Title: Particle/Astro Observations 1

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Abstract:

High-Energy Astrophysical Neutrinos

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Chargeless, weakly-interacting neutrinos are ideal astronomical messengers because they travel through space without scattering, absorption, or deflection. They provide the only unobstructed view of cosmic accelerators. But this weak interaction also makes them notoriously difficult to detect, leading to neutrino observatories requiring large-scale detectors. The IceCube experiment discovered PeV-energy neutrinos originating beyond the Sun, with energies bracketed by those of TeV-energy gamma rays and EeV-energy extragalactic cosmic rays. In this chapter, we discuss the IceCube neutrino telescope, the status of the observation of cosmic neutrinos, and what neutrinos can tell us about the nonthermal Universe. Besides the search for the sources of Galactic and extragalactic cosmic rays, the scientific missions of IceCube and similar instruments under construction in the Mediterranean Sea and Lake Baikal include the observation of Galactic supernova explosions, the search for dark matter, and the study of neutrinos themselves.

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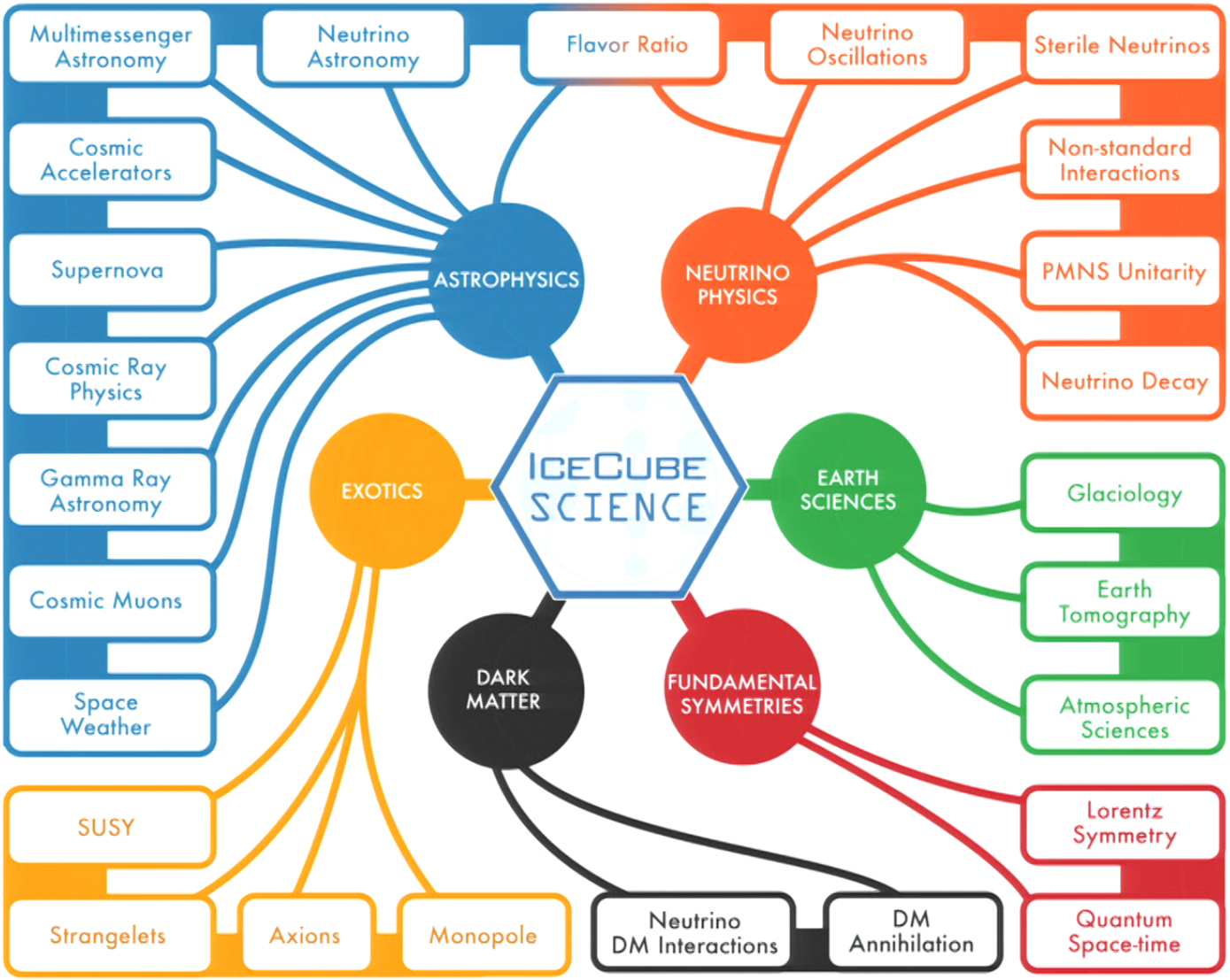
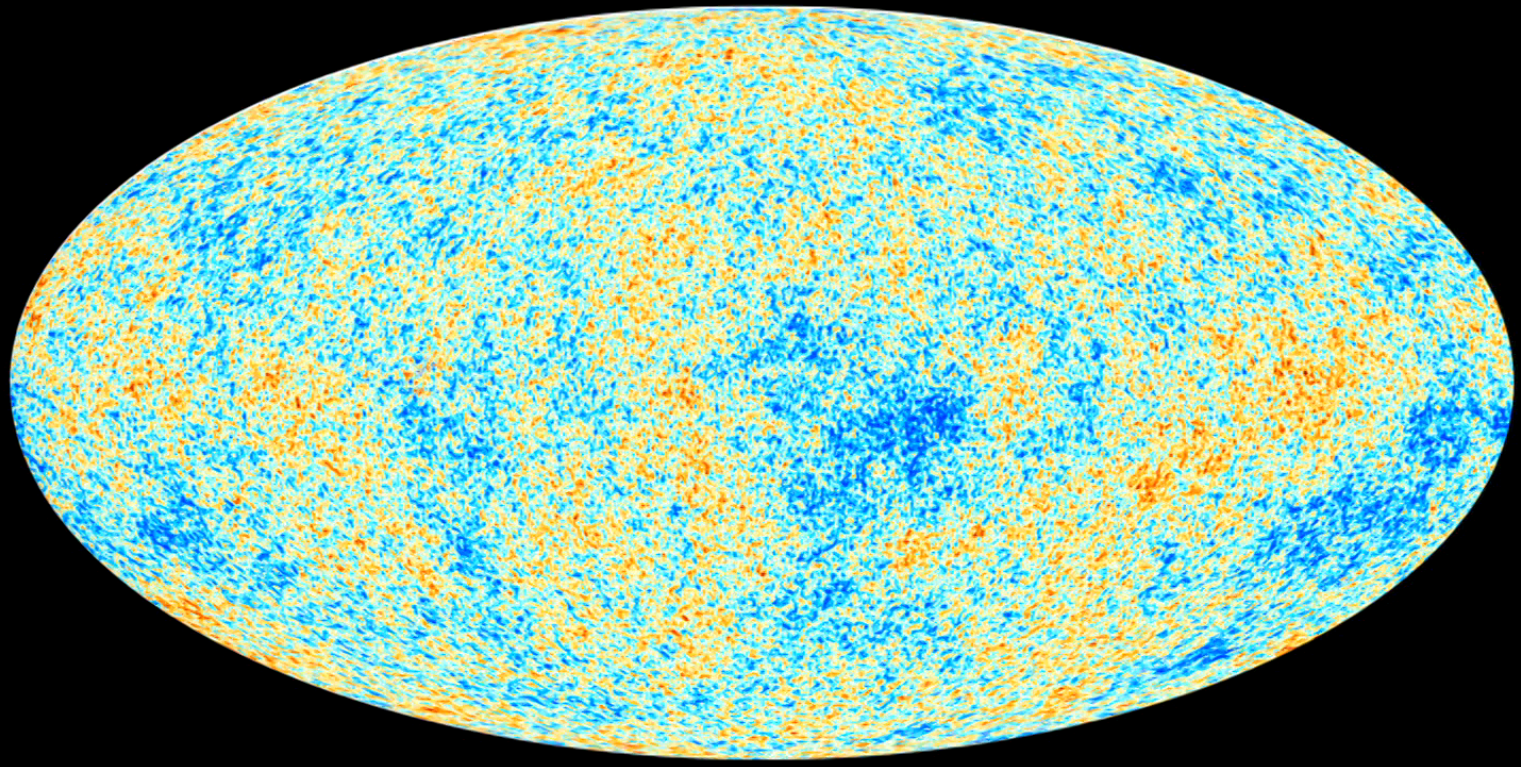

IceCube Science
Astrophysics
Multimessenger Astronomy
Neutrino Astronomy
Cosmic Accelerators
Supernova
Cosmic Ray Physics
Gamma Ray Astronomy
Cosmic Muons
Space Weather
Neutrino Physics
Flavor Ratio
Neutrino Oscillations
Sterile Neutrinos
Non-standard Interactions
PMNS Unitarity
Neutrino Decay
Exotics
SUSY
Strangelets
Axions
Monopole
Earth Sciences
Glaciology
Earth Tomography
Atmospheric Sciences
Dark Matter
Neutrino DM Interactions
DM Annihilation
Fundamental Symmetries
Lorentz Symmetry
Quantum Space-time

