Photons signaling a QCD phase transition in neutron star mergers

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arXiv:1305.7397, PRD 88, 083006 (2013)

Gamma Ray Bursts as brighter standard candles

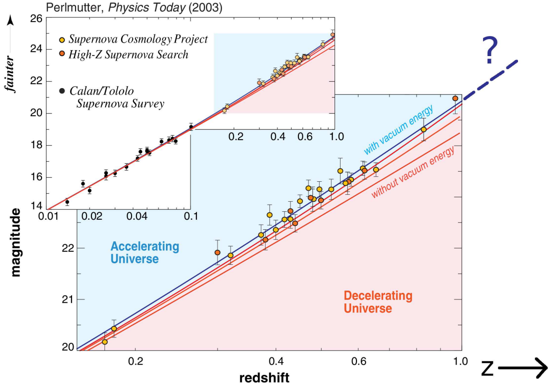
short GRBs thought to signal neutron star-neutron star mergers

Total energy of burst:
$E_{\mathrm{tot}} \simeq 10^{51} - 10^{53}$ erg

Visible at cosmological distances $z > 1$

1. Use microphysics to predict common spectral feature → standard candle for larger z

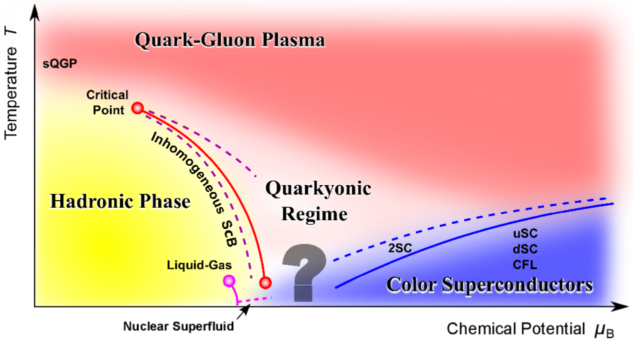
Type Ia Supernovae



Perlmutter, *Physics Today* (2003)

2. Solidfy short GRB - neutron star merger relationship

An opportunity to probe QCD phase diagram



Low temperature (individual) Neutron stars thought to probe high density phases of nuclear matter

Collision raises temperature, closer to possible first order transition

Can we find a signal?

Outline

1. Neutron star mergers: what happens and how often
2. Conditions of matter during a merger
3. Interesting region of QCD phase diagram
4. Collective mode and its coupling to photos
5. Energy loss and rates
6. Future and conclusions

Neutron star binaries

- binary merger rate $2 - 60(10^6\ \mathrm{yr})^{-1}$ per galaxy

C. Kim, V. Kalogera and D. R. Lorimer, Ap. J. **584** (2003) 985

- expected to be origin of "short" Gamma Ray Bursts (SGRBs) (along with neutron star-black hole mergers)

- primary motivation for gravitational wave detectors

LIGO/Virgo collaboration, Class. Quantum Grav. **27**, 173001, (2010)

Author	NS–NS		BH–NS		Method
	LIGO	AdLIGO	LIGO	AdLIGO	
Kim et al. [142]	5e-3	27			Empirical
Nakar et al. [194]		∼2		∼20.0	SGRBs
Guetta & Stella [126]	7.0e-3	22	7.0e-2	220	SGRBs
Voss & Tauris [318]	6.0e-4	2.0	1.2e-3	4.0	Pop. Synth. - SFR
de Freitas Pacheco et al. [79]	8.0e-4	6.0			Pop. Synth. - SFR
Kalogera et al. [139]	1.0e-2	35	4.0e-3	20	Pop. Synth. - NS–NS
O'Shaughnessy et al. [214]	1.0e-2	10	1.0e-2	10	Pop. Synth. - NS–NS

Event rate estimates from SFR=star formation rate, NS-NS=observed population of binary NSs

Faber & Rasio, *Living Rev. Relativity*, **15** (2012)

