Photons signaling a QCD phase transition in neutron star mergers

Lance Labun

Leung Center for Cosmology and Particle Astrophysics (LeCosPA)
Department of Physics, National Taiwan University

arXiv:1305.7397, PRD 88, 083006 (2013)

Motivation from Cosmology/Astrophysics

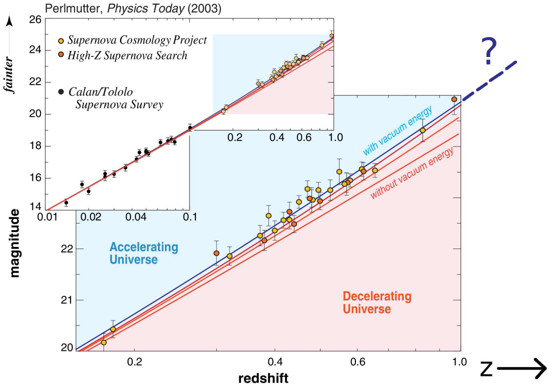
short GRBs thought to signal neutron star-neutron star mergers

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

Visible at cosmological distances $z > 1$

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

Type Ia Supernovae



2. Solidfy short GRB - neutron star merger relationship

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]		$\sim$2		$\sim$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)

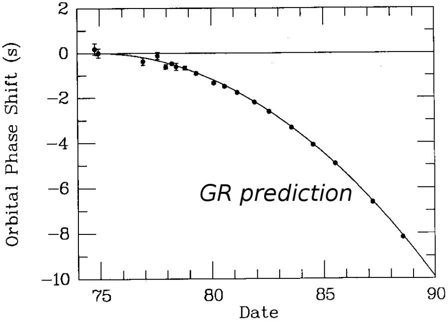
Why and how neutron star binaries merge

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 $r_{\rm coll} \simeq 2R_*$

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)

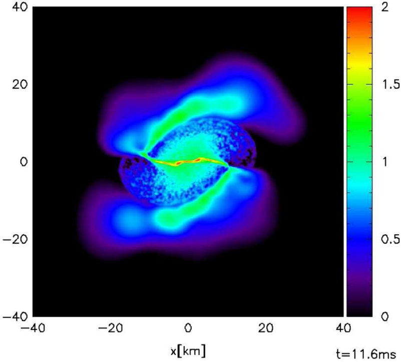
Near surface of initial stars : $n/n_{\rm sat} \simeq 0.15 - 0.6$

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

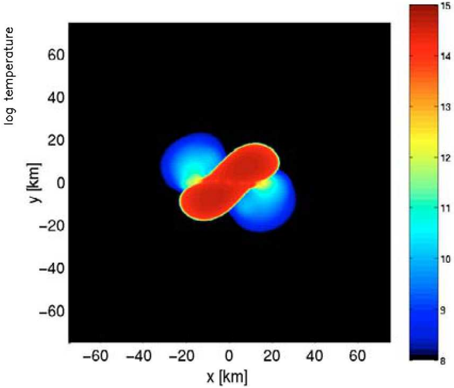
Expected density $n/n_{\rm sat} \simeq 0.3 - 2.4$

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

Numerical simulation



left, temperature in units MeV



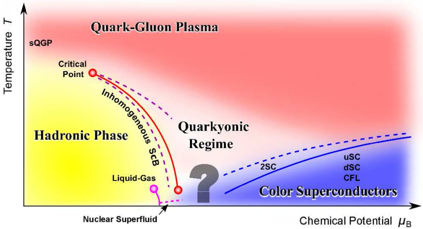
right: log plot of density in g/cm^3

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

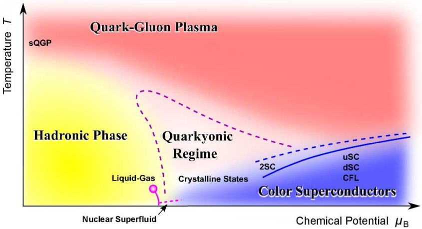
Bauswein, Janka & Oechslin, PRD 82 (2010) 084043;

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

Sensitive region of the QCD phase diagram



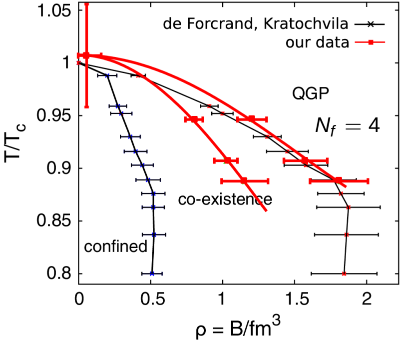
Fukushima & Sasaki, arXiv:1301.6377



- 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:

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

- 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 $\tau_{\rm weak}^{-1} \simeq \frac{1}{T^4}\ \frac{dE}{dt}\Big|_{\rm Urca}$

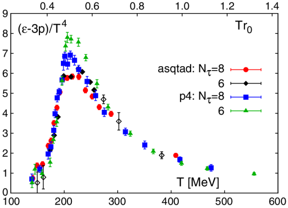
e.g. in quark phases $u + e^- \to d + \nu_e$, $d \to u + e^- + \bar{\nu}_e$

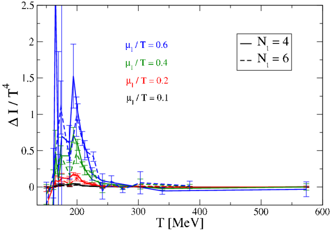
- Merger timescale: final orbital period $\tau_{\rm merger} \sim 1\,{\rm ms}$

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



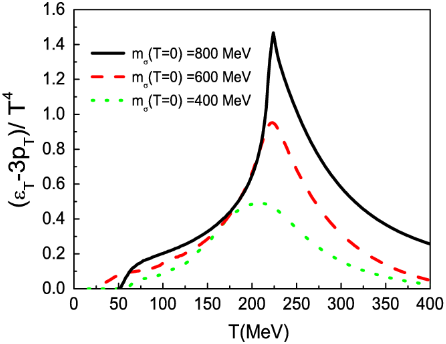


Lattice results:

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)

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

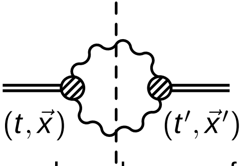
Spectral representation : $\frac{1}{\omega}\mathtt{Im}\left[G_{\mu\mu,\nu\nu}(\omega,\vec{k})\right] = \frac{\rho_\sigma(\omega)}{\omega} \simeq \frac{9}{\pi}\zeta$

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

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



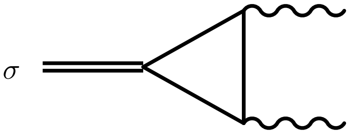
hadron level theory — no explicit quark or gluon degrees of freedom

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
$\Rightarrow$ 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 $k \ll 50\ \mathrm{GeV}$

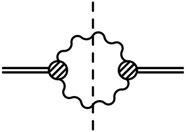
parameters from $\sigma - f_0$ meson in vacuum
** assume in-medium properties contained in spectral function $\rho_\sigma(\omega,\vec{k})$

Photon production: two cases

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

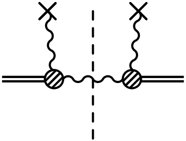
a) final state → two real photons

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



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)

Energy loss rates

Obtain energy release by integrating weighted with k^μ

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

Dense plasma → Refractive medium: finite mean free path
$l_f \sim (e m_\mathrm{P})^{-1} \sim 100\ \mathrm{fm}$
$\Rightarrow$ effective photon mass: fix photon energy from medium to vacuum:
$\vec{k}^2_\mathrm{vac} = \omega^2$

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

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

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

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

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!

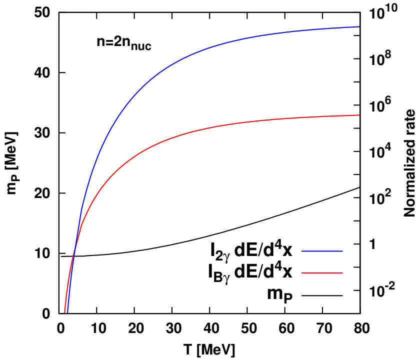
Compare to heat conduction

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

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

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

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



Other sources of photons

- Thermal emission: phenomenologically simple background
$$\sigma_{SB} T^4 \simeq 4 \times 10^{21}\,\frac{\mathrm{MeV}}{\mathrm{fm}^2\,\mathrm{s}} \qquad \text{(Stefan-Boltzmann estimate)}$$
- Bulk viscosity–anomaly
$$\frac{dE}{dVdt} l_f \simeq 4.4 \times 10^{12}\,(100\,\mathrm{fm})\frac{\mathrm{MeV}}{\mathrm{fm}^3\,\mathrm{s}} \qquad \text{at } T \sim 30 \text{ MeV}$$

Emitted from surface layer: $\sim l_f = 100\ \mathrm{fm}$
estimate assumes $\zeta/T^3 \sim O(1)$ – can be enhanced near transition

