

Supernova Neutrinos

Neutrinos Beyond the Solar System

The Physics of Neutrinos: Progress and Puzzles

The 87th Compton Lecture Series

Enrico Fermi Institute, University of Chicago



Andrew T. Mastbaum

The Physics of Neutrinos: Progress and Puzzles

The 87th Compton Lecture Series

Agenda



March 31	Little, Neutral, Mysterious: An Introduction to Neutrino Physics
April 7	Lost and Found: Solar Neutrinos and Oscillations
April 14	Supernova Neutrinos: Neutrinos From the Beyond the Solar System
April 21	Neutrinos in Cosmology (Dr. Marco Raveri, KICP)
April 28	Neutrino Physics at Nuclear Reactors
May 5	How Small Is Small? Neutrino Mass and Neutrinoless Double-Beta
May 12	How Many Neutrinos Are There? Sterile Neutrinos
May 19	Long-Baseline Neutrino Oscillations and CP Violation
May 26	<i>No lecture</i>
June 2	Where We Are/Where We're Going: Open Questions and Future

Supernovae & Neutrinos

Supernova

Supernova



**Extremely
powerful
explosion**

Most powerful nuclear
bomb ever tested

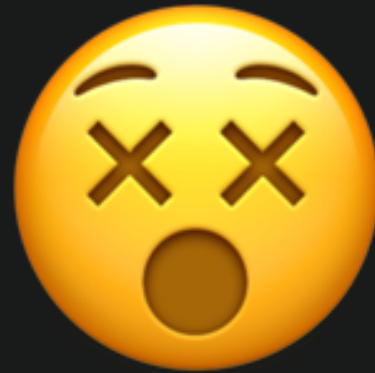
× 1,000,000,000,000,000,000,000,000,000
(a billion billion billion)

Supernova



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× 1,000,000,000,000,000,000,000,000,000
(a billion billion billion)



**The death
of a
large star**

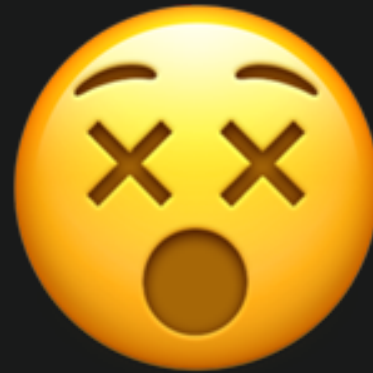
When stars eventually
run out of their
nuclear fuel

Supernova



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**The death
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When stars eventually
run out of their
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**Produce
heavy
elements**

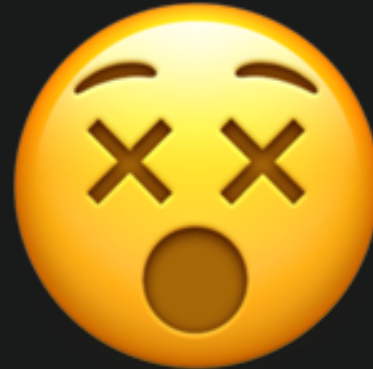
A source of heavy elements
essential to form planets,
galaxies, people, etc.

Supernova



**Extremely
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Most powerful nuclear
bomb ever tested
 $\times 1,000,000,000,000,000,000,000,000,000$
(a billion billion billion)



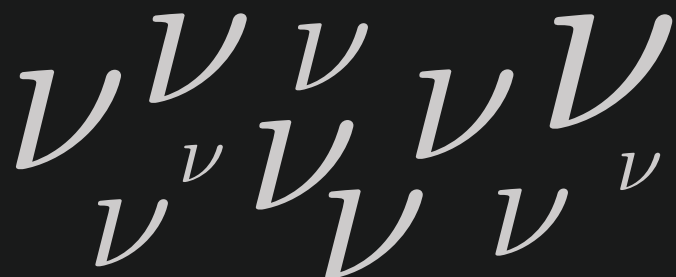
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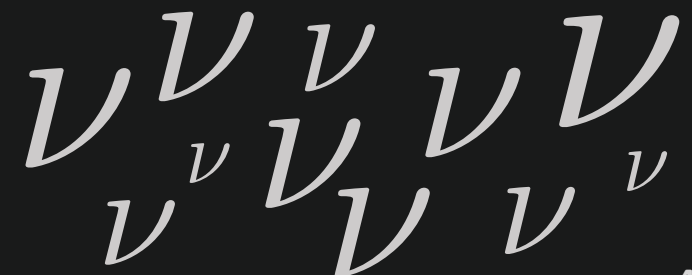


**Produce
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A source of heavy elements
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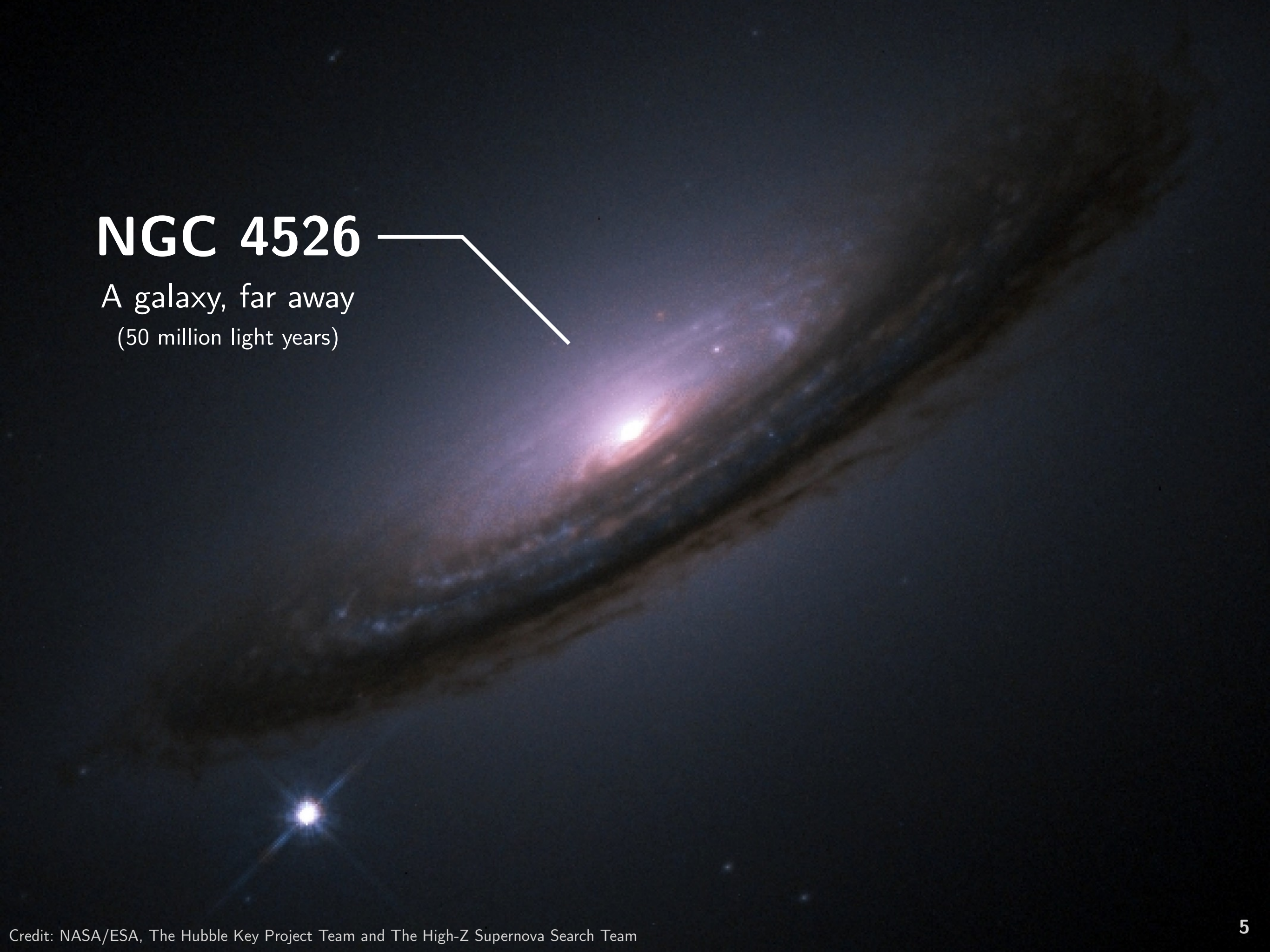
Plus: Oodles of neutrinos!





NGC 4526

A galaxy, far away
(50 million light years)





NGC 4526

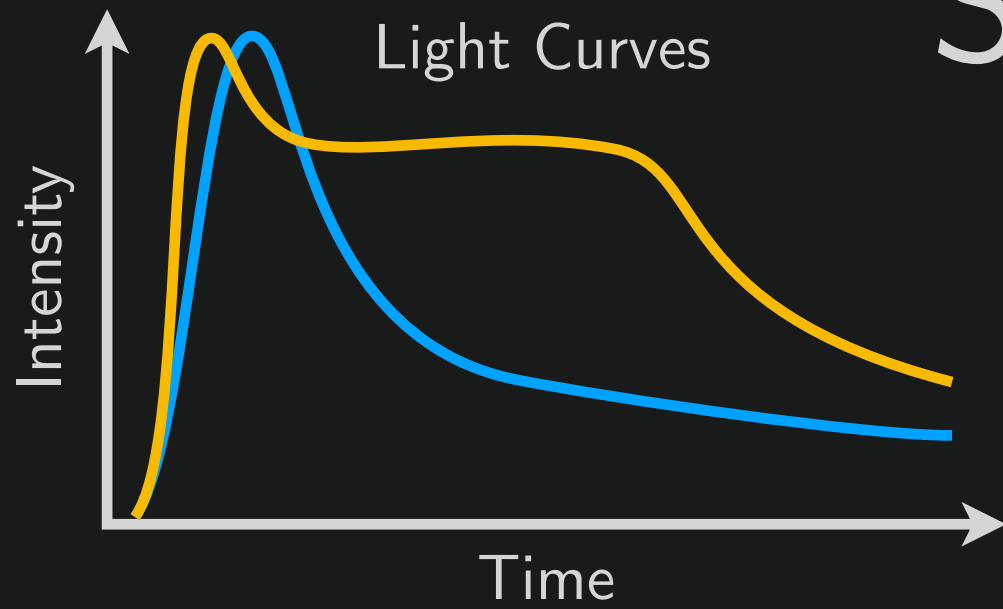
A galaxy, far away
(50 million light years)

Supernova 1994D

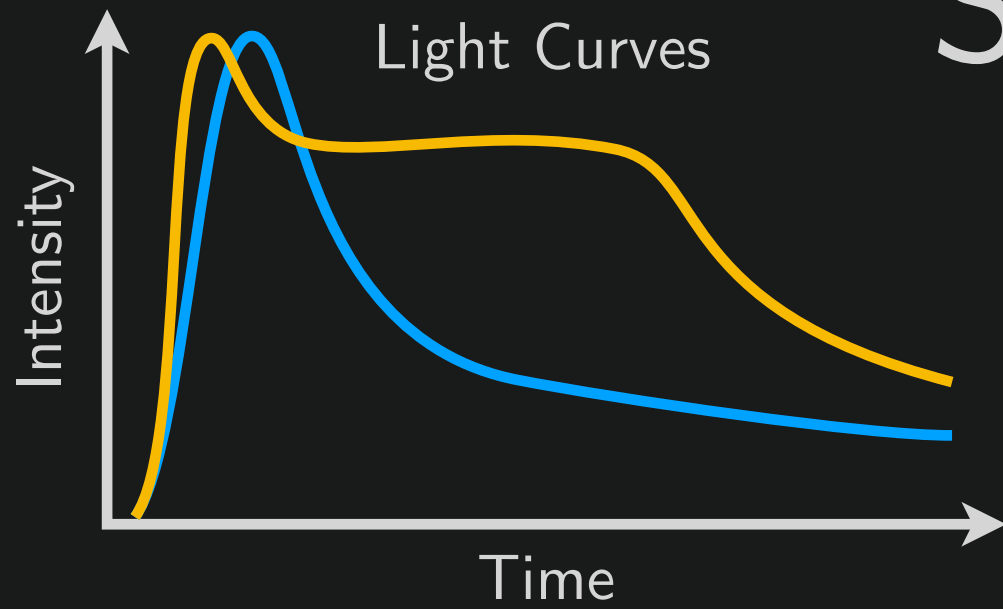
Type Ia Supernova

Supernova Taxonomy

Supernova Taxonomy

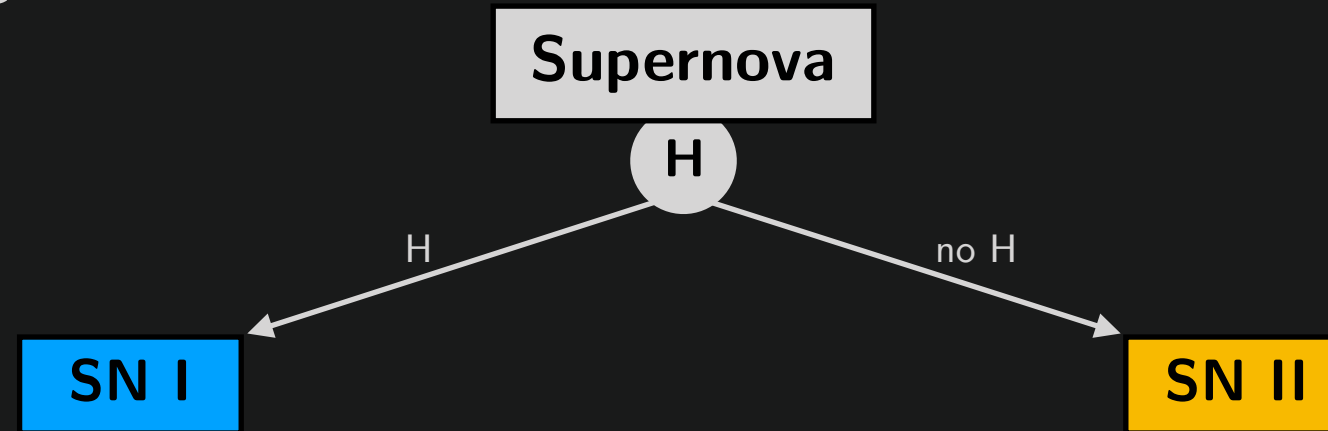
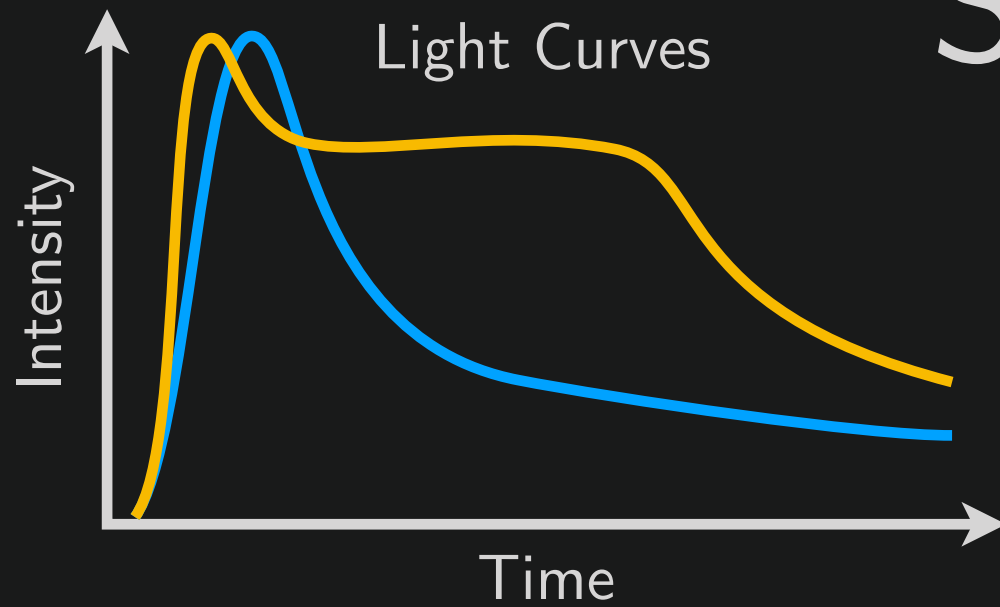


Supernova Taxonomy

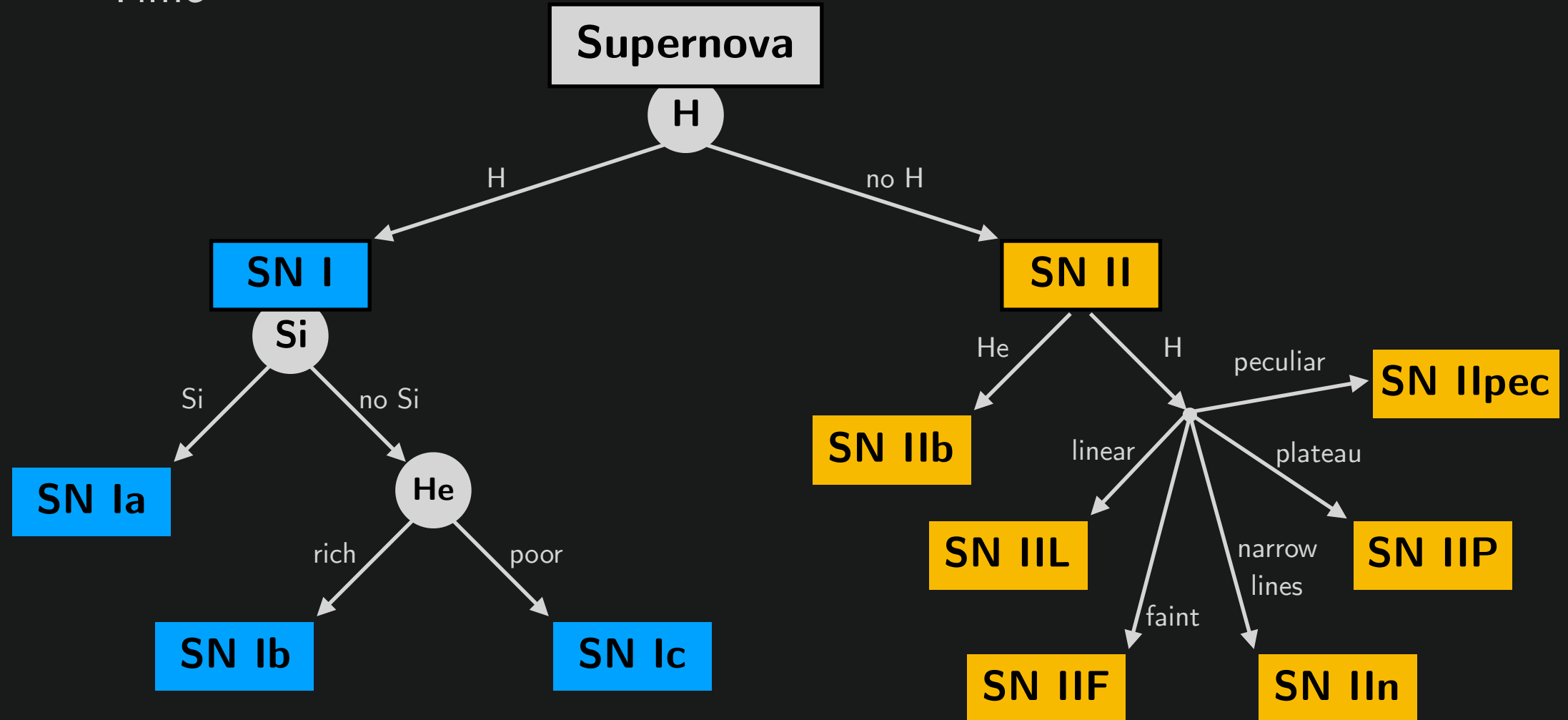
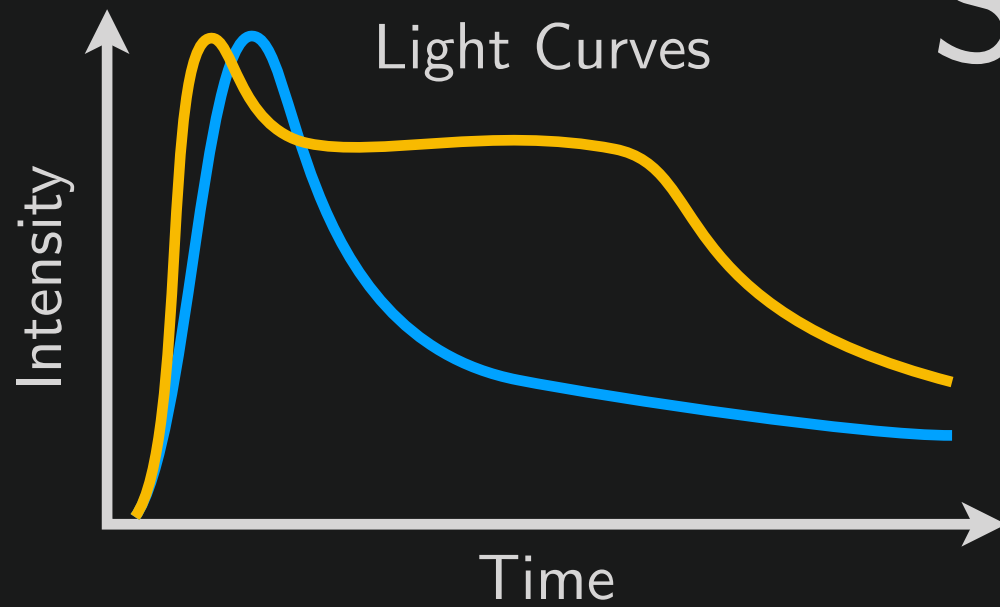


Supernova

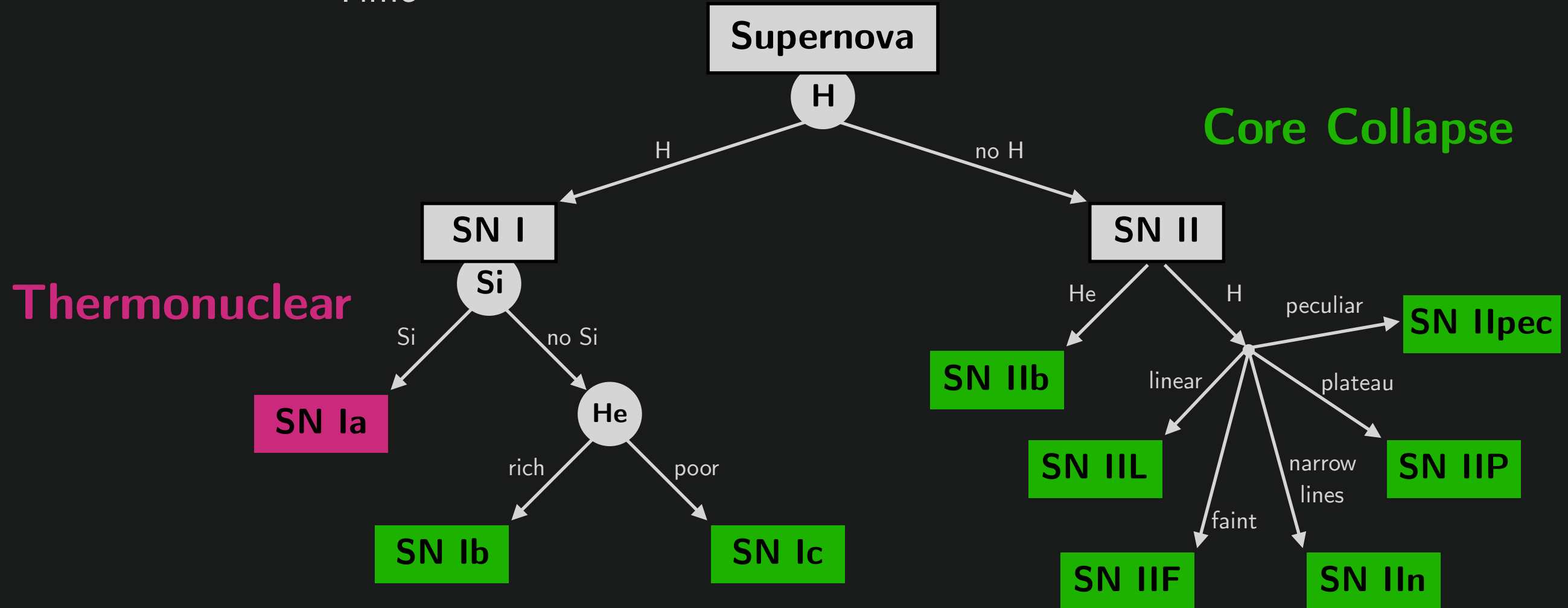
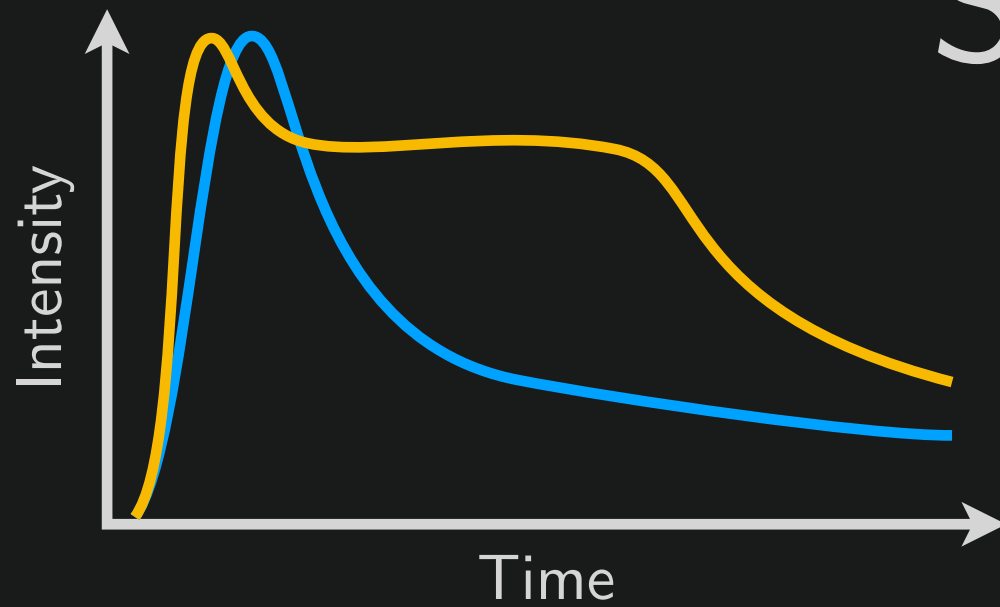
Supernova Taxonomy



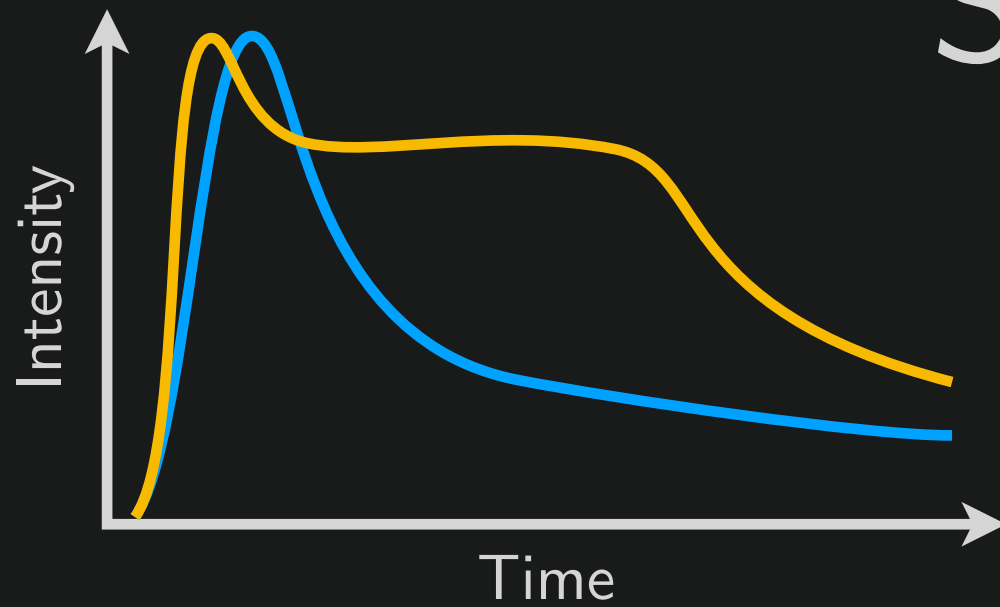
Supernova Taxonomy



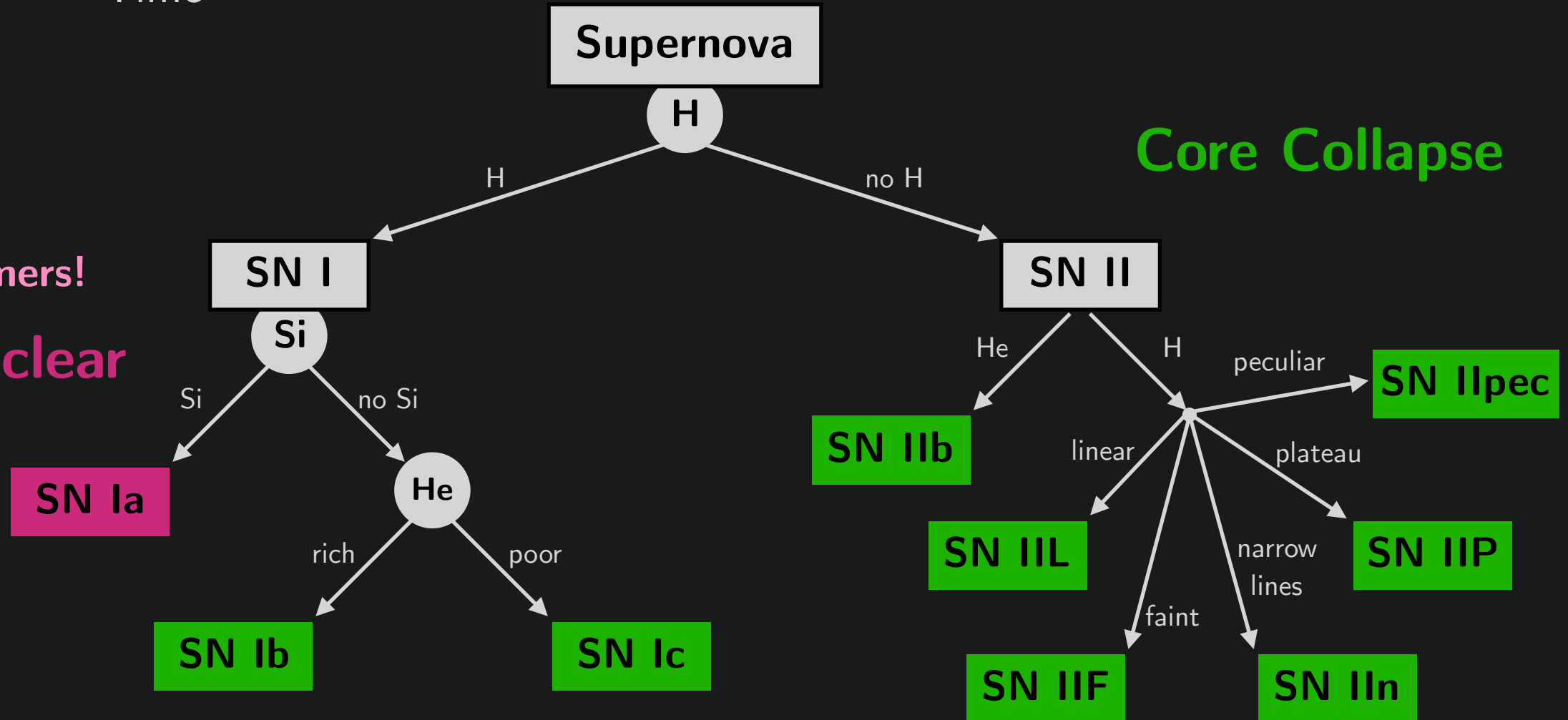
Supernova Taxonomy



Supernova Taxonomy

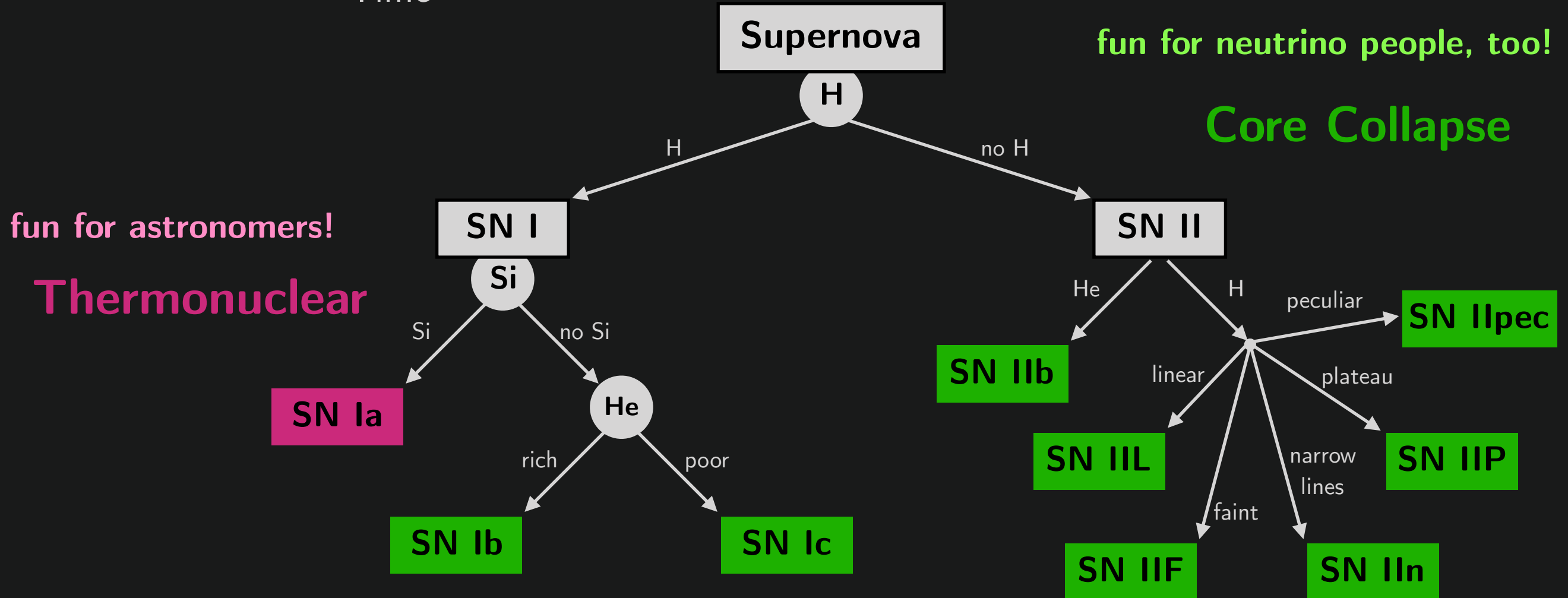
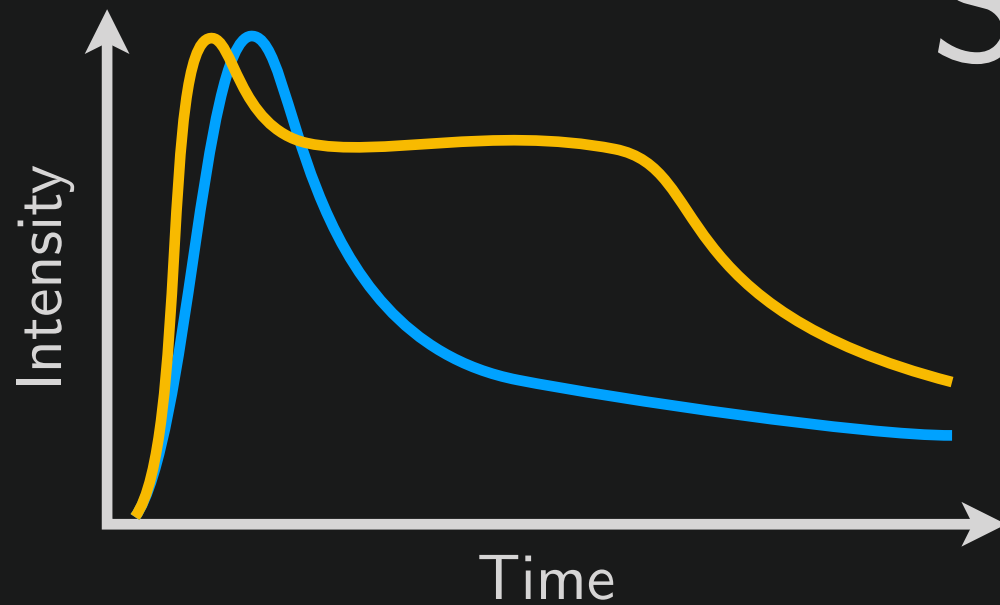


fun for astronomers!
Thermonuclear



Core Collapse

Supernova Taxonomy



Core-Collapse Supernovae



**Extremely
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Most powerful nuclear
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× 1,000,000,000,000,000,000,000,000,000
(a billion billion billion)

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Before



After



Credit: David Malin, Anglo-Australian Observatory

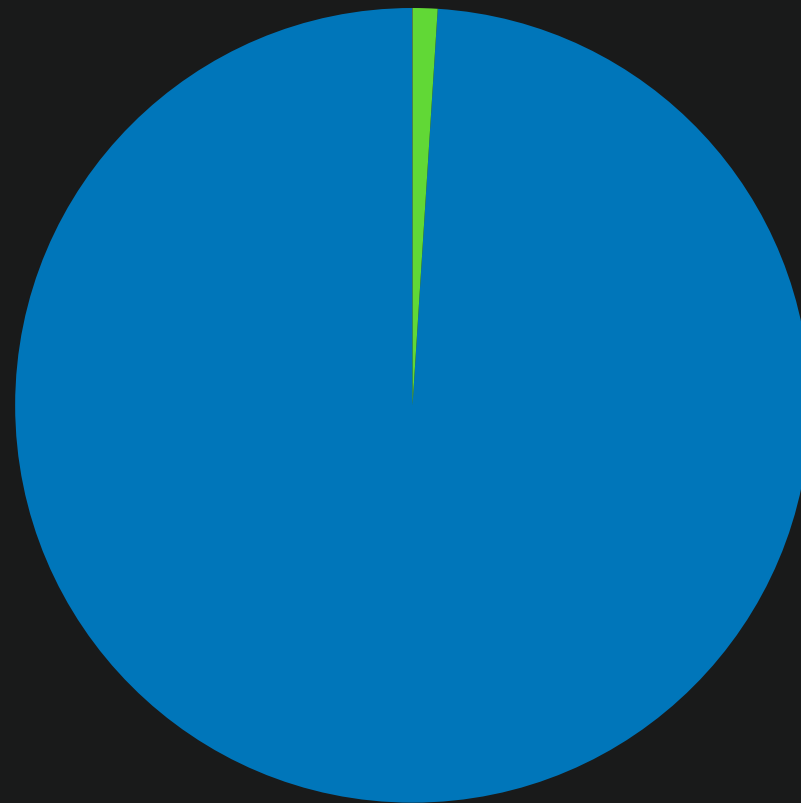
Core-Collapse Supernovae



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Supernova Energy Loss

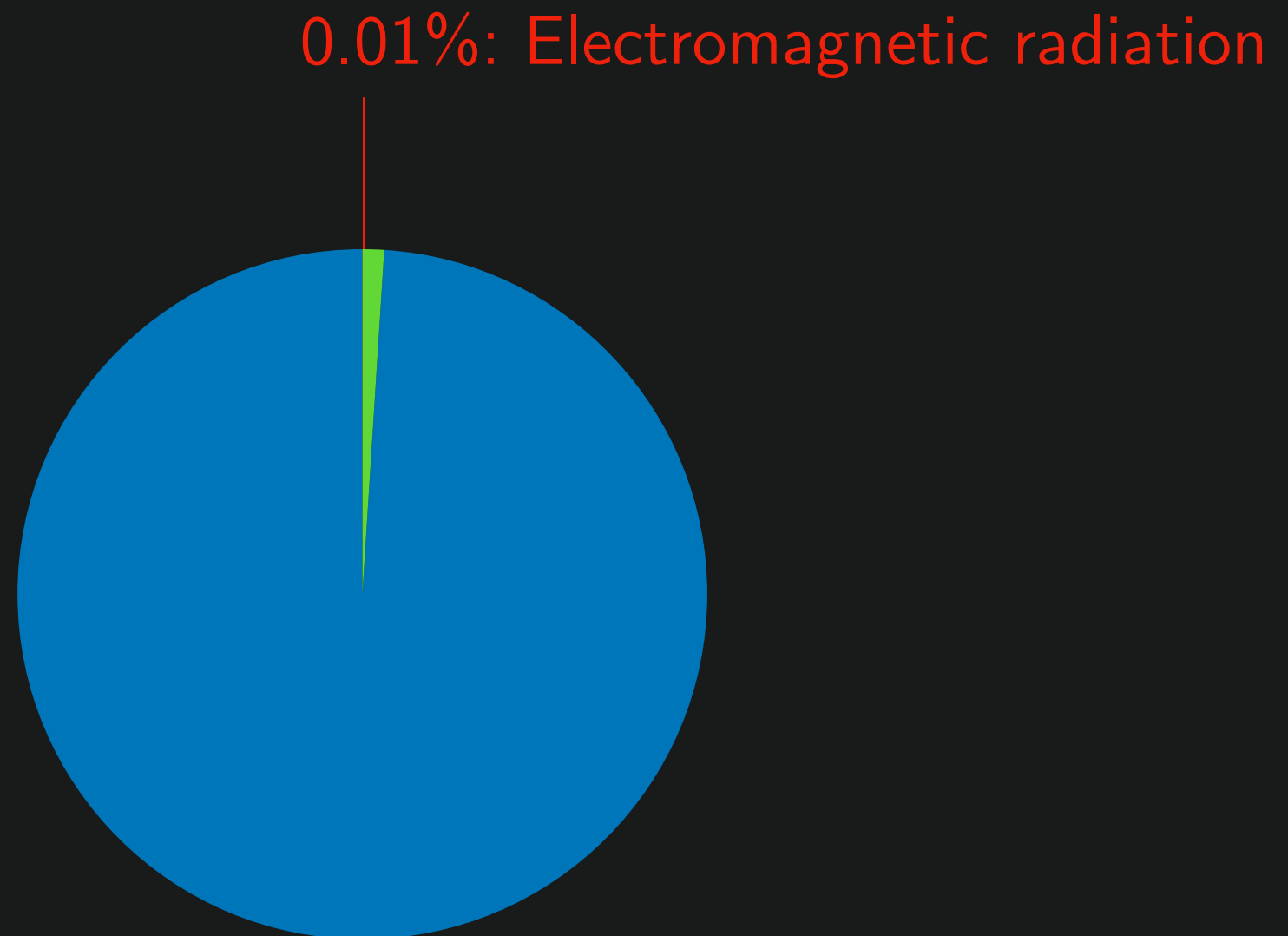
Core-Collapse Supernovae



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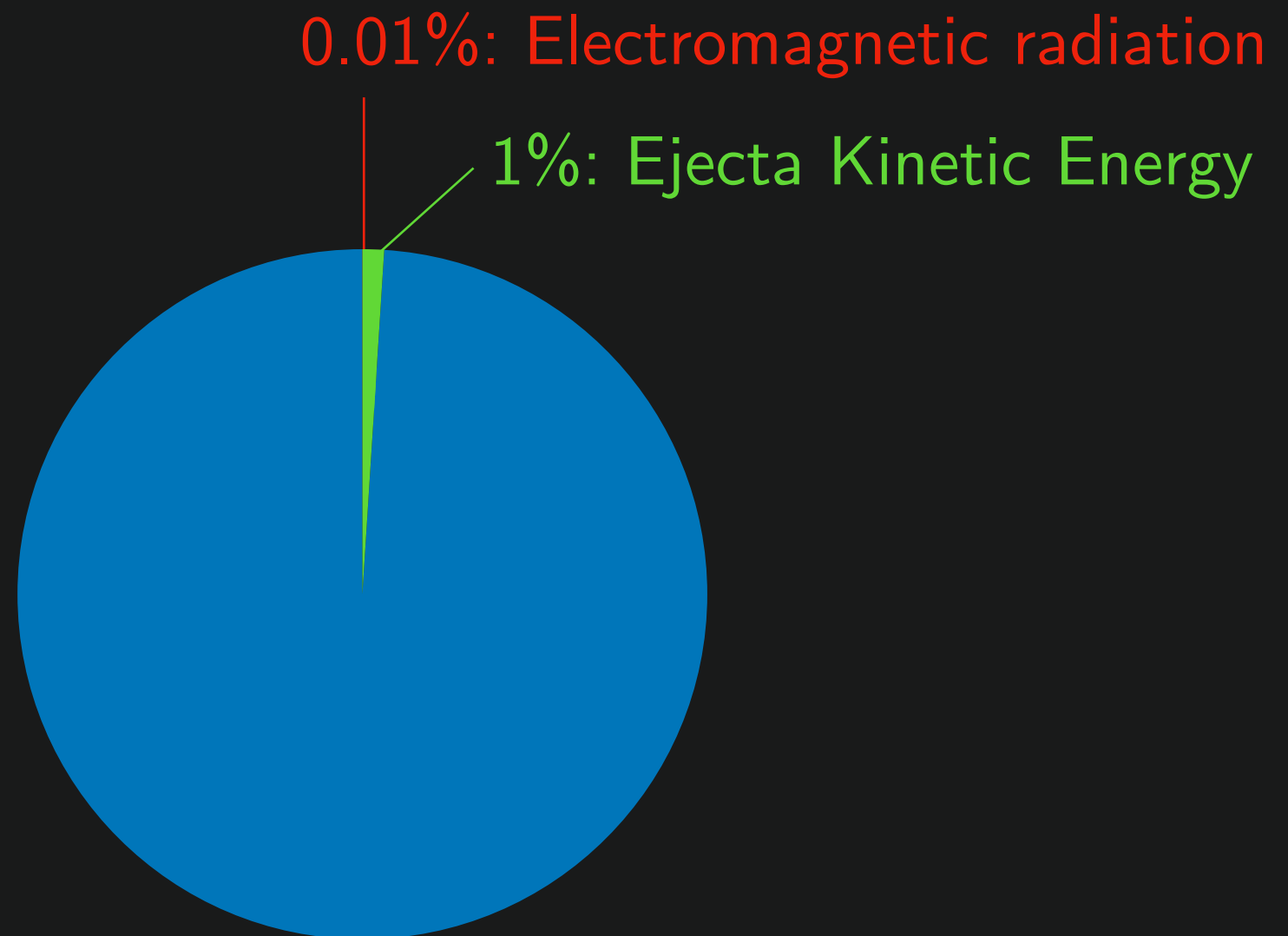
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Supernova Energy Loss

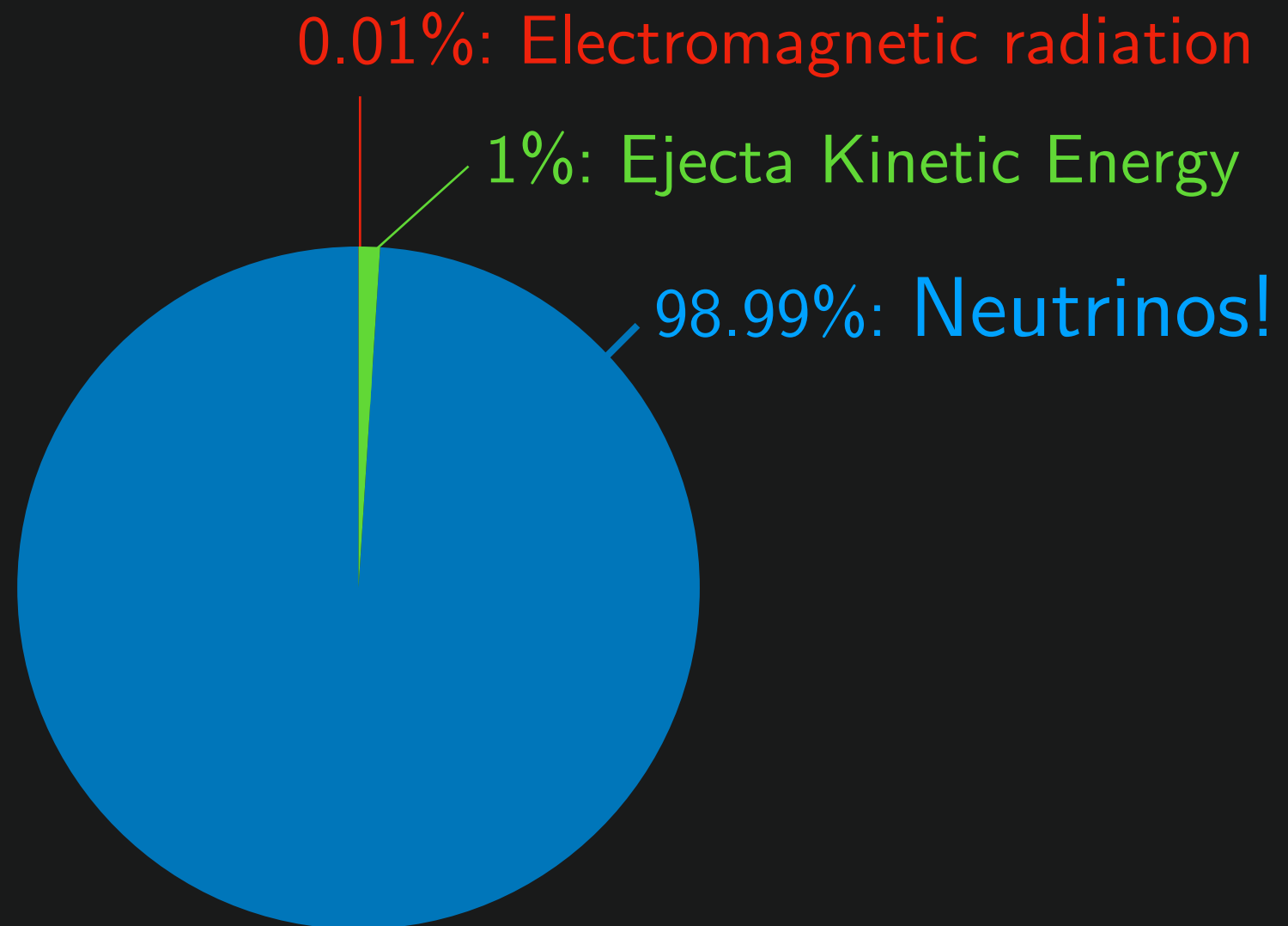
Core-Collapse Supernovae



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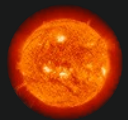


