Probing QCD phase transitions with neutrinos from neutron-star mergers

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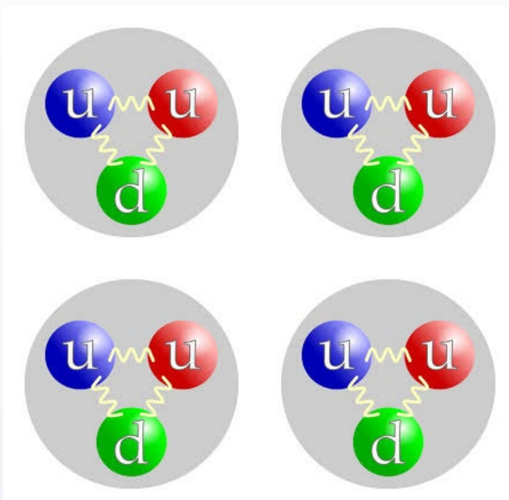
Outline

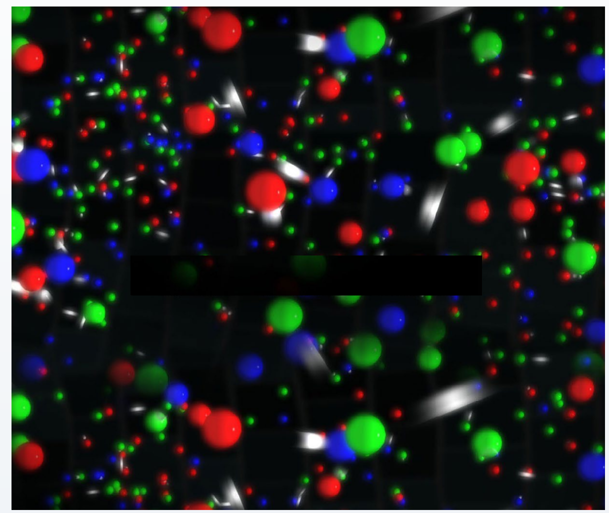
1. What are QCD phase transitions?
2. What are neutron-star mergers?
3. How can QCD phase transitions affect neutrino emissions?
4. What are the neutrino signatures from remnants of neutron-star mergers
5. Summary

1. QCD phase transitions

QCD phase transition

hadrons | **quarks**



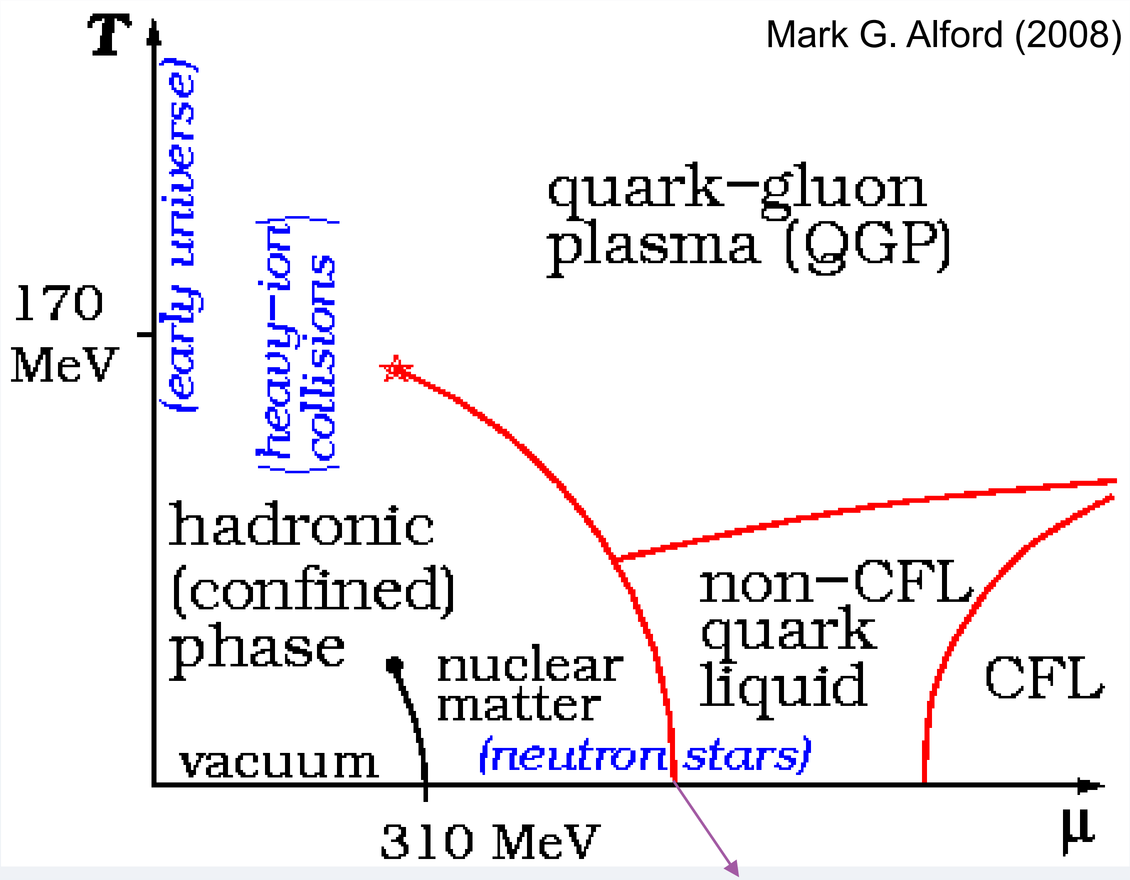


Nuclear saturation density ~$2 \times 10^{15} g\ cm^{-3}$

Temperature ~ 10^{12} K

Deconfinement

QCD phase diagram



Nuclear saturation density ~$2 \times 10^{15} g\ cm^{-3}$

Models for QCD – some examples

Hadron phase:

NLWM (non-linear Walecka model)

QMC model

Unparied quark phase:

NJL (Nambu-Jona Lasinio) model

MIT Bag model *

$$\mathcal{L} = \left[\frac{i}{2}\left(\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - \left(\partial_{\mu}\bar{\psi}\right)\gamma^{\mu}\psi\right) - B\right]\theta_{v}(x) - \frac{1}{2}\bar{\psi}\psi\Delta_{s}$$

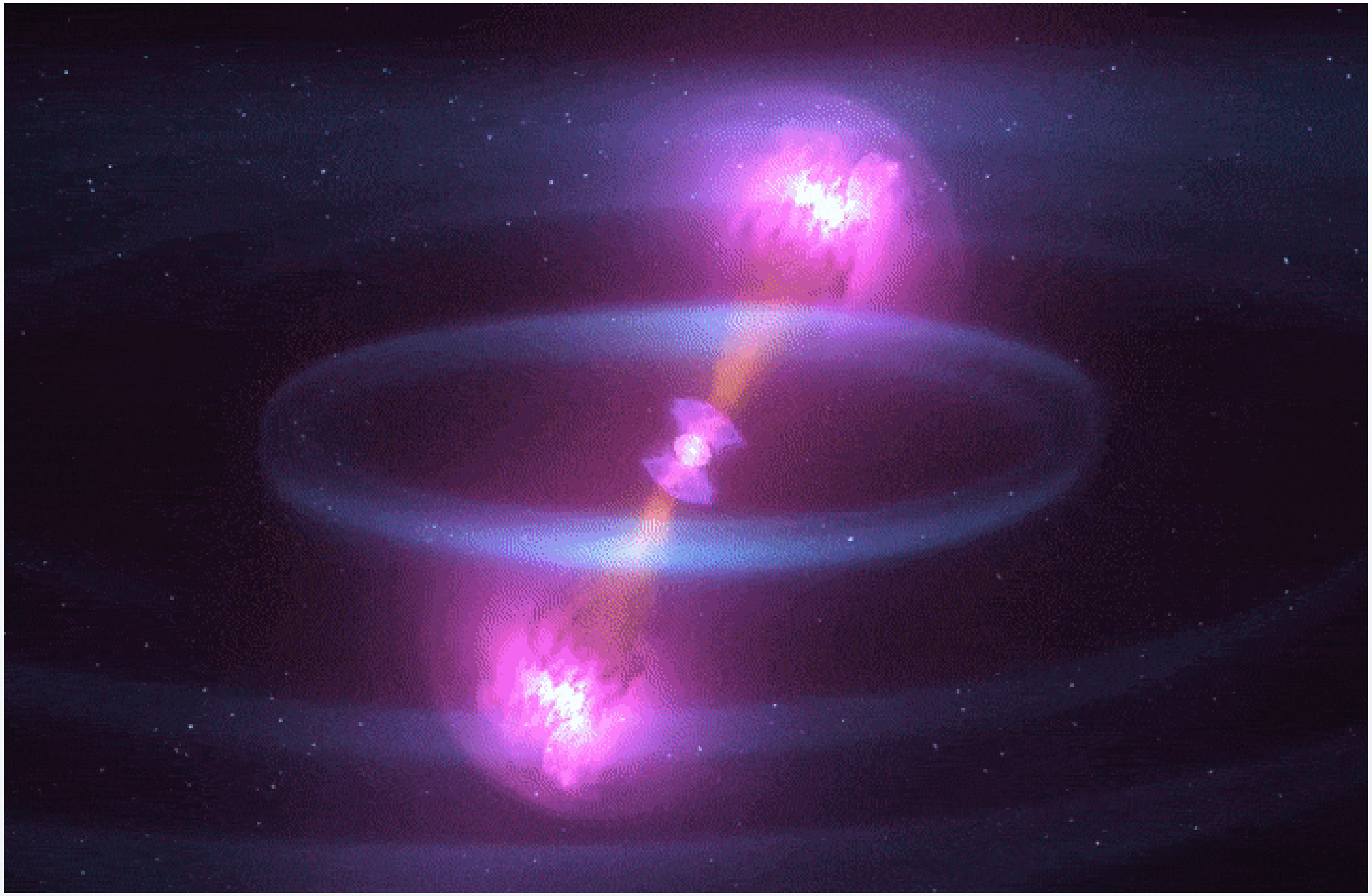
...

CFL (color flavored locked) phase:

Perturbation theory

2. Neutron-star mergers as laboratory for QCD phase transition

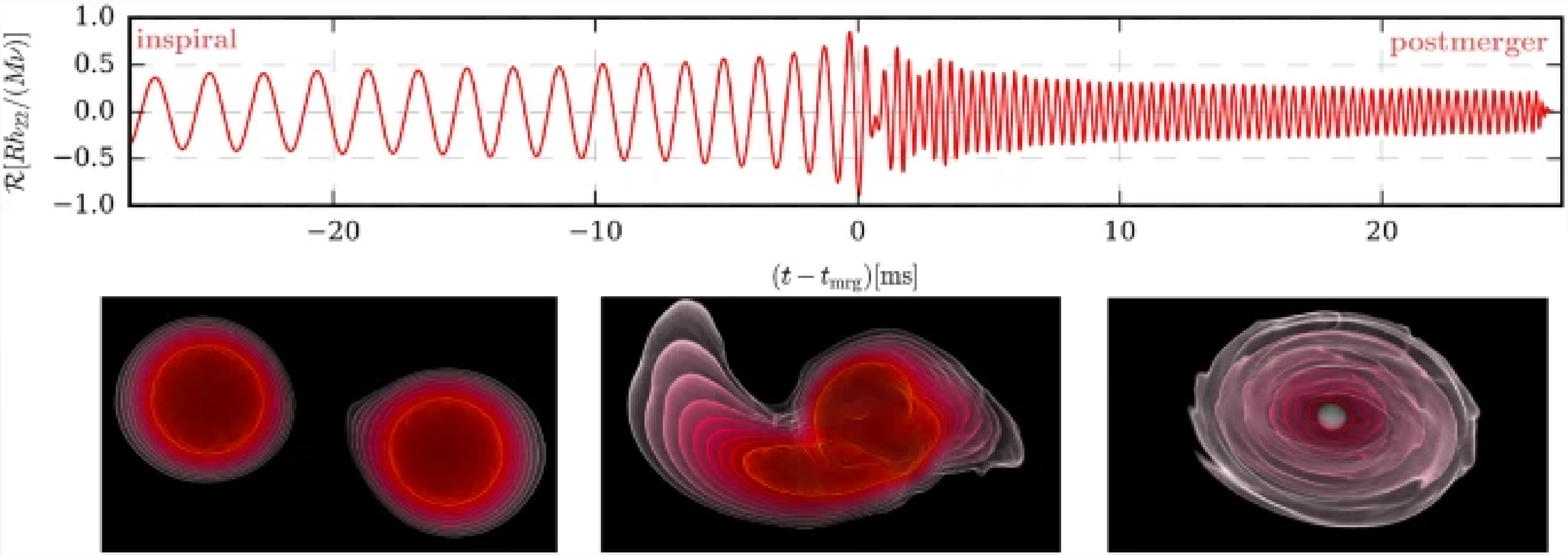
Neutron star — neutron star merger



Credit: NASA’s Goddard Space Flight Center/CI Lab

GW signals from NS-NS merger

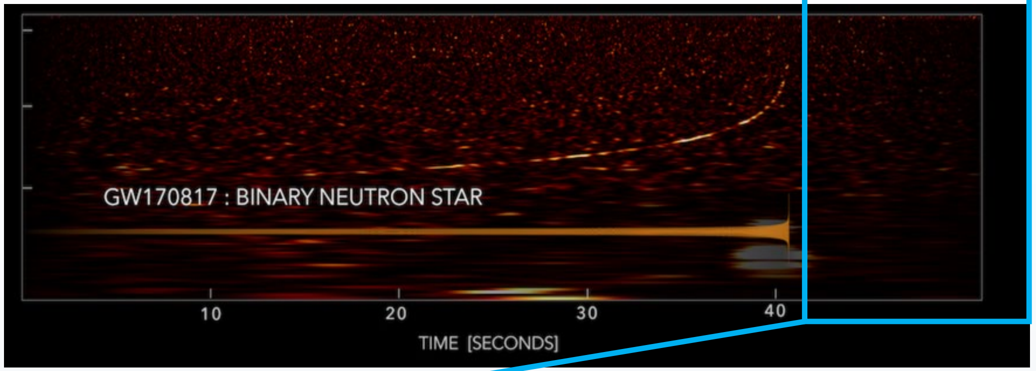
Dietrich, T., Hinderer, Gen Relativ Gravit 53, 27

