

The Equation of State (EOS) and Relic Neutrinos from Neutron Star Mergers

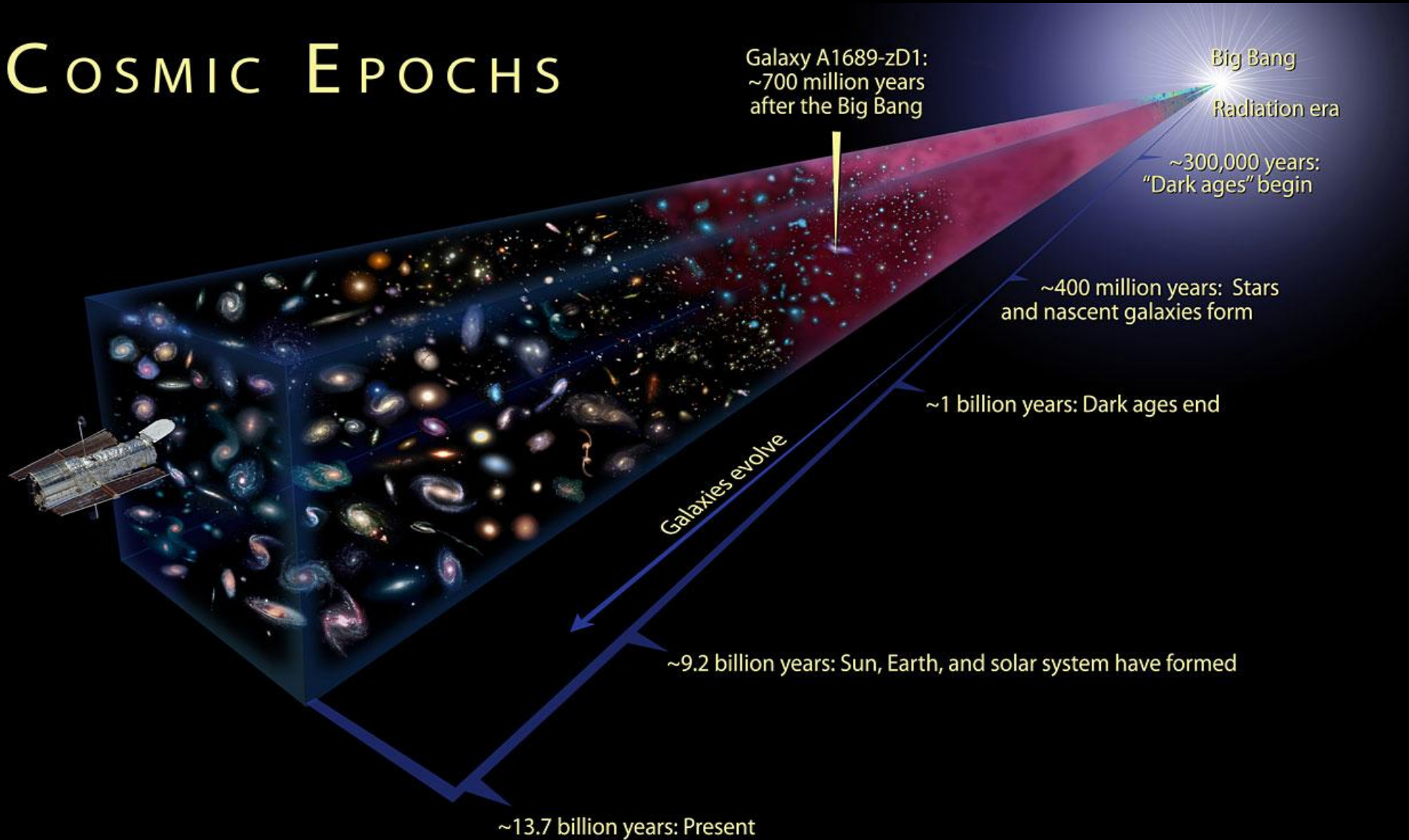
Liliana Caballero
University of Guelph

Theory Canada 17
University of Regina, June 7, 2025

200,000 relic neutrinos from collapsars and
200 relic neutrinos from neutron star mergers
pass through a human body per second

Relic neutrinos

COSMIC EPOCHS



Supernova relic neutrinos

The Diffuse Supernova Neutrino Background is detectable in Super-Kamiokande

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(Dated: May 1, 2009)

New Test of Supernova Electron Neutrino Emission using Sudbury Neutrino Observatory Sensitivity to the Diffuse Supernova Neutrino Background

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(Dated: 18 August 2005)

Modern Physics Letters A | Vol. 35, No. 25, 2030011 (2020) | Brief Review

Review of uncertainties in the cosmic supernova relic neutrino background

G. J. Mathews , L. Boccioli, J. Hidaka, and T. Kajino

Diffuse supernova neutrinos: oscillation effects, stellar cooling and progenitor mass dependence

Cecilia Lunardini^{1,2} and Irene Tamborra³

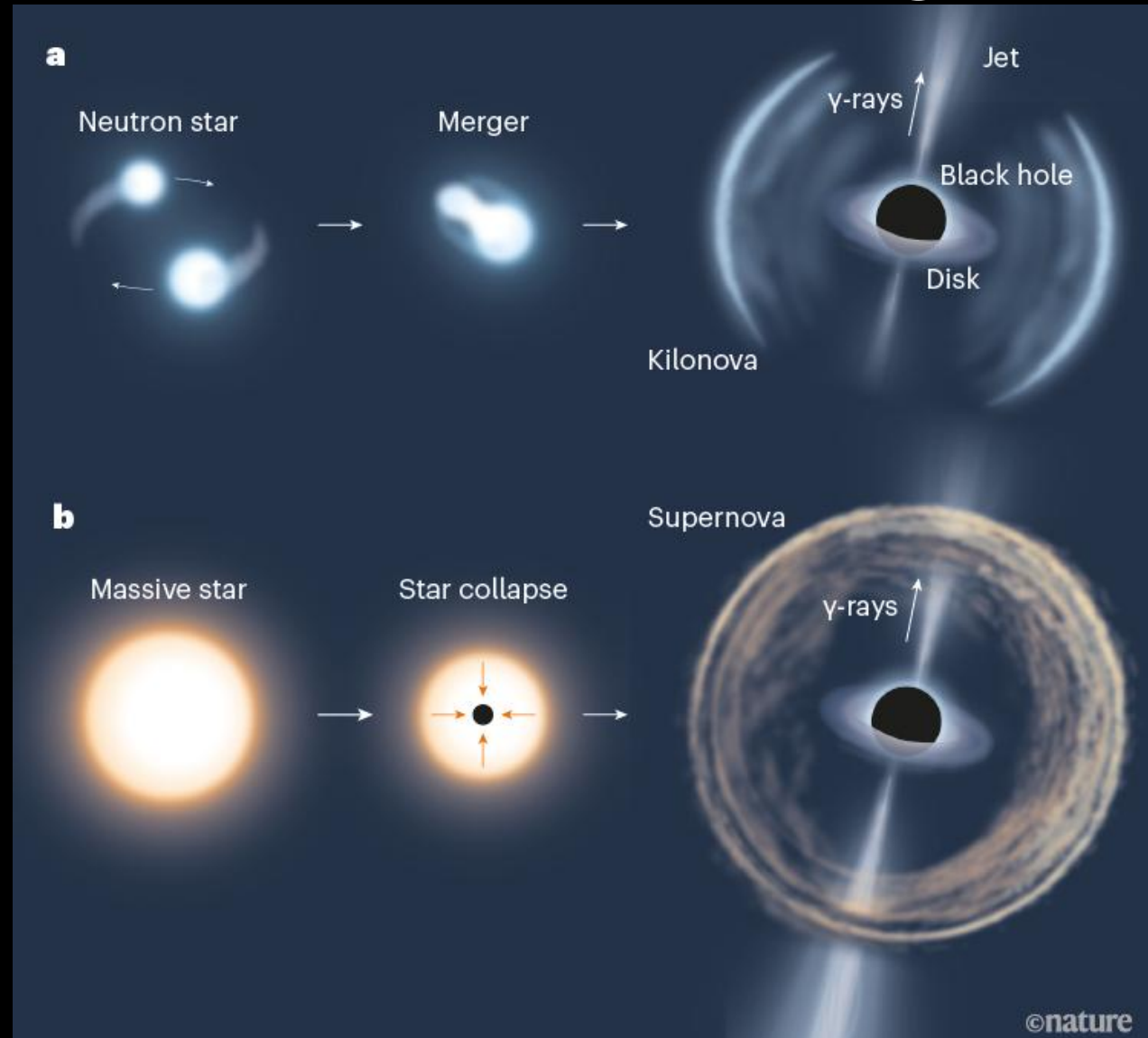
Published 4 July 2012 • Published under licence by IOP Publishing Ltd

[Journal of Cosmology and Astroparticle Physics](#), [Volume 2012](#), [July 2012](#)