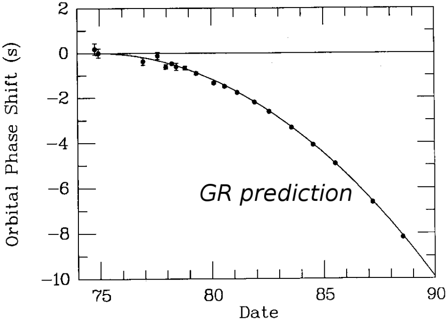
Why and how neutron star binaries merge

1. quasi-equilibrium decay due to Gravitational radiation

$$\frac{dE_{\mathrm{GW}}}{dt} \simeq -\frac{32}{5}\frac{\mu^2}{M^2}\frac{M}{r}\left(\frac{GM}{r}\right)^4$$

$$M = m_1 + m_2 \quad \mu = \frac{m_1 m_2}{M}$$

Radiates angular momentum making orbit more circular



Pulsar B1913+16

Other binary pulsars now identified —

Hailed as one of most precise tests of General Relativity

milliseconds before the collision

Kinematics of collision follow from radiation loss

contact at $r_{\mathrm{coll}} \simeq 2R_*$

Kinetic+Potential energy of binary system with GR corrections:

$$K + V = -\frac{\mu x}{2}\left(1 - \frac{3}{4}(1 + \frac{\mu}{9M})x - (27 - 19\frac{\mu}{M} + \frac{2\mu^2}{3M^2})\frac{x^2}{8} + ...\right)$$

GR gauge invariant variable:

$$x = (GM\omega)^{2/3} \simeq \frac{GM}{r} \simeq v^2$$

Subtracting Newtonian potential $V \simeq -G\mu Mx/r$

$$v_r^2 = \left(19 - \frac{5\mu}{3M}\right)\frac{x^2}{4} \simeq 0.20c^2$$

- estimated correction $\sim +5\%$ dissipation of angular momentum

Conditions of the matter in the collision

From radial velocity at collision, $v_r^2 \simeq 0.2c^2$
lower estimate of kinetic energy per baryon

$$\frac{E}{N} \simeq \frac{1}{2}\frac{m_N}{1+\delta M/M}v_r^2 \simeq 85\ \mathrm{MeV} \simeq T$$

(mass defect $\delta M/M$ corrects gravitational binding in counting baryons)

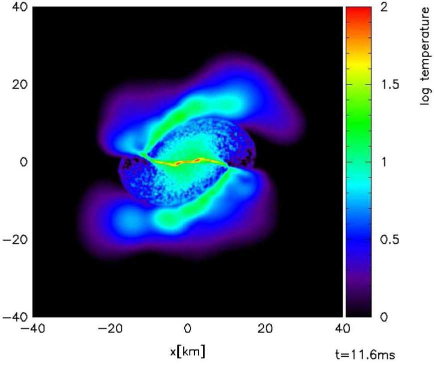
Near surface of initial stars : $n/n_{\mathrm{sat}} \simeq 0.15 - 0.6$

Conservation of baryon number where matter overlaps in collision
$\Rightarrow$ amplify density by factor $2 - 4$

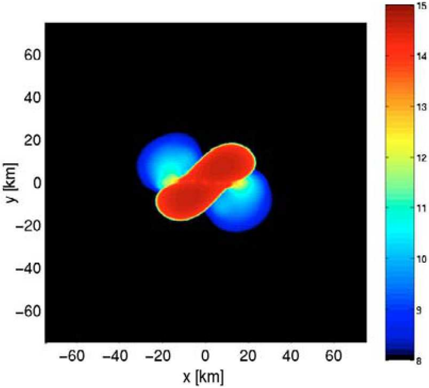
Expected density $n/n_{\mathrm{sat}} \simeq 0.3 - 2.4$

Baryonic chemical potential $\mu_B \simeq 944 - 1240\ \mathrm{MeV} \simeq 3\mu_q$

Numerical simulation



left, temperature in units MeV



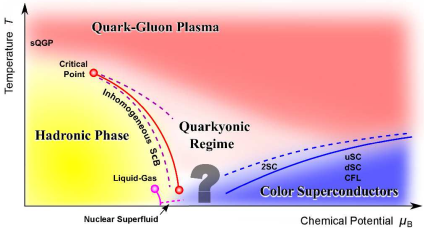
right: log plot of density in g/cm^3

$n_{\rm sat} \rightarrow 10^{14}{\rm g/cm}^3$

Bauswein, Janka & Oechslin, PRD 82 (2010) 084043;

Oechslin, Bauswein & Janka, A & A, 467, 395 (2007).

