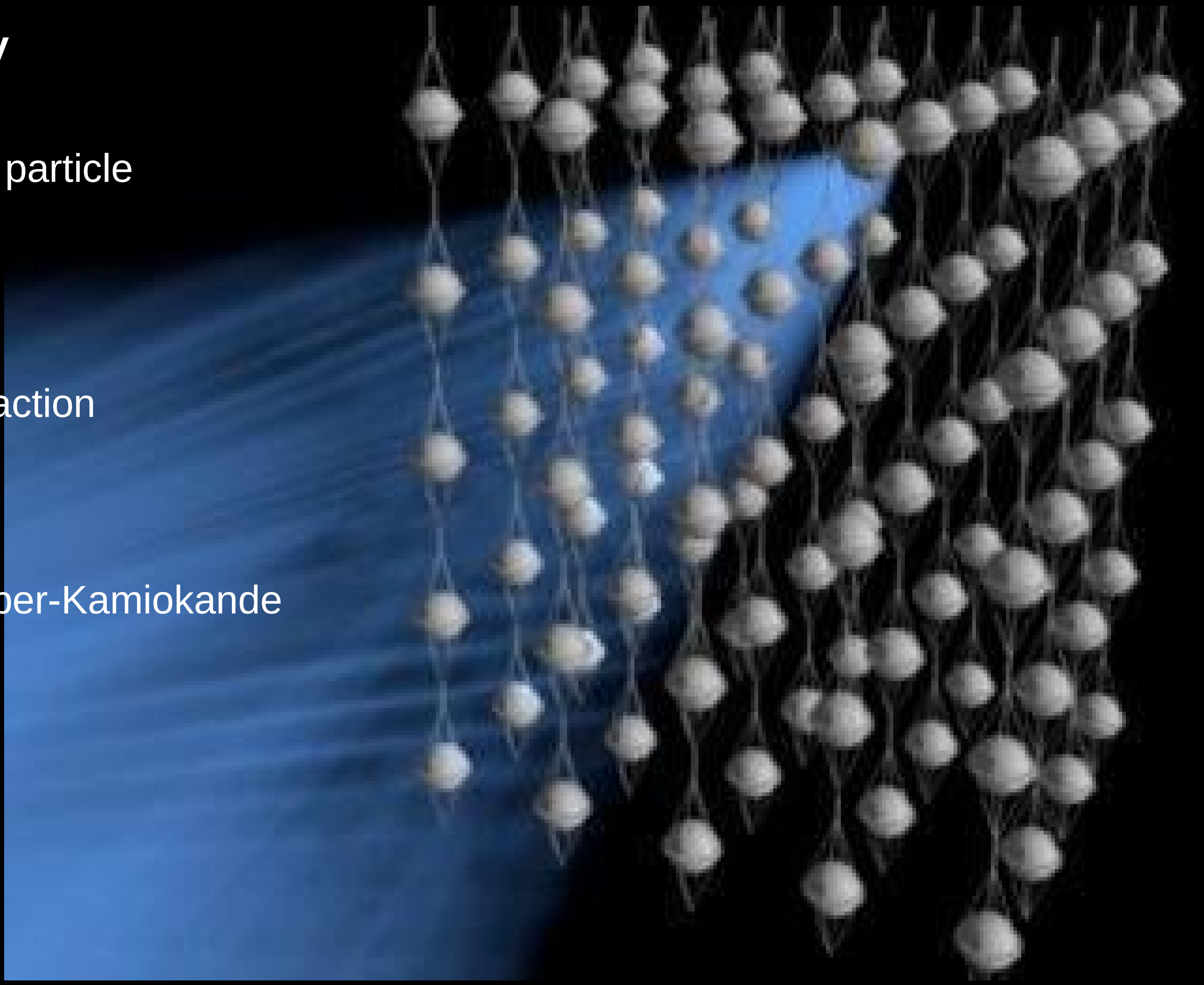
Neutrino Astronomy

1. Introduction
- neutrino elementary particle

2. Neutrino detection
- Chemistry
- Čerenkov
- Particle-matter interaction

3. Experiments
- Homestake
- KamiokaNDE → super-Kamiokande
- Antares
- IceCube

4. Conclusion
- Future
- Multi-messenger



Laurent Chevalier
CEA-Saclay Paris-Saclay University

preliminary remarks

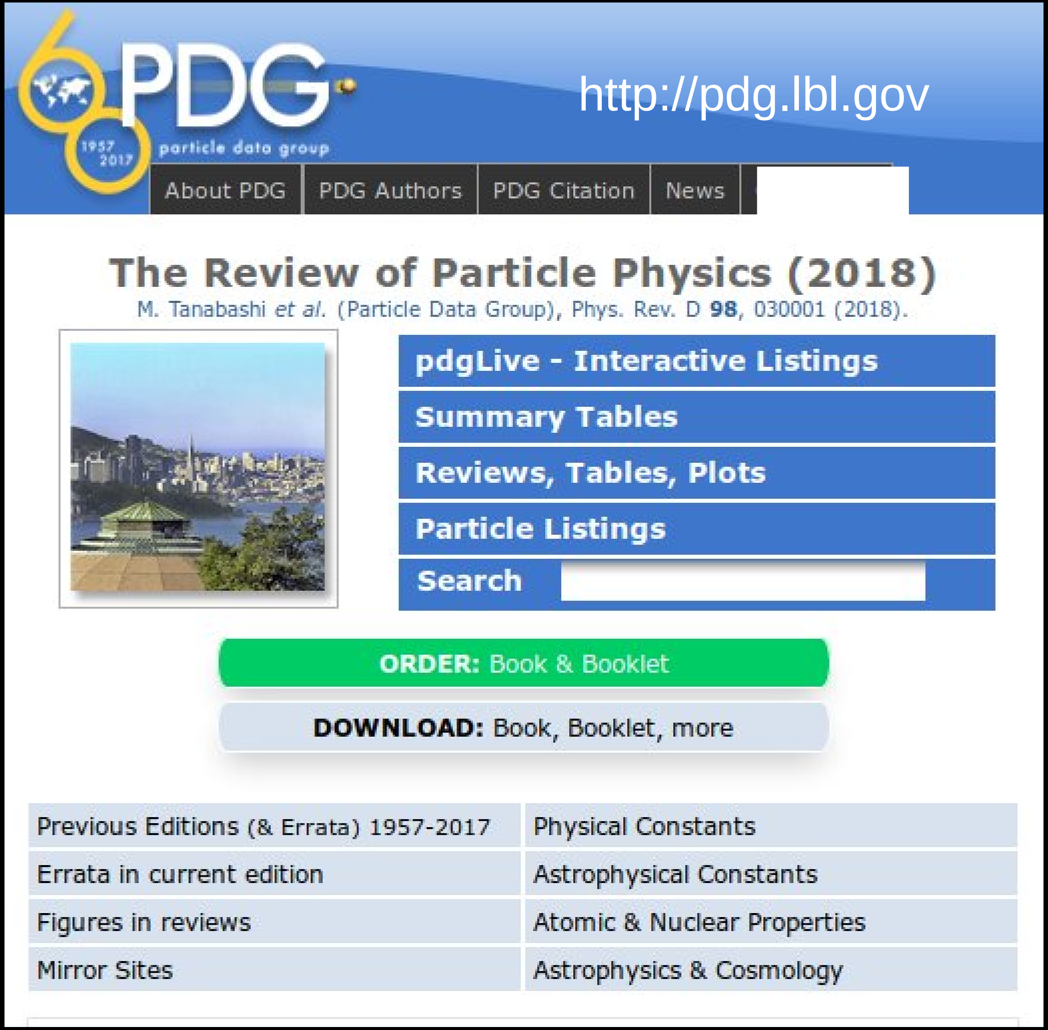
http://pdg.lbl.gov

-Antoine Kouchner APC / Antares, KM³
antoine.kouchner@u-paris.fr

- Federica Bradascio CEA / IceCube
federica.bradascio@cea.fr

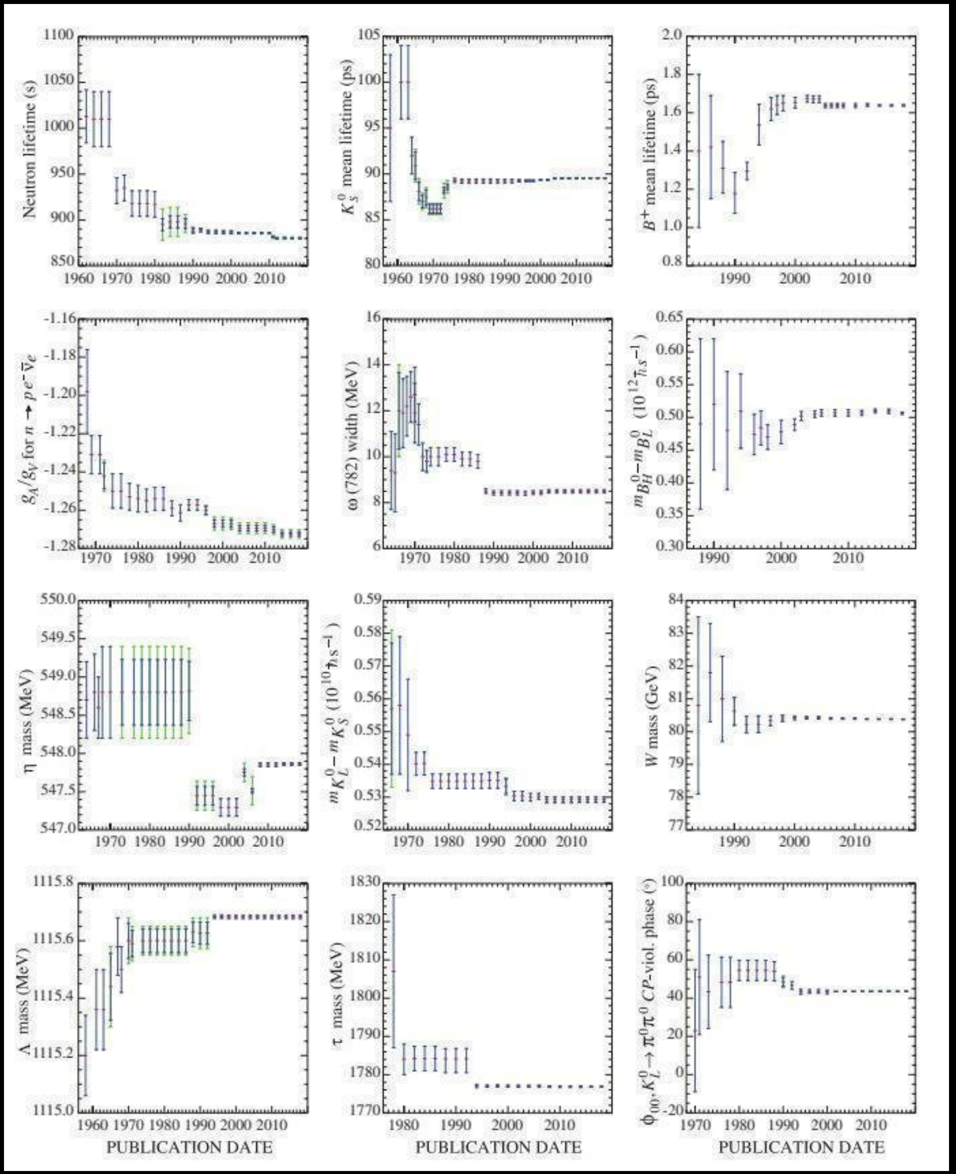
-Fabian Schüssler CEA / Multimessager
fabian.schussler@cea.fr

- Michel Spiro



preliminary remarks

- measurements
- measurement errors



Neutrino Astronomy

1. Introduction

- neutrino elementary particle

2. Neutrino detection

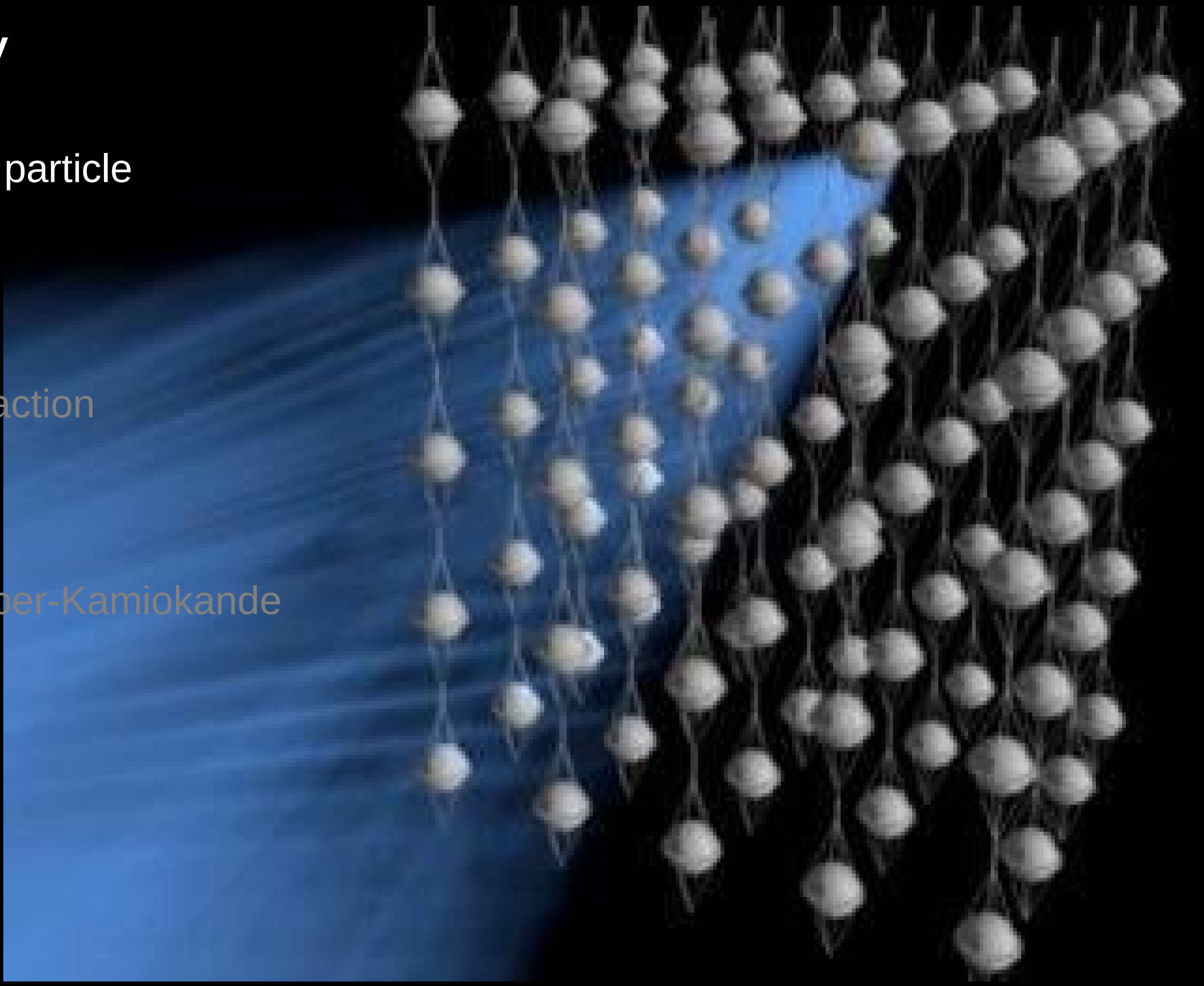
- Chemistry
- Čerenkov
- Particle-matter interaction

3. Experiments

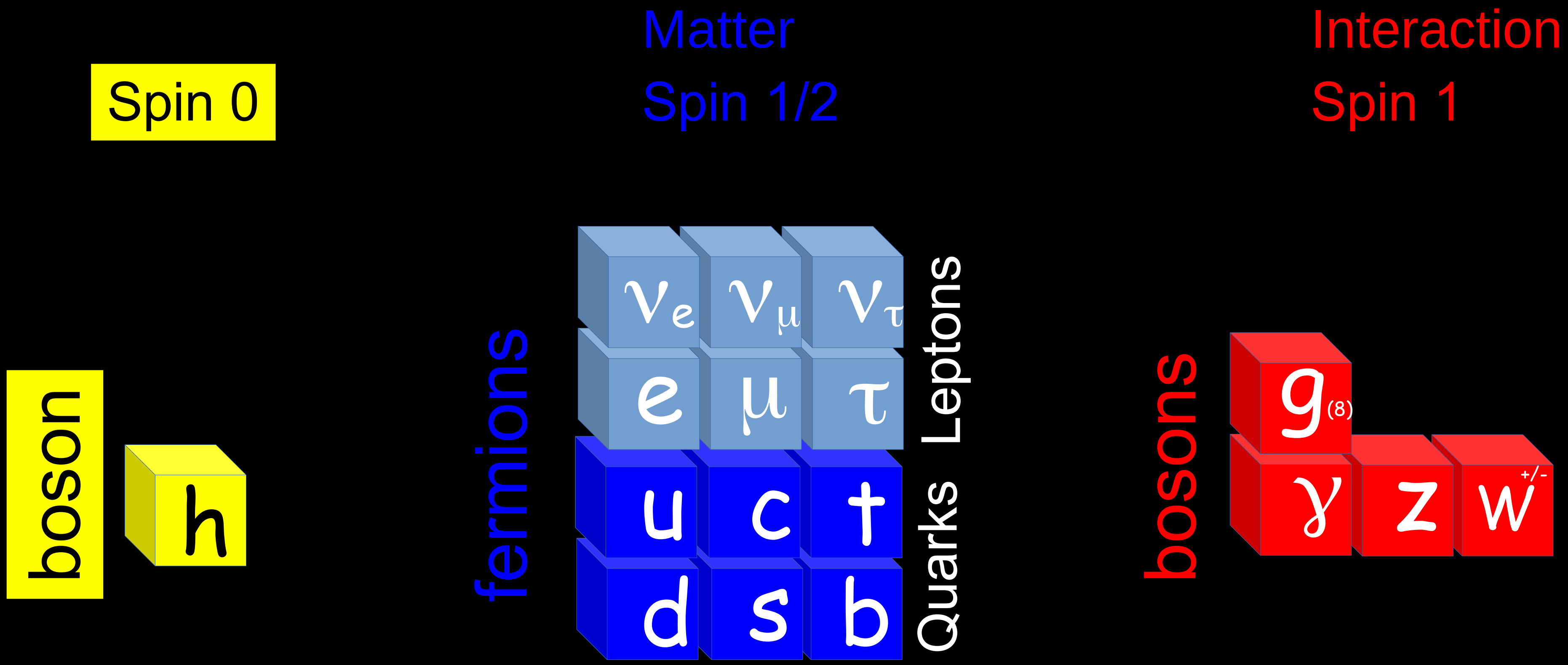
- Homestake
- KamiokaNDE → super-Kamiokande
- Antares
- IceCube

4. Conclusion

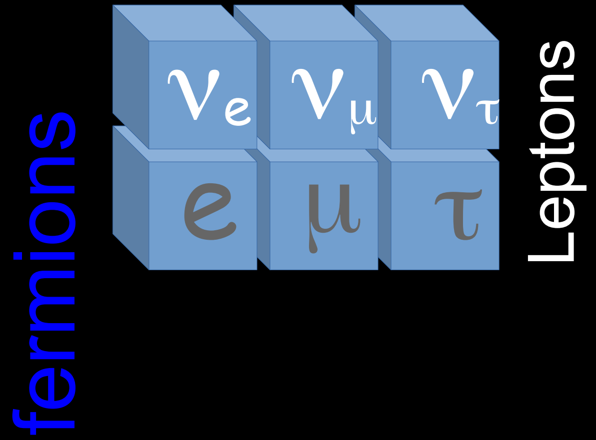
- Future
- Multi-messenger



Standard Model



Standard Model → minimal



1930 Wolfgang Pauli
$n \rightarrow p + e^- + ?$

1956 Clyde Cowan & Frederick Reines
Neutrino observation

1957 Bruno Pontecorvo
Neutrino oscillation prediction

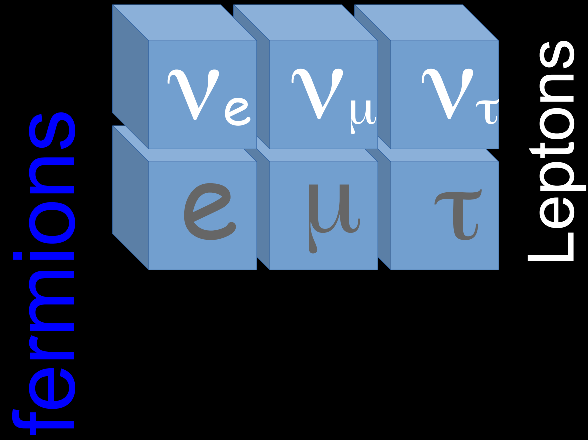
1967 Steven Weinberg, Abdus Salam & Sheldon Glashow
Neutrinos massless & Left-handed

1998 Super-Kamiokande & SNO
Neutrino oscillation observation
$\bar{\nu}_e + p \rightarrow n + e^+$

Neutrinos have mass

1. Introduction Remarks

Standard Model → 3 flavors



1962 ν_μ Leon Lederman, Melvin Schwartz & Jack Steinberger

1977 ν_τ Martin Perl

Neutrino oscillation → neutrino have mass →

eigenstates of the weak interaction
≠
eigenstates of mass

Mixing matrix for
- neutrinos: PMNS
- quarks: CKM

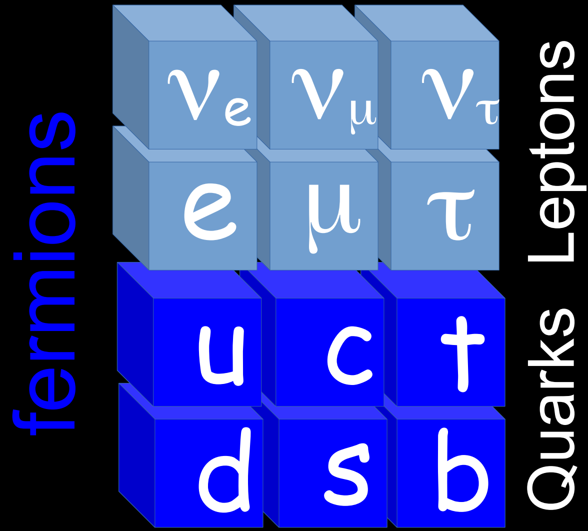
Standard Model → 26 free parameters

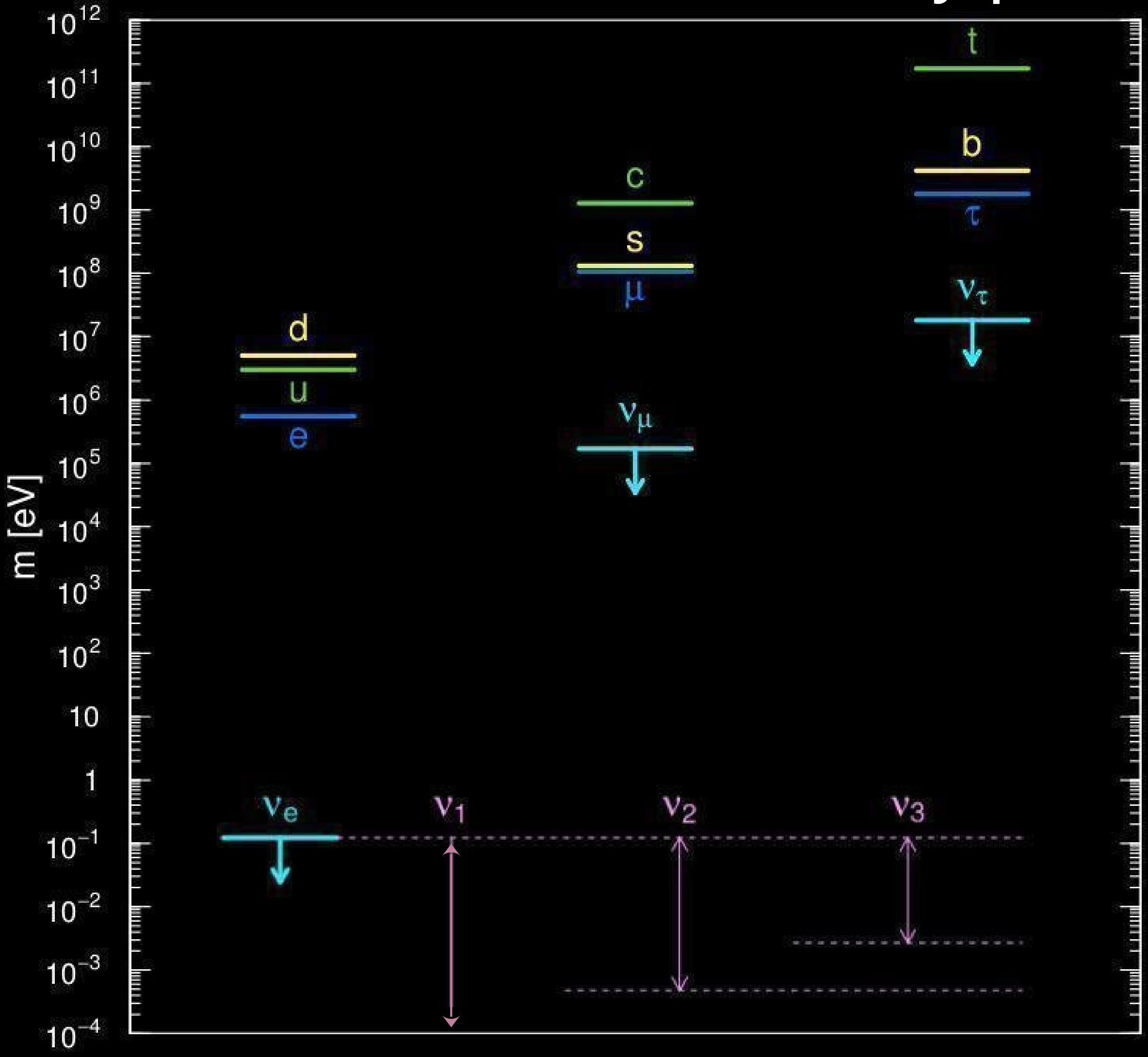
- 3 cts de Couplage — g_1, g_2, g_3 (α, α_s, α_W)
- 12 couplage de Yukawa ätt — masses 6 quarks, 6 leptons
- 1+3 phase + angles de Mélange — Matrice CKM (états propres de masse ≠ états propres de I. faible)
- 1+3 " " — Matrice PMNS (neutrinos)
- 2 cste pour le potentiel de Higgs — ou Masse W ou Z et masse de Higgs
- 1 angle θ — Violation CP fort (?)