Supernova Energy Loss

A Giant Star

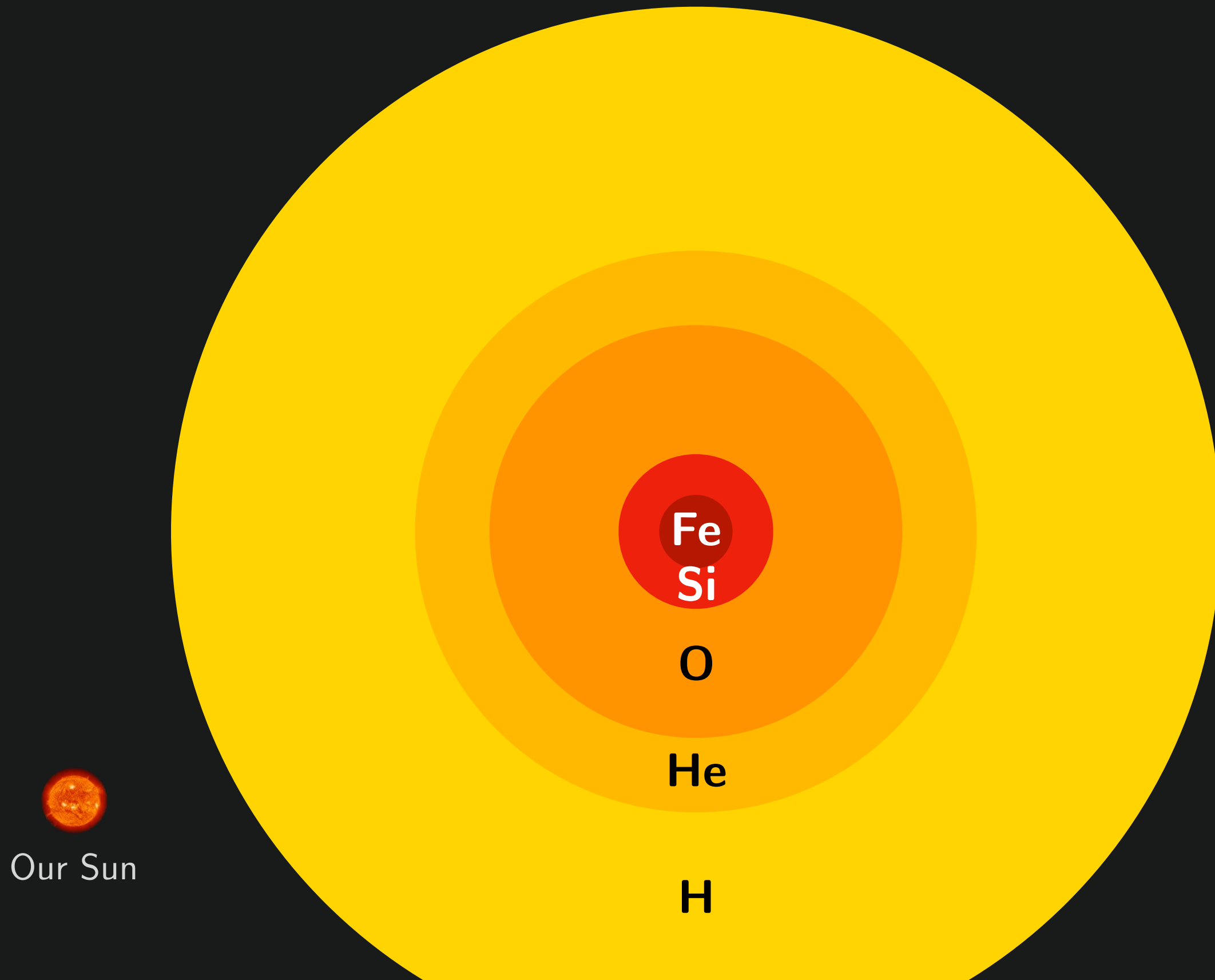


A Giant Star

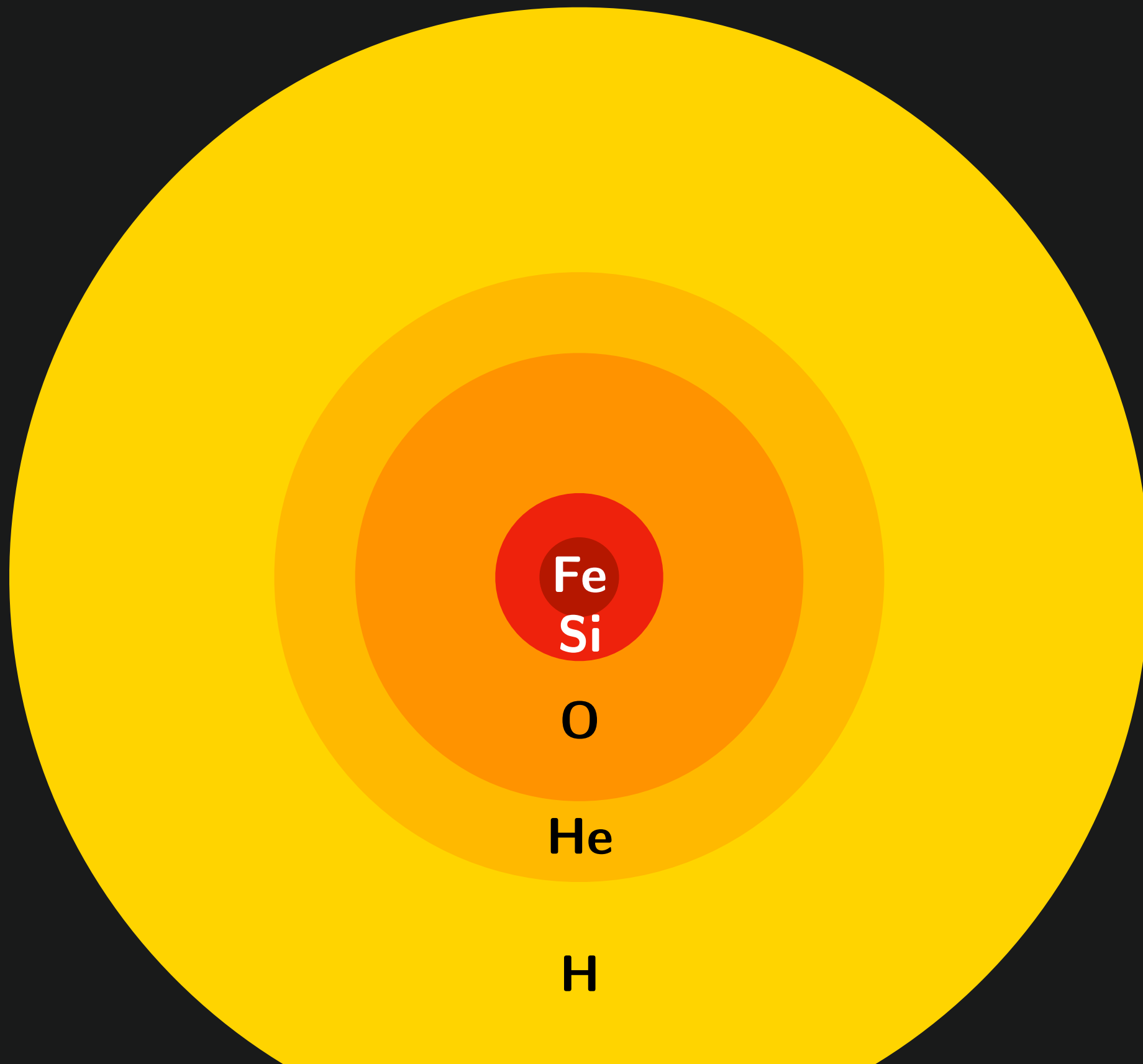


Our Sun

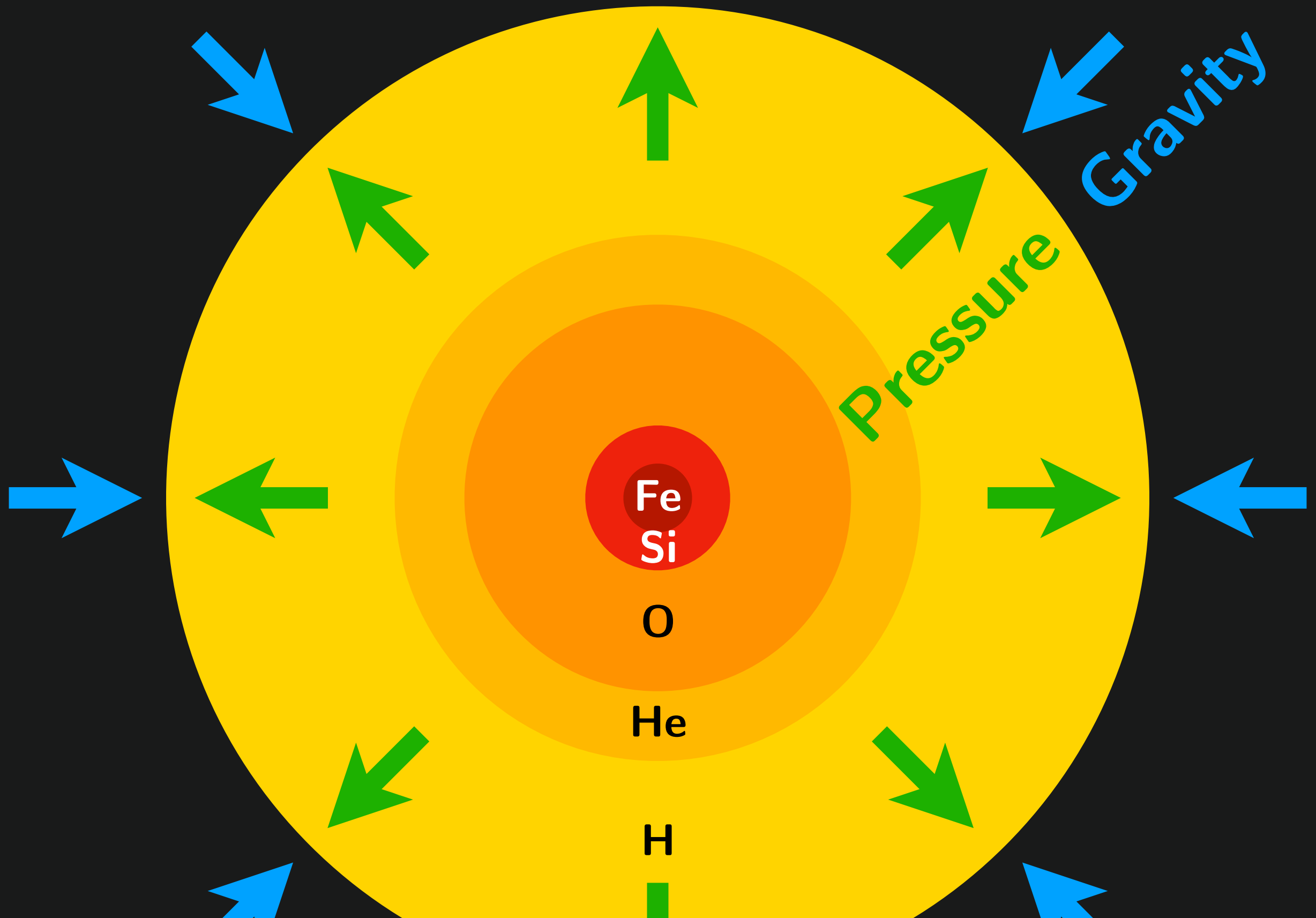
A Giant Star



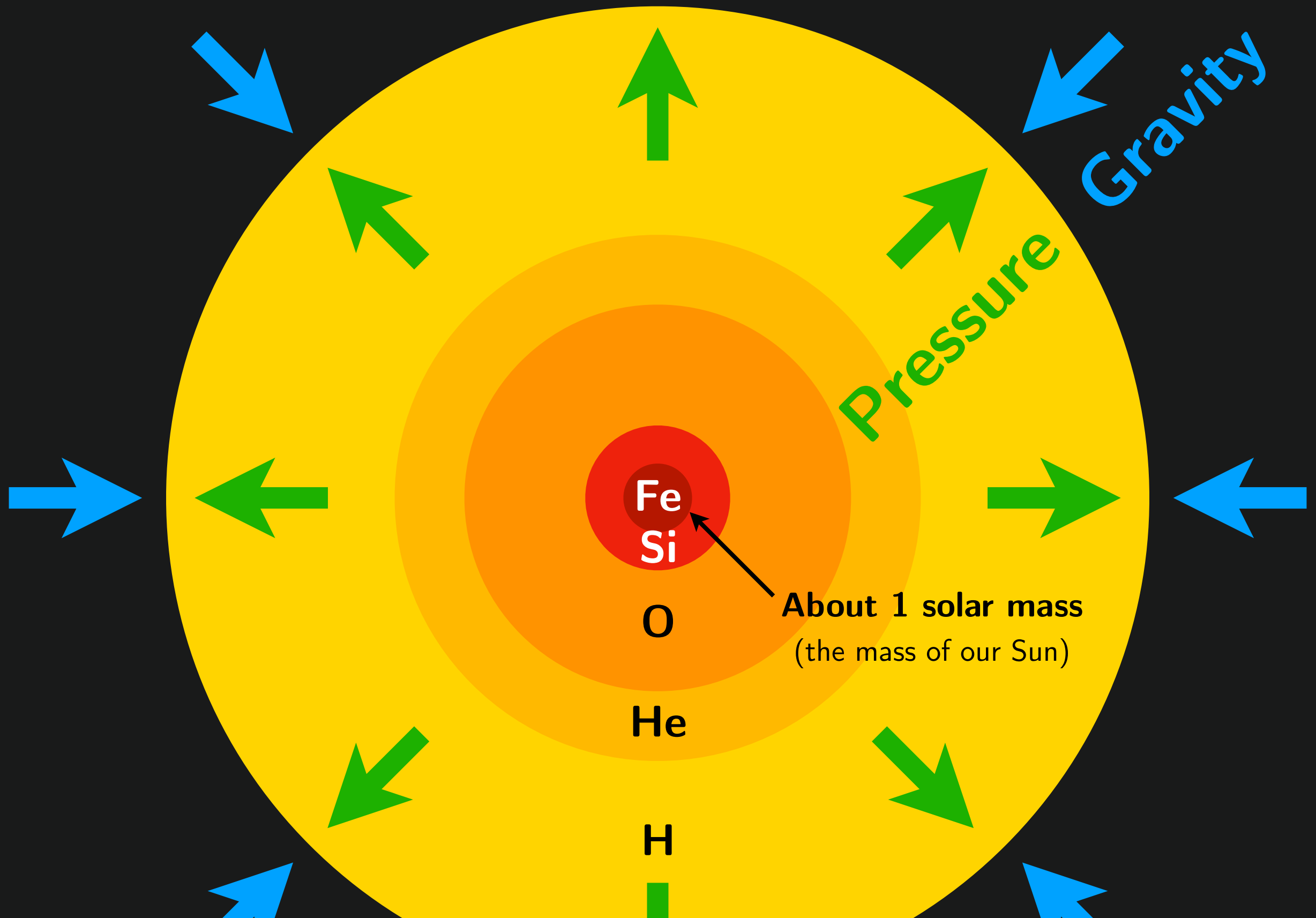
A Giant Star in Trouble



A Giant Star in Trouble



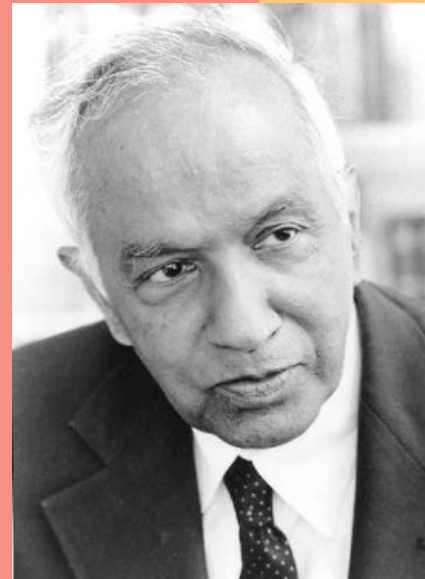
A Giant Star in Trouble



Fe

The Chandrasekhar Limit

(c) UChicago

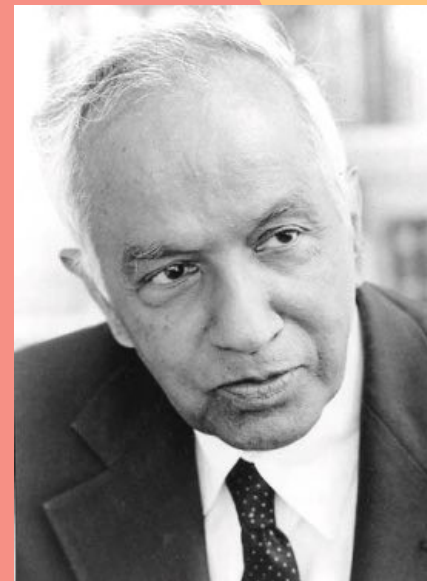


**Subrahmanyan
Chandrasekhar**

Fe

The Chandrasekhar Limit

(c) UChicago



Subrahmanyan
Chandrasekhar

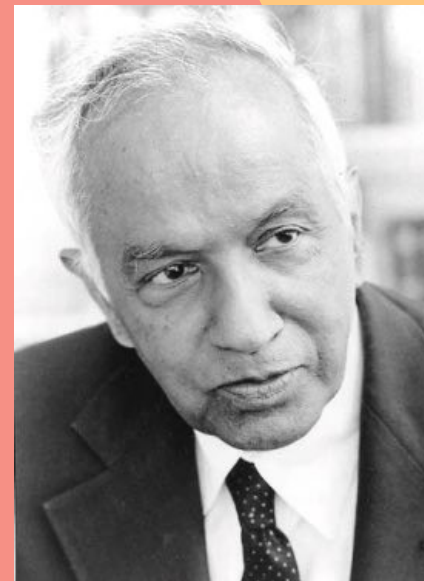


UChicago faculty
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Fe

The Chandrasekhar Limit

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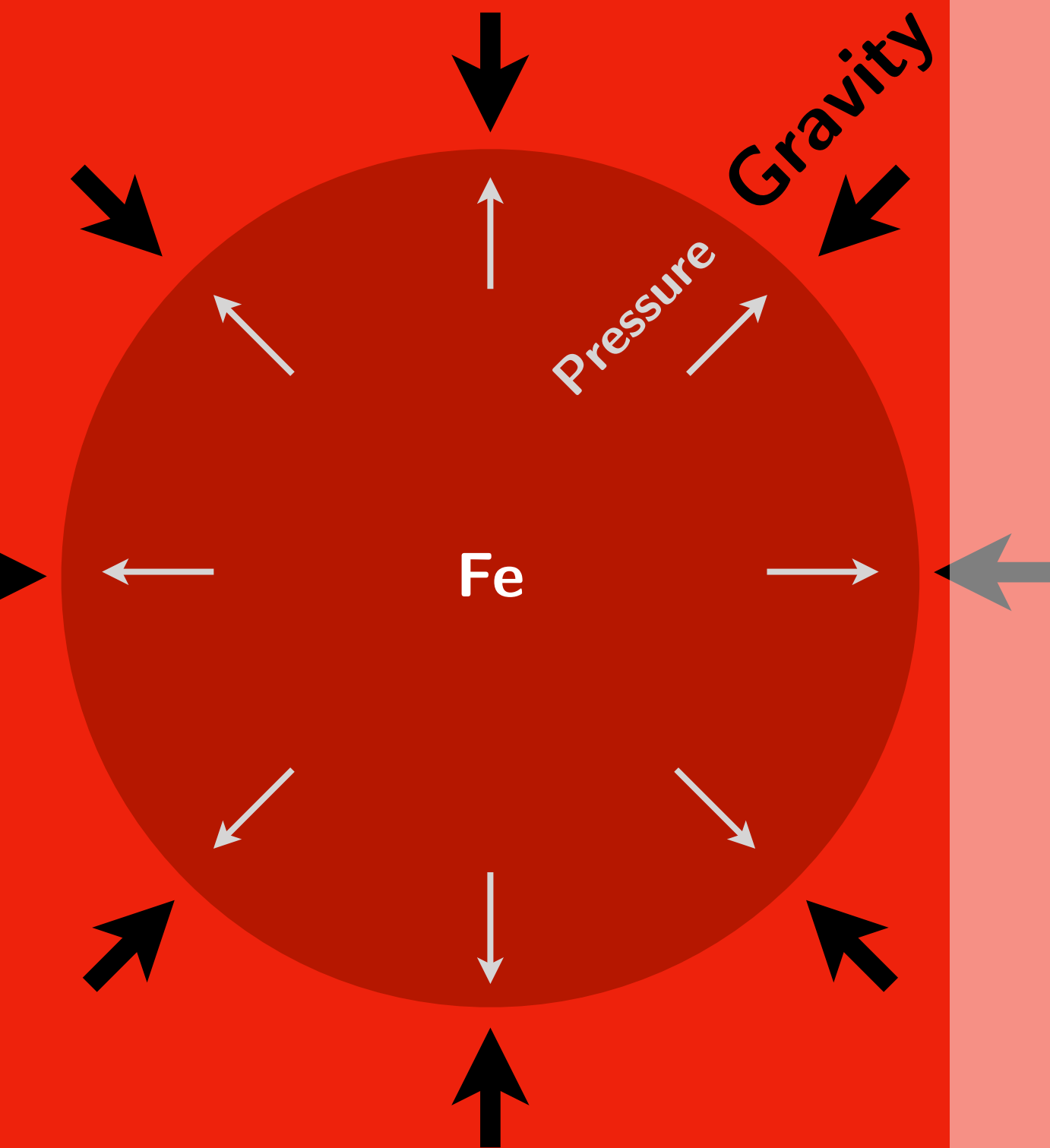


**Subrahmanyan
Chandrasekhar**



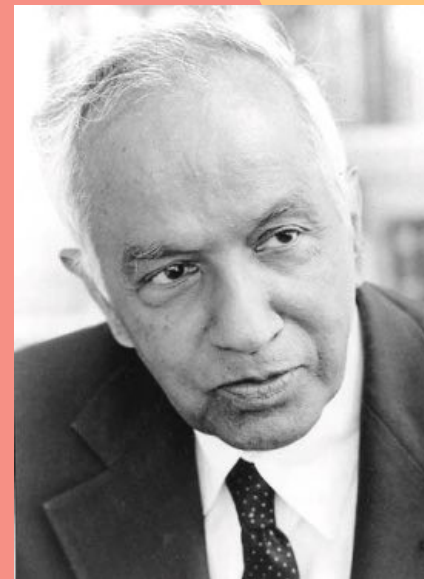
**UChicago faculty
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The Chandrasekhar Limit

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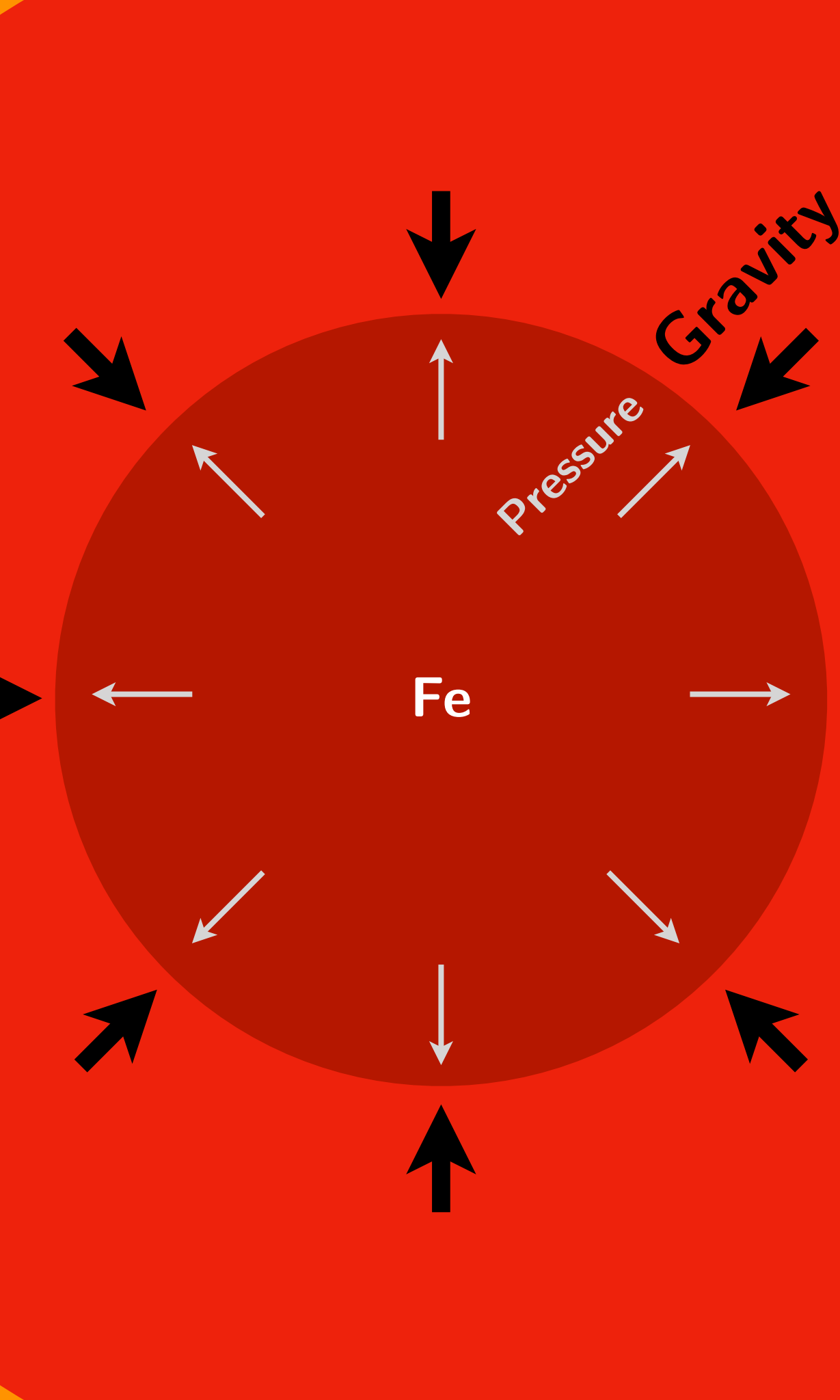


Subrahmanyan
Chandrasekhar



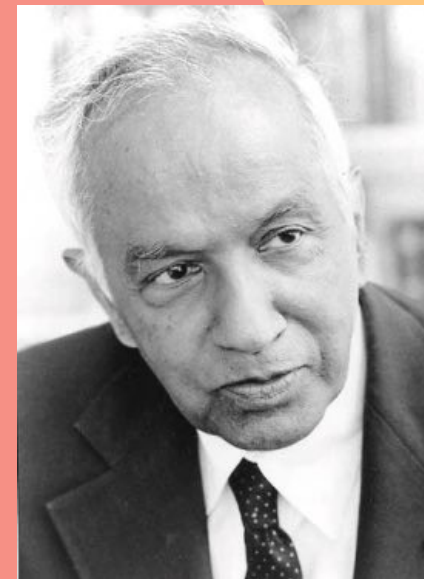
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The Chandrasekhar Limit

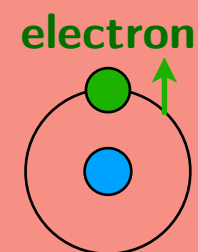
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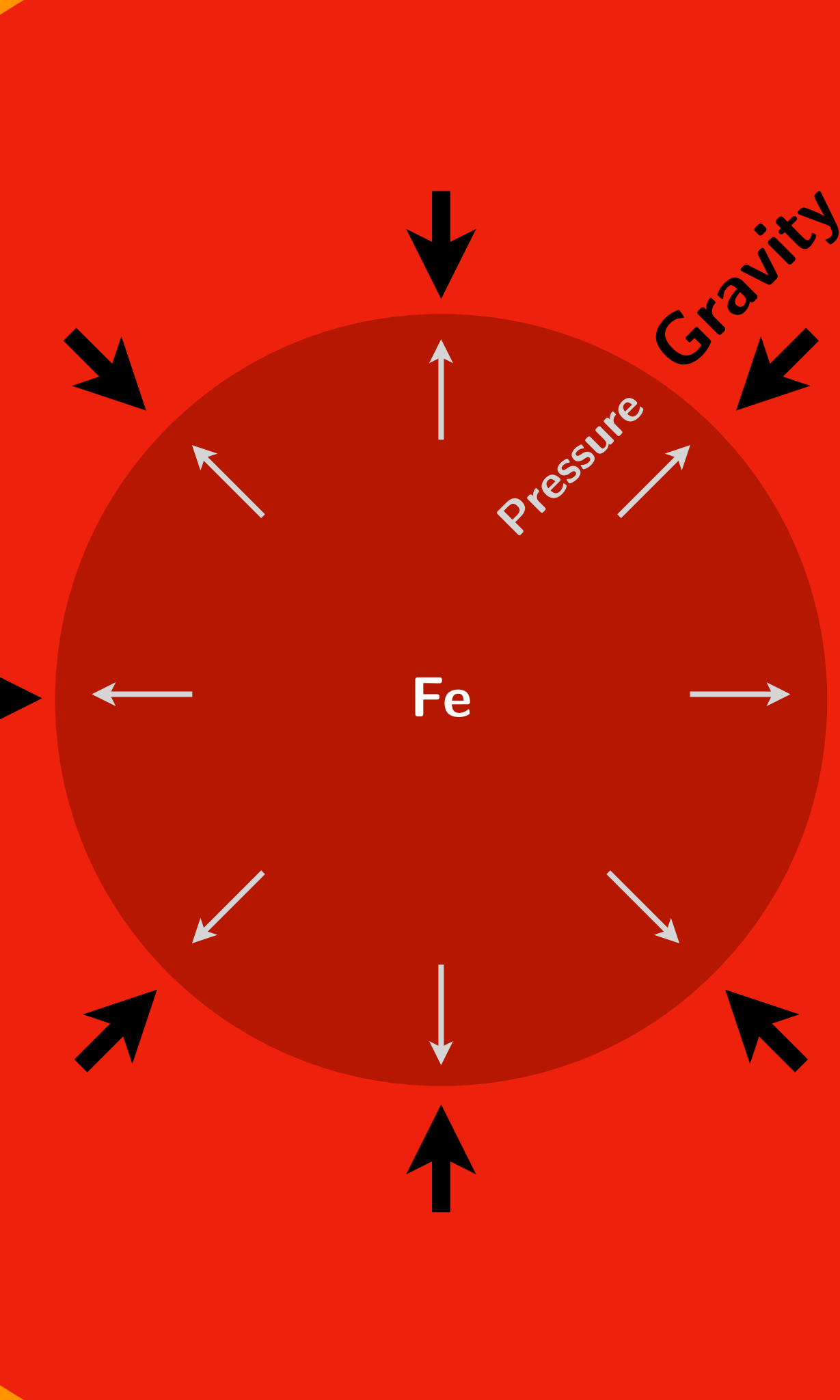
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Chandrasekhar



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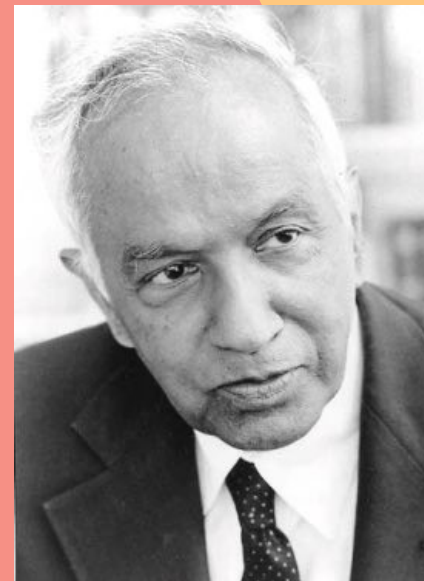


Hydrogen



The Chandrasekhar Limit

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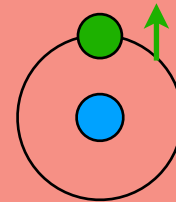
Subrahmanyan
Chandrasekhar



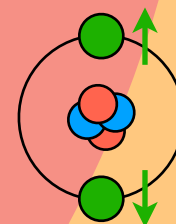
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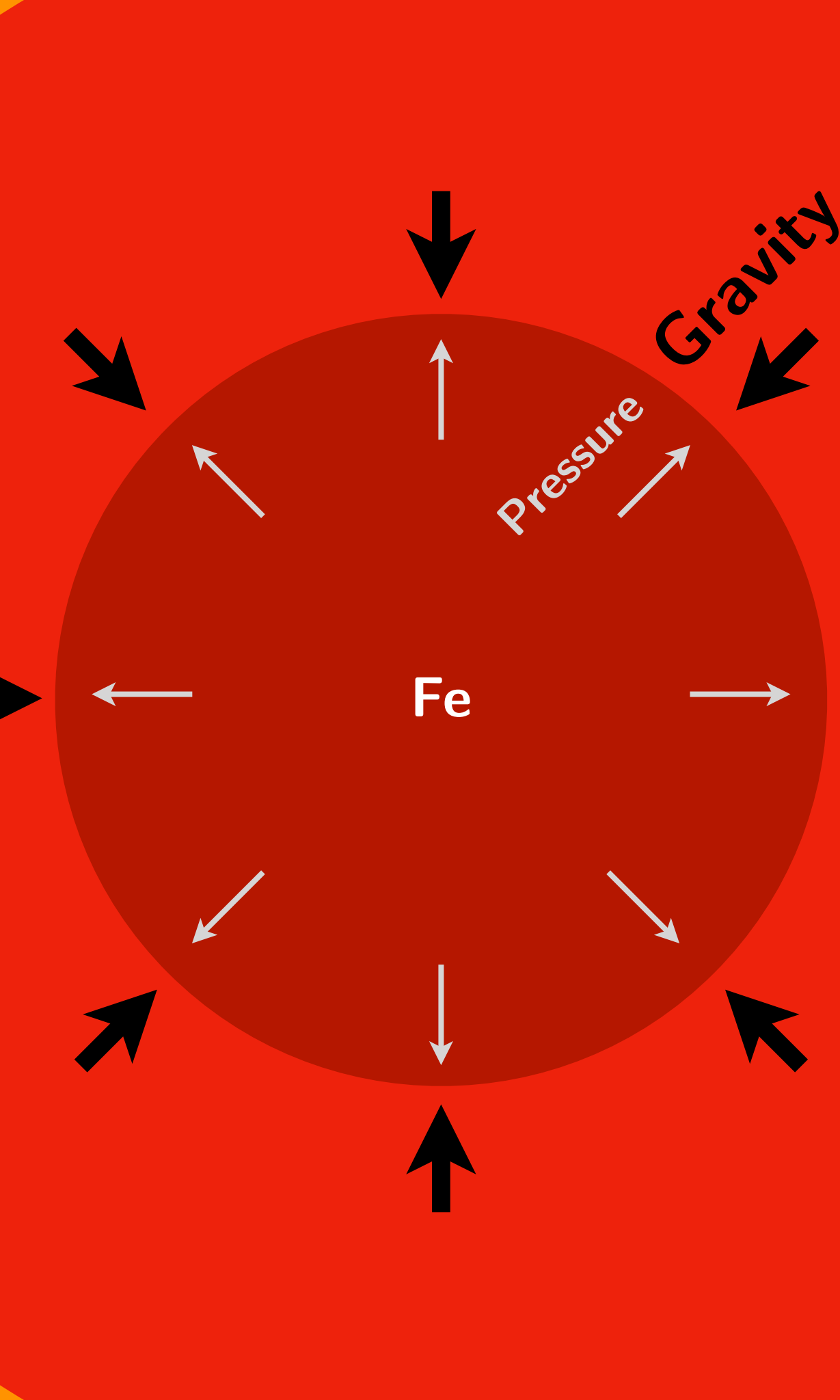
electron



Hydrogen

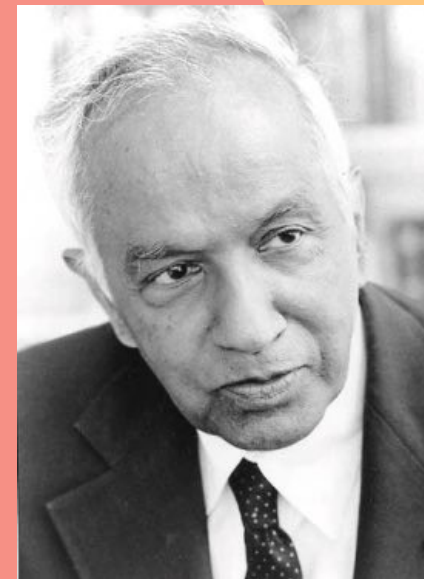


Helium



The Chandrasekhar Limit

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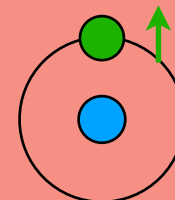
Subrahmanyan
Chandrasekhar



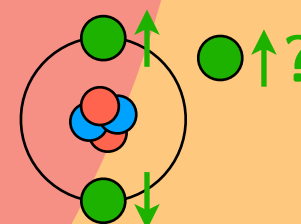
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electron

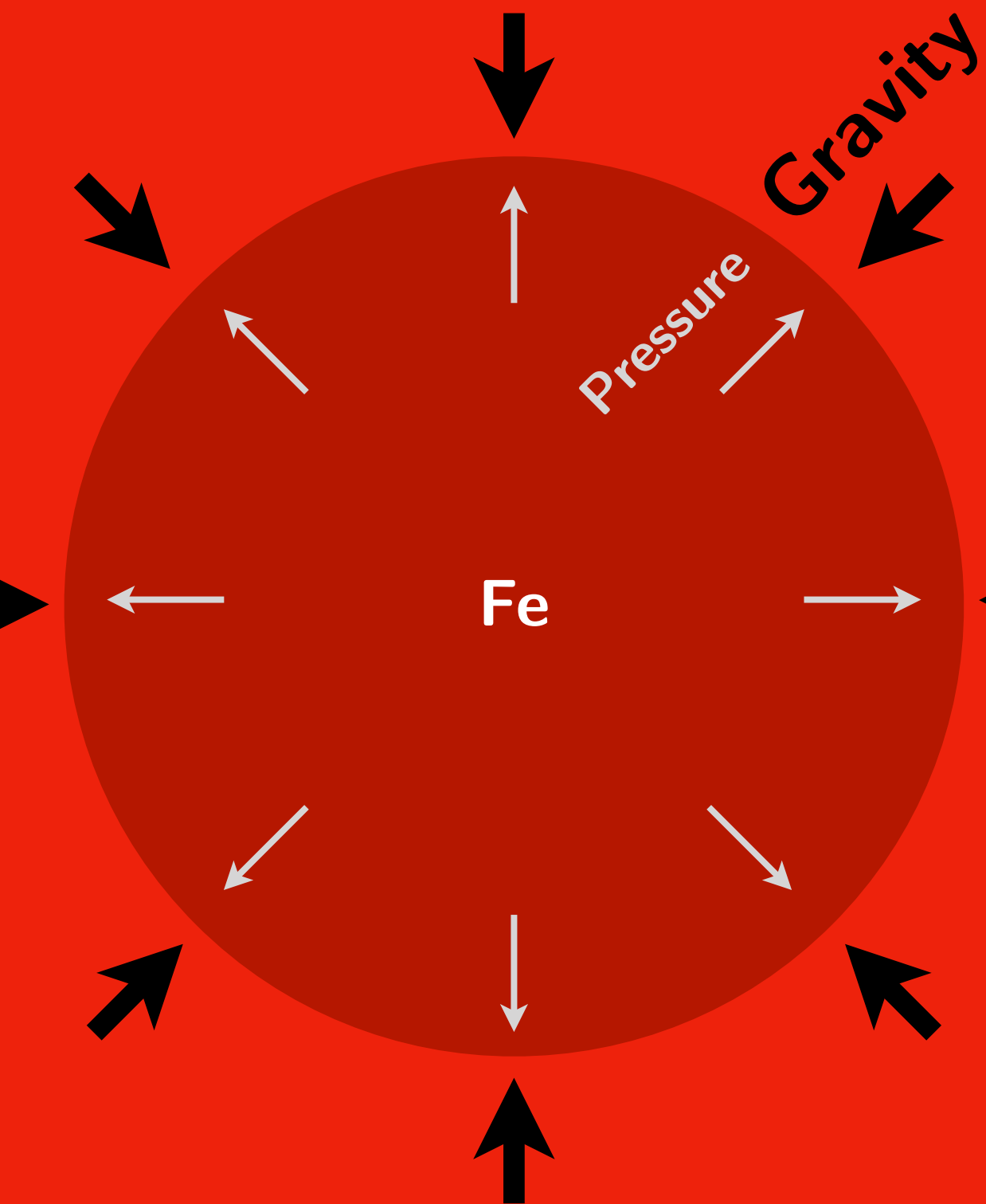


Hydrogen



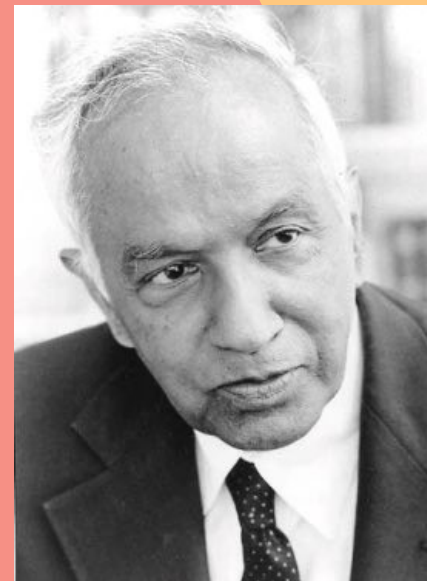
Helium

Pauli Exclusion Principle



The Chandrasekhar Limit

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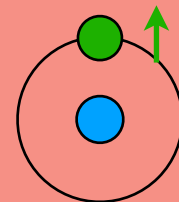
Subrahmanyan
Chandrasekhar



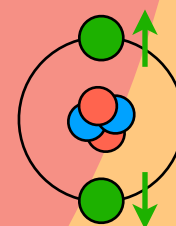
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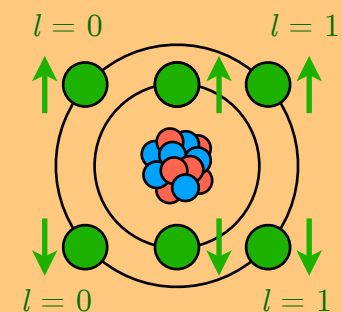
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Hydrogen

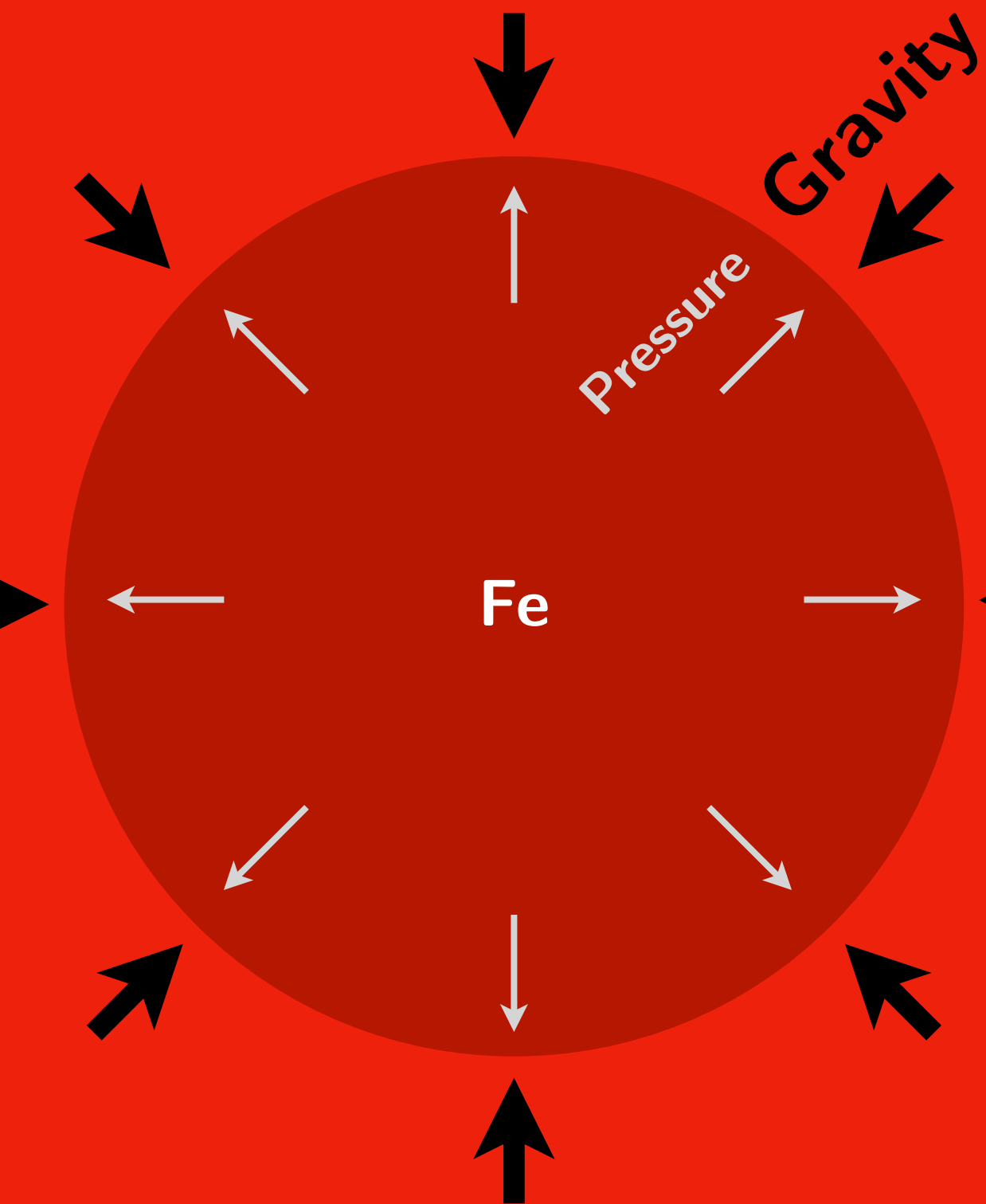


Helium



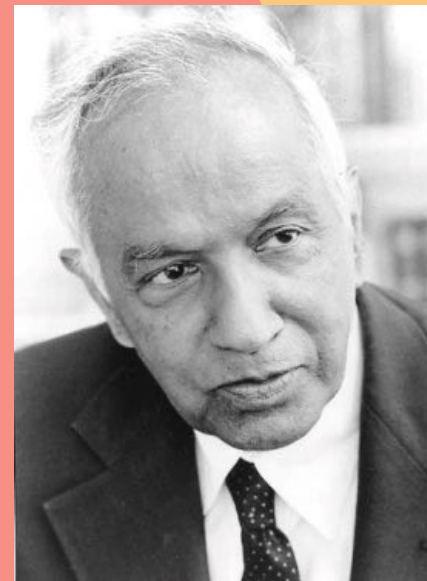
Carbon

Pauli Exclusion Principle



The Chandrasekhar Limit

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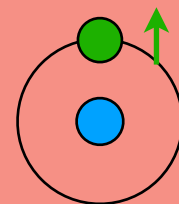
Subrahmanyan
Chandrasekhar



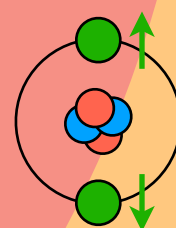
UChicago faculty
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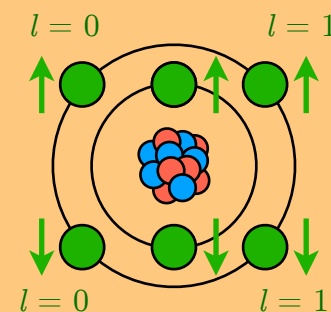
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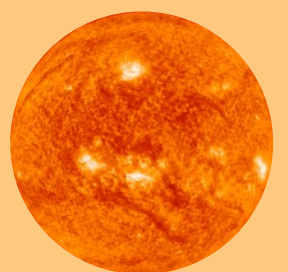
Hydrogen



Helium

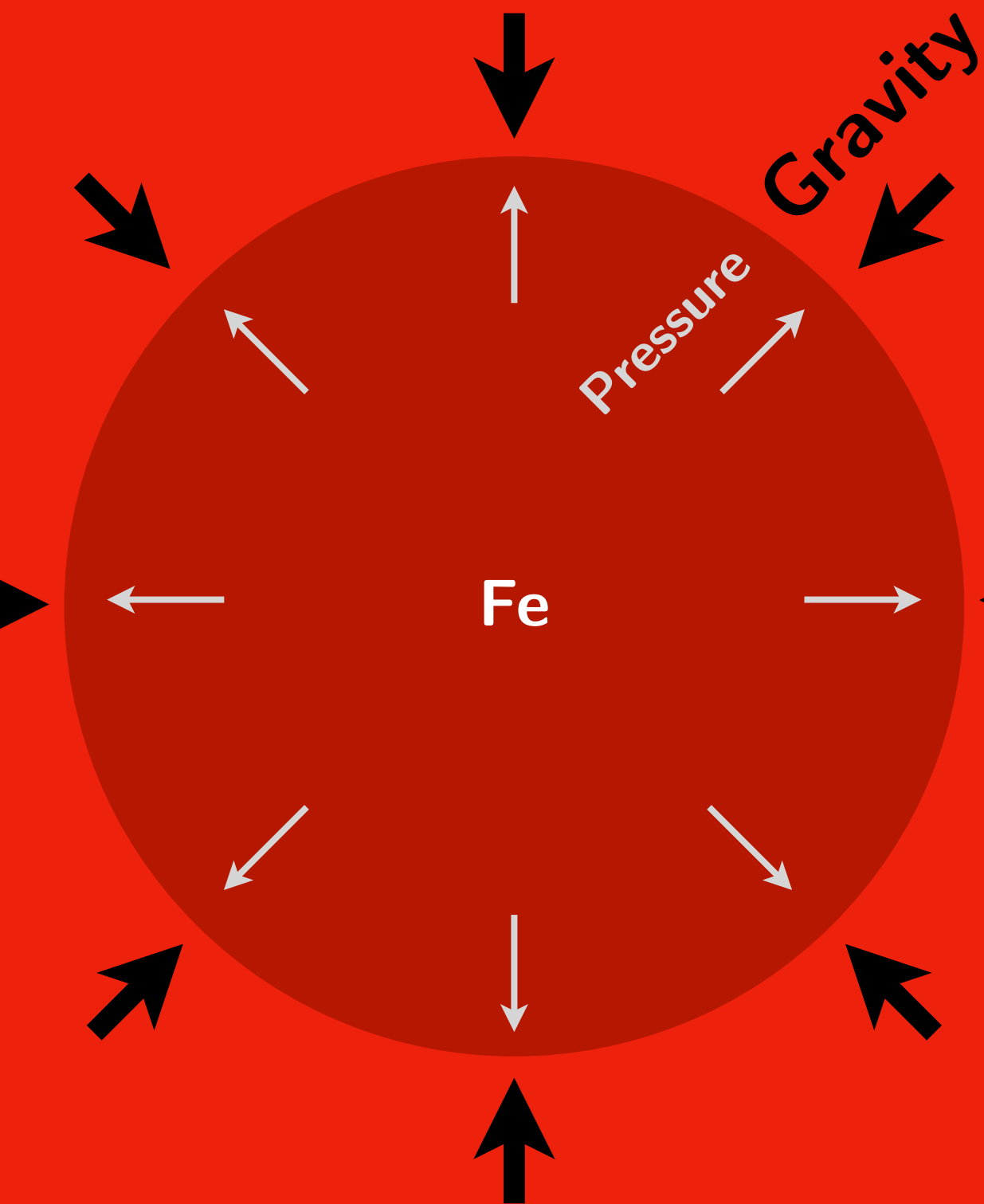


Carbon



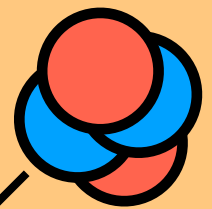
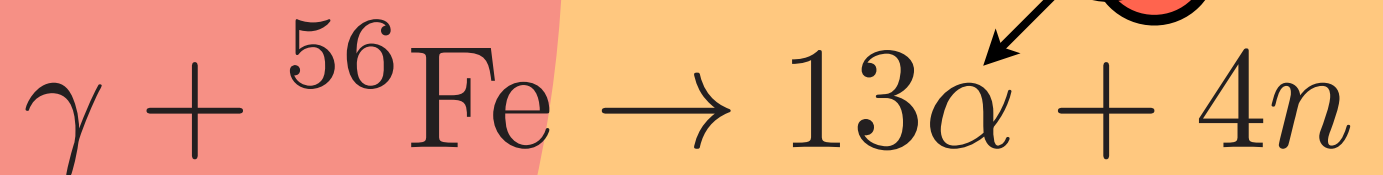
Star

