ion Collisions

Contents

- Motivations : why Neutron Stars ?
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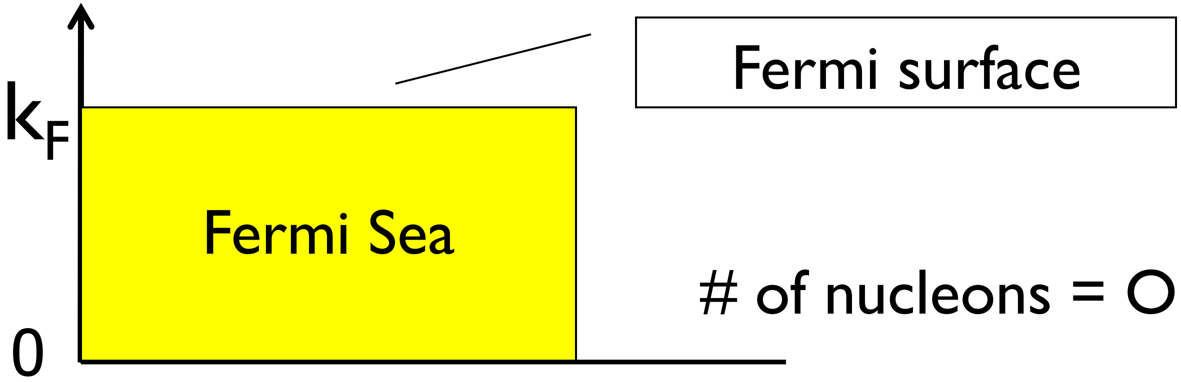
How to treat dense matter inside NS ?

- ✓ Construct Lagrangian (symmetry)
- ✓ Obtain pressure & energy density vs number density
- ✓ Solve TOV equation



# of nucleons = O(10^57)

How to construct Lagrangian ?

- ✓ All known symmetries

energy-momentum conservation,
special relativity, parity, time-reversal,
charge-conjugation, G-parity, …

- ✓ put all known (relevant) fields (particles)

proton, neutron, pion, kaon, hyperons, electron,
muon, …

- ✓ Perturbative approach is unavoidable

Dense Matter : Conventional Approach [Serot & Walecka]

$$\mathscr{L} = \bar{\psi}(i\gamma_\mu \partial^\mu - M)\psi$$

$$B = \int d^3x\, \bar{\psi}\gamma^0\psi = \int d^3x\, \psi^\dagger\psi$$

$$iG^0_{\alpha\beta}(x' - x) = i\int \frac{d^4k}{(2\pi)^4}\, G^0_{\alpha\beta}(k)e^{-ik\cdot(x'-x)}$$

Baryon propagator above the Fermi surface

holes inside Fermi sea

$$G^0_{\alpha\beta}(k) = \frac{1}{2E(k)}\left\{(\gamma_\mu K^\mu + M)_{\alpha\beta}\left[\frac{1-\theta(k_F - |\mathbf{k}|)}{k_0 - E(k) + i\varepsilon} + \frac{\theta(k_F - |\mathbf{k}|)}{k_0 - E(k) - i\varepsilon}\right] - (\gamma_\mu \tilde{K}^\mu + M)_{\alpha\beta}\left[\frac{1}{k_0 + E(k) - i\varepsilon}\right]\right\}$$

anti-baryon propagator

$$\gamma_\mu K^\mu \equiv E(k)\gamma^0 - \boldsymbol{\gamma}\cdot\mathbf{k}$$

$$\gamma_\mu \tilde{K}^\mu \equiv -E(k)\gamma^0 - \boldsymbol{\gamma}\cdot\mathbf{k}$$

Propagator

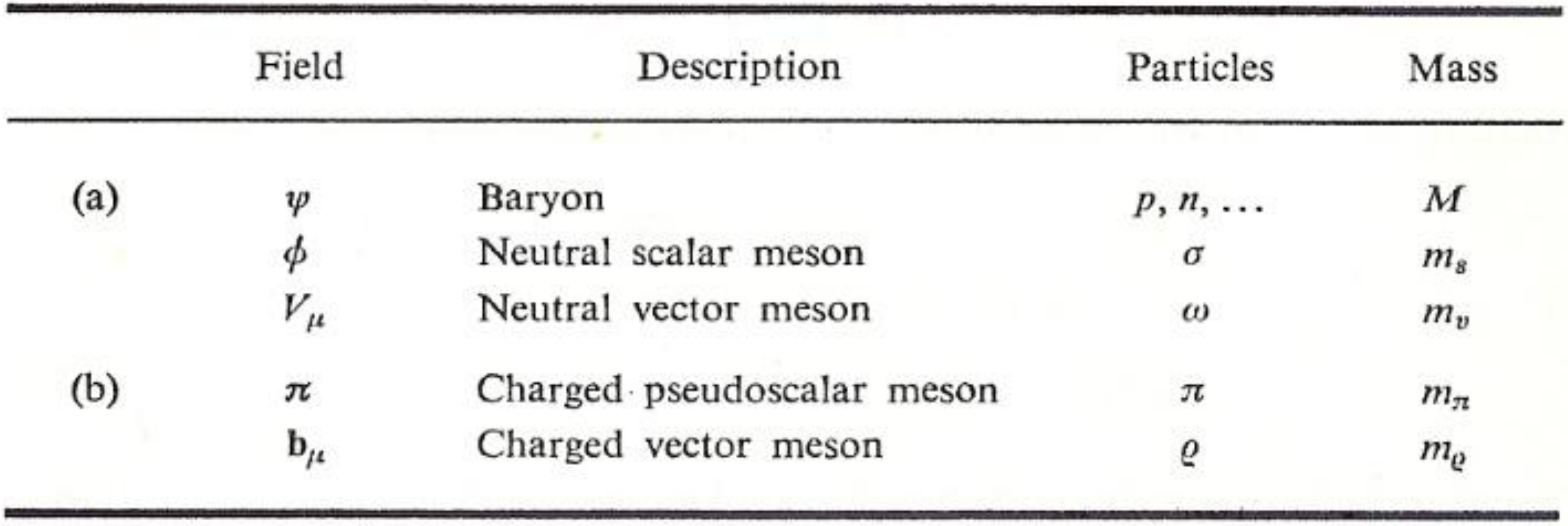
$$\not{k} \equiv \gamma^0 k^0 - \boldsymbol{\gamma} \cdot \mathbf{k}$$

$$\boxed{G^0_{\alpha\beta}(k) = (\not{k} + M)_{\alpha\beta}\left\{\frac{1}{k_\mu{}^2 - M^2 + i\varepsilon} + \frac{i\pi}{E(k)}\,\delta(k_0 - E(k))\,\theta(k_F - |\,\mathbf{k}\,|)\right\}}$$

Effect of finite density
(Pauli exclusion principle)

Free propagator of
baryons & antibaryons

Scalar-Vector Theory



	Field	Description	Particles	Mass
(a)	ψ	Baryon	$p, n, \ldots$	M
	ϕ	Neutral scalar meson	σ	m_s
	V_μ	Neutral vector meson	ω	m_v
(b)	π	Charged pseudoscalar meson	π	m_π
	$\mathbf{b}_\mu$	Charged vector meson	ϱ	m_ϱ

$$\boxed{\begin{aligned}\mathscr{L}_{\mathrm{I}} = {} & \bar{\psi}[\gamma_\mu(i\partial^\mu - g_v V^\mu) - (M - g_s\phi)]\psi + \tfrac{1}{2}(\partial_\mu\phi\partial^\mu\phi - m_s{}^2\phi^2) \\ & - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}m_v{}^2 V_\mu V^\mu + \delta\mathscr{L}\end{aligned}}$$

$$F_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu$$

Q) How to treat quantum effects in dense matter ?

- ✓ Mean field Approach:
  Quantum effects are absorbed in the coupling constants in the effective Lagrangian

  => fixed by experiments

- ✓ Hartree-Fock Approach:
  Explicit calculation with wave functions summing all diagrams (with density dependent propagator)

Mean Field Approach (scalar & vector fields)

$$\phi \to \langle \phi \rangle \equiv \phi_0$$

$$V_\mu \to \langle V_\mu \rangle \equiv \delta_{\mu 0} V_0$$

$$\phi_0 = \frac{g_s}{{m_s}^2} \langle \bar{\psi}\psi \rangle \equiv \frac{g_s}{{m_s}^2} \varrho_s$$

$$V_0 = \frac{g_v}{{m_v}^2} \langle \psi^\dagger \psi \rangle \equiv \frac{g_v}{{m_v}^2} \varrho_B$$

$$B \equiv \int_V d^3x\, B^0 = \int_V d^3x\, \psi^\dagger \psi$$

$$[i\gamma_\mu \partial^\mu - g_v \gamma^0 V_0 - (M - g_s \phi_0)]\psi = 0$$

$$M^* = M - g_s \phi_0$$

Mean Field Approach

$$\mathscr{L}_{\mathrm{MFT}} = \bar{\psi}[i\gamma_\mu\partial^\mu - g_v\gamma^0 V_0 - (M - g_s\phi_0)]\psi - \tfrac{1}{2}m_s{}^2\phi_0{}^2 + \tfrac{1}{2}m_v{}^2 V_0{}^2$$

$$\varrho_B = \frac{\gamma}{(2\pi)^3}\int_0^{k_F} d^3k = \frac{\gamma}{6\pi^2}\,k_F{}^3$$

$$\mathscr{E} = \frac{g_v{}^2}{2m_v{}^2}\varrho_B{}^2 + \frac{m_s{}^2}{2g_s{}^2}(M - M^*)^2 + \frac{\gamma}{(2\pi)^3}\int_0^{k_F} d^3k\,(\mathbf{k}^2 + M^{*2})^{1/2}$$

$$p = \frac{g_v{}^2}{2m_v{}^2}\varrho_B{}^2 - \frac{m_s{}^2}{2g_s{}^2}(M - M^*)^2 + \frac{1}{3}\,\frac{\gamma}{(2\pi)^3}\int_0^{k_F} d^3k\,\frac{\mathbf{k}^2}{(\mathbf{k}^2 + M^{*2})^{1/2}}$$

$$M^* = M - \frac{g_s{}^2}{m_s{}^2}\,\frac{\gamma}{(2\pi)^3}\int_0^{k_F} d^3k\,\frac{M^*}{(\mathbf{k}^2 + M^{*2})^{1/2}}$$

$$E_F{}^* \equiv (k_F{}^2 + M^{*2})^{1/2}$$

$$M^* = M - \frac{g_s{}^2}{m_s{}^2}\,\frac{\gamma M^*}{4\pi^2}\left[k_F E_F{}^* - M^{*2}\ln\left(\frac{k_F + E_F{}^*}{M^*}\right)\right]$$

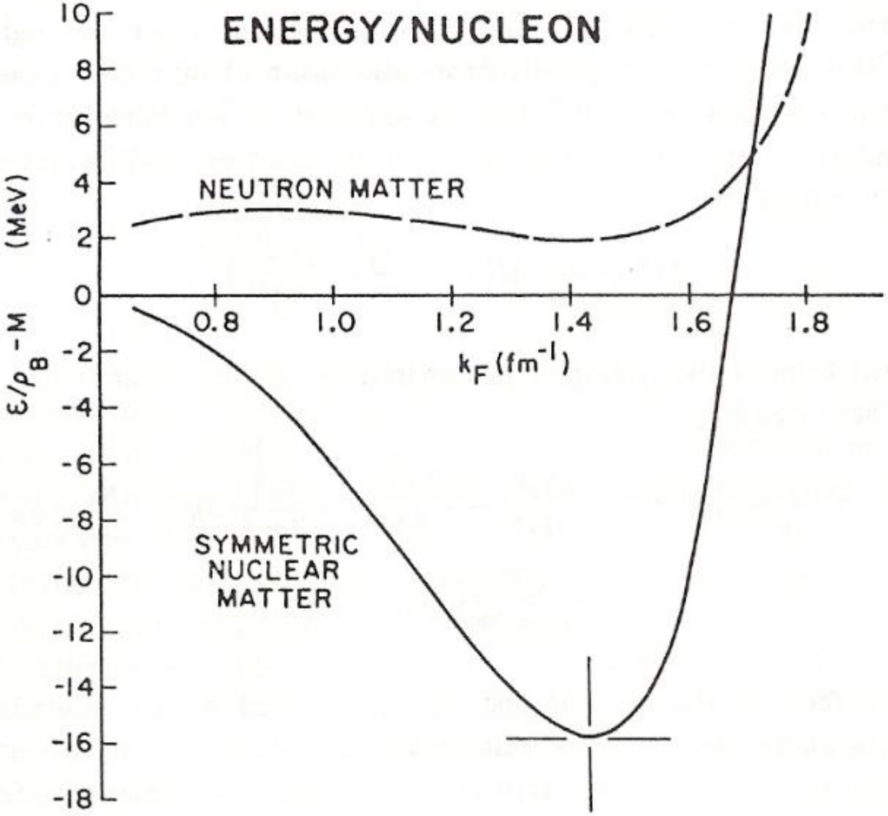
Constraints

$$\left(\frac{E - BM}{B}\right)_0 = -15.75 \text{ MeV}$$

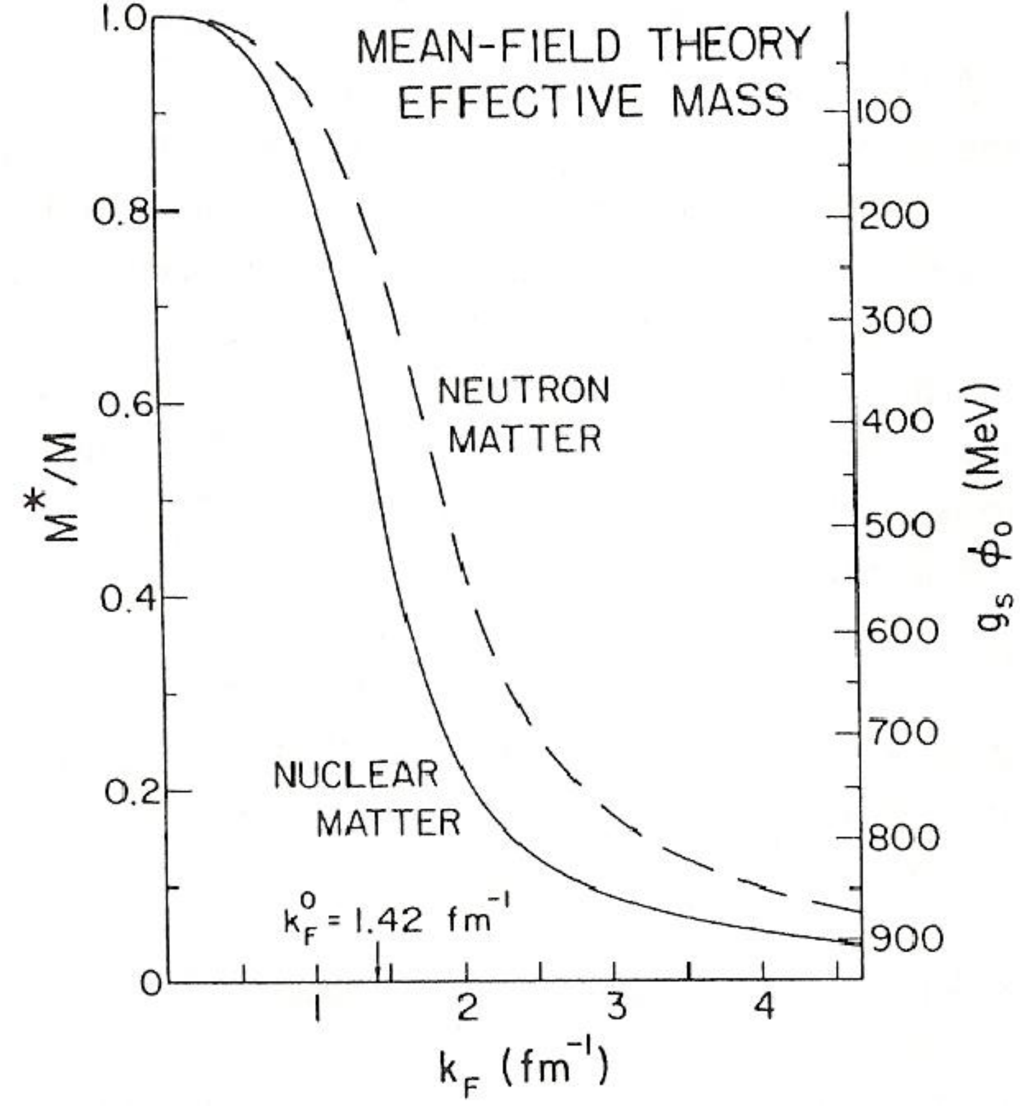
$$k_F{}^0 = 1.42 \text{ fm}^{-1}$$

$$C_s{}^2 \equiv g_s{}^2(M^2/m_s{}^2) = 267.1$$

$$C_v{}^2 \equiv g_v{}^2(M^2/m_v{}^2) = 195.9$$



Nucleon Effective Mass



There are many more realistic models for dense nucleonic matter

- ✓ Two-body potential (fitted to NN scattering)
- ✓ Three-body term (suggested by theory, fitted by few body-nuclei & nuclear matter saturation property)

But, those terms are uncertain at high density.
Especially symmetry energy is very uncertain

Symmetry Energy

C.M.Ko (A&M)

EOS of asymmetric nuclear matter

$$E(\rho,\delta) \approx E(\rho,\delta=0) + E_{\rm sym}(\rho)\delta^2, \quad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

Symmetry energy $$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{\rm sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$$

Symmetry energy coefficient $E_{\rm sym}(\rho_0) \approx 30$ MeV

Slope $L = 3\rho_0 \left.\frac{\partial E_{\rm sym}(\rho)}{\partial\rho}\right|_{\rho=\rho_0}$ theoretical values -50 to 200 MeV

Curvature $K_{\rm sym} = 9\rho_0^2 \left.\frac{\partial^2 E_{\rm sym}(\rho)}{\partial^2\rho}\right|_{\rho=\rho_0}$ theoretical values -700 to 466 MeV

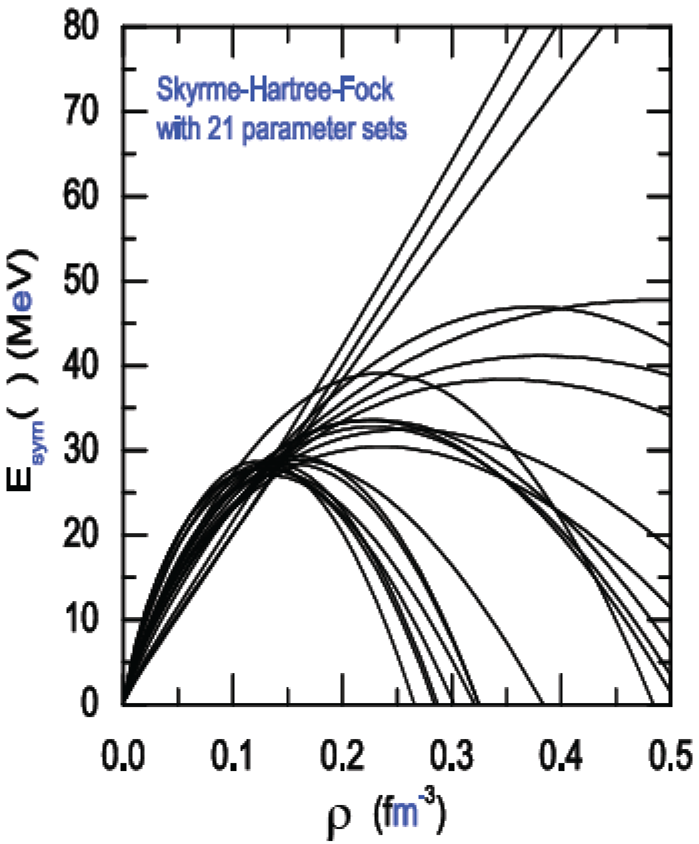
Nuclear matter Incompressibility $K(\delta) = K_0 + K_{\rm asy}\delta^2, \quad K_{\rm asy} = K_{\rm sym} - 6L$

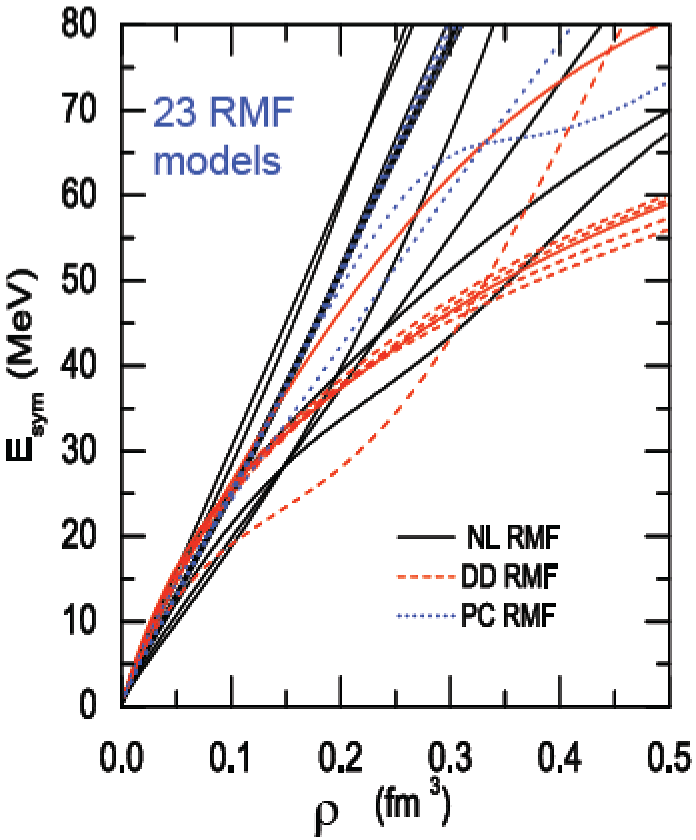
Empirically, $K_0 \sim 230 \pm 10$ MeV, $K_{\rm asy} \sim -500 \pm 50$ MeV, $L \sim 88 \pm 25$ MeV

$E_{\rm sym}(\rho) \sim 32\,(\rho/\rho_0)^\gamma$ with $0.7<\gamma<1.1$ for $\rho<1.2\rho_0$

Symmetry energy at high densities is practically undetermined !

