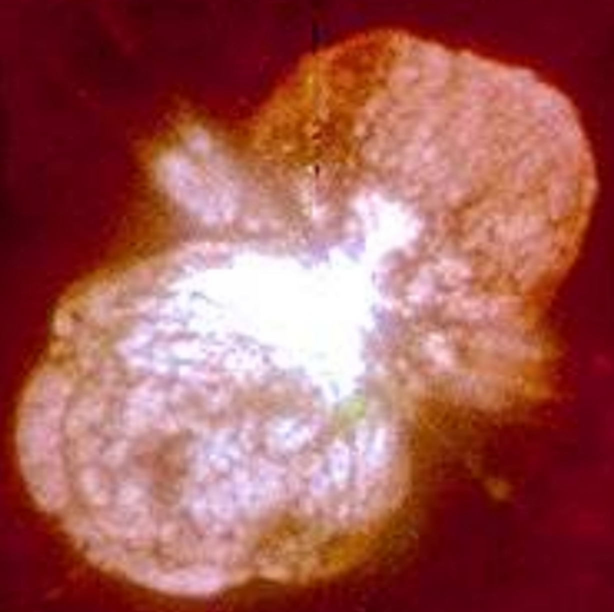
The Neutrino Signal From Pair Instability Supernovae



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Pair Instability Supernovae

- 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)

