SNEWS 2.0: The New Plan for the Next Galactic Supernova

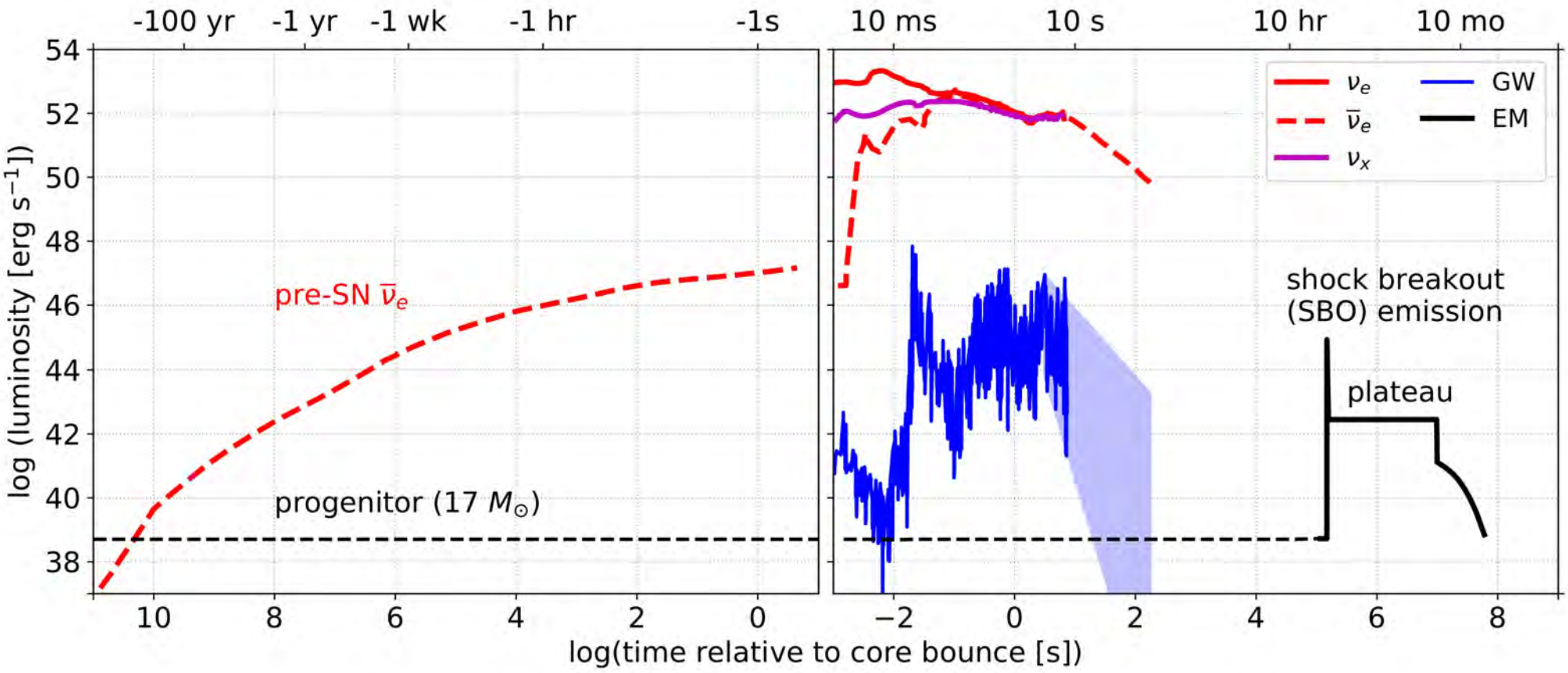
Jim Kneller
NC State + SNEWS 2.0

SNEWS is supported by the National Science Foundation including grants PHY-1506069, PHY-1505960, & PHY-2209534.

https://snews2.org/

- The next supernova in the Milky Way will be an incredible opportunity to see the details of how a star explodes.
- The rate of supernovae in our Galaxy is ~ 2 / century and we have no idea when the next one will occur.
- Neutrinos are the first / clearest sign that the explosion has begun.

Nakamura et al. MNRAS **461**, 3296 (2016)



SUPERNOVA EARLY ALERT NETWORK

First International Workshop

Boston University
Boston, MA

September 11-12, 1998

A meeting of neutrino experimenters, supernova theorists and astronomers to plan the world-wide response to the next Galactic core collapse supernova.

Topics for Discussion:

- **The neutrino signal and triangulation:** what will the individual experiment signals look like? How well will it be possible to point to the supernova by combining neutrino burst timing information from different neutrino experiments?
- **Inter-experiment connection:** alert implementation and data exchange issues.
- **Connection with the astronomical community**: how can we organize astronomer responses to have the best possible chance of observing early supernova light?

- The Supernova Early Warning System (SNEWS) is (was) a global network of detectors looking for coincident bursts of neutrinos.
- It has been running since 1998, fully automated since 2005, with virtually zero downtime.

Fast forward 20 years

- There are now many more, larger and more sensitive neutrino and DM detectors, which offers the possibility of doing more than just issuing an alert.
- Passing alerts between facilities is now very common and the attitude of astronomers towards alerts has changed.

SuperNova Early Warning System

SNEWS 2.0 Workshop

Supernova Neutrinos in the Multi-Messenger Era

June 14-17, 2019
Laurentian University, Sudbury, Canada

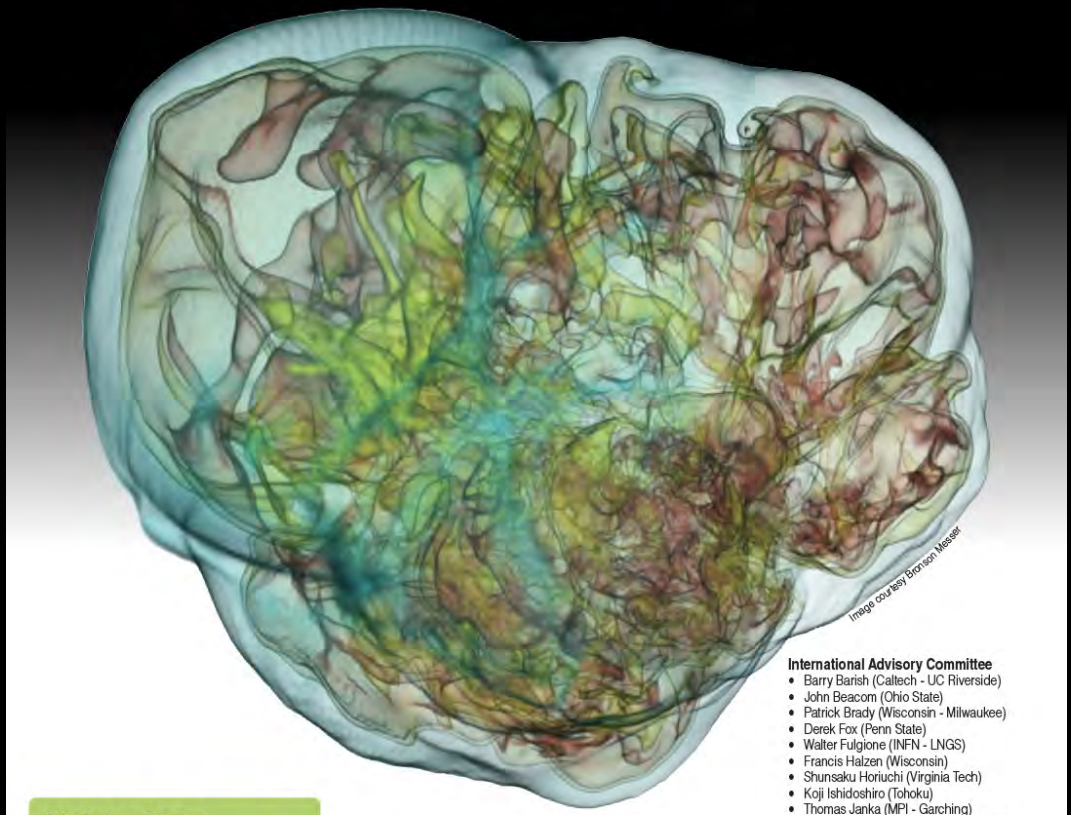


Image courtesy Bronson Messer

Workshop Topics
- Supernova neutrino detection
- Multi-messenger signals
- Astronomical alert networks
- Alert dissemination
- Pointing with neutrinos
- Pre-supernova alerts

Scientific Organizing Committee
- Alec Habig (Minnesota Duluth)
- Erik Katsavounidis (MIT)
- Rafael Lang (Purdue)
- Danny Milisavljevic (Purdue)
- Kate Scholberg (Duke)
- Clarence Virtue (Laurentian)

Local Organizing Committee
- Erica Caden (SNOLAB)
- Blaire Flynn (SNOLAB)
- Doug Hallman (Laurentian)
- Christine Kraus (Laurentian)
- Samantha Kuula (SNOLAB)
- Caio Licciardi (Laurentian)
- Nancy MacKenzie (SNOLAB)
- Silvia Scorza (SNOLAB)
- Curtis St. Jean (Laurentian)
- Clarence Virtue (Laurentian)

