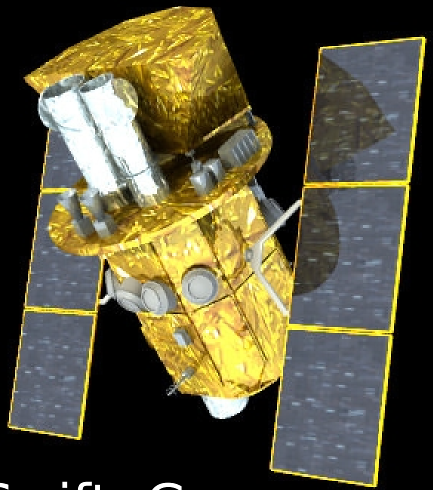
Neutrinos and multi-messenger signals

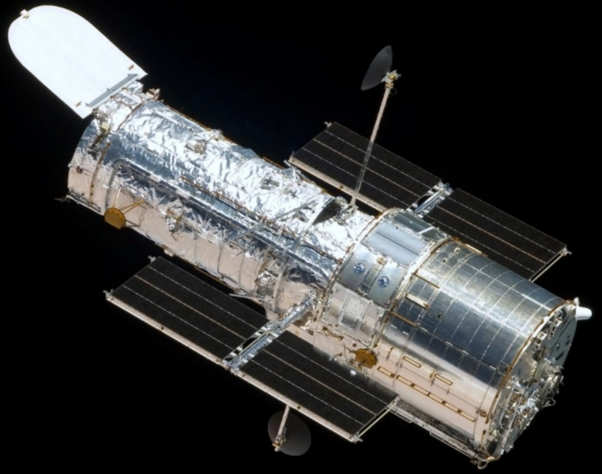
Liliana Caballero
University of Guelph

Canadian Multi-messenger Astrophysics Workshop
January 30th 2020

We are ready!



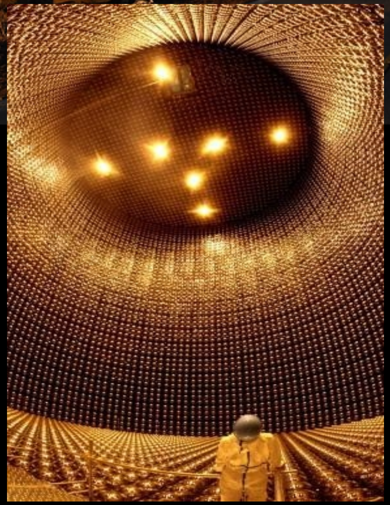
Swift: Gamma-rays



Hubble Space Telescope

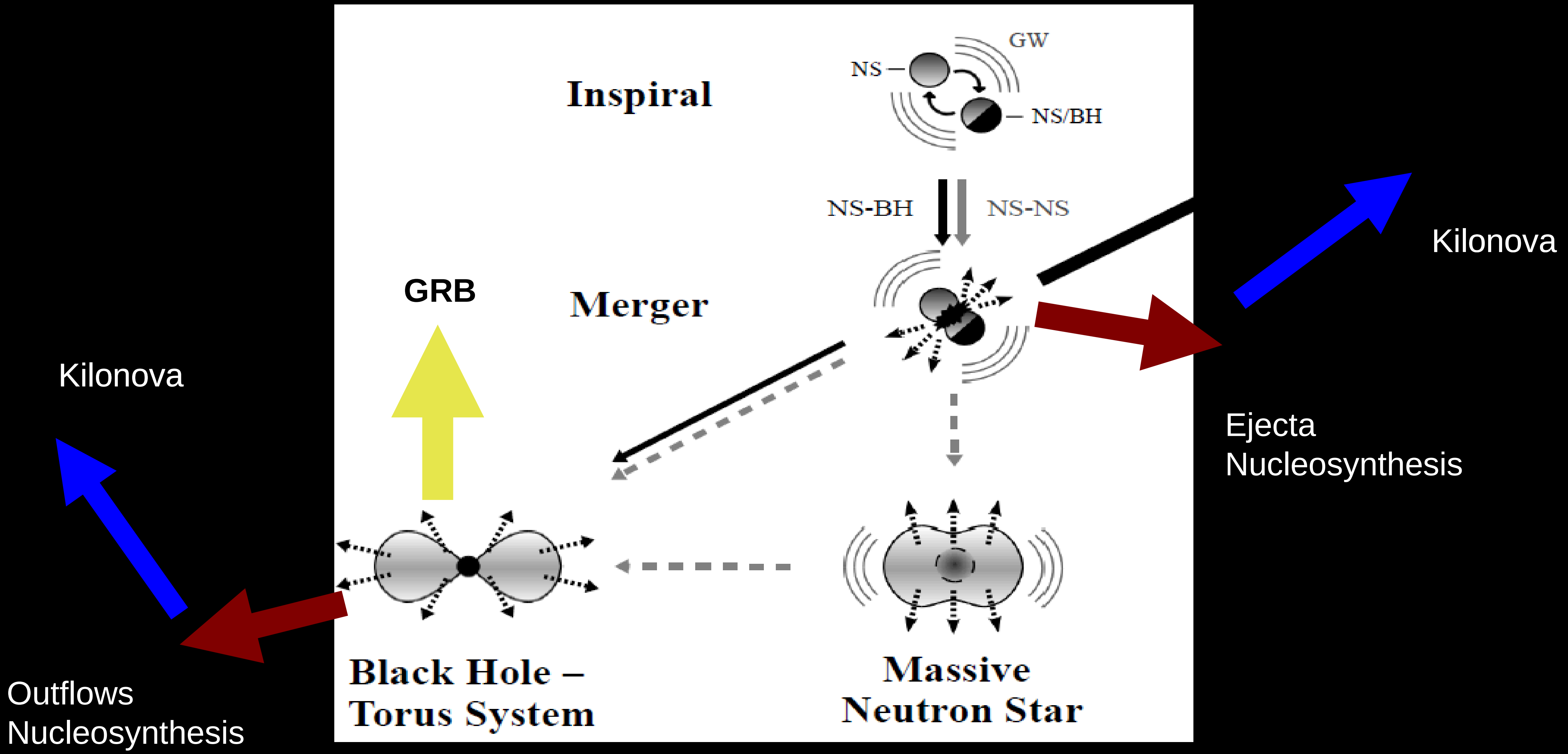
LIGO: Gravitational Waves

Las Campanas



SuperK: Neutrinos

Multi-messenger astronomy



O. Just et al MNRA, 2015

See B. Metzger (2018) and ref therein

Neutrinos and r-process nucleosynthesis
Neutrinos from neutron-star mergers
Relic neutrinos