- There has been a revival of interest in PISNe in recent years.

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

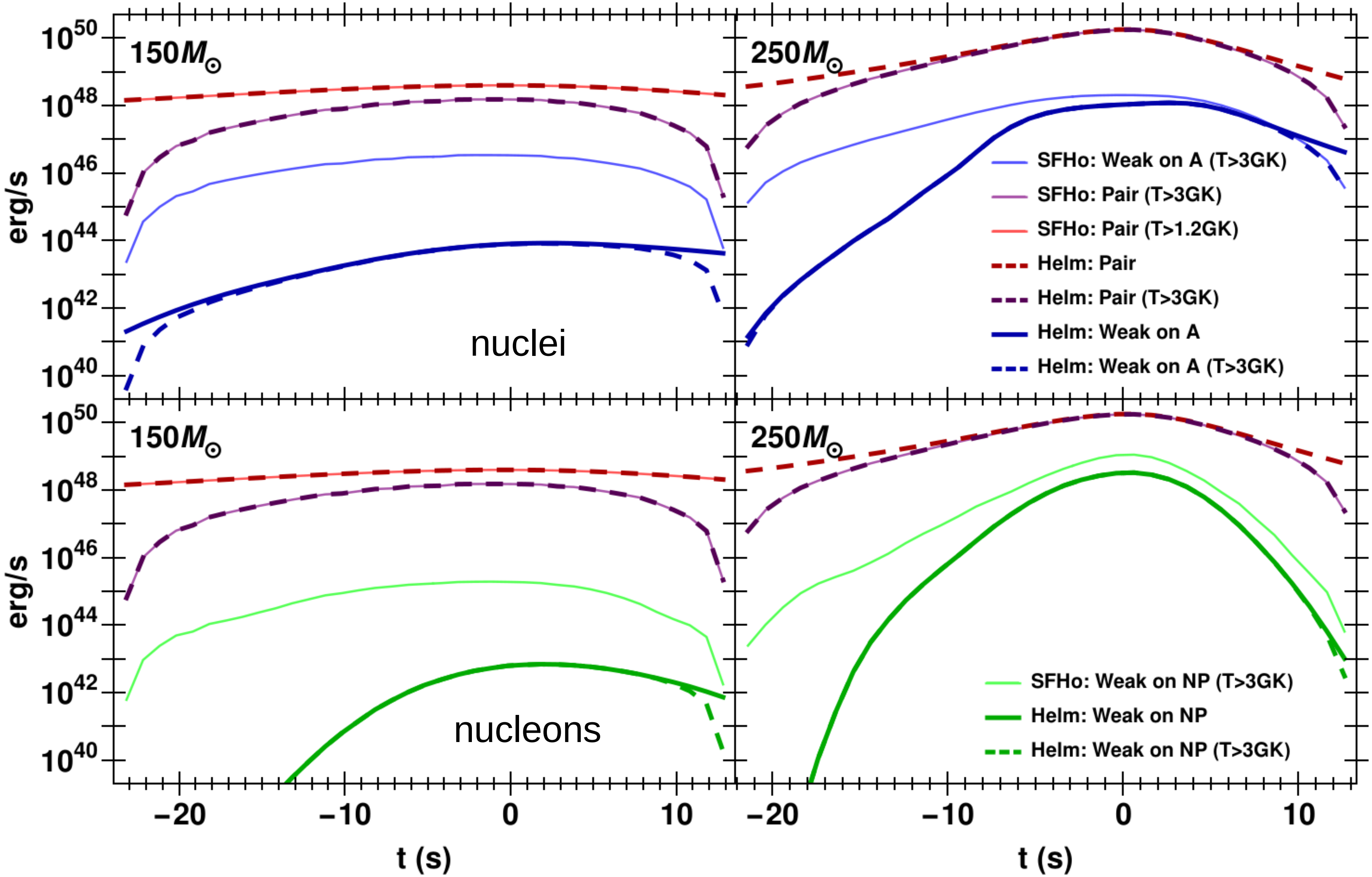
Langer et al, A&A 475 **L19** (2007)