Pauli Exclusion Principle



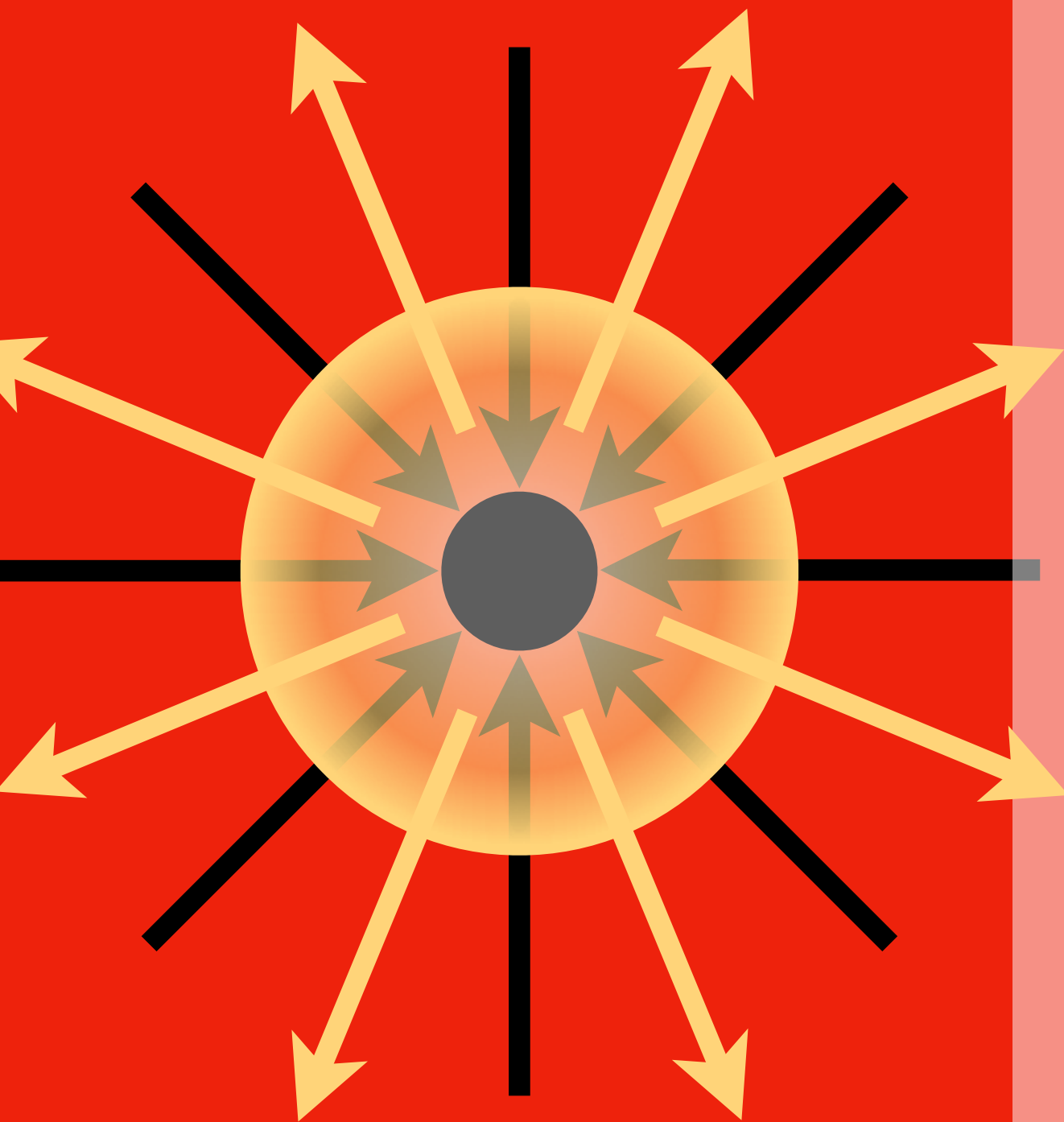
Electron Capture

Further energy loss
through **neutrinos**



Photodissociation

This **endothermic** reaction
absorbs 124 MeV of energy



1

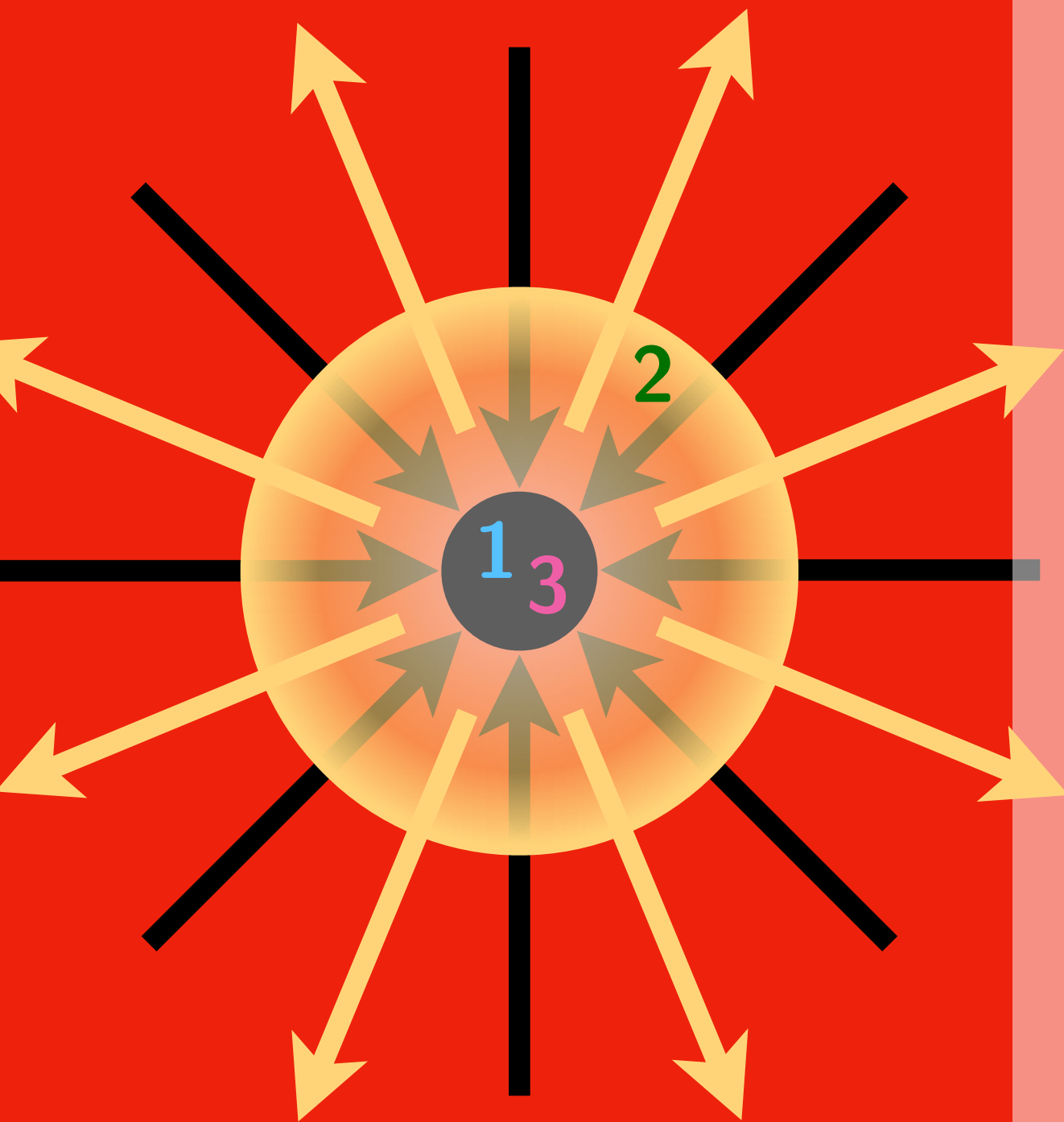
Gravity crushes the core into
a proto-**neutron star**

2

The object reaches the density of
a **nucleus**, stops, and **bounces**

3

A **shock wave** moves outward,
leading to an explosion



Neutrino Production

1. Capture Phase



Early on, these come right out

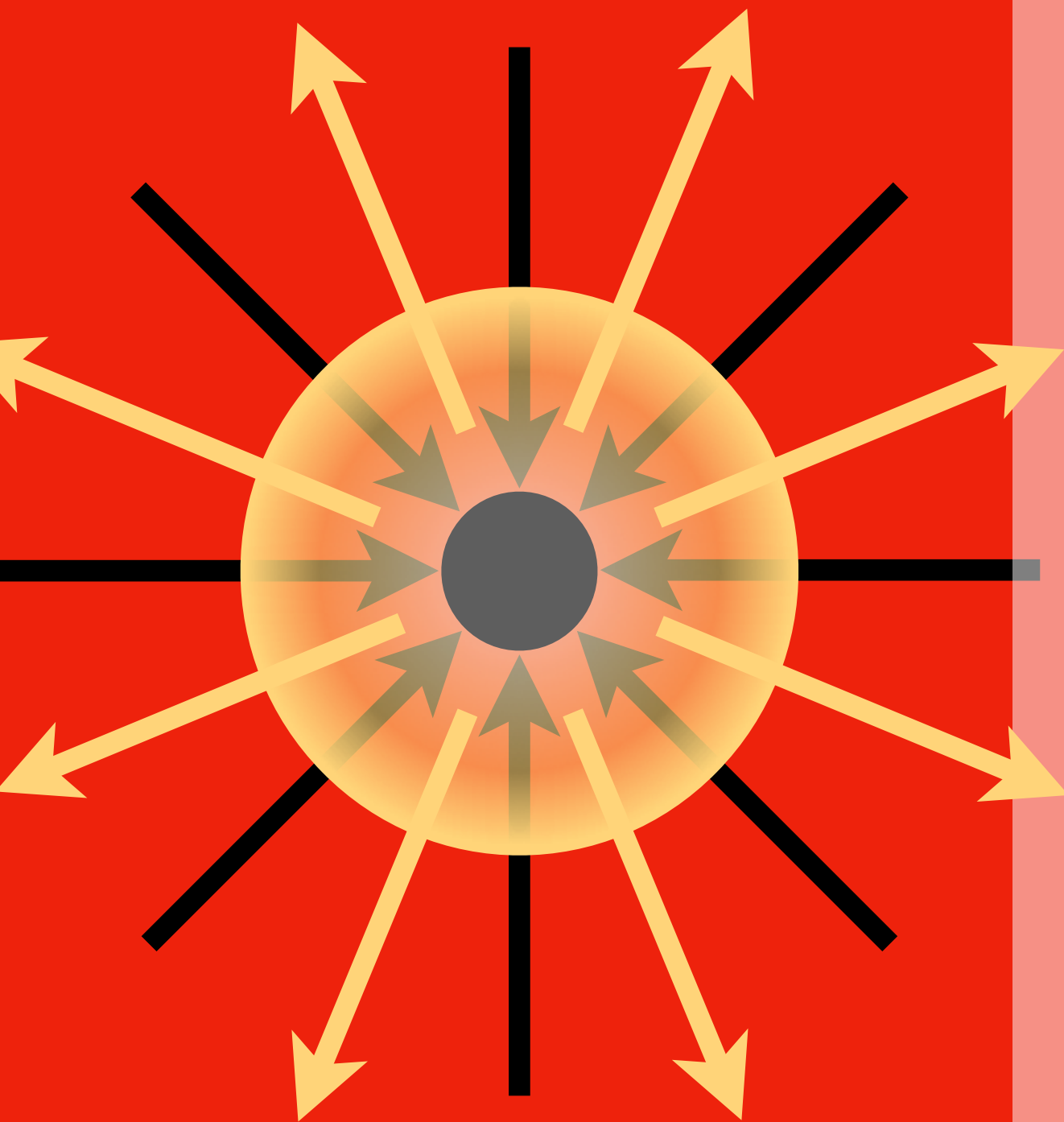
2. Neutronization Burst

Neutrinos are trapped behind the very dense shock wave, until it grows and the density is reduced

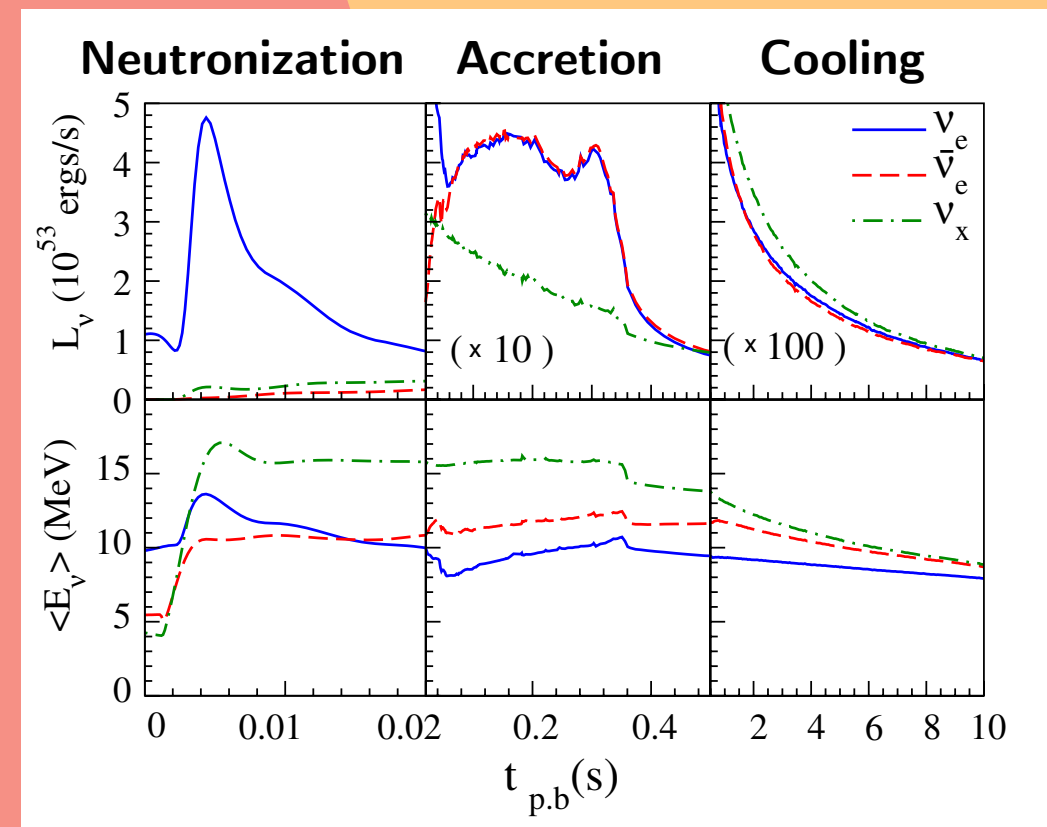
3. The Proto-Neutron Star

This is extremely hot and produces many neutrino/antineutrino pairs

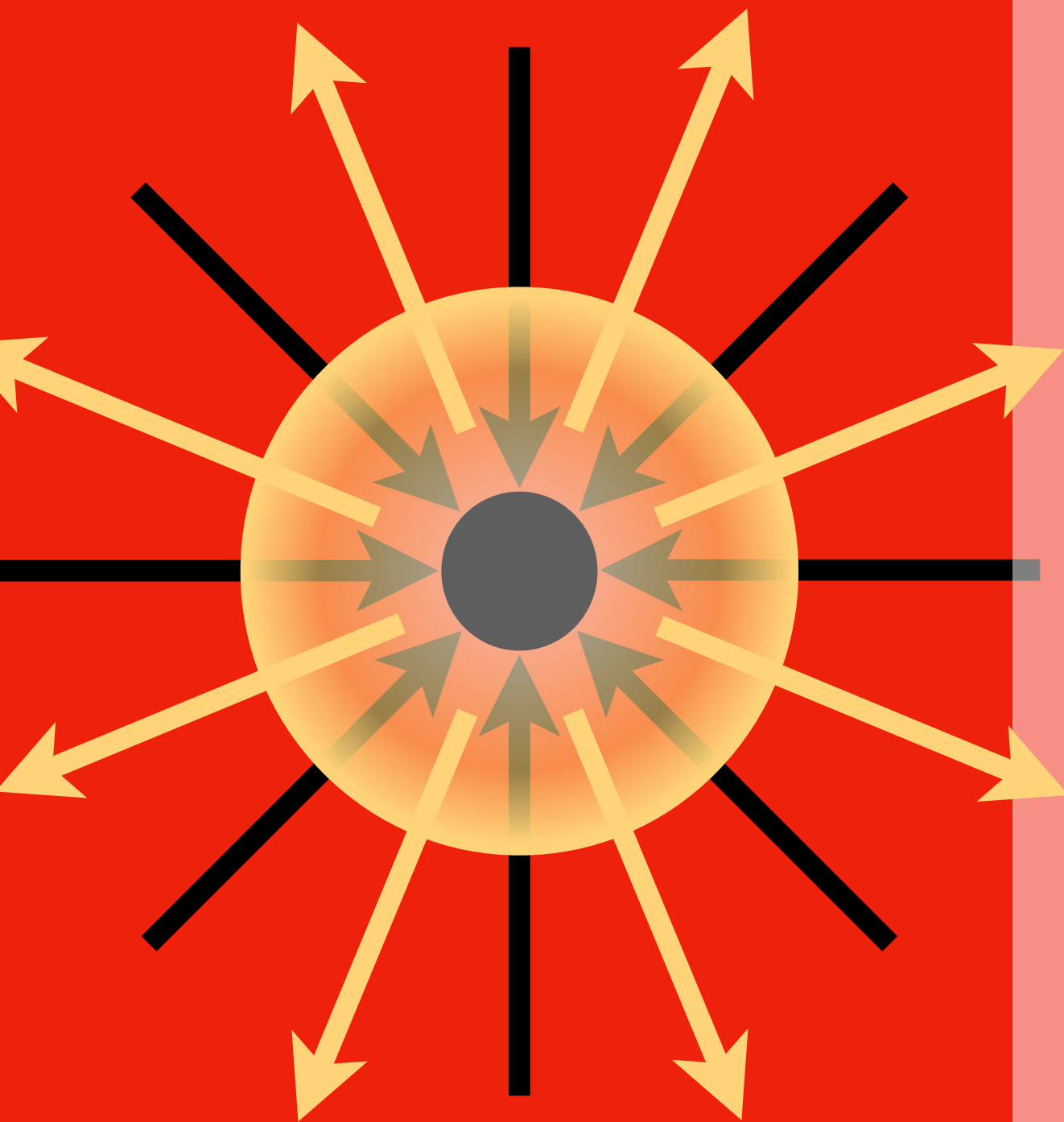




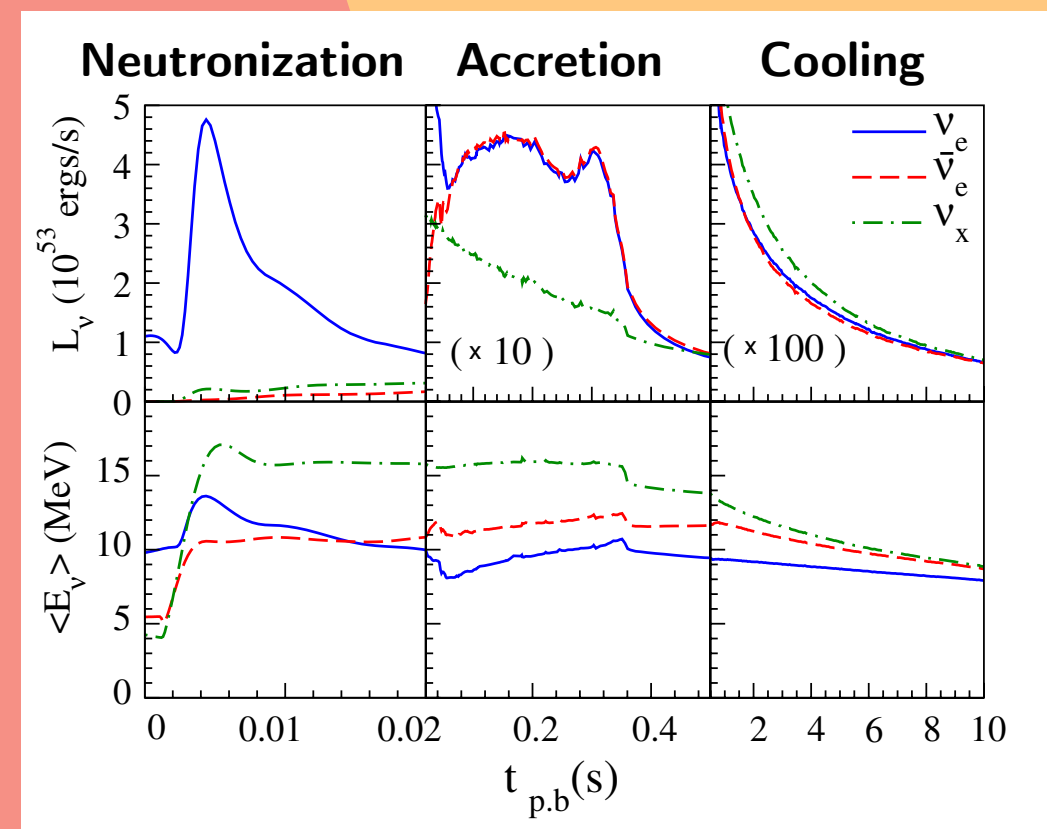
Models make a definite prediction for the **timing** and **energy** of neutrinos expected on Earth



Phys. Rev. D **89**, 013011 (2014)



Models make a definite prediction for the **timing** and **energy** of neutrinos expected on Earth



Phys. Rev. D **89**, 013011 (2014)

We expect about **3 per century** close enough to detect a burst

SN1987A

February 23, 1987

Large Magellanic Cloud
(170,000 light years away)

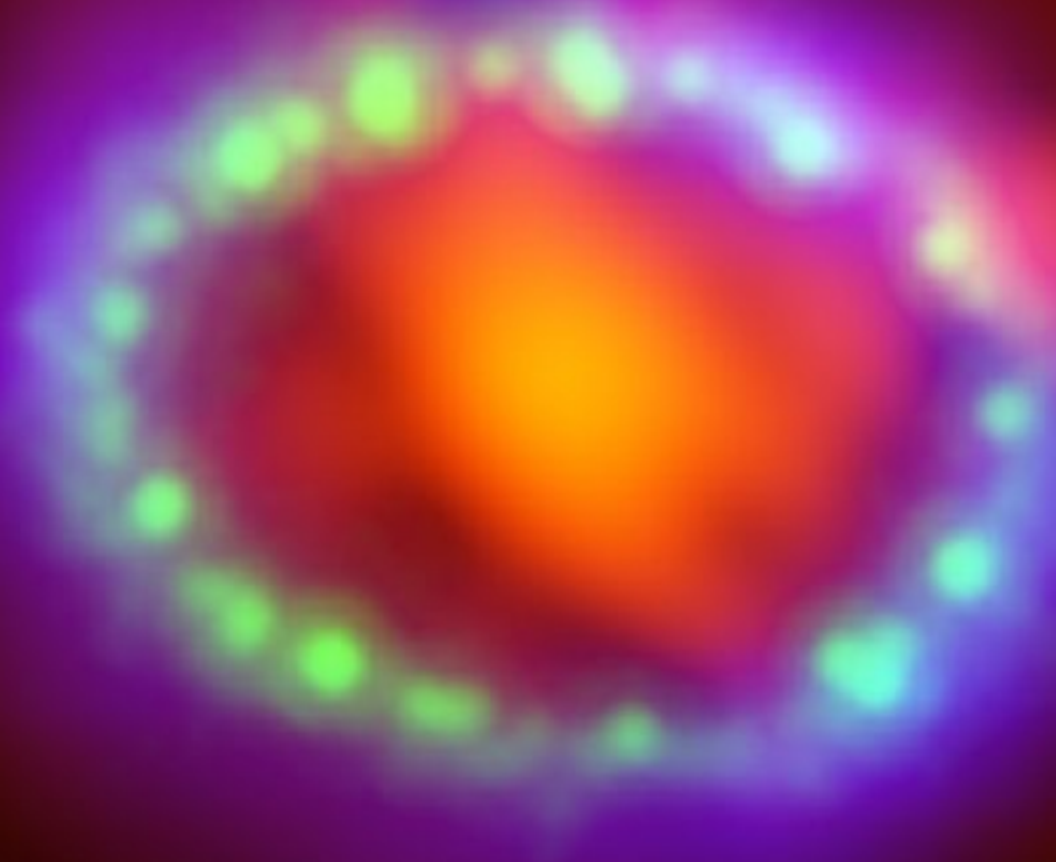
Type II Supernova

SN1987A

February 23, 1987

Large Magellanic Cloud
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Type II Supernova

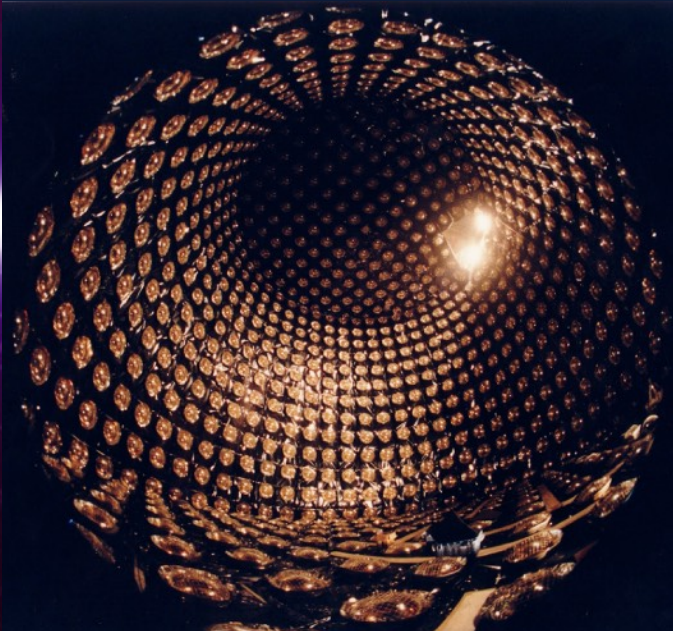


1987

NEUTRINO *DETECTORS*

1987 NEUTRINO

Kamiokande-II
Japan



(c) Kamioka Observatory, ICRR
University of Tokyo

IMB
USA

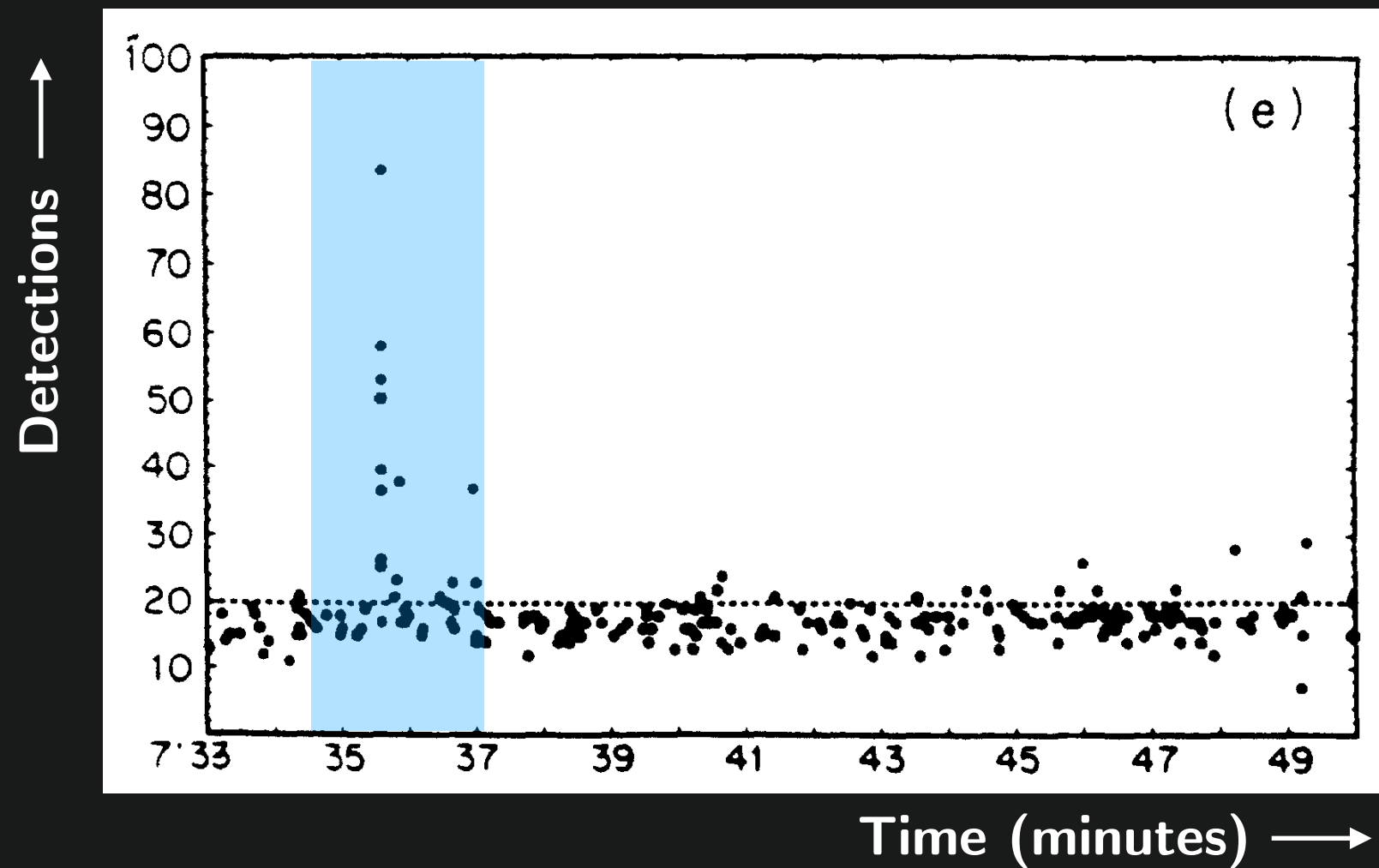


J. Vander Velde,
<http://www-personal.umich.edu/~jcv>

Baksan
Russia



(c) Institute for Nuclear Research
of Russian Academy of Sciences



Kamiokande-II Experiment

Kamioka, Hida, Japan

February 23, 1987, 07:53 UTC

**The world's
collection of
supernova
neutrino data...**

SN1987A Neutrinos

The world's
collection of
supernova
neutrino data...

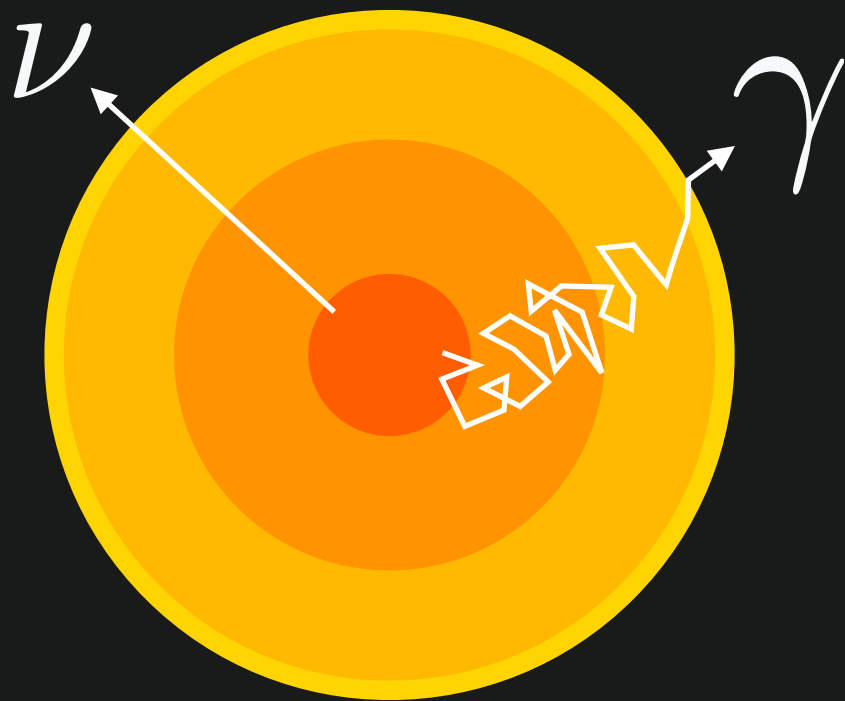
Exp.	Time (s)	Energy (MeV)	Angle (degrees)
K-II	0	20.0	18
K-II	0.107	13.5	40
K-II	0.303	7.5	108
K-II	0.324	9.2	70
K-II	0.507	12.8	135
K-II	0.686	6.3	68
K-II	1.541	35.4	32
K-II	1.728	21.0	30
K-II	1.915	19.8	38
K-II	9.219	8.6	122
K-II	10.433	13.0	49
K-II	12.439	8.9	91
IMB	0	38	80
IMB	0.412	37	44
IMB	0.650	28	56
IMB	1.141	39	65
IMB	1.562	36	33
IMB	2.684	36	52
IMB	5.010	19	42
IMB	5.582	22	104
Baksan	0	12.0	
Baksan	0.435	17.9	
Baksan	1.710	23.5	
Baksan	7.687	17.6	
Baksan	9.099	20.3	

SN1987A

What can **neutrinos** teach us about **supernovae**?

SN1987A

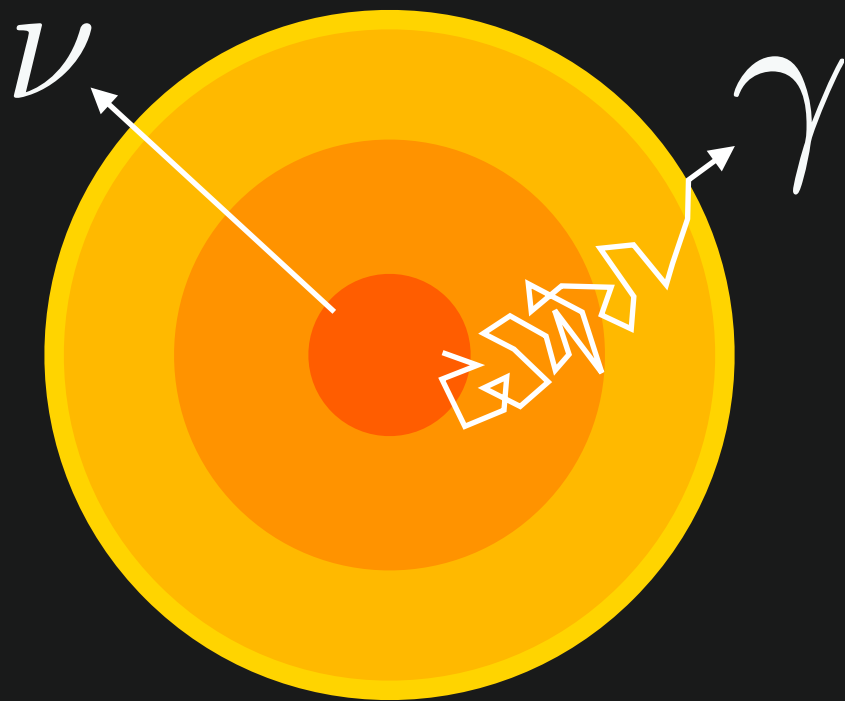
What can **neutrinos** teach us about **supernovae**?



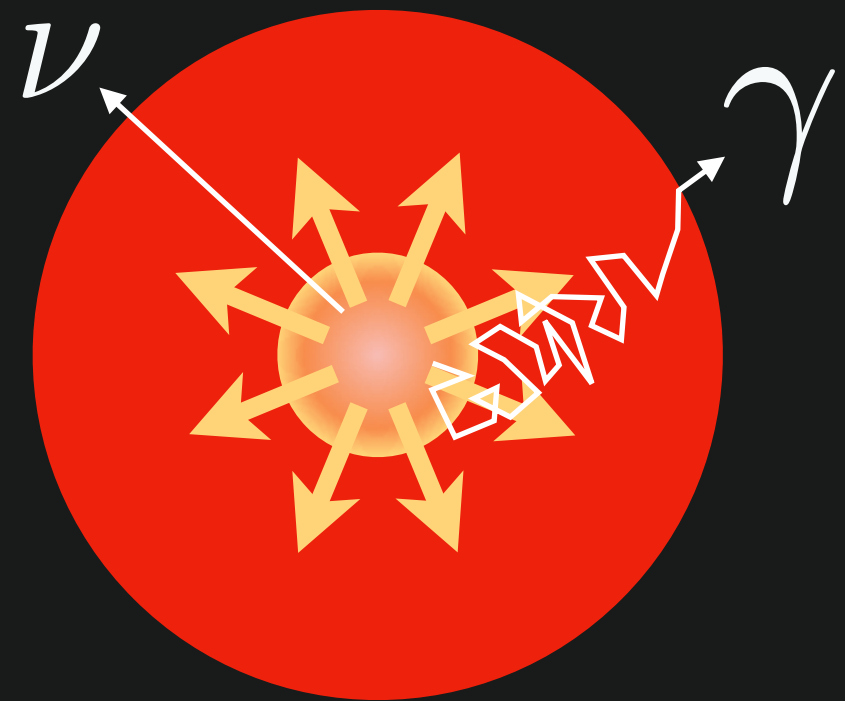
The Sun

SN1987A

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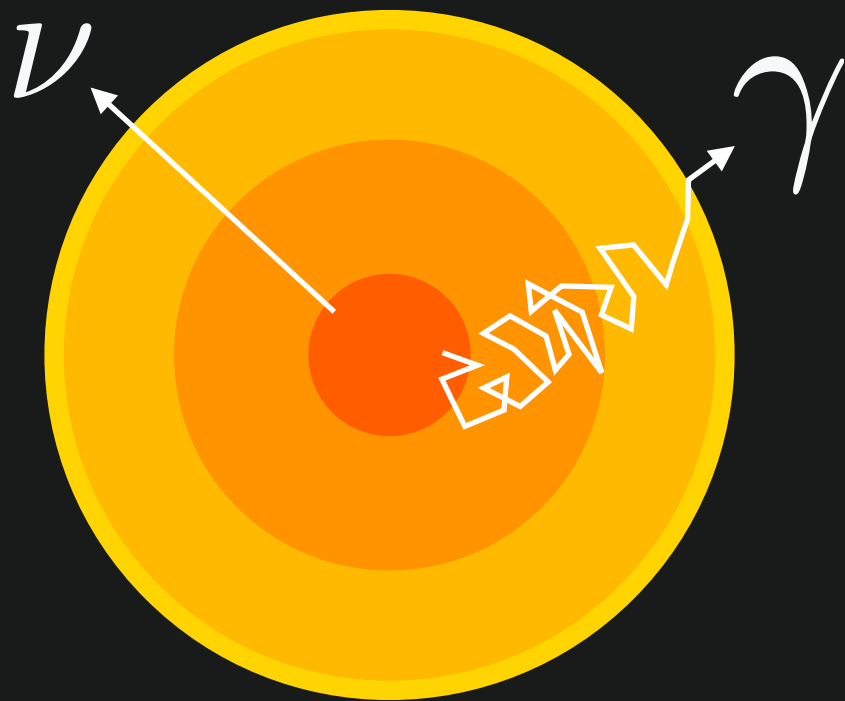
The Sun



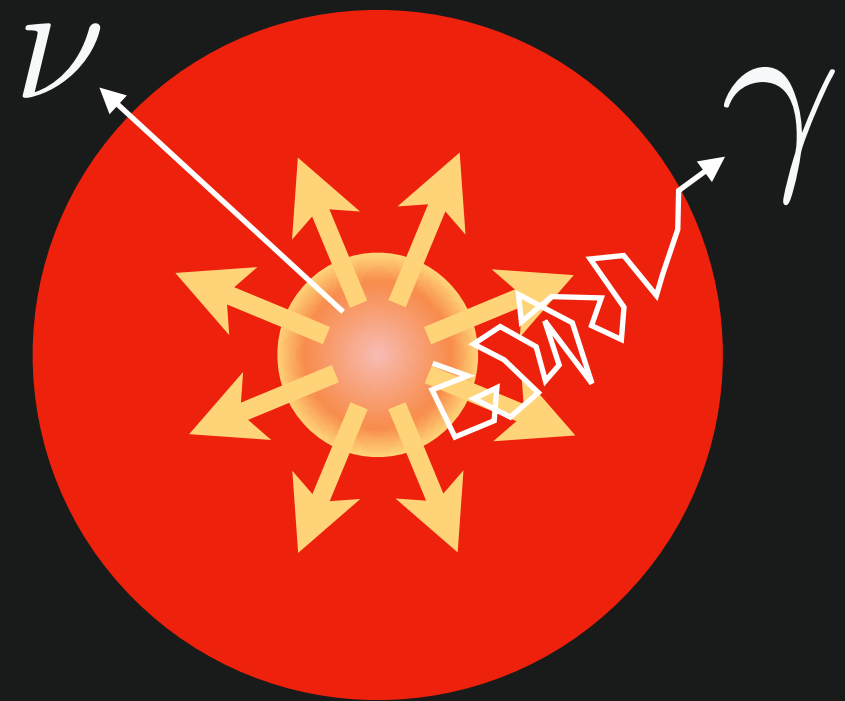
Supernova

SN1987A

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The Sun

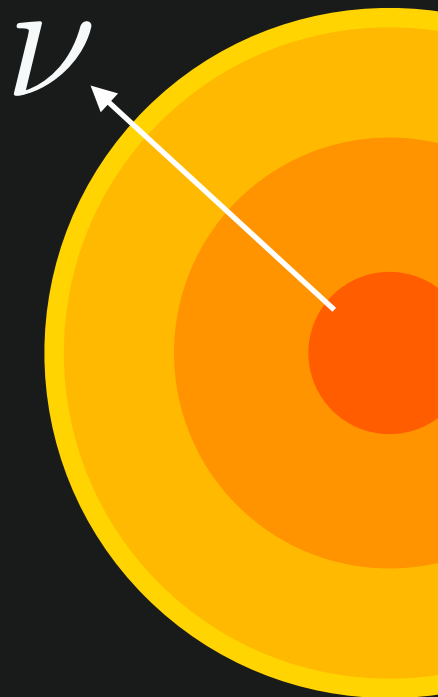


Supernova

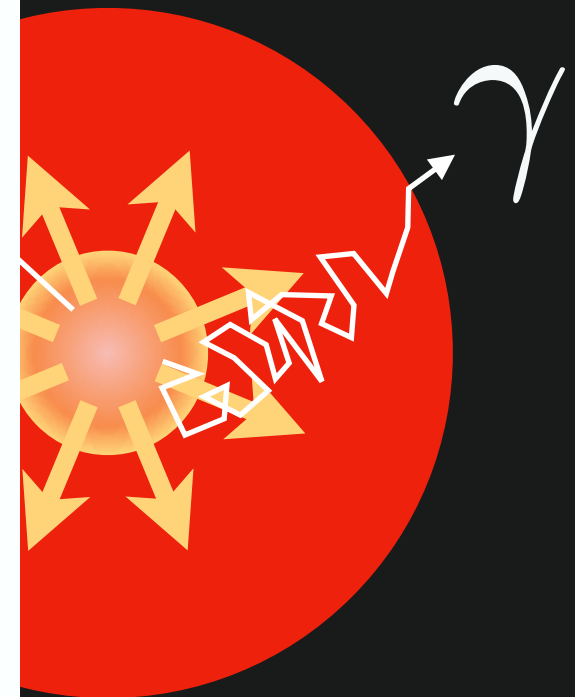
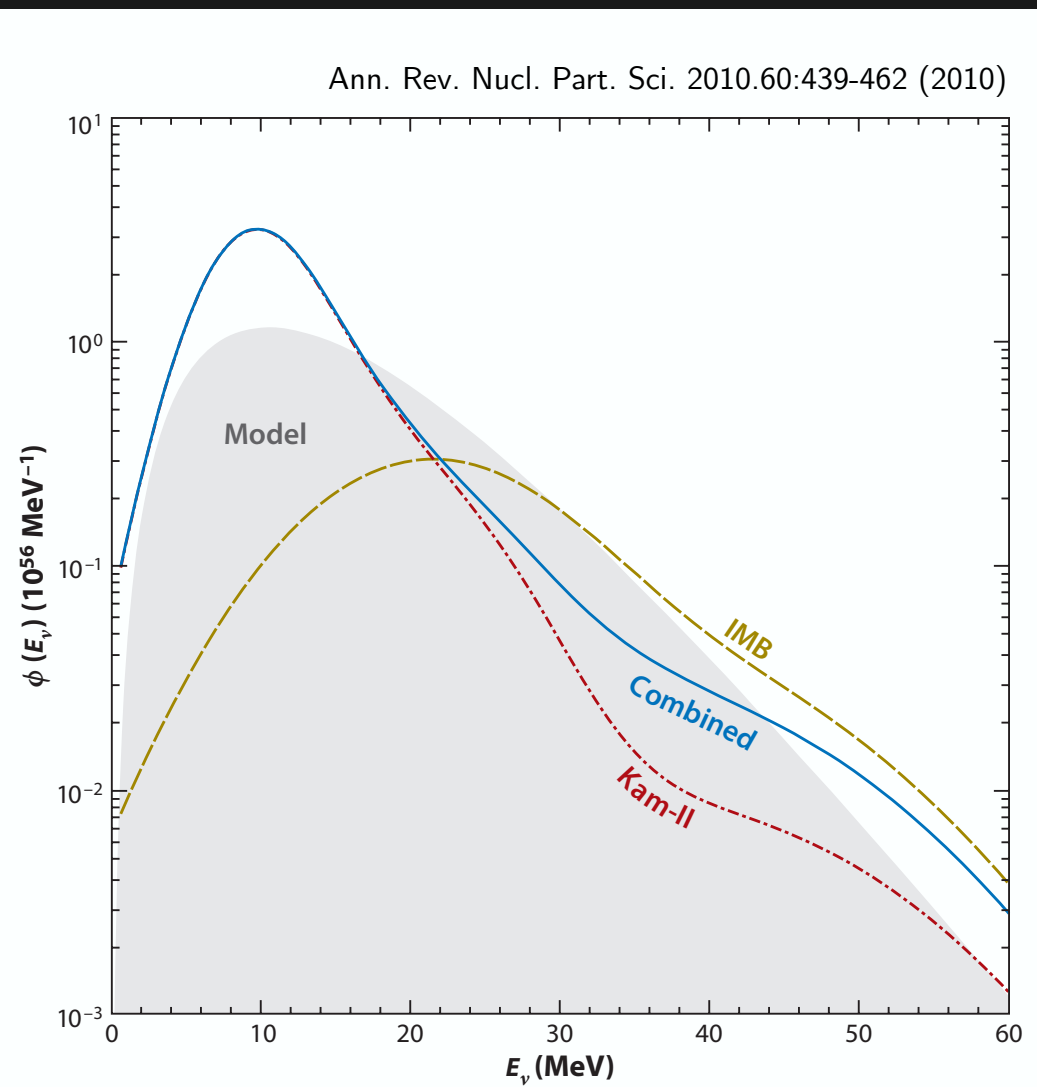
A validation of the basic supernova dynamics model,
based on neutrino **energy** and **timing** measurements

SN1987A

What can **neutrinos** teach us about **supernovae**?



The S



pernova

Neutrino **energies** (and **times**)

A validation compatible with the theory
based on neutrino **energy** and **timing** measurements

SN1987A

What can **supernovae** teach us about **neutrinos**?

SN1987A

What can **supernovae** teach us about **neutrinos**?

1. How heavy are neutrinos?

$$m_\nu \lesssim 14 \text{ eV} \left(\frac{E}{10 \text{ MeV}} \right) \sqrt{\frac{E}{\Delta E} \times \frac{\Delta T_{\text{obs}}}{10 \text{ s}} \times \frac{50 \text{ kpc}}{D}}$$

Compare the observed time spread to the intrinsic time spread of the burst

$$m_{\nu_e} \lesssim 30 \text{ eV} \quad (\text{smaller than } 0.006\% \text{ the electron's mass})$$

SN1987A

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2. Do neutrinos decay?

Well, some of them made it to Earth from 50 kpc away, so

$$\text{Lifetime } \tau_{\bar{\nu}_e} \gtrsim 1.5 \times 10^5 \left(m_{\nu_e} / E_{\bar{\nu}_e} \right) \text{ years}$$

~~SN1987A~~

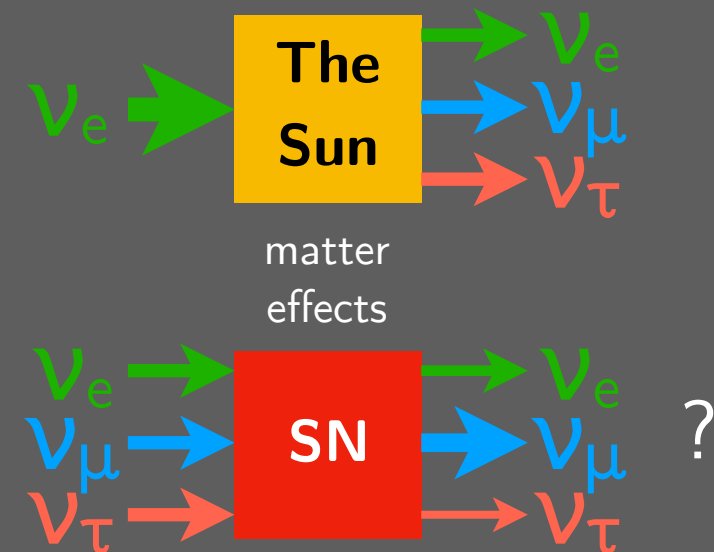
What can **supernovae** teach us about **neutrinos**?

~~SN1987A~~

What can **supernovae** teach us about **neutrinos**?

3. Neutrino Oscillations

Matter-enhanced (MSW) oscillations in the supernova material affect the ratios of $\nu_e/\nu_\mu/\nu_\tau$ as a function of energy

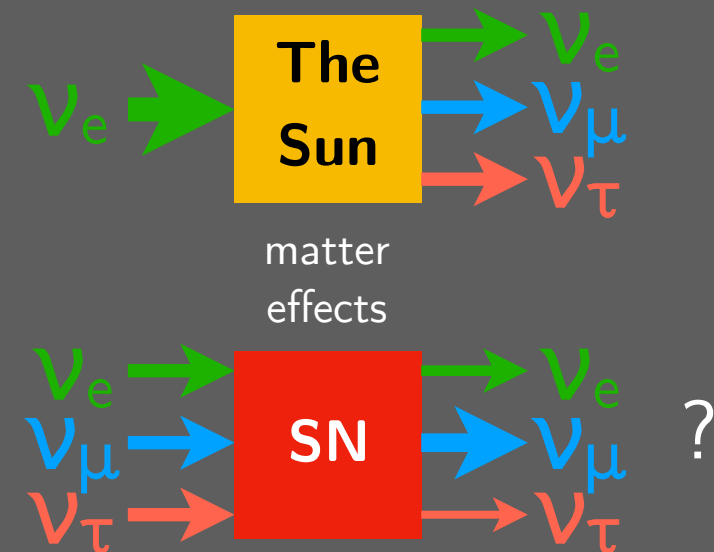


~~SN1987A~~

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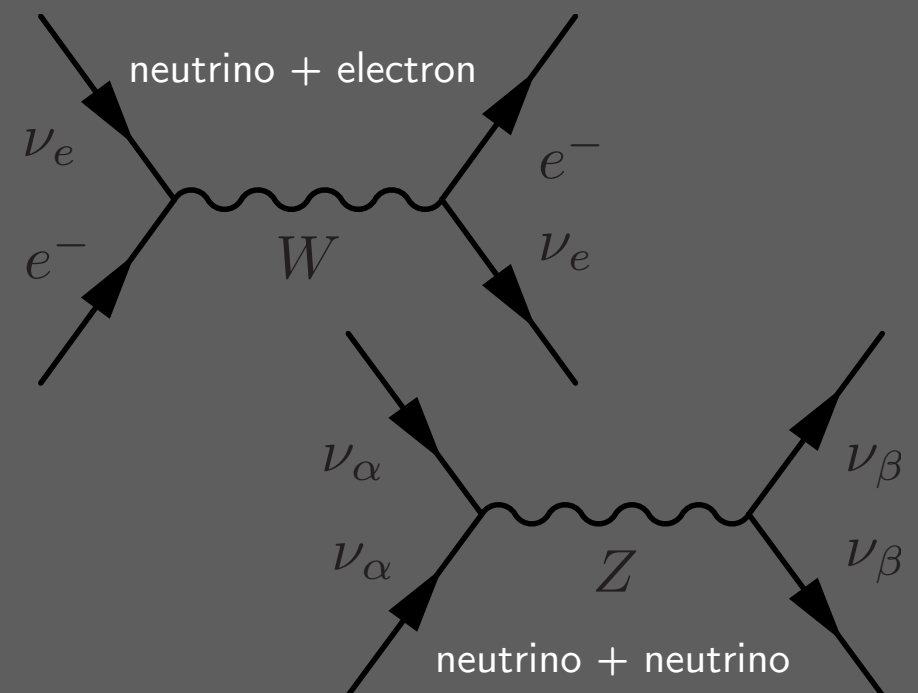
Matter-enhanced (MSW) oscillations in the supernova material affect the ratios of $\nu_e/\nu_\mu/\nu_\tau$ as a function of energy



4. Neutrino-neutrino interactions

The environment in the collapse is so dense that neutrino interactions with **other neutrinos** are believed to be important

We can test the Standard Model by measuring the neutrino **energy** spectrum

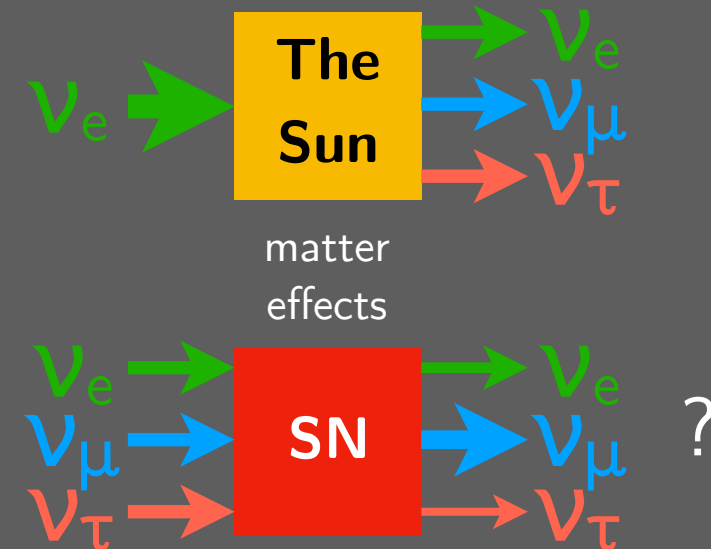


SN1987A

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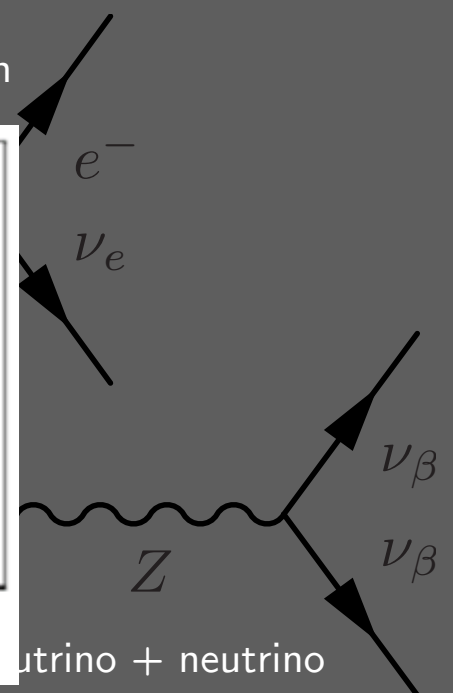
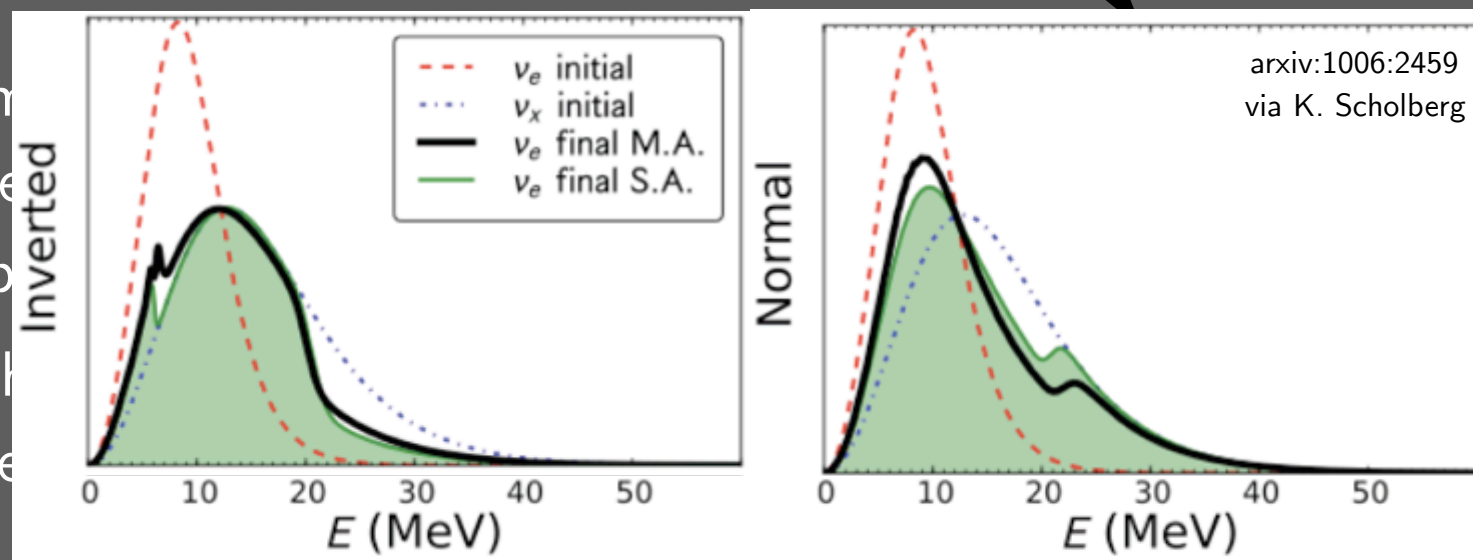
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4. Neutrino-neutrino interactions

The environment
neutrino interactions

We can test the
neutrino

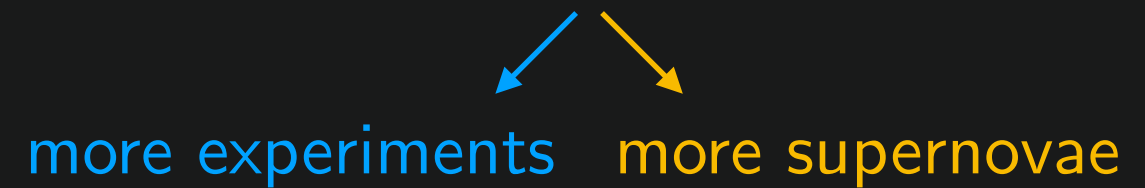


The Next One

To study supernova models in detail, we need **more data**


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The Next One

To study supernova models in detail, we need **more data**


more experiments more supernovae

Models predict ~ 3 supernovae
in our galaxy per century

1987 was 31 years ago

Maybe time for another?

