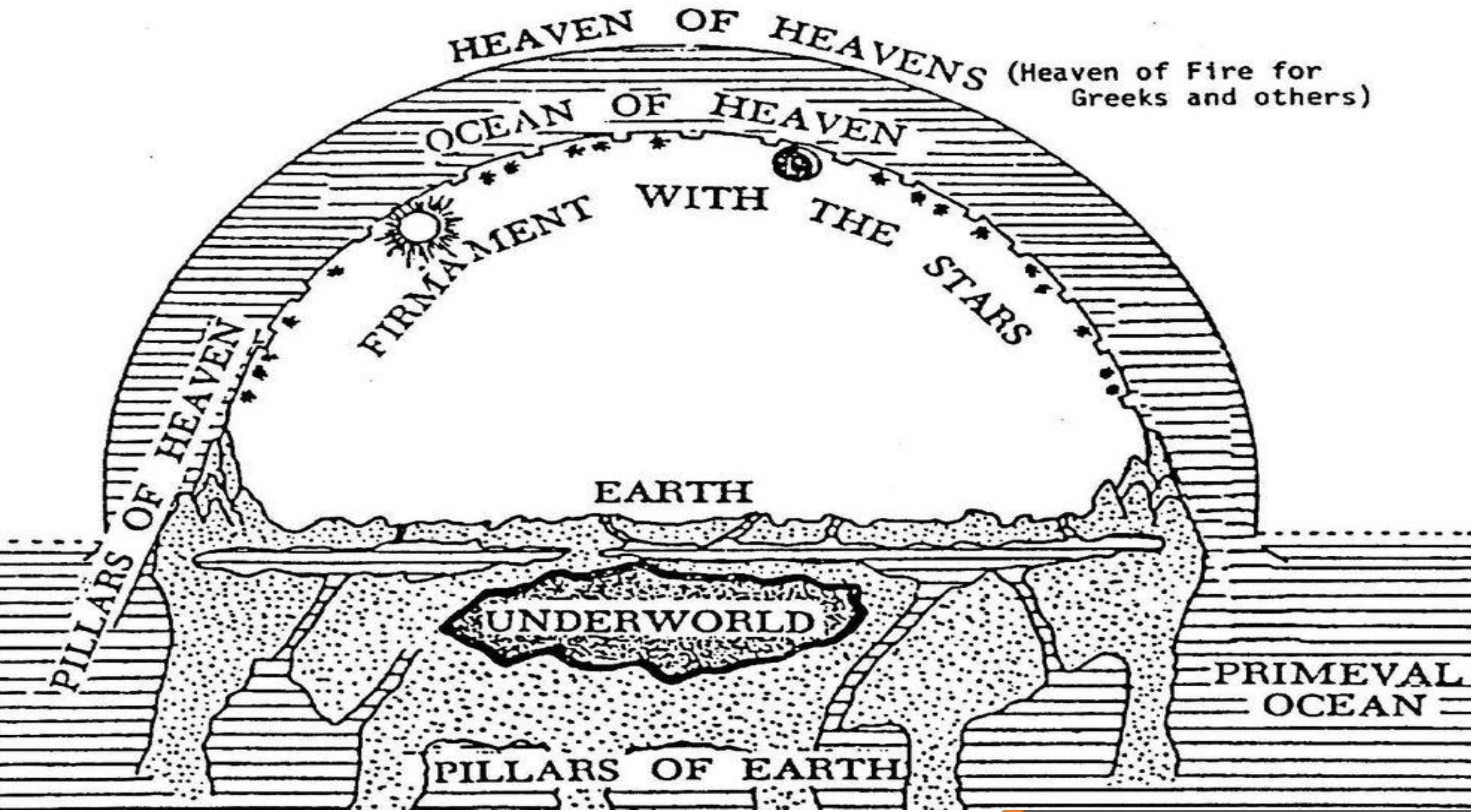
Adventures in ~~(Neutrino)~~ Physics

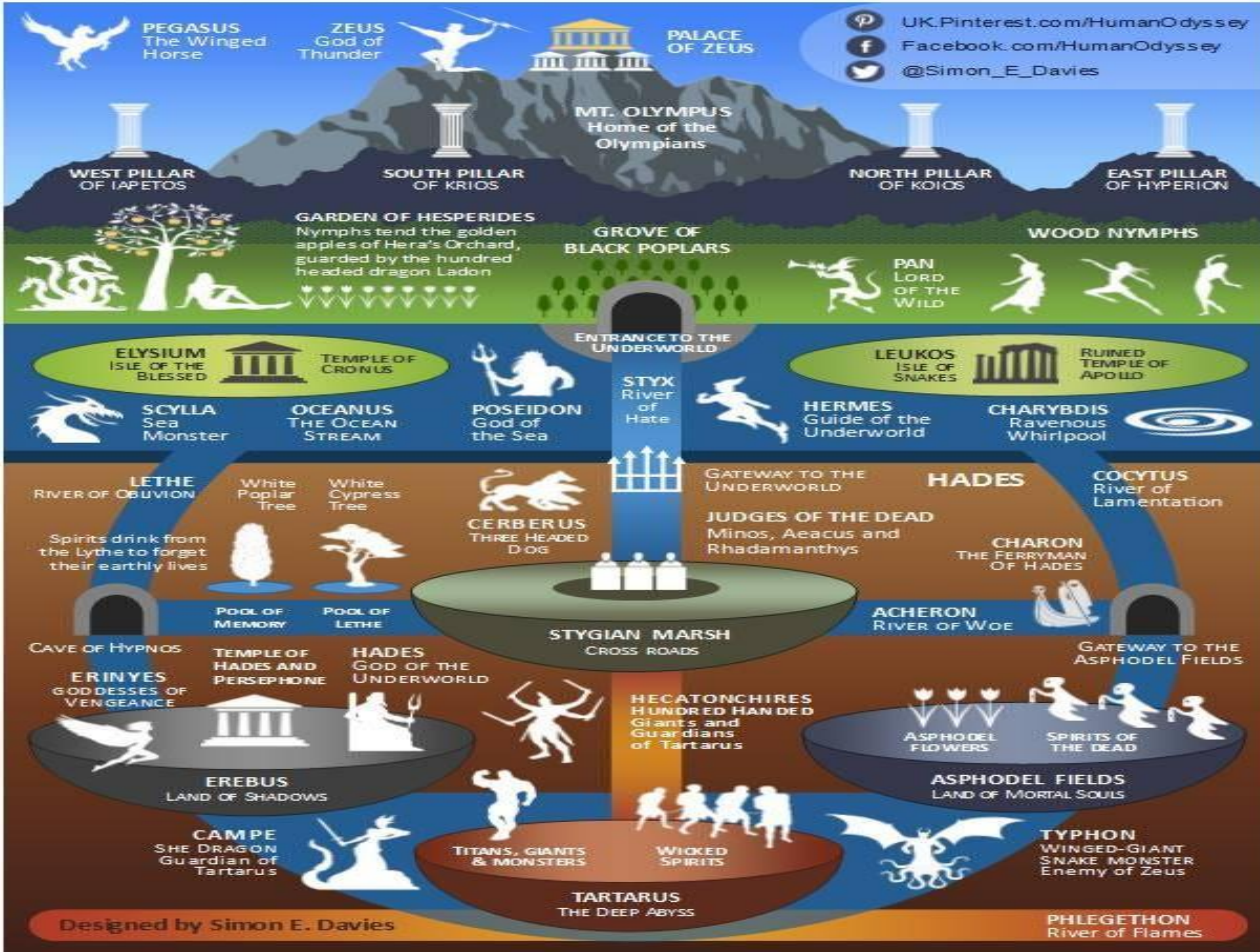
Ed Tatar

July 21, 2025

Ancient Greek Cosmology

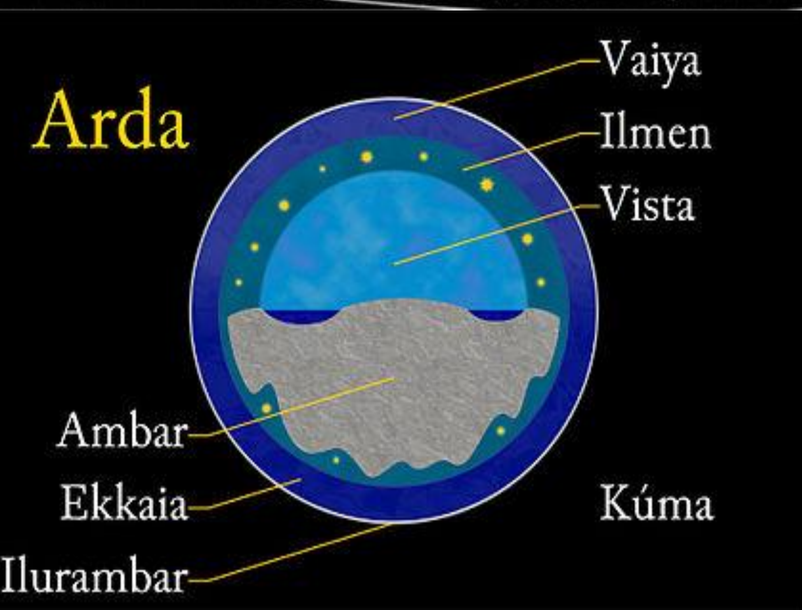


The Greek Cosmos: Gods & Monsters of the Classical Age



Tolkien's Cosmology

Divine Beings and Middle-earth



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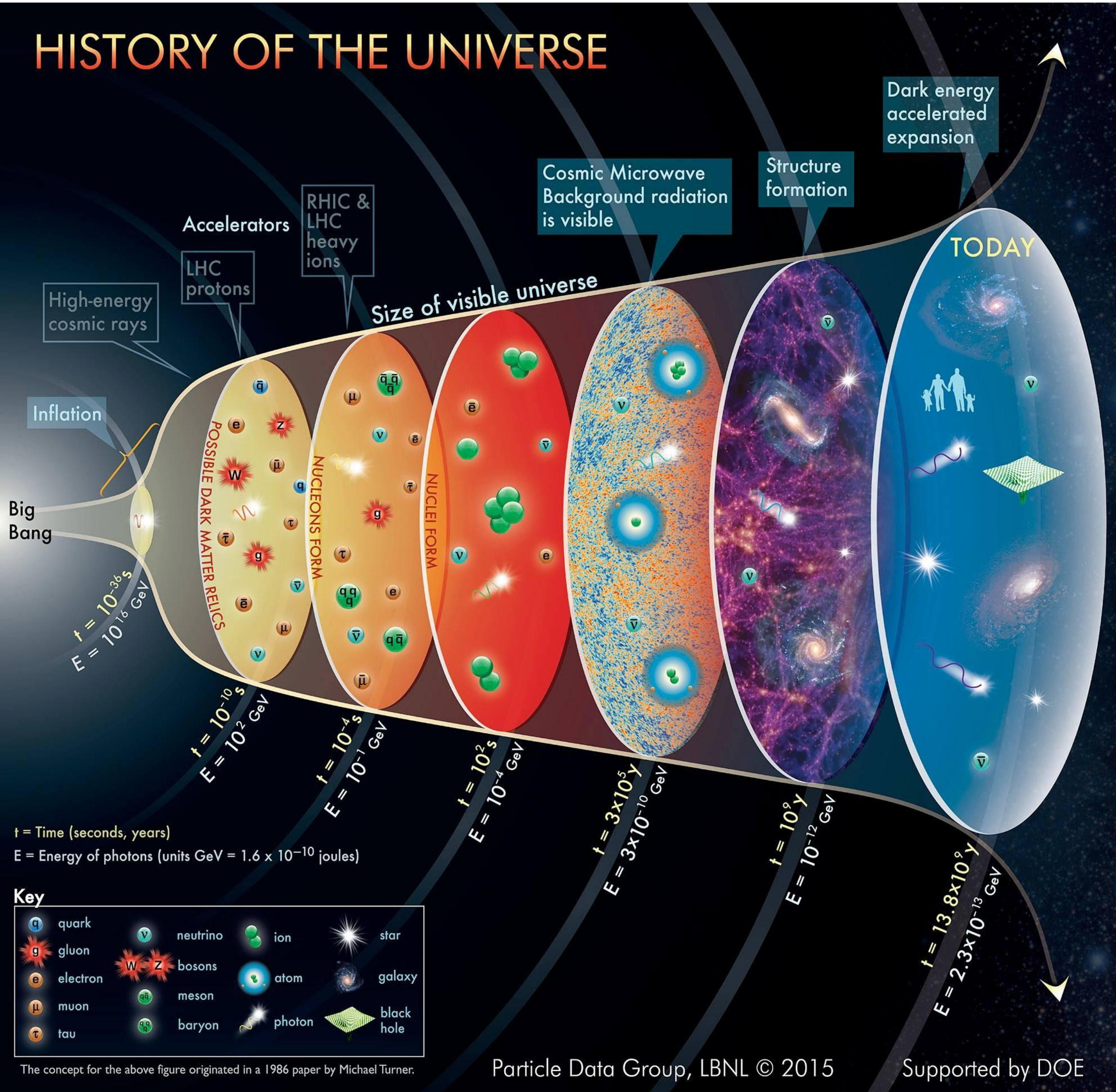
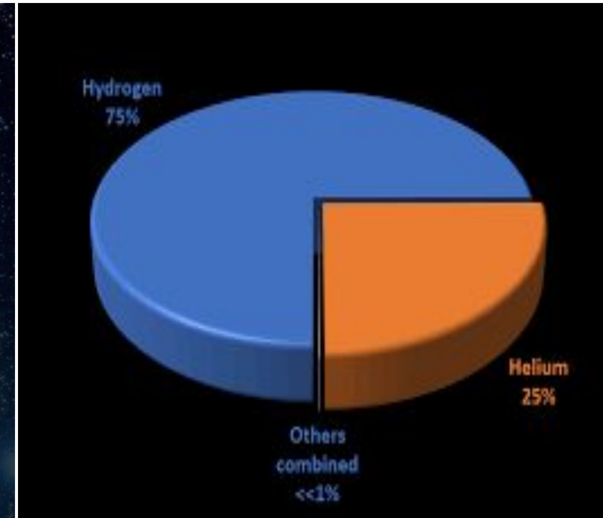
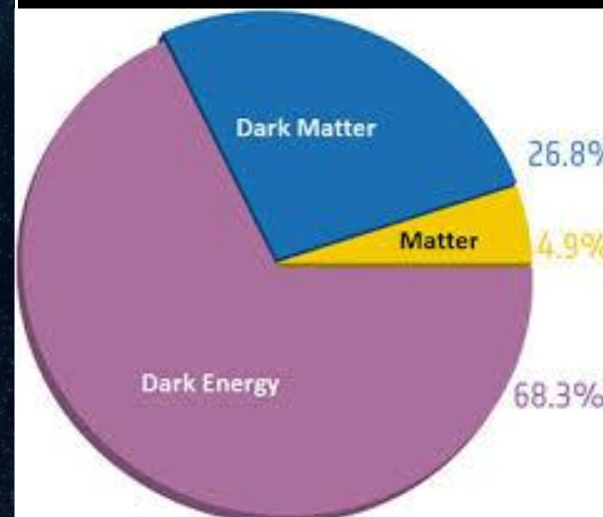
Cosmology of the Anthropocene







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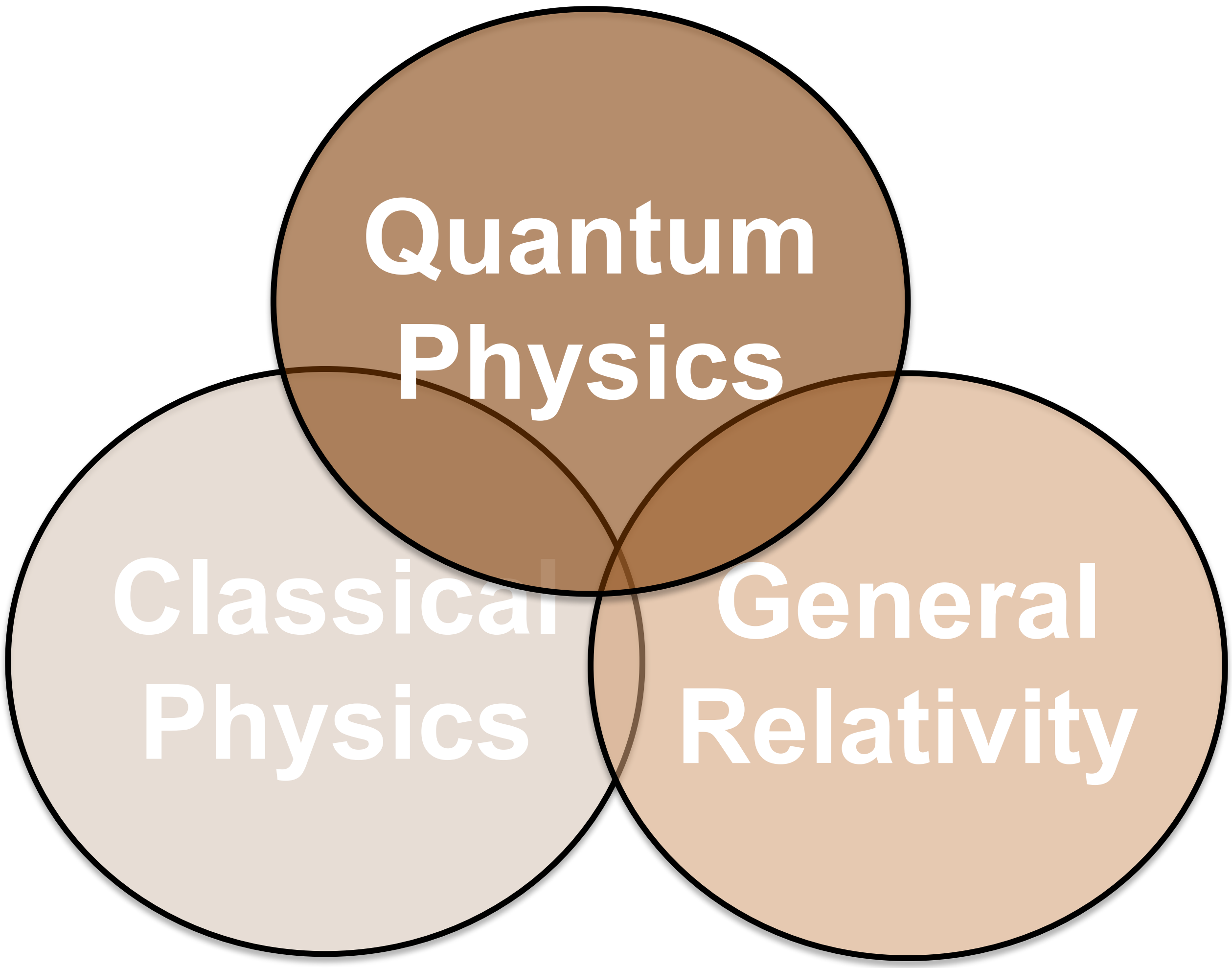
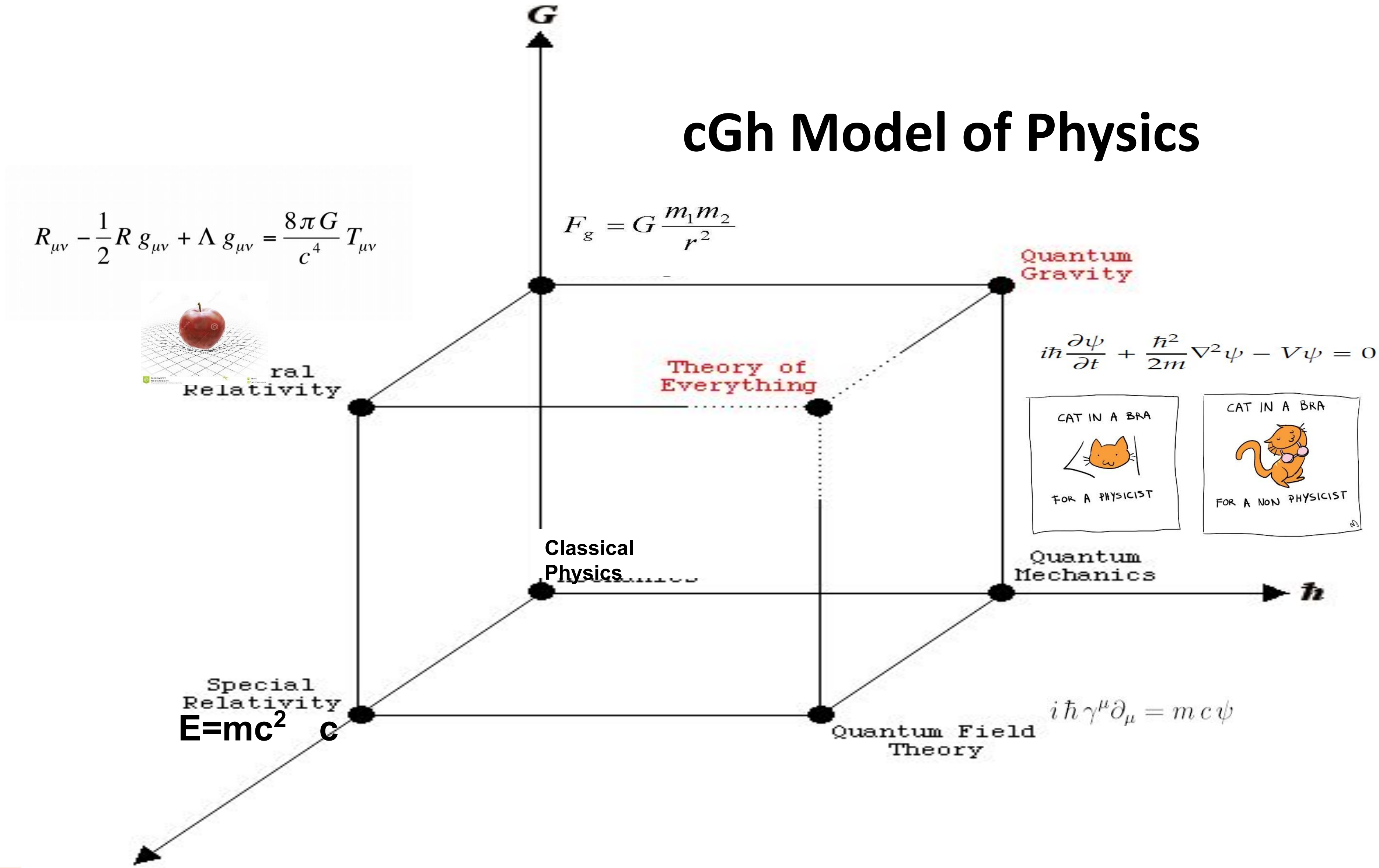

Quantum Physics
Classical Physics
General Relativity

cGh Model of Physics



How to generate relativistic quantum field theories

$\mathscr{L} = i\hbar c\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - mc^2\bar{\psi}\psi$

$\psi \rightarrow e^{i\theta(x)}\psi$

$U(1)$

$A_{\mu} \rightarrow A_{\mu} + \partial_{\mu}\lambda$

Free Lagrangian → Invariance under local gauge transformations → New gauge fields (particles) are needed → New Lagrangian

$$\mathscr{L} = [i\hbar c\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - mc^2\bar{\psi}\psi] - \left[\frac{1}{16\pi}F^{\mu\nu}F_{\mu\nu}\right] - (q\bar{\psi}\gamma^{\mu}\psi)A_{\mu}$$