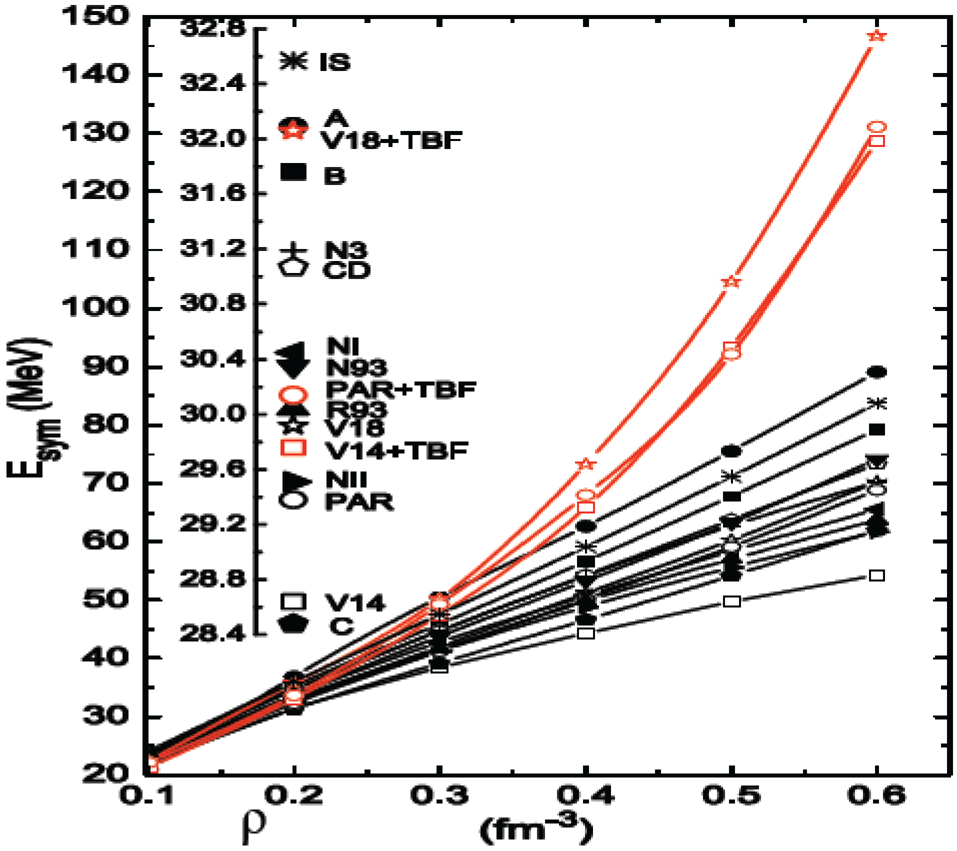
Symmetry energy from phenomenological models





Symmetry energy from Bruckner Hartree-Fock Approach

Z.H. Li et al., PRC74, 047304 (2006)



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Kaon condensation in dense matter

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 this lecture are rather independent of the details of EoS as long as they are "soft"

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 !

neutron (udd)
proton (uud)

- ✓ without electrons

Neutral kaon (d-bar,s) condensation

- ✓ with electrons

K^- (u-bar, s) condensation

quark – anti-quark attraction

Meson Exchange Model

$$\mathcal{L}_K = \partial_\mu \bar{K} \partial_\mu K - (m_K^2 - g_{\sigma K} m_K \sigma) K \bar{K} + i g_{\omega K} \omega_0 \bar{K} \overleftrightarrow{\partial}_t K$$

Kaon is interacting with baryons through the exchange of sigma & omega mesons

$$\omega_K = \left[m_K^2 + \boldsymbol{k}^2 - g_{\sigma K} m_K \sigma + (g_{\omega K} \omega_0)^2 \right]^{1/2} + g_{\omega K} \omega_0$$

$$\omega_{\bar{K}} = \left[m_K^2 + \boldsymbol{k}^2 - g_{\sigma K} m_K \sigma + (g_{\omega K} \omega_0)^2 \right]^{1/2} - g_{\omega K} \omega_0$$

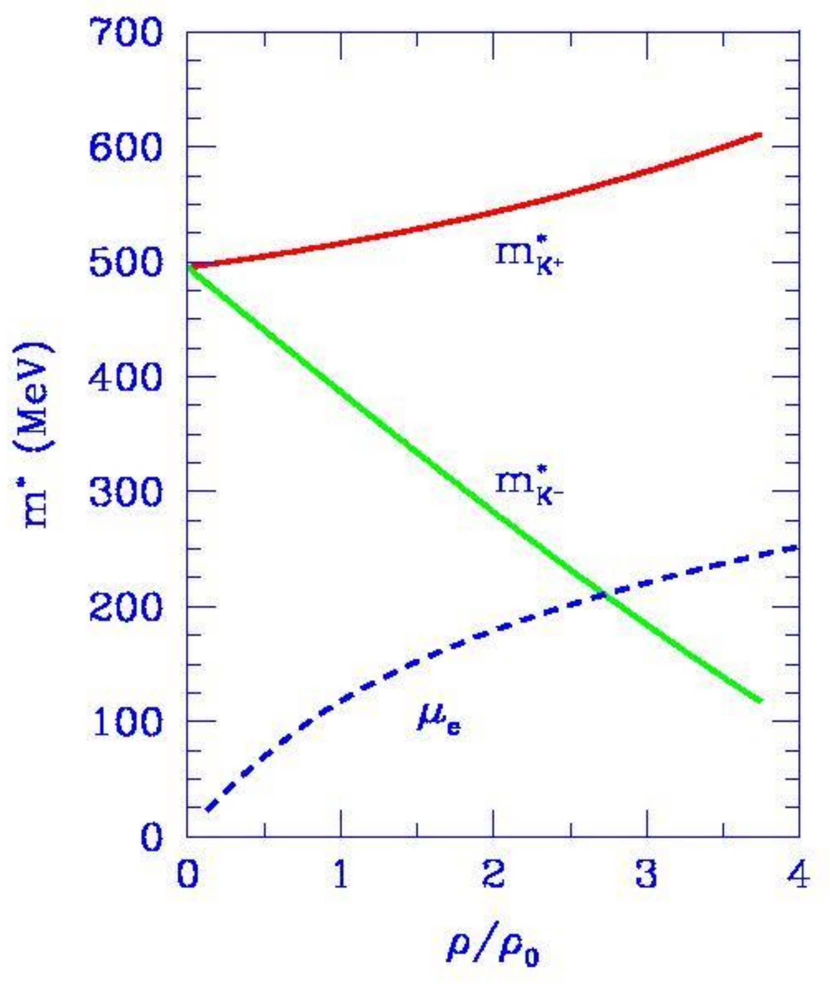
K-

Scalar & vector : both attractive

$$K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix} \quad \text{and} \quad \bar{K} = (K^- \quad \bar{K}^0)$$

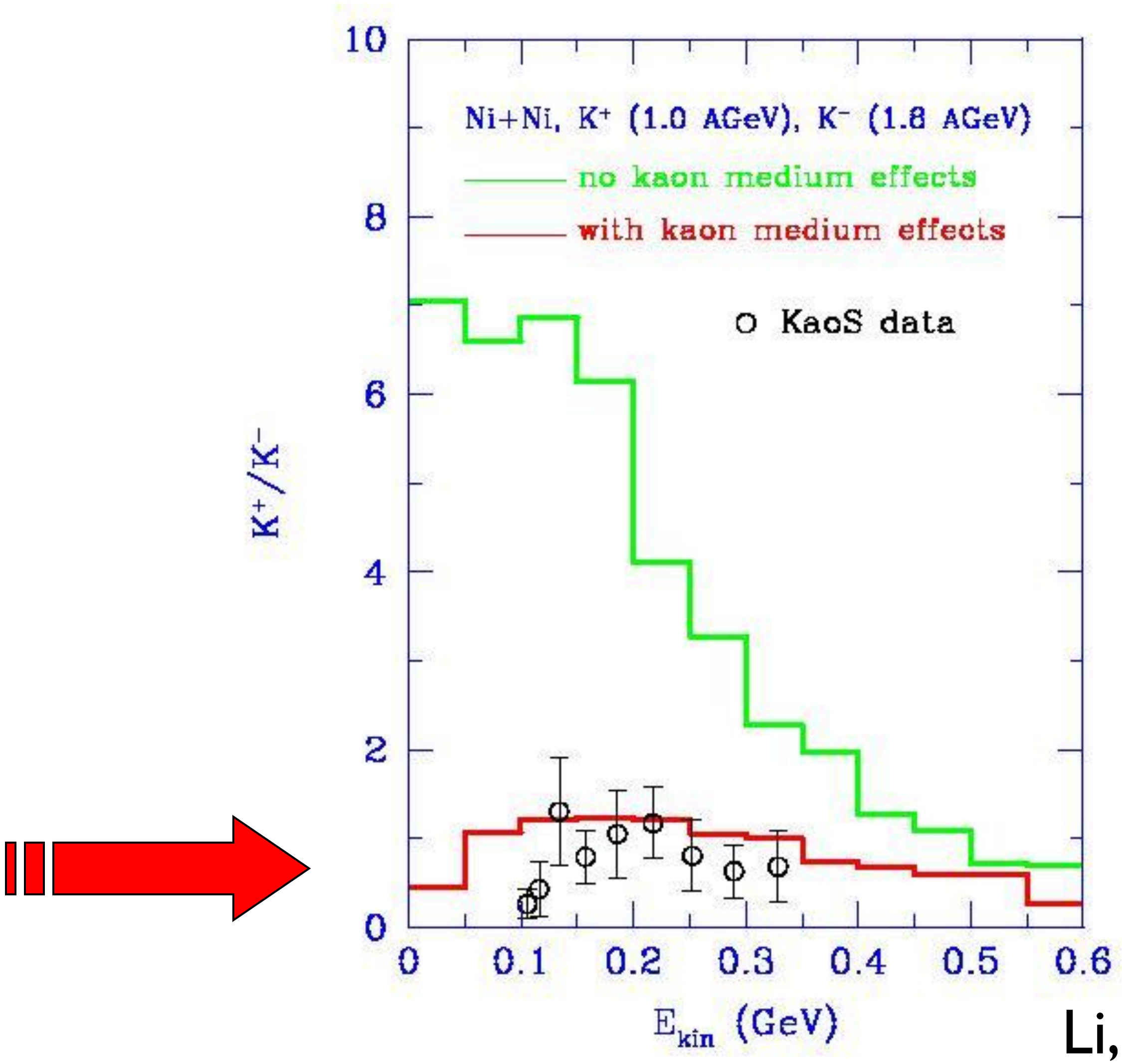
Can we test "Dropping K^- Mass" on earth ?

kaon effective chemical potential



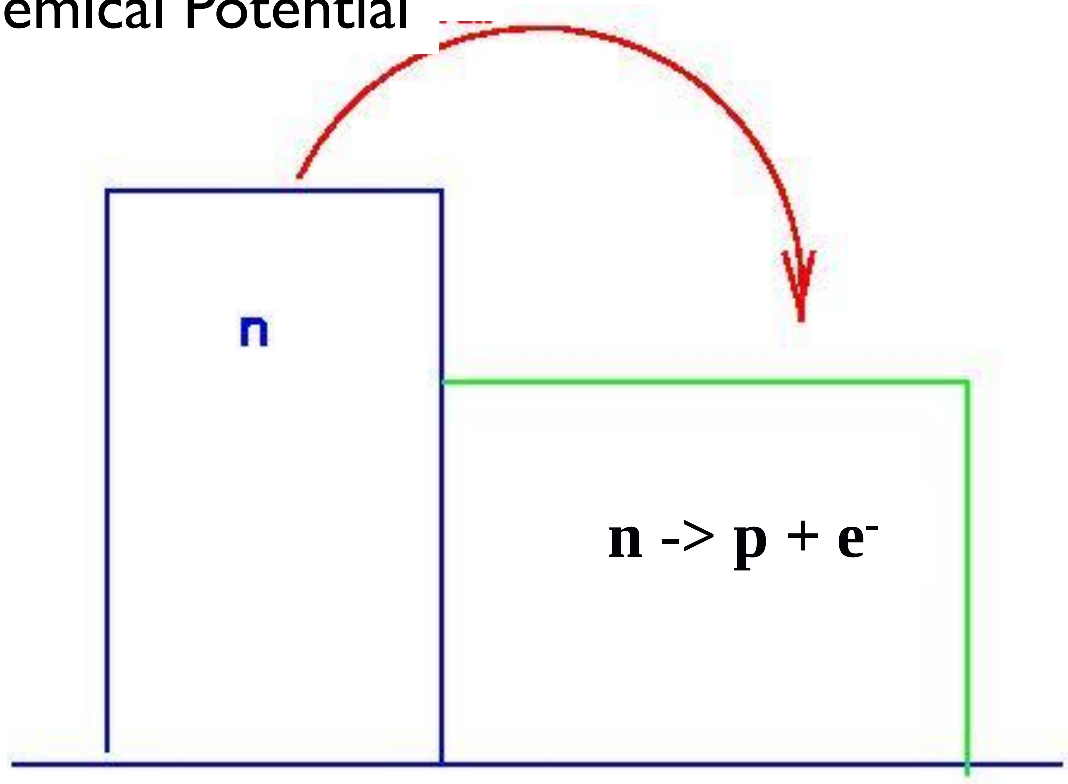
q-q repulsion
q-$\underline{q}$ attraction

Kaon Production in Heavy Ion Collision supports Dropping K^- mass !



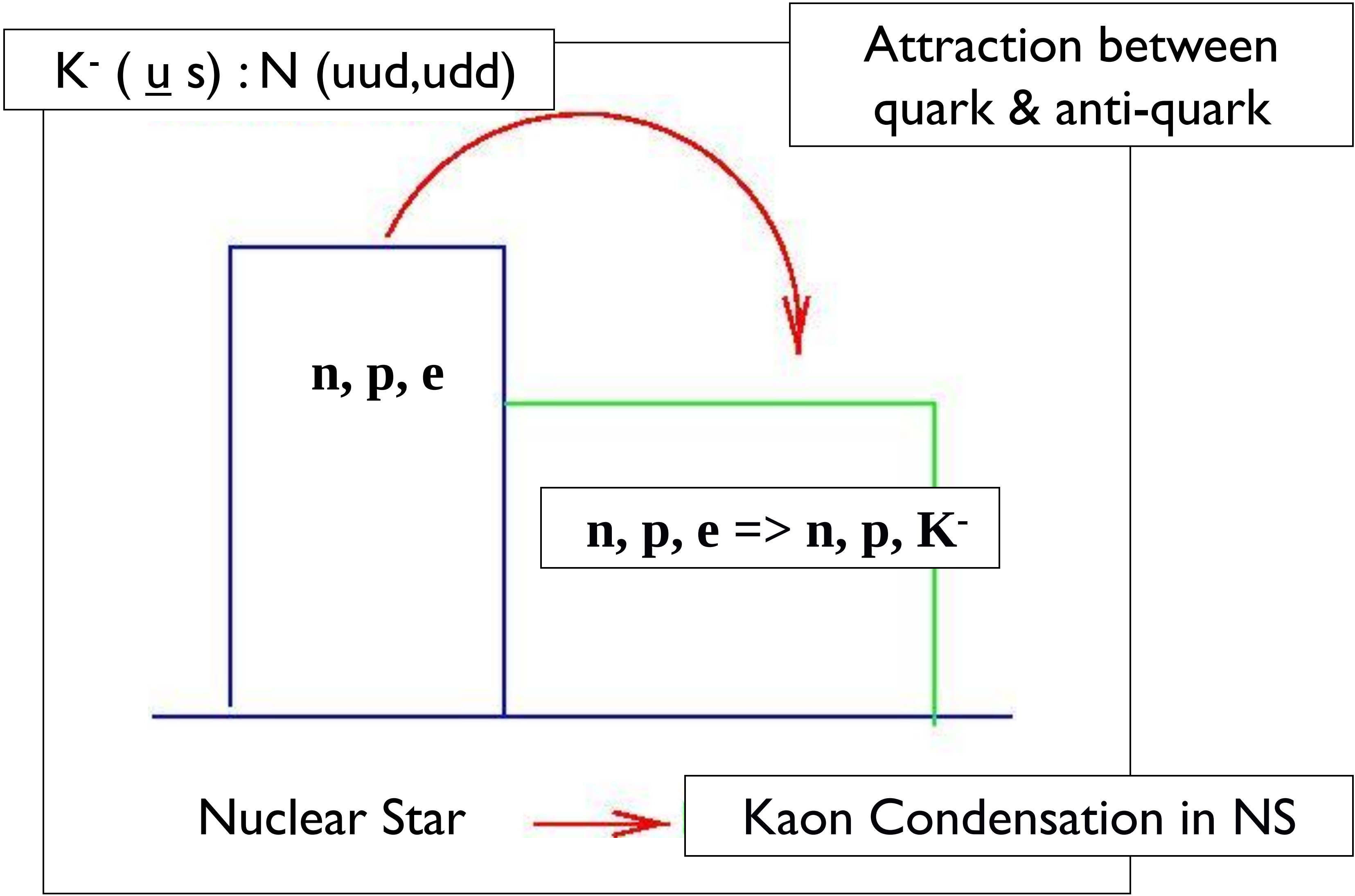
Li,Lee,Brown,PRL(1997)

Neutron Star vs Nuclear Star


Chemical Potential

Neutron Star → Nuclear Star

Kaons in Nuclear Star



K^- ($\underline{u}$ s) : N (uud,udd)

