Relic and Nascent Neutrinos

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Nuclear Physics in Astrophysics X
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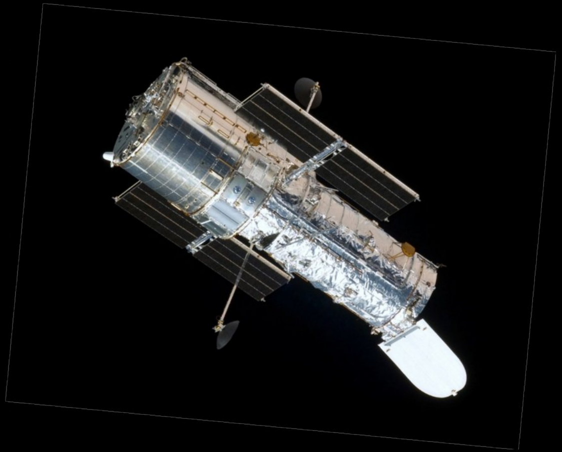
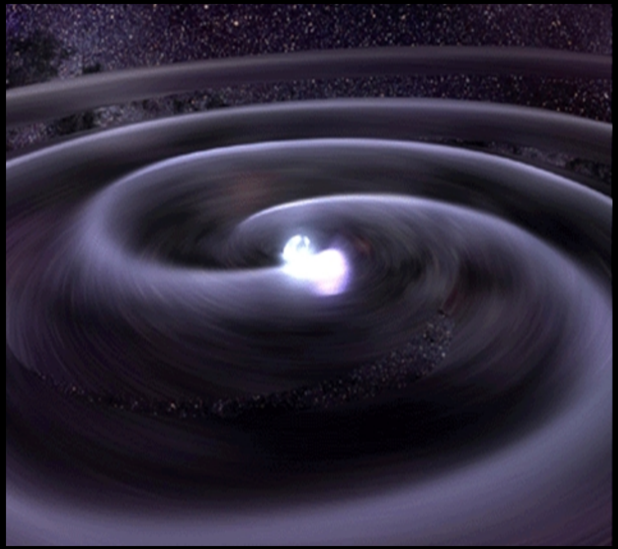
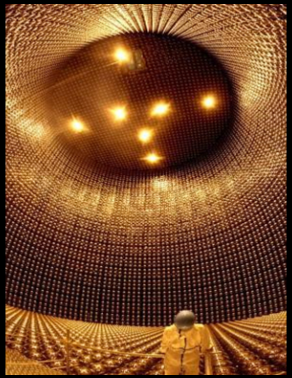
Neutrino and multi-messengers



Hubble Space Telescope



Swift: Gamma-rays



SuperK: Neutrinos

LIGO: Gravitational Waves

- Neutrinos determine the evolution of supernovae, collapsars, and neutron star mergers

- Neutrino signals combined with other observations will lead to better understanding of several phenomena such as Gamma Ray Burst, and the synthesis of heavy elements

- Diffuse background: neutrinos have been emitted since the formation of the first compact objects

Nucleosynthesis

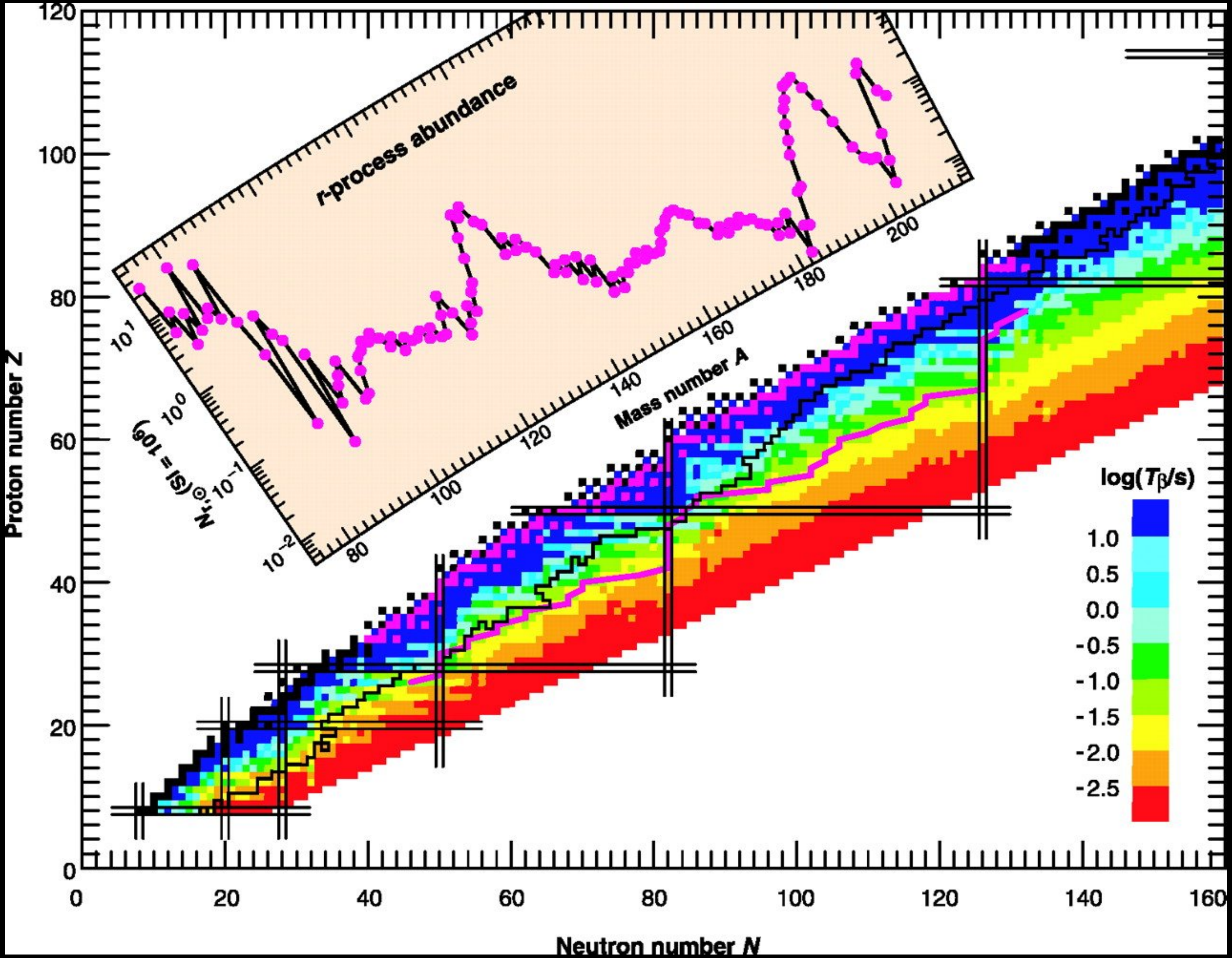
Electron fraction

$$Y_e = \frac{1}{1+{}^{n}/_{p}}$$

Proton rich

$Y_e = 0.5$

Neutron rich



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

$\nu_e + n \leftrightarrow e + p$

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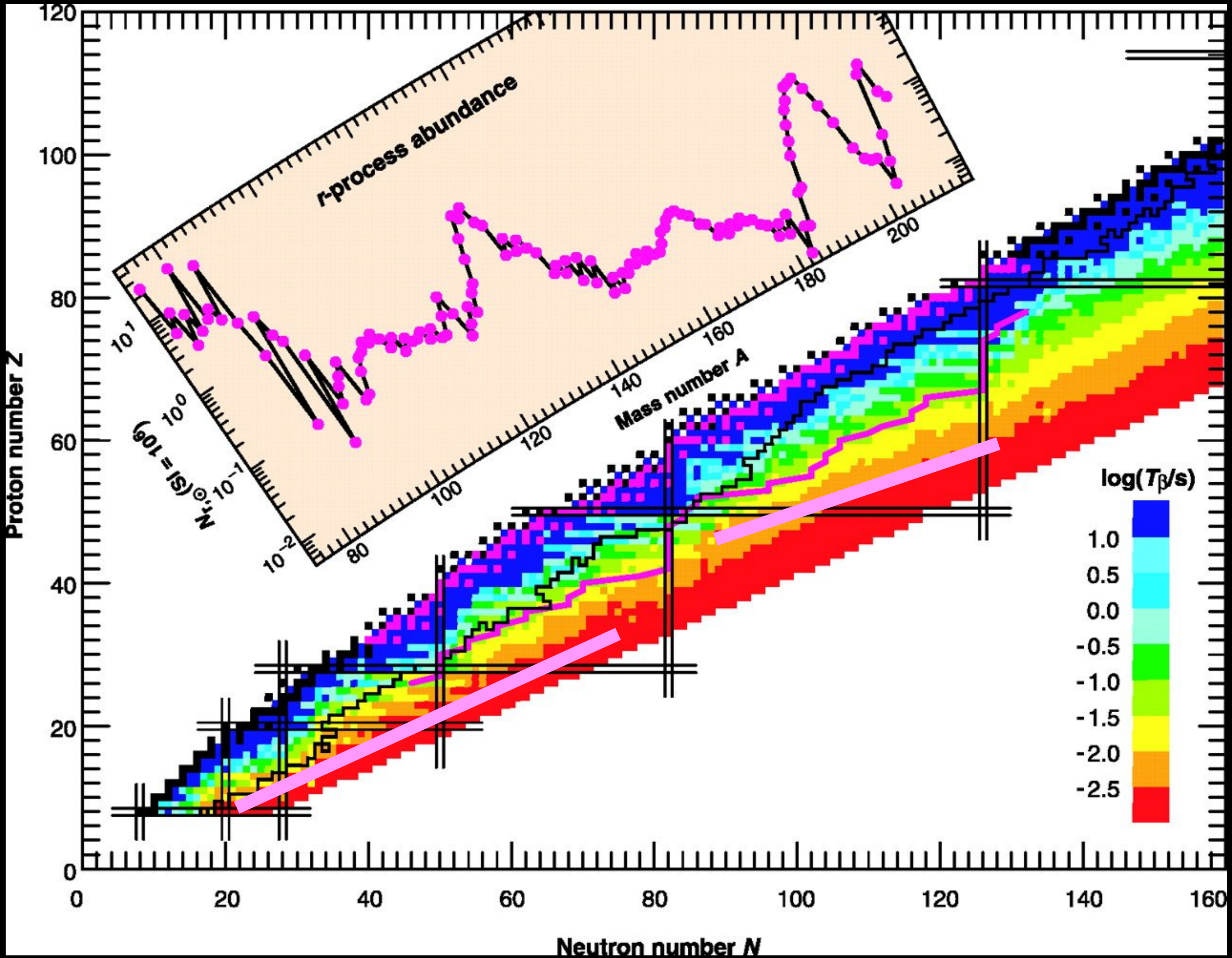
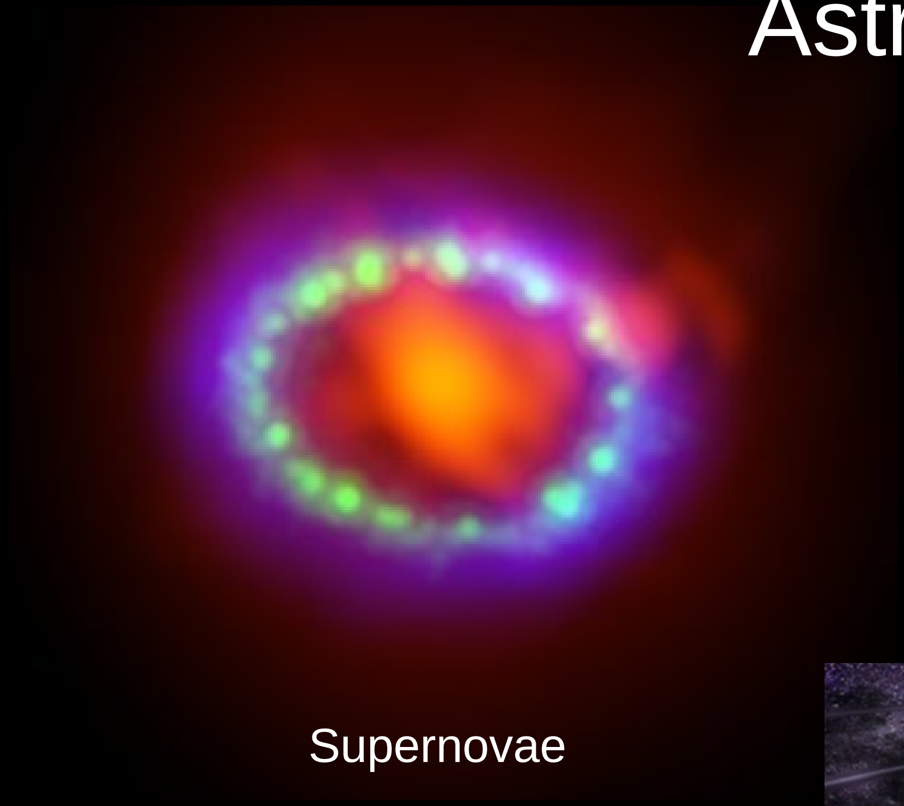