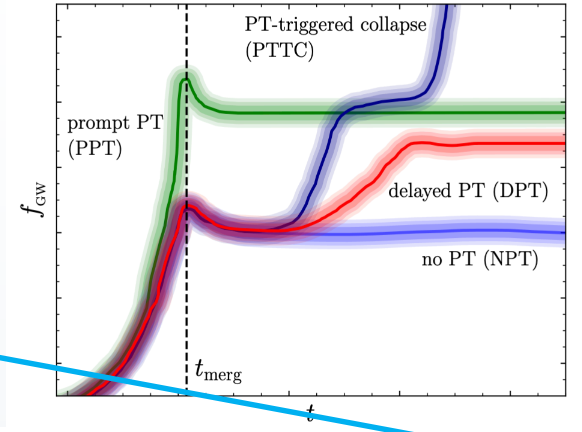


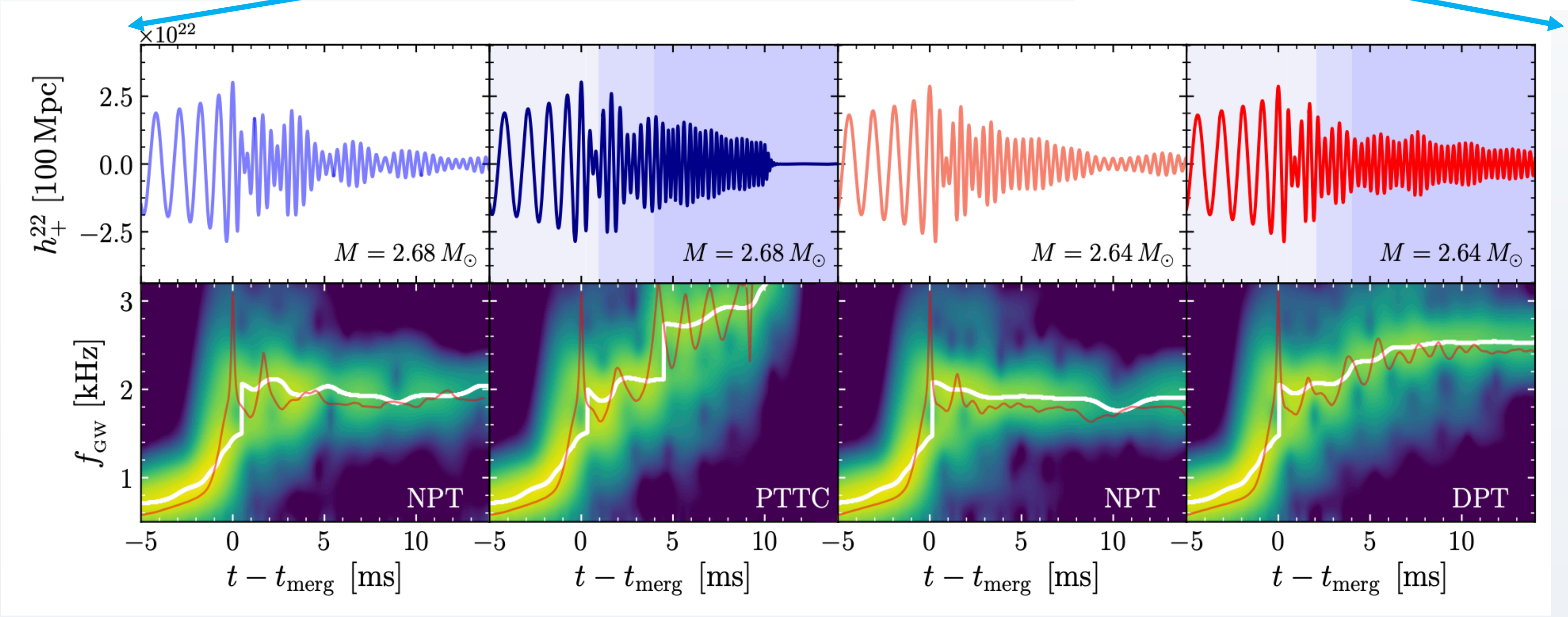
Inspiral | Merger | Ring-down

NS + NS | merger + ejecta | HMNS + disk

Missing physics in the ring-down phase







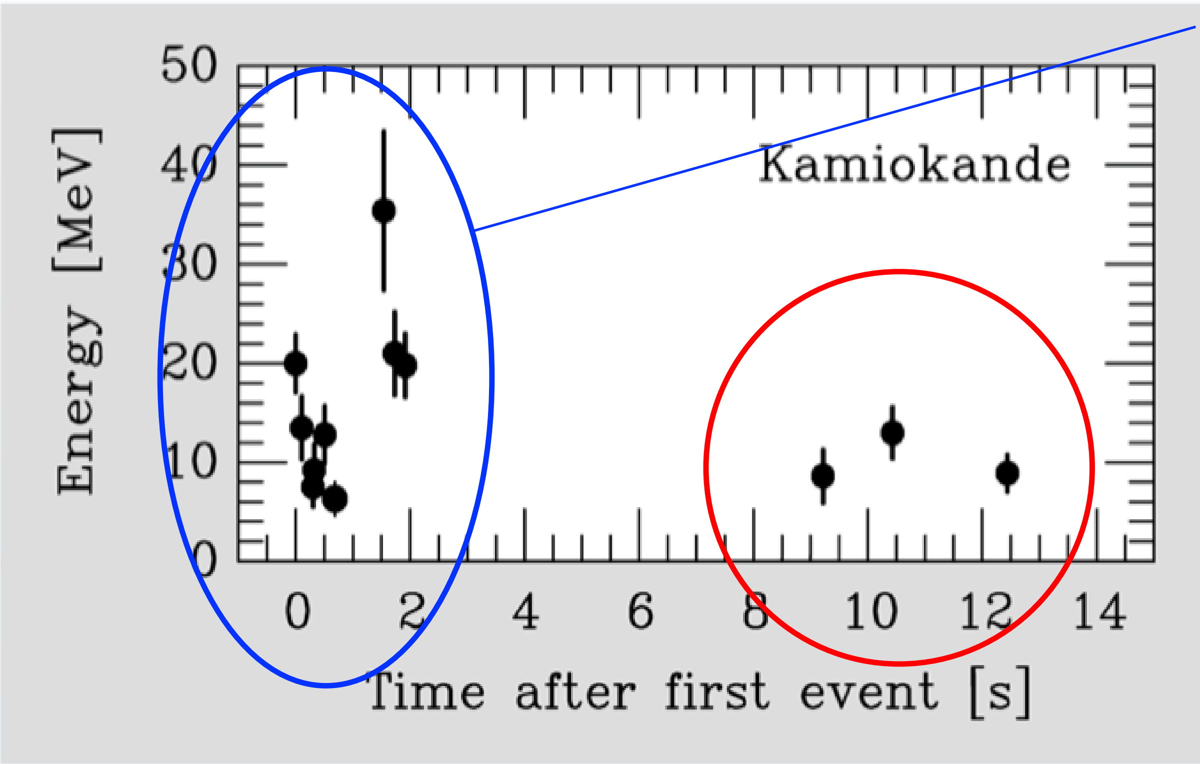
Lukas R. Weih (2019)

3.Neutrinos from QCD phase transition

Previous neutrino detection

— imply QCD phase transition

Supernova SN1987A



First neutrino burst

Possible second burst of neutrino emission (due to phase transition)

Ben (2011)

Neutrino Reactions

A. Perego (2014)

Reaction
$e^- + p \leftrightarrow n + \nu_e$
$e^+ + n \leftrightarrow p + \bar{\nu}_e$
$e^- + (A, Z) \leftrightarrow \nu_e + (A, Z-1)$
$N + \nu \leftrightarrow N + \nu$
$(A, Z) + \nu \leftrightarrow (A, Z) + \nu$
$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$
$N + N \leftrightarrow N + N + \nu + \bar{\nu}$

(i) neutrino nucleon scattering:

$$\nu_i + \{\mathrm{n}, \mathrm{p}\} \rightarrow \nu_i + \{n, p\}$$

(ii) neutrino emission:

$$\mathrm{p} + e^- \rightarrow \nu_e + n$$

$$\mathrm{n} + e^+ \rightarrow \bar{\nu}_e + p$$

(iii) neutrino absorption:

$$\nu_\mathrm{e} + \mathrm{n} \rightarrow p + \mathrm{e}^-$$

$$\bar{\nu}_\mathrm{e} + \mathrm{p} \rightarrow n + \mathrm{e}^+$$

Neutrinos from QCD phase transition

$$L_{\nu,\mathrm{ns}} \sim \frac{\Delta E_{\mathrm{ns}}}{t_{\mathrm{diff,ns}}} \approx \frac{c}{3}\Delta E_{\mathrm{ns}} R_{\mathrm{ns}}^{-2} \lambda_{\mathrm{scatter}}$$

phase	process	λ(T=5 MeV)	λ(T=30 MeV)
Nuclear Matter	$\nu n \to \nu n$	200 m	1 cm
	$\nu_e n \to e^- p$	2 m	4 cm
Unpaired Quarks	$\nu q \to \nu q$	350 m	1.6 m
	$\nu_e d \to e^- u$	120 m	4 m
CFL	λ_{3B}	100 m	70 cm
	$\nu \phi \to \nu \phi$	$\geq$ 10 km	4 m

S. Reddy (2003)

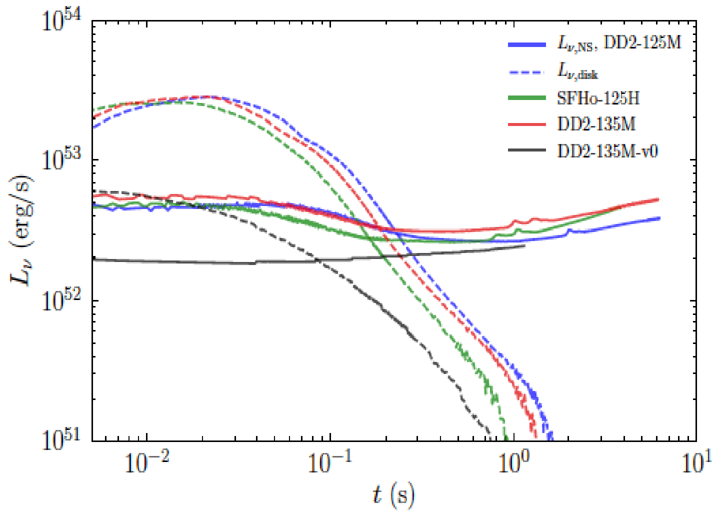
$$\lambda_{3\mathrm{B}} \sim \nu H \to \nu H$$

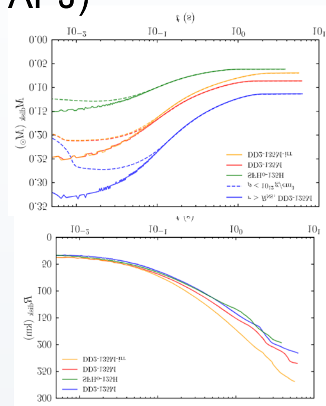
H: CFL Goldstone boson

4. Neutrino emission from remnant of neutron-star mergers

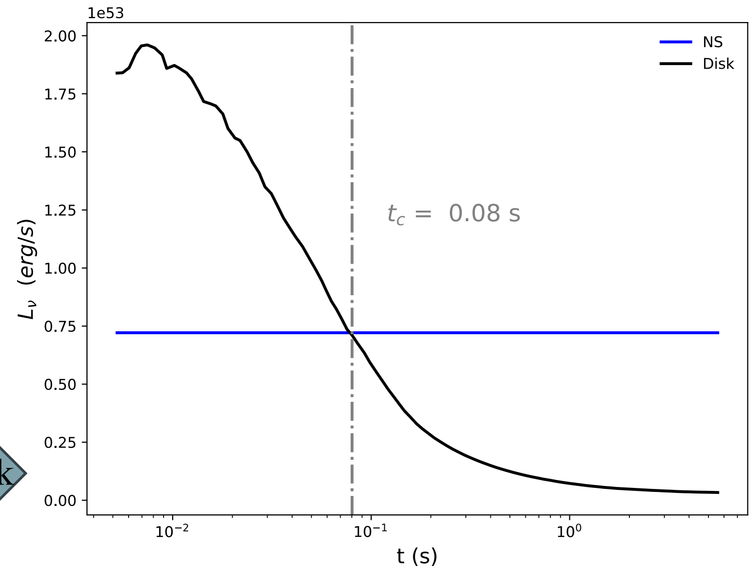
Neutrino emission — method

Sho Fujibayashi (2020, APJ)