Where that puts us in the QCD phase diagram

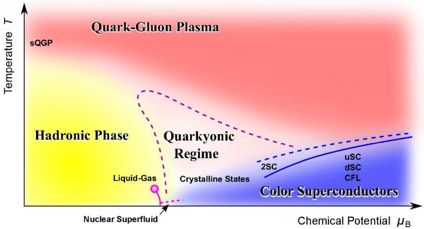


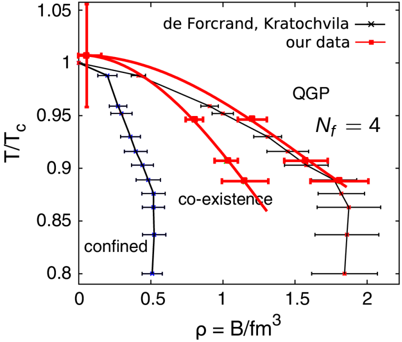
Fukushima & Sasaki, arXiv:1301.6377

- quarkyonic phase?
- order of transition?

Li, Alexandru, Liu and Meng,

PRD 82, 054502 (2010)⟶





Comparison of timescales

QCD timescales in general many orders of magnitude shorter:

$$\tau_{\rm QCD} \lesssim 10^{-20}\ \mathrm{s} \ll \tau_{\rm weak} \sim 10^{-7} - 10^{-6}\ \mathrm{s} \quad \ll \tau_{\rm merger} \sim 10^{-3}\ \mathrm{s}$$

- QCD timescales:

kinetic equilibrium: $\tau \simeq (n\sigma v)^{-1} \sim 10^{-23}\,s$
bulk transport: thermal conductivity ($\sim 10^{-20}$ s), energy loss (we show: $\sim 10^{-14}$ s)

- Weak interactions: “fast” Urca processes $\tau_{\rm weak}^{-1} \simeq \frac{1}{T^4}\ \frac{dE}{dt}\Big|_{\rm Urca}$

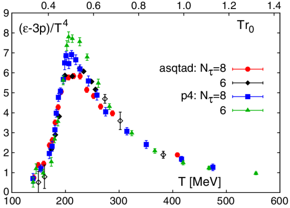
e.g. in quark phases $u + e^- \to d + \nu_e$, $d \to u + e^- + \bar{\nu}_e$

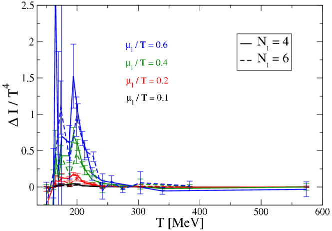
- Merger timescale: final orbital period $\tau_{\rm merger} \sim 1\,\mathrm{ms}$

numerical simulations see system relax (quasi-)equilibrium state
$\tau \sim 5 - 10$ ms

★ Matter close to equilibrium with respect to QCD processes
We will find that all timescales remain shorter than $\tau_{\rm weak}$
→ self-consistent to neglect weak flavor changing reactions

Energy-momentum trace peaks near phase change

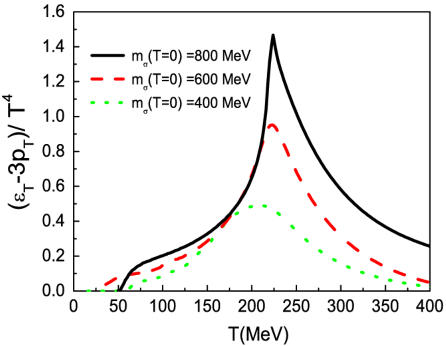




Lattice results:
MILC, PRD 80, 014504 (2009);

PoS LATTICE, 2008, 171 (2008)

$$g_{\mu\nu}\Theta^{\mu\nu} = \Theta^{\mu}_{\mu} = \varepsilon - 3p$$



O(4) model (same universality class as QCD) same qualitative behavior across models and parameters