International Advisory Committee
- Barry Barish (Caltech - UC Riverside)
- John Beacom (Ohio State)
- Patrick Brady (Wisconsin - Milwaukee)
- Derek Fox (Penn State)
- Walter Fulgione (INFN - LNGS)
- Francis Halzen (Wisconsin)
- Shunsaku Horiuchi (Virginia Tech)
- Koji Ishidoshiro (Tohoku)
- Thomas Janka (MPI - Garching)
- David Kaplan (Wisconsin - Milwaukee)
- Mansi Kasliwal (Caltech)
- Robert Kirshner (Moore Foundation / Harvard)
- Art McDonald (Queens)
- Bronson Messer (ORNL)
- Tony Mezzacappa (UTK - ORNL)
- Masayuki Nakahata (ICRR)
- Evan O'Connor (Stockholm)
- Dan Scolnic (Duke)
- Peter Shawhan (Maryland)
- Irene Tamborra (Niels Bohr Institute)
- Cristina Volpe (APC - Paris7)
- Chris Walter (Duke)

https://snews2.0.snolab.ca

Proudly sponsored by:

LaurentianUniversity UniversitéLaurentienne

SNOLAB

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

Sudbury

SCIENCE NORTH SCIENCE NORD

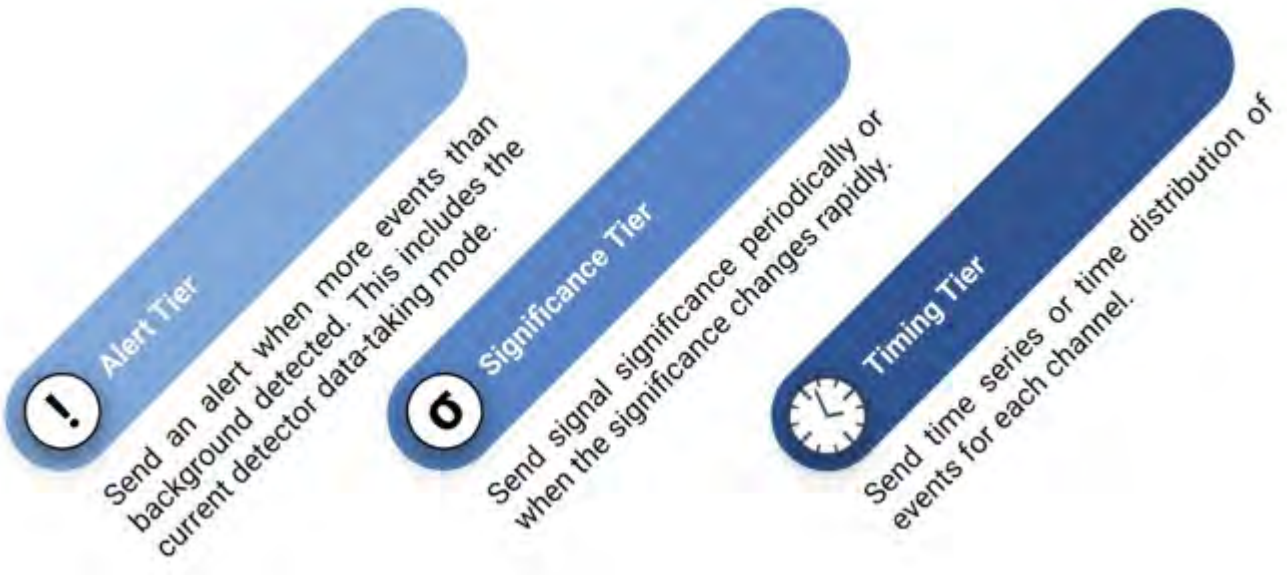
SNEWS 2.0

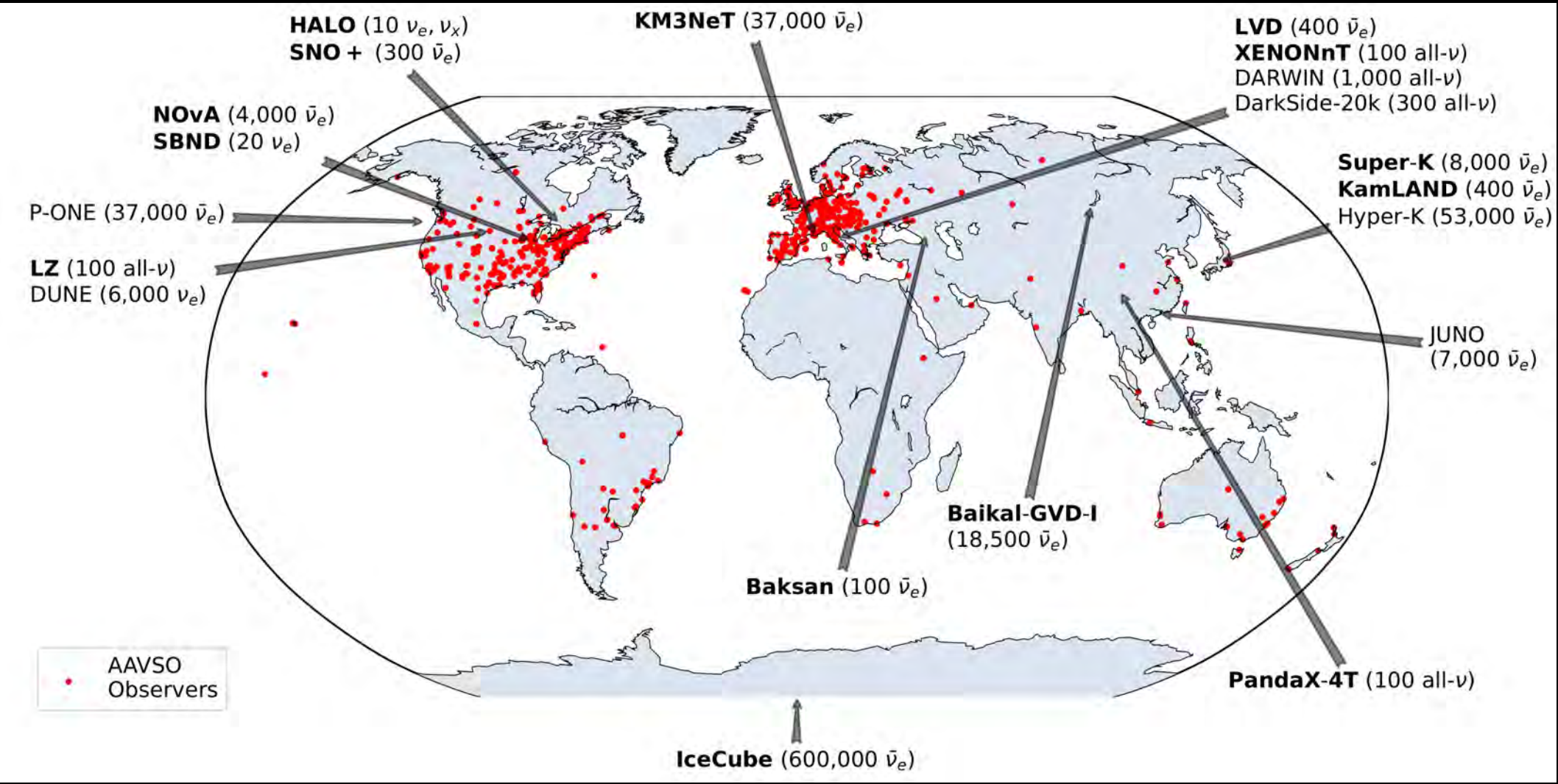
- SNEWS 2.0 is a new plan for what to do when the next nearby supernova occurs.

  Al Kharusi et al, New J. Phys. **23** 031201 (2021)

- The goals of SNEWS 2.0 are to:
  - reduce the threshold for generating alerts in order to gain sensitivity,
  - reduce alert latency,
  - combine pointing information from individual experiments and enhance it with timing multilateration (triangulation),
  - implement a pre-supernova alert for nearby SN candidates,
  - develop a follow-up observing strategy to prepare the astronomical community for the next galactic supernova,
  - engage amateur astronomer and citizen science communities.

- The first goal of SNEWS 2.0 was to rewrite the codebase for passing information between detectors and SNEWS.
  - The new coincidence system uses HOPSKOTCH from SCiMMA
- SNEWS 2.0 is currently running in parallel with SNEWS 1.0 which will be switched off (probably) mid 2026.
- Detectors can sign up for different levels of data exchange.
  - MOUs are currently being signed by SNEWS and the detectors.




HALO (10 ν_e, ν_x)
SNO + (300 $\bar{\nu}_e$)
KM3NeT (37,000 $\bar{\nu}_e$)
LVD (400 $\bar{\nu}_e$)
XENONnT (100 all-ν)
DARWIN (1,000 all-ν)
DarkSide-20k (300 all-ν)
NOvA (4,000 $\bar{\nu}_e$)
SBND (20 ν_e)
Super-K (8,000 $\bar{\nu}_e$)
KamLAND (400 $\bar{\nu}_e$)
Hyper-K (53,000 $\bar{\nu}_e$)
P-ONE (37,000 $\bar{\nu}_e$)
LZ (100 all-ν)
DUNE (6,000 ν_e)
JUNO
(7,000 $\bar{\nu}_e$)
Baikal-GVD-I
(18,500 $\bar{\nu}_e$)
Baksan (100 $\bar{\nu}_e$)
AAVSO
Observers
PandaX-4T (100 all-ν)
IceCube (600,000 $\bar{\nu}_e$)

- SNEWS 2.0 is organized into 3 divisions.

- SNEWS 2.0 has published / submitted 7 papers so far (with 2 more coming soon).
- We have much more to do.