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

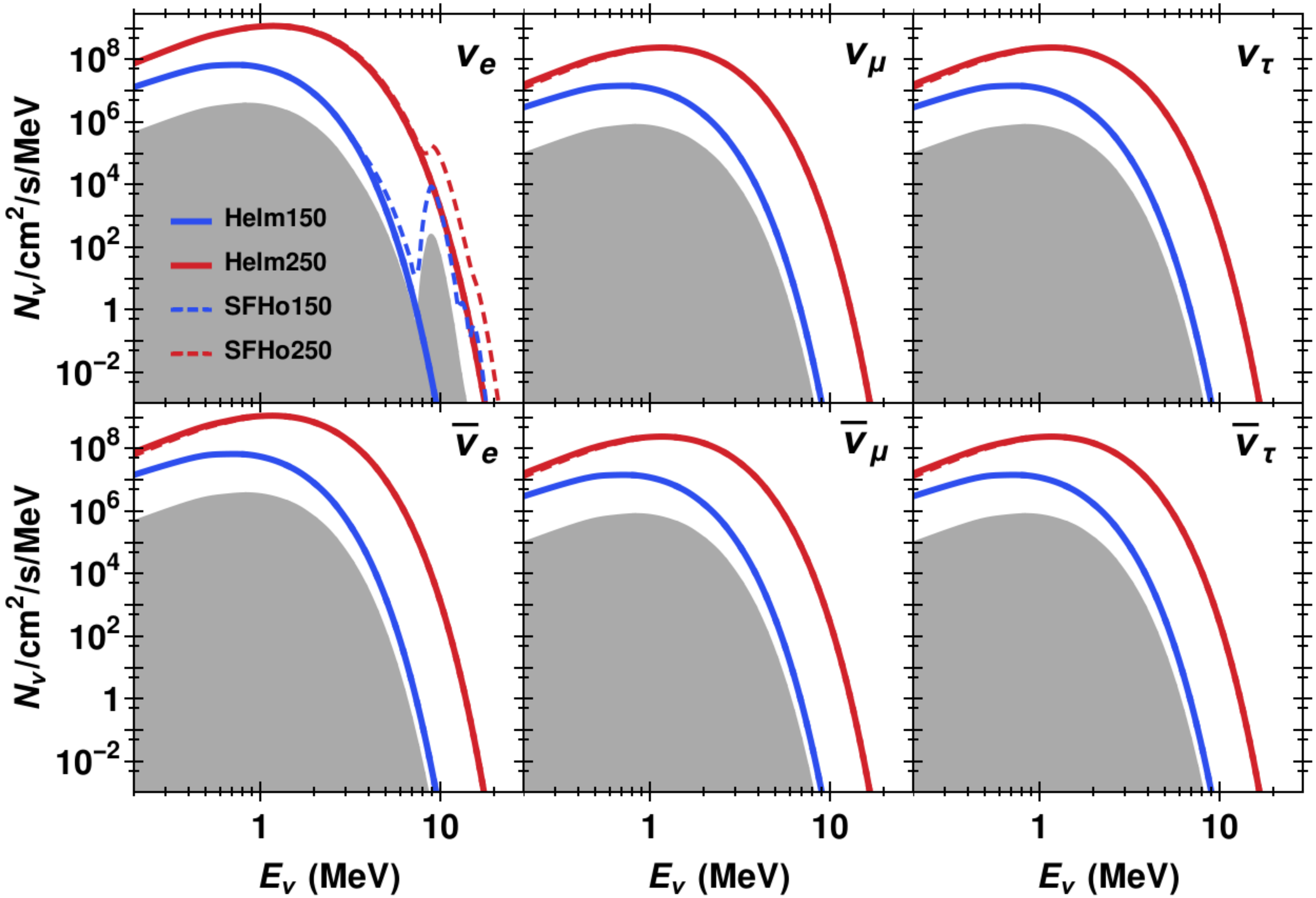
- PISNe can occur at non-zero metallicities i.e. the nearby Universe.
- PISNe are an explanation for some superluminous supernovae.
  - Less energetic PISN may be hidden among other classes.

