EQUATION OF STATE, NEUTRON STAR MERGERS, AND NEUTRINOS

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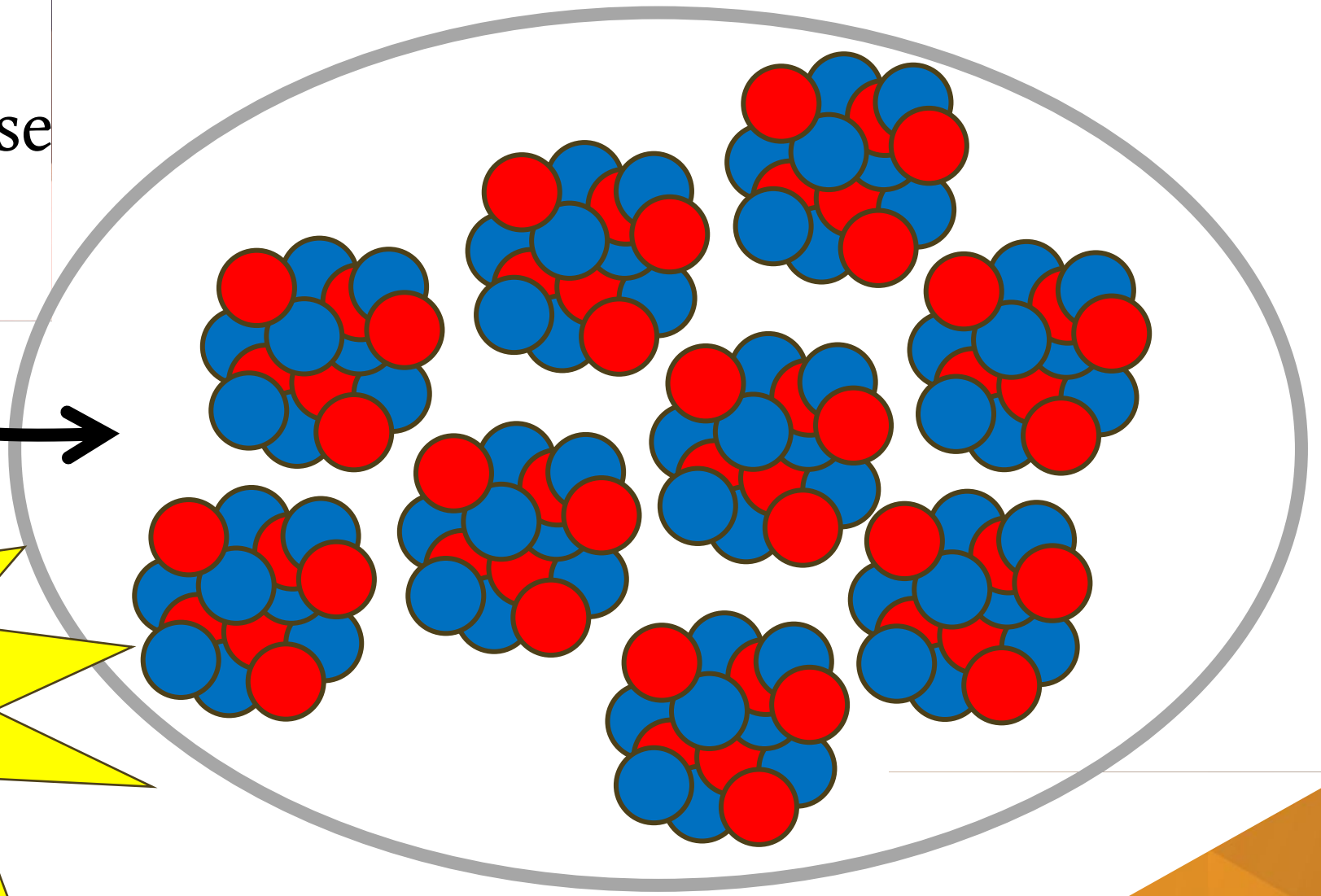
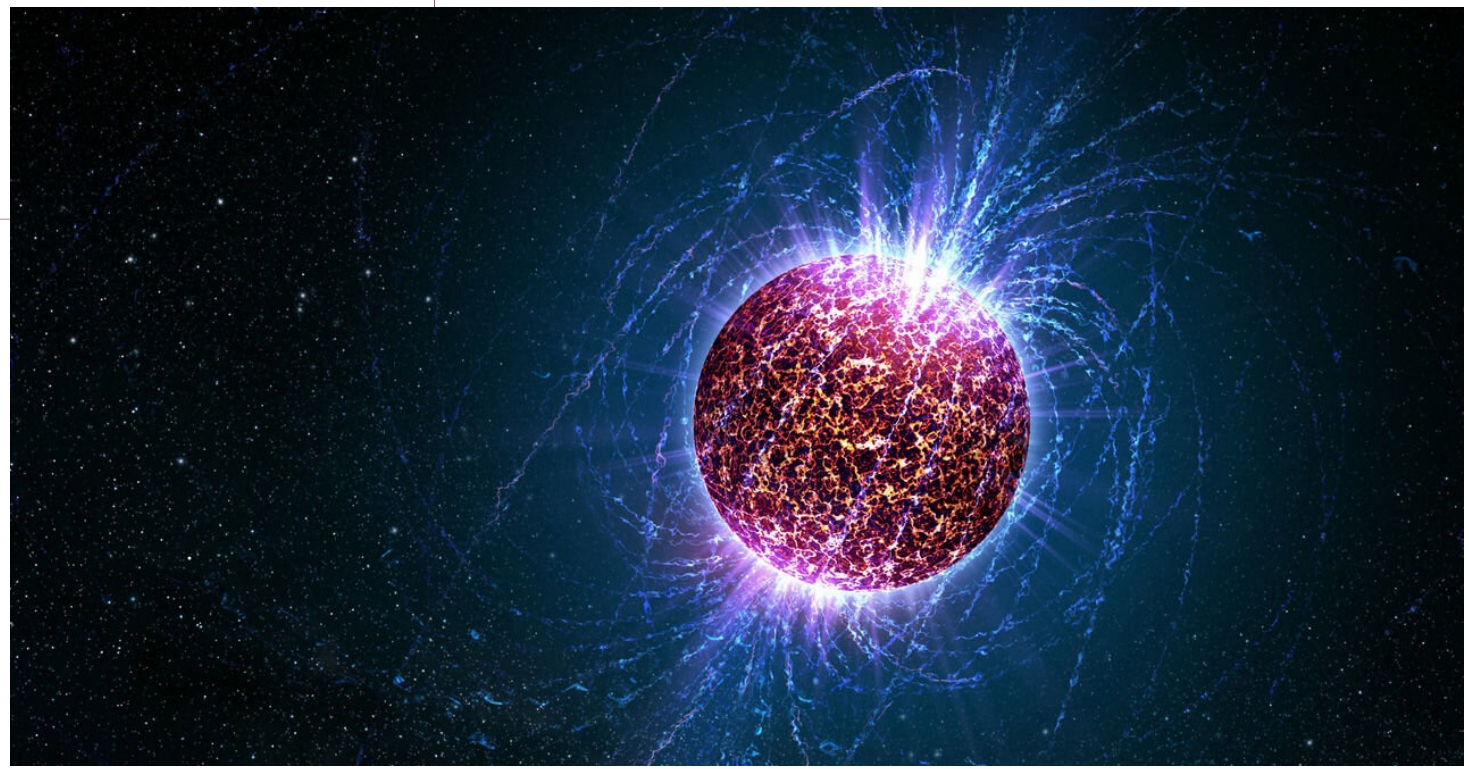
UG PHYSICS