Task	2025		2026				2027				2028		Responsible Personnel
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	
Pointing Algorithms	**SNEWPDAG v1.0**. Alpha: - light-curve cross-correlation - flavor-dependent pointing		**SNEWPDAG v2.0**. Beta: - light-curve cross correlation for pointing - flavor-dependent pointing - Automatic generation of HEALPix skymaps					**SNEWPDAG v3.0** - Fully functional light curve and flavor-dependent pointing - Automatic generation of HEALPix maps - Integration with publishing tools to post map links to snews2.org and GCN					**Scholberg** (Duke) **Westerdale** (UCR) Tseng (Oxford)
Fire Drills	Internal SNEWS Drill	Internal SNEWS Drill	Internal SNEWS Drill	Internal SNEWS Drill	Internal SNEWS Drill	Internal SNEWS Drill	Internal SNEWS Drill	Internal SNEWS Drill	Internal SNEWS Drill	Internal SNEWS Drill	Internal SNEWS Drill	Internal SNEWS Drill	**Habig** (UMD) **BenZvi** (UR) **Pablo** (AAVSO) Winslow (MIT) O'Sullivan (Uppsala)
			Community Fire Drill with AAVSO		**Community Fire Drill** with AAVSO		**Community Fire Drill** with AAVSO		**Community Fire Drill** with AAVSO		**Community Fire Drill** with AAVSO		
Multi-messenger follow-up	- Candidate vetting - Application development - Community engagement - Development of educational materials			AAVSO Webinar	- Candidate vetting - Community engagement - Preliminary Analysis of RSG sample			AAVSO Webinar	- Candidate vetting - Community engagement - Analysis of RSG sample			AAVSO Webinar	**Pablo** (AAVSO) **Milisavljevic** (Purdue) Coleiro (UPC) Pointon (BCIT) Horiuchi (VT/U. Tokyo)
Signal modeling	**SNEWPY 2.0**: - 3, 4-flavor transformations - Earth matter effects - New CCSN models		**SNEWPY 3.0**: - Integration with MARLEY (CEvNS channel) - Integration of presupernova models - New CCSN models					**SNEWPY 4.0**: - Integration with vESPER + Xenon codes - New CCSN models					**Kneller** (NC State) **Patton** (Trinity) **Scholberg** (Duke) **Westerdale** (UCR) **Wolfs** (UR) Colomer (ULB) O'Connor (Stockholm) Migenda (KCL) Sheshukov (JINR)
	Presupernova RSG models: - RSG grid models generated with MESA - v1.0 of the catalog available on Zenodo				**Presupernova RSG models**: - v2.0 of the catalog available on Zenodo				**Presupernova RSG models**: - v3.0 catalog				
Cyber infrastructure	**SNEW CS + PT v1.5** - Mult-detection channels (beta) - Integration with GCN (beta)		**SNEWS CS + PT v2.0** - Full support for neutrino time series - Full support for flavor-dependent detection channels - Finalized GCN format + fire drills					**SNEWS CS + PT v2.5** - Automated support for monthly tests - Integration / support for new detectors					**Habig** (UMD) **BenZvi** (UR)
			Workshop & Hackathon		Decommissioning of SNEWS 1.0			Workshop & Hackathon				Workshop & Hackathon	**All PIs**

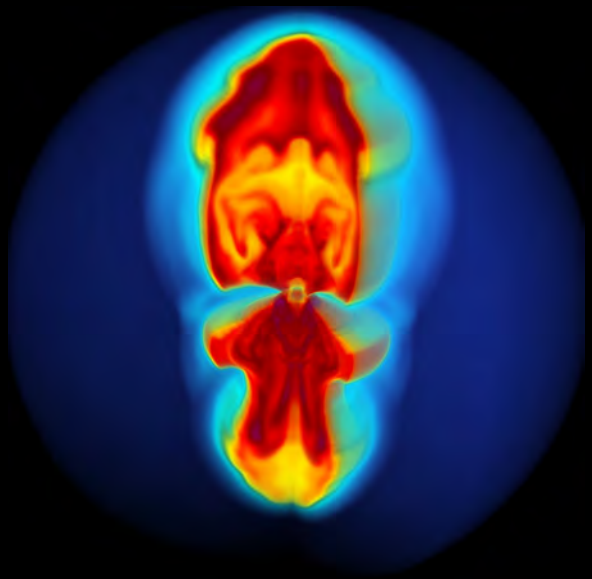
Signal Modeling

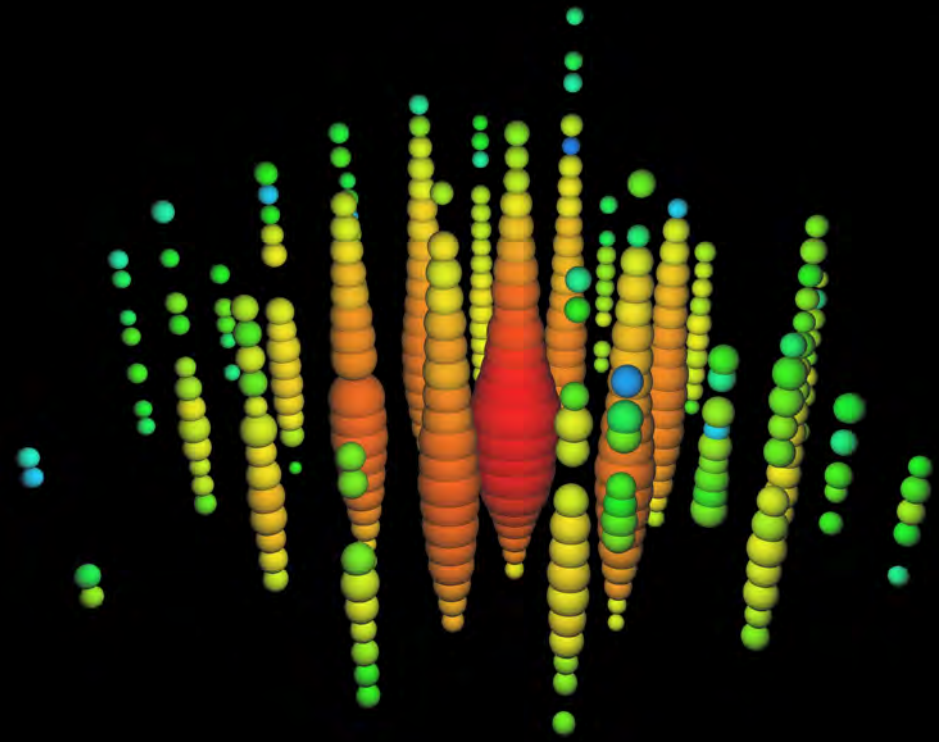
- Signal Modeling aims to support SNEWS 2.0 by providing theoretical models of the neutrino flux at Earth from all possible transient astrophysical sources.
- The models can be used to understand detector response, design algorithms, and for the fire drills.

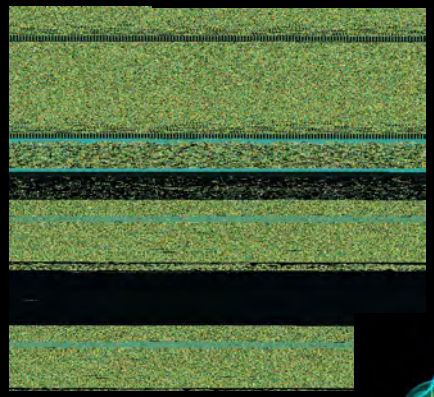
snewpy

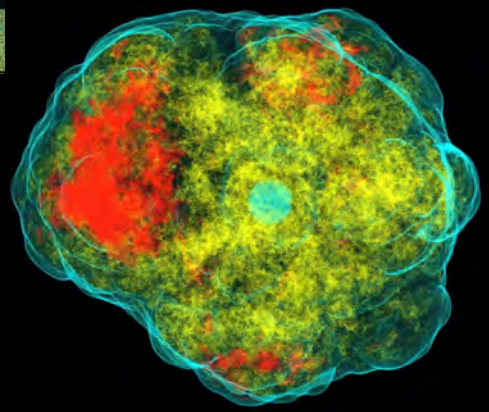
https://github.com/SNEWS2/snewpy

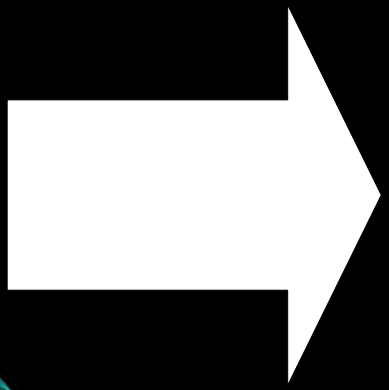
Current release is 1.5.
Version 2.0 is coming soon