Are we ready?

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SuperNova Early Warning System

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A network of 7 neutrino detectors

Super-Kamiokande
Japan

KamLAND
Japan

Daya Bay
China

Borexino
Italy

LVD
Italy

HALO
Canada

IceCube
South Pole

Alerts to the astronomical community

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snews.bnl.gov

"No nearby core collapses have occurred since
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Be there! Join the mailing list!

Supernova Neutrino Detectors

Supernova Neutrino Detectors

MicroBooNE
USA

IceCube Lab

50 m

+ , Can

SBND,
USA

Jinping,
China

20 m

Everyone
is looking for
supernova neutrinos!

LO,
ada

Super-Kamiokande

Electrical Machinery Room

Access Tunnel

Height 54m
Width 48m
Compartment Length 49.5m

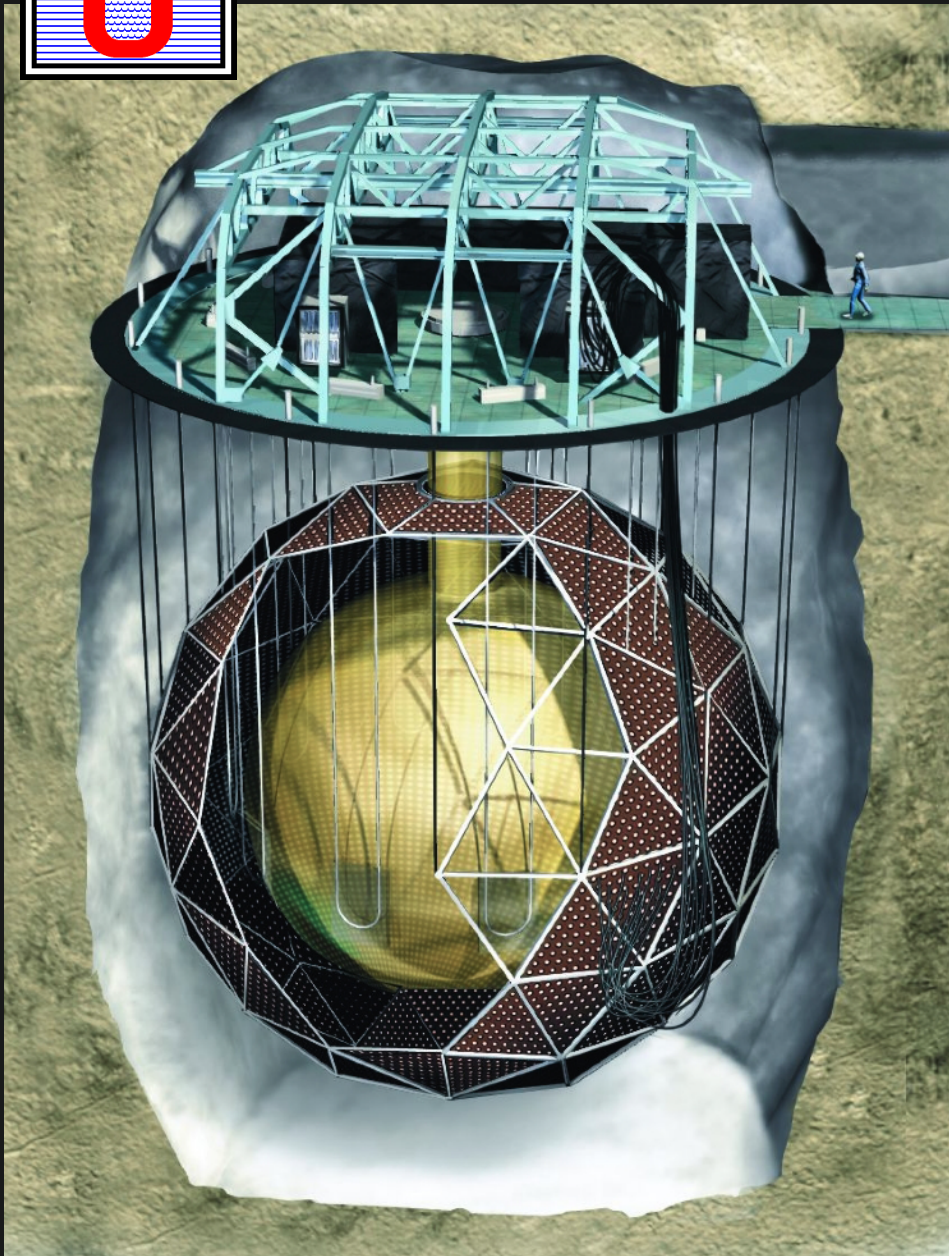
Japan

LVD,
Italy

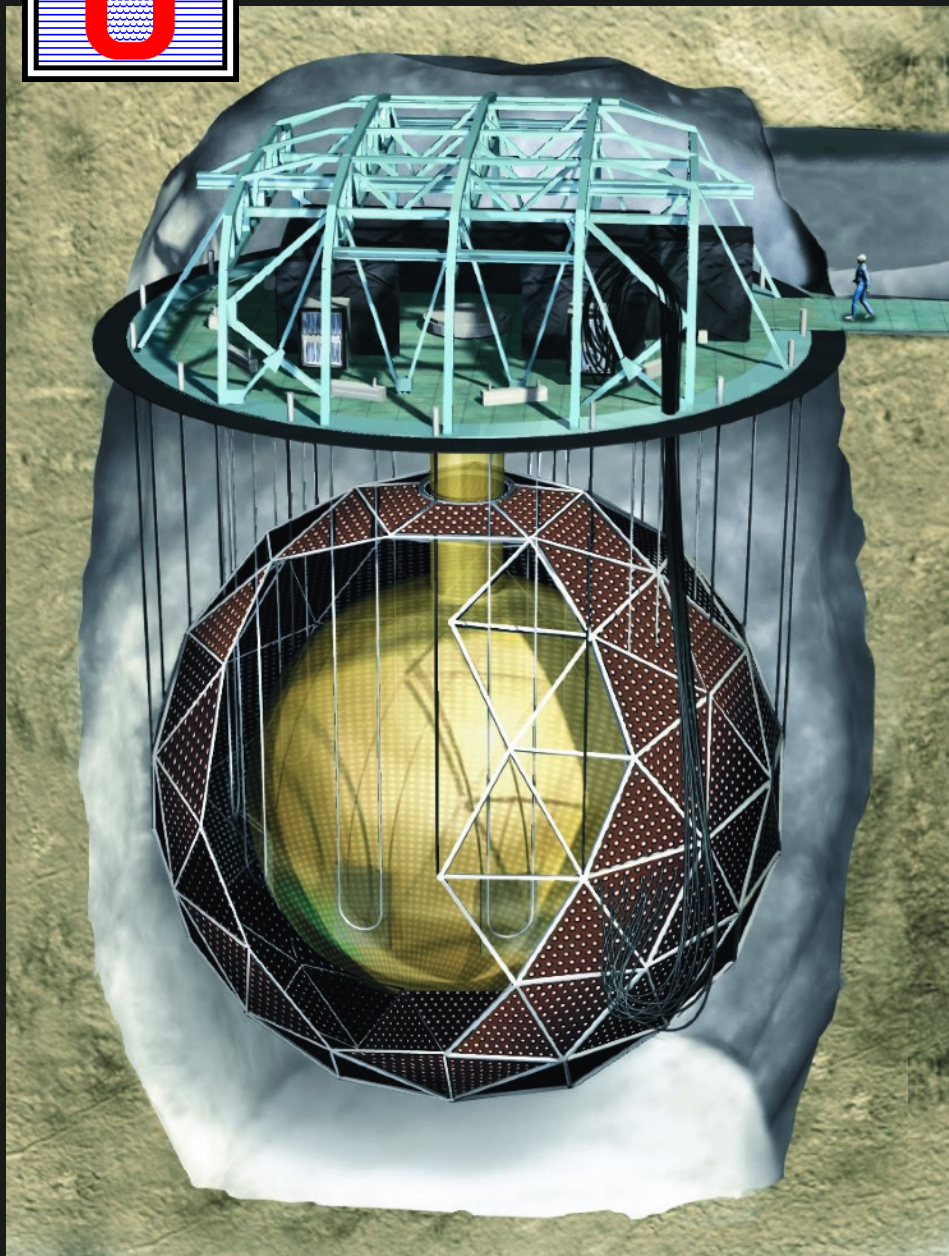
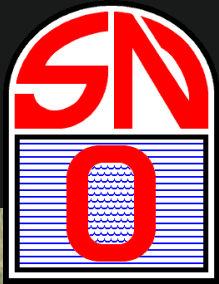
MINOS, US

Daya Bay,
China

Supernova Neutrinos in SNO+

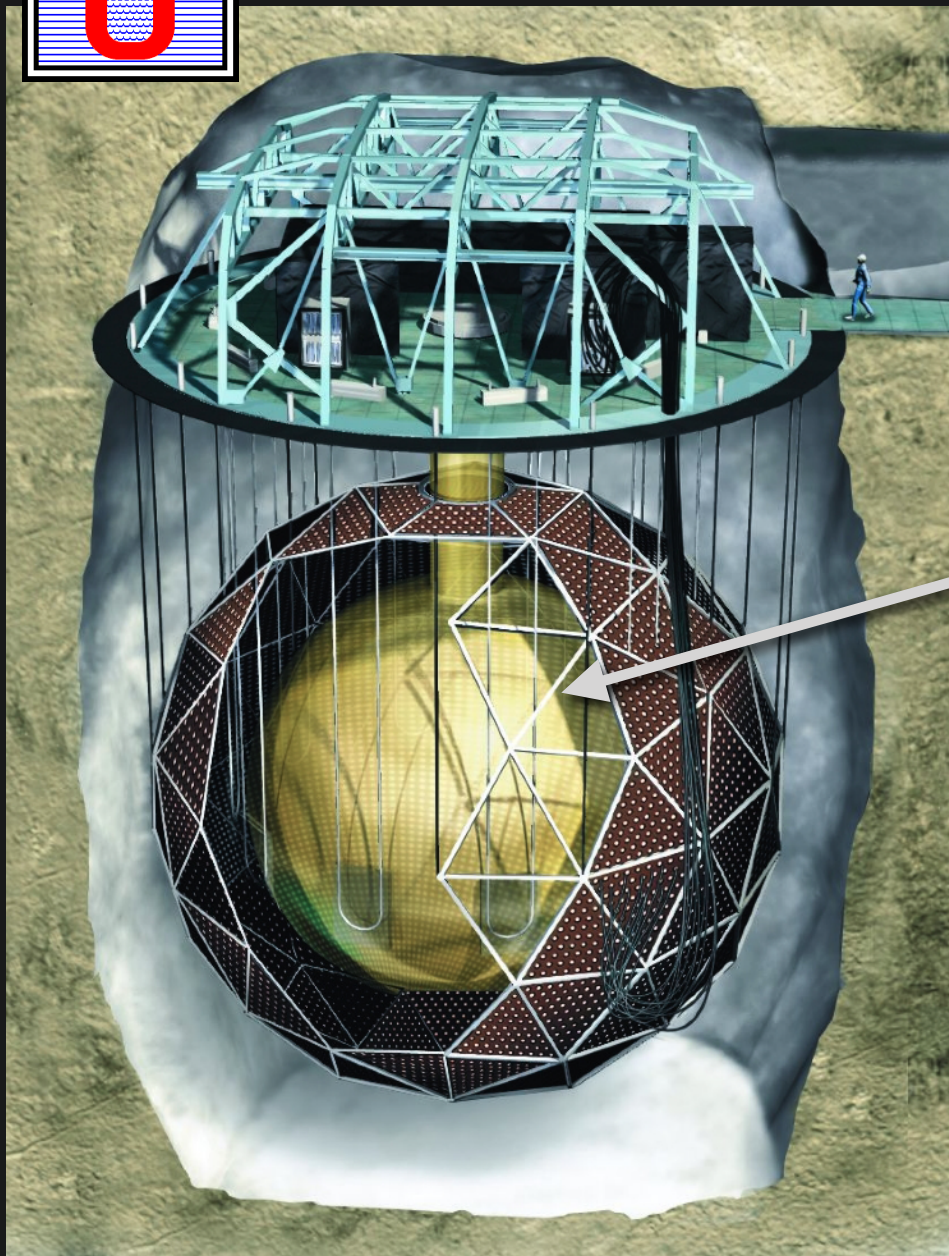


Supernova Neutrinos in SNO+



↓ 6800 feet underground!

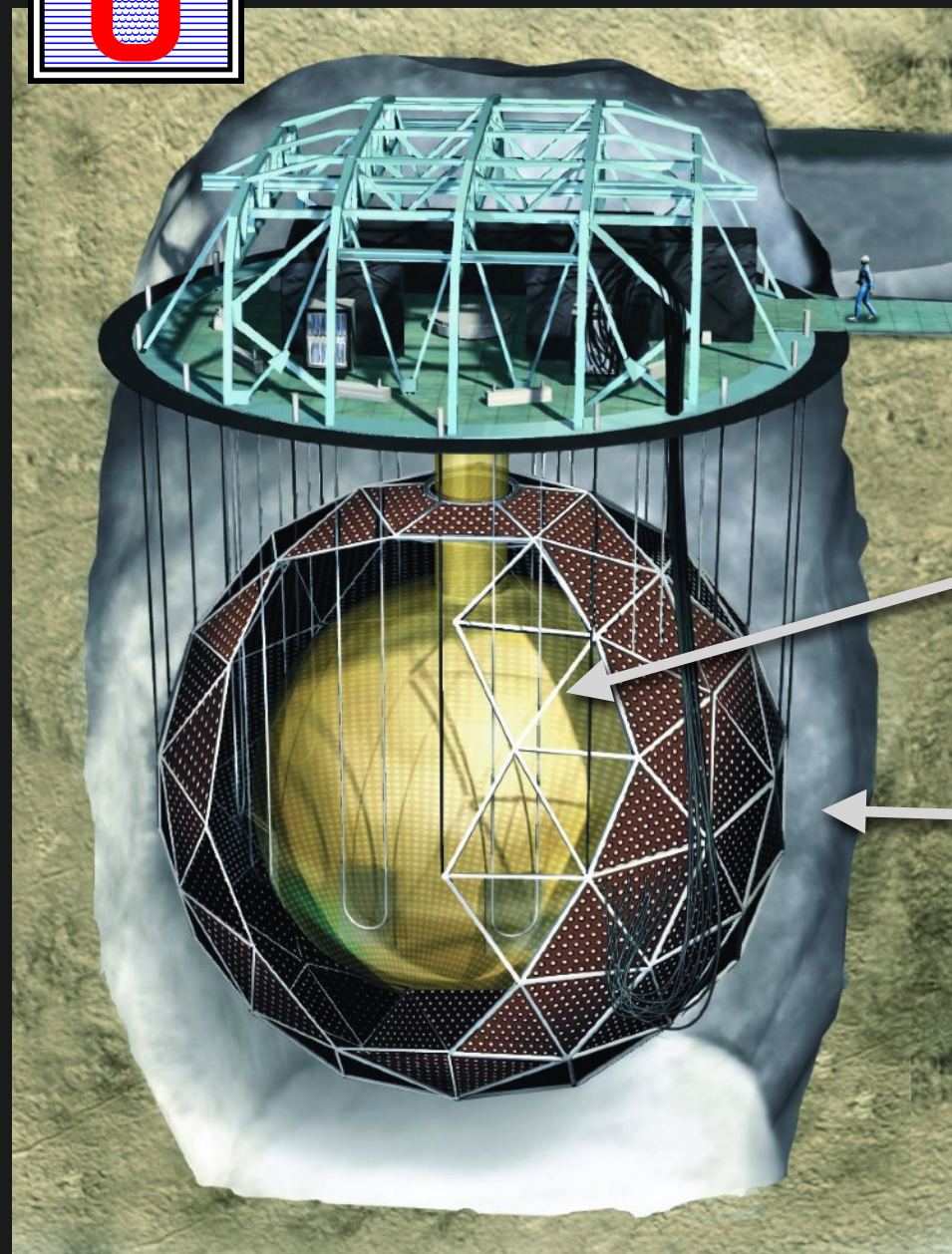
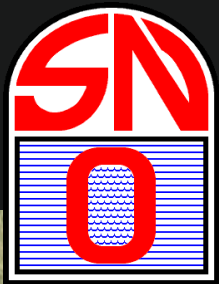
Supernova Neutrinos in SNO+



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1,000 tonnes heavy water ($^2\text{H}_2\text{O}$)
inside a 12 meter diameter acrylic sphere

Supernova Neutrinos in SNO+

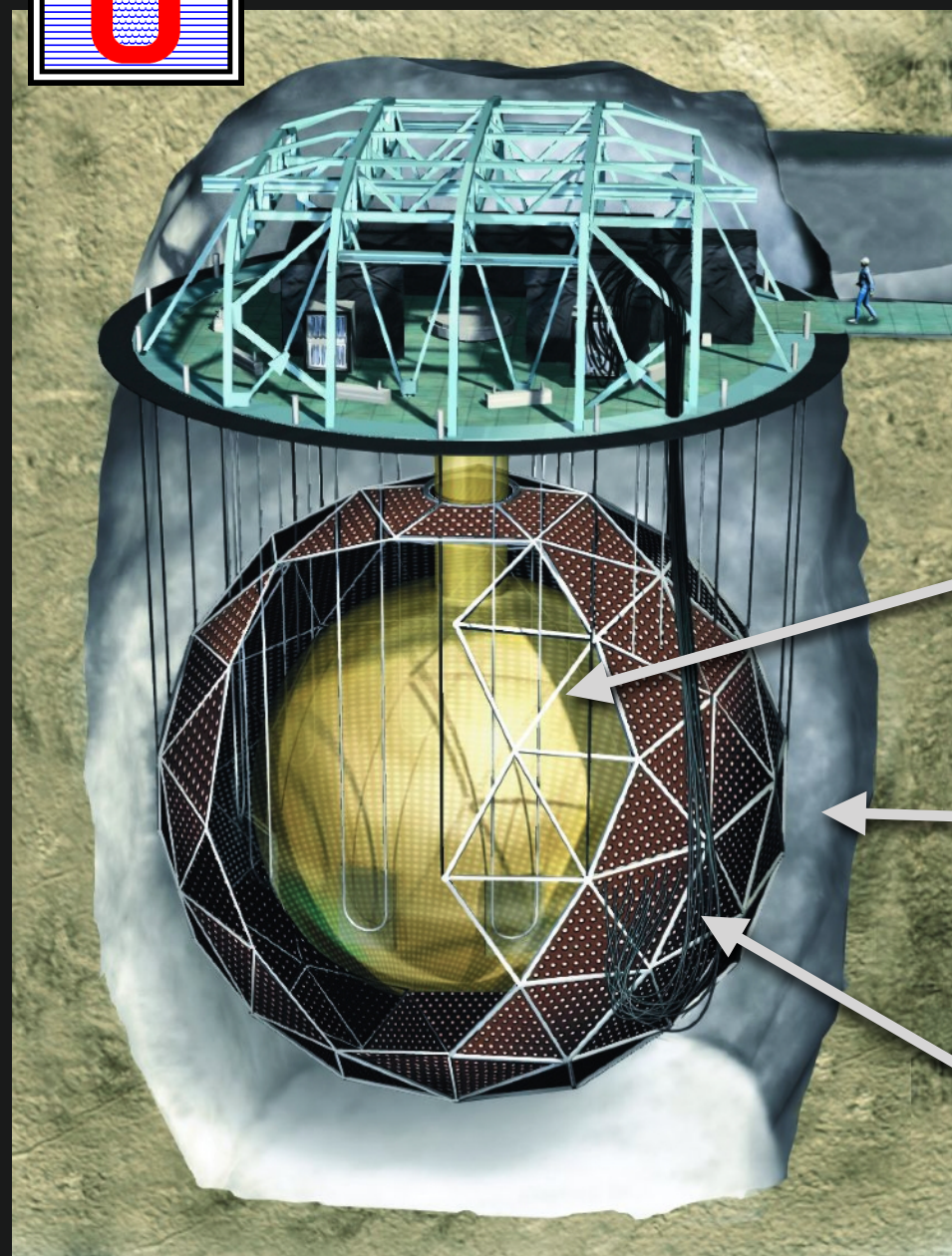


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Supernova Neutrinos in SNO+



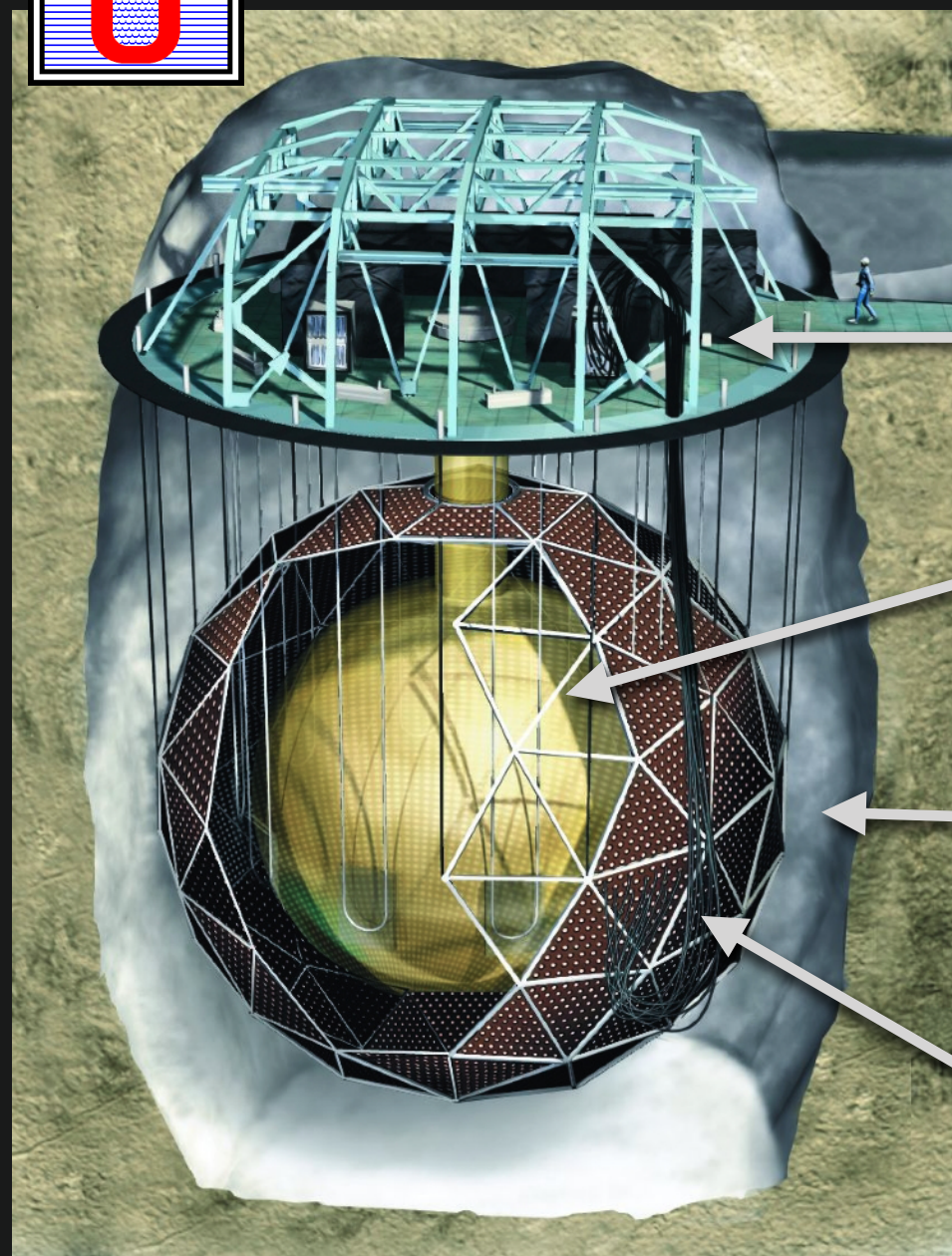
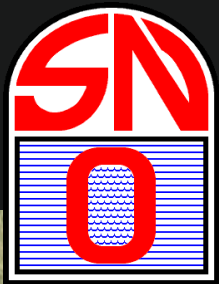
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Supernova Neutrinos in SNO+



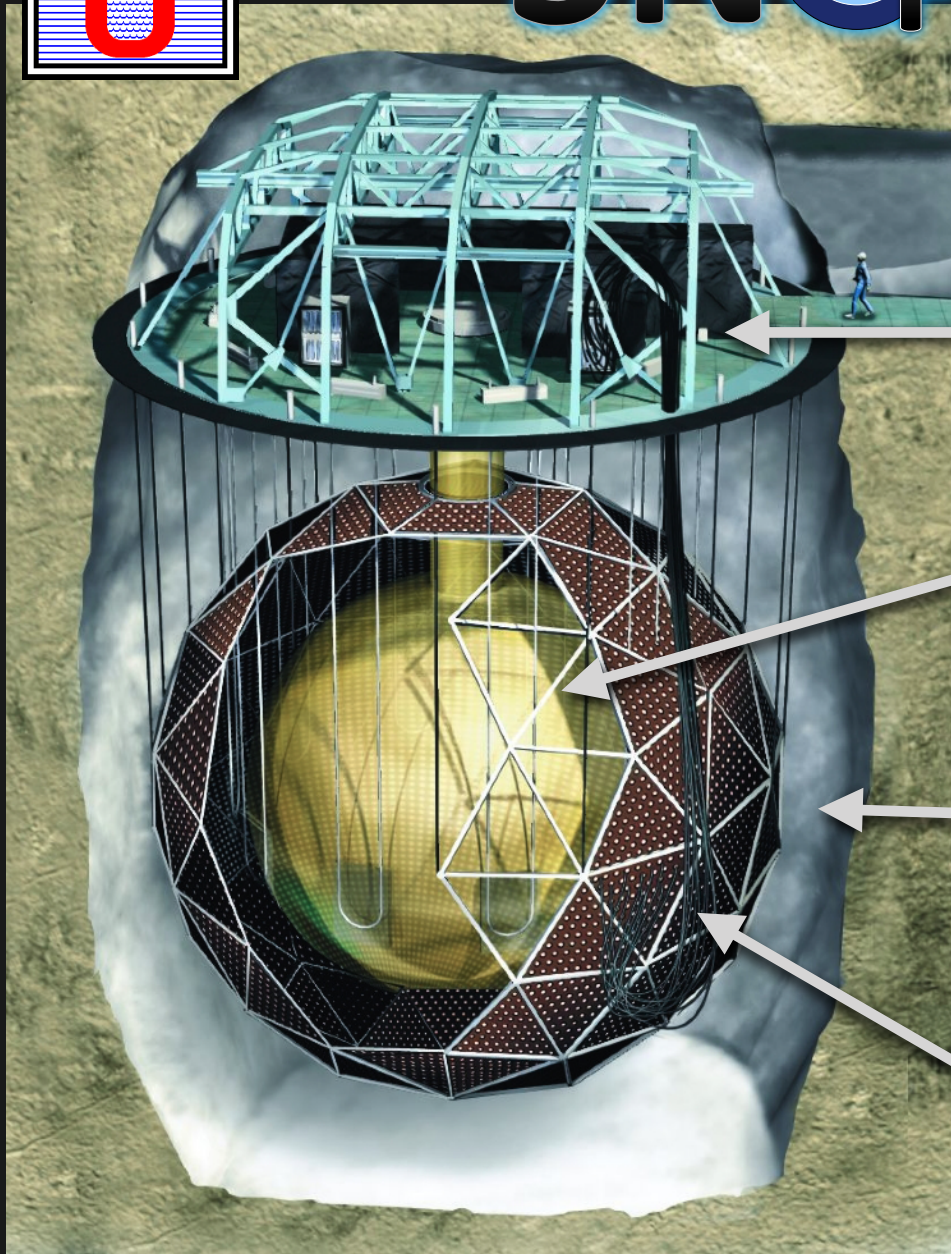
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Supernova Neutrinos in SNO+



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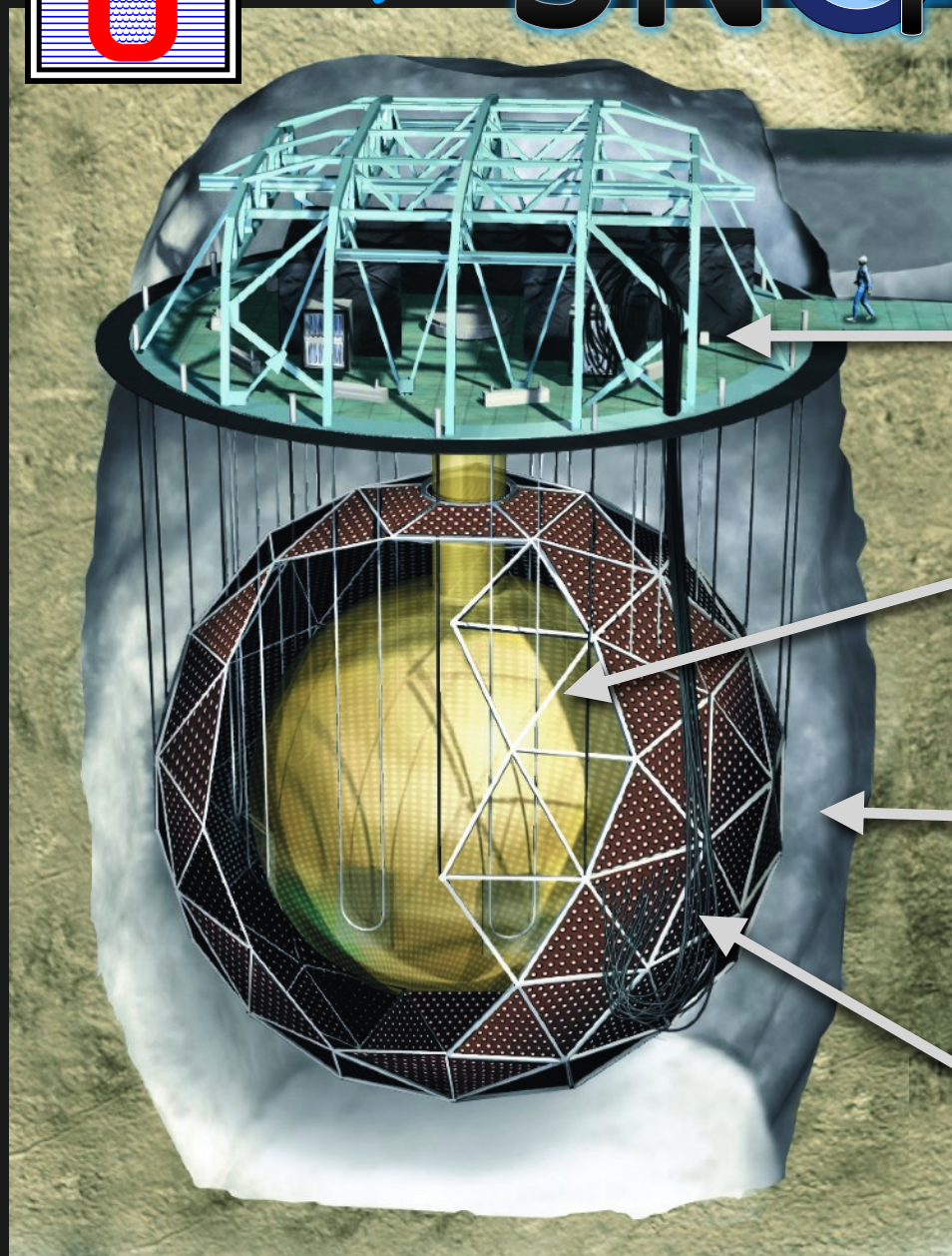
(upgraded)

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6800 feet underground!

(upgraded)

Electronics & Instrumentation

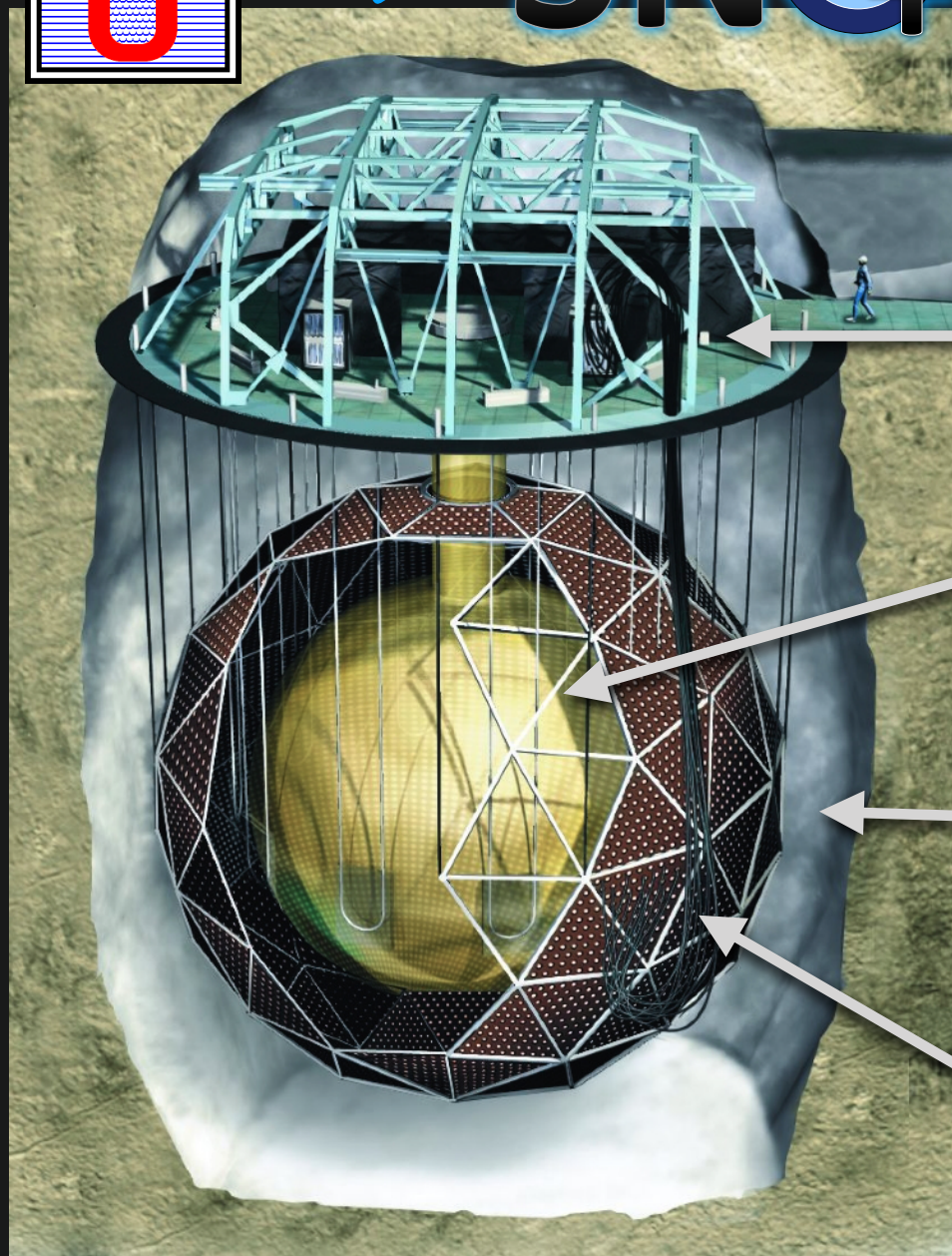
780 tonnes scintillator (LAB)

~~1,000 tonnes heavy water ($^2\text{H}_2\text{O}$)~~

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Supernova Neutrinos in SNO+



6800 feet underground!

(upgraded)

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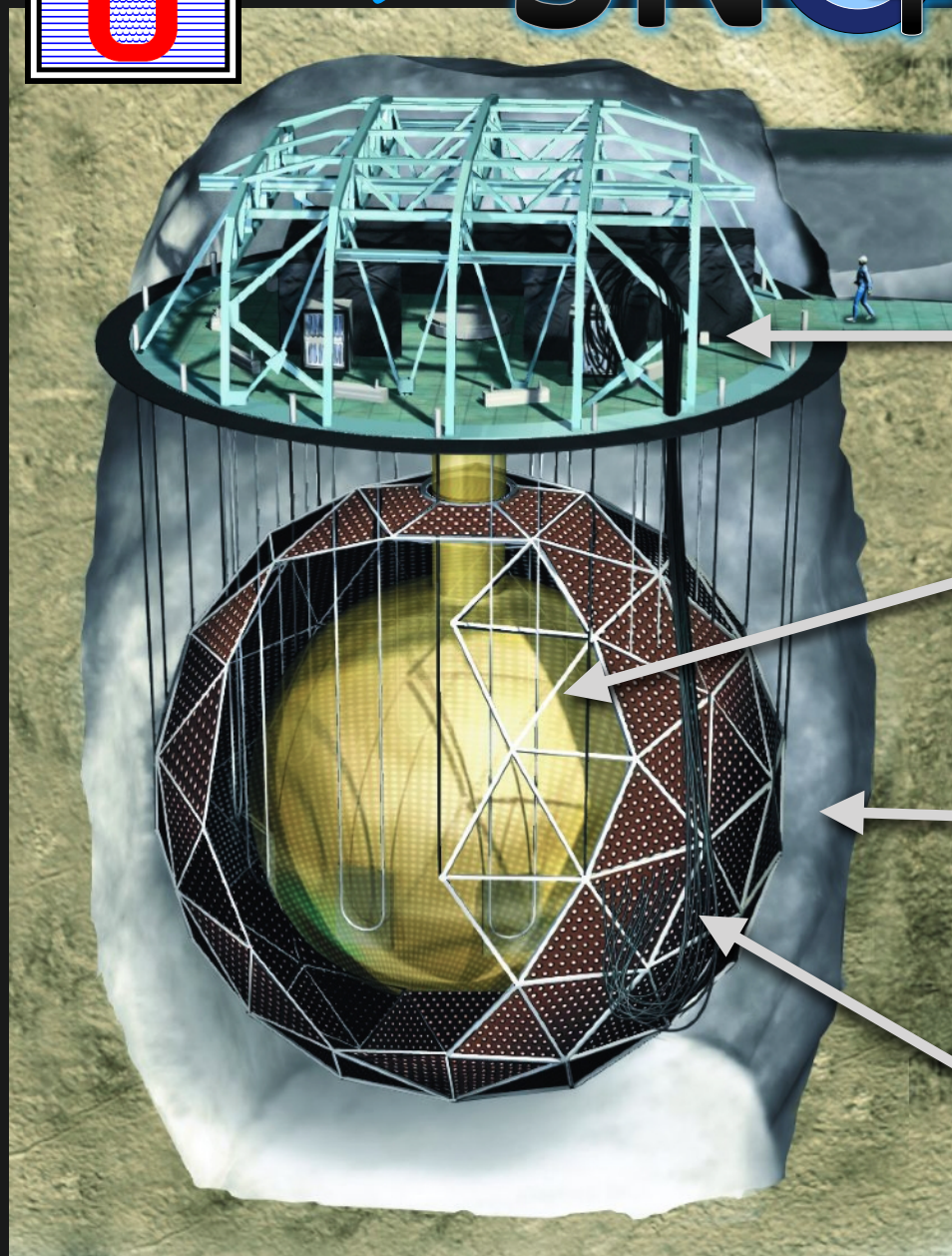
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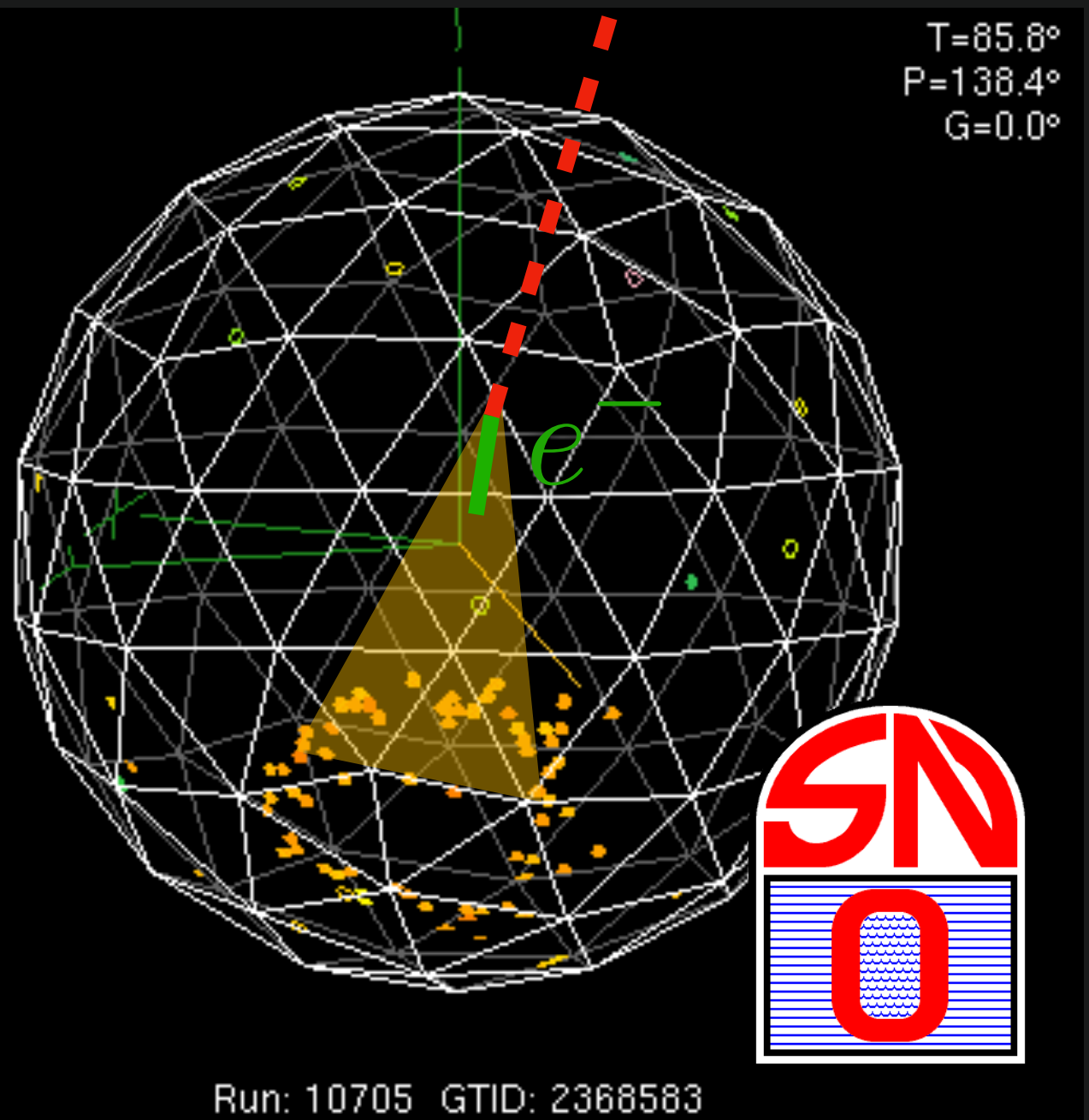
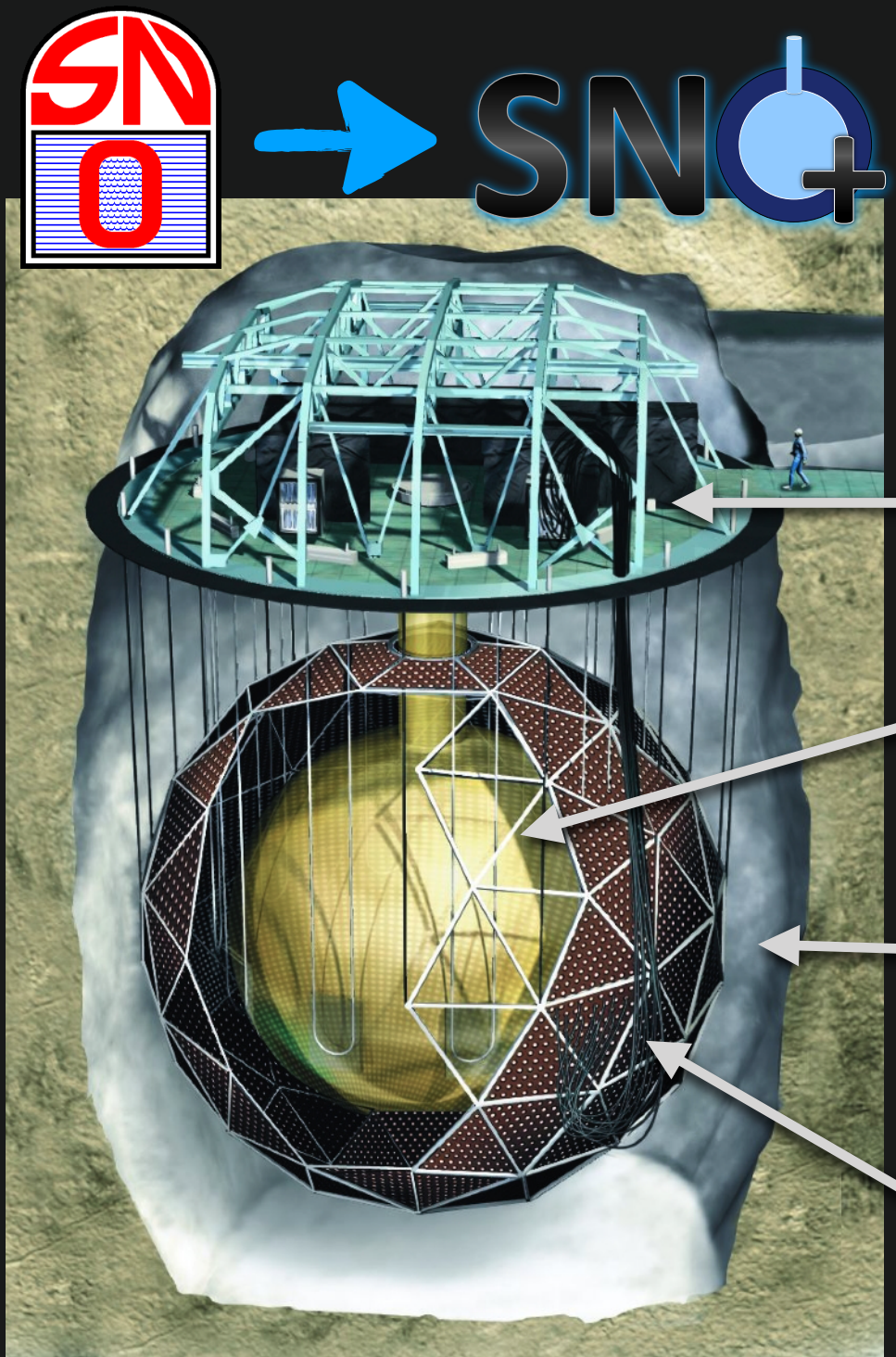
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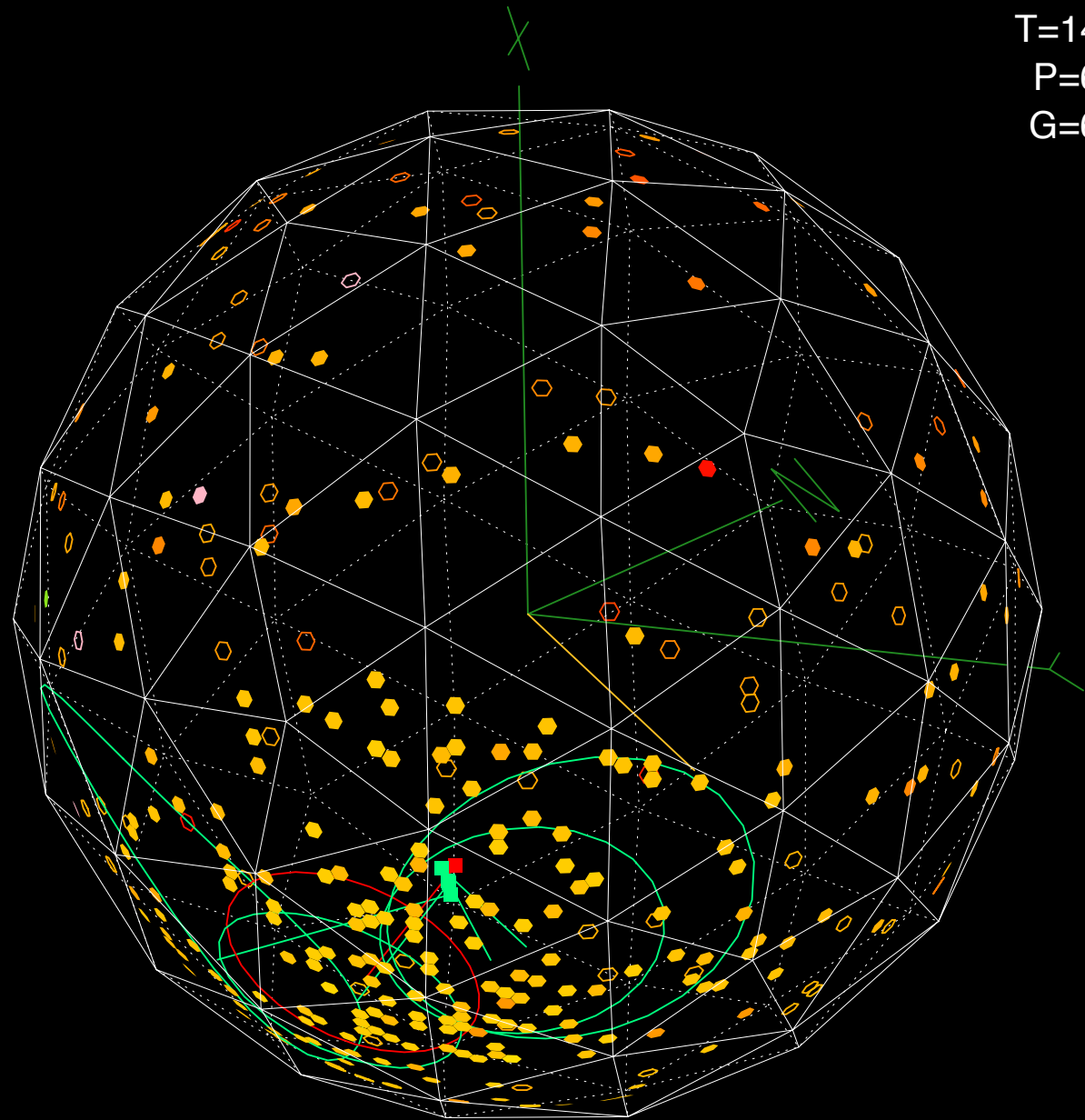
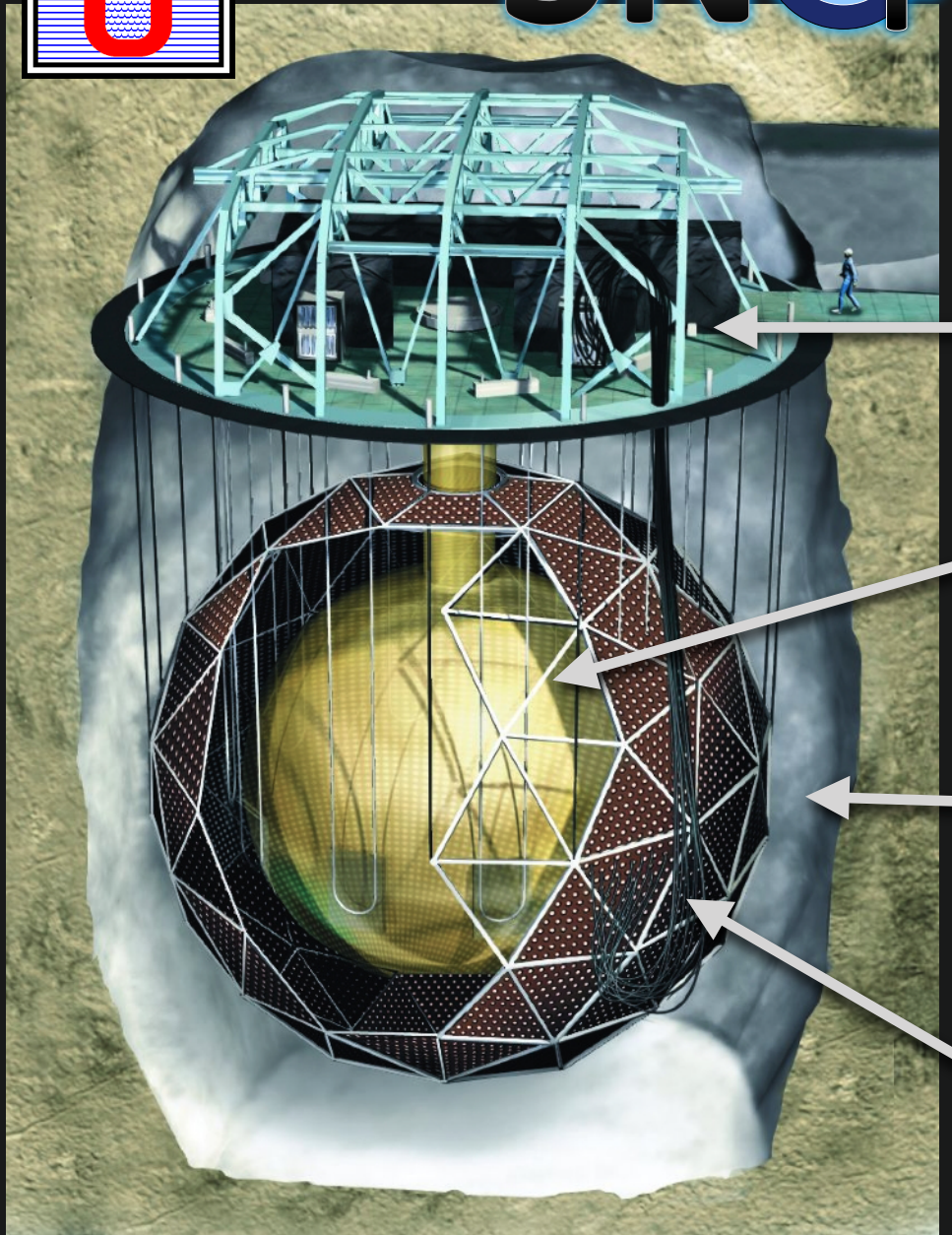
New hold-down rope net