Ultra-dense system

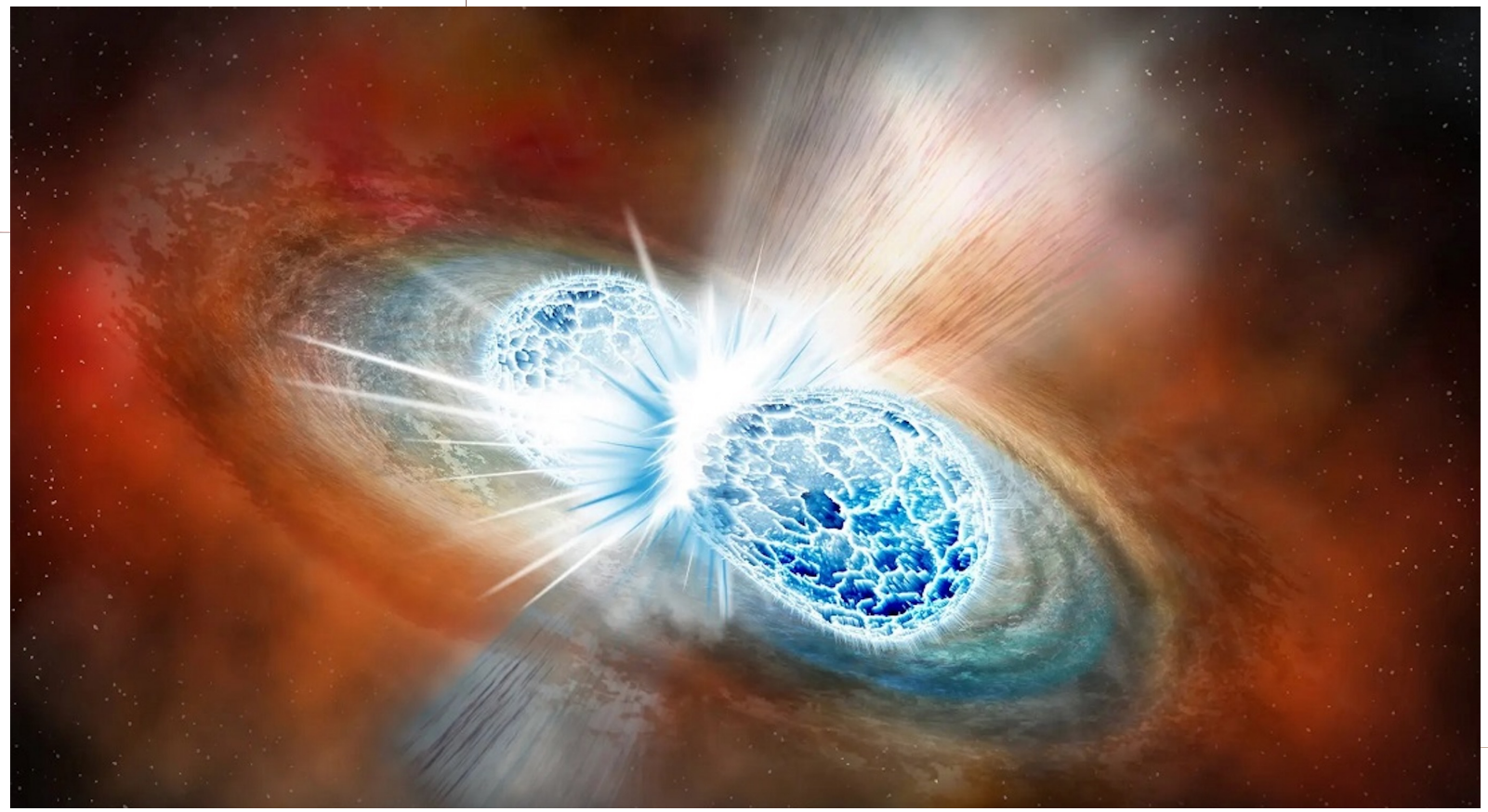


Equation of state

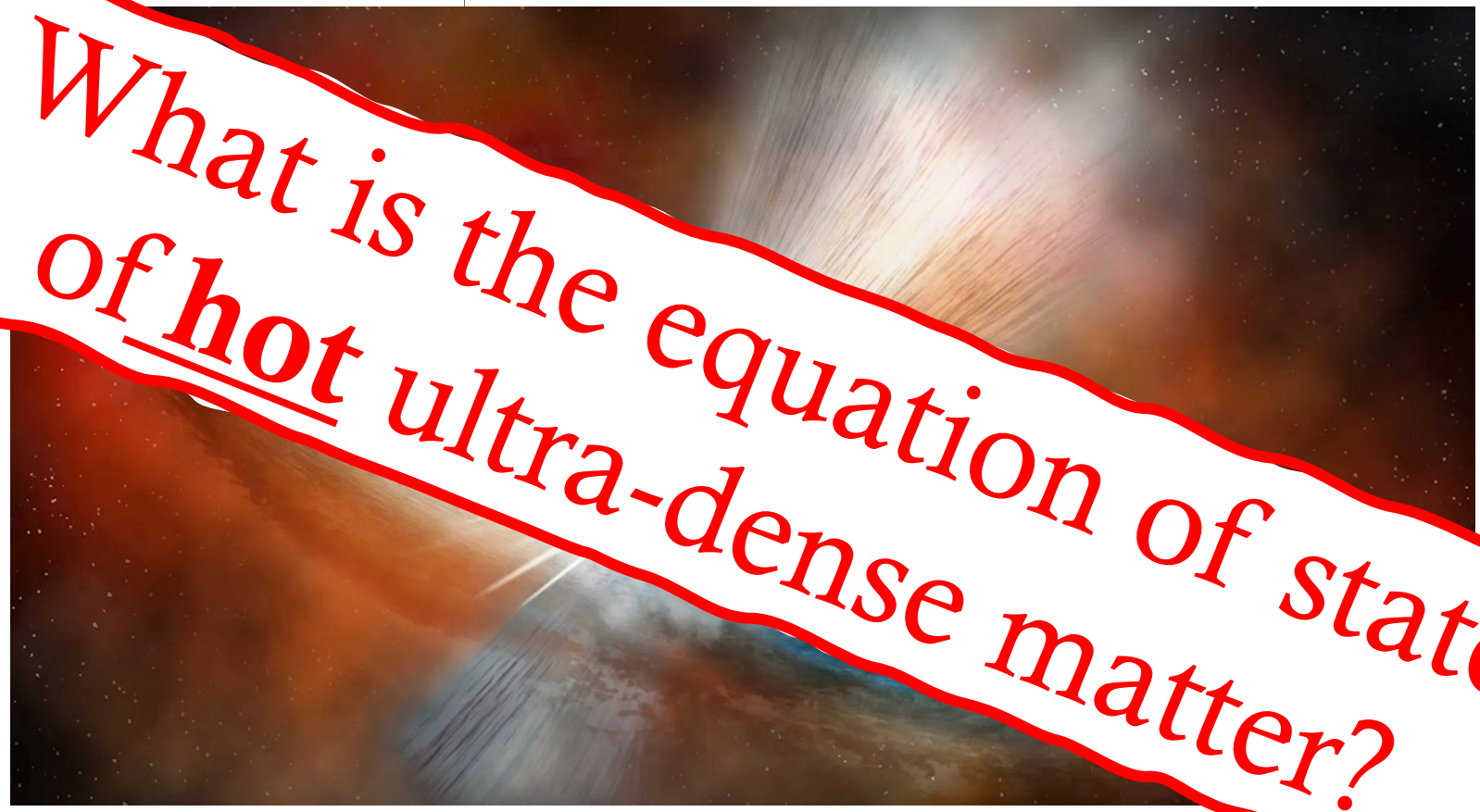
$$P = P(n, T, Y_e, \ldots)$$



Casey Reed/Penn State University



Robin Dienel, Institution for Sciences



What is the equation of state of **hot** ultra-dense matter?

Robin Dienel, Institution for Sciences

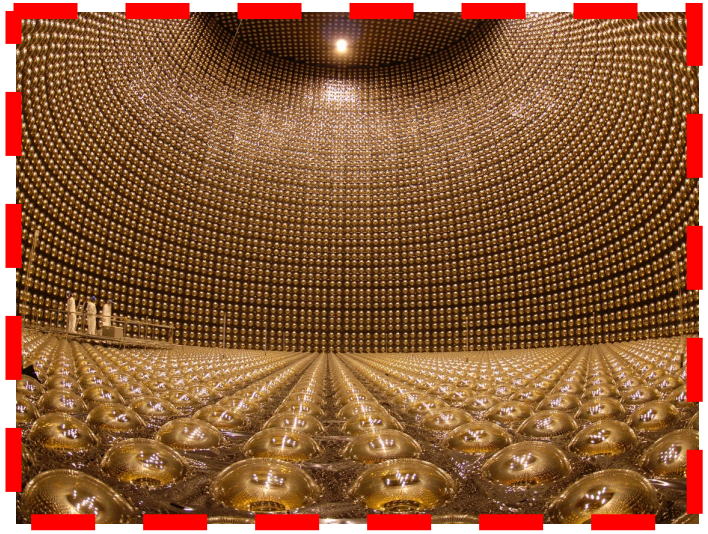
HOW DO YOU GAIN INFORMATION ABOUT A NEUTRON STAR MERGER?

NASA

Photons

The Virgo Collaboration

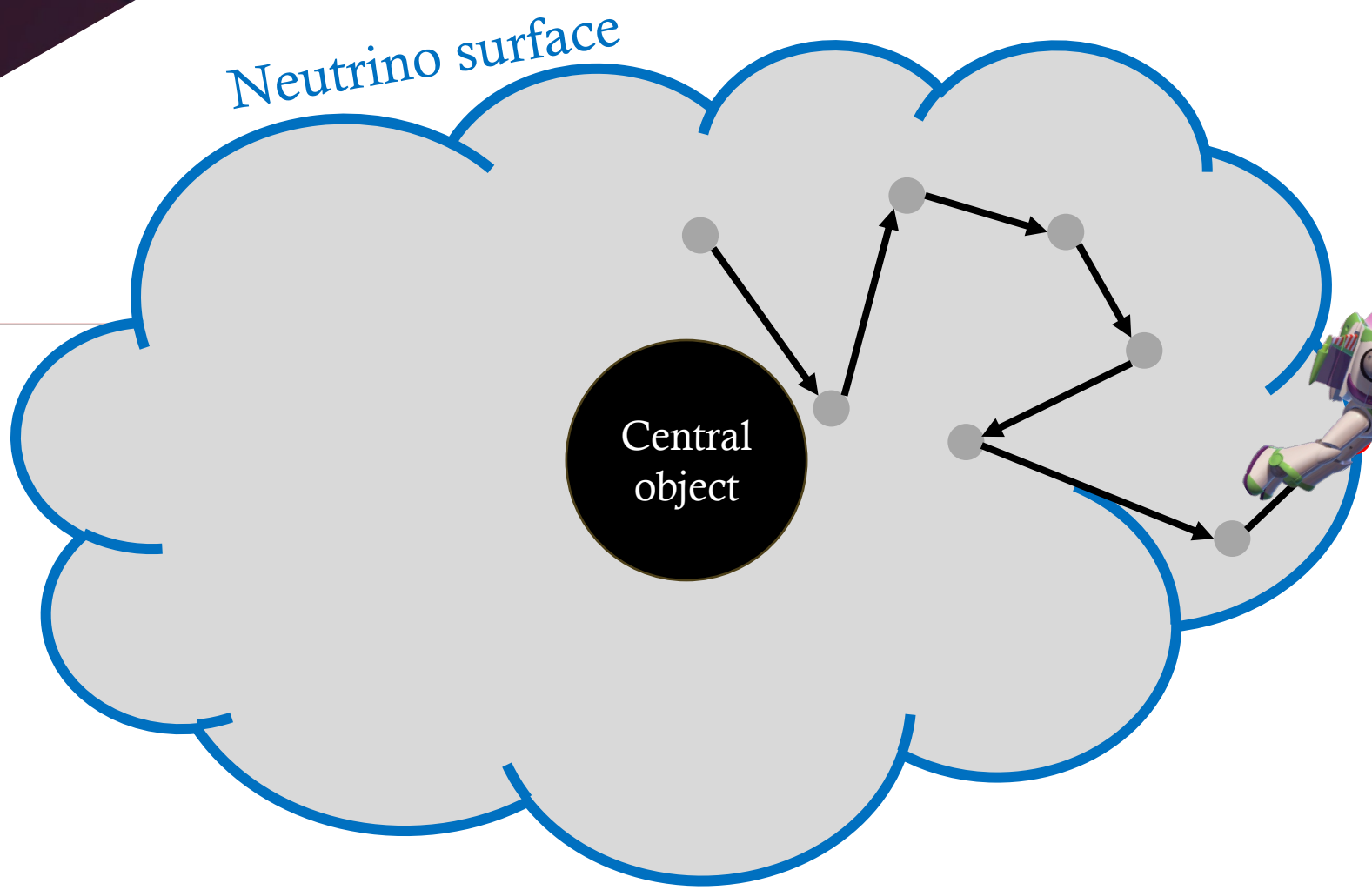
Gravitational waves



Kamioka Observatory, ICRR, University of Tokyo

Neutrinos

High density, neutrinos are trapped



Neutron-rich ejecta around the central object

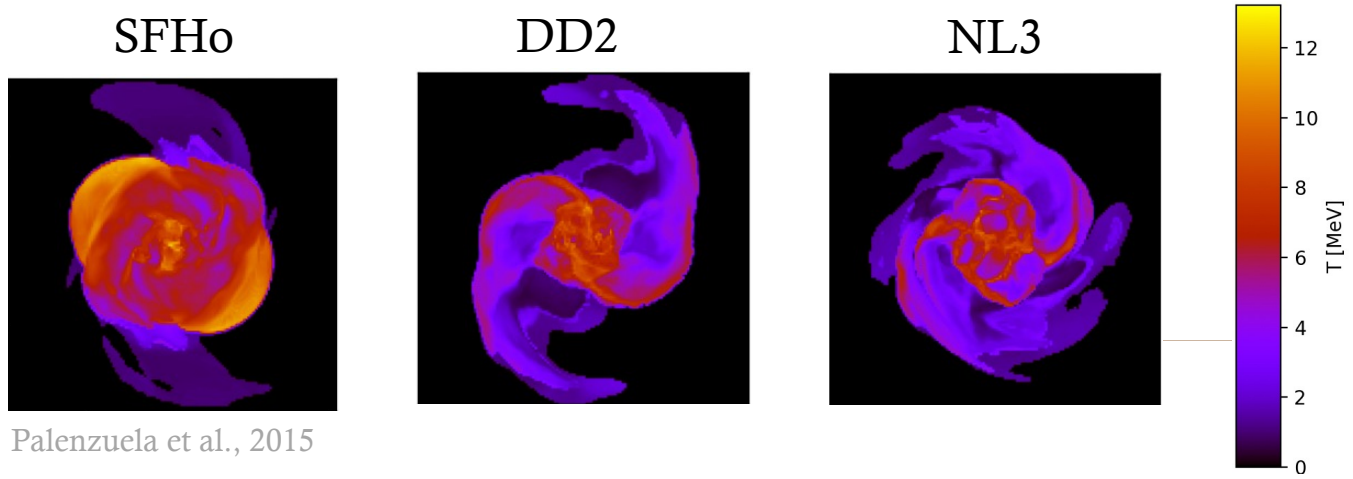
$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$
$$p + e^- \leftrightarrow n + \nu_e$$