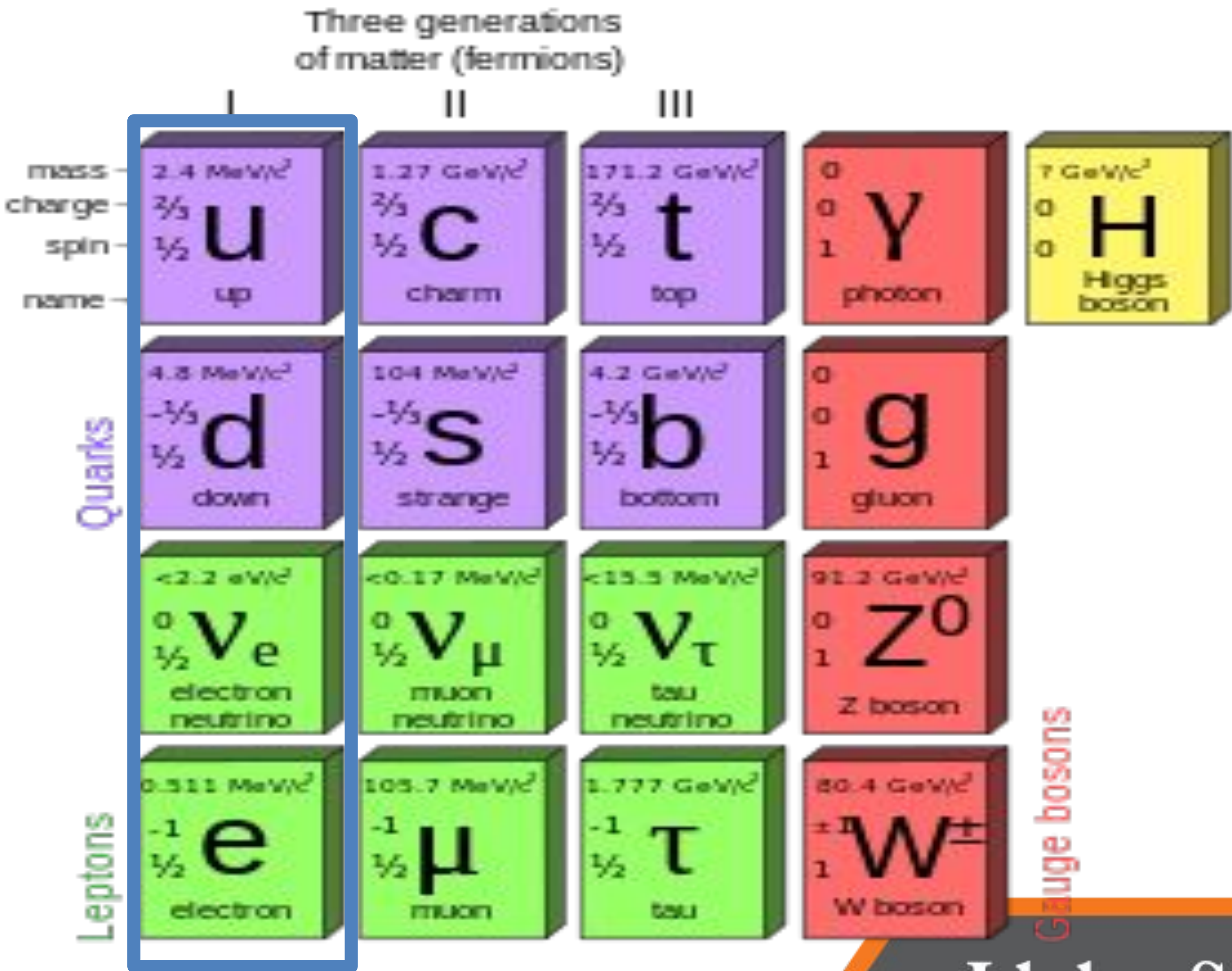
$$\frac{\partial}{\partial x_{\mu}}\left(\frac{\partial \mathcal{L}}{\partial(\partial\phi/\partial x_{\mu})}\right) - \frac{\partial \mathcal{L}}{\partial \phi} = 0$$

$$F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$$

$$\partial_{\mu}F^{\mu\nu} = j^{\nu}$$

$$i\hbar\gamma^{\mu}\partial_{\mu}\psi - mc\psi = 0$$

U(1) × SU(2) × SU(3)


Three generations of matter (fermions)
I
II
III
mass
charge
spin
name
2.4 MeV/c²
⅔
½
u
up
1.27 GeV/c²
⅔
½
c
charm
171.2 GeV/c²
⅔
½
t
top
0
0
1
γ
photon
? GeV/c²
0
0
H
Higgs boson
4.8 MeV/c²
-⅓
½
d
down
104 MeV/c²
-⅓
½
s
strange
4.2 GeV/c²
-⅓
½
b
bottom
0
0
1
g
gluon
<2.2 eV/c²
0
½
νe
electron neutrino
<0.17 MeV/c²
0
½
νμ
muon neutrino
<15.5 MeV/c²
0
½
ντ
tau neutrino
91.2 GeV/c²
0
1
Z⁰
Z boson
0.511 MeV/c²
-1
½
e
electron
105.7 MeV/c²
-1
½
μ
muon
1.777 GeV/c²
-1
½
τ
tau
80.4 GeV/c²
±1
1
W±
W boson
Quarks
Leptons
Gauge bosons

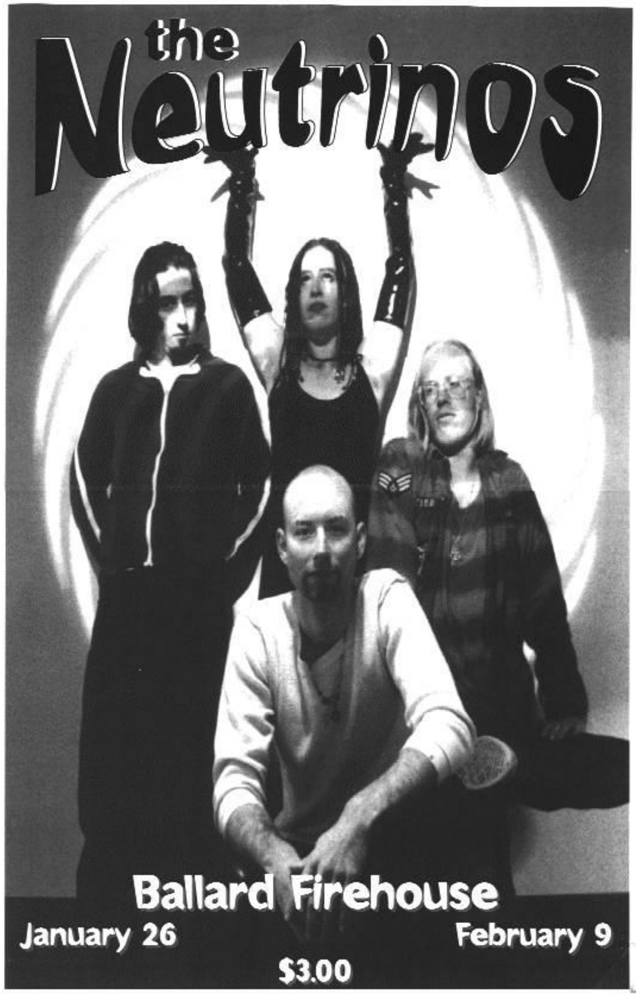
Free parameters in the Standard Model:

- ✦ 9 fermion masses (+ 3 m_ν)
- ✦ 3 CKM mixing angles +1 phase
- ✦ 1 electromagnetic coupling constant α
- ✦ 1 strong coupling constant α_s
- ✦ 1 weak coupling constant G_F
- ✦ 2 Z_0 and W masses
- ✦ 1 Higgs mass ➜ 21 free parameters

$$M_H \cong \frac{2M_W + M_Z}{2}$$

$$M_H^2 \cong M_t M_Z$$

$$M_H \cong \frac{M_W + M_t}{2}$$



- Neutrinos are (almost) massless
- Neutrinos only interact via the Weak force
- Neutrinos are left-handed
  - anti-neutrinos are right-handed
- Neutrinos are electrically neutral
- Neutrinos have three flavors
  - Electron, muon, tau

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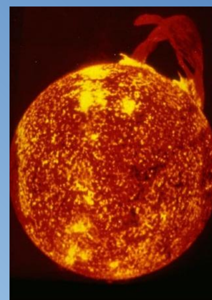
Neutrino Facts

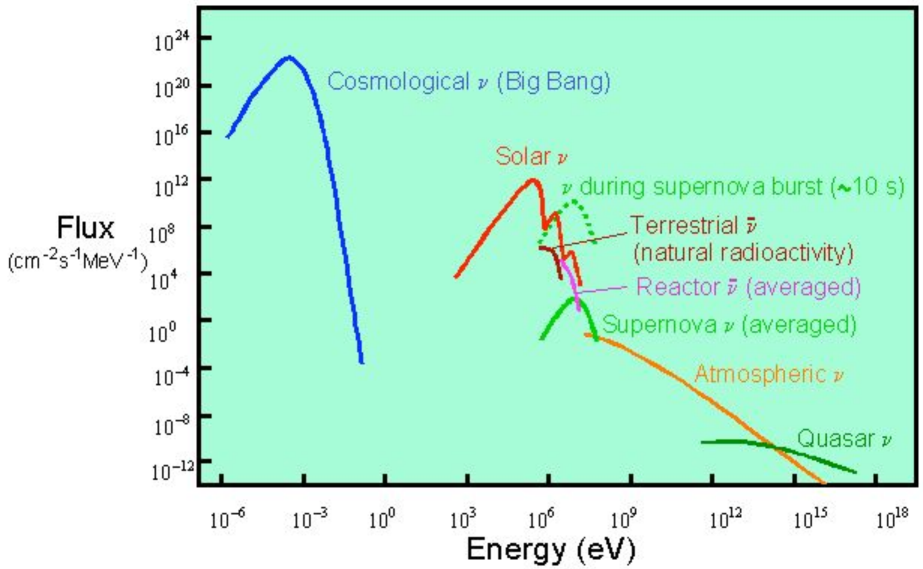
ν flux on Earth from Sun

$6.5\times10^{14}/(m^2\ s)$



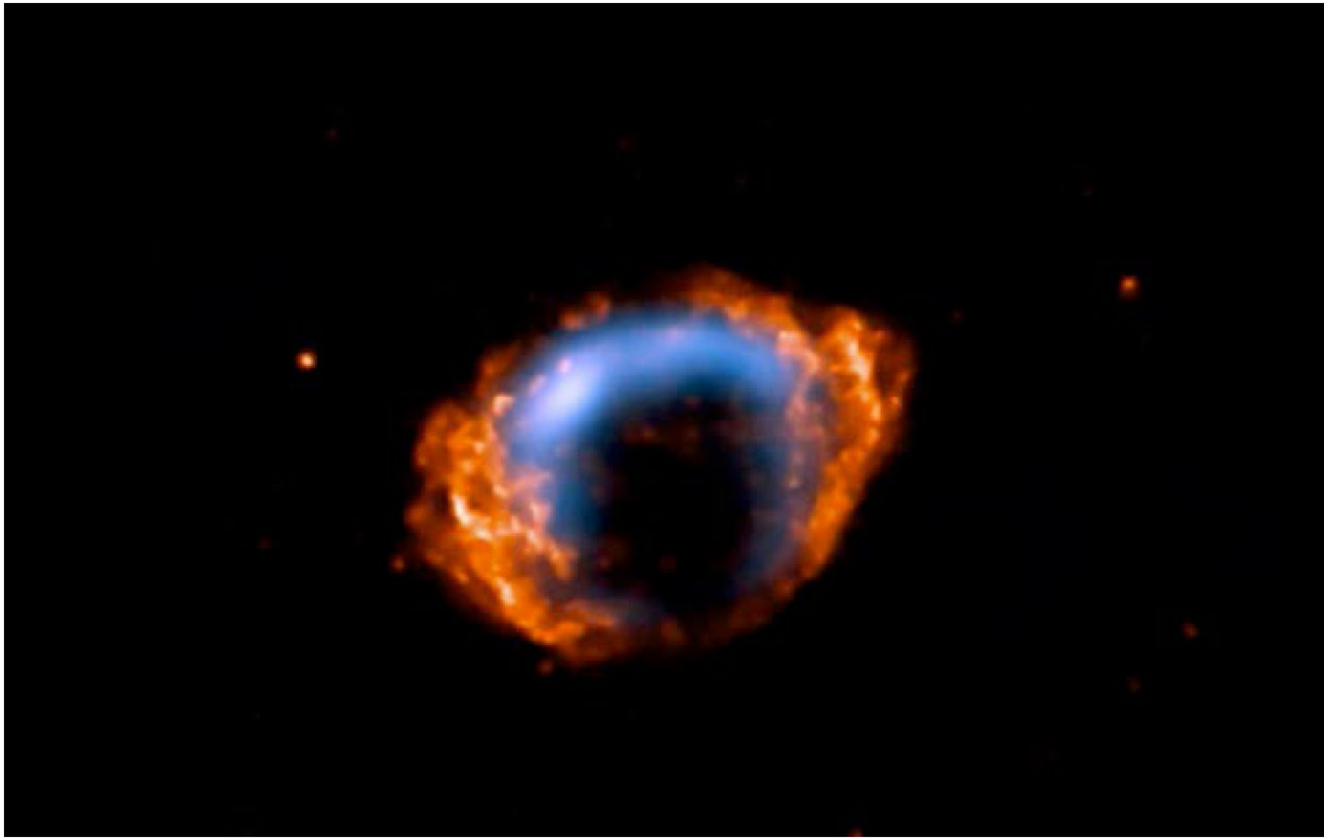
Neutrino from sun will pass through 5 LY of solid lead