Nucleosynthesis

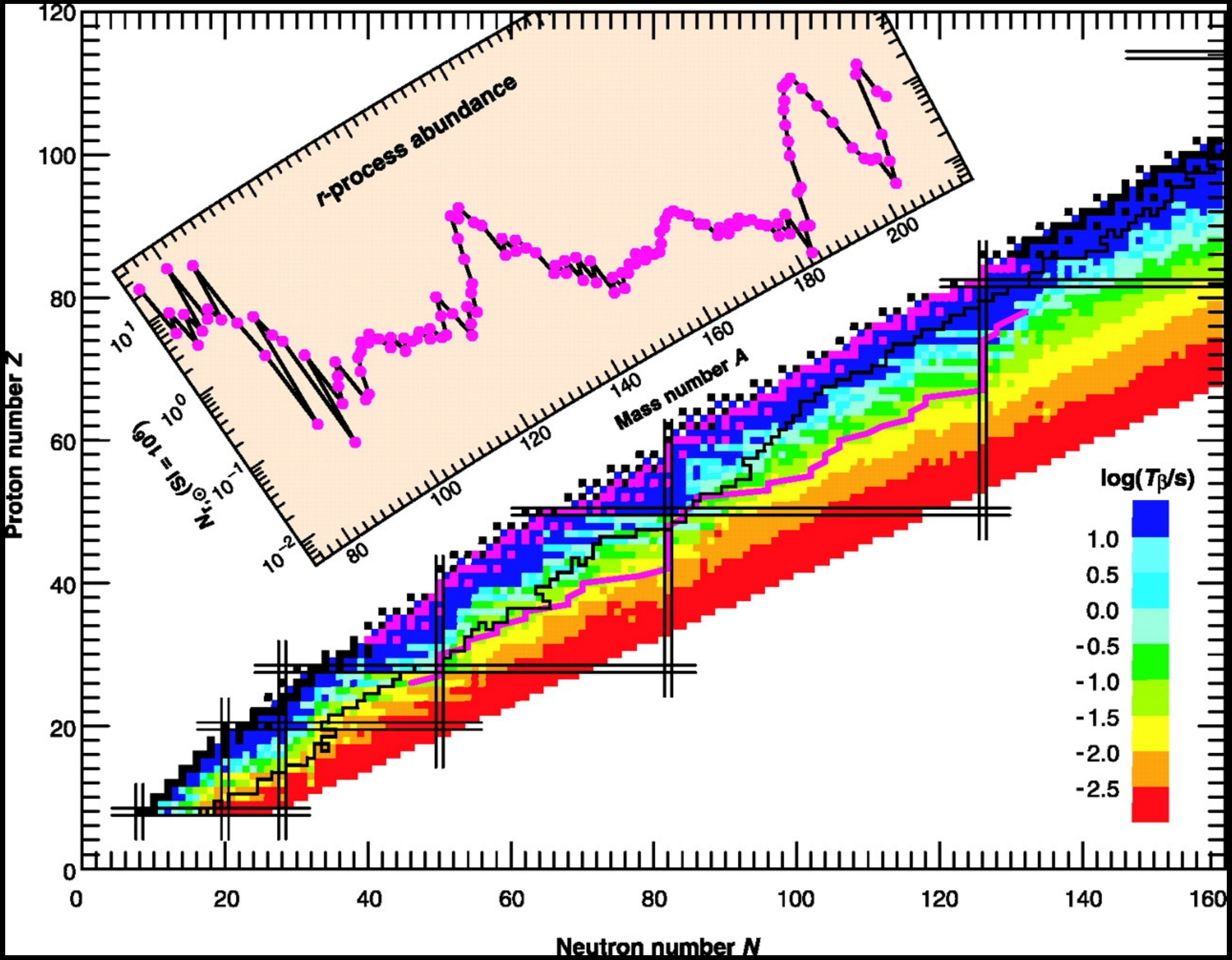
Electron fraction

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

Proton rich

$Y_e = 0.5$

Neutron rich



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

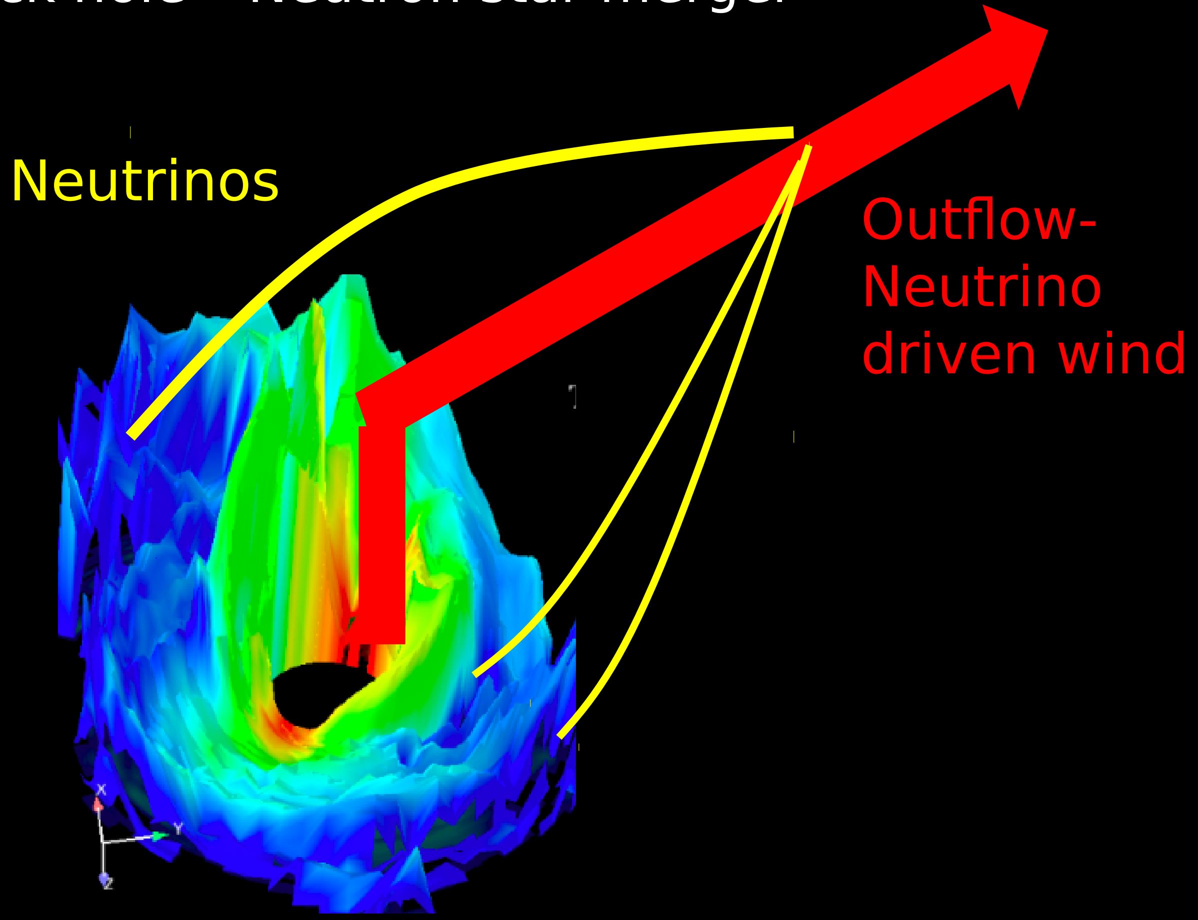
$\nu_e + n \leftrightarrow e + p$

Nucleosynthesis

Black hole – Neutron star merger

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

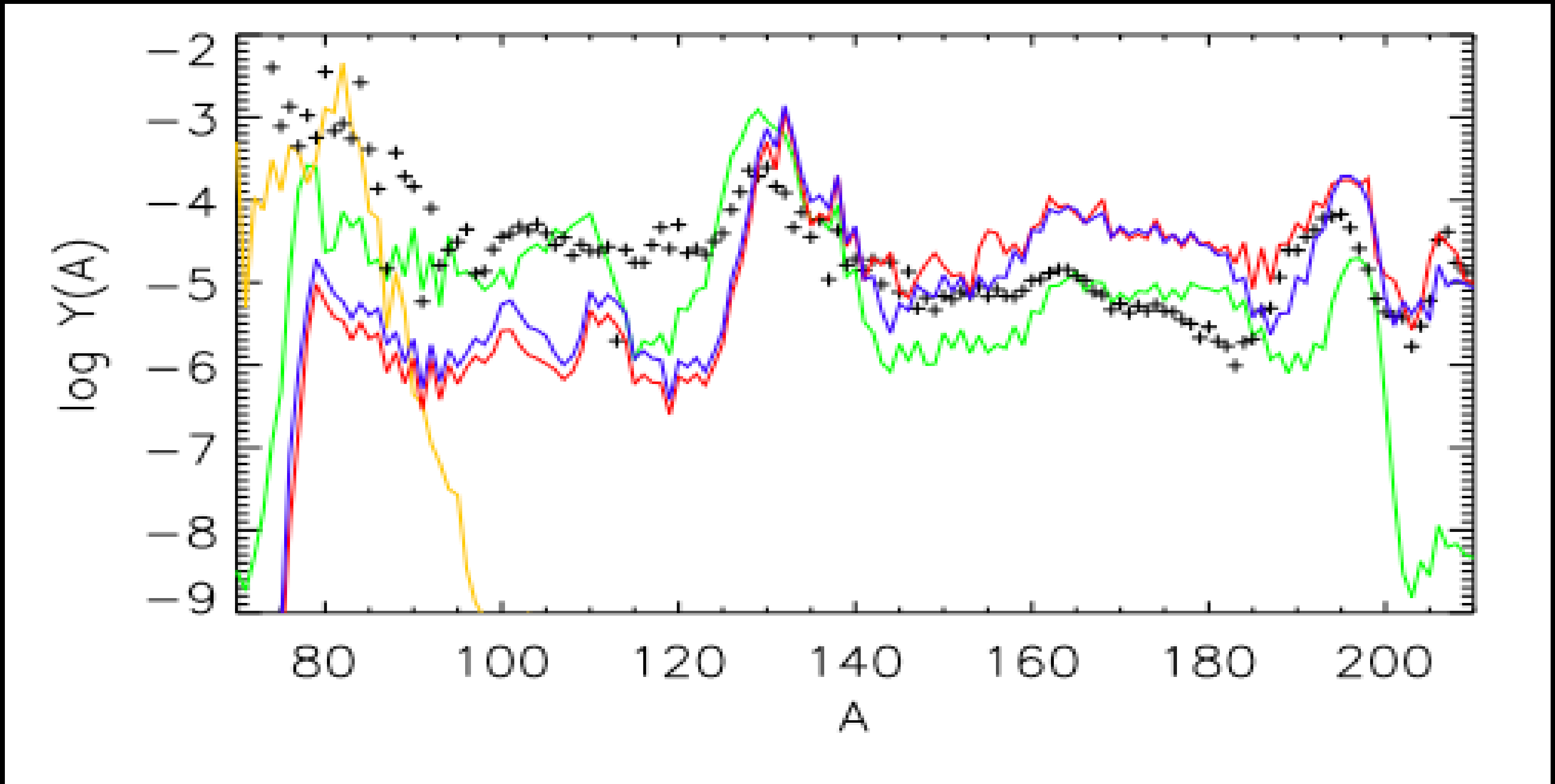
$$\nu_e + n \leftrightarrow e + p$$



Yields depend on neutrinos and outflow conditions

Nucleosynthesis

Caballero, McLaughlin, Surman. ApJ 2012



No GR: only first peak achieved.