Citation Cecilia Lunardini and Irene Tamborra JCAP07(2012)012

DOI 10.1088/1475-7516/2012/07/012

Collapsars and NS mergers



Remnant: black hole accretion disk

Relic Neutrinos

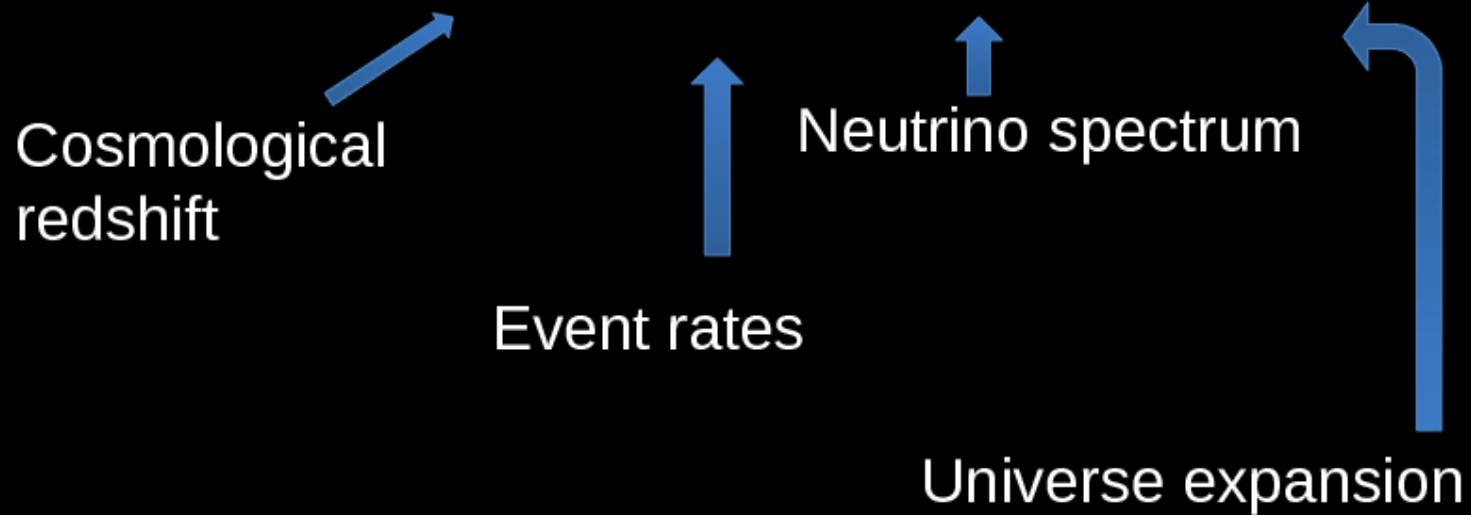
$$\frac{dF}{dE_o} = c \int (1+z_c) R(z_c) \frac{dN}{dE_\infty} \frac{dt}{dz_c} dz_c$$

