Prospects for detecting quark star features with IceCube

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UPPSALA UNIVERSITET

Supervisors: Erin O'Sullivan & Jakob Beise

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Introduction

➢ **Aim:** study the **capability** of IceCube to detect **sharp features** from the **hadron-quark phase transition** present in the formation of a **quark star**

But, what is a quark star?

→Compact object: remnant of a star that has burn all its nuclear fuel

→Composed by deconfined quark matter

***We can use neutrinos to identify the quark deconfinment!**

Phase transition driven Core-collapse SNe

In a nutshell

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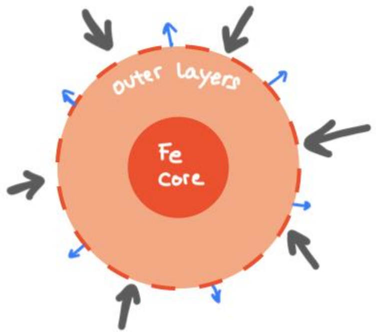
1. Massive star
No nuclear burning
gravity overcomes pressure



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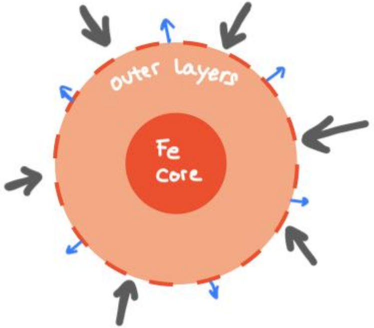

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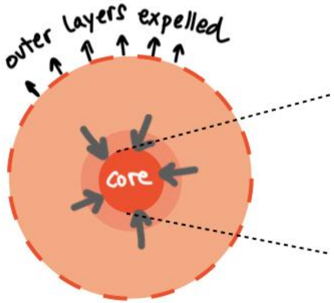

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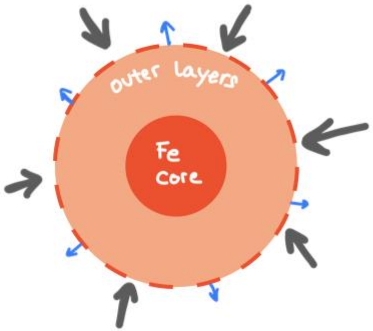

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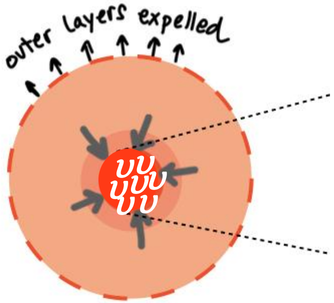

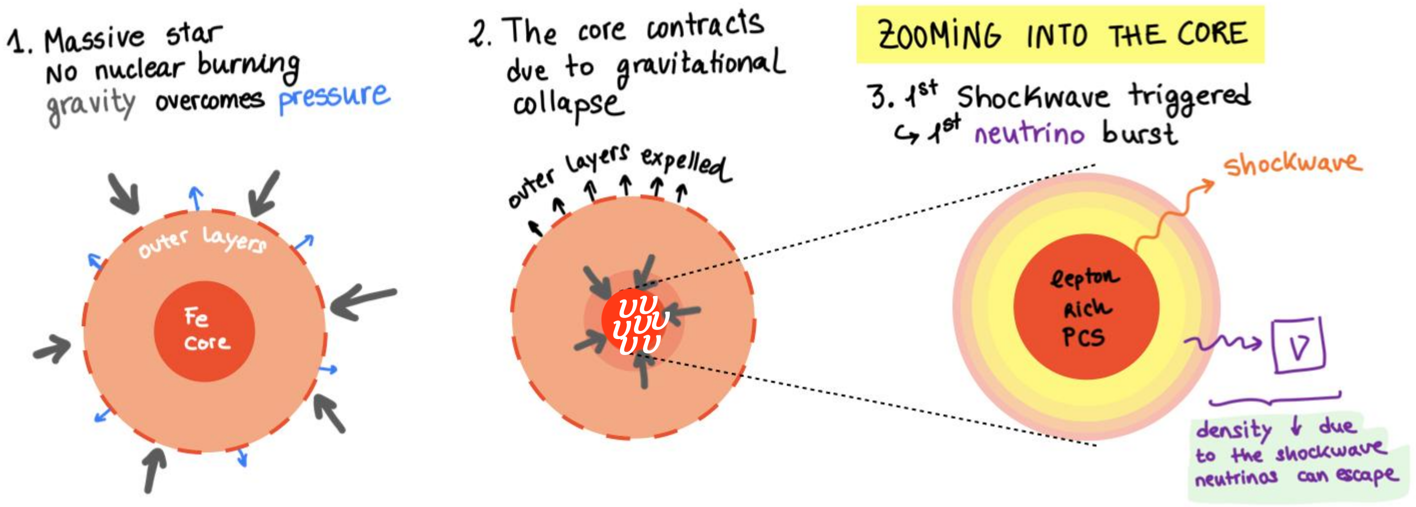
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3. 1st Shockwave triggered
↳ 1st neutrino burst
shockwave
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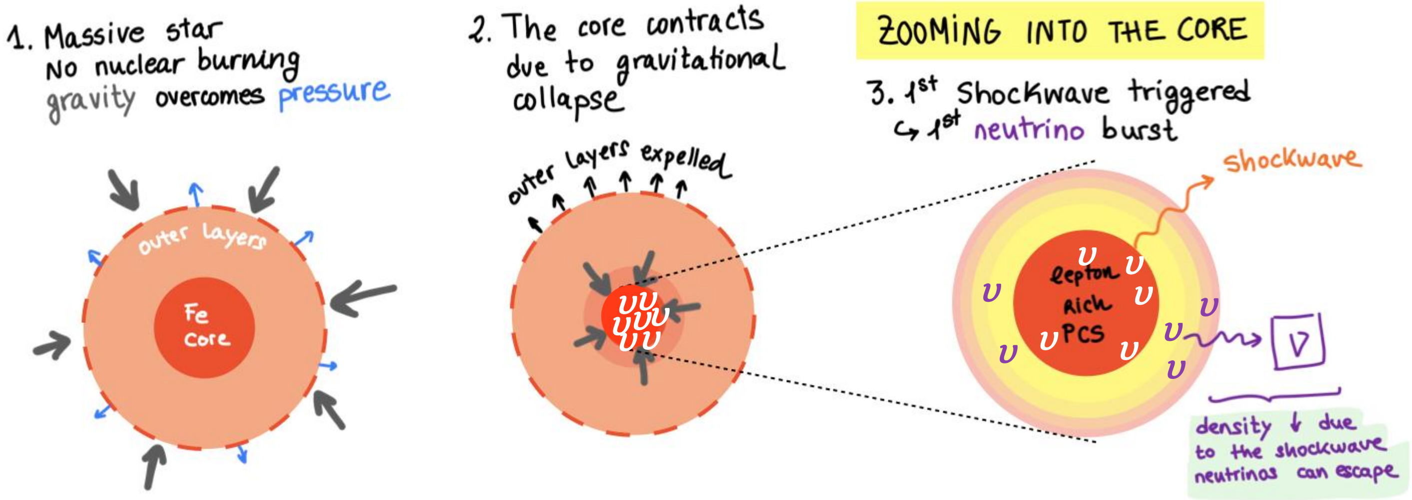
ν
density ↓ due to the shockwave neutrinos can escape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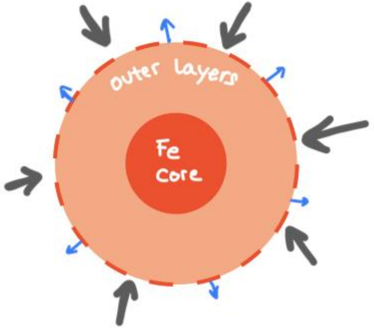

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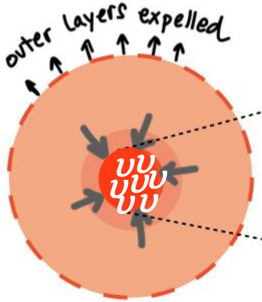

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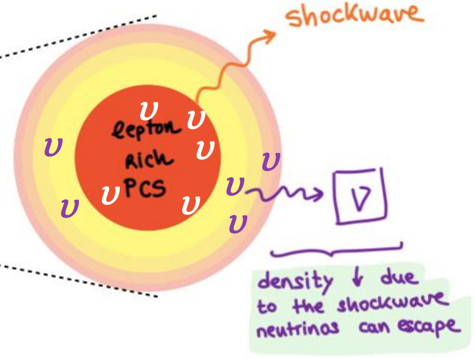
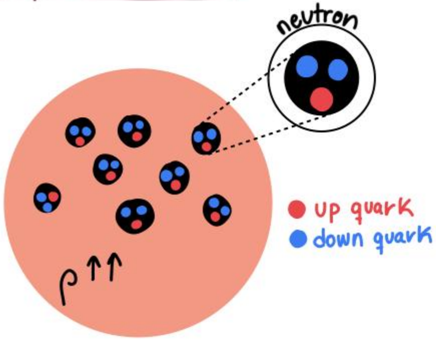


4. Proto neutron star
↳ high density can trigger
H-Q phase transition



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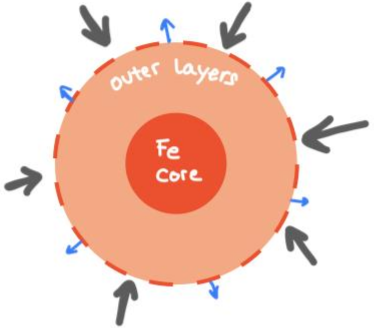