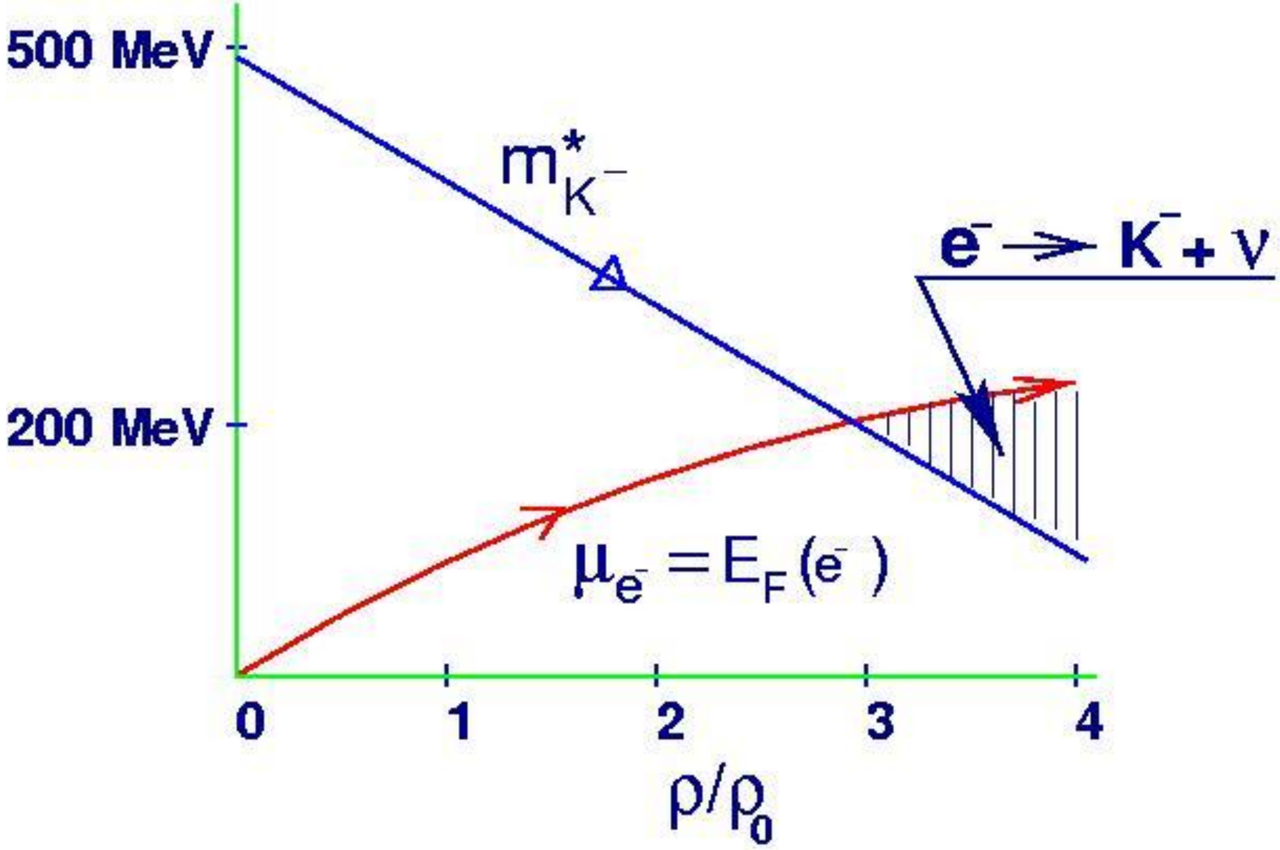
Attraction between quark & anti-quark

n, p, e

n, p, e => n, p, K^-

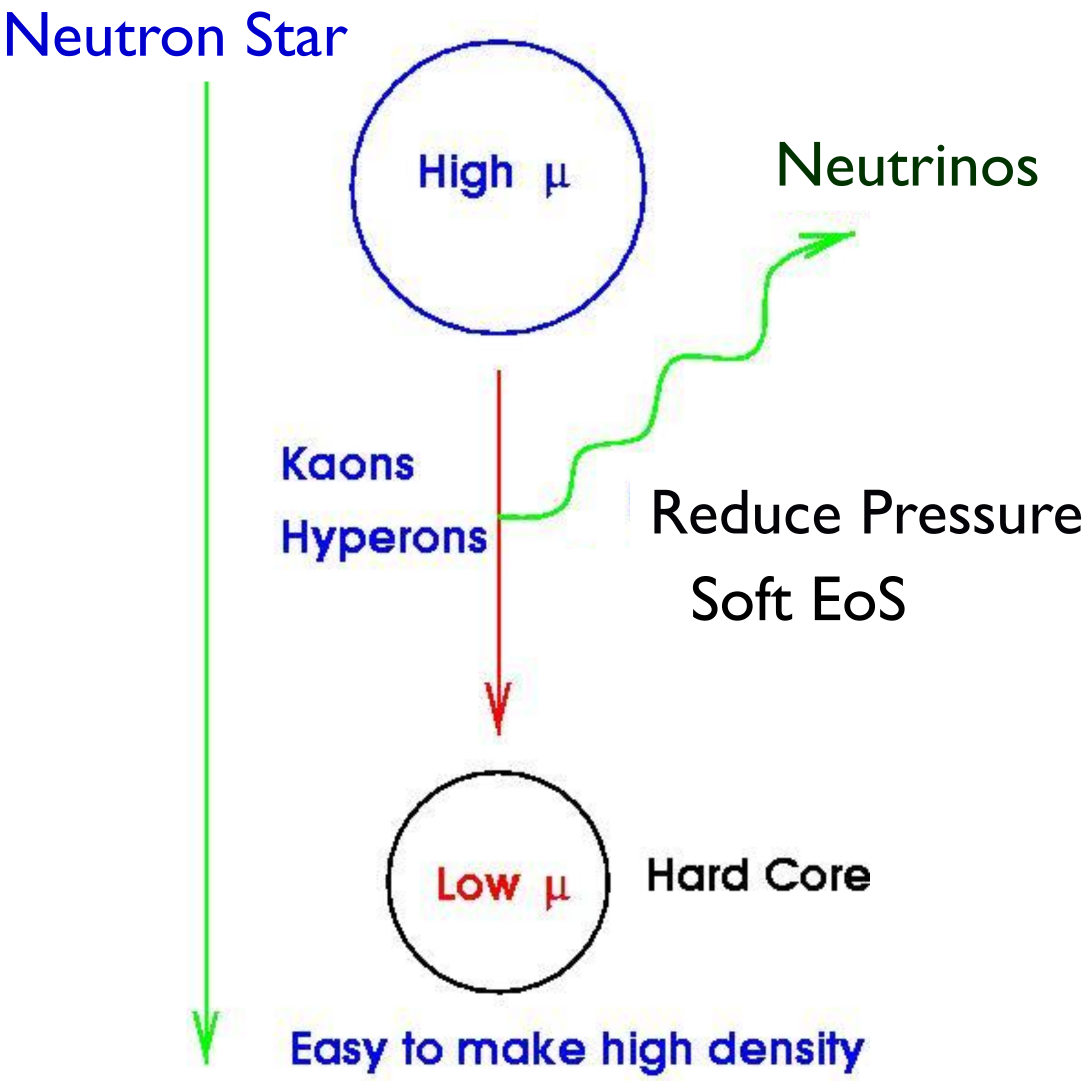
Nuclear Star → Kaon Condensation in NS

Kaon Condensation in Dense Matter



ρ_0 = nuclear matter density

Astrophysical Implications



Neutron Star

High μ

Neutrinos

Kaons

Hyperons

Reduce Pressure

Soft EoS

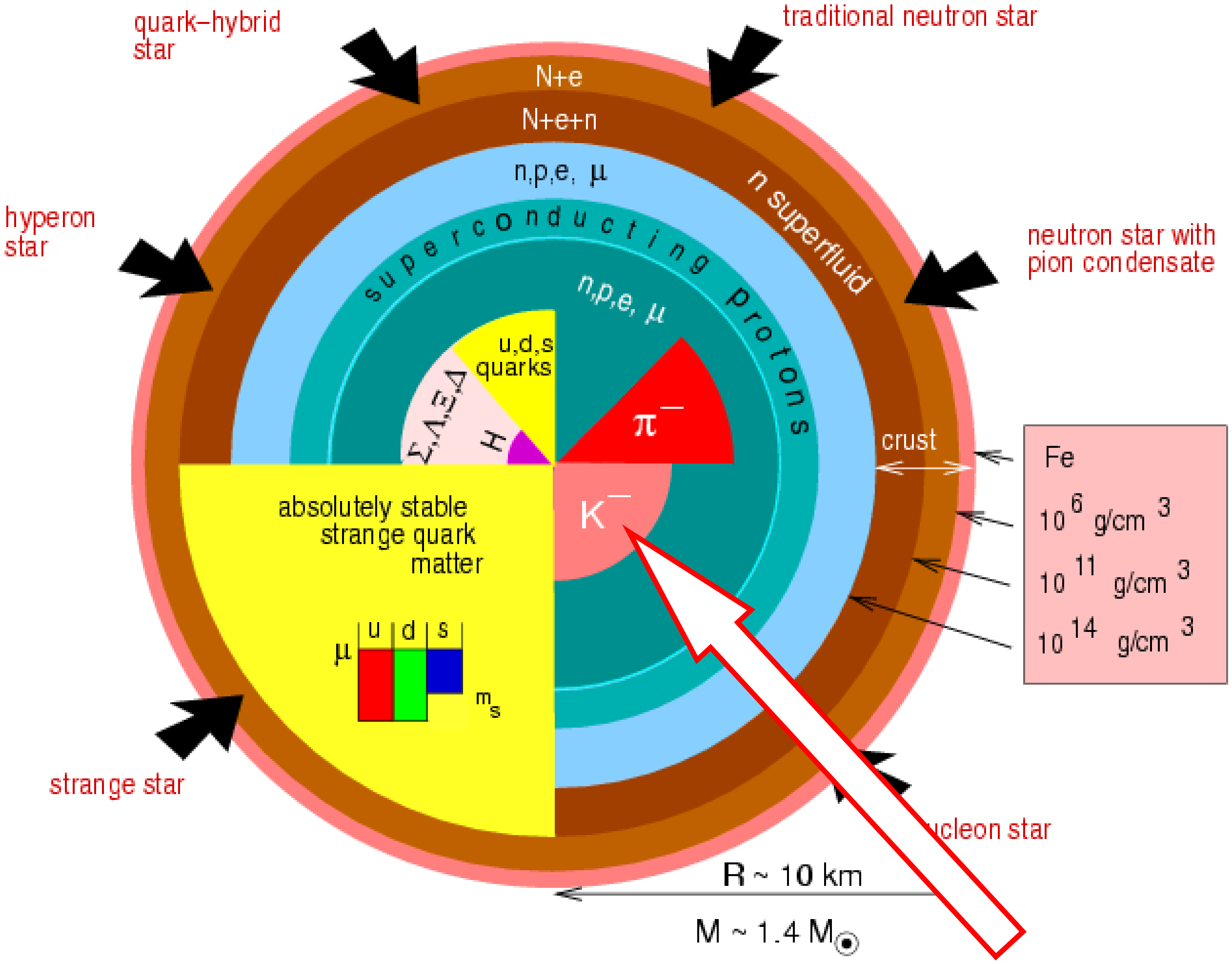
Low μ

Hard Core

Easy to make high density

Formation of low mass Black Hole

Neutron/Strange/Quark Star ?



How to describe kaon condensation ?

- ✓ Meson exchange model in mean field level is not sufficient
- ✓ Multiple-meson interactions has to be included
- ✓ Chiral Perturbation Approach is one of the systematic approaches with given symmetries!

SU(3) Chiral Perturbation Theory

$$\mathcal{L} = \tfrac{1}{4} f^2 \mathrm{Tr}\ \partial U \partial U^\dagger + \tfrac{1}{2} f^2 r \mathrm{Tr}\ [\mathcal{M}(U + U^\dagger - 2) + \mathrm{h.c}]\,.$$

$$U = \exp(\sqrt{2} i M / f)$$

$$M = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

$$\mathcal{M} = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}$$

Baryon-Meson Interaction

$$\mathcal{L} = +\mathrm{Tr}\,\bar{B}(i\not{\partial} - m_B)B + i\mathrm{Tr}\,\bar{B}\gamma^\mu[V_\mu, B]$$
$$+\mathrm{DTr}\,\bar{B}\gamma^\mu\gamma_5\{A_\mu, B\} + \mathrm{FTr}\,\bar{B}\gamma^\mu\gamma_5[A_\mu, B]$$

$$B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p^+ \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n^0 \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix}$$

$$V_\mu = \tfrac{1}{2}\left\{\xi_L^\dagger \partial_\mu \xi_L + \xi_R^\dagger \partial_\mu \xi_R\right\}$$

$$A_\mu = \tfrac{1}{2} i\left\{\xi_L^\dagger \partial_\mu \xi_L - \xi_R^\dagger \partial_\mu \xi_R\right\}$$

$$U(\phi) \equiv \xi_L(\phi)\xi_R^\dagger(\phi)$$

How to obtain EOS (equation of state) ?

- Construct Lagrangian based on symmetries
- Mean field approximation (locally uniform matter)
- momentum-eigenstates are good quantum states.
  - particles are not local
  - collective excitations (e.g. superconductivity)
- Obtain pressure/energy-density vs density: p(r),e(r)
- TOV equation : with given central density

Condensed Kaon Fields

$$\langle K^- \rangle = v_K e^{-i\mu t} \qquad \theta \simeq \frac{\sqrt{2} v_K}{f} \qquad x = \rho_p / \rho$$

$$\boxed{\begin{aligned}\varepsilon_K = & -f^2 \frac{\mu^2}{2} \sin^2\theta + 2 m_K^2 f^2 \sin^2\frac{\theta}{2} + \mu x \rho \\ & -\mu(1+x)\rho \sin^2\frac{\theta}{2} - 2 f^2 a_{\bar{K}} \rho \sin^2\frac{\theta}{2},\end{aligned}}$$

$$n_K = -\frac{1}{V}\frac{\partial \Omega_{\rm tot}}{\partial \mu} = f^2(\mu \sin^2\theta + 4b \sin^2\tfrac{1}{2}\theta)$$

$$b = \sum_B (Y_B + q_B) n_B / (4f^2)$$

Y : baryon hyper-charge
q : baryon e-charge

Charge Neutrality (Theomodynamic Potential)

$$\Omega = \varepsilon_N + \varepsilon_{K^-} + \varepsilon_L - \mu(\rho_p - \rho_{K^-} - \rho_e - \rho_\mu)$$

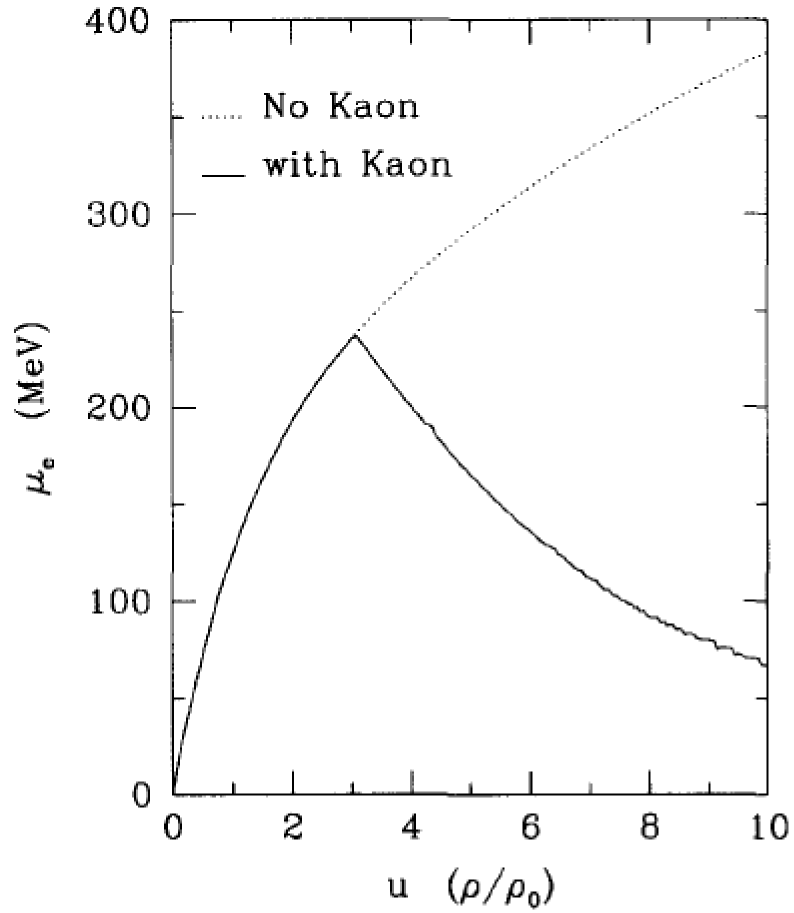
$$\boxed{\mu = \mu_n - \mu_p = \mu_e = \mu_\mu = \mu_{K^-}}$$

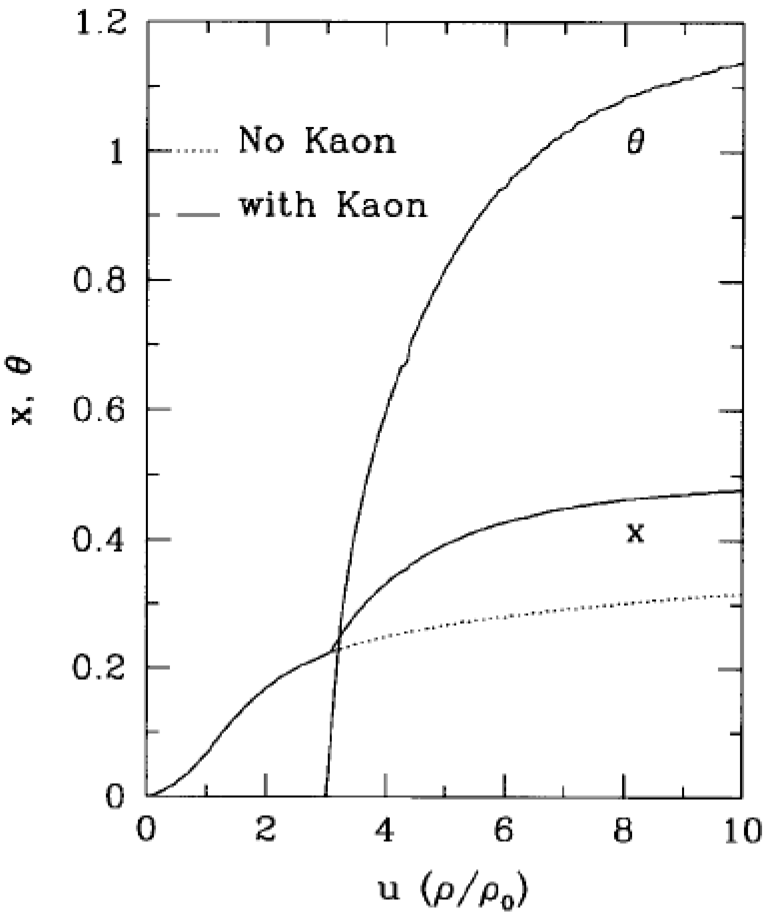
$$\varepsilon_L = \varepsilon_e + \eta(\mu - m_\mu)\varepsilon_\mu$$

$$\varepsilon_e = \frac{\mu^4}{4\pi^2} \qquad \varepsilon_\mu = \frac{m_\mu^4}{8\pi^2}\left[t(1+2t^2)\sqrt{1+t^2} - \ln(t + \sqrt{1+t^2})\right]$$

$t = \frac{k_{F_\mu}}{m_\mu}$, and $k_{F_\mu}^2 = \mu^2 - m_\mu^2$

Comparison of EOS with/without kaon





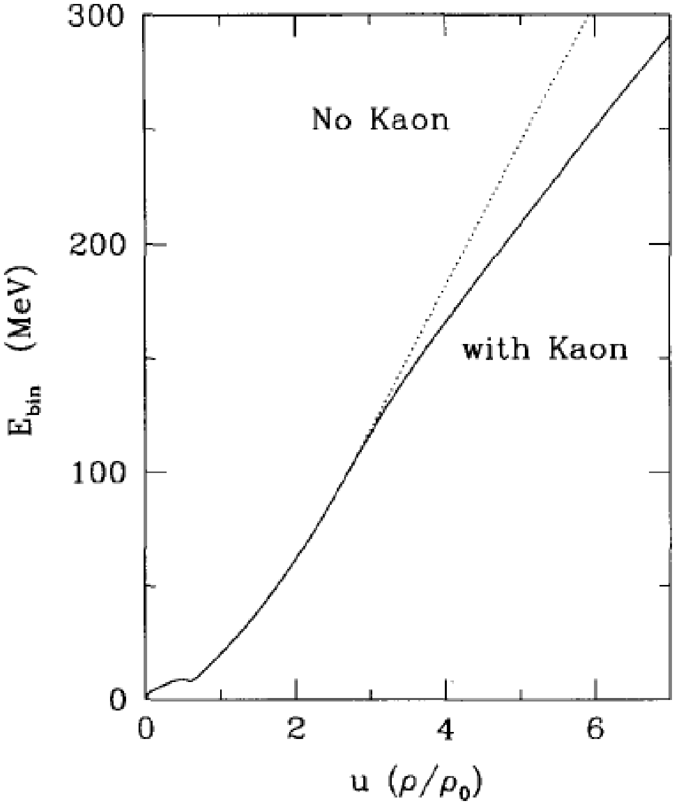
TOV equation

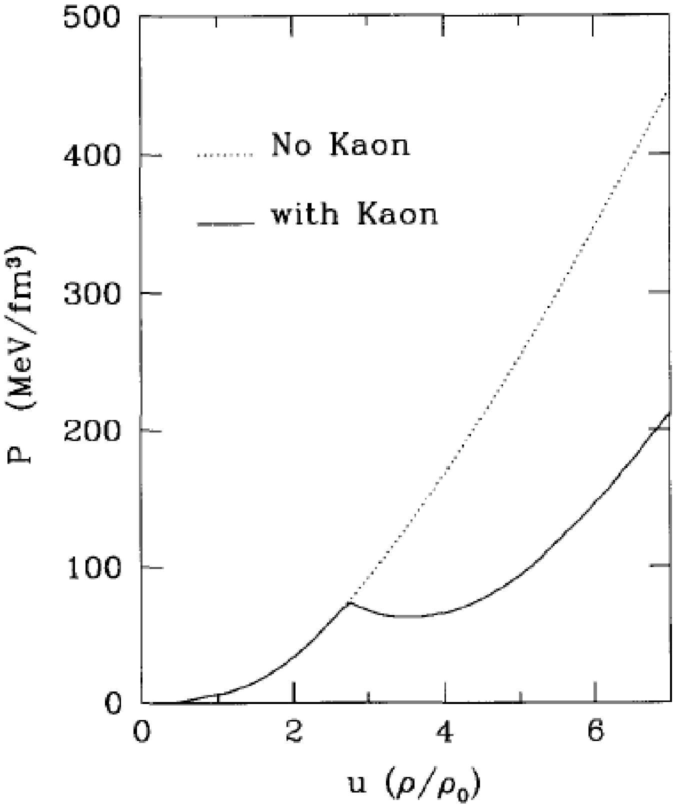
$$\frac{dm}{dr} = 4\pi r^2 \rho,$$

$$\frac{dP}{dr} = -\frac{\rho m}{r^2}\left(1 + \frac{P}{\rho}\right)\left(1 + \frac{4\pi P r^3}{m}\right)\left(1 - \frac{2m}{r}\right)^{-1},$$

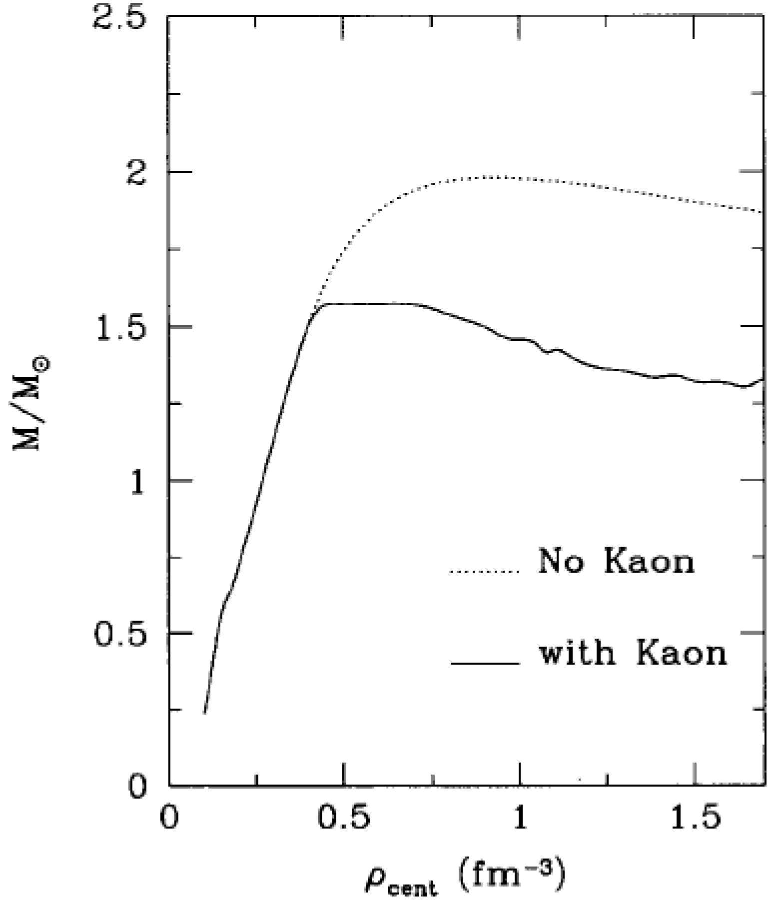
$$\frac{d\Phi}{dr} = -\frac{1}{\rho}\frac{dP}{dr}\left(1 + \frac{P}{\rho}\right)^{-1}.$$

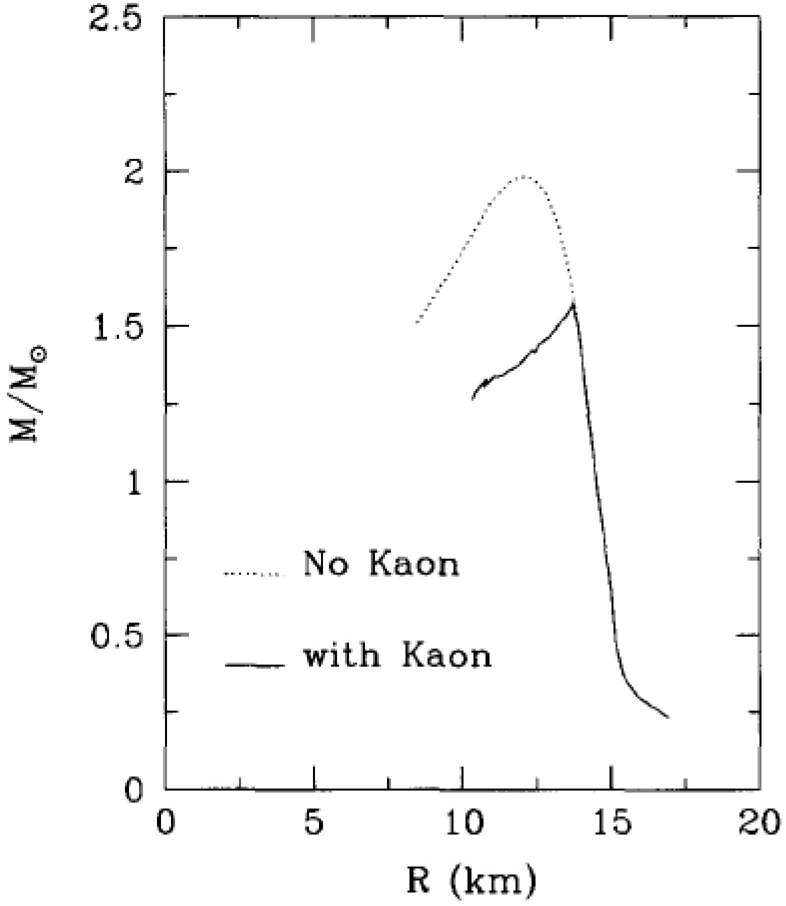
$$P = \rho^2 \left(\frac{\partial(\varepsilon/\rho)}{\partial \rho} \right)$$