More redshifted

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

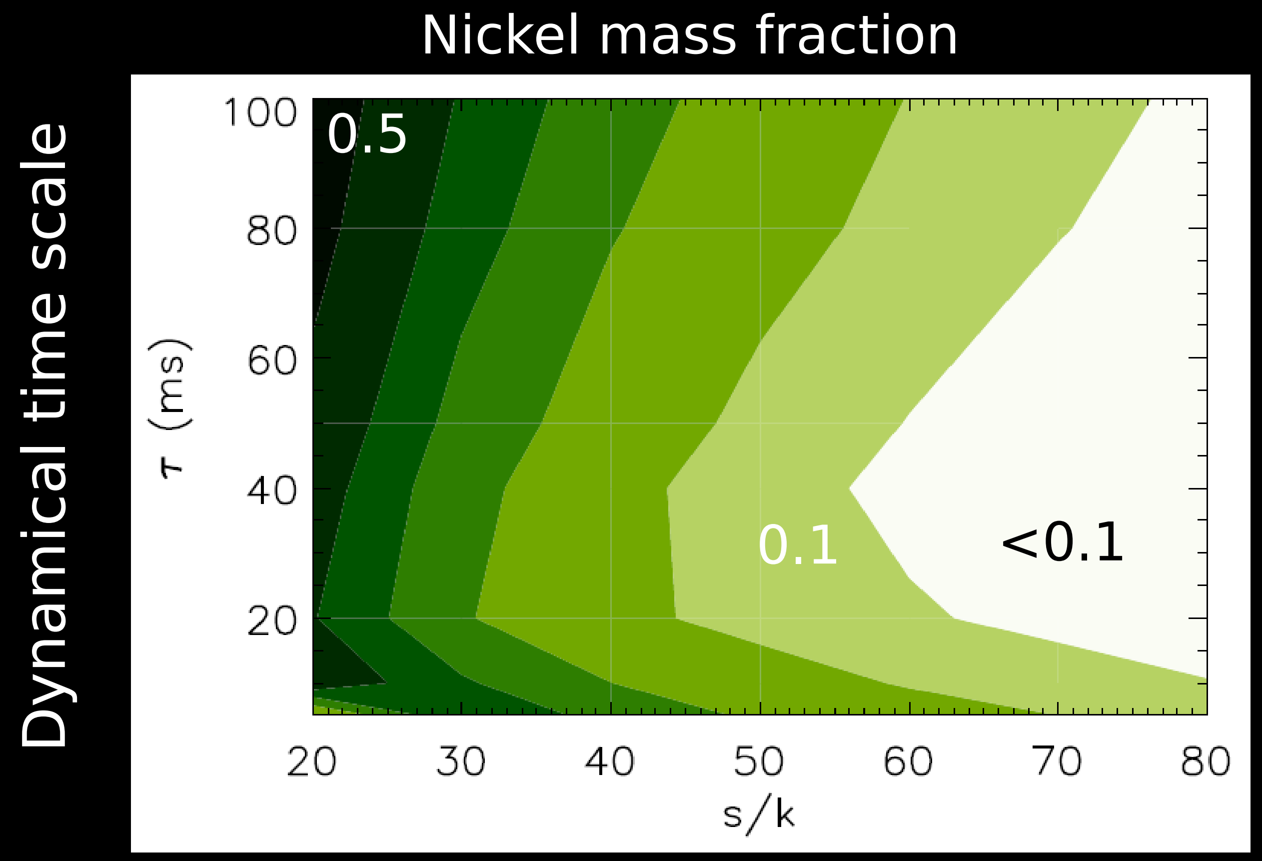
$$\nu_e + n \longleftrightarrow e + p$$

GR neutrinos are less energetic. Material remains neutron rich

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

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

Outflow parameter space



Surman, Caballero, McLaughlin, Just, Janka, J. Phys. G. (2014)

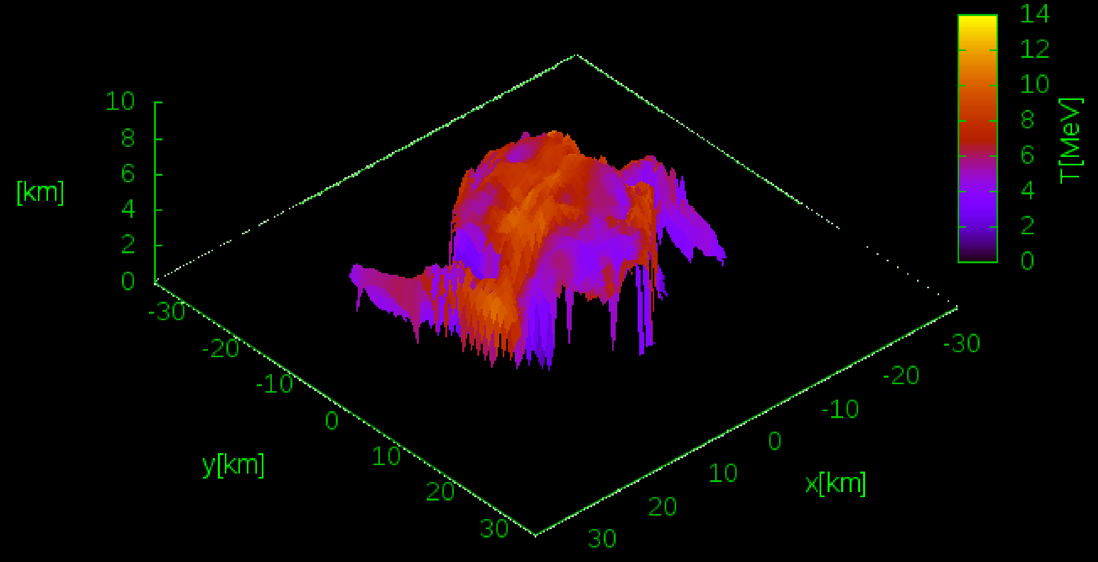
^{56}Ni is the (A>4) most abundant element.
For mildly heated outflows over half of the outflow material is ejected as ^{56}Ni