PROCEDURE

Hydrodynamic simulation → Equation of state $P=P(n,\varepsilon,\ldots)$ → Neutrino surface → Spectrum of emitted neutrinos → Comparison with observations

This is where I come into play…

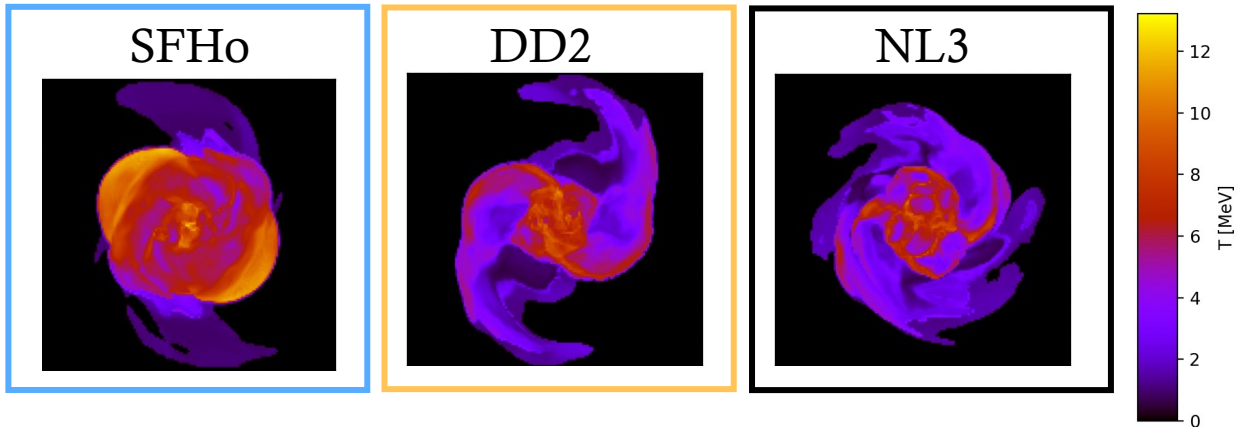
Equation of state = Lagrangian describing nuclear interaction