↳ 26 paramètres libres

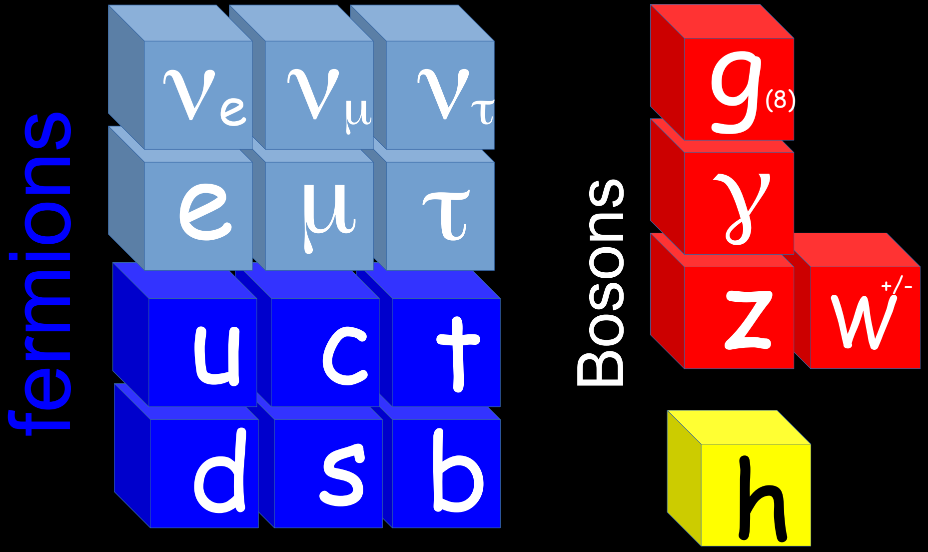
elementary particles

Standard Model





Standard Model



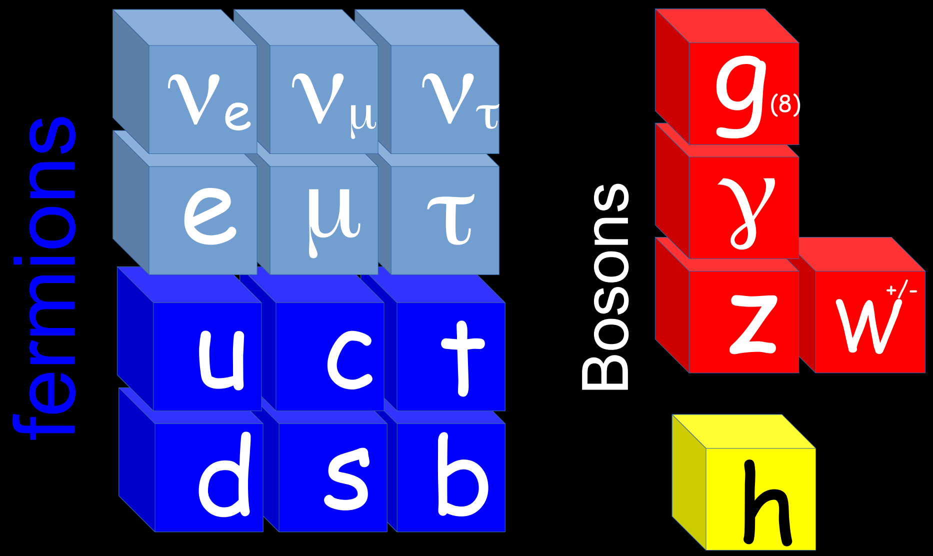
Quantum Field Theory

Gauge theory, Lorentz invariant

$SU(3)_C \times SU(2)_L \times U(1)_Y$

BSS
Higgs mechanism
$U(1)_Q$

Standard Model



Symmetries

- CPT conservation

  theorem in Minkowski space

- CP-violation for Weak Interaction

  Parity maximal violation & C idem

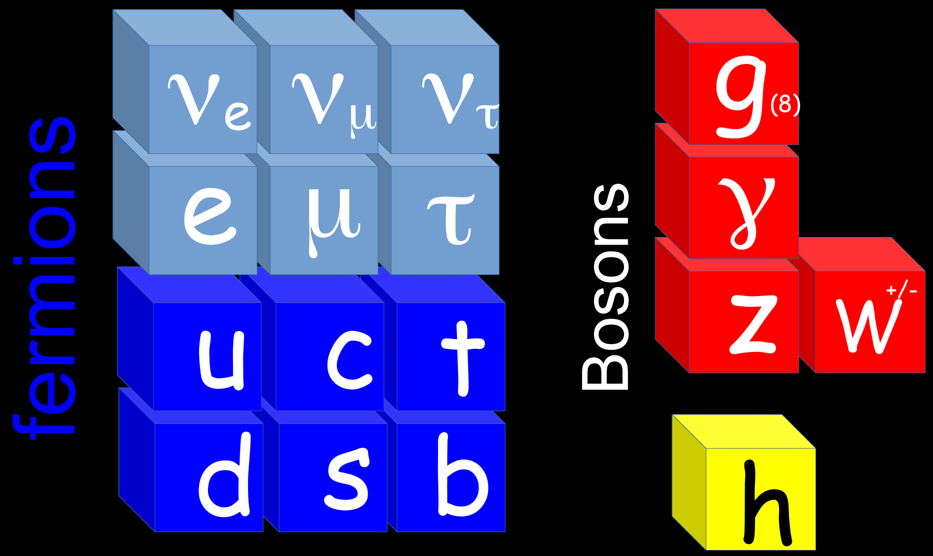
  particle = left-handed + right-handed

→ right-handed neutrino ???

1. Introduction

Remarks

Standard Model



⇒ Lagrangian contains only Dirac terms {Quarks, leptons | neut…}

Higgs mechanism ⇒ Yukawa coupling to all fermions

Right neutrino doesn't have known coupling to anything!

But should be added to the Lagrangian because its mass!

⇒ neutrino mass ? Beyond the standard Model!

1. Introduction

Neutrino Astronomy: a prob → why

→ travel long distances w.o be affected

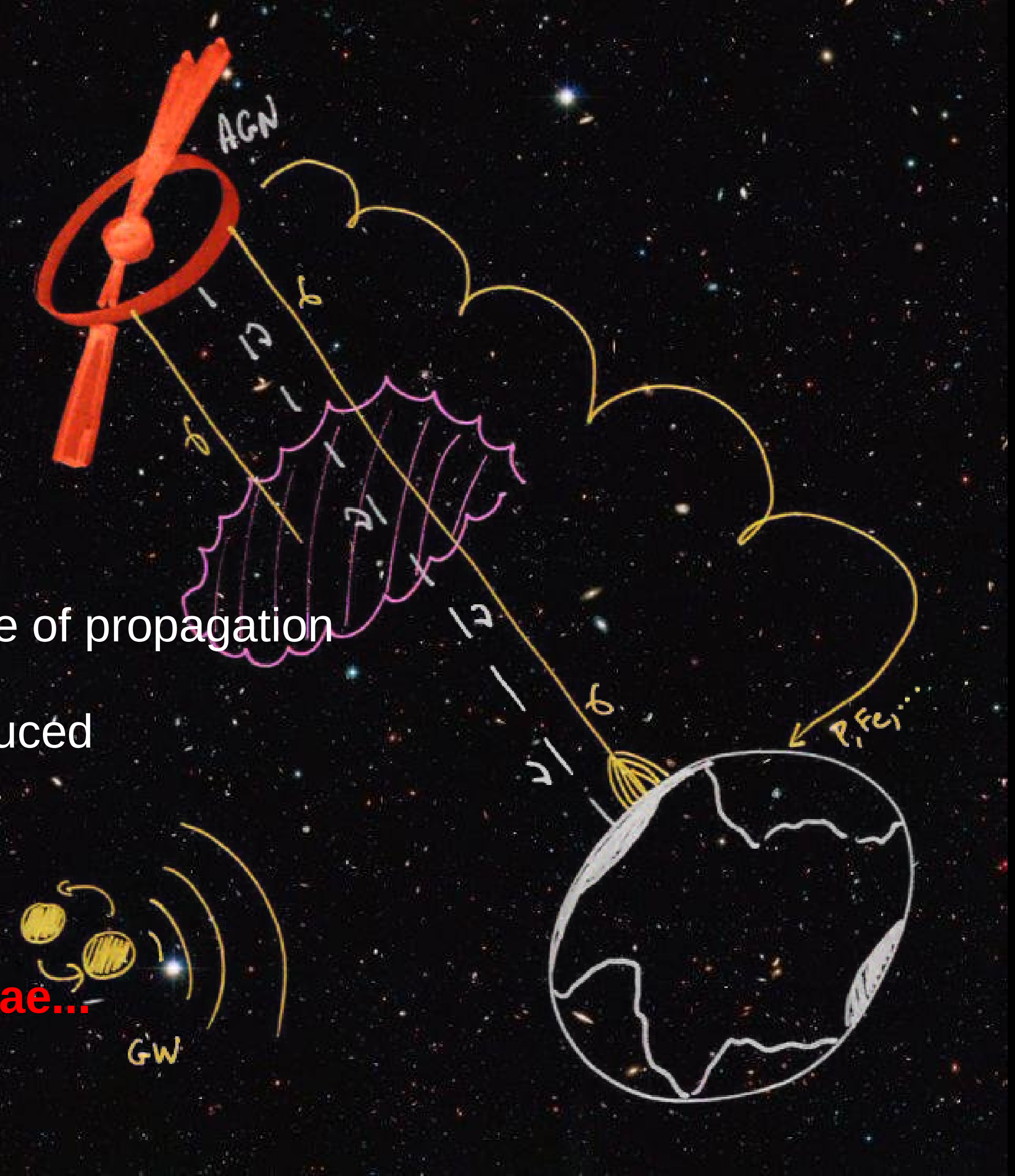
- neutrino interact very weakly with matter
  Solar neutrino ~10^{11} cm^{-2} .s^{-1}

- neutrino is neutral
  insensitive to the magnetic field along its line of propagation

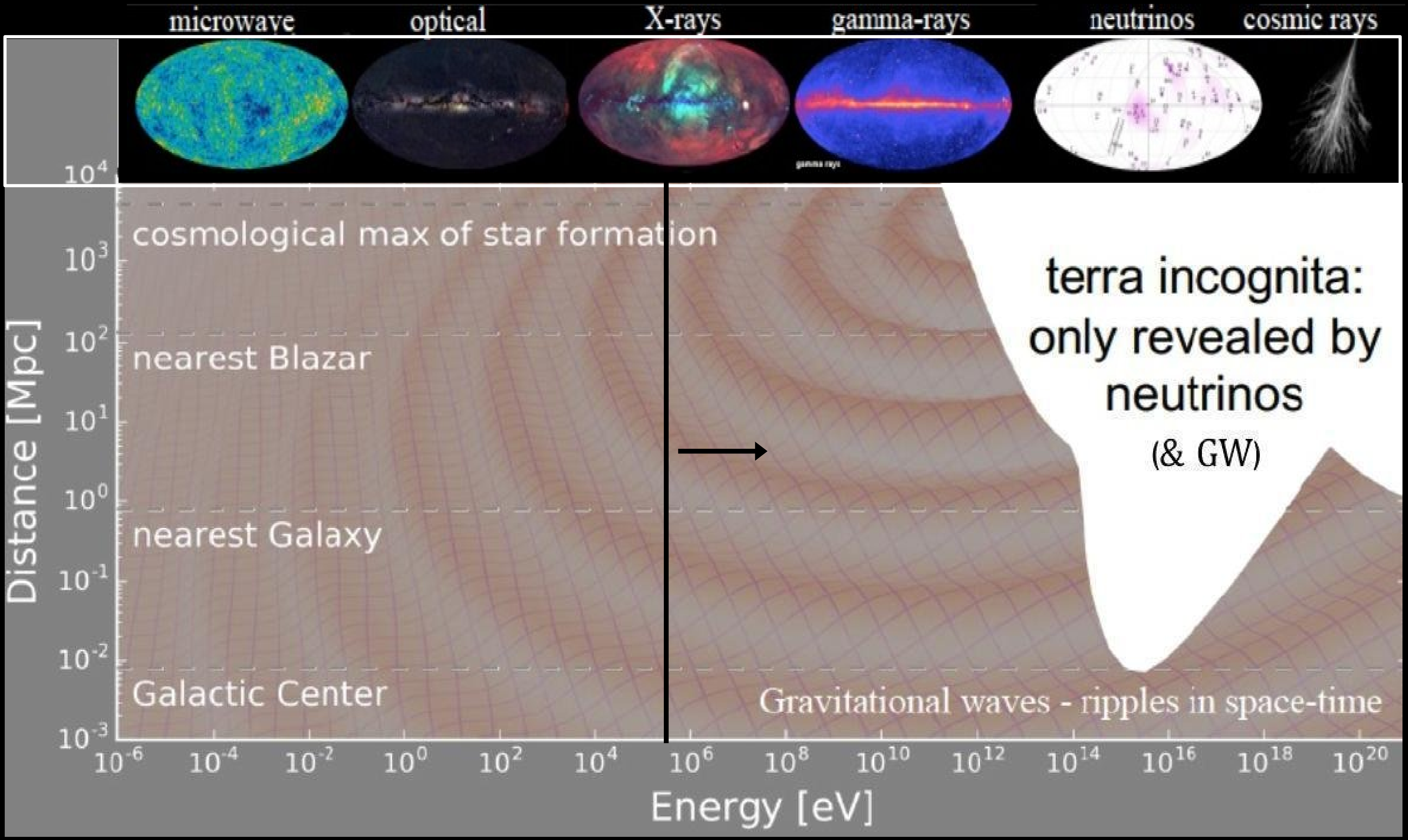
- neutrino is light (Σm_ν < 0.1 eV?) easily produced

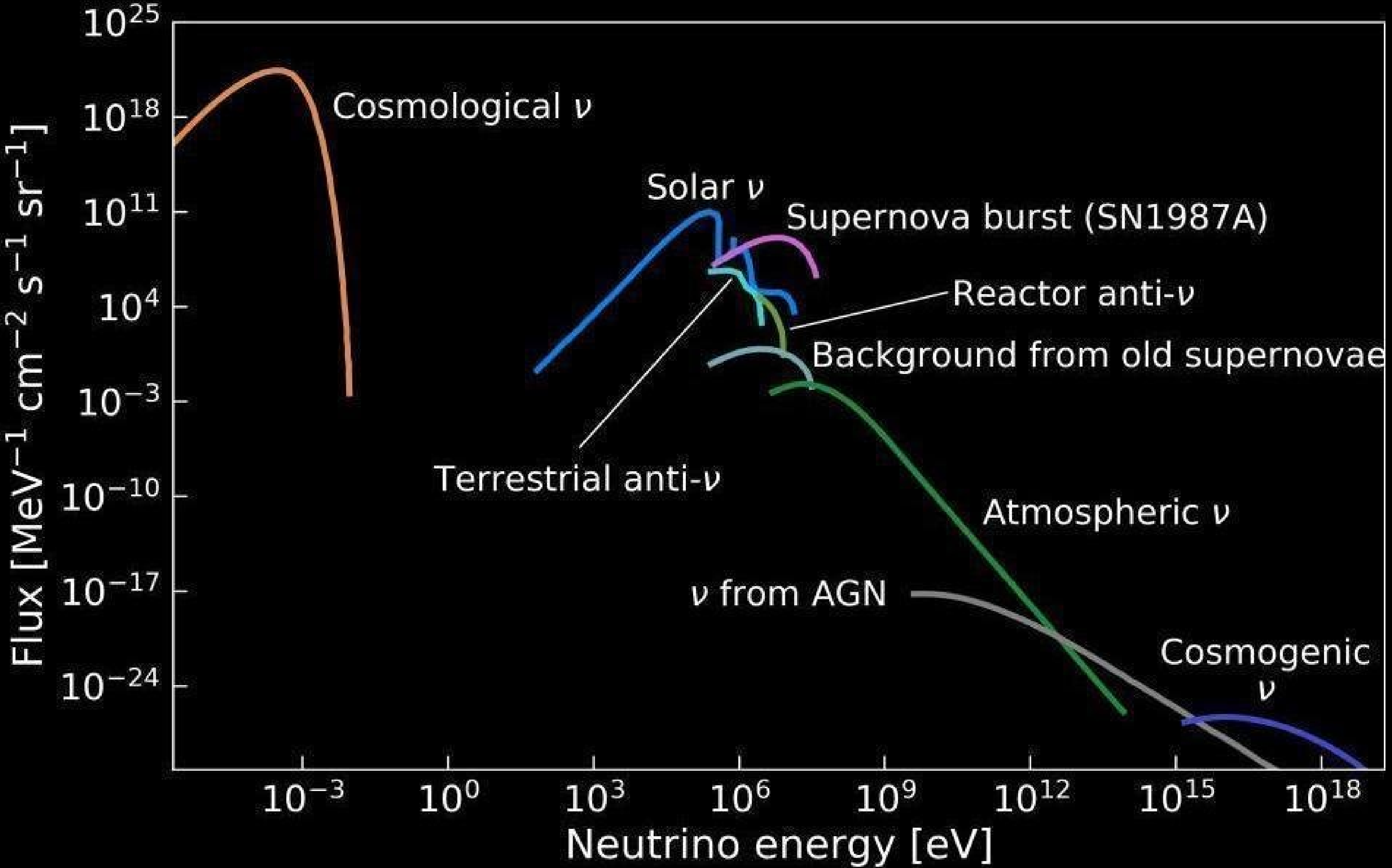
- neutrino with high energy can be produced
  in cosmic accelerators:

→ **Tool to understand AGN, GRBs, supernovae...**

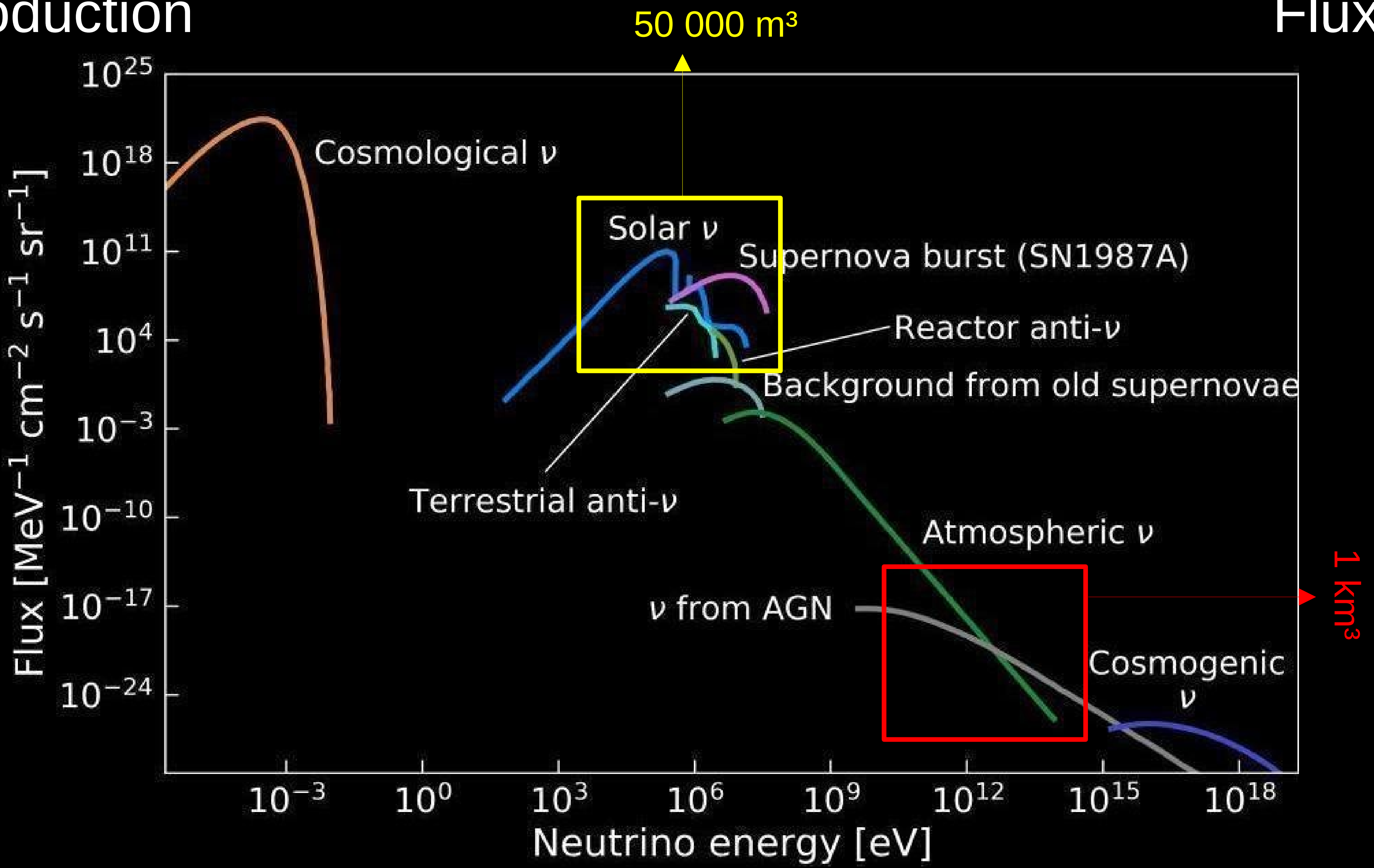


Remarks

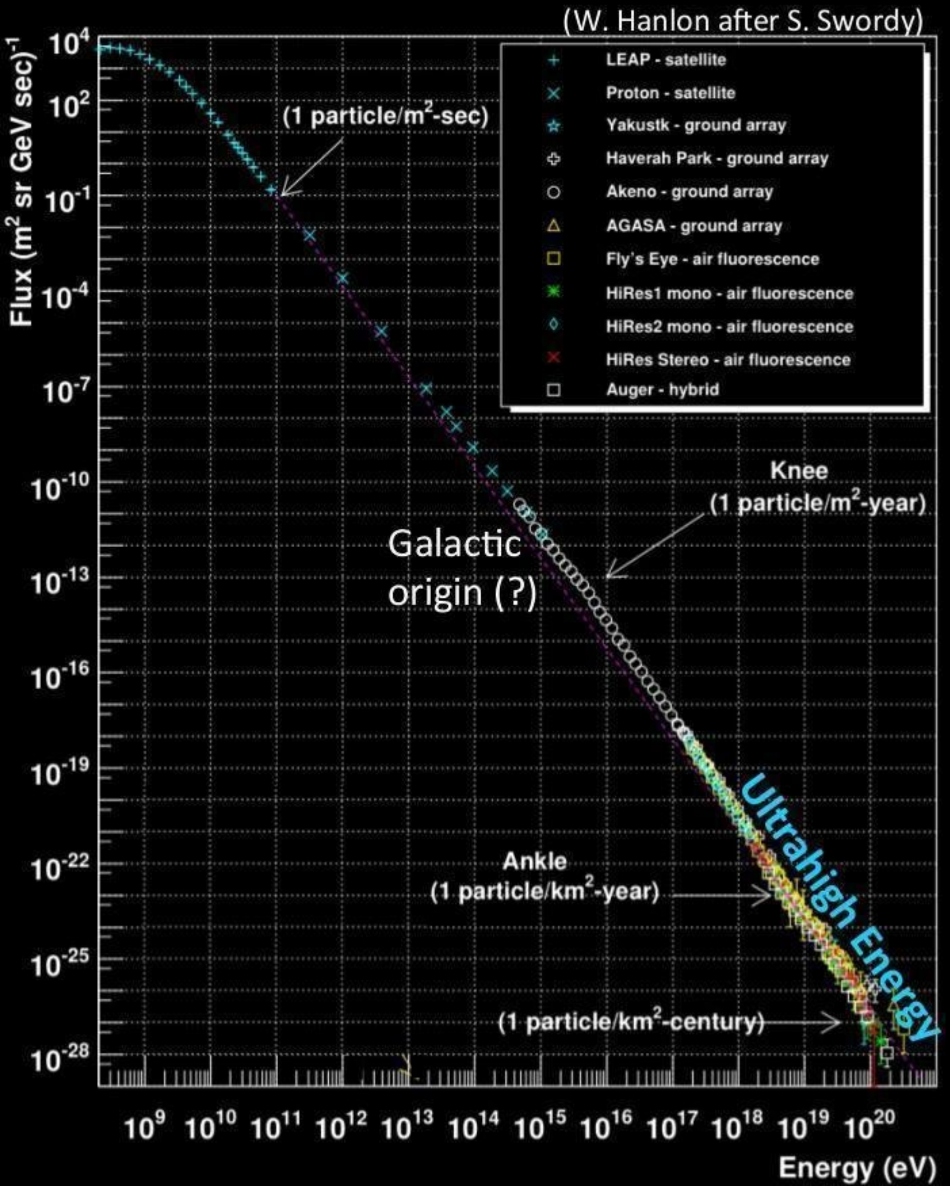

microwave
optical
X-rays
gamma-rays
neutrinos
cosmic rays
cosmological max of star formation
nearest Blazar
nearest Galaxy
Galactic Center
terra incognita:
only revealed by
neutrinos
(& GW)
Gravitational waves - ripples in space-time
Distance [Mpc]
Energy [eV]
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8} 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20}


Cosmological ν
Solar ν
Supernova burst (SN1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
Flux [MeV⁻¹ cm⁻² s⁻¹ sr⁻¹]
Neutrino energy [eV]
10^25
10^18
10^11
10^4
10^-3
10^-10
10^-17
10^-24
10^-3
10^0
10^3
10^6
10^9
10^12
10^15
10^18