Neutron star mergers

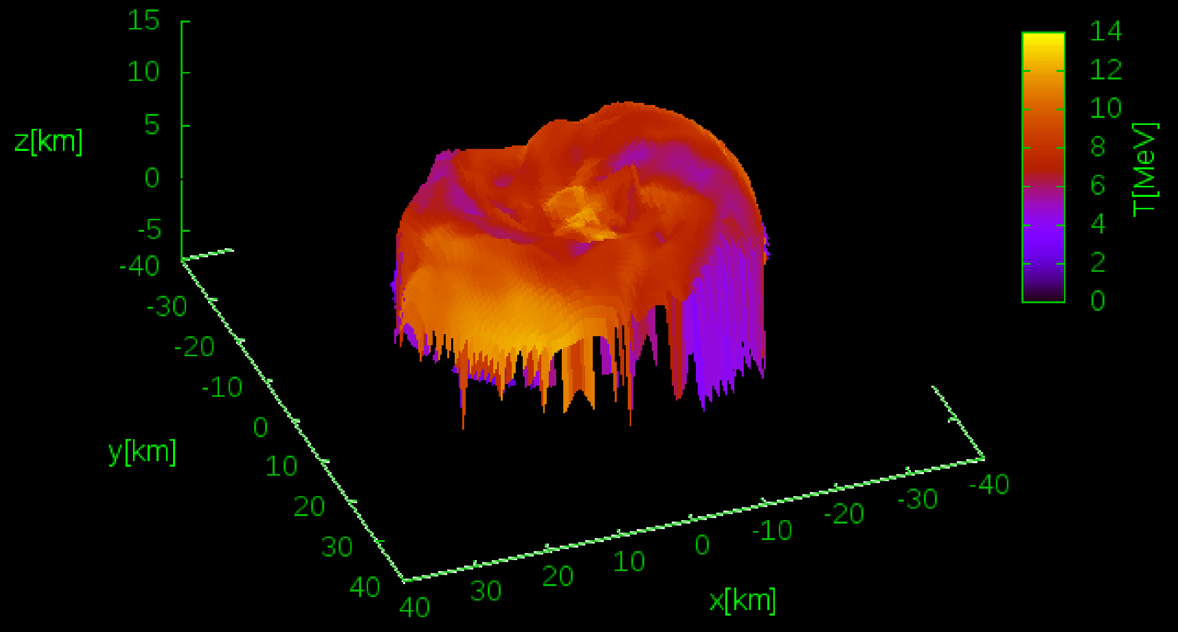
Neutrinos from NS-NS mergers

Electron antineutrino surfaces

q=1



NL3



SFHo

O. L. Caballero (2016)

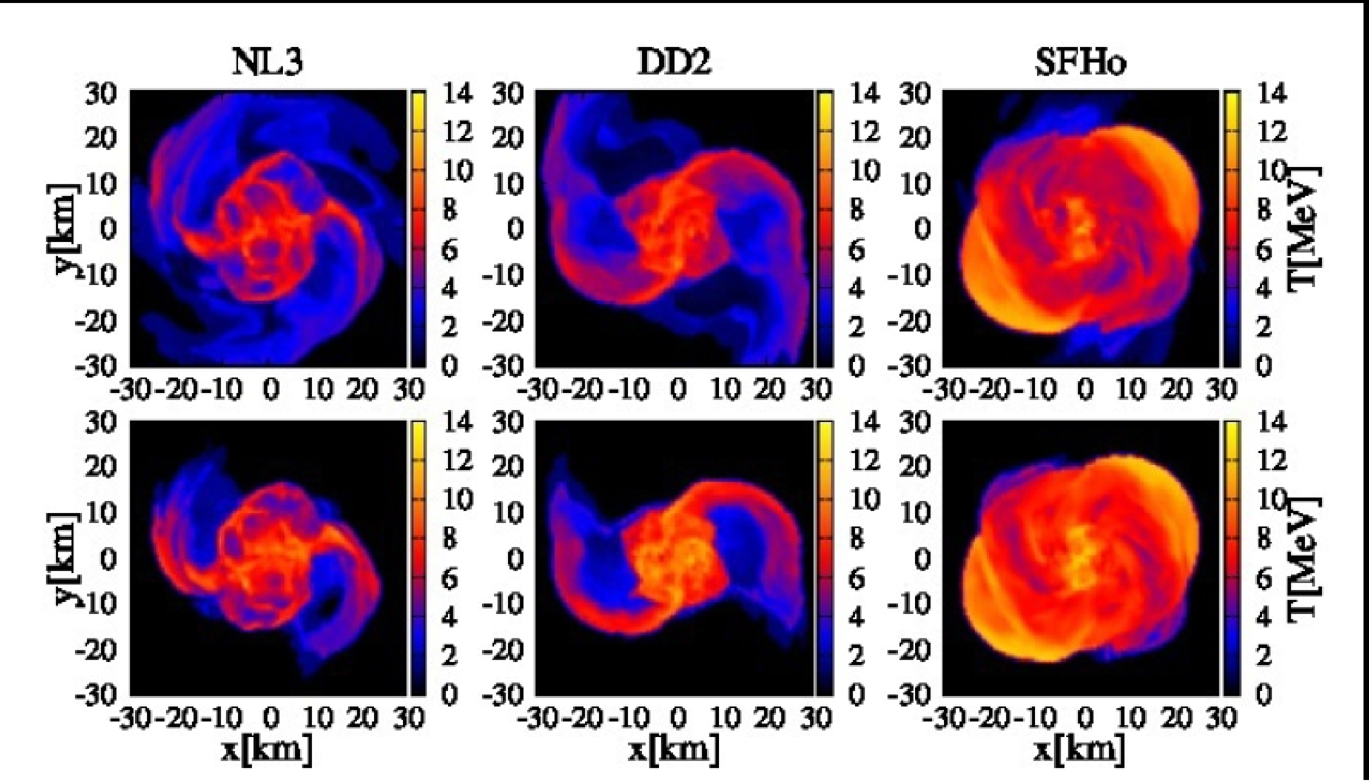
Could we add constraints to the EoS from neutrino detections?

Higher peak neutrino temperatures are found with SFHo (soft) EoS

C. Palenzulela et al 2015, PRD

e-neutrino

e-antineutrino



q=1

Time [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]
2.5 (NL3)	18.5 (22.4)	15.2 (18.3)	0.71	18.1
3.0 (DD2)	18.3 (22.1)	14.6 (17.4)	1.1	28.2
3.2 (SFHo)	24.6 (29.7)	23.5 (28.3)	3.5	120.8

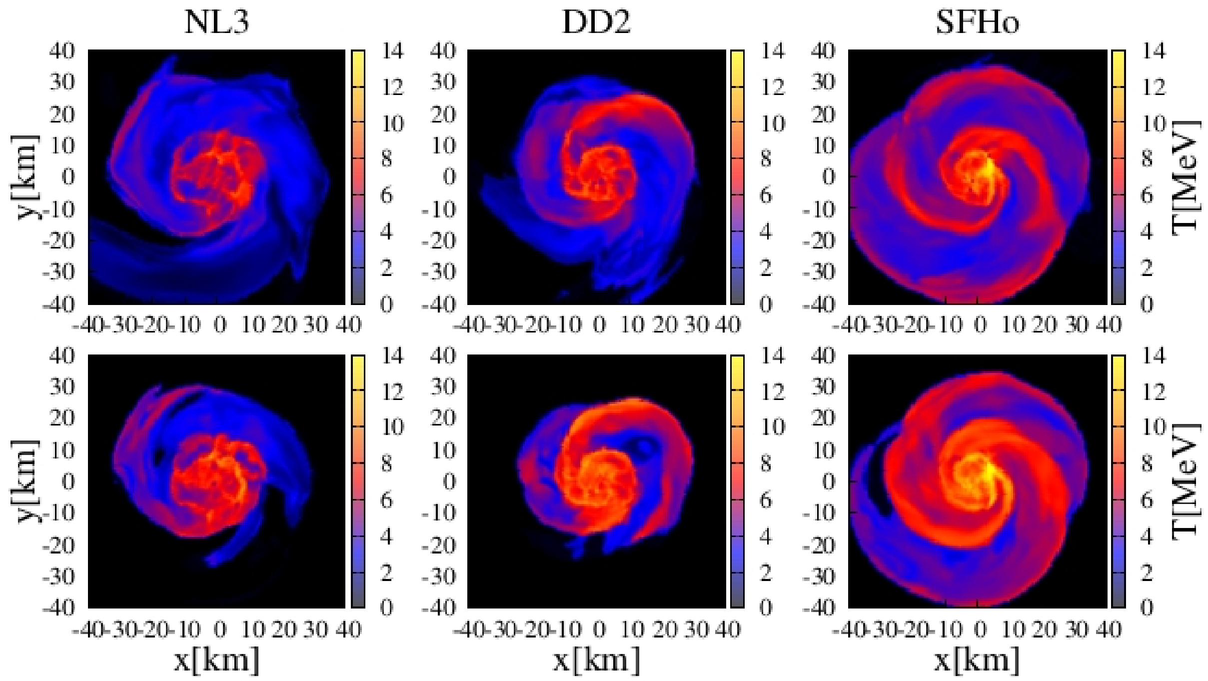
Supernova:
R= 1/ms,
L=10^{52} erg/s,
E~ 11 MeV,
t=10 sec