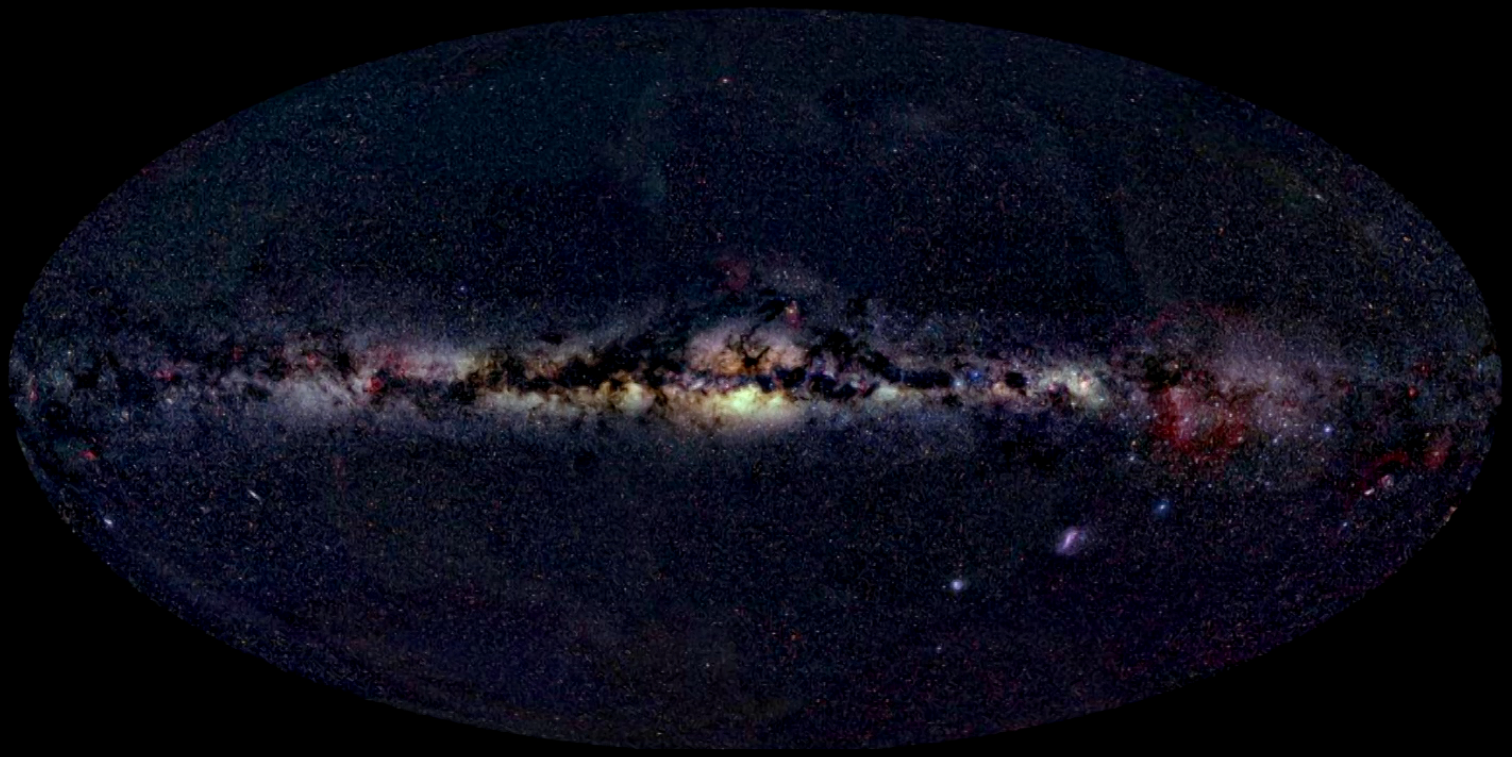
Cosmic Horizons – Microwave Radiation

380.000 years after the Big Bang



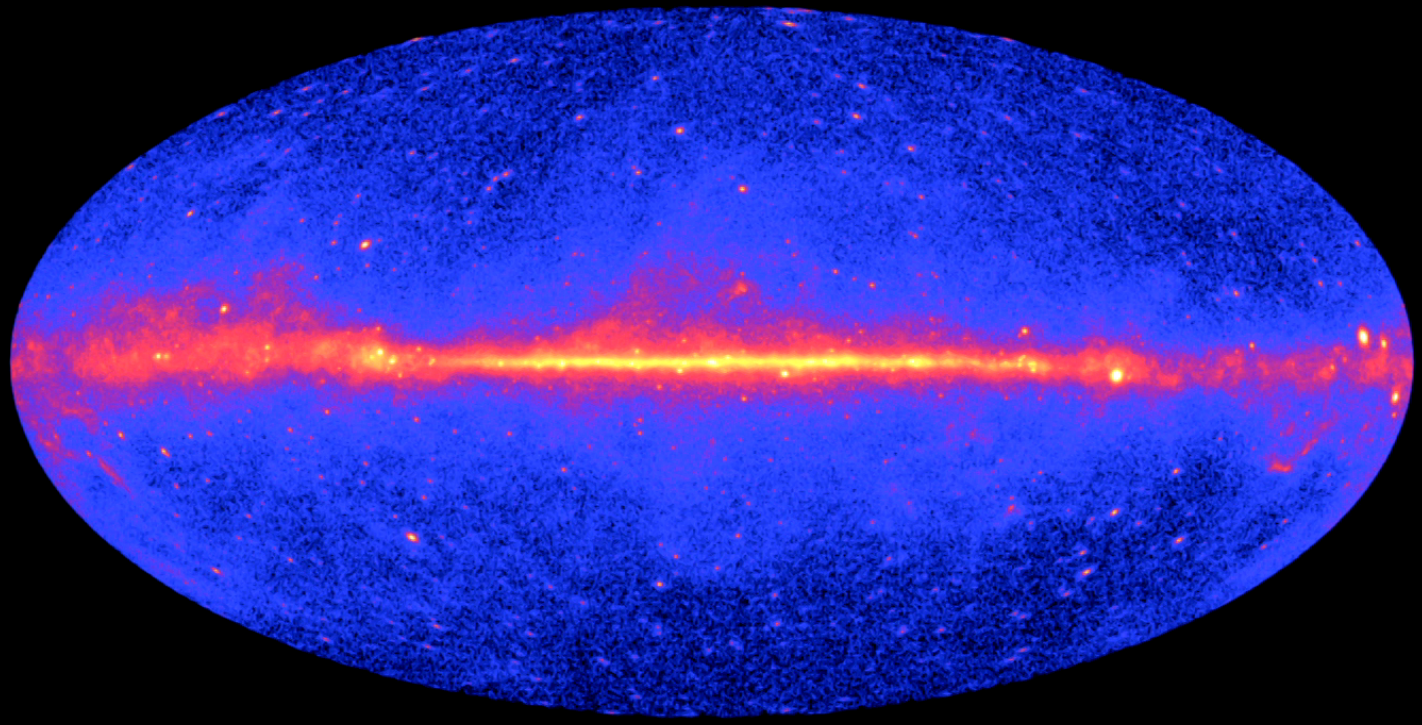
wavelength = 1 mm ⇔ energy = 10^{-4} eV

Cosmic Horizons – Optical Sky



wavelength = 10^{-6} m ⇔ energy = 1 eV

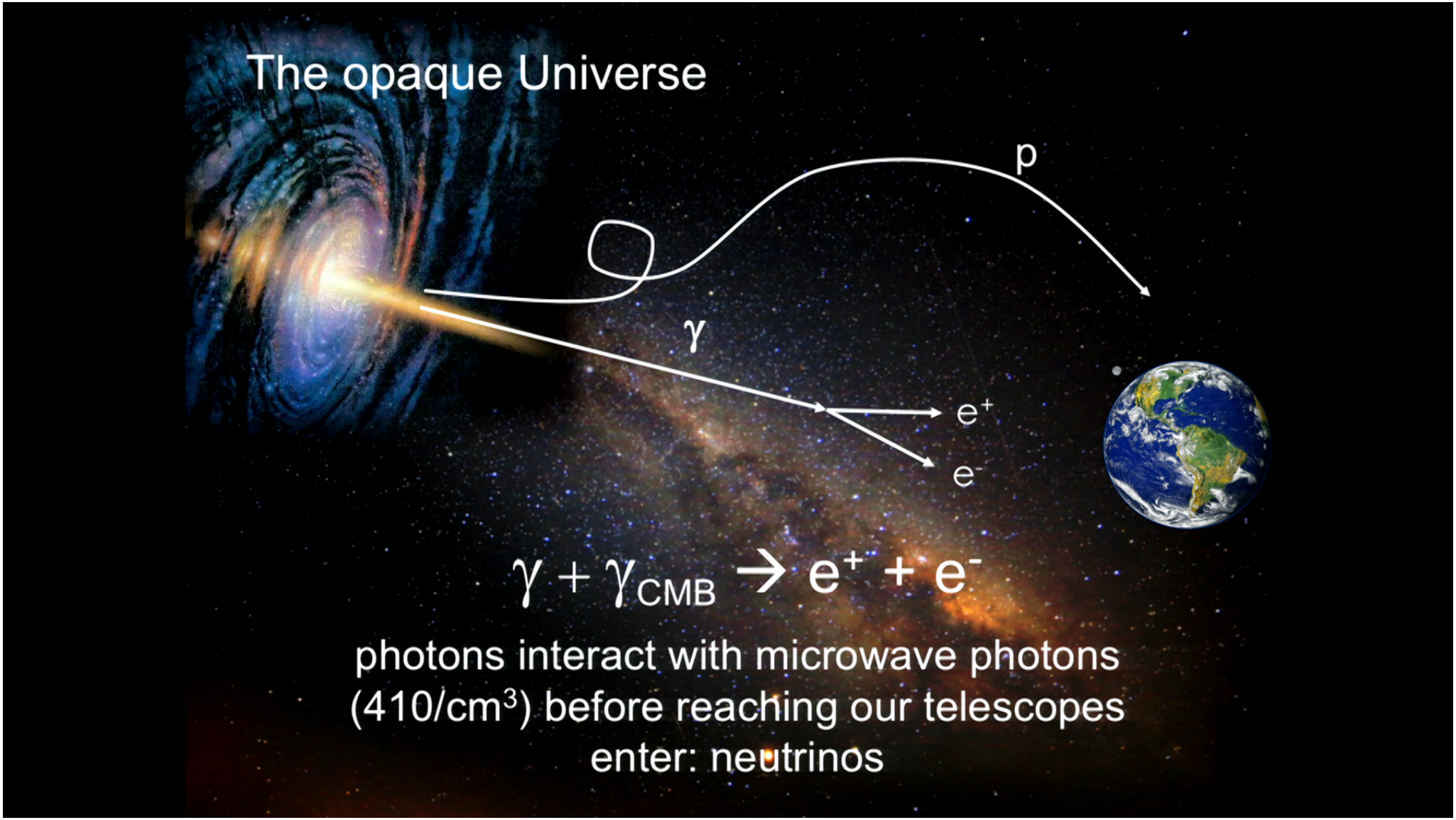
Cosmic Horizons – Gamma Radiation

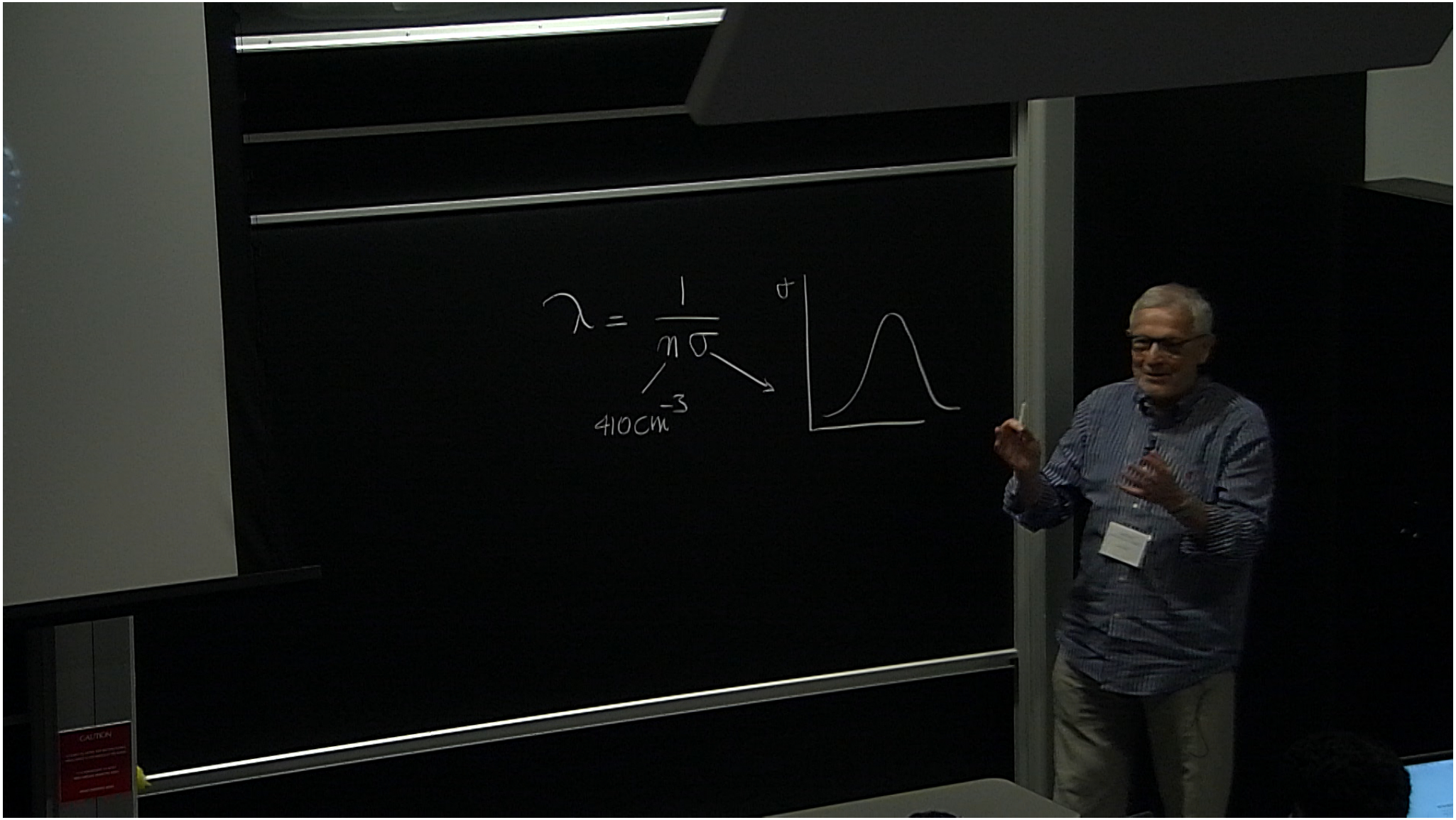


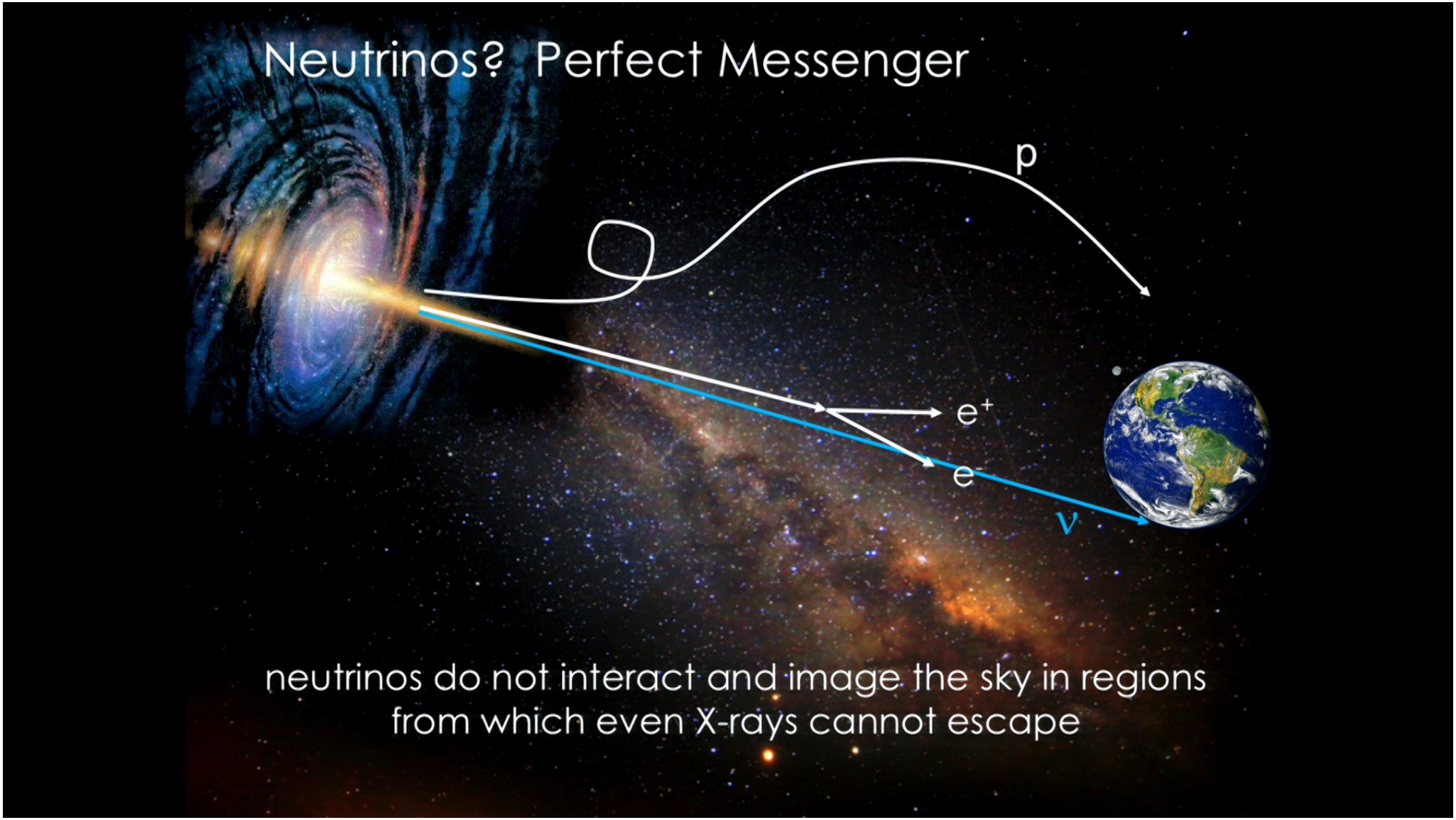
wavelength = 10^{-15} m $\Leftrightarrow$ energy = 10^{9} eV

