SNEWPY

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For the SNEWS 2.0 collaboration

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SNEWS

- The next supernova in the Milky Way will be an incredible opportunity to see inside an exploding star.
- The rate of supernovae in our Galaxy is ~ 3 / century and we have no idea when the next one will occur.
  - We don't want to miss it!

- The Supernova Early Warning System (SNEWS) is a global network of detectors looking for coincident bursts of neutrinos.
- The most likely source of coincident bursts is a supernova or compact-object merger in the Milky Way.
- It has been running since 2005 but has yet to send out an alert.

SNEWS 2.0

- Gravitational Wave astronomy and advances in telescope technology has changed the attitude towards alerts.
- SNEWS has become much more active and wants to do more.
  - Pre-supernova neutrinos
  - Pointing / Triangulation
  - Connect with EM follow up
- See the recently published SNEWS 2.0 White Paper

Al Kharusi et al, arXiv:2011.00035

- LIGO deliberately created false events so that astronomers could practice EM follow-up campaigns.
- SNEWS wants to also conduct 'fire drills' to practice the follow-up from a Galactic SN.

- To facilitate these fire drills (and also to give detector collaborations more realistic data to work with), we have collected several hundred supernova simulations from different groups.
  - Most are CCSN including BH forming cases,
  - we also have SN Ia and PISN.

- The CCSN models include those by
  - Nakazato et al. 2013, 2015
  - Suhkbold 2015
  - O’Connor 2013 and 2015 1D GR1D models
  - Warren, O’Connor & Couch 2020 1D STIR models...

- Most of the simulations cannot be used in their raw form
- They do not account for:
  - flavor transformation within the SN,
  - the decoherence outside the SN on the trip to Earth,
  - Earth matter effects

Flavor transformation in supernovae

The neutrino spectra emitted at the neutrinosphere are distorted as the neutrinos propagate to Earth.

In order to simulate a burst signal properly we need to account for:

- neutrino self-interactions,
- BSM effects (such as sterile flavors, NSI, neutrino decay)
- a dynamic MSW effect in the SN plus turbulence, and Earth matter
- decoherence
- Not all effects are present at all epochs of neutrino emission.
  - Earth matter, decoherence and dynamic MSW effect are well understood.
  - Lack of suitable simulations limits our understanding of turbulence.
  - Neutrino self interactions are not well understood and are computationally very demanding.
- Computing the flavor transformation well for a single simulation can take 10^4 - 10^6 CPU hours.

SNEWPY

- SNEWPY is a software pipeline in four parts to bridge the gap between simulation and detector signals:
  - to_snowglobes: takes a simulation data set and turns it into a time series of neutrino fluxes and/or a total fluence at Earth. Prescriptions for the flavor transformation inside the SN can be included plus decoherence.
  - run_snowglobes: sends the time series through the SNOwGLoBES software for all the neutrino detectors SNOwGLoBES can model.
  - SNOwGLoBES: given a neutrino spectrum it computes the number of events in various channels for various kinds of neutrino detectors.
  - from_snowglobes: collates the output from SNOwGLoBES into observable channels.

- SNEWPY is designed so that data can be inserted or extracted at the connections between its components.
  - For example: the SN Ia and PISN models that come with SNEWPY already have the flavor transformation included.

- to_snowglobes is the part where a most of the physics in the neutrino signal is introduced.
- The user selects a simulation to use, a flavor prescription and a distance to the supernova.
- SNEWPY has a custom interface to each simulation data set.
  - There is no need to supply simulation data in a particular format
- The interface extracts (or constructs) the unoscillated spectra at the neutrinosphere Φ.
- The flux at Earth from a supernova at a distance d is then computed as

$$F_e = \frac{1}{4\pi d^2}\left[p_{ee}\Phi_e + p_{ex}\Phi_x\right] \qquad F_x = \frac{1}{4\pi d^2}\left[p_{xe}\Phi_e + p_{xx}\Phi_x\right]$$

$$\bar{F}_e = \frac{1}{4\pi d^2}\left[\bar{p}_{ee}\bar{\Phi}_e + \bar{p}_{ex}\bar{\Phi}_x\right] \qquad \bar{F}_x = \frac{1}{4\pi d^2}\left[\bar{p}_{xe}\bar{\Phi}_e + \bar{p}_{xx}\bar{\Phi}_x\right]$$

- SNEWPY has 15 prescriptions are available for the p and $\overline{\text{p}}$’s.