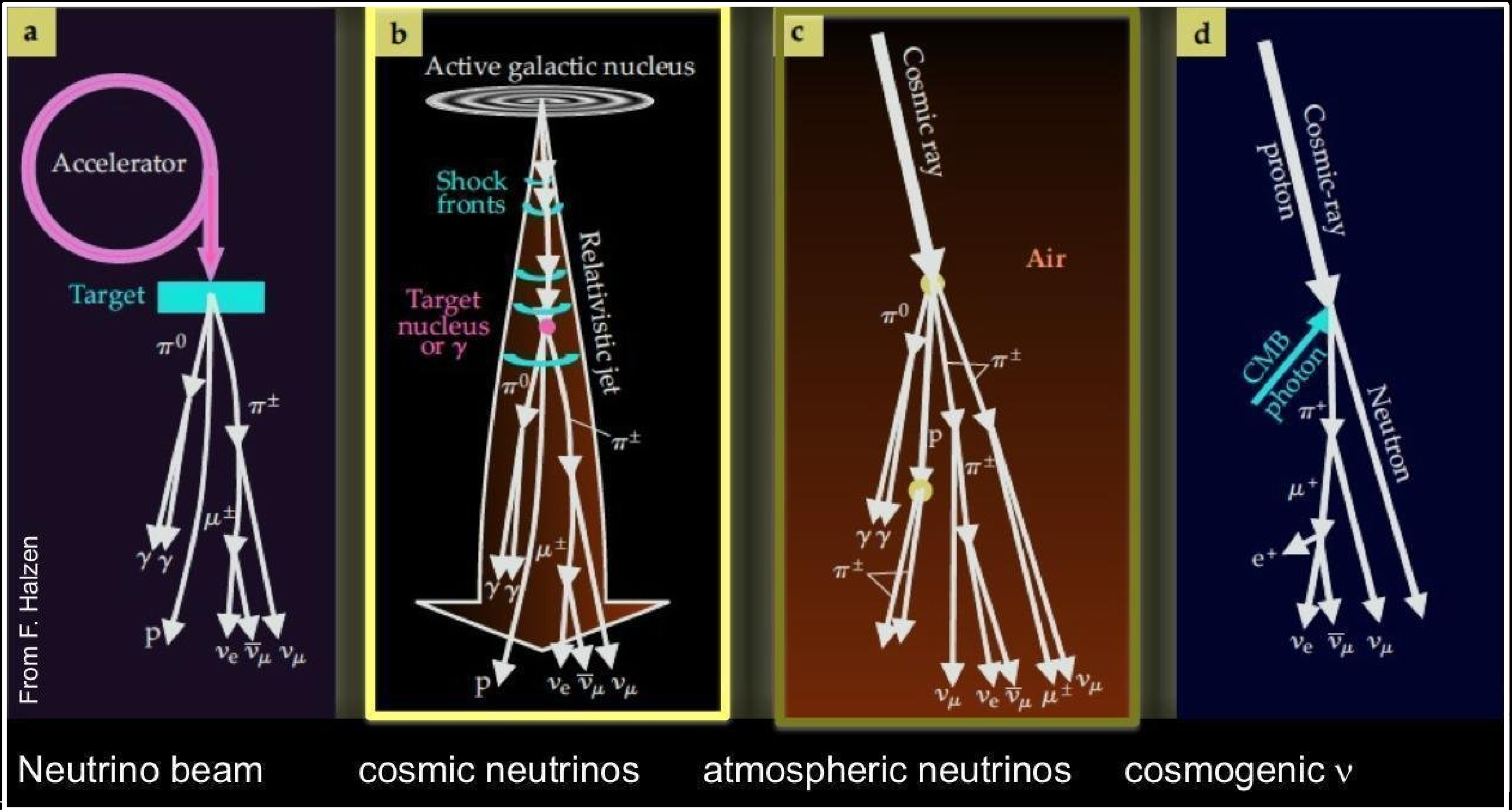
Flux


50 000 m³
Flux [MeV⁻¹ cm⁻² s⁻¹ sr⁻¹]
Cosmological ν
Solar ν
Supernova burst (SN1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
1 km³
Neutrino energy [eV]

1. Introduction

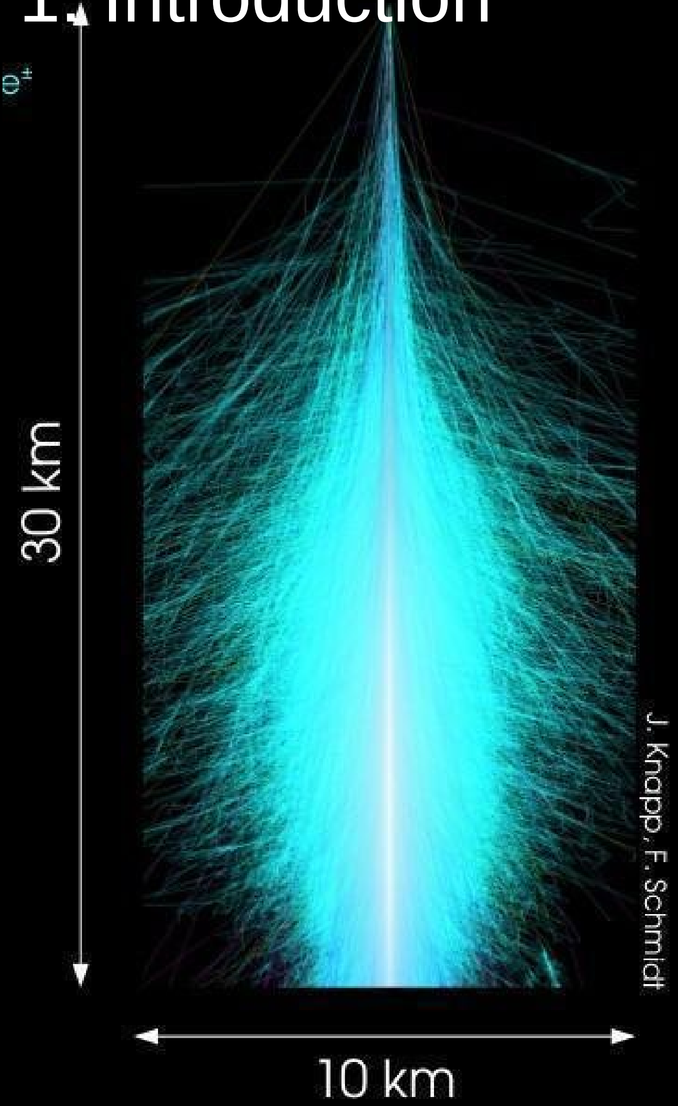


1. Introduction production

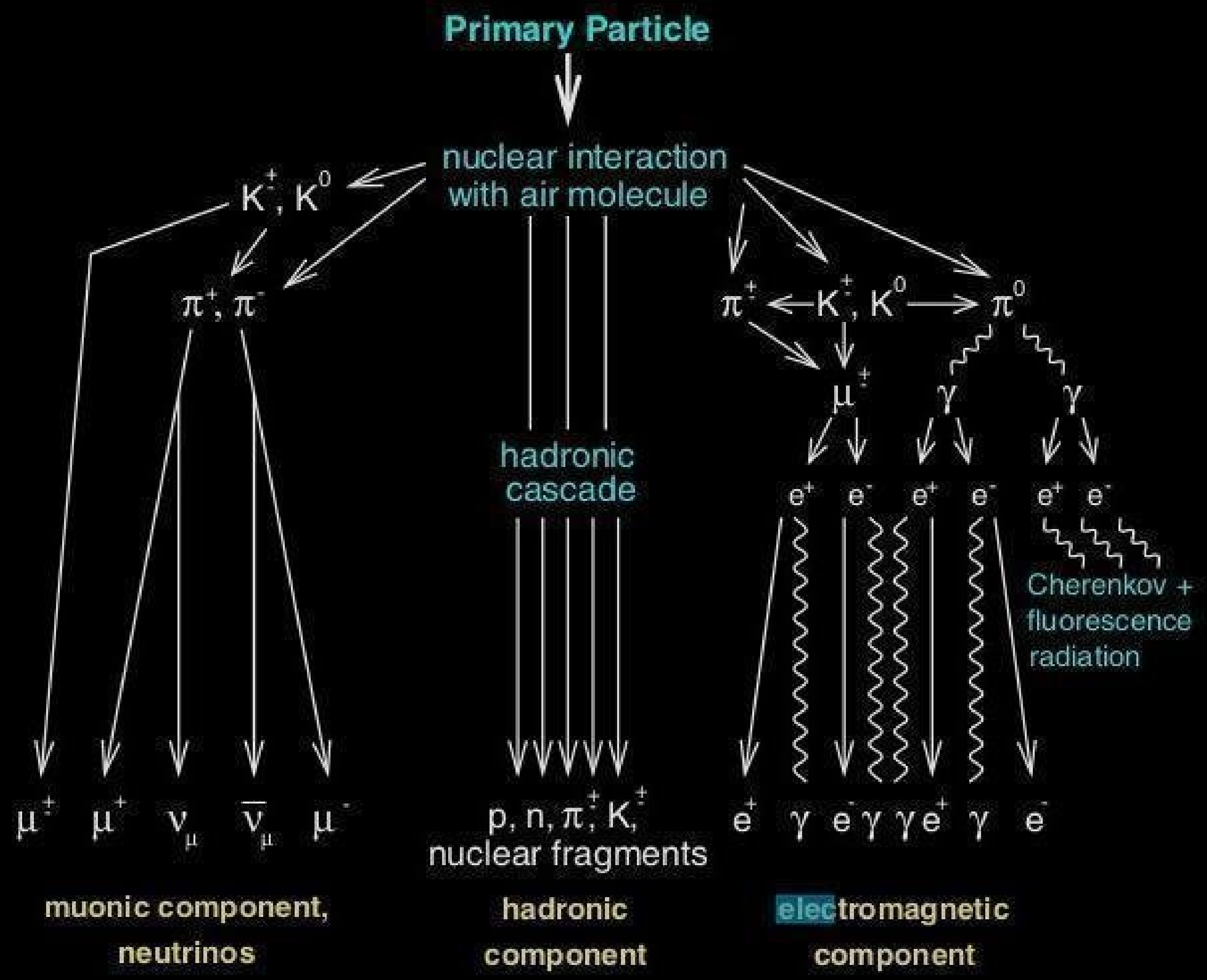


1. Introduction

Main bkg



At sea level muons
80% of the cosmic ray flux



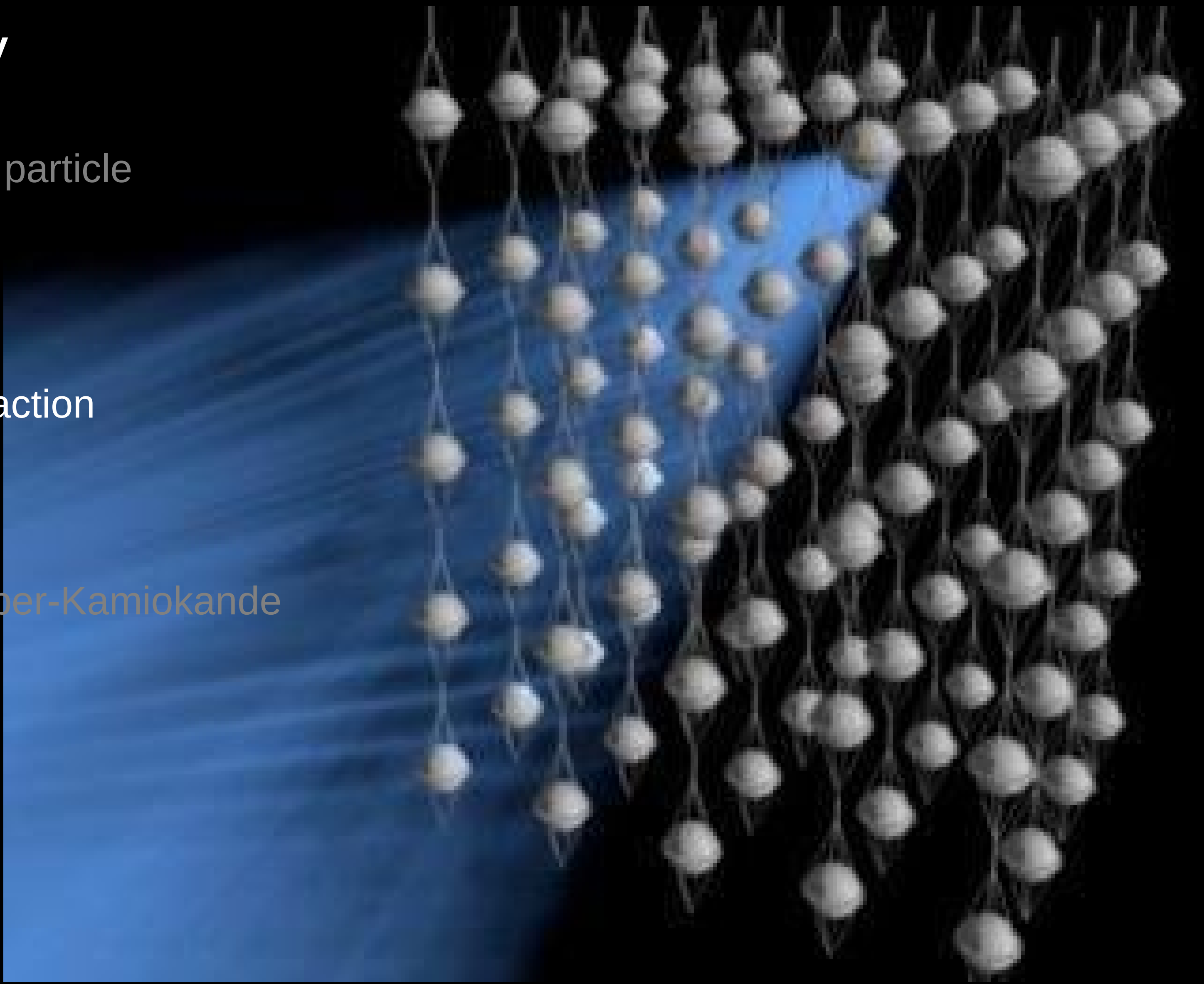
Neutrino Astronomy

1. Introduction
   - neutrino elementary particle

2. Neutrino detection
   - Chemistry
   - Čerenkov
   - Particle-matter interaction

3. Experiments
   - Homestake
   - KamiokaNDE → super-Kamiokande
   - Antares
   - IceCube

4. Conclusion
   - Future
   - Multi-messenger



radiochemical neutrino detection

neutrino capture

ν_e + (A,Z) → (A,Z+1)*+ e-

(* means $T_{1/2}$)

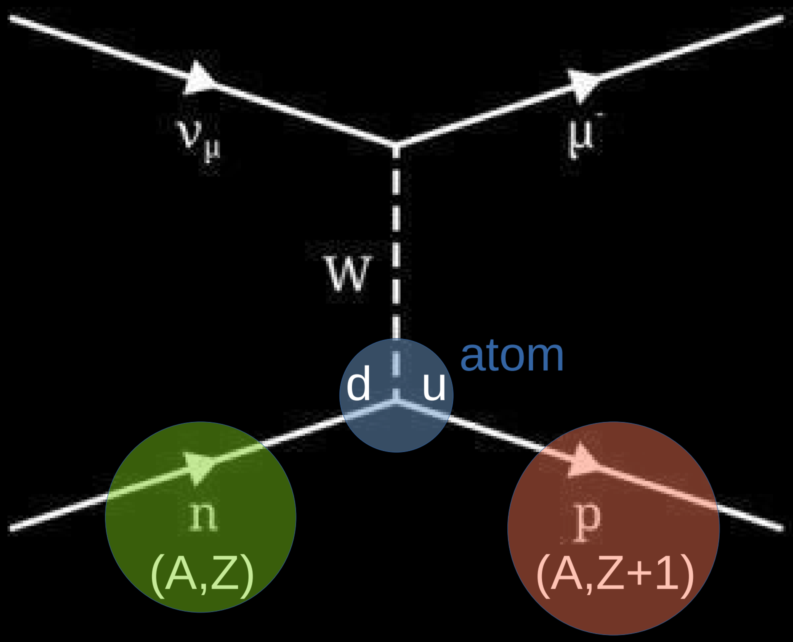
successful examples

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar^{+} + e^-$

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

efficiency

about 1 neutrino capture per sec per 10^{36} target atoms



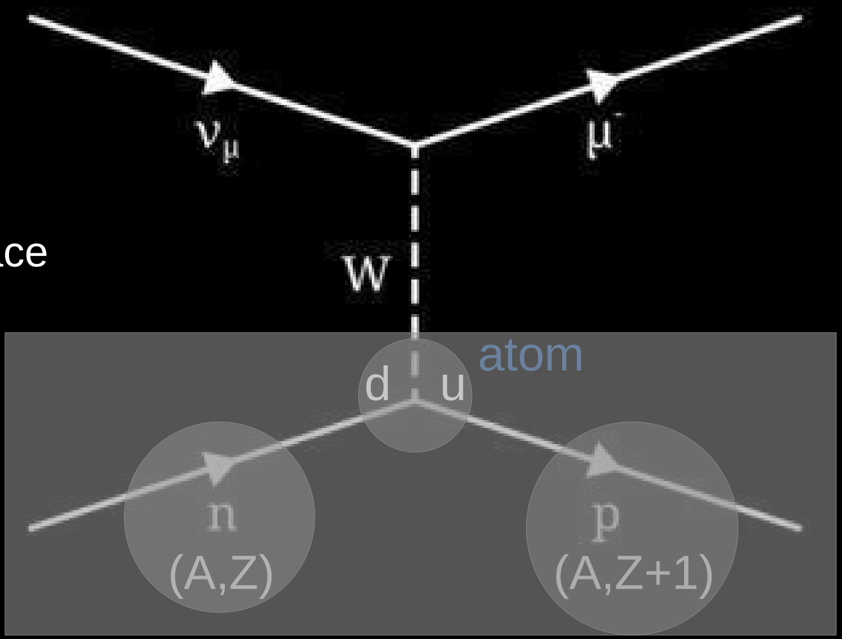
Čerenkov radiation, real time detection

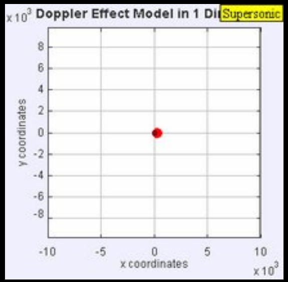
Relativistic* charged particles through a medium
refractive index $n > 1 / \beta$

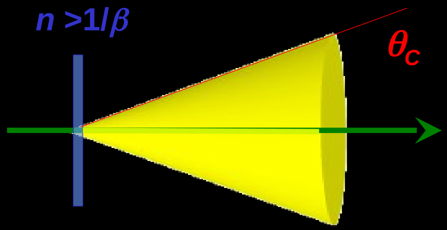
Čerenkov radiation is tangent to a cone θ_C around the trace
$\cos(\theta_C) = 1 / n\beta$

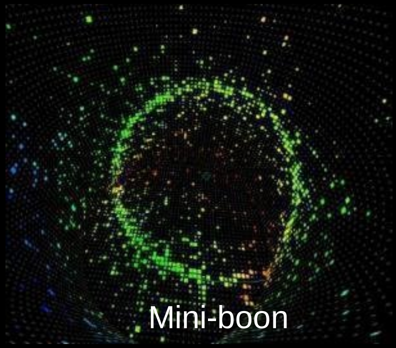
Radiation is due to the polarization of the medium and a dynamic variation of the dipole moment of the molecules of the medium (I.e water)

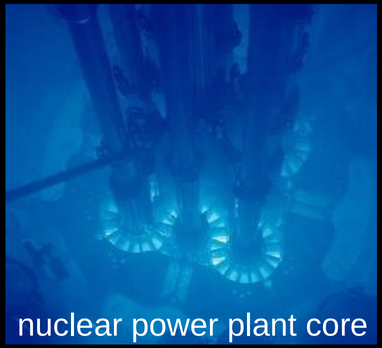
Number of photons is proportional to $Z^2 \sin^2(\theta_C)$







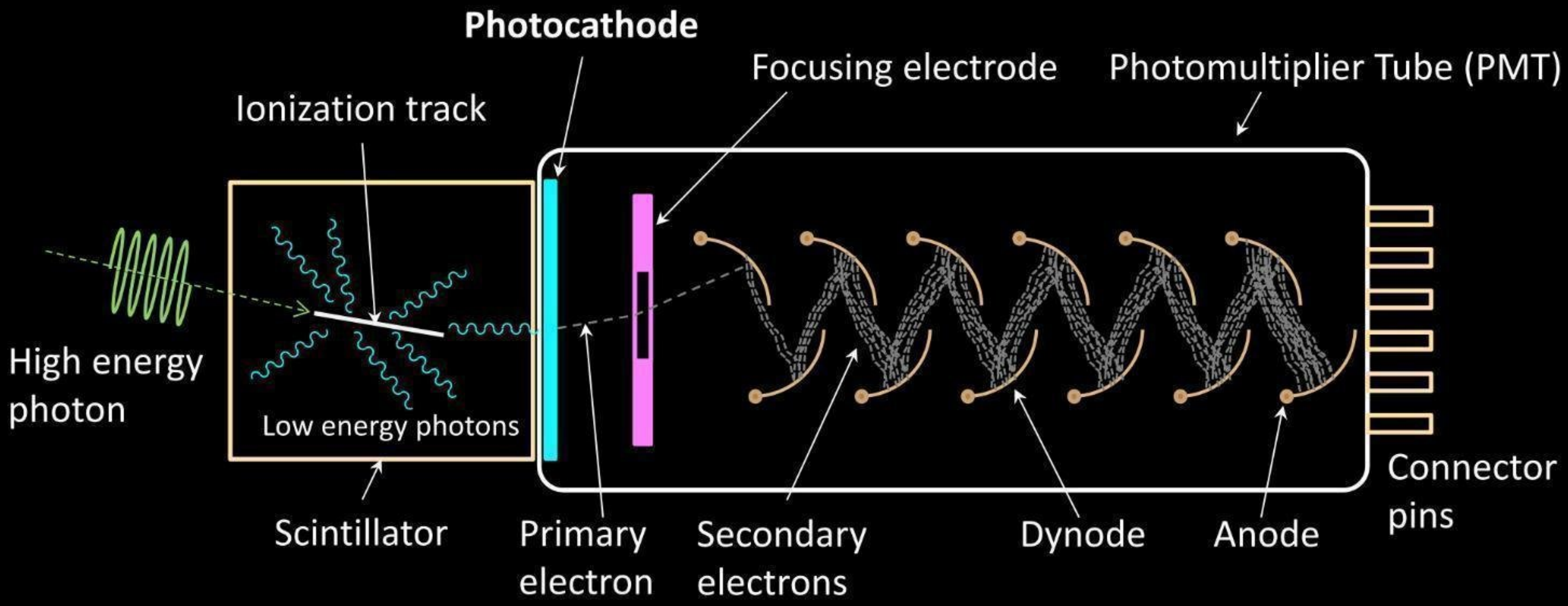




* Relativistic means that the particle moves faster than the light in the medium

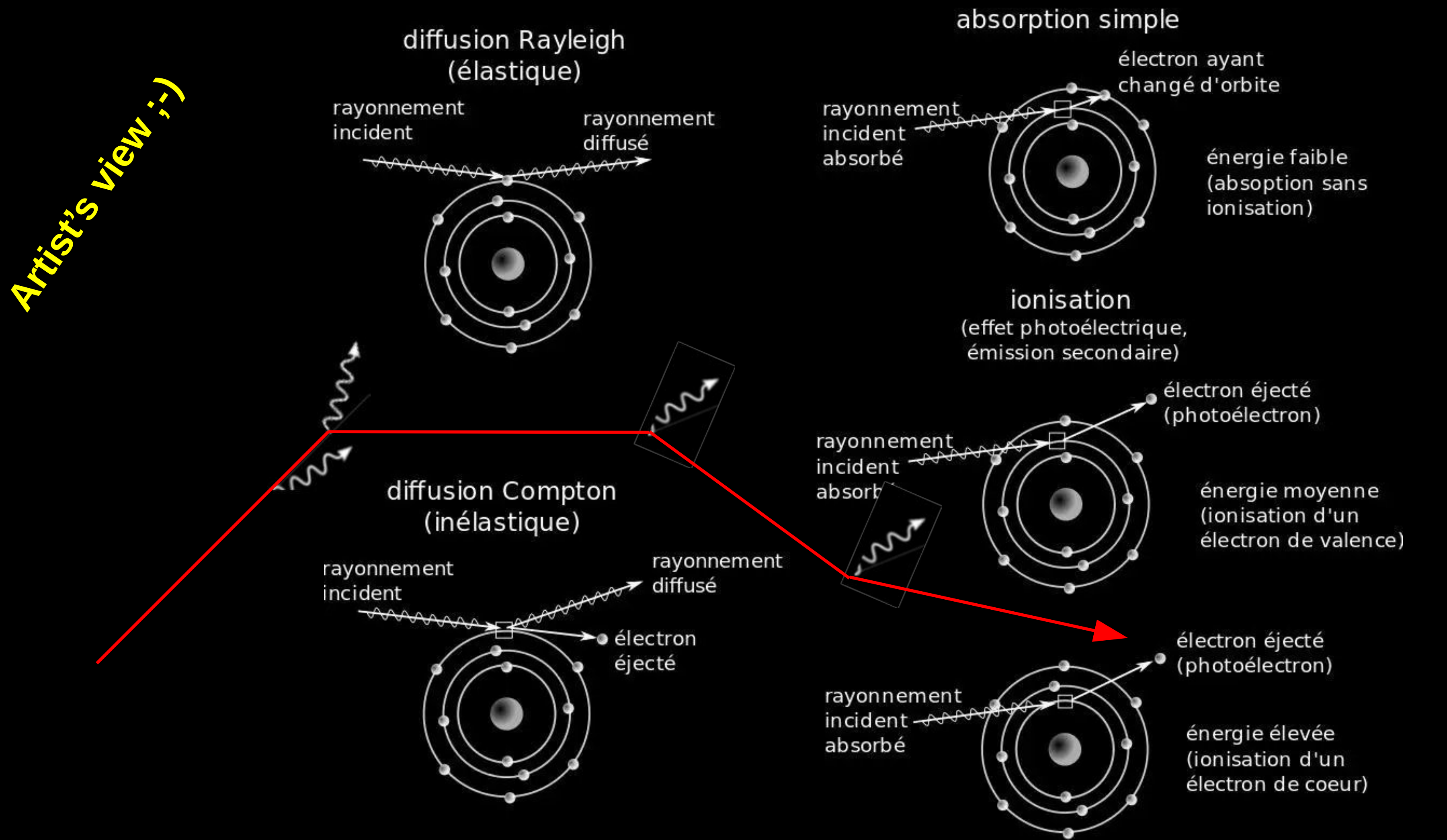
Photomultiplier ← photoelectric effect ← Albert Einstein 1905

ɣ → e- + amplification (1ɣ ~pC → gain 10^7)