The neutrino signal from PISNe

- The neutrino signal from PISNe differs from other supernovae.
- 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 $M_\odot$
- The explosion is followed using FLASH 4.3 with Aprox19 and the Helmholtz Equation of State (EOS).
  - see Gilmer *et al*. ApJ **846** 100 (2017) for more details
- We then post-process the simulations using NuLib to compute the neutrino luminosity and spectra.
- The emission due to thermal processes is straight forward.
- For the weak emission we adopt two approaches:
  - use the composition of the isotopes in Aprox19 and the Helmholtz EOS
  - identify those zones with T > 3 GK and use the SFHo EOS (which assumes Nuclear Statistical Equilibrium)

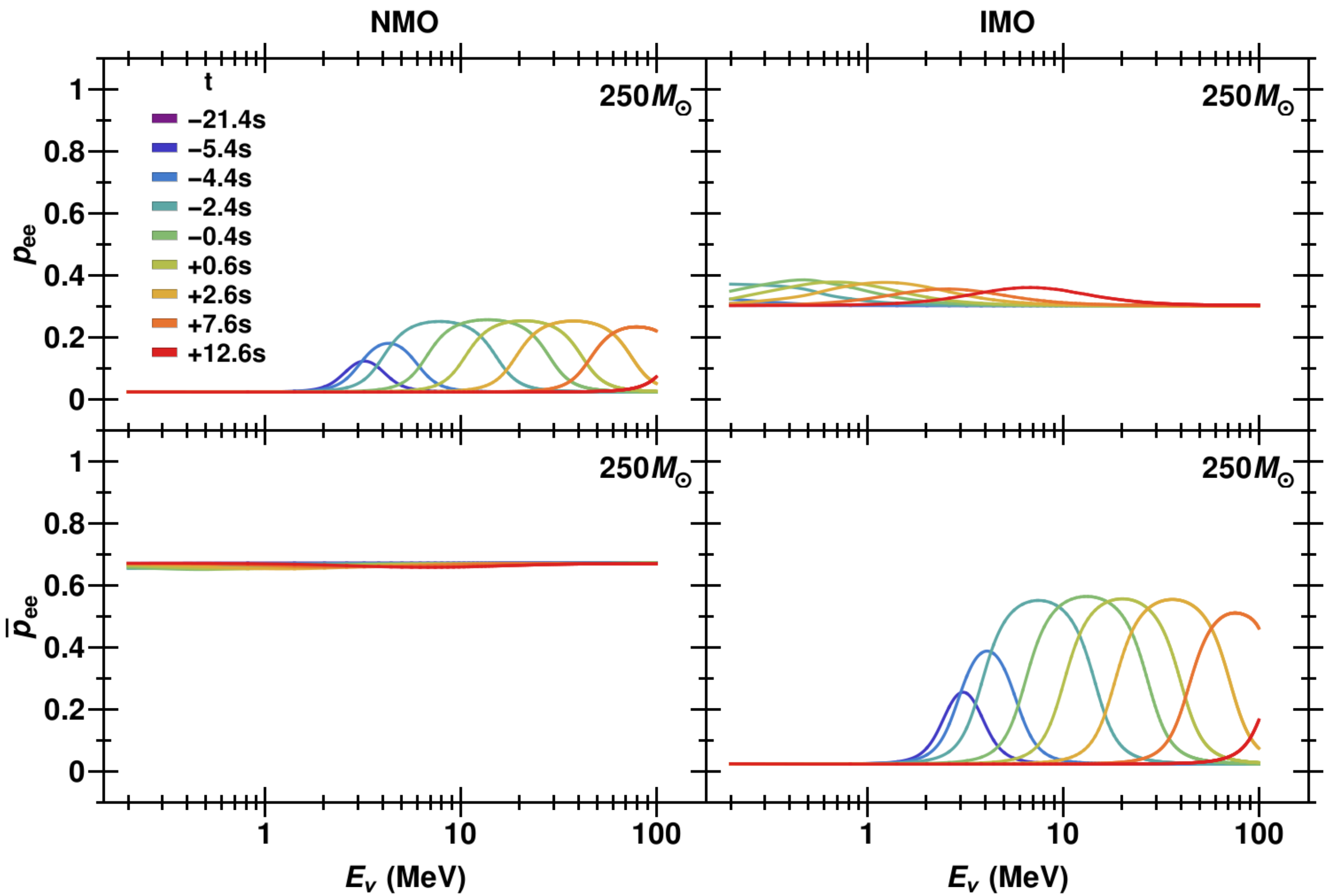


- Most of the emission is due to thermal processes.
- The SFHo EOS predicts much more neutrino emission due to weak processes than the Helmholtz EOS.