For three flavors:

- No Oscillations and Complete Exchange
- Adiabatic MSW in both mass orderings
- NonAdiabatic MSW H resonance in both mass orderings
- Two Flavor Decoherence at the H resonance in both mass orderings.
- Three Flavor Decoherence
- Neutrino Decay of the heaviest mass state to the lightest with variable lifetime and neutrino mass, in both mass orderings,

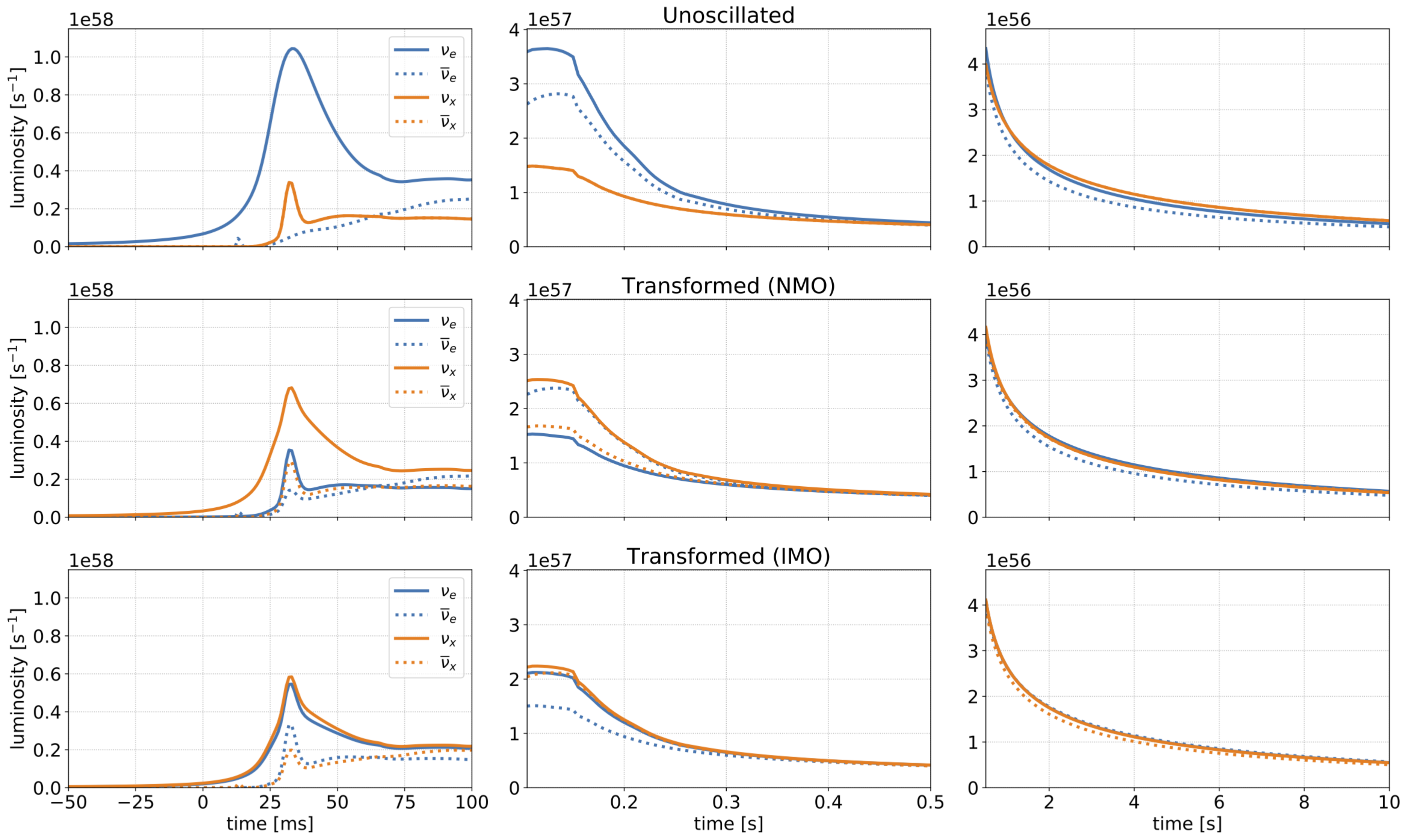
For four flavors:

- Adiabatic MSW of four flavors in both mass orderings
- MSW where the ‘outer’ es resonance is non adiabatic, for both mass orderings.