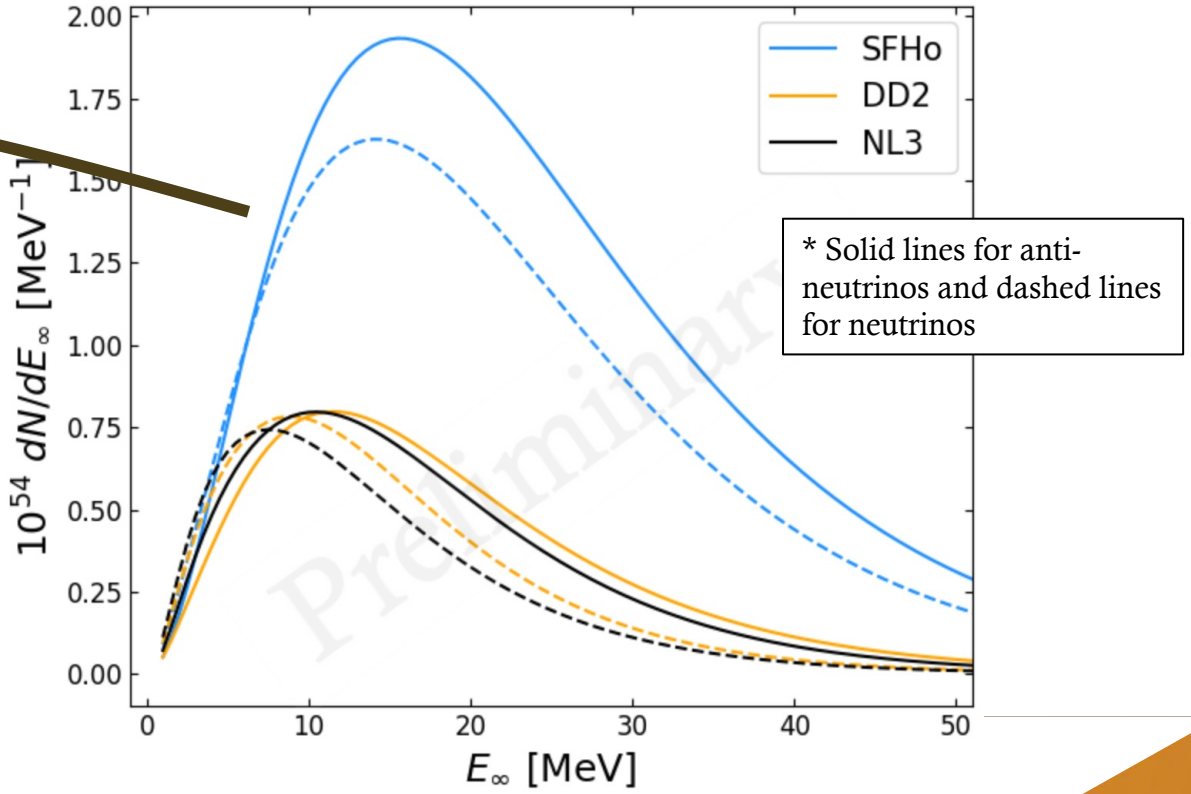


Palenzuela et al., 2015

EFFECT OF THE EQUATION OF STATE

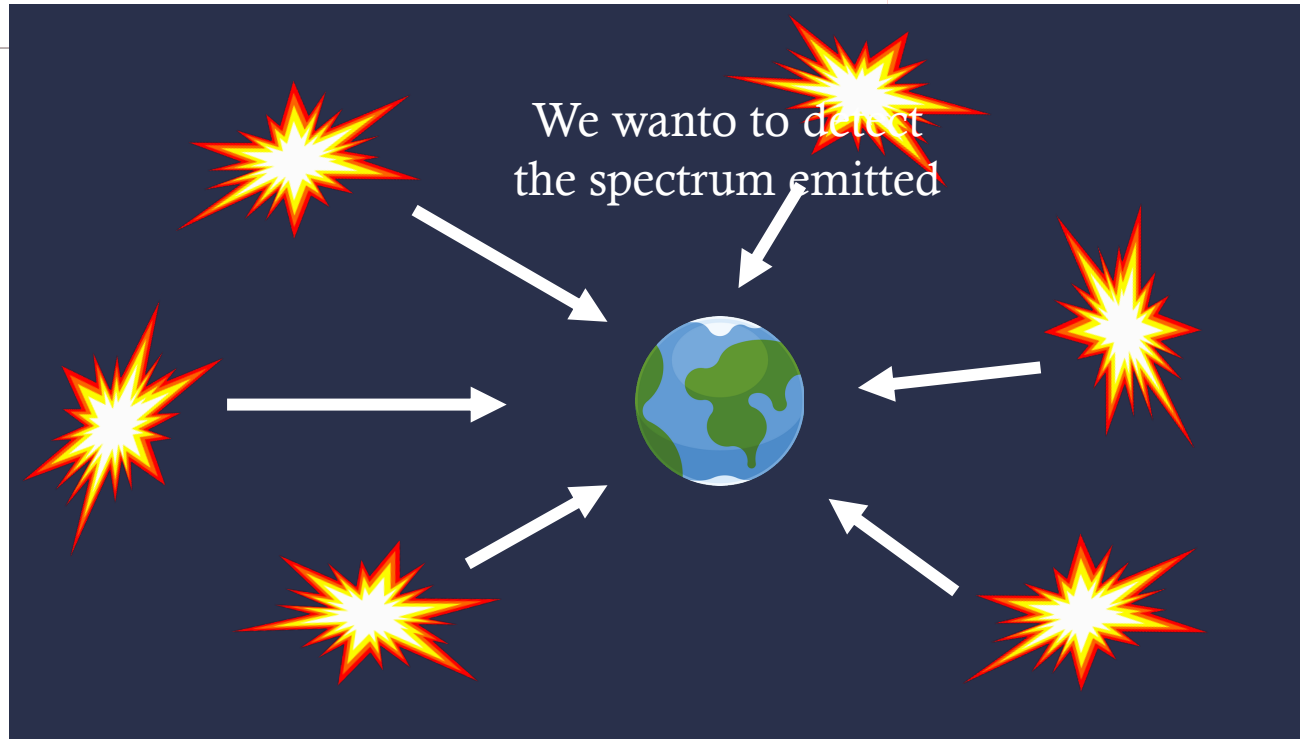
SFHo produces a different spectrum





* Solid lines for anti-neutrinos and dashed lines for neutrinos

DIFFUSE NEUTRINO BACKGROUND

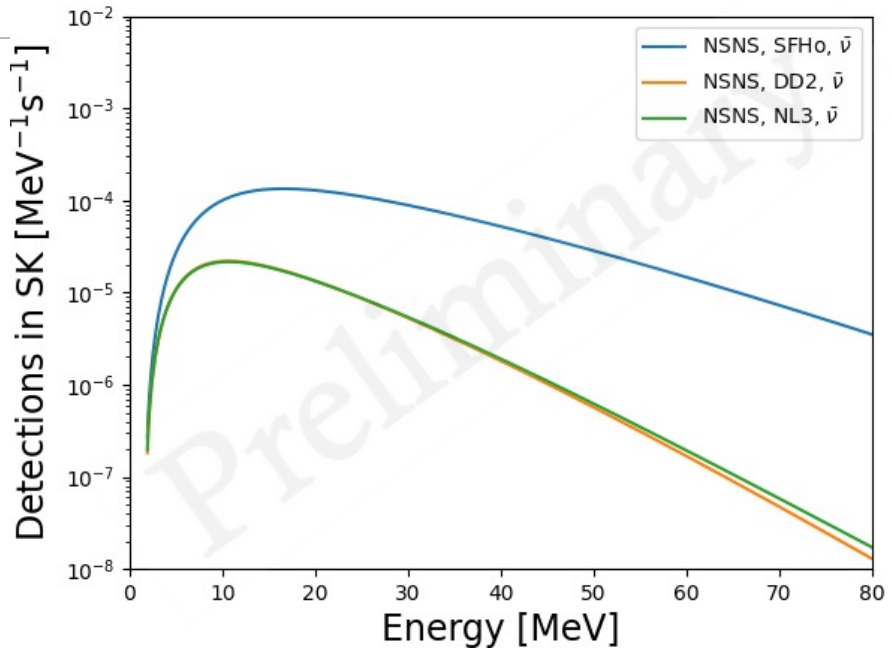


Flux on Earth

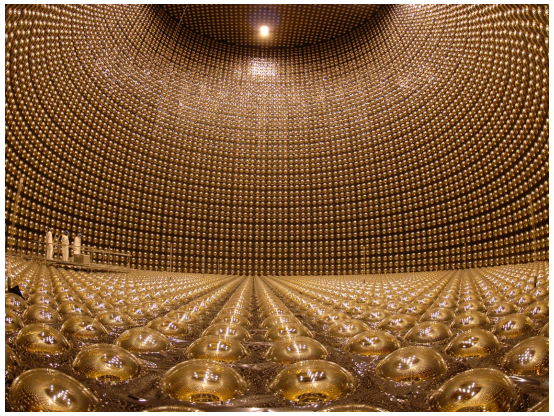
$$\Phi(E) = \sum_i \left(\frac{dN}{dE}\right)_i$$

Contribution of all mergers

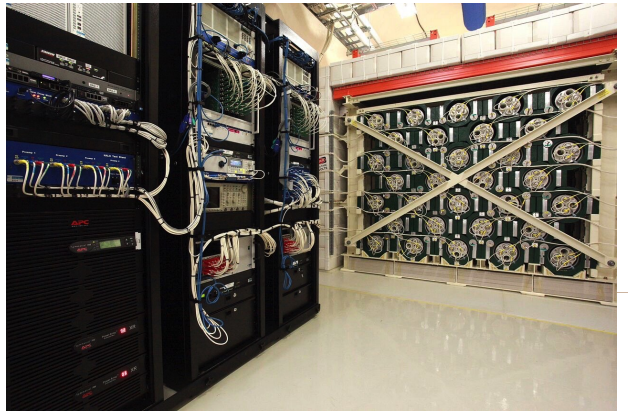
PREDICTIONS VS OBSERVATIONS



Which equation of state fits observations the best?



Kamioka Observatory, ICRR, University of Tokyo



SNOLAB

SUMMARY

Binary neutron star merger = Extreme conditions

We can gain information using neutrinos

Equation of state impacts the number of neutrinos

Comparison between theory and experiments = Constraints

Thank you!

The research was conducted at the University of Guelph, which resides on the treaty lands and territory of the Mississaugas of the Credit. We recognize this gathering place where we work and learn is home to many past, present, and future First Nations, Inuit, and Métis peoples.

Area (dA)
Height (z)
Temperature (T)

For 1 cell:

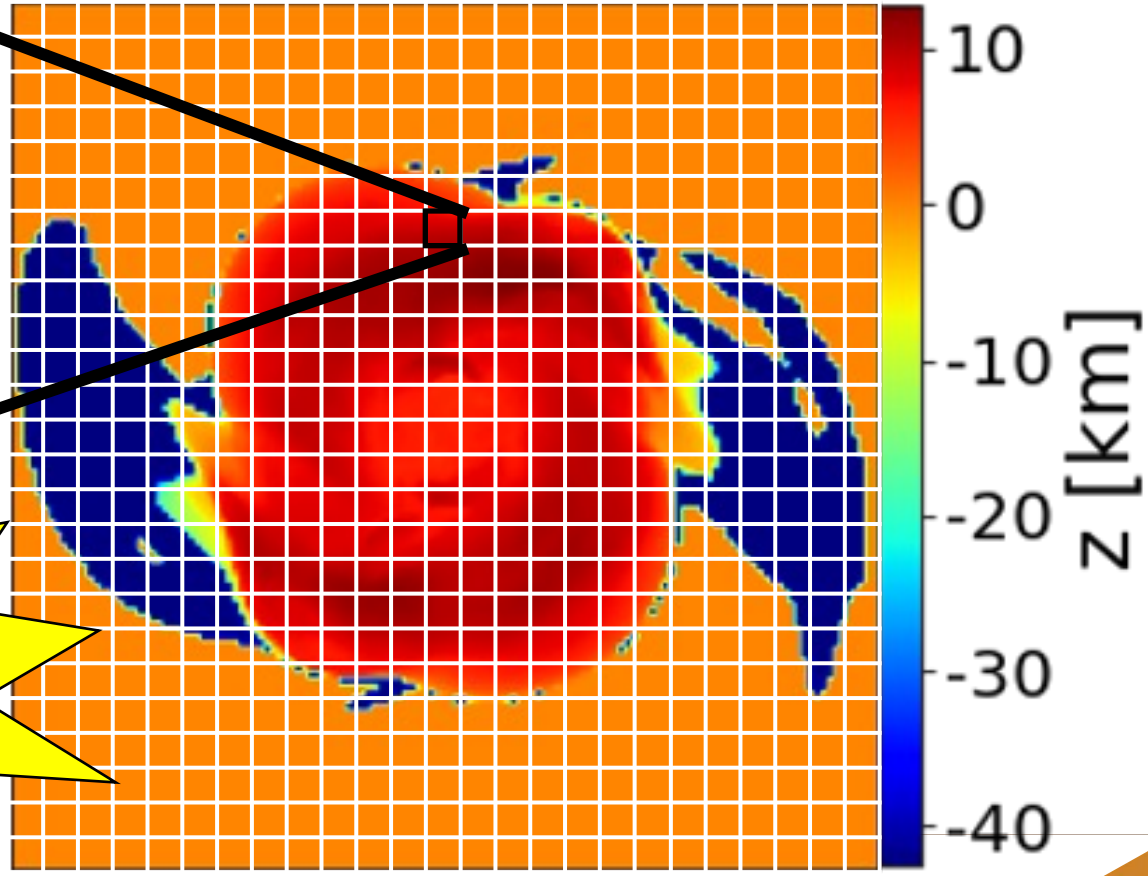
$$dN(E) \sim E^2 f(E,T) dA$$

Neutrinos (s=1/2): Fermi-Dirac!

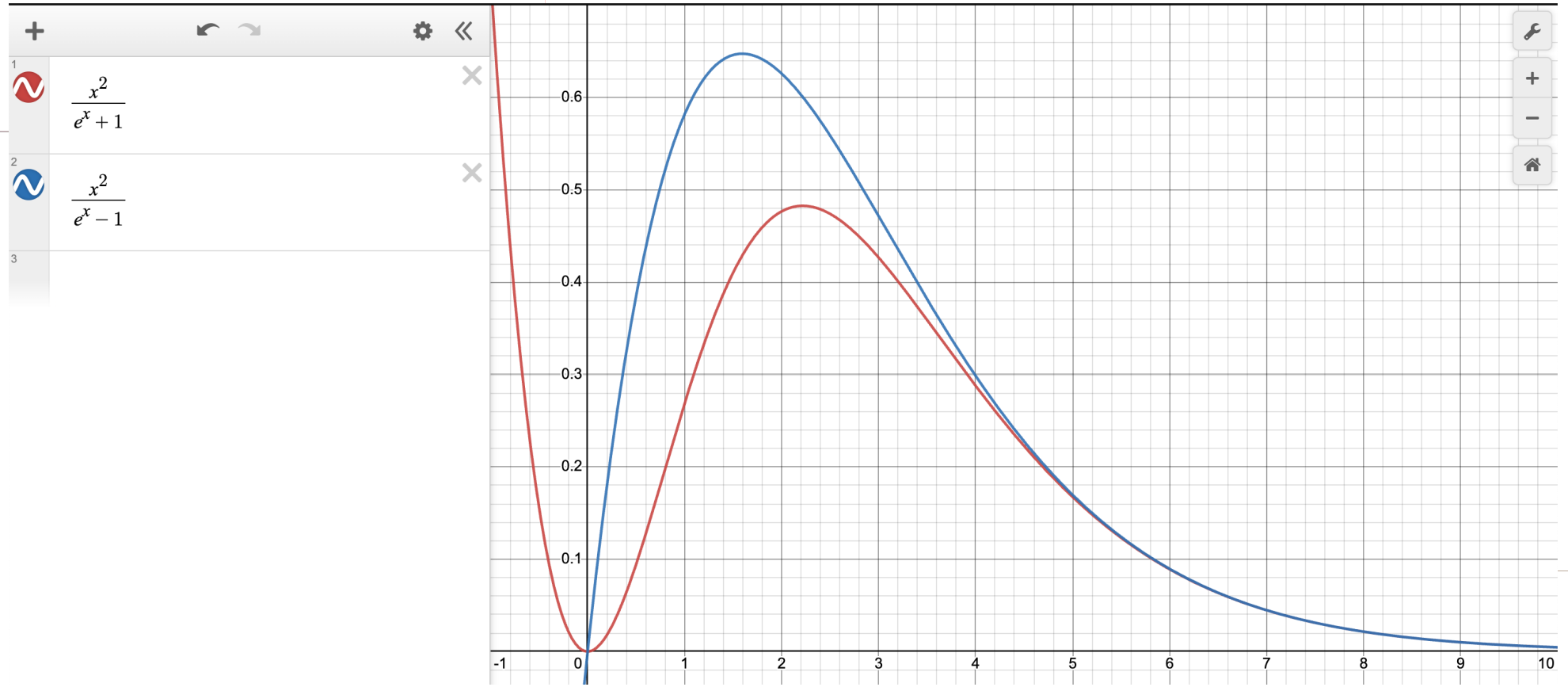
The spectrum looks like a sum of blackbody spectra…