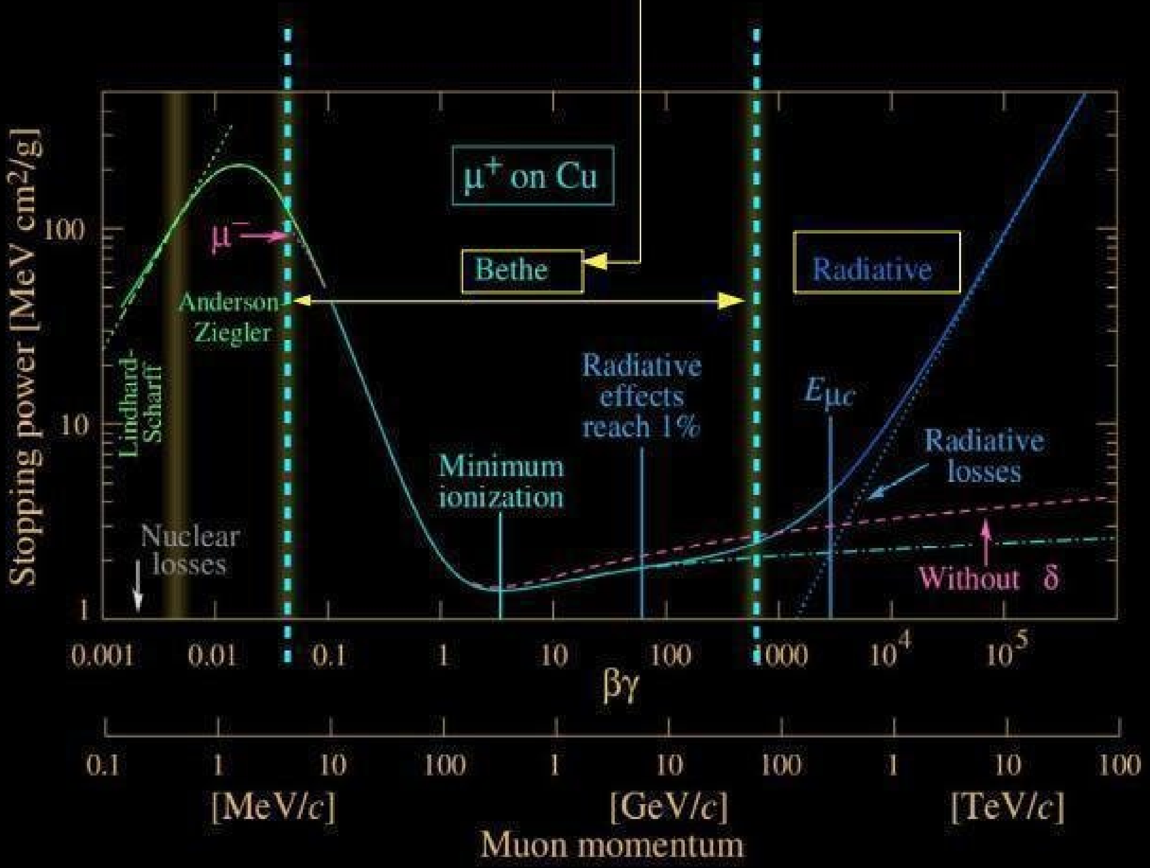


2. Neutrino detection

particle-matter interaction



$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



2. Neutrino detection — particle-matter interaction

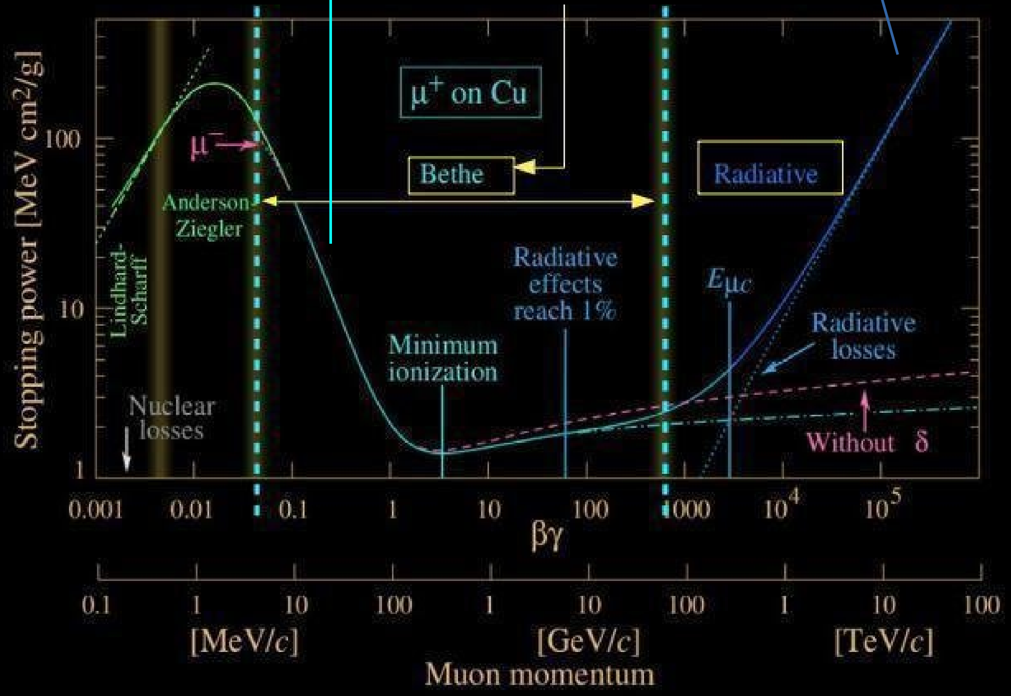
$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2}\left[\frac{1}{2}\ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Remarks:

$$\frac{dE}{dx} \; \alpha \; \frac{1}{\beta^2} \ln(\beta^2\gamma^2)$$

$$\beta\gamma = \frac{P}{m}$$

$$\frac{dE}{dx} \# \begin{cases} Z \ln(P/m) \rightarrow E > 300 \text{ GeV} \\ Z \ln(P/m) \rightarrow E < 300 \text{ GeV} \end{cases}$$

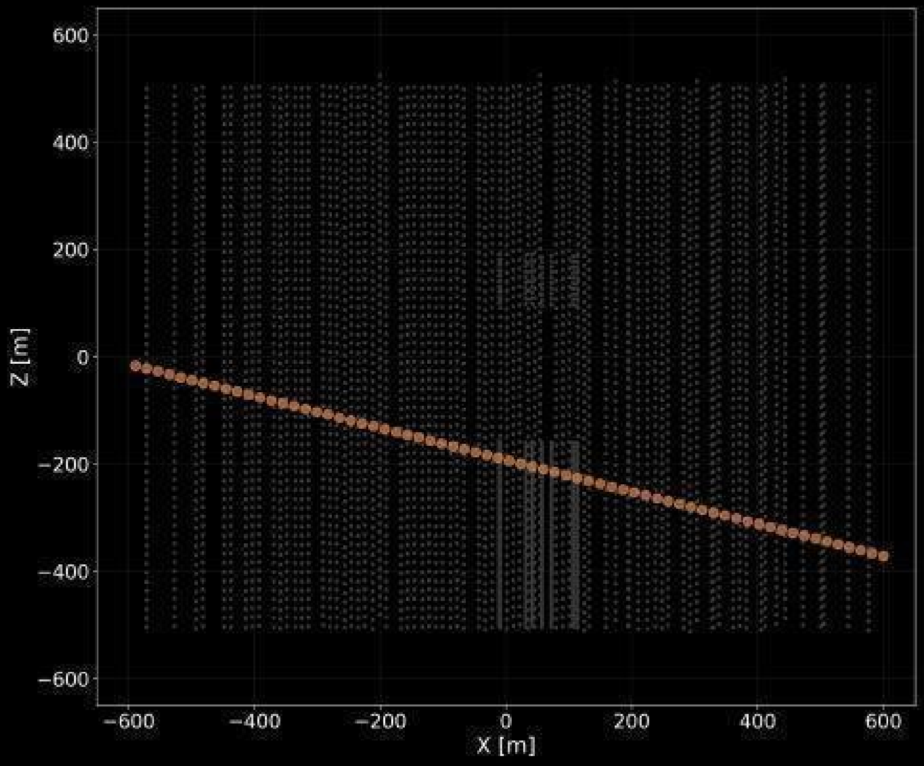


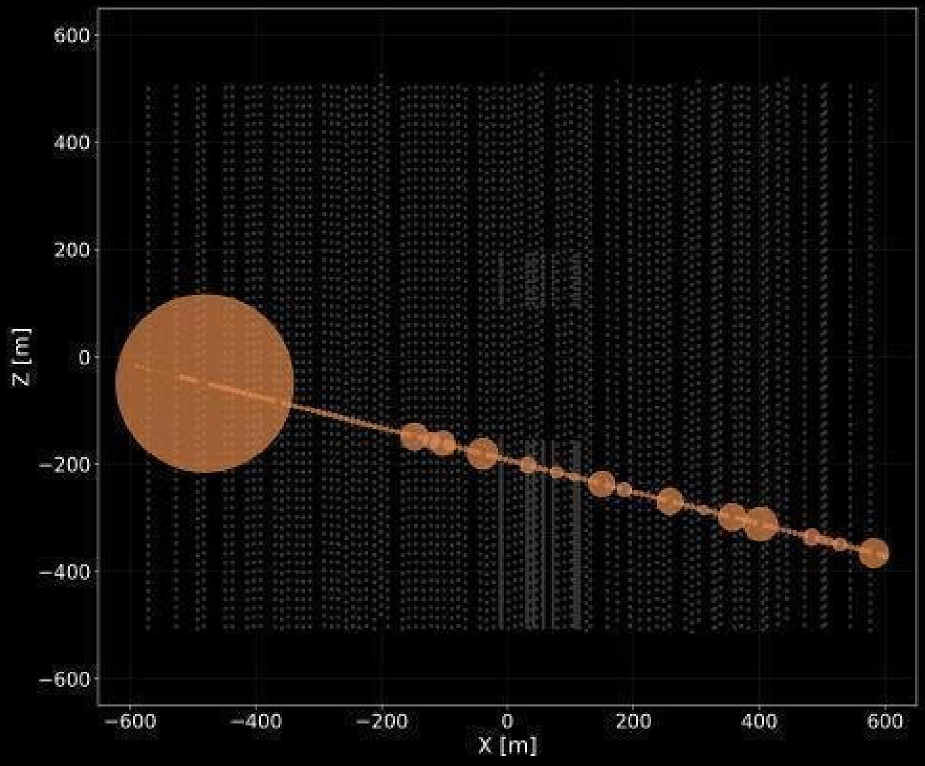
2. Neutrino detection particle-matter interaction

Example : Ice Cube

Z ln(P/m) → E < 300 GeV

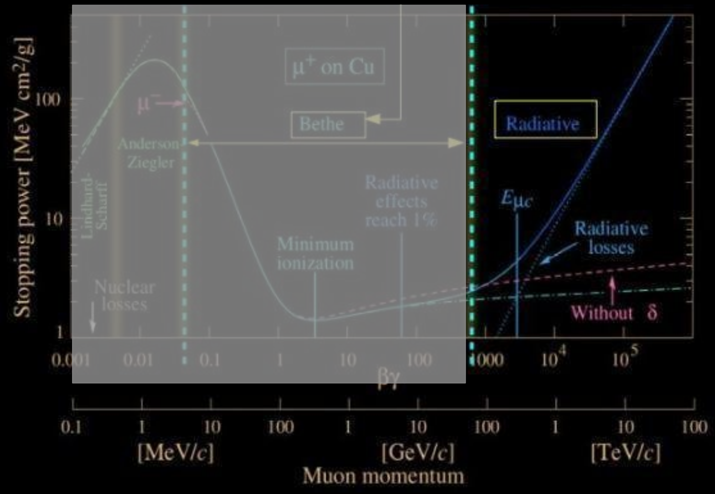
Z ln(P/m) → E > 300 GeV

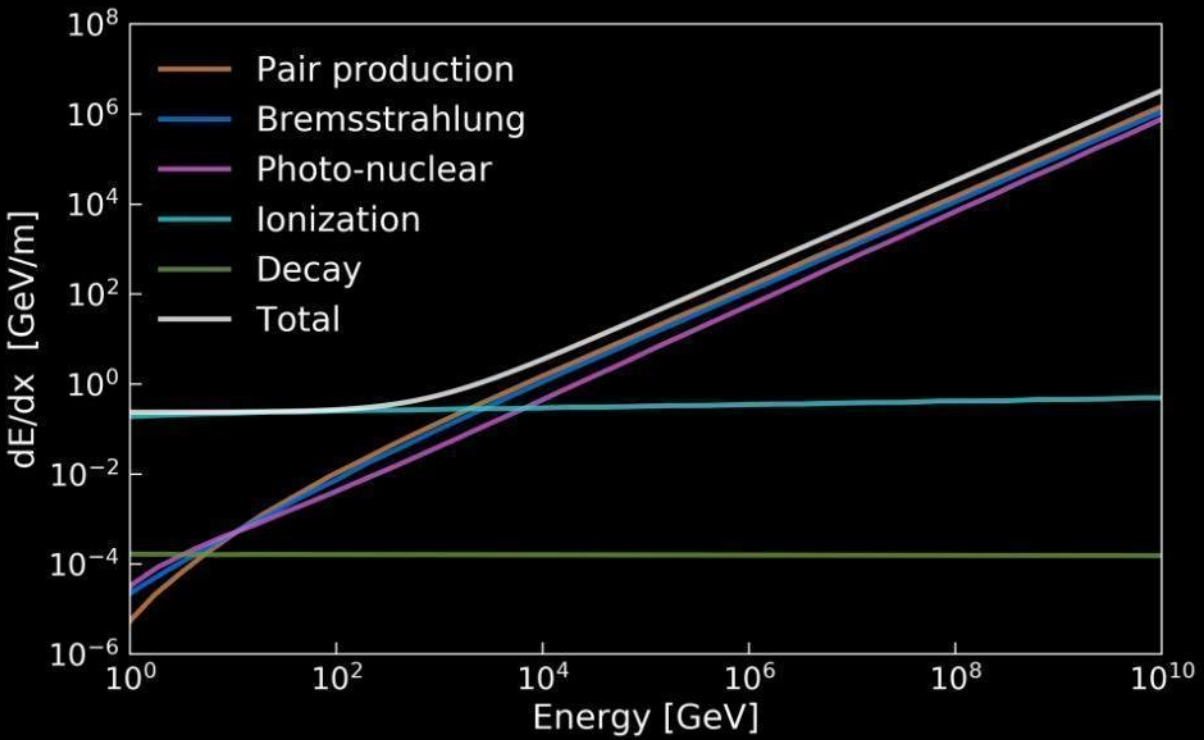




Example : Ice Cube

$$\frac{dE}{dx} = a(E) + b(E)E \qquad a(E) = 0.24 \text{ GeV m}^{-1} \text{ and } b(E) = 0.00032 \text{ m}^{-1} \text{ for ice}$$





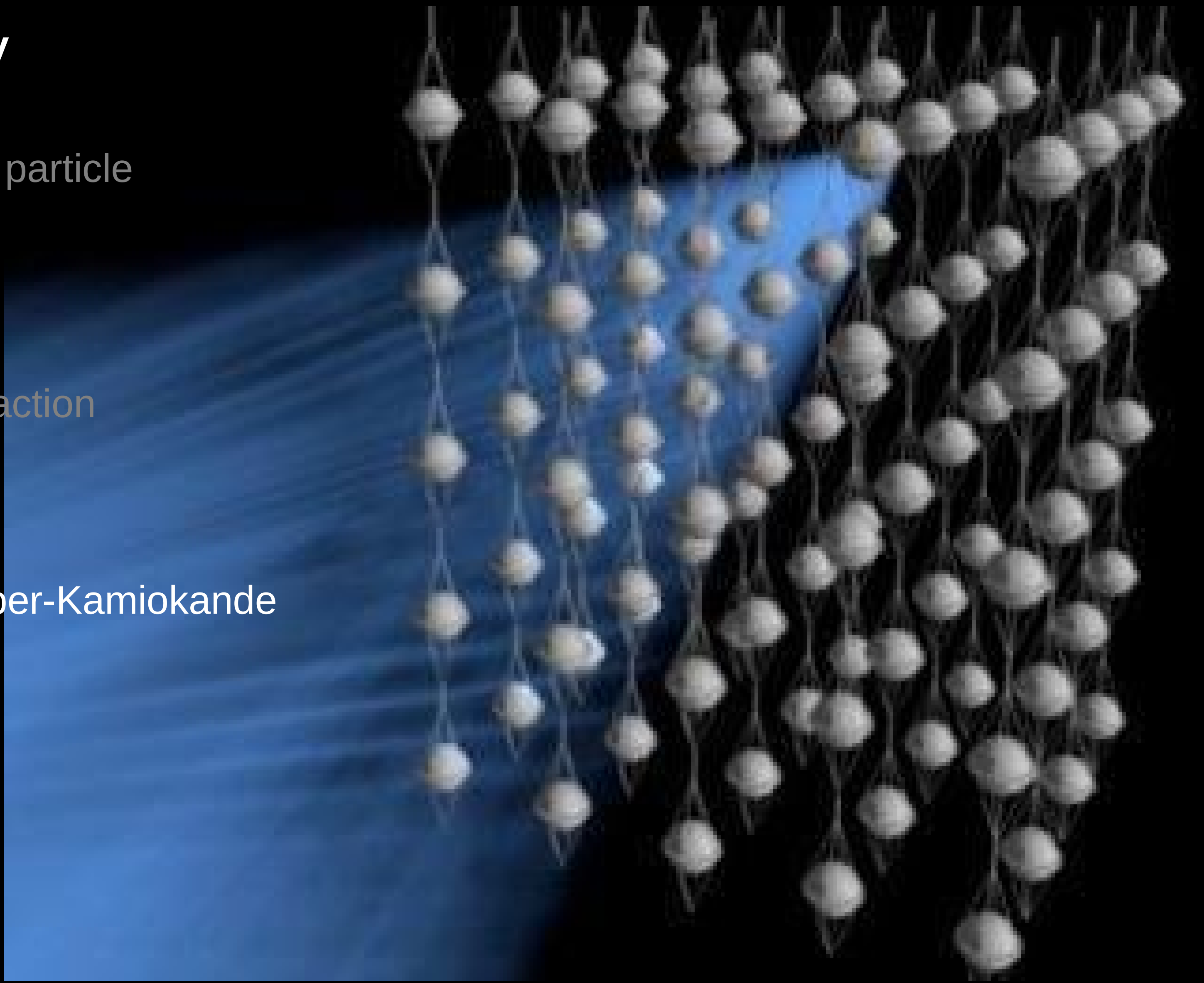
Neutrino Astronomy

1. Introduction
   - neutrino elementary particle

2. Neutrino detection
   - Chemistry
   - Čerenkov
   - Particle-matter interaction

3. Experiments
   - Homestake
   - KamiokaNDE → super-Kamiokande
   - Antares
   - IceCube

4. Conclusion
   - Future
   - Multi-messenger



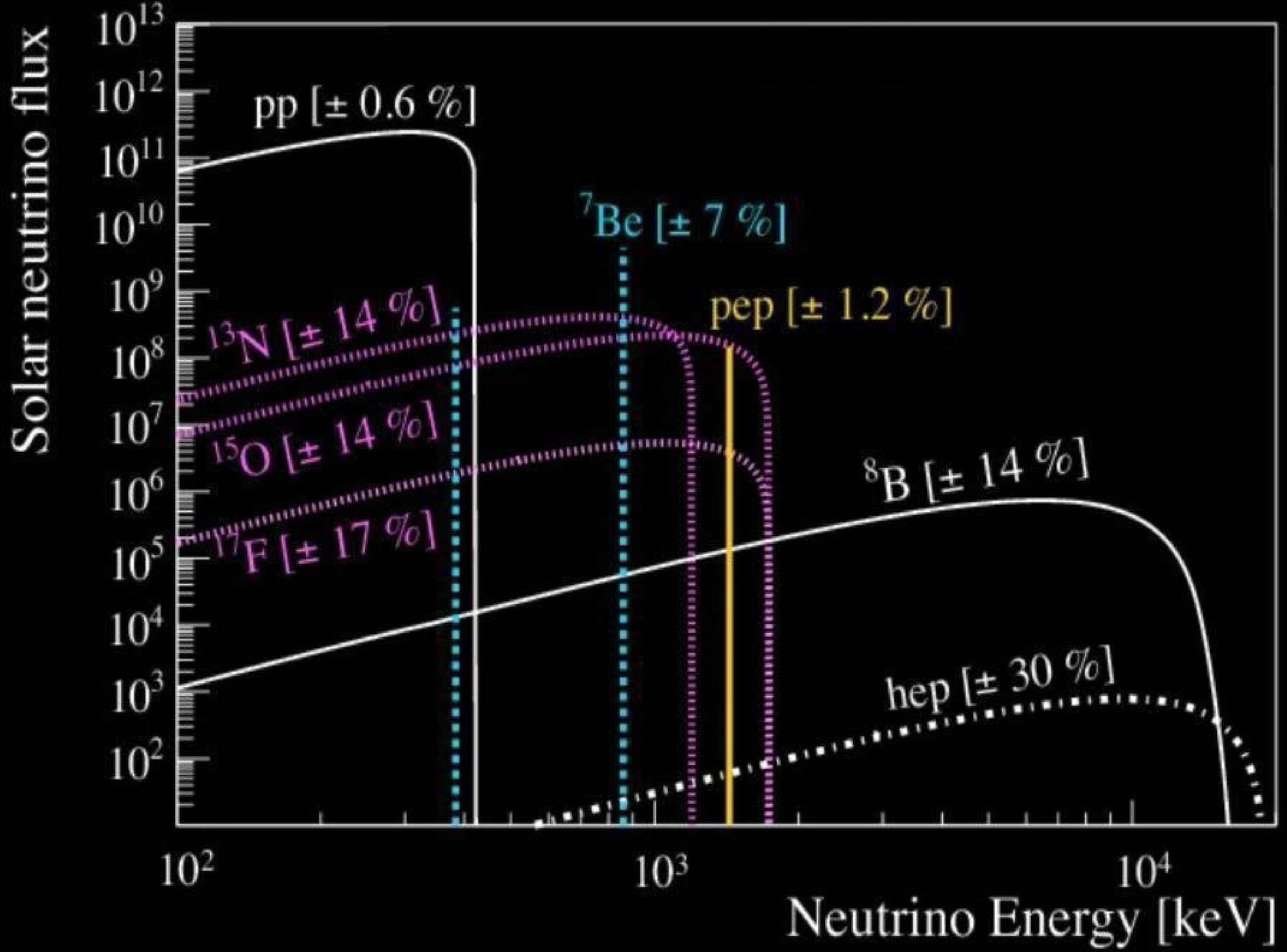
Homestake → Solar neutrino

1960 Raymond Jr. Davis
Brookhaven Solar Neutrino Experiment
South Dakota, old gold mine
1 478 meters underground

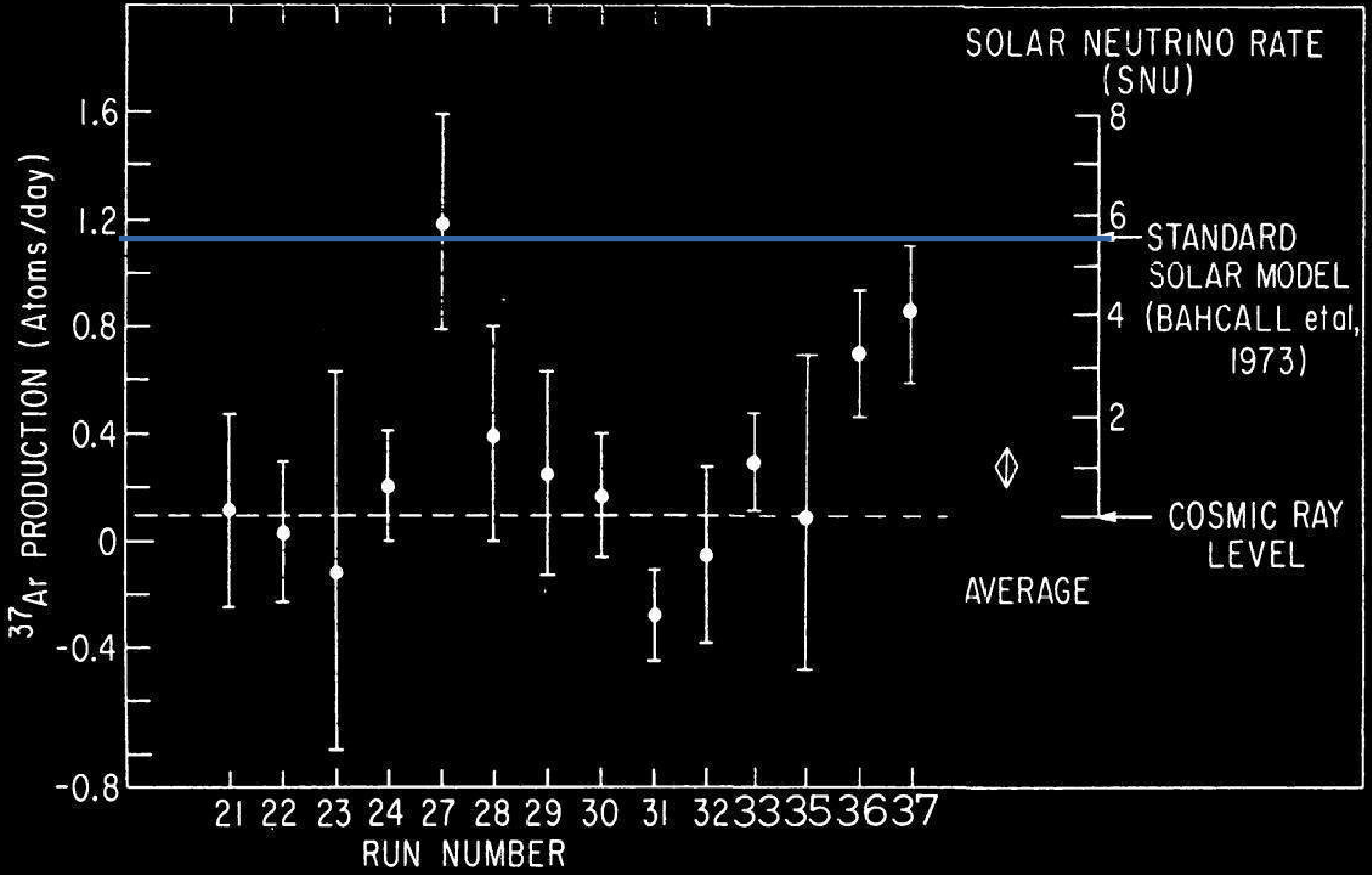
detector:

- only sensitive to ν_e
- $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar^{+} + e^{-}$
- threshold → 0.814 MeV
- 400 m³ perchlorethylene
- counting Ar (0.5 atom/day)

Number	Reaction	Solar terminations (%)	Maximum neutrino energy (Mev)
1	$p + p \rightarrow {}^2H + e^+ + \nu$	99.75	0.420
	or		
2	$p + e^- + p \rightarrow {}^2H + \nu$	0.25	1.44 (monoenergetic)
3	${}^2H + p \rightarrow {}^3He + \gamma$		
4	${}^3He + {}^3He \rightarrow {}^4He + 2p$	86	
	or		
5	${}^3He + {}^4He \rightarrow {}^7Be + \gamma$		
6	${}^7Be + e^- \rightarrow {}^7Li + \nu$		0.861 (90%), 0.383 (10%) (both monoenergetic)
7	${}^7Li + p \rightarrow 2{}^4He$	14	
	or		
8	${}^7Be + p \rightarrow {}^8B + \gamma$		
9	${}^8B \rightarrow {}^8Be^* + e^+ + \nu$		14.06
10	${}^8Be^* \rightarrow 2{}^4He$	0.02	


Solar neutrino flux
10^13
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
pp [± 0.6 %]
7Be [± 7 %]
pep [± 1.2 %]
13N [± 14 %]
15O [± 14 %]
17F [± 17 %]
8B [± 14 %]
hep [± 30 %]
10^2
10^3
10^4
Neutrino Energy [keV]

Homestake → Solar neutrinos → missing a factor ~3 ???