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

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

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

Extra Slides

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

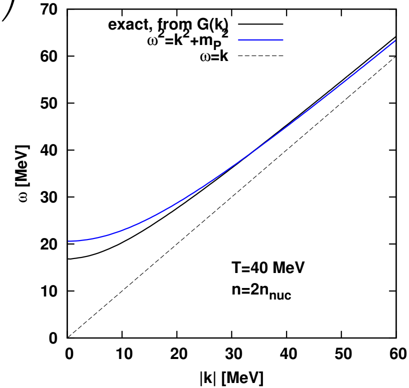
$$m_{\mathrm{P}}^2 = \frac{1}{2}\sum_f (Q_f e)^2 \left(\frac{T^2}{3} + \frac{\mu_f^2}{\pi^2}\right) \simeq (10 - 20\ \mathrm{MeV})^2$$

Mean free path

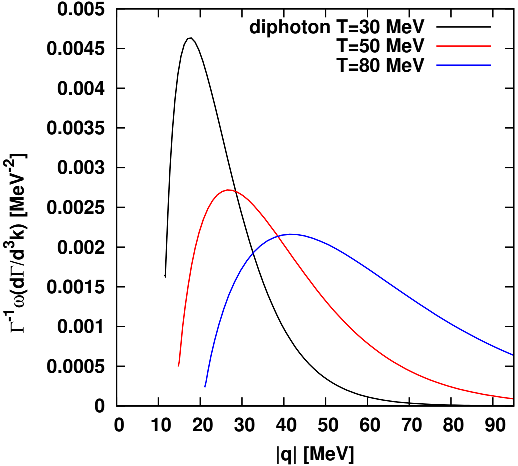
$l_f \sim (e m_{\mathrm{P}})^{-1} \sim 100\ \mathrm{fm}$

from Im [photon self-energy]

$\Rightarrow$ only boundary layer releases energy



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

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 $\pi \rightarrow 2\gamma$

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

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

★ large rate due to cross section (σ=a few×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:

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

Fuzzy picture of neutron stars

Nuclear “saturation” density

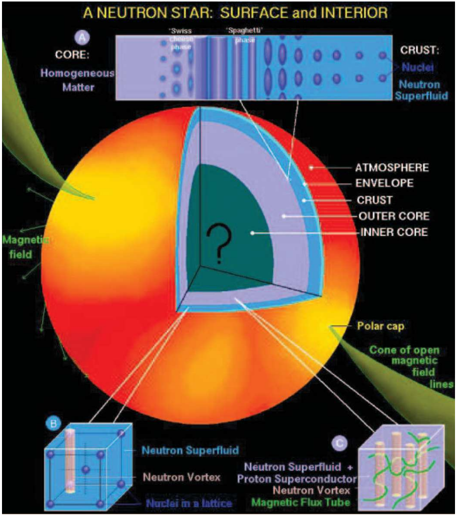
$$n_{\text{sat}} \simeq 0.17\,\text{fm}^{-3}$$

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

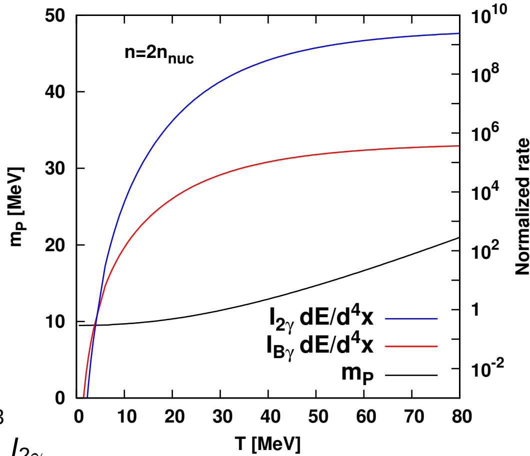
J. Ellis, Nucl. Phys. B **22**, 478 (1970); M. Chanowitz and J. Ellis, Phys. Lett. B **40**, 397 (1972)