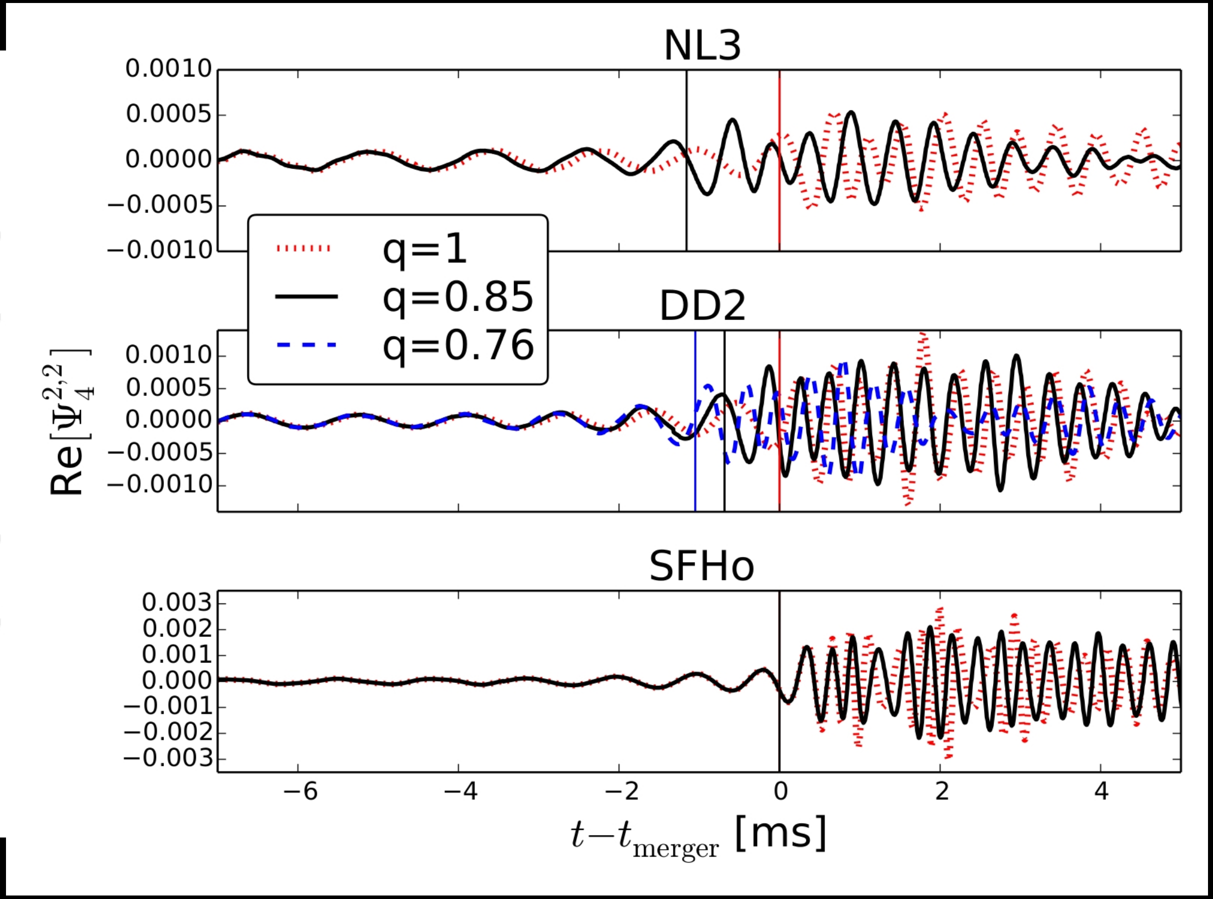
Merger of unequal mass magnetized NSs

Effect of the EoS, (CQG 2016, L. Lehner et al)

Reduction of the mass ratio disrupts the star earlier

q=0.85





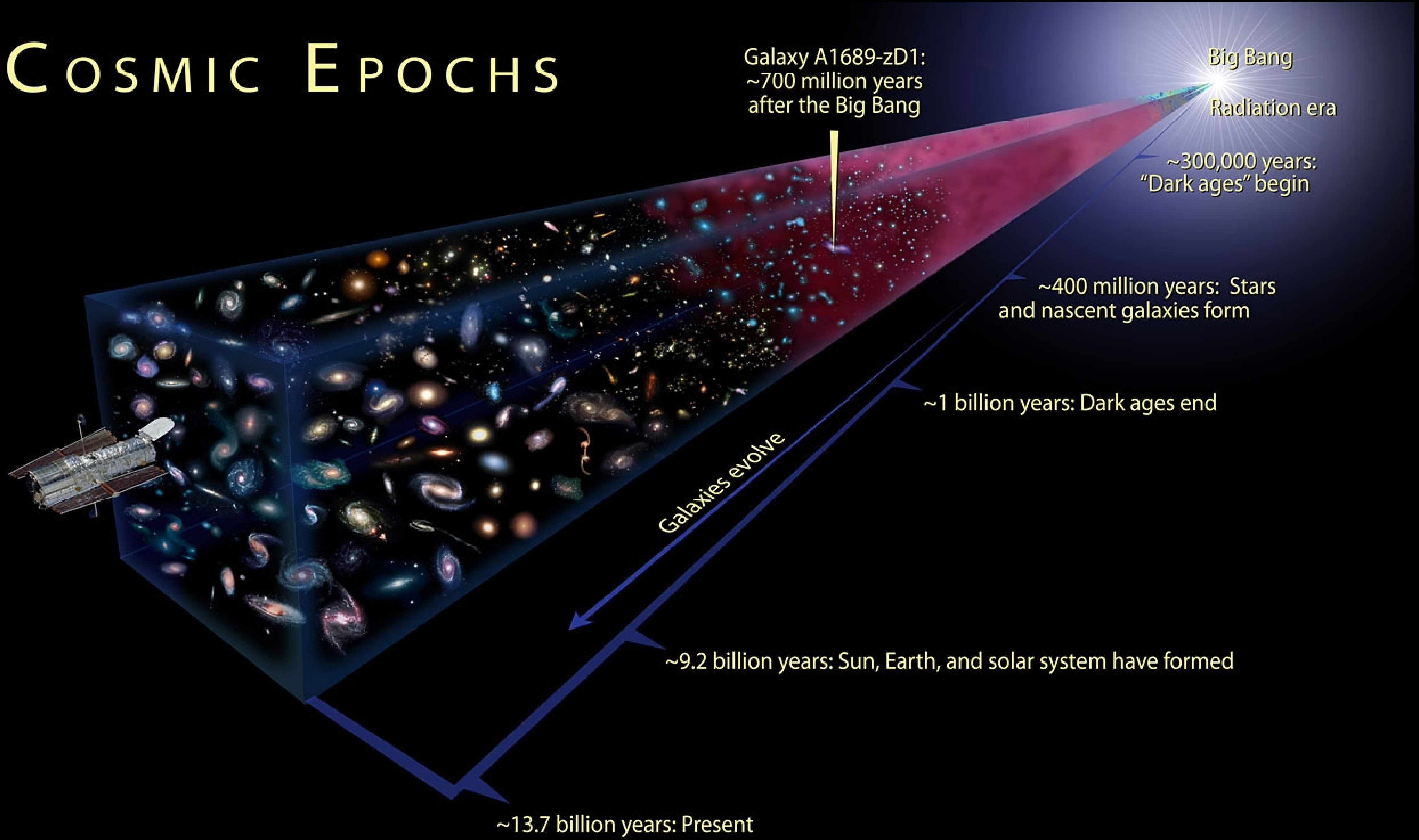
Tidal effects are more pronounced with stiffer EoS

Neutrinos in SK: NS-NS merger at 10 kpc

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

Larger changes with soft EoS when q decreases

Relic neutrinos



Relic Neutrinos

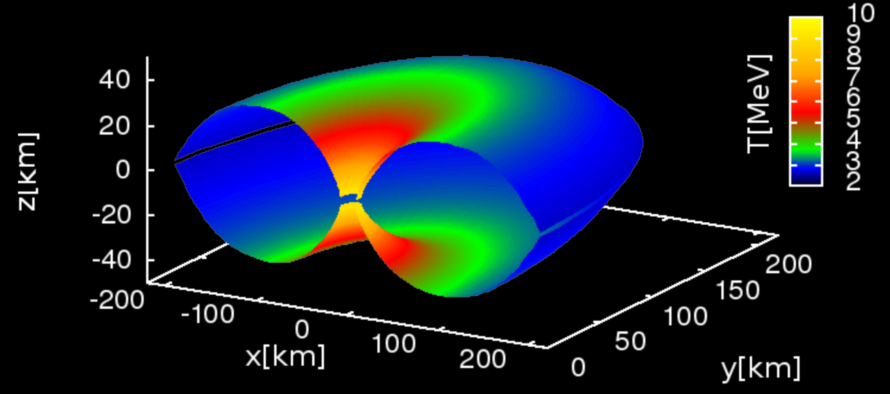
$$\frac{dF}{dE_o} = c\int (1+z_c) R(z_c) \frac{dN}{dE_\infty} \frac{dt}{dz_c} dz_c$$