Mass, radius profile of disk



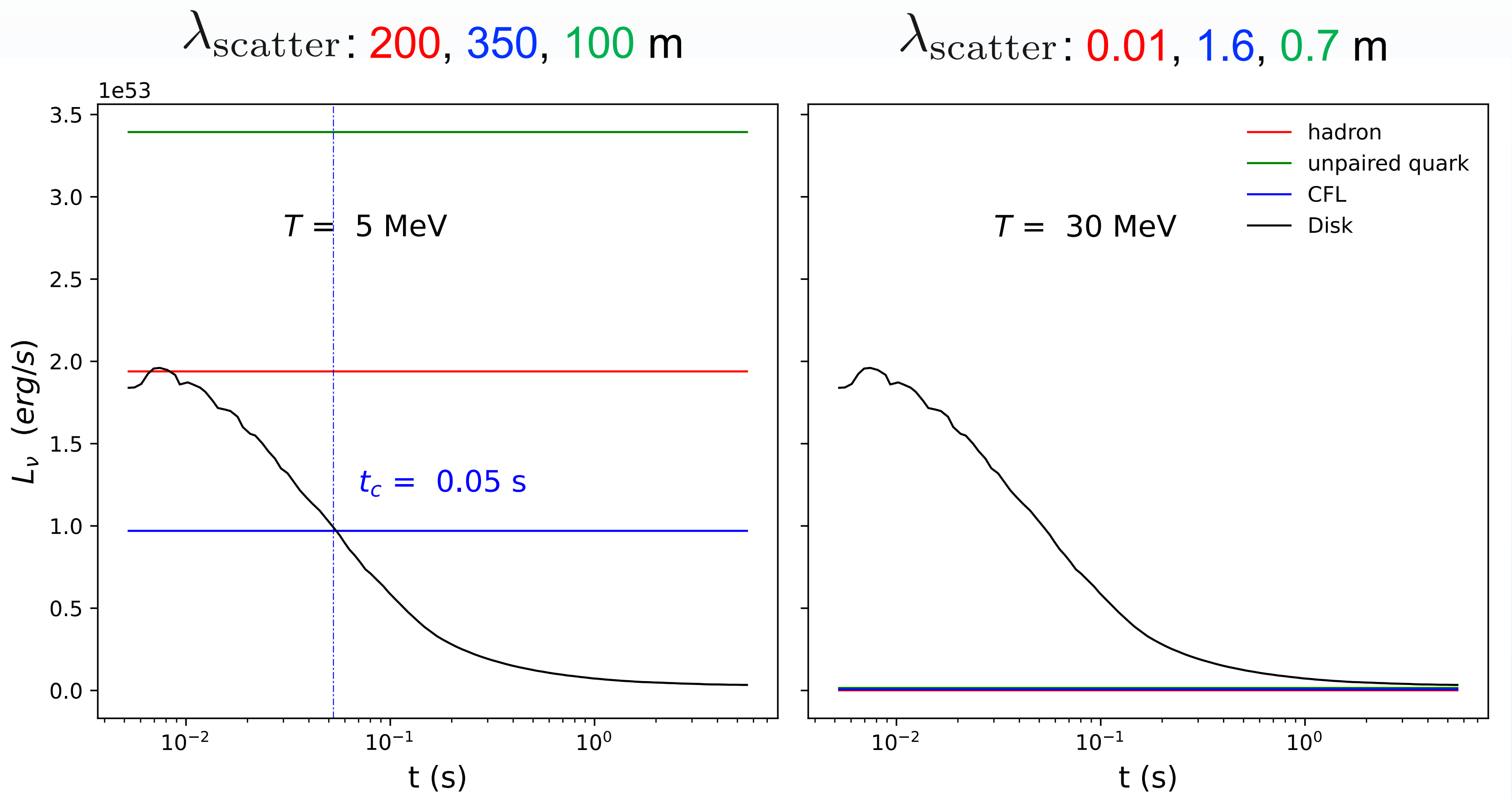
Neutrino transport:

- leakage-based scheme
- neutrino absorption

$$L_{\nu,\rm disk} \sim 0.5\frac{\Delta E_{\rm grav}}{t_{\rm disk}}$$

$$L_{\nu,\rm ns} \sim \frac{\Delta E_{\rm ns}}{t_{\rm diff,ns}} \approx \frac{c}{3}\Delta E_{\rm ns} R_{\rm ns}^{-2} \lambda_{\rm scatter}$$

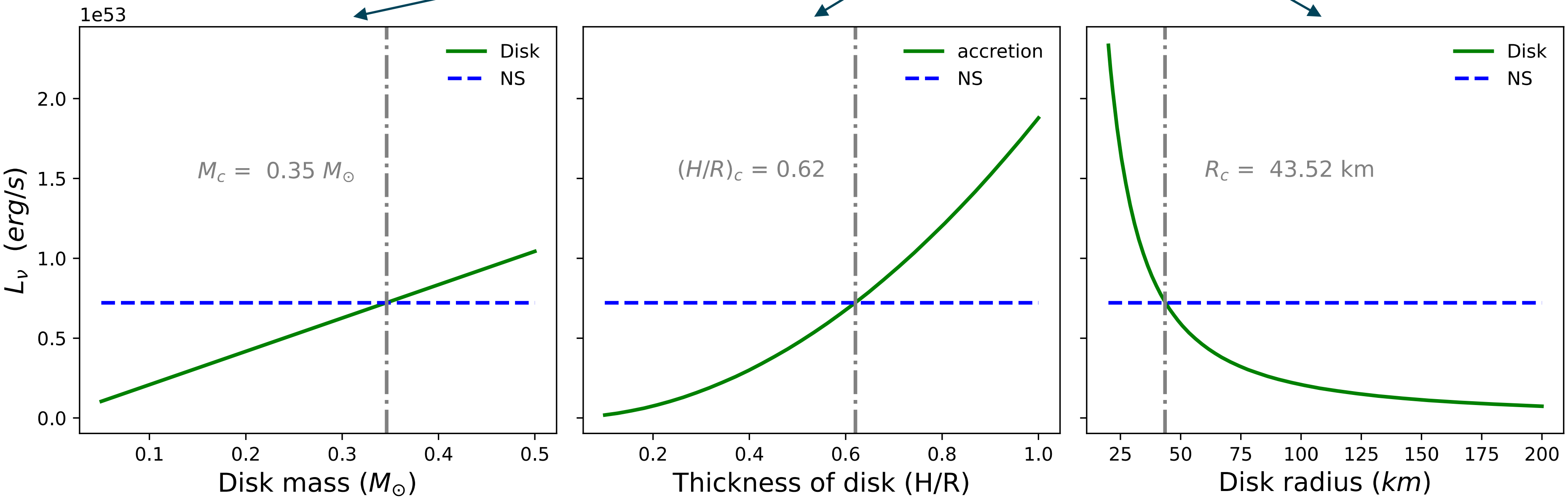
Neutrino emission — affect by NS



Neutrino emission — affect by disk

A. Perego (2014)

$$L_{\nu,\mathrm{disc}} \sim 0.5\,\frac{\Delta E_{\mathrm{grav}}}{t_{\mathrm{disc}}} \approx 8.35\cdot 10^{52}\,\frac{\mathrm{erg}}{\mathrm{s}}\left(\frac{M_{\mathrm{ns}}}{2.5\,M_\odot}\right)^{3/2}\left(\frac{\alpha}{0.05}\right)\left(\frac{M_{\mathrm{disc}}}{0.2\,M_\odot}\right)\left(\frac{H/R}{1/3}\right)^{2}\left(\frac{R_{\mathrm{disc}}}{100\,\mathrm{km}}\right)^{-3/2}\left(\frac{R_{\mathrm{ns}}}{25\,\mathrm{km}}\right)^{-1}$$



Ejecta mass | Thermal energy of disk | Thermal vs gravity

Next step: treatment of neutrino transport

Radiative transport:

absorption emission scattering

$$\left(\frac{1}{c}\frac{\partial}{\partial t} + \hat{\mathbf{\Omega}} \cdot \nabla\right) I_\nu(\hat{\mathbf{\Omega}}) = -\kappa_\nu(\hat{\mathbf{\Omega}}) I_\nu(\hat{\mathbf{\Omega}}) + j_\nu(\hat{\mathbf{\Omega}}) + \iint \mathrm{d}\Omega' \, \mathrm{d}\nu' \; \sigma(\nu, \hat{\mathbf{\Omega}}; \nu', \hat{\mathbf{\Omega}}') \, I_{\nu'}(\hat{\mathbf{\Omega}}')$$

General relativistic radiative transport:

absorption emission scattering

$$\frac{\mathrm{d}\mathcal{I}(x^\beta, k^\beta)}{\mathrm{d}\xi} = -k^\alpha u_\alpha \Big|_\xi \left[-\chi_0(x^\beta, k^\beta) \mathcal{I}(x^\beta, k^\beta) + \eta_0(x^\beta, k^\beta) + \int \mathrm{d}^4 k'^\beta \sigma(x^\beta; k^\beta, k'^\beta) \mathcal{I}(x^\beta, k^{\beta\prime}) \right]$$

Next step: treatment of neutrino transport

General relativistic radiative transport:

Methods	Pros	Cons	Example (Ref)
Leakage schemes	Easy to calculate	Easy to broke	ASL scheme Perego et al. (2016)
Moments-based radiation transport	Acceptable accuracy	Expensive	Grey moment scheme Foucart et al. 2016b
Monte-Carlo radiation transport	Most accurate	Most expensive	Foucart et al. 2020

5. Summary

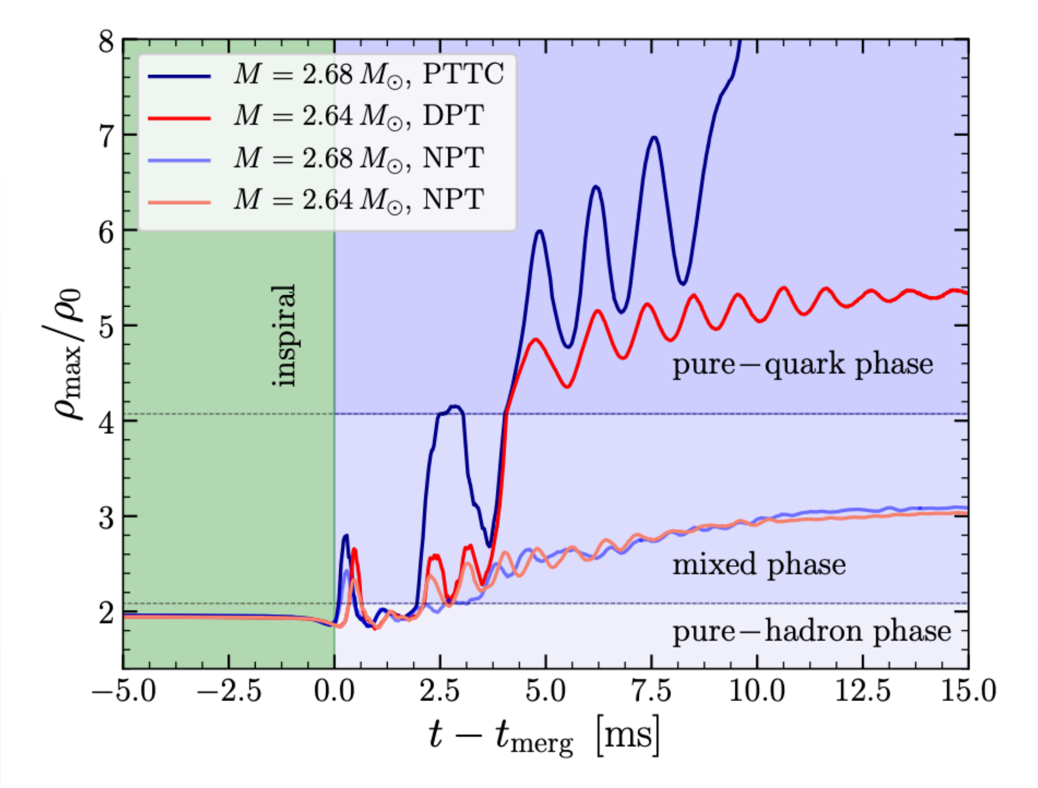
Summary

1. QCD phase transition is a fundamental particle property that can be probe by celestial objects.
2. Remnant of neutron star merger is highly dependent on nuclear physics.
3. Neutrino as one of the multi-messengers can be a helpful tool to study the remnant of Neutron-star mergers, especially when QCD phase transition happens.

Back-up slides

Neutrino emission — QCD phase transition

Density profiles of various neutron-star mergers



Lukas R. Weih (2019)

Density profiles before 10 ms are useful indicator of QCD phase transition

Standard model of particles

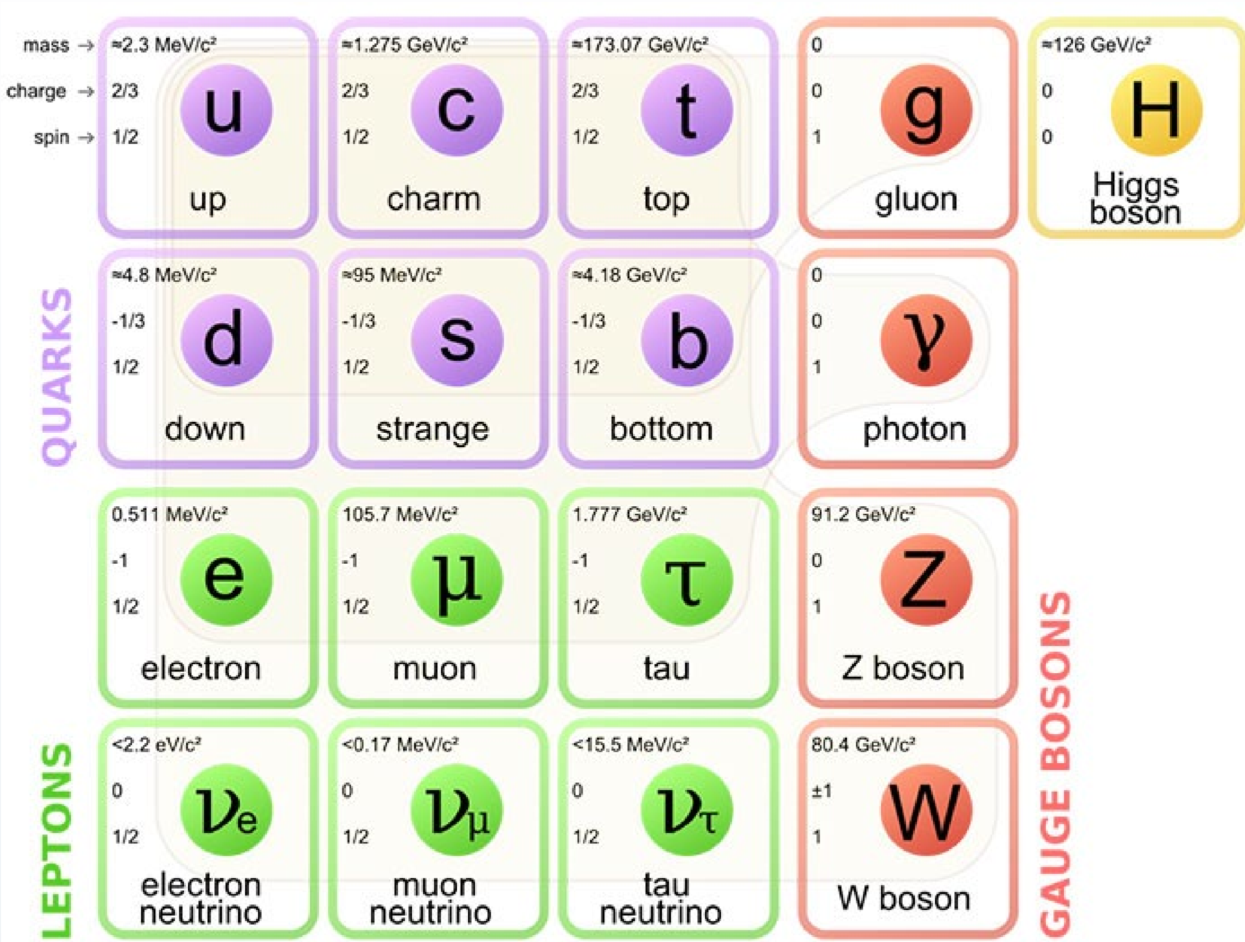
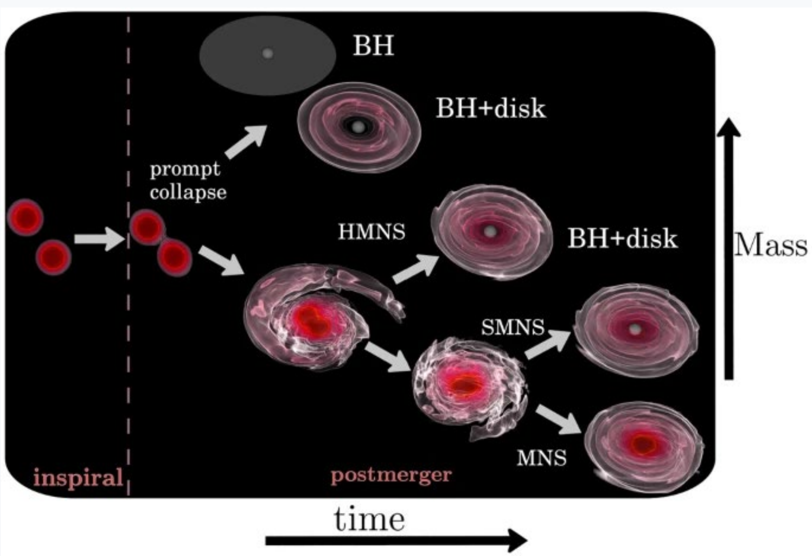