$\bar{\nu}_e + p \leftrightarrow e^+ + n$

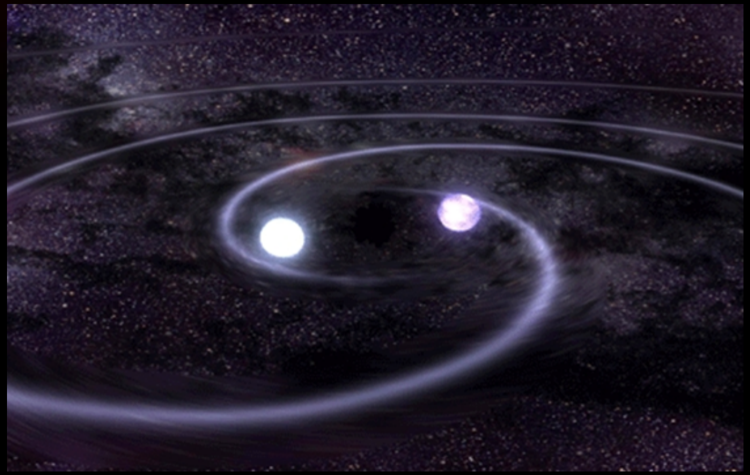
$\nu_e + n \leftrightarrow e + p$

Astrophysical scenarios



Supernovae

Collapsars



Mergers

Passage through dense matter

Neutrino emission is influenced by the properties of nuclear matter: nucleon-nucleon interaction

Neutrinos oscillate between flavor states

Neutrino spectrum is affected by strong gravitational fields

Neutrino Surface

At high temperatures (~ 10 MeV) matter is dissociated

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

$\nu_e + n \rightarrow e + p$

$\nu + \bar{\nu} \rightarrow e + e^+$

Charged Current

$\nu + n \rightarrow \nu + n$

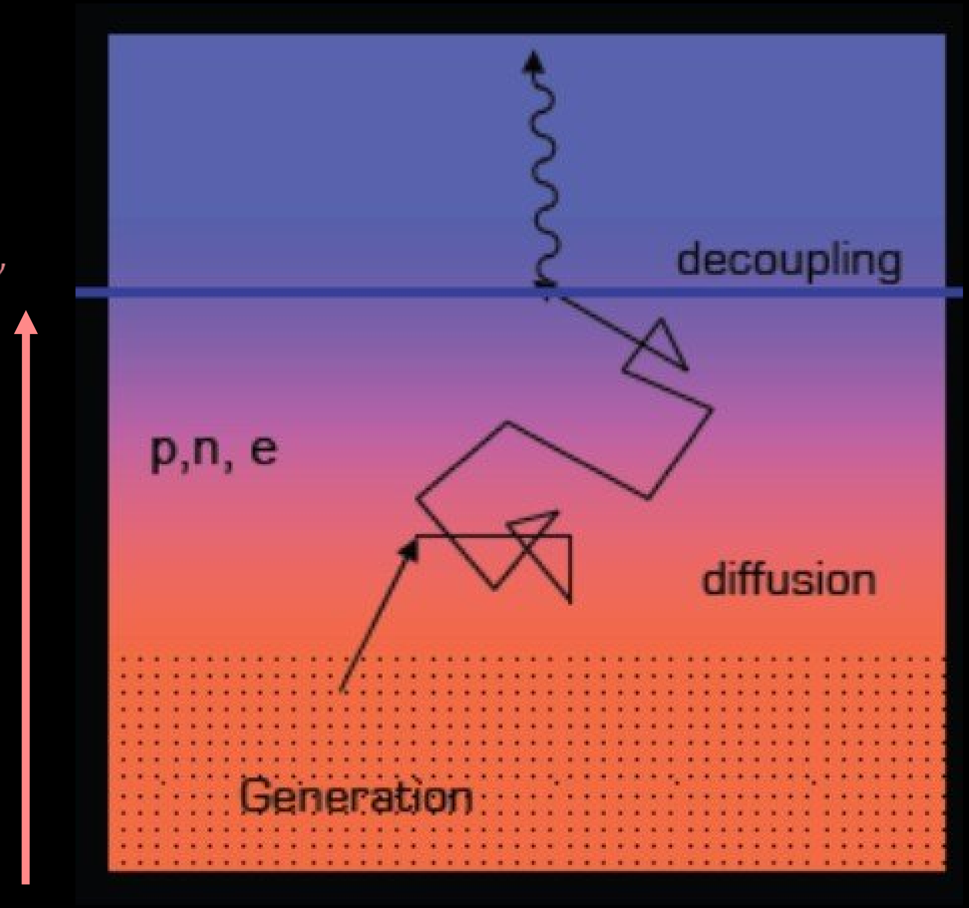
$\nu + p \rightarrow \nu + p$

$\nu + e \rightarrow \nu + e$

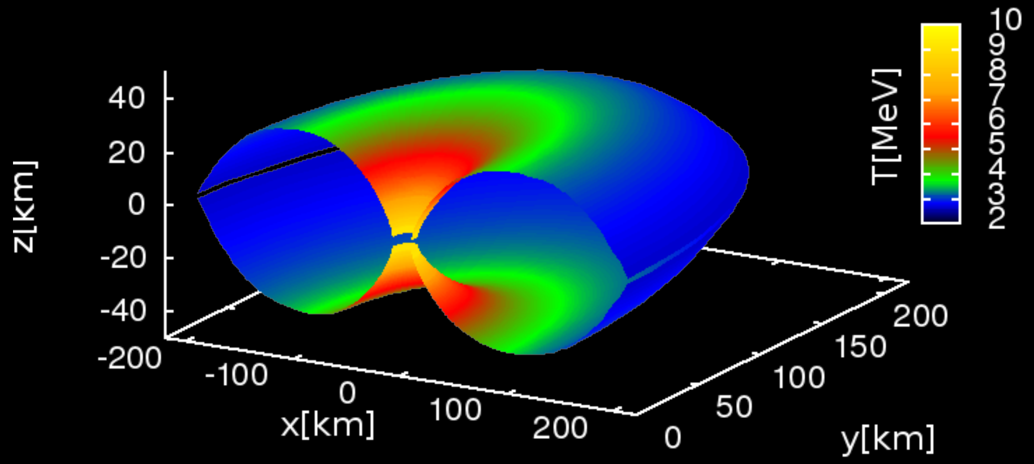
Neutral Current (All flavors)