300/6 relic ν/ cm^3
T=1.95K
$V\sim10^6 m/s$ $\lambda\sim10^{-3}m$



Flux on earth of neutrinos from various sources, in function of energy

- ~10 SN/s in the Universe
- ~multiple SN/day discovered
- ~1SN/50-100 yrs in the Milky Way
- >1 SN/year within 10 Mpc



SN Explosion ~140 yrs ago. @ 8 kpc

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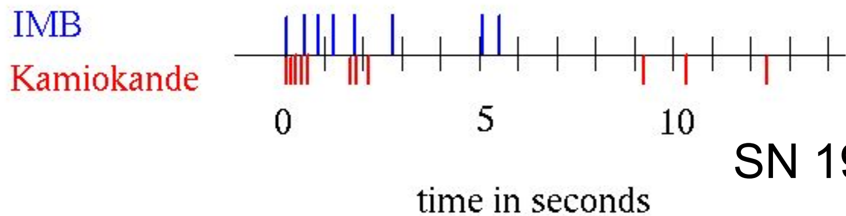
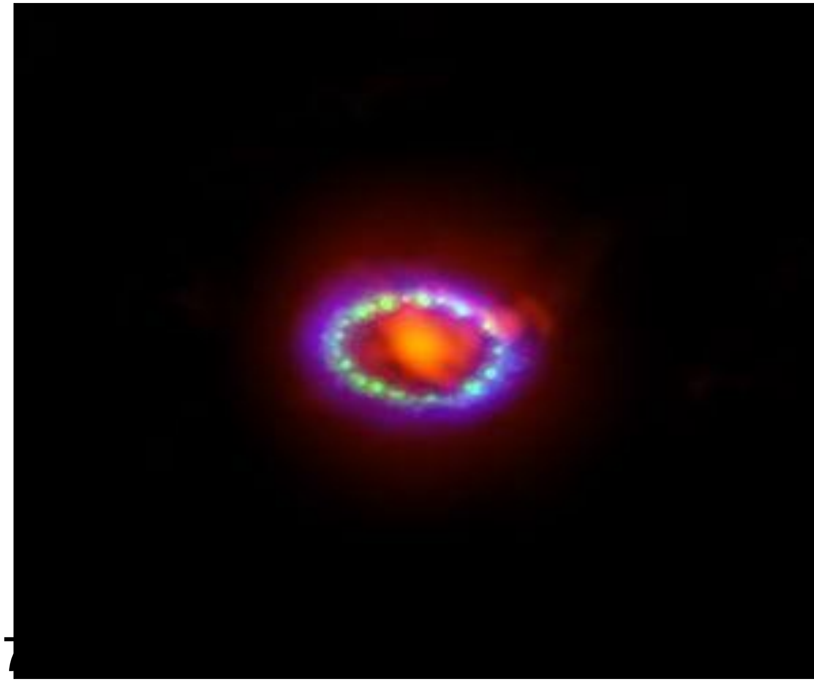


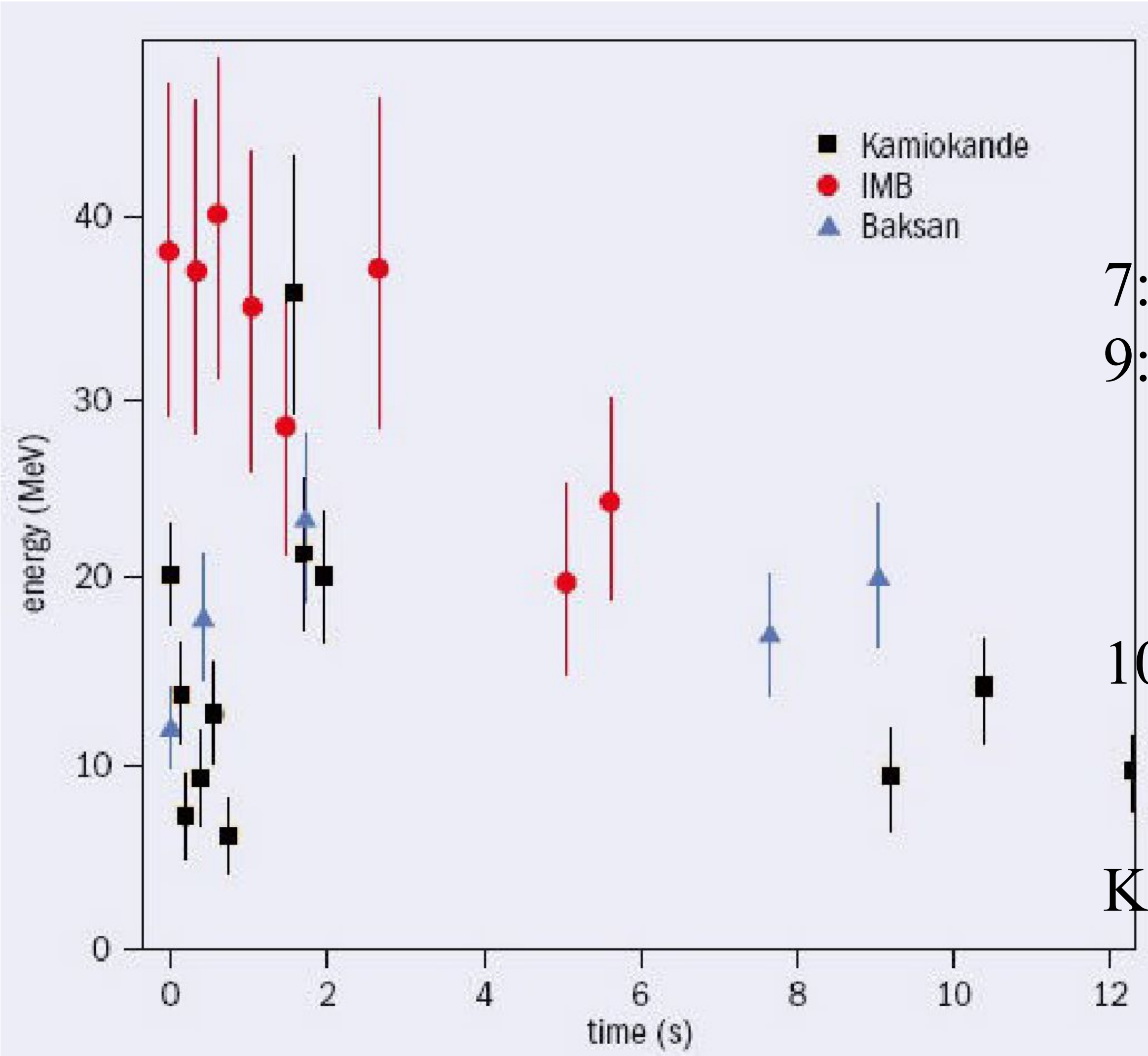
SN 1987



7:36 Neutrinos observed

9:30 Amateur astronomer observes Tarantula Nebula in LMC (168kly). Nothing unusual.

10:30 LMC photographed, SN1987A observed.

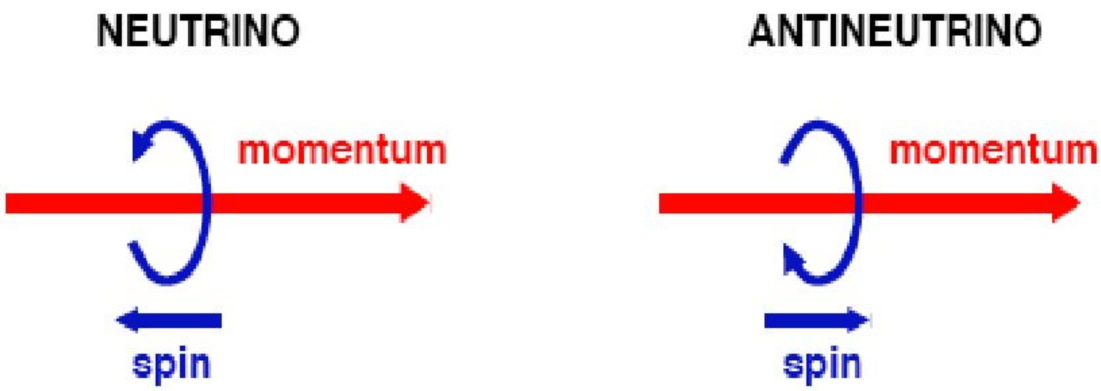


SN 1987A
AntiNeutrino Events

7:36 Neutrinos observed
9:30 Amateur astronomer observes Tarantula Nebul in LMC (168kly). Nothing unusual.
10:30 LMC photographed, SN1987A observed.

Kamiokande II, IMB, Baksan:

$$\bar{\nu}_e + p \rightarrow n + e^+$$



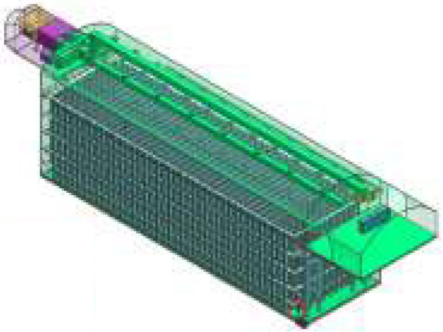
Weak interactions only couple to left-handed ν's, or right-handed $\bar{\nu}$'s

This is a pure V-A interaction (maximally parity violating). Weak current has the form:

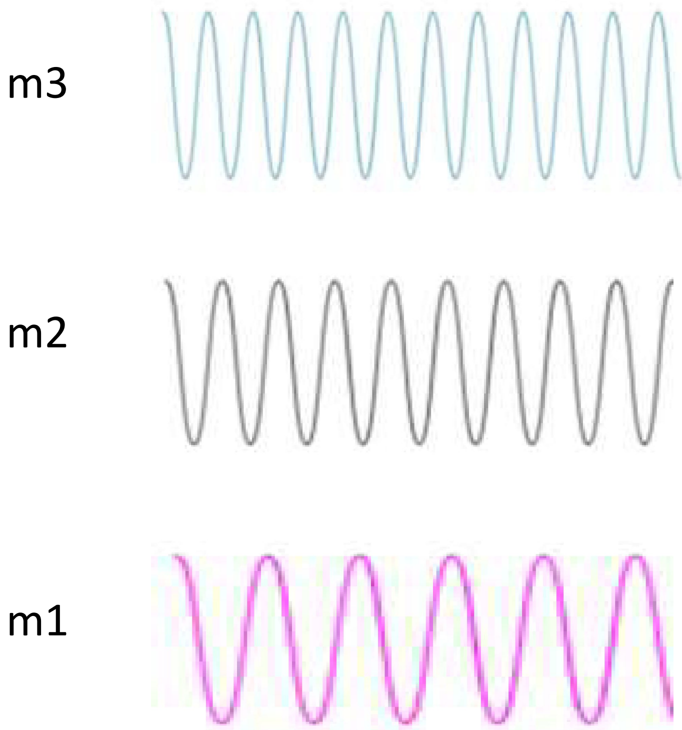
$$j_\mu = \bar{\psi}\gamma_\mu(1-\gamma_5)\psi$$

Right-handed ν's either don't exist, or are sterile (don't interact).