Cosmic Horizons – Gamma Radiation

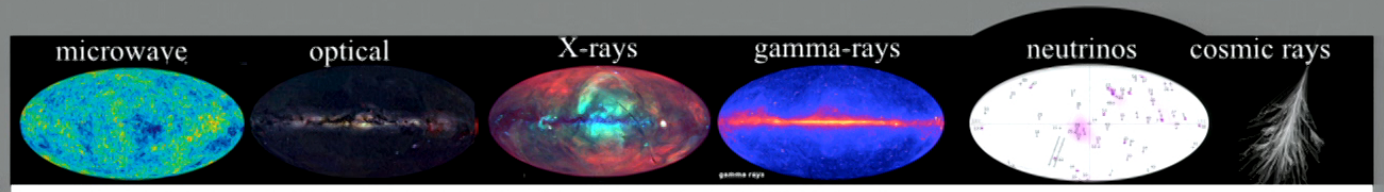
energy = 10^{15} eV

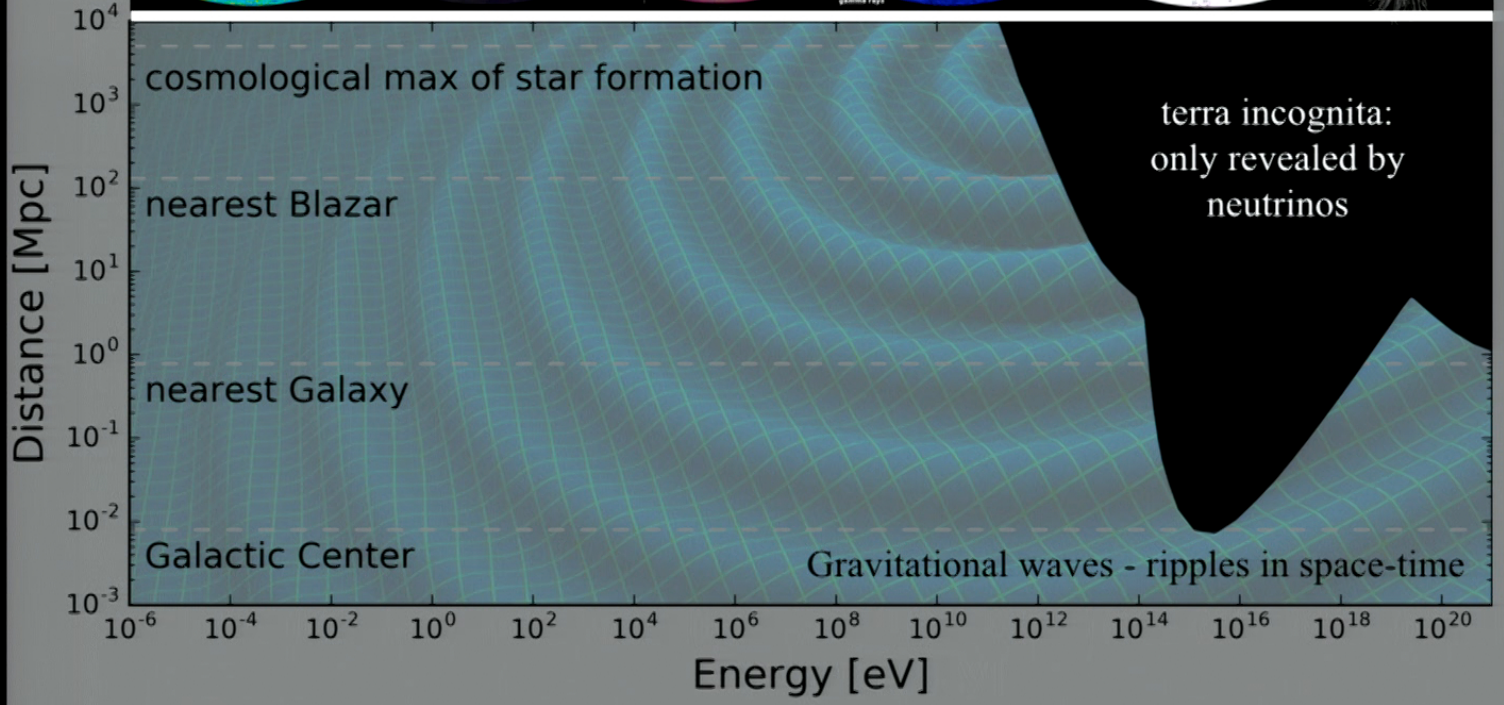

The opaque Universe
p
γ
e+
e-
γ + γCMB → e+ + e-
photons interact with microwave photons
(410/cm3) before reaching our telescopes
enter: neutrinos


$\lambda = \frac{1}{n\sigma}$
$410\,cm^{-3}$
σ


Neutrinos? Perfect Messenger
p
e+
e-
ν
neutrinos do not interact and image the sky in regions
from which even X-rays cannot escape

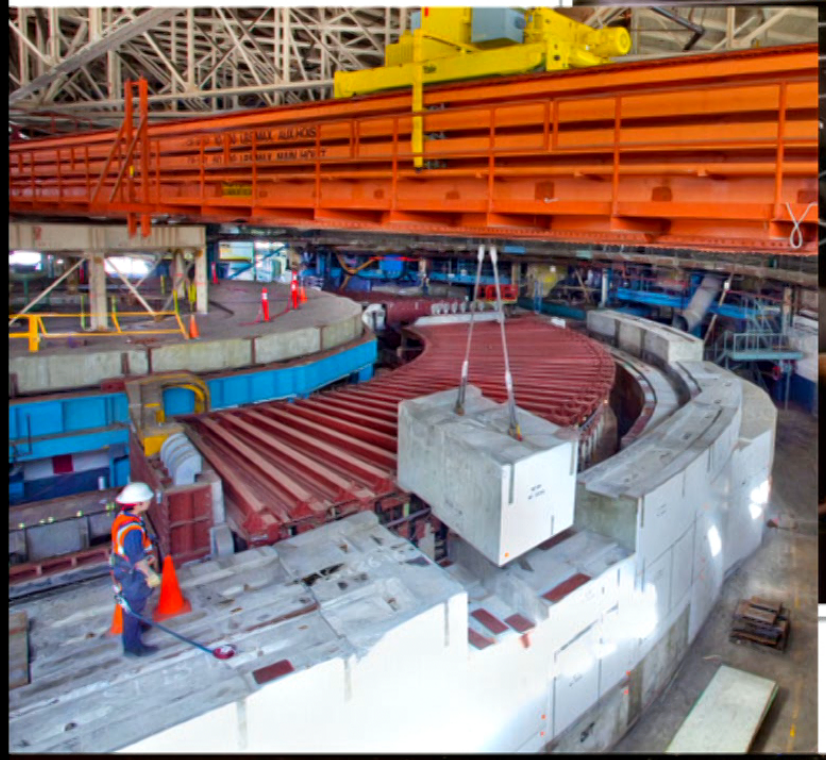
Multi-Messenger Astronomy

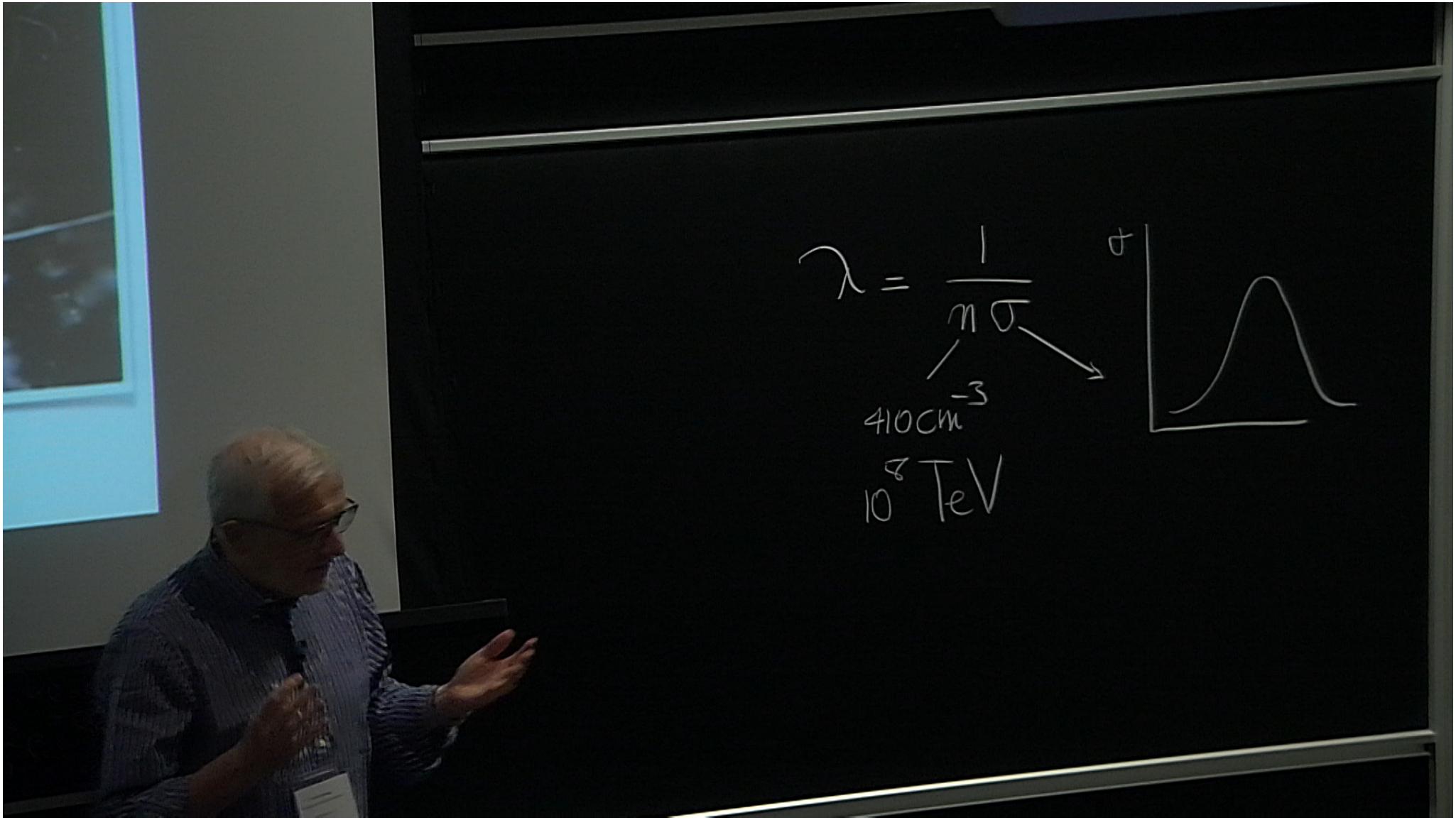




20% of the Universe is opaque to the EM spectrum

energy ~ [magnetic field B] x [accelerator's size R]