$Y_e = Y_p = \frac{1}{1+n/p}$

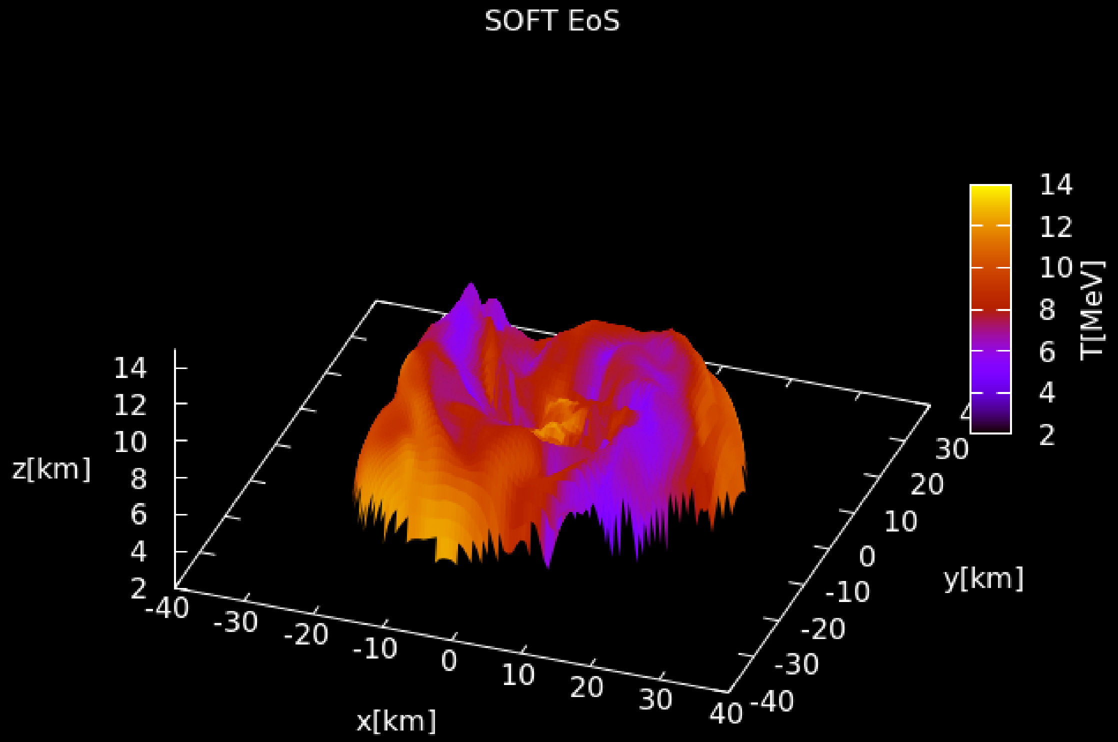
h_ν



Electron anti-neutrino surfaces



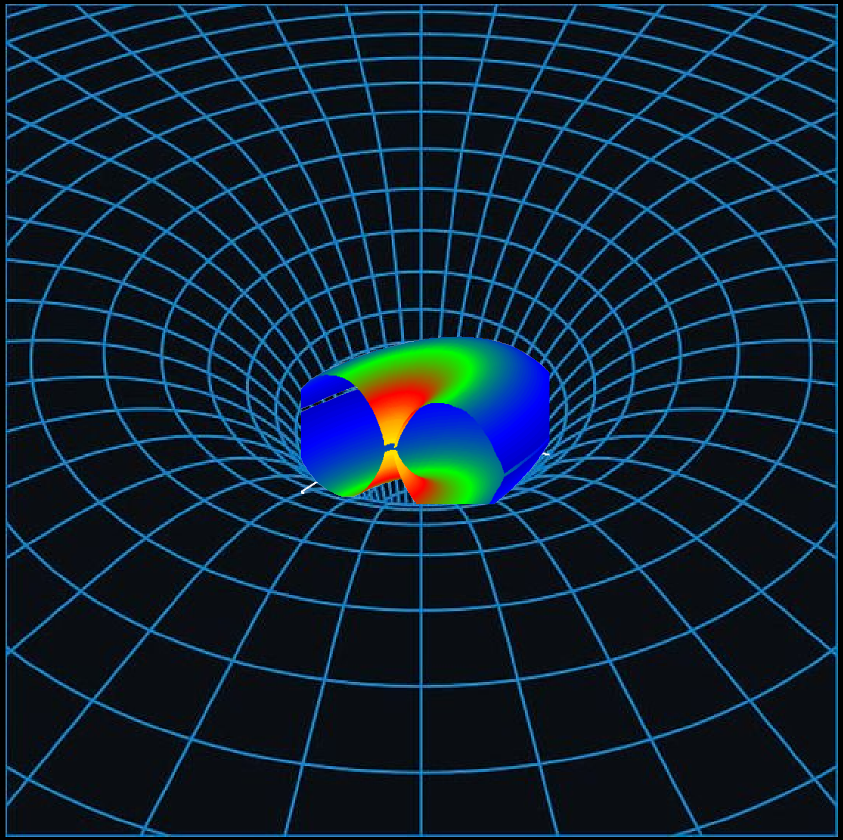
Steady state black hole accretion disk



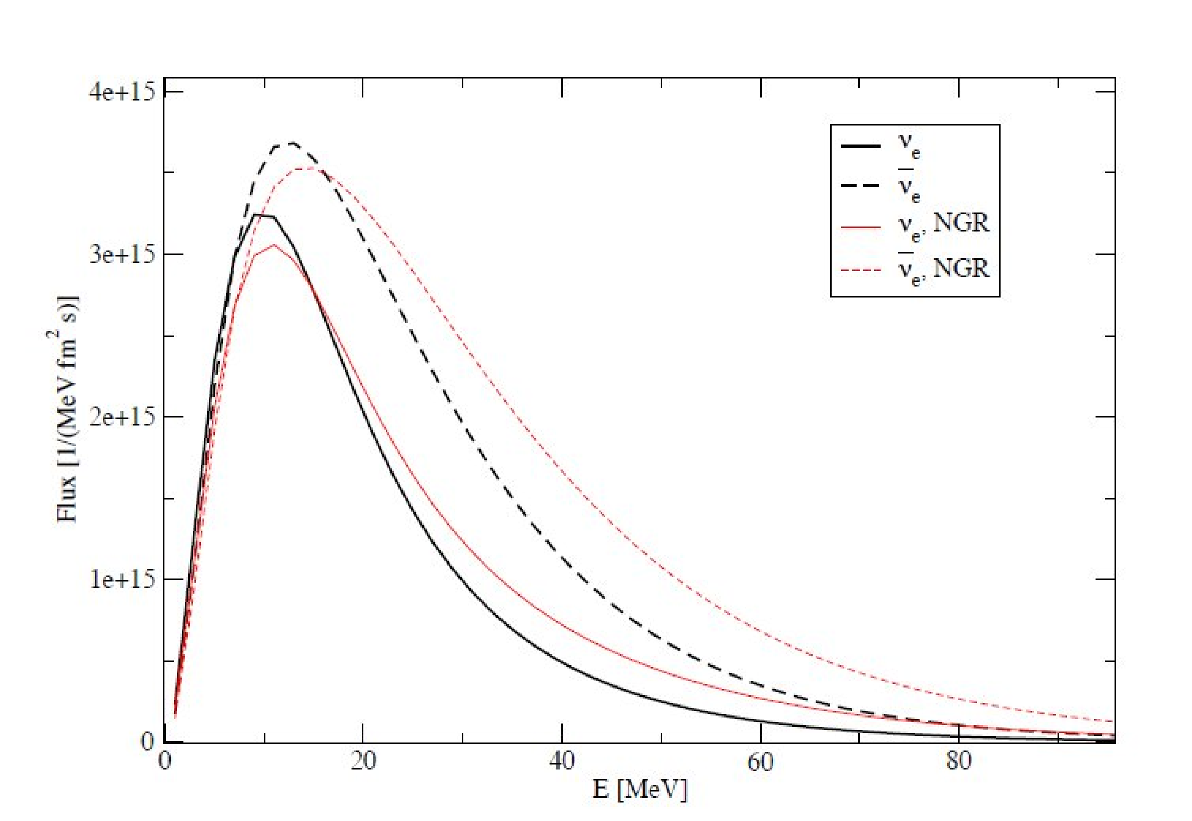
Binary neutron star merger

Neutrinos under strong gravity

Neutrinos are deflected and redshifted



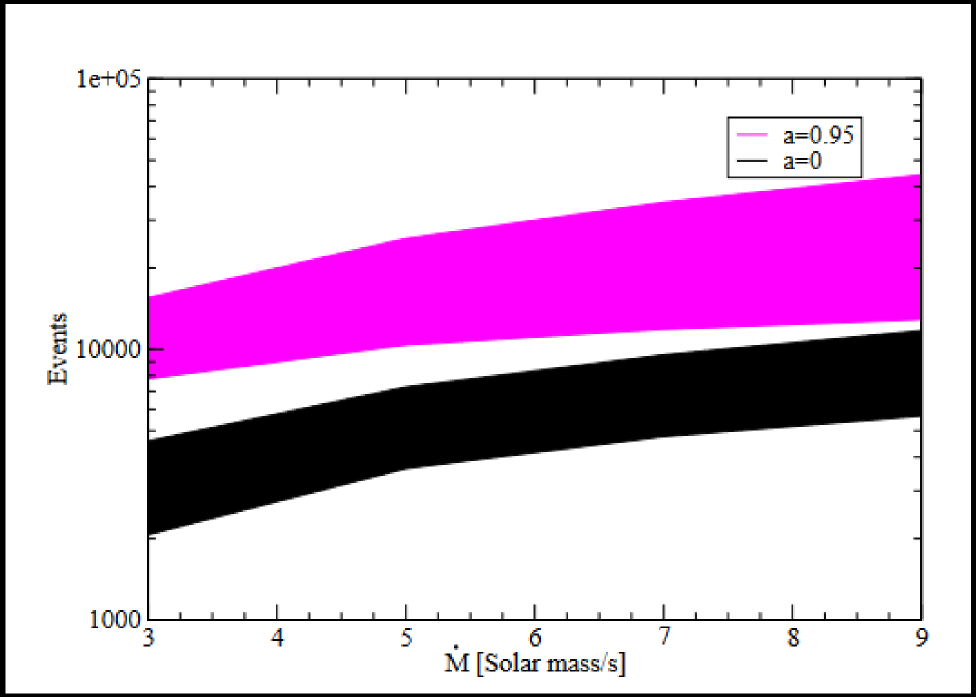
Observer at (x,z)=(40,48) km



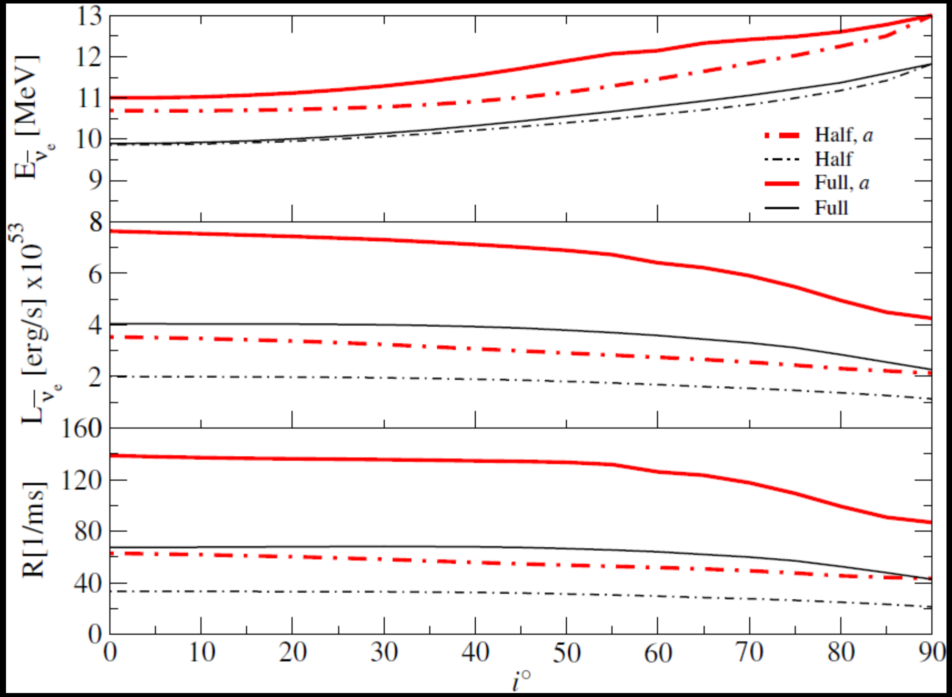
O. L. Caballero J. Phys. Conf. Ser. (2013)

High energy tail of the flux is reduced

Detection in SuperK from a disk at 10 kpc



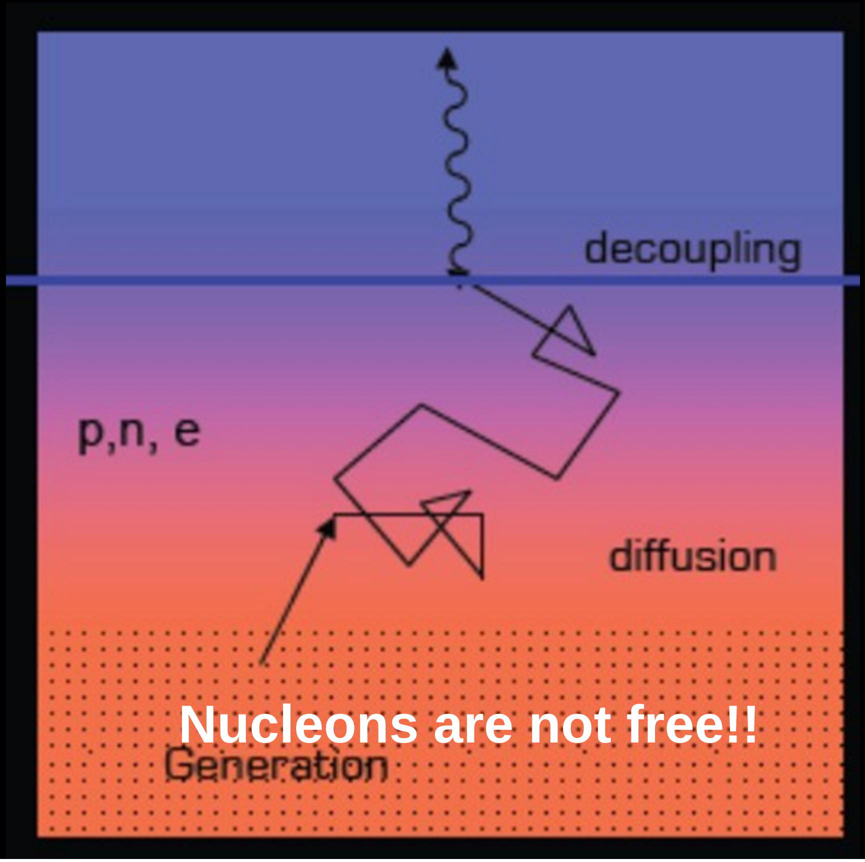
Black hole spin affects detection
Caballero, Zielinski* et al PRD 2016