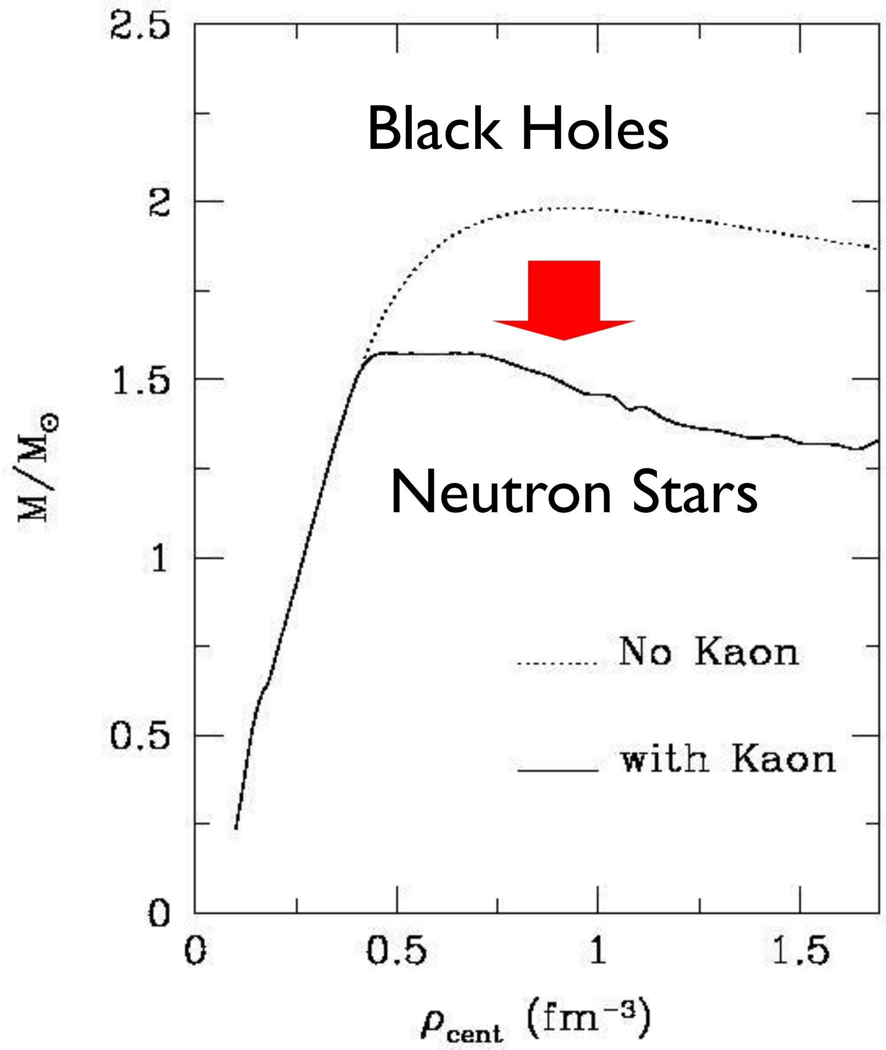


Cold neutron star : an example





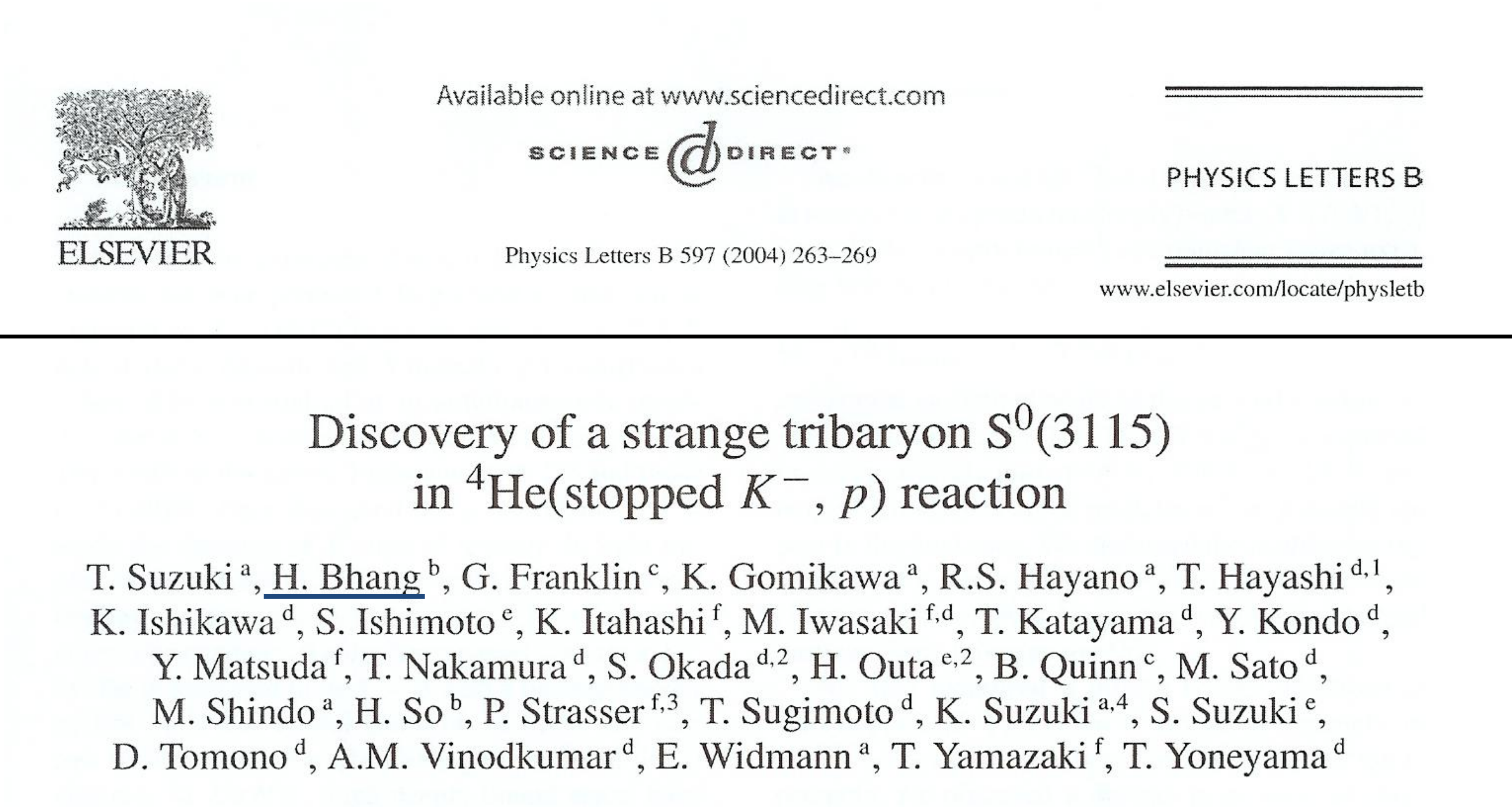
Role of kaon condensation



Kaonic Nuclear Bound States

Is kaon-nuclear attraction is strong enough to trigger kaon condensation ?

Yamazaki et al.



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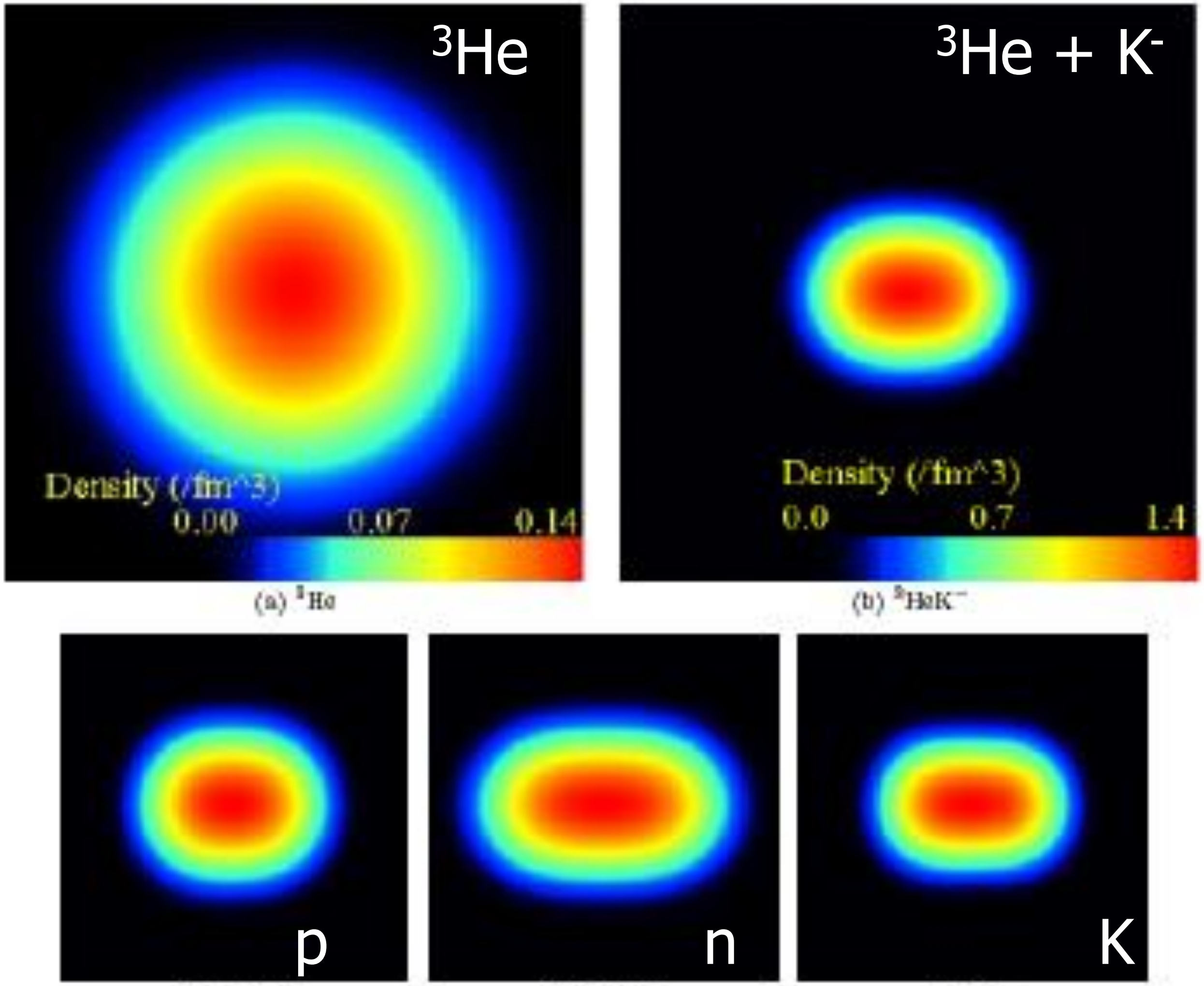
Discovery of a strange tribaryon $S^0(3115)$ in ^{4}He(stopped K^-, p) reaction

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



(a) ^{3}He (b) ^{3}HeK$^-$

(c) Proton (d) Neutron (e) K$^-$

FIG. 1: Calculated density contours of ppnK$^-$. Comparison between (a) usual ^{3}He and (b) ^{3}HeK$^-$ 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.

Dote et al.

Kaonic Nuclei - Mini Strange Star

Very strong K^--p attraction

- ✓ deep discrete bound states:
  with binding energy ~ 100 MeV
- ✓ Strong in-medium KN interactions.
- ✓ Precursor to kaon condensation.

What is critical density for kaon condensation ?

Kaon Condensation `a la Vector Manifestation

- ✓ Conventional approach (bottom-up):
  - from zero density to higher density
- ✓ Top-down approaches :
  - from fixed point (high density) to lower density
  - possibility in AdS/CFT

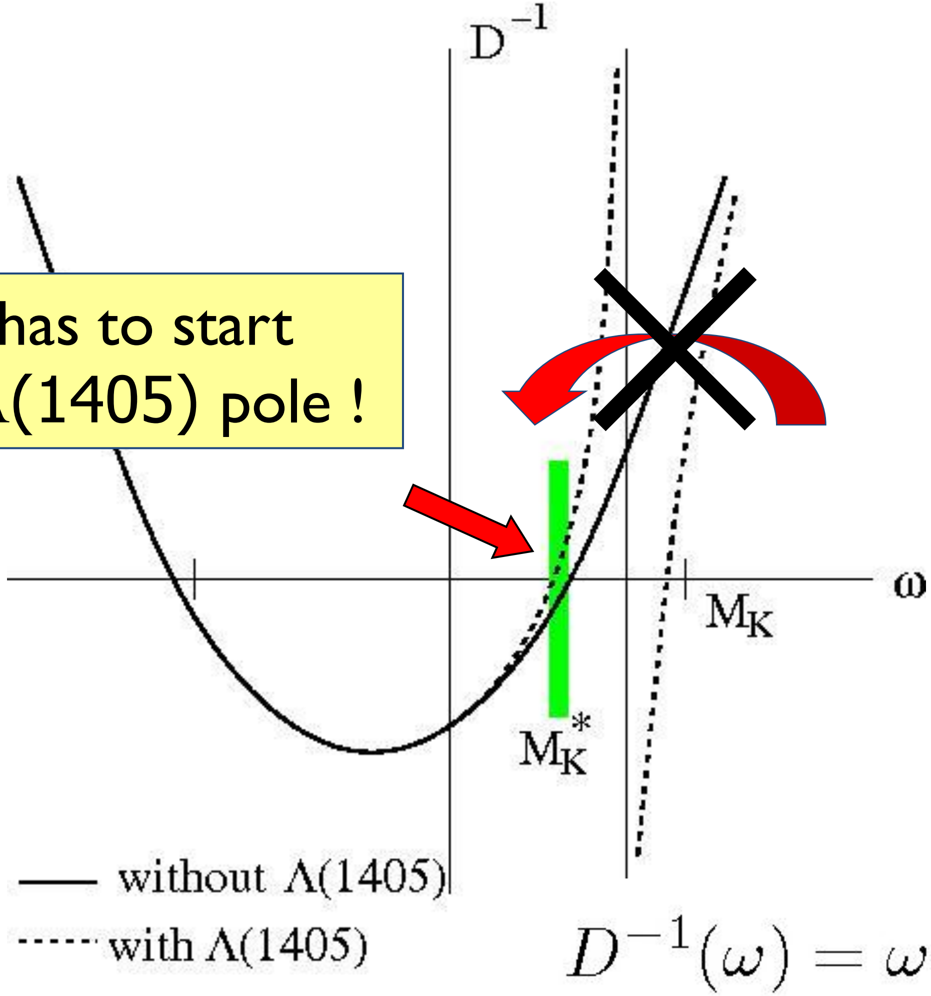
Problems in bottom-up approach

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

- ✓ Problem of L(1405)
  pole position of L(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 !

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

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

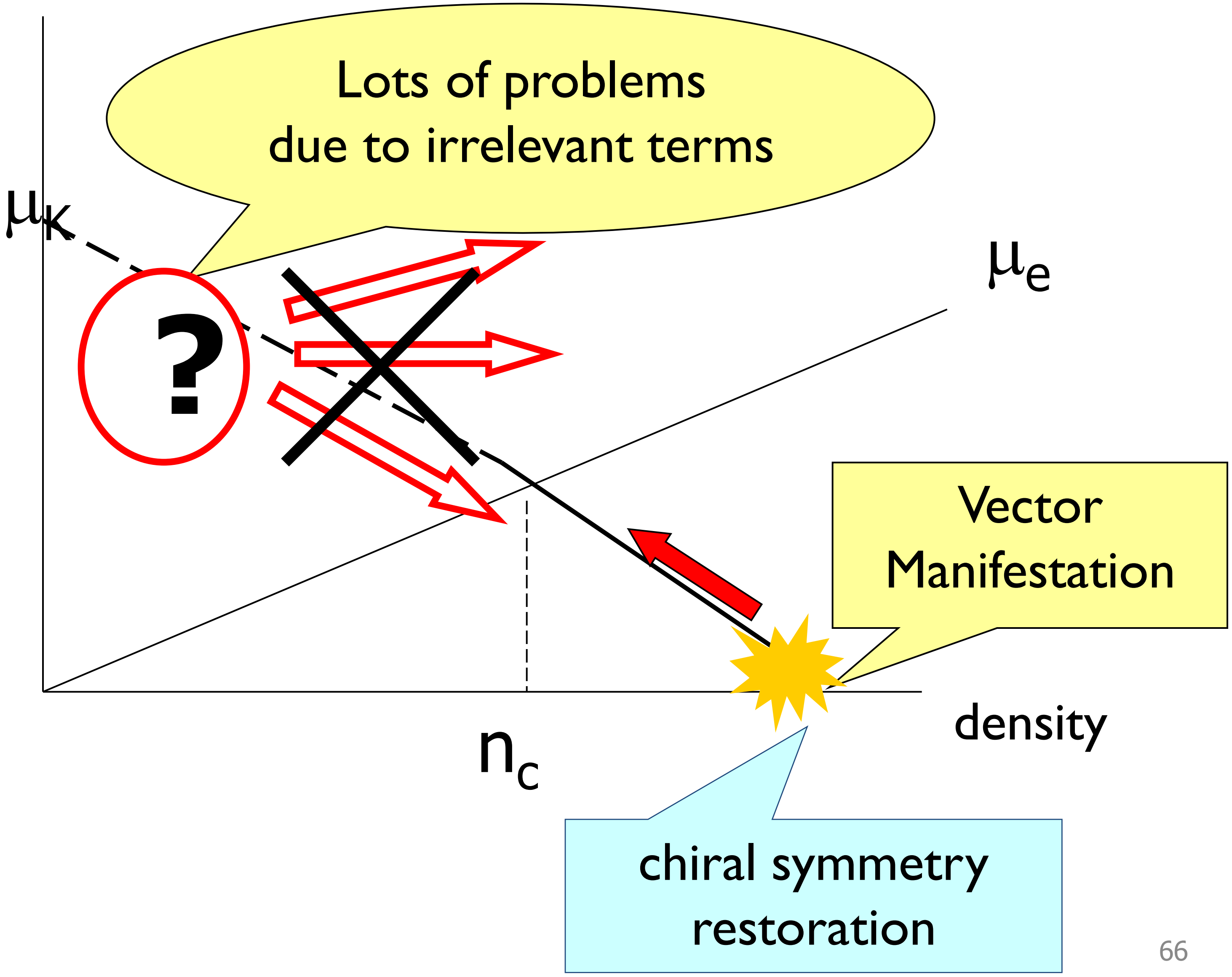
An example of Top-down approaches

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 ?

Kaon Condensation `a la HY Vector Manifestation

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

Kaon condensation from fixed point



Lots of problems
due to irrelevant terms

Vector
Manifestation

chiral symmetry
restoration

A Hybrid-Approach: Weinberg-Tomozawa term

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

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

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

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

BR scaling is needed !

$$\boxed{F_\pi \to f_\pi^\star \approx 0.8 F_\pi}$$

Deeply bound pionic atoms [Suzuki et al.]

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

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

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

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

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

Enhancement at fixed point due to BR & VM

Fixed point of chiral symmetry restoration

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

ρ–mass drops to zero around 4 n_0

Brown/Rho [PR 396 (2004) 1]

Kaon potential at critical density without BR & VM

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

10% p, n_c=3.1 n_0

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

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

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 !

Simple extrapolation from fixed point (maybe too simple)

$a^* (4n_0) = 1 \longrightarrow a^* (3n_0) = 4/3$

Value at the matching scale

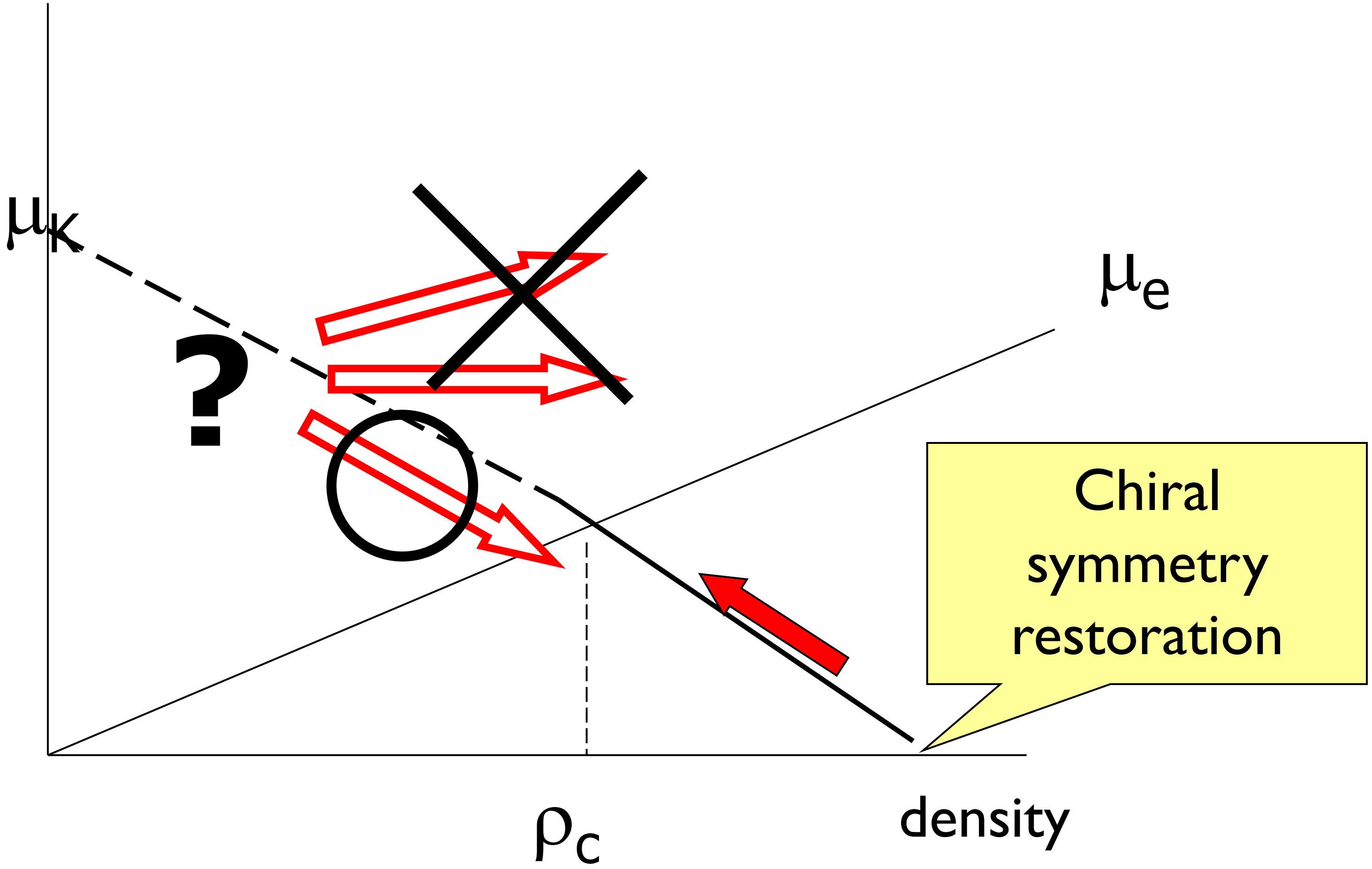
$\Lambda_M = 1.1$ GeV

$$\boxed{m_K^*(3n_0) = a^* m_K/4 = 165 \text{ MeV}}$$

Essence of kaon condensation

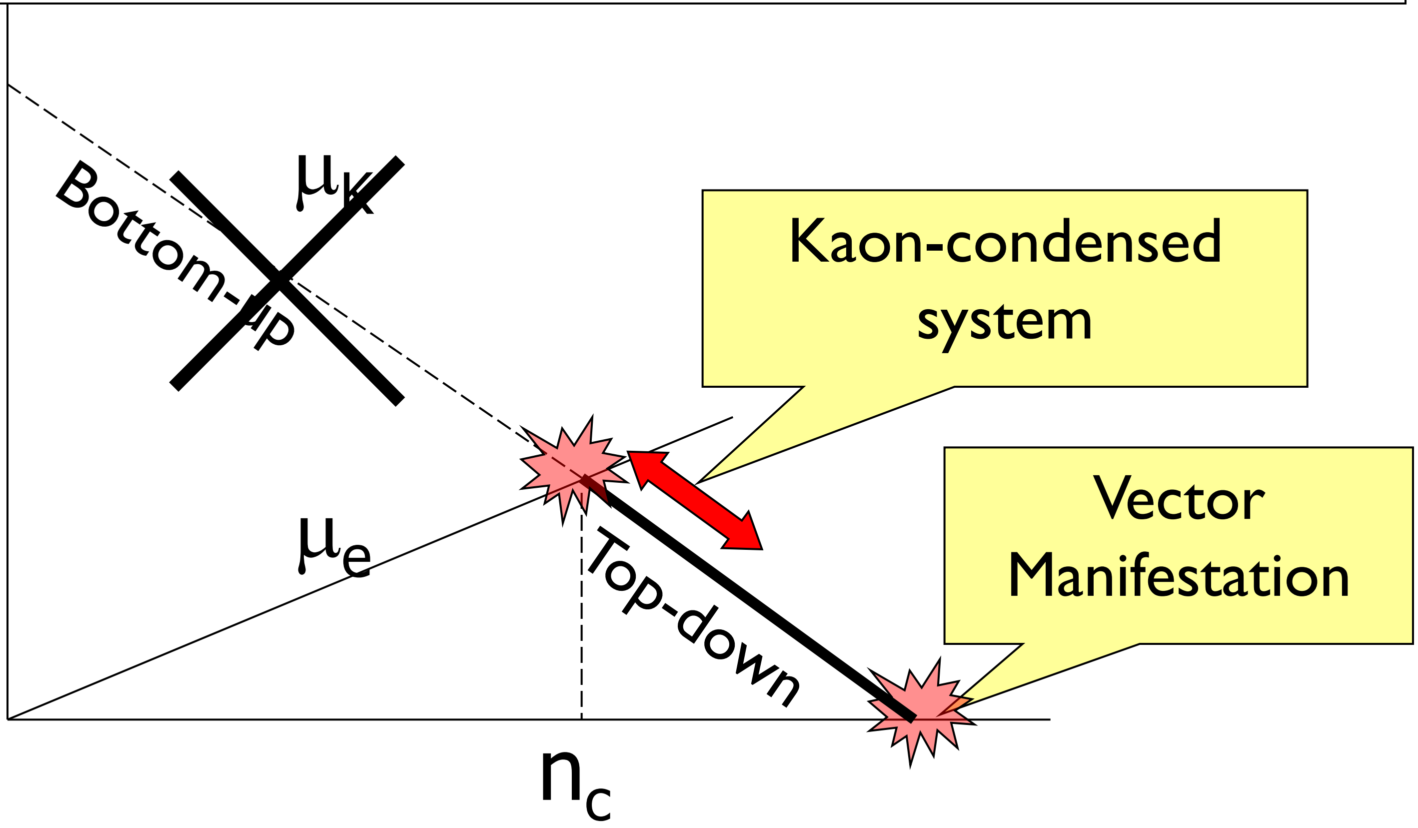
Fixed-point approach gives
the essential part of kaon condensation

Kaon condensation from fixed point approach



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 !