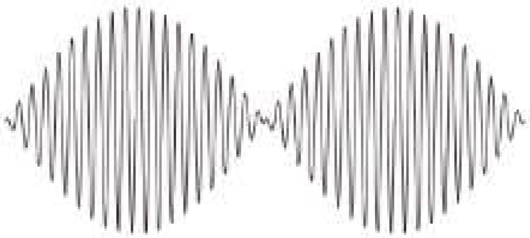
Oscillations



Muon neutrino → e, μ, or τ



Superposition of waves of different masses (frequencies)



Amplitude of beat gives mixing angle sin2θ
Wavelength reads mass[2] differences

$$\Delta m_{31}^2 \equiv m_3^2 - m_1^2$$

Probability: $P(\nu_\alpha \to \nu_\beta, t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)$

Neutrino detection | PMNS Matrix U_{PMNS} | Neutrino in flight

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

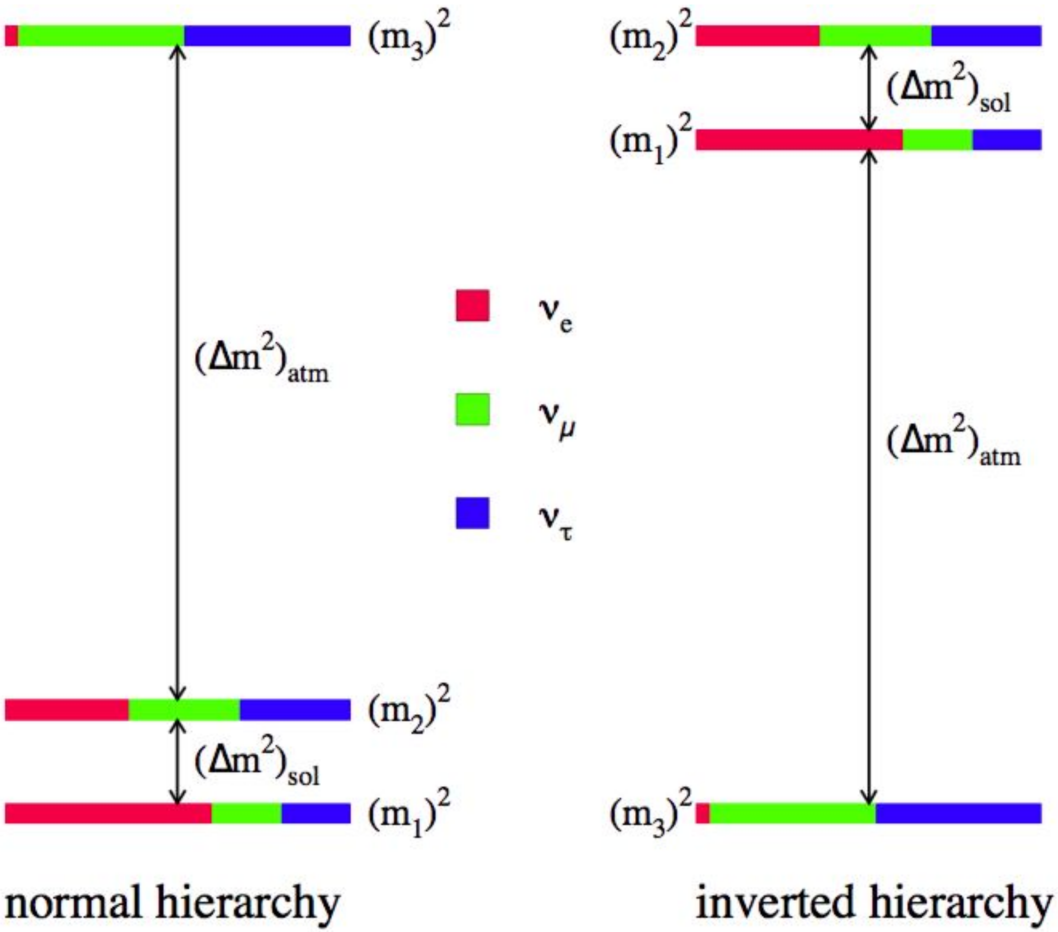
$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) \;\simeq\; & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\ & + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{\mathrm{CP}}) \\ & + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2, \end{aligned}$$

where $\Delta_{ij} \equiv \Delta m^2_{ij}\, L/4E_\nu$, and $a \equiv G_F N_e/\sqrt{2}$, N_e is the number density of electrons in the Earth.

- Normal vs. Inverted Ordering
- CPV phase δ_{CP}.
- $\mathrm{Sin}^2\theta_{23}$, octant degeneracy

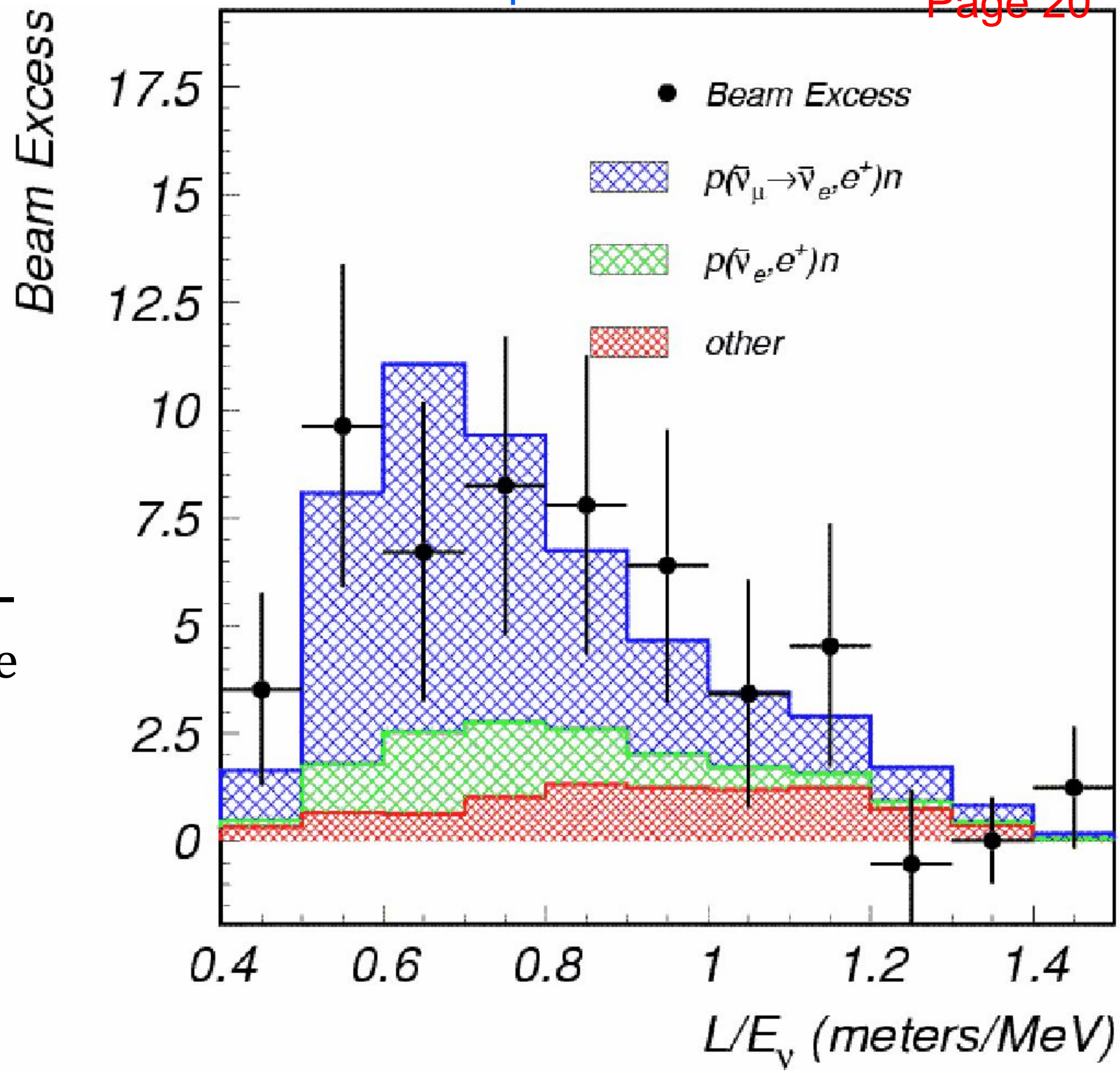
Parameter	Central Value	Relative Uncertainty
θ_{12}	0.5903	2.3%
θ_{23} (NO)	0.866	4.1%
θ_{23} (IO)	0.869	4.0%
θ_{13} (NO)	0.150	1.5%
θ_{13} (IO)	0.151	1.5%
Δm^2_{21}	7.39×10^{-5} eV^2	2.8%
Δm^2_{32} (NO)	2.451×10^{-3} eV^2	1.3%
Δm^2_{32} (IO)	-2.512×10^{-3} eV^2	1.3%



LSND experiment Los Alamos

detected more $\bar{\nu}_e$ than expected (3.8σ excess)

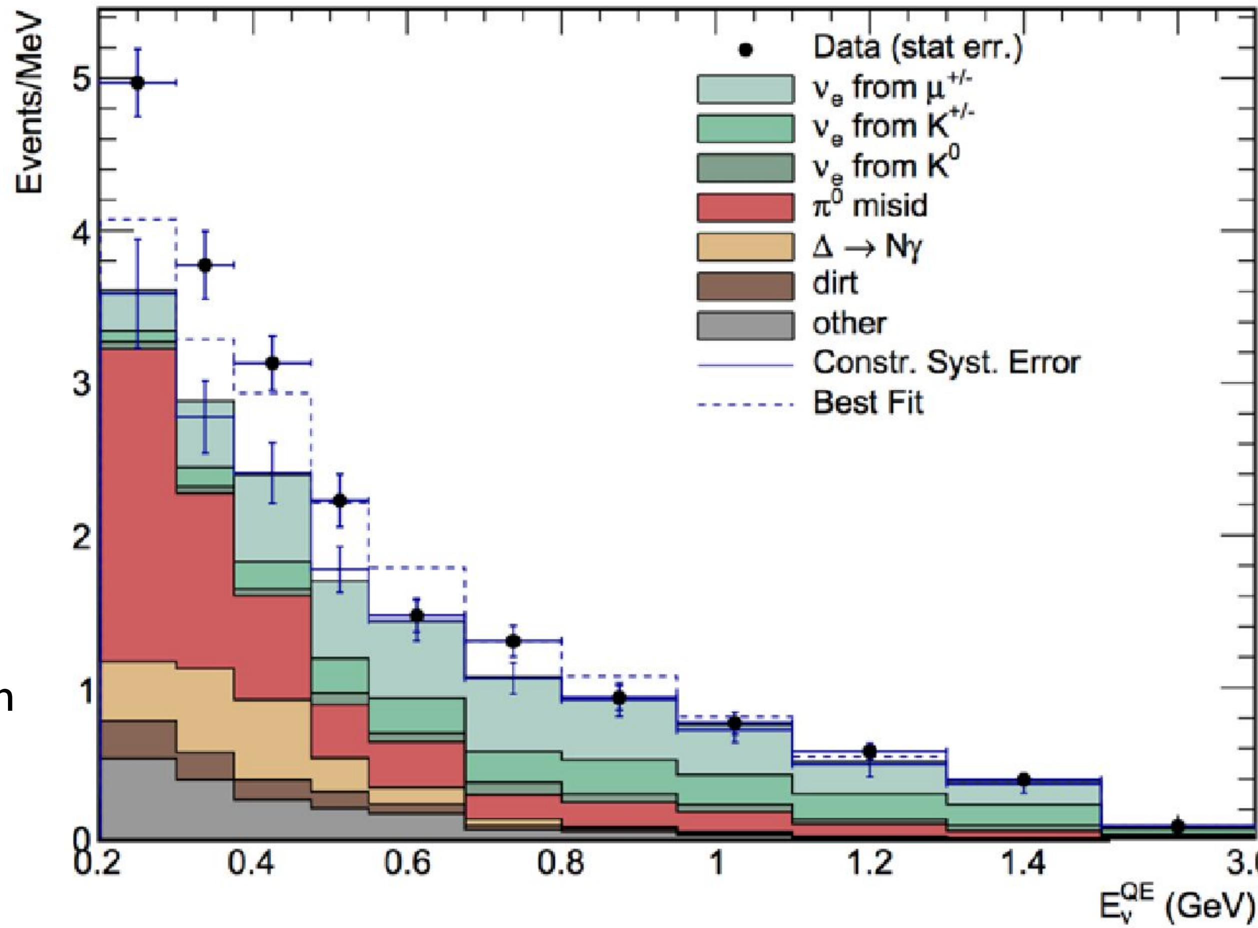
hep-ex/0104049



MiniBooNE's low energy excess

Event excess: 381.2 ± 85.2 (4.5σ)

arXiv:1805.12028 (30 May 2018)