Li & Huang, PRD80, 034023 (2009)

Energy-momentum Trace as collective mode

Collective modes described in finite temperature field theory, allows consistent inclusion of low-energy effective couplings

Energy-momentum two-point function (=propagator of collective mode)

$$\langle \Theta_{\mu\mu}(t,\vec{x})\Theta_{\mu\mu}(t',\vec{x}')\rangle = G_{\mu\mu,\nu\nu}(t,\vec{x};t',\vec{x}')$$

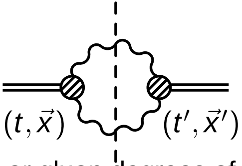
Spectral representation : $\frac{1}{\omega}\mathtt{Im}\left[G_{\mu\mu,\nu\nu}(\omega,\vec{k})\right] = \frac{\rho_\sigma(\omega)}{\omega} \simeq \frac{9}{\pi}\zeta$

ζ= bulk viscosity, the dissipation that damps collective mode

see Kapusta & Gale, Finite-T Field Theory; Meyer JHEP **1004**, 099 (2010)

decay of collective mode seen in imaginary part of polarization

$$\Gamma = \mathtt{Im}\Pi =$$



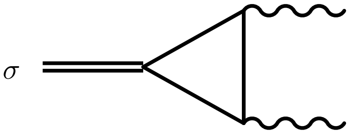
hadron level theory — no explicit quark or gluon degrees of freedom

How photons couple: Triangle anomaly

Effective theory for collective mode

$$\langle 0|\Theta^{\mu}_{\mu}|\sigma\rangle = m_\sigma^2 f_\sigma$$

(like pion low-energy parameters)



Quarks carry electric charge
⇒ photons couple through loop

$$\mathcal{L}_{\rm eff} = g_{\sigma\gamma\gamma}\sigma F^{\mu\nu}F_{\mu\nu}$$

Ellis & Lanik, PLB **175**, 83 (1986)

Matching onto 2-photon width of $f_0(600)$ meson: [PDG]
(lowest state with right quantum numbers)

$$g_{\sigma\gamma\gamma} \simeq (50\,\mathrm{GeV})^{-1} \quad m_\sigma \simeq 550\,\mathrm{MeV} \quad f_\sigma \simeq 100\,\mathrm{MeV}$$

[Basar, Kharzeev, Skokov, Phys. Rev. Lett. **109**, 202303 (2012)]

★ Effective theory valid for momenta $k \ll 50\ \mathrm{GeV}$

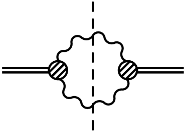
parameters from $\sigma - f_0$ meson in vacuum
** assume in-medium properties contained in spectral function $\rho_\sigma(\omega, \vec{k})$

Photon production: two cases

Calculate imaginary part of photon polarization (at $k \ll 50\ \mathrm{GeV}$)

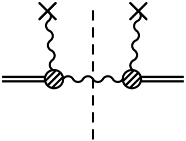
a) final state → two real photons

$$\Gamma = \mathtt{Im}\Pi =$$



b) recoils off external magnetic field → one photon

$$\Gamma = \mathtt{Im}\Pi =$$



subdominant to 2-photon unless stellar $|\vec{B}| \sim 100 B_{\mathrm{QED}}$

$B_{\mathrm{QED}} = 4.41 \times 10^{13}$ Gauss – (in fact, magnetic fields of this scale and higher are inferred from observations)

Photons in-medium and energy emitted

In hot dense matter of charged particles, photon has self-energy due to fluctuations into fermion pairs. For $|\vec{k}|, \omega \gg T, |\mu_f|$, plasma mass

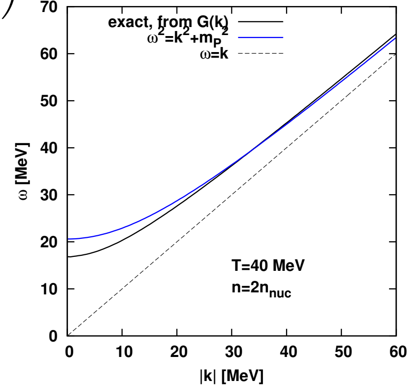
$$m_{\mathrm{P}}^2 = \frac{1}{2}\sum_f (Q_f e)^2 \left(\frac{T^2}{3} + \frac{\mu_f^2}{\pi^2}\right) \simeq (10 - 20\ \mathrm{MeV})^2$$