Cosmological
redshift

Event rates

Neutrino spectrum

Universe expansion



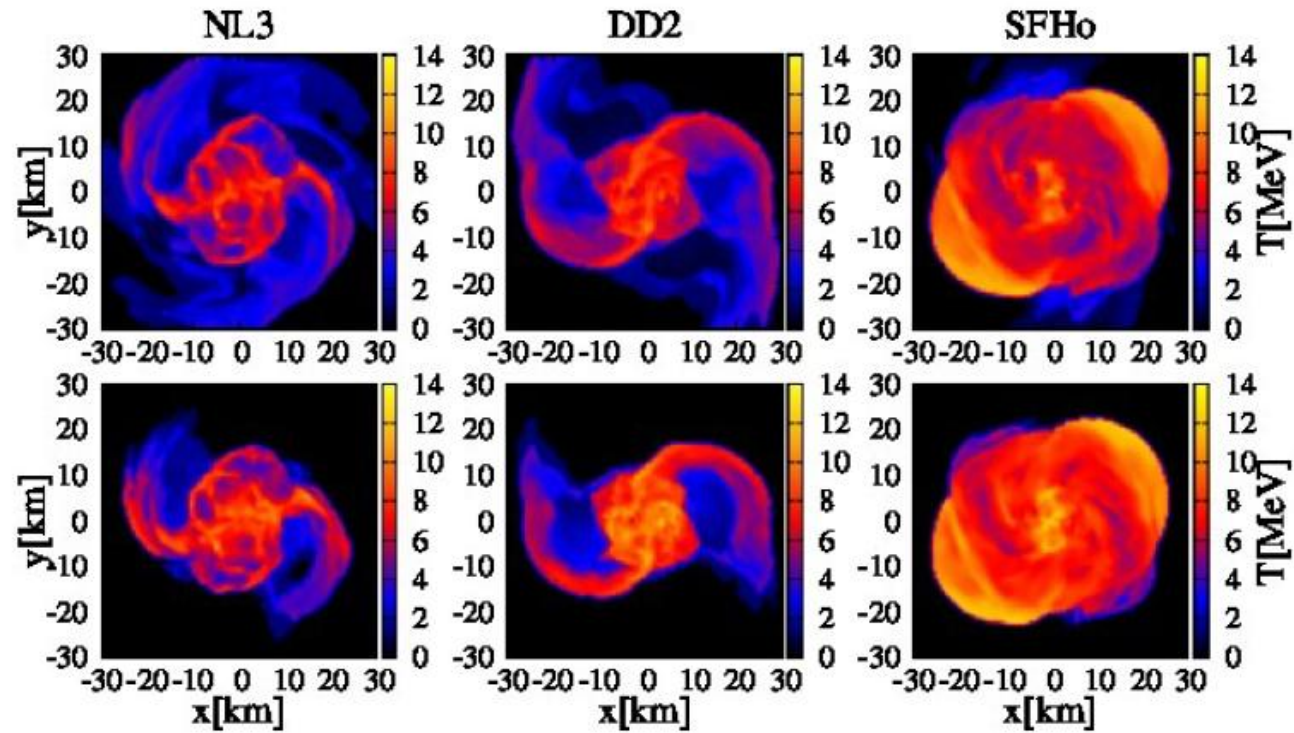
Spectra

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

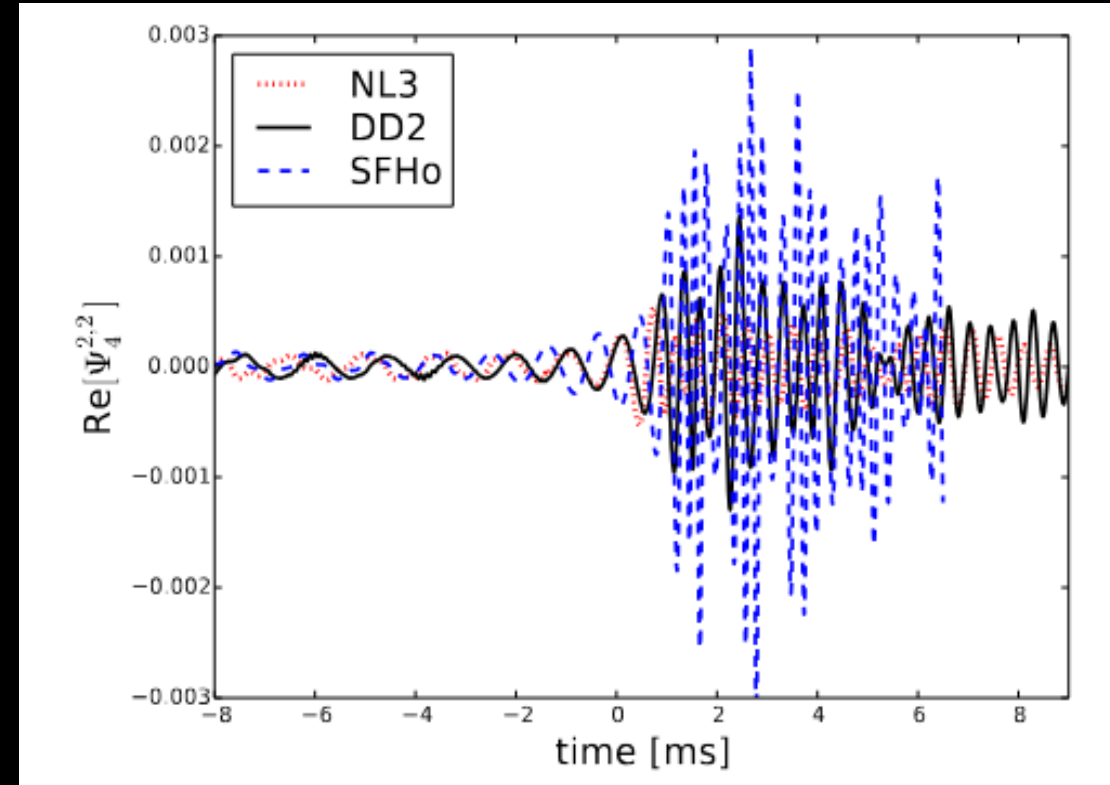
Isolated Neutron Star merger : EoS

Early evolution

e-neutrino



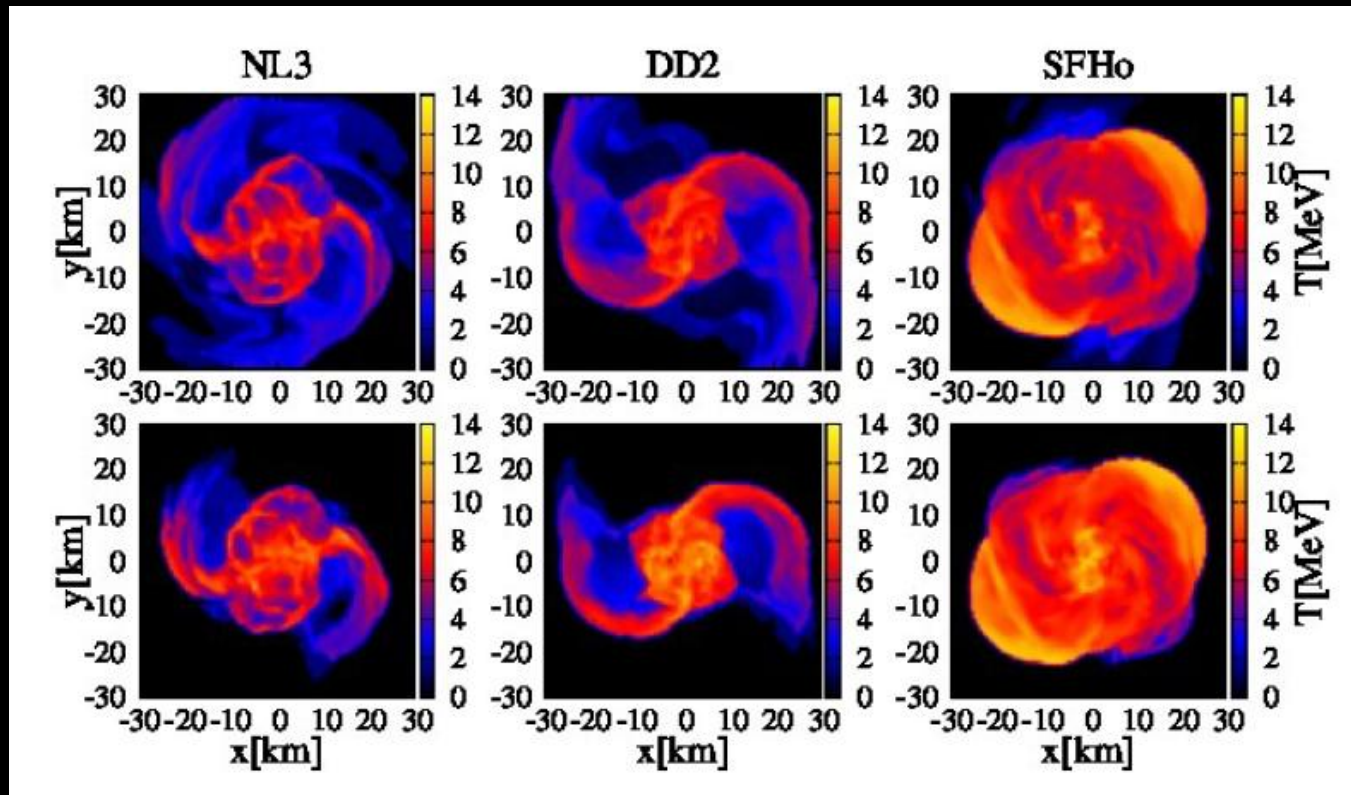
e-antineutrino



Could we add constraints to the EoS from neutrino detections?

e-neutrino

e-antineutrino



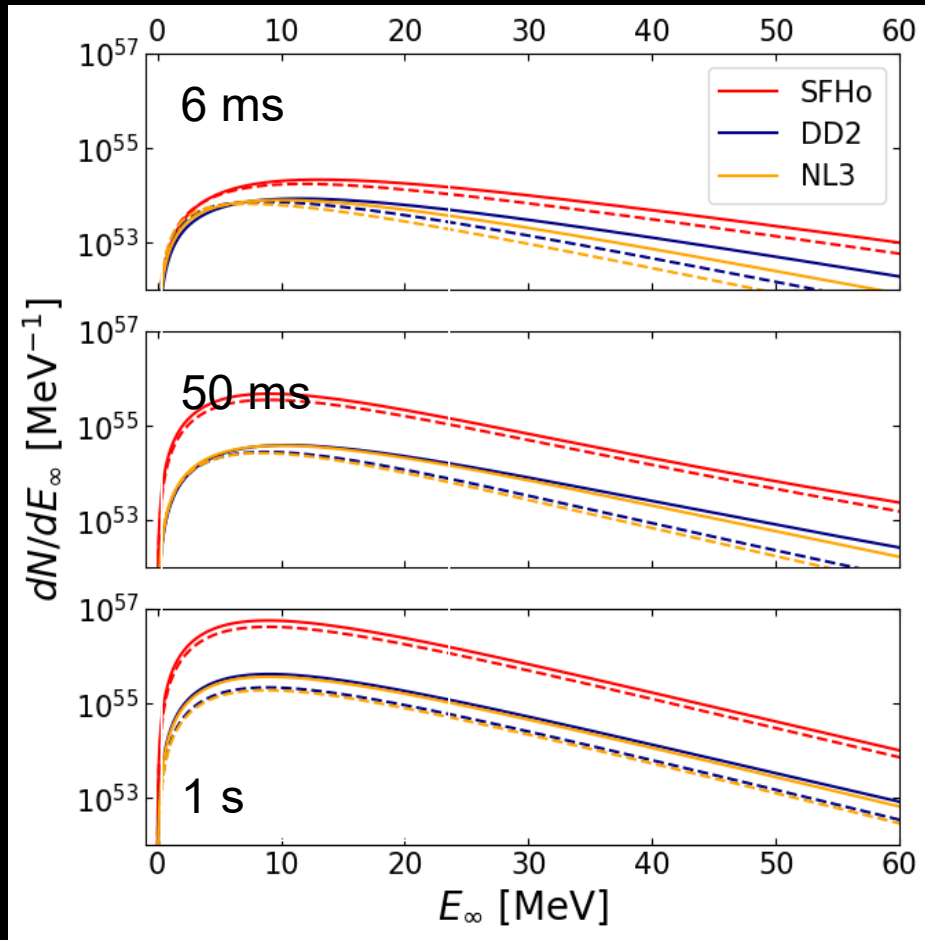
Time [ms]	$\langle E_{\bar{\nu}_e} \rangle$ [MeV]	$\langle E_{\nu_e} \rangle$ [MeV]	$L_{\bar{\nu}_e}$ [10^{53} erg/s]	R_ν [#/ms]
2.5 (NL3)	18.5 (22.4)	15.2 (18.3)	0.71	18.1
3.0 (DD2)	18.3 (22.1)	14.6 (17.4)	1.1	28.2
3.2 (SFHo)	24.6 (29.7)	23.5 (28.3)	3.5	120.8

Supernova:
 $R = 1/\text{ms}$, $E \sim 11$ MeV,

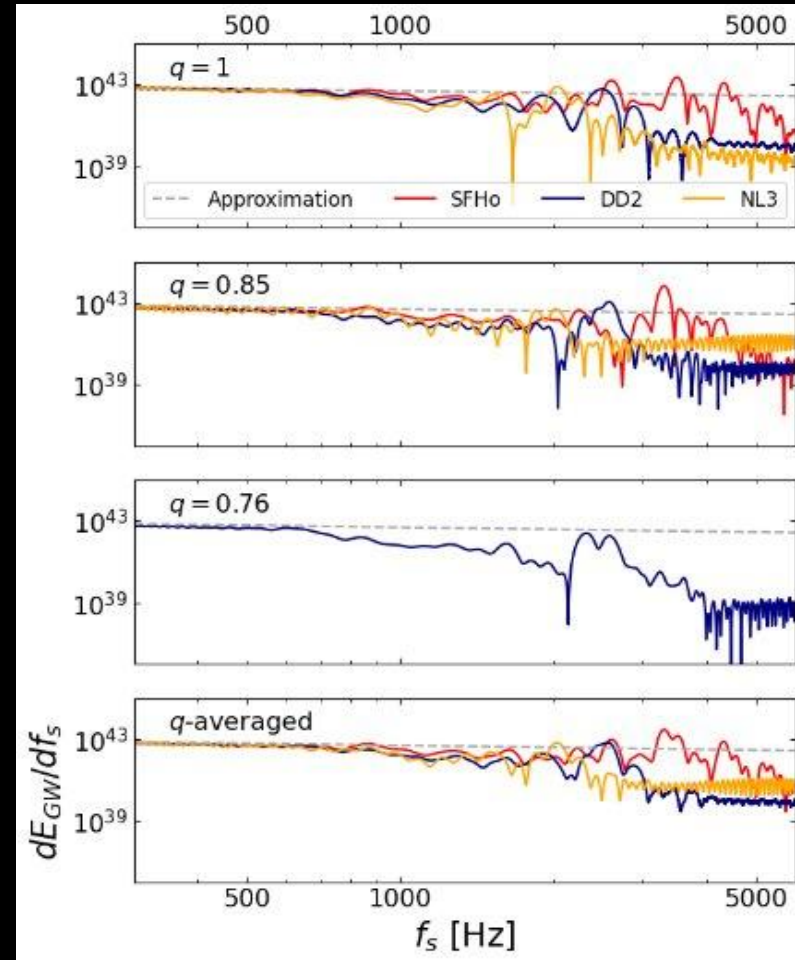
$L = 10^{52}$ erg/s
 $t = 10$ sec

Isolated NS merger spectra

Neutrinos



Gravitational Waves



$$\frac{dE_{GW}}{df_s} = \frac{(G\pi)^{2/3}}{3} \frac{qM_{tot}^{5/3}}{(1+q)^2 f_s^{1/3}}$$

Given several observations of GW and neutrinos we could add constraints to the EoS