Other anomalies:

DANSS 1804.04046

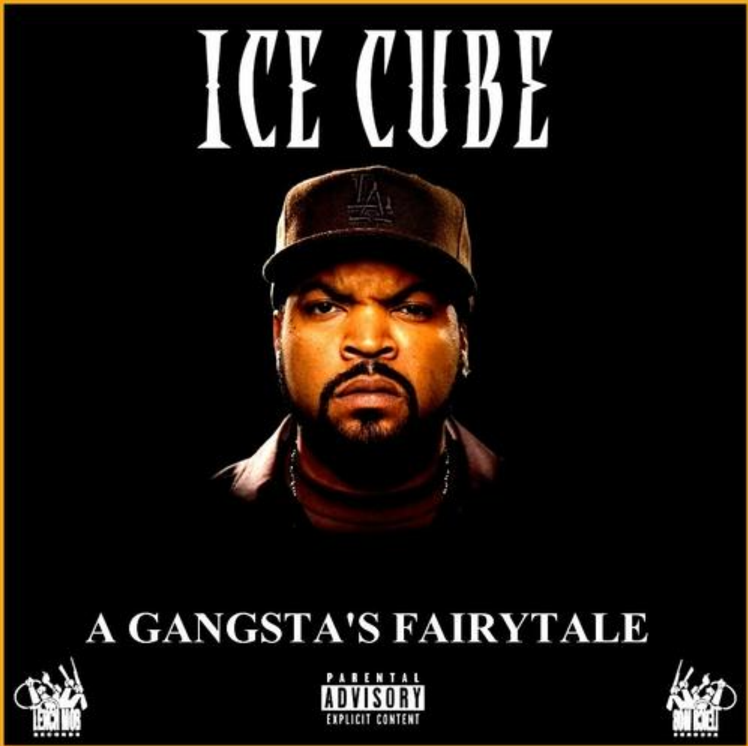
Neutrino-4 1809.10561

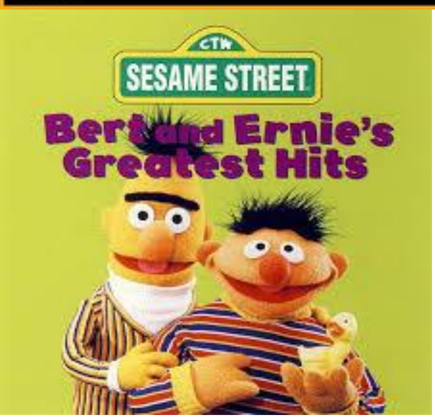
How to explain?

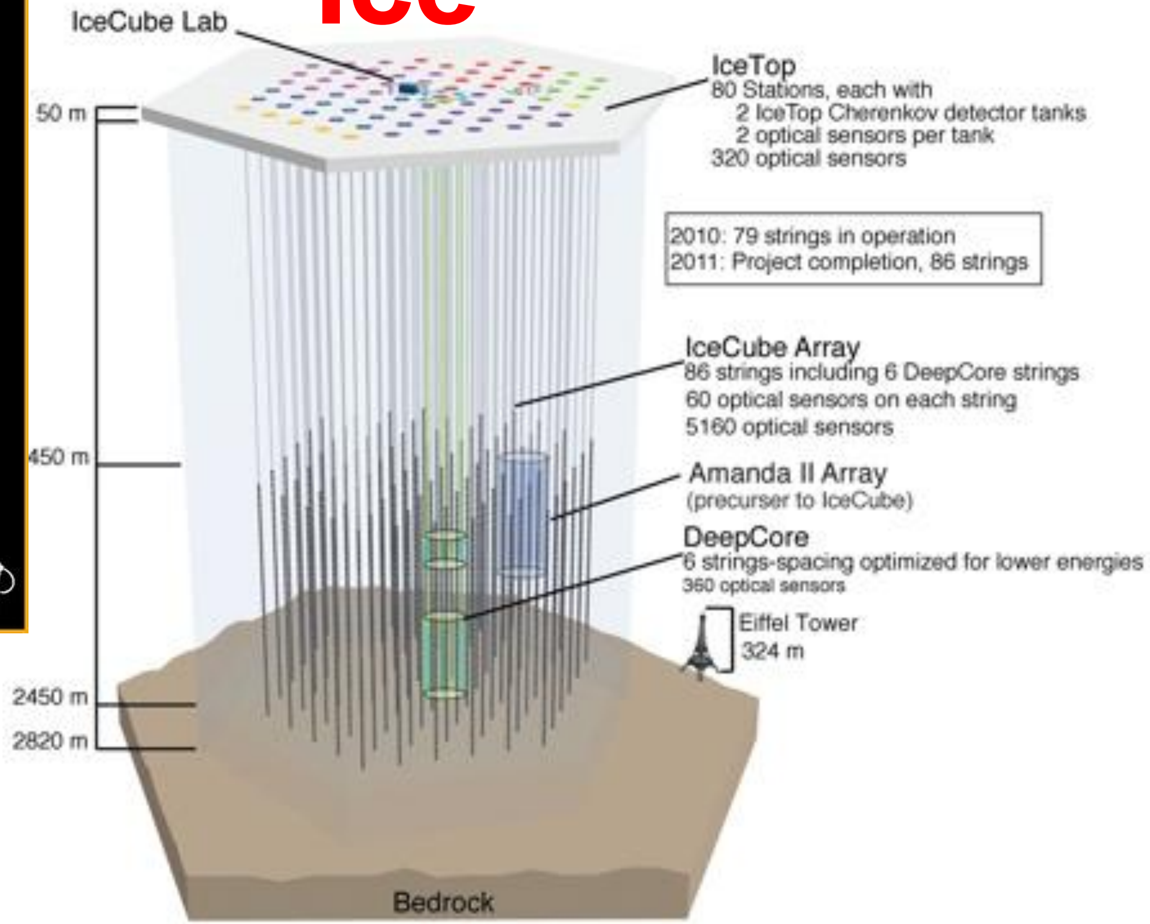
Sterile ν at the eV scale in tension with data

Cosmological bounds also in tension with sterile scenario

Ice^3



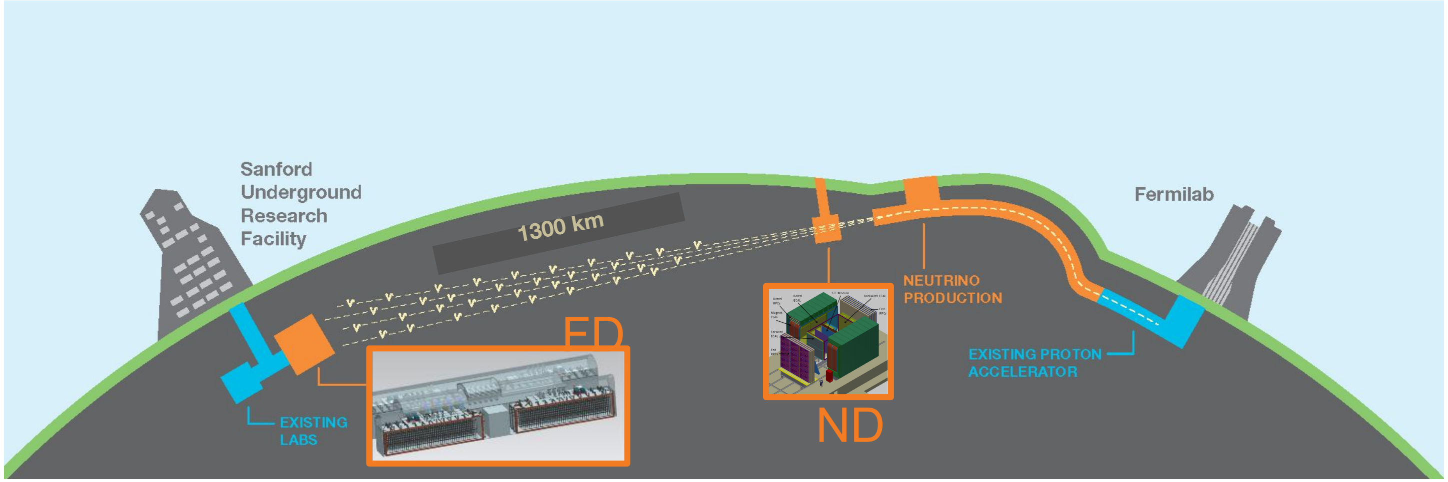




2-3 PeV (10^{15} eV !!!)

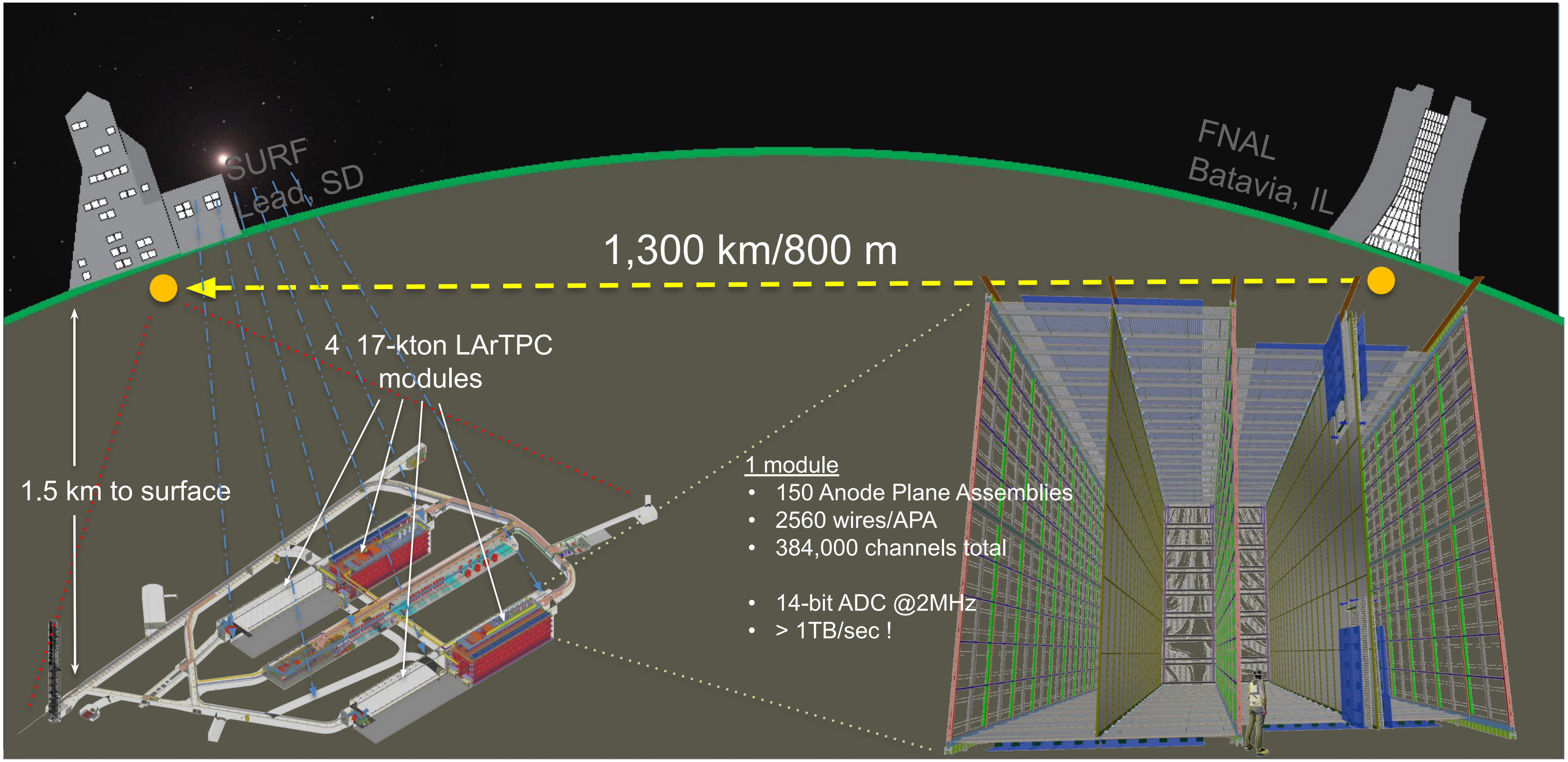
"Mysterious Cosmic Rays Shooting from Ground…", ANITA, E=0.6 EeV, D. B. Fox et al. arXiv:1809.09615