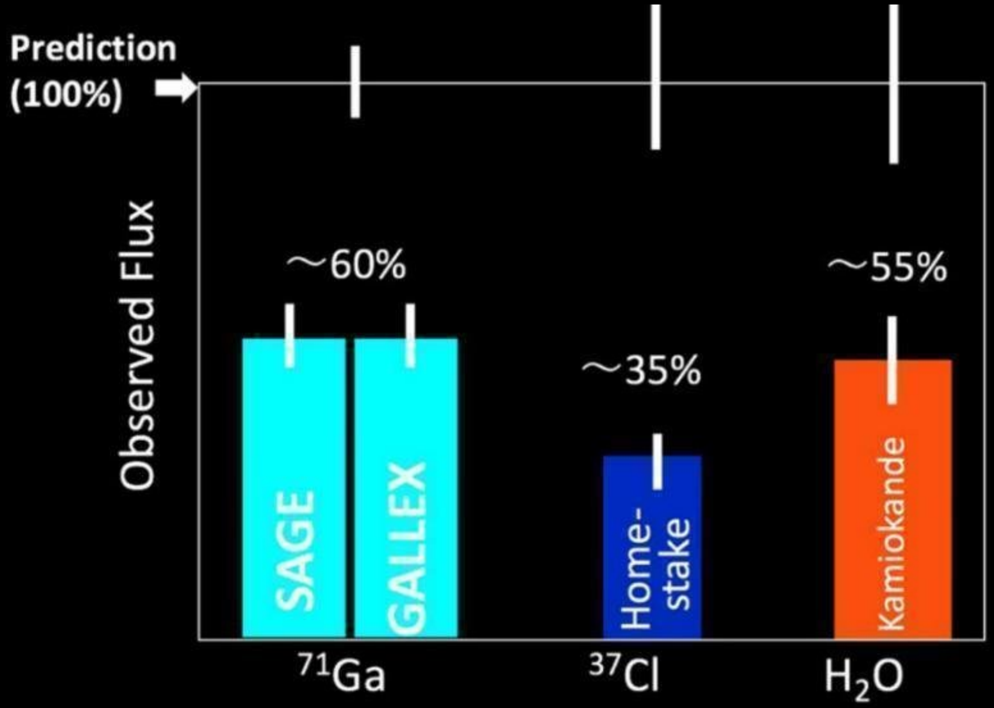


Homestake → Solar neutrino   Birth of neutrino astronomy

solar neutrino problem

new experiments: chemistry or Čerenkov

- Kamiokande (1987) → SNA 1987 A → Super-Kamiokande
- SAGE & GALLEX ← ^{71}Ga chemistry
- SNO → neutrino oscillations
- Antares
- IceCube



Kamiokande

1984 Kamiokande I
proton decay & neutrino oscillation
Japan Mozumi zinc mine
1000 meters underground

detector:
Čerenkov
ν_e from ^8B
8000 m³ (~10^{33} nucleons)
1000 PMTs, 50 cm
threshold → 10 MeV

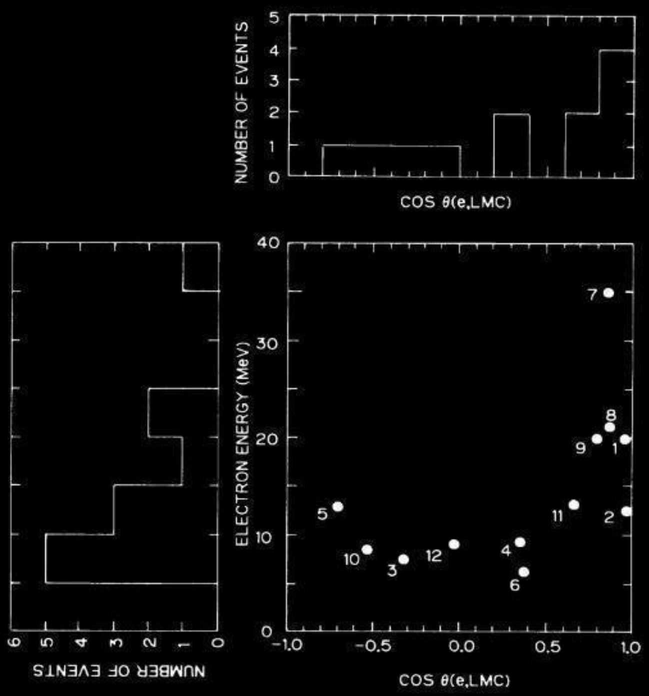
1987 Kamiokande II idem → SNA 1987 A
Large Magellanic Cloud

PHYSICAL REVIEW LETTERS 6 APRIL 1987

twelve electron events
:tron angle in the last
1987A. The errors on
dard-deviation Gauss-

lectron :nergy MeV)	Electron angle (degrees)
.0 ± 2.9	18 ± 18
.5 ± 3.2	15 ± 27
.5 ± 2.0	108 ± 32
.2 ± 2.7	70 ± 30
.8 ± 2.9	135 ± 23
.3 ± 1.7	68 ± 77
.4 ± 8.0	32 ± 16
.0 ± 4.2	30 ± 18
.8 ± 3.2	38 ± 22
.6 ± 2.7	122 ± 30
.0 ± 2.6	49 ± 26
.9 ± 1.9	91 ± 39

ent with isotropy.
: data of 16:09. 21



PHYSICAL REVIEW LETTERS 6 APRIL 1987

electromagnetic
(optic) counterpart

[1]I. Shelton, International Astronomical Union (IAU) Circular No. 4316. Note also that R. H. McNaught subsequently communicated visual magnitude of 6.0 on 23.44 UT February. The first confirmed observation of optical brightening was by G. Garradd, 23.44 February (IAU Circular No. 4316). The last confirmed evidence of no optical brightening was by Shelton, 23.059–23.101 February (IAU Circular No. 4330). There was a possible observation of no optical brightening by A. Jones at 23.39 February (IAU Circular No. 4340).

Kamiokande

1984 Kamiokande I
proton decay & neutrino oscillation
Japan Mozumi zinc mine
1000 meters underground

detector:
Čerenkov
ν_e from ^8B
8000 m³ (~10^{33} nucleons)
1000 PMTs, 50 cm
threshold → 10 MeV

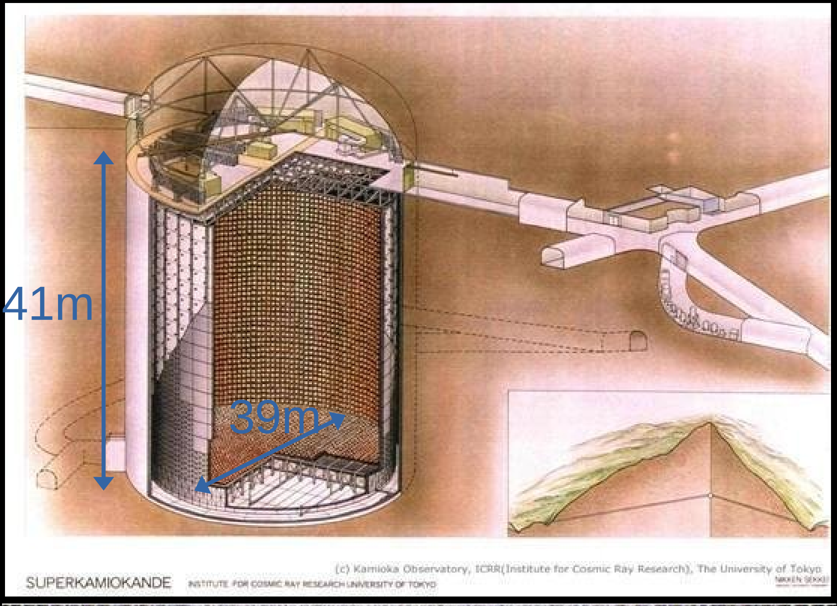
1987 Kamiokande II idem → SNA 1987 A
Large Magellanic Cloud
24 neutrinos detected in ~10 s
3 hours before the electromagnetic signal
Typical energy ~10 MeV

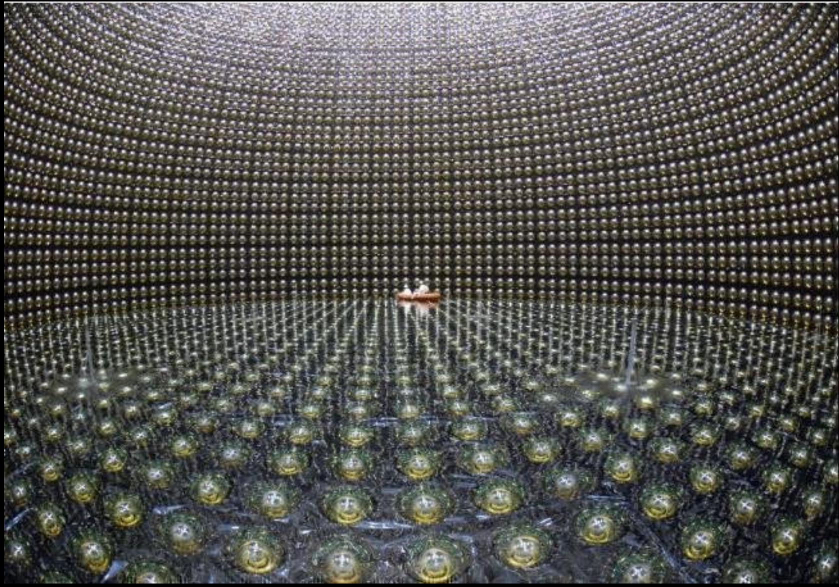
Super-Kamiokande

1996 Takaaki Kajita
Japan Mozumi zinc mine
1000 meters underground

detector:

sensitive to ν_e, ν_μ, ν_τ
11 146 photomultiplier, 50 cm
threshold → 4.5 MeV
50 220 m^3



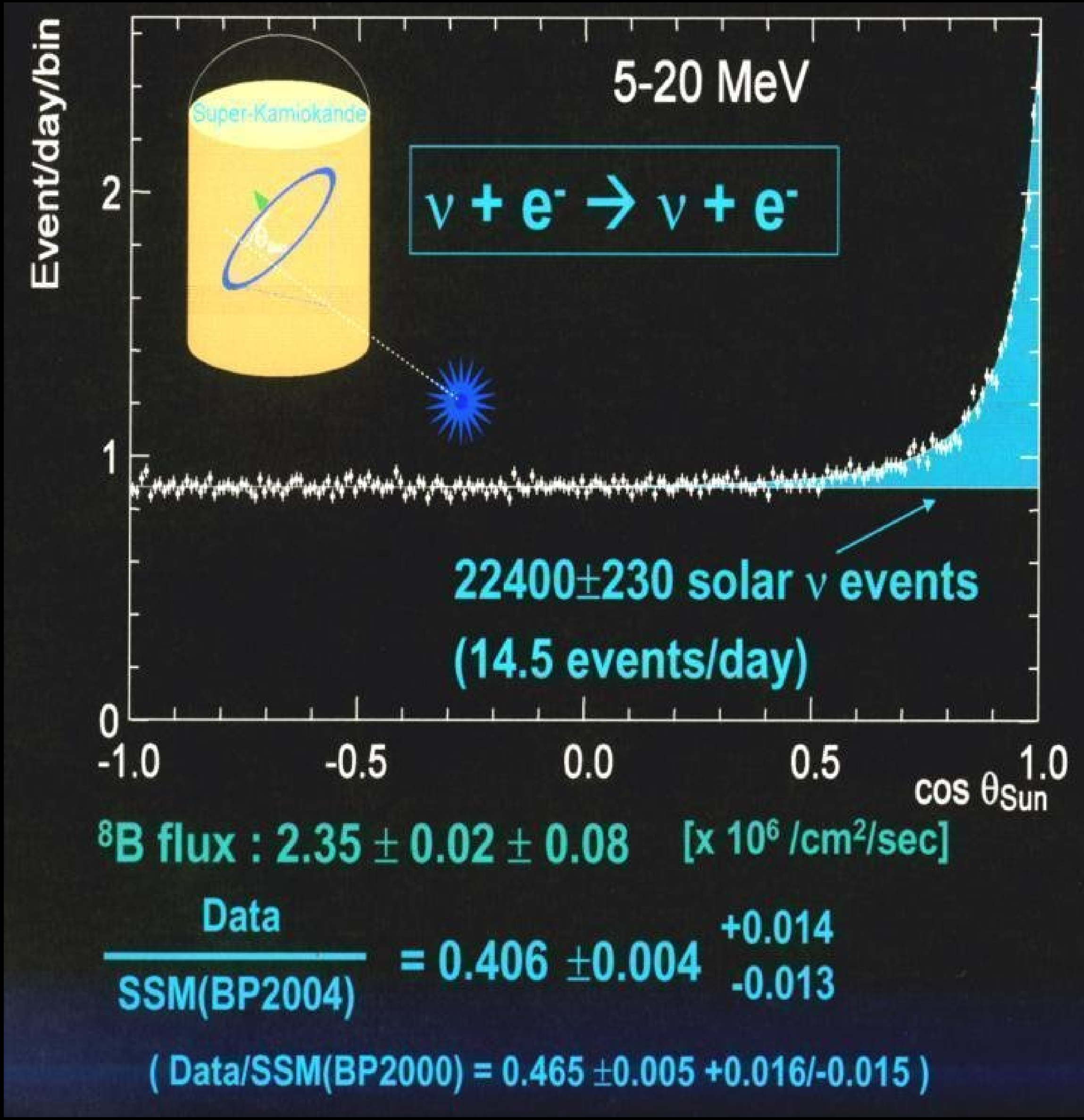


Super-Kamiokande

1996 Takaaki Kajita
Japan Mozumi zinc mine
1000 meters underground

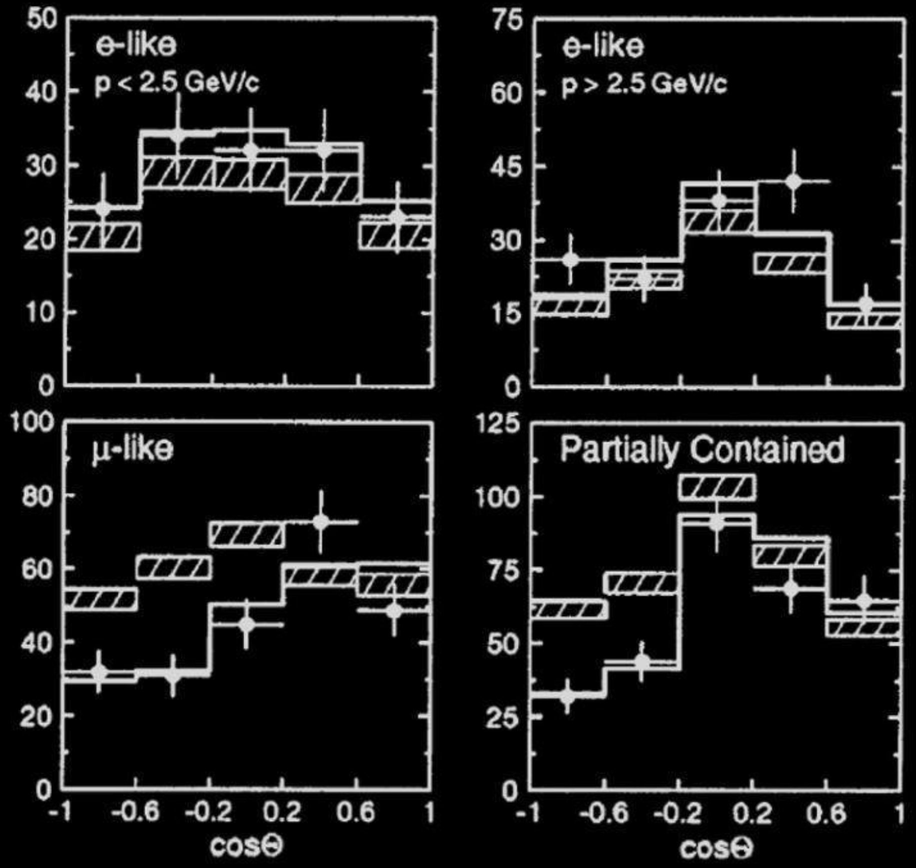
detector:

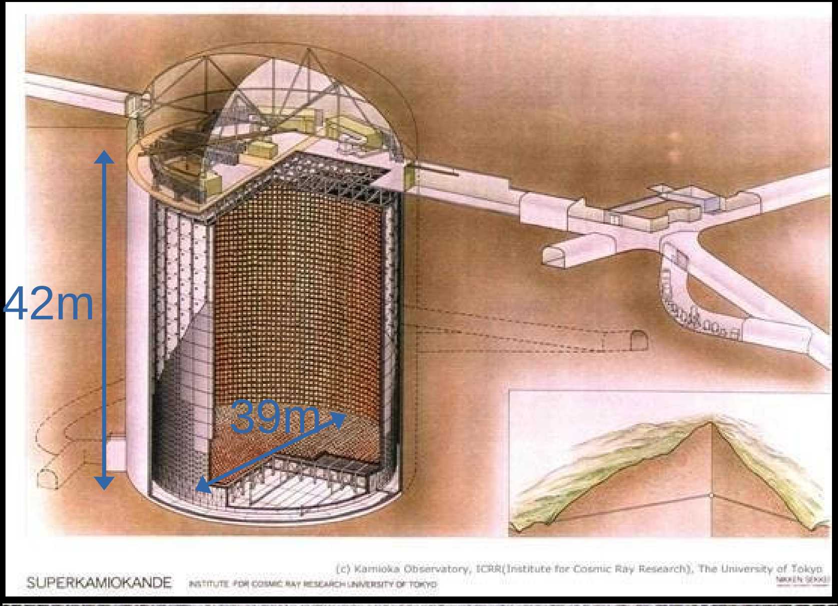
sensitive to ν_e, ν_μ, ν_τ
11 146 photomultiplier, 50 cm
threshold → 4.5 MeV
50 220 m³