Cosmological redshift

Neutrino spectrum

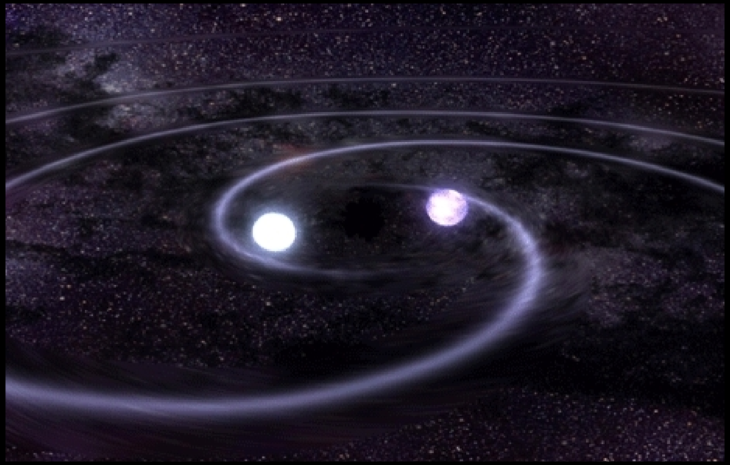
Event rates

Universe expansion

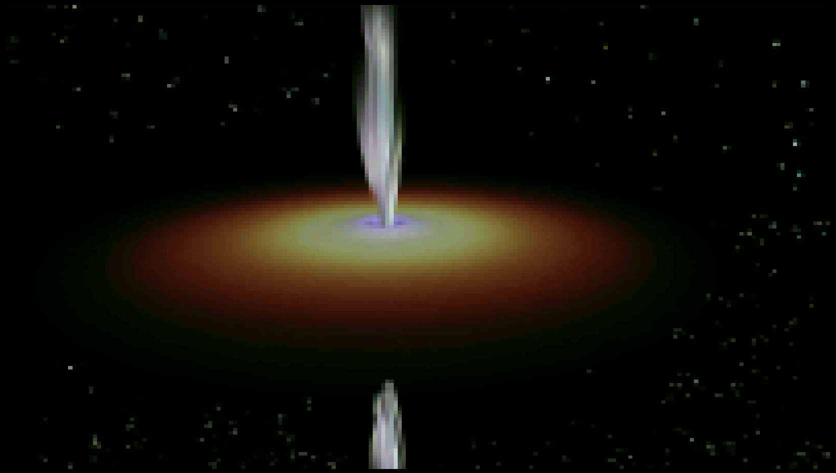


Accretion disk relic neutrinos

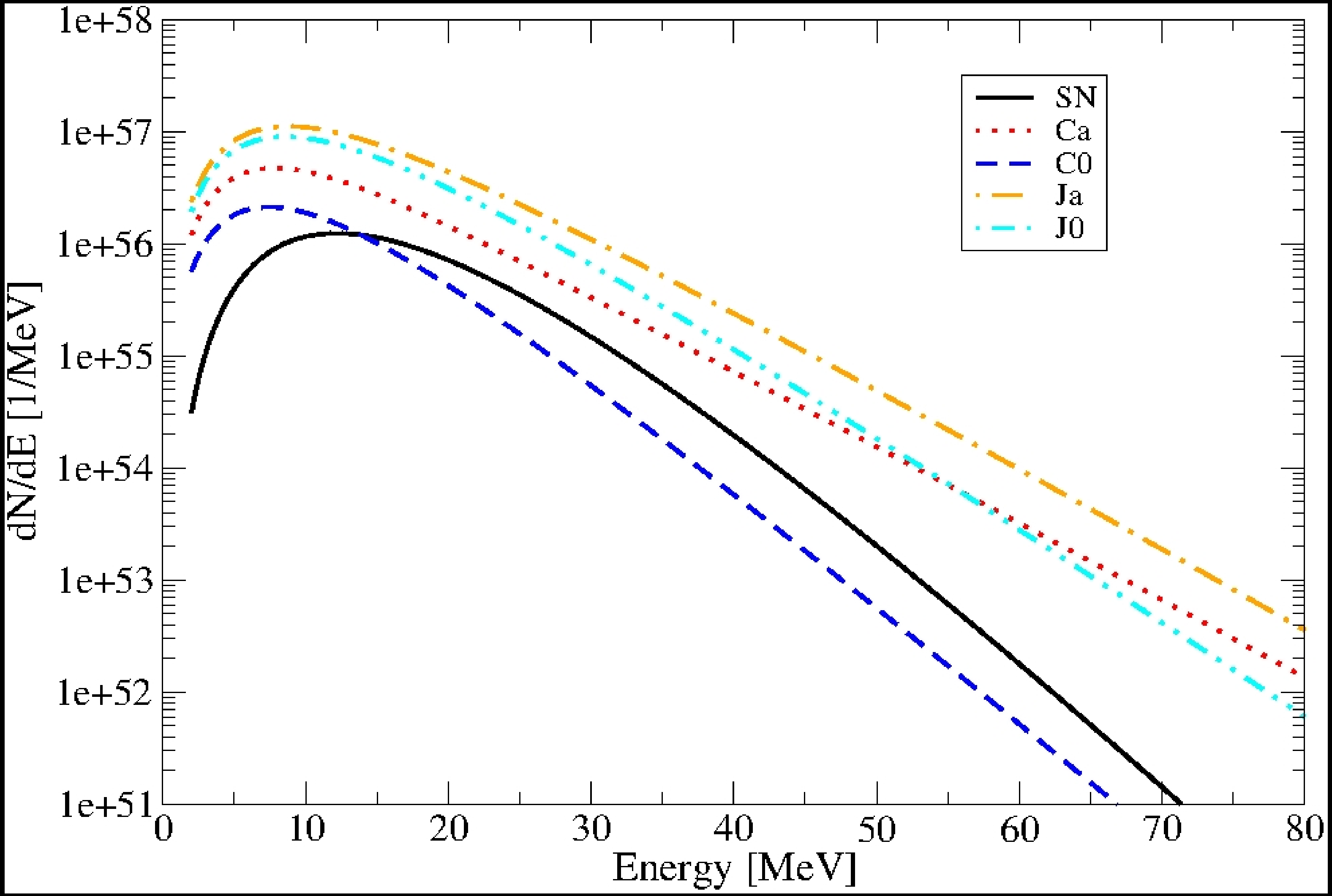
Mergers: Neutron star- Neutron star
Neutron star -Black Hole