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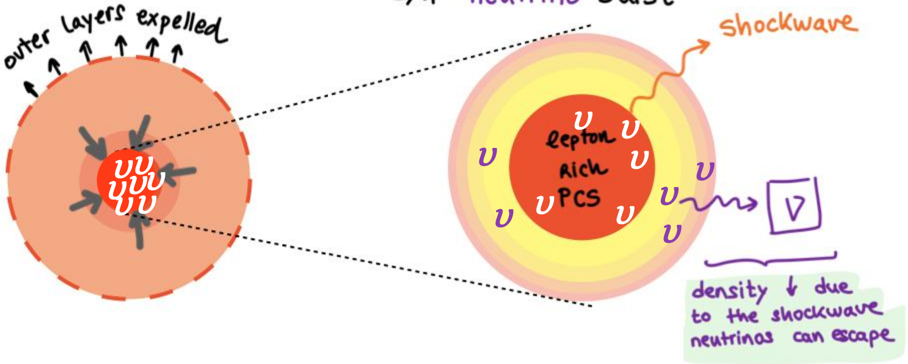

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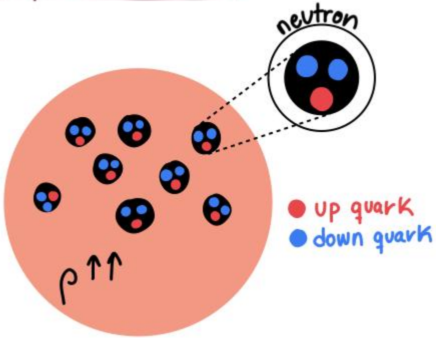

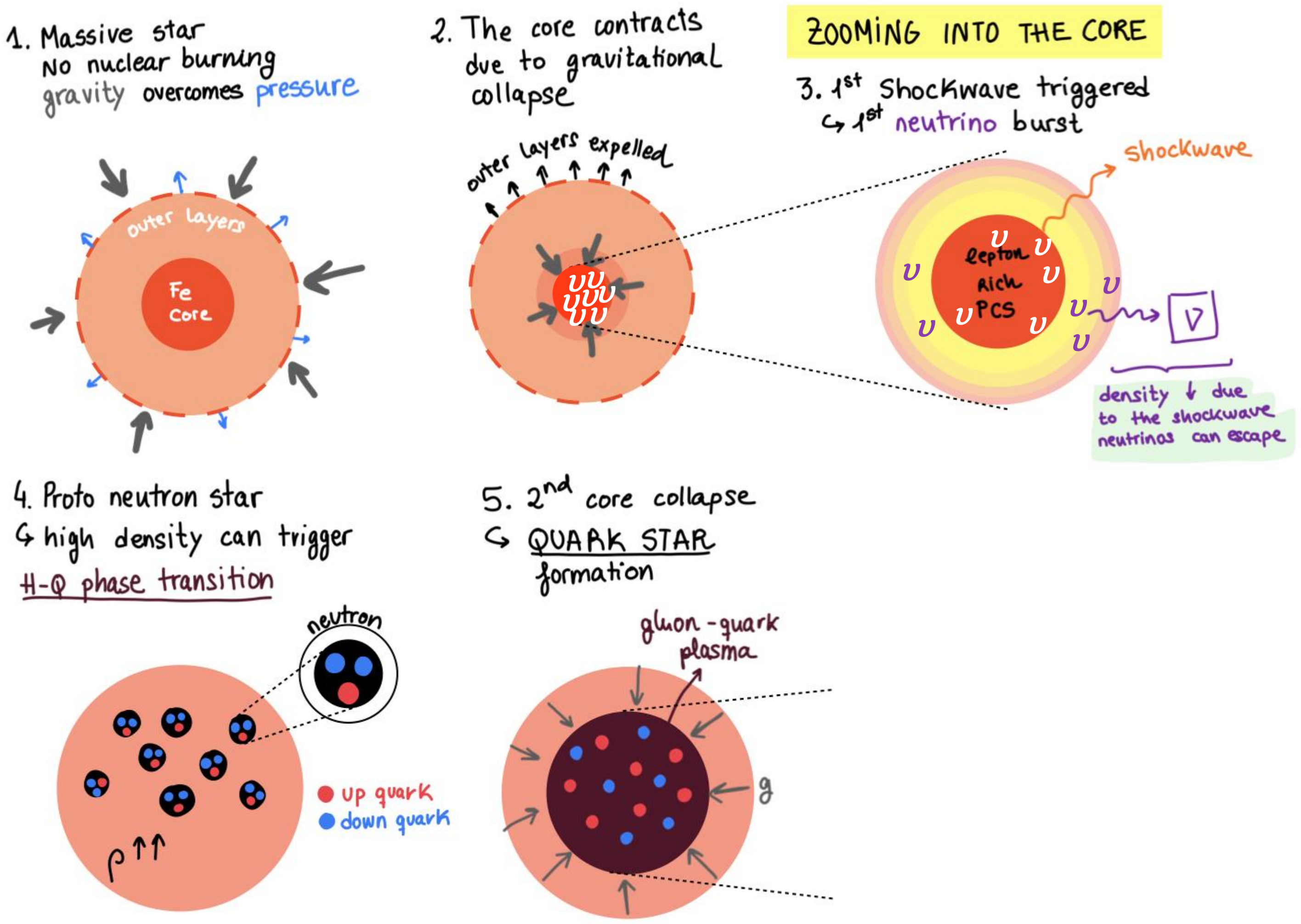

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↳ QUARK STAR
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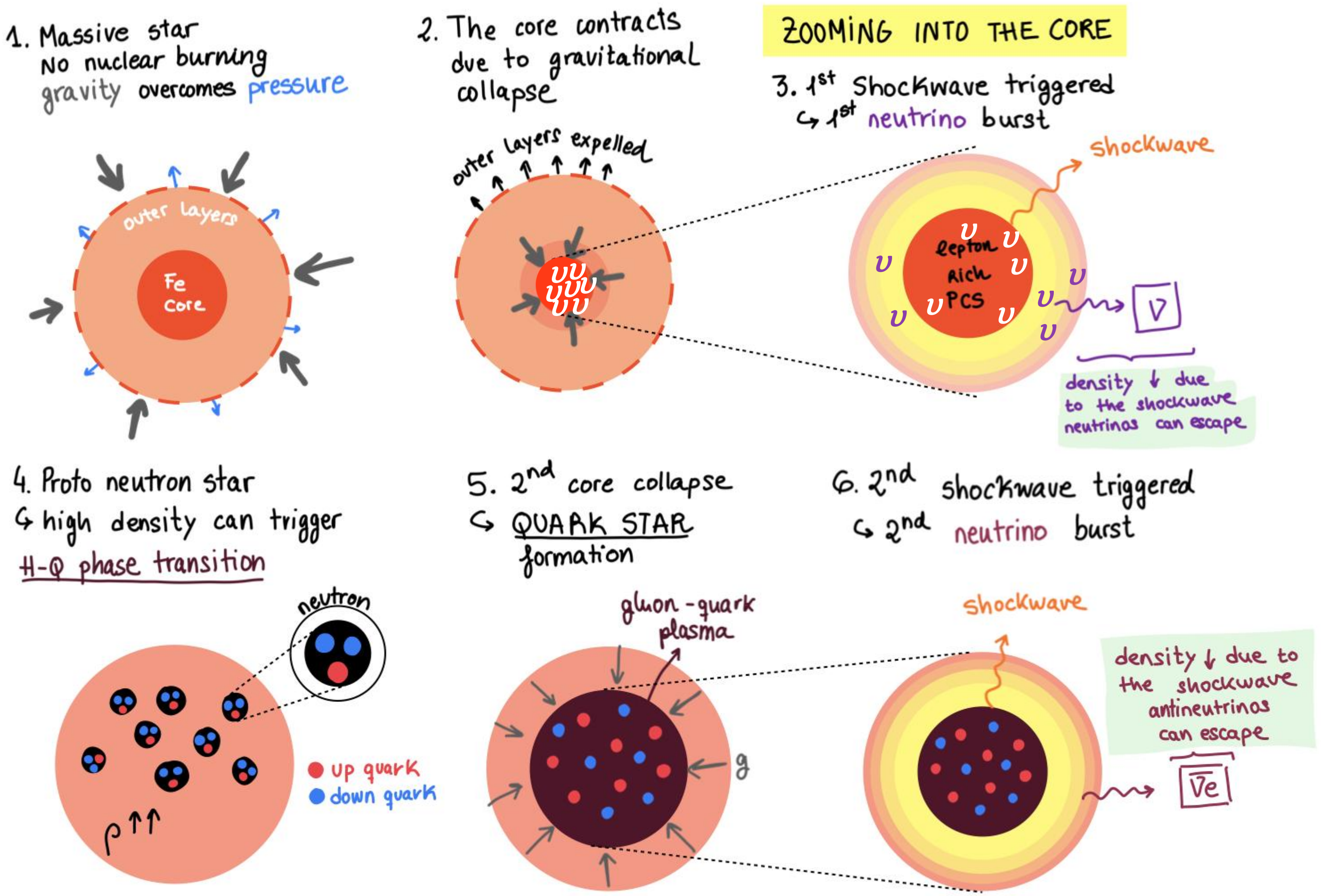
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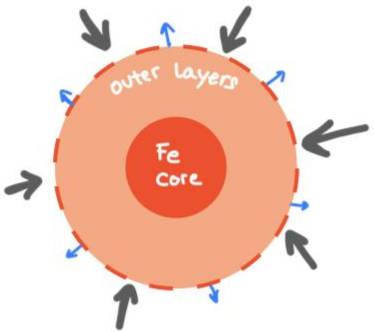