We could detect neutrinos from: Milky way and satellite galaxies in SK

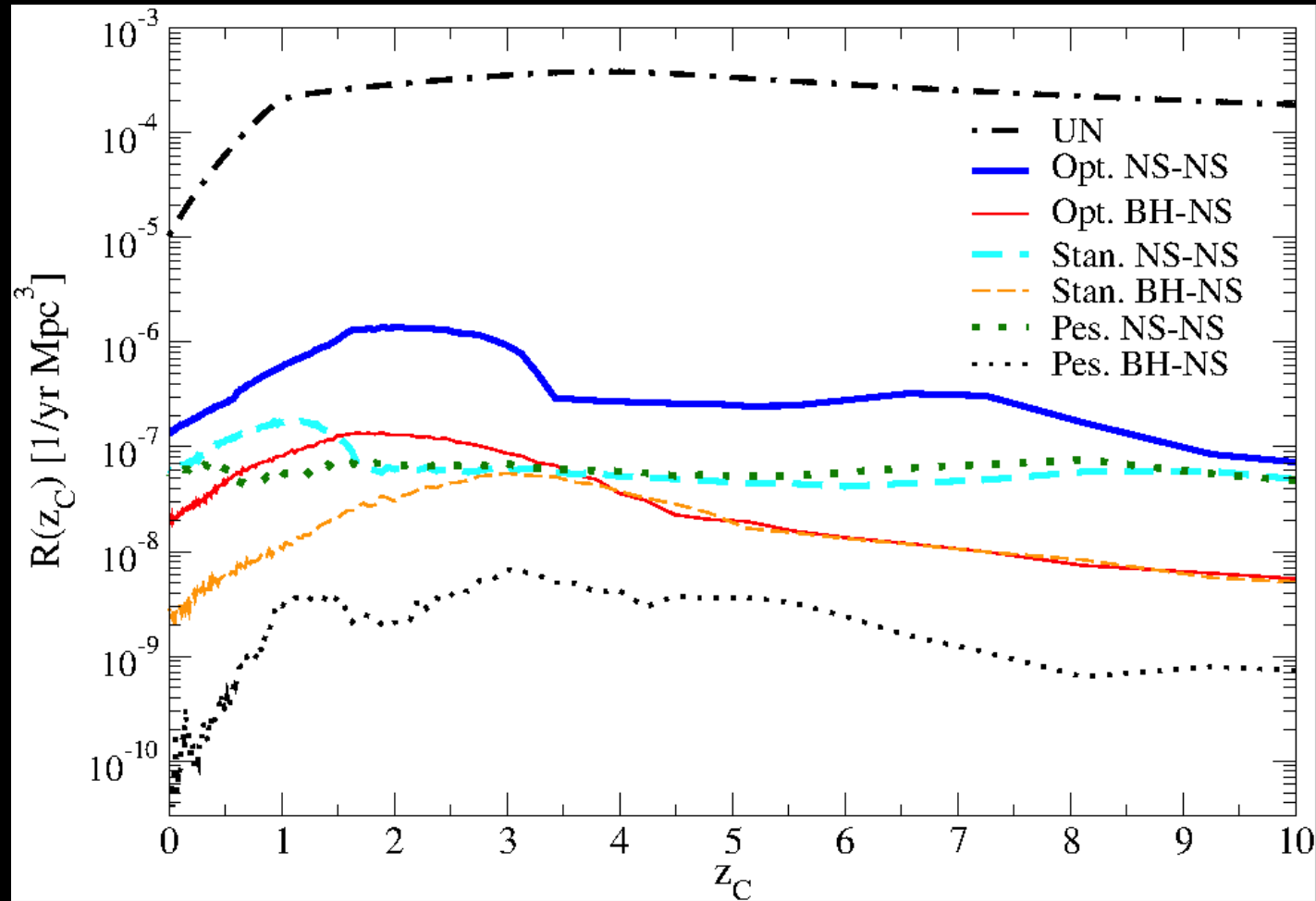
Andromeda (780 kpc) in HK

Mergers are rare.....

Relic events Formation rates

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

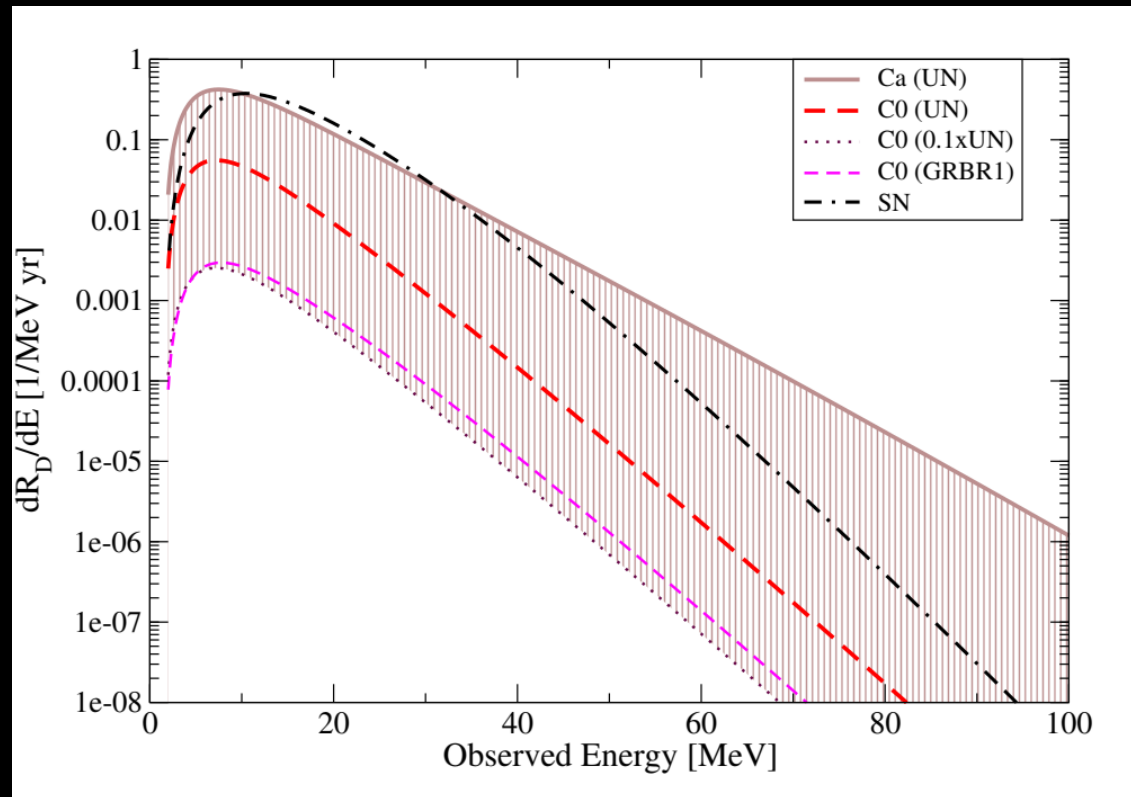
Formation rates



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

Neutrino Detection Rates : Relic Collapsars

T. Schilbach*, O. L. C, McLaughlin, PRD, 2019



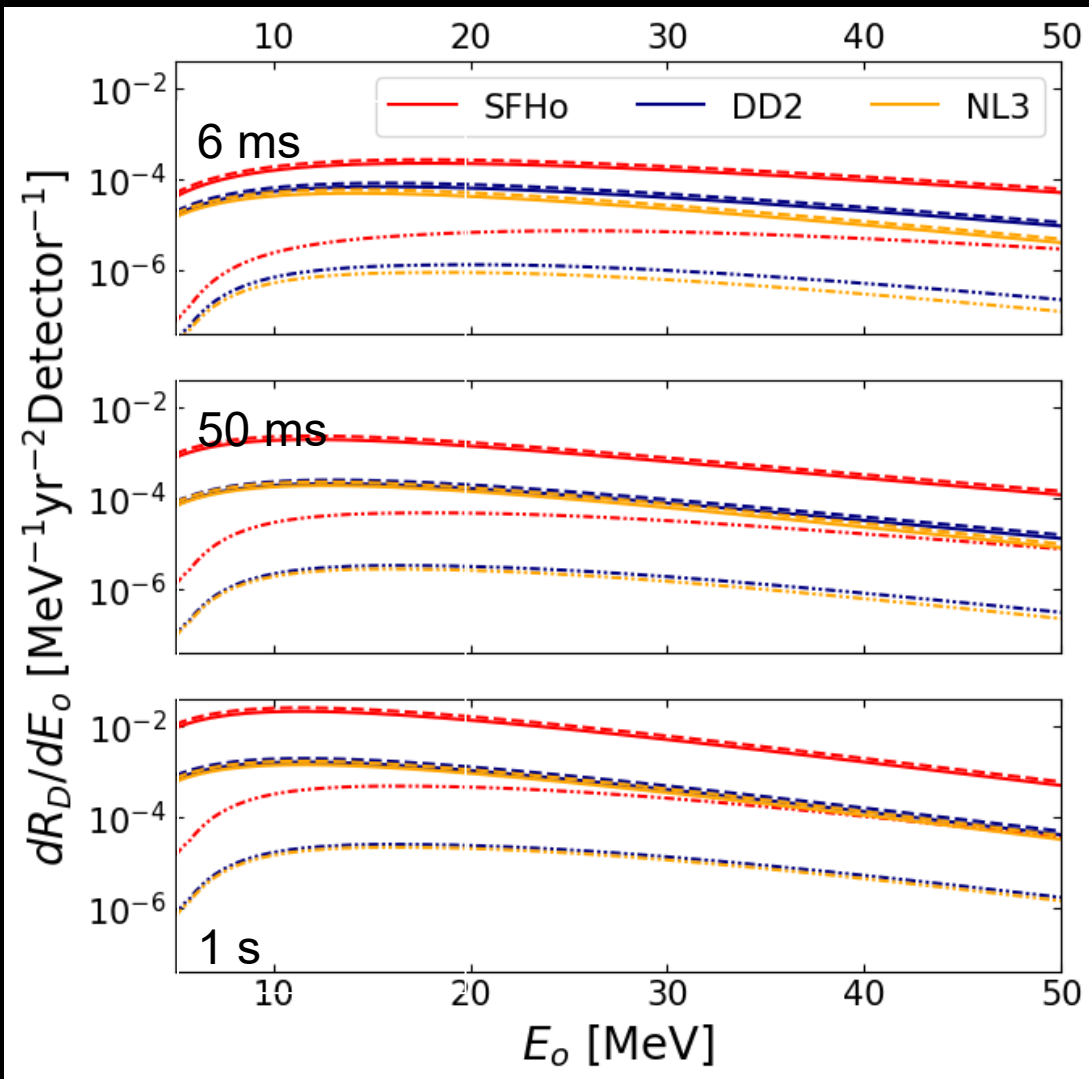
$$R_D = N_T \int_{E_{th}} \sigma(E_o) \frac{dF}{dE_o} dE_o.$$