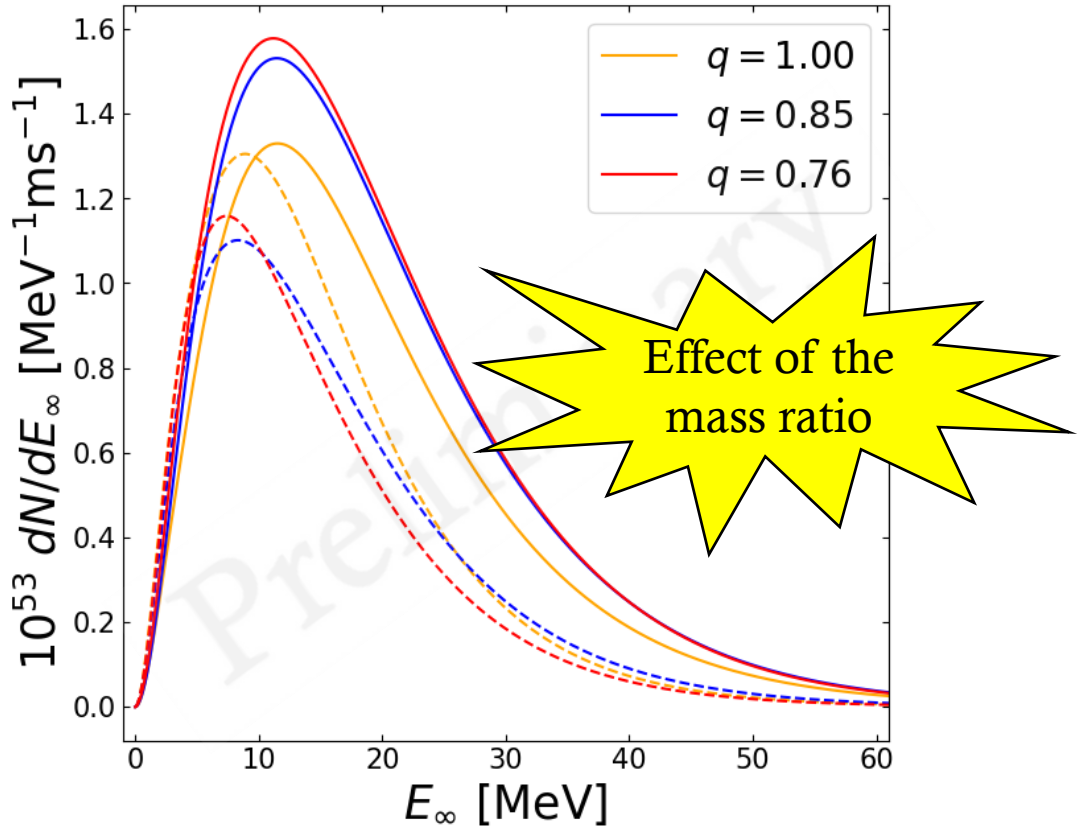
For the whole surface:

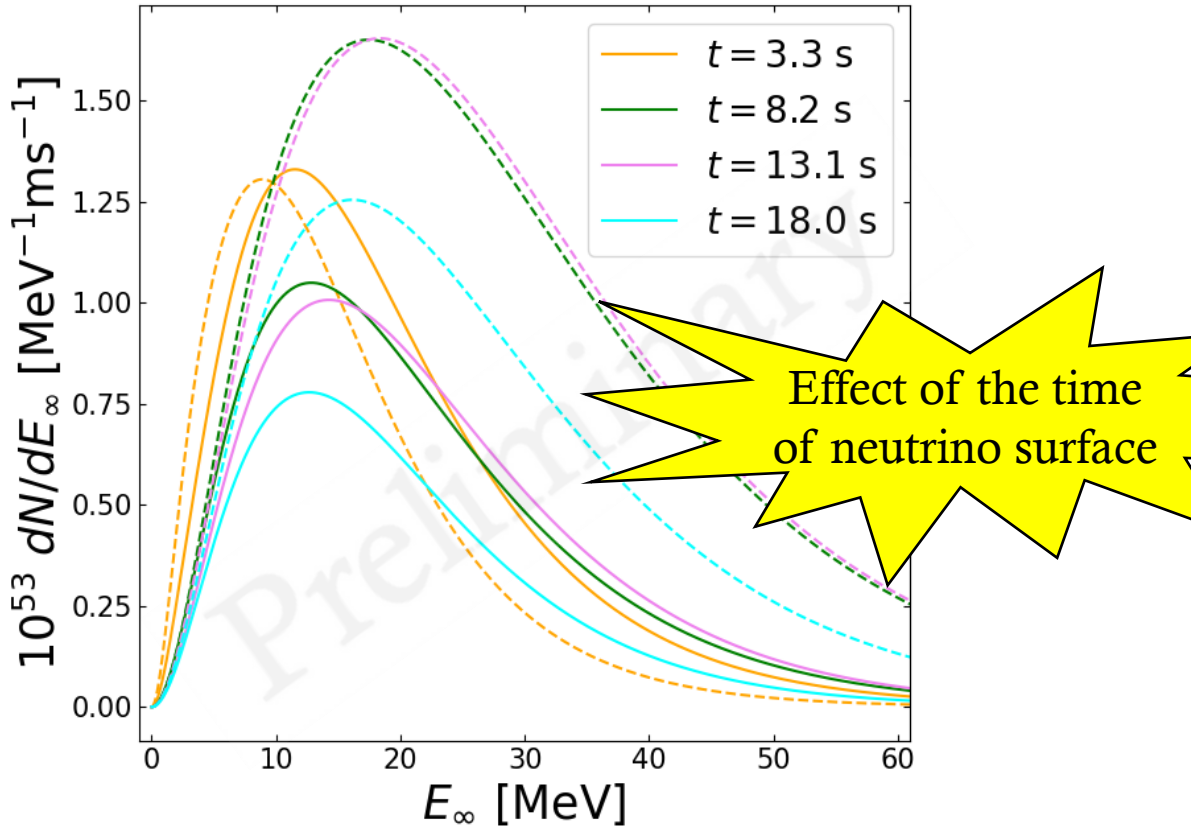
$$N(E) \sim \sum_{ij} E^2 f(E)\, dA$$

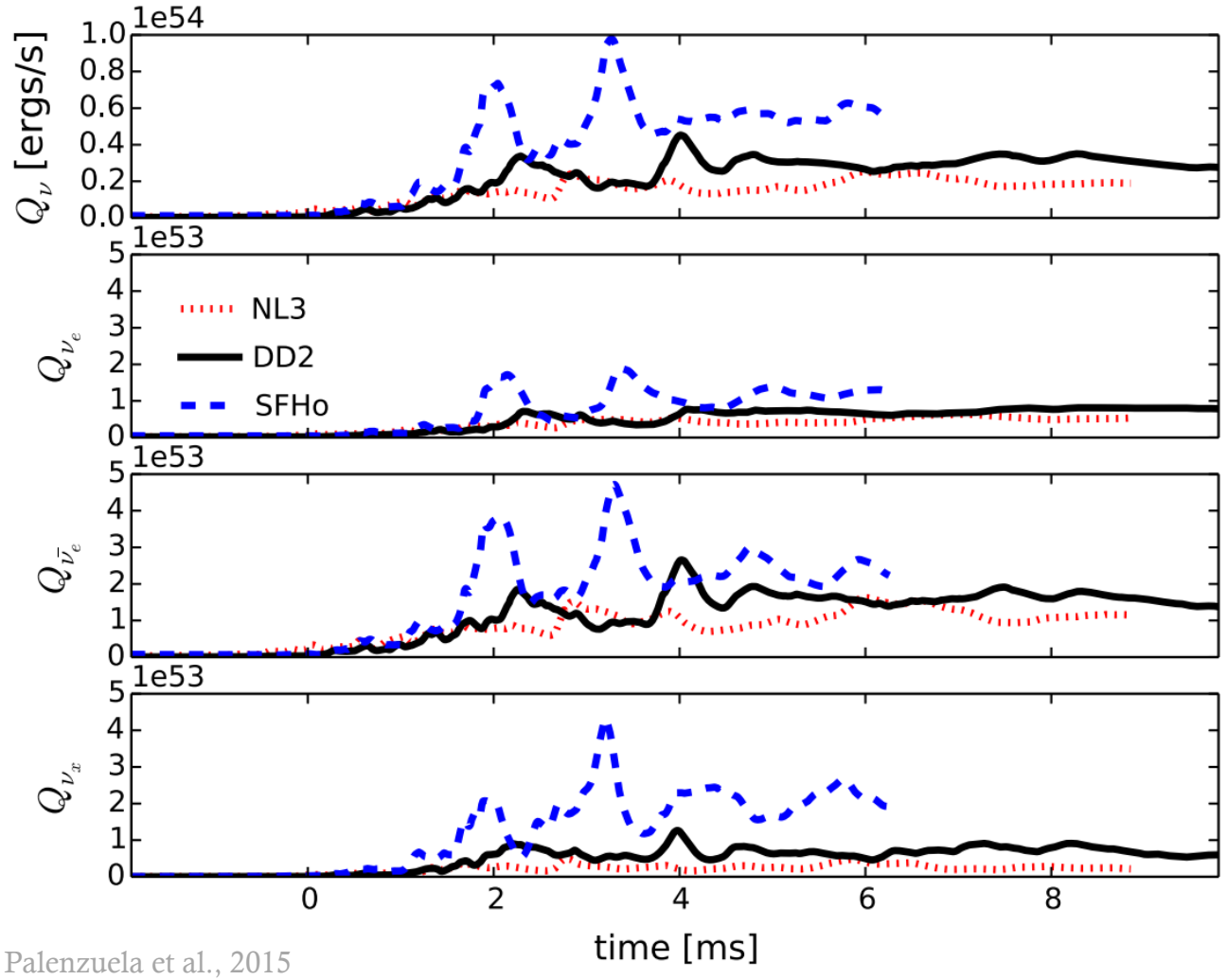


FERMI-DIRAC VS BOSE-EINSTEIN




$q = 1.00$
$q = 0.85$
$q = 0.76$
$10^{53}\ dN/dE_\infty\ [\mathrm{MeV}^{-1}\mathrm{ms}^{-1}]$
E_∞ [MeV]
Effect of the mass ratio


$t = 3.3$ s
$t = 8.2$ s
$t = 13.1$ s
$t = 18.0$ s
$10^{53}\ dN/dE_\infty\ [\mathrm{MeV}^{-1}\mathrm{ms}^{-1}]$
E_∞ [MeV]
Effect of the time of neutrino surface