Supernova Neutrinos in SNO+



Supernova Neutrinos in SNO+



T=149.1°
P=63.6°
G=66.0°

Run: 15873 GTID: 939



Supernova Neutrinos in SNO+



Supernova Neutrinos in SNO+



Main Course: Inverse Beta Decay



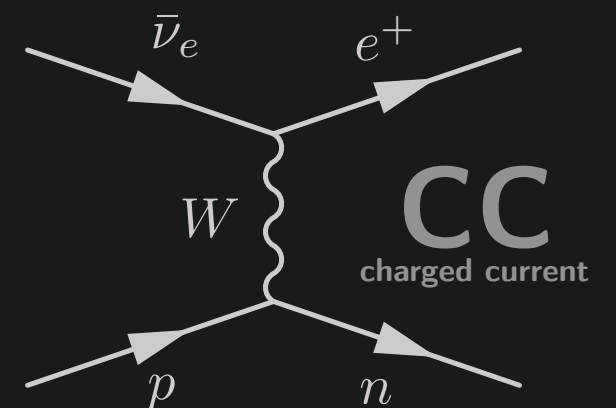
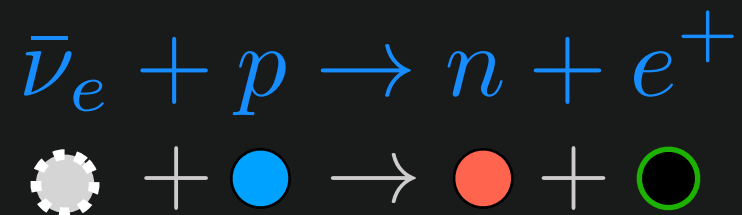
Supernova Neutrinos in SNO+



Main Course: Inverse Beta Decay



(Cowan & Reines, 1956)

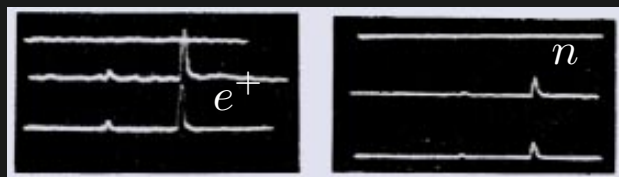




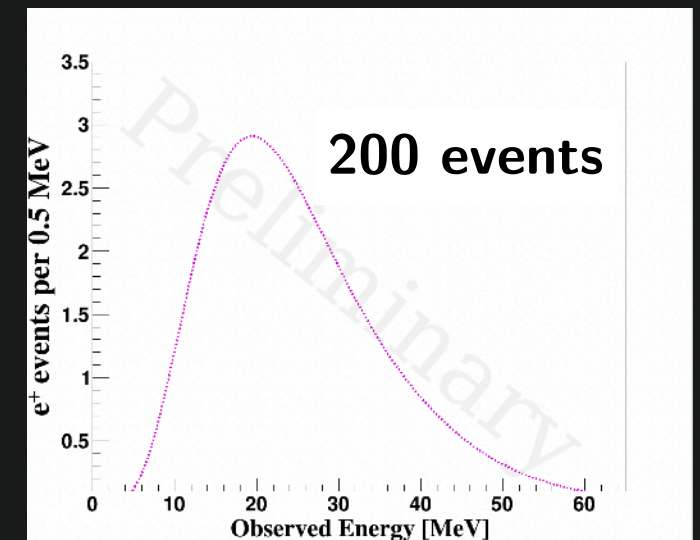
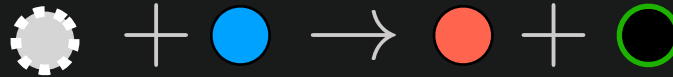
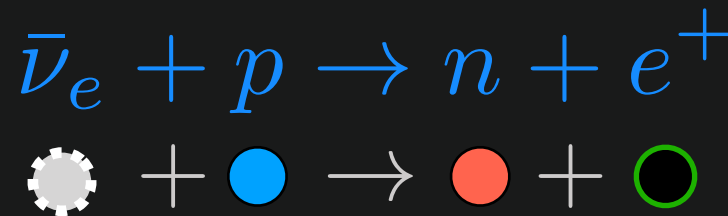
Supernova Neutrinos in SNO+



Main Course: Inverse Beta Decay



(Cowan & Reines, 1956)



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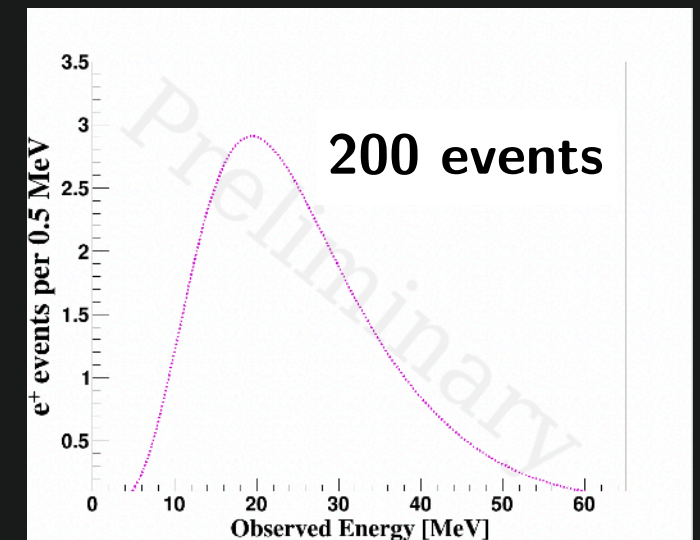
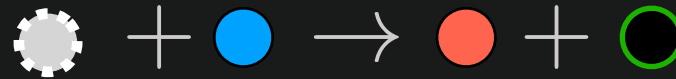
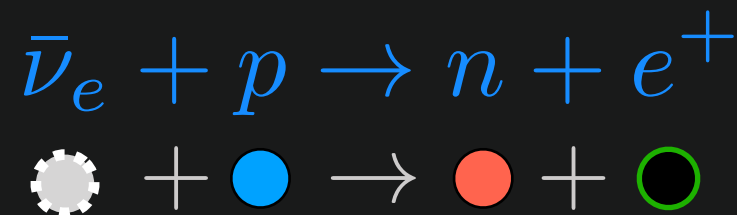


Supernova Neutrinos in SNO+

🍲 Main Course: Inverse Beta Decay



(Cowan & Reines, 1956)



J. Rumble, SNO+, TAUP 2017

🍦 Dessert: Proton Elastic Scattering

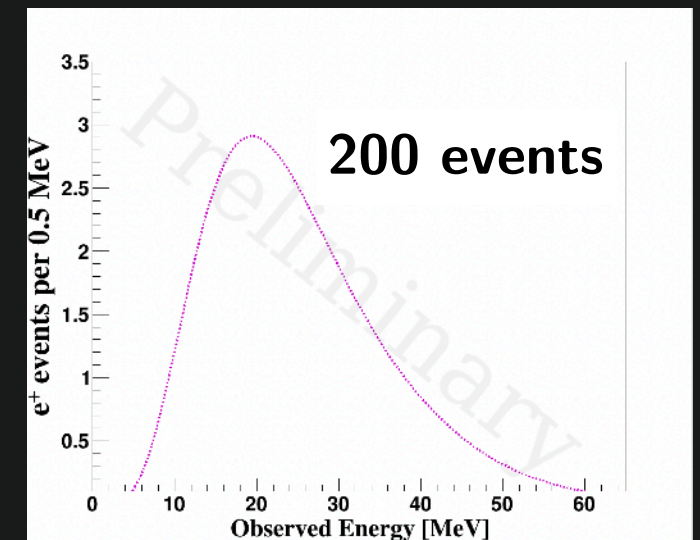
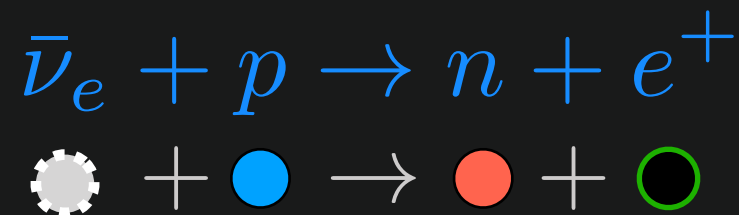


Supernova Neutrinos in SNO+

🍽️ Main Course: Inverse Beta Decay



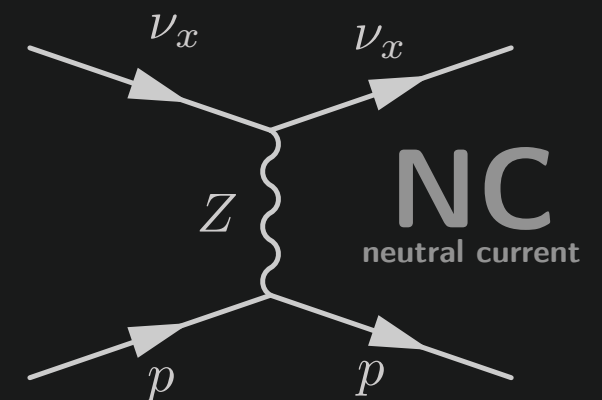
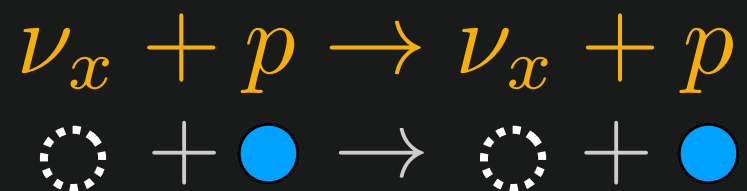
(Cowan & Reines, 1956)



J. Rumble, SNO+, TAUP 2017

🍦 Dessert: Proton Elastic Scattering

Any type (ν_x) of neutrino gives a proton a kick





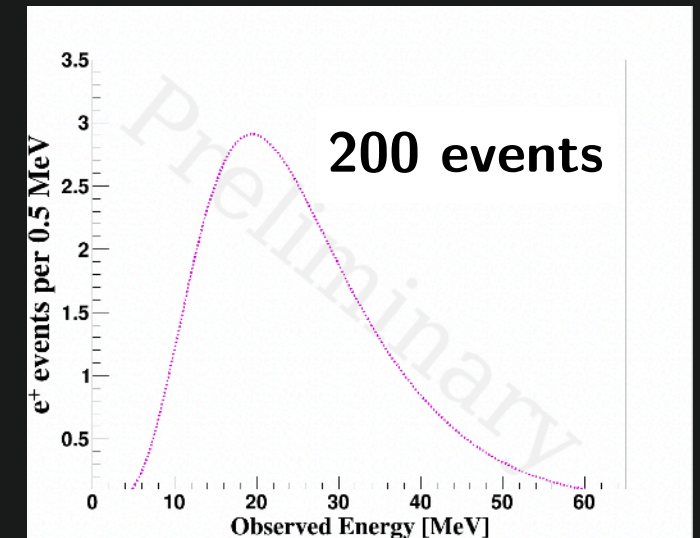
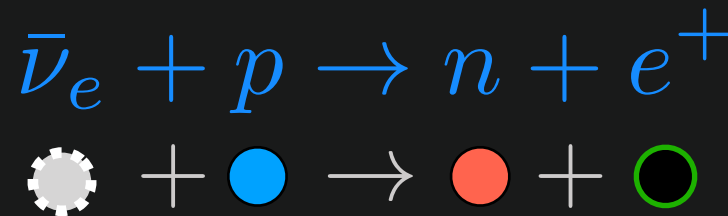
Supernova Neutrinos in SNO+



Main Course: Inverse Beta Decay



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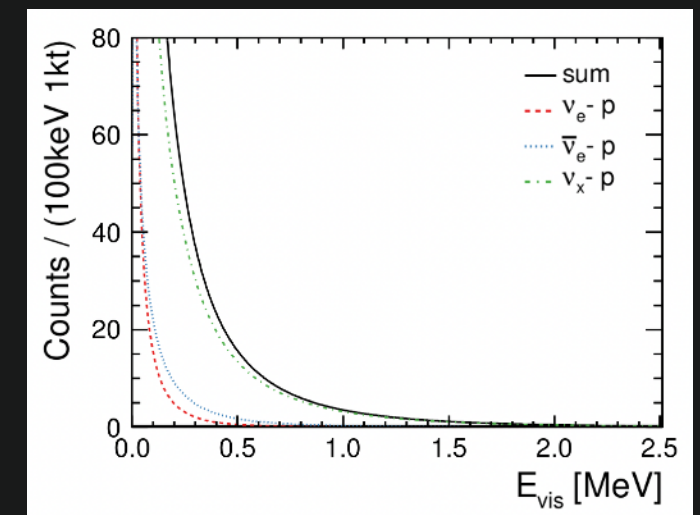
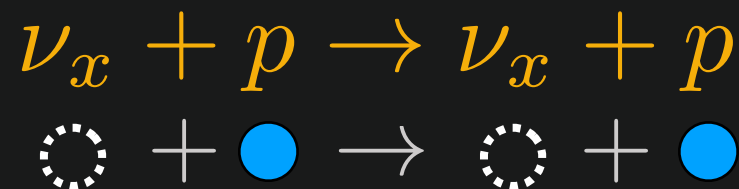


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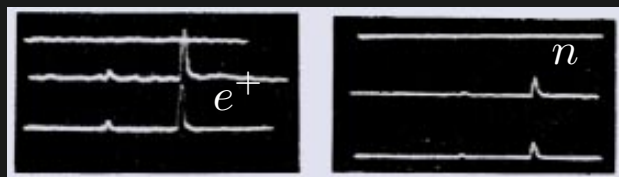
J. Rumleskie, SNO+, TAUP 2017



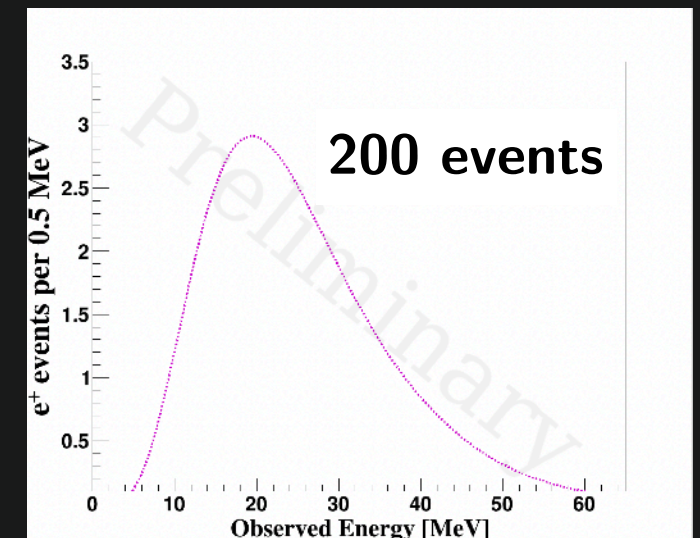
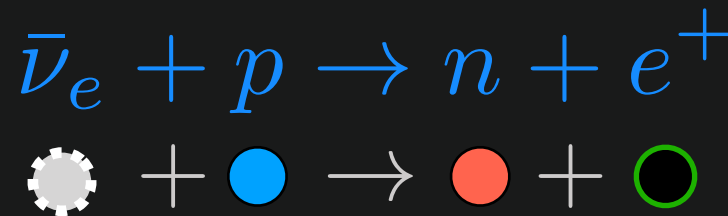
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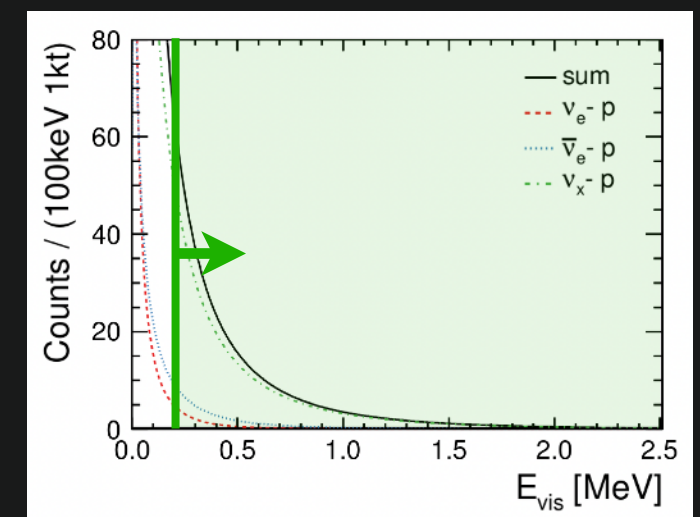
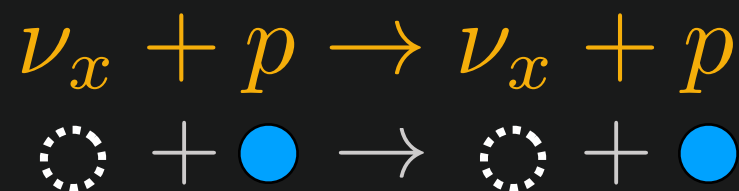


J. Rumleskie, SNO+, TAUP 2017



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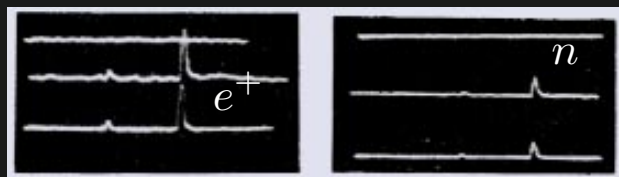
J. Rumleskie, SNO+, TAUP 2017



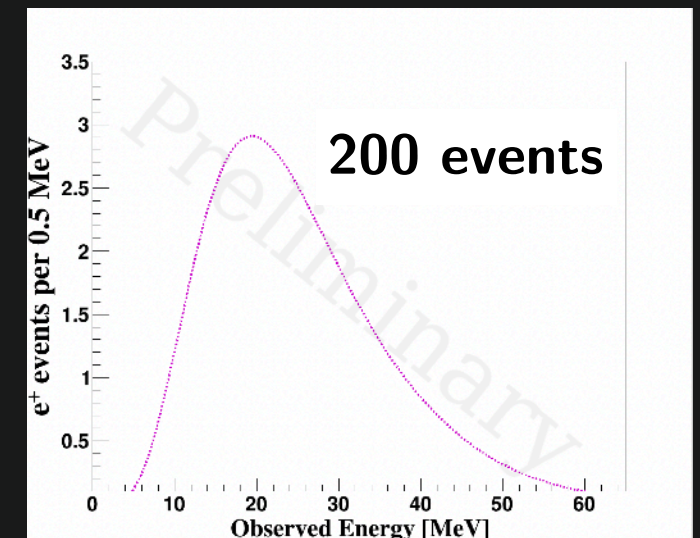
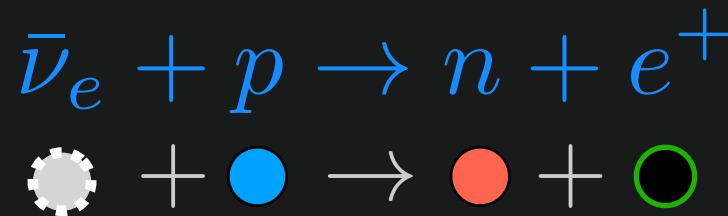
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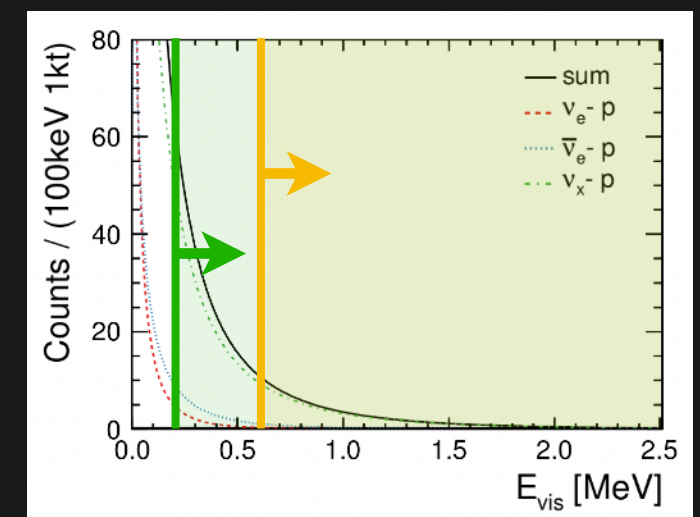
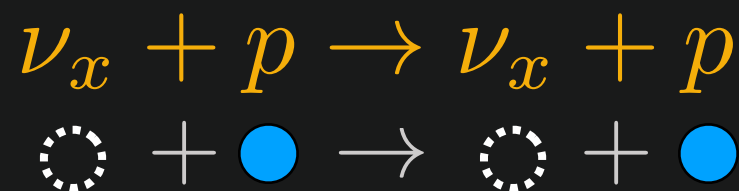


J. Rumleskie, SNO+, TAUP 2017



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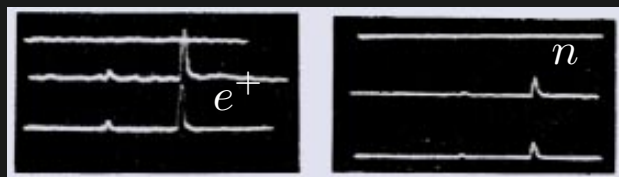
J. Rumleskie, SNO+, TAUP 2017



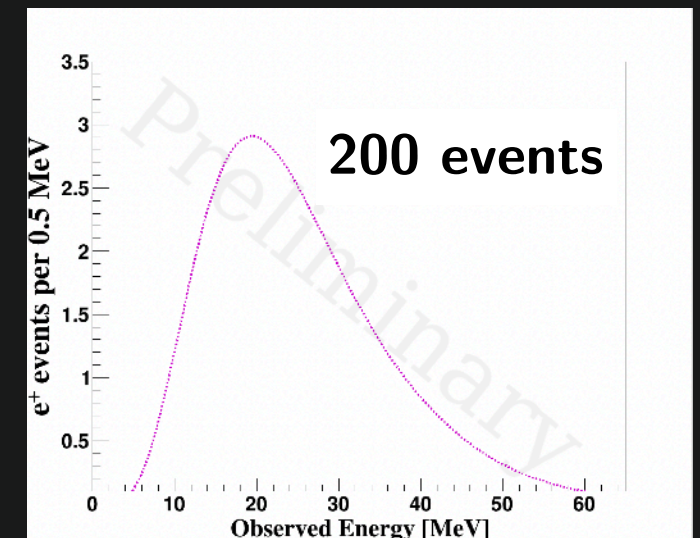
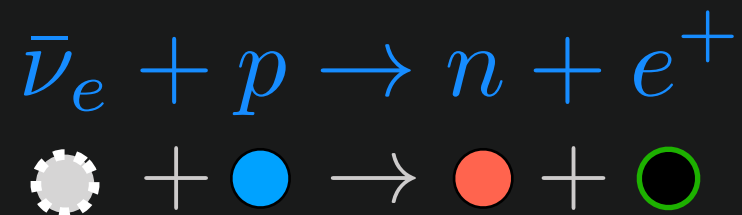
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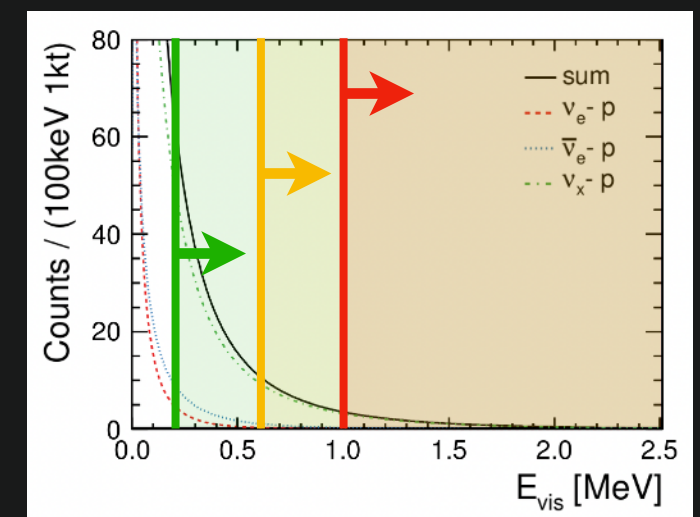
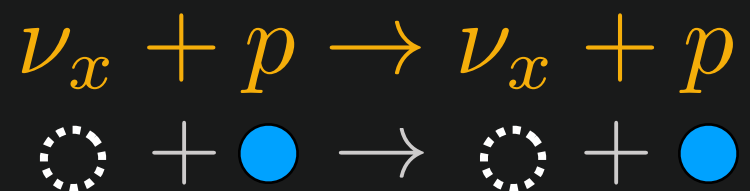


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Any type (ν_x) of neutrino gives a proton a kick



J. Rumleskie, SNO+, TAUP 2017

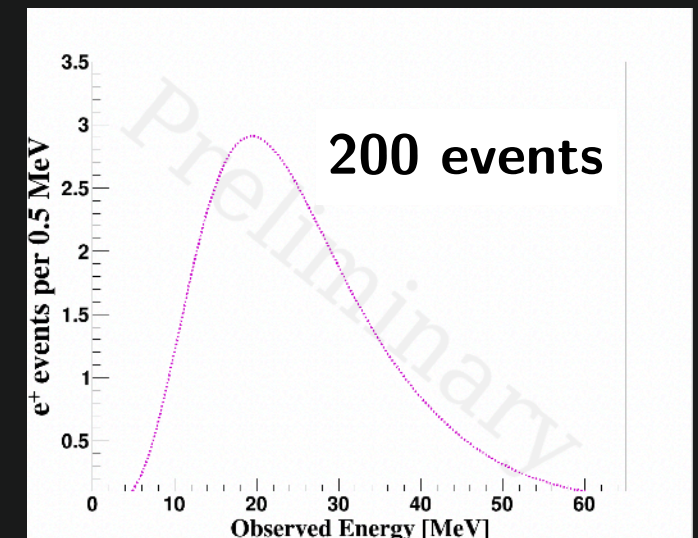
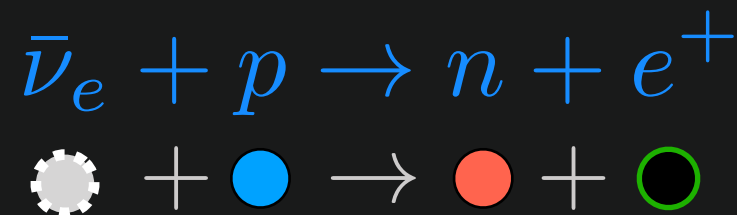


Supernova Neutrinos in SNO+

🍲 Main Course: Inverse Beta Decay



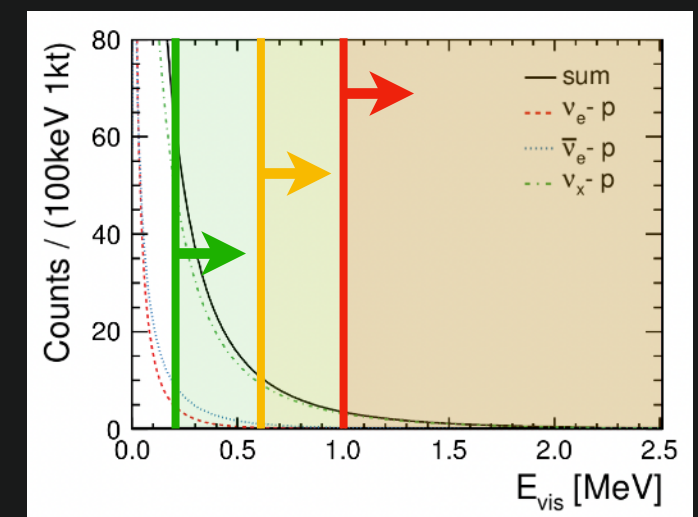
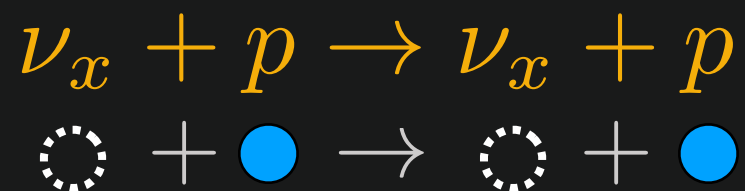
(Cowan & Reines, 1956)



J. Rumleskie, SNO+, TAUP 2017

🍦 Dessert: Proton Elastic Scattering

Any type (ν_x) of neutrino gives a proton a kick



J. Rumleskie, SNO+, TAUP 2017



Menu:

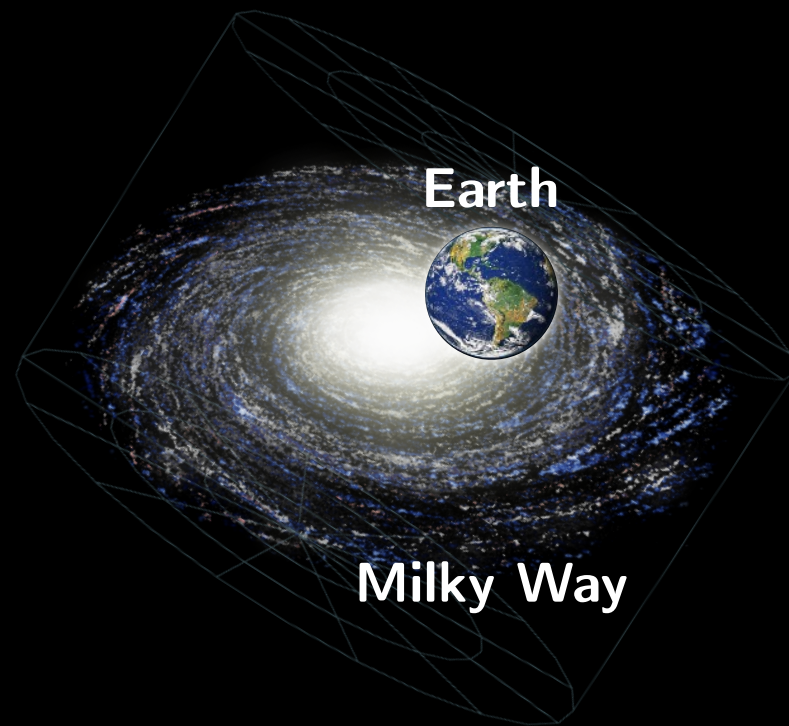
NC	$\nu_x + p \rightarrow \nu_x + p$	429 events?
CC	$\bar{\nu}_e + p \rightarrow n + e^+$	195 events
CC	$\bar{\nu}_e + {}^{12}\text{C} \rightarrow {}^{12}\text{B} + e^+$	7 events
CC	$\nu_e + {}^{12}\text{C} \rightarrow {}^{12}\text{N} + e^-$	3 events
NC	$\nu_x + {}^{12}\text{C} \rightarrow {}^{12}\text{C}^* + \nu'$	44 events
CC/NC	$\nu_x + {}^{12}\text{C} \rightarrow {}^{11}\text{C}/{}^{11}\text{B} + X$	2 events
CC/NC	$\nu_x + e^- \rightarrow \nu_x + e^-$	13 events

Hundreds of events
for a supernova at 10 kpc
(33,000 light years)

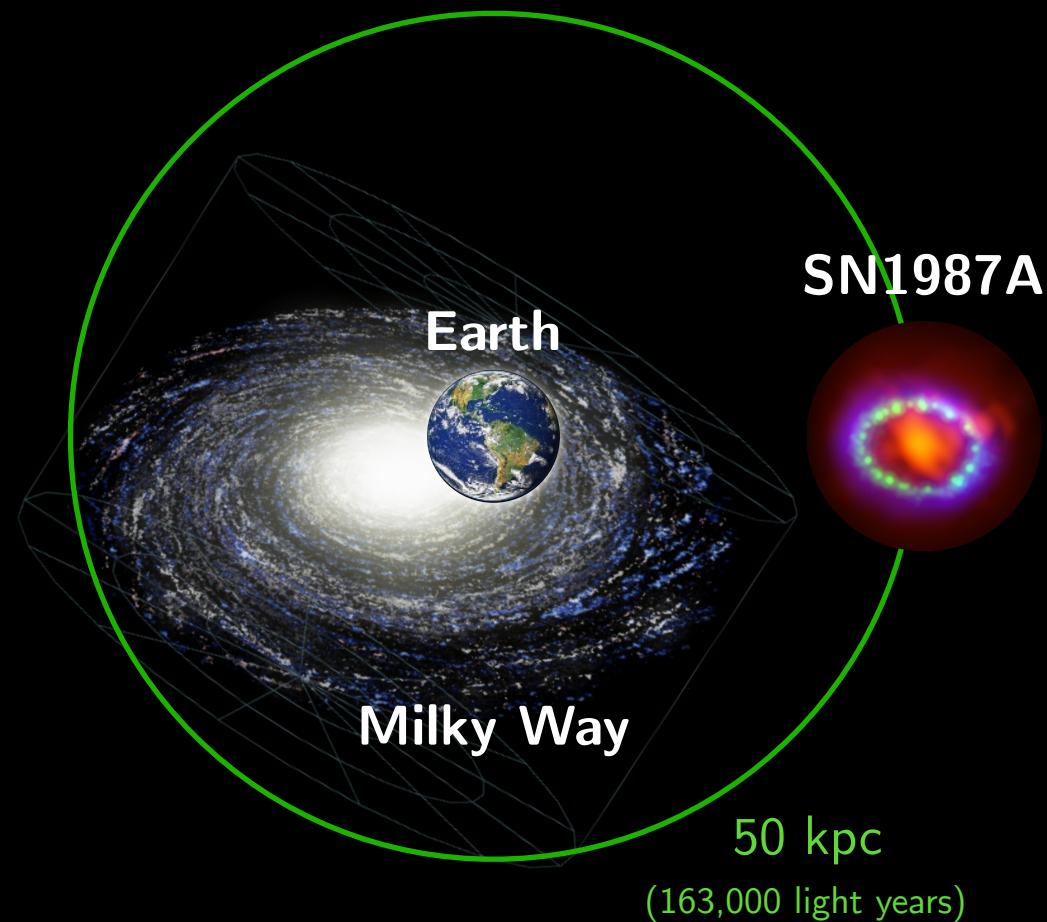
Thousands across all detectors

Patience...?

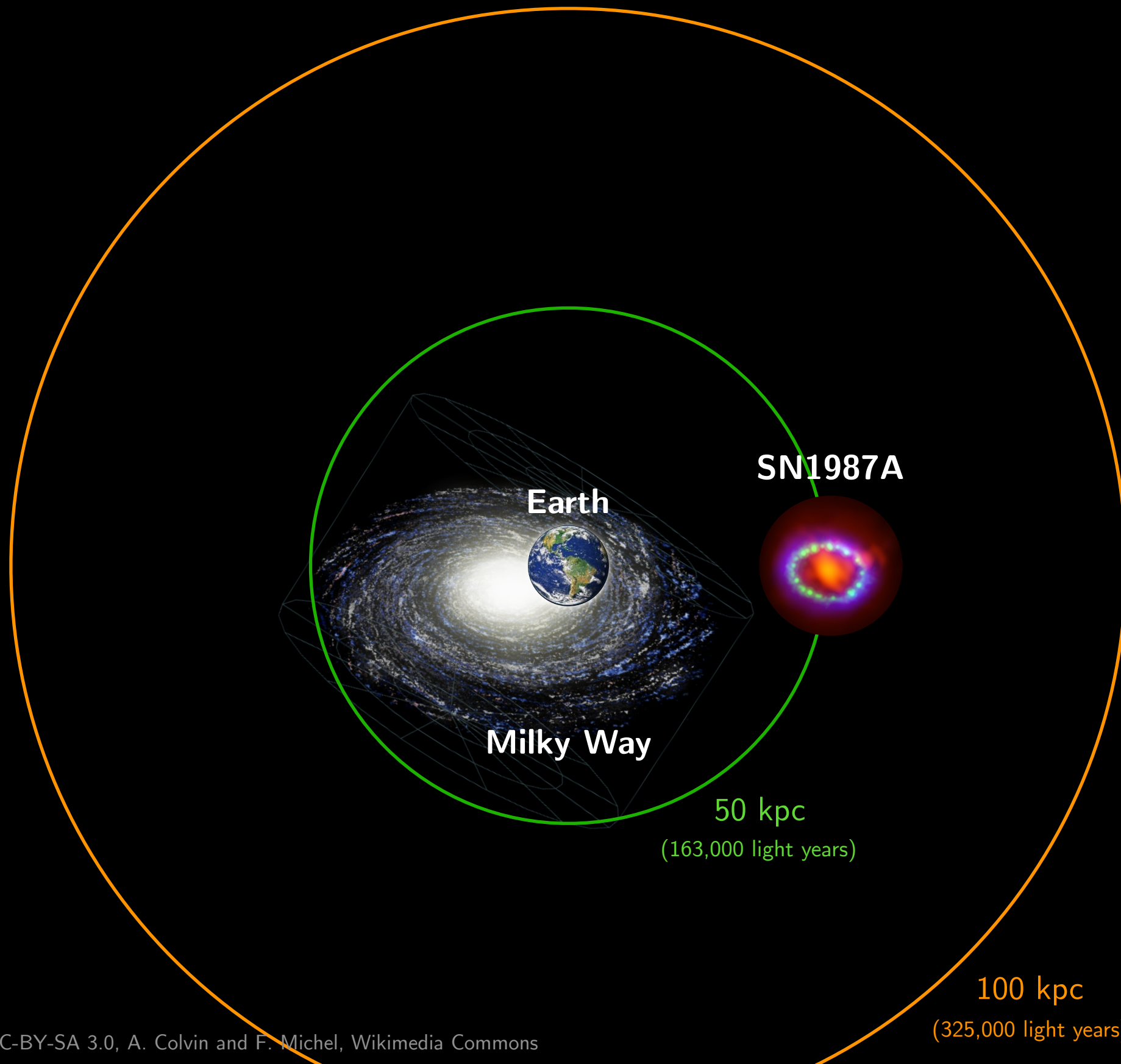
Diffuse Supernova Neutrino Background (DSNB)



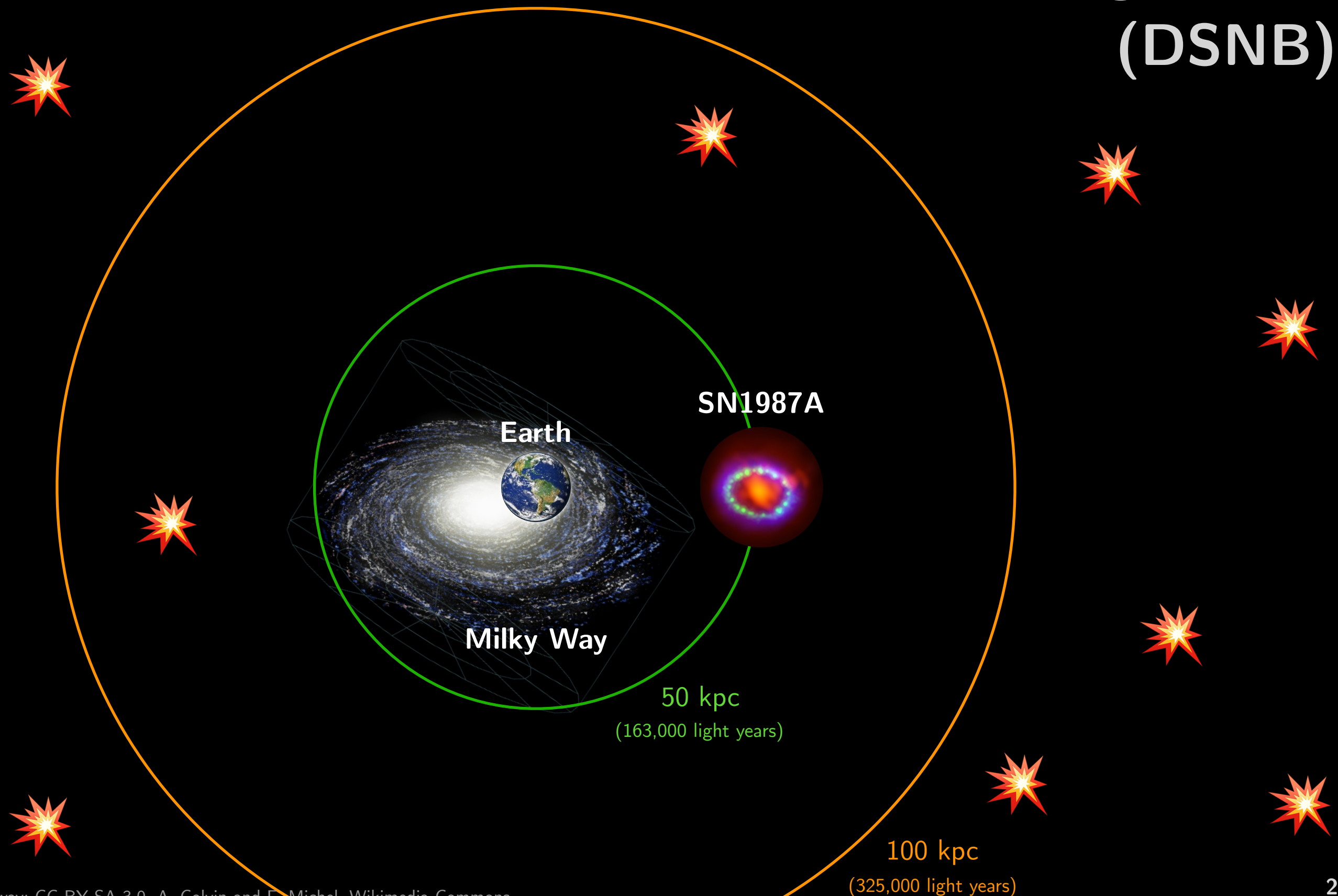
Diffuse Supernova Neutrino Background (DSNB)



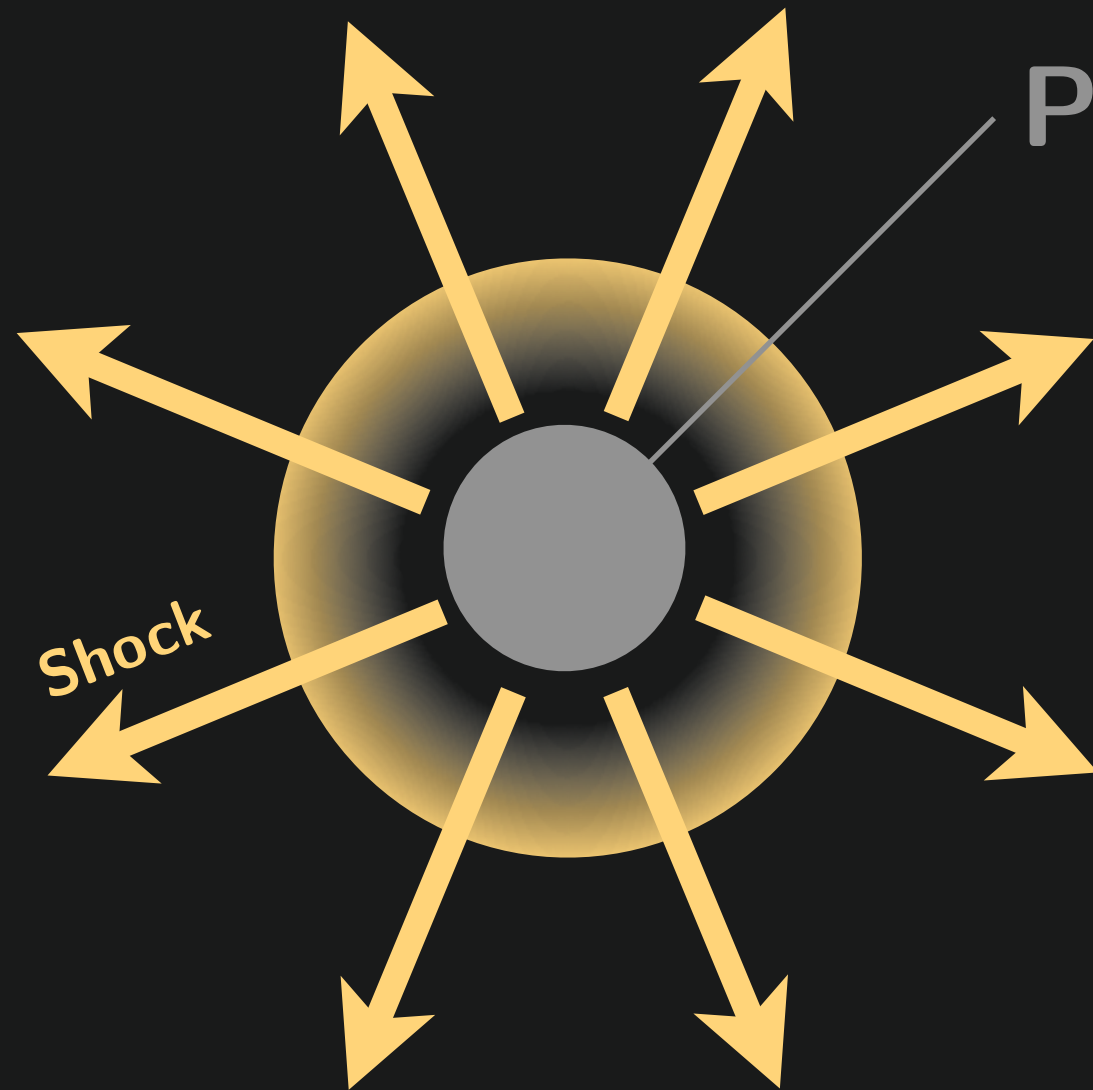
Diffuse Supernova Neutrino Background (DSNB)