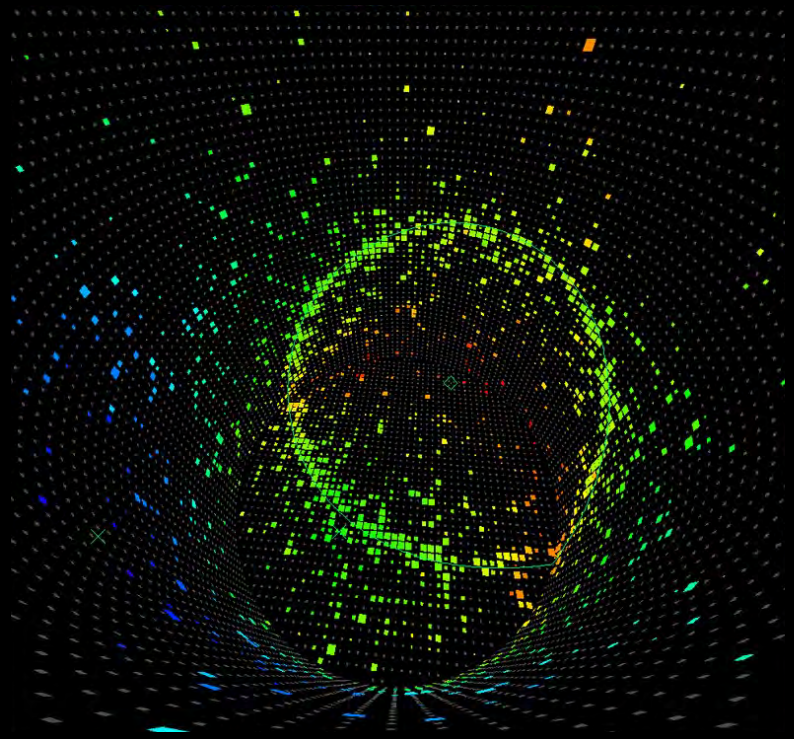












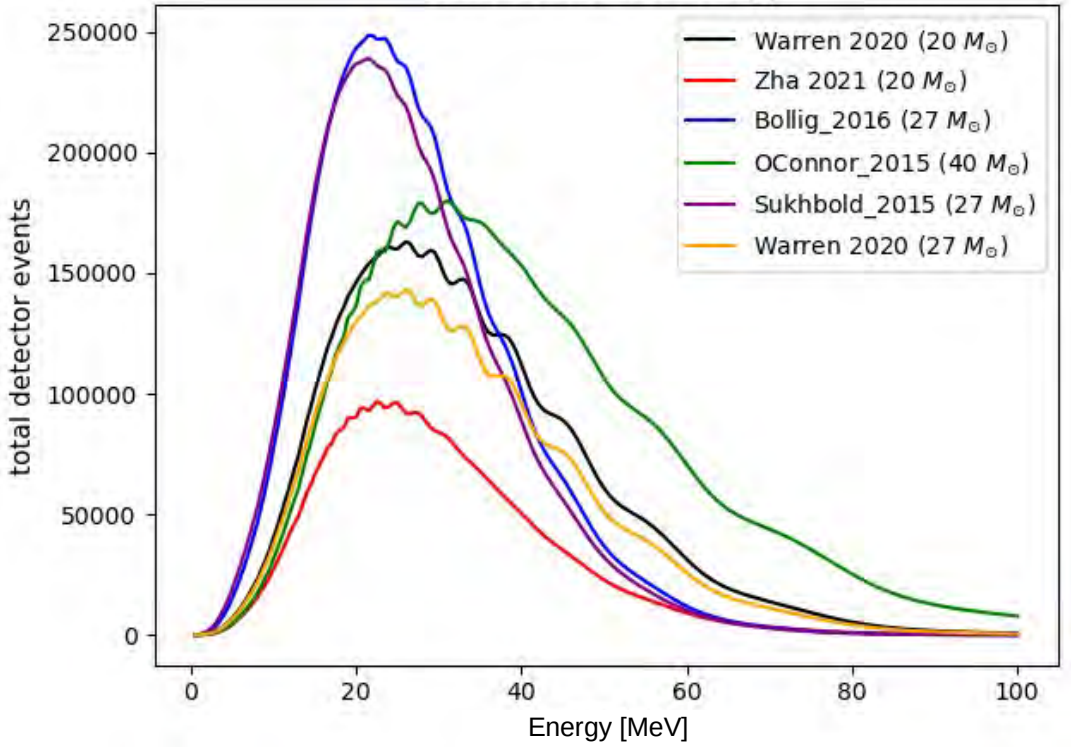
- SNEWPY is a python package with code elements that allow a user to bridge the gap between supernova simulations and detector signals.
- The code elements can:
  - turn a supernova simulation into either a time series of neutrino fluxes (or a total fluence) at Earth, including the effect of flavor transformation.
  - send the time series through an event rate calculator such as SNOwGLoBES or event generator such as sntools or MARLEY*.
  - collate the output into the observable channels.

- SNEWPY is designed so that data can be inserted or extracted at the connections between its components.
  - e.g. a simulation has already accounted for flavor transformation.

* coming soon

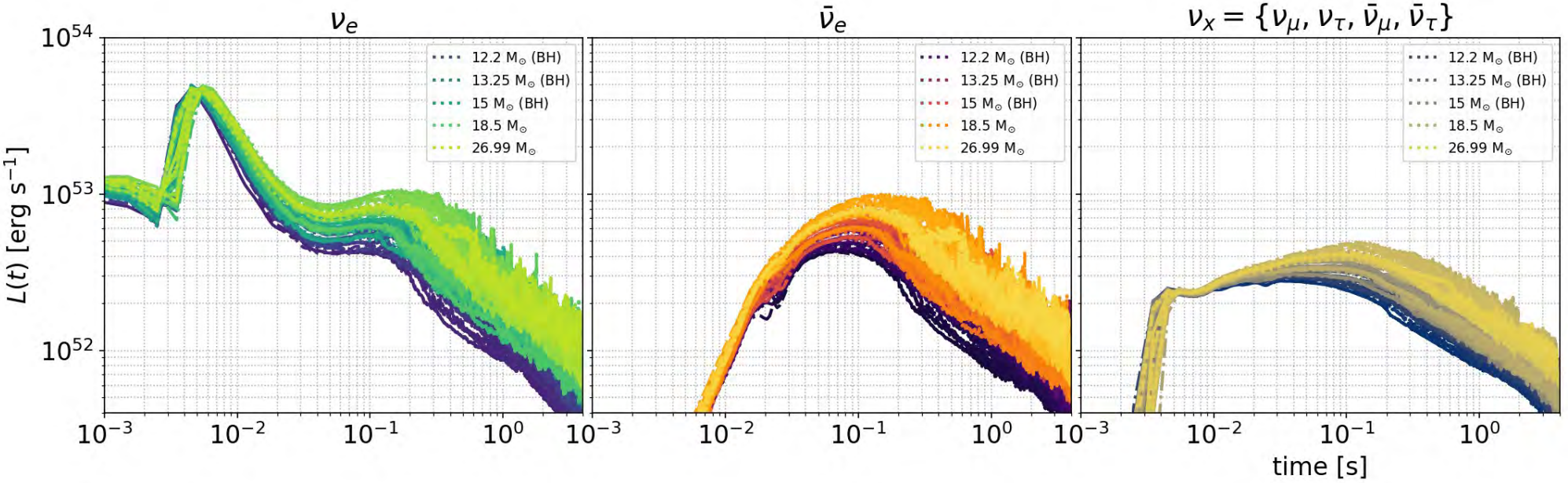
Experiment	Type	Mass (kt)	Location	11.2 $M_\odot$	27.0 $M_\odot$	40.0 $M_\odot$
Super-K	$H_2O/\bar{\nu}_e$	32	Japan	4000/4100	7800/7600	7600/4900
Hyper-K	$H_2O/\bar{\nu}_e$	220	Japan	28K/28K	53K/52K	52K/34K
IceCube	String/$\bar{\nu}_e$	2500*	South Pole	320K/330K	660K/660K	820K/630K
KM3NeT	String/$\bar{\nu}_e$	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	

Table taken from Al Kharusi et al,
New J. Phys. **23** 031201 (2021)



The Models

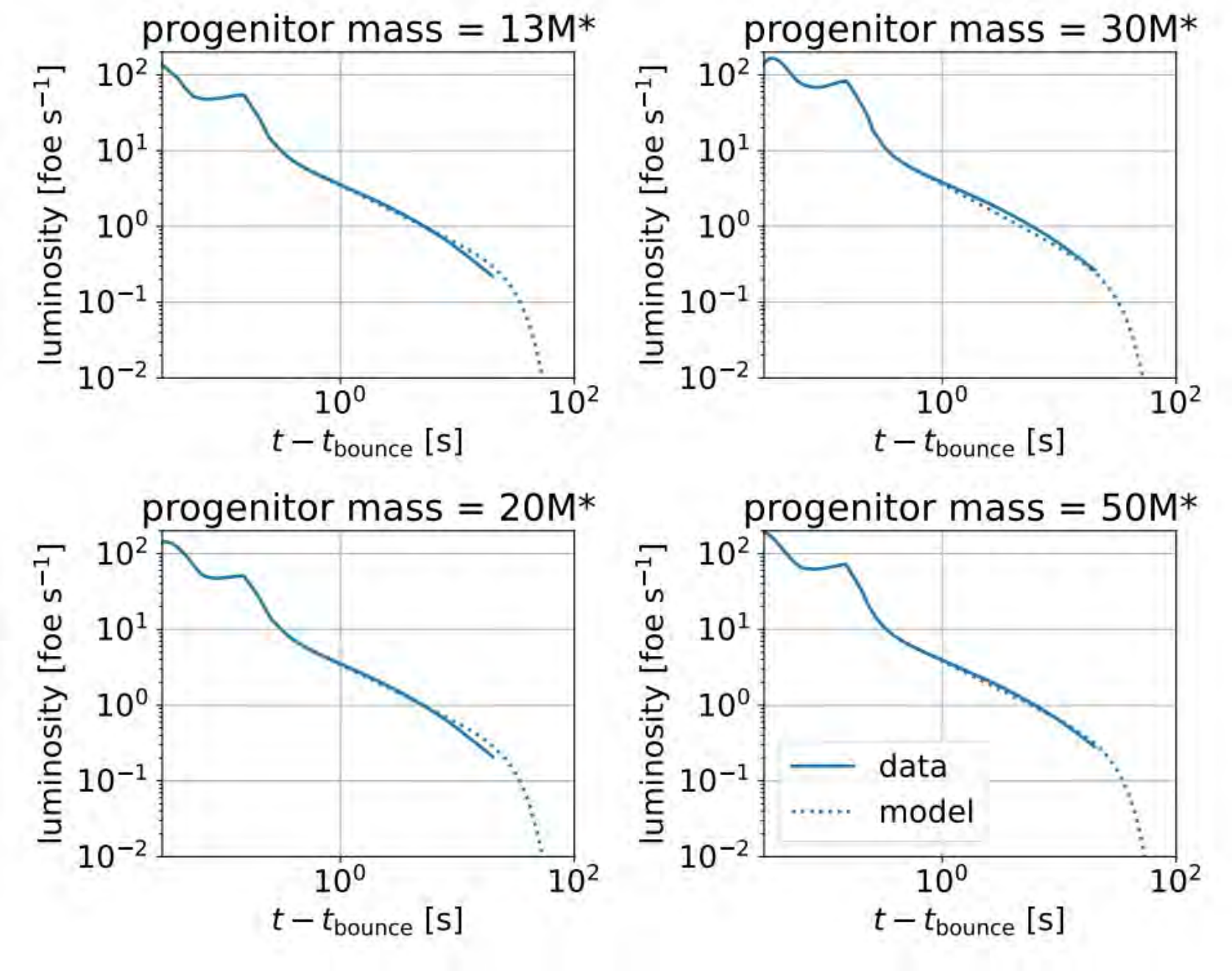
- SNEWPY has access to >800 supernova simulations from different groups.
  - Most are CCSN (including BH forming cases) in 1D
  - Fornax models from Burrows & Vartanyan
  - We have some 3D models of SN Ia and PISN.