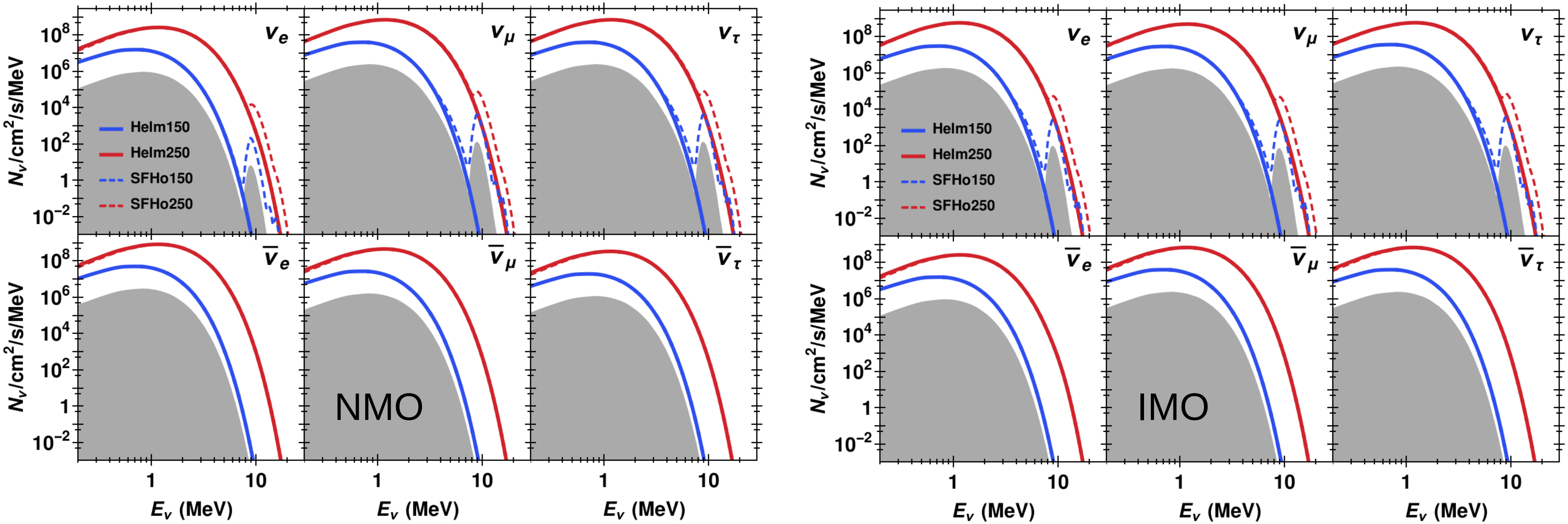


- The spectrum for P250 is 'hotter' than for P150
- There is a 'bump' in the spectrum at E ~ 10 MeV in ν_e using the SFHo EOS that is not present in the Helmholtz EOS.
  - the origin of the spectral feature is electron capture on ^{59}Cu.

- We compute the neutrino flavor evolution as a function of time and energy for both neutrino mass orderings: NMO and IMO
  - The shock affects the neutrinos in the P250 model.
  - The flavor evolution for the P150 model is very close to adiabatic.



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



- At Earth most of the electron type neutrinos and antineutrinos have converted to mu and tau flavors.
- The flux of electron antineutrinos is ~10 times larger for the NMO than the IMO.

The Signal At Earth

- The neutrino flux at Earth is run through SNOwGLoBES for a representative set of detectors.