Image source: Wikimedia Commons

NS-NS merger

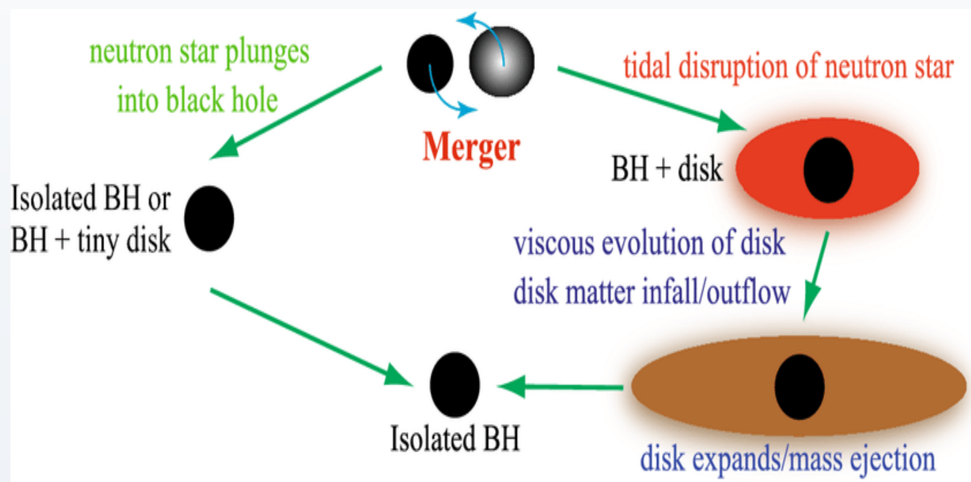
- Remnant: massive NS or BH



Tim Dietrich (2021)

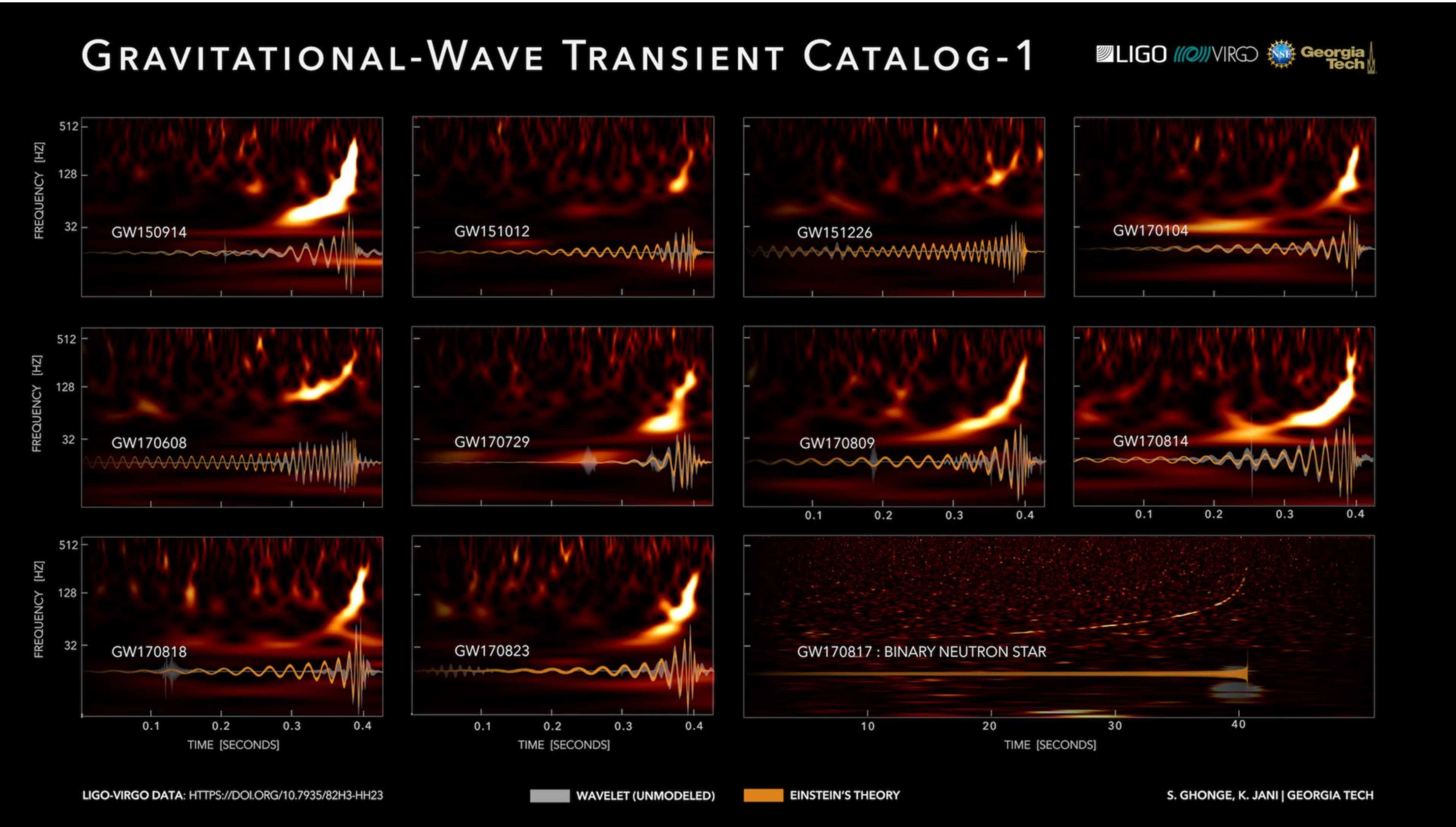
NS-BH merger

- Remnant: BH

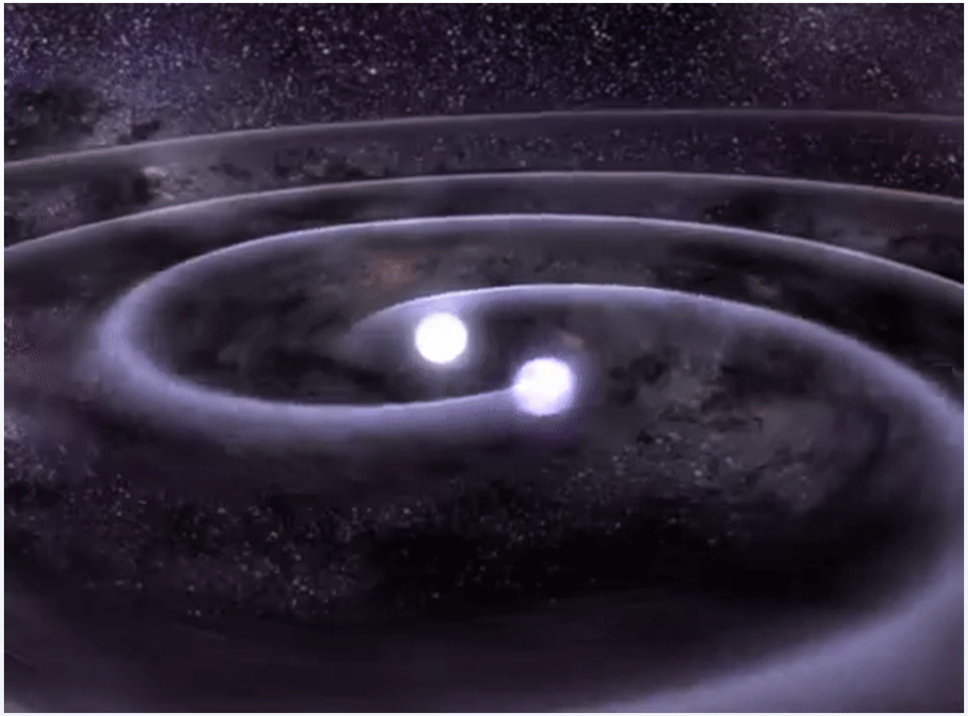


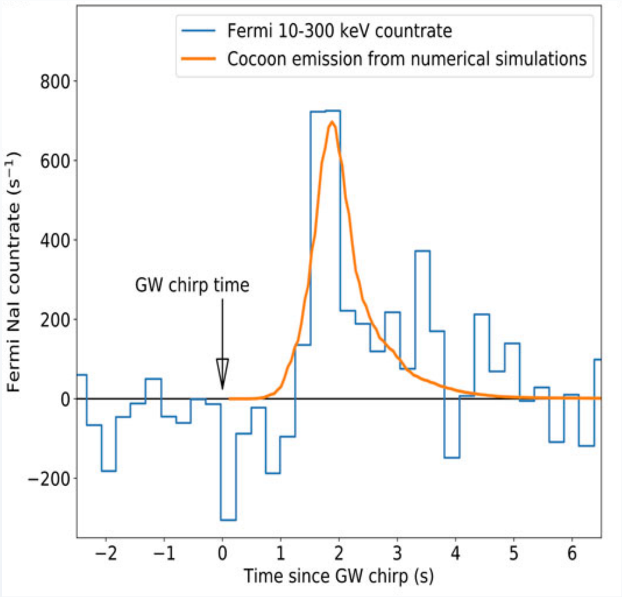
Shibata and Hotokezaka (2019)

GW signal — BH coalescence vs NS merger



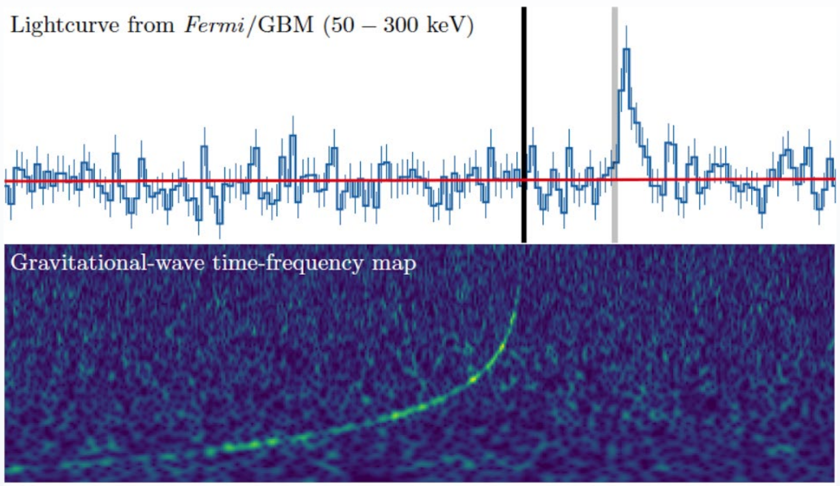
Signals from NS-NS merger





Makhathini et al. (2020)

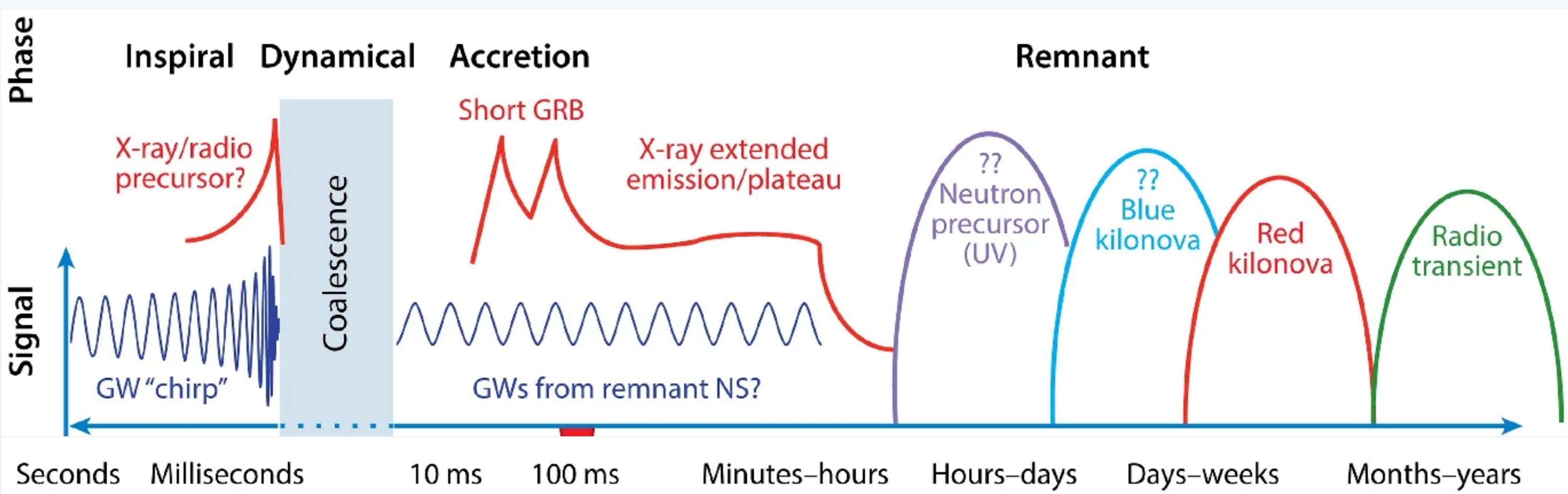
Signals from NS-NS merger GW170817



What do we get?