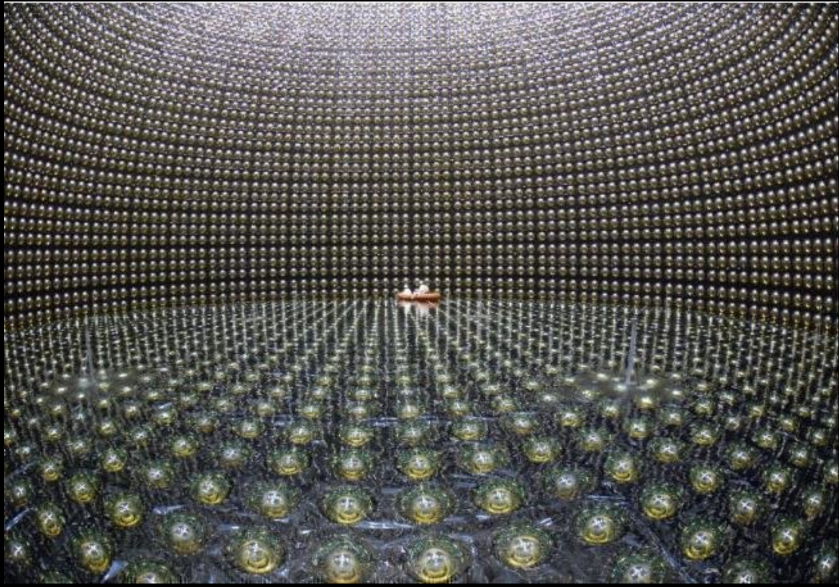


Super-Kamiokande

Neutrino oscillation observation

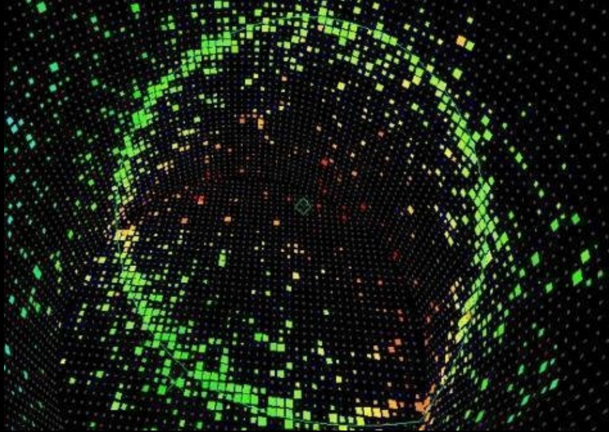


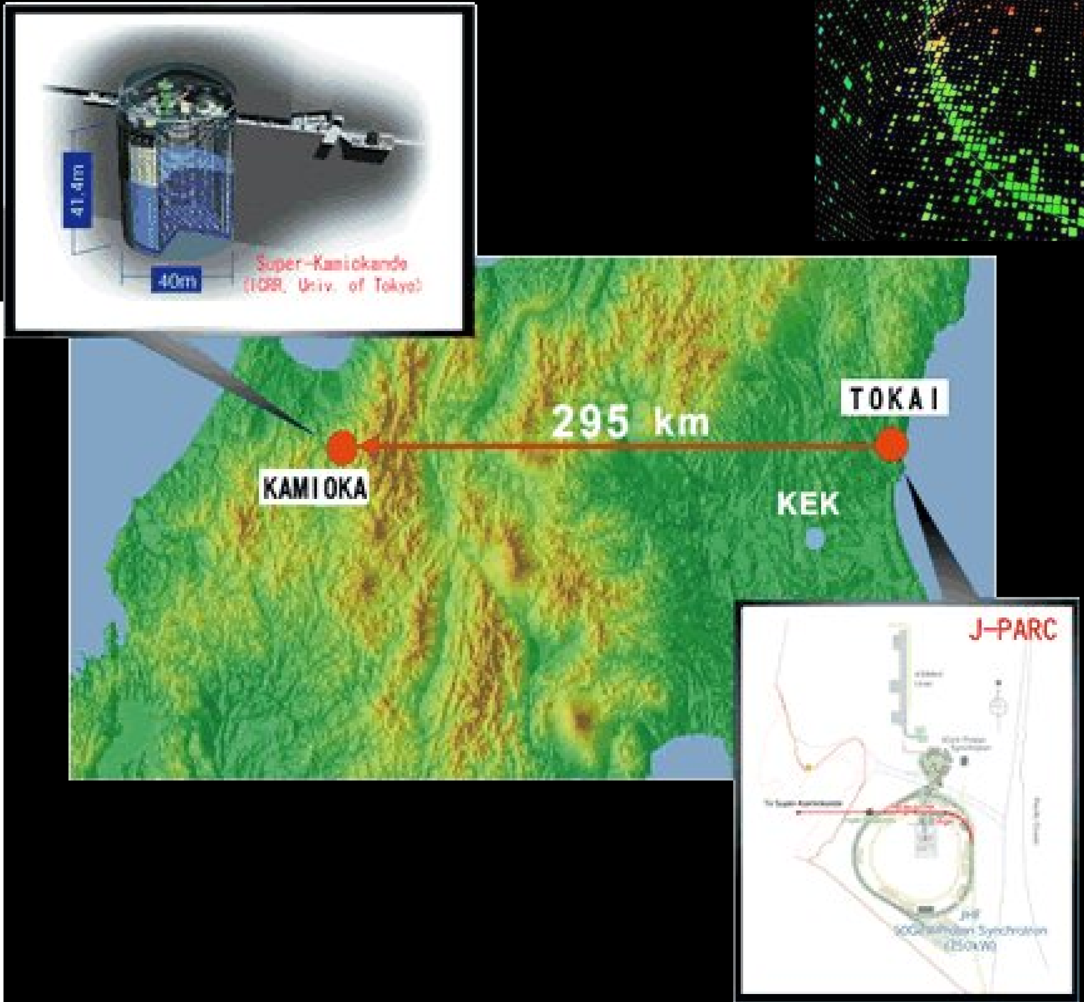


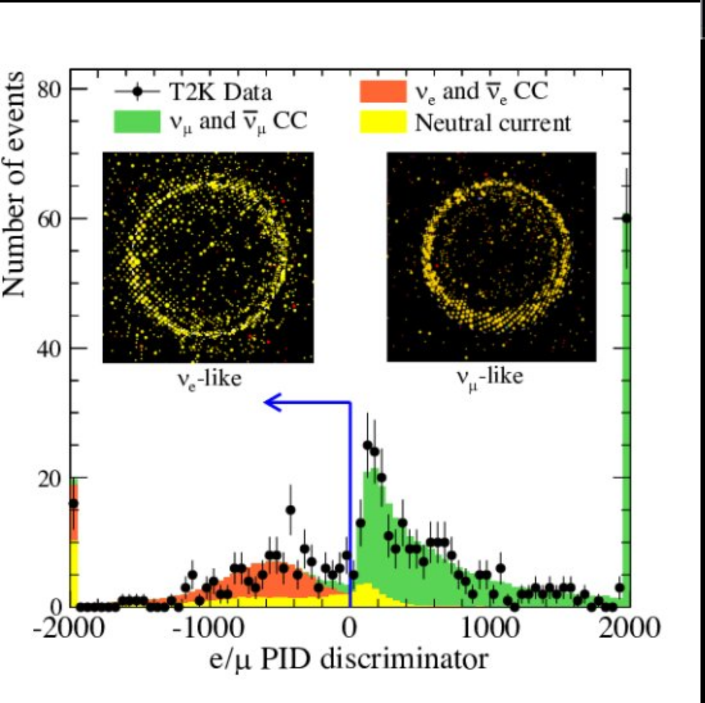


Super-Kamiokande ← T2K

2010

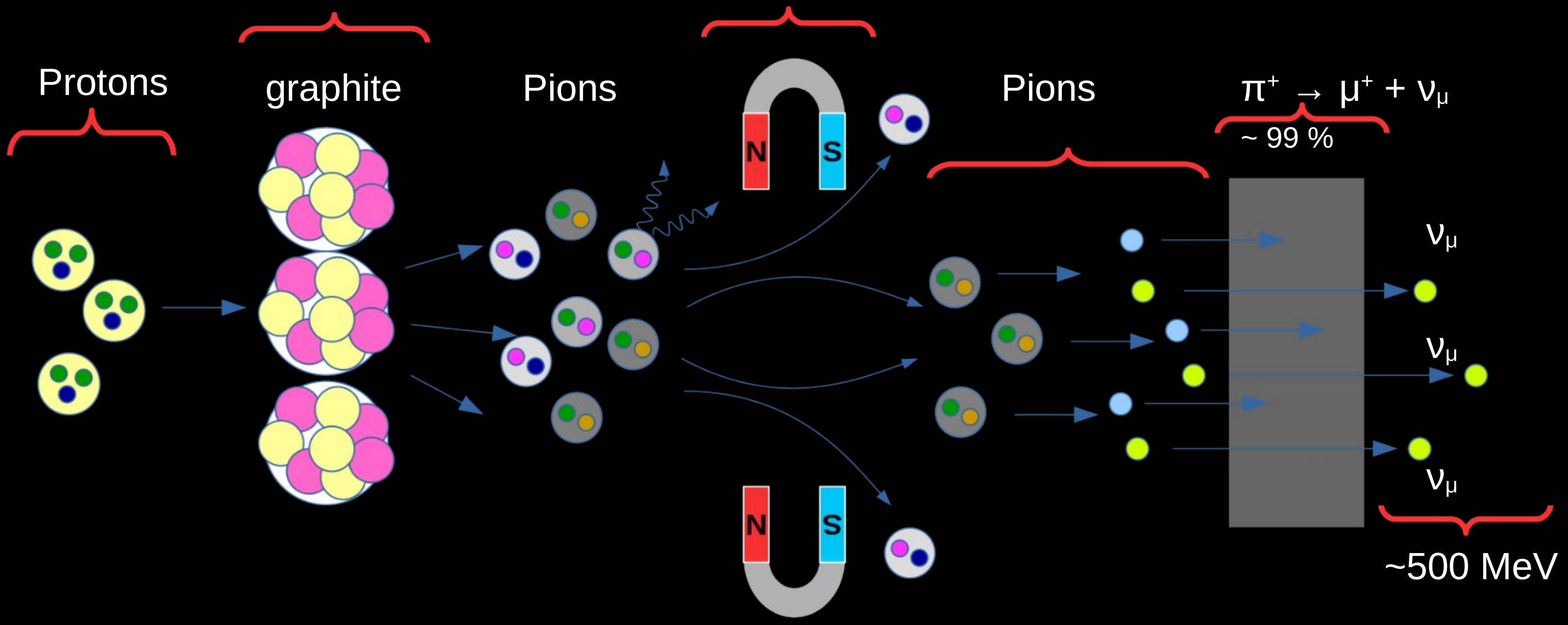






Super-Kamiokande ← T2K

2010

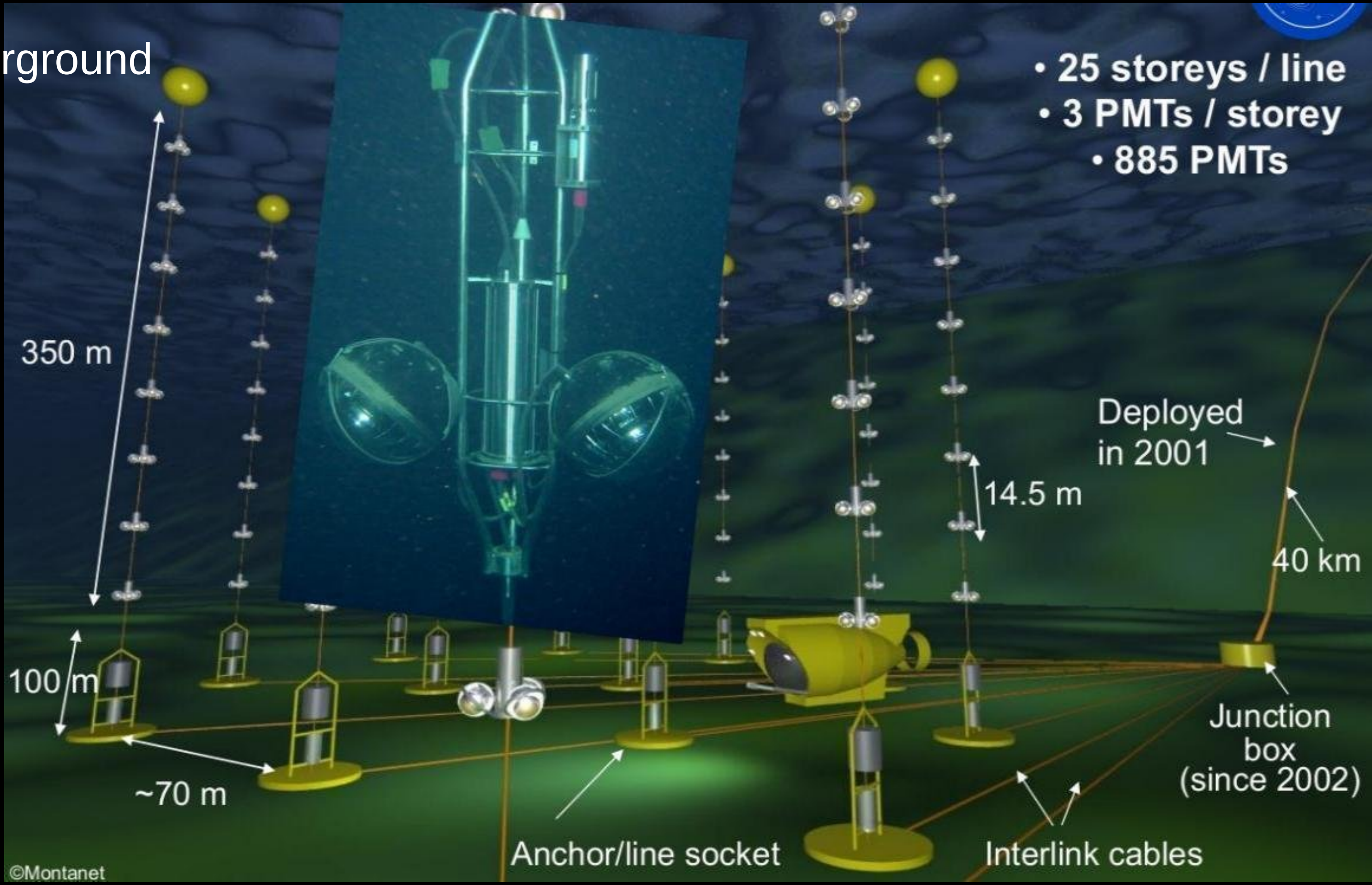


Antares

1987 → 2008 completed → 2022 finished
Toulon, France
2 500 meters underground
more a prototype
→ Km3net

detector:
~0,1 km2

Problems
bio-luminescence
ocean current



Ice Cube

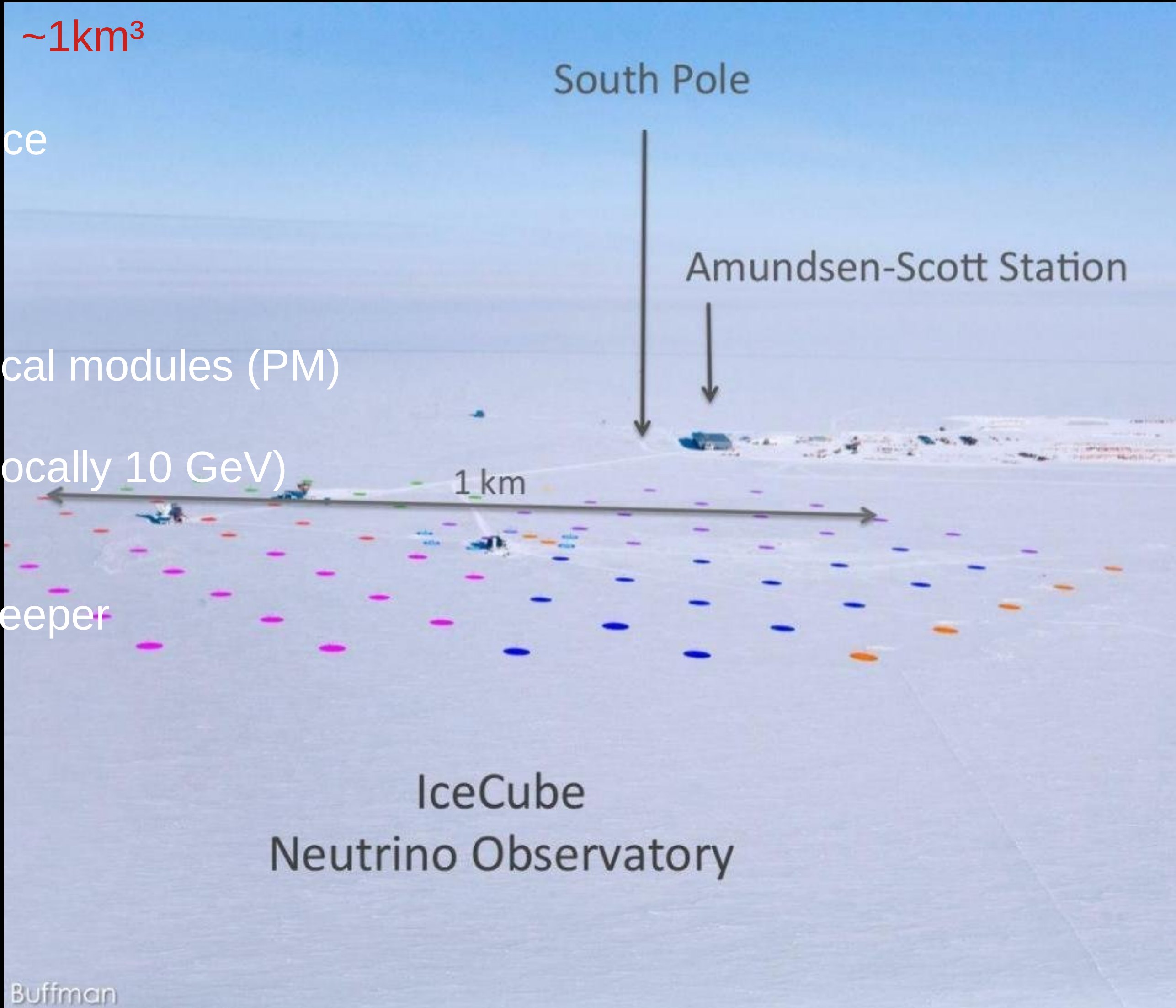
2004 South pole
1450 to 2450 meters under-ice

detector:

sensitive to ν_e, ν_μ, ν_τ

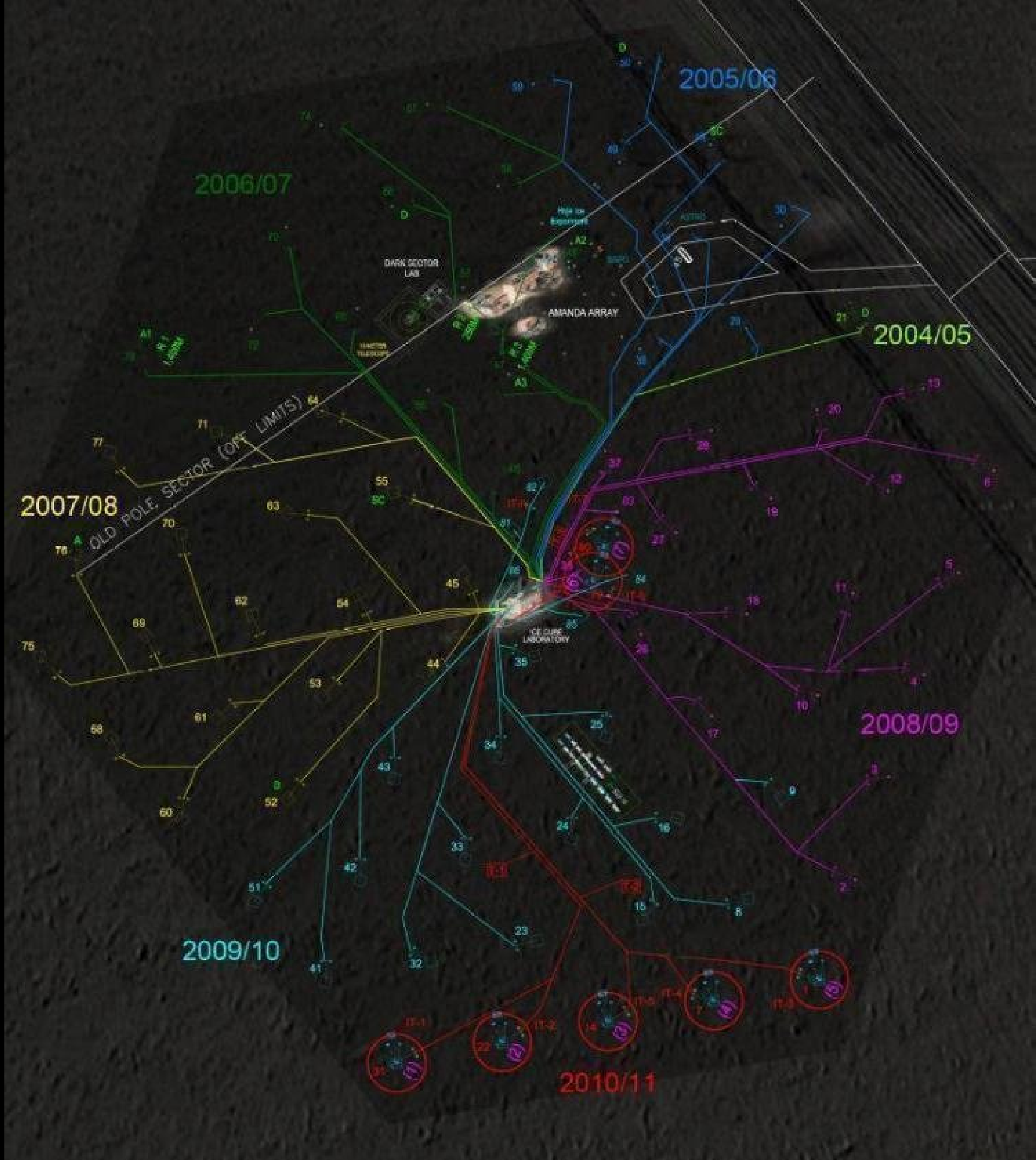
5160 (86*60) digital optical modules (PM)
~25 cm (10 inch)
300 TeV to 1 EeV (and locally 10 GeV)

problem:
air bubble in ice → go deeper



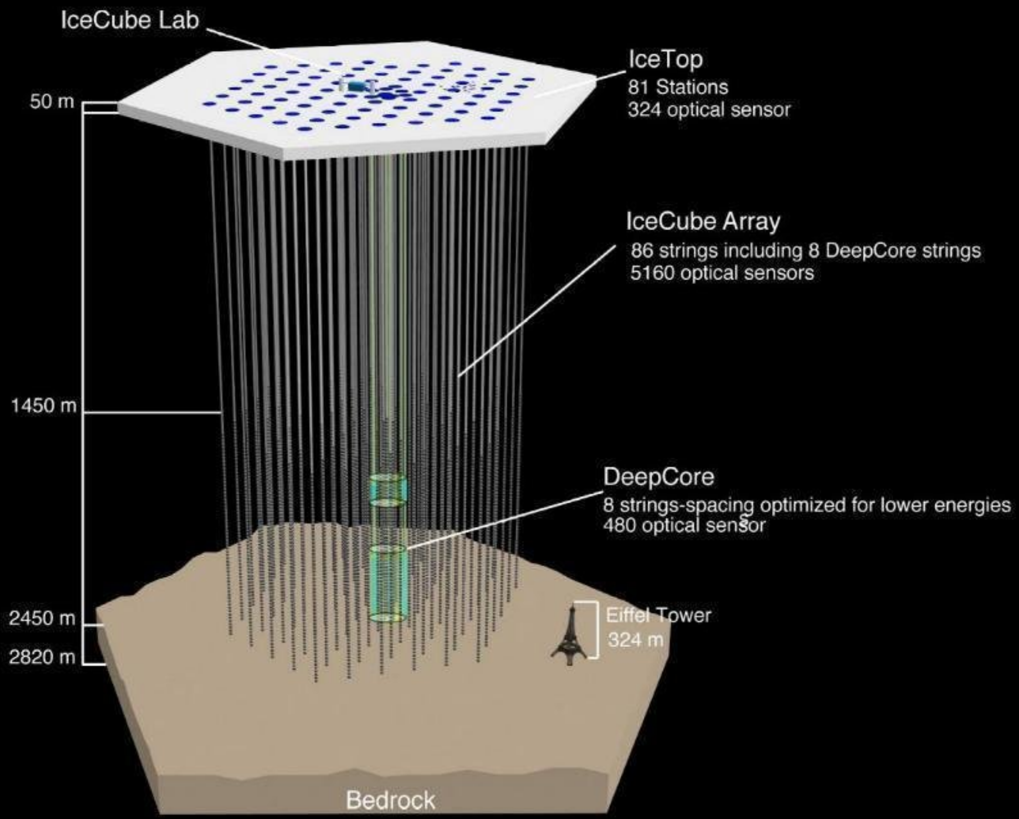
< 50 m drill & > 50 m
hot water drilling 2 m/mn

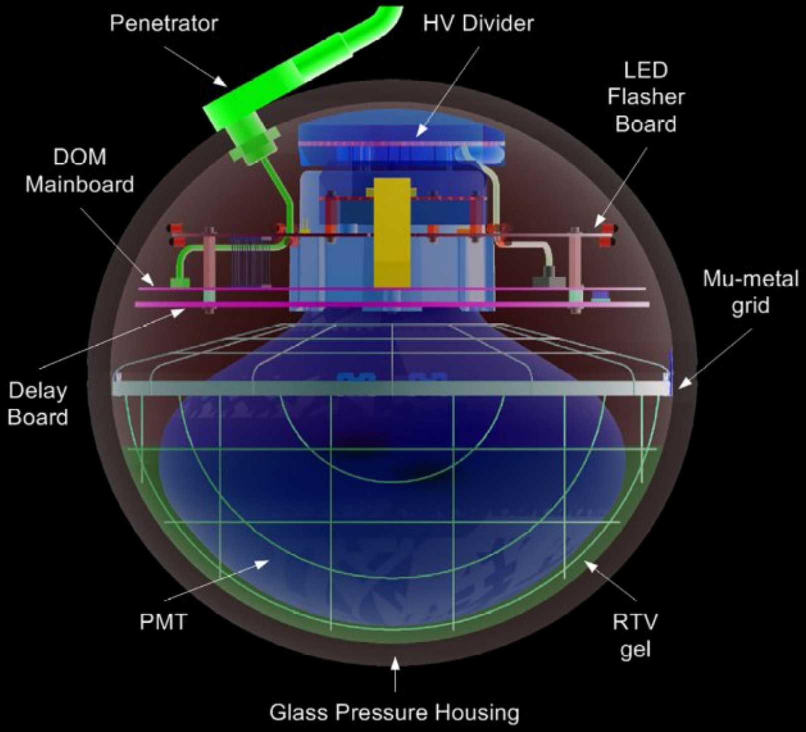
Ice Cube



~$1 km^3$

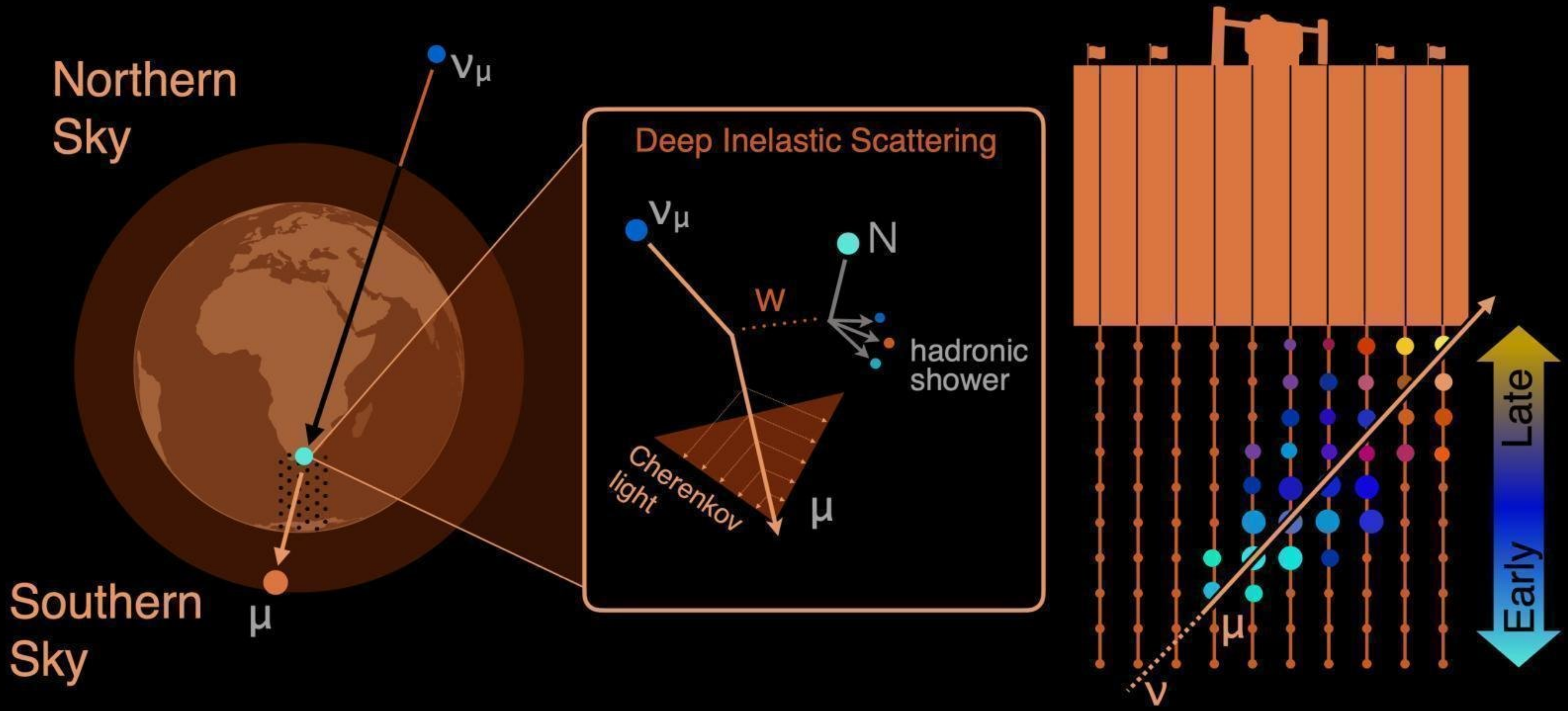
Ice Cube


IceCube Lab
IceTop
81 Stations
324 optical sensor
50 m
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensor
Eiffel Tower
324 m
2450 m
2820 m
Bedrock


Penetrator
HV Divider
LED
Flasher
Board
DOM
Mainboard
Mu-metal
grid
Delay
Board
PMT
RTV
gel
Glass Pressure Housing

Ice Cube

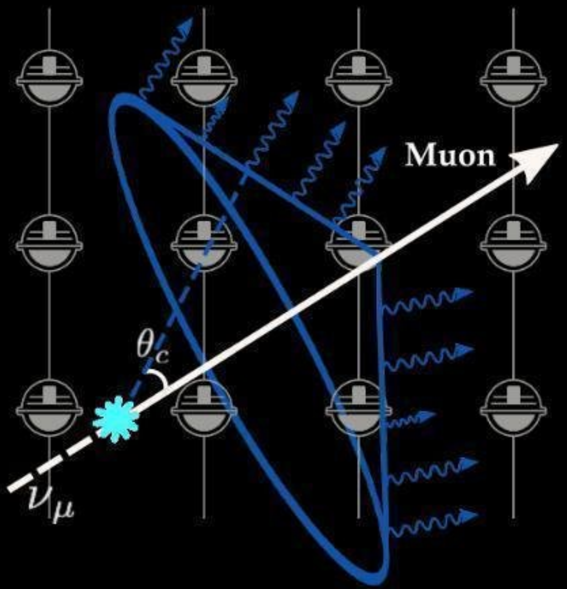
Federica Bradascio



Ice Cube

Federica Bradascio

Tracks

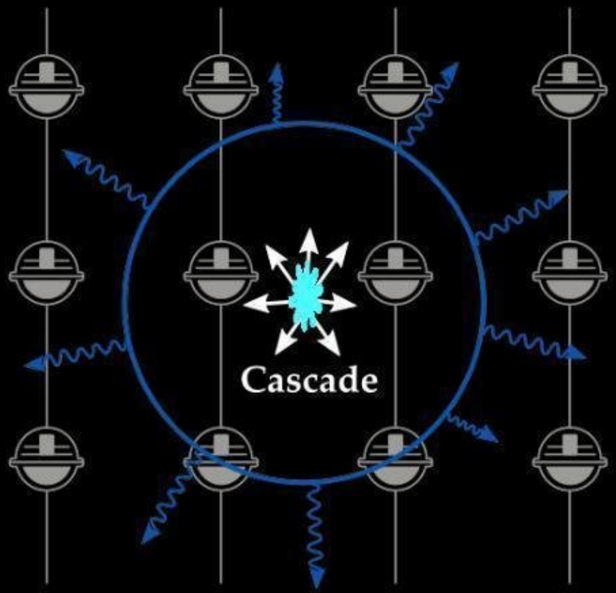


$$\nu_\mu + N \rightarrow \mu + X$$

Good angular resolution 0.1-1 deg

Neutrino astronomy

Cascades

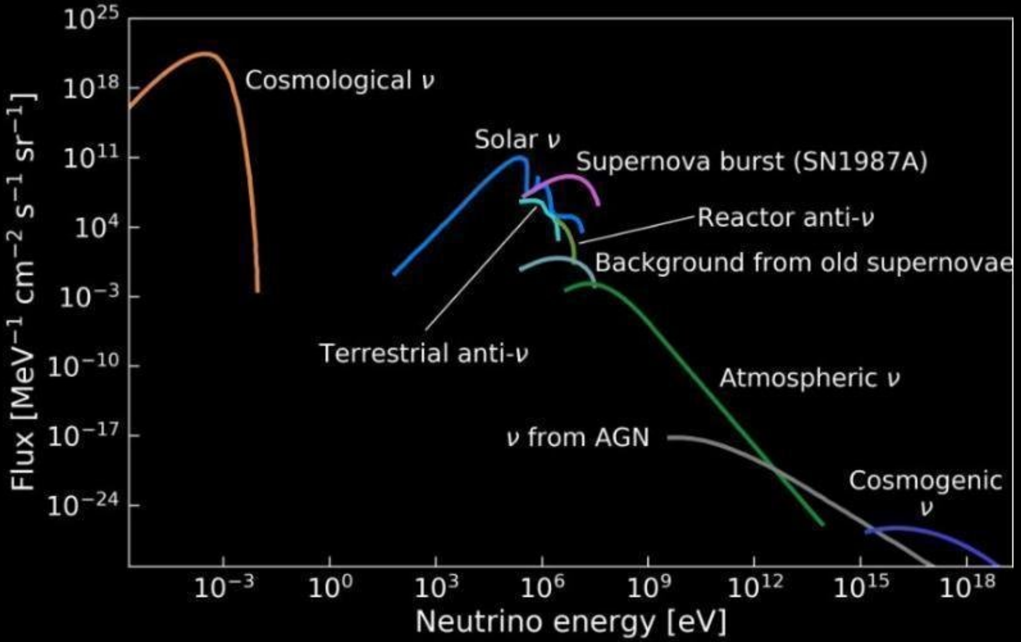


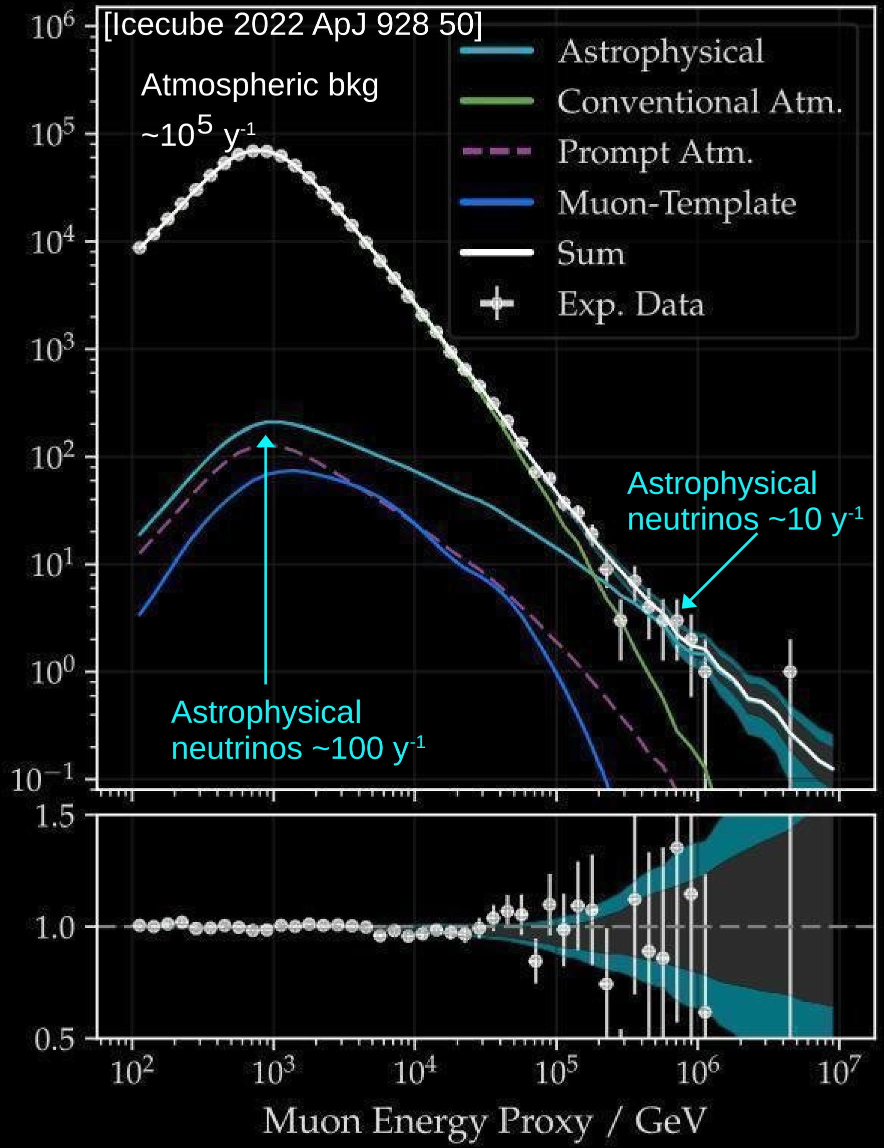
$$\nu_X + N \rightarrow \nu_X + X, \quad \nu_e + N \rightarrow e + X$$