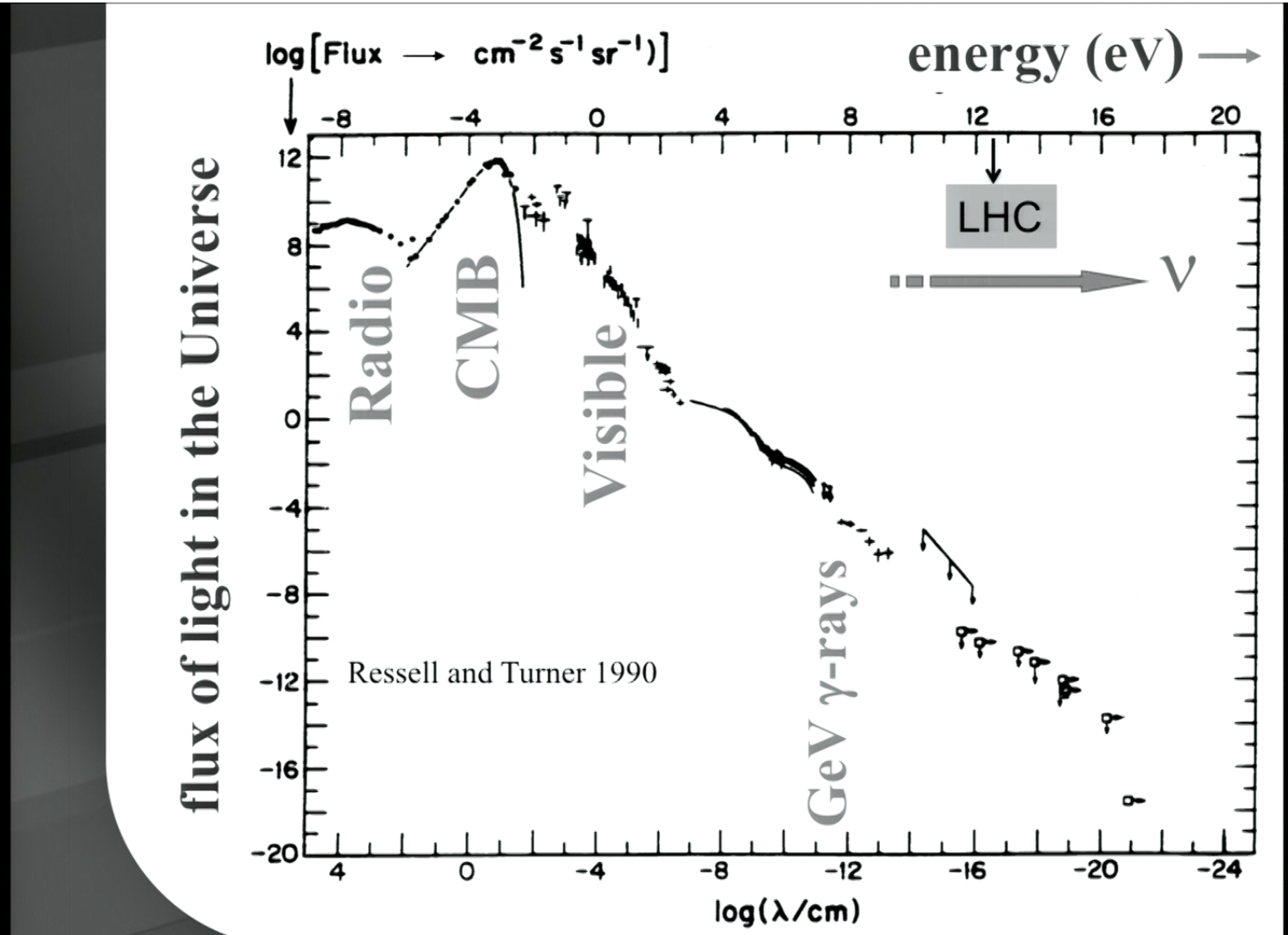


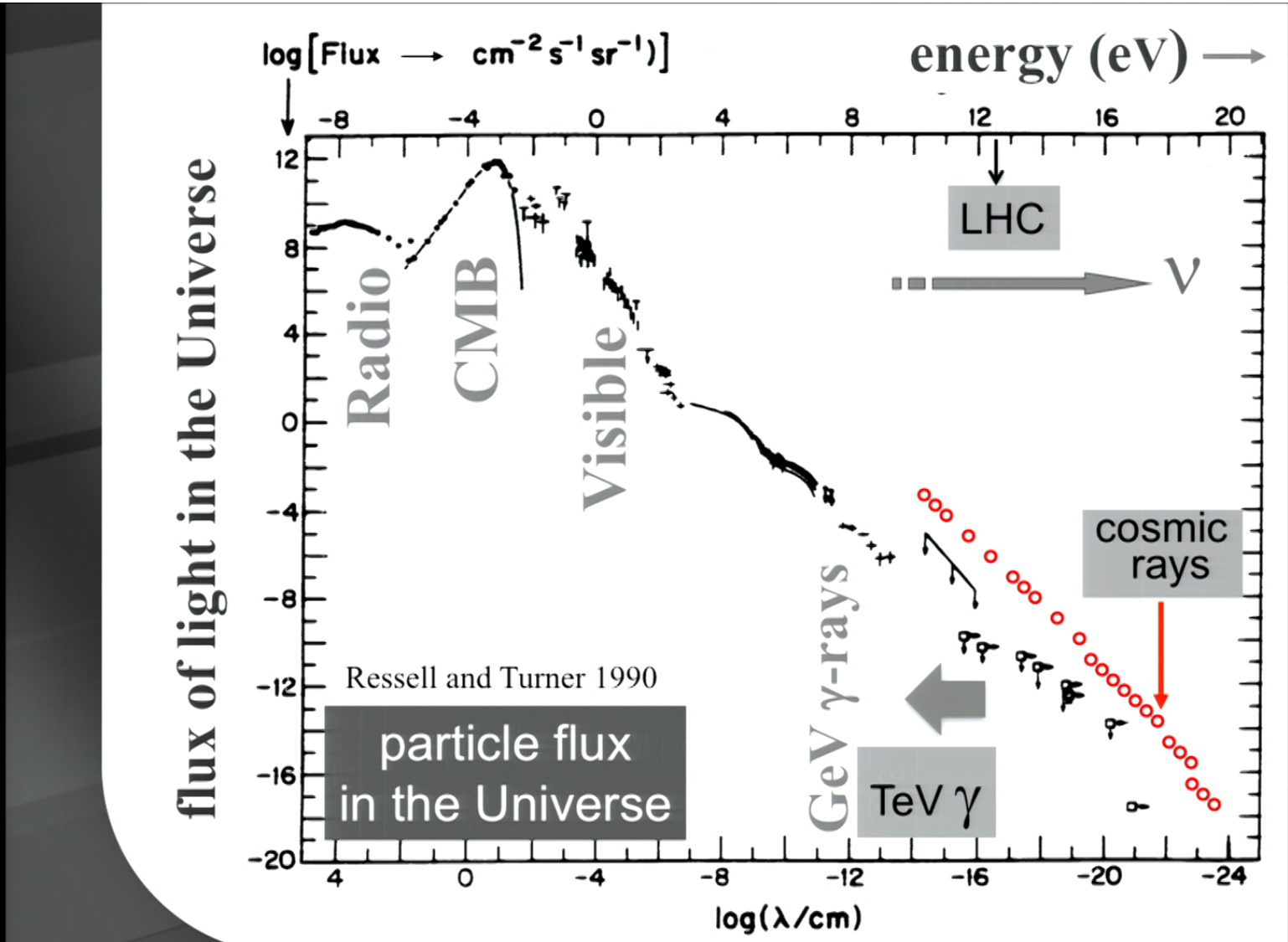

λ = 1 / nσ
σ
410cm^-3
10^8 TeV

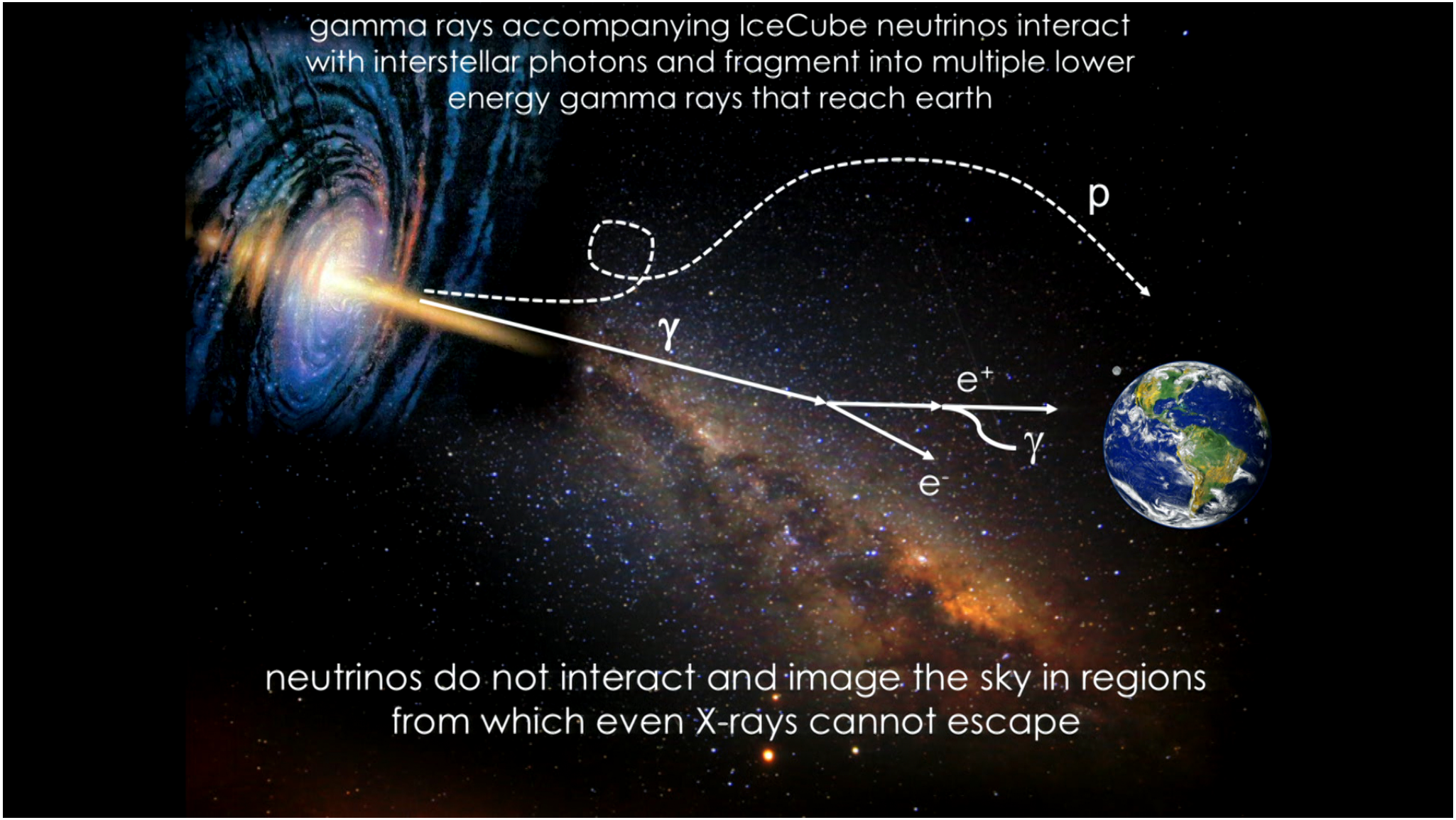
Neutrinos? Perfect Messenger

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

- … but difficult to detect: how large a detector?


log [Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
flux of light in the Universe
Radio
CMB
Visible
GeV γ-rays
LHC
ν
Ressell and Turner 1990
log(λ/cm)


log [Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
flux of light in the Universe
log(λ/cm)
Radio
CMB
Visible
GeV γ-rays
LHC
ν
cosmic rays
TeV γ
Ressell and Turner 1990
particle flux in the Universe


gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth
p
γ
e+
γ
e-
neutrinos do not interact and image the sky in regions from which even X-rays cannot escape

cosmic accelerators ?

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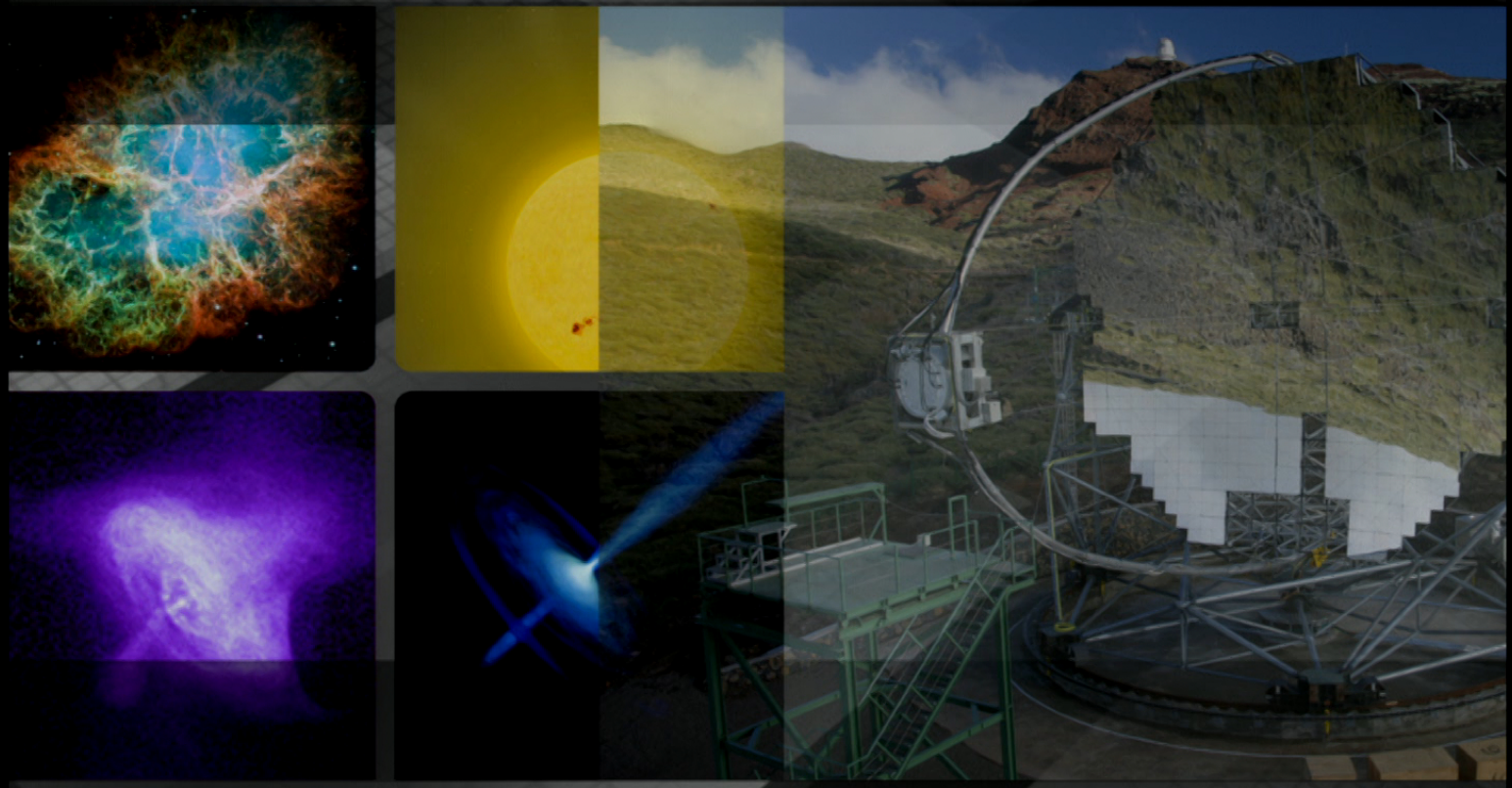
university of wisconsin
http://icecube.wisc.edu



The real voyage is not to travel to new landscapes,
but to see with new eyes. . . Marcel Proust