- SNEWPY 2.0 will come with the data for even more simulations, including pre-supernova models

- Many of the models only simulate 1-2 seconds of the supernova.
- `SNEWPY 2.0` will include methods for extrapolating the neutrino emission in time.

see Ekanger et al PRD, 106 686 (2022) for details



- Extended versions of the Nagazato (2013) models

The Flavor Prescriptions

- Almost all the simulations available to `SNEWPY` do not account for:
  - flavor transformation within the SN,
  - decoherence and whatever else might happen outside the SN on the trip to Earth,
  - Earth matter effects

- Computing the flavor transformation well (i.e. solve the Schrodinger equation or something like it) for many tens of snapshots taken from a single simulation can take 10^4 - 10^6 CPU hours.

- SNEWPY bypasses this bottleneck by using prescriptions* for the flavor transformation.
- The flux at Earth from a supernova at a distance d is computed using the equation.

$$\begin{pmatrix} F_e \\ F_\mu \\ F_\tau \end{pmatrix} = \frac{1}{4\pi d^2} \begin{pmatrix} p_{ee} & p_{e\mu} & p_{e\tau} \\ p_{\mu e} & p_{\mu\mu} & p_{\mu\tau} \\ p_{\tau e} & p_{\tau\mu} & p_{\tau\tau} \end{pmatrix} \begin{pmatrix} \Phi_e \\ \Phi_\mu \\ \Phi_\tau \end{pmatrix}$$

* mostly

- SNEWPY has multiple prescriptions for the flavor transformation in the supernova.

For three flavors:

- No Oscillations and Complete Exchange
- Adiabatic MSW in both mass orderings
- Non-Adiabatic MSW H resonance in both mass orderings
- Two Flavor Decoherence in the H resonance mixing channel in both mass orderings.
- Three Flavor Decoherence
- *Numerical calculation of the matter effect for a given density profile*

For four flavors:

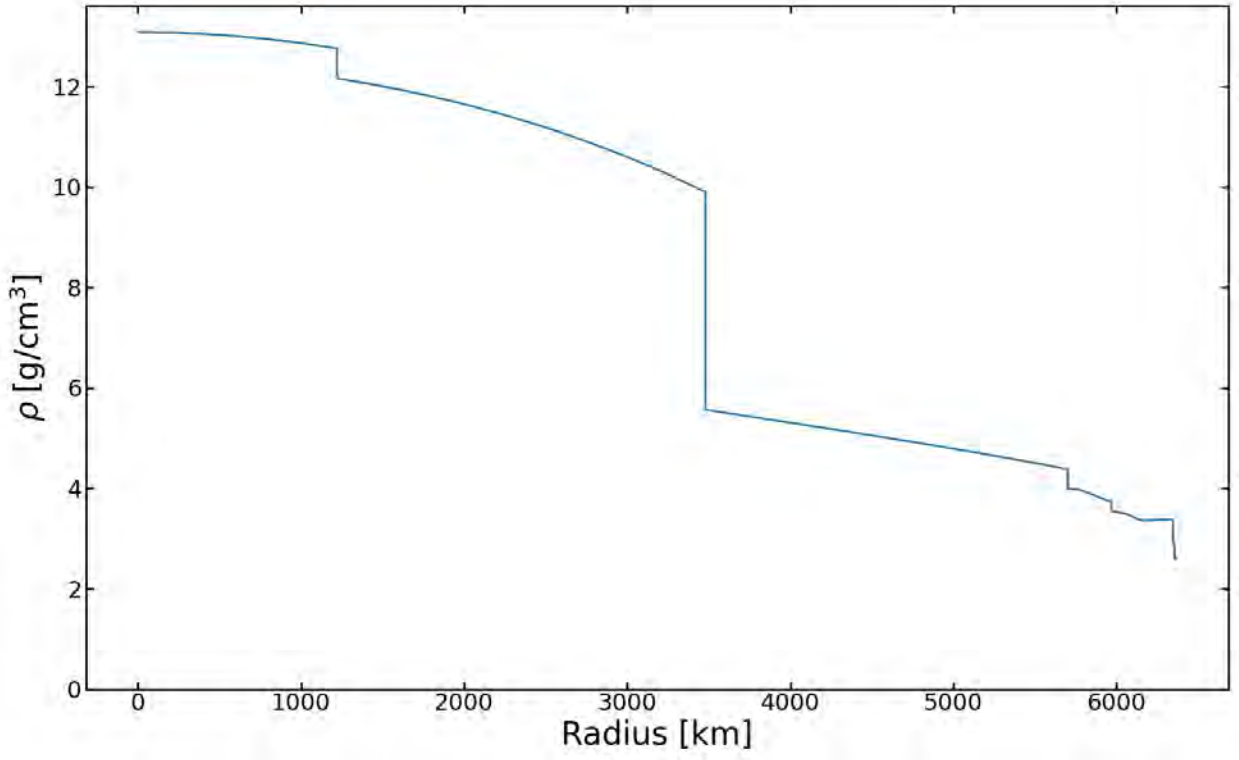
- Adiabatic MSW of four flavors in both mass orderings
- A four-flavor MSW where the ‘outer’ es resonance is non adiabatic, for both mass orderings.

- `SNEWPY 2.0` will introduce ‘modifiers’ that allow for additional flavor transformation in the vacuum and Earth-Matter.
  - We have worked with the astropy developers to help with the Earth-Matter calculations.

- The SN flavor prescriptions and modifiers can be chained together.

BEMEWS

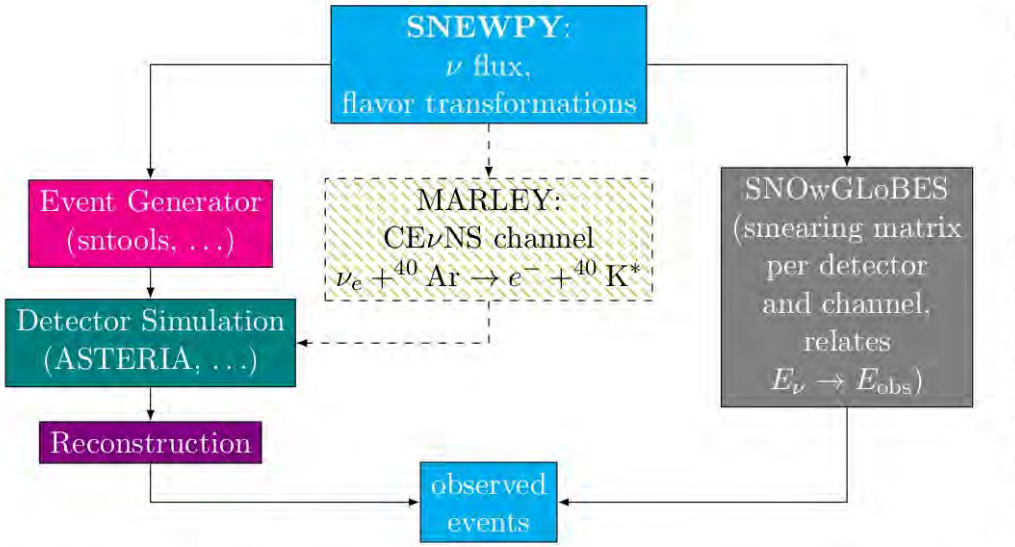
- BEMEWS is a python module for calculating the Earth-Matter Effect upon neutrinos.
- The module numerically solves the Schrodinger equation for a given neutrino trajectory through the Earth.
  - BEMEWS uses the PREM but this can be swapped for something else.