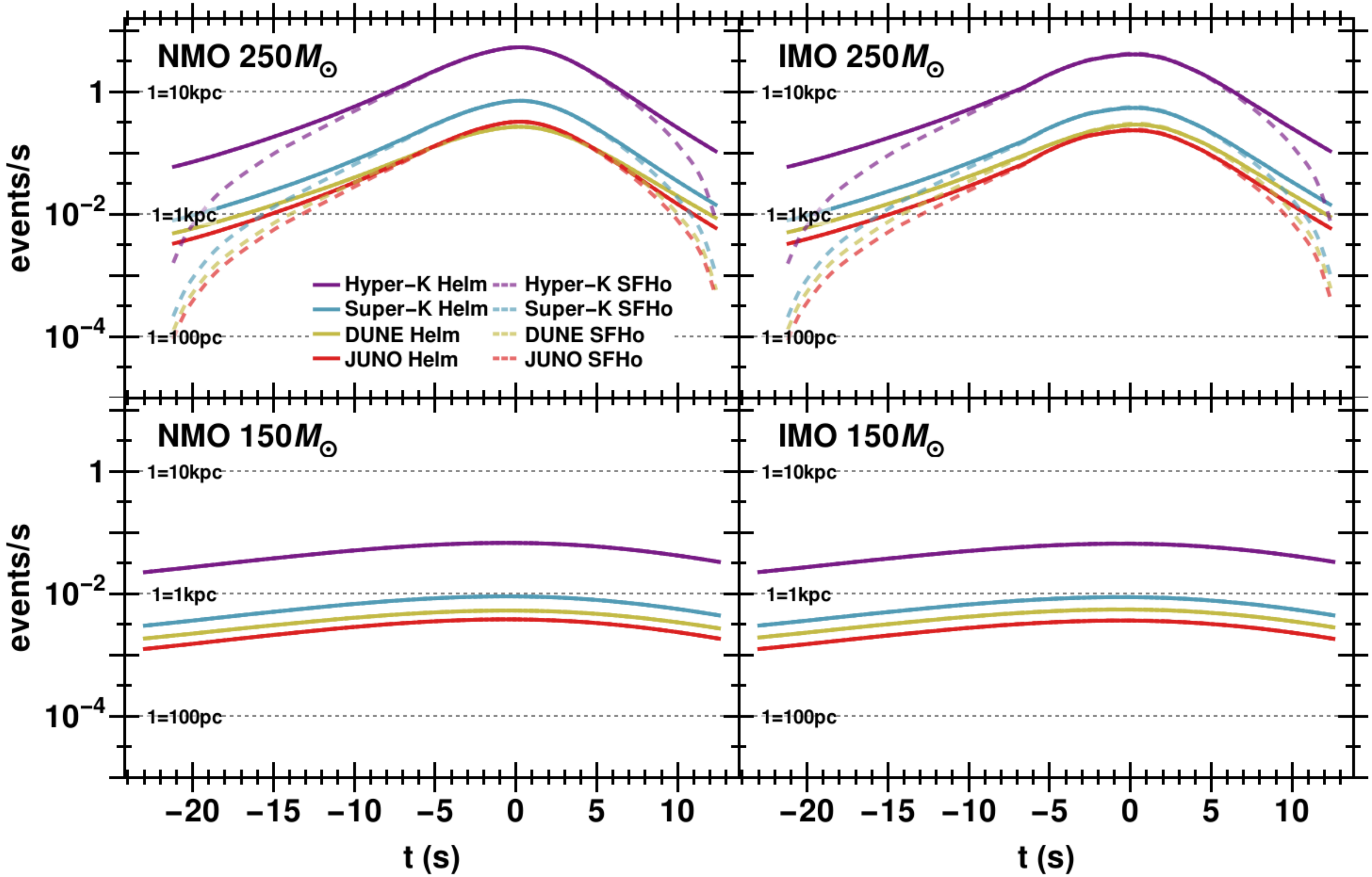
Detector	Type	Mass [kt]
SuperKamiokande (30% PMT coverage)	Water Cerenkov	50
HyperKamiokande	Water Cerenkov	374
DUNE	Liquid Argon	40
JUNO	Scintillator	20

- SuperK, HyperK and JUNO are mainly sensitive to electron antineutrinos; DUNE is mainly sensitive to electron neutrinos.
- The PISN is placed at the standard distance $d = 10$ kpc.

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 only detect neutrinos from P250.
- There is ~5% difference between the two EOS's for P250.
- There is a ~20% difference between the two mass orderings for P250 model.

- The number of events for P250 is ~10^2 larger than for a Type Ia and ~10^3 smaller than a core-collapse supernova (CCSN).
- The signal extends over ~10 s and peaks midway through.
  - the signal from Type Ia lasts (at most) 5 s
  - the signal from a CCSN lasts 10 s but decays exponentially.



Nearby Very Massive Stars

- 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 PISN

- There are many stars within the Milky Way and the Large Magellanic Cloud with masses above 100 $M_\odot$
- η Carinae at a distance of d = 2.3 kpc, has a ZAMS mass greater than 100 $M_\odot$

Kashi and Soker, ApJ **723** 602 (2010)

Clemental *et al.*, MNRAS **447** 2445 (2015)