- Short gamma-ray burst
- Gravitational waves
- Kilonova (afterglow)

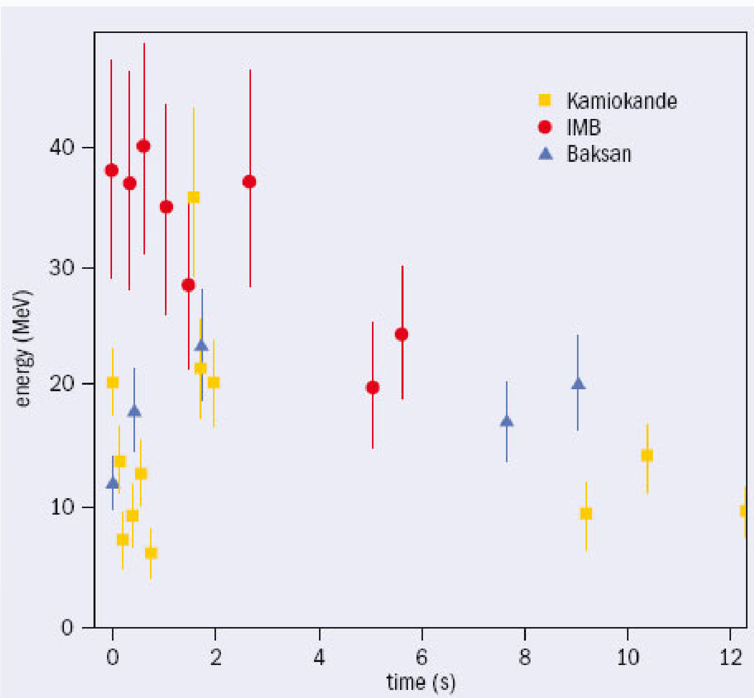
[Credit: LIGO, Virgo, Fermi, Swope, DLT40]



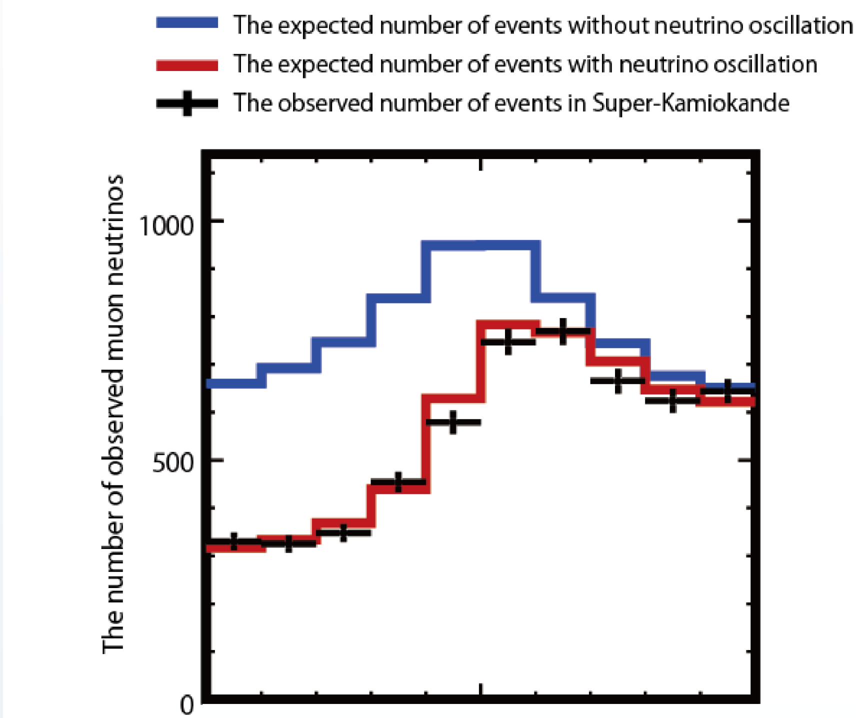
Fernández, Metzger (2016)

Previous neutrino detection

Supernova



Neutrino oscillation



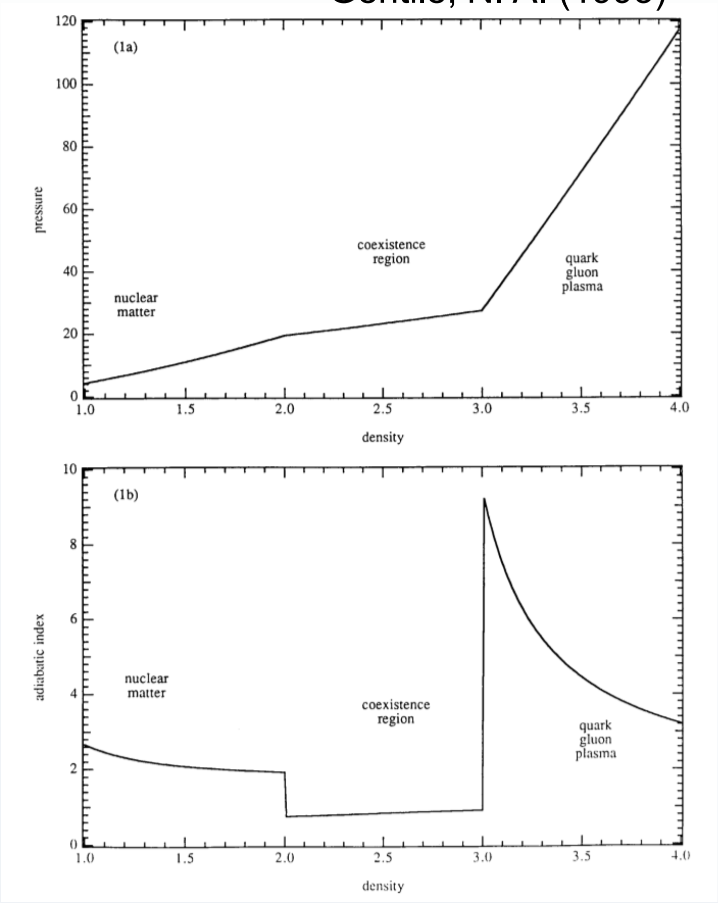
Nakahata M (2007)

[Credit: Super-K]

Neutrinos from QCD phase transition

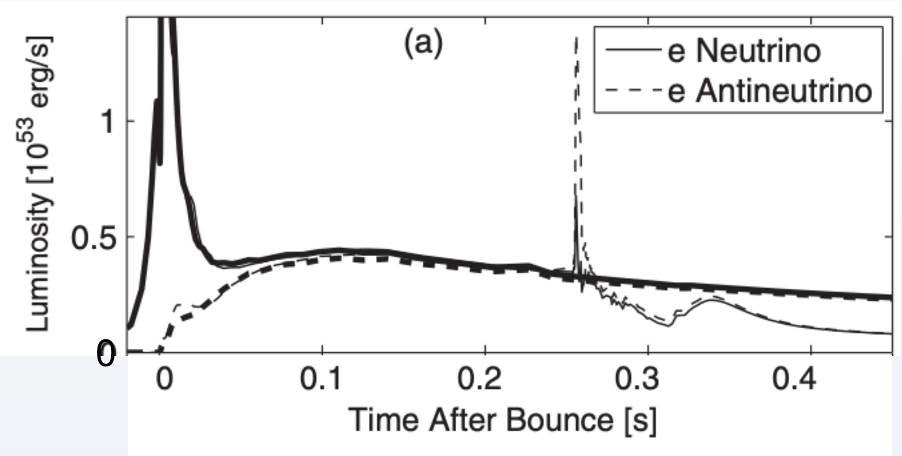
— burst of neutrino emissions

Gentile, N. A. (1993)



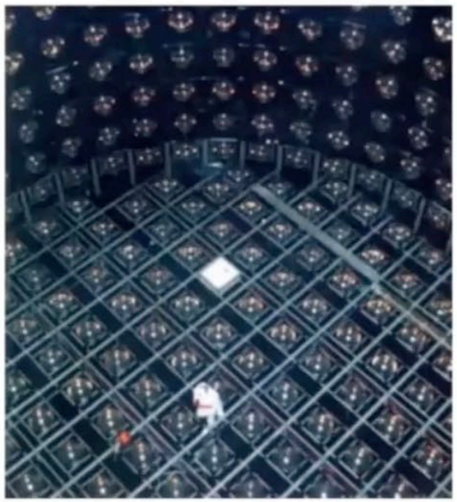
Core-collapse supernova

phase transition
→ second shock reach neutrino sphere
→ second neutrino burst



Could neutron star merger generate neutrino burst?

Neutrino instruments

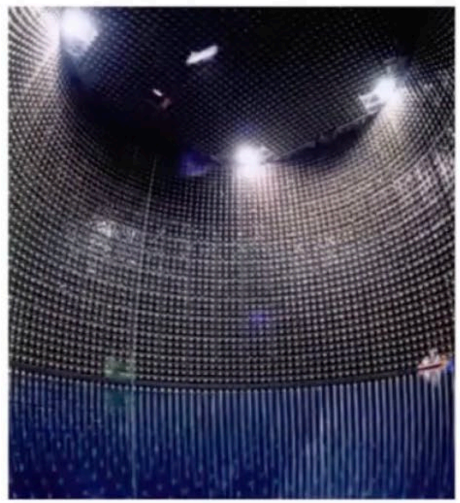


Kamiokande

(1983-1996)

- Atmospheric and solar neutrino "anomaly"
- Supernova 1987A

Birth of neutrino astrophysics

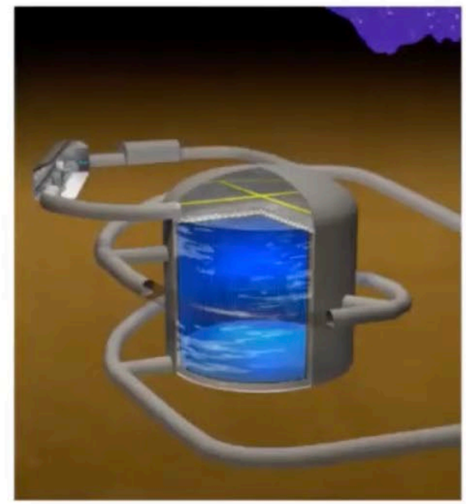


Super-Kamiokande

(1996 - ongoing)

- Proton decay: world best-limit
- Neutrino oscillation (atm/solar/LBL)
  - All mixing angles and $\Delta m^2 s$

Discovery of neutrino oscillations



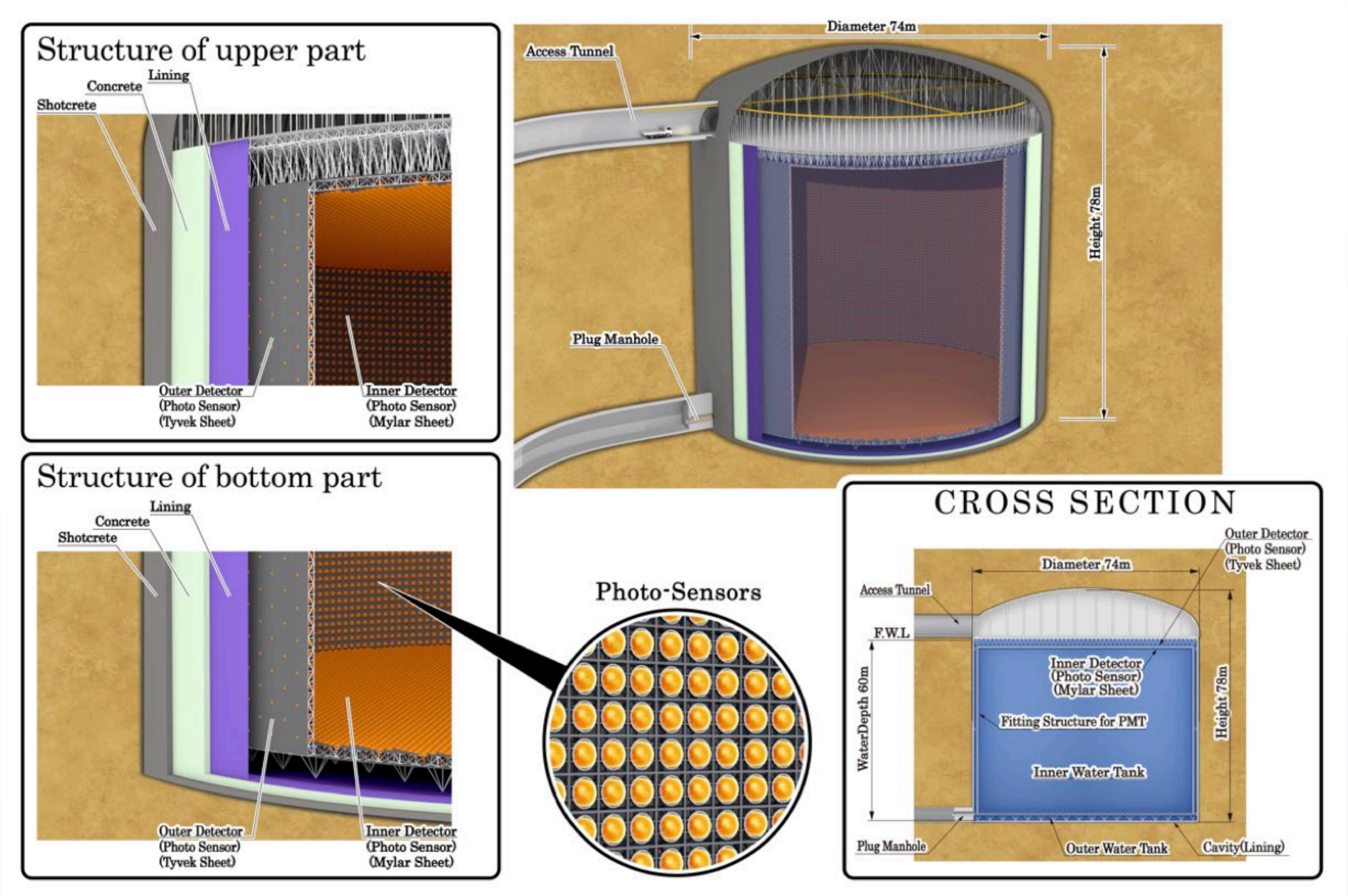
Hyper-Kamiokande

(start operation in 2027)