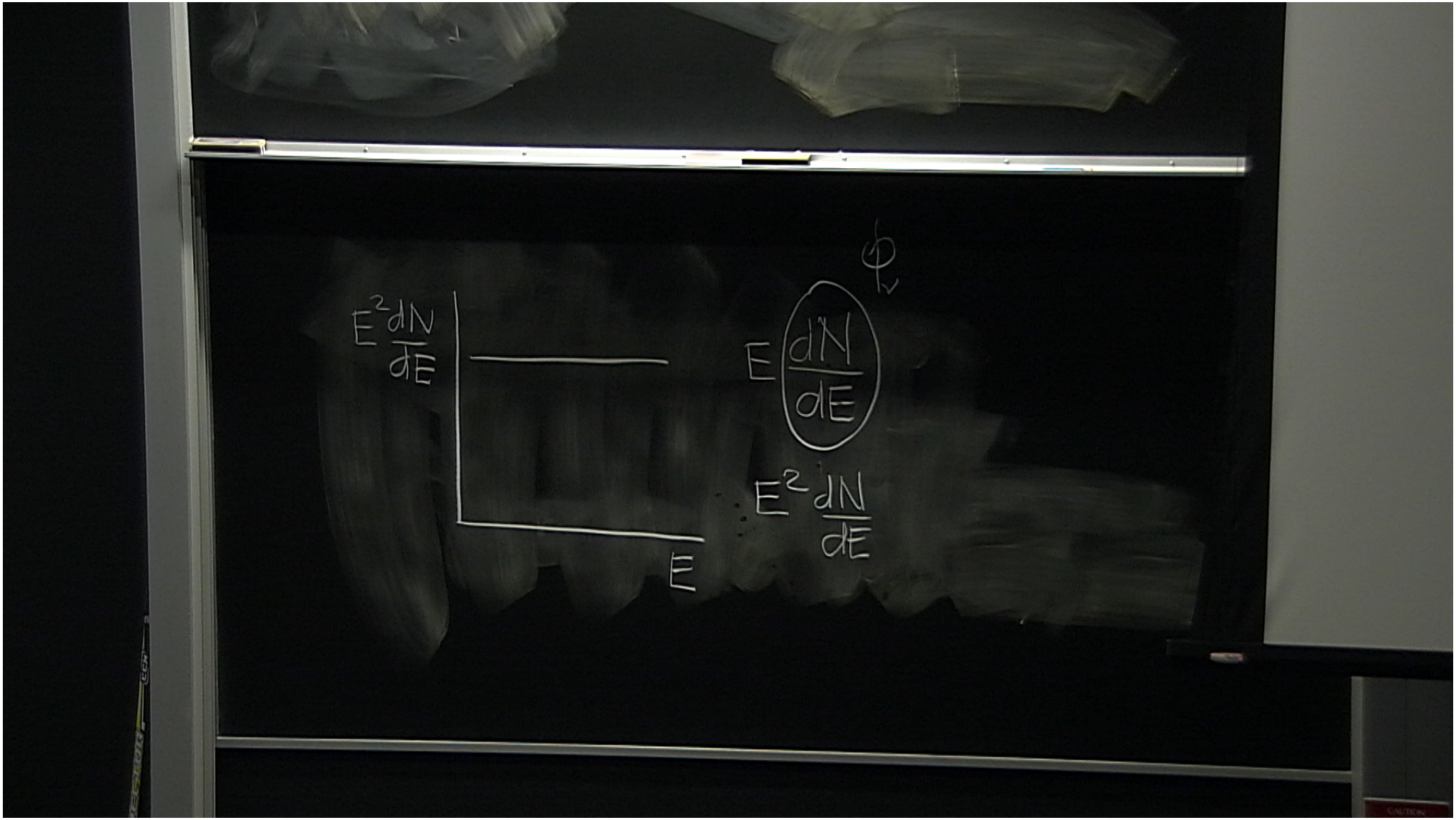
definitions

- flux $\left(particles\ per\ GeV\ per\ cm^2\ per\ s \right)$ $\quad \frac{dN}{dE} = c\rho$
- luminosity $\quad L = E^2 \frac{dN}{dEdt(d\Omega)}$
- density $\left(velocity \times \rho = total\ flux \right)$ $\quad \rho = \frac{4\pi}{c} \int \frac{dN}{dE} dE$
- energy density $\quad \rho_E = \frac{4\pi}{c} \int E \frac{dN}{dE} dE$
- mean free path $\quad \lambda = \frac{1}{n_{tar}\sigma}$
- energy loss distance $\quad R = \frac{E_f}{E_i} \lambda$

cosmic ray accelerators (preamble)

- best buy theory or why we believe that new astroparticle physics instrumentation will reveal the sources of the cosmic rays.

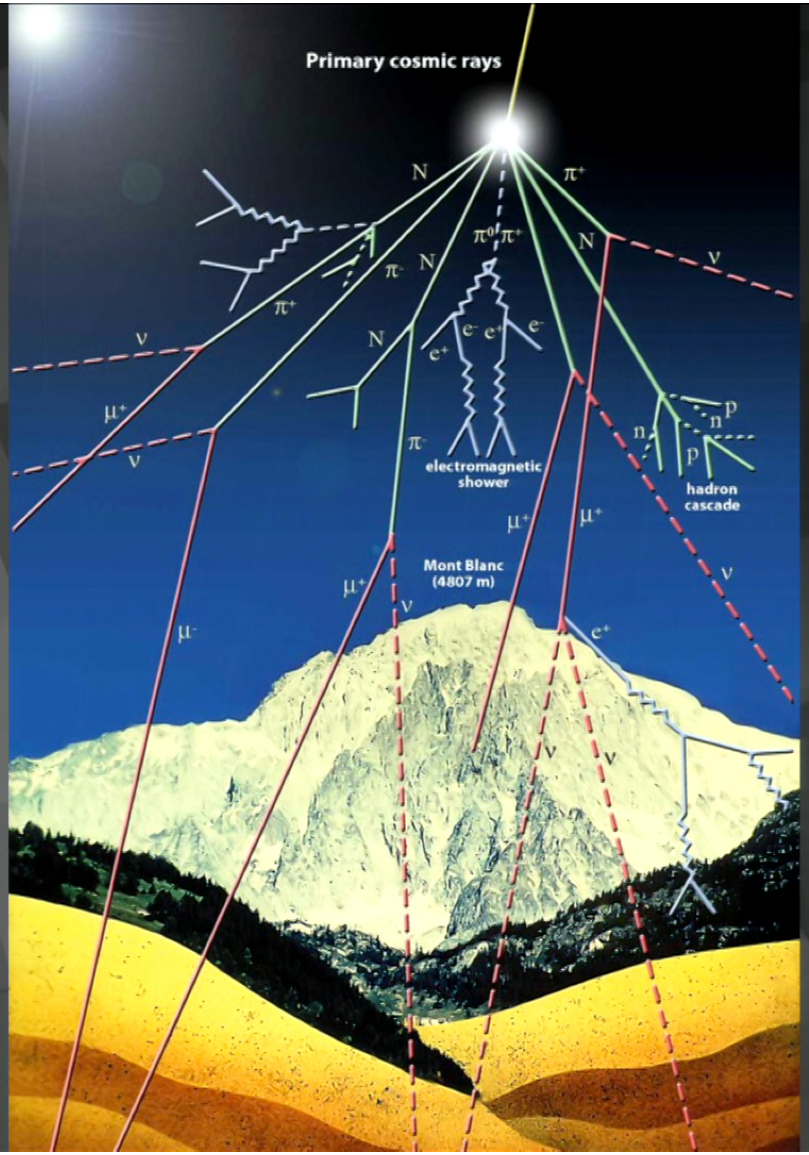
- cosmic rays, gamma rays and neutrinos
  - → many 1000 km^2 air shower arrays
  - → large arrays of ground-based gamma ray telescopes
  - → kilometer-cube neutrino detectors