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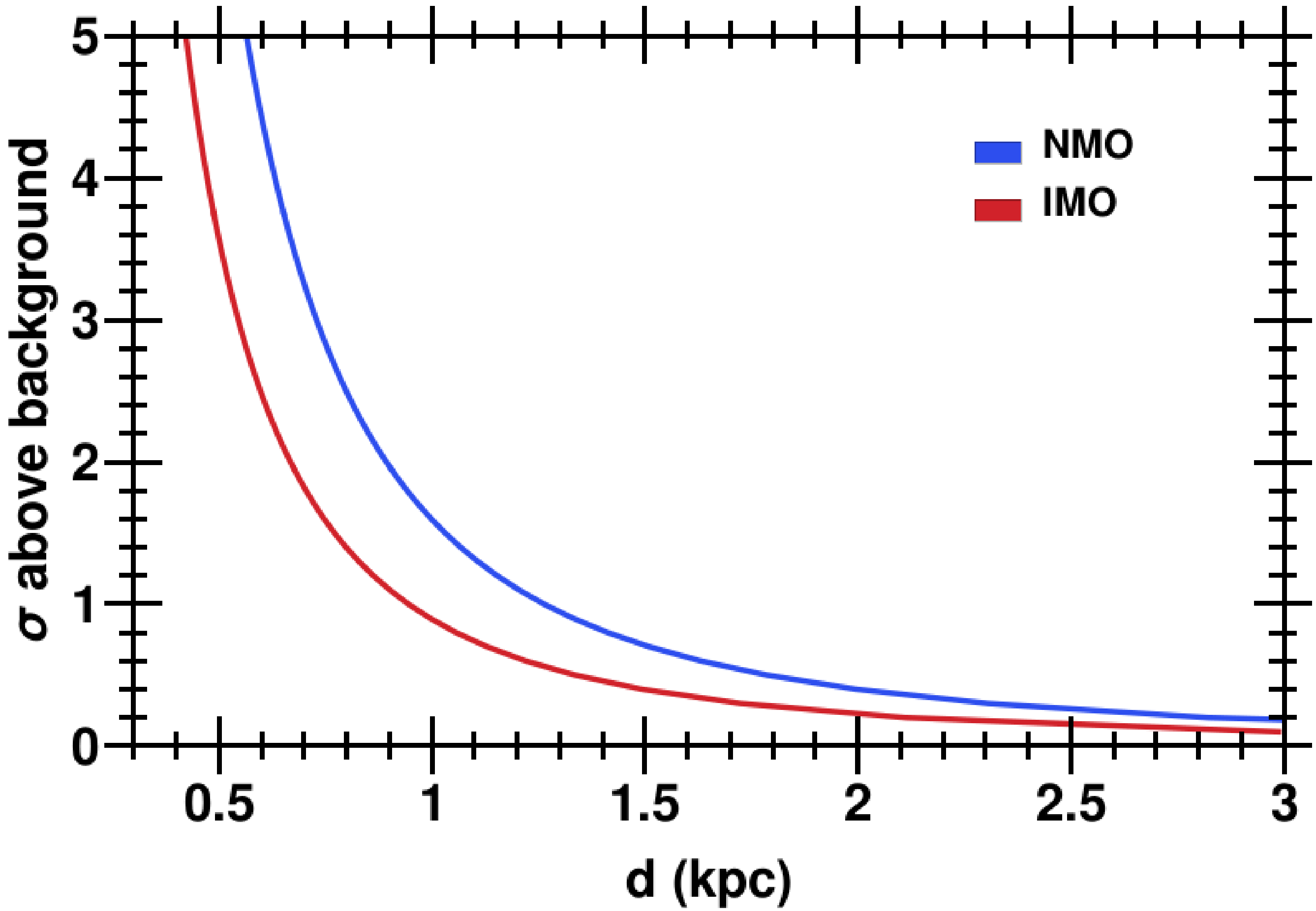
Summary