Using SNEWPY

- SNEWPY has a lot of flexibility and can be used for many different things.

Core-Collapse Supernovae



Data from Segev BenZvi.

Experiment	Type	Mass [kt]	Location	11.2 $M_\odot$	27.0 $M_\odot$	40.0 $M_\odot$
Super-K	$H_2O/\bar{\nu}_e$	32	Japan	4000/4100	7800/7600	7600/4900
Hyper-K	$H_2O/\bar{\nu}_e$	220	Japan	28K/28K	53K/52K	52K/34K
IceCube	String/$\bar{\nu}_e$	2500*	South Pole	320K/330K	660K/660K	820K/630K
KM3NeT	String/$\bar{\nu}_e$	150*	Italy/France	17K/18K	37K/38K	47K/38K
LVD	$C_nH_{2n}/\bar{\nu}_e$	1	Italy	190/190	360/350	340/240
KamLAND	$C_nH_{2n}/\bar{\nu}_e$	1	Japan	190/190	360/350	340/240
Borexino	$C_nH_{2n}/\bar{\nu}_e$	0.278	Italy	52/52	100/97	96/65
JUNO	$C_nH_{2n}/\bar{\nu}_e$	20	China	3800/3800	7200/7000	6900/4700
SNO+	$C_nH_{2n}/\bar{\nu}_e$	0.78	Canada	150/150	280/270	270/180
NOνA	$C_nH_{2n}/\bar{\nu}_e$	14	USA	1900/2000	3700/3600	3600/2500
Baksan	$C_nH_{2n}/\bar{\nu}_e$	0.24	Russia	45/45	86/84	82/56
HALO	Lead/ν_e	0.079	Canada	4/3	9/8	9/9
HALO-1kT	Lead/ν_e	1	Italy	53/47	120/100	120/120
DUNE	Ar/ν_e	40	USA	2700/2500	5500/5200	5800/6000
MicroBooNe	Ar/ν_e	0.09	USA	6/5	12/11	13/13
SBND	Ar/ν_e	0.12	USA	8/7	16/15	17/18
DarkSide-20k	Ar/any ν	0.0386	Italy	-	250	-
XENONnT	Xe/any ν	0.006	Italy	56	106	-
LZ	Xe/any ν	0.007	USA	65	123	-
PandaX-4T	Xe/any ν	0.004	China	37	70	-

Data computed by Evan O'Connor

Type Ia and PISN Supernovae

- Type Ia supernovae (SN Iae) are the disruption of a CO white dwarf due to explosive burning of the carbon.

- Pair Instability Supernovae (PISNe) are the disruption of a star due to explosive burning in a CO core that becomes unstable due to electron-positron pair production.
  - the mass of the CO core lies in the range $64\ M_\odot < M_{CO} < 133\ M_\odot$

Heger & Woosley, ApJ **567** 532 (2002)

Chatzopoulos & Wheeler, ApJ **748** 42 (2012)

Langer et al, A&A 475 **L19** (2007)