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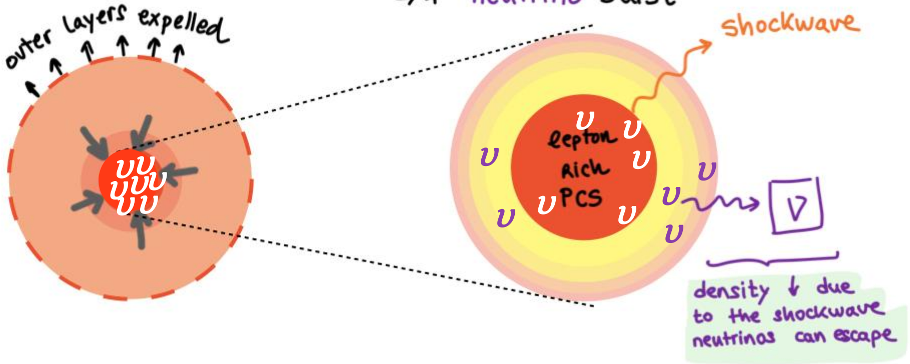

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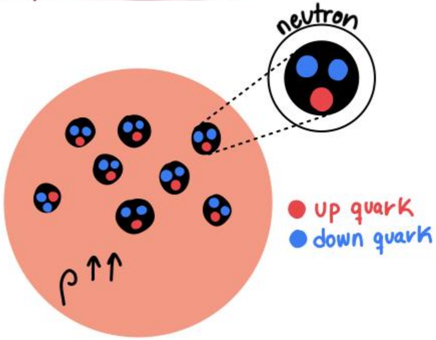

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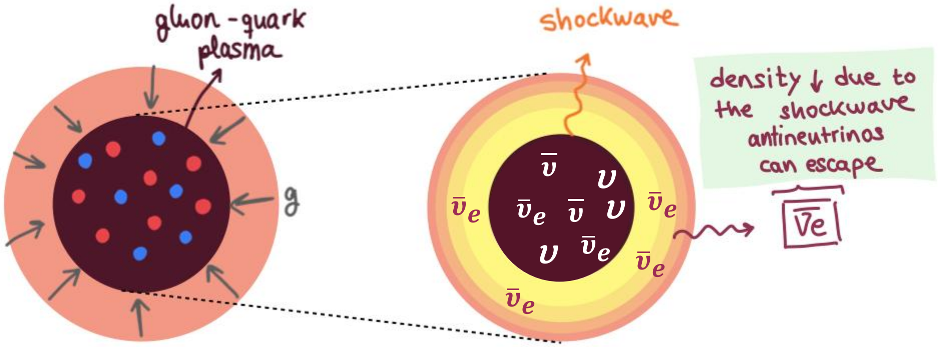
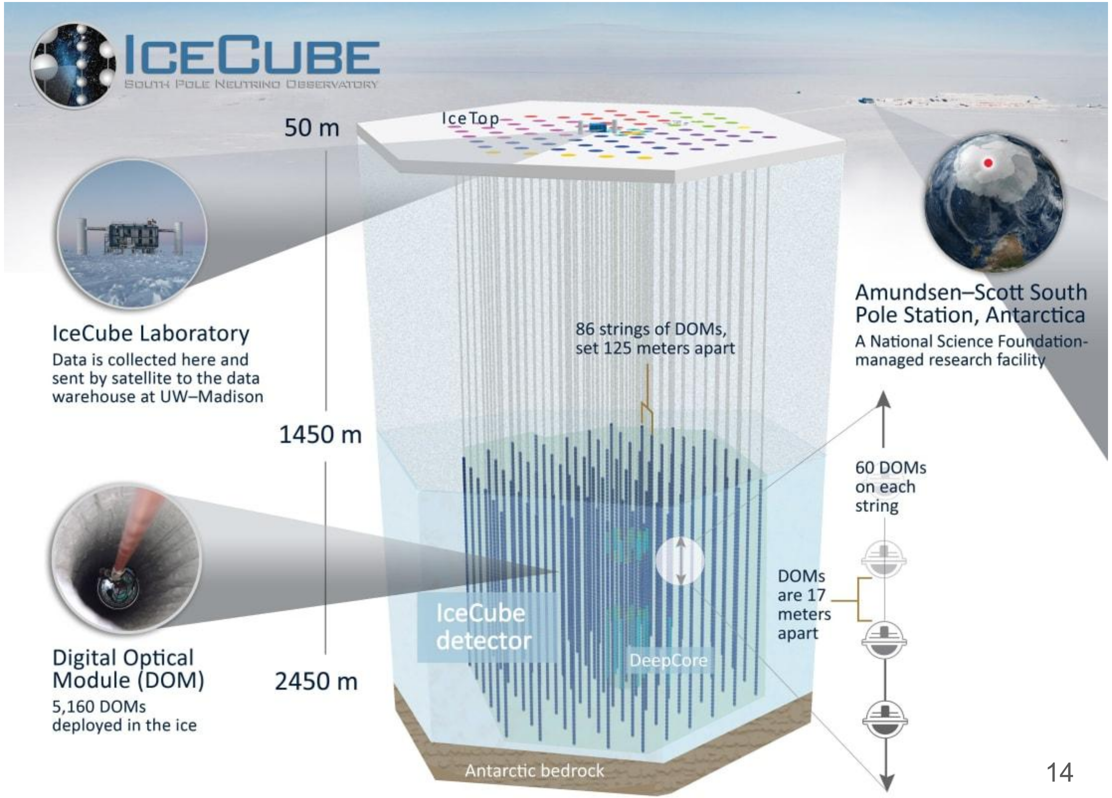


IceCube: neutrino detection

- IceCube: neutrino observatory in Antarctica
- 1km^3

➢ 5160 Digital Optical Modules (DOMs)

➢ Detection of the neutrino-induced **Cherenkov radiation**



Observable features

We would observe a second peak on the emission signal:
→from the second shock wave (PNS collapse due to phase-transition)

- Burst of electron antineutrinos: $\boxed{\overline{\nu}_e}$

➔ Detectable via inverse beta decay
➔ (10 MeV range)

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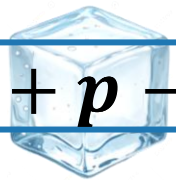

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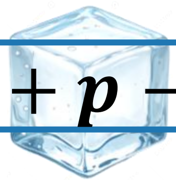

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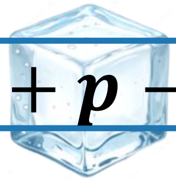

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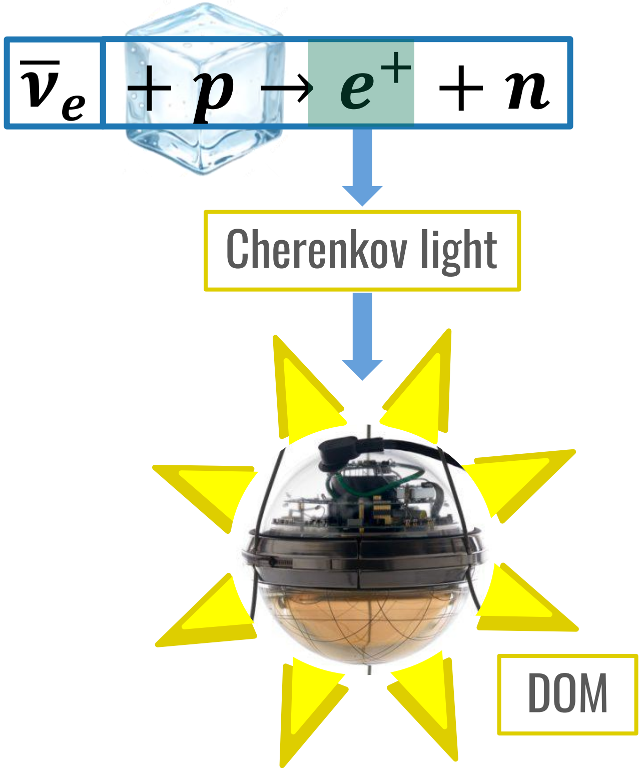

Simulation set up and results

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Simulation setup

- **GR1D:** simulate the CCSNe (flexible EoS module to include quark and hadron matter)

  DD2F (hadron) + RDF (quark)

- **ASTERIA:** simulate IceCube and IceCube Gen2 response to the $\overline{\upsilon}_e$ signal

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Geometry	Sensor	k	$\epsilon_\tau^{\max}$ [%]
IceCube	DOMs	4800	88.3
	HQE DOMs	360	84.6
Gen2	mDOMs	9760	95.8
Gen2+WLS	mDOMs*	9760	95.8

MODEL RDF-1.2 (s30a28)