Observer’s inclination

Strongly interacting nucleons

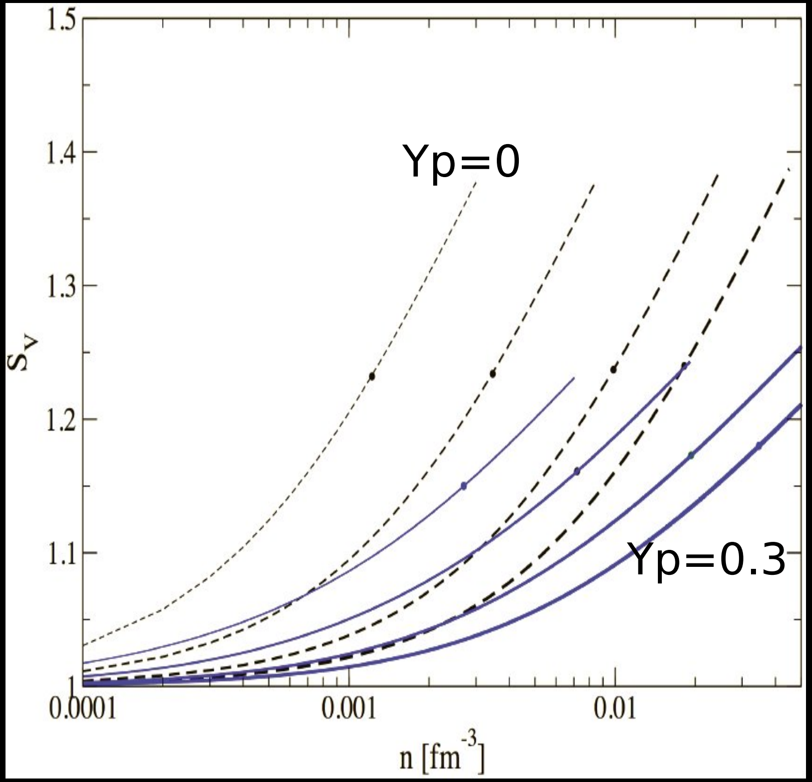
models of the nuclear force



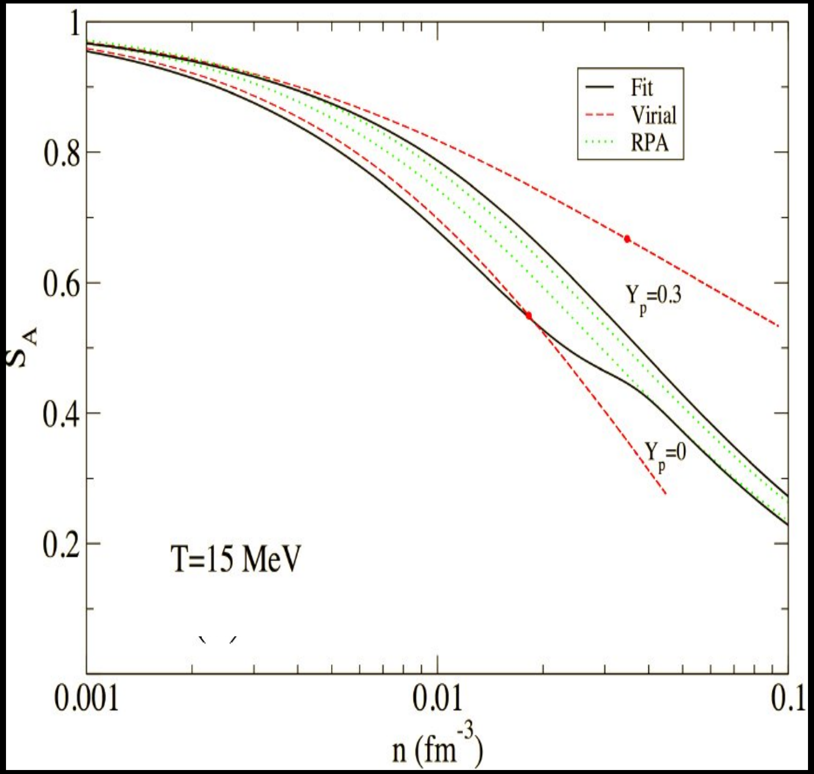
$$\frac{1}{V}\frac{d\sigma}{d\Omega} = \frac{G_F^2 E_\nu^2}{16\pi^2}\Big(g_a^2(3-\cos\theta)(n_n+n_p)S_A + (1+\cos\theta)n_n S_V\Big).$$

Virial EOS: Neutrinos in Nuclear matter

C. Horowitz, O. L. Caballero et al PRC (2017)

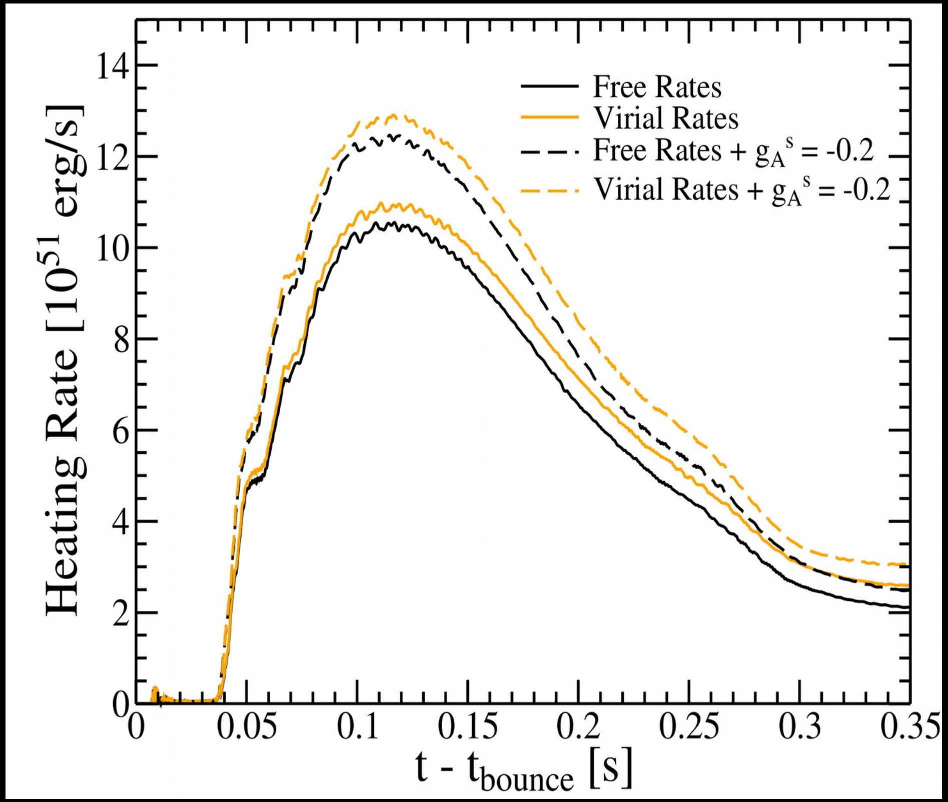


Matter fluctuations



Spin fluctuations

Virial EOS: one dimensional Supernova simulations

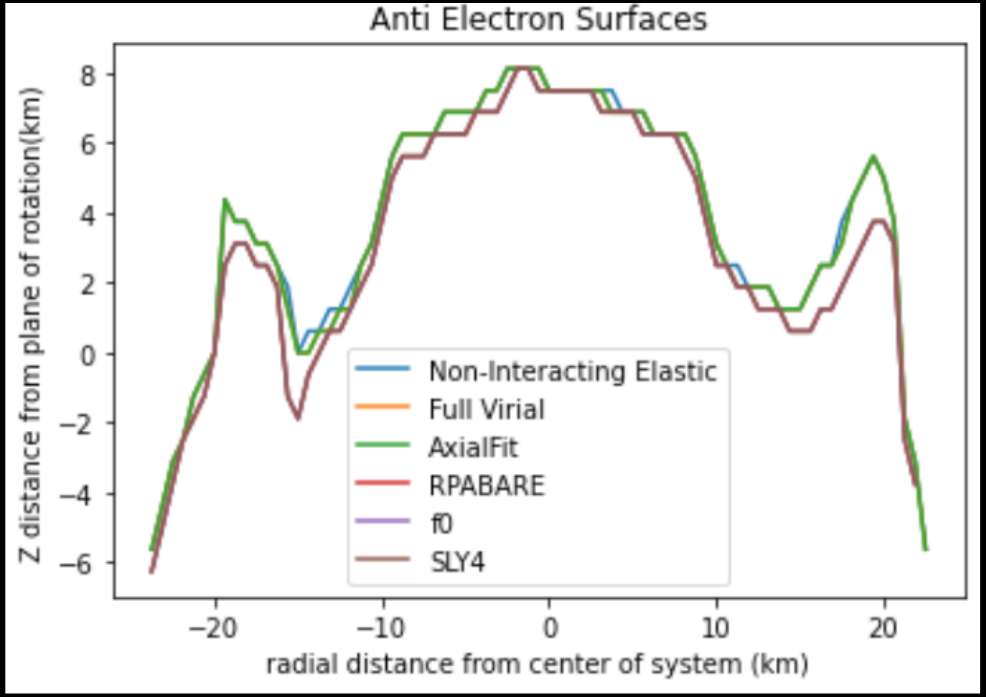


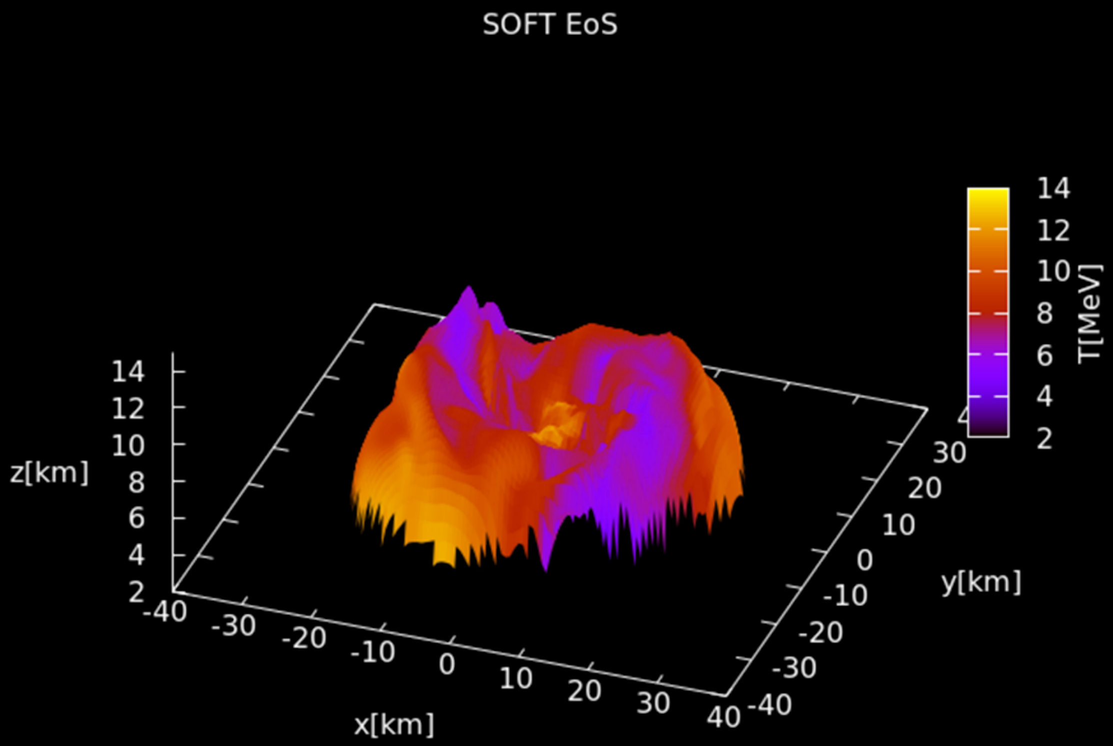
C. Horowitz, O. L. C. et al PRC (2017)

Increased neutrino heating rates facilitate the Supernova explosion

5% increase from virial EOS
20% from strange quark contribution to nucleon spin

Binary neutron star mergers





Neutrino surface with nucleonic interactions (neutral current), R. Anderson*, O. L. Caballero, Stay TUNED