Fully active calorimeter

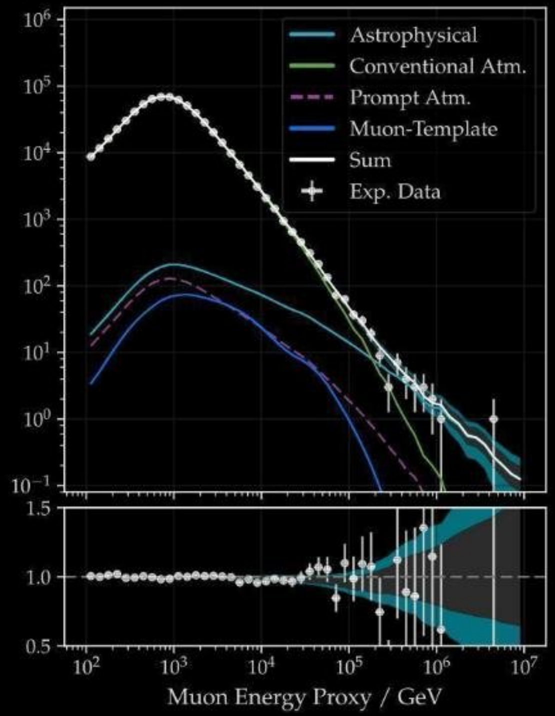
Good energy resolution ~15%

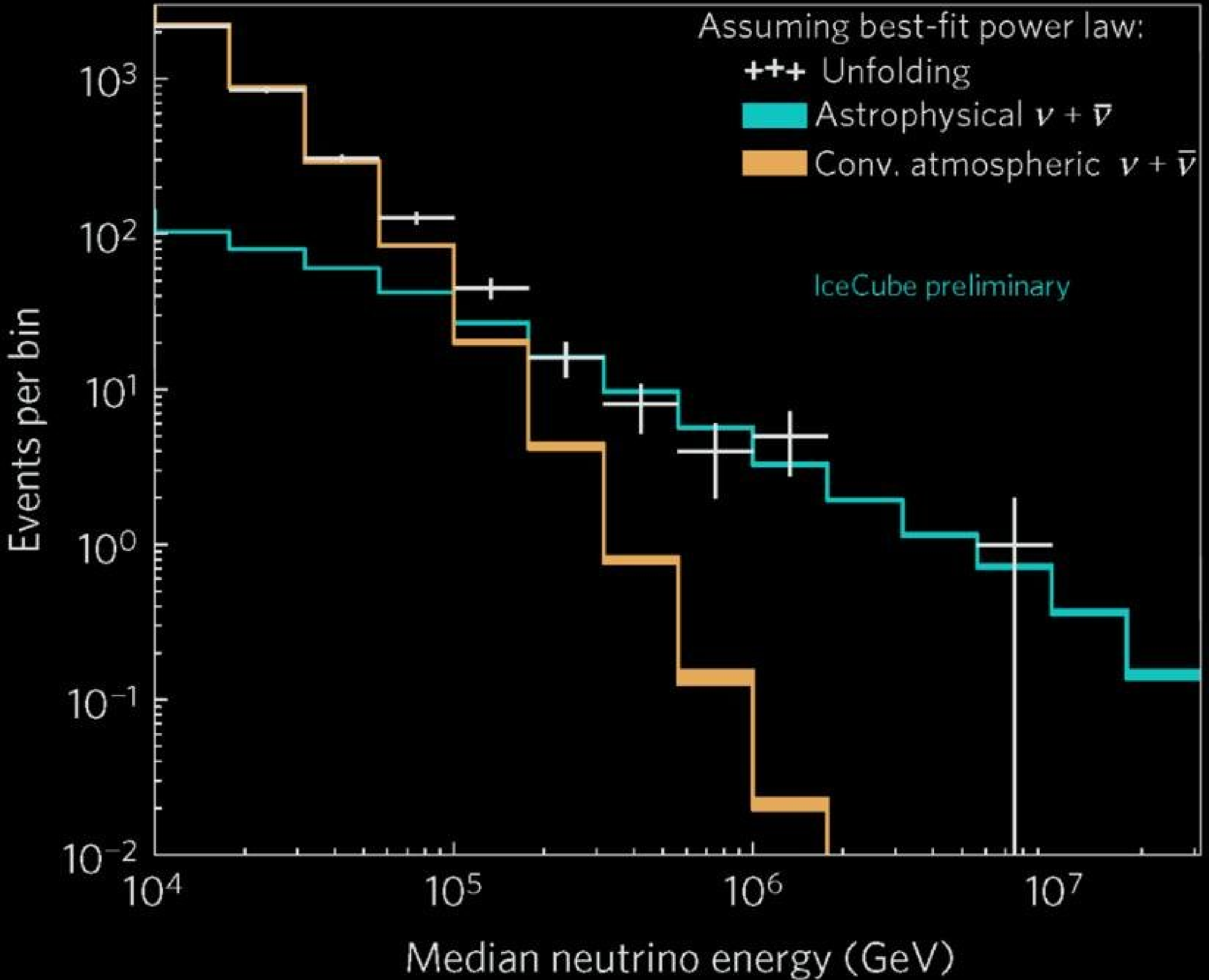
Ice Cube


Cosmological ν
Solar ν
Supernova burst (SN1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
Flux [MeV⁻¹ cm⁻² s⁻¹ sr⁻¹]
Neutrino energy [eV]


[Icecube 2022 ApJ 928 50]
Atmospheric bkg
~10^5 y^-1
Astrophysical
Conventional Atm.
Prompt Atm.
Muon-Template
Sum
Exp. Data
Astrophysical neutrinos ~10 y^-1
Astrophysical neutrinos ~100 y^-1
Muon Energy Proxy / GeV

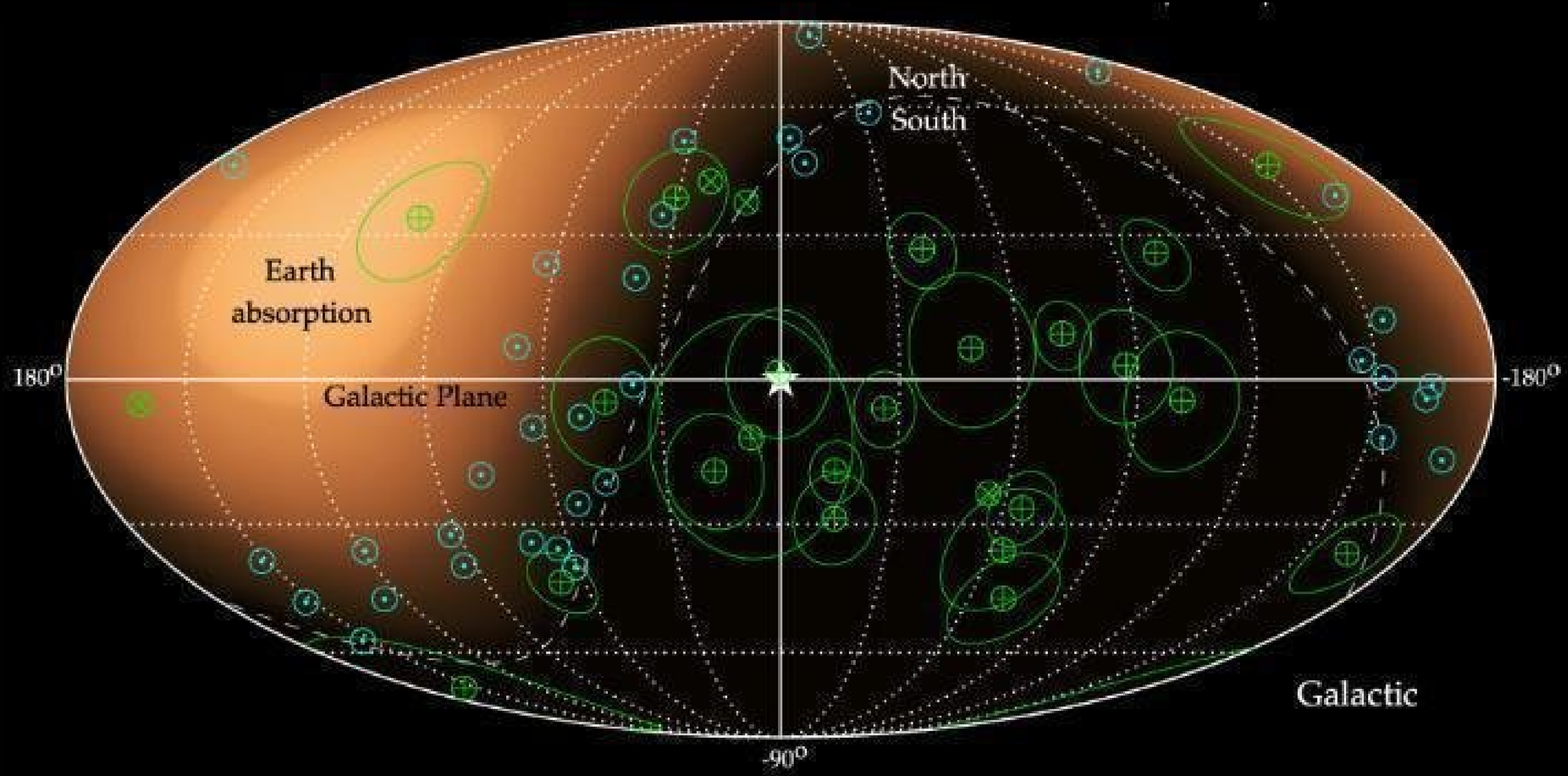
Ice Cube


Astrophysical
Conventional Atm.
Prompt Atm.
Muon-Template
Sum
Exp. Data
Muon Energy Proxy / GeV


Assuming best-fit power law:
+++ Unfolding
Astrophysical ν + ν̄
Conv. atmospheric ν + ν̄
IceCube preliminary
Events per bin
Median neutrino energy (GeV)

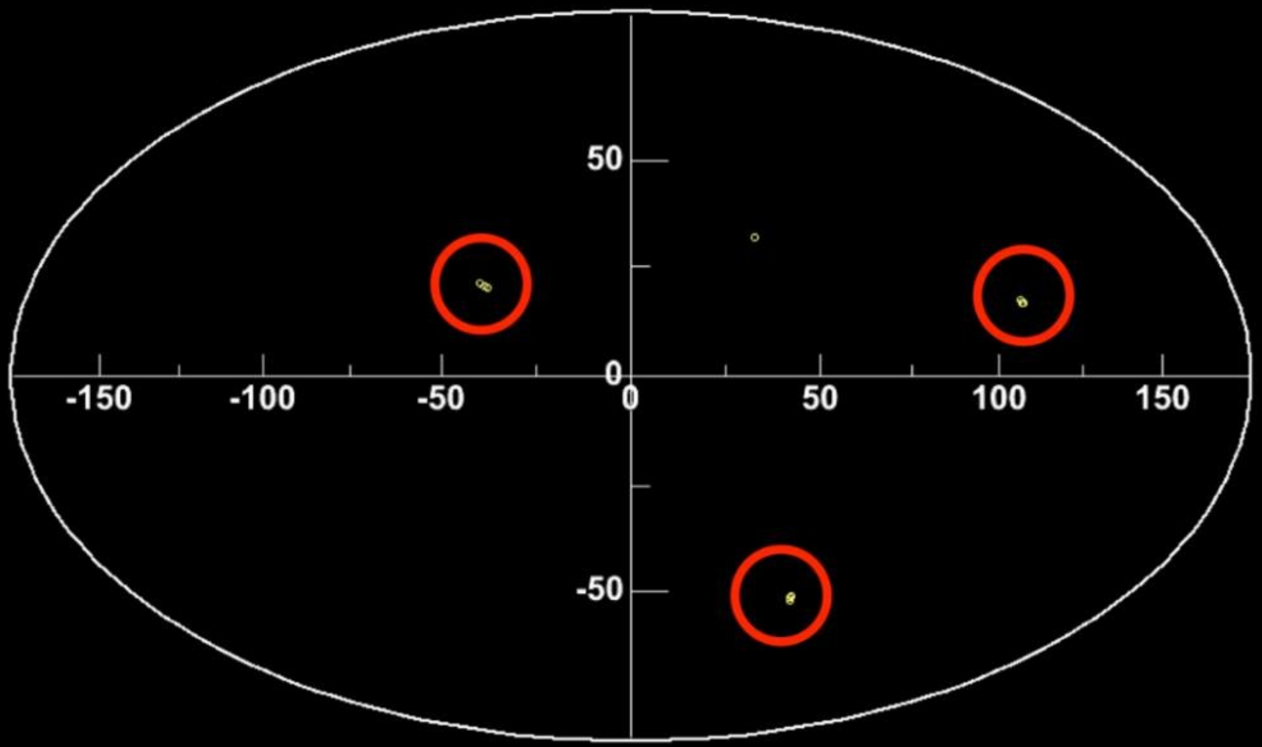
Ice Cube

Selection → need various bands of the electromagnetic spectrum
AGN → ~2 evts per month
Evidence for neutrinos from flaring blazar TXS 0506+056 (3σ)
Evidence for neutrinos from nearby Seyfert galaxy NGC 1068 (4.3σ)

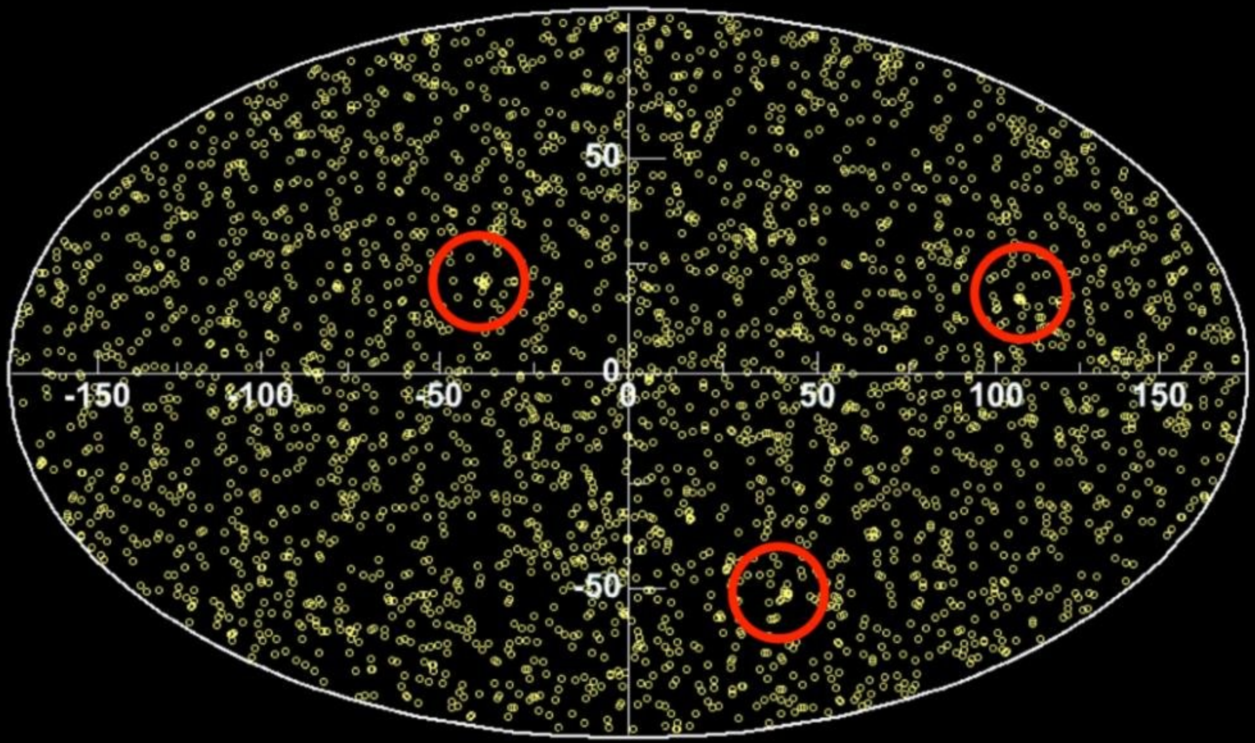


Ice Cube

Selection → need various bands of the electromagnetic spectrum
AGN → ~2 evts per month
Evidence for neutrinos from flaring blazar TXS 0506+056 (3σ)
Evidence for neutrinos from nearby Seyfert galaxy NGC 1068 (4.3σ)



Selection → need various bands of the electromagnetic spectrum
AGN → ~2 evts per month
Evidence for neutrinos from flaring blazar TXS 0506+056 (3σ)
Evidence for neutrinos from nearby Seyfert galaxy NGC 1068 (4.3σ)