Collapsar : rotating massive star collapsing to black hole



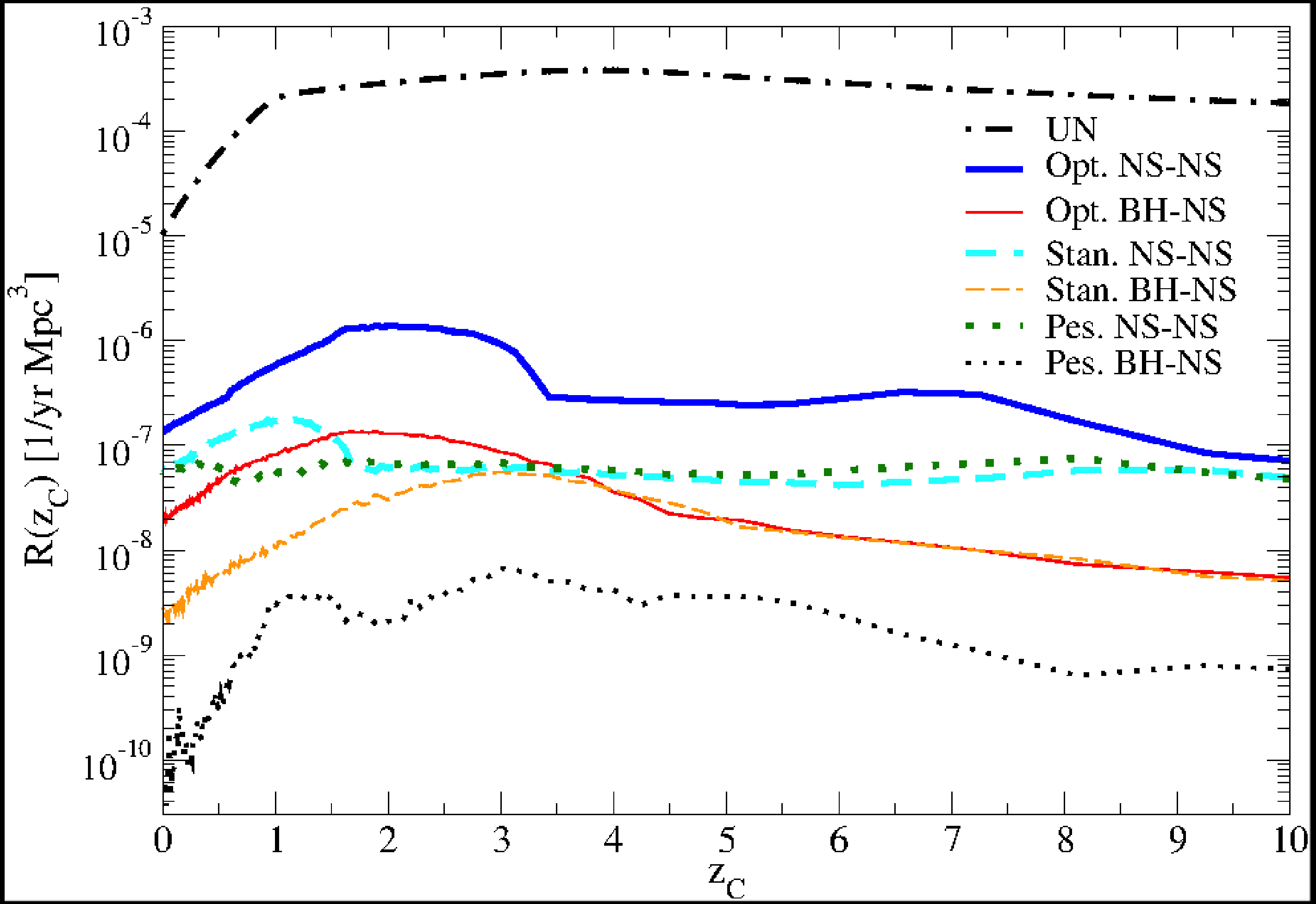
Neutrino Spectra from accretion disks



Observed at 10 kpc from the source

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

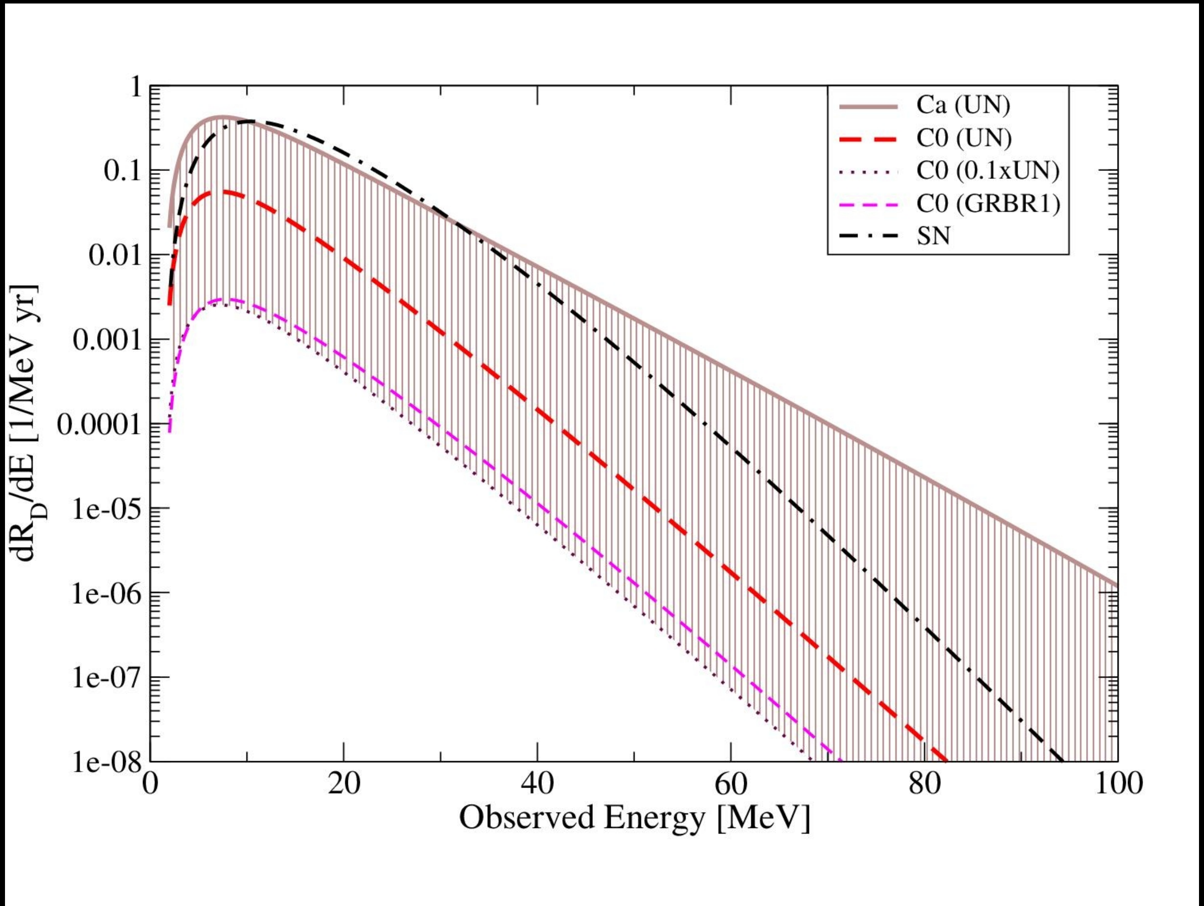
Accretion disk formation rates



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. Caballlero, McLaughlin (PRD, 2018)

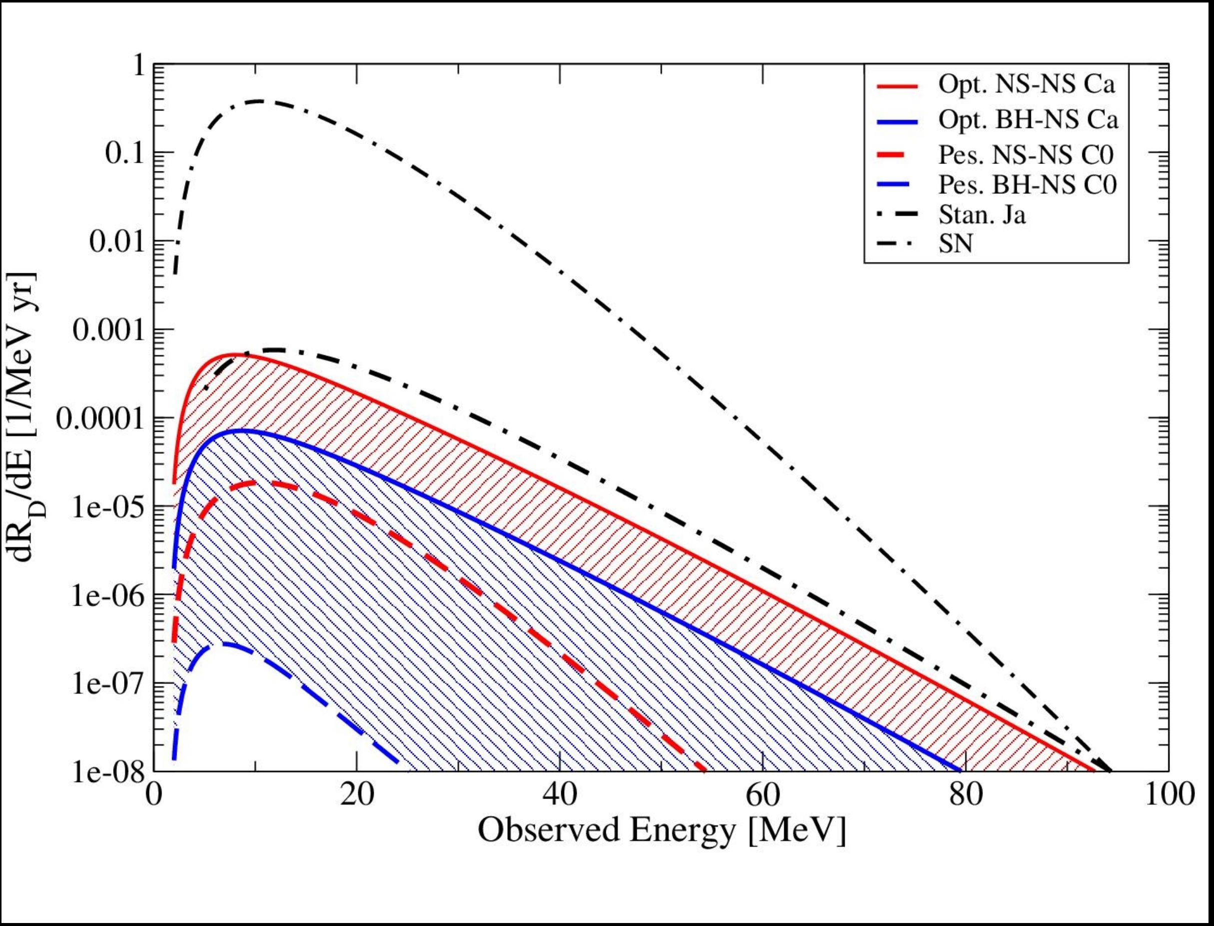


Scenario	Formation Rate	Disk Model	$\dot{M}$ $[M_\odot/s]$	R_D SK [1/yr]	R_D HK [1/yr]
Collapsar	UN	Ca	9	5.2	91
	0.1xUN	C0	3	0.02	0.35
NS-NS Merger	Opt.	Ca	7	7.0×10^{-3}	0.12
	Pes.	C0	3	2.7×10^{-4}	0.004
	Opt.	Ja	-	3.3×10^{-2}	0.57
	Pes.	J0	-	4.5×10^{-3}	0.08
	Stan.	Ja	-	1.0×10^{-2}	0.17
BH-NS Merger	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: 3-25 neutrinos from Collapsars
HiperK in 10 years: ~900 from collapsars, 6 from NS-NS

Collapsar relic neutrinos at SuperK and HyperK

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



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, 2 from NS-NS

Conclusions

Neutrinos provide information about the explosive stellar mechanisms by direct detection and by their influence on their byproducts (e.g. heavy element synthesis).