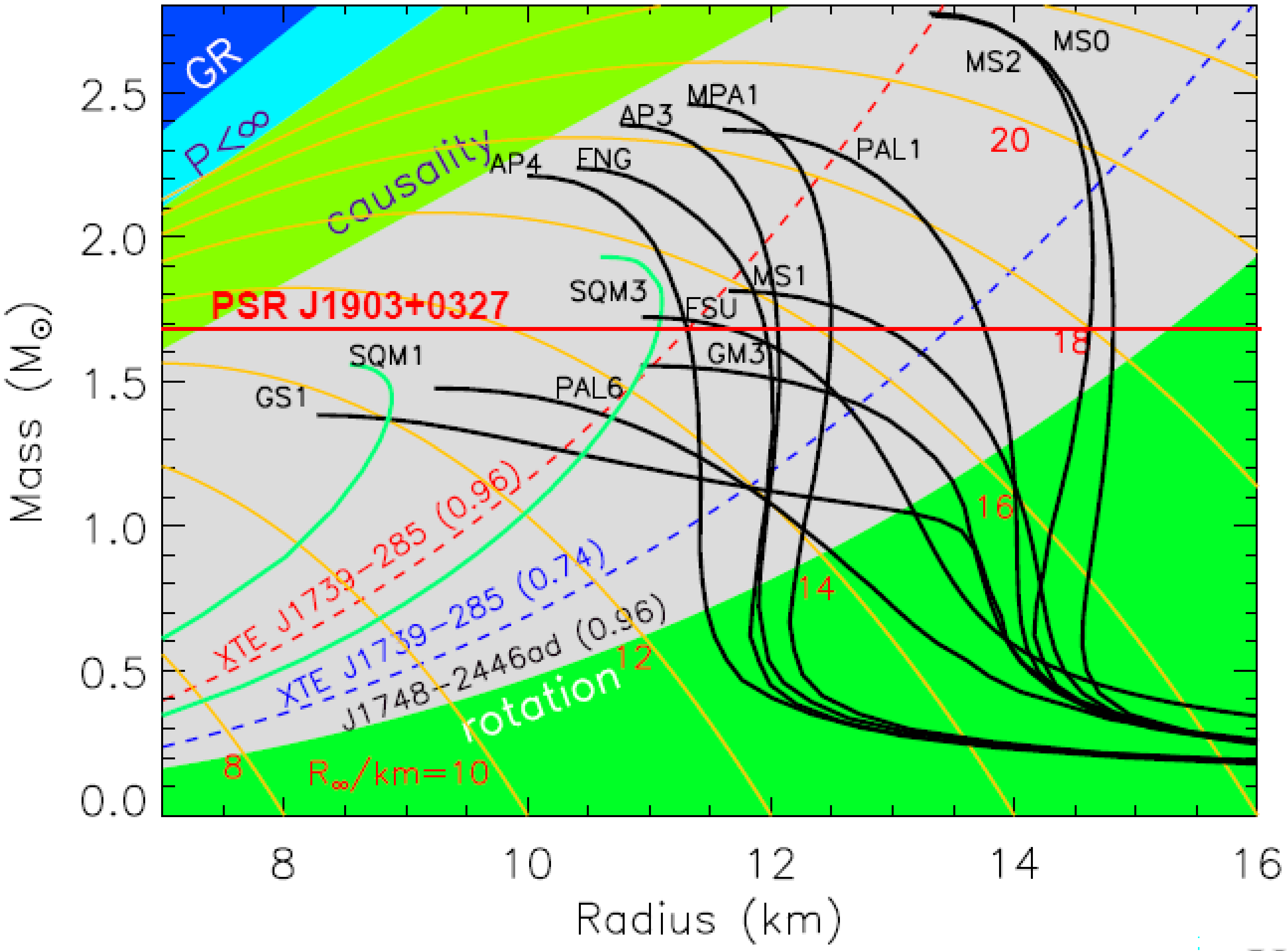
Kaon-condensed system

Vector Manifestation

After kaon condensation, the system will follow the line guided by fixed-point analysis

Open Question:

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



arXiv:0907.3219v1

Contents

- Motivations : why Neutron Stars ?
- Kaon Condensation & Issues in Hadronic Physics
- Observations & Astrophysical Issues

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]

Nature 467, 1081 (Oct. 28, 2010)

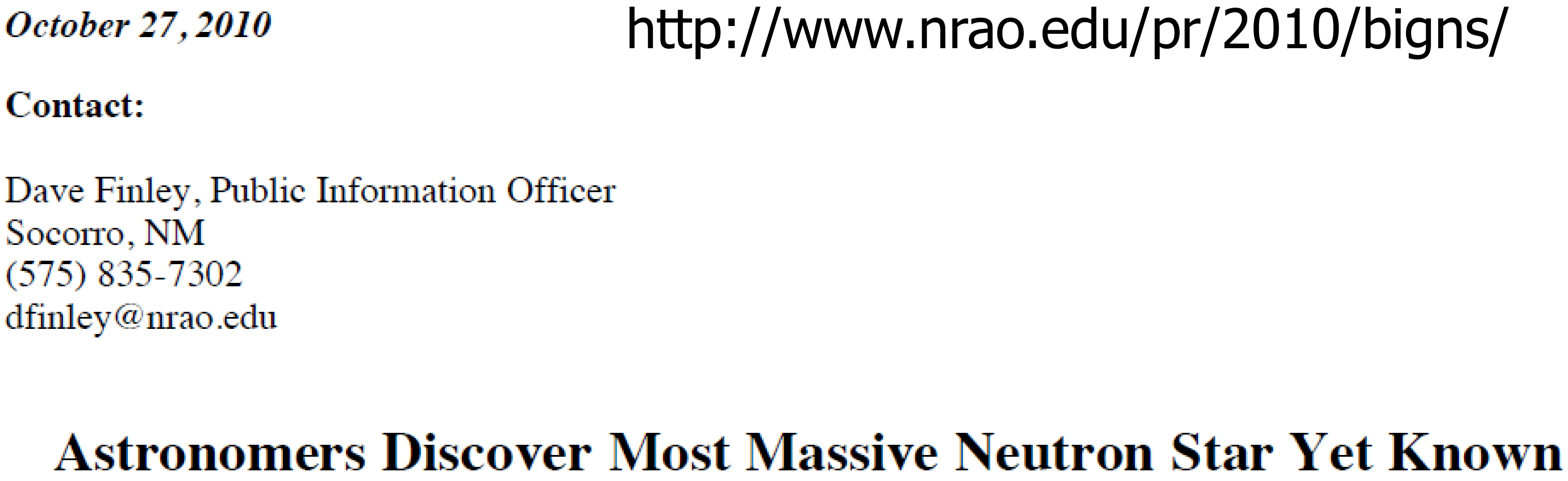
PSR J1614-2230

(Millisecond Pulsas & White Dwarf Binary)

1.97 ± 0.04 Msun

(measurement based on Shapiro delay)

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



October 27, 2010

Contact:

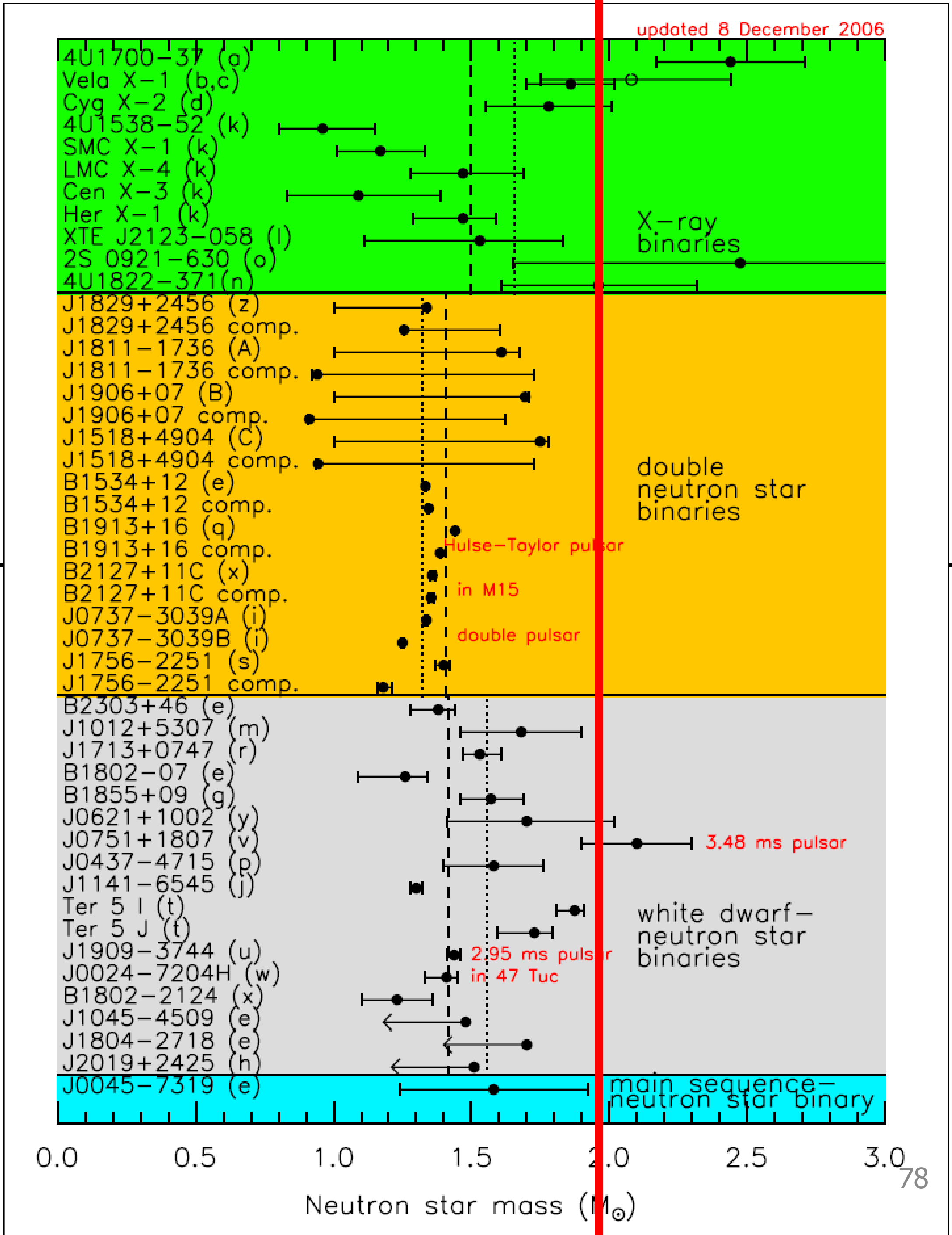
Dave Finley, Public Information Officer
Socorro, NM
(575) 835-7302
dfinley@nrao.edu

Astronomers Discover Most Massive Neutron Star Yet Known

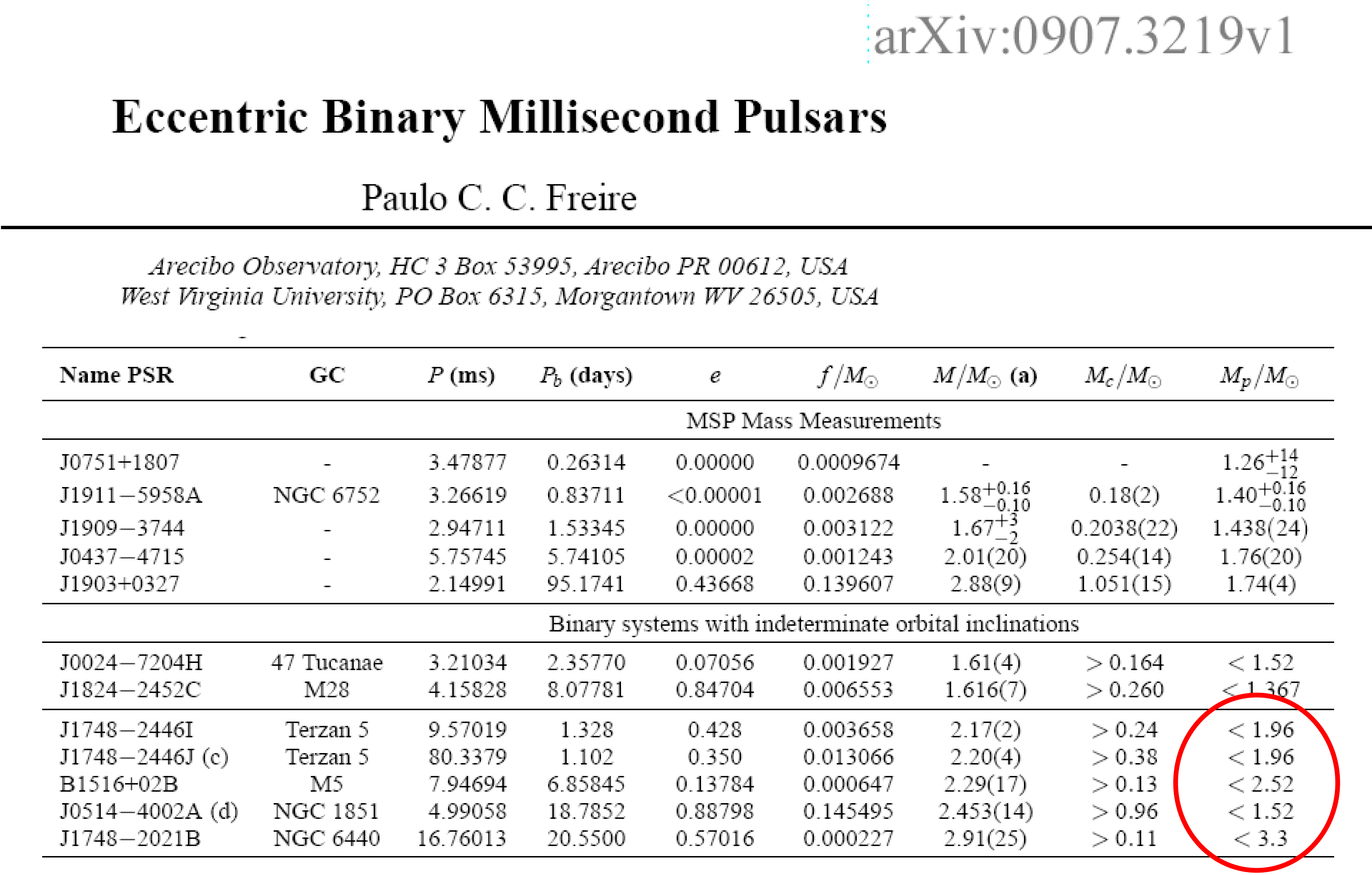
Announcement in NRAO homepage

Why do they claim that
this is the most massive NS yet known ?

- What happened to other NS's whose masses were estimated to be bigger than 2 solar mass?
- What's wrong with them?



Lattimer & Prakash (2007)



arXiv:0907.3219v1

Eccentric Binary Millisecond Pulsars

Paulo C. C. Freire

Arecibo Observatory, HC 3 Box 53995, Arecibo PR 00612, USA
West Virginia University, PO Box 6315, Morgantown WV 26505, USA

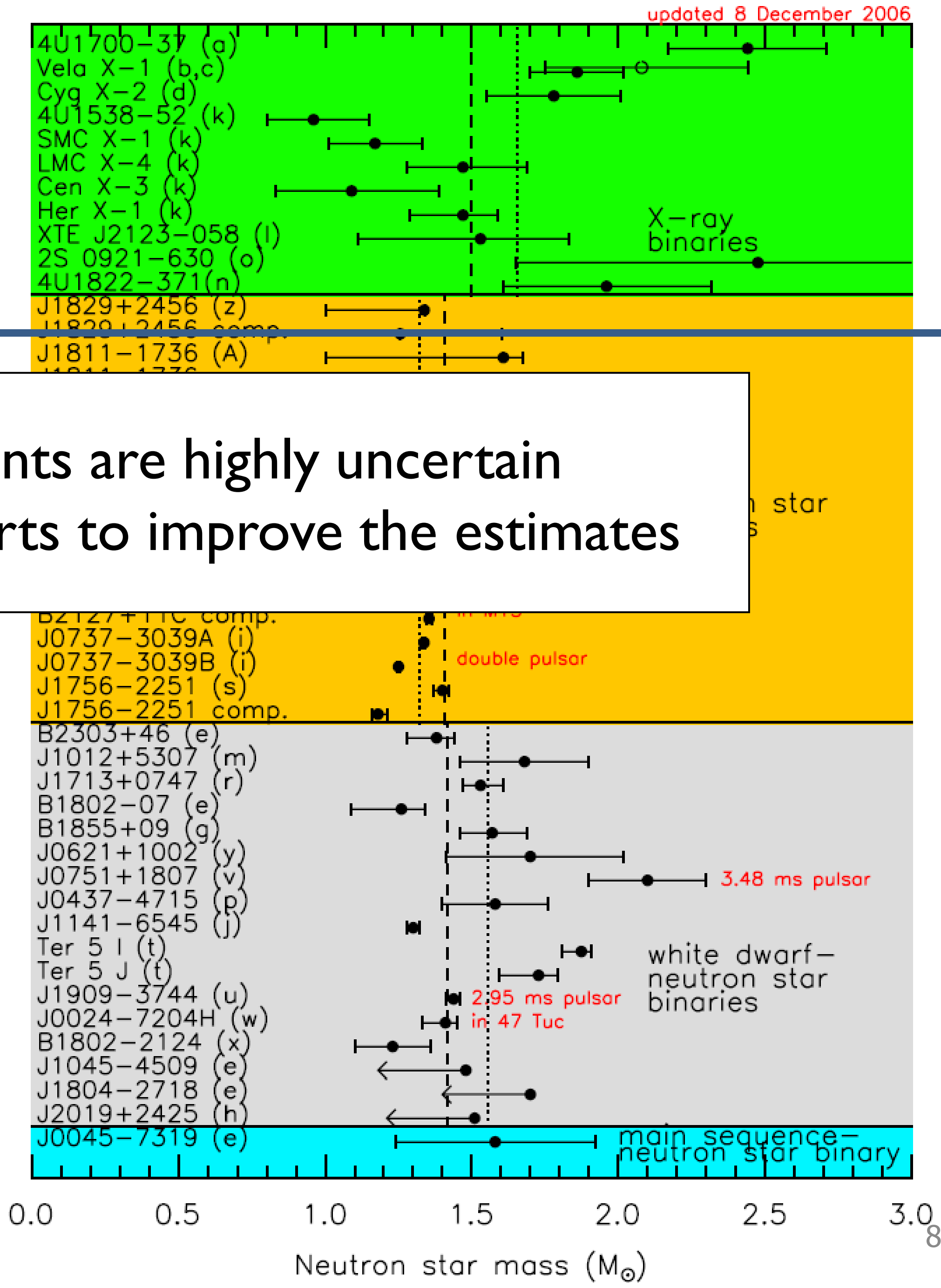
Name PSR	**GC**	P **(ms)**	P_b **(days)**	e	$f/M_\odot$	$M/M_\odot$ **(a)**	$M_c/M_\odot$	$M_p/M_\odot$
				MSP Mass Measurements				
J0751+1807	-	3.47877	0.26314	0.00000	0.0009674	-	-	1.26^{+14}_{-12}
J1911−5958A	NGC 6752	3.26619	0.83711	<0.00001	0.002688	$1.58^{+0.16}_{-0.10}$	0.18(2)	$1.40^{+0.16}_{-0.10}$
J1909−3744	-	2.94711	1.53345	0.00000	0.003122	1.67^{+3}_{-2}	0.2038(22)	1.438(24)
J0437−4715	-	5.75745	5.74105	0.00002	0.001243	2.01(20)	0.254(14)	1.76(20)
J1903+0327	-	2.14991	95.1741	0.43668	0.139607	2.88(9)	1.051(15)	1.74(4)
				Binary systems with indeterminate orbital inclinations				
J0024−7204H	47 Tucanae	3.21034	2.35770	0.07056	0.001927	1.61(4)	> 0.164	< 1.52
J1824−2452C	M28	4.15828	8.07781	0.84704	0.006553	1.616(7)	> 0.260	< 1.367
J1748−2446I	Terzan 5	9.57019	1.328	0.428	0.003658	2.17(2)	> 0.24	< 1.96
J1748−2446J (c)	Terzan 5	80.3379	1.102	0.350	0.013066	2.20(4)	> 0.38	< 1.96
B1516+02B	M5	7.94694	6.85845	0.13784	0.000647	2.29(17)	> 0.13	< 2.52
J0514−4002A (d)	NGC 1851	4.99058	18.7852	0.88798	0.145495	2.453(14)	> 0.96	< 1.52
J1748−2021B	NGC 6440	16.76013	20.5500	0.57016	0.000227	2.91(25)	> 0.11	< 3.3

What's wrong with these observations?