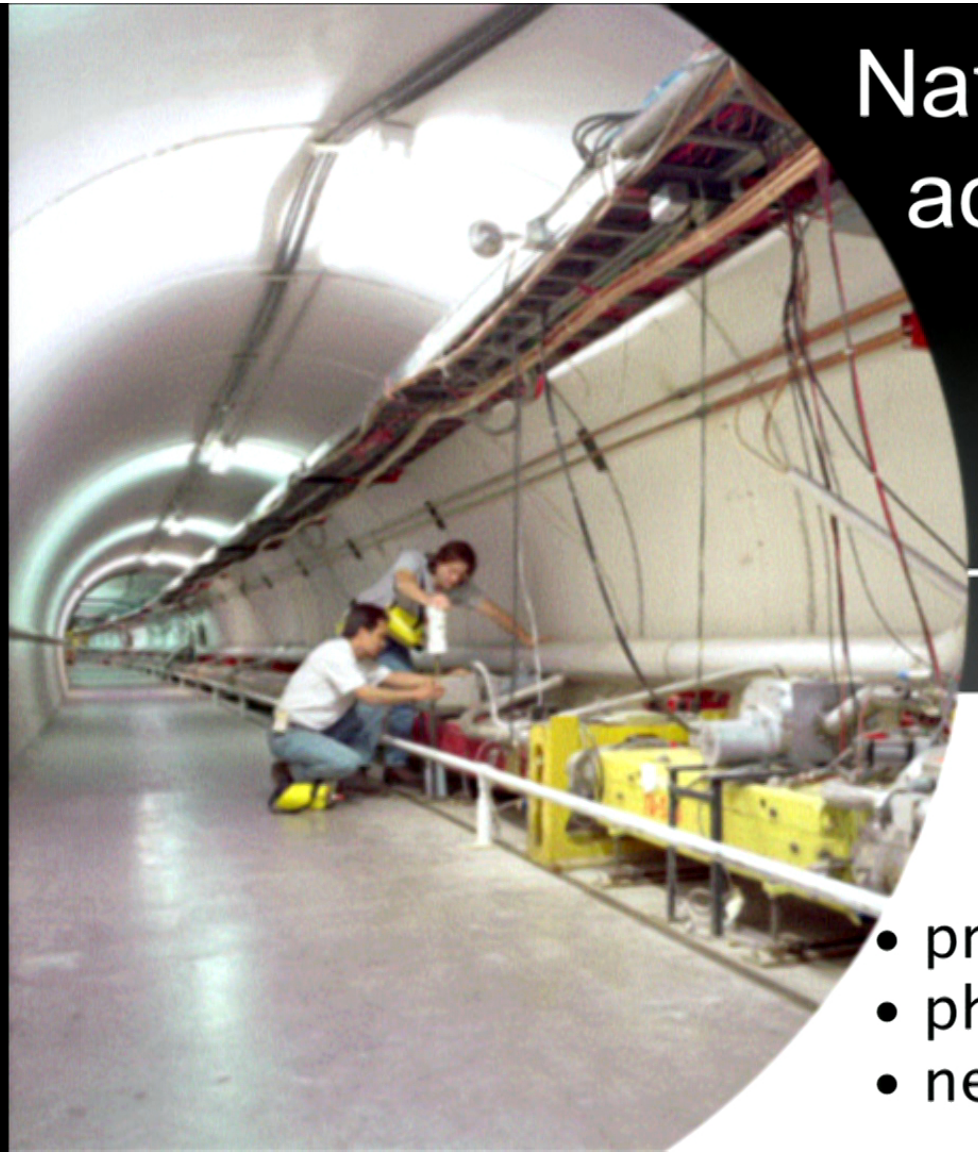

$E^2 \frac{dN}{dE}$
E
$E \frac{dN}{dE}$
Φ_ν
$E^2 \frac{dN}{dE}$

cosmic rays

Victor Hess
in 1912
discovers
radiation
from space

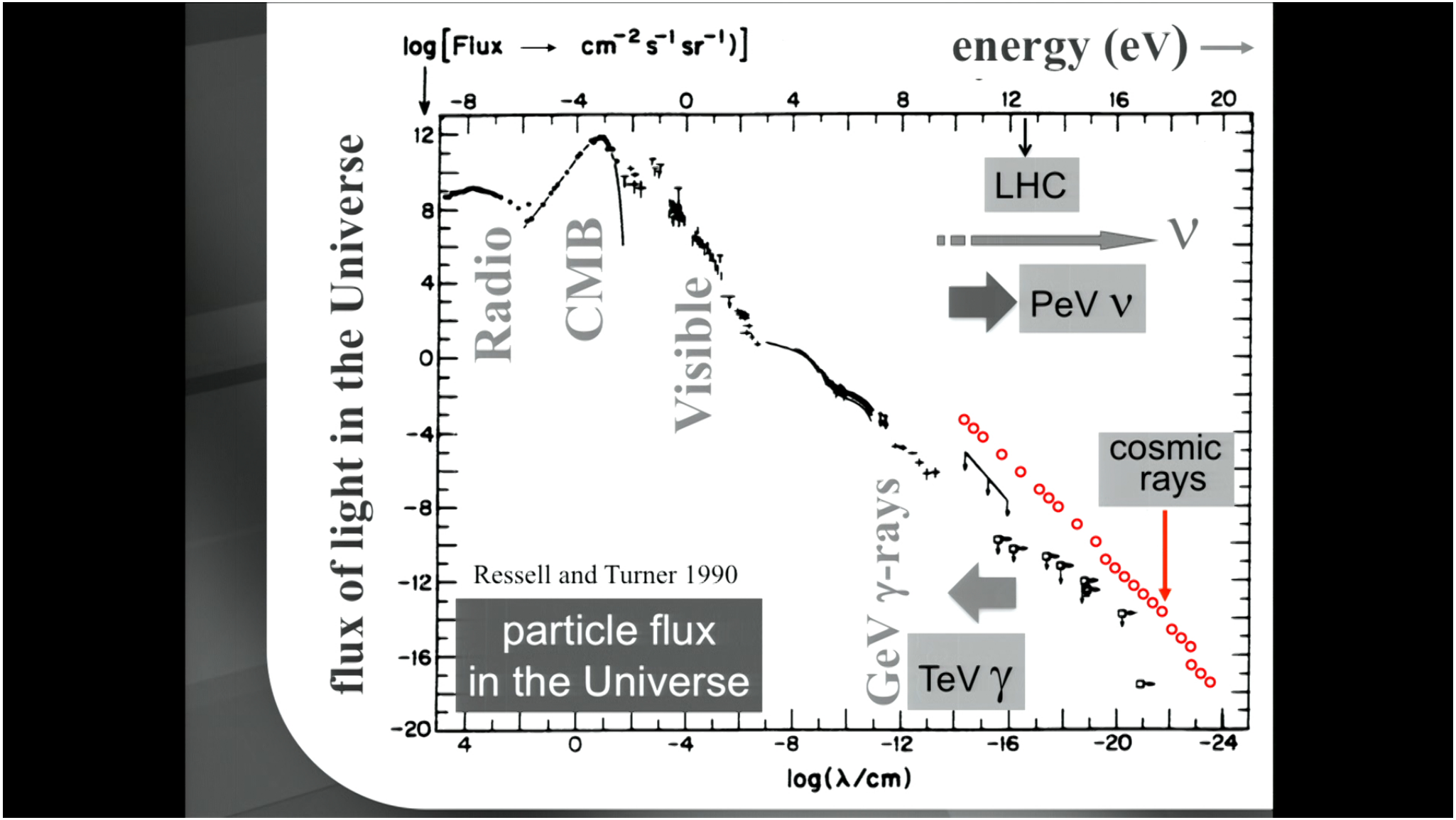
the oldest
puzzle
in astronomy



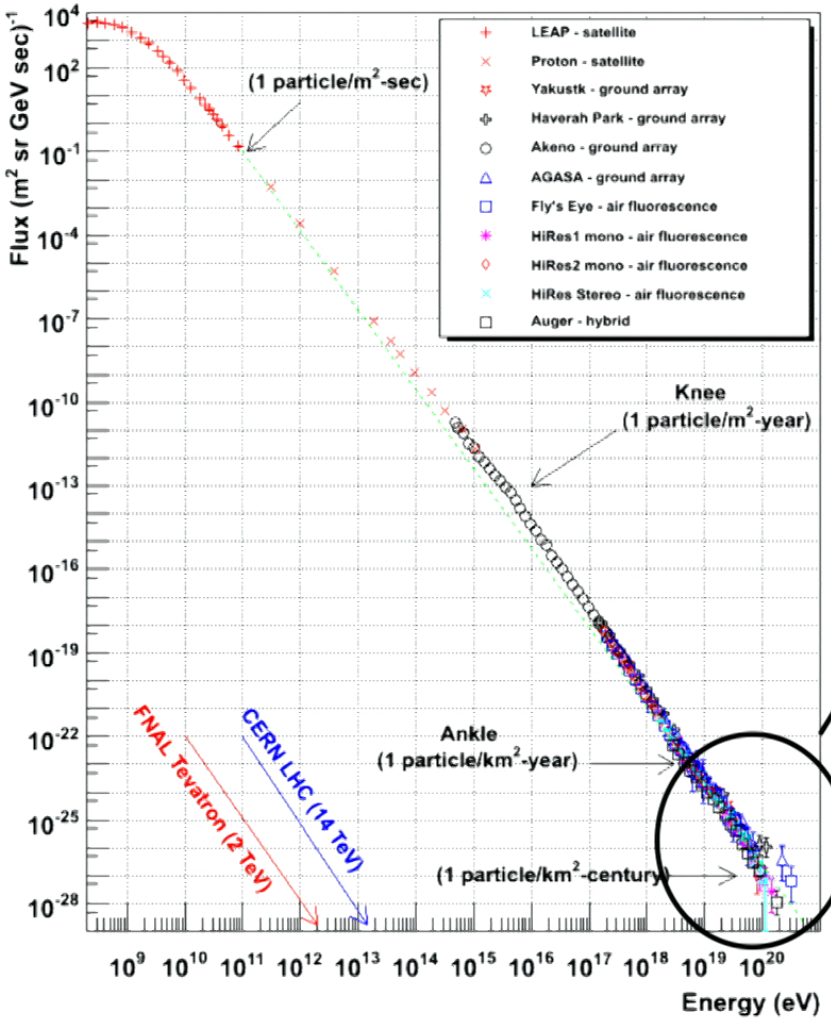


Nature's accelerators?

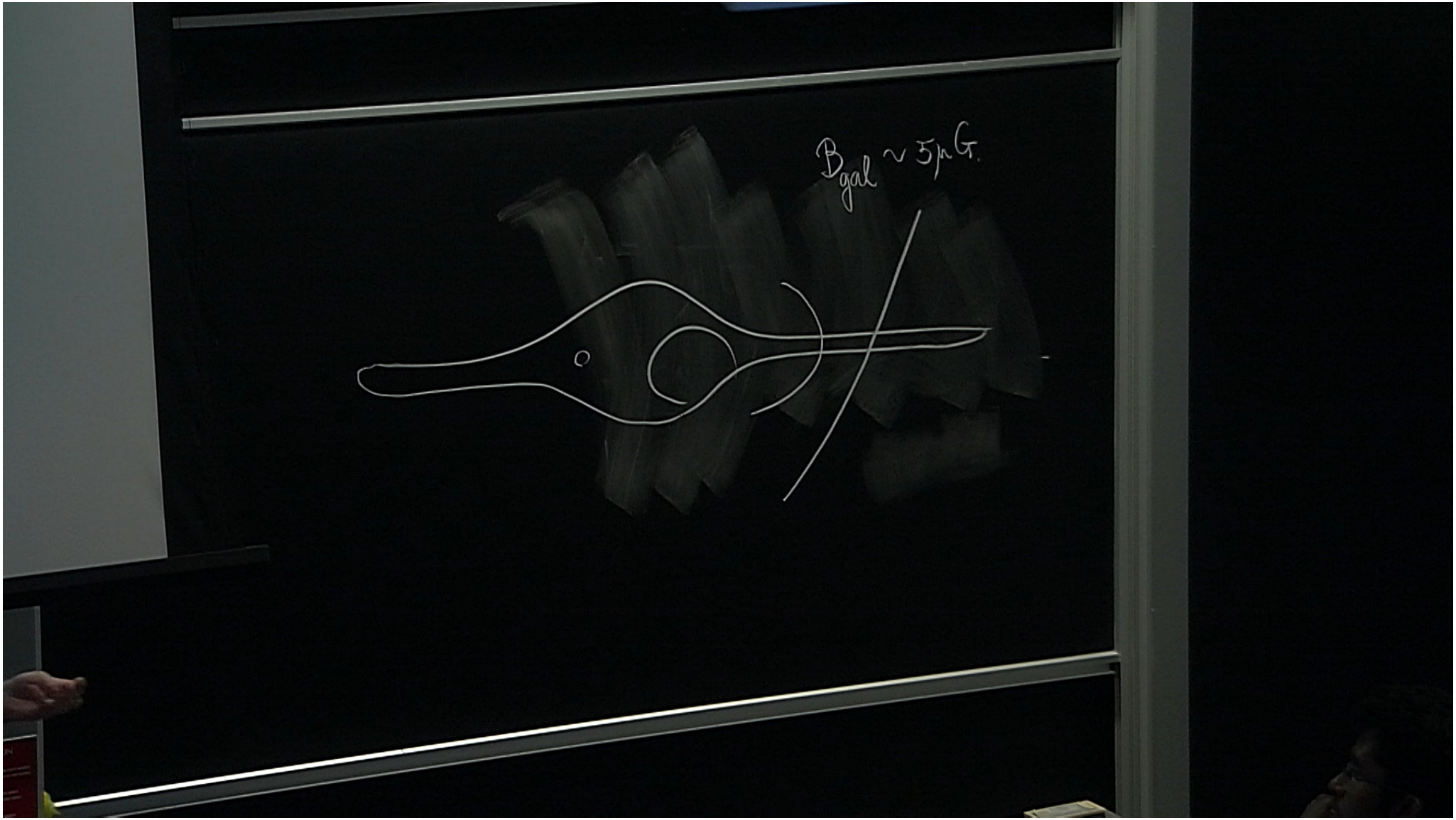
- protons > 10^8 TeV
- photons > 10^2 TeV
- neutrino > 10^3 TeV


log [Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
flux of light in the Universe
log(λ/cm)
Radio
CMB
Visible
GeV γ-rays
LHC
ν
PeV ν
cosmic rays
TeV γ
Ressell and Turner 1990
particle flux in the Universe

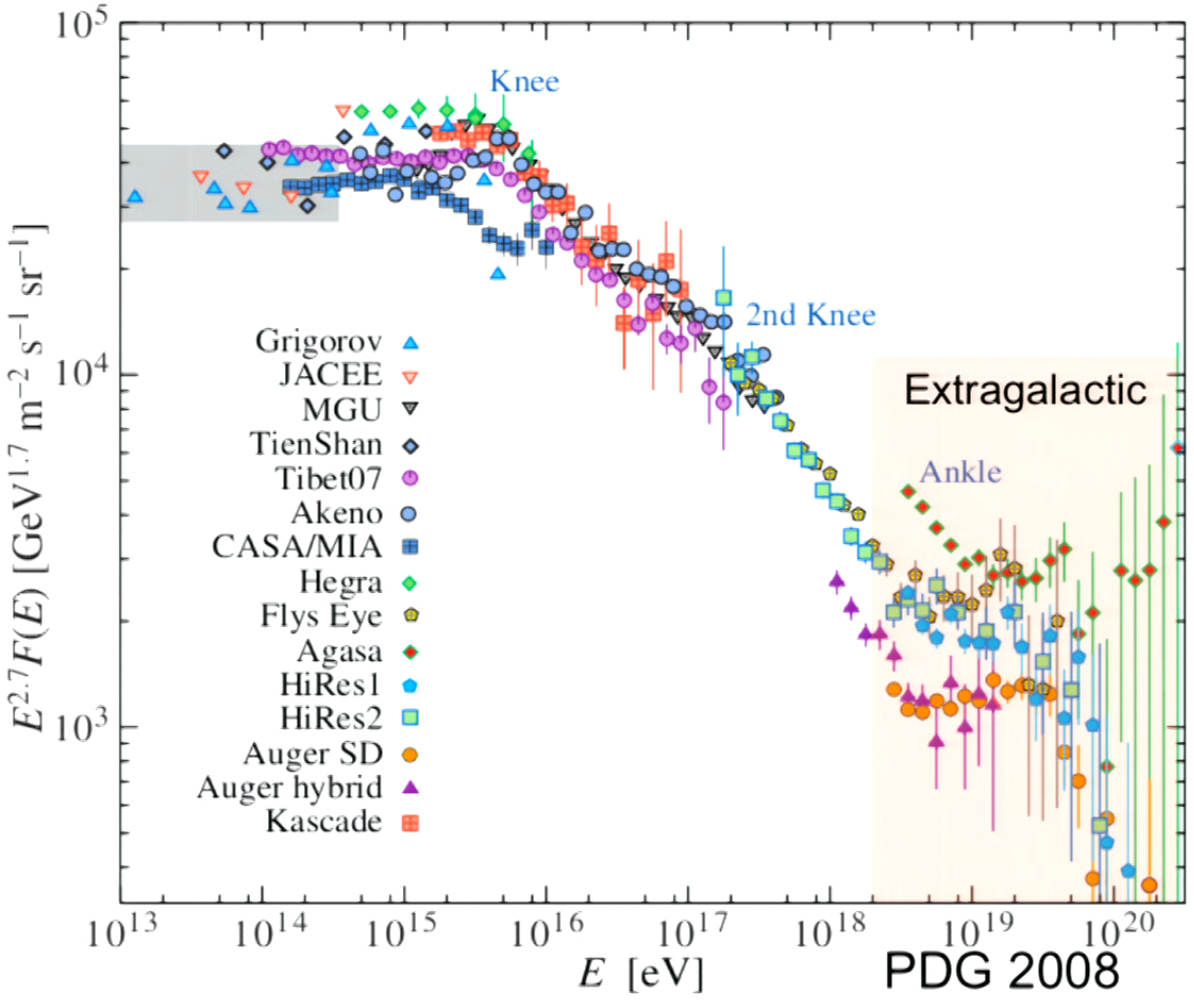
Cosmic Ray Spectra of Various Experiments