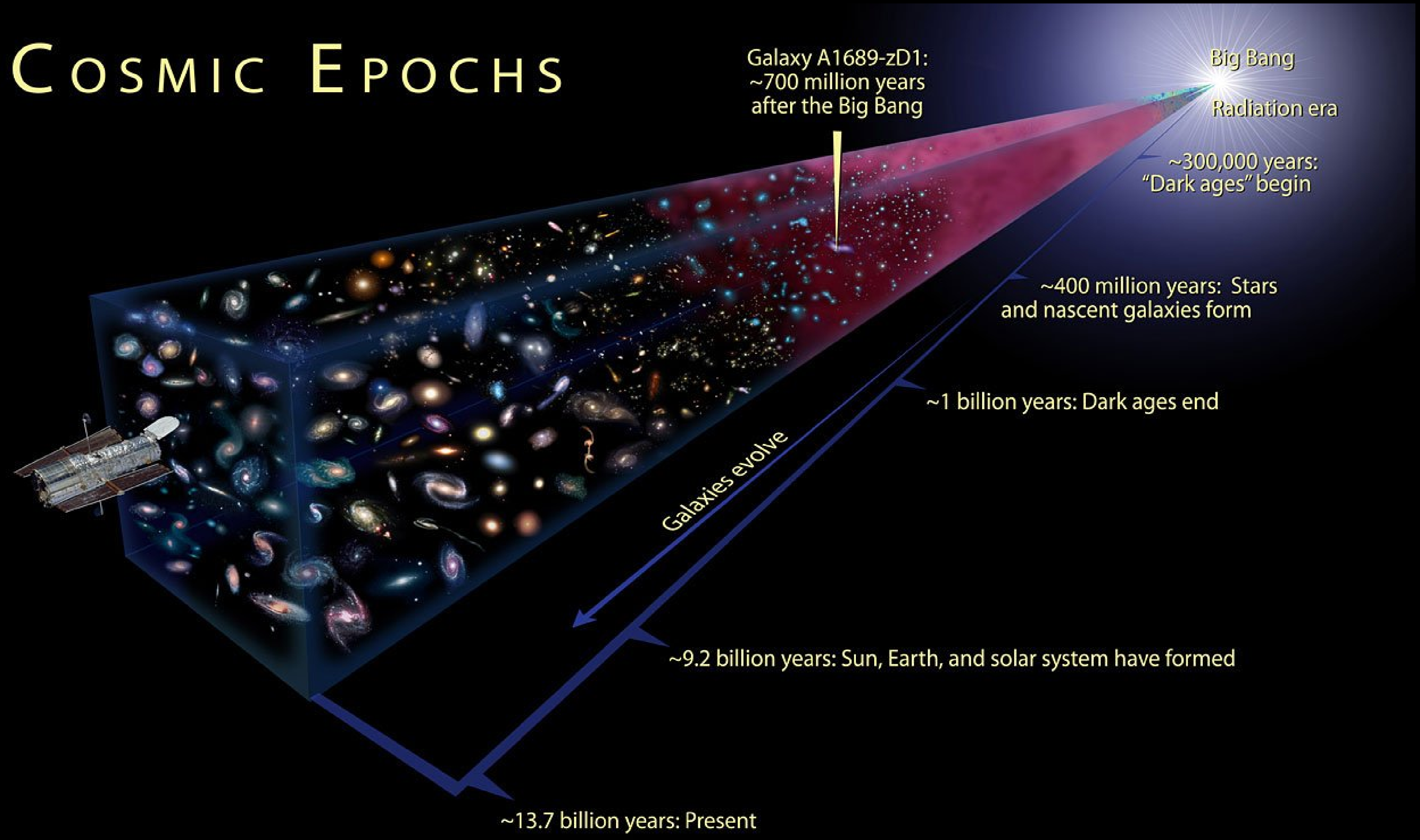
(CQG 2016, L. Lehner et al)

Event rates

- Supernovae: 1 per century in the Milky Way
- Binary neutron-star mergers: 100 per million years in the Milky Way

Advanced LIGO estimates for neutron star mergers: 8-12 events per year (reaching 485 Mpc)

Relic neutrinos



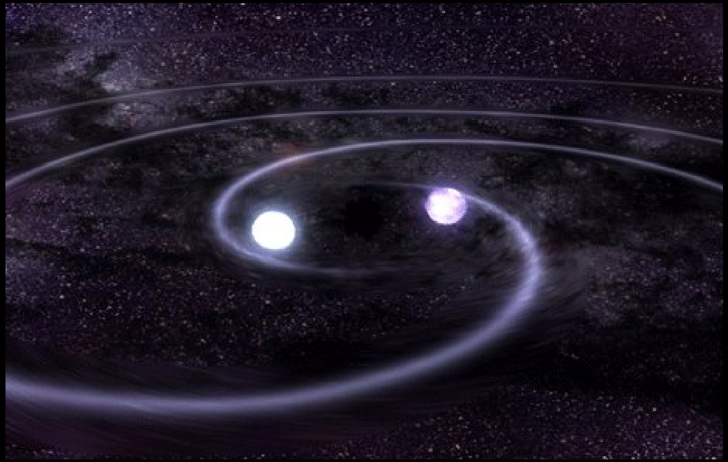
Accretion disk relic neutrinos

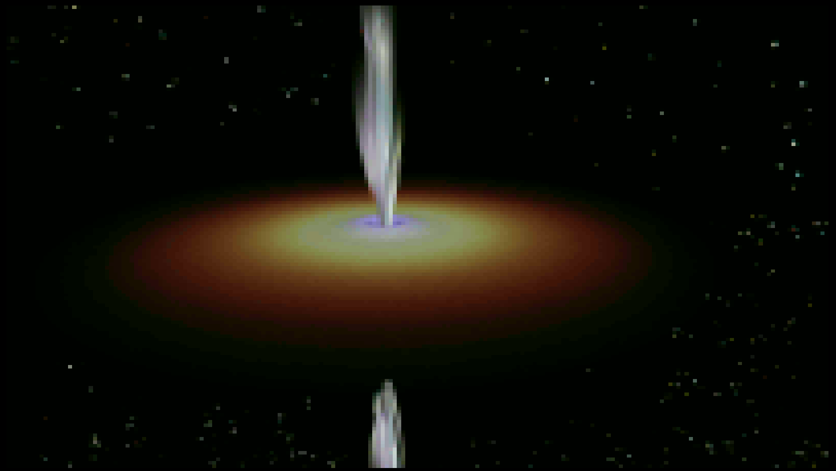
Mergers:

- Neutron star- Neutron star
- Neutron star -Black Hole

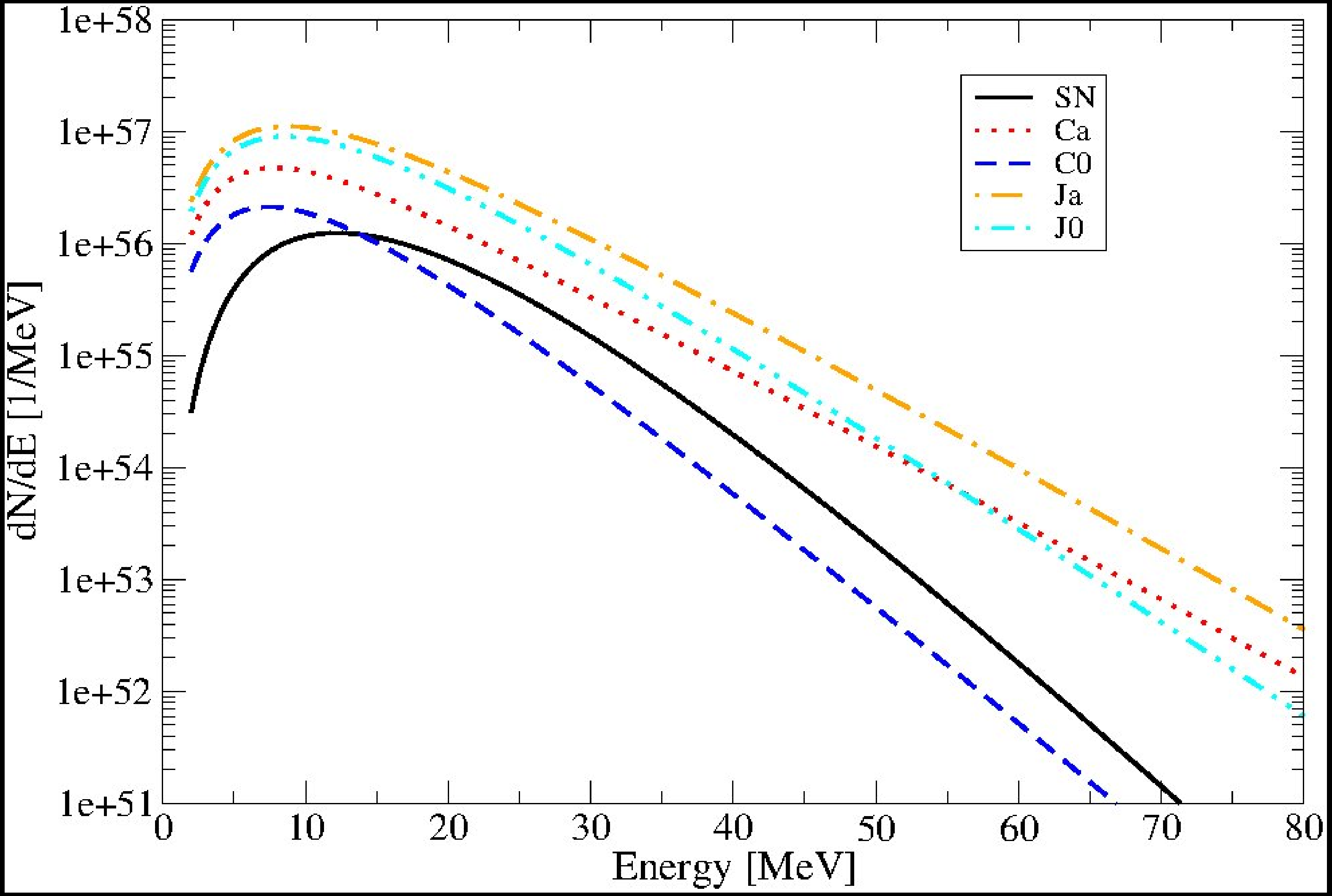
Collapsars :

- rotating massive star collapsing to black hole





Neutrino spectra from accretion disks



Observed at 10 kpc from the source

T. Schilbach*, O. L. Caballero, McLaughlin (PRD, 2018)

Relic Neutrinos

Flux

$$\frac{dF}{dE_o} = c\int (1+z_c)\, R(z_c)\, \frac{dN}{dE_\infty}\, \frac{dt}{dz_c}\, dz_c$$