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

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

1. X-ray Pulsars

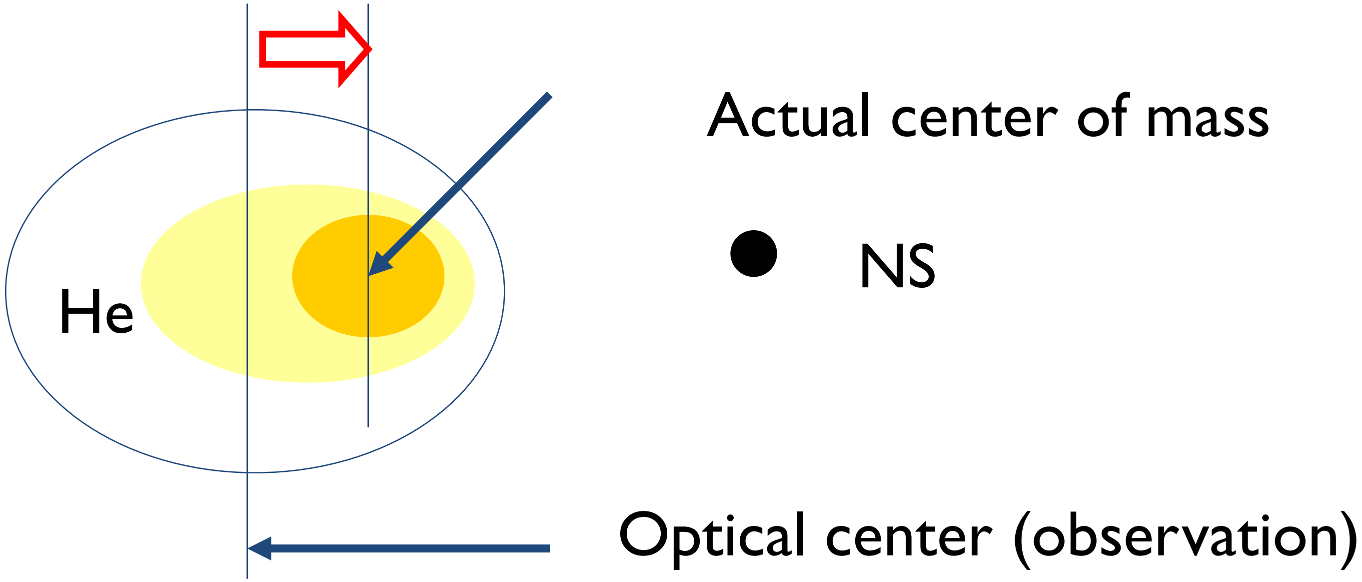


- Mass measurements are highly uncertain
- Many recent efforts to improve the estimates

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]



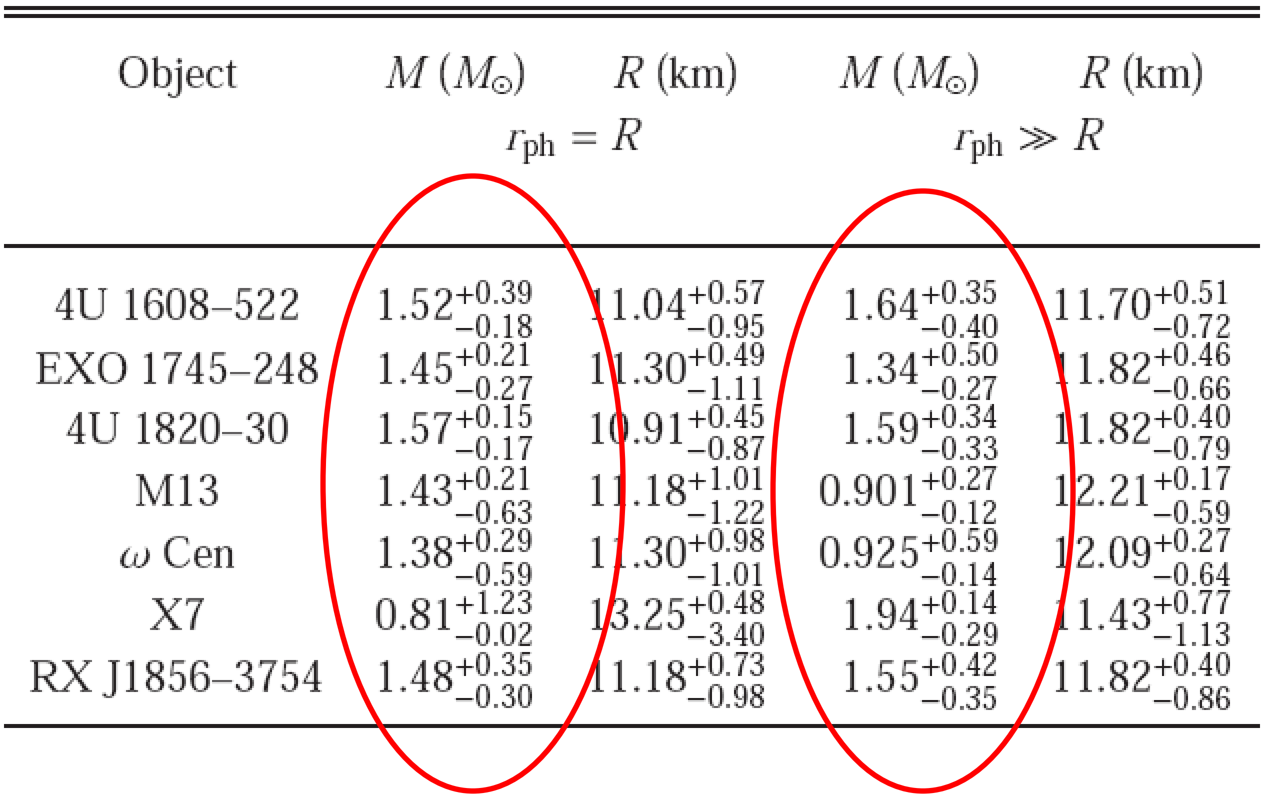
He

Actual center of mass

● NS

Optical center (observation)

Steiner, Lattimer, Brown, arXiv:1005.0811

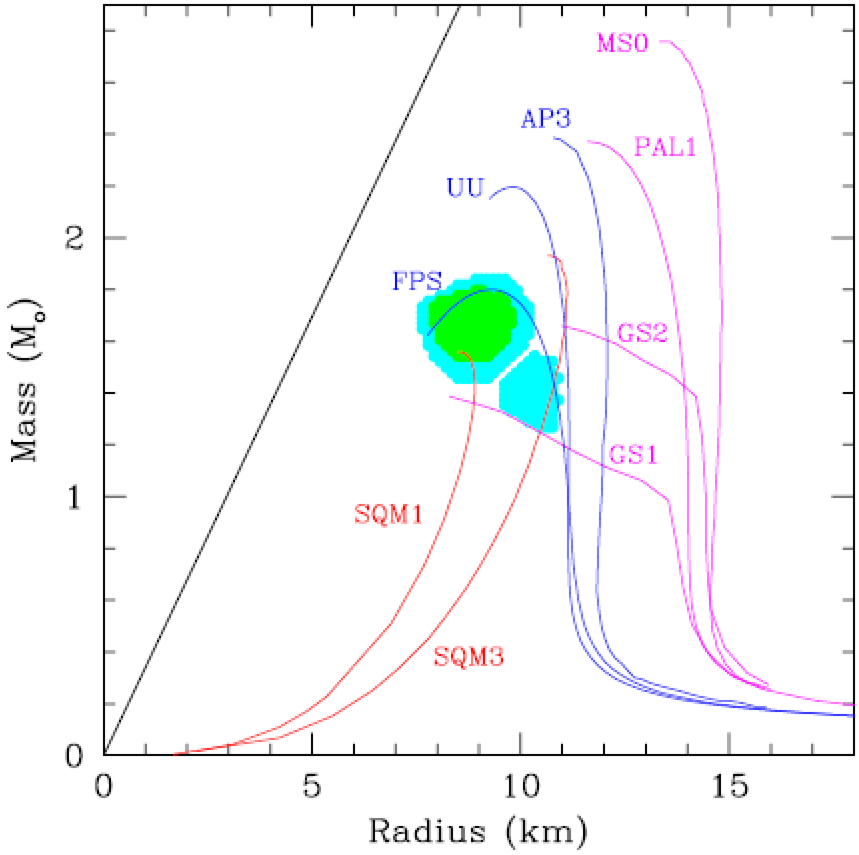


Object	M ($M_\odot$)	R (km)	M ($M_\odot$)	R (km)
	$r_{ph} = R$		$r_{ph} \gg R$	
4U 1608–522	$1.52^{+0.39}_{-0.18}$	$11.04^{+0.57}_{-0.95}$	$1.64^{+0.35}_{-0.40}$	$11.70^{+0.51}_{-0.72}$
EXO 1745–248	$1.45^{+0.21}_{-0.27}$	$11.30^{+0.49}_{-1.11}$	$1.34^{+0.50}_{-0.27}$	$11.82^{+0.46}_{-0.66}$
4U 1820–30	$1.57^{+0.15}_{-0.17}$	$10.91^{+0.45}_{-0.87}$	$1.59^{+0.34}_{-0.33}$	$11.82^{+0.40}_{-0.79}$
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_{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

$$M = 1.7\ M_\odot \text{ and } R = 9 \text{ km}$$

$$M = 1.4\ M_\odot \text{ and } R = 11 \text{ km}$$

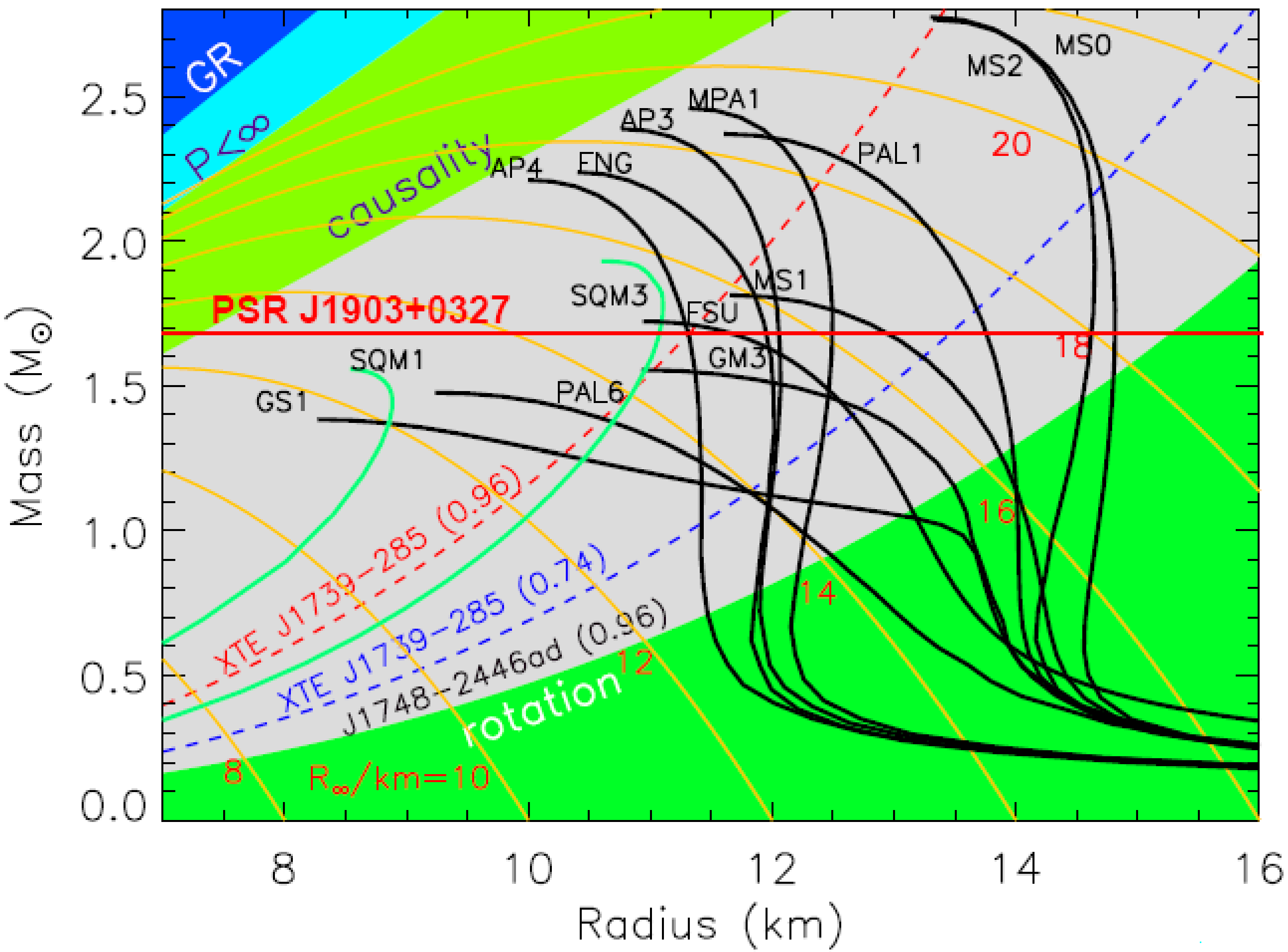
2 sigma error

2. 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

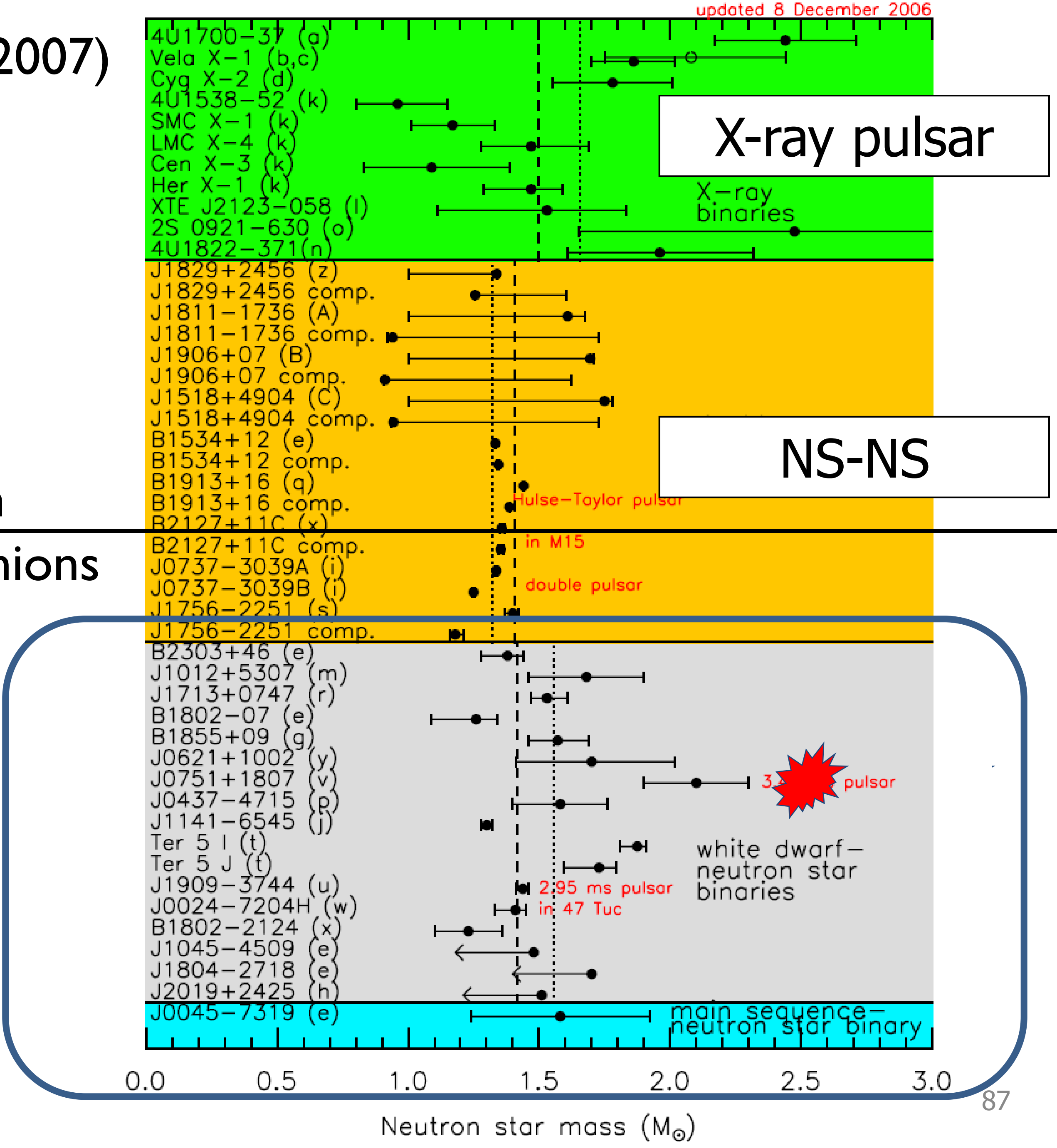
Note that *OBSERVERS* considered PSR J1903+0327 as the most massive NS observed until 2009.



arXiv:0907.3219v1

3. Neutron Stars with White Dwarf companions

Lattimer & Prakash (2007)



WD-NS Binary

Proven uncertainties in high-mass NS in NS-WD

Pulsar J0751+1807

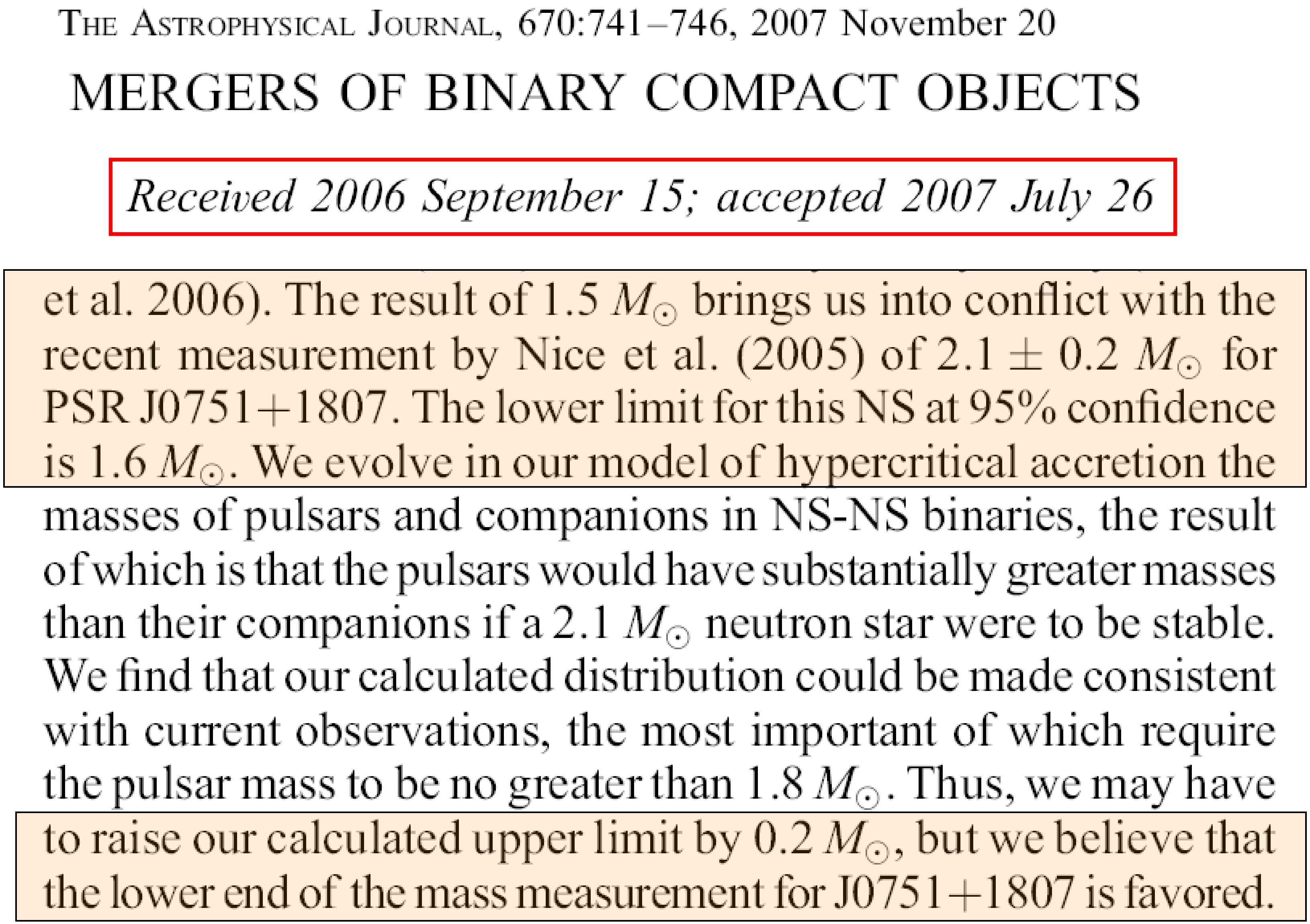
2.1 ± 0.2 solar mass

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



The Astrophysical Journal, 670:741–746, 2007 November 20

MERGERS OF BINARY COMPACT OBJECTS

Received 2006 September 15; accepted 2007 July 26

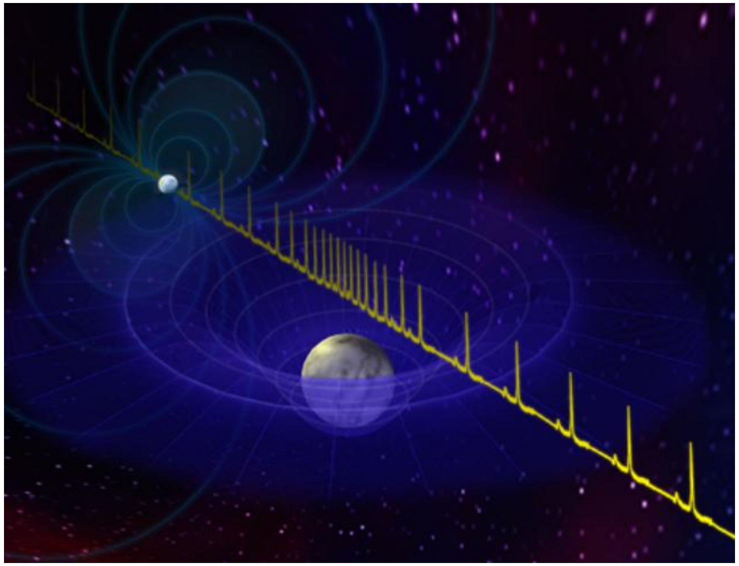
et al. 2006). The result of 1.5 $M_\odot$ brings us into conflict with the recent measurement by Nice et al. (2005) of 2.1 ± 0.2 $M_\odot$ for PSR J0751+1807. The lower limit for this NS at 95% confidence is 1.6 $M_\odot$. We evolve in our model of hypercritical accretion the masses of pulsars and companions in NS-NS binaries, the result of which is that the pulsars would have substantially greater masses than their companions if a 2.1 $M_\odot$ neutron star were to be stable. We find that our calculated distribution could be made consistent with current observations, the most important of which require the pulsar mass to be no greater than 1.8 $M_\odot$. Thus, we may have to raise our calculated upper limit by 0.2 $M_\odot$, but we believe that the lower end of the mass measurement for J0751+1807 is favored.