DUNE Oscillation Strategy

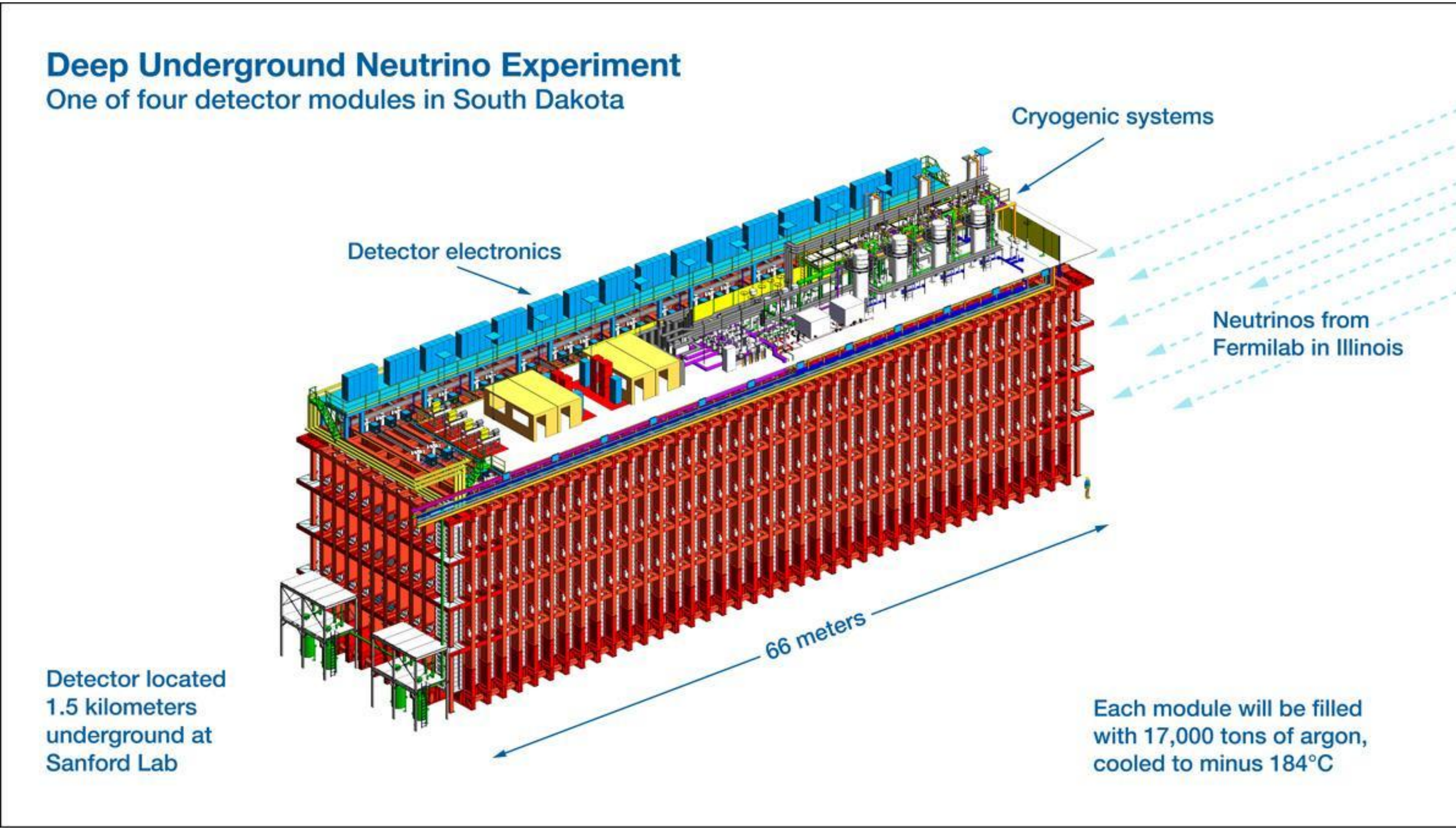


- **Near Detector at Fermilab:** measurements of unoscillated beam
- **40 kt LAr Far Detector at SURF:** measure oscillated ν and $\bar{\nu}$ spectra

Deep Underground Neutrino Experiment




google.com
MAP LEGEND
United States
Davis Campus
MJD
Majorana Demonstrator
Neutrinoless double-beta decay
LUX
Large Underground Xenon experiment
First generation dark matter
LZ
Proposed Second generation dark matter
Yates Shaft
Ross Shaft
DUNE at LBNF
Proposed Deep Underground Neutrino Experiment at the Long-Baseline Neutrino Facility
4850 Level—four 10kT liquid argon detectors
Experiment Hall
Proposed Third generation dark matter experiment and 1 T neutrinoless double-beta decay experiment
Ross Campus
MJD
Majorana Demonstrator
Electroforming laboratory
BHSU Underground Campus
Low-Background Counting
CASPAR
Compact Accelerator System for Performing Astrophysical Research


Deep Underground Neutrino Experiment
One of four detector modules in South Dakota
Cryogenic systems
Detector electronics
Neutrinos from Fermilab in Illinois
66 meters
Detector located 1.5 kilometers underground at Sanford Lab
Each module will be filled with 17,000 tons of argon, cooled to minus 184°C