- The calculation is 3 flavor, does neutrinos and antineutrinos simultaneously, and can be done for multiple energies.
- It takes `BEMEWS` $\mathcal{O}$(10 ms) to do the calculation per neutrino on a regular workstation / laptop.
- `BEMEWS` can be run standalone or with `SNEWPY`.

```
from astropy.time import Time
from astropy.coordinates import SkyCoord, EarthLocation, AltAz

from snewpy.flavor_transformation import *
from snewpy.neutrino import *

#- skycoordinates of neutrino source
Betelgeuse = SkyCoord.from_name('Betelgeuse')

#- neutrino detector
SuperK = EarthLocation.of_site('SuperK')
UTcoffset = +9*u.hour

#- when the supernova occured
time = Time('2021-5-26 23:14:00') - UTcoffset

#- altaz of supernovae at detector
sn_altaz = Betelgeuse.transform_to(AltAz(obstime=time, location=SuperK))

#- set up flavor mixing, assuming the NMH
mix_params = MixingParameters(MassHierarchy.NORMAL)

SupernovaTransition = AdiabaticMSW(mix_params)
EarthMatterTransition = EarthMatter(sn_altaz , mix_params)

transformation = Catenate(SupernovaTransition,
                          VacuumTransition,
                          AtEarthTransformation=EarthMatterTransition)
```

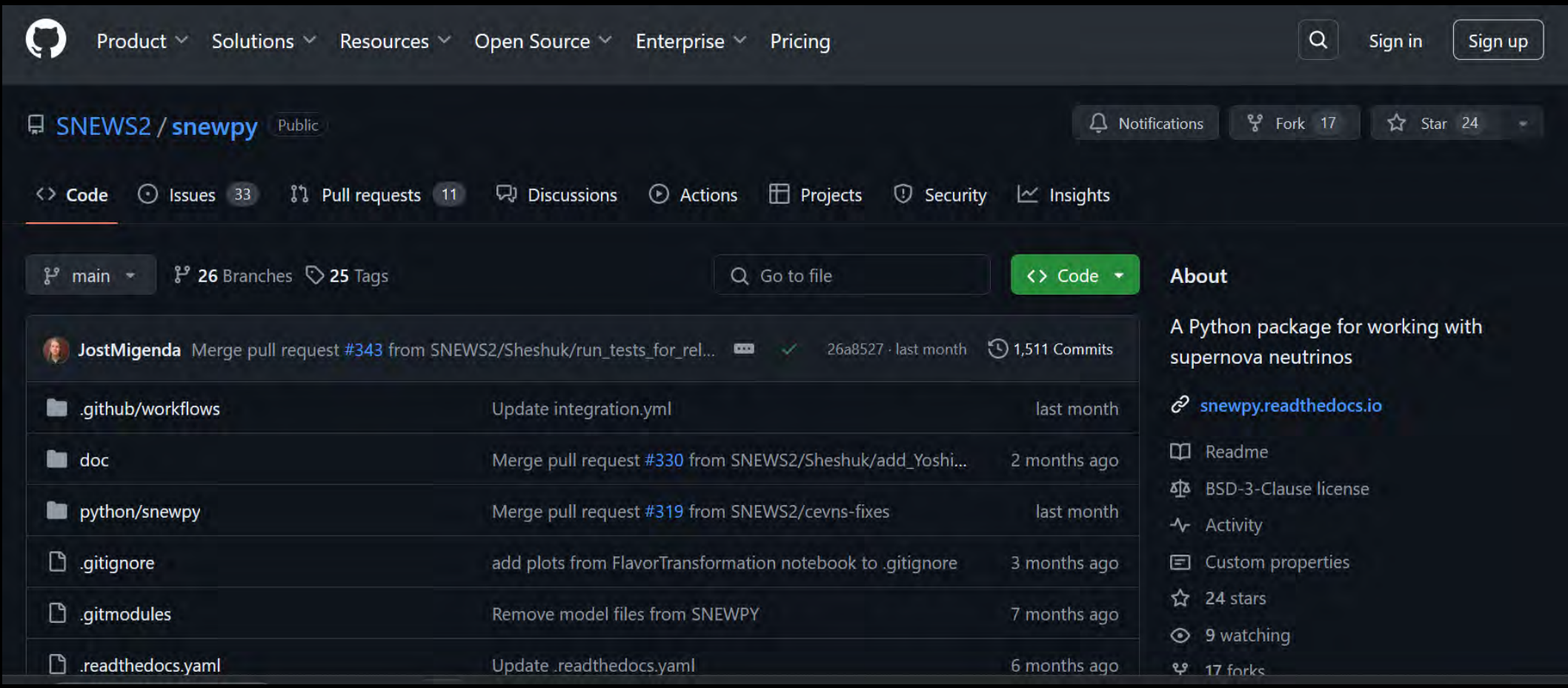
The interface with other codes



- SNEWPY 2.0 no longer requires the user to *install* SNOwGLoBES
  - installing SNOwGLoBES was a common user problem with SNEWPY because SNOwGLoBES required installing a lot of other software.
- Instead, SNEWPY 2.0 uses the SNOwGLoBES data files and does the calculation itself.
  - this means we also avoid writing / reading a lot of files to / from disk so it's much faster.

- Example script

SNEWPY can be downloaded from GitHub



Summary

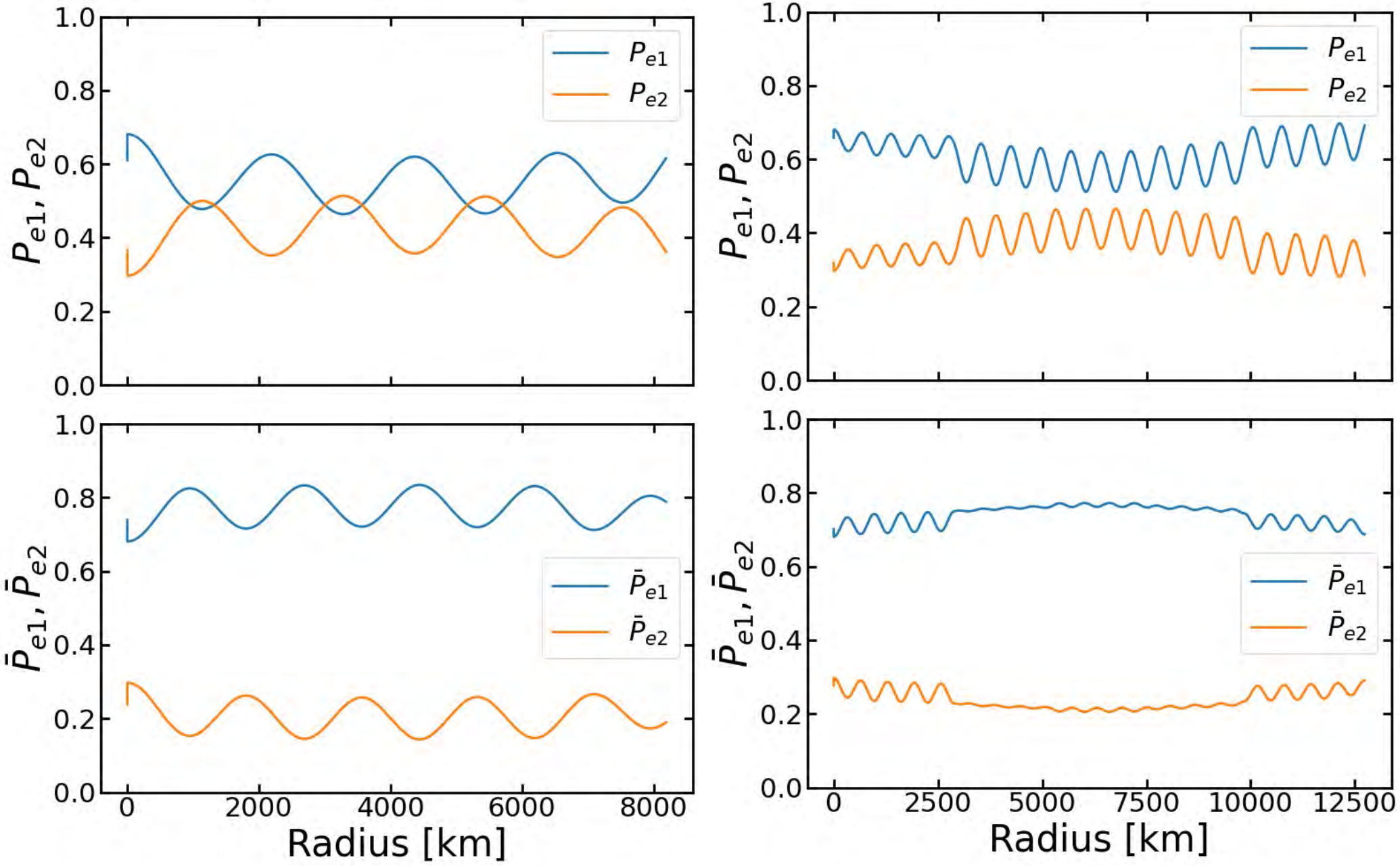
- SNEWS 2.0 is the new plan for what to do when the next nearby supernova occurs.
- The new system is up and running, now the goal is to optimize the system to identify the progenitor.

- SNEWPY is a bridge between supernova simulations and detector signals.
- Version 2.0 is being finalized and will be released soon.
- Please send us your suggestions for new features.