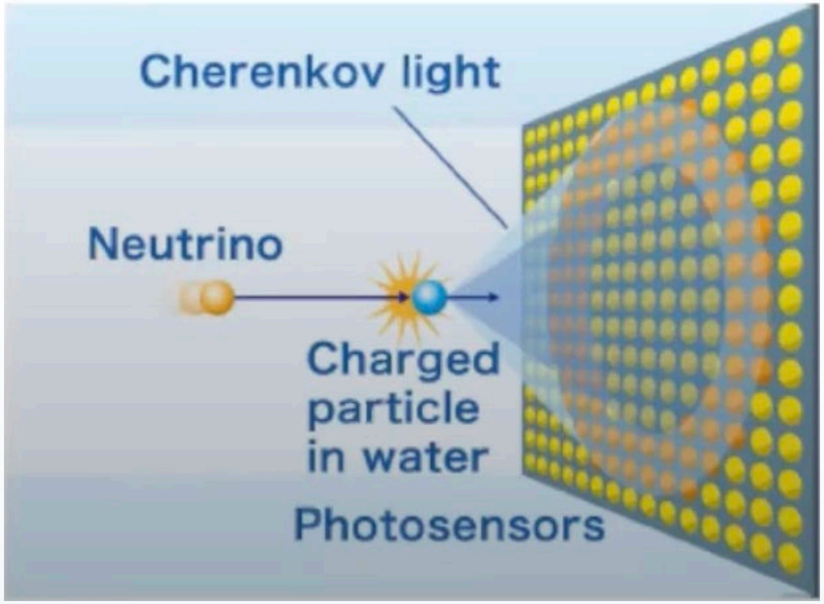
- Extended search for proton decay
- Precision measurement of neutrino oscillation including CPV and MO
- Neutrino astrophysics

Explore new physics

Details about Hyper-K instrument

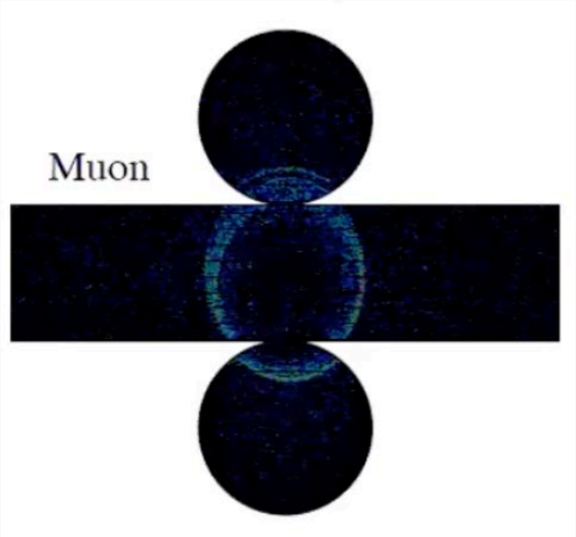


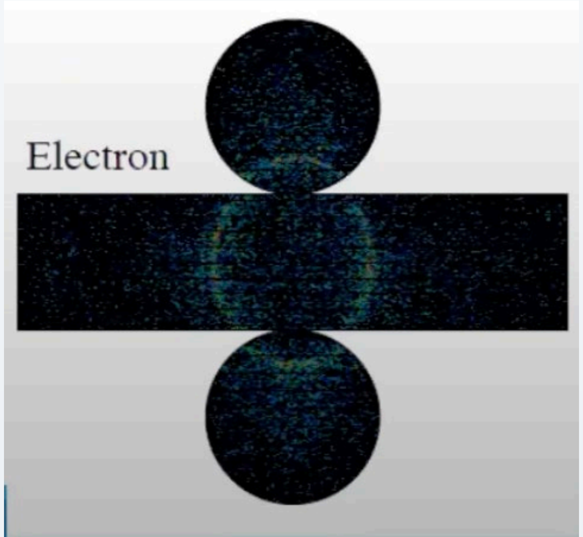
How does Hyper-K works?



Observe the Cherenkov Ring from charged particles

- Optical "Sonic Boom" from faster than light (in water) particles





>99% μ/e separation

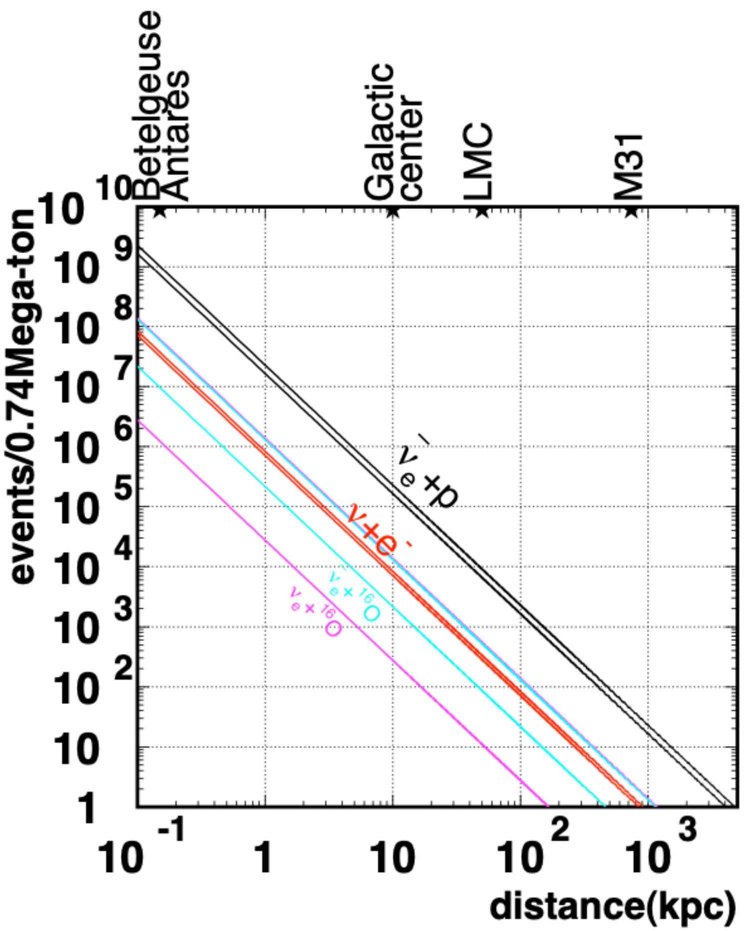
Length -> momentum

Details about Hyper-K instrument

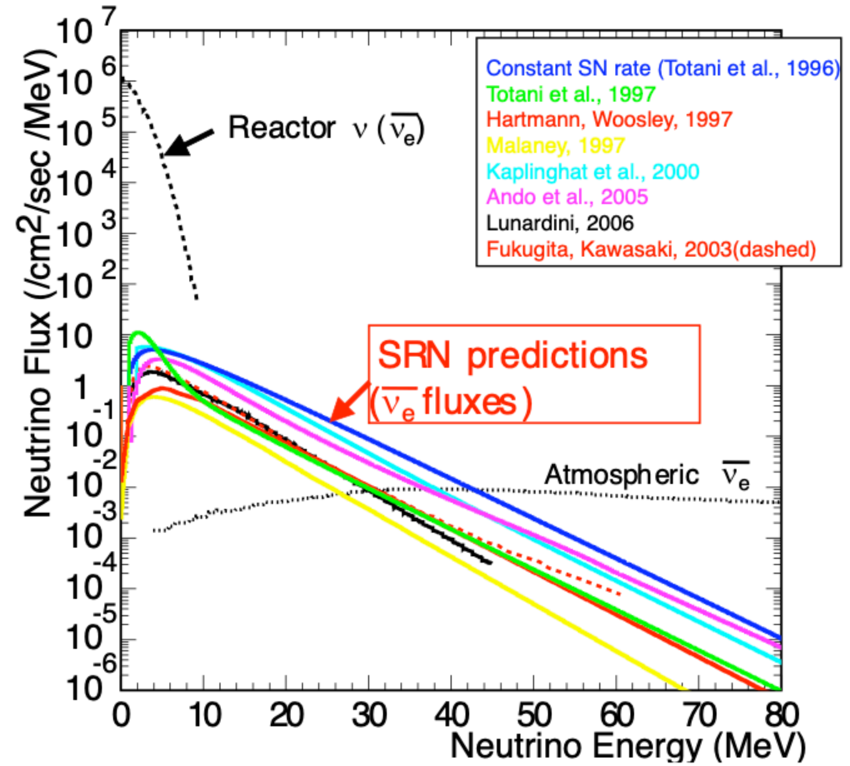
	KAM	SK	HK-3TankLD	HK-1TankHD
Depth	1,000 m	1,000 m	650 m	650 m
Dimensions of water tank				
diameter	15.6 m ϕ	39 m ϕ	74 m ϕ	74 m ϕ
height	16 m	42 m	60 m	60 m
Total volume	4.5 kton	50 kton	774 kton	258 kton
Fiducial volume	0.68 kton	22.5 kton	560 kton	187 kton
Outer detector thickness	$\sim$ 1.5 m	$\sim$ 2 m	1 $\sim$ 2 m	1 $\sim$ 2 m
Number of PMTs				
inner detector (ID)	948 (50 cm ϕ)	11,129 (50 cm ϕ)	40,000 (50 cm ϕ)	40,000 (50 cm ϕ)
outer detector (OD)	123 (50 cm ϕ)	1,885 (20 cm ϕ)	20,000 (20 cm ϕ)	6,700 (20 cm ϕ)
Photo-sensitive coverage	20%	40%	13%	40%
Single-photon detection efficiency of ID PMT	unknown	12%	24%	24%
Single-photon timing resolution of ID PMT	$\sim$ 4 nsec	2-3 nsec	1 nsec	1 nsec

Hyper-Kamiokande Design Report (2018)

Detectability of Hyper-K in general

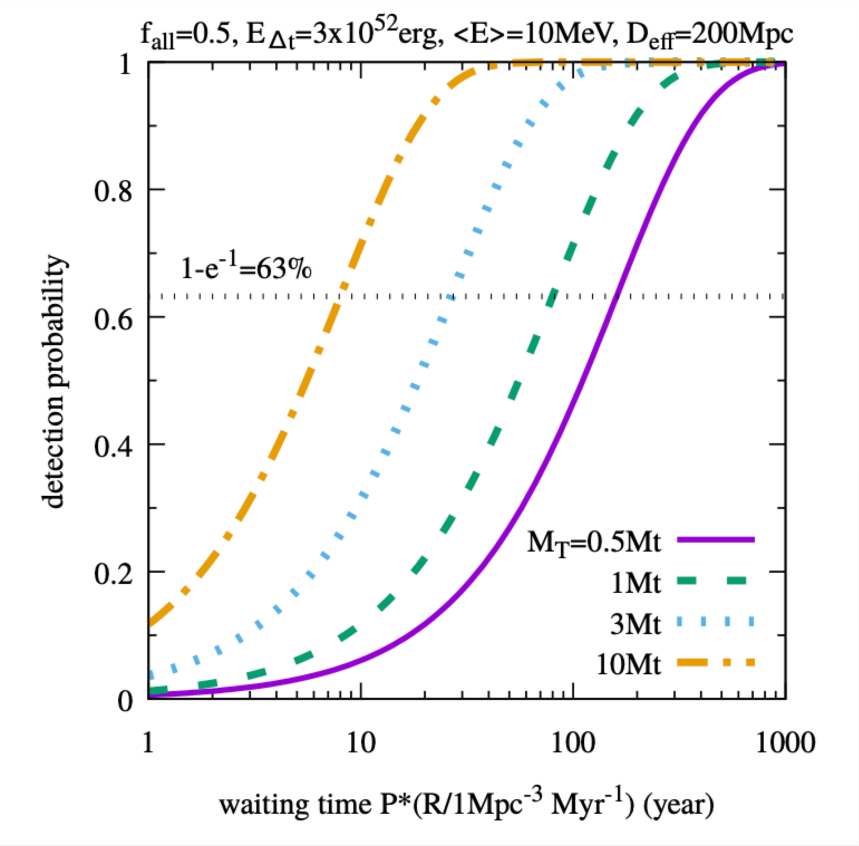


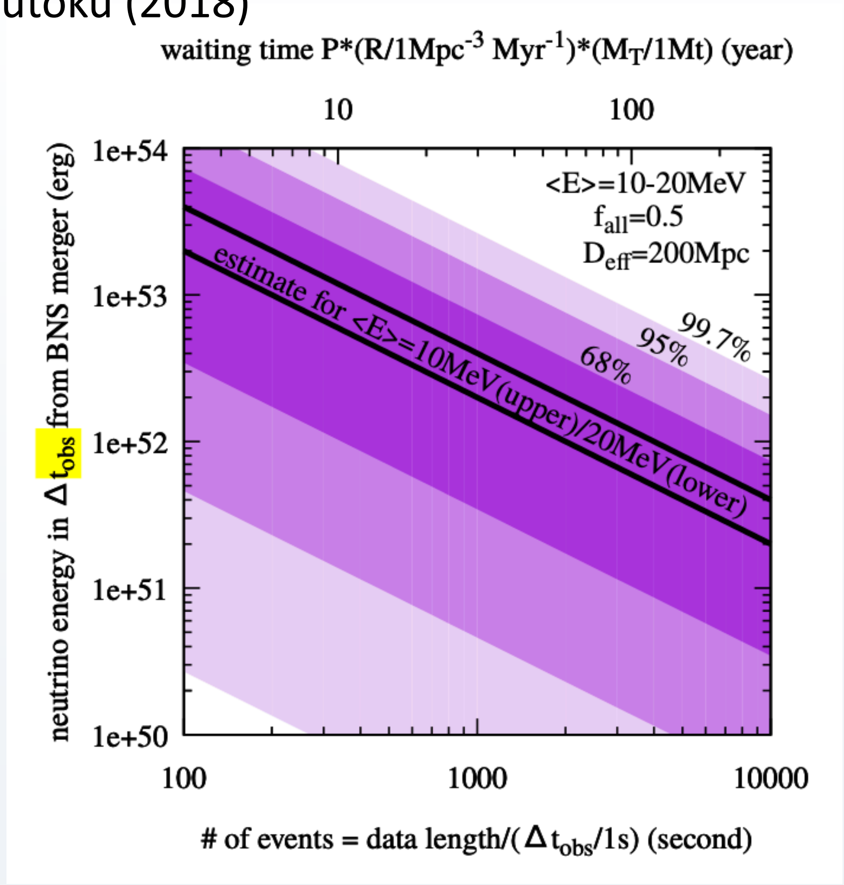
Abe K (2011)