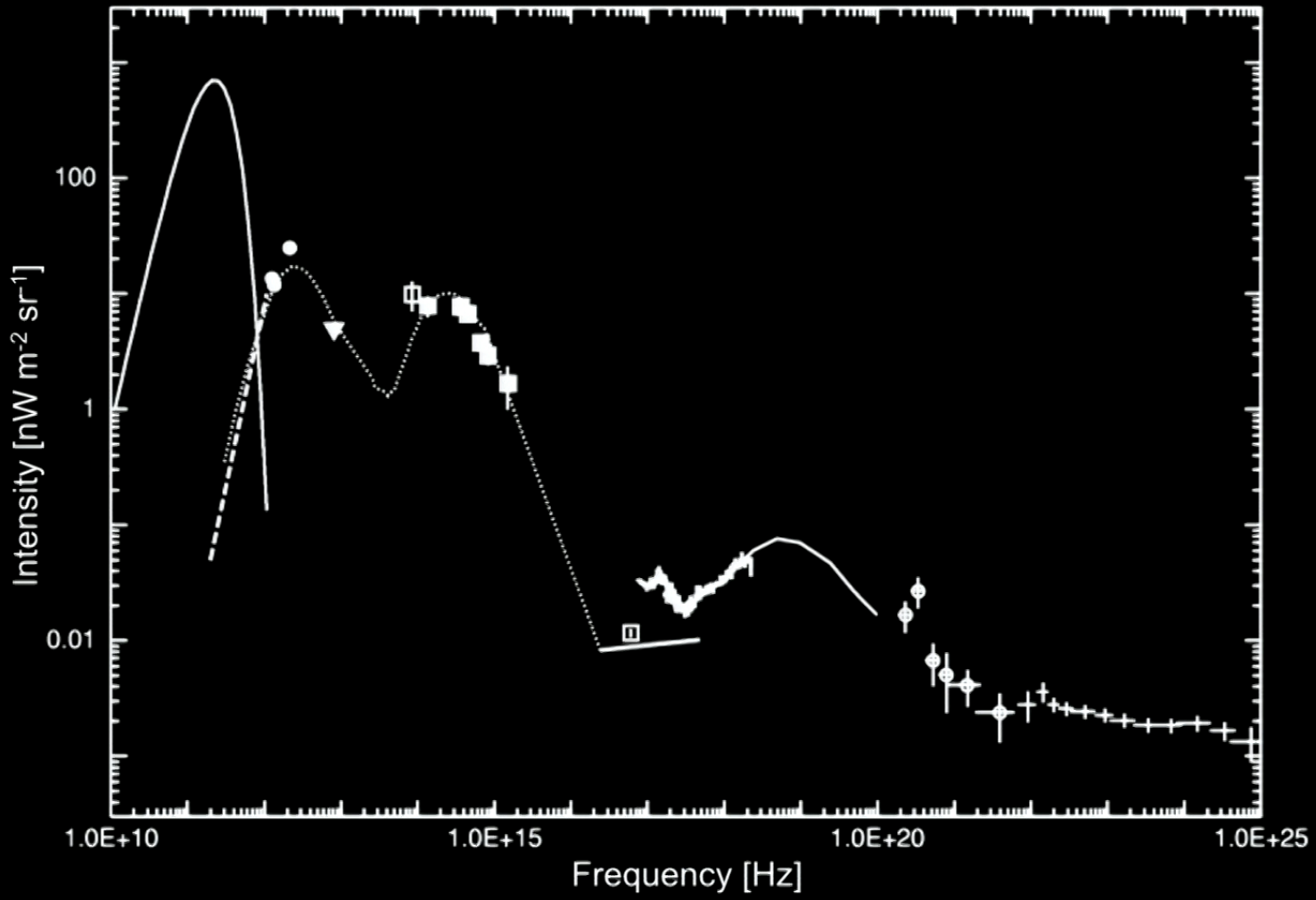
populate the Universe

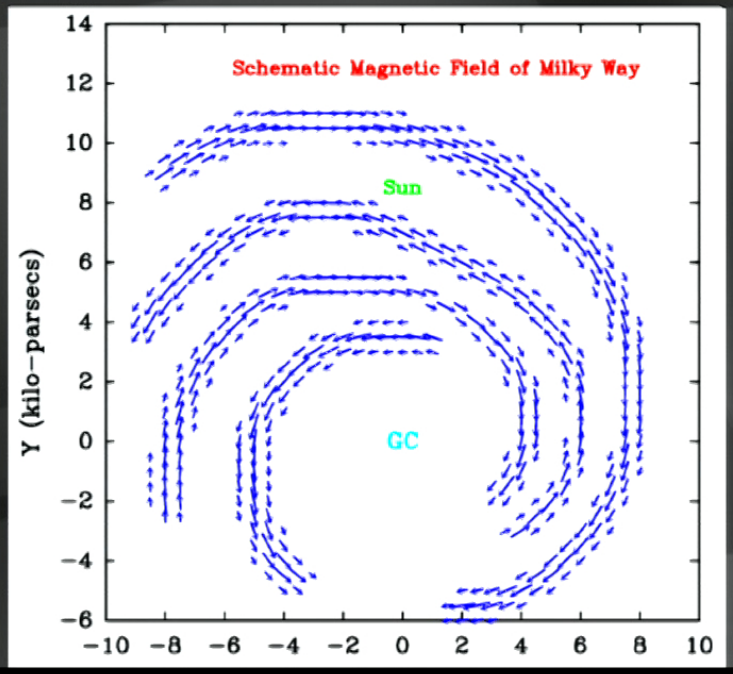

$B_{gal} \sim 5\mu G.$

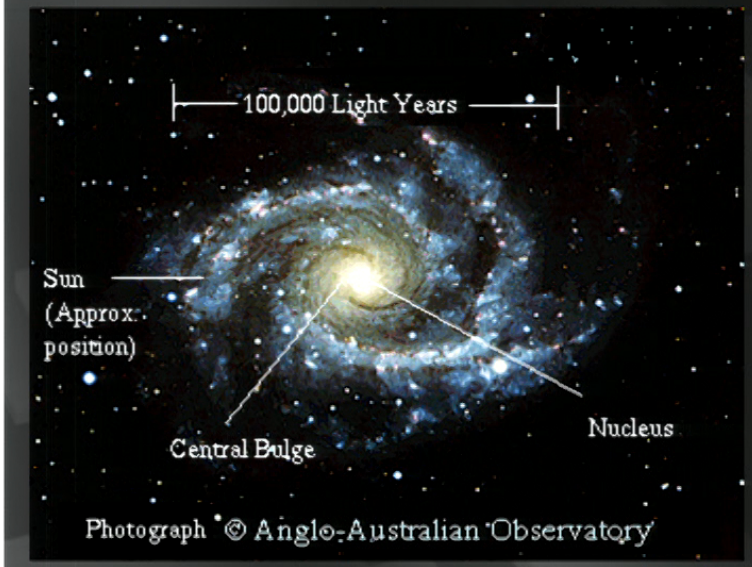
cosmic rays

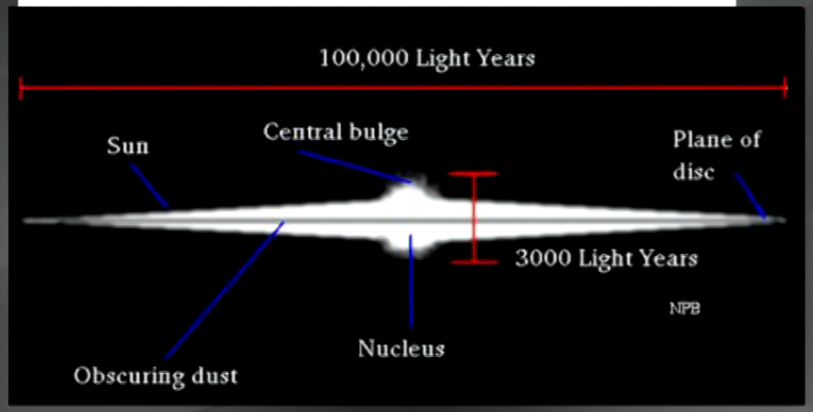

Knee
2nd Knee
Ankle
Extragalactic
Grigorov
JACEE
MGU
TienShan
Tibet07
Akeno
CASA/MIA
Hegra
Flys Eye
Agasa
HiRes1
HiRes2
Auger SD
Auger hybrid
Kascade
$E^{2.7}F(E)$ [GeV$^{1.7}$ m^{-2} s^{-1} sr^{-1}]
E [eV]
10^5
10^4
10^3
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
PDG 2008

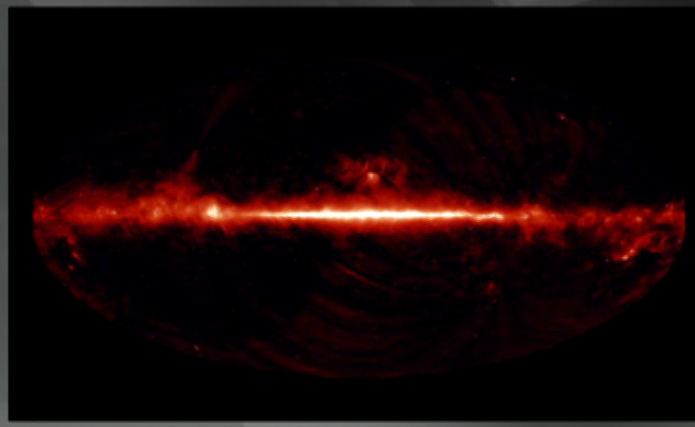
extragalactic background light (EBL)

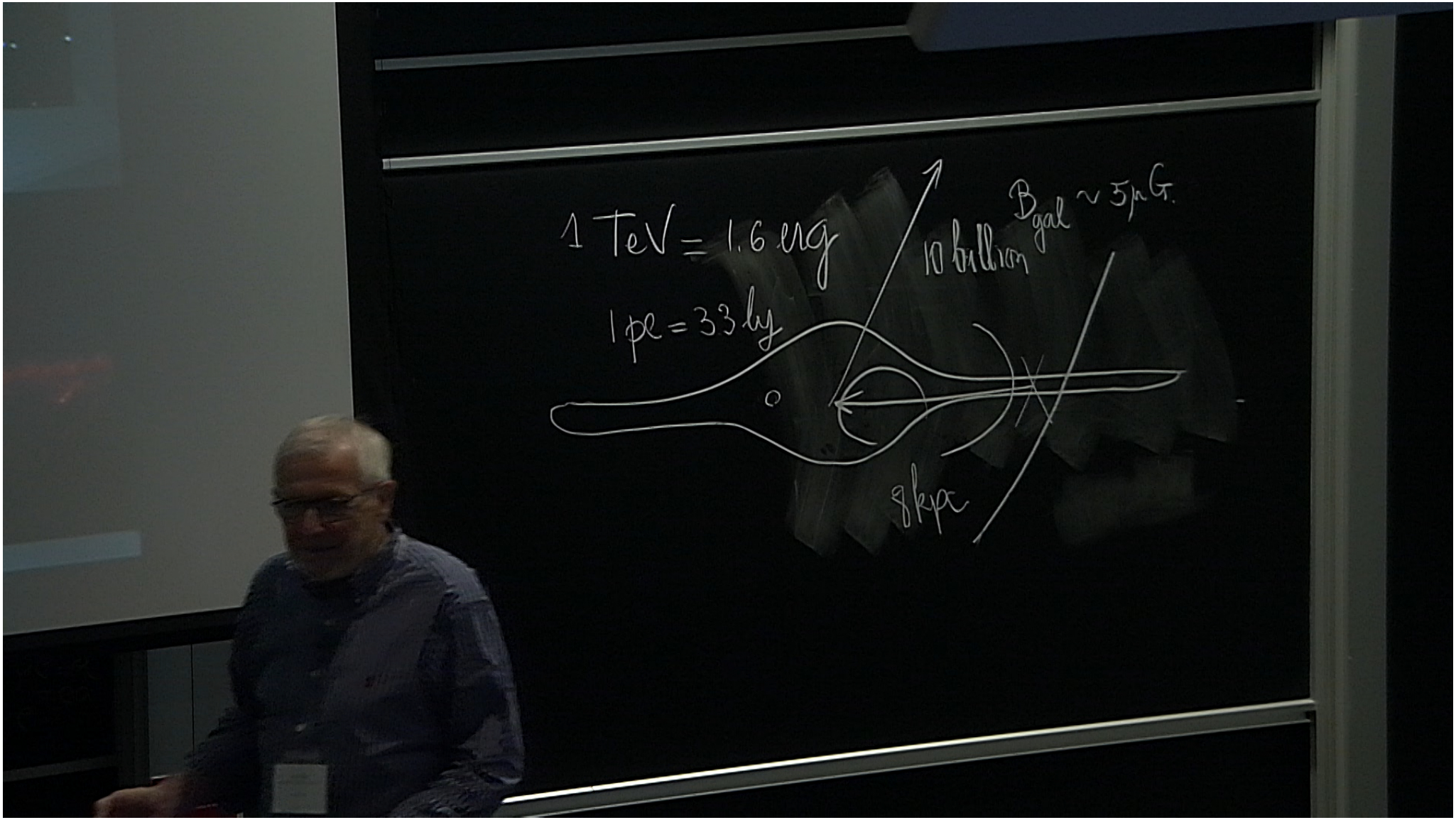


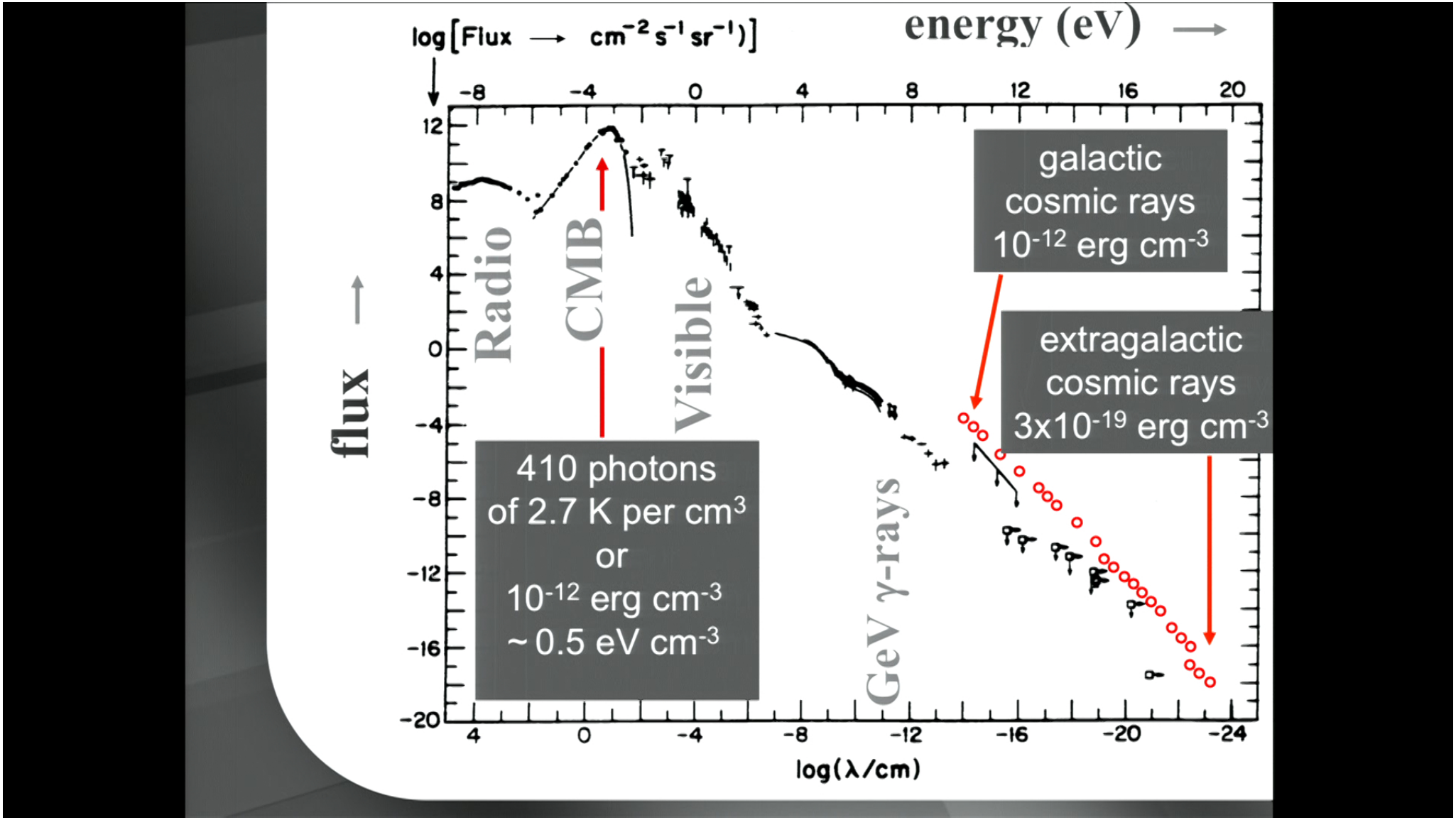

Schematic Magnetic Field of Milky Way
Sun
GC
Y (kilo−parsecs)
14
12
10
8
6
4
2
0
−2
−4
−6
−10 −8 −6 −4 −2 0 2 4 6 8 10