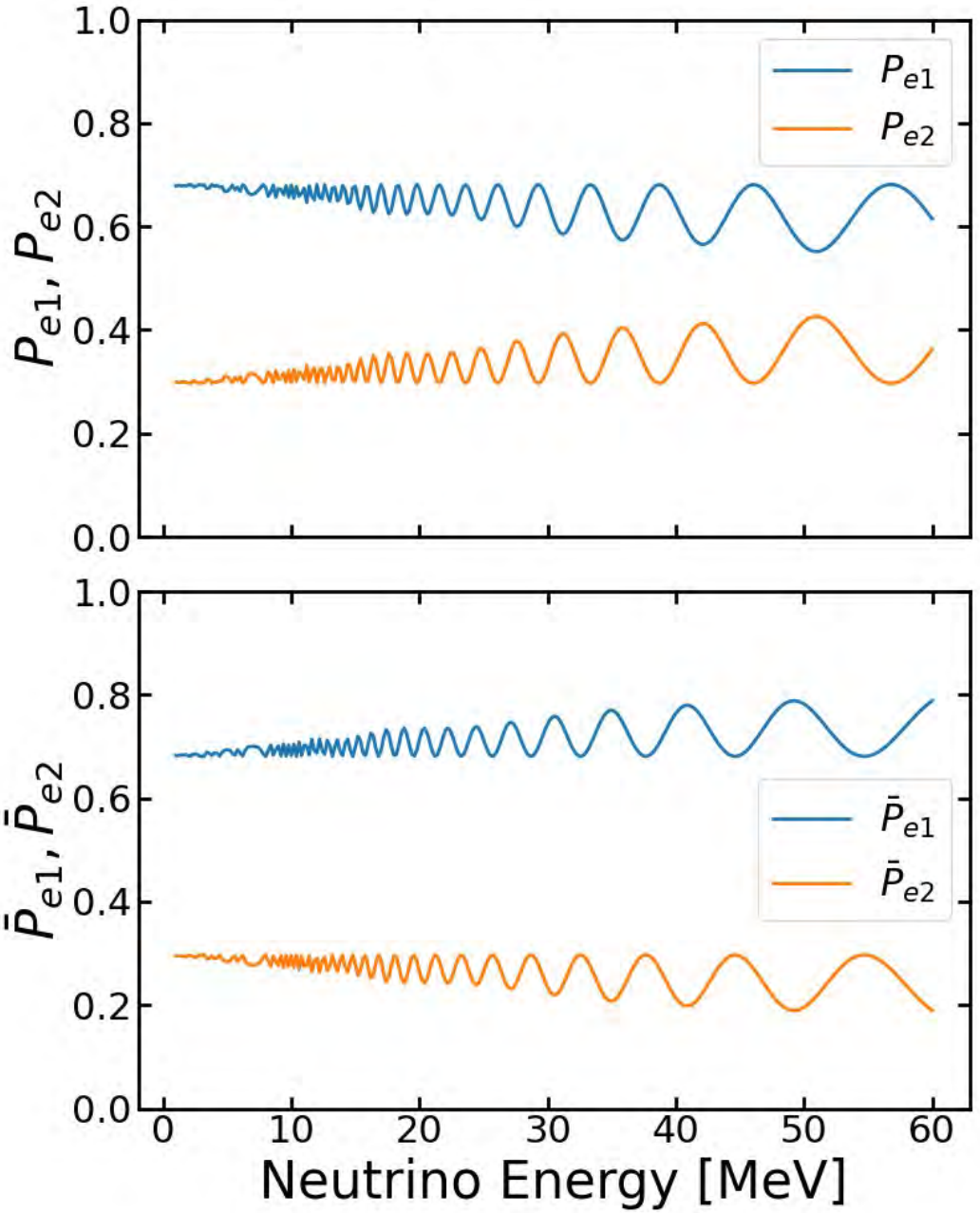
Altitude = -40º

E = 20 MeV

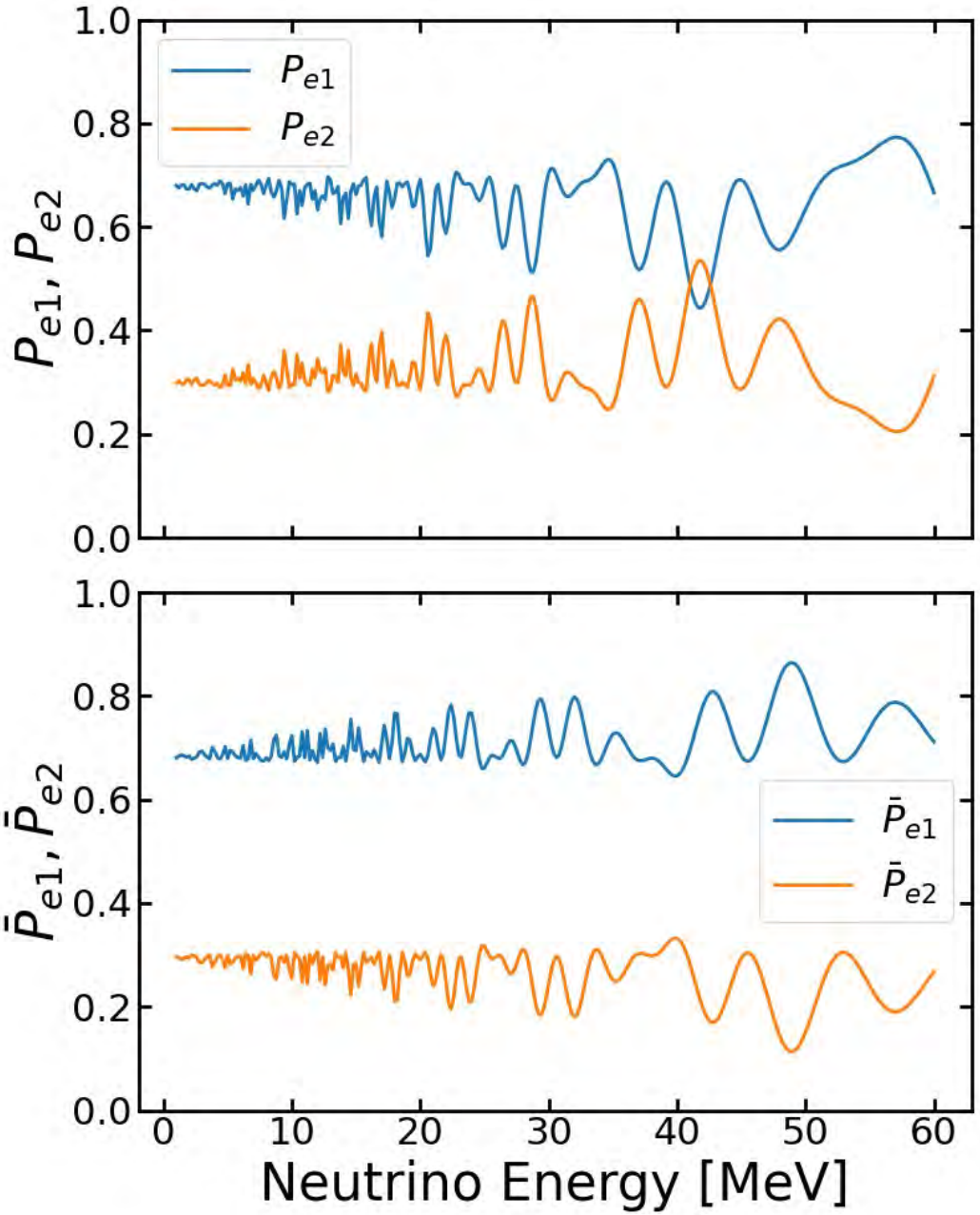
Altitude = -90º



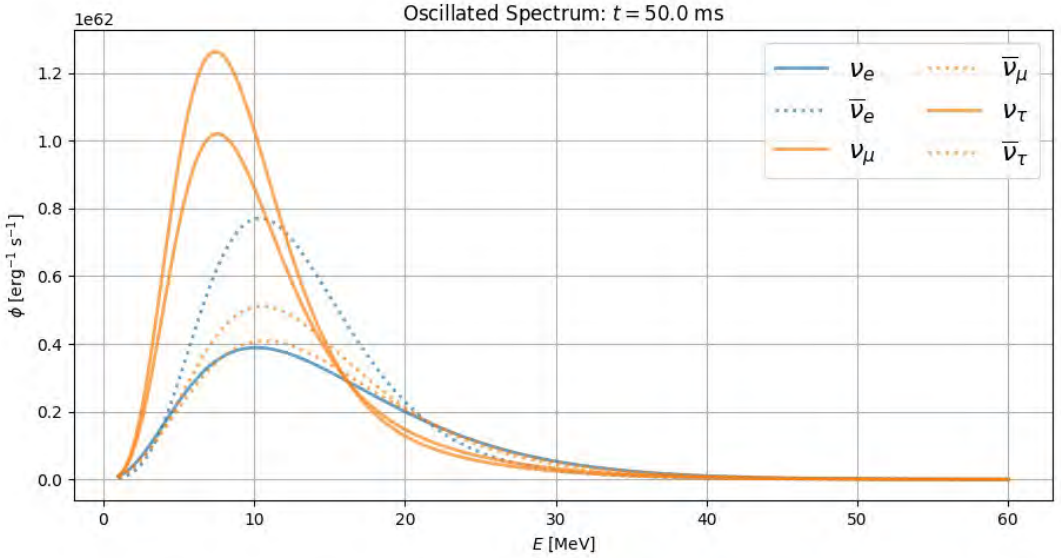
Altitude = -40º

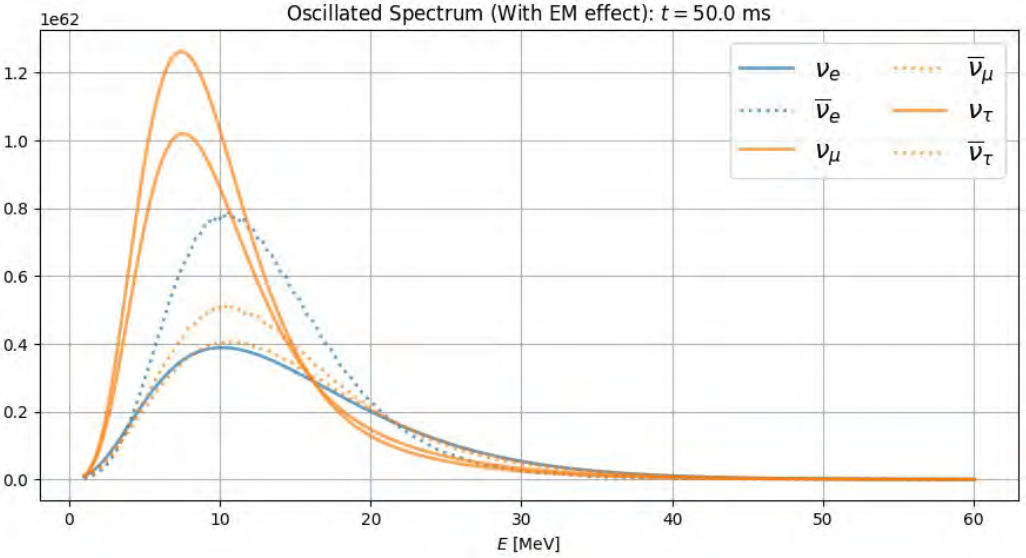


Altitude = -90º

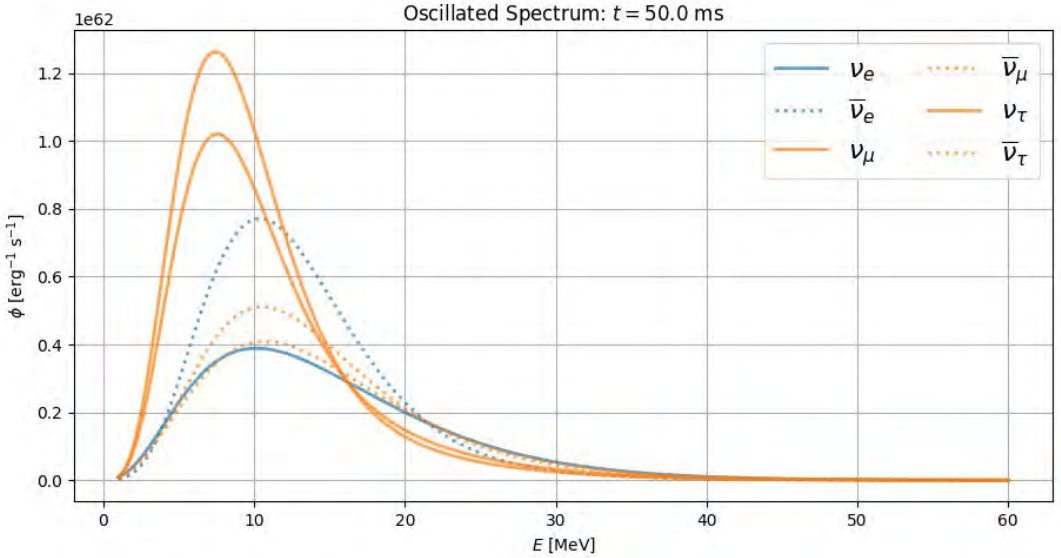