Detectability of Hyper-K for NS merger

Koutarou Kyutoku (2018)

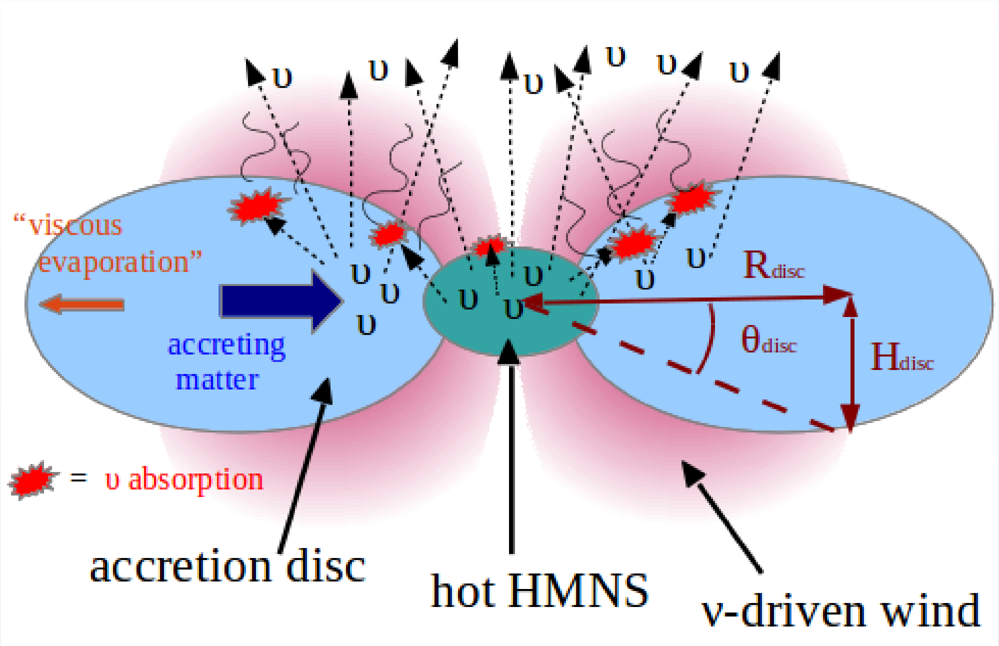




HK: ~0.37Mt

Number of events to be emitted before first HK detection

Neutrino flux from NS-NS postmerger disk



A. Perego (2014)

1. Neutrino emission
    a. Massive NS
    b. Accretion disk
2. Neutrino absorptoion
    a. Absorbed by disk -> puff matter

Neutrinos from NS merger

1. NSNS-NS

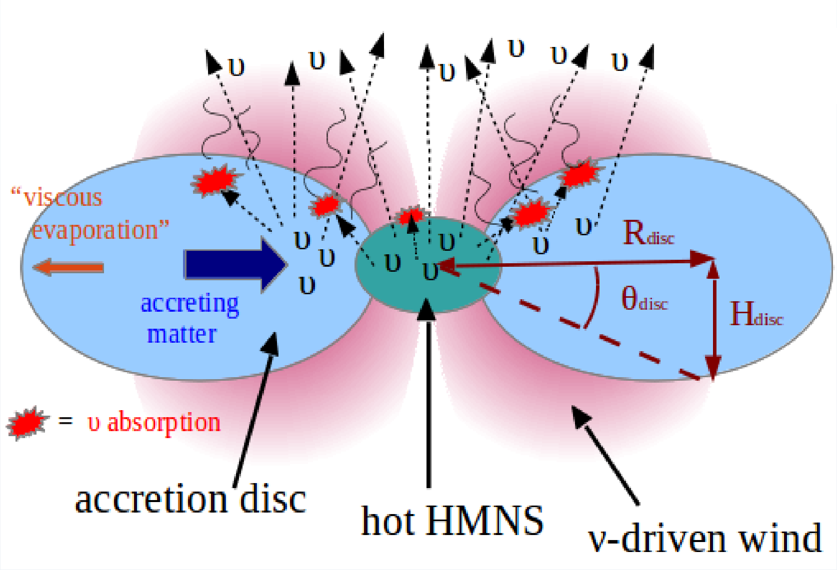
- Delayed collapse or long-standing NS
- $M_t > 2.8 M_\odot$

2. NSNS-BH

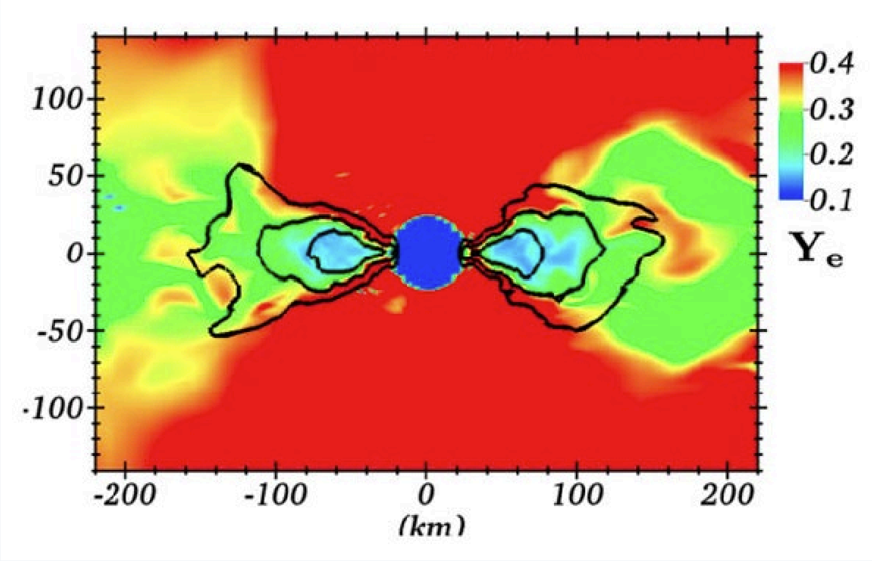
- Prompt collapse
- $M_t \lesssim 2.8 M_\odot$

3. NSBH

- With mass ejecta
- $M_{BH} \lesssim 5 M_\odot$



A. Perego (2014)

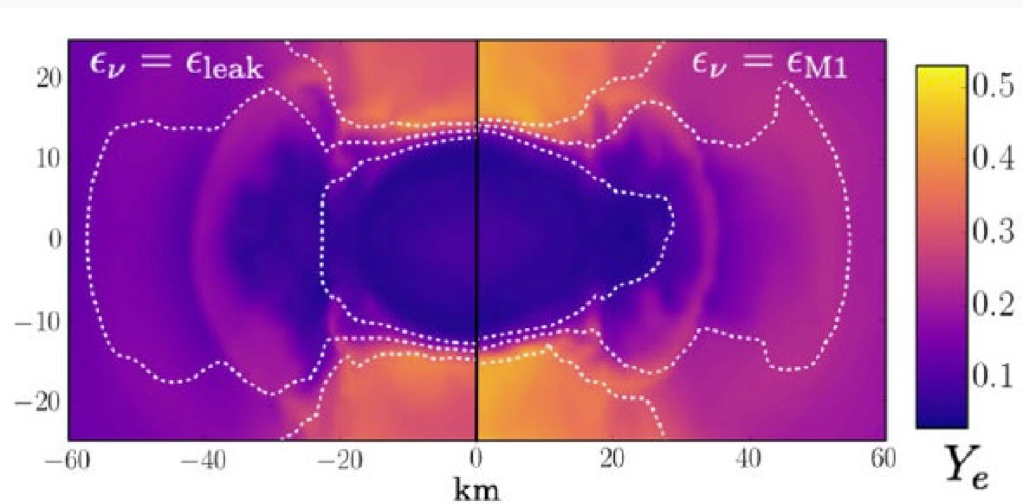


Foucart et al. (2015)

Neutrino flux from postmerger disk

NS-NS

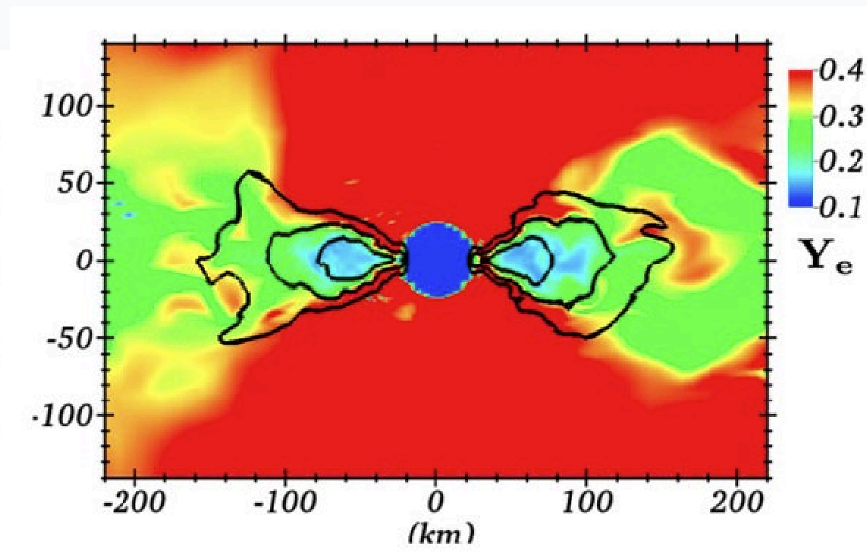
- Leakage scheme: $Y_e \sim 0.1$
- Moment transport: $Y_e \sim 0.15 - 0.2$



Foucart et al. (2016)

NS-BH

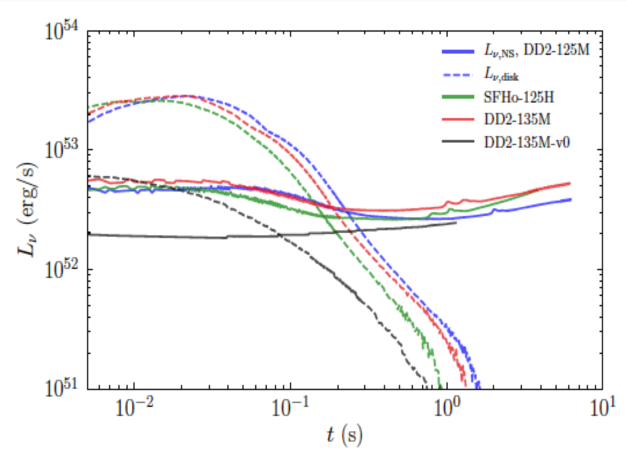
- Neutrino reabsorption: $Y_e \sim 0.2 - 0.4$



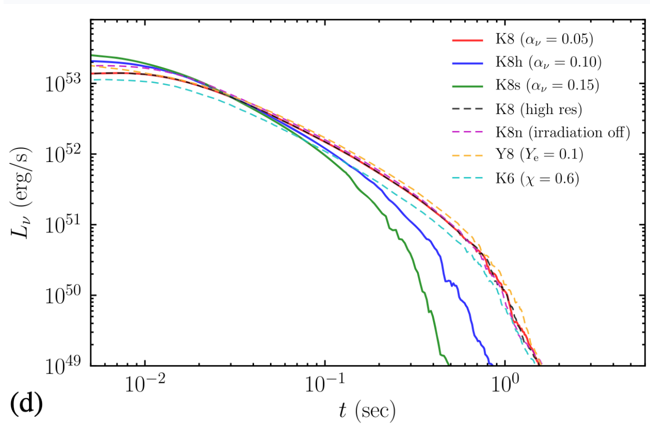
Foucart et al. (2015)

Neutrino emissions from NS-X merger

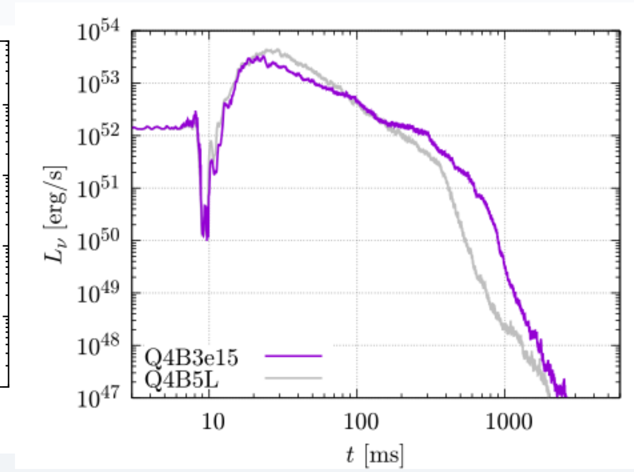
1. NSNS-NS   2. NSNS-BH   3. NSBH



Sho Fujibayashi (2020, APJ)