Explosion model: quark star remnant

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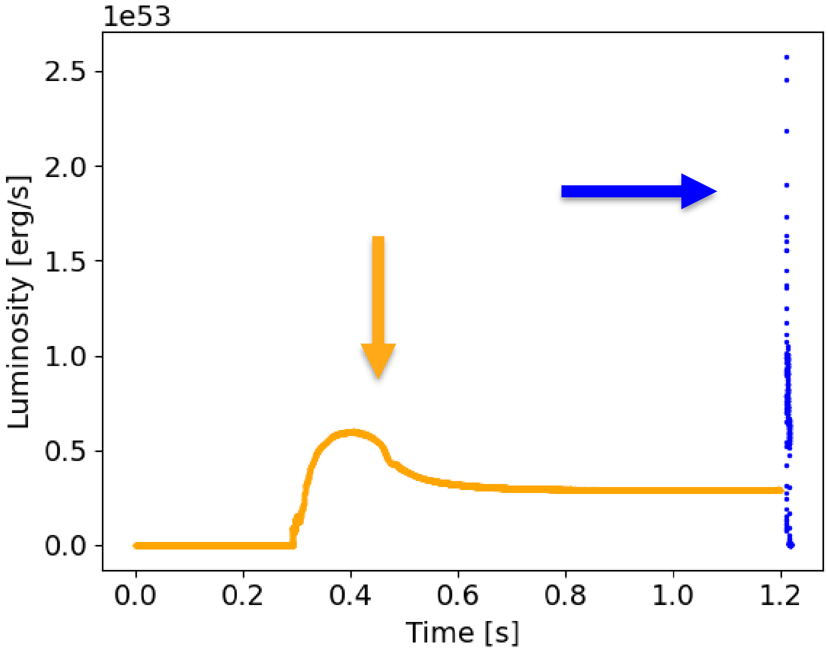
Simulations: quark star remnant

Neutrino emission in a phase transition driven supernovae

-First collapse emission

-Phase transition emission



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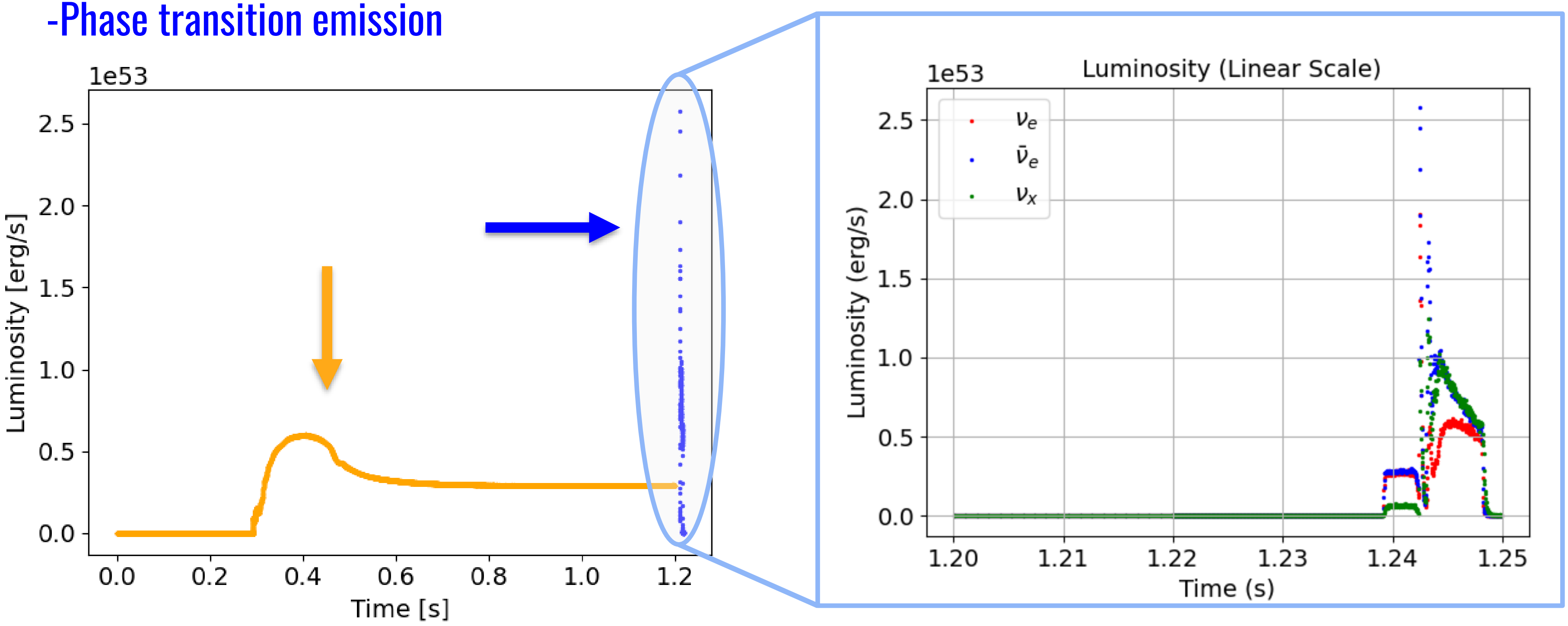

ASTERIA: detection simulation

SIGNAL HYPOTHESIS	→	OUR MODEL	TS_H1= p(TS| H1)
NULL HYPOTHESIS	→	NO PT CCSN	TS_H0= p(TS| H0)

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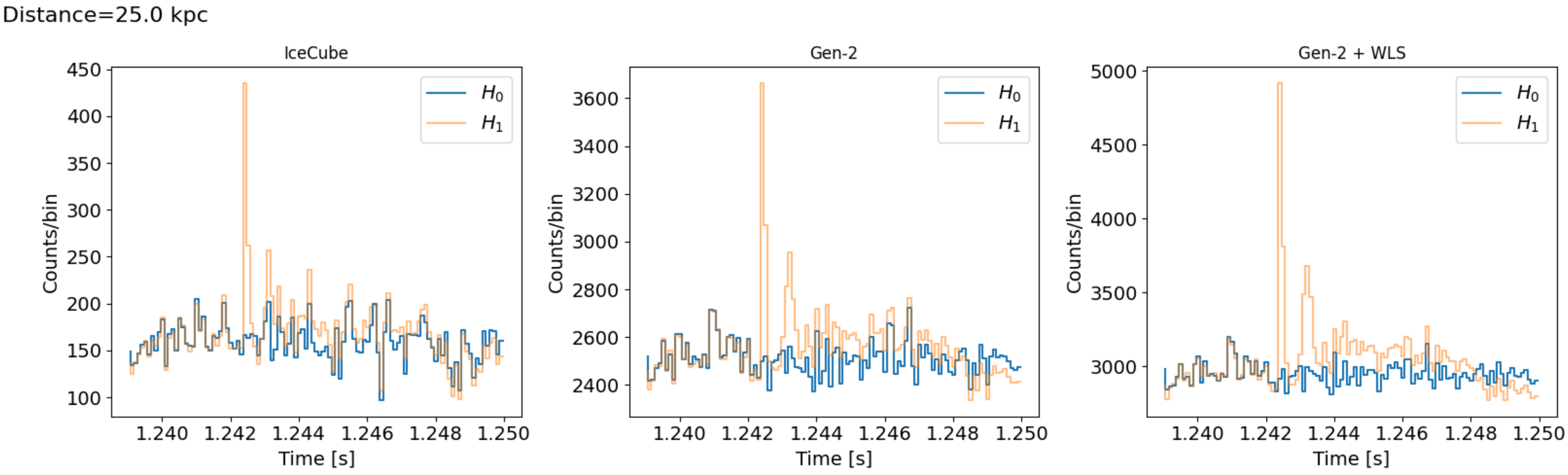
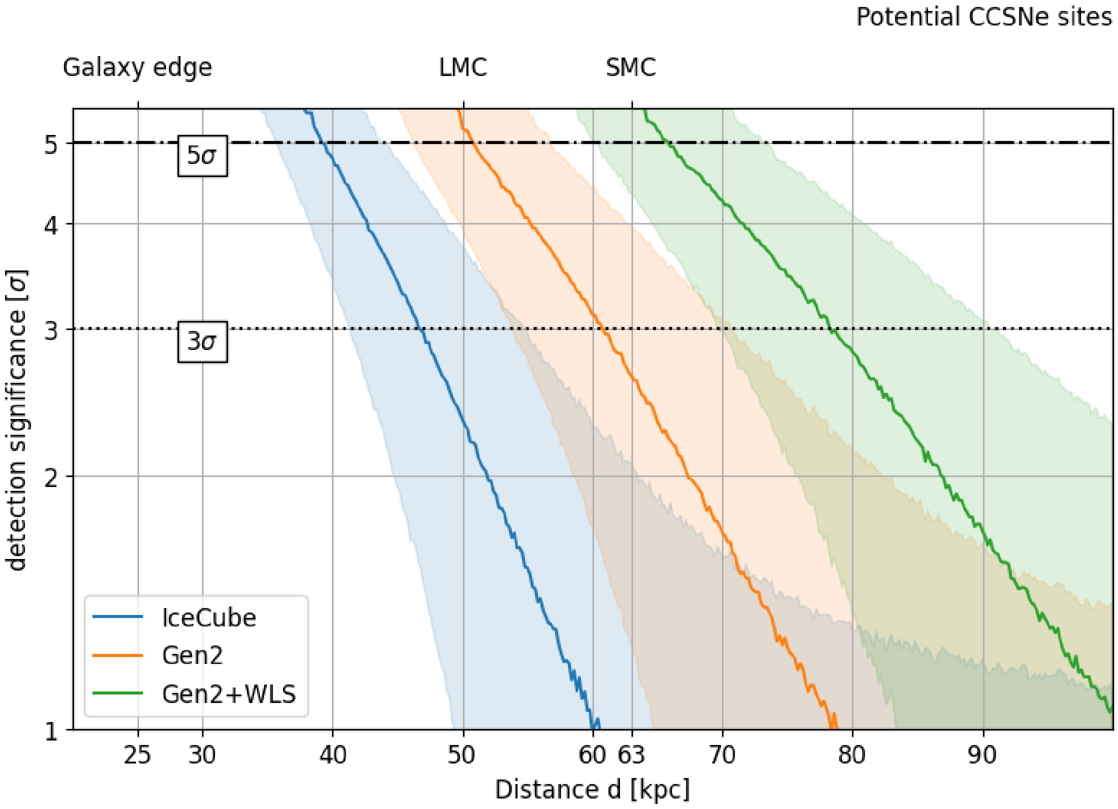