Palenzuela et al., 2015

SNOWGLOBES

Flux on Earth

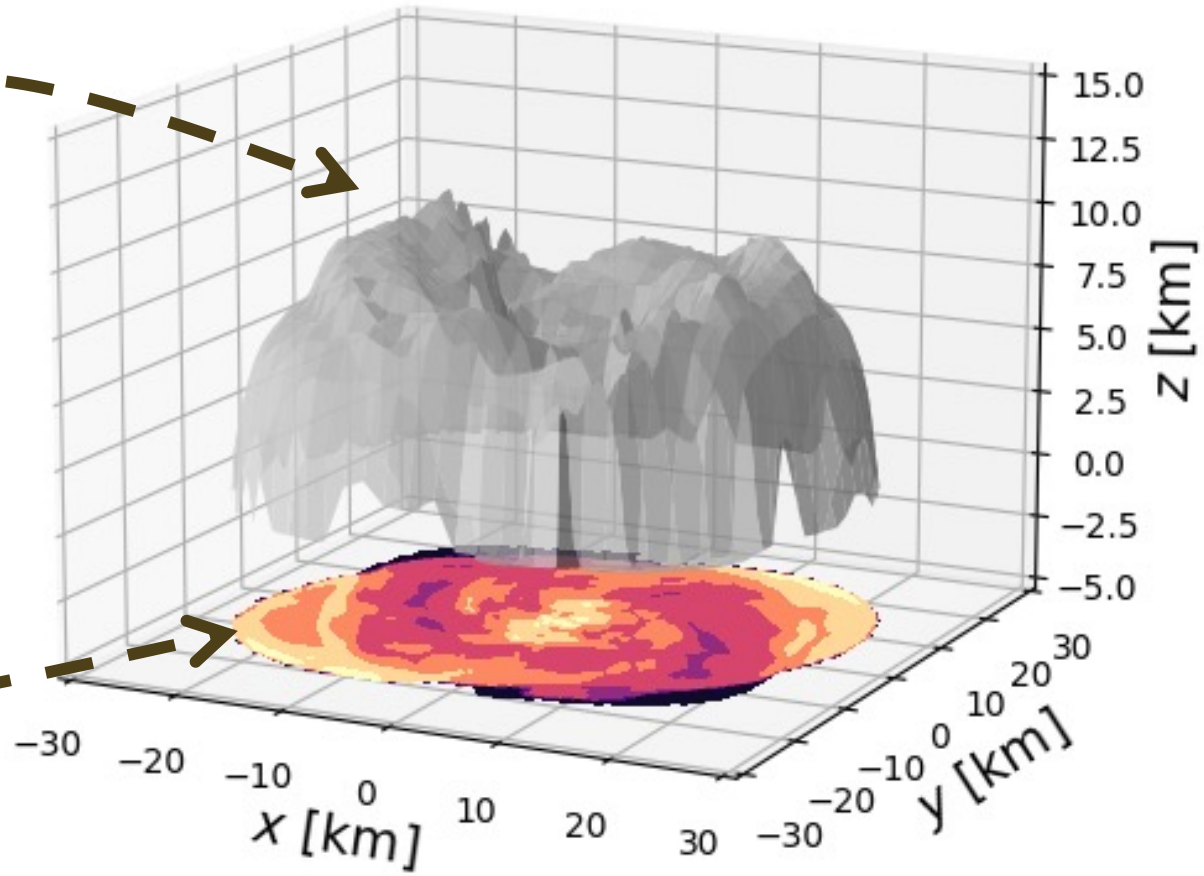
Neutrino detector

Detection rate

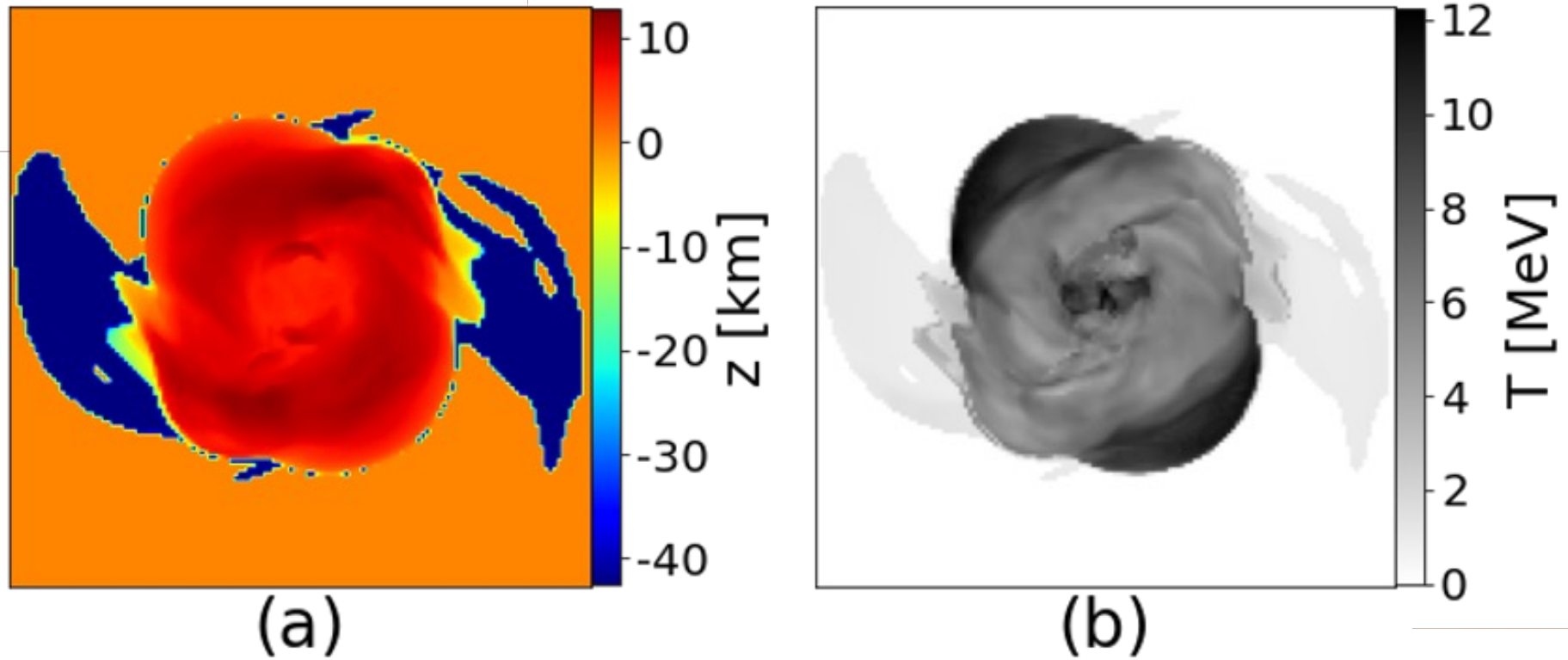
NEUTRINO SURFACE

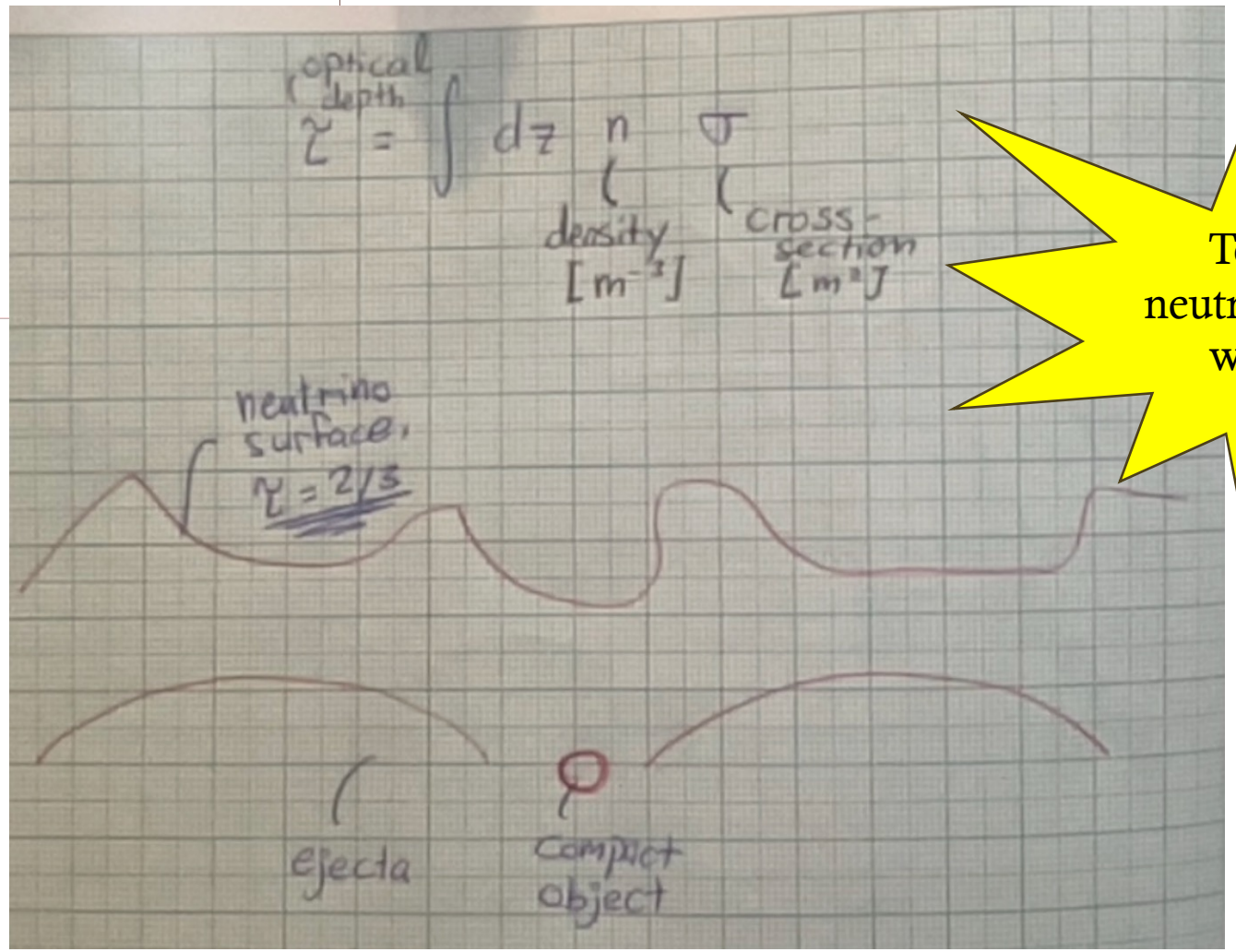
Height map

Temperature map



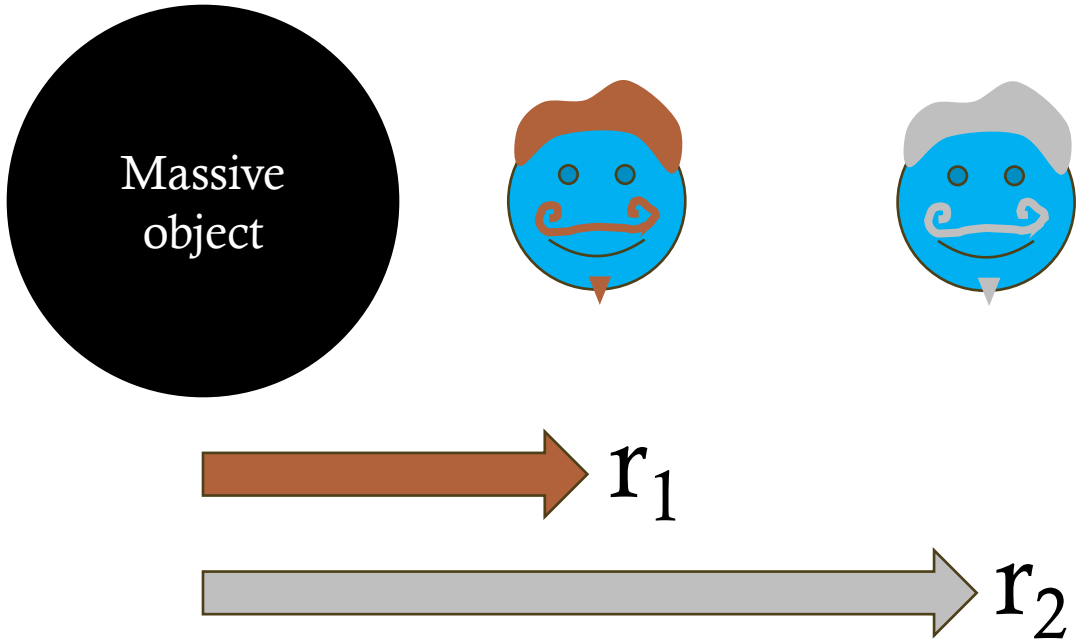
* This is only the top half…


10
0
-10
-20
-30
-40
z [km]
(a)
12
10
8
6
4
2
0
T [MeV]
(b)