Given several observations of q and GW neutrinos we could decipher the EoS

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

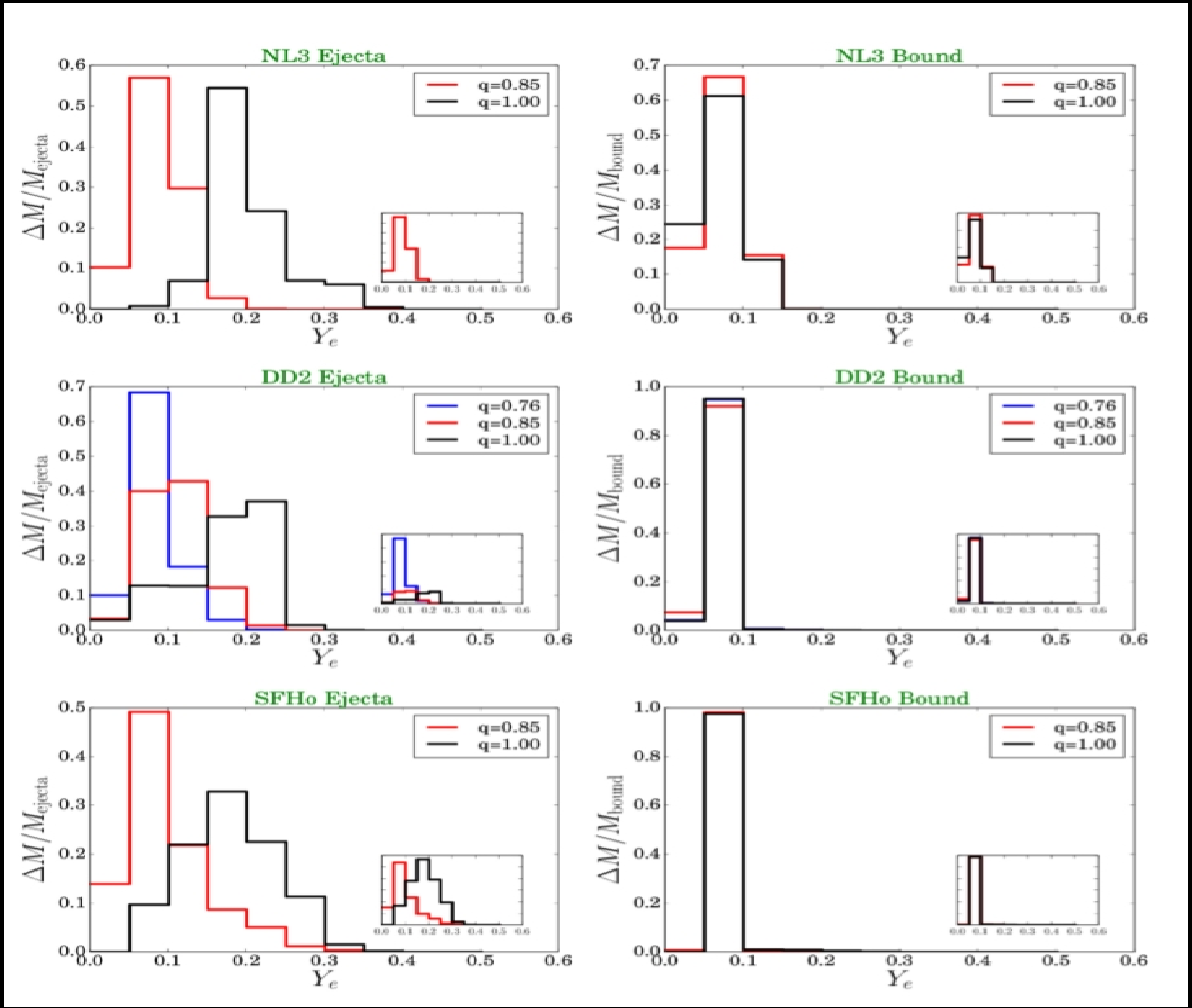
Neutrinos from the past can tell us about the star formation rate, mergers and collapsar rates, and cosmic metallicity

Collaborators

- Tyson Schilbach* (U. Of Guelph), G. McLaughlin (North Carolina State University), R. Surman (University of Notre Dame)
- Luis Lehner (Perimeter Institute), Carlos Palenzuela (University of the Balearic Islands), David Neilsen (Bringham Young U.), Steve Liebling (Long Island U.), Evan O’Connor (North Carolina State University)

Electron fraction distribution for unbound and bound material

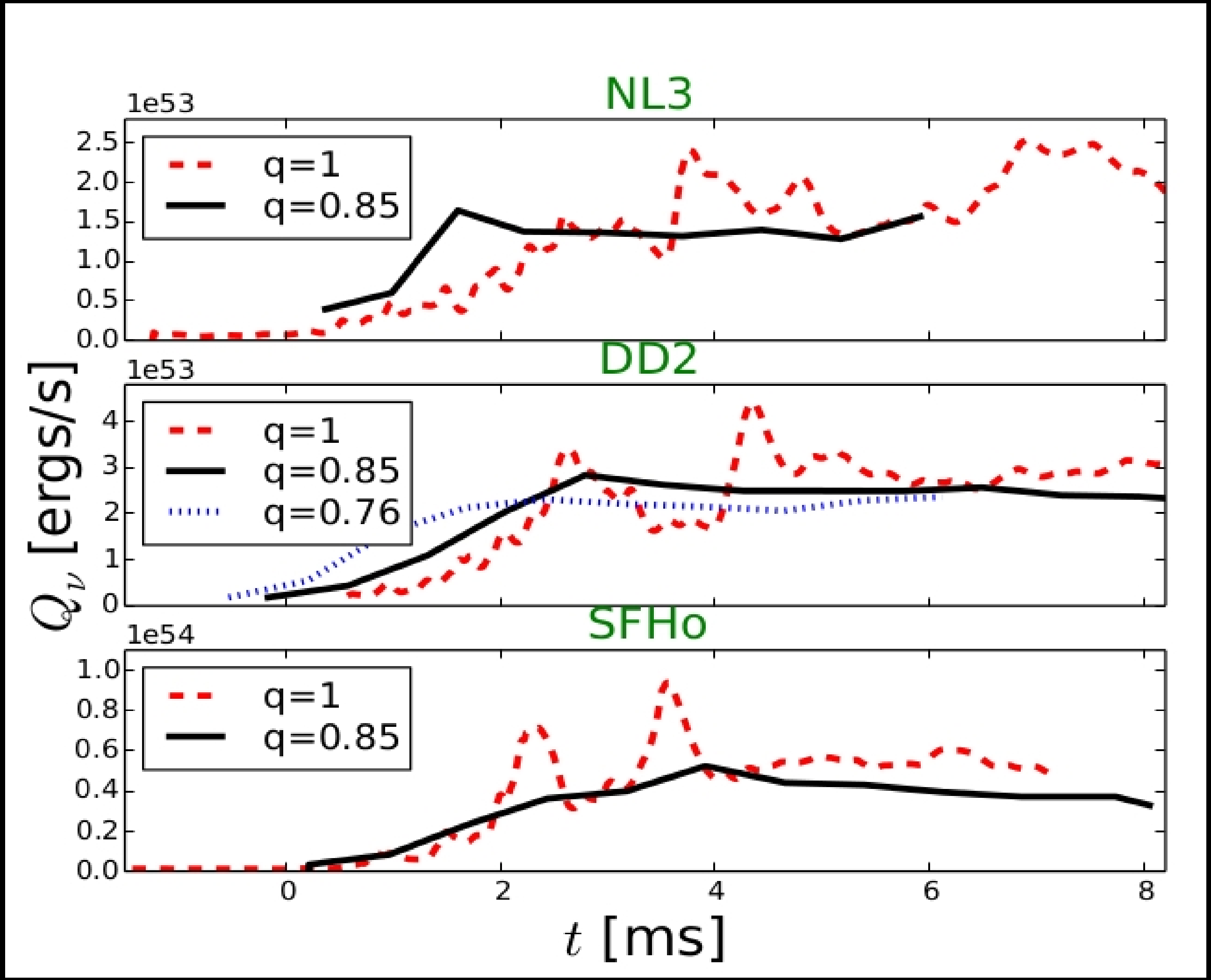
Electron fraction decreases as q decreases, compatible with r-process nucleosynthesis and kilonova



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			

Neutrino luminosity evolution



Luminosity oscillates for q=1

Density at different times DD2 EoS q=1