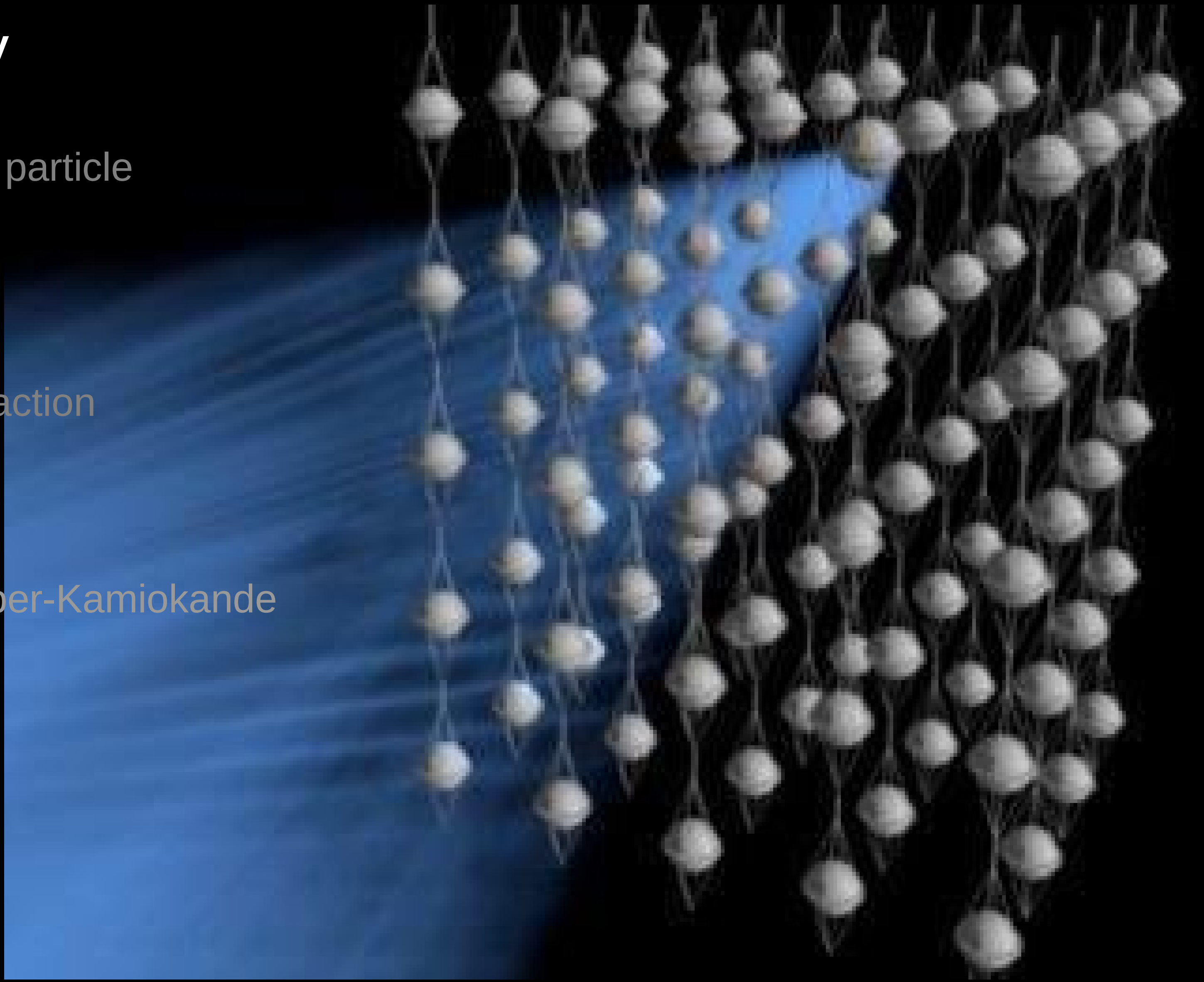
Neutrino Astronomy

1. Introduction
   - neutrino elementary particle

2. Neutrino detection
   - Chemistry
   - Čerenkov
   - Particle-matter interaction

3. Experiments
   - Homestake
   - KamiokaNDE → super-Kamiokande
   - Antares
   - IceCube

4. Conclusion
   - Future
   - Multi-messenger

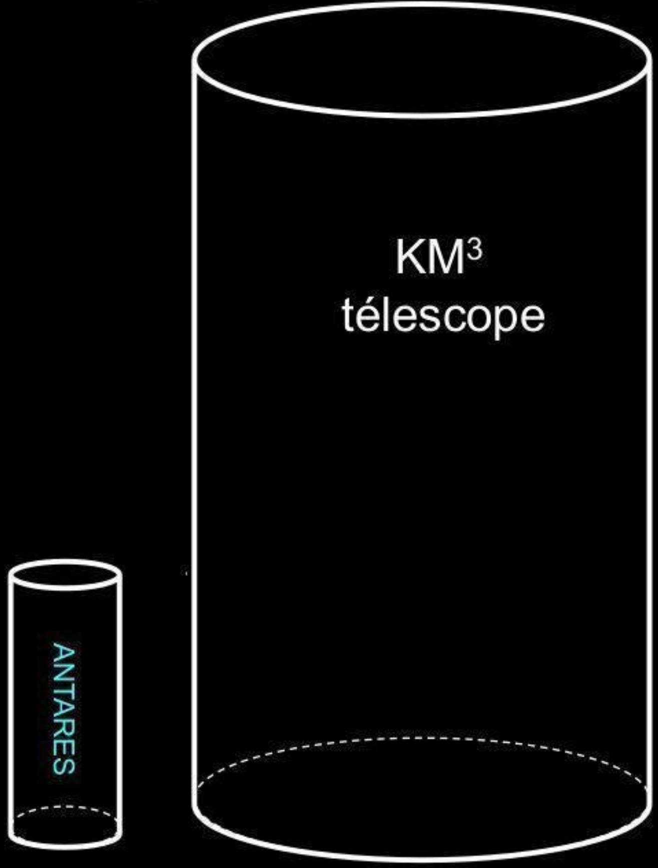


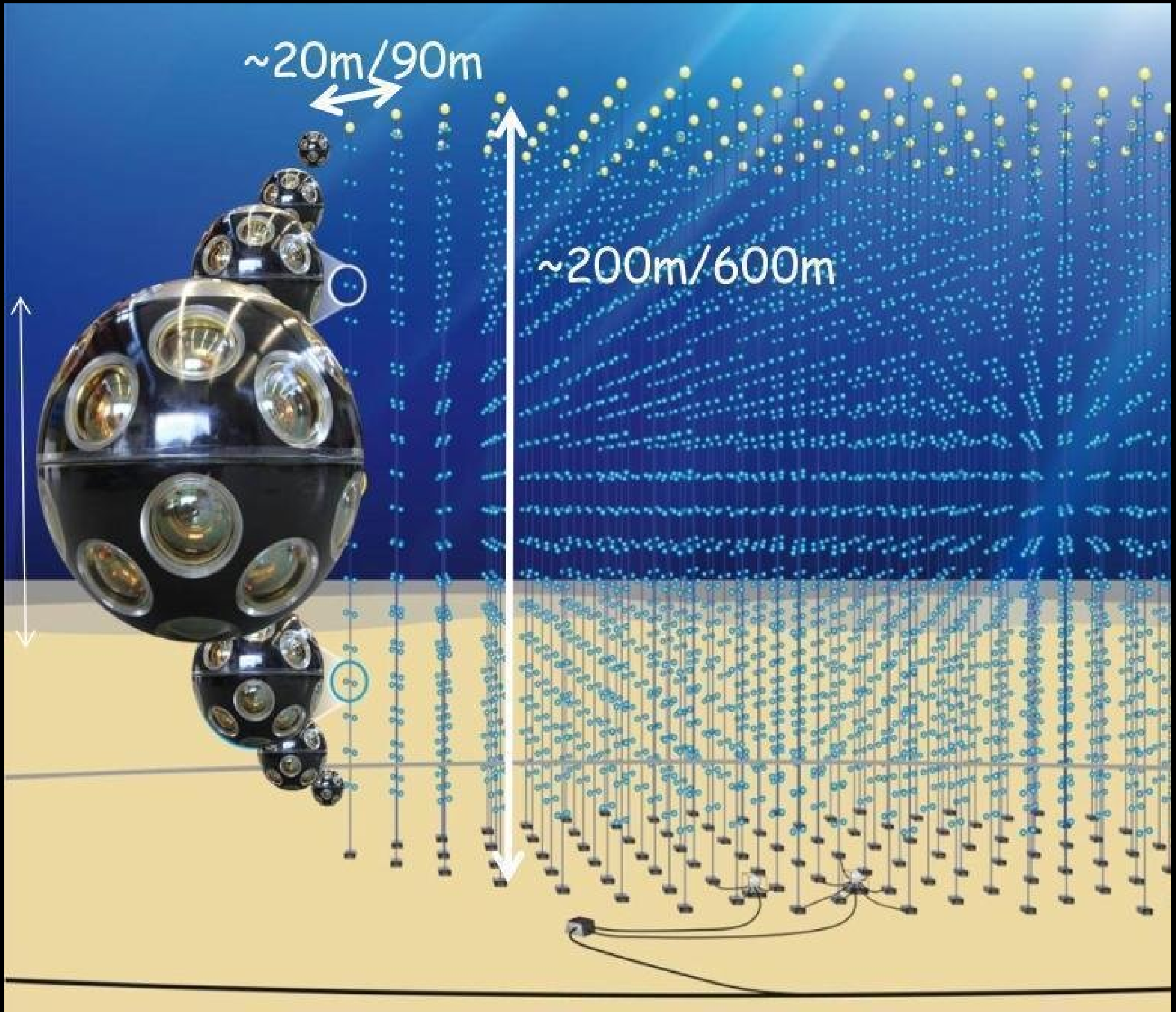
4. Conclusion

Future

1987 Antares

1987 Km3net → 2026





4. Conclusion

1987 Antares

1987 Km3net → 2026
2 sites: Toulon/France & Sicile/Italie

Future

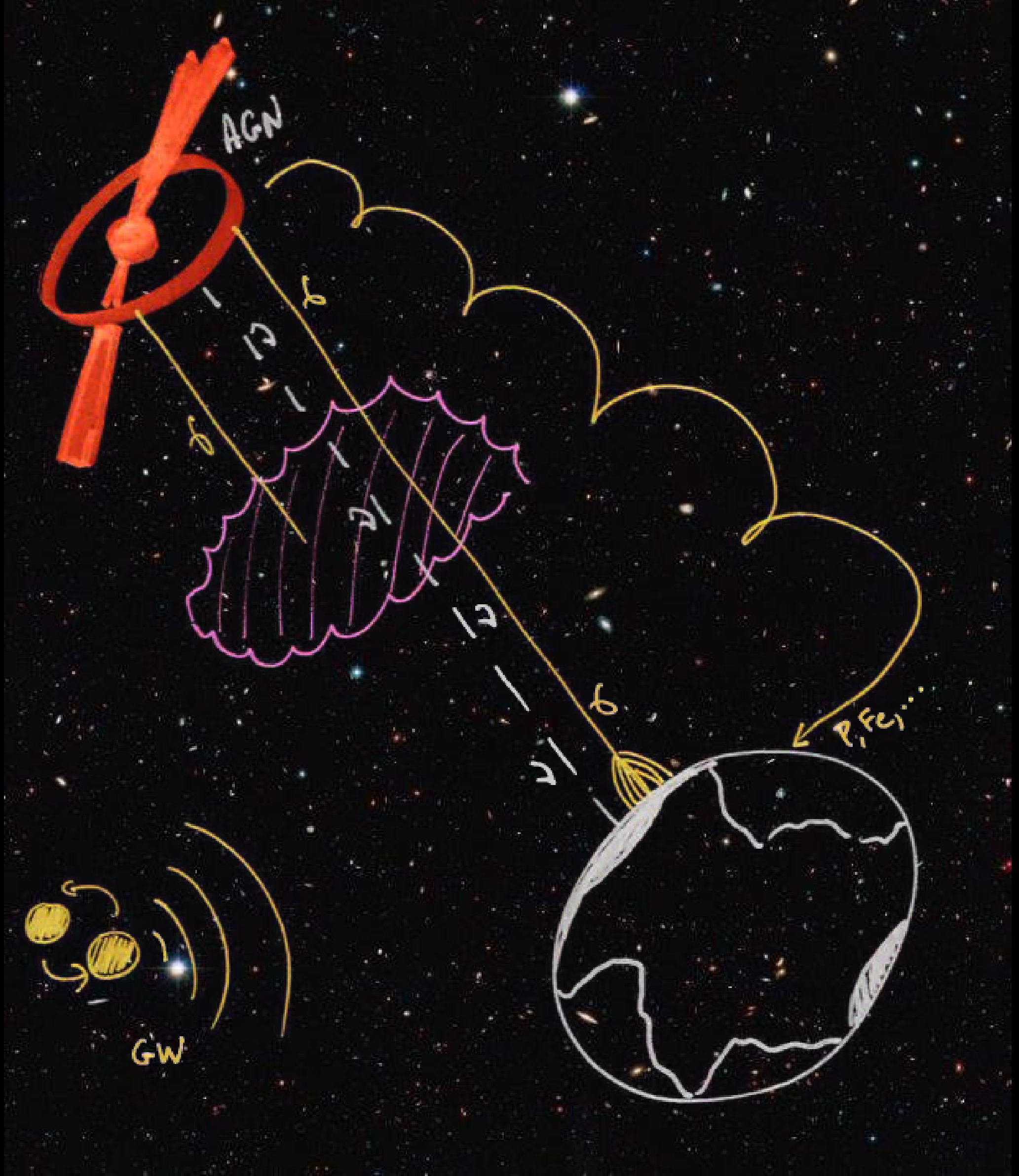
4. Conclusion

Multi-messenger

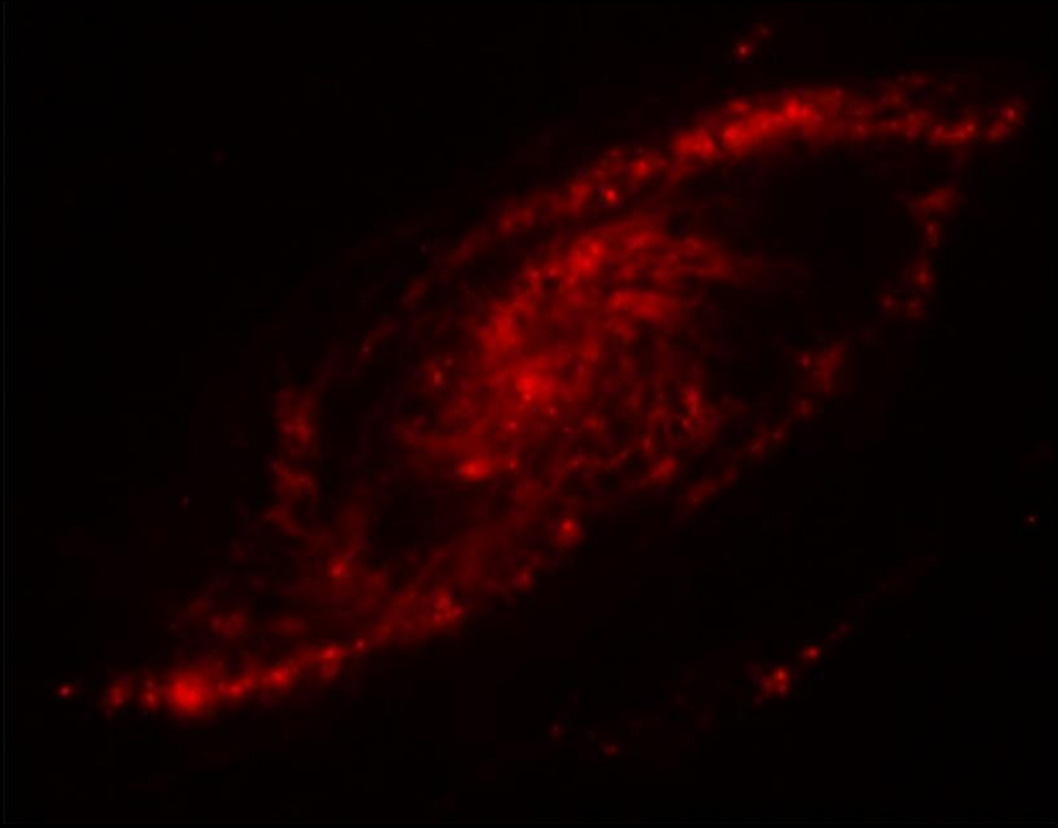
All information (radiations) should be used to constrain any astrophysics model

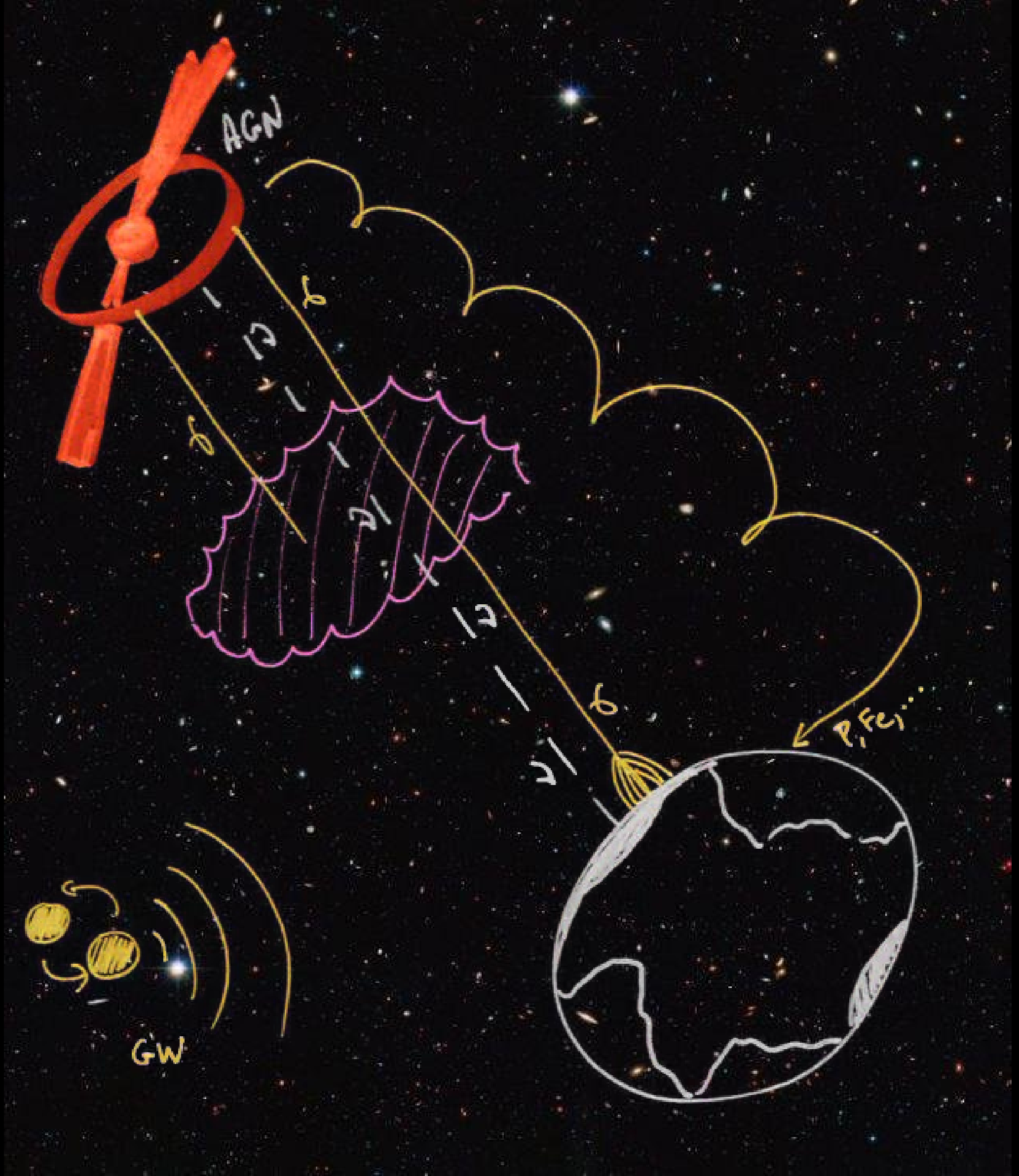
- optic
- Infra-red
- X
- radio
- GW

Optics

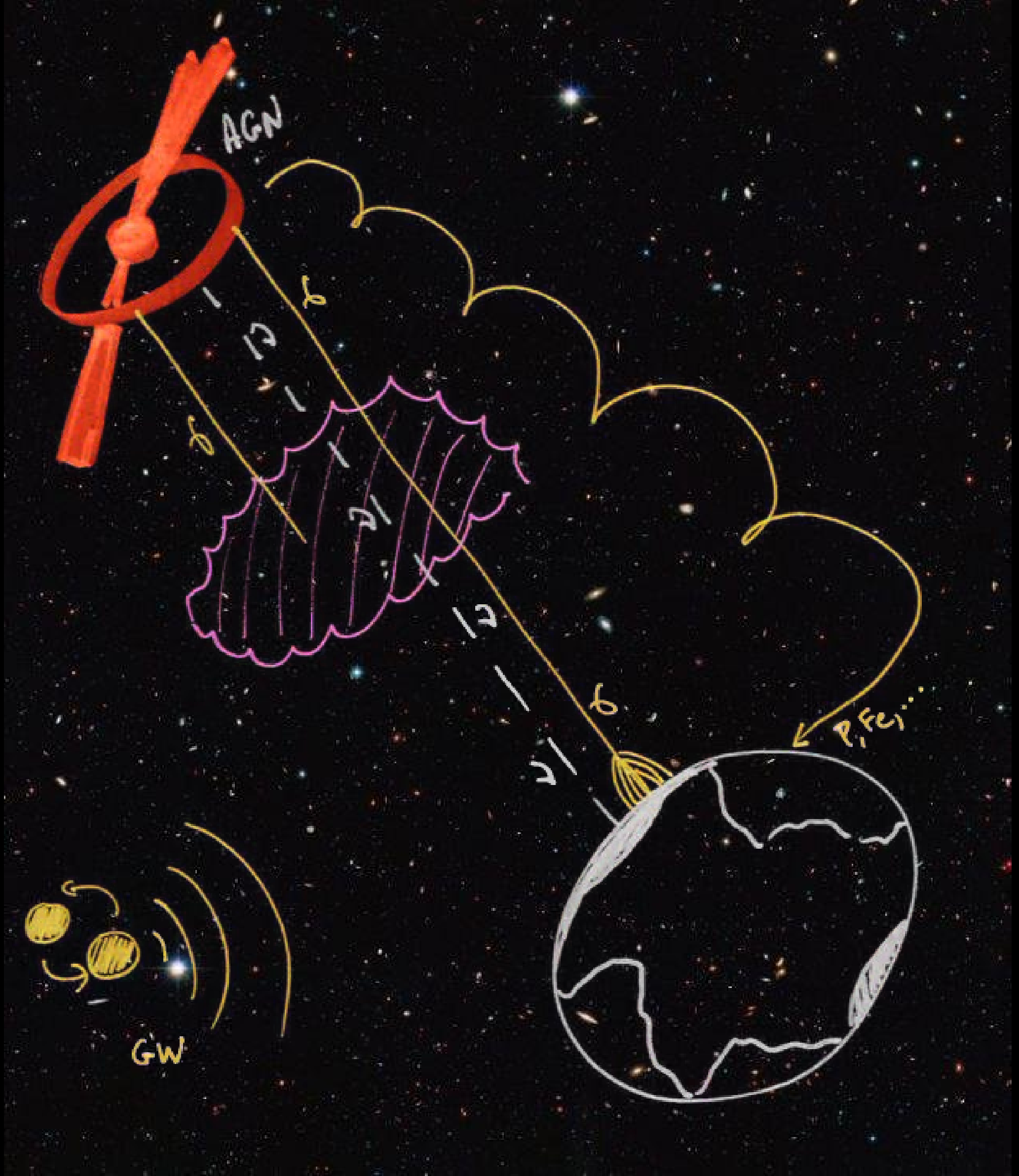


Infra-red

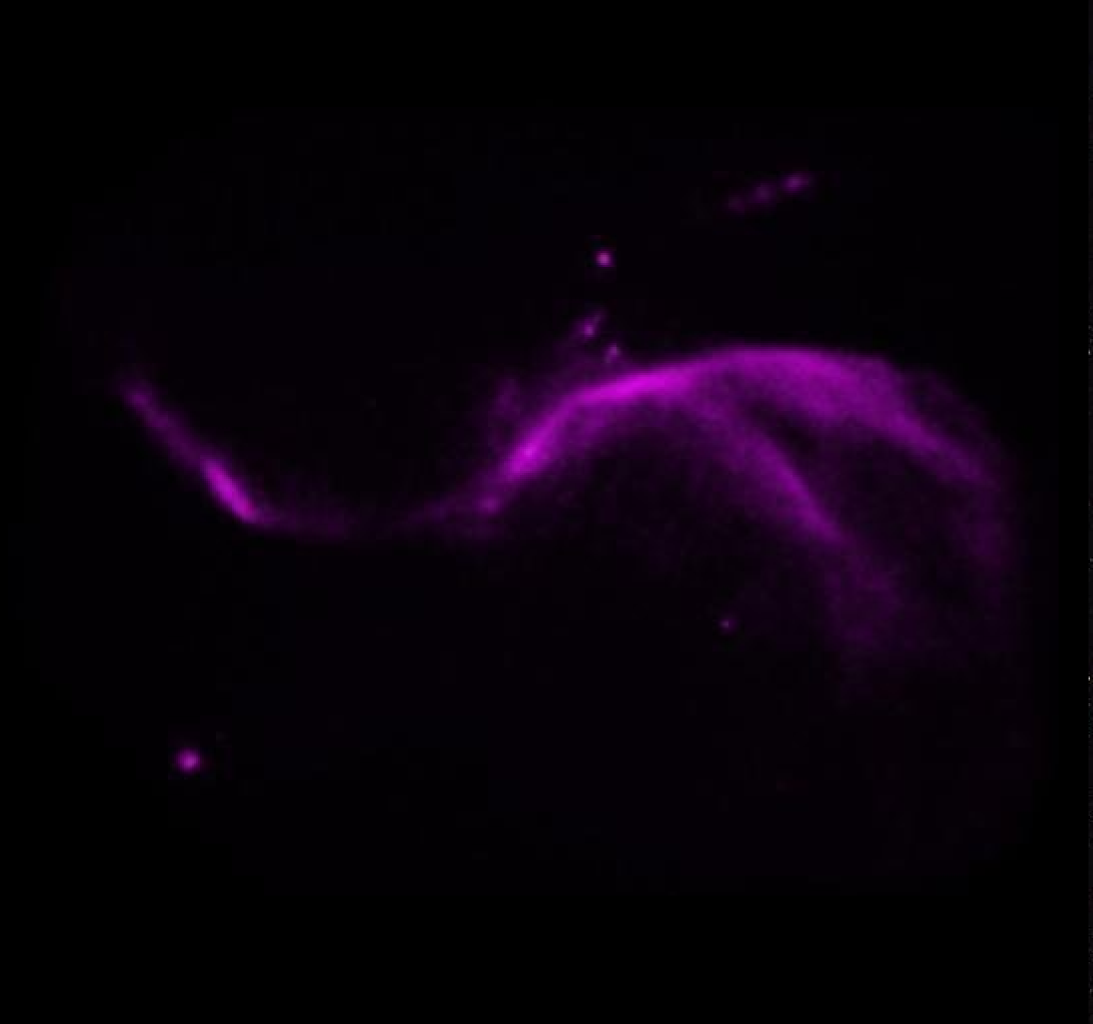


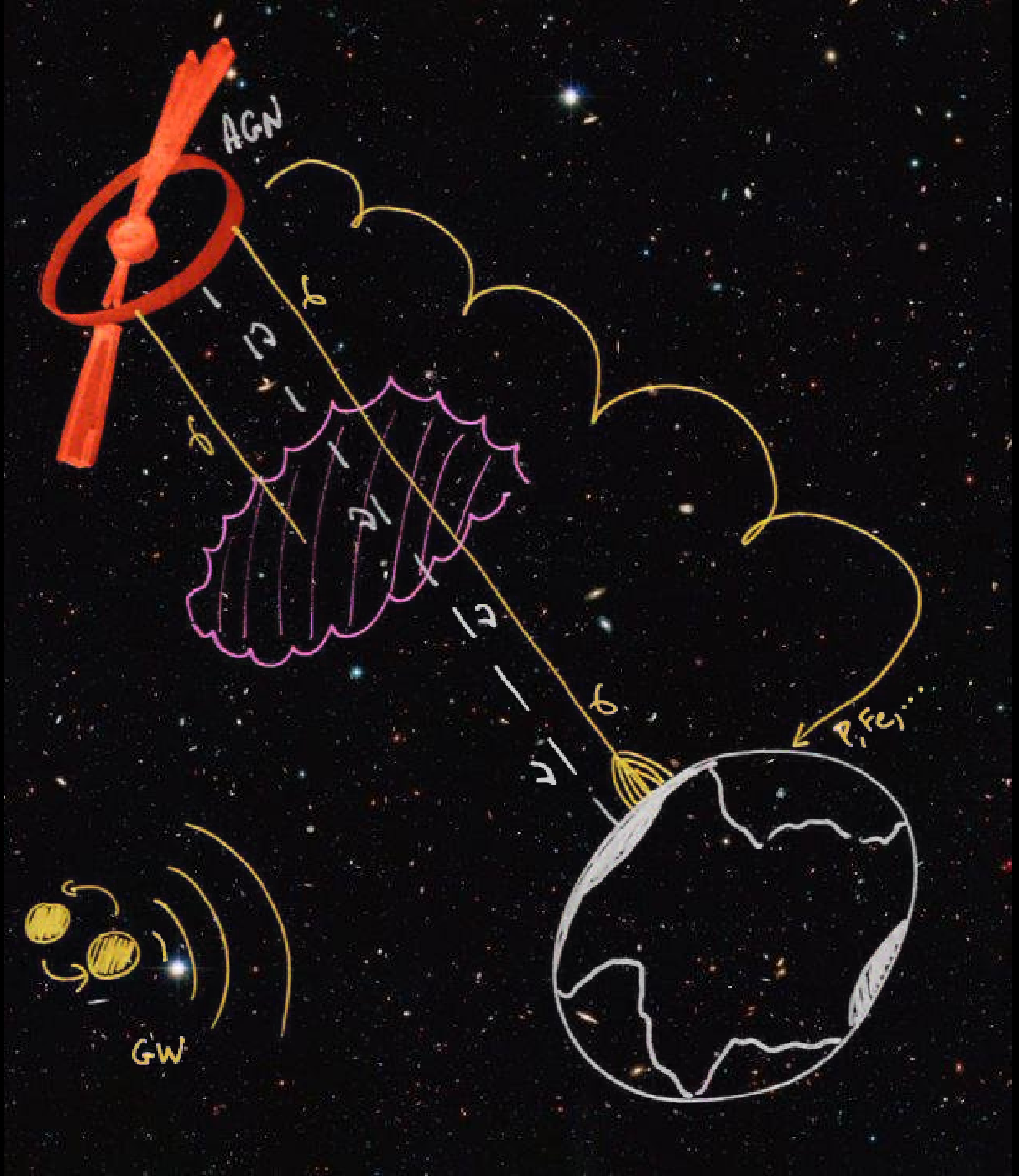


X

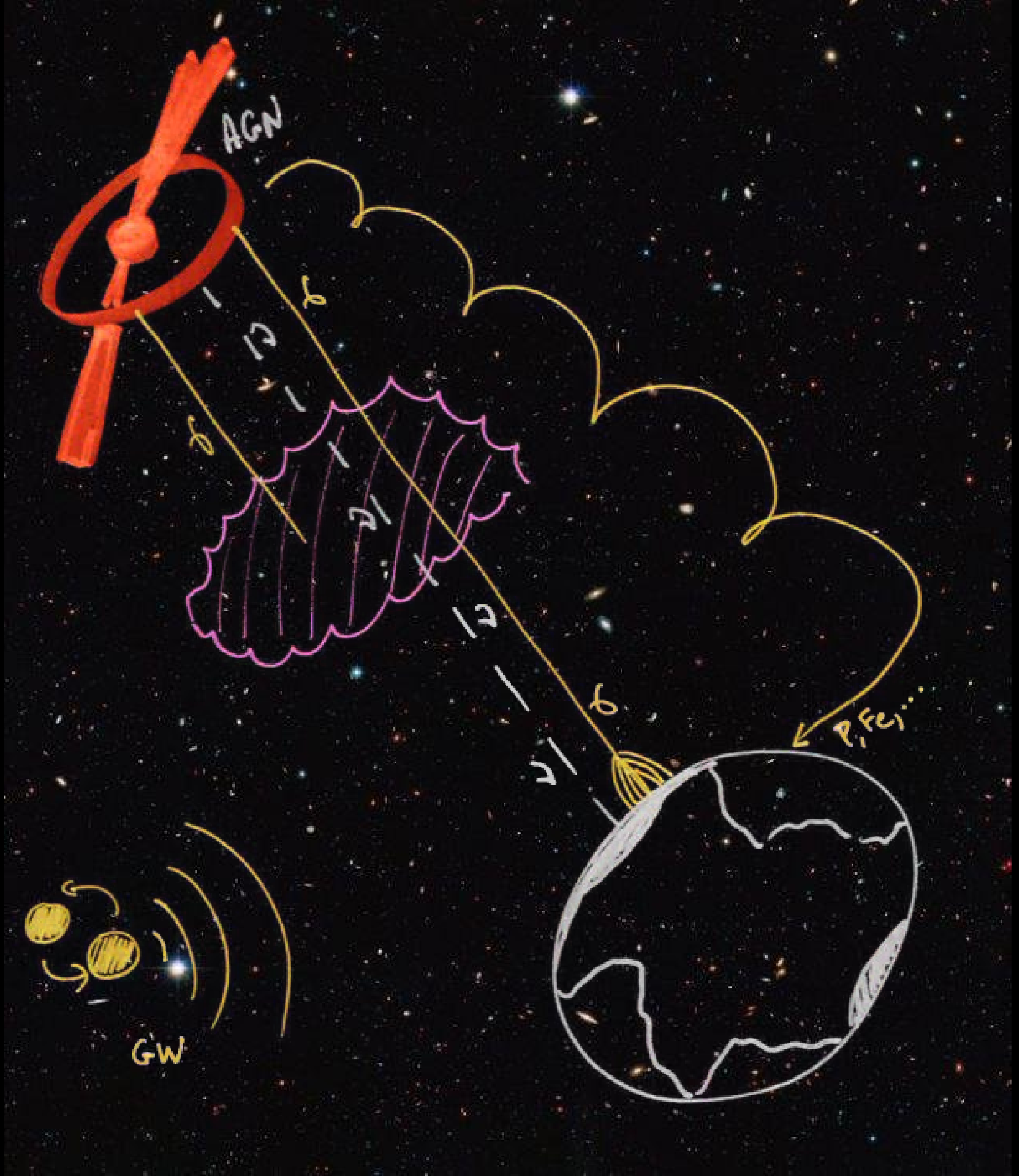


Radio





All



Thanks for your patience !