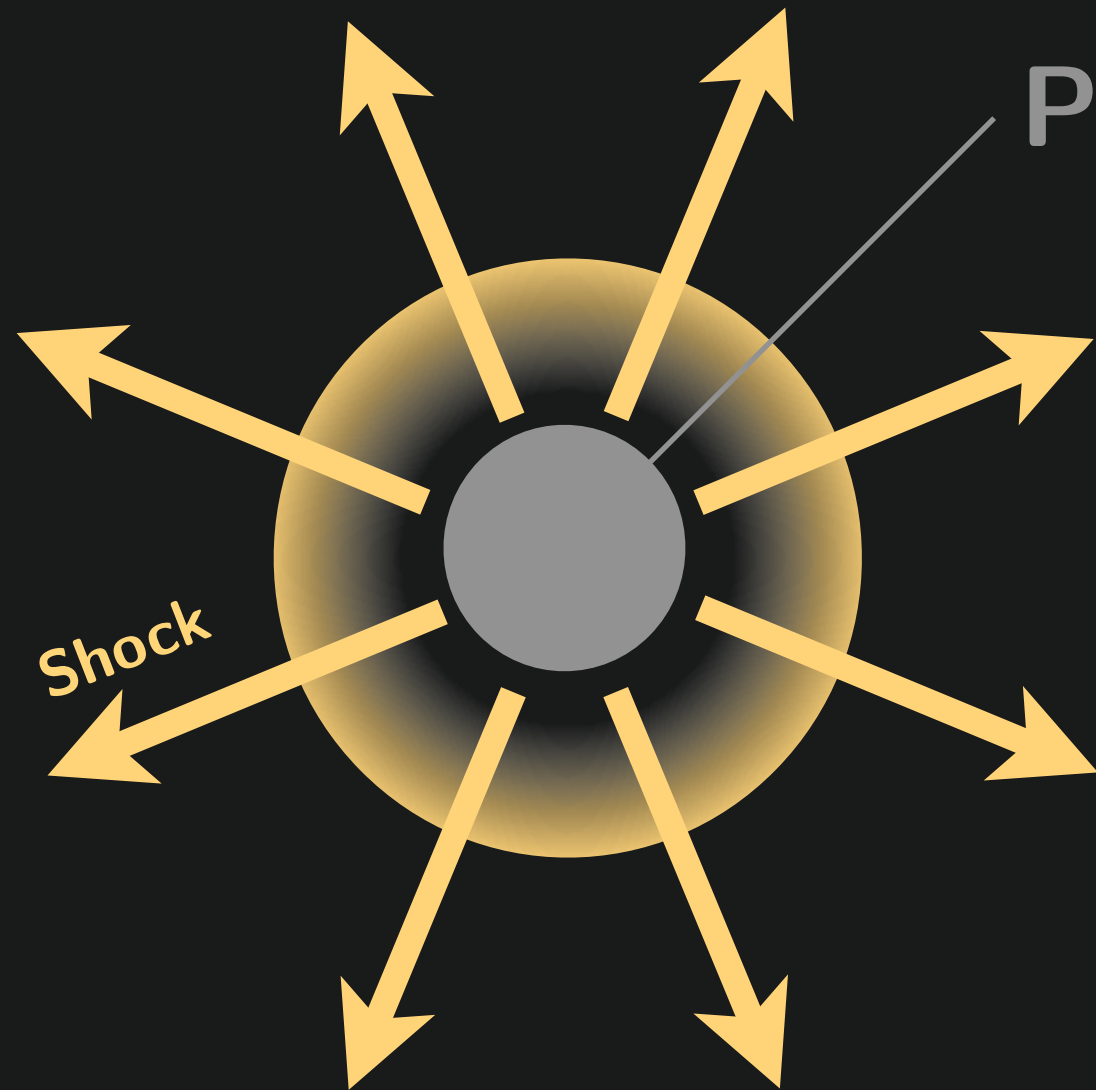
Diffuse Supernova Neutrino Background (DSNB)



Diffuse Supernova Neutrino Background (DSNB)



Diffuse Supernova Neutrino Background (DSNB)



Proto-Neutron Star

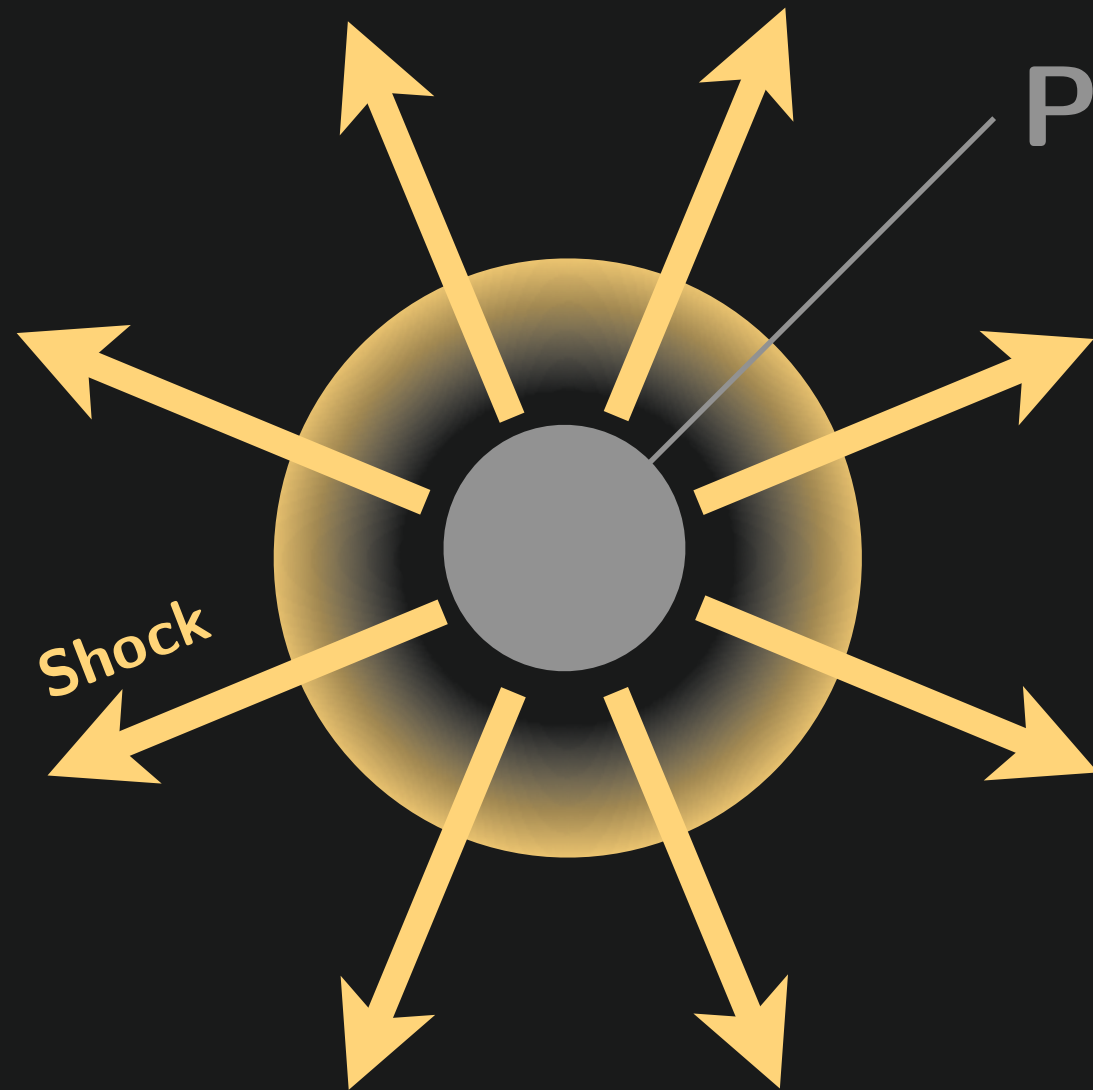
Production of neutrino-antineutrino pairs

$$\gamma \rightarrow \nu + \bar{\nu}$$

$$e^+ + e^- \rightarrow \nu + \bar{\nu}$$

$$e^\pm + N \rightarrow e^\pm + N + \nu + \bar{\nu}$$

Diffuse Supernova Neutrino Background (DSNB)



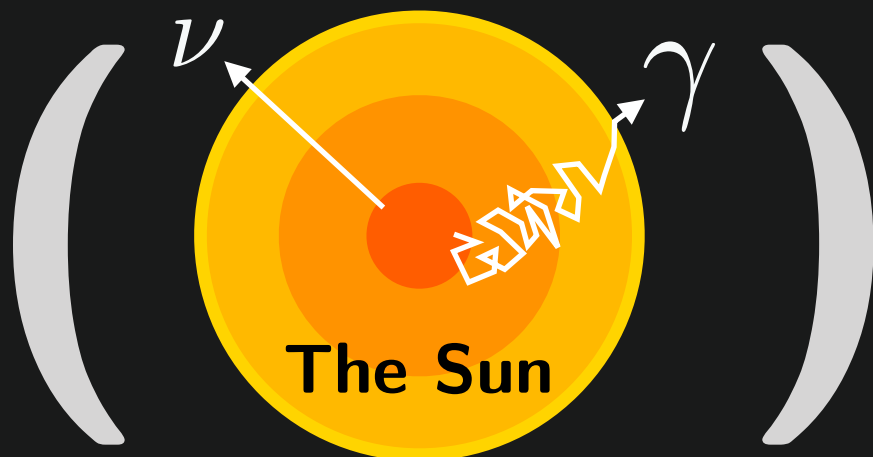
Proto-Neutron Star

Production of neutrino-antineutrino pairs

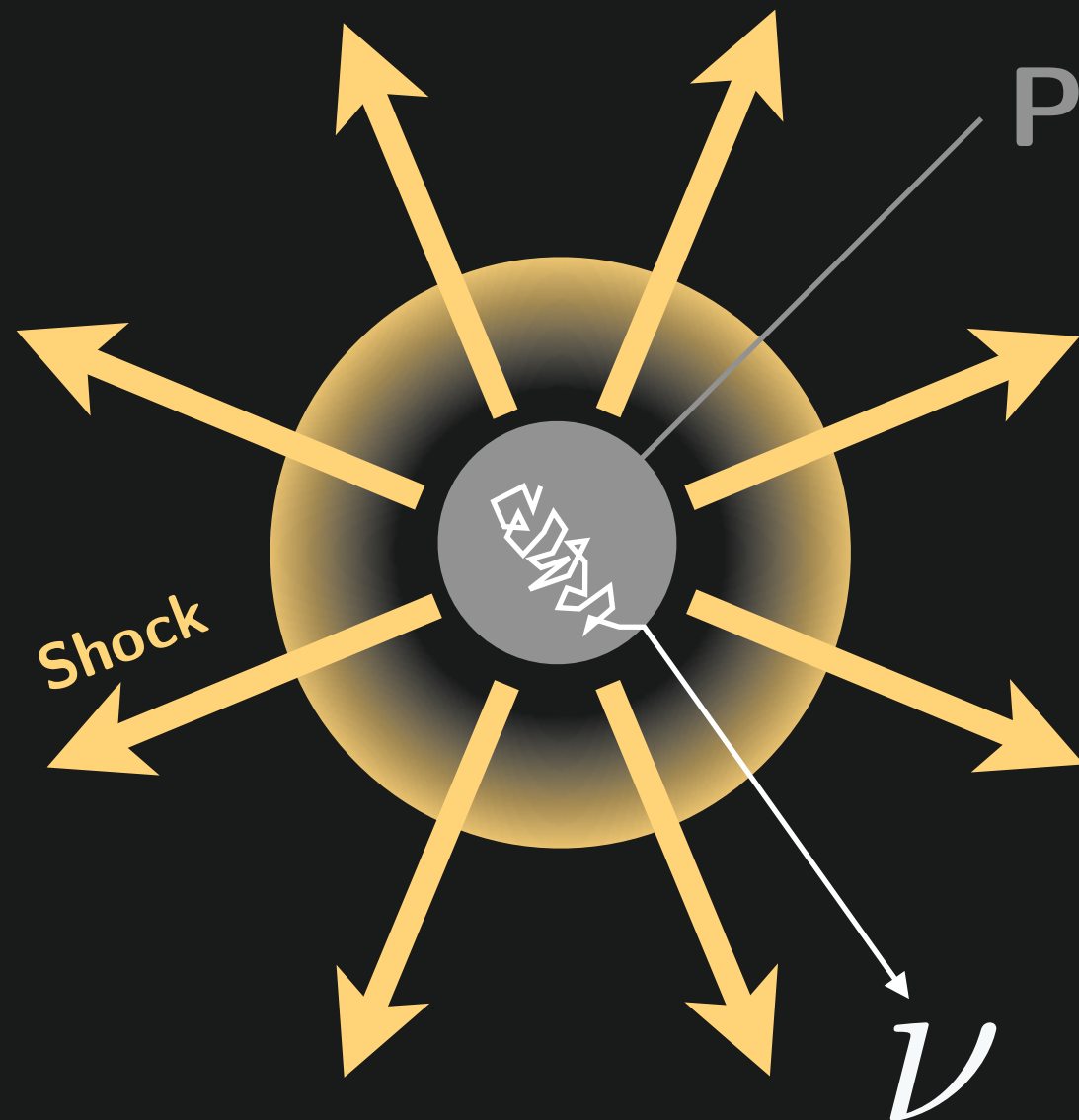
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Diffuse Supernova Neutrino Background (DSNB)



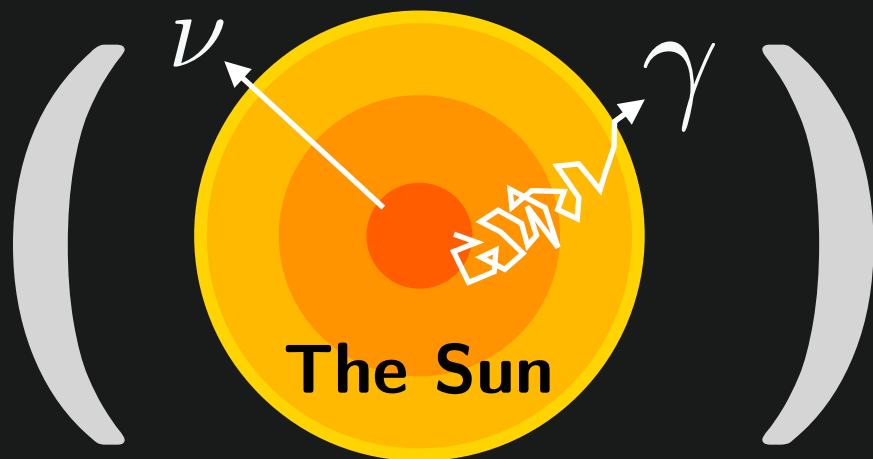
Proto-Neutron Star

Production of neutrino-antineutrino pairs

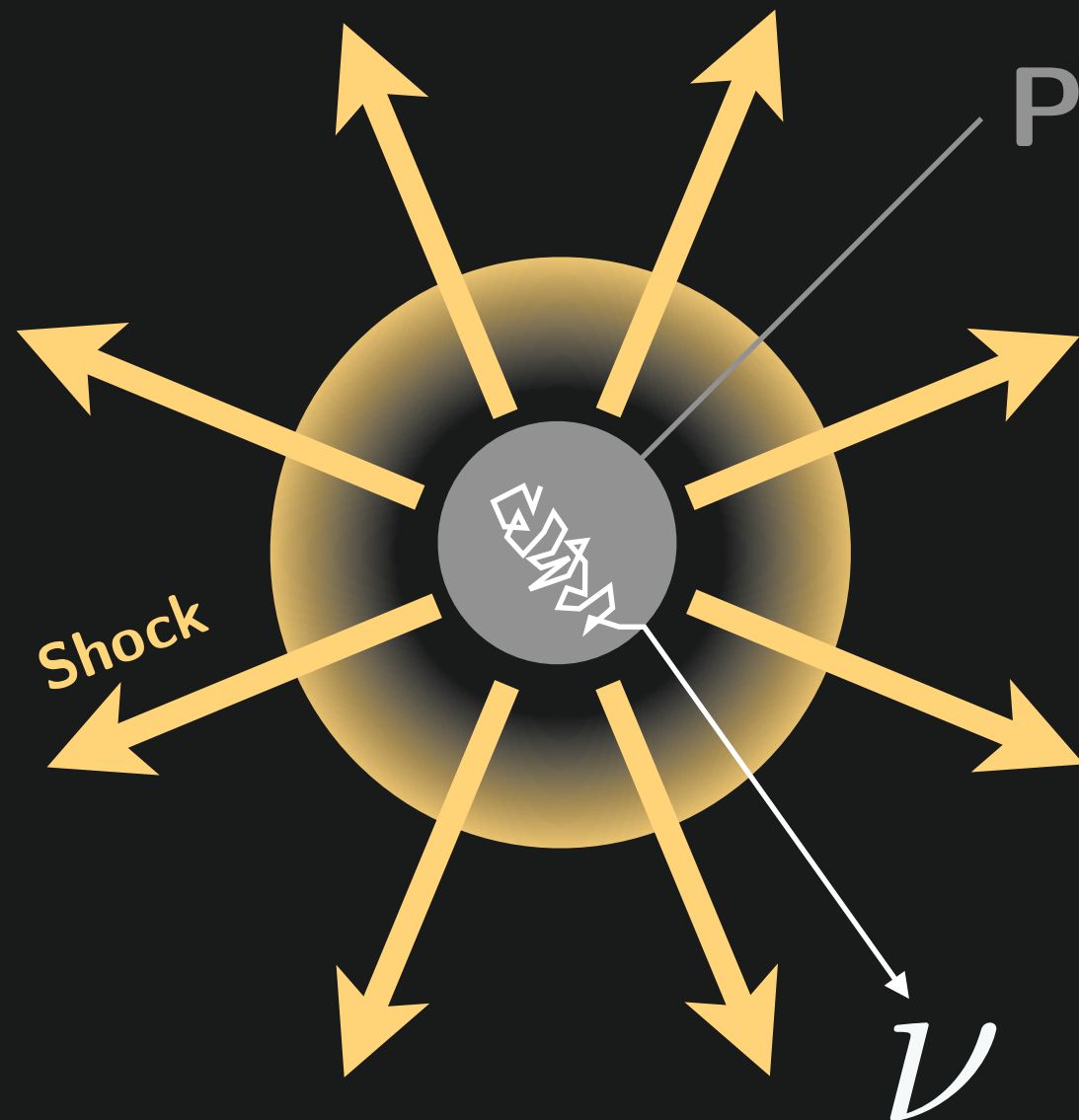
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Diffuse Supernova Neutrino Background (DSNB)



Proto-Neutron Star

Production of neutrino-antineutrino pairs

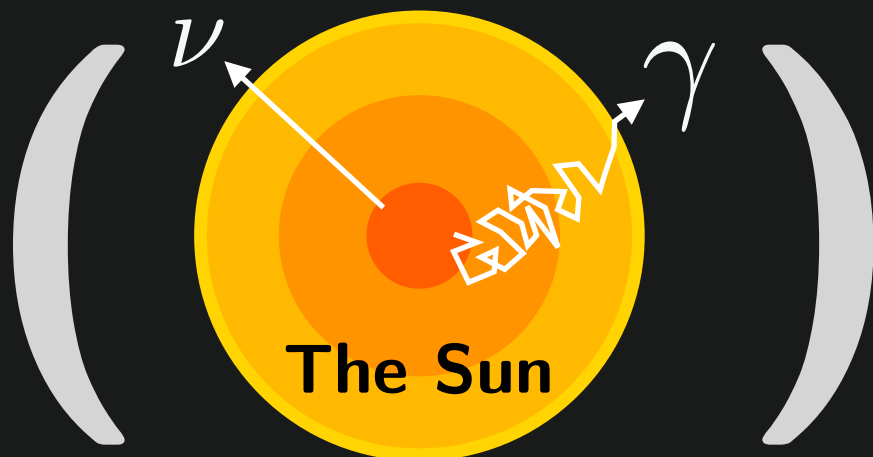
$$\gamma \rightarrow \nu + \bar{\nu}$$

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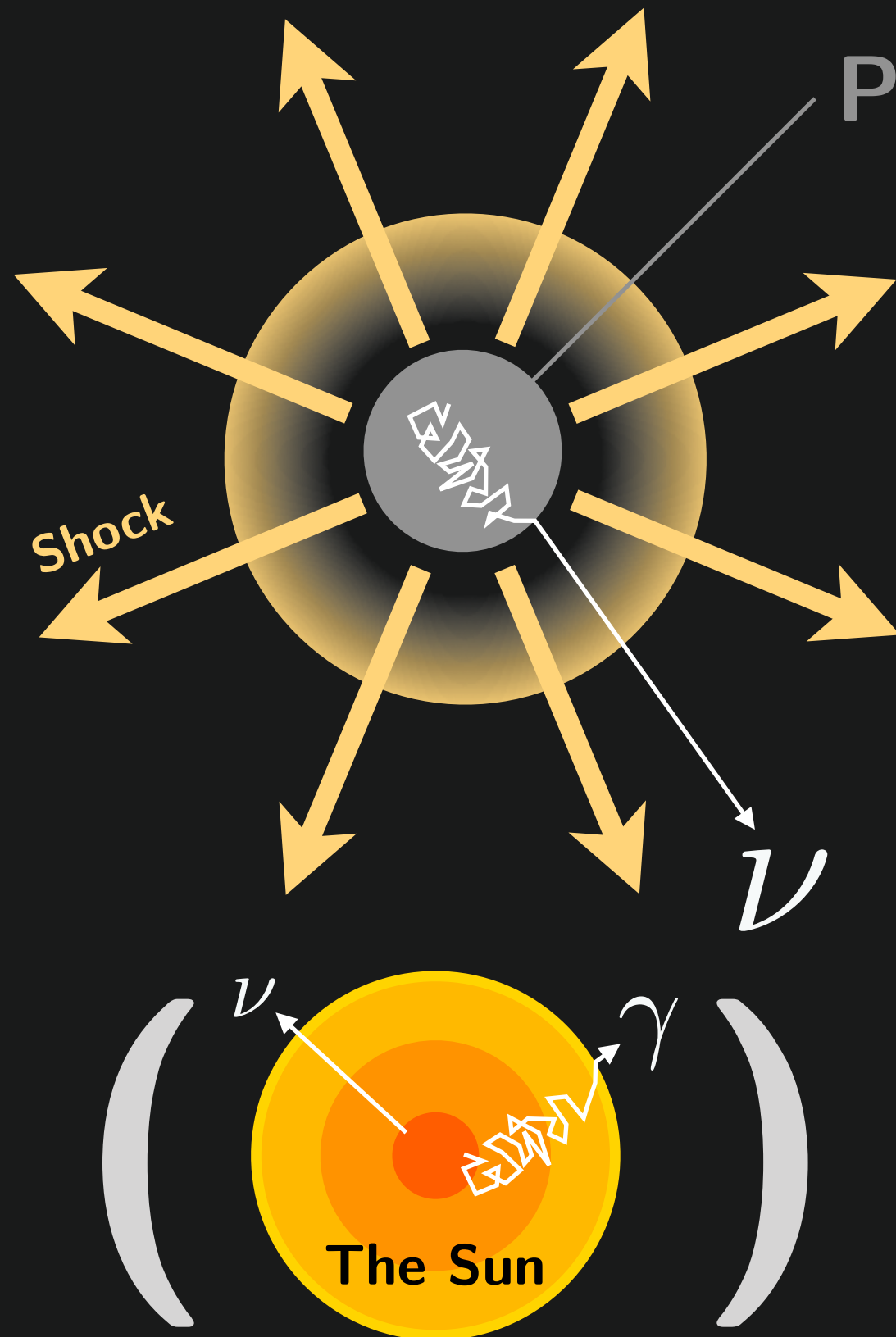
**Emerge with an averaged energy distribution
given by the temperature, T**

$$\frac{dN(E)}{dE} = \frac{E_\nu^{\text{tot}}}{6} \frac{120}{7\pi^4} \frac{E^2}{T^4} \left[\exp\left(\frac{E}{T}\right) + 1 \right]^{-1}$$

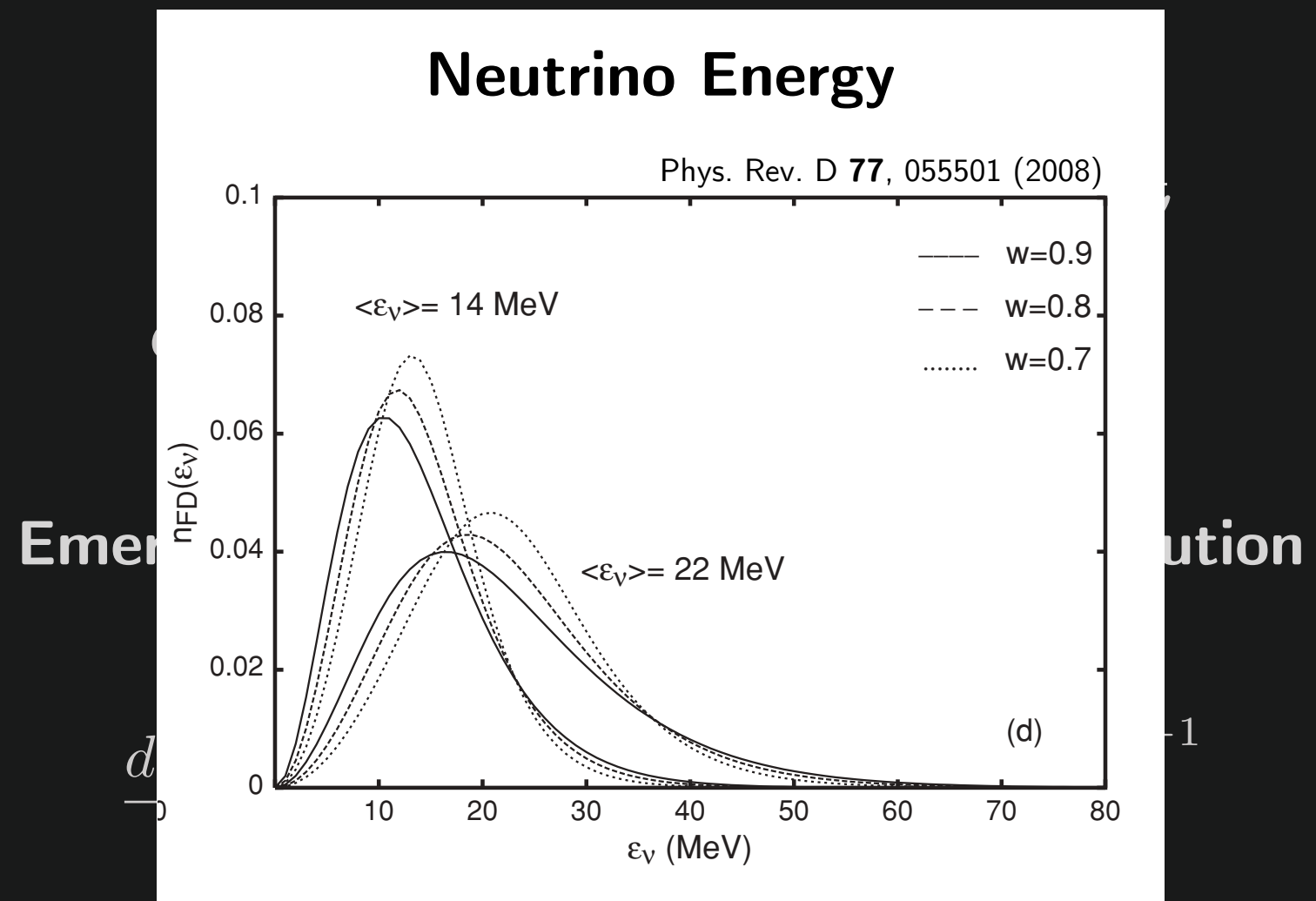


The Sun

Diffuse Supernova Neutrino Background (DSNB)

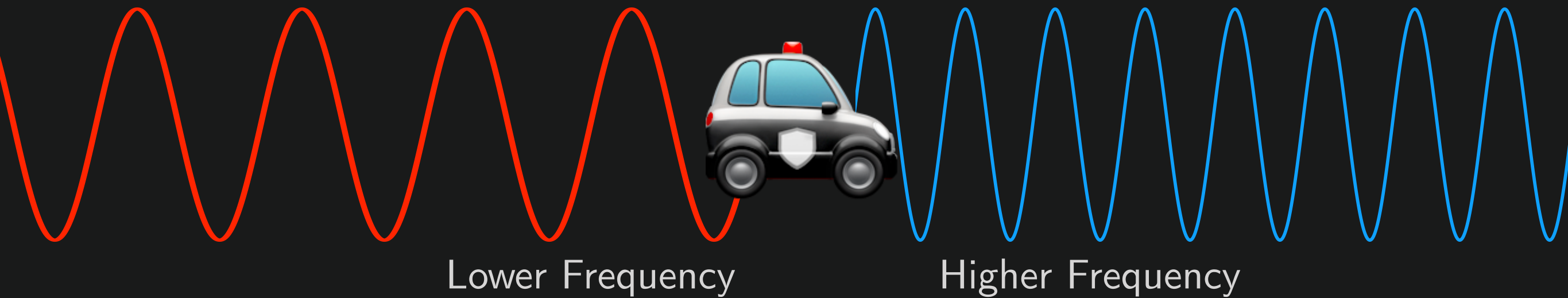


Production of neutrino-antineutrino pairs



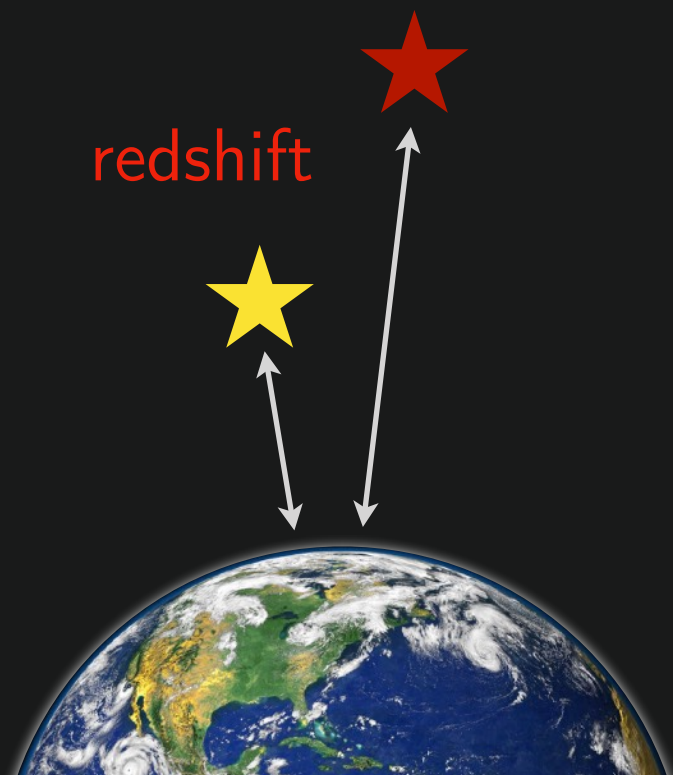
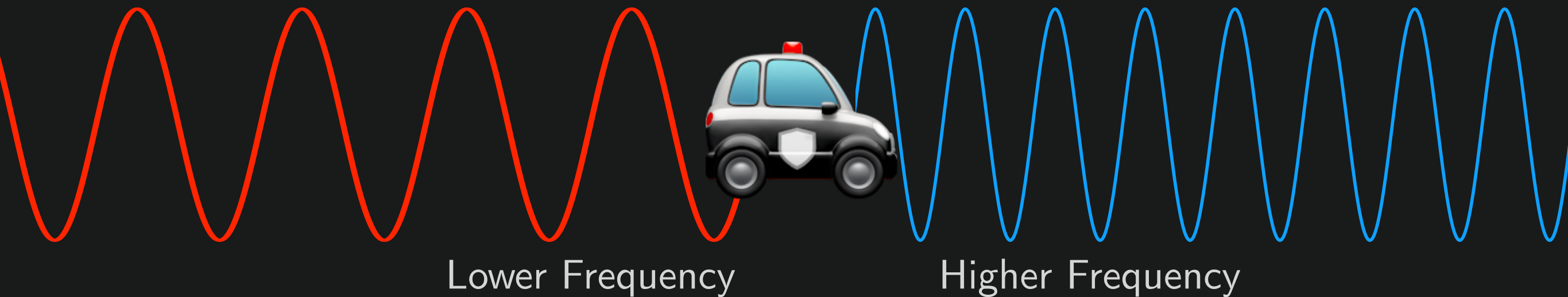
Diffuse Supernova Neutrino Background (DSNB)

The Doppler Effect



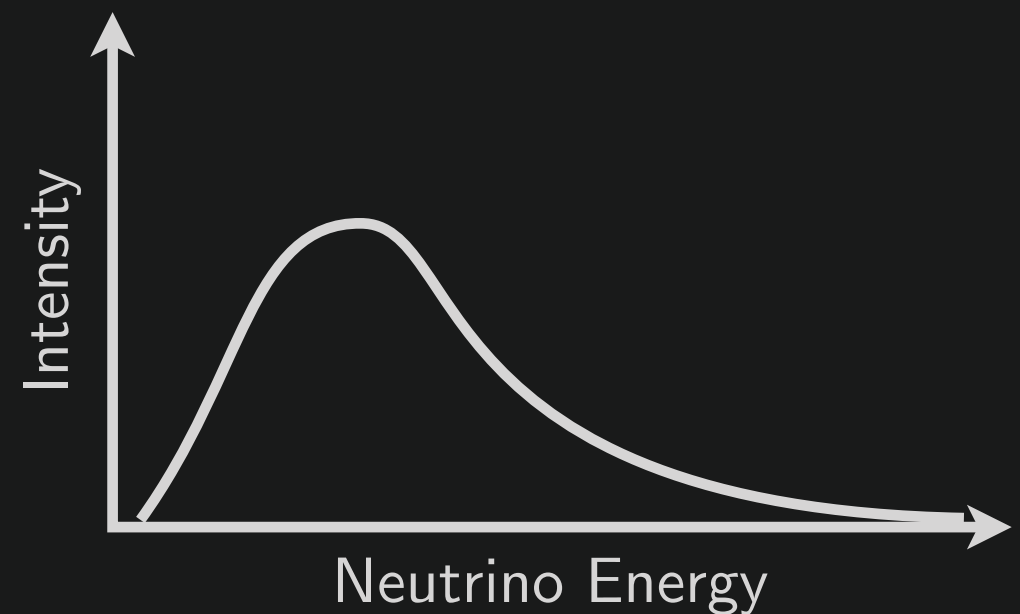
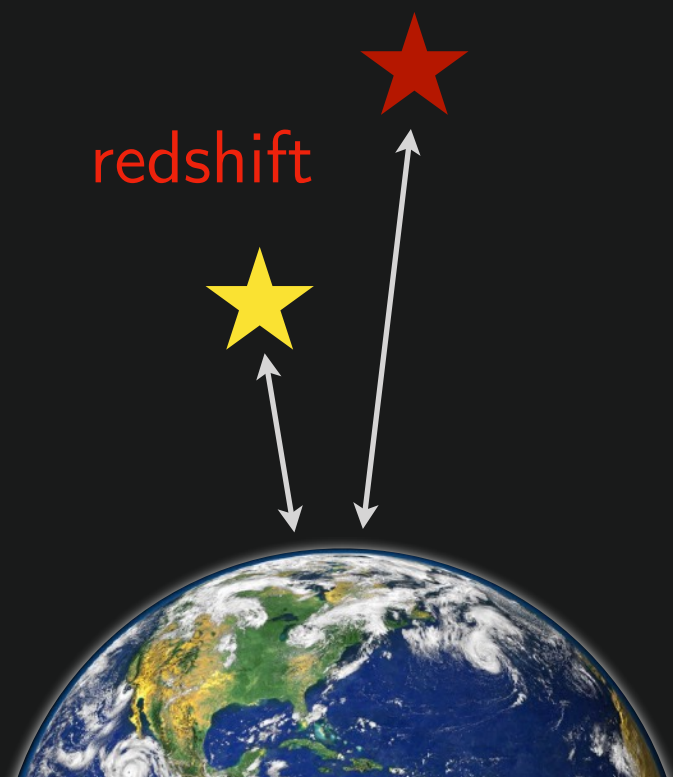
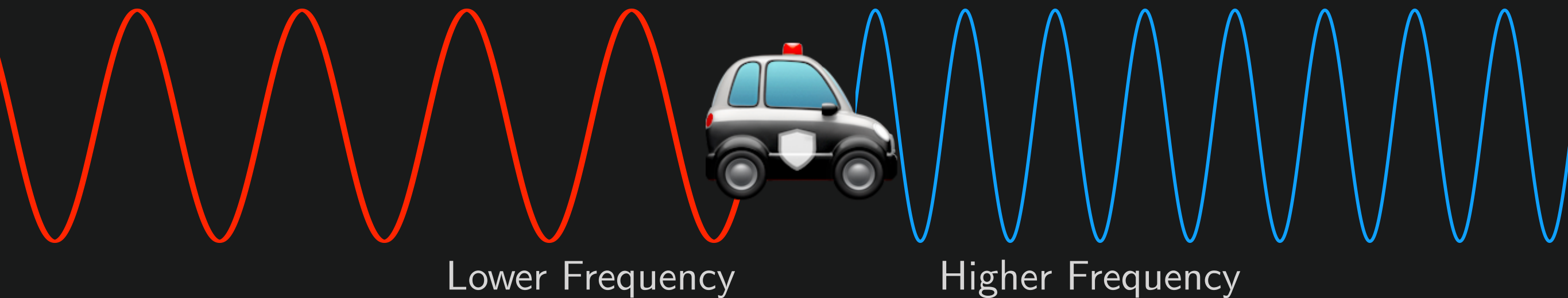
Diffuse Supernova Neutrino Background (DSNB)

The Doppler Effect



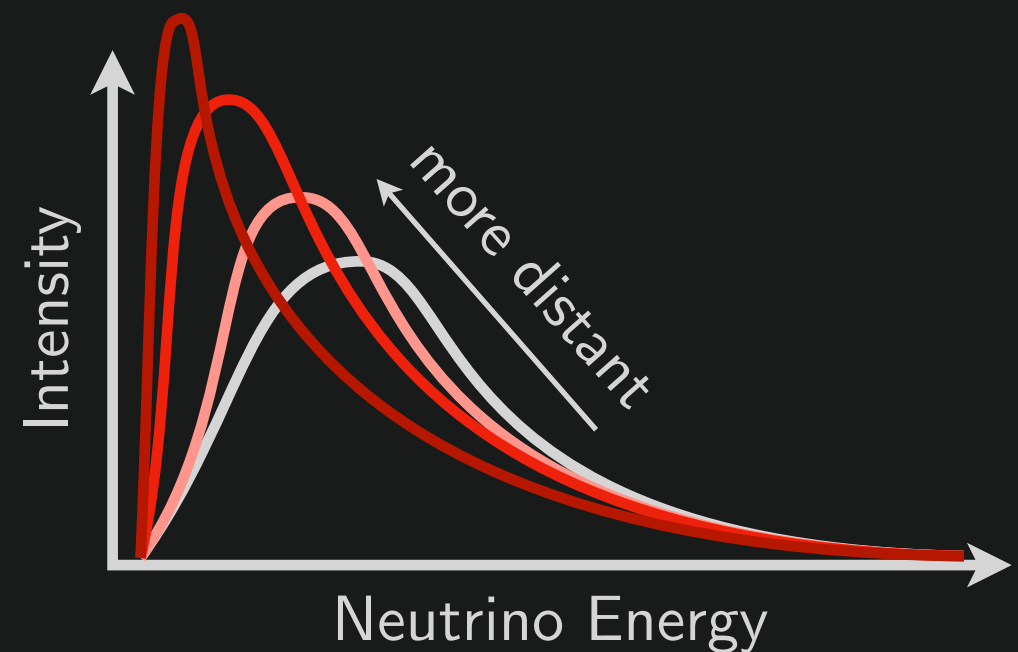
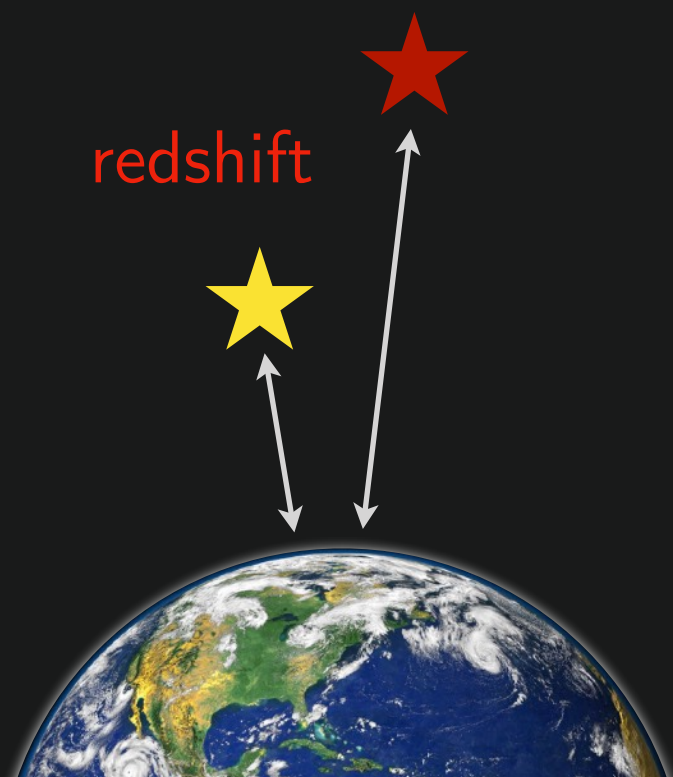
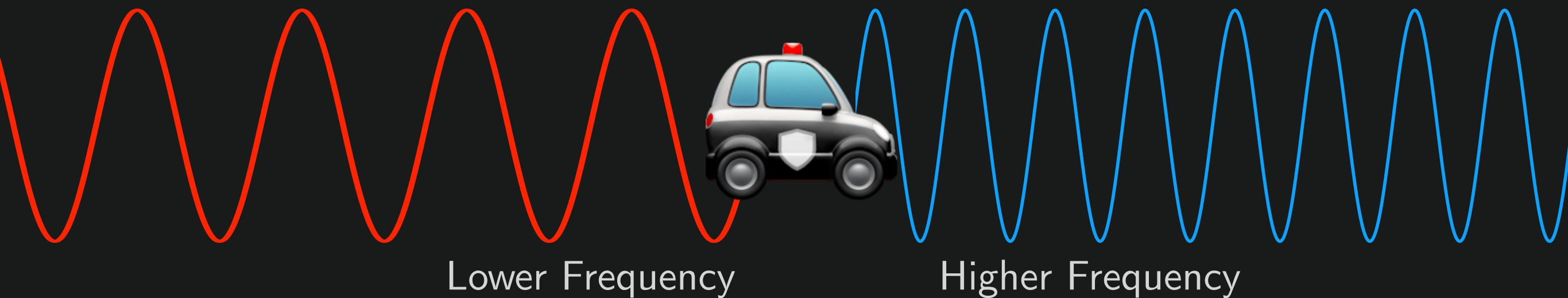
Diffuse Supernova Neutrino Background (DSNB)

The Doppler Effect

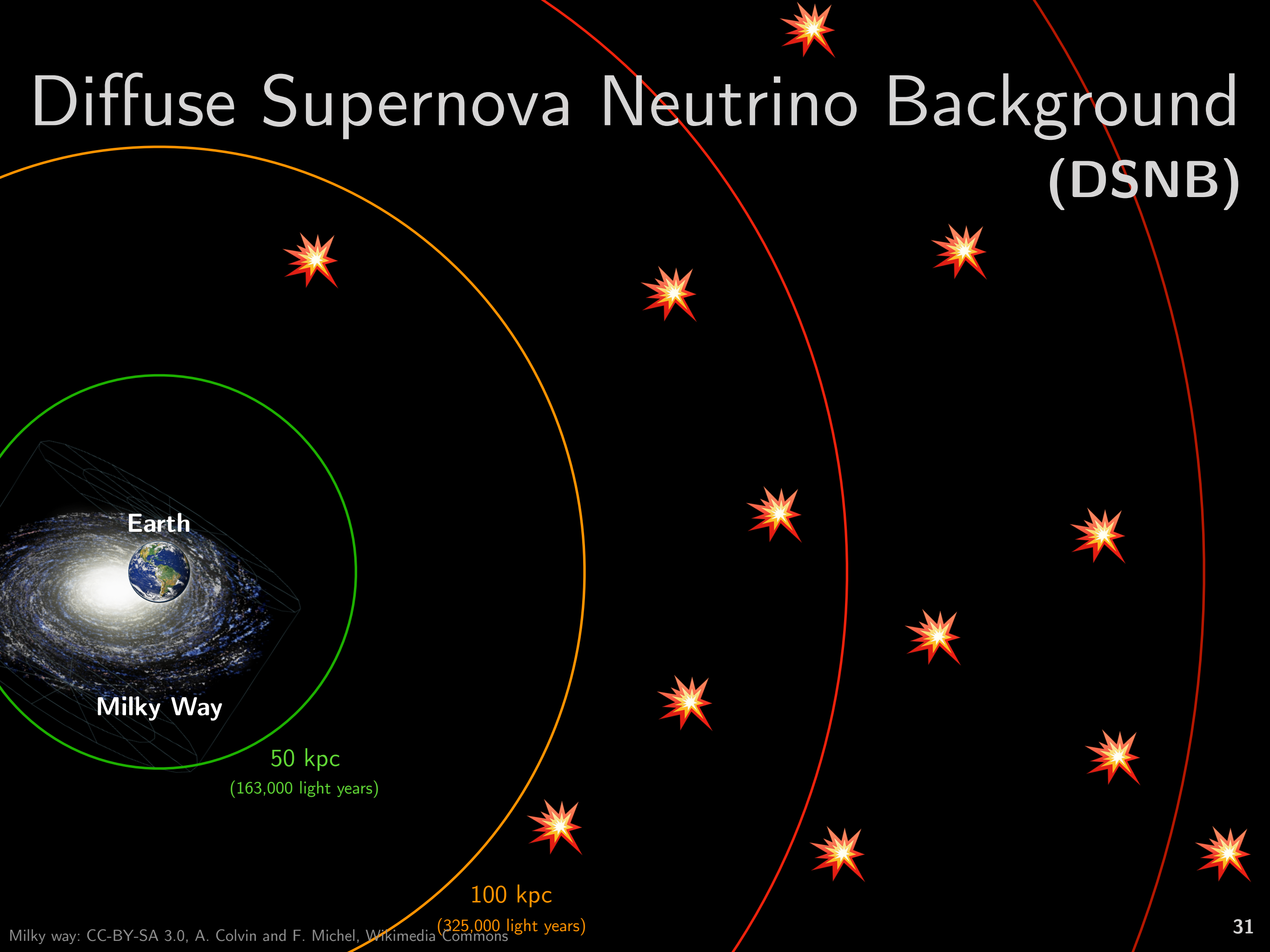


Diffuse Supernova Neutrino Background (DSNB)

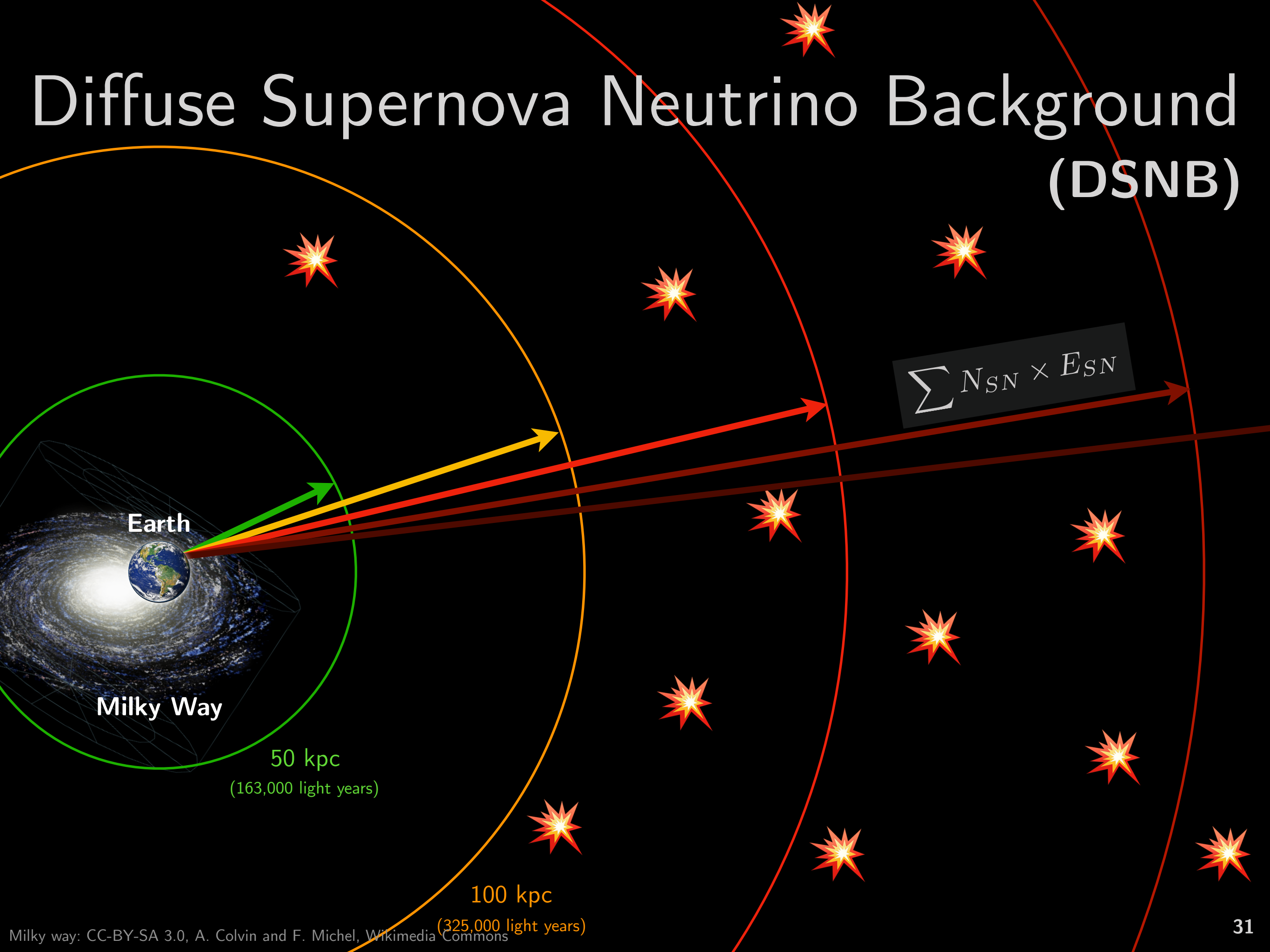
The Doppler Effect



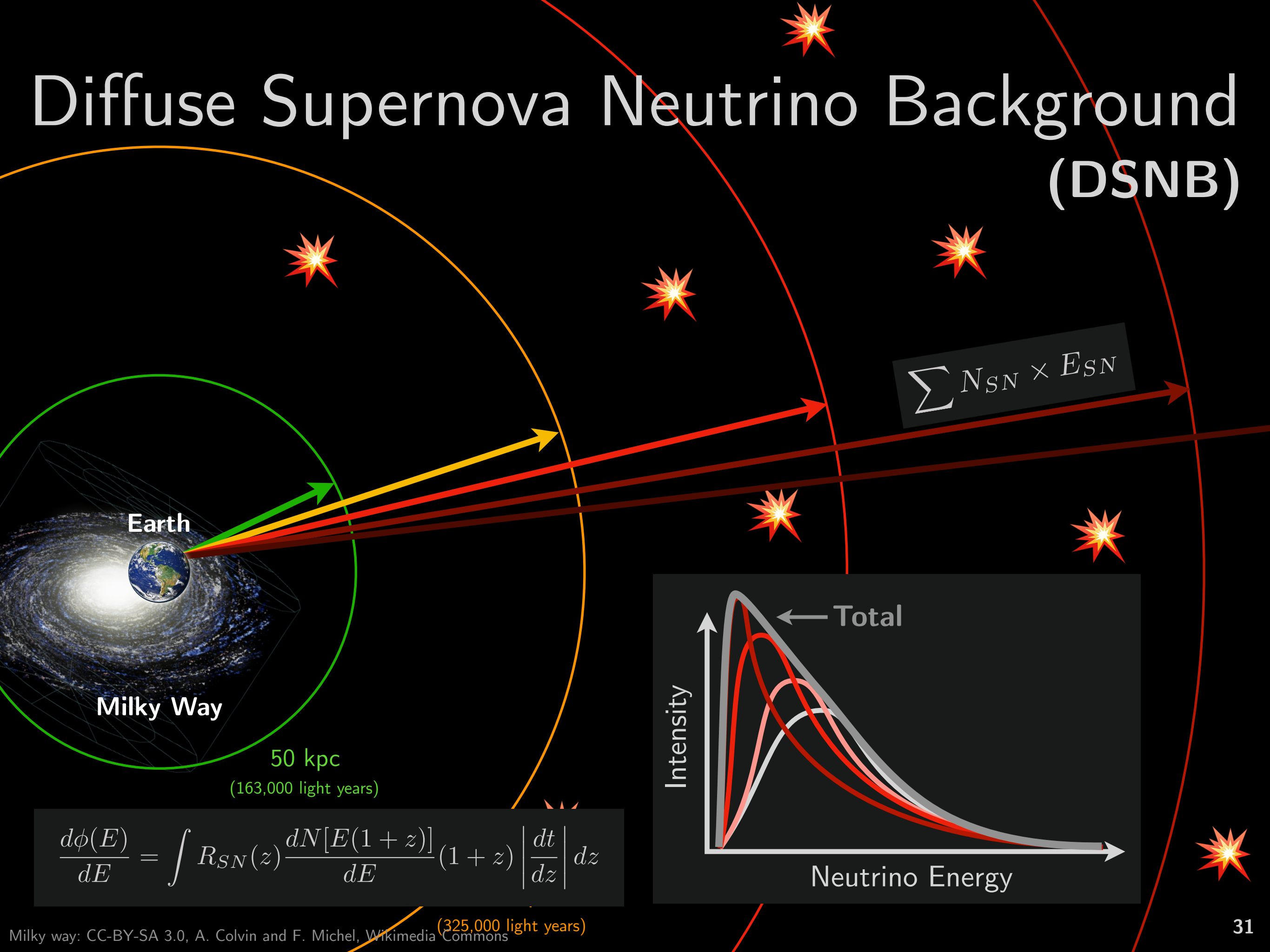
Diffuse Supernova Neutrino Background (DSNB)