Detection significance



Detector	Distance at 5σ [kpc]
IceCube	$39.05\,^{+4.72}_{-3.49}$
Gen2	$50.74\,^{+5.81}_{-4.46}$
Gen2 + WLS	$65.86\,^{+7.02}_{-5.67}$

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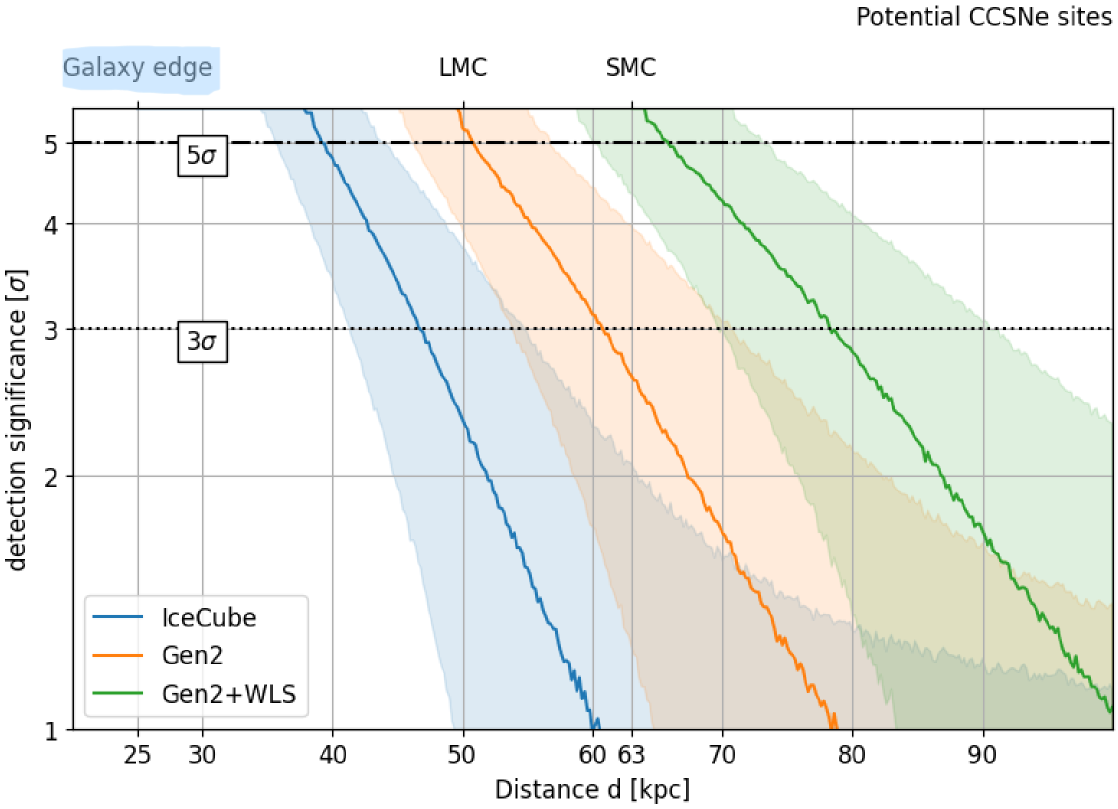

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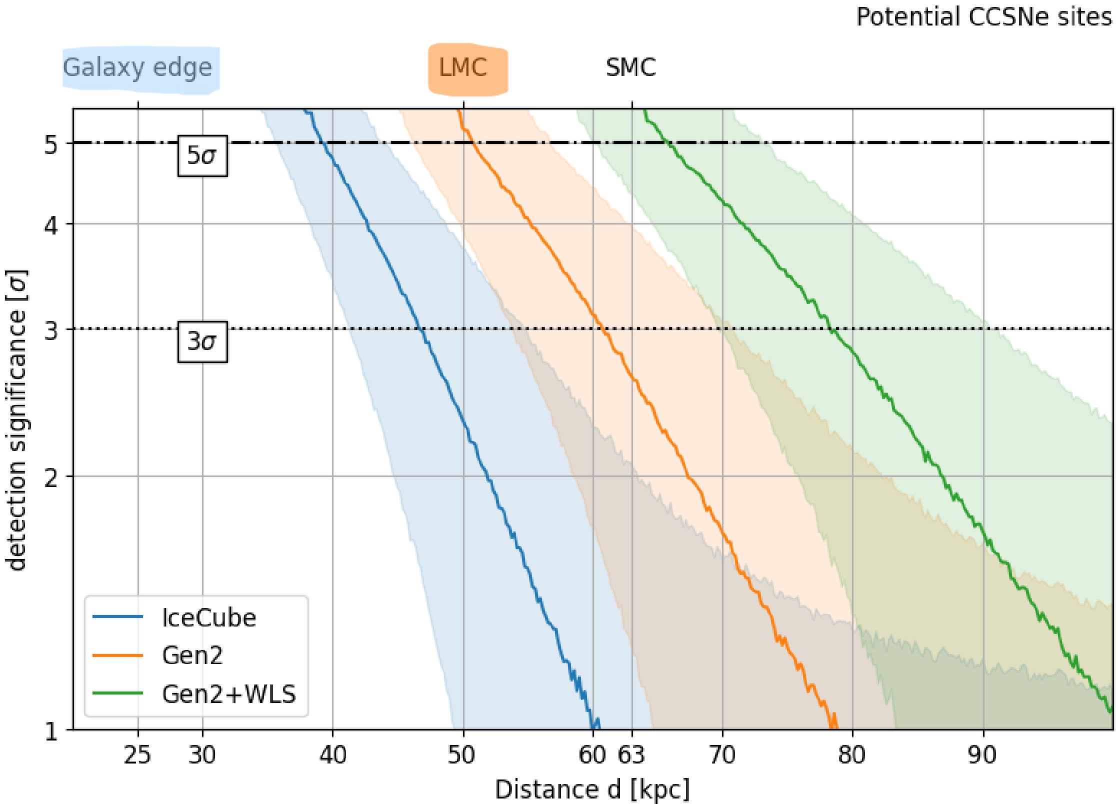
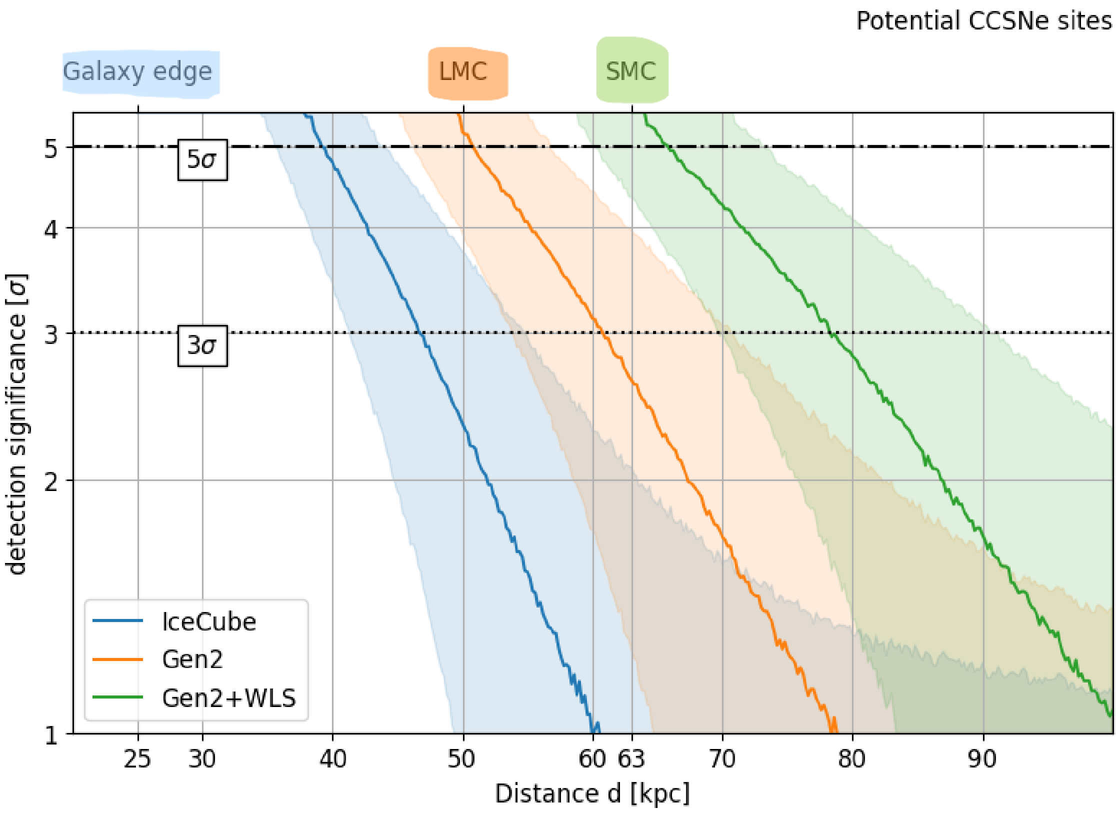
Detection significance



Detector	Distance at 5σ [kpc]
IceCube	$39.05\,^{+4.72}_{-3.49}$
Gen2	$50.74\,^{+5.81}_{-4.46}$
Gen2 + WLS	$65.86\,^{+7.02}_{-5.67}$