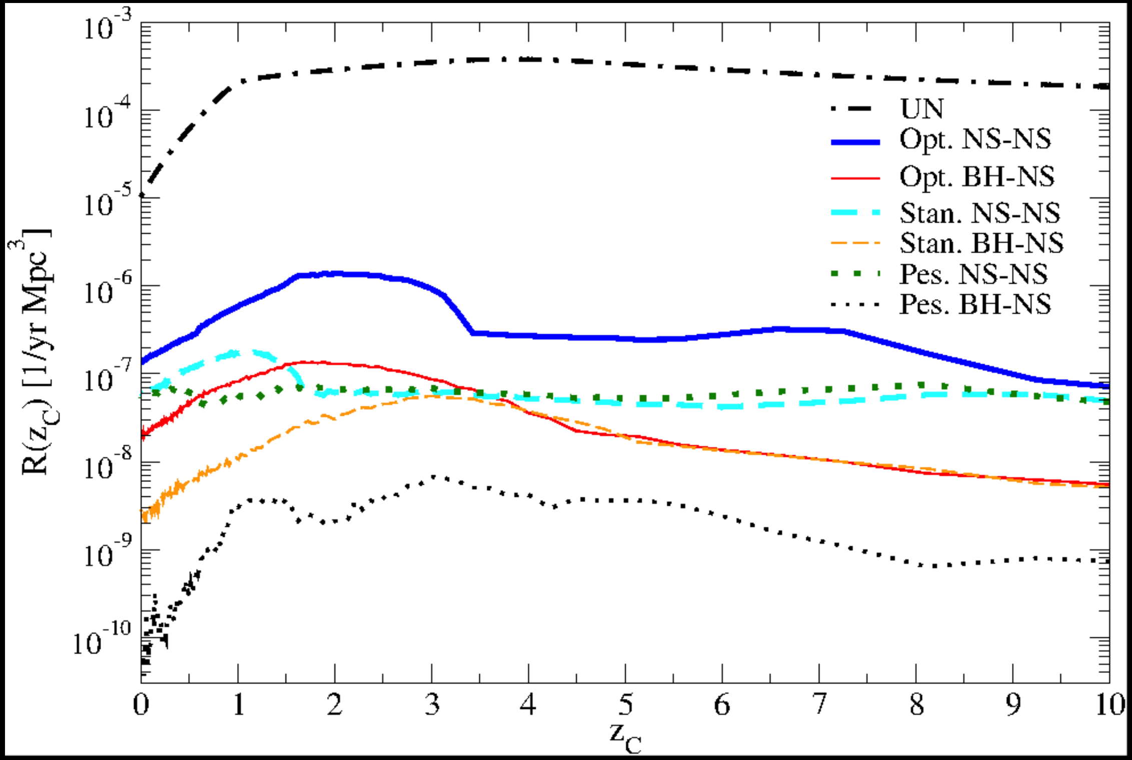
Cosmological redshift

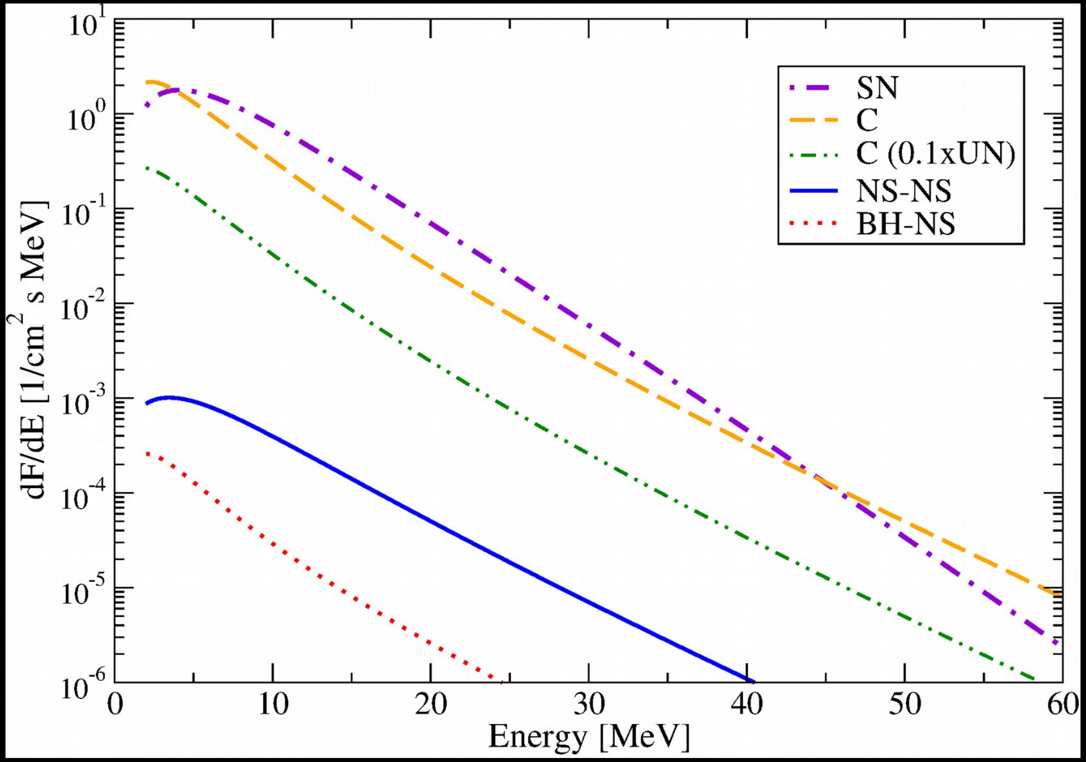
Event rates

Neutrino spectrum

Universe expansion

Event rates and diffuse fluxes

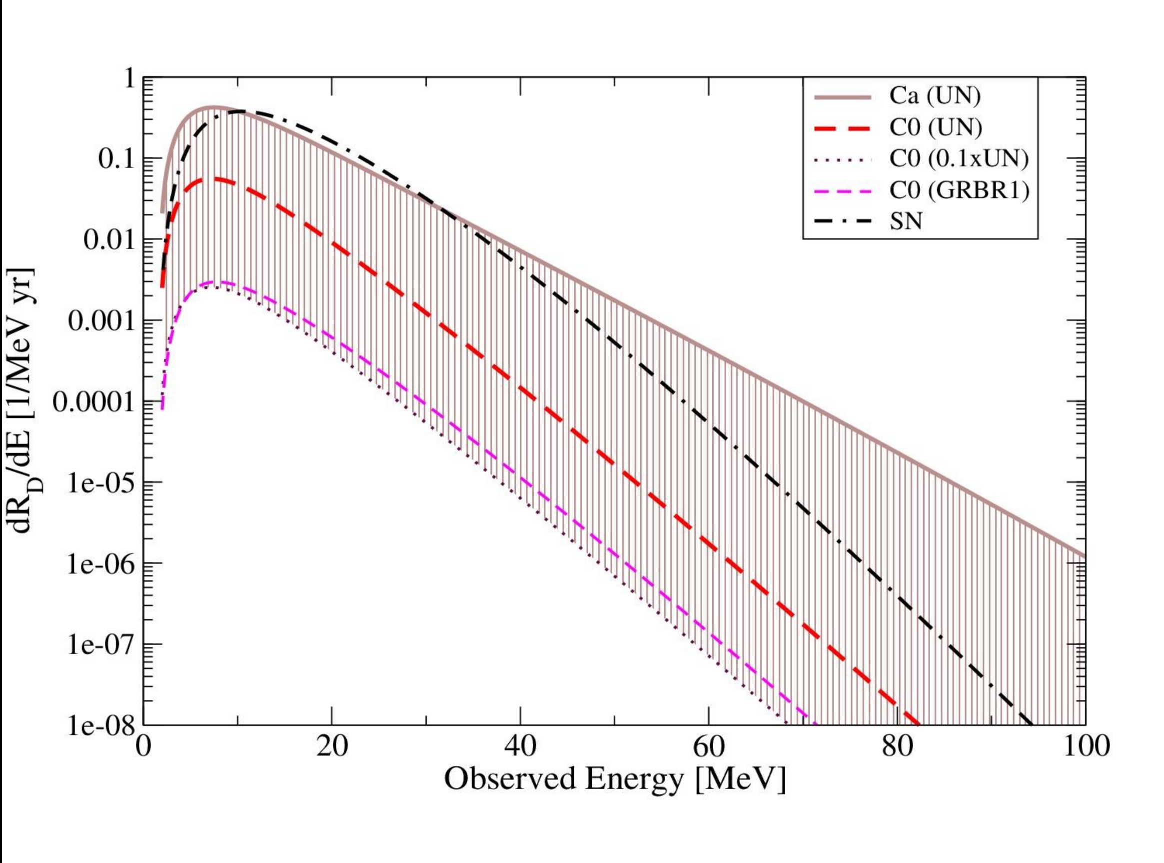




SN and UN rates from GRB burst from *Swift,* Yuksel et al ApJ (2008), PLB (2013)
Merger rates Dominik et al ApJ (2013)

Collapsar relic neutrinos at SuperK and HyperK

T. Schilbach*, O. L. Caballero, McLaughlin (PRD, 2018)



$$R_D = N_T \int_{E_{th}} \sigma(E_o) \frac{dF}{dE_o} dE_o.$$

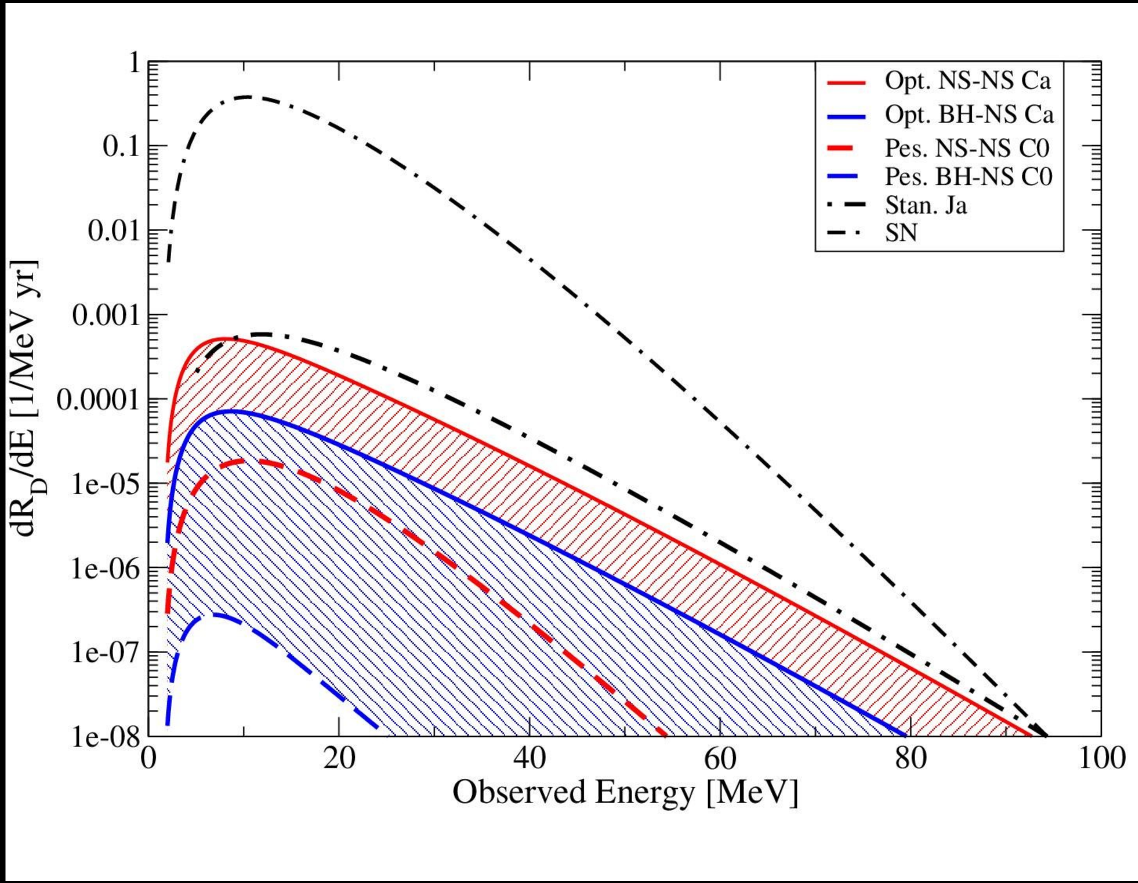
Scenario	Formation Rate	Disk Model	$\dot{M}$ $[M_\odot/s]$	R_D SK [1/yr]	R_D HK [1/yr]
Collapsar	UN	Ca	9	5.2	91
	0.1xUN	C0	3	0.02	0.35
NS-NS Merger	Opt.	Ca	7	7.0×10^{-3}	0.12
	Pes.	C0	3	2.7×10^{-4}	0.004
	Opt.	Ja	-	3.3×10^{-2}	0.57
	Pes.	J0	-	4.5×10^{-3}	0.08
	Stan.	Ja	-	1.0×10^{-2}	0.17
BH-NS Merger	Opt.	Ca	7	1.0×10^{-3}	1.7×10^{-2}
	Pes.	C0	3	2.4×10^{-6}	4.2×10^{-5}
	Opt.	Ja	-	4.7×10^{-3}	8×10^{-2}
	Pes.	J0	-	4.4×10^{-5}	8×10^{-4}

SuperK in 5 years: 0.1-25 neutrinos from Collapsars

HiperK in 10 years: ~900 from collapsars, 6 from NS-NS

Merger relic neutrinos at SuperK and HyperK

T. Schilbach*, O. L. Caballlero, McLaughlin (PRD,2018)



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SuperK in 5 years: 0.1-25 neutrinos from Collapsars
HiperK in 10 years: ~900 from collapsars, 2 from NS-NS

Conclusions

Neutrinos carry information from the interior of compact objects. Their detection (or by-products e.g. heavy element synthesis) will shed light on fundamental physics, and help interpret multi-messenger signals

We could detect neutrinos from:
- Milky way and satellite galaxies in SuperK
- Andromeda (780 kpc) in HyperK

Neutrinos from the past can tell us about the star formation rate, mergers and collapsar rates, and cosmic metallicity.