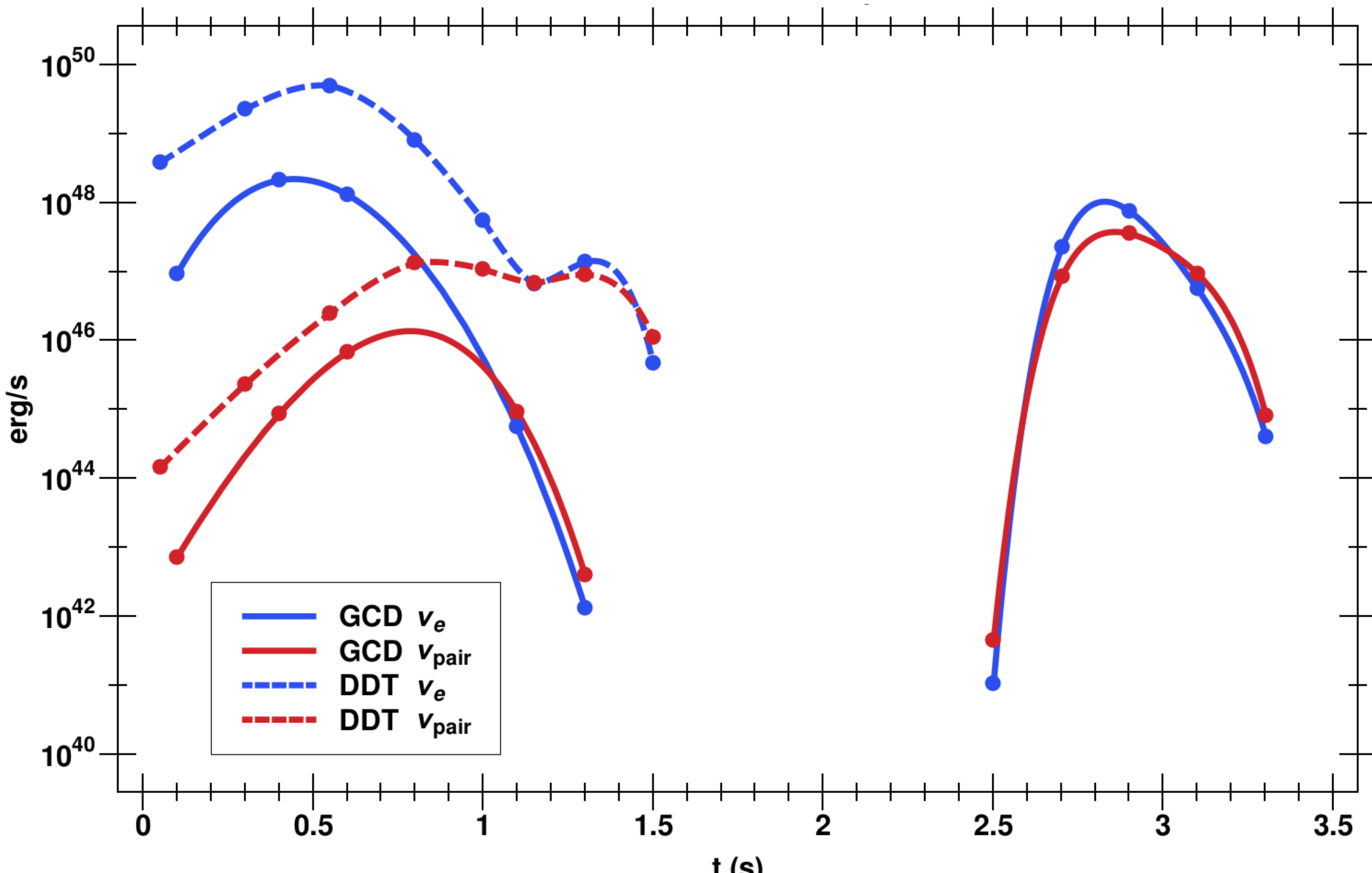
Georgy et al, A&A **599** L5 (2017)

- SN Iae and PISNe also produce neutrino bursts when they explode.
  - From how far can we detect a SN Ia or PISN neutrino burst?
  - Is a SN Ia or PISN burst different from the neutrino burst from a CCSN?
  - Can the burst from a SN Ia tell us how white dwarf exploded?
  - Do PISN occur in the Milky Way or nearby galaxies?
  - How reliable are the predictions?
    - are they sensitive to the Equation of State or the line of sight?
  - Can a burst tell us something about the neutrino?

- For many further details see
  - Wright *et al*. PRD **96** 103008 (2017)
  - Wright *et al*. PRD **95** 043006 (2017)
  - Wright *et al*. PRD **94** 025026 (2016)
- See also Odrzywolek & Plewa A&A **529** A156 (2011).

- To compute the signal from a SN IA we took two simulations:
  - the N100ν DDT simulation from Seitenzahl *et al*. PRD **92** 124013 (2015), Seitenzahl *et al*. MNRAS **429** 1156 (2013)
  - a GCD simulation from Seitenzahl *et al*. A&A **592** A57 (2016)

- We then post-process the simulations using NuLib to compute the neutrino luminosity and spectra.
  - O'Connor ApJSS **219** 21 (2015)
  - Sullivan et al. ApJ **816** 44 (2016)



erg/s
10^{50}
10^{48}
10^{46}
10^{44}
10^{42}
10^{40}
0
0.5
1
1.5
2
2.5
3
3.5
t (s)
GCD ν_e
GCD ν_{pair}
DDT ν_e
DDT ν_{pair}

- For both models we compute the neutrino flavor evolution through the mantle as a function of time and energy for both neutrino mass orderings using an exact 3-flavor neutrino evolution code SQA.
  - the density profiles evolve with time and posses moving shocks.