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



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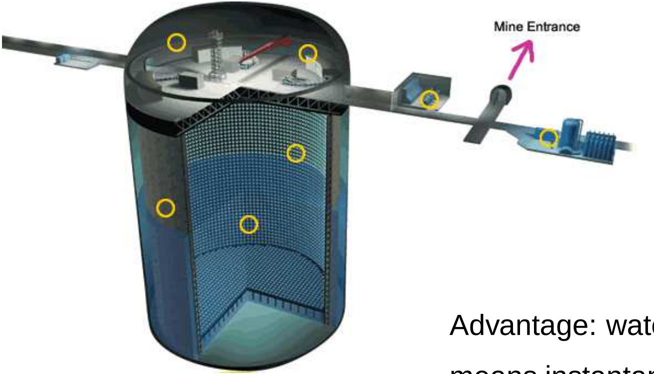
$$\left.\frac{dE}{d^4x}\right|_{2\gamma} \propto 7.13\frac{\mathrm{TeV}}{\mathrm{fm}^3\mathrm{s}}\frac{\zeta}{s}\frac{s}{s_0}\left(\frac{T}{20\,\mathrm{MeV}}\right)^3 I_{2\gamma}$$

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

Experimental Input, Now...

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

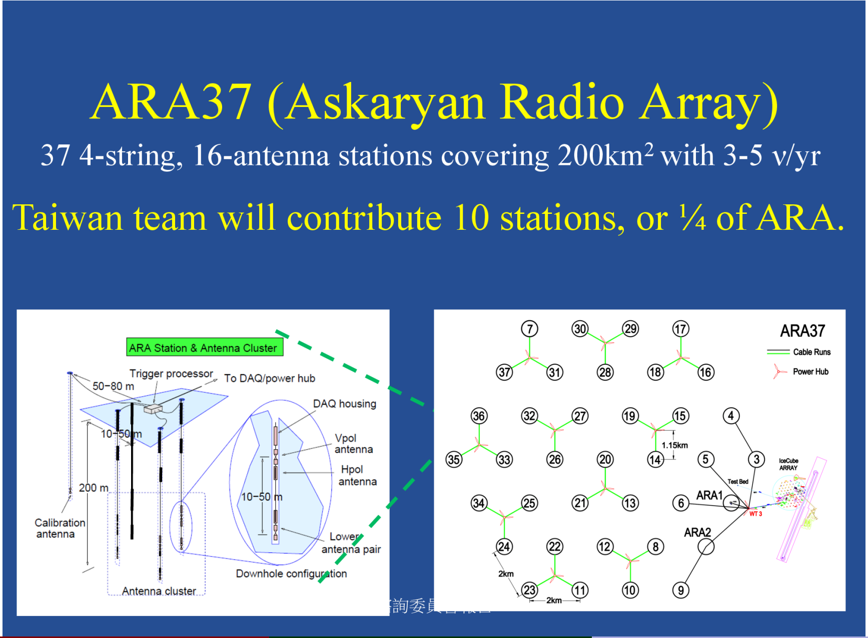


from SuperK's website

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,... Coming

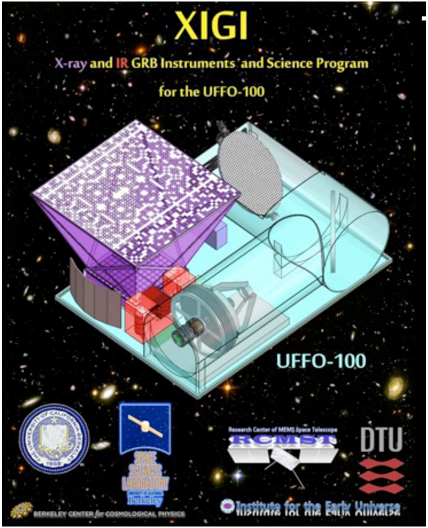
UFFO = Ultra Fast Flash Observatory

- slewing mirror: millisecond response to GRB

$\gtrsim$ 50 events/year

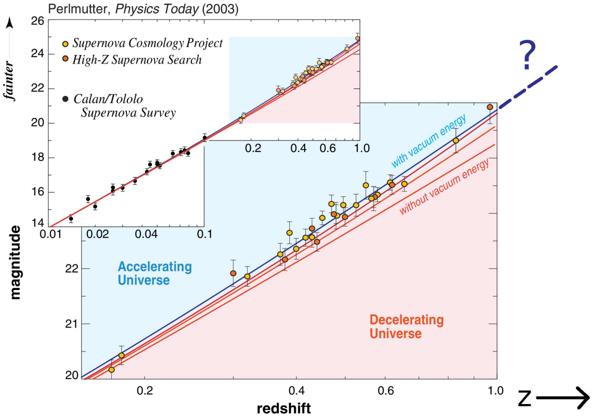
Correlate events with neutrinos and high energy cosmic rays

LeCosPA/NTU project!



Brighter standard candles needed!

Type Ia Supernovae



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

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