Mean free path

$l_f \sim (e m_{\mathrm{P}})^{-1} \sim 100\ \mathrm{fm}$

from Im [photon self-energy]

$\Rightarrow$ only boundary layer releases energy



Energy loss rates

Obtain energy release by integrating weighted with k^μ

$$\Gamma^\mu_{2\gamma} = \int \frac{d^3k_1}{(2\pi)^3 2\omega_1} \frac{d^3k_2}{(2\pi)^3 2\omega_2} (k_1^\mu + k_2^\mu) \omega_1 \omega_2 \frac{d\Gamma_{2\gamma}}{d^3k_1 d^3k_2}$$

As for refractive media, keep photon energy fixed in transiting from medium to vacuum: $\vec{k}^2_{\rm vac} = \omega^2$

Energy emitted from plasma: $\dfrac{dE}{dVdt} = \Gamma^0$

$$\left.\frac{dE}{d^4x}\right|_{2\gamma} = 7.13 \frac{\mathrm{TeV}}{\mathrm{fm}^3\mathrm{s}} \frac{\zeta}{s} \frac{s}{s_0} \left(\frac{m_{\rm P}}{15\,\mathrm{MeV}}\right)^{10} I_{2\gamma}(m_{\rm P}/T)$$

$$\left.\frac{dE}{d^4x}\right|_{B\gamma} = 5.51 \frac{\mathrm{GeV}}{\mathrm{fm}^3\mathrm{s}} \frac{\zeta}{s} \frac{s}{s_0} \left(\frac{m_{\rm P}}{15\,\mathrm{MeV}}\right)^{6} \frac{\vec{B}^2}{B^2_{\rm QED}} I_{B\gamma}(m_{\rm P}/T)$$

$s_0 =$ entropy of (u, d, e) plasma at $T = 50$ MeV and $2n_{\rm nuc}$

Energy loss and surface cooling

Timescale of energy loss:

$$\frac{1}{\tau_E} = \frac{1}{\varepsilon}\frac{dE}{dVdt} \simeq (10^{-6}\,\mathrm{s})^{-1}\left(\frac{m_{\mathrm{P}}}{15\,\mathrm{MeV}}\right)^{10}\frac{\zeta}{s}\,\frac{s/\varepsilon}{(s/\varepsilon)_0} I_{2\gamma}$$

entropy-to-energy ratio s/ε normalized to $T = 50$ MeV and $2n_{\mathrm{sat}}$ Much less than weak reaction timescale!

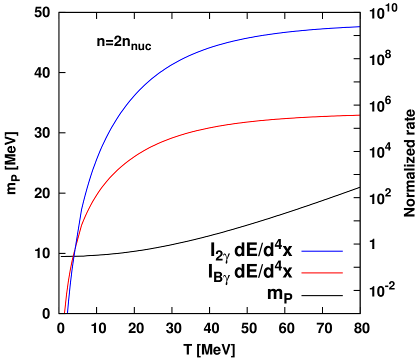
Conduction of thermal energy

$$\tau_\kappa = \frac{c_V R^2}{\kappa} = 2\,10^{-21}\,\mathrm{s}\,\frac{R^2}{l_f^2}$$

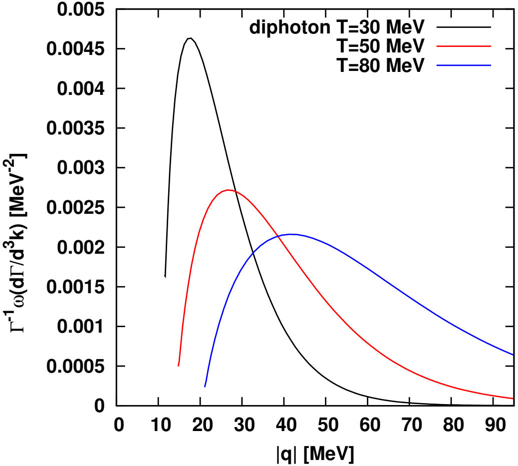
$c_V \simeq \pi^2 \sum_f n_f T/\mu_f$

thermal conductivity $\kappa \simeq \sum_f \mu_f^2/\alpha_s$

Heiselberg & Pethick, PRD **48**, 2916 (1993)