- We put the flavor transformation probabilities and the emission spectra together to get the neutrino spectra at Earth.

- The neutrino flux at Earth is processed using the 2nd and 3rd parts of SNEWPY for a representative set of detectors.

Detector	Type	Mass [kt]
SuperKamiokande (30% PMT coverage)	Water Cerenkov	50
HyperKamiokande	Water Cerenkov	374
DUNE	Liquid Argon	40
JUNO	Scintillator	20

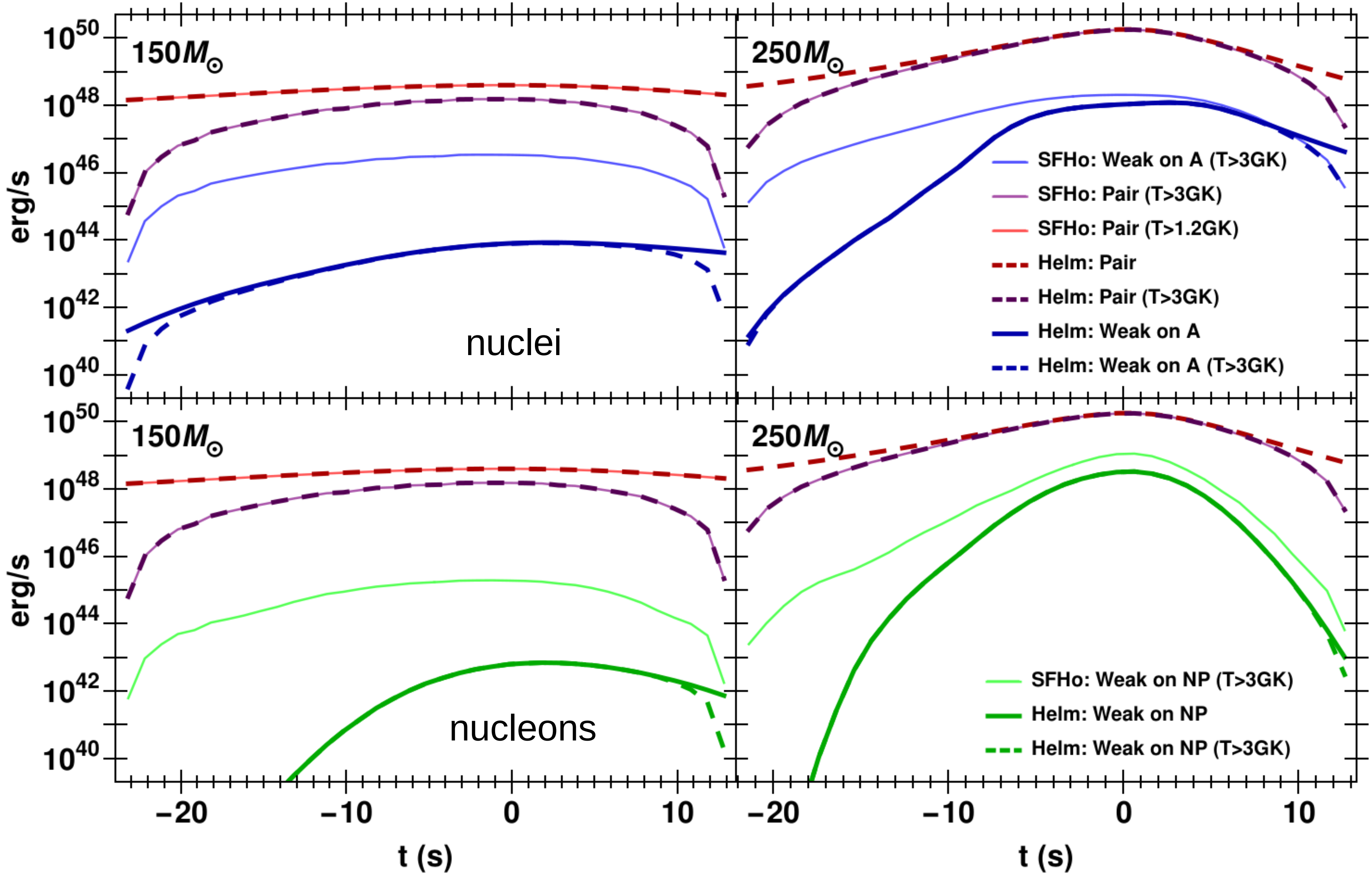
- The SN is placed at the standard distance d = 10 kpc.