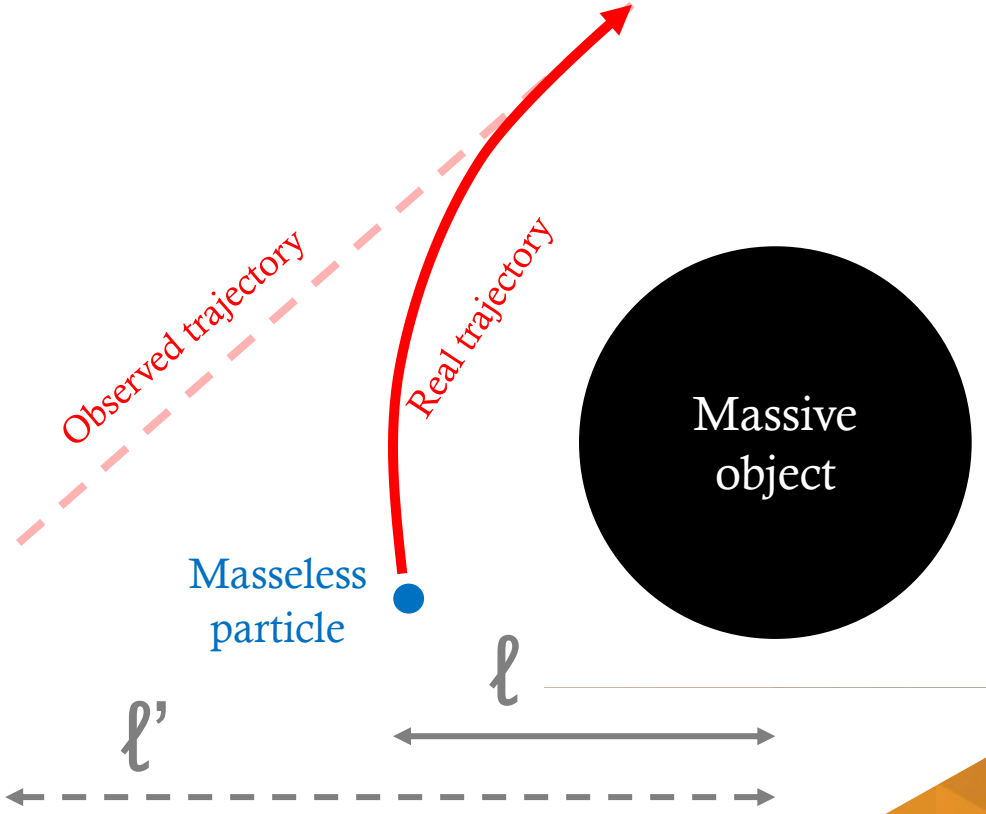


To obtain the neutrino surface, we want $\tau = 2/3$

TIME DILATION



BENDING OF TRAJECTORIES



NEUTRINO SPECTRUM

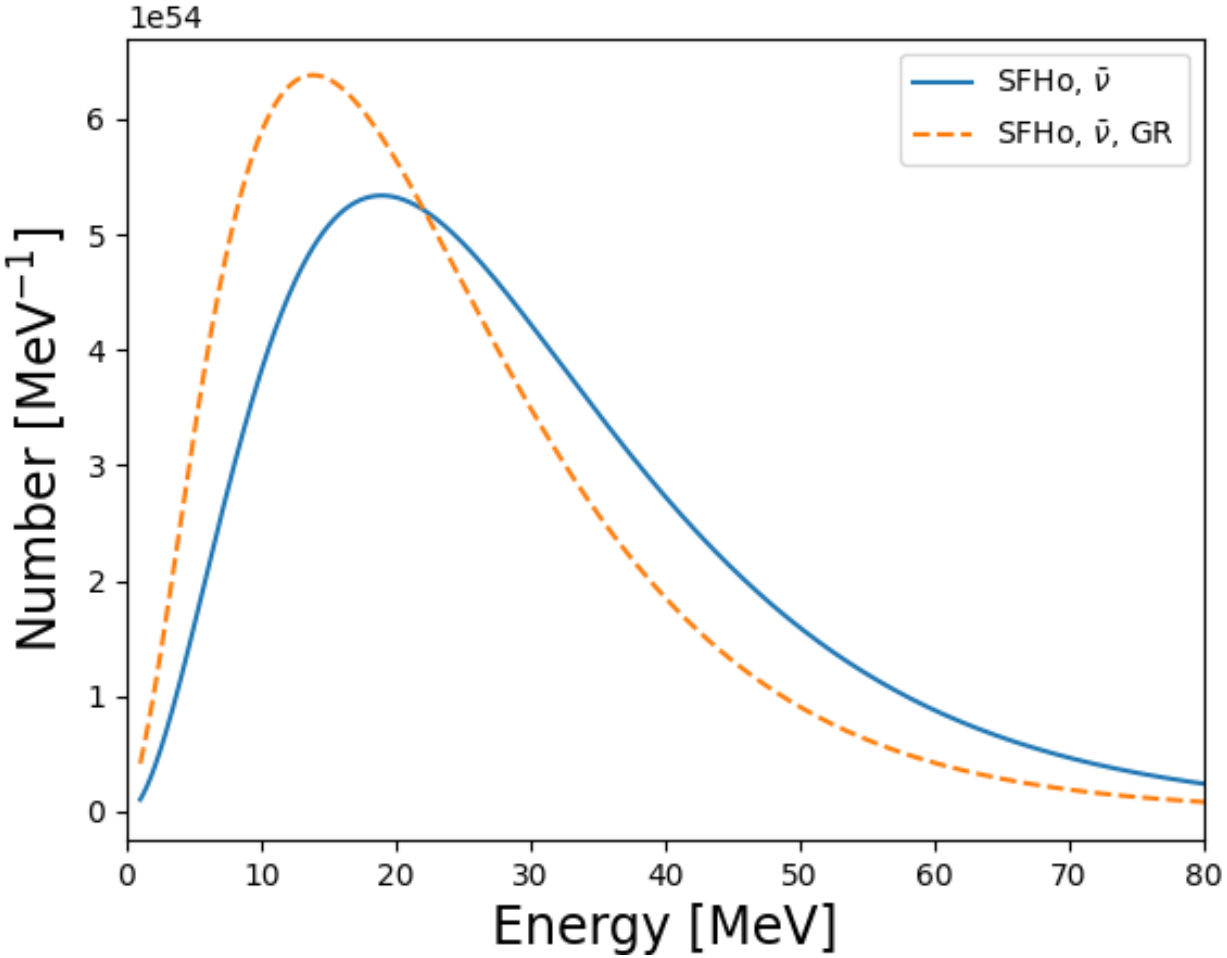
$$\frac{dN}{dE} = \frac{2c}{(\hbar c)^3 4\pi^2} \int \frac{E^2}{e^{E/T} + 1} dAdt$$

Spectrum emitted by a surface element dA close to the massive object

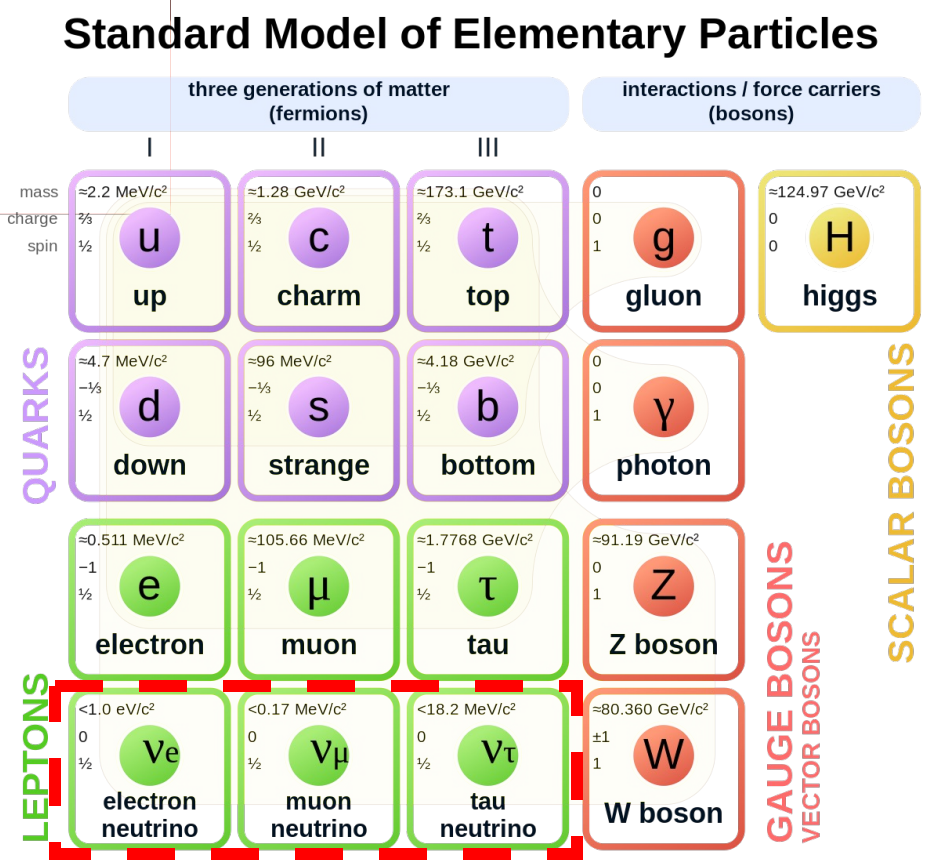
Spectrum emitted by a surface element dA at infinity

$$\frac{dN}{dE} = \frac{2c}{(\hbar c)^3 4\pi^2} \int \frac{E^2(1+z)^2}{e^{E(1+z)/T} + 1} dAdt$$