Direct photon spectrum



"direct"=no secondary scattering

Differential spectrum
Function of T and density

★ candidate feature(s) to identify NS merger as source

★ source of cosmic rays

to do:
calculate e^+e^- conversion, plasma scattering

differs from massive particle spectrum due to nontrivial dispersion relation

Other sources of photons

- Thermal emission: large but phenomenologically simple

$$\sigma_{SB}T^4 \simeq 4\times 10^{21}\,\frac{\mathrm{MeV}}{\mathrm{fm^2\,s}} \quad \text{(Stefan-Boltzmann estimate)}$$

- Conformal anomaly–phase change

$$\frac{dE}{dVdt}l_f \simeq 4.4\times 10^{12}\,(100\,\mathrm{fm})\frac{\mathrm{MeV}}{\mathrm{fm^3\,s}} \quad \text{at } T\sim 30\text{ MeV}$$

smaller, but distinguishable as spectral component
estimate assumes $\zeta/T^3 \sim O(1)$ – can be enhanced near transition

- Electromagnetic bremstrahlung, $p+p\to p+p+\gamma$ (also e^-)

$$\left.\frac{dE}{dVdt}\right|_{brem} l_f = n_p\frac{2}{3}\alpha\dot{v}^2\gamma^6 \simeq 7.2\times 10^9\,\frac{\mathrm{MeV}}{\mathrm{fm^3\,s}}(100\,\mathrm{fm})$$

Suppressed by small QED coupling, smaller number of charged particles $n_p \simeq 0.01 n_B$

Opportunities with pions$\longrightarrow$ neutrinos

Nucleon-nucleon scattering into pions

1. Further source of photons:

$N + N \rightarrow N + N + \pi^0$ for $N = n, p$, then decay $\pi \rightarrow 2\gamma$

$$\frac{dE}{dVdt}\bigg|_{\pi} \updownarrow_{f,\pi} = m_\pi \sigma n_B^2 vF \simeq 5.3 \times 10^{18}\ (n_B^{-1/3}) \frac{\mathrm{MeV}}{\mathrm{fm^3\,s}}$$

$F \sim e^{-m_\pi/T}$= statistical factor for Pauli blocking in degenerate gas

★ large rate due to cross section (σ=a few$\times$10μb)

★ also expected to be distinct spectral component due to pion mass

2. Source of prompt neutrinos

$n + n \rightarrow n + p + \pi^- \quad n + p \rightarrow n + n + \pi^+ \quad n + p \rightarrow p + p + \pi^-$

charged pions subsequently decay into charged lepton plus neutrino

$\Rightarrow$ if muon, then up to 3 neutrinos per NN collision:

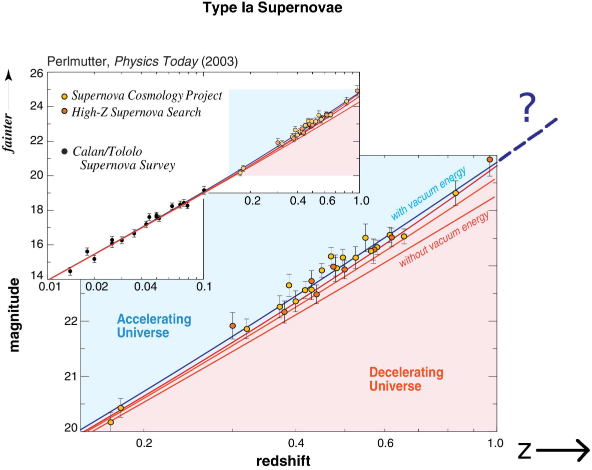
$$3\ \frac{dN}{dVdt}\bigg|_{\pi} l_{f,\pi} = \sigma_{NN\pi} n_B^2 vF \simeq 3.9 \times 10^{16}\ (n_B^{-1/3}) \frac{1}{\mathrm{fm^3\,s}}$$