Detection significance



Detector	Distance at 5σ [kpc]
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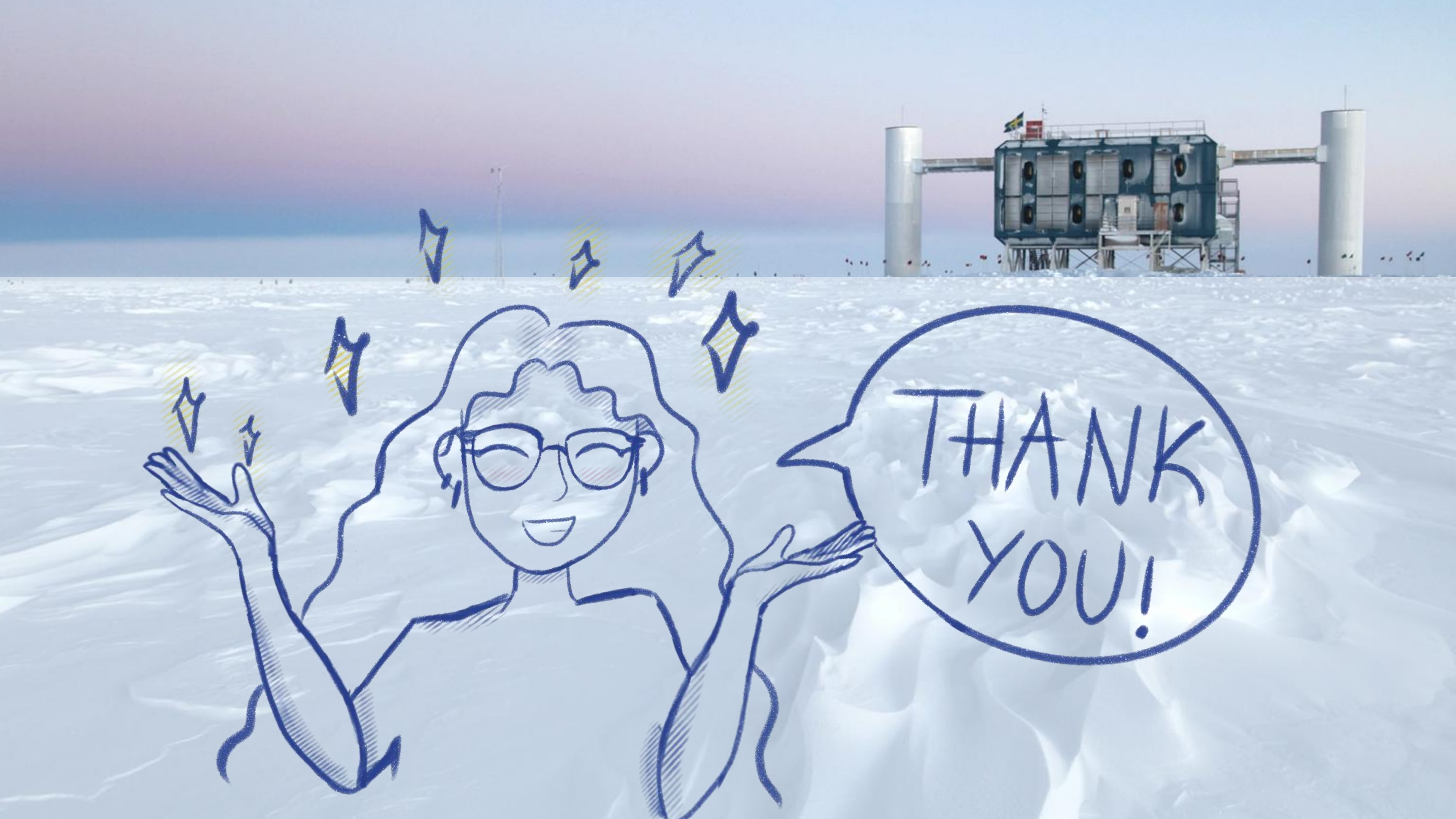
Conclusions

- We could see such an event even at high distances 
- However, the **likelihood for a SN** is not that high, we expect **1 every 100 years within the Milky Way**
- Only SN1987A
- Next generation detectors would **enhance our detection of sharp features**
- Insights for the QCD phase-diagram + sate of matter at the early universe
- …one day we *could* **discover quark stars**!

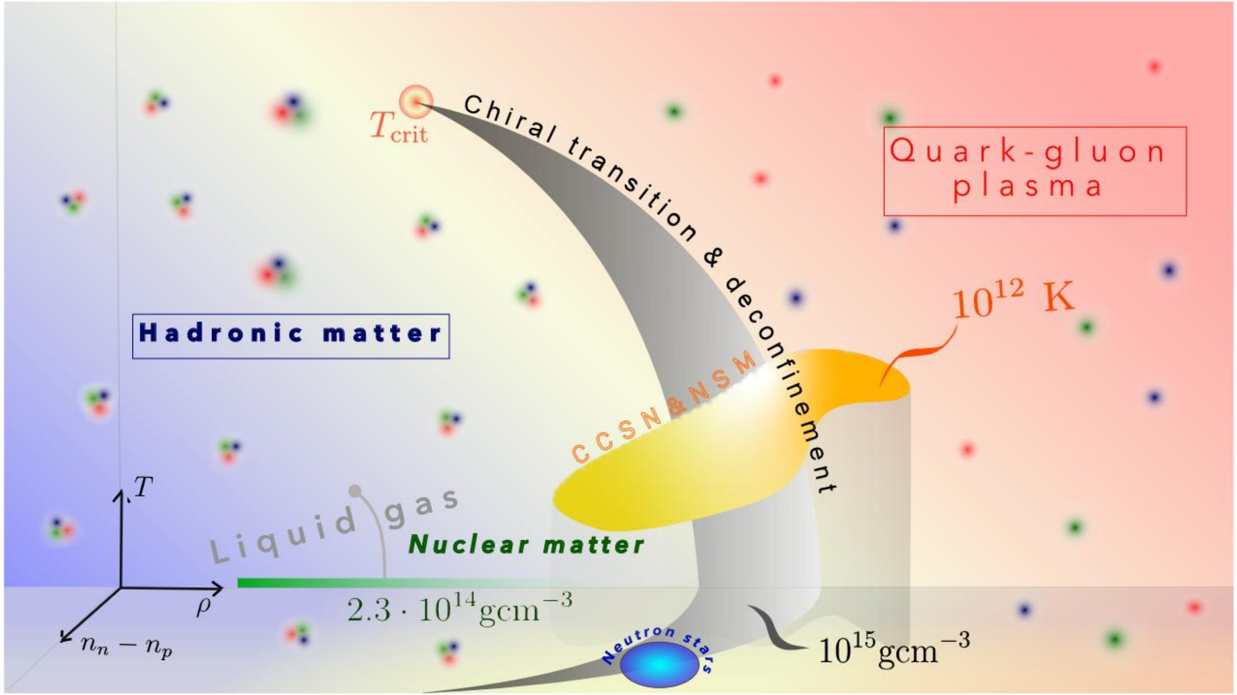

THANK YOU!