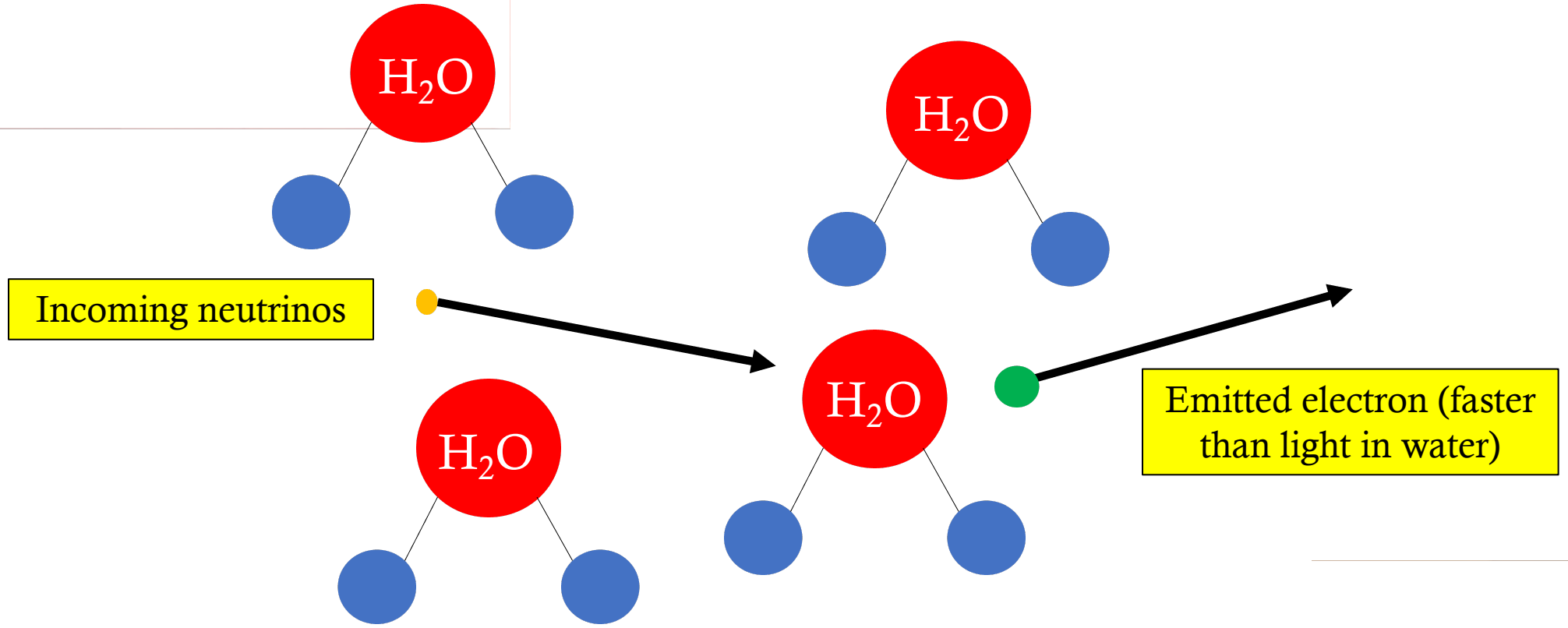
SPECTRUM + GR


1e54
SFHo, $\bar{\nu}$
SFHo, $\bar{\nu}$, GR
Number [MeV^{-1}]
Energy [MeV]
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80

STANDARD MODEL & NEUTRINOS

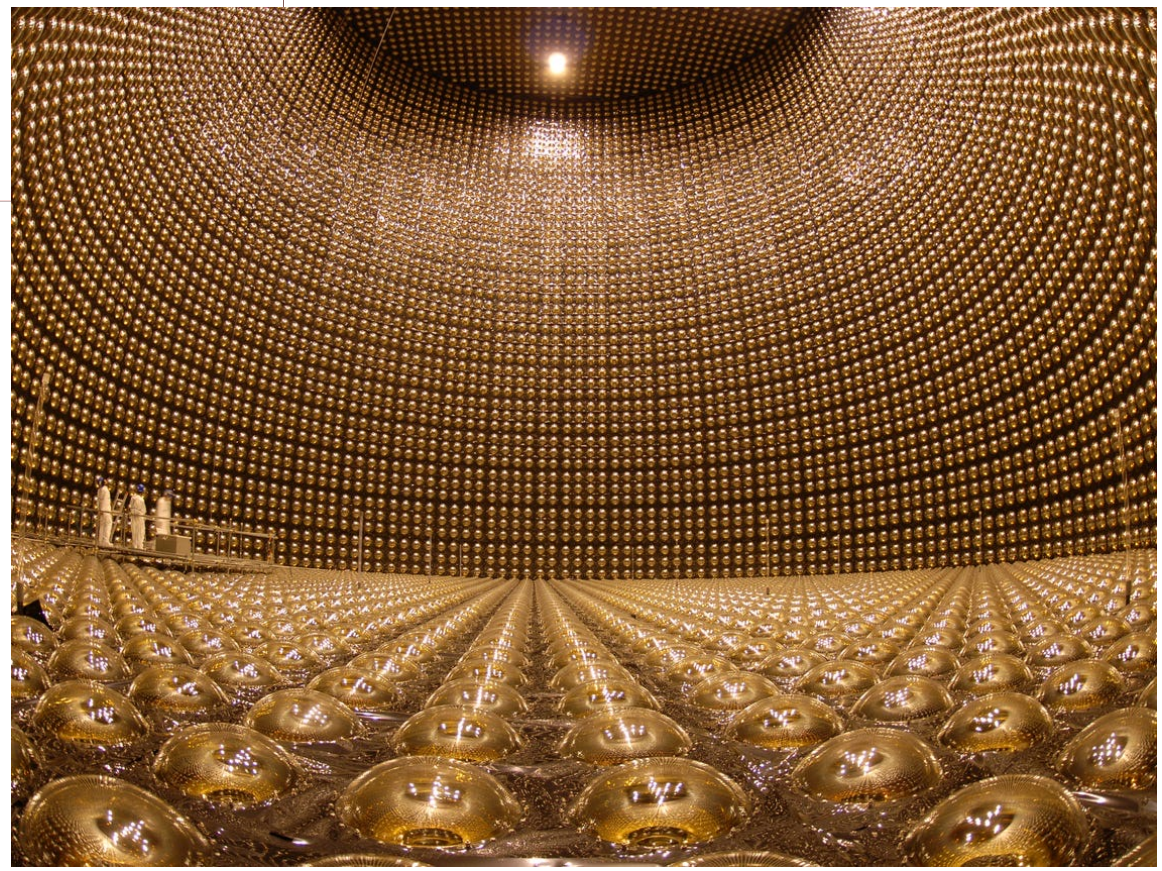


WATER CHERENKOV DETECTORS



SUPER-KAMIOKANDE

32 kt of pure water



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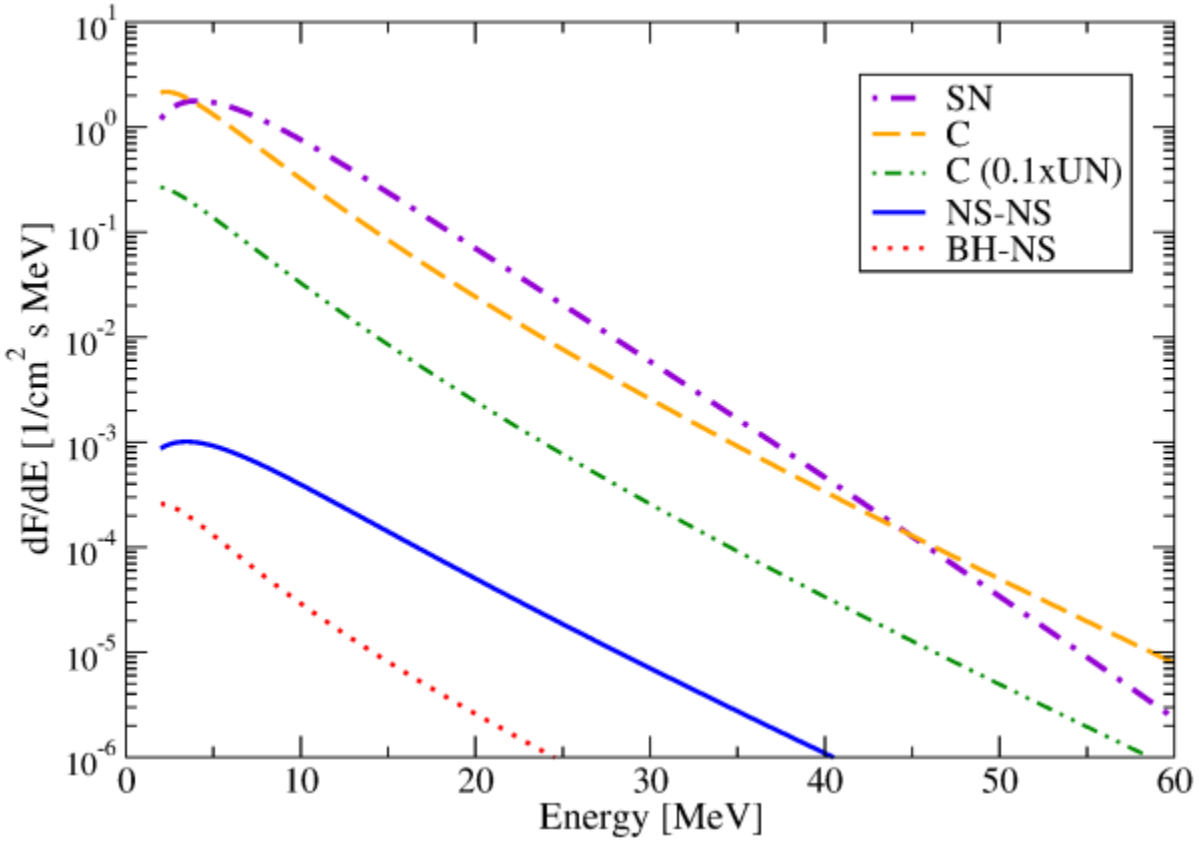
11 129 detectors

DIFFUSE MEV NEUTRINO BACKGROUND



Schilbach et al., 2018

PREDICTION OF DETECTION IN SUPER-KAMIOKANDE