Conclusions

- Neutron star mergers are violent, involving high densities and moderate temperatures $T \sim 20 - 100\ \mathrm{MeV}$
- QCD processes very fast $\Rightarrow$ nuclear matter equilibriates, probe new region of phase diagram
- Photon emission due to dissipation of collective modes depends on bulk properties ζ, κ of matter during collision
- Knowing QCD physics even qualitatively provides opportunity as a source of cosmic rays and signatures may be able to identify NS mergers
- More exotic phenomenology when considering also magnetic field

Extra Slides

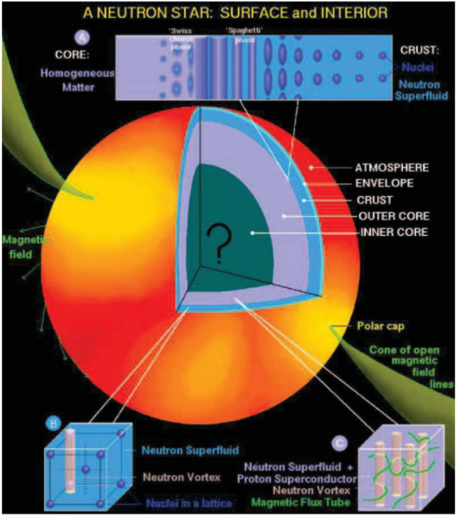
Brighter standard candles needed!



Extend Hubble measurement to $z > 1$, Probe dark energy

e.g. possible time dependent Equation of state $w = w_0 + w_1(1-a) + ...$

Fuzzy picture of neutron stars



Nuclear "saturation" density

$$n_{\text{sat}} \simeq 0.17\,\text{fm}^{-3}$$

1. crust: mostly neutrons

$0.2\% - 2\%$ protons believed in a Wigner-Seitz lattice of neutron-rich nuclei

neutron superfluid suggested by glitch phenomenon

2. core: ??

Lattimer & Prakash, Science 304, 536 (2004); PhysRept 442, 109 (2007)

How photons couple, 1: Conformal anomaly

Energy-momentum Trace Θ^μ_μ breaks Scale invariance
(quantum effect, running of the coupling constant)
$\Rightarrow$ anomalous source of dilatational current

$$\partial_\mu S^\mu = \Theta^\mu_\mu = \frac{\beta(\alpha)}{4\alpha} G^a_{\mu\nu} G^{a,\mu\nu} + \sum_f (1+\gamma_f) m_f \bar{q}_f q_f$$

β=QCD renormalization group function, γ_f=quark anomalous dimension
** also small, explicit breaking by quark masses

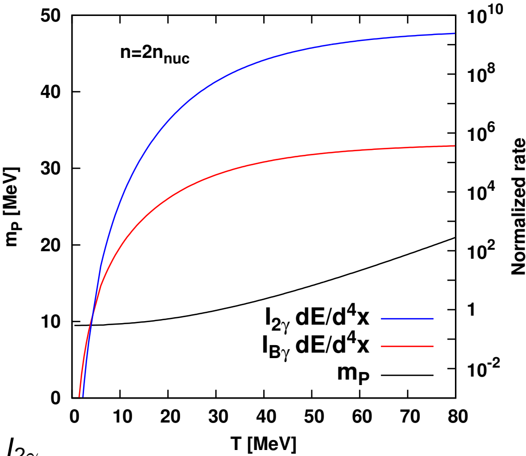
J. Ellis, Nucl. Phys. B **22**, 478 (1970); M. Chanowitz and J. Ellis, Phys. Lett. B **40**, 397 (1972)

Low-energy effective theory for broken symmetry:
acting on vacuum Θ^μ_μ operator creates scalar, color singlet σ meson

$$\langle 0 | \Theta^\mu_\mu | \sigma \rangle = m_\sigma^2 f_\sigma$$

Ellis & Lanik, Phys. Lett. B **150**, 289 (1985), **175**, 83 (1986)