SK in 5 years: 3-25 neutrinos

HK in 10 years: ~900 neutrinos

Neutrino Detection Rates: Relic NS mergers

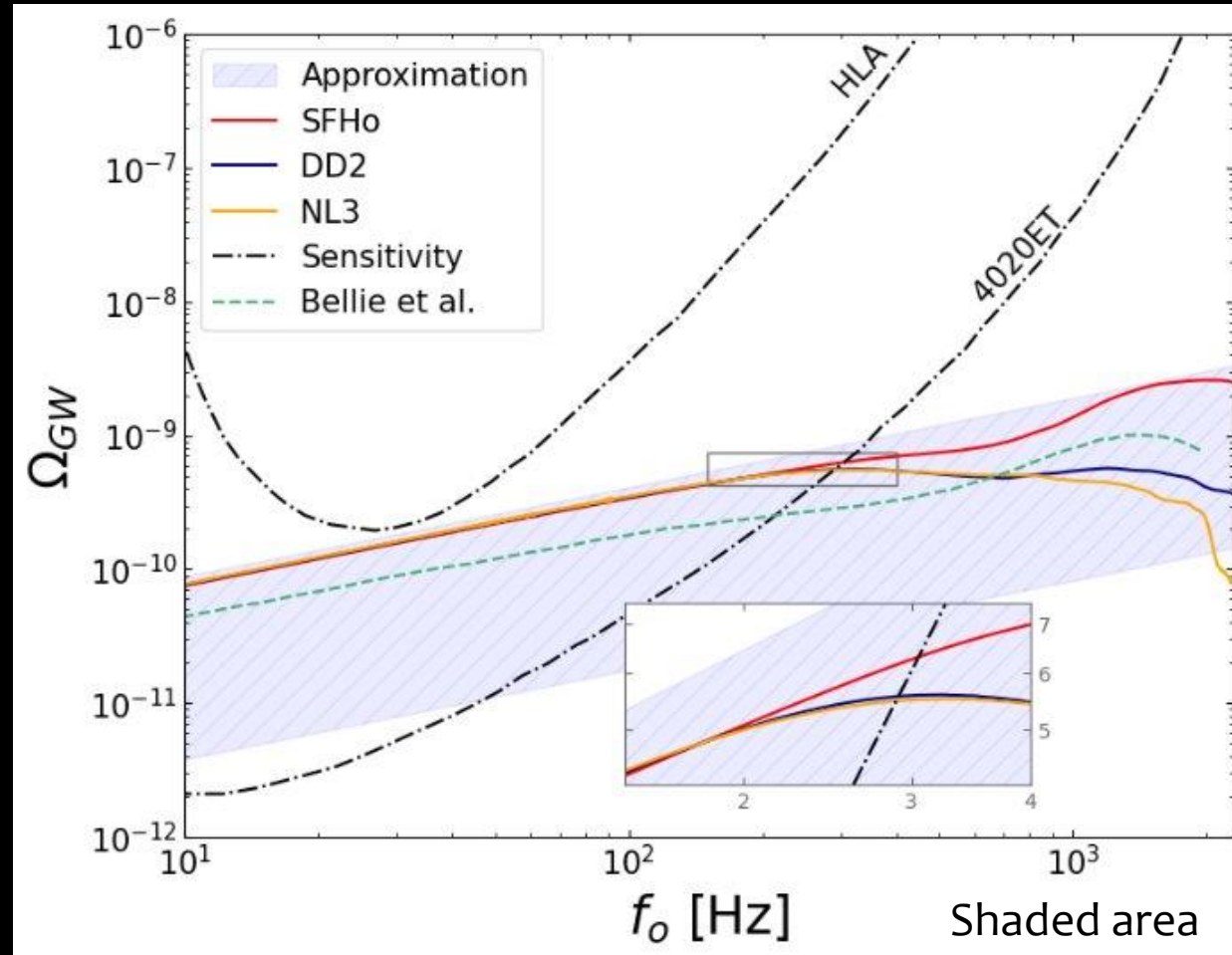
P. Deguire*, OLC, L. Lehner, PRD 2025



For a 1 sec merger in Hk-Gd
~ 4 neutrinos in 10 years for SFHo
~3 neutrinos in 100 years for NL3

HK-Gd Solid
HK dashed
DUNE dotted-dashed

NS mergers: Stochastic gravitational wave background



$$\frac{dE_{GW}}{df_s} = \frac{(G\pi)^{2/3}}{3} \frac{qM_{tot}^{5/3}}{(1+q)^2 f_s^{1/3}}$$

EOS Signatures could be observed in a range of hundreds of Hz

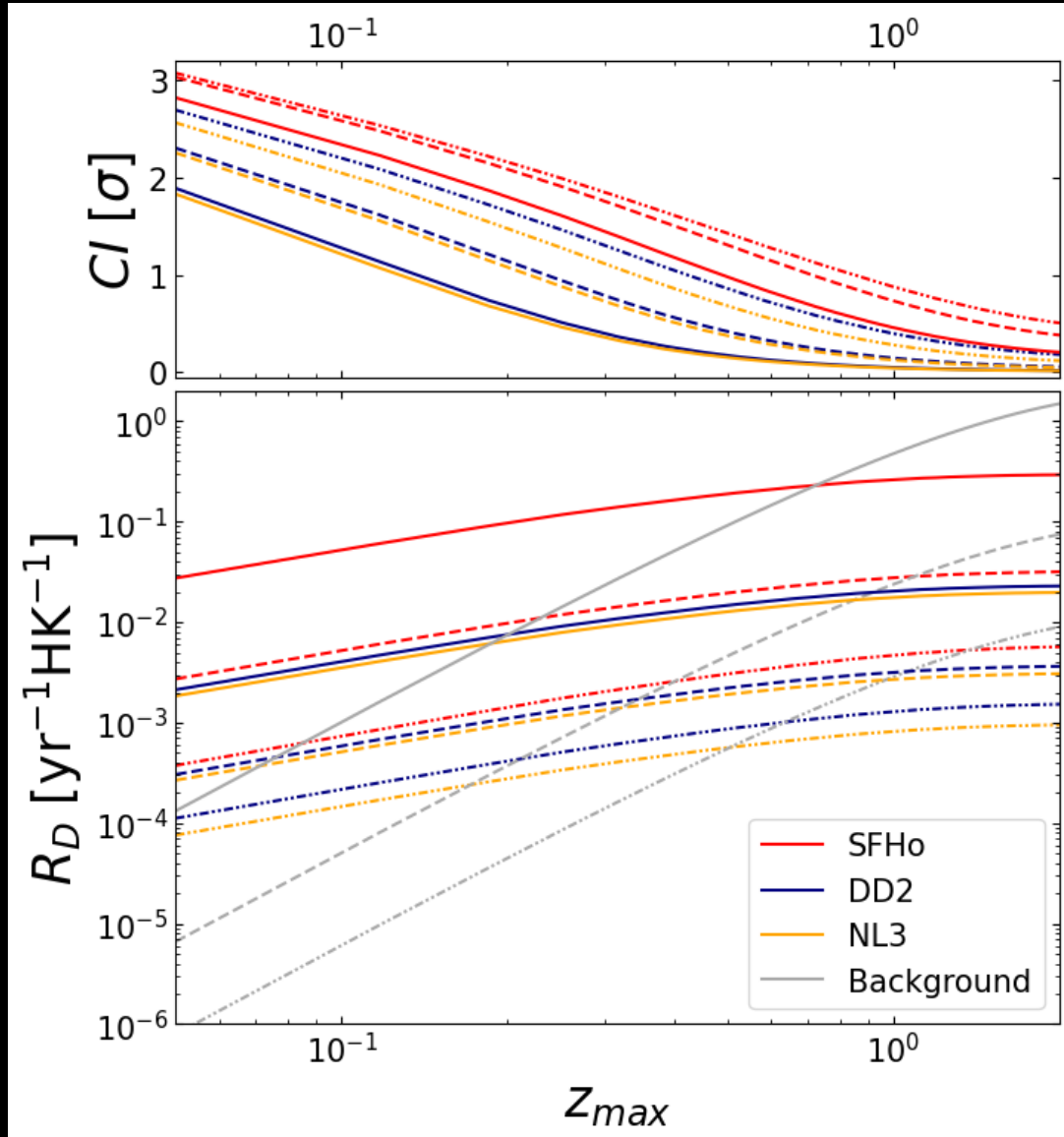
...Relic neutrinos are buried in the SN
and background noise !