Diffuse Supernova Neutrino Background (DSNB)



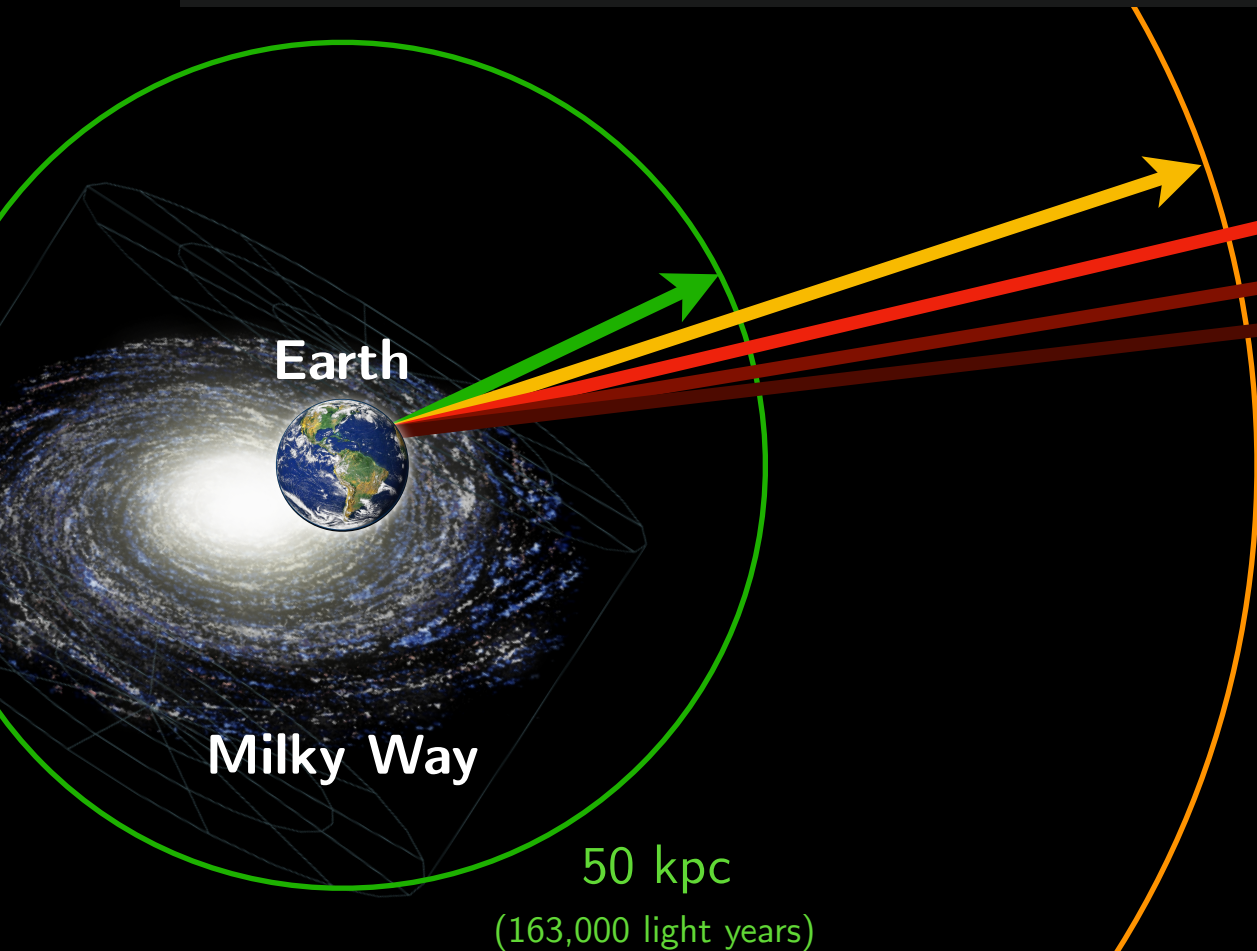
Diffuse Supernova Neutrino Background (DSNB)



$$\frac{d\phi(E)}{dE} = \int R_{SN}(z) \frac{dN[E(1+z)]}{dE} (1+z) \left| \frac{dt}{dz} \right| dz$$

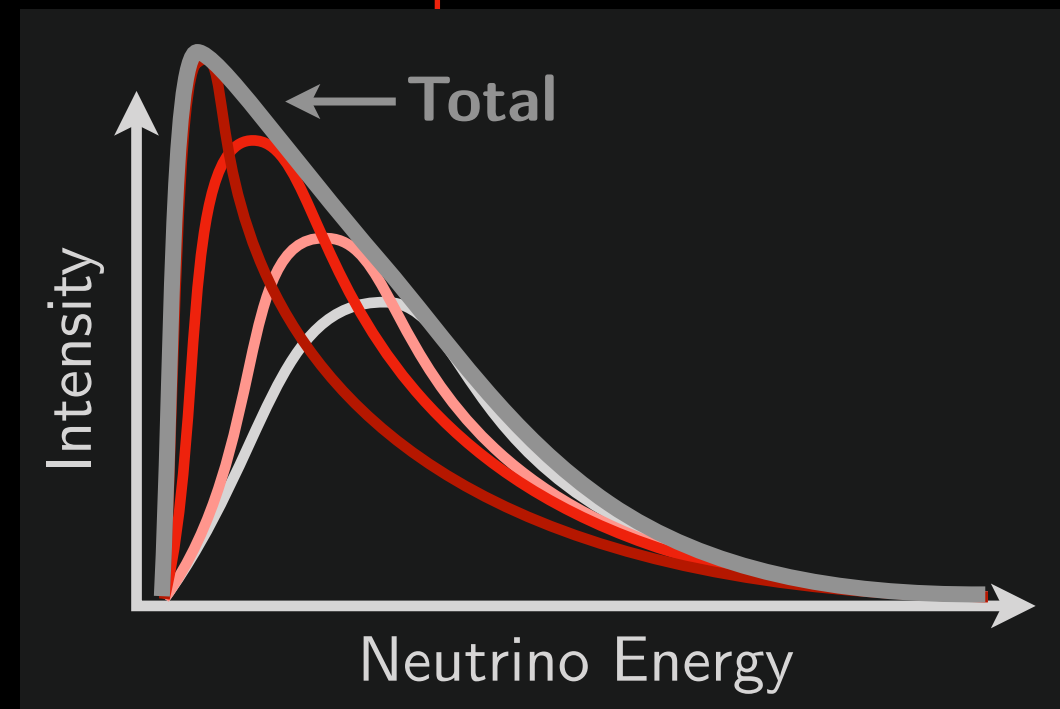
Diffuse Supernova Neutrino Background (DSNB)

This provides an average measurement of the **total number** and the **energy** of core-collapse supernova neutrinos



$$\sum N_{SN} \times E_{SN}$$

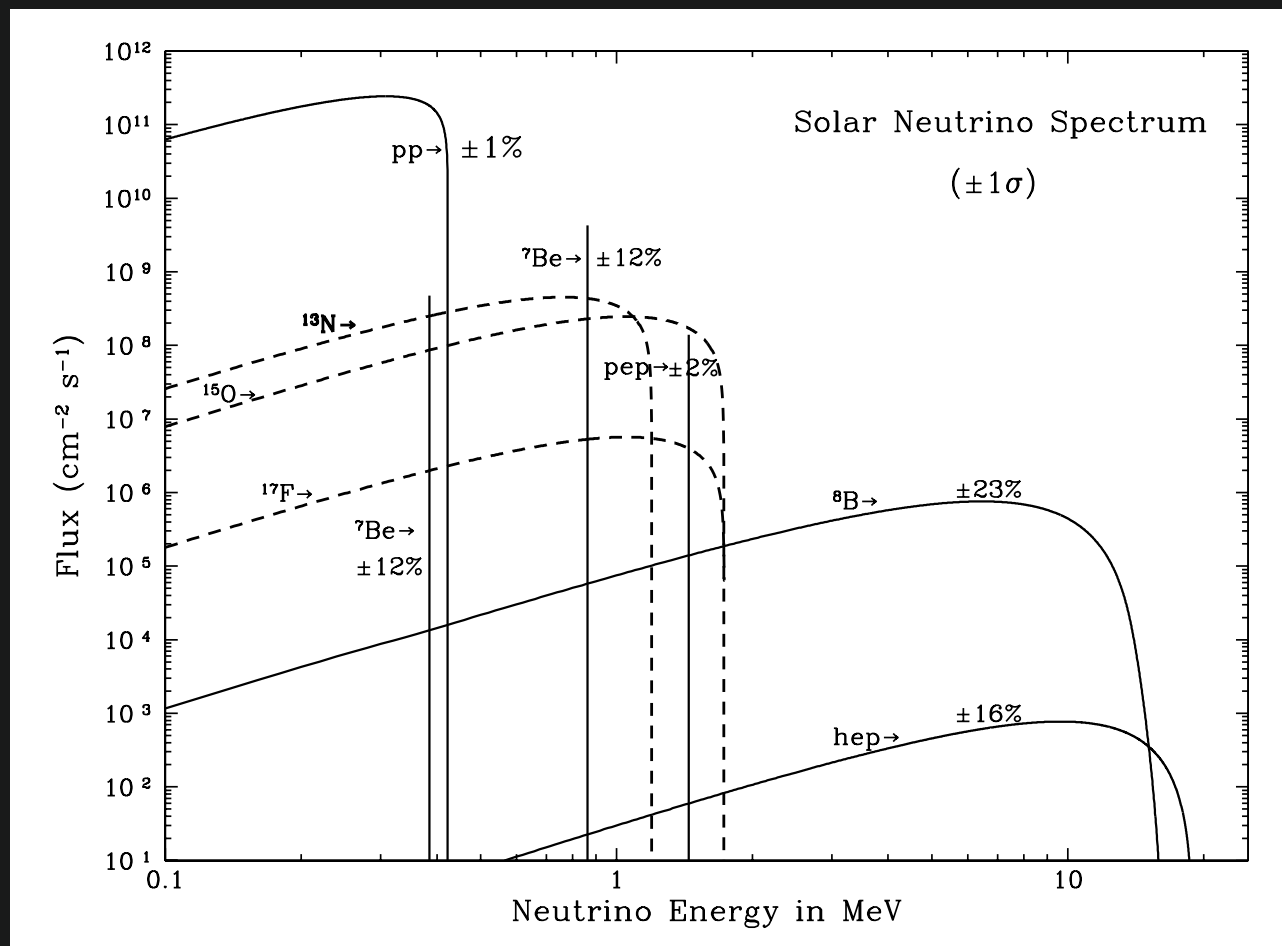
$$\frac{d\phi(E)}{dE} = \int R_{SN}(z) \frac{dN[E(1+z)]}{dE} (1+z) \left| \frac{dt}{dz} \right| dz$$



Diffuse Supernova Neutrino Background (DSNB)

Solar Neutrino Fluxes, on Earth

i.e., how many neutrinos per unit area, per second

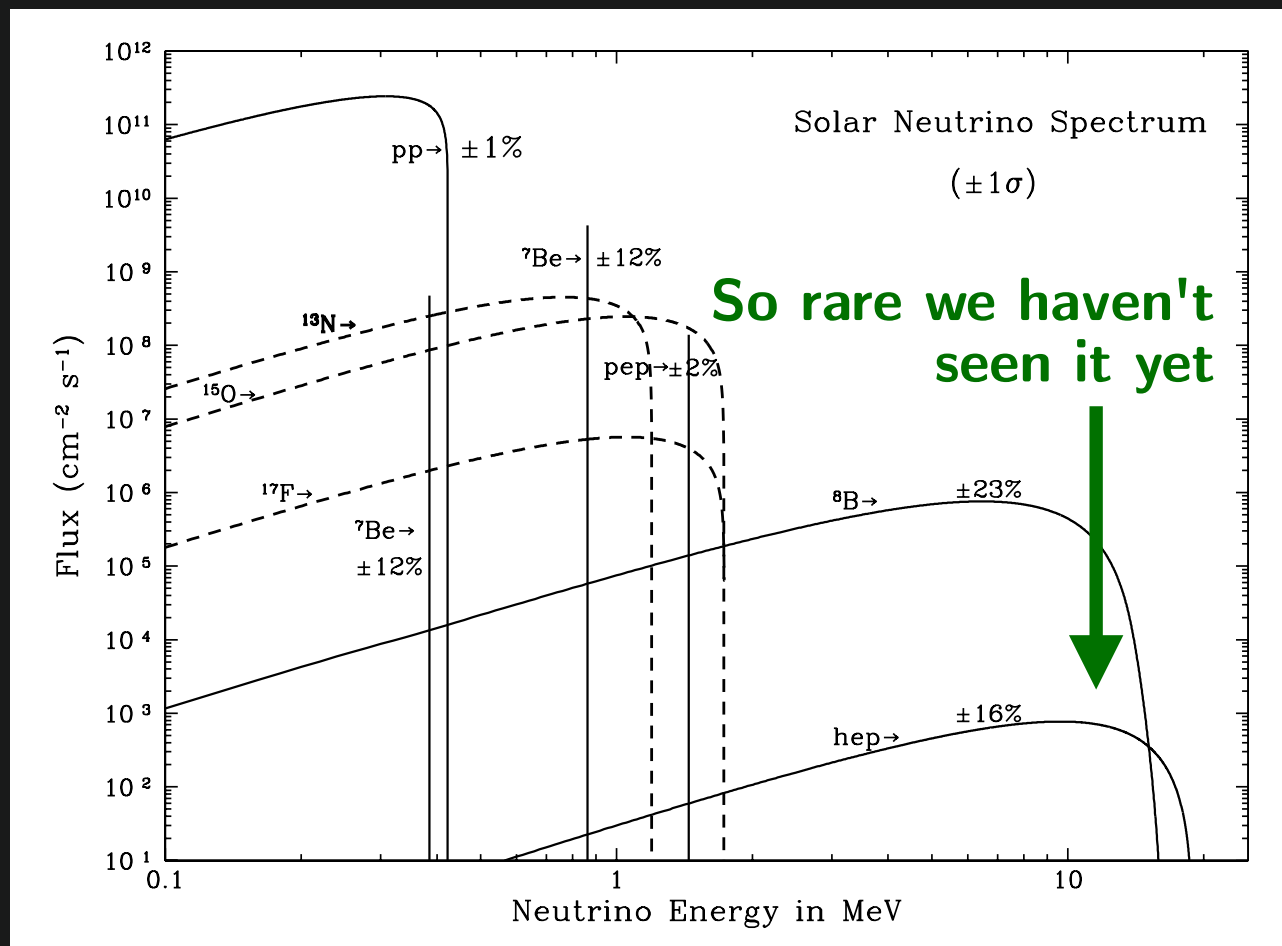


Astrophys. J. 621(1):L85-L88, 2005.

Diffuse Supernova Neutrino Background (DSNB)

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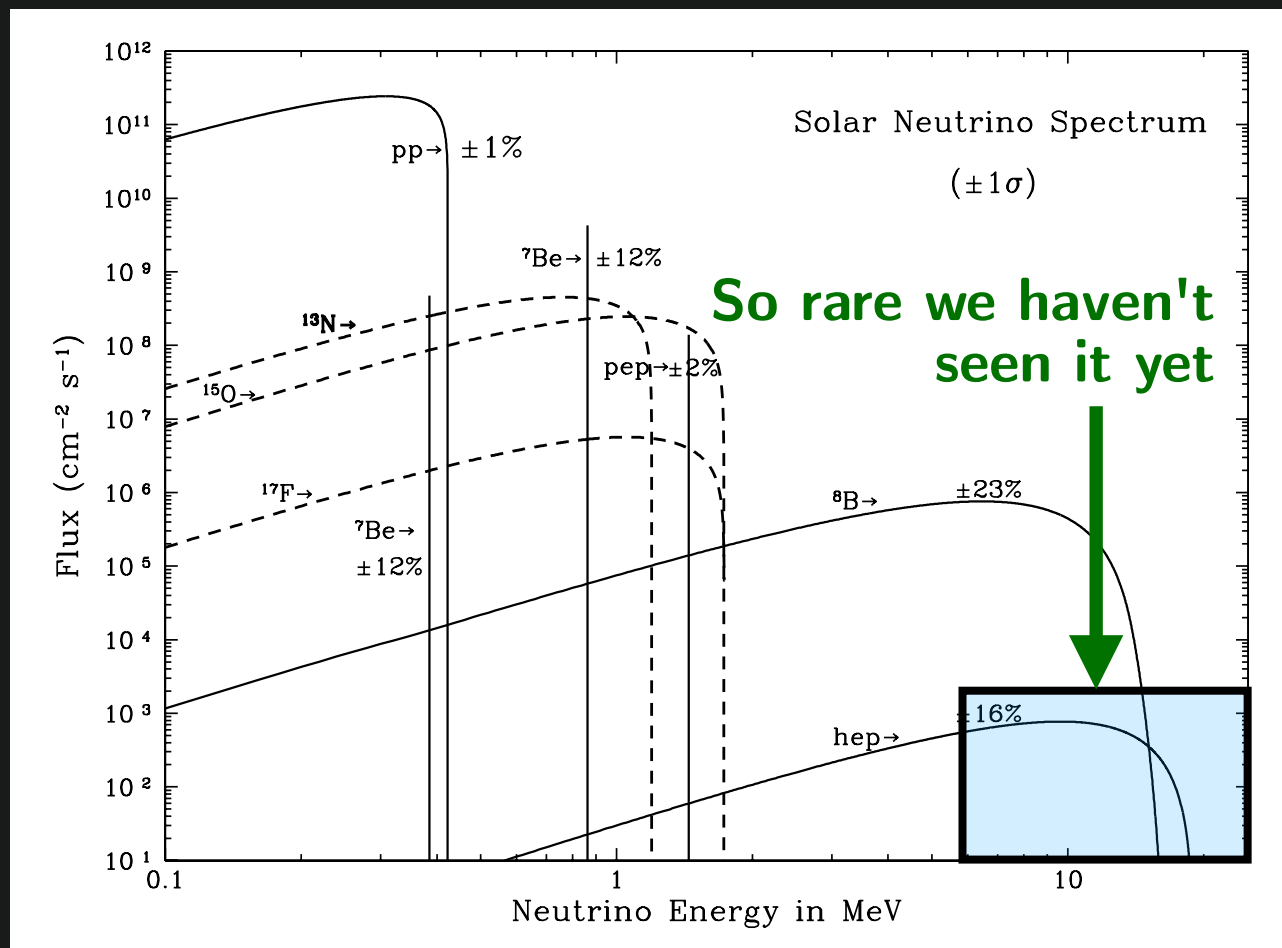


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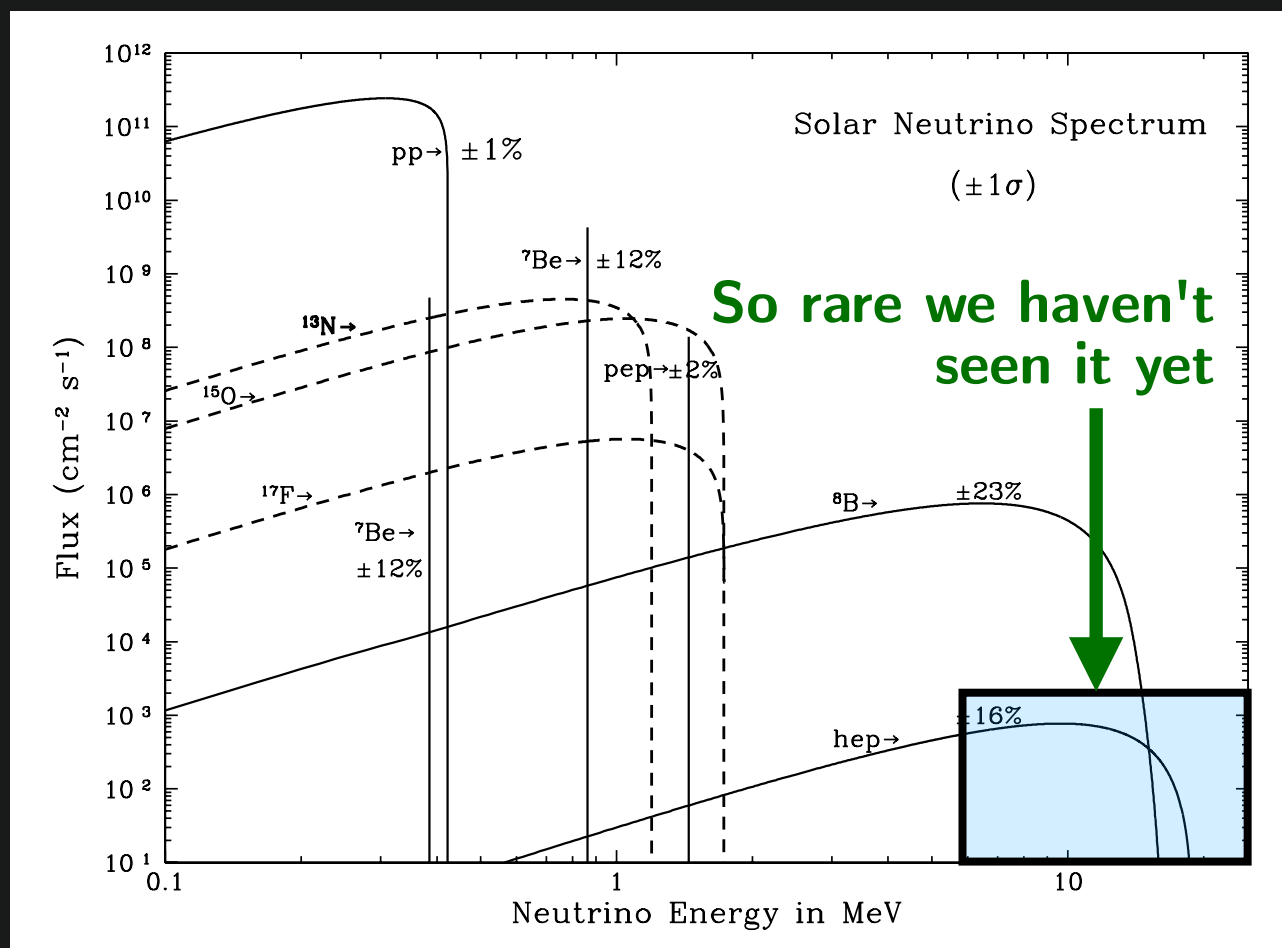


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Diffuse Supernova Neutrino Background (DSNB)

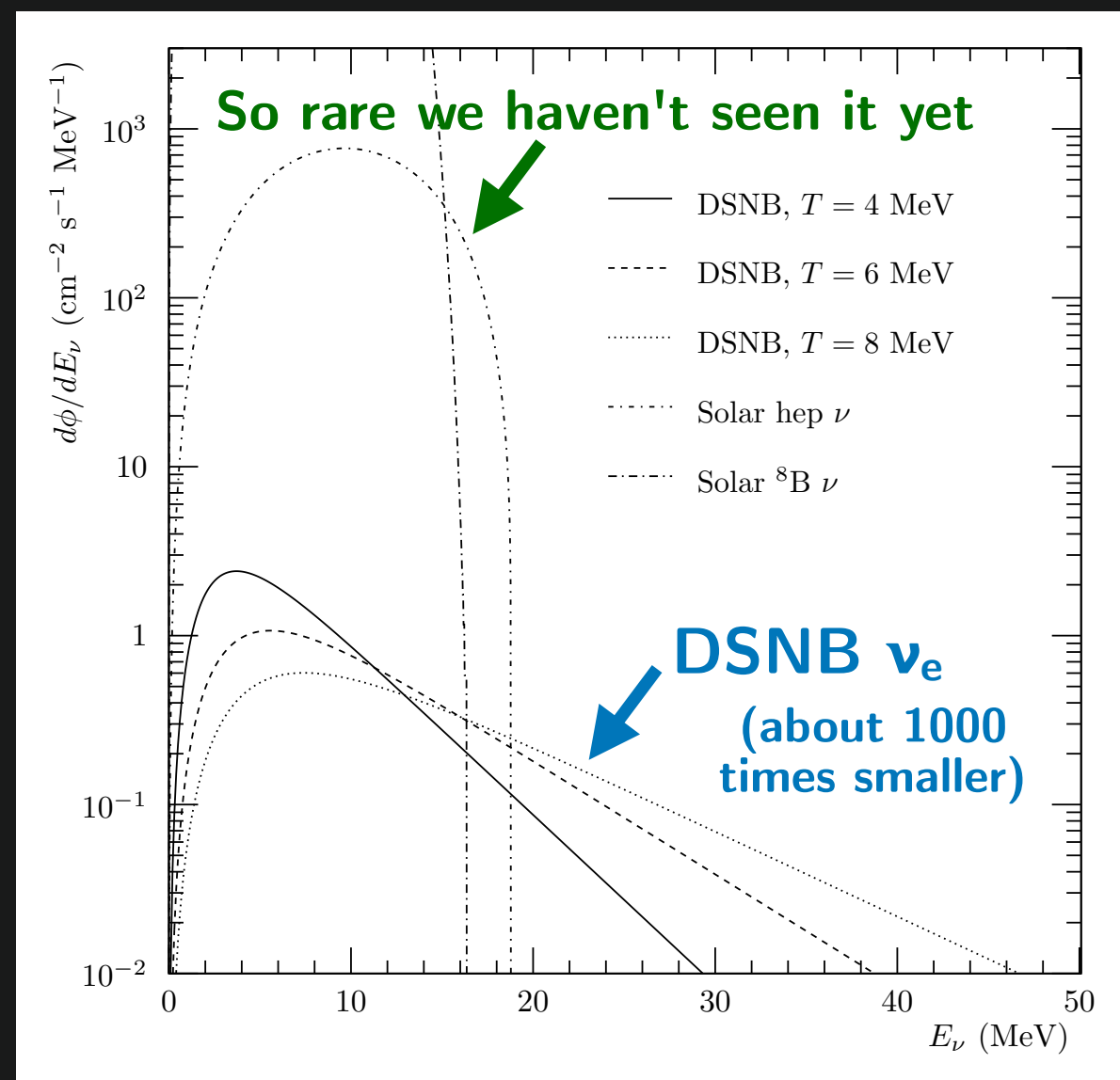
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i.e., how many neutrinos per unit area, per second



Astrophys. J. 621(1):L85-L88, 2005.

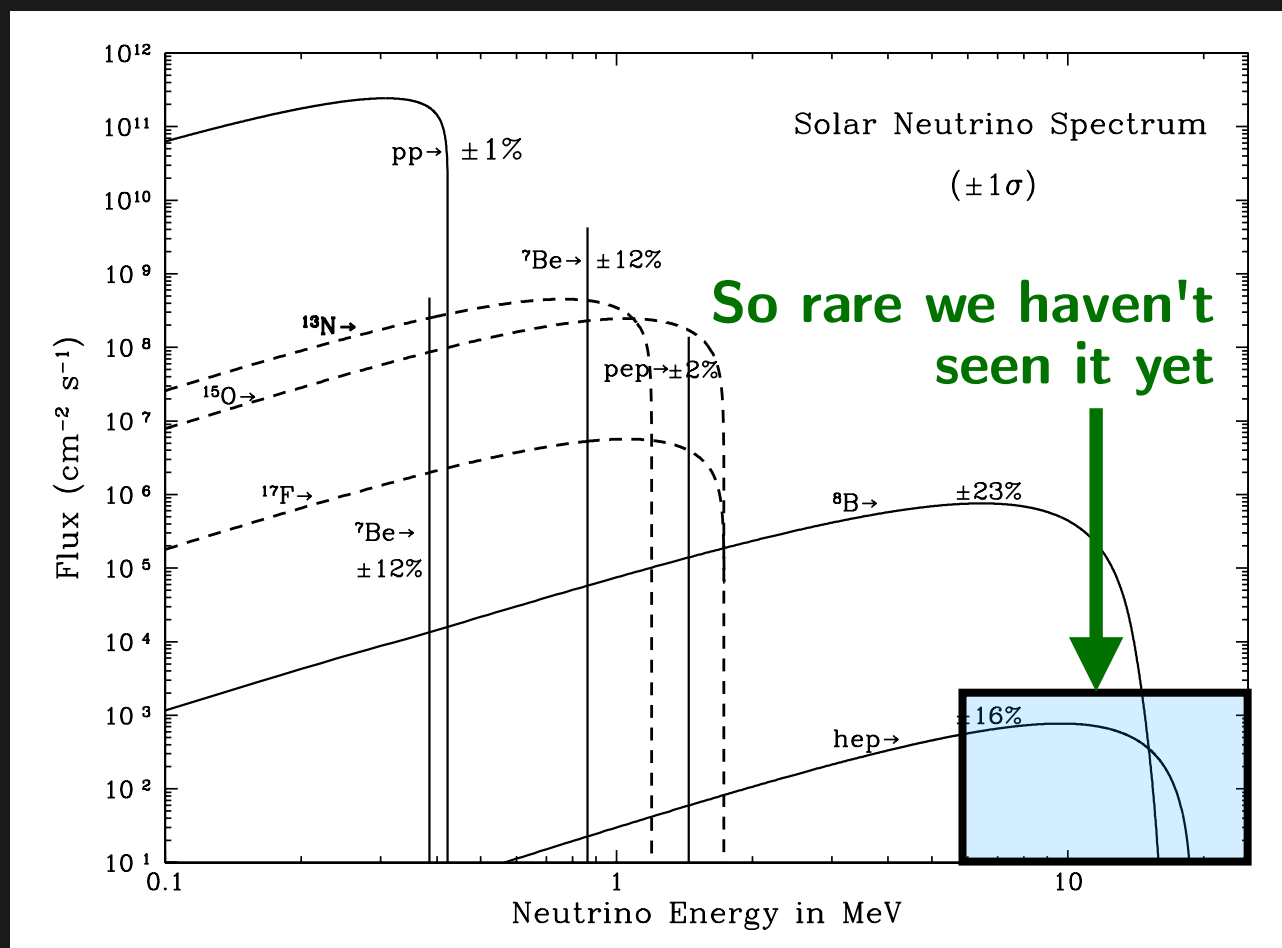
DSNB ν_e Flux, on Earth



Diffuse Supernova Neutrino Background (DSNB)

Solar Neutrino Fluxes, on Earth

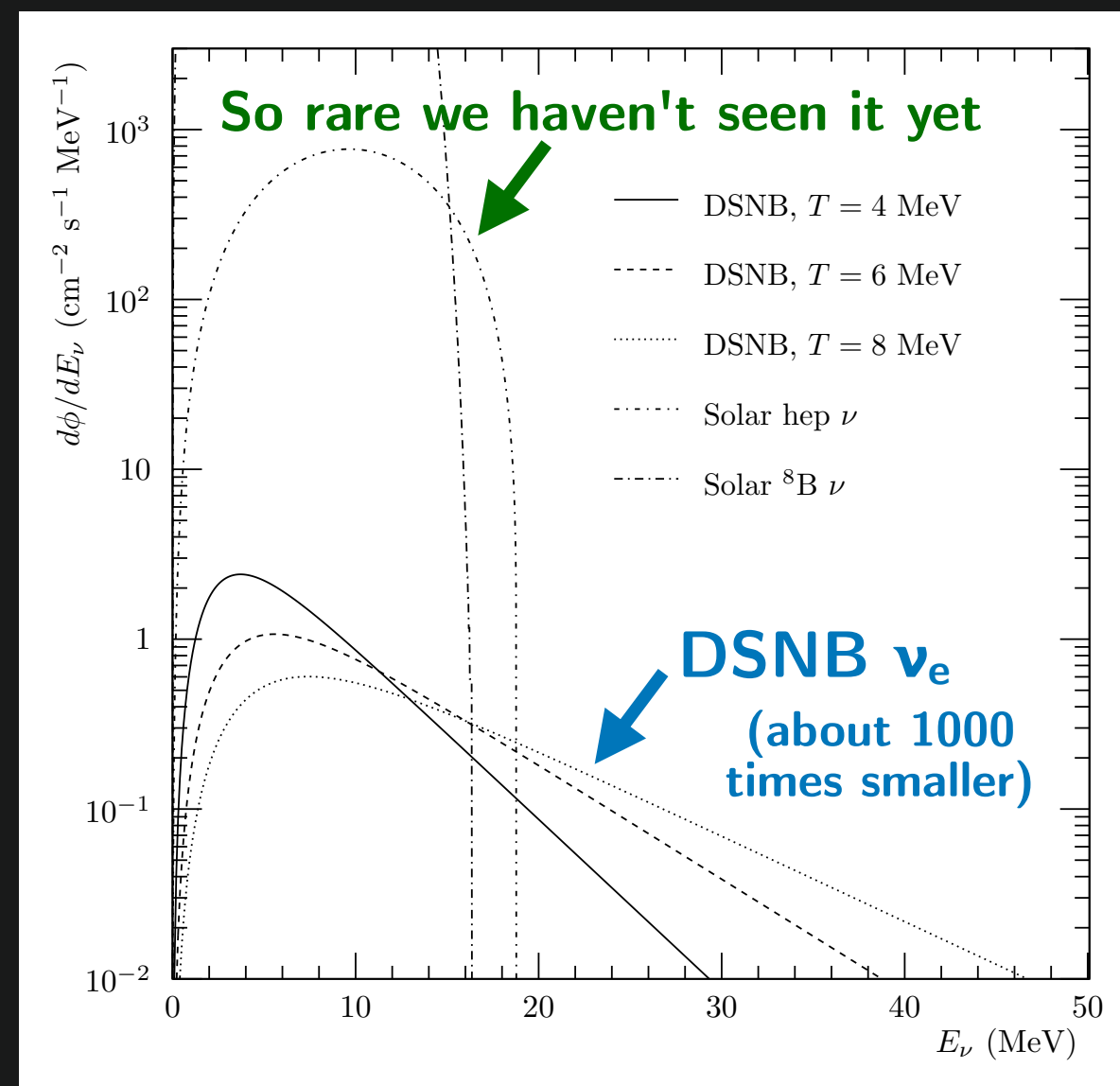
i.e., how many neutrinos per unit area, per second



Astrophys. J. 621(1):L85-L88, 2005.

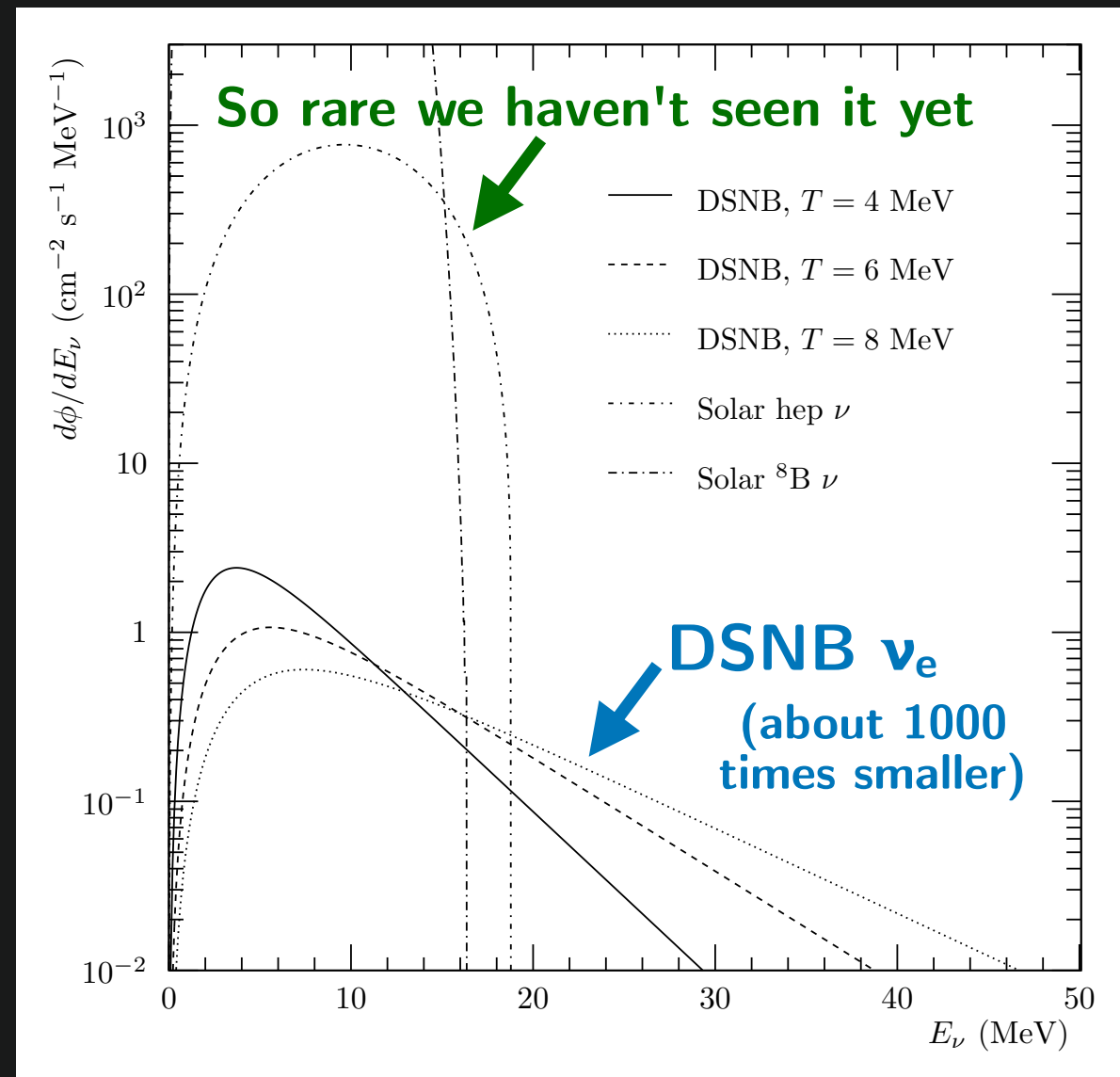
It's really faint!
But sort of like solar neutrinos

DSNB ν_e Flux, on Earth



Diffuse Supernova Neutrino Background (DSNB)

DSNB ν_e Flux, on Earth



Diffuse Supernova Neutrino Background (DSNB)

CONSTRAINING THE **HEP SOLAR NEUTRINO** AND
DIFFUSE SUPERNOVA NEUTRINO BACKGROUND
FLUXES WITH THE SUDBURY NEUTRINO
OBSERVATORY

Andrew T. Mastbaum

A DISSERTATION

in

Physics and Astronomy

Presented to the Faculties of the University of Pennsylvania

in

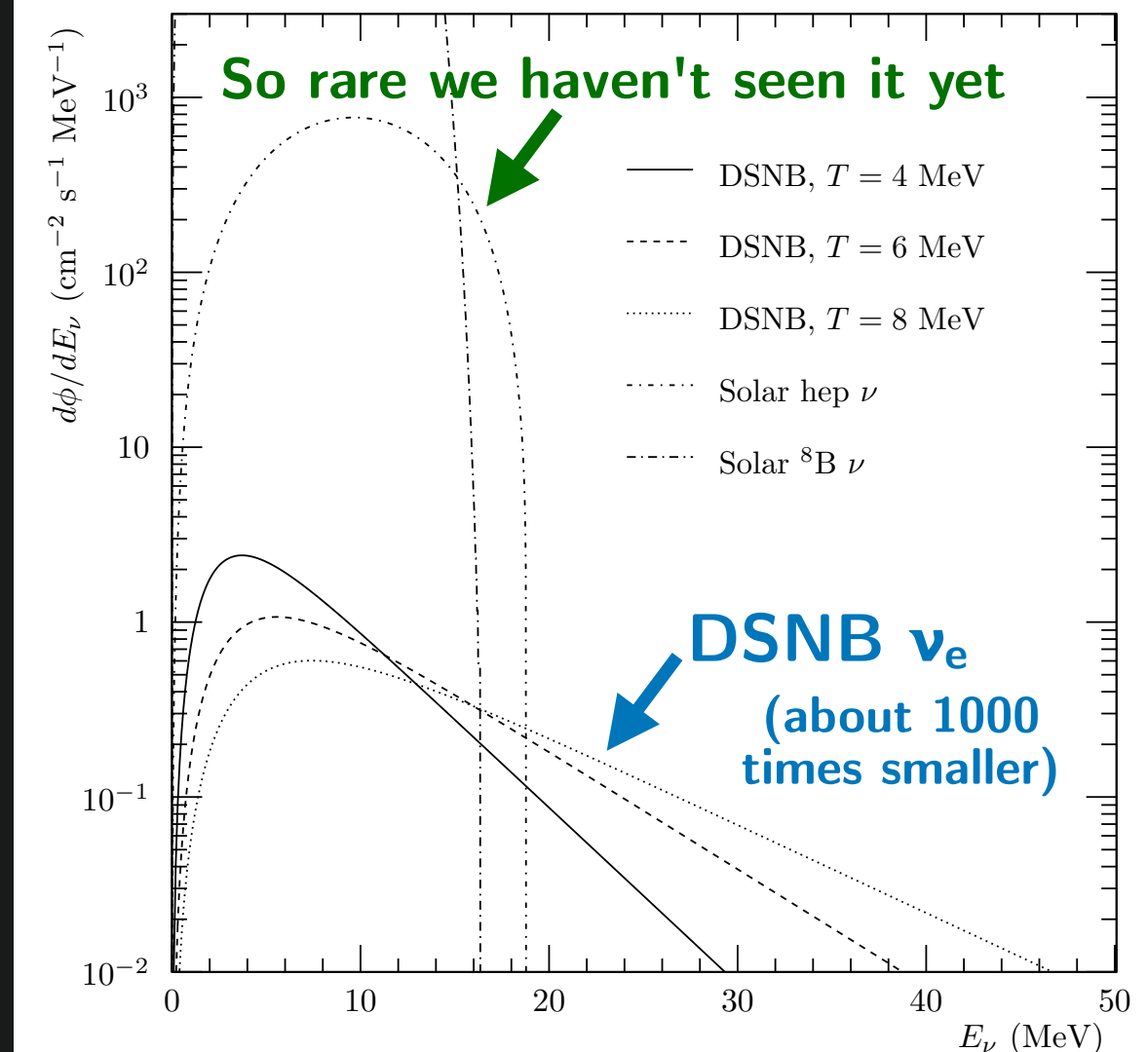
Partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy

2016

My Ph.D. thesis again, 2016



DSNB ν_e Flux, on Earth



Diffuse Supernova Neutrino Background

Searching with the SNO Experiment (DSNB)

Diffuse Supernova Neutrino Background

Searching with the SNO Experiment (DSNB)



Sudbury Neutrino Observatory

Sudbury, Ontario, Canada

1000 tonnes Heavy Water

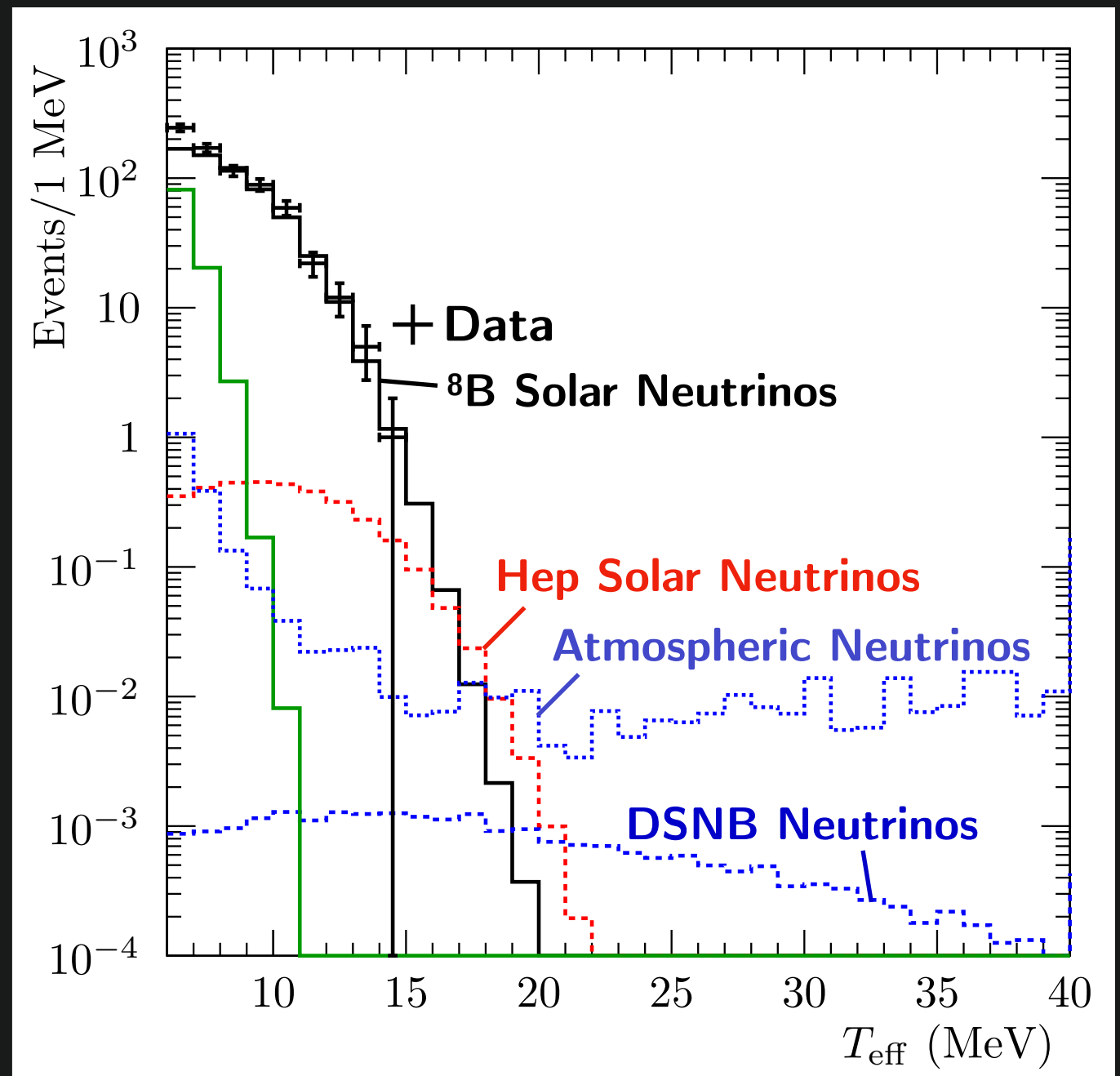
Diffuse Supernova Neutrino Background

Searching with the SNO Experiment (DSNB)



Sudbury Neutrino Observatory

Sudbury, Ontario, Canada
1000 tonnes Heavy Water



Diffuse Supernova Neutrino Background

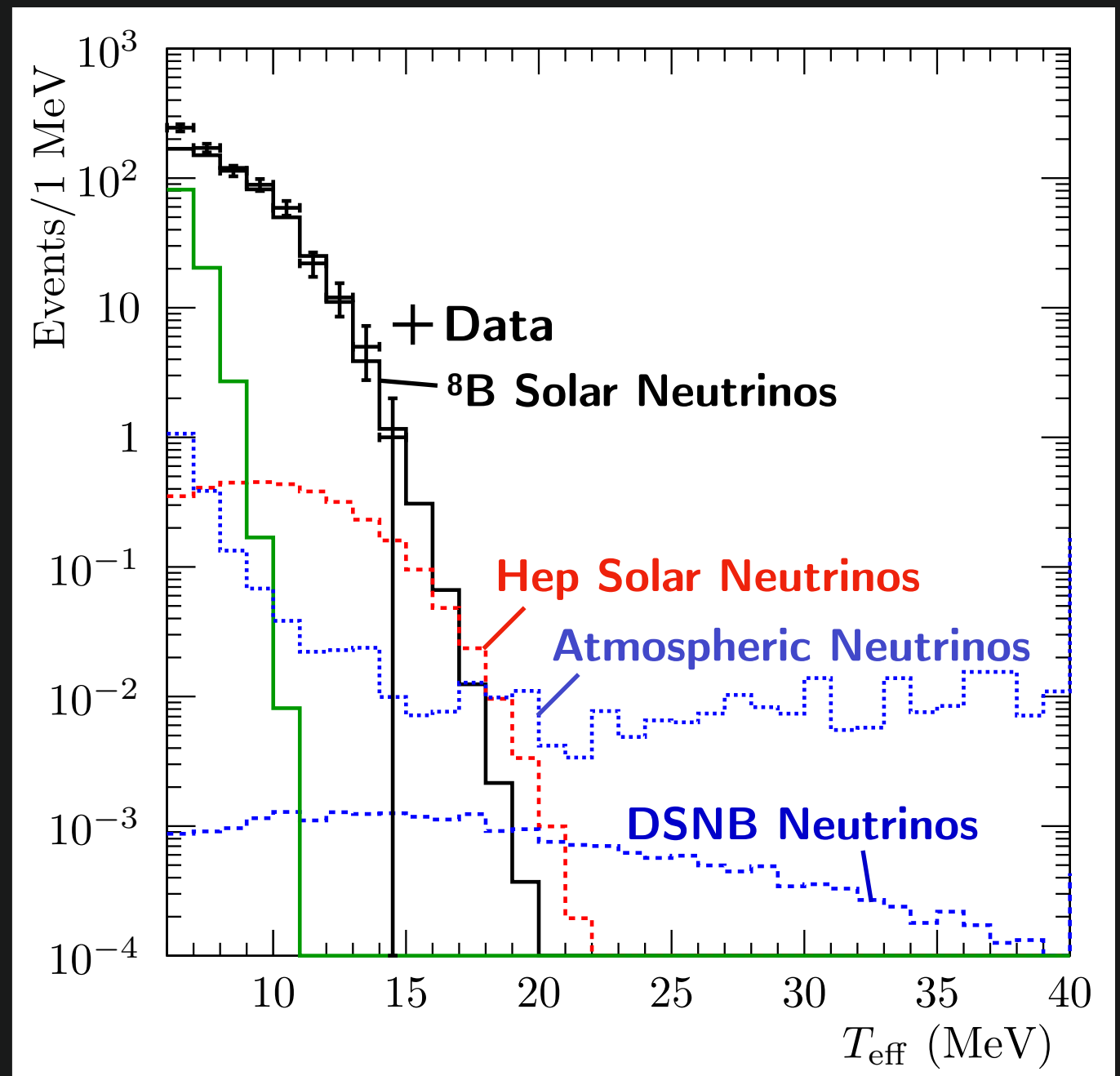
Searching with the SNO Experiment (DSNB)