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]



Nature 467, 1081 (Oct. 28, 2010)

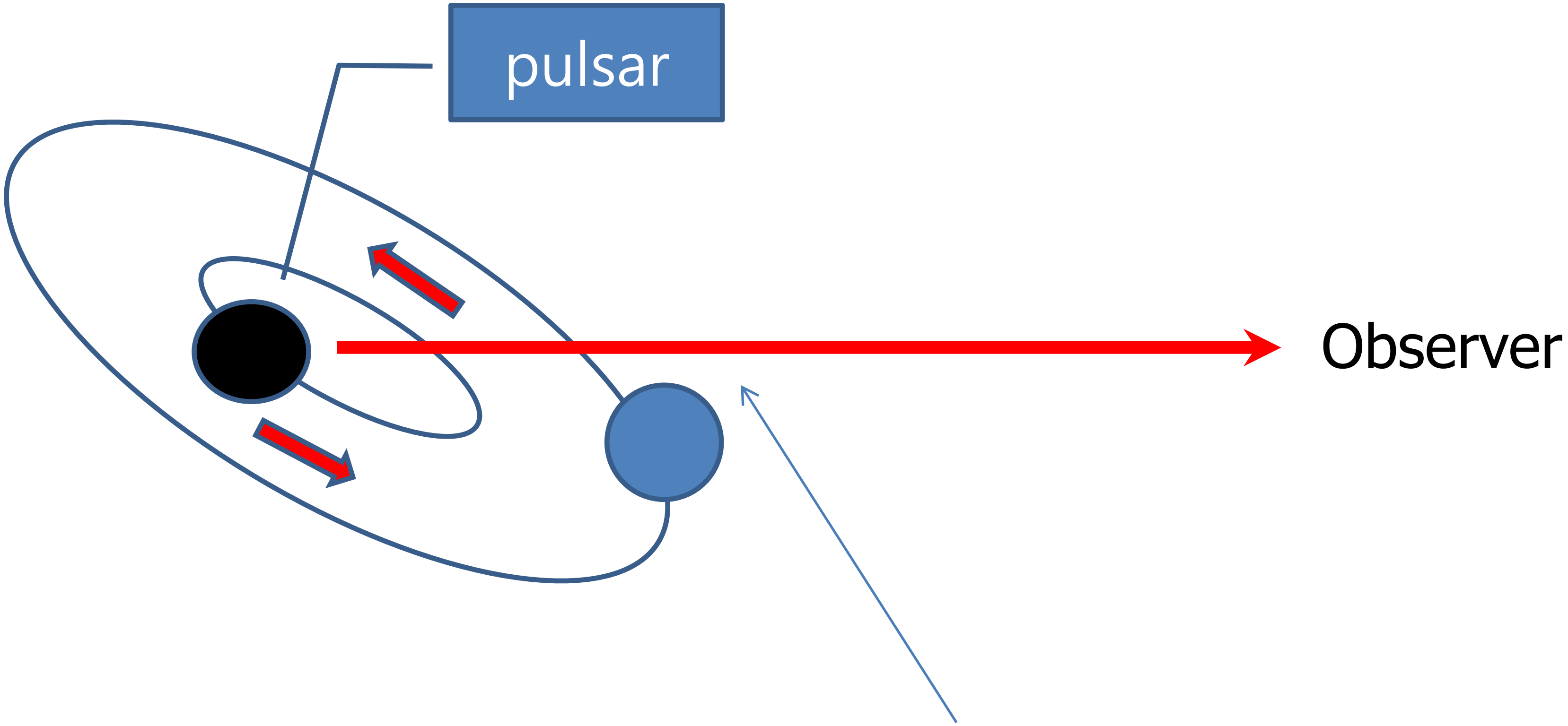
PSR J1614-2230

(Millisecond Pulsas & White Dwarf Binary)

1.97 ± 0.04 Msun

(measurement based on Shapiro delay)

Shapiro delay

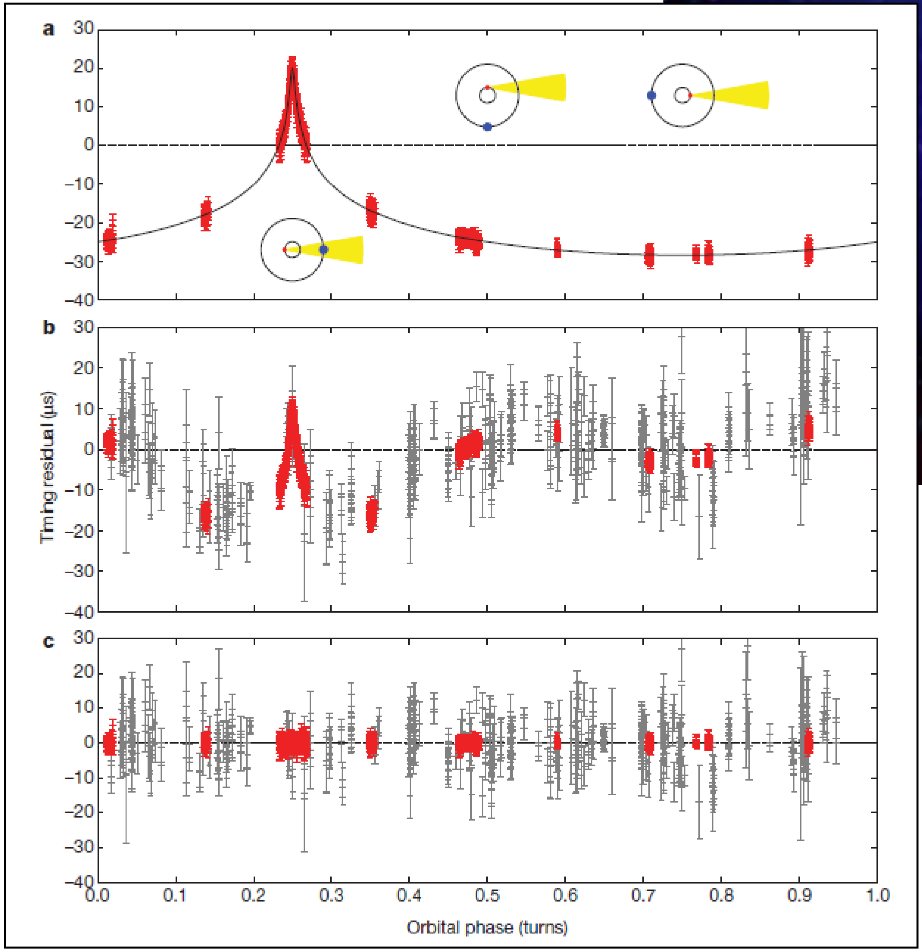


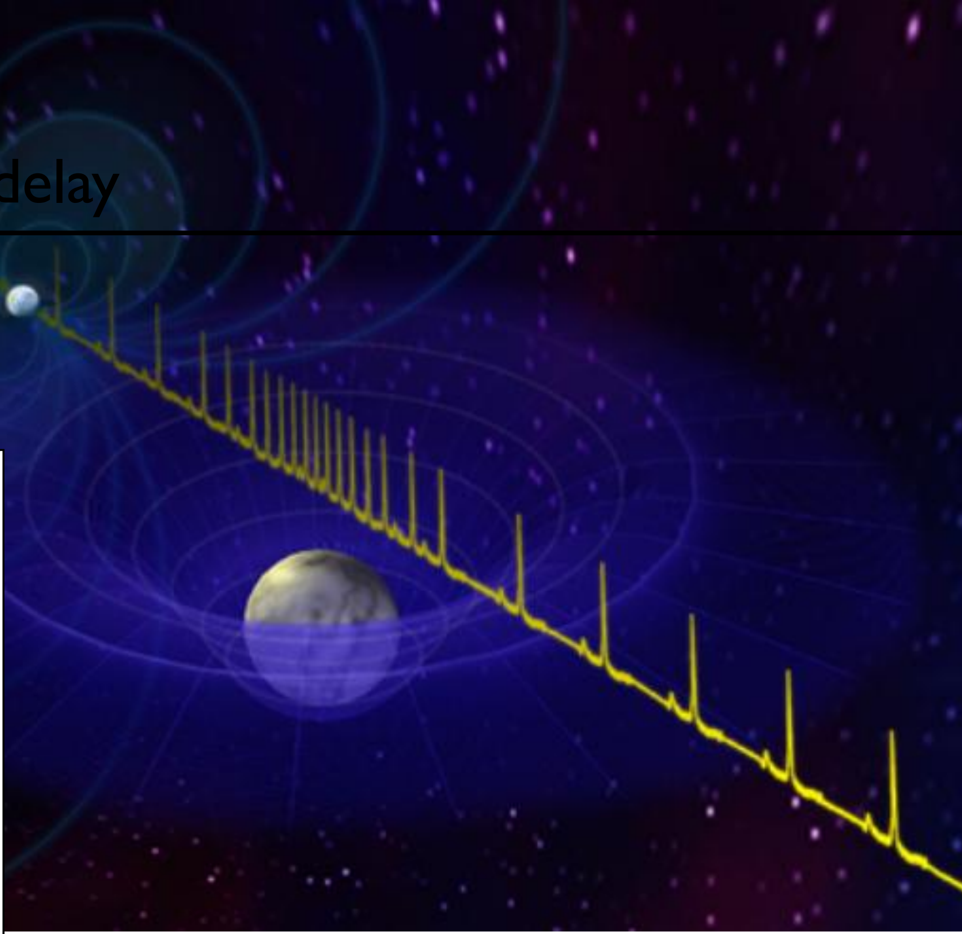
pulsar

Observer

Additional red shift due to the gravity of companion star

Shapiro delay

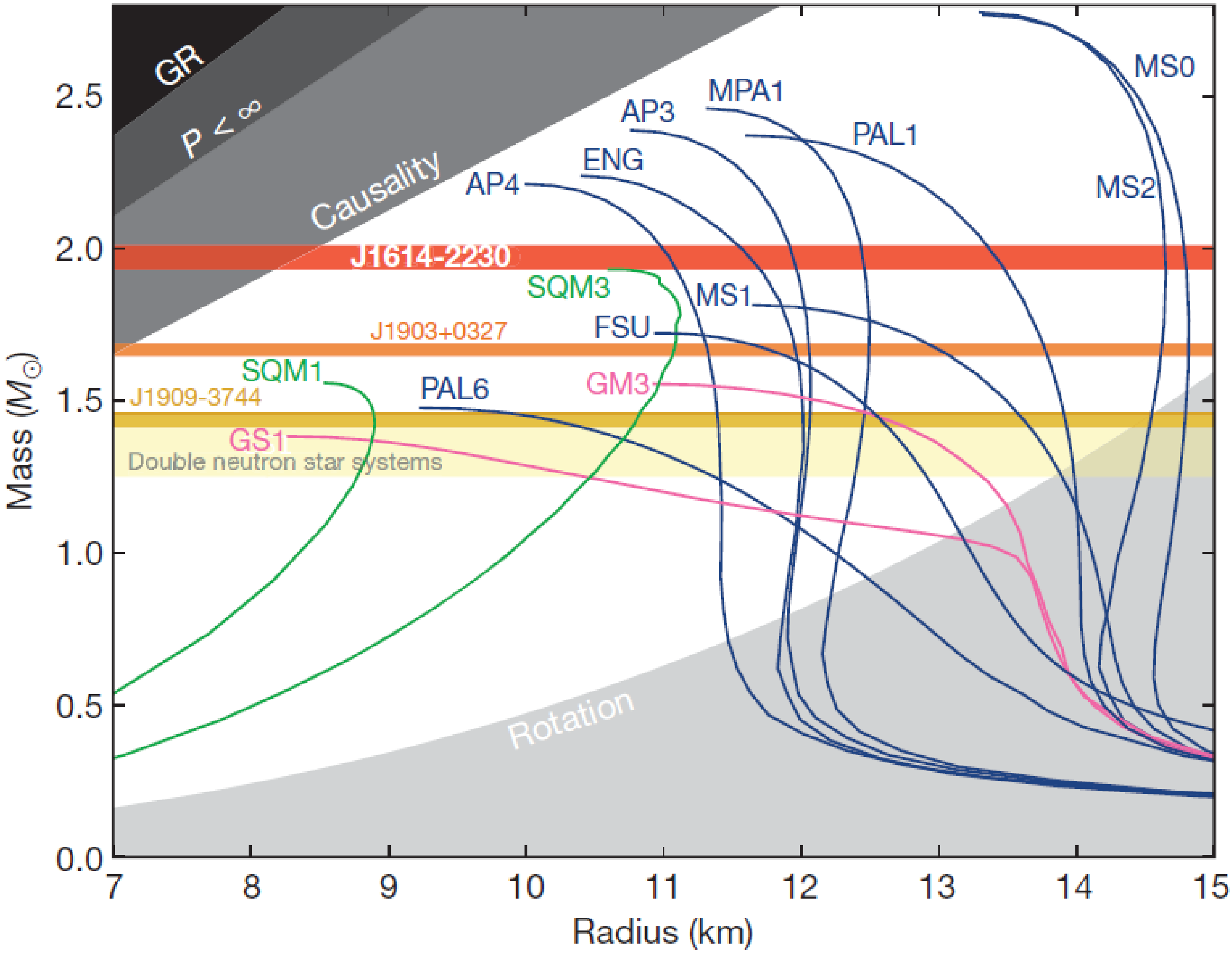




http://www.nrao.edu/pr/2010/bigns/

Nature 467, 1081

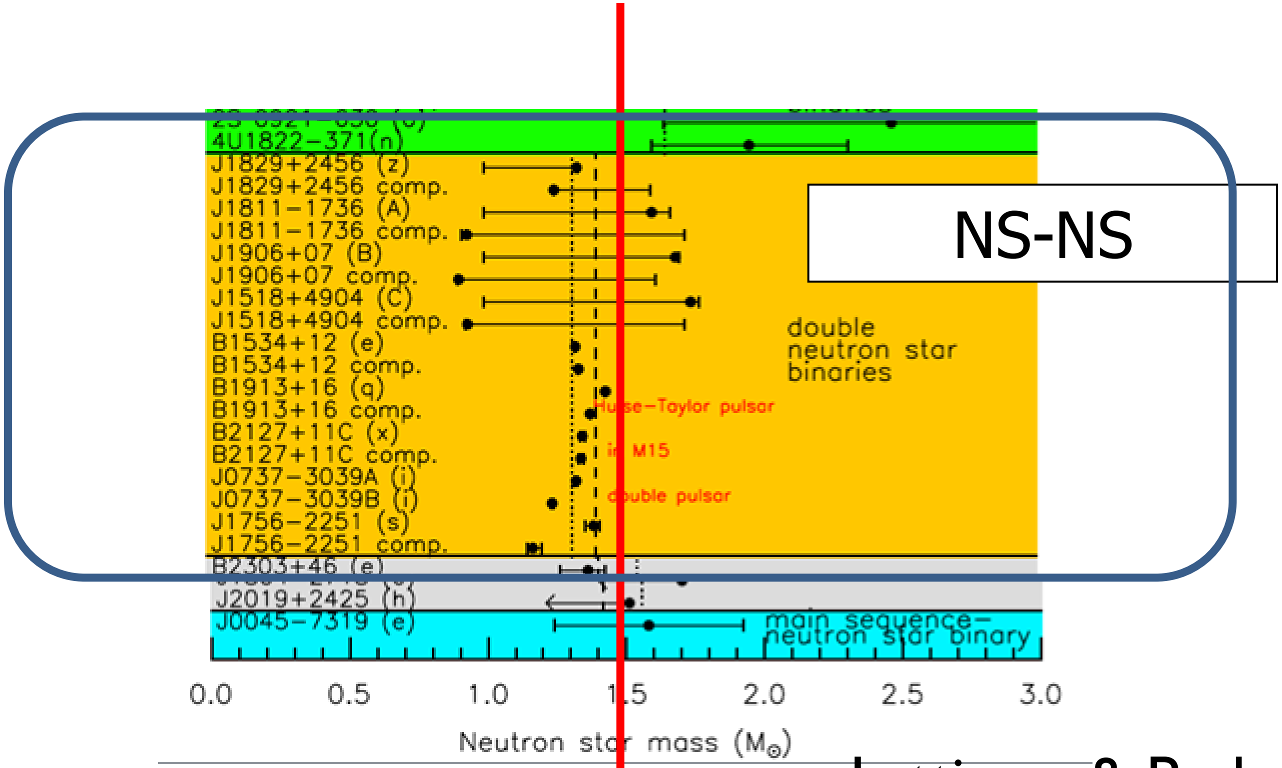
Nature 467, 1081



If this limit is firm, maximum neutron star mass should be at least 1.97 Msun

Q) IF maximum NS mass is confirmed to be 1.97 Msun

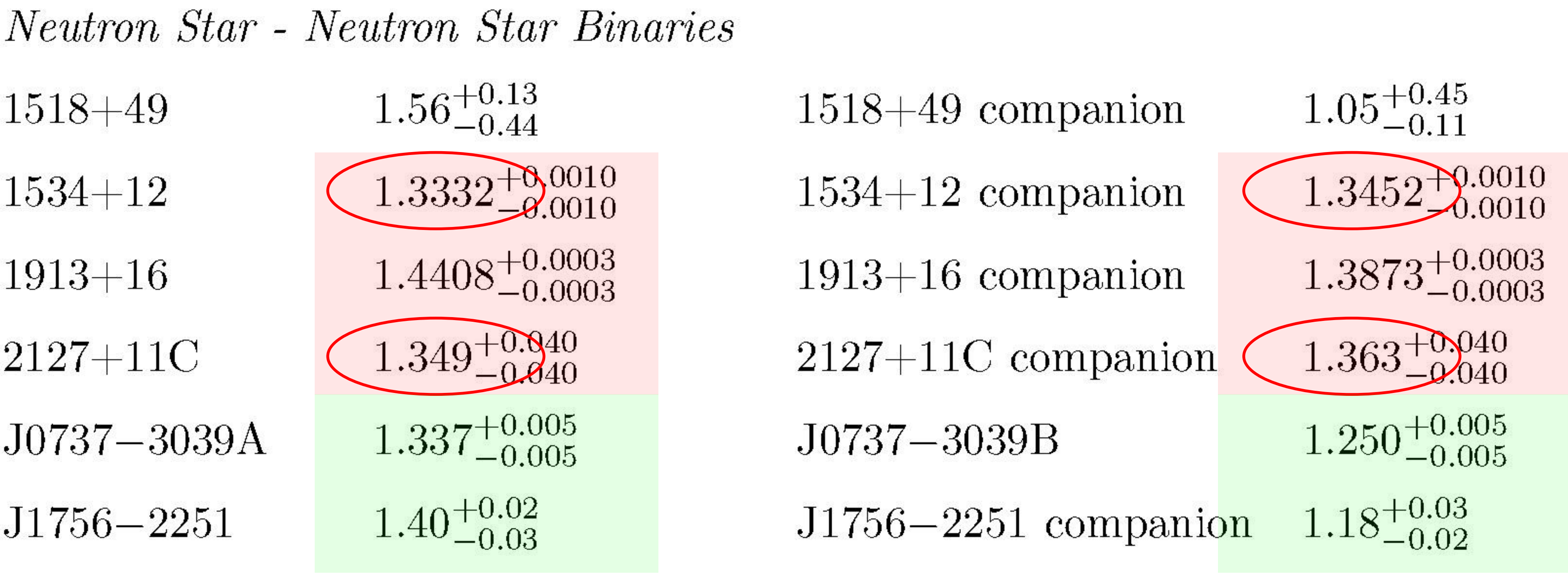
- Why all well-measured NS masses in NS-NS binaries are < 1.5 Msun ?
- Maybe, new-born NS mass is constrained by the stellar evolution, independently of maximum mass of NSs.