Use a multi-messenger approach ...

Use coincidence with GW up to a given
cosmological redshift, Z_{max} , to search for
neutrinos in observatories in a fixed time
window

Kyutoku and Kashiyama PRD 2018, Lin and Lunardini PRD 2020

EoS: A multi-messenger approach to relics



For 1 sec merger: R (1σ)

2 neutrinos/year, $Z_{max}=0.49$ for SFHo

0.004/year, $Z_{max}=0.12$ for NL3

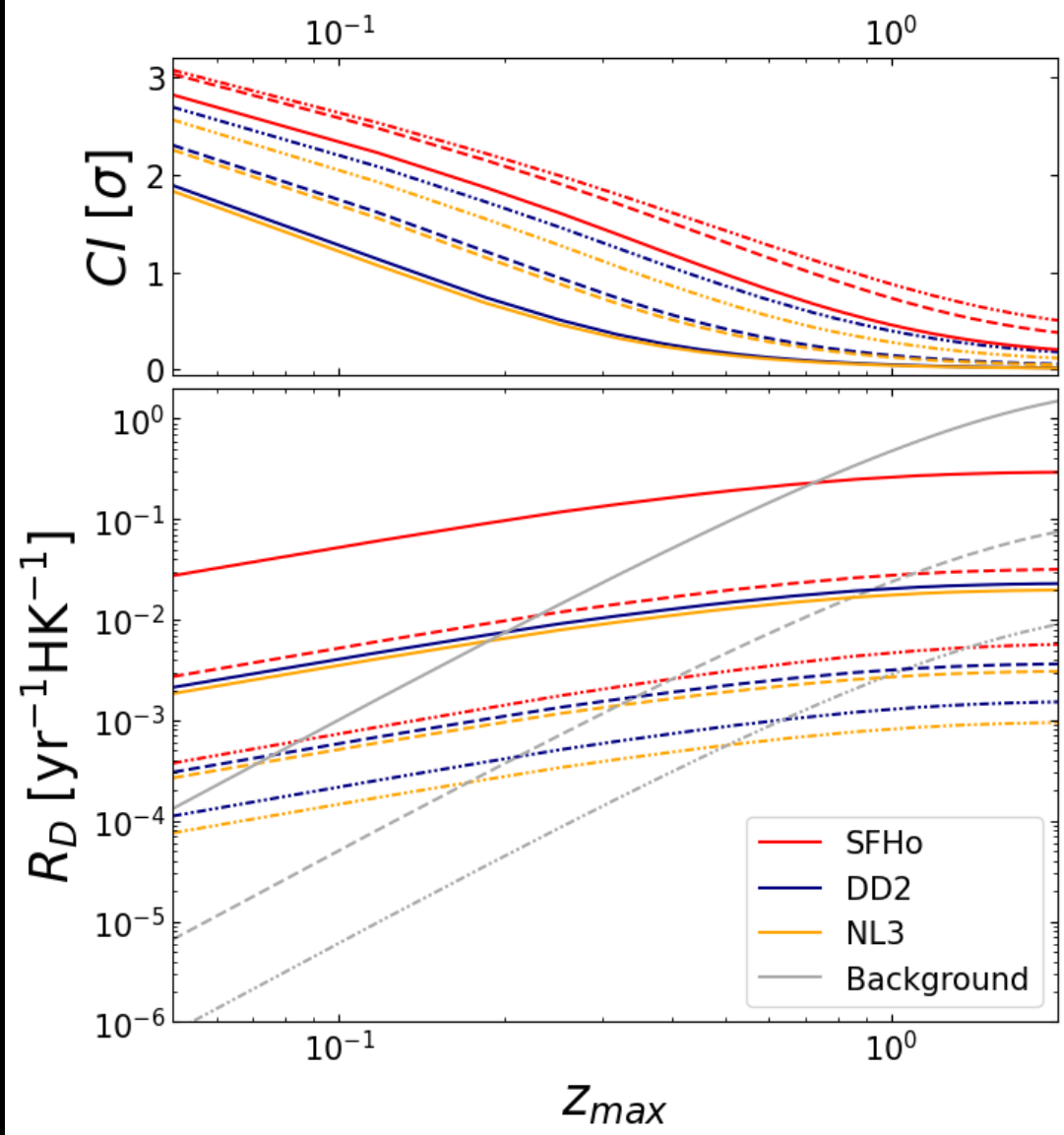
Shorter time windows improve confidence

1 sec Solid

50 ms dashed

6 ms dotted-dashed

EoS "distinguishability"



Δt_e	Effective observation time		
	SFHo DD2	SFHo NL3	DD2 NL3
[ms]	[HK·yr]	[HK·yr]	[HK·yr]
6	6.9e2(2.0e4)	4.9e2(1.4e4)	2.1e4(6.0e5)
50	7.0e1(2.1e3)	6.6e1(2.0e3)	8.2e4(2.7e6)
1000	7.7e0(2.4e2)	7.5e0(2.3e2)	2.5e4(8.2e5)

TABLE IV: The total effective observation time (in years) that a HK-Gd detector would need to run for to tell apart two different EOS. Results obtained with pessimistic merger rates appear in parenthesis.

Summary

Observations with MeV neutrinos: **comprehensive** analysis of multi-messenger signals

Relic neutrino flux from Collapsars is comparable to relic neutrino flux from SN

We provided a framework for the detection of relic neutrinos from NS-NS mergers

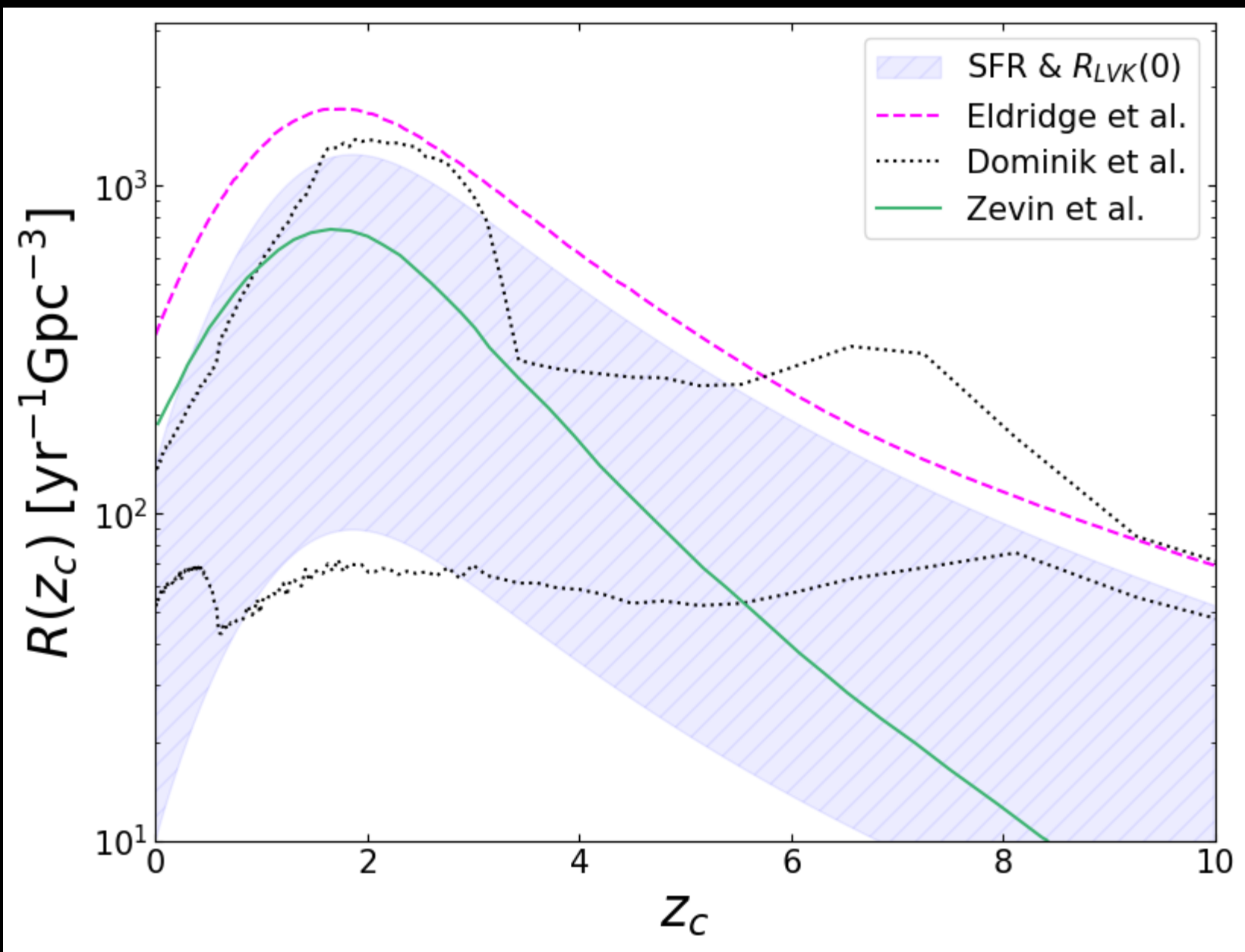
Feasible: An observational campaign of about 10 years in a HK-like detector will allow to distinguish between EOS types.