Sudbury Neutrino Observatory

Sudbury, Ontario, Canada

1000 tonnes Heavy Water



Too small to see, but we can rule out some funny business

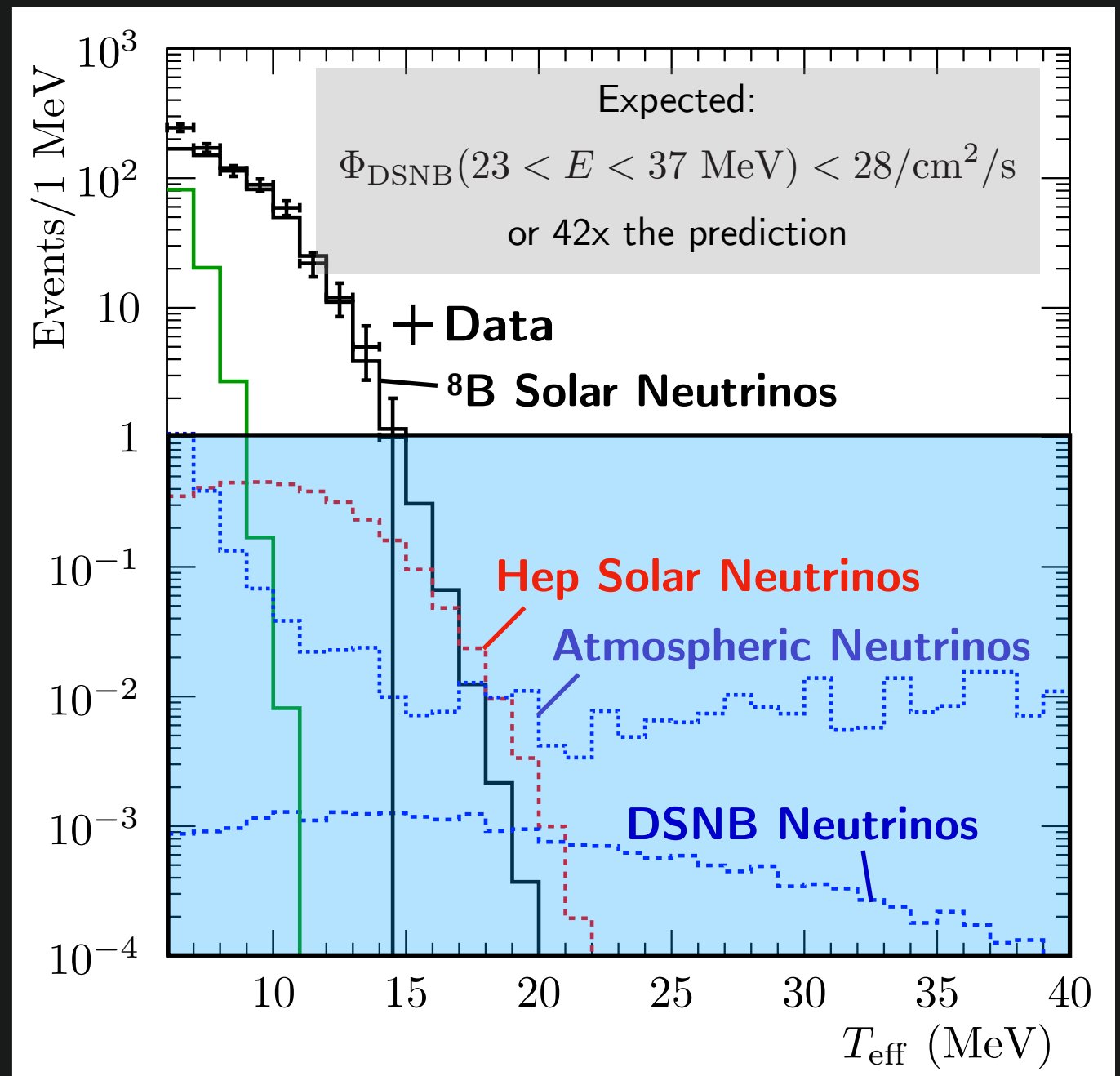
Diffuse Supernova Neutrino Background

Searching with the SNO Experiment (DSNB)



Sudbury Neutrino Observatory

Sudbury, Ontario, Canada
1000 tonnes Heavy Water



Too small to see, but we can rule out some funny business

Diffuse Supernova Neutrino Background (DSNB)

Super-Kamiokande + Gd

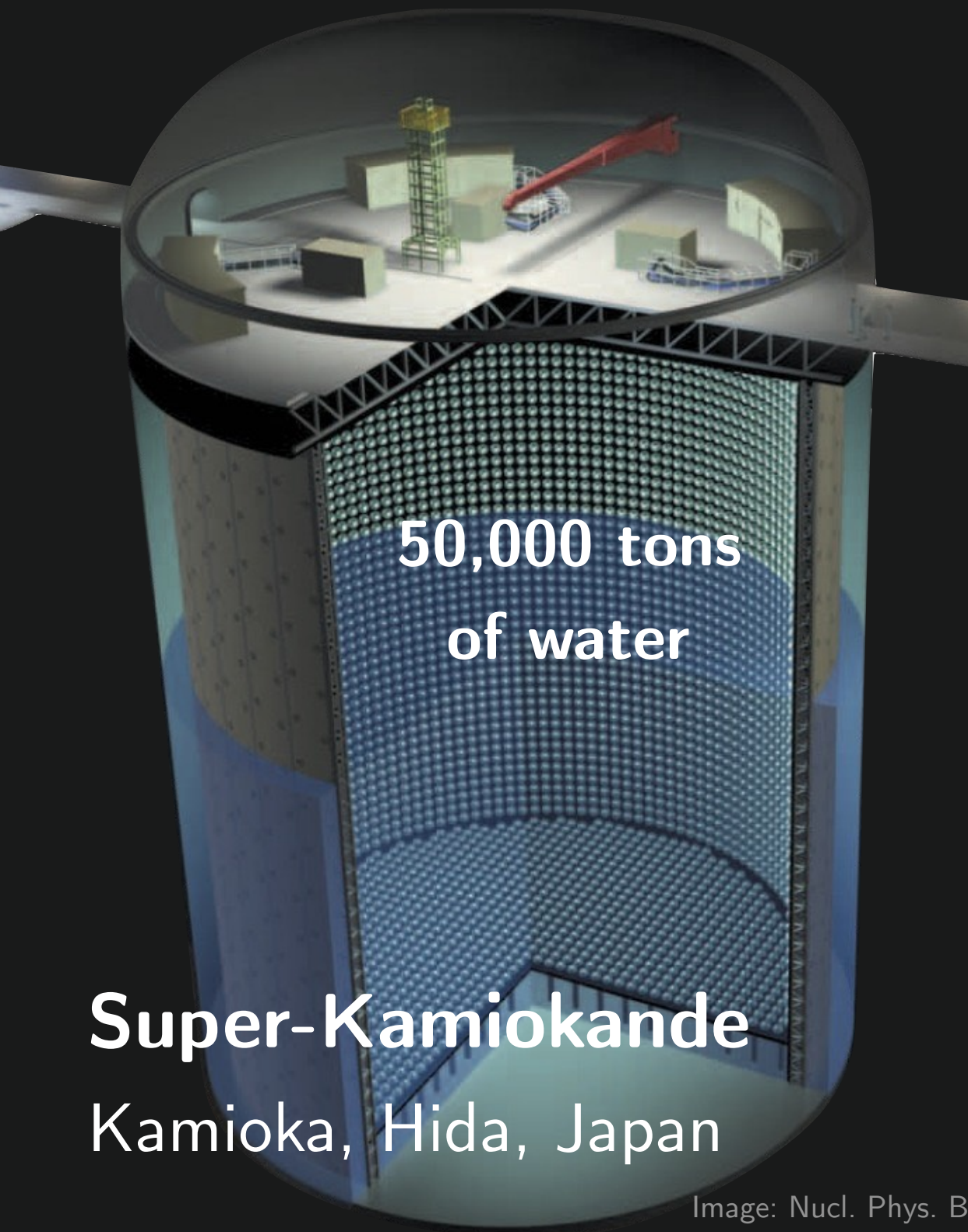
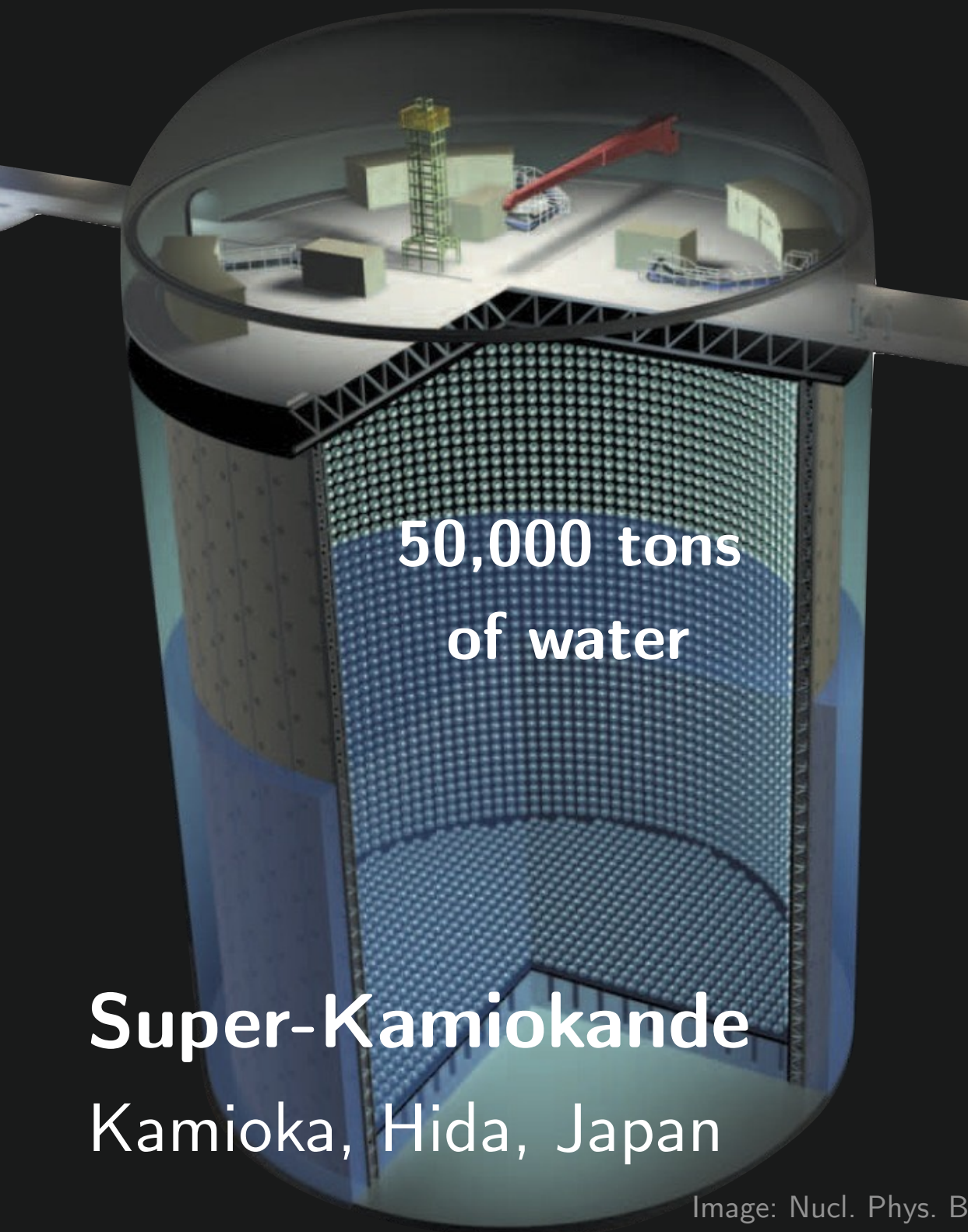


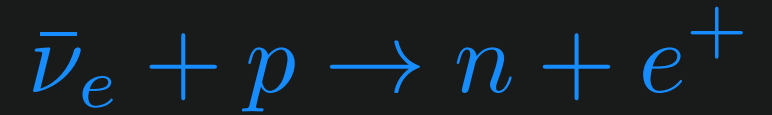
Image: Nucl. Phys. B 908:14 (2016)

Diffuse Supernova Neutrino Background (DSNB)

Super-Kamiokande + Gd



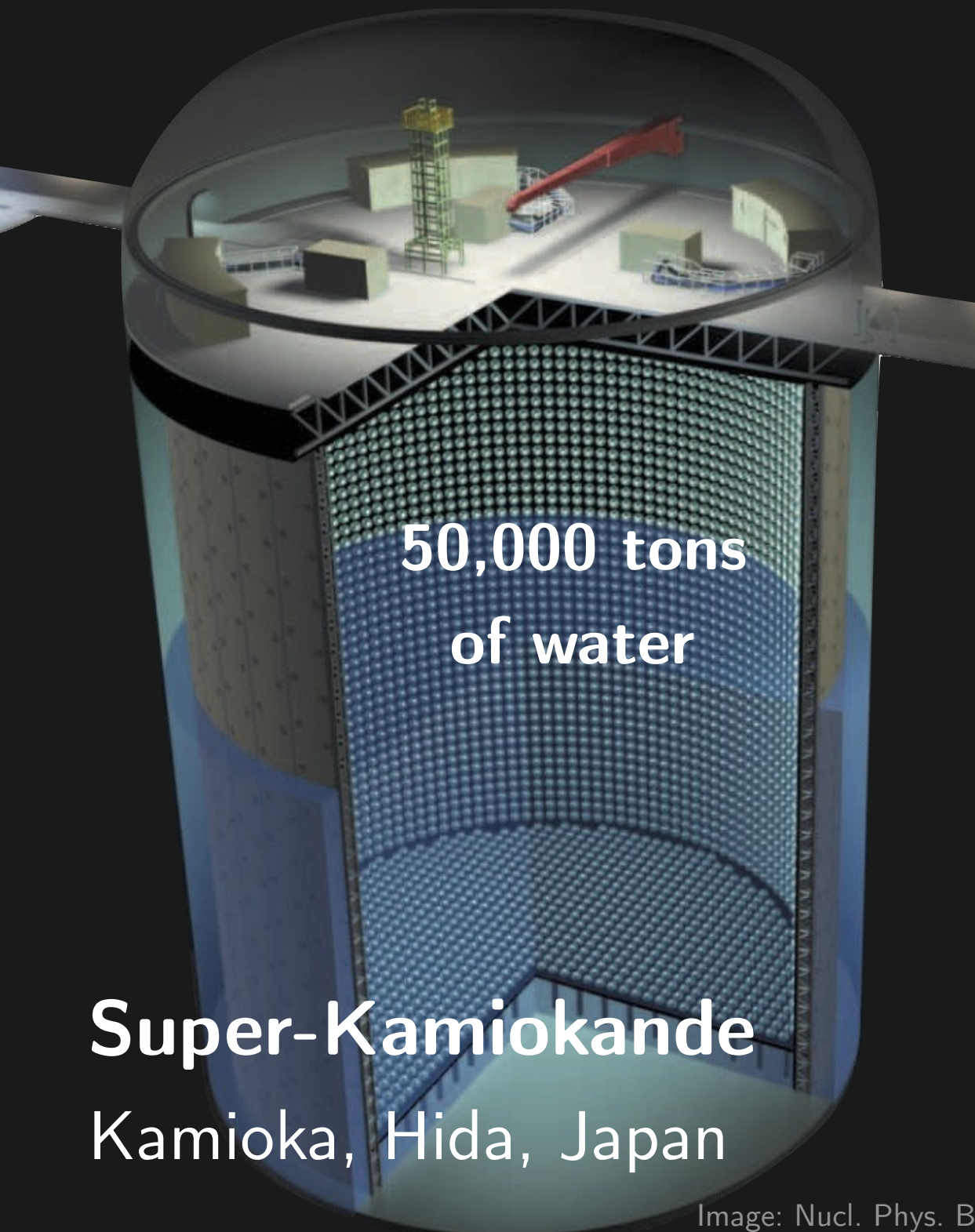
Looking for DSNB
electron antineutrinos
via inverse beta decay



(Cowan & Reines, 1956)

Diffuse Supernova Neutrino Background (DSNB)

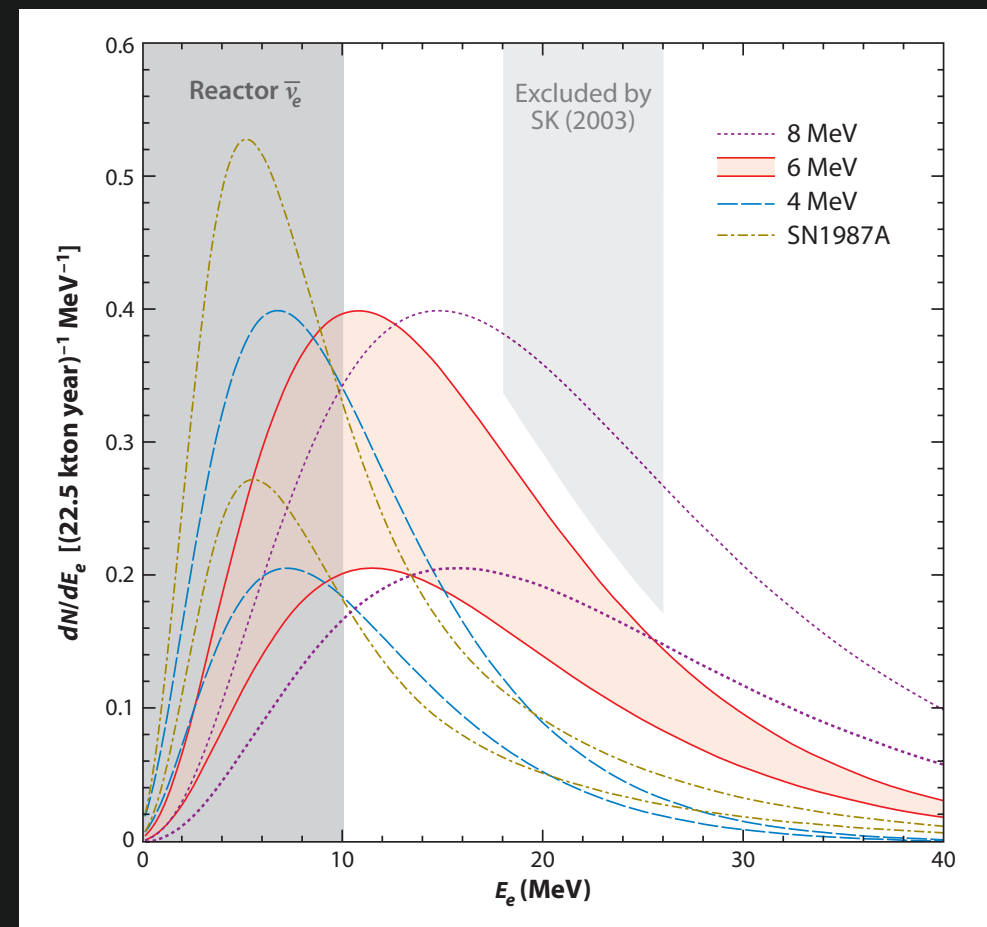
Super-Kamiokande + Gd



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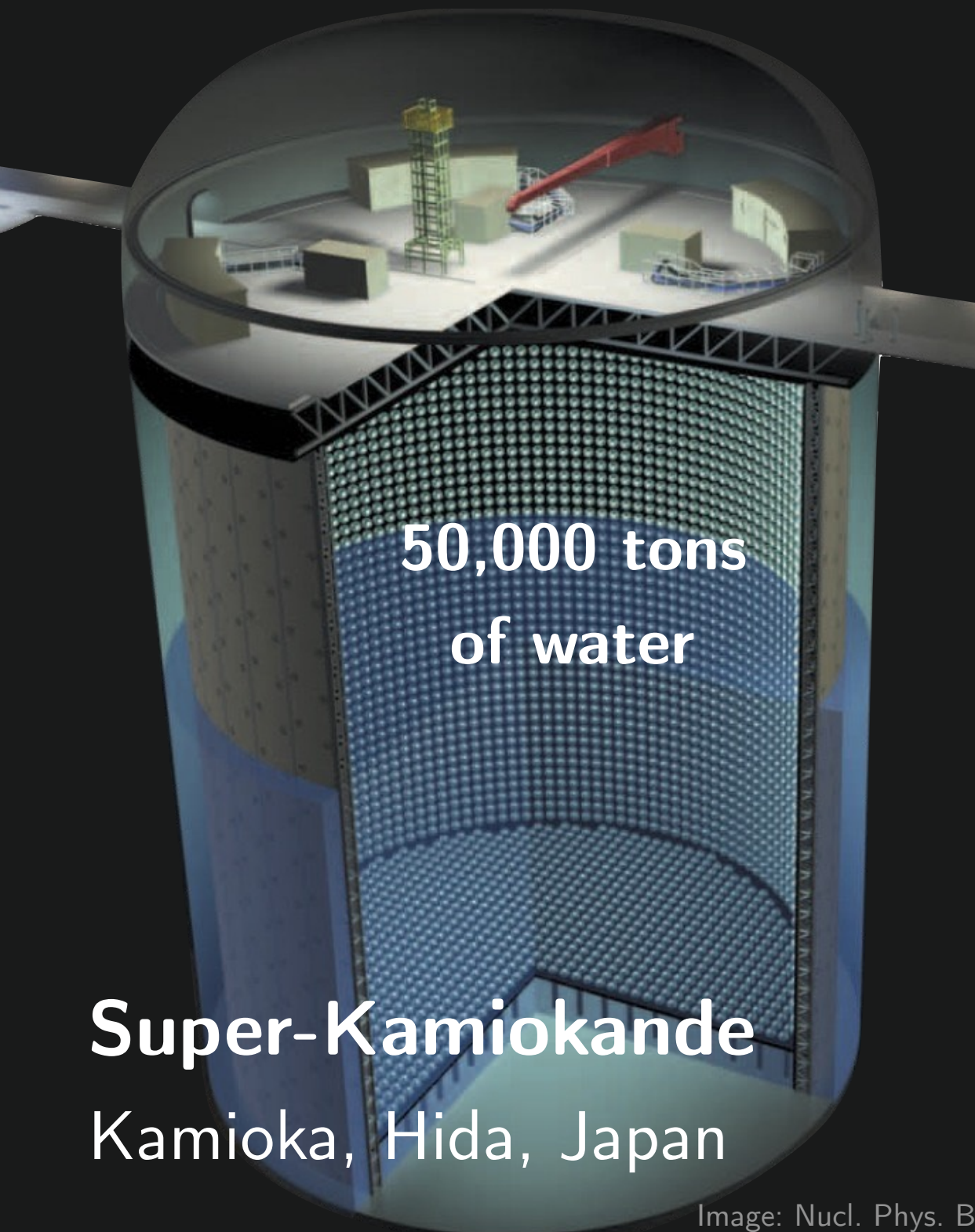
(Cowan & Reines, 1956)



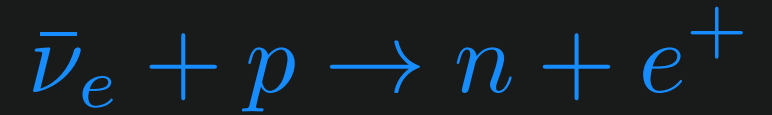
Ann. Rev. Nucl. Part. Sci. 2010.60:439-462 (2010)

Diffuse Supernova Neutrino Background (DSNB)

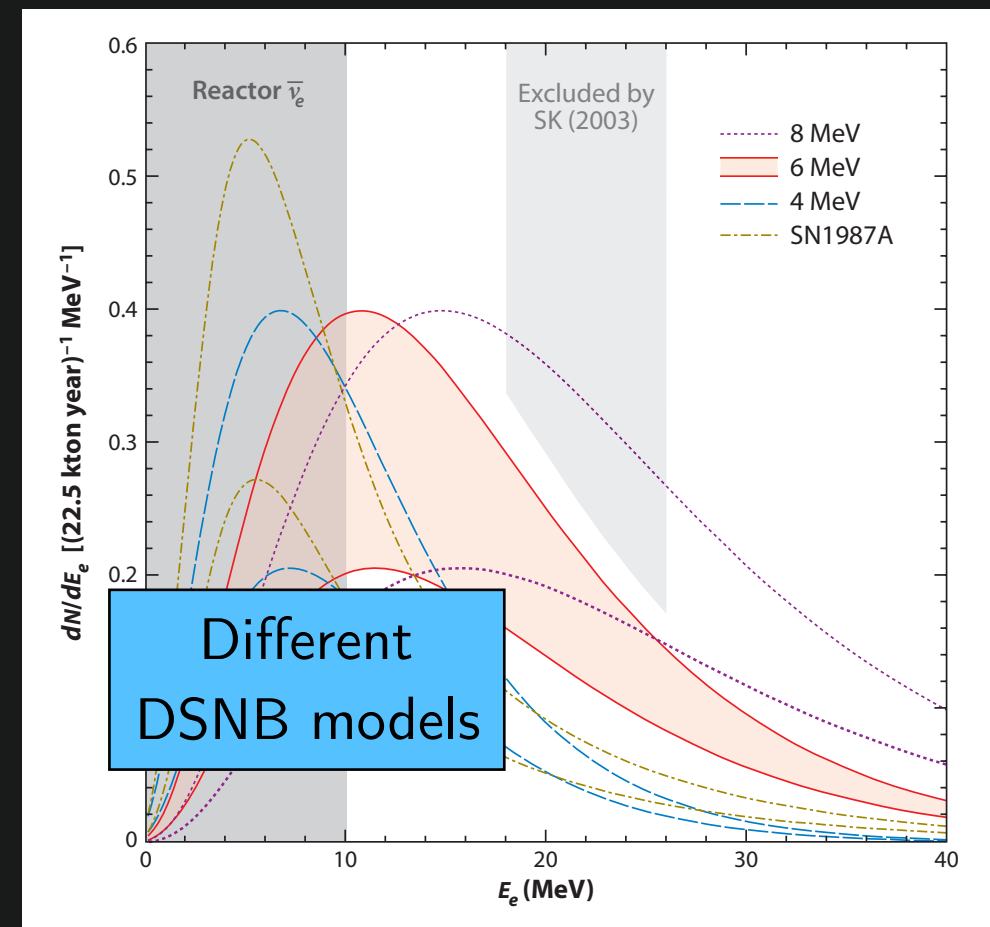
Super-Kamiokande + Gd



Looking for DSNB
electron antineutrinos
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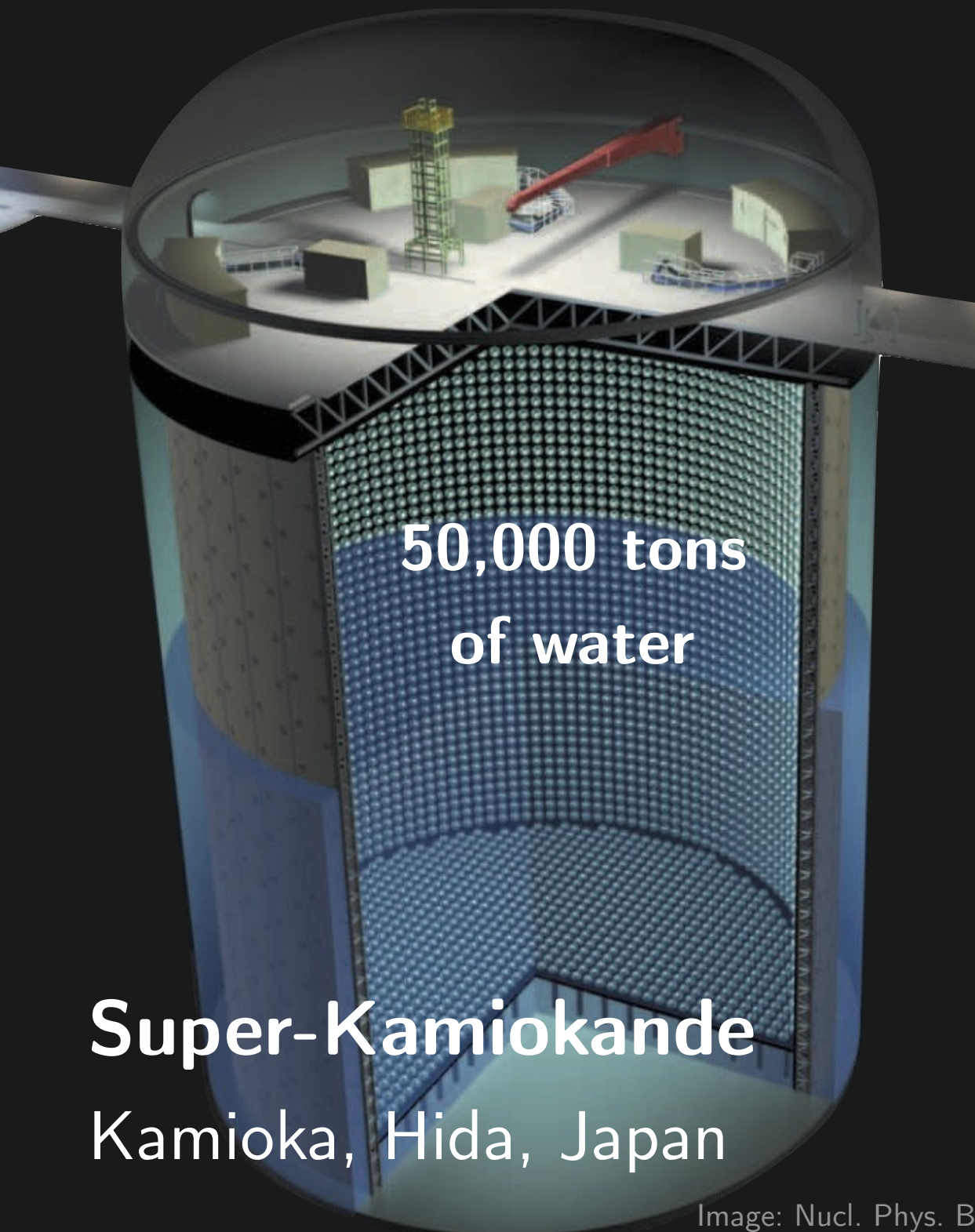
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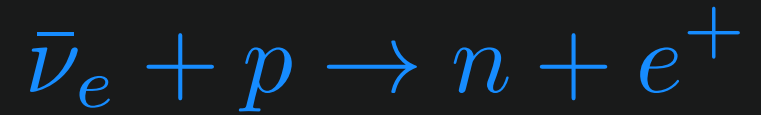
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Diffuse Supernova Neutrino Background (DSNB)

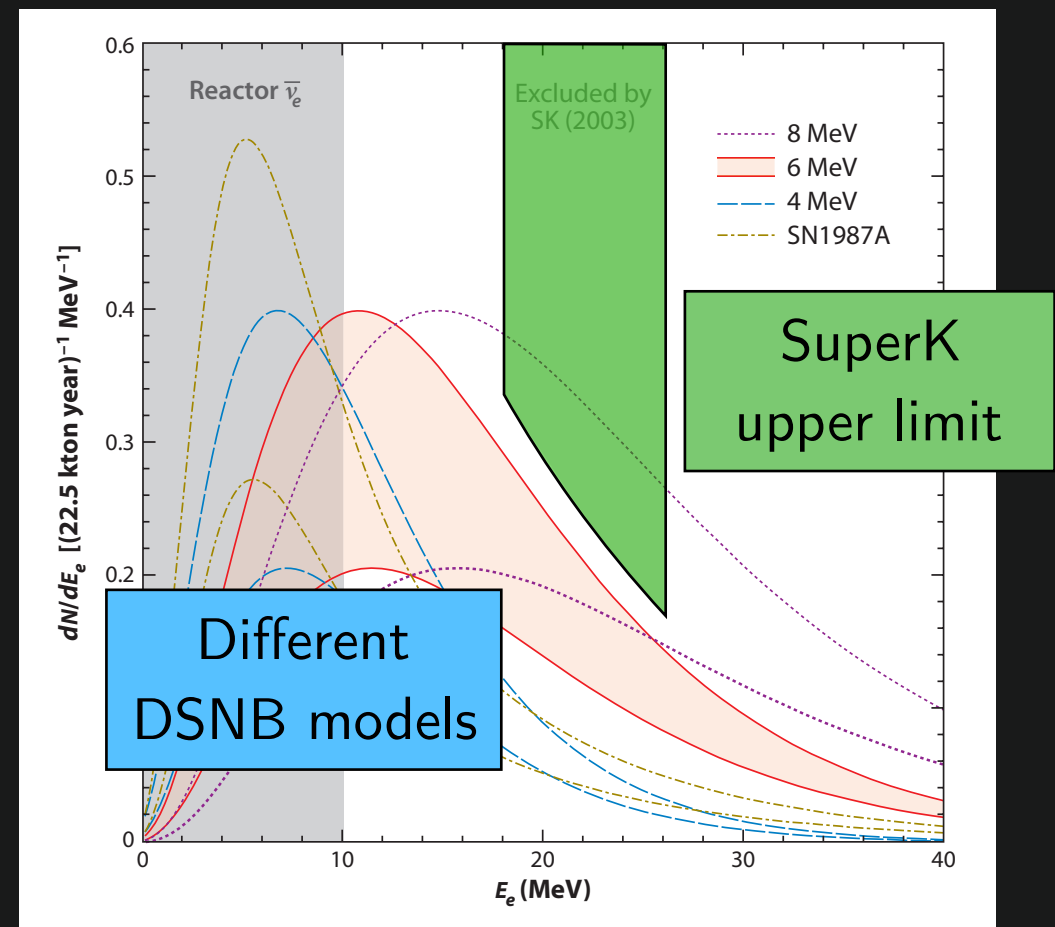
Super-Kamiokande + Gd



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electron antineutrinos
via inverse beta decay



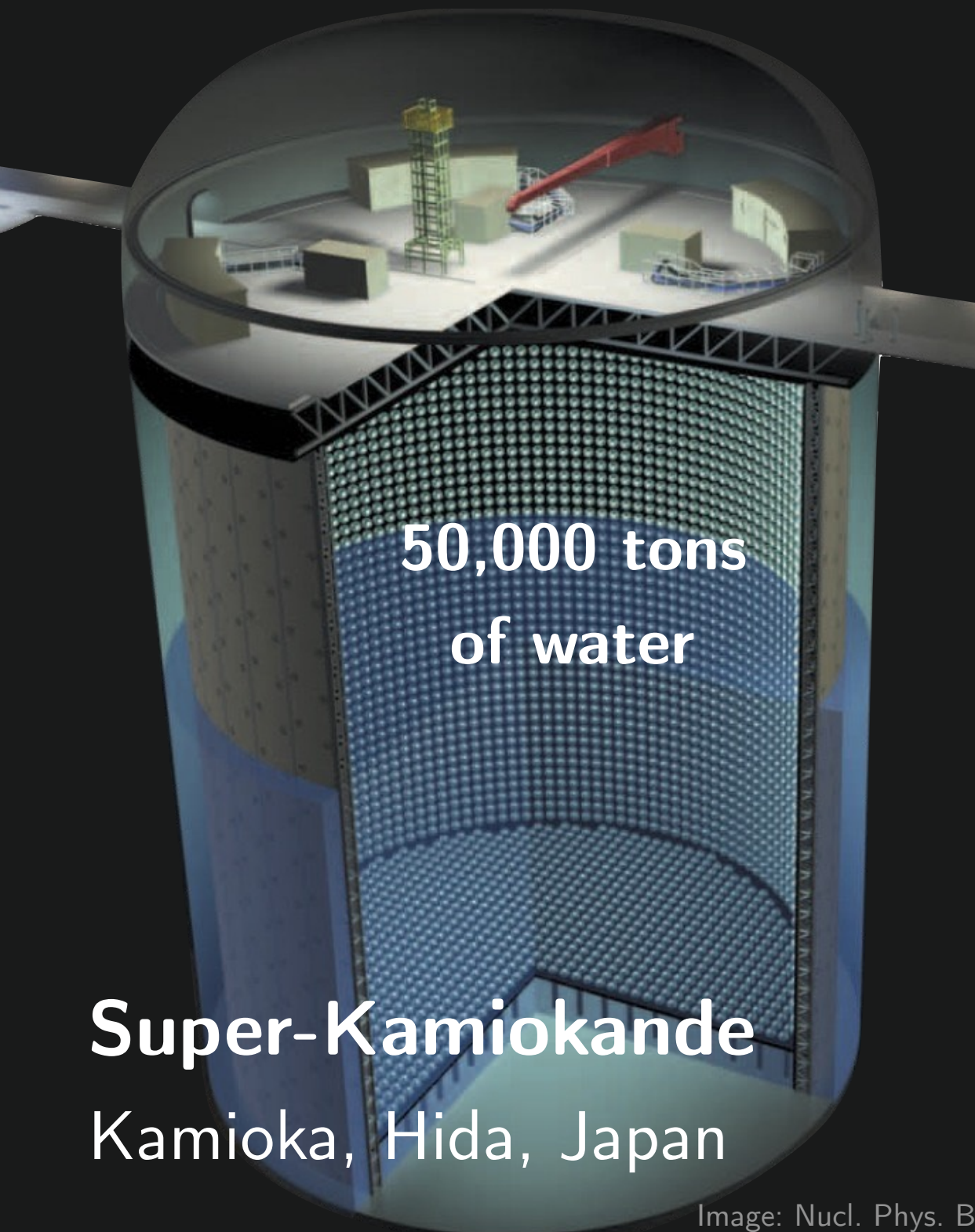
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Diffuse Supernova Neutrino Background (DSNB)

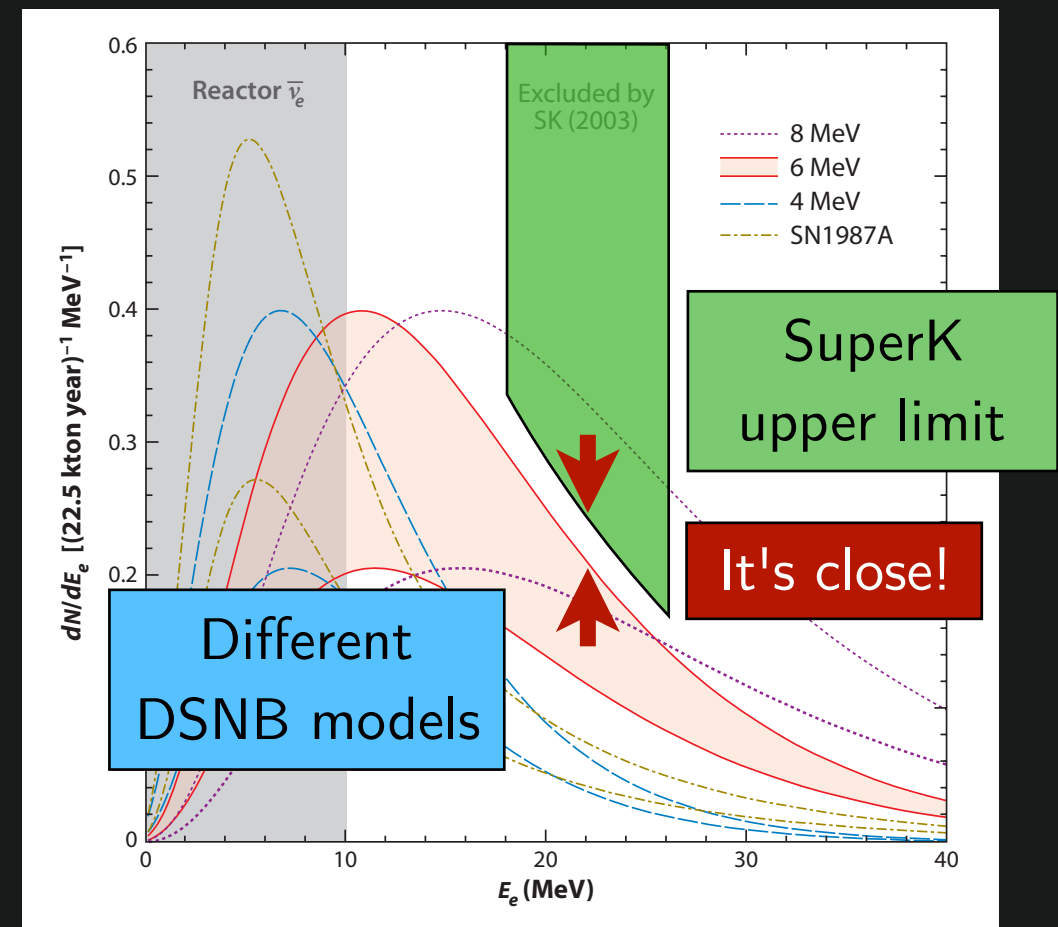
Super-Kamiokande + Gd



Looking for DSNB
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(Cowan & Reines, 1956)



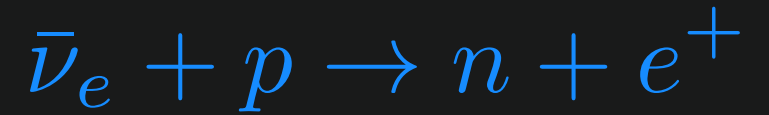
Ann. Rev. Nucl. Part. Sci. 2010.60:439-462 (2010)

Diffuse Supernova Neutrino Background (DSNB)

Super-Kamiokande + Gd



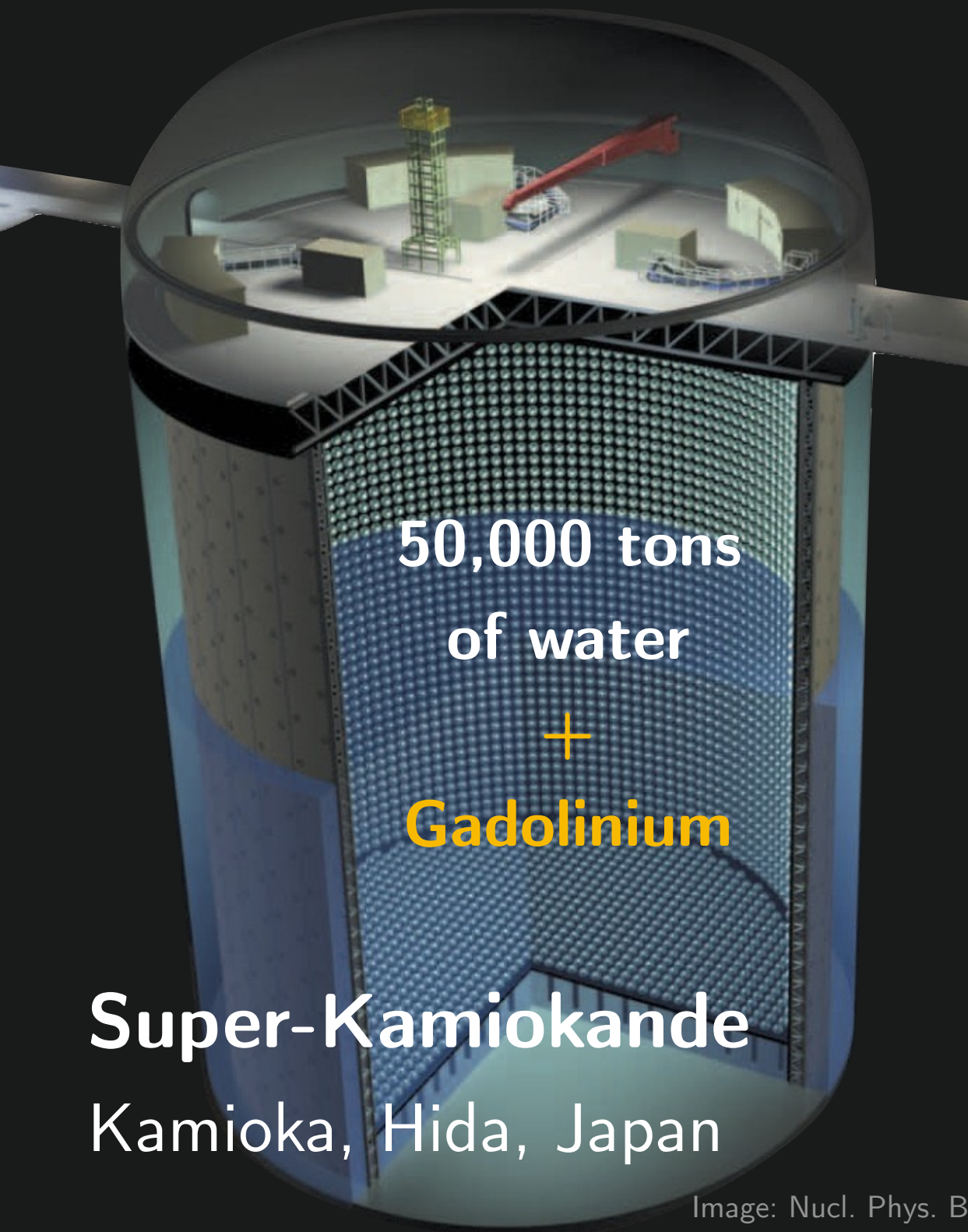
Looking for DSNB
electron antineutrinos
via inverse beta decay



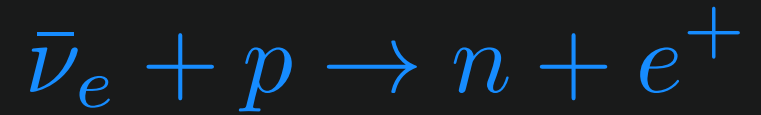
(Cowan & Reines, 1956)

Diffuse Supernova Neutrino Background (DSNB)

Super-Kamiokande + Gd



Looking for DSNB
electron antineutrinos
via inverse beta decay



(Cowan & Reines, 1956)

64
Gd
Gadolinium
157.25

By adding **gadolinium**, the ability to detect neutrons (and therefore inverse beta decay) is greatly improved

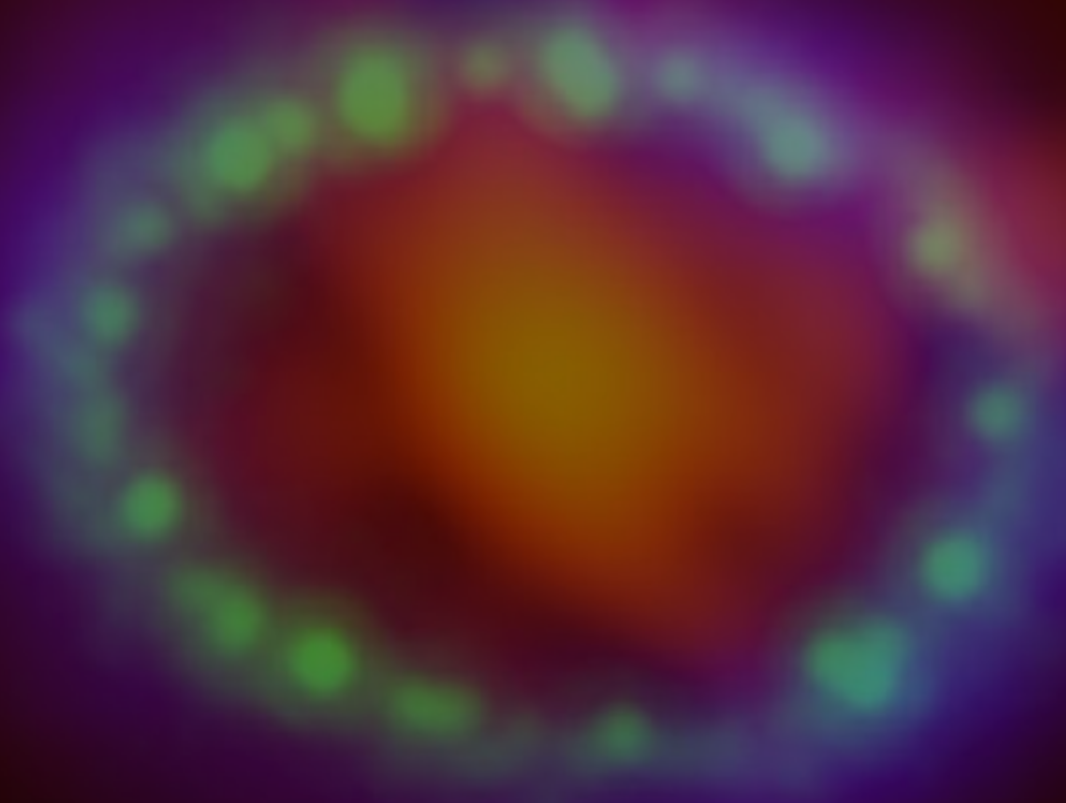
There's hope that Super-Kamiokande will detect the DSNB soon!

(this work starts in **June!**)

Super-Kamiokande
Kamioka, Hida, Japan

Supernova Neutrinos

Supernova Neutrinos



Supernova Neutrinos

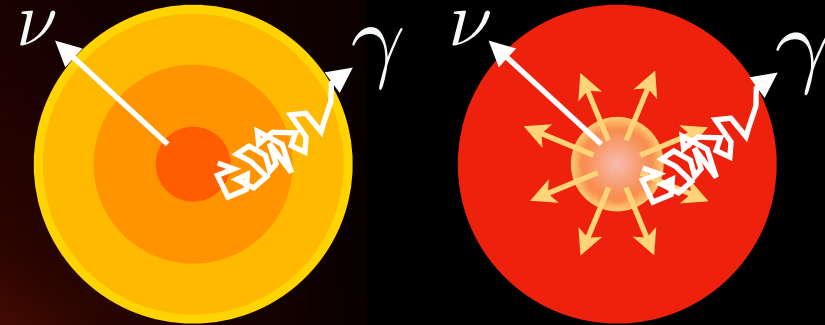


**Enormously powerful events
crucial to the existence of the
universe as we know it**

Supernova Neutrinos



Enormously powerful events
crucial to the existence of the
universe as we know it

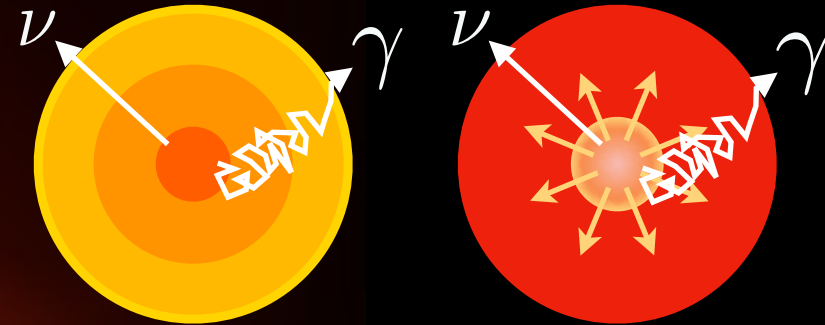


Like with the Sun, neutrinos
can teach us about SNe,
and SNe about neutrinos

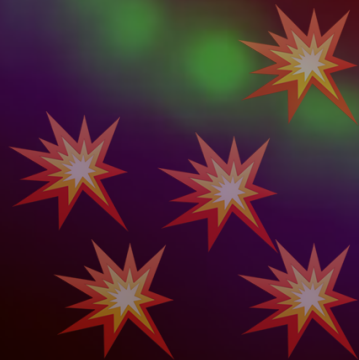
Supernova Neutrinos



Enormously powerful events
crucial to the existence of the
universe as we know it



Like with the Sun, neutrinos
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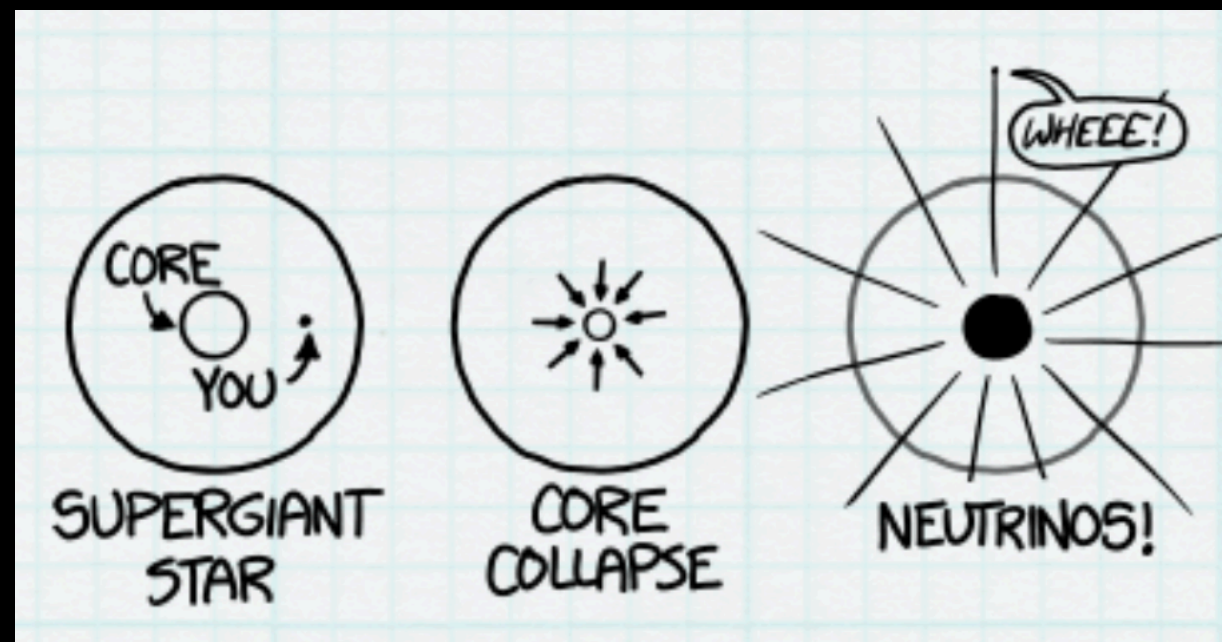


While we wait for a SNe neutrino burst,
we can study the DSNB, and learn about
the average behavior of supernovae

Supernova Neutrinos



"How close would you have to be to a supernova to get a lethal dose of **neutrino** radiation?"



<https://what-if.xkcd.com/73/>

Next Week

Saturday, April 21, 2018

"study of the origin, evolution, and
eventual fate of the universe"



Neutrino Cosmology

with

Dr. Marco Raveri

KICP, UChicago

What can **the structure of the universe**
teach us about **neutrinos**, and vice versa?



Thank You!