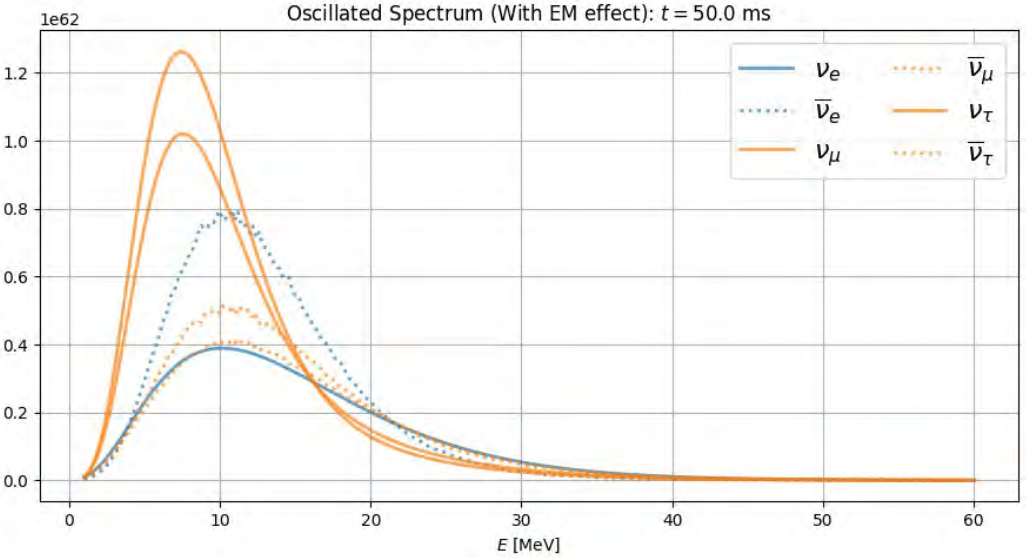
Adiabatic MSW, NMO, Altitude = -40º



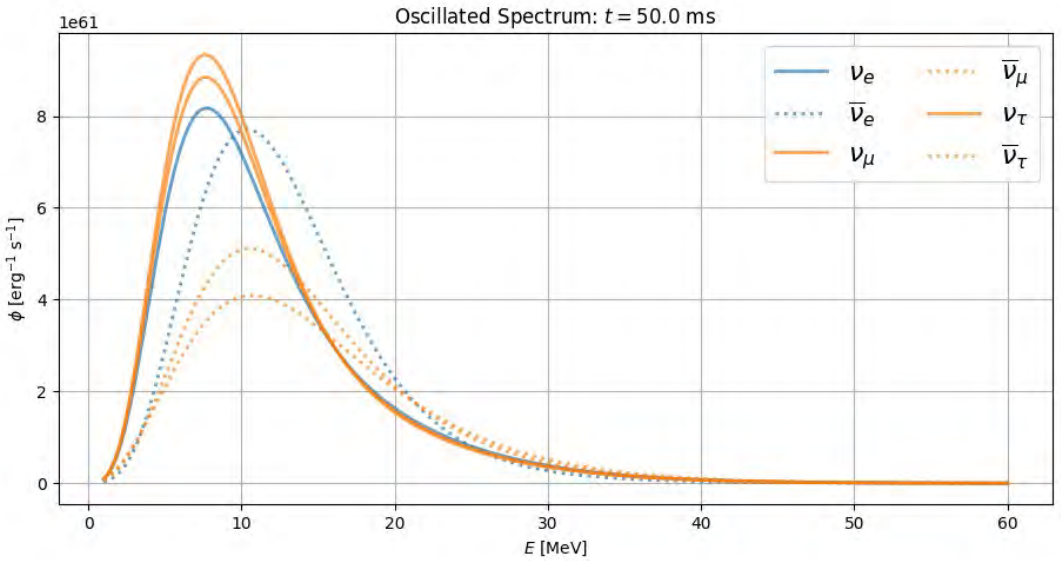


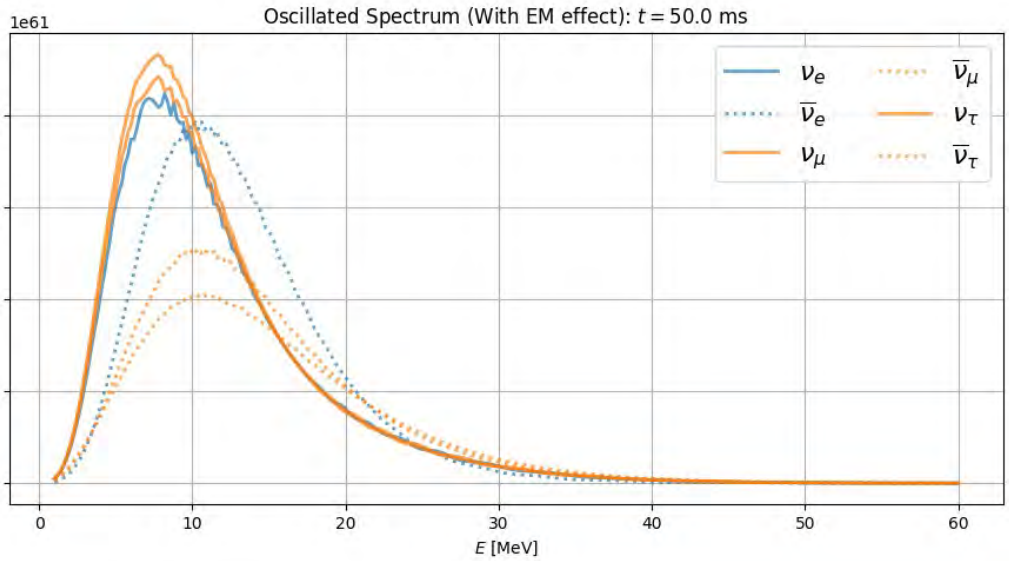
Adiabatic MSW, NMO Altitude = -90º





Non-Adiabatic MSW H resonance, NMO, Altitude = -40º





Non-Adiabatic MSW H resonance, NMO, Altitude = -90º