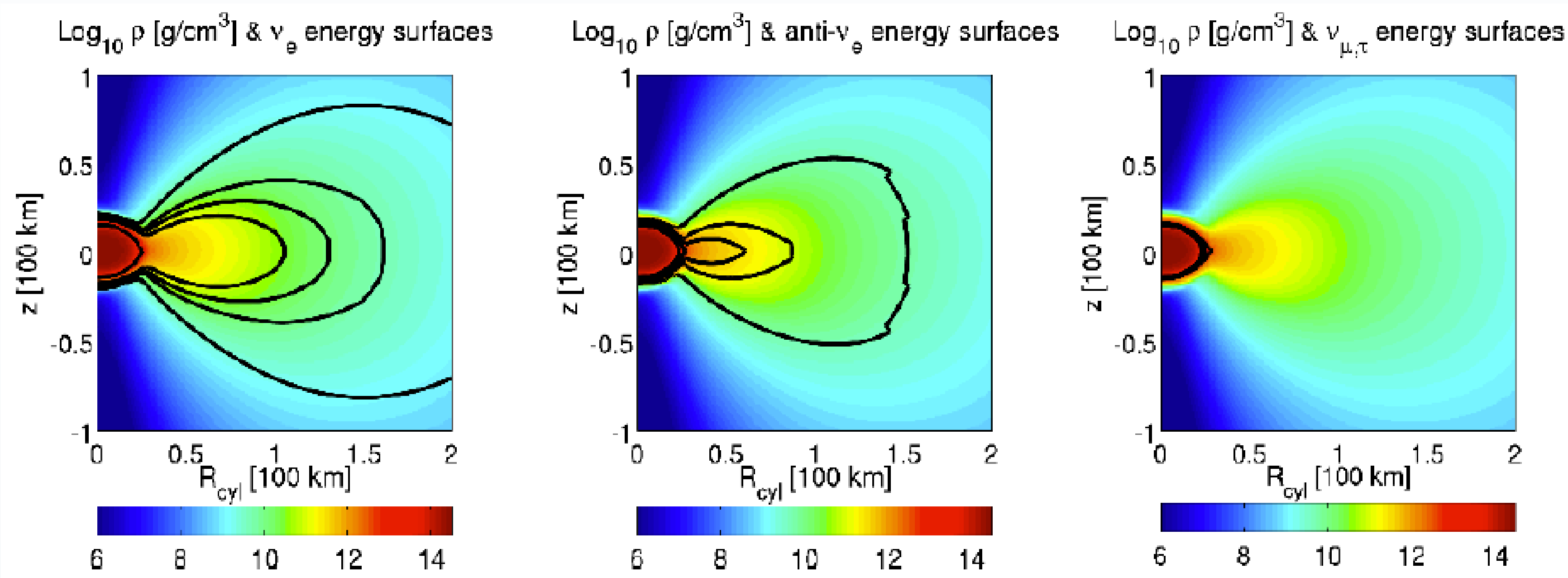
Sho Fujibayashi (2020, PRD)



Kota Hayashi (2023)

Neutrino energy hierarchy

$$\epsilon_{\nu_x} > \epsilon_{\bar{\nu}_e} > \epsilon_{\nu_e}$$



A. Perego (2014)

E = 4.62MeV; 10.63MeV; 16:22MeV; 24.65MeV; 56.96MeV

Motivations

- Why neutrinos?
- What happened after neutron star merge?
- What can we learn from the dense matter in the remnant disk?
- Can we tell the difference between NS-NS and NS-BH merge via neutrino alone?

Why neutrinos?

- Weak interaction -MeV
- Low absorption rate
- What can neutrinos tell us?

Calculations:

1. BB from disk vs disk+NS vs extended disk from NSBH
2. Heating mechanisms: shock vs B-field driven turbulence vs QCD phase transition
3. Transport scheme: leakage vs moment transport

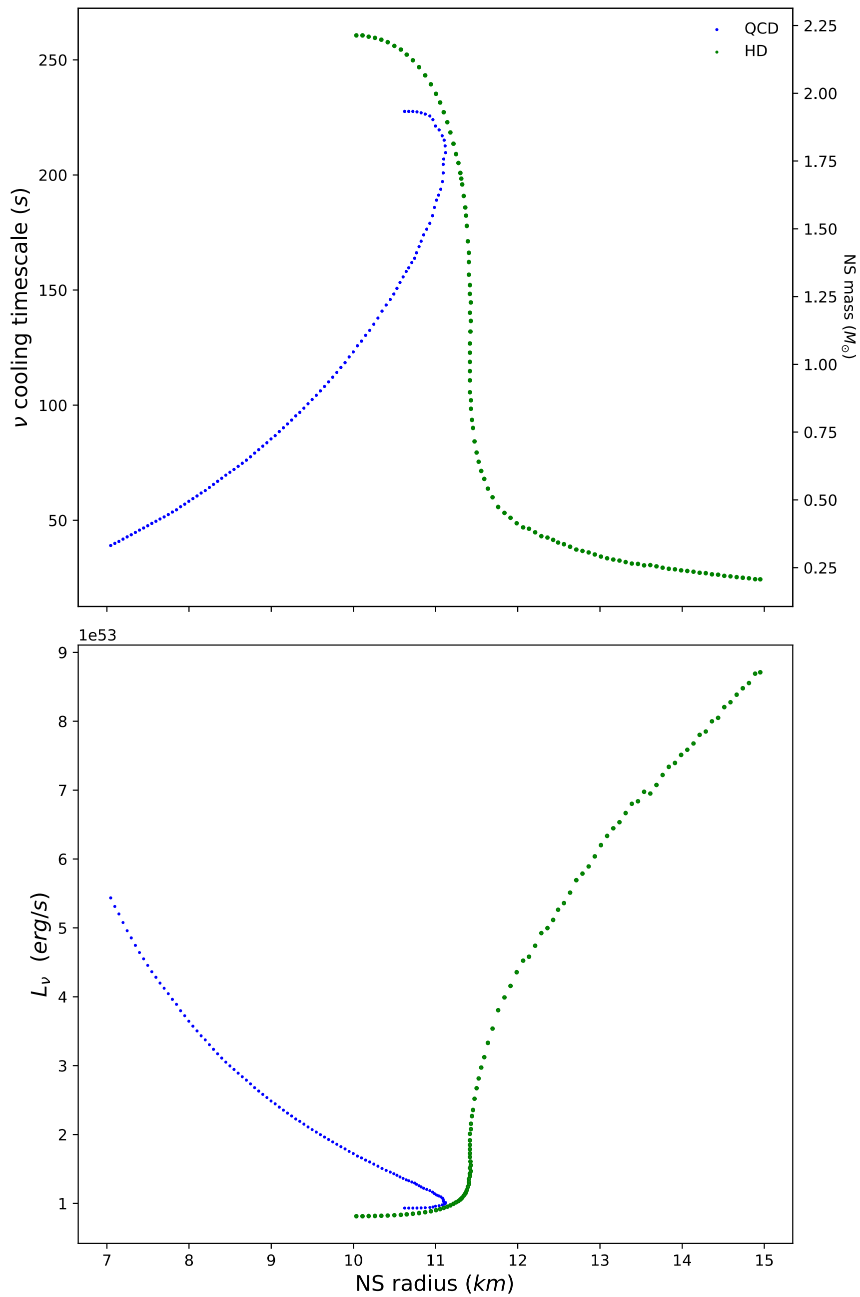
Estimate the number of NS-X neutrino detection

Neutrino cooling timescale

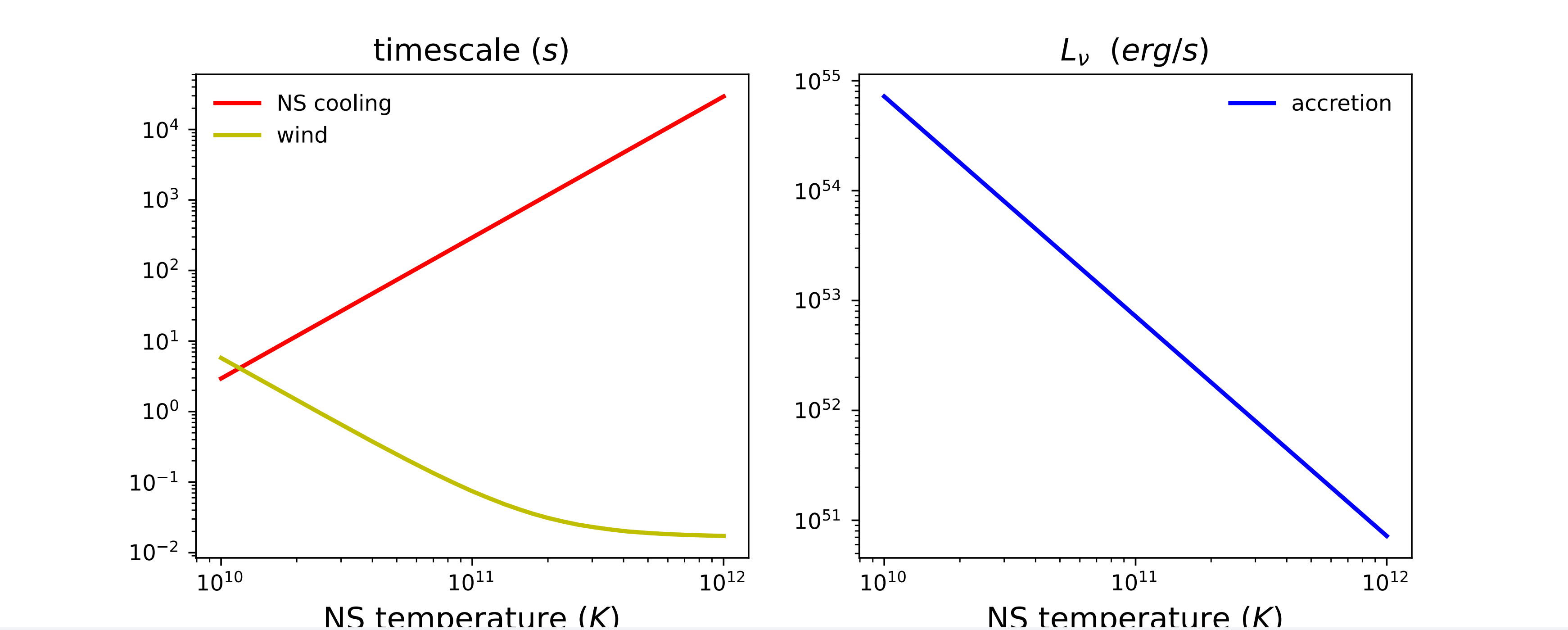
Predict the GW lagging time

Pars with disk

Same mass ->
different EOS ->
different Lv



Pars with disk



$$t_{\rm cool,ns} \sim 1.88\,{\rm s}\left(\frac{R_{\rm ns}}{25\,{\rm km}}\right)^2\left(\frac{\rho_{\rm ns}}{10^{14}{\rm g/cm^3}}\right)\left(\frac{k_{\rm B}T_{\rm ns}}{15\,{\rm MeV}}\right)^2$$

$$L_{\nu,\rm ns} \sim \frac{\Delta E_{\rm ns}}{t_{\rm diff,ns}} \approx 1.86\cdot 10^{52}\,\frac{\rm erg}{\rm s}\left(\frac{\Delta E_{\rm ns}}{3.5\cdot 10^{52}{\rm erg}}\right)\left(\frac{R_{\rm ns}}{25\,{\rm km}}\right)^{-2}\left(\frac{\rho_{\rm ns}}{10^{14}{\rm g/cm^3}}\right)^{-1}\left(\frac{k_{\rm B}T_{\rm ns}}{15\,{\rm MeV}}\right)^{-2}.$$

QCD Lagrangian – an example

The QCD interation is described by a Lagrangian

Full QCD Lagrangian

$$\mathcal{L}^0_{\mathrm{QCD}} = \bar{q} i \gamma^\mu \left(\partial_\mu + i g_s \frac{\lambda_\alpha}{2} G^\alpha_\mu \right) q - \frac{1}{4} G^\alpha_{\mu\nu} G^{\alpha\mu\nu}$$

Effective Lagrangian

$$\mathcal{L} = \frac{1}{4} f_\pi^2 \left[Tr \nabla_0 \Sigma \nabla_0 \Sigma^\dagger - v^2 \vec{\nabla} \Sigma \vec{\nabla} \Sigma^\dagger \right] + f_\pi^2 \left[\frac{a}{2} Tr \tilde{M} (\Sigma + \Sigma^\dagger) + \frac{\chi}{2} Tr M (\Sigma + \Sigma^\dagger) \right].$$

Color-flavor locked phase

$$\mathscr{L}_{Wx}(x) = \frac{G}{\sqrt{2}} l_\mu(x) \mathscr{J}^\mu_W(x) + \mathrm{H.C.},$$

QCD Lagrangian – Hadron phase

NLWM (non-linear Walecka model)

$$\mathcal{L} = \sum_B \bar{\psi}_B \left[\gamma_\mu \left(i\partial^\mu - g_{vB}V^\mu - g_{\rho B}\mathbf{t}\cdot\vec{b}^\mu\right) - \left(M - g_{sB}\phi - g_{\delta B}\mathbf{t}\cdot\vec{\delta}\right)\right]\psi_B$$
$$+ \frac{1}{2}\left(\partial_\mu\phi\partial^\mu\phi - m_s^2\phi^2 - \frac{1}{3}\kappa\phi^3 - \frac{1}{12}\lambda\phi^4\right) - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_v^2 V_\mu V^\mu$$
$$- \frac{1}{4}\vec{B}_{\mu\nu}\cdot\vec{B}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{b}_\mu\cdot\vec{b}^\mu + \frac{1}{2}\left(\partial_\mu\vec{\delta}\partial^\mu\vec{\delta} - m_\delta^2\vec{\delta}^2\right),$$

QMC model

$$E_B^{\mathrm{bag}} = \sum_q n_q \frac{\Omega_q}{R_B} - \frac{Z_B}{R_B} + \frac{4\pi}{3}{R_{\mathrm{B}}}^3 B_N$$

QCD Lagrangian – Quark phase

NJL (Nambu-Jona Lasinio) model

$$\mathcal{L} = \bar{q}\left(i\gamma^{\mu}\partial_{\mu} - m\right)q + g_S \sum_{a=0}^{8}\left[\left(\bar{q}\lambda^a q\right)^2 + \left(\bar{q}i\gamma_5\lambda^a q\right)^2\right]$$
$$+ g_D\left\{\det\left[\bar{q}_i\left(1+\gamma_5\right)q_j\right] + \det\left[\bar{q}_i\left(1-\gamma_5\right)q_j\right]\right\},$$

MIT Bag *

$$\mathcal{L} = \left[\tfrac{i}{2}\left(\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - \left(\partial_{\mu}\bar{\psi}\right)\gamma^{\mu}\psi\right) - B\right]\theta_v(x) - \tfrac{1}{2}\bar{\psi}\psi\Delta_s$$