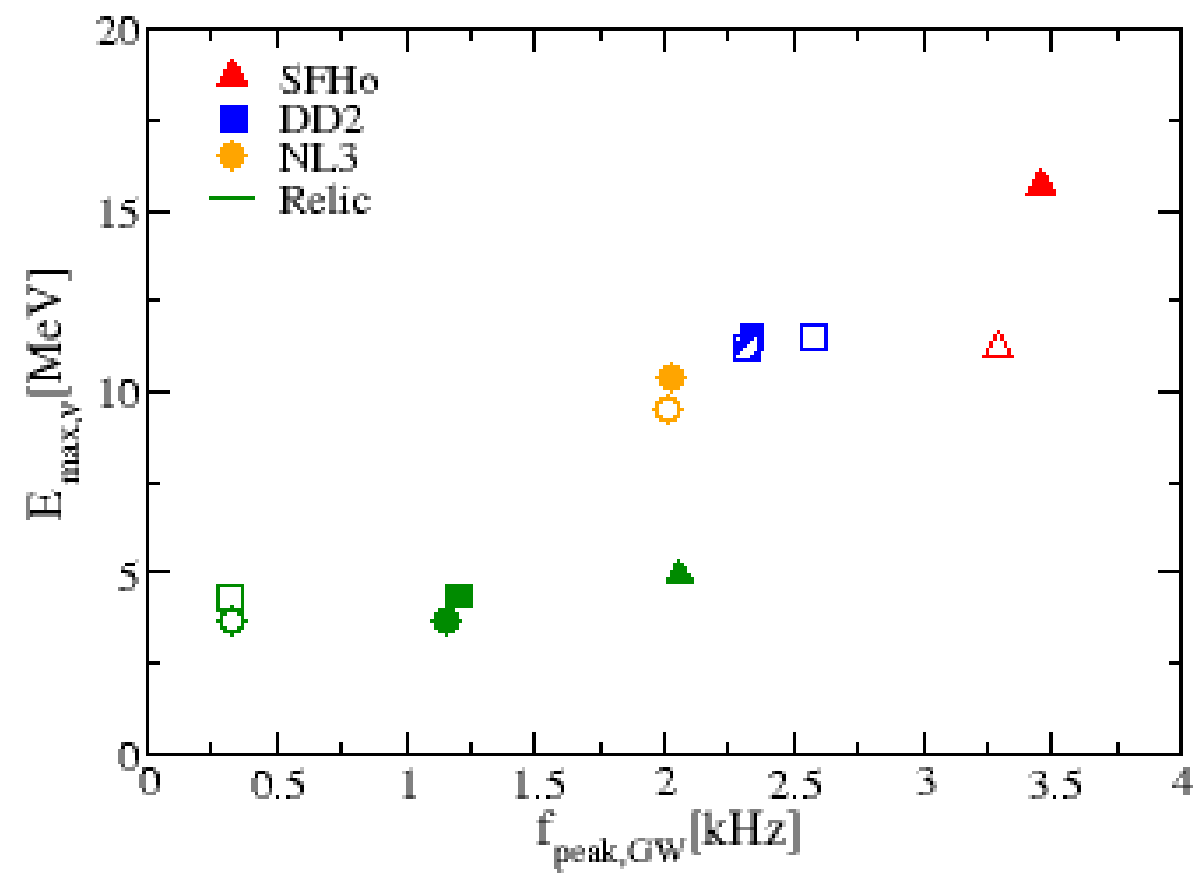
Stochastic GWs will also add constraints to the EOS in a detectable range of hundreds of Hz

Collaborators

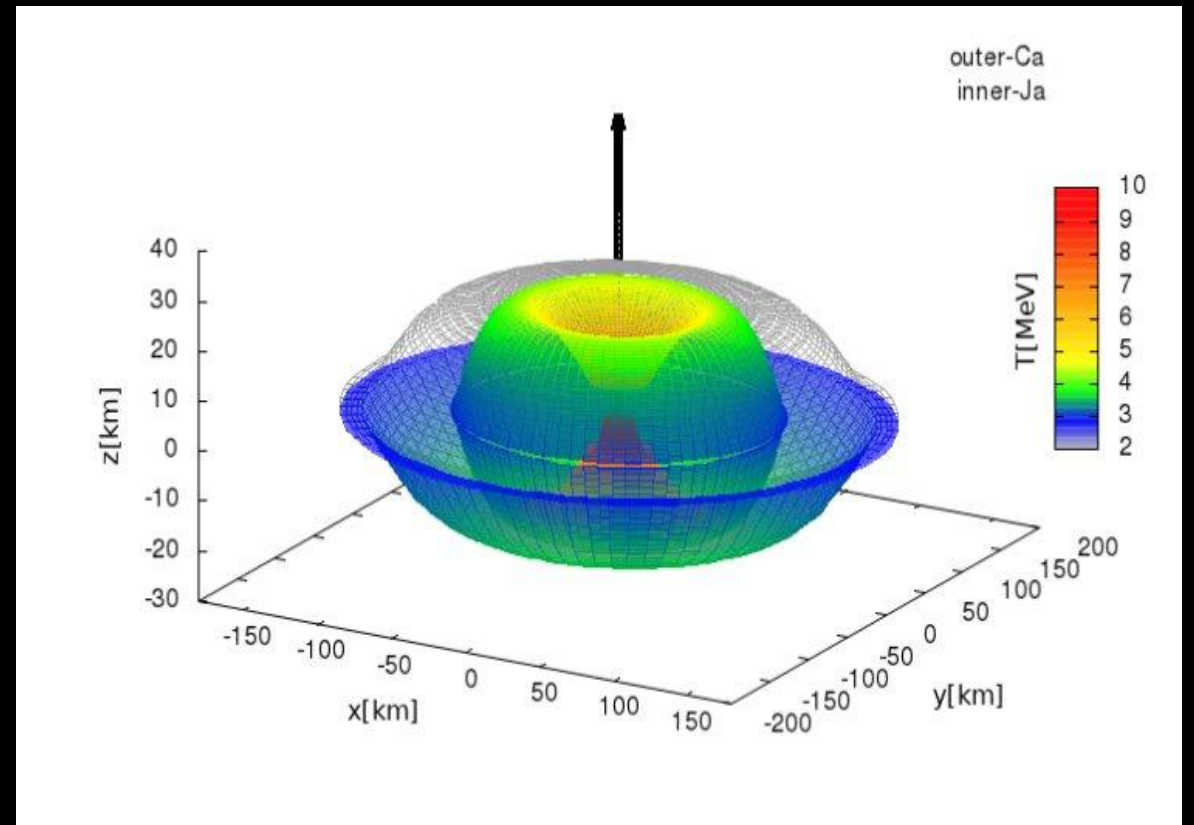
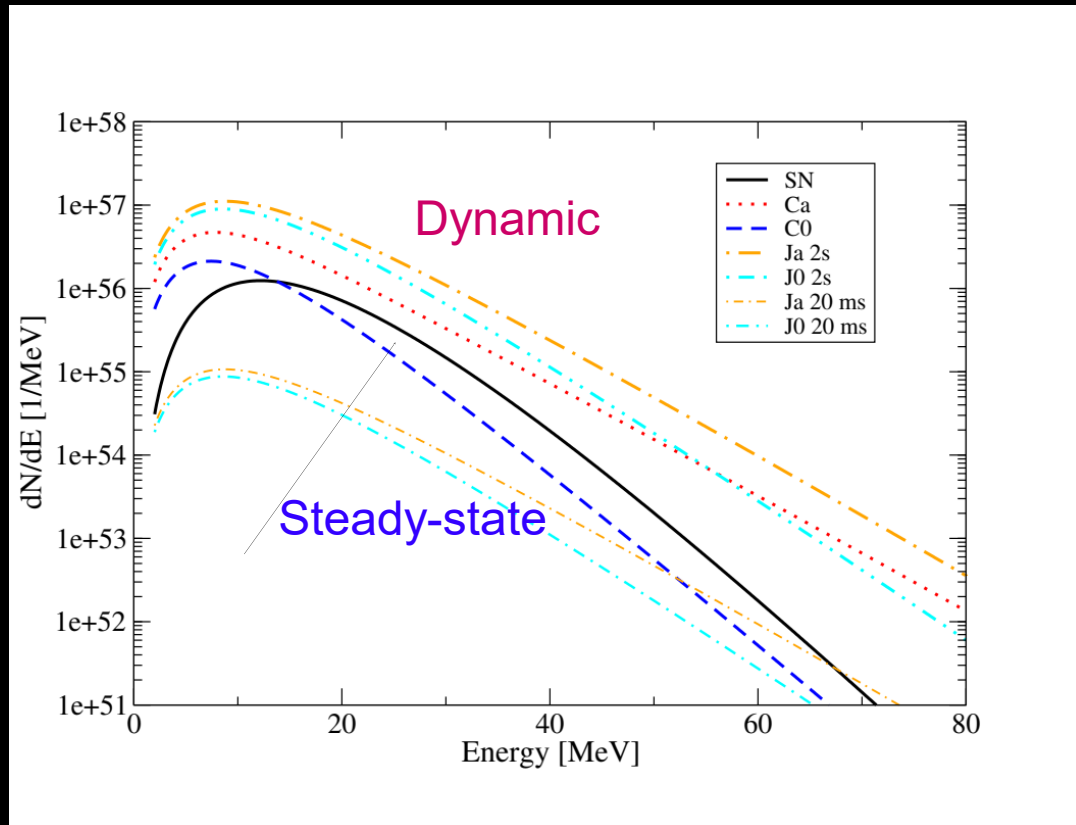
- Paul Deguire*, Tyson Schilbach* (U. Of Guelph)
- G. McLaughlin (North Carolina State University), L. Lehner (Perimeter Institute), C. Palenzuela (University of the Balearic Islands), D. Neilsen (Bringham Young U.), S. Liebling (Long Island U.), E. O'Connor (North Carolina State University)