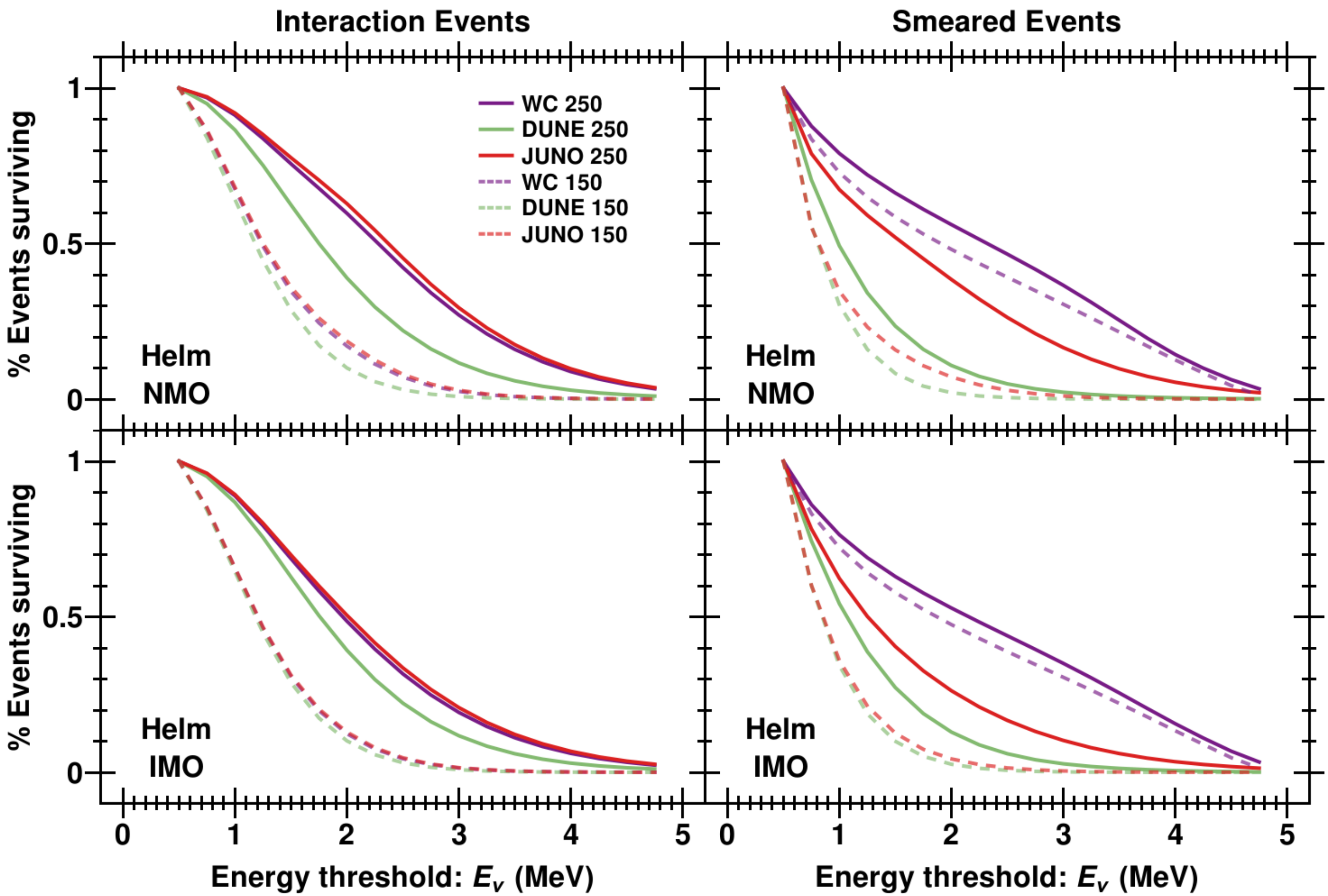
- The neutrino signal from a PISN is well understood and found to be very different from Type Ia and CCSN.
- The emission is dominated by thermal processes (pair annihilation), not weak processes.
  - There is little sensitivity to the composition and EOS.

- A PISN within the Milky Way can be seen 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.
- A large PISN has a 20% difference between neutrino mass orderings, a small PISN has almost none.

Thank you



- Using the neutrino emission from the P250 model, the PISN would have to be very close in order to observe a statistically significant signal in IceCube.



- As the detector thresholds increase we miss events.
  - A threshold is worse for the P150 than the P250 model because the P150 spectrum is cooler.