Model	Detector	NMO	IMO	Unoscillated
DDT	HyperK	0.253	0.560	1.152
	SuperK	0.034	0.076	0.154
	DUNE	0.025	0.066	0.138
	JUNO	0.014	0.032	0.063
GCD	HyperK	0.0178	0.0319	0.0666
	SuperK	0.0024	0.0043	0.0089
	DUNE	0.0015	0.0033	0.0069
	JUNO	0.0010	0.0018	0.0037

- HyperK can detect neutrinos from a DDT closer than ~7 kpc.
- SuperK, DUNE and JUNO can detect neutrinos from a DDT if the distance is less than ~2 kpc.
- HyperK can detect neutrinos from a GCD closer than ~2 kpc.
- SuperK, DUNE and JUNO would require the GCD to be closer than 1 kpc.

Pair Instability Supernovae

- PISNe are an explanation for some superluminous supernovae.
  - Less energetic PISNe may be hidden among other classes.
- Estimates of the PISN rate compared to the CCSN rate in the local Universe are uncertain but typically get 1:1000.
  - e.g. Langer *et al.* A&A **475** L19 (2007) assume stars with ZAMS masses between 140 $M_\odot$ < M_{ZAMS} < 250 $M_\odot$ explode as PISNe
- To compute the signal from a PISN we start with two GENEC progenitor models: P150 and P250.
  - at the point where pair creation begins the CO core mass of P150 is 65.7 $M_\odot$, the core mass of P250 is 126.7 $M_\odot$
- These two models span the range of PISNe signals.



- Unlike SN Ia, most of the emission is due to thermal processes.

- Again we computed the neutrino flavor evolution for both neutrino mass orderings using SQA.
- We put the flavor transformation probabilities and the emission spectra together to get the neutrino spectra at Earth.

- The spectra at Earth are then processed using the 2nd and 3rd components of SNEWPY for a PISN at 10 kpc using the same suite of detectors as for the SN Ia..

Model	Detector	NMO		IMO		Unoscillated	
		Helm	SFHo	Helm	SFHo	Helm	SFHo
P150	HyperK	1.77	1.78	1.74	1.75	3.02	3.05
	SuperK	0.24	0.24	0.23	0.23	0.40	0.41
	DUNE	0.14	0.14	0.15	0.15	0.25	0.25
	JUNO	0.10	0.10	0.10	0.10	0.17	0.17
P250	HyperK	52.23	50.08	43.32	41.98	85.70	84.19
	SuperK	6.98	6.69	5.79	5.61	11.46	11.26
	DUNE	2.95	2.78	3.17	3.06	5.30	5.20
	JUNO	3.13	3.00	2.48	2.40	5.06	4.97

- At 10 kpc HyperK can detect neutrinos from both P150 and P250.
  - HyperK could detect neutrinos from a P250 PISN in the LMC.
- SuperK, DUNE and JUNO can detect a few neutrinos from P250 at 10 kpc
- There is a ~20% difference between the two mass orderings for P250 model.

Summary

- SNEWPY is a new bridge across the gulf between supernova simulations and detector signals.
- Version 1.0 is publicly available and is going through beta testing.
  - https://github.com/SNEWS2/snewpy/releases/tag/v1.0.0
  - https://zenodo.org/record/4498941
- Please send us your suggestions for new features.

- The neutrino signal from a SN Ia and a PISN are well understood and found to be very different from a CCSN.
  - A SN Ia would have to be quite close to be seen even with Hyper K.
  - DUNE, JUNO and SuperK can observe a large PISN in the Milky Way, HyperK can observe a large PISN in the LMC.

Thank you