Energy loss rates



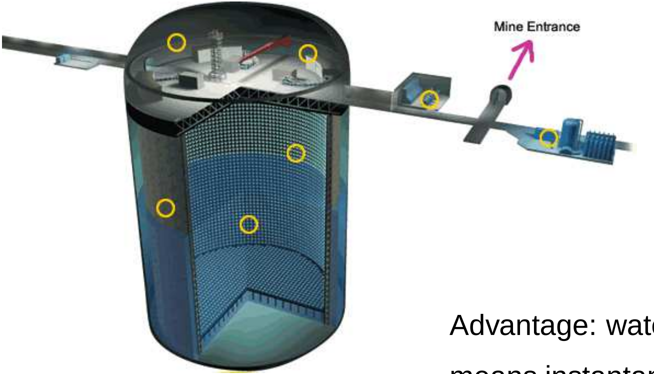
$s_0 =$ entropy of (u, d, e) plasma at $T = 50$ MeV and $2n_{\rm nuc}$

$$\left.\frac{dE}{d^4x}\right|_{2\gamma} \propto 7.13\,\frac{\rm TeV}{\rm fm^3 s}\,\frac{\zeta}{s}\,\frac{s}{s_0}\left(\frac{T}{20\,\rm MeV}\right)^3 I_{2\gamma}$$

$$\left.\frac{dE}{d^4x}\right|_{B\gamma} \propto 5.51\,\frac{\rm GeV}{\rm fm^3 s}\,\frac{\zeta}{s}\,\frac{s}{s_0}\left(\frac{T}{20\,\rm MeV}\right)^3 \frac{\vec{B}^2}{B^2_{\rm QED}} I_{B\gamma}$$

Experimental Input, Now...

Super Kamiokande, ARA (LeCosPA/NTU project),
... IceCube and other neutrino
experiments

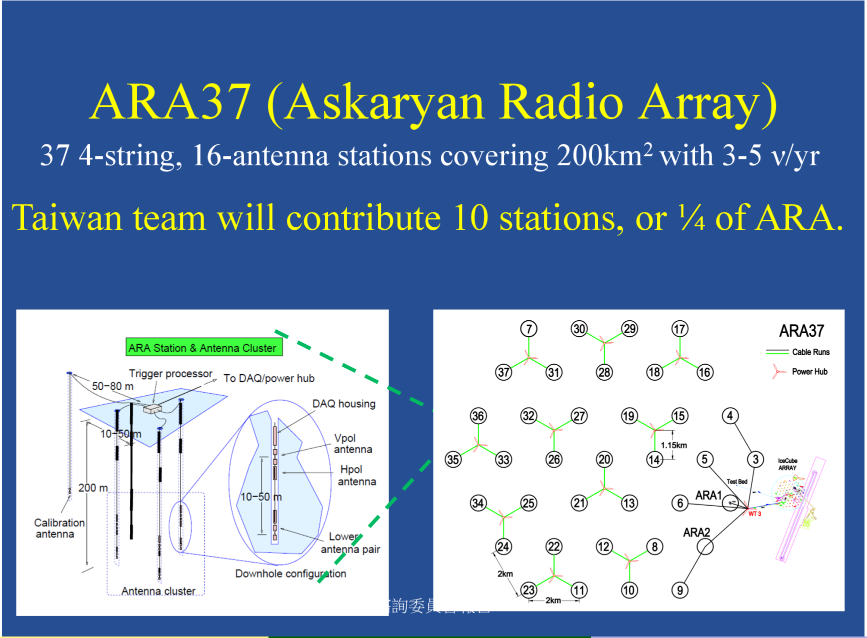


from SuperK's website

Advantage: watching whole sky

means instantaneous detection and coverage of events

Experimental Input, ... and Coming



ARA37 (Askaryan Radio Array)

37 4-string, 16-antenna stations covering 200km^2 with 3-5 ν/yr

Taiwan team will contribute 10 stations, or ¼ of ARA.

Experimental Input,... and Coming

UFFO = Ultra Fast Flash Observatory

- slewing mirror: millisecond response to GRB

$\gtrsim$ 50 events/year

Correlate events with neutrinos and high energy cosmic rays

LeCosPA/NTU project!