Collaborators

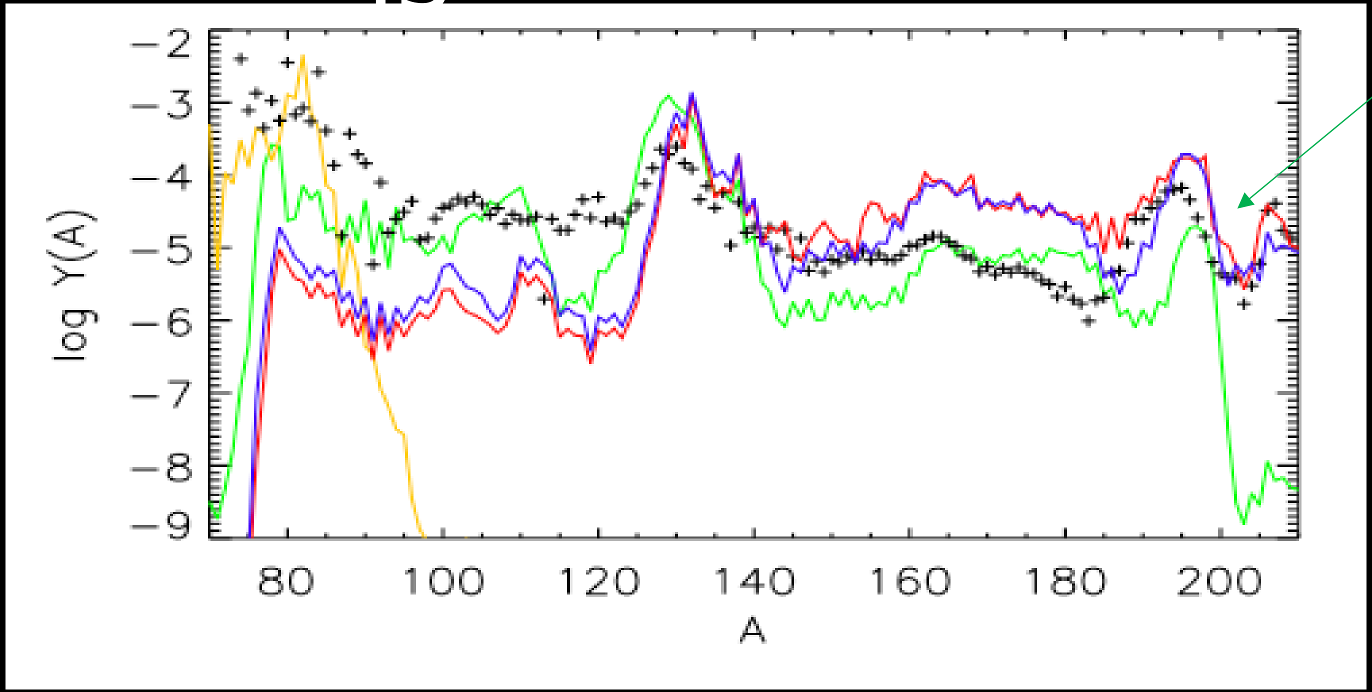
- Tyson Schilbach*, Tash Zielinski*, Rajan Anderson* (U. Of Guelph)
- G. McLaughlin (North Carolina State University), C. Horowitz (Indiana U.), A. Passtore (U . of York), A. Schwenk (TU Darmstadt), Evan O'Connor (North Carolina State University)

NSERC
CRSNG

SuperK

$E_{\bar{\nu}_e} > 5\text{MeV}$				
R_D [1/yr]	Collapsar		NS-NS ($\times 10^{-3}$)	
$\dot{M}$	$a = 0$	$a = 0.95$	$a = 0$	$a = 0.95$
$3M_\odot/s$	0.5	2.3	0.4	1.7
$5M_\odot/s$	0.8	3.4	0.7	2.1
$7M_\odot/s$	1.0	4.4	0.8	2.3
$9M_\odot/s$	1.3	5.2	−−	−−
SN	5.3			
$11 < E_{\bar{\nu}_e} < 30\text{MeV}$				
$3M_\odot/s$	0.2	1.2	0.23	1.1
$5M_\odot/s$	0.3	1.8	0.4	1.3
$7M_\odot/s$	0.4	2.3	0.5	1.4
$9M_\odot/s$	0.5	2.6	−−	−−
SN	3.3			

Nucleosynthesis



Gold

No GR: only first peak achieved.

More redshifted

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

$$\nu_e + n \longleftrightarrow e + p$$

GR neutrinos are less energetic. Material remains neutron rich

Caballero, McLaughlin, Surman. ApJ 2012

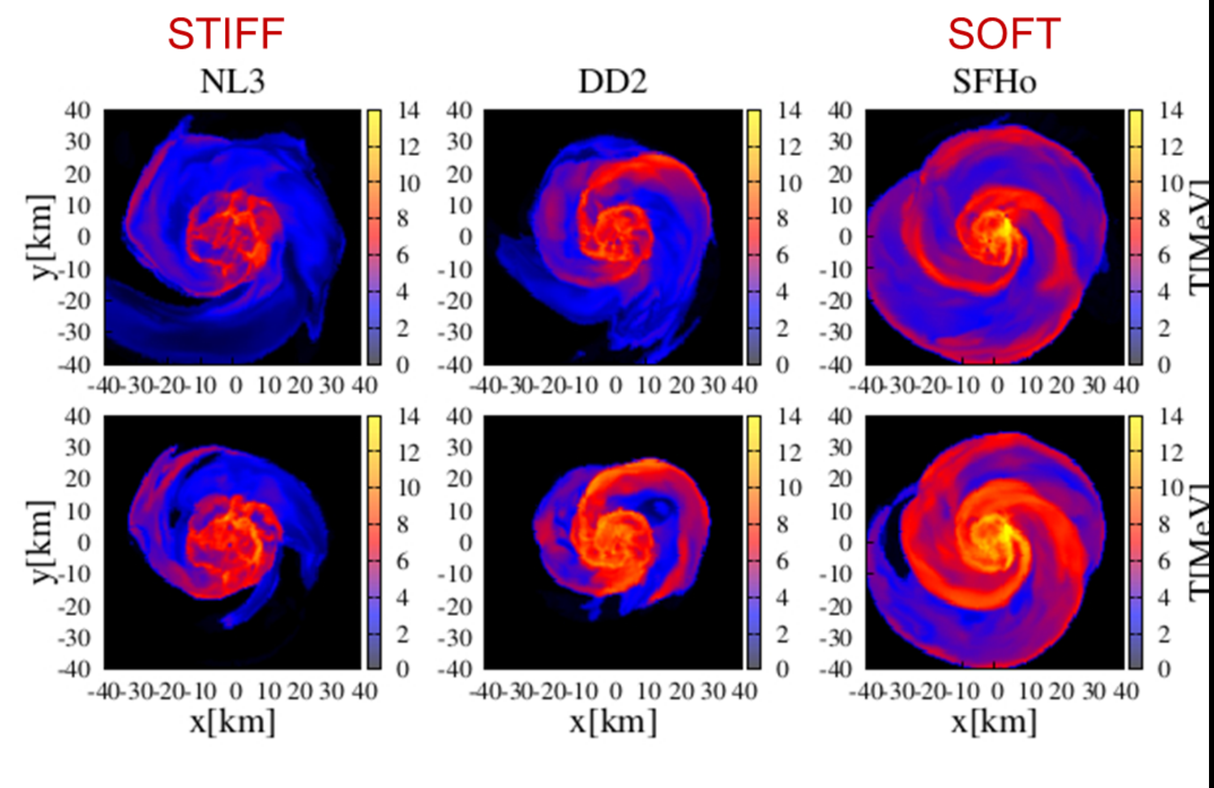
Yellow = Newtonian neutrinos
Green = Static disk and a=0
Red = Rotating disk and a=0
Blue = Rotating disk and a=0.6

Outflow model
Low entropy S/k=20
Fast outflow t=5 ms

Merger of unequal mass magnetized NSs

EoS	q	t [ms]	$\langle E_{\bar{\nu}_e} \rangle$ [MeV]	$\langle E_{\nu_e} \rangle$ [MeV]	$L_{\bar{\nu}_e}$ [10^{53} erg/s]	R_ν [#/ms]
NL3	1.0	3.4	18.5 (22.4)	15.2 (18.3)	0.7	18
NL3	0.85	3.0	15.6 (18.7)	12.6 (15.1)	0.8	18
DD2	1.0	3.3	18.3 (22.1)	14.6 (17.4)	1.1	28
DD2	0.85	2.8	18.1 (21.7)	15.1 (18.0)	1.0	25
DD2	0.76	2.4	19.7 (23.9)	14.8 (17.9)	1.3	36
SFHo	1.0	3.5	24.6 (29.7)	23.5 (28.3)	3.5	121
SFHo	0.85	3.9	17.8 (21.3)	15.3 (17.9)	2.0	50

Neutrinos in SuperK: NS-NS merger at 10 kpc



(CQG 2016, L. Lehner et al)

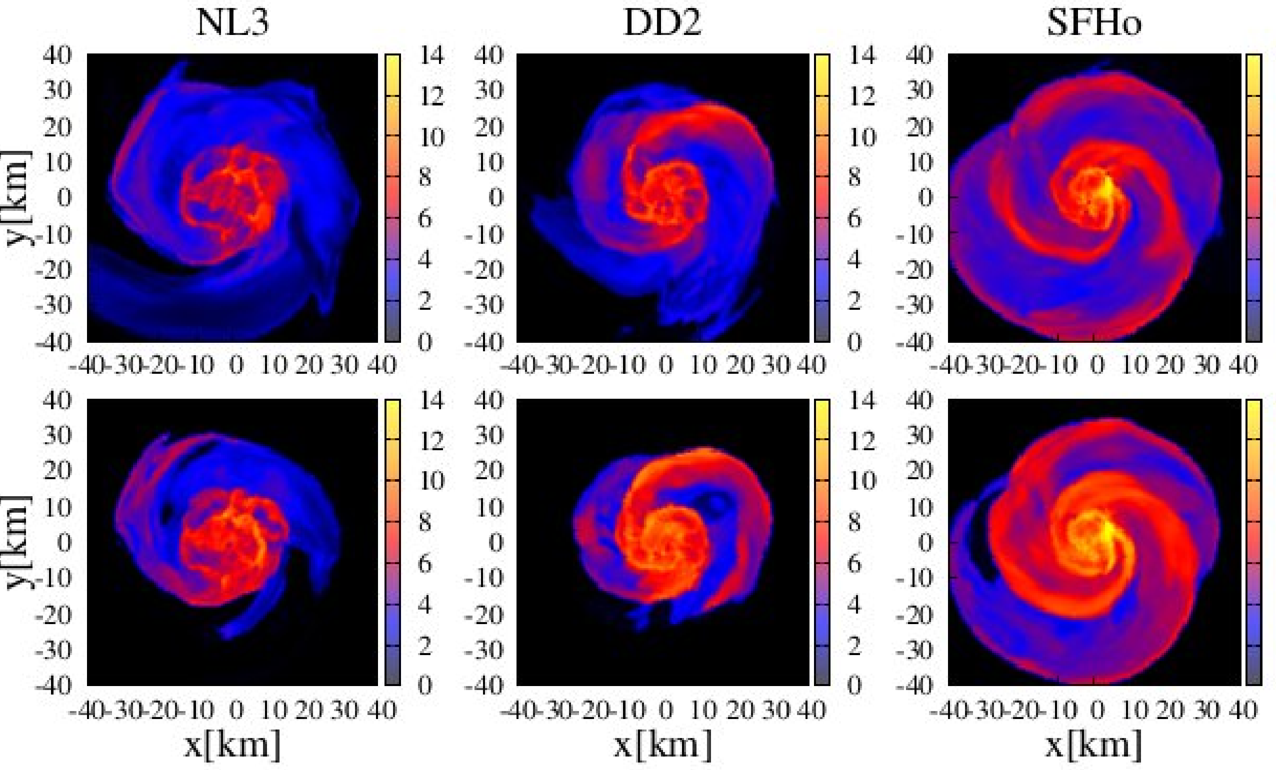
Larger changes with soft EoS when q decreases