Timeline

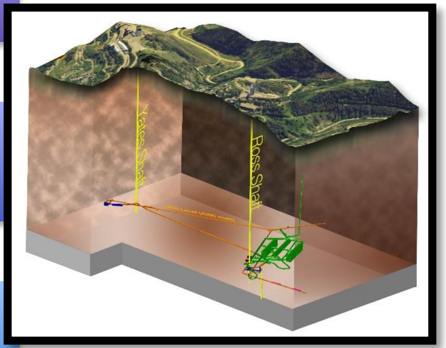
2018: protoDUNEs at CERN

2019: Technical Design Report

2019: Far Site Primary Excavation Begins

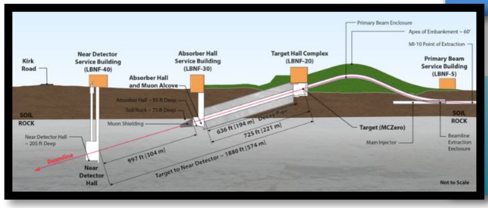
2026: First Module Installation Begins

2026: Neutrino Beam Available

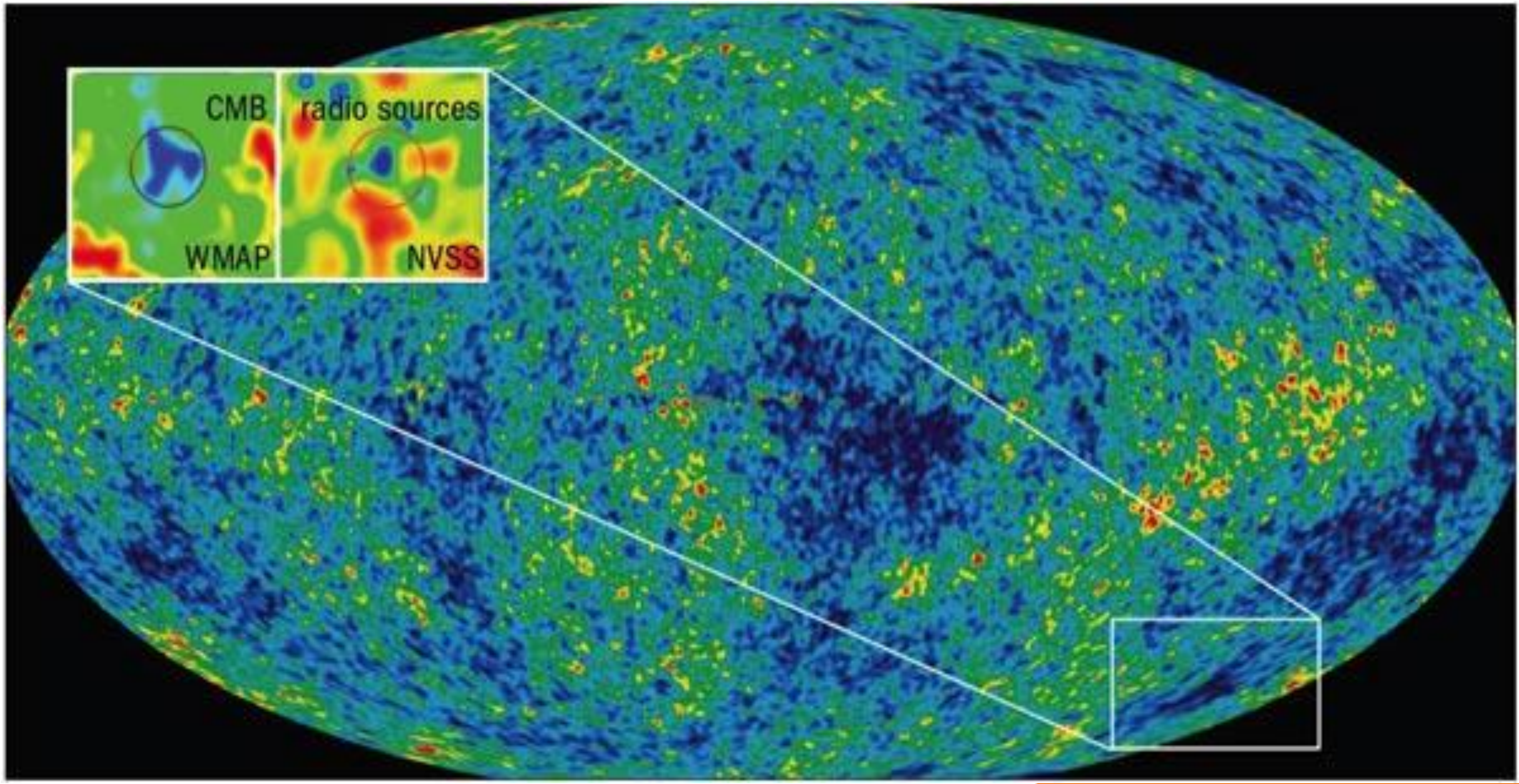


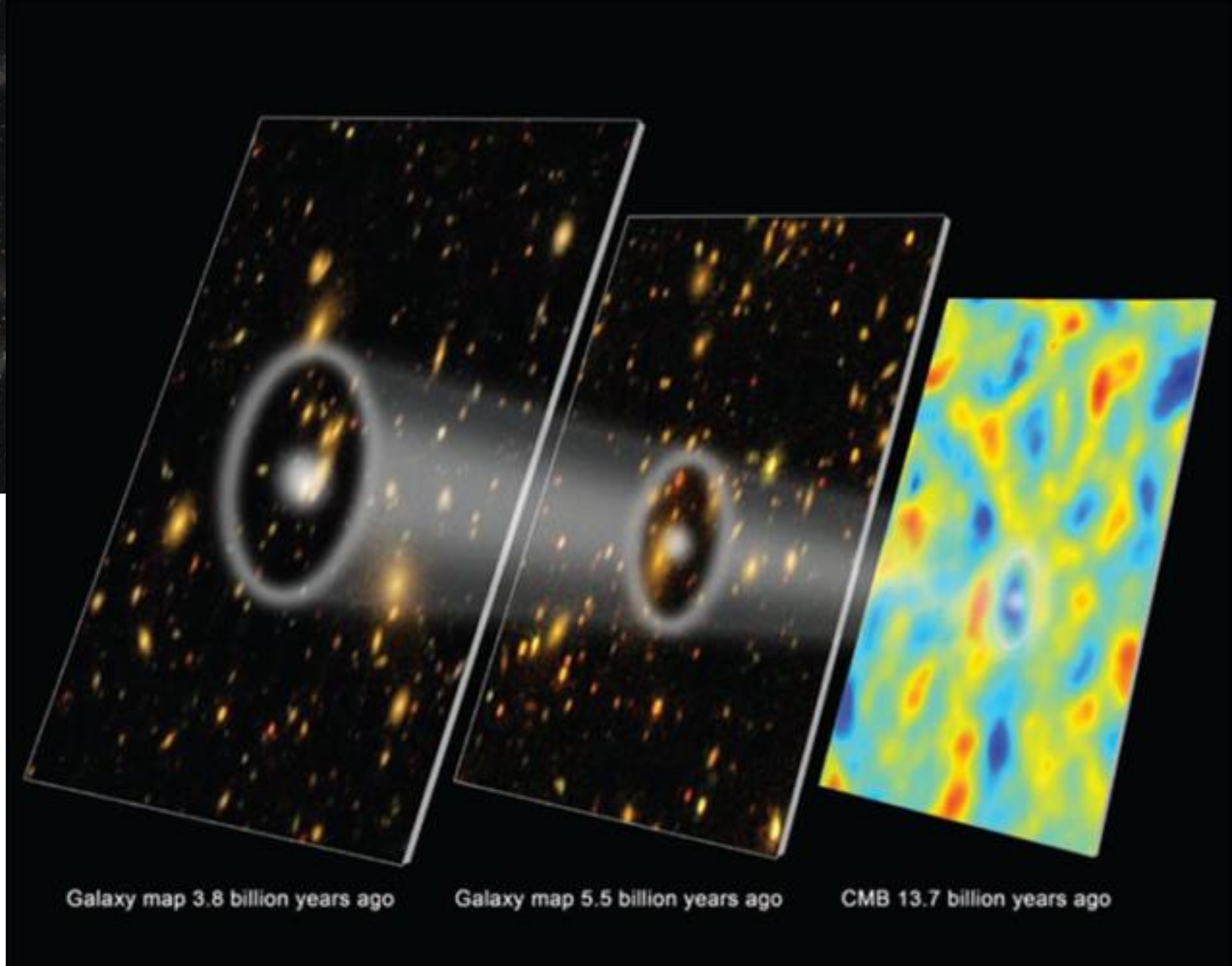
Physics data as soon as 1st module complete

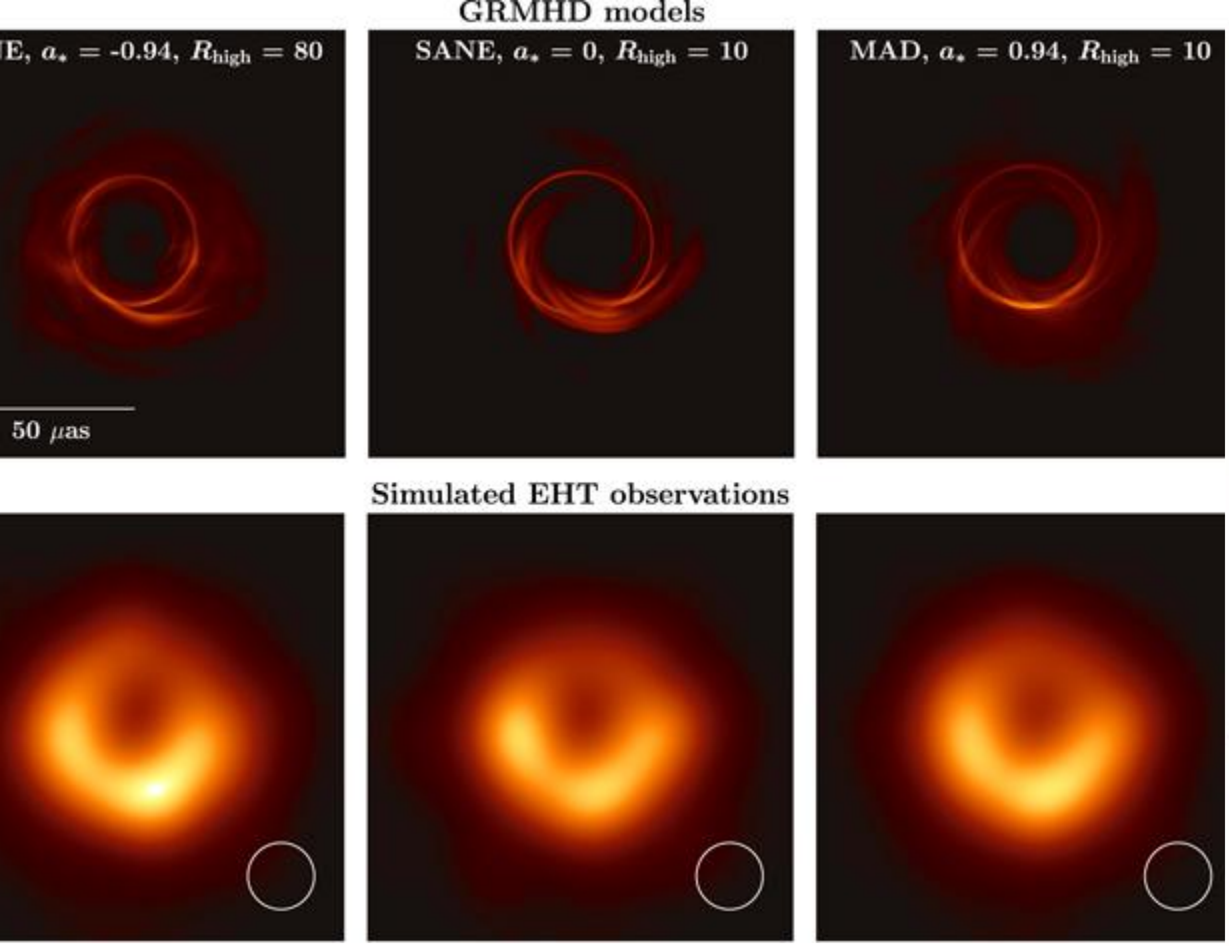
- Atmospheric νs
- SNB and solar νs
- Baryon number violation
- Detector calibration

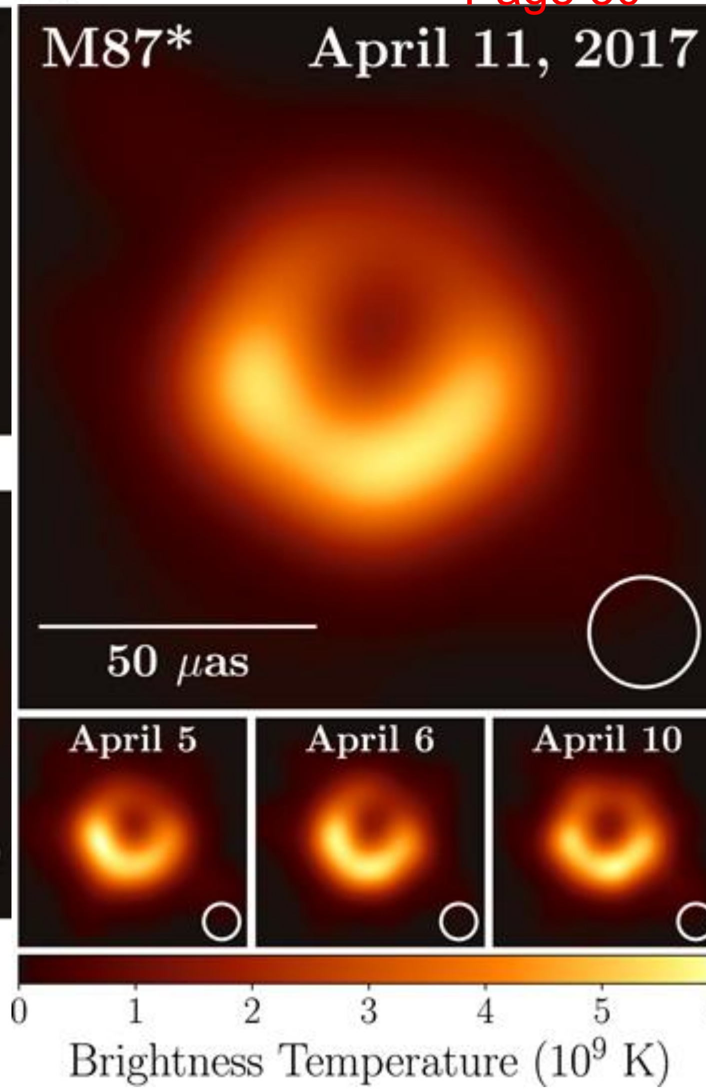


CMB




Galaxy map 3.8 billion years ago
Galaxy map 5.5 billion years ago
CMB 13.7 billion years ago

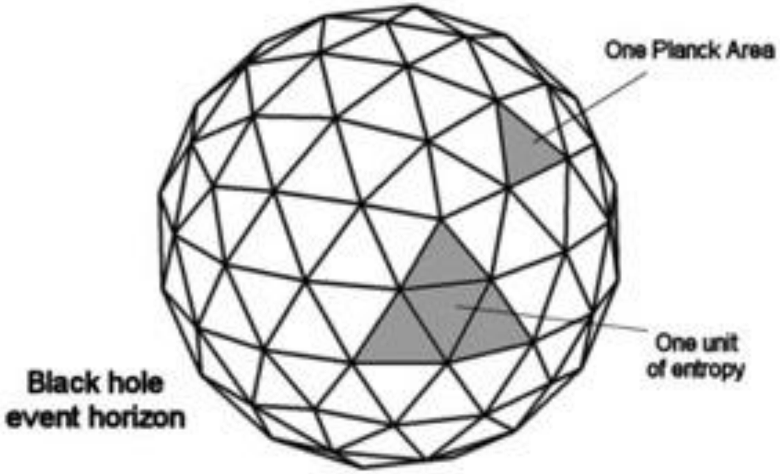




K. Akiyama et al.,
The Astrophys. J. Lett., **875**, L1 (2019)
Event Horizon Telescope Coll.

M87 Distance: 16.4 Mpc (53.5 Mly)

$$M = (6.5 \pm 0.7) \times 10^9 M_\odot$$



$$r_s = \frac{2GM}{c^2}$$

Planck Temperature = $\sqrt{\frac{\hbar c^5}{G k_B^2}}$ $= 1.42 \times 10^{32}$ K

Planck Mass = $\sqrt{\frac{\hbar c}{G}}$ $= 2.2 \times 10^{-8}$ kg

Planck Time = $\sqrt{\frac{G\hbar}{c^5}}$ $= 5.4 \times 10^{-44}$ s

Planck Length = $\sqrt{\frac{G\hbar}{c^3}}$ $= 1.6 \times 10^{-35}$ m

Planck Energy = $\sqrt{\frac{\hbar c^5}{G}}$ $= 1.22 \times 10^{19}$ GeV

Planck Density = $\frac{c^5}{G^2 \hbar}$ $= 5.16 \times 10^{93}$ g/cm^2

GZK limit ~5×10^{19} eV

3.2×10^{20} eV, D.J. Bird et al., Phys. Rev. Lett., 71, 3401 (1993)

The End