Neutrino Spectra from accretion disks long term evolution



Observed at 10 kpc from the source
T. Schilbach*, O. L. C, McLaughlin PRD (2019)

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

Isolated NS: Equation of State (EOS)

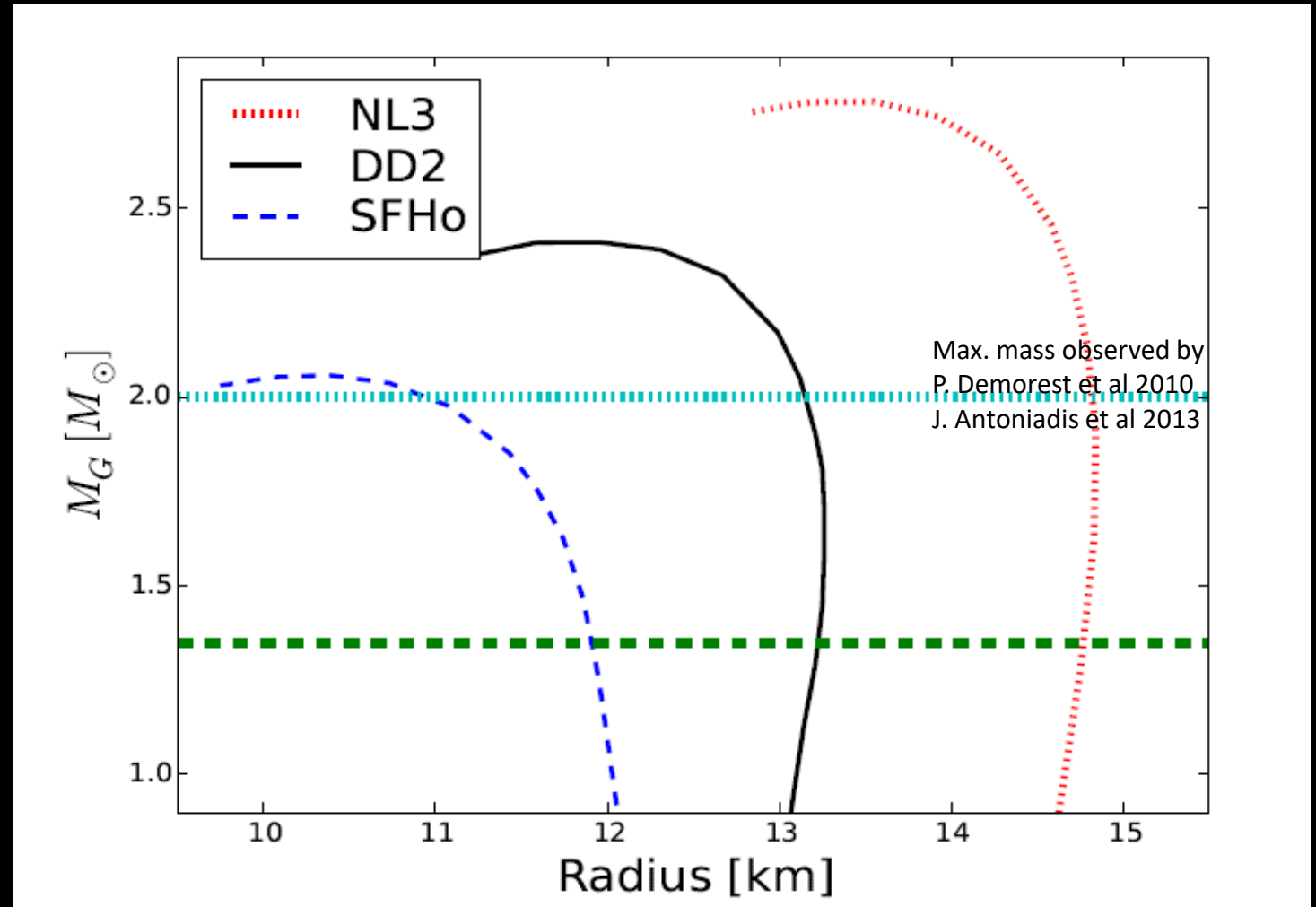
NS mass = 1.35 solar masses

Statistical model (Hempel et al 2010) with the Relativistic Mean Field interactions:

NL3: Lalazissis et al (2008) , **stiff**

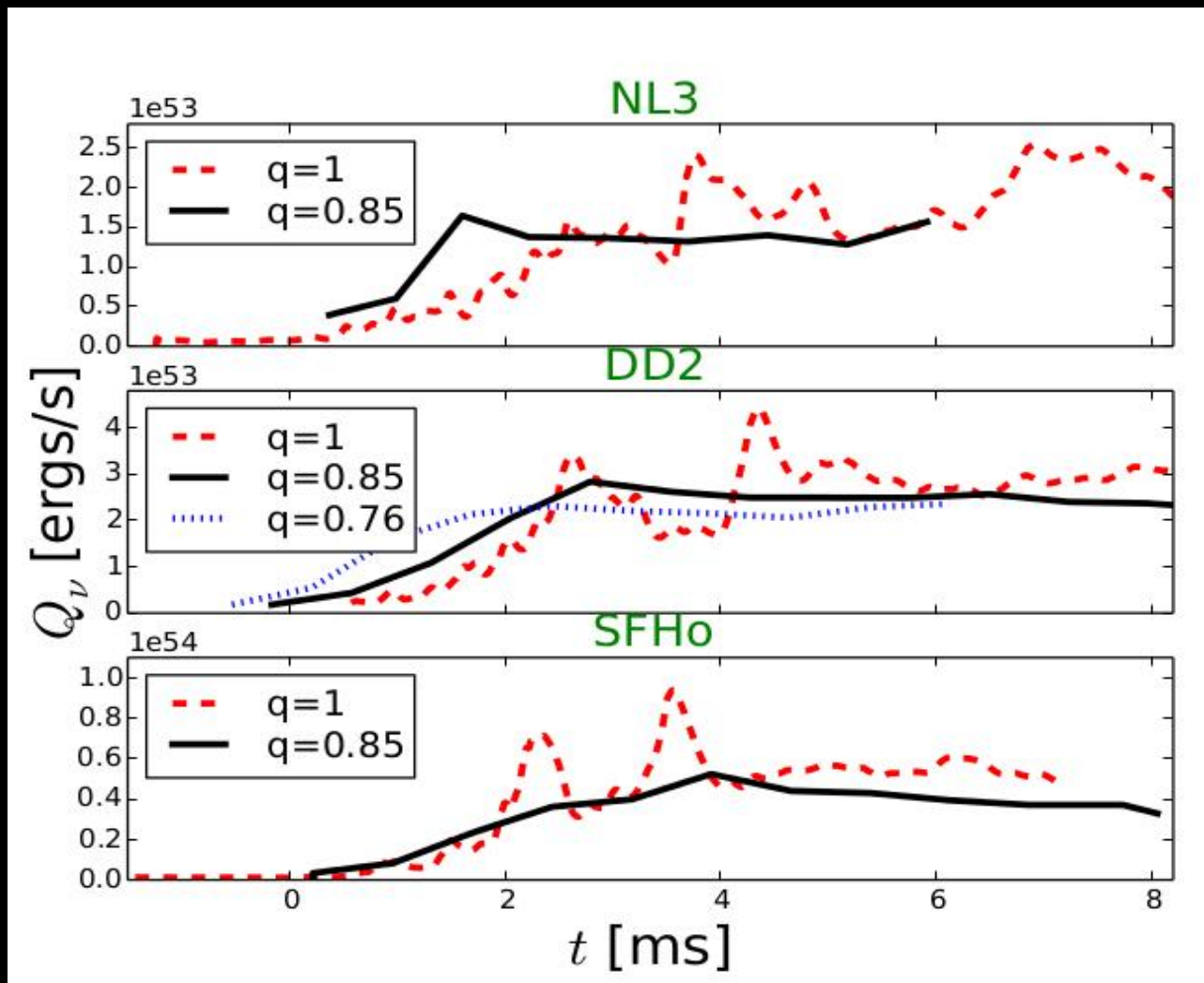
DD2: Typel et al (2012)

SFHo: Steiner et al (2012) , **soft**



Neutrino luminosity evolution

Density at different times DD2 EoS
 $q=1$



Luminosity oscillates for $q=1$