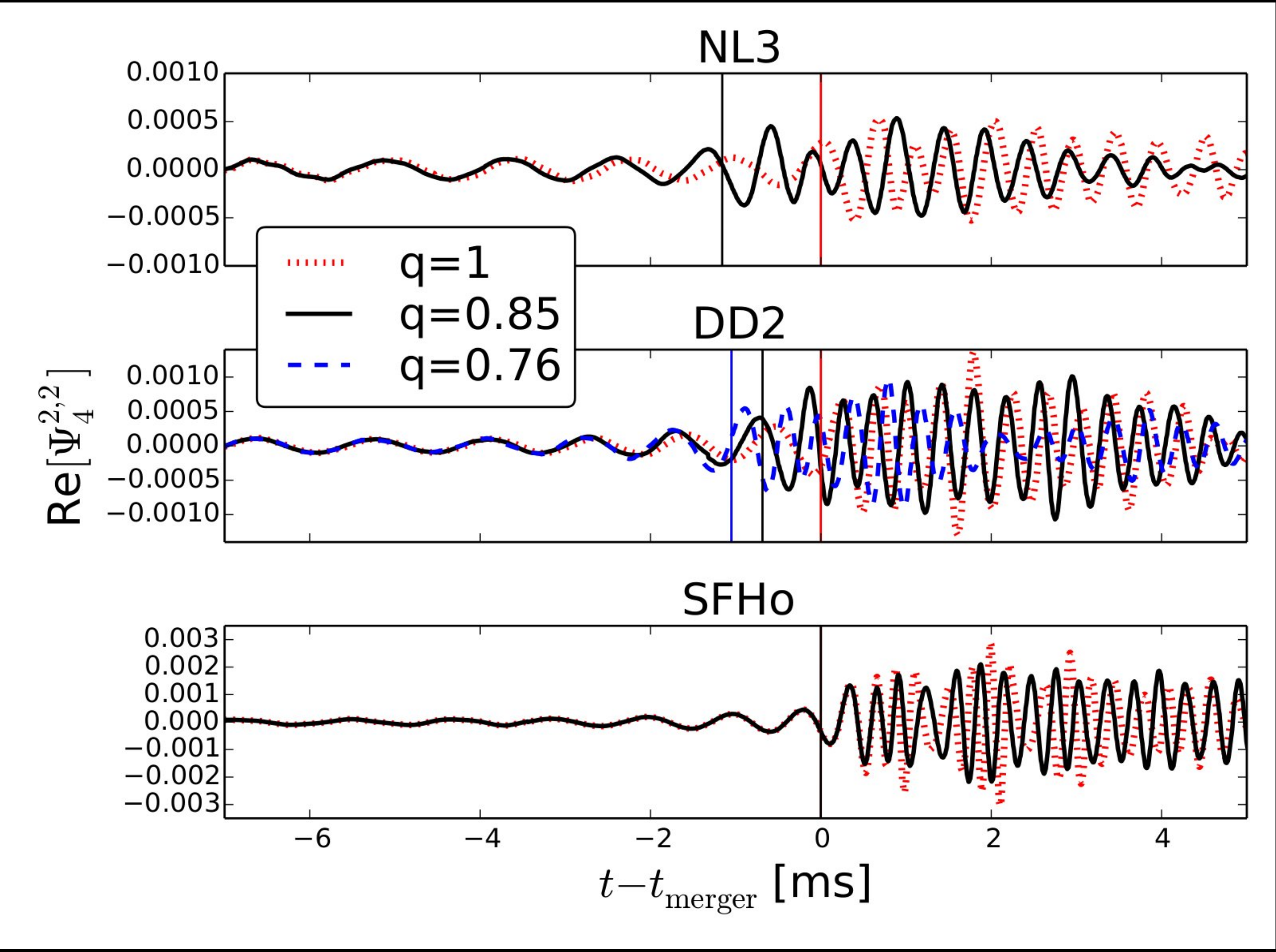
Merger of unequal mass magnetized NSs

(CQG 2016, L. Lehner et al)

Effect of the mass ratio

$q=m_1/m_2$ q=0.85



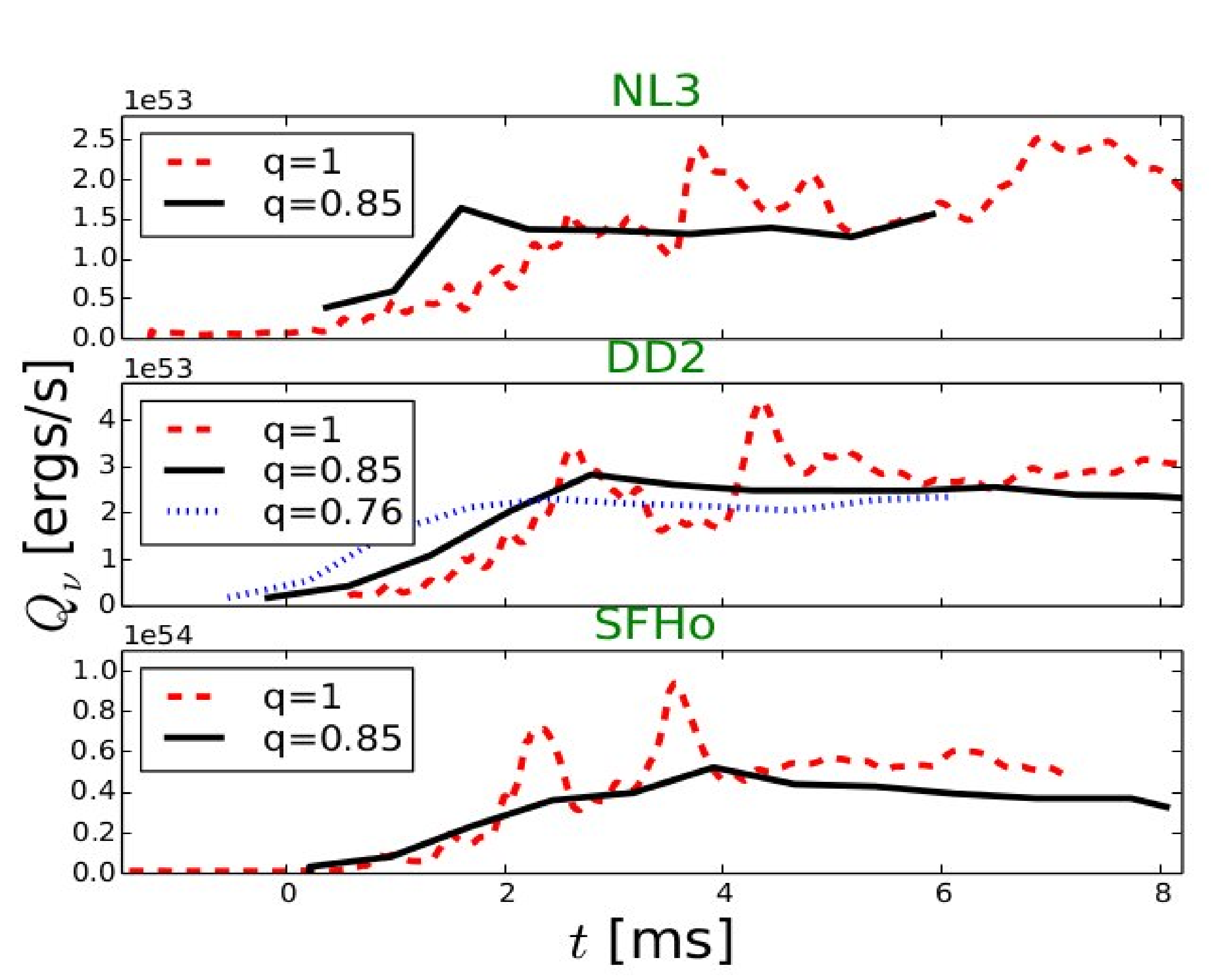


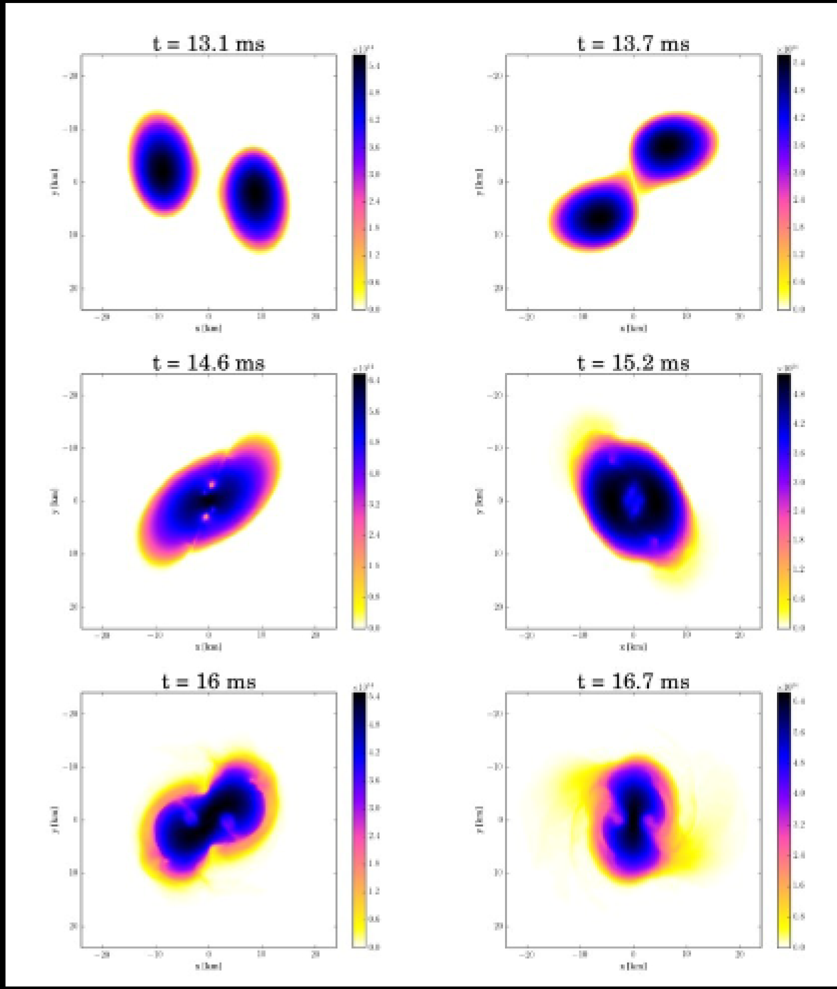
Tidal effects are more pronounced with stiffer EoS

Reduction of the mass ratio disrupts the star earlier

As q decreases the stronger are the tidal effects

Neutrino luminosity evolution





Luminosity oscillates for q=1

Electron fraction distribution for unbound and bound material

Electron fraction decreases as q decreases, compatible with r-process nucleosynthesis and kilonova