NS-NS

Lattimer & Prakash (2007)

Double NS binaries



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	$1.18^{+0.03}_{-0.02}$

- All masses are < 1.5 $M_\odot$

Astrophysical Issues

Formation & Evolution of NS Binaries

arXiv:0907.3219v1

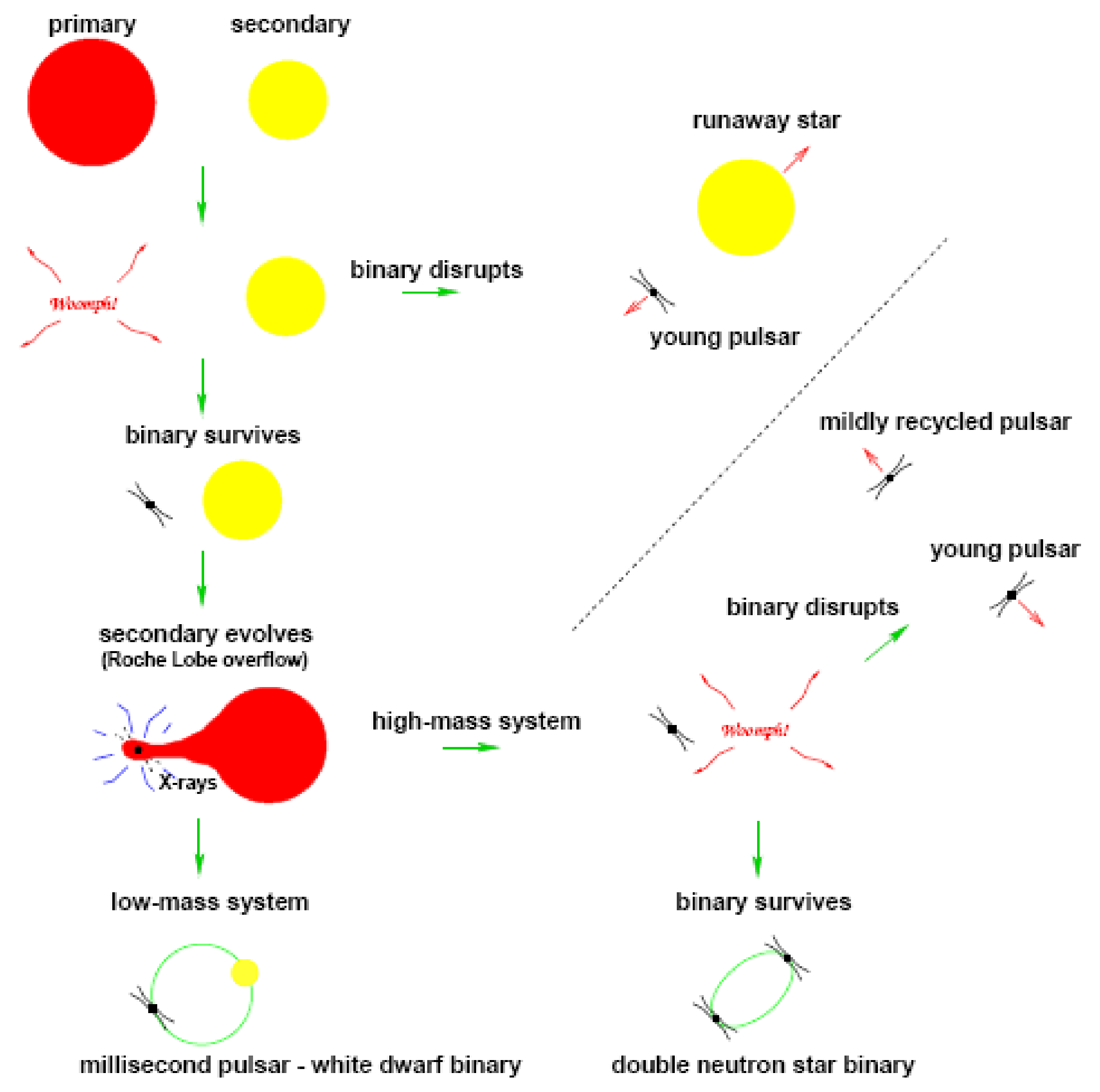
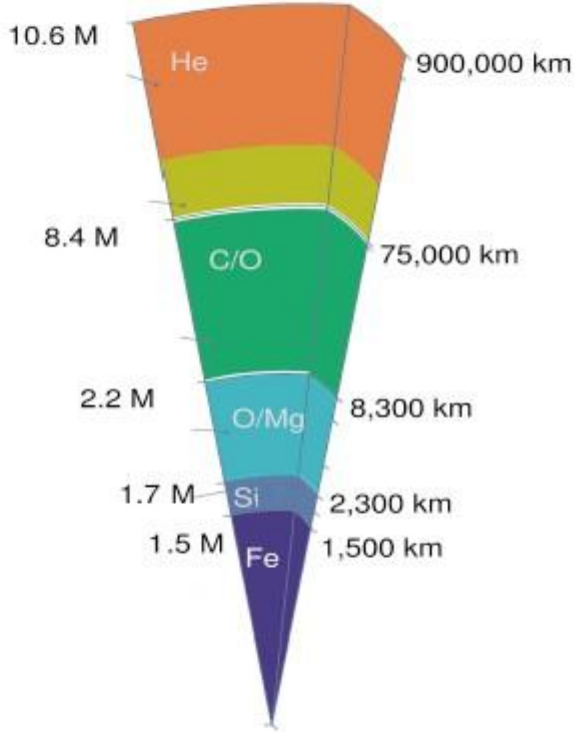


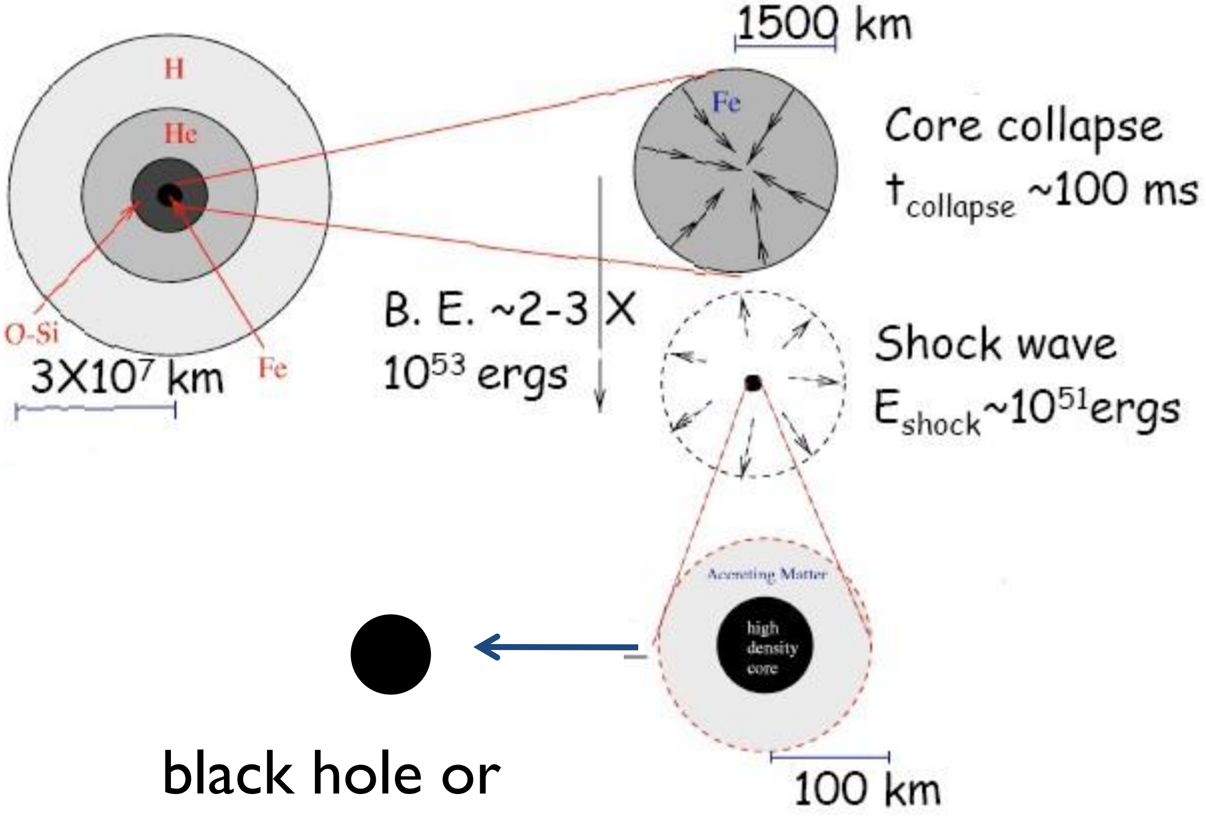
FIGURE 1. Formation of millisecond pulsars. From Lorimer (2008).

Accretion process is essential in understanding NS binaries

One has to understand formation of black hole/neutron star

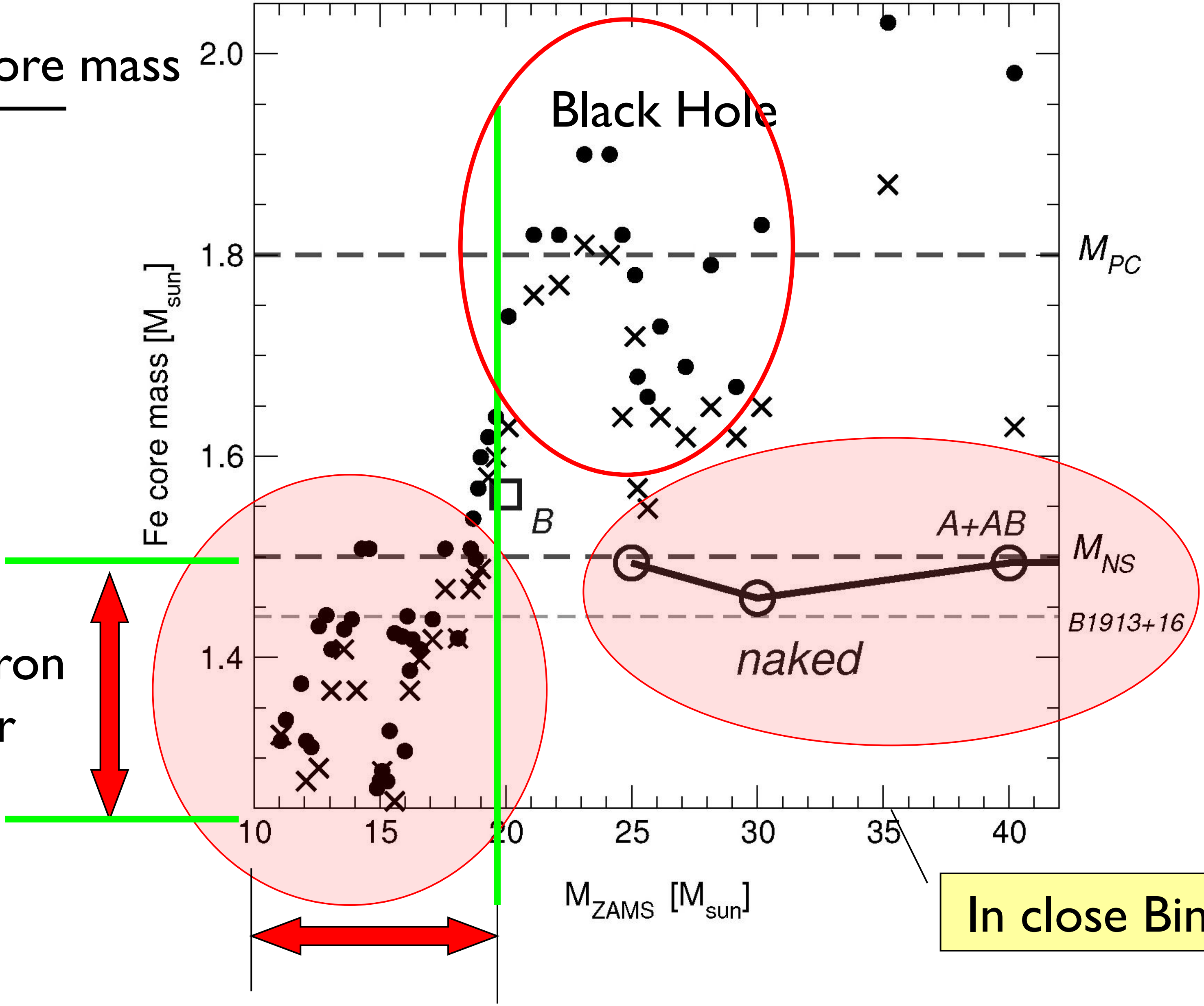


Giant Star



black hole or neutron star

Fe core mass



Neutron Star

In close Binaries

Fresh NS mass from Fe core collapse

Both in single & close binaries

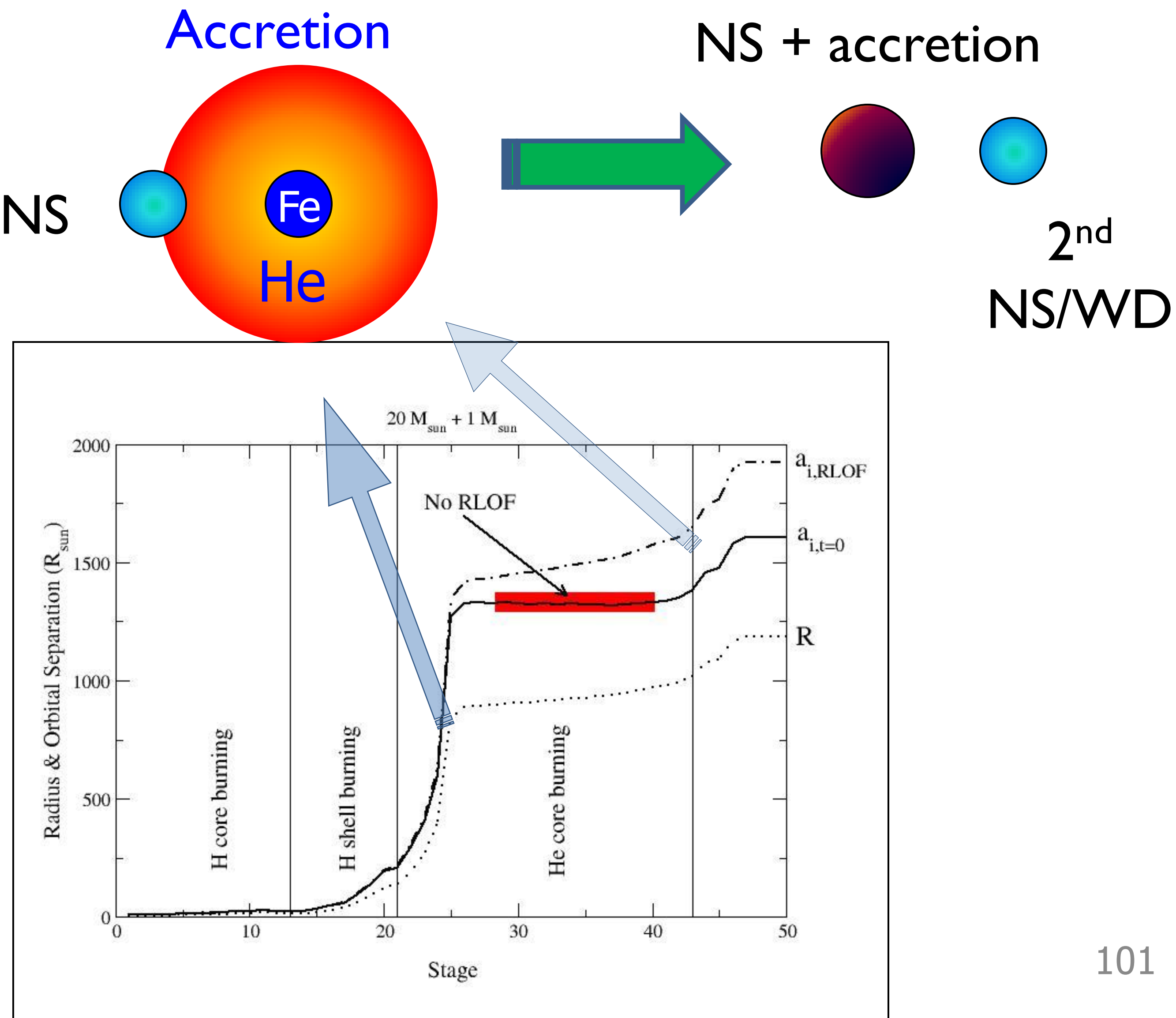
Fe core mass → NS mass = 1.3 - 1.5 Msun

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

Fe

He

1^{st}-born NS

NS + accretion

2^{nd} NS/WD

Evolution of Companion

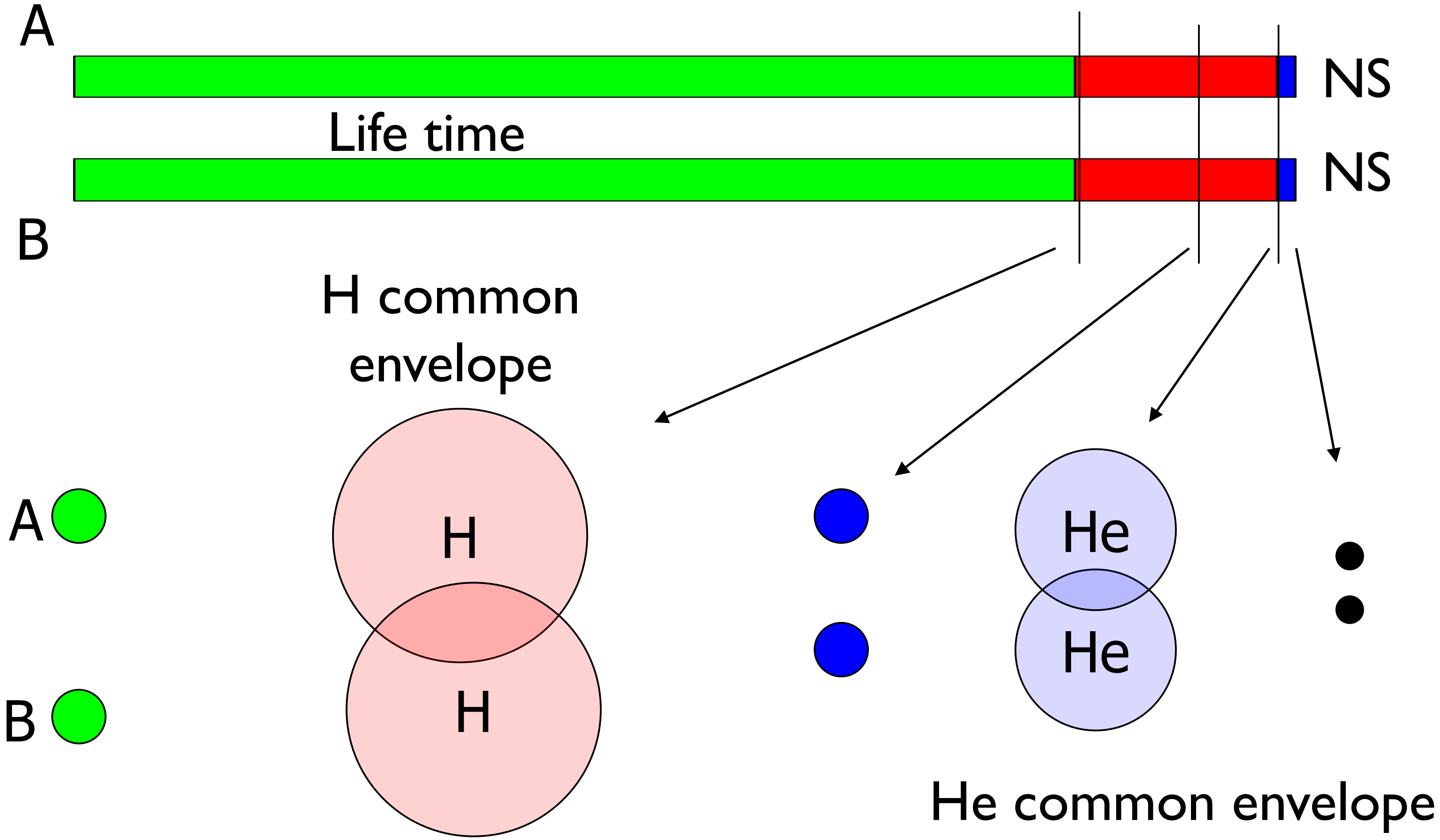
Supercritical Accretion onto first-born NS

- 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 : $\Delta T < 1\%$

Formation of NS-NS Binary



A

NS

Life time

NS

B

H common envelope

A

B

H

H

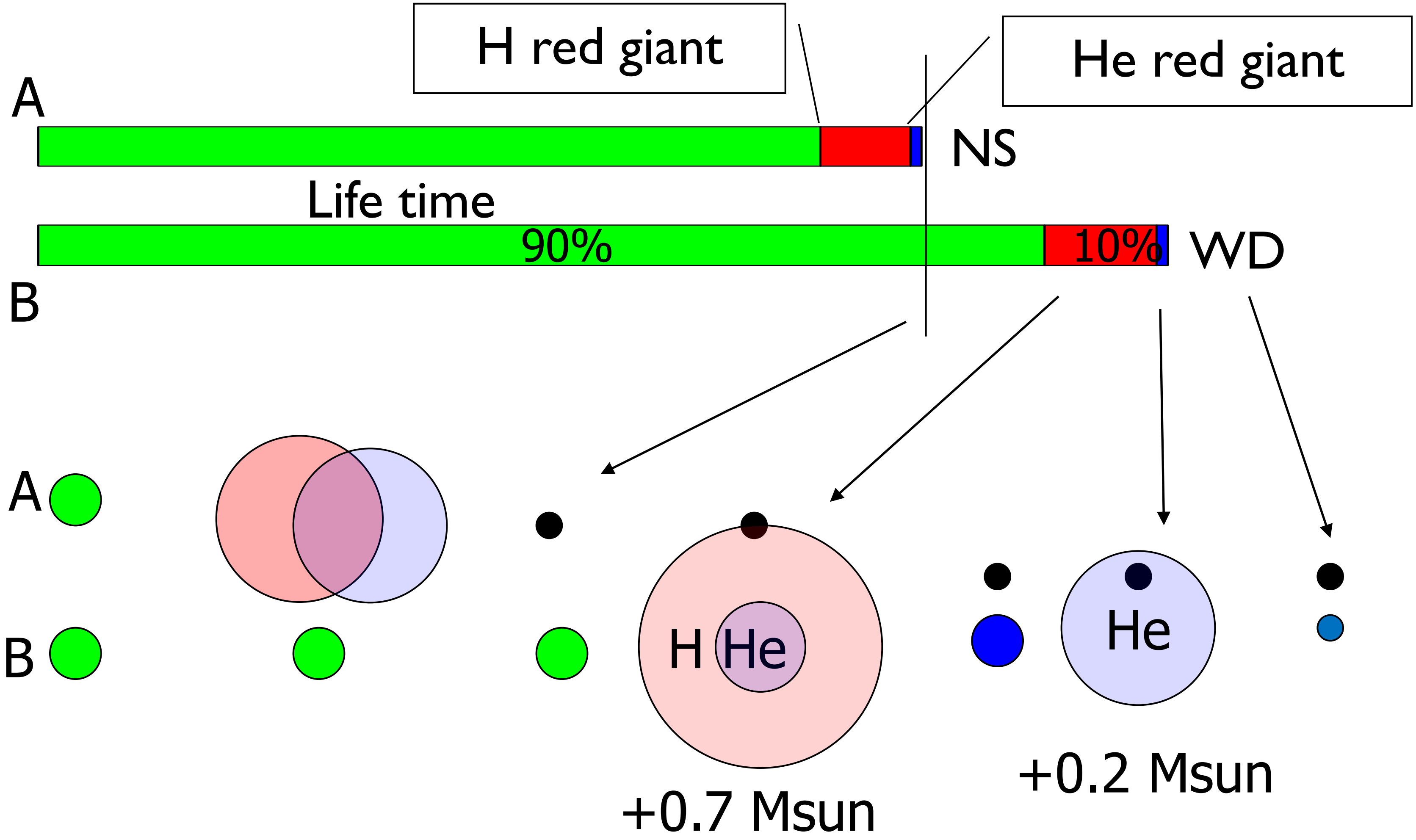
He

He

He common envelope

No accretion : nearly equal mass NS-NS binary!

Case 2 : $\Delta T > 10\%$ Formation of NS-WD Binary



H red giant

He red giant

A

NS

Life time

90%

10%

WD

B

A

B

H

He

He

+0.7 Msun

+0.2 Msun

Supercritical Accretion:

First born NS should accrete $0.9\ M_\odot$!

Consequences of Supercritical Accretion

- NS-NS Binary
  - nearly equal mass progenitors
  - no time for the accretion after NS formation
  - NS masses in NS-NS binaries are all below 1.5 msun
- High-mass NS-WD Binary
  - mass difference of progenitors are large
  - some time for the supercritical accretion after NS birth
  - formation of higher-mass NS
- Many other possibilities depending on the initial conditions of binaries

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