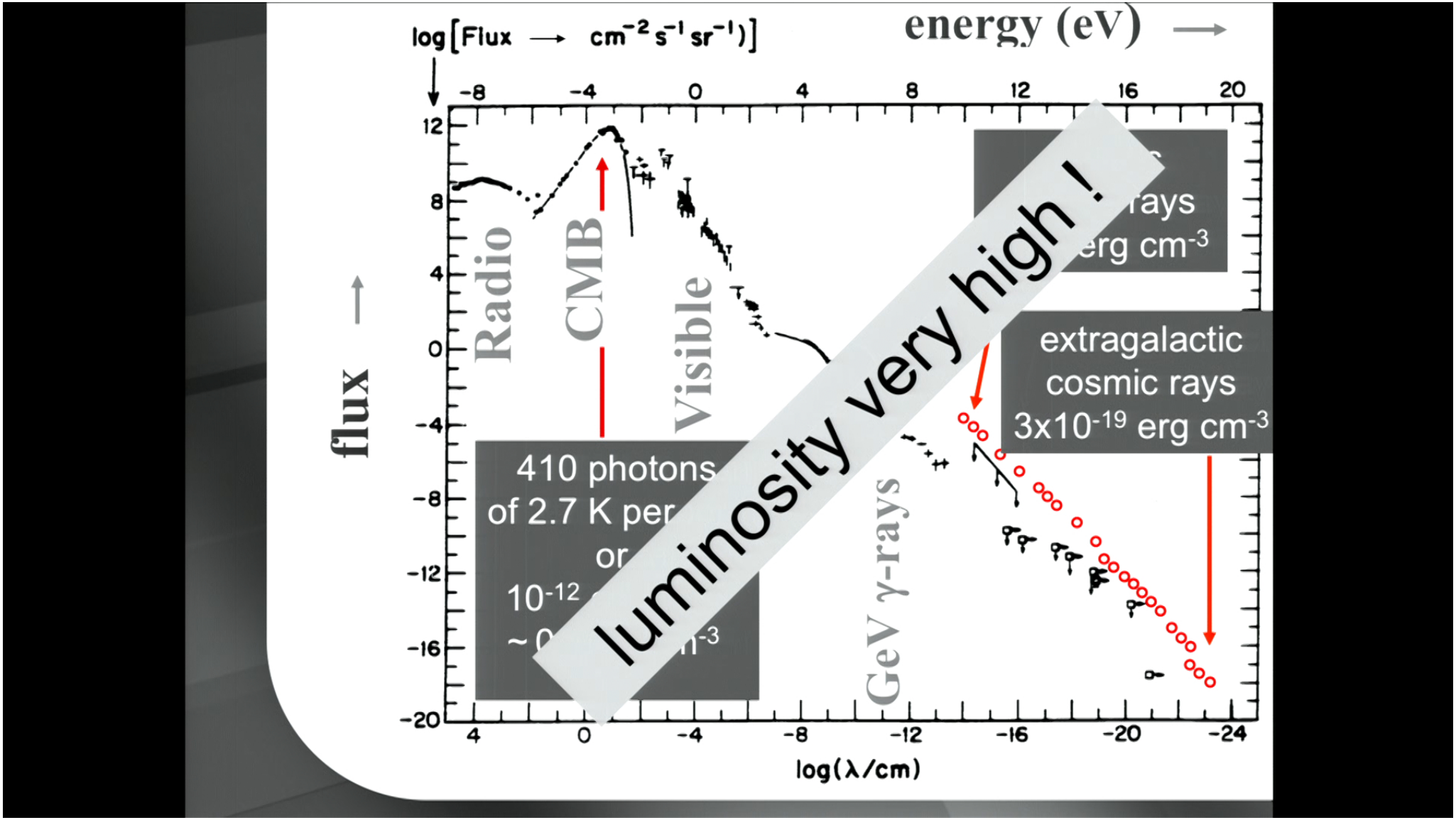

100,000 Light Years
Sun
(Approx.
position)
Central Bulge
Nucleus
Photograph © Anglo-Australian Observatory


100,000 Light Years
Sun
Central bulge
Plane of
disc
3000 Light Years
NPB
Nucleus
Obscuring dust

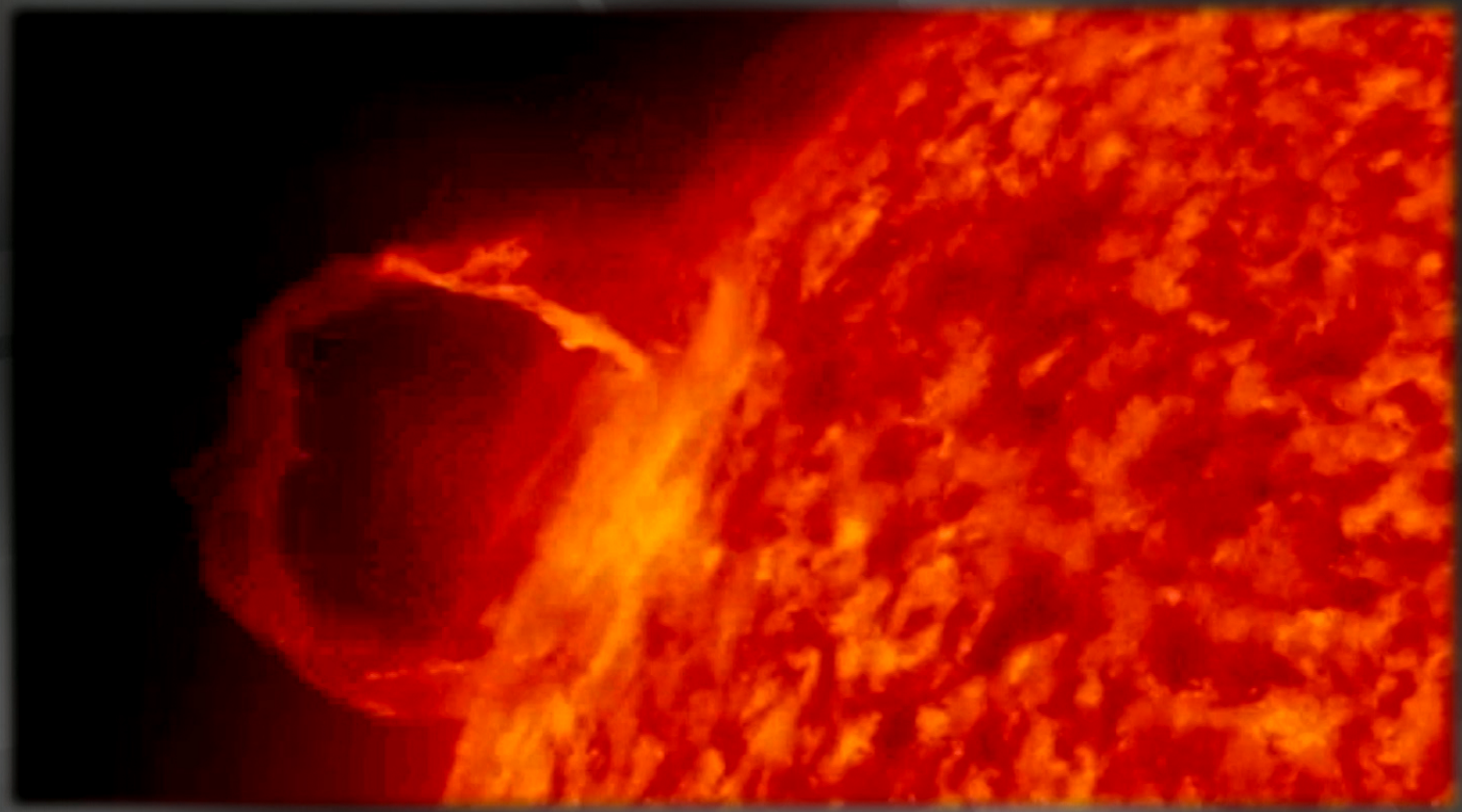



1 TeV = 1.6 erg
1 pc = 33 ly
10 billion
$B_{gal} \sim 5 \mu G$
8 kpc

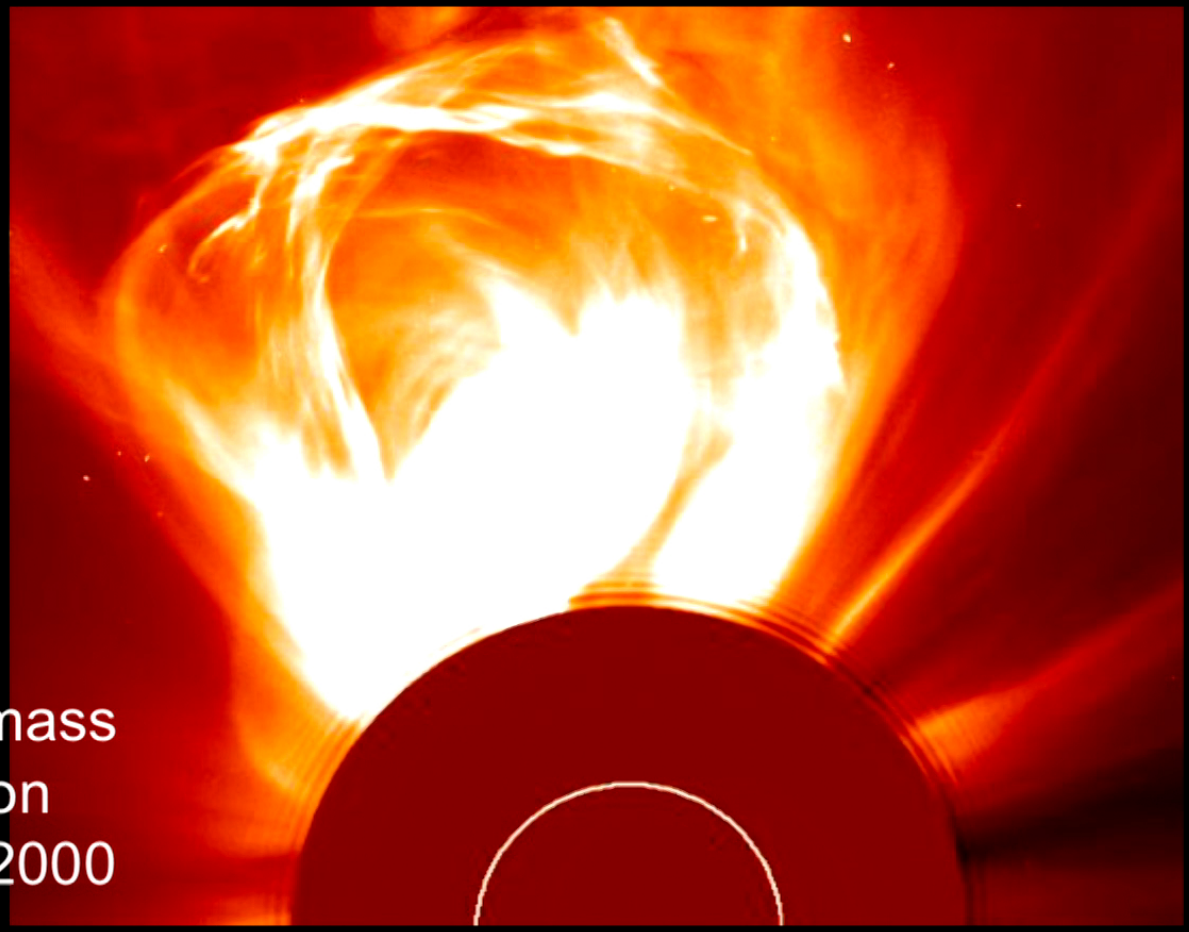

log [Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
flux →
Radio
CMB
Visible
GeV γ-rays
galactic cosmic rays 10-12 erg cm-3
extragalactic cosmic rays 3x10-19 erg cm-3
410 photons of 2.7 K per cm3 or 10-12 erg cm-3 ~ 0.5 eV cm-3
log(λ/cm)


log [Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
flux →
log(λ/cm)
Radio
CMB
Visible
GeV γ-rays
luminosity very high !
extragalactic
cosmic rays
3x10-19 erg cm-3
410 photons
of 2.7 K per
or
10-12

the sun constructs an accelerator



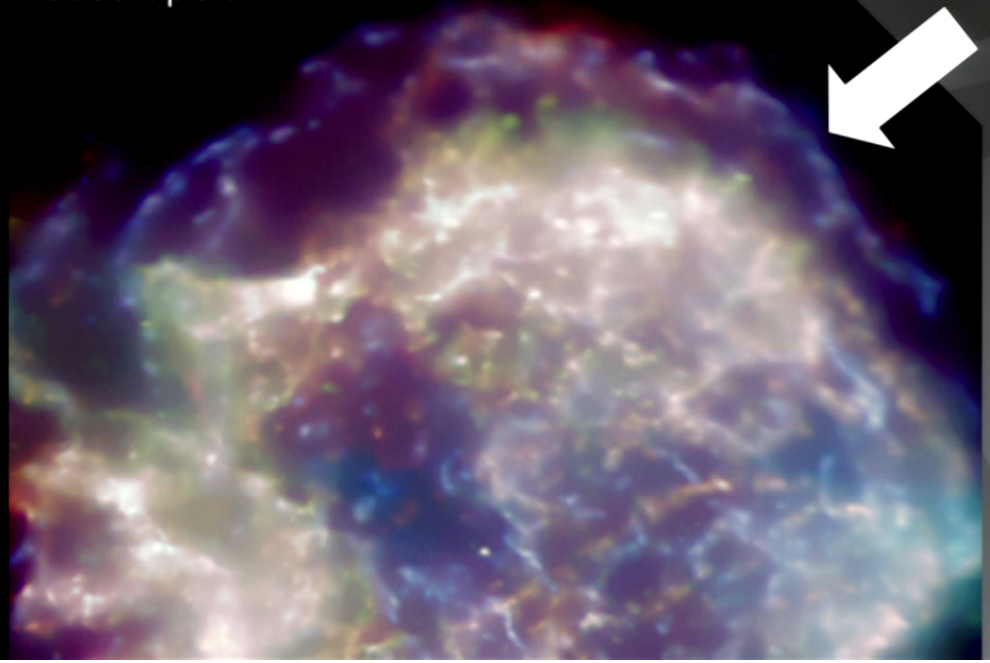
the sun constructs an accelerator