Backup slides

UPPSALA UNIVERSITET

ICECUBE

QCD phase diagram

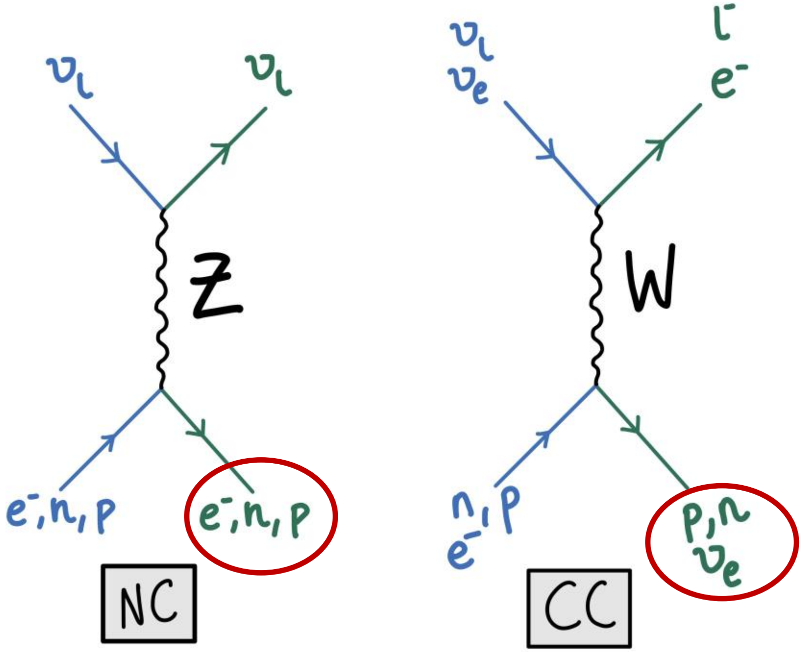


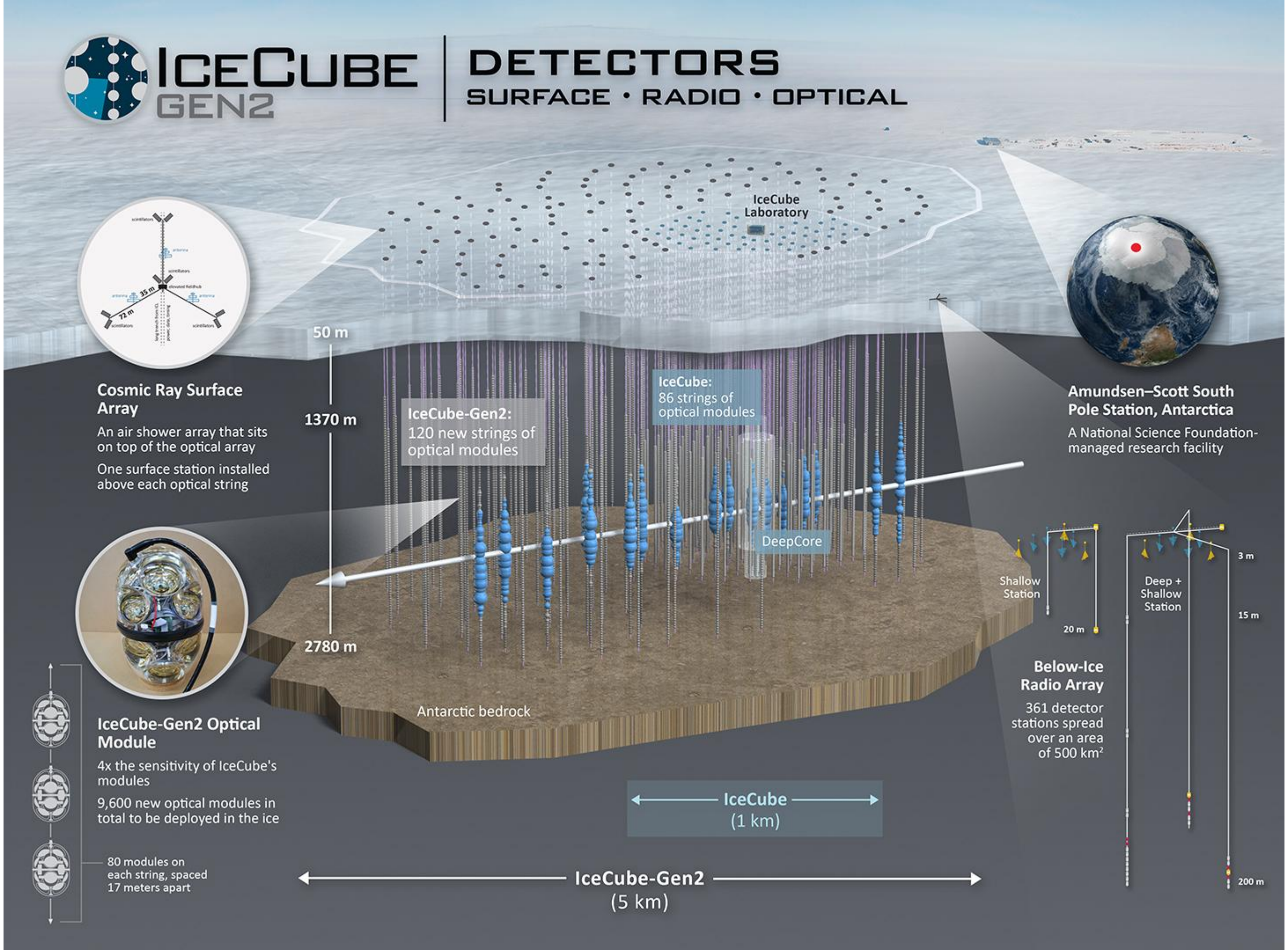
Ghostly messengers

→Weakly interacting particles → NC / CC

They travel trough space without interacting, we cannot observe them directly

We observe the product of their interaction with matter

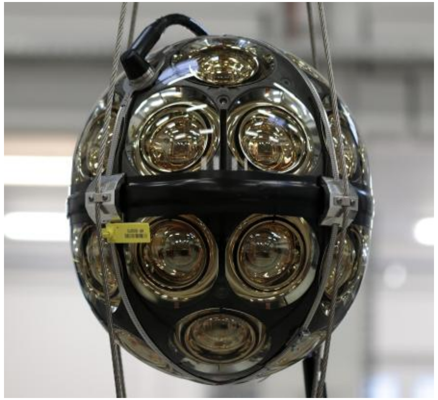



ICECUBE GEN2
DETECTORS
SURFACE • RADIO • OPTICAL
IceCube Laboratory
Cosmic Ray Surface Array
An air shower array that sits on top of the optical array
One surface station installed above each optical string
50 m
1370 m
2780 m
IceCube-Gen2:
120 new strings of optical modules
IceCube:
86 strings of optical modules
DeepCore
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
Shallow Station
Deep + Shallow Station
3 m
20 m
15 m
200 m
Below-Ice Radio Array
361 detector stations spread over an area of 500 km²
Antarctic bedrock
IceCube-Gen2 Optical Module
4x the sensitivity of IceCube's modules
9,600 new optical modules in total to be deployed in the ice
80 modules on each string, spaced 17 meters apart
IceCube (1 km)
IceCube-Gen2 (5 km)

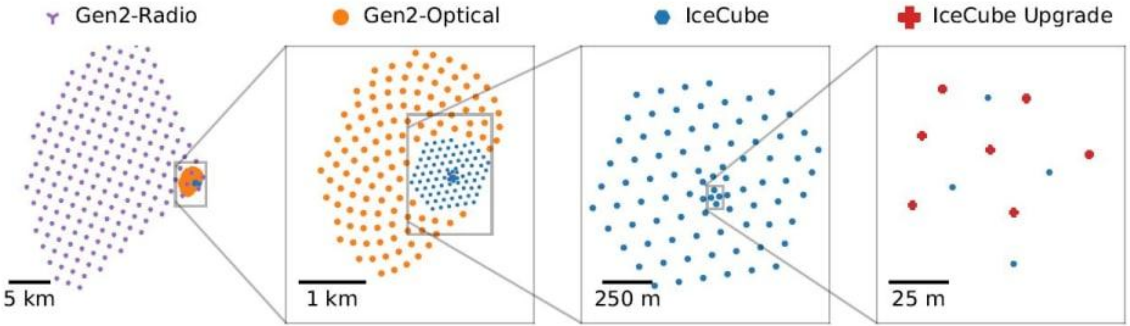
IceCube: Optical modules

DOM

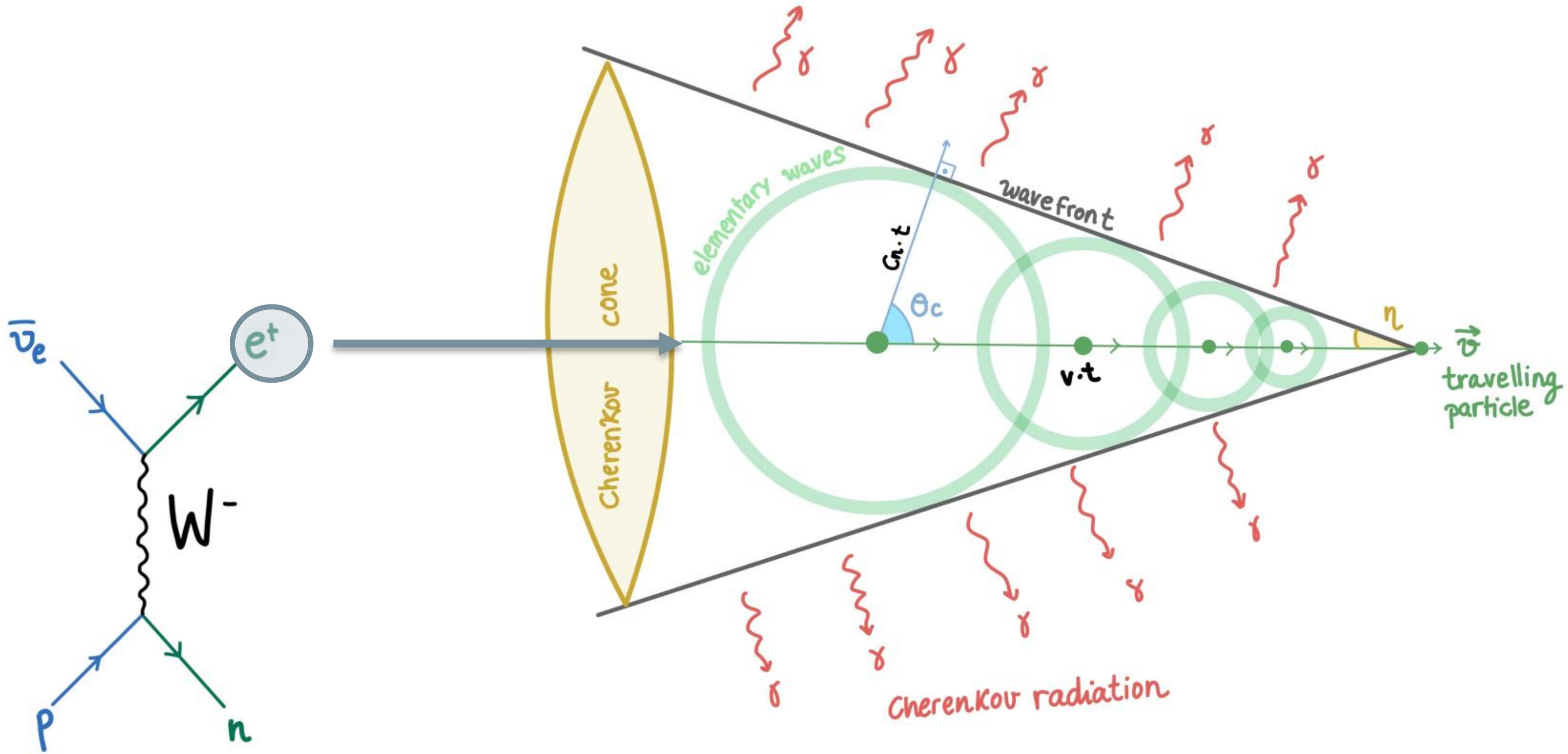
mDOM



IceCube Gen2



Cherenkov radiation



Analysis method:

1. Calculate a signal and null hypothesis (cutting the peak)

2. Evaluate a TS:

   TS=max signal

   TS_H0= p(TS| H0)

   TS_H1= p(TS| H1)

→Probability of TS to be in the H0 / H1 hypotheses

INCLUDING 10^8 BACKGROUND TRIALS (ENHANCE STATISTICS)

3. Find detection significance as a function of the distance

→Transform the p-value in a Z-score

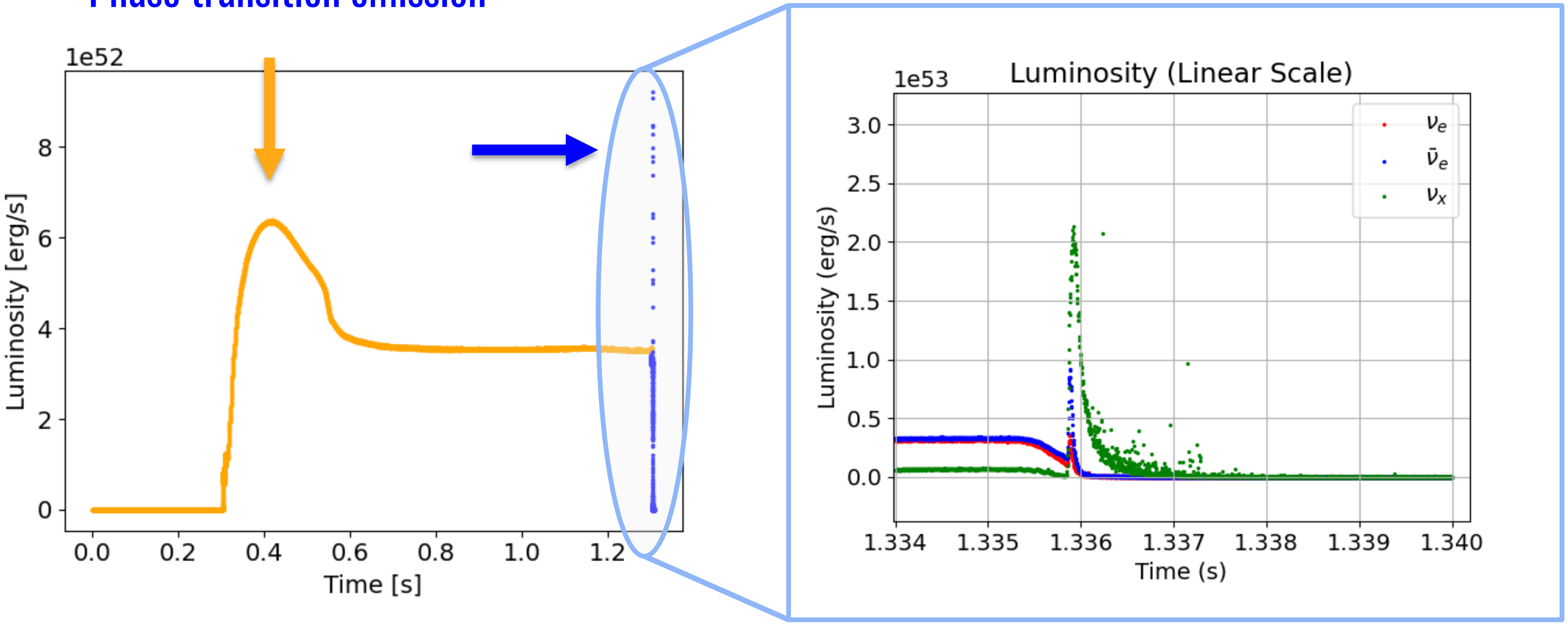
(how many standard deviations a value is from the mean under the null hypothesis)

Simulations: delayed black hole

Neutrino emission in the phase transition driven supernovae

-First collapse emission

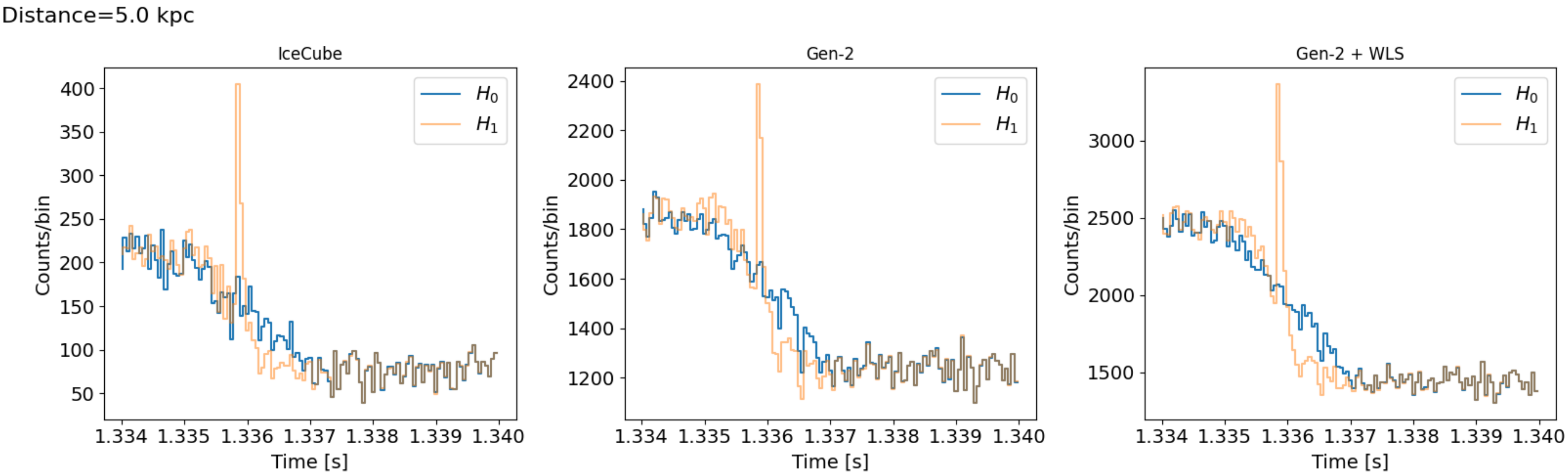
-Phase transition emission



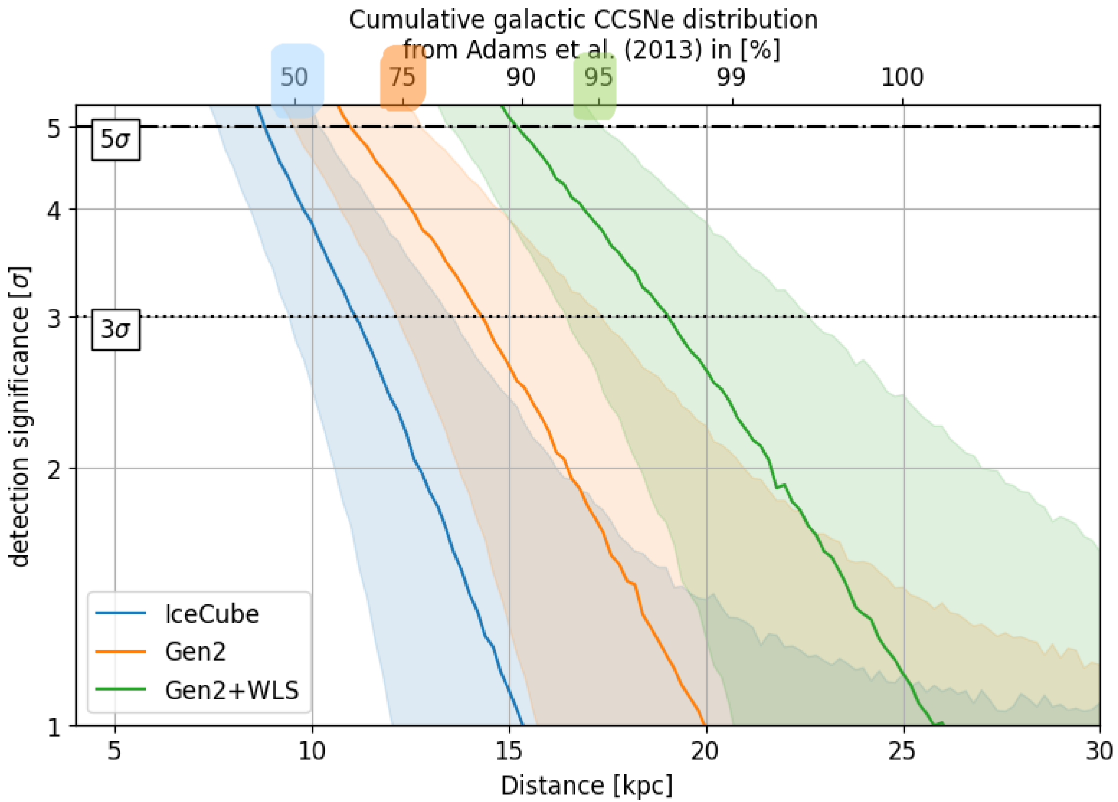
ASTERIA: detection simulation

SIGNAL HYPOTHESIS → OUR MODEL — TS_H1= p(TS| H1)

NULL HYPOTHESIS → NO PT CCSN — TS_H0= p(TS| H0)



Detection significance



Detector	Distance at 5σ [kpc]
IceCube	$8.79\ ^{+1.39}_{-1.18}$
Gen2	$10.97\ ^{+1.80}_{-4.82}$
Gen2 + WLS	$15.19\ ^{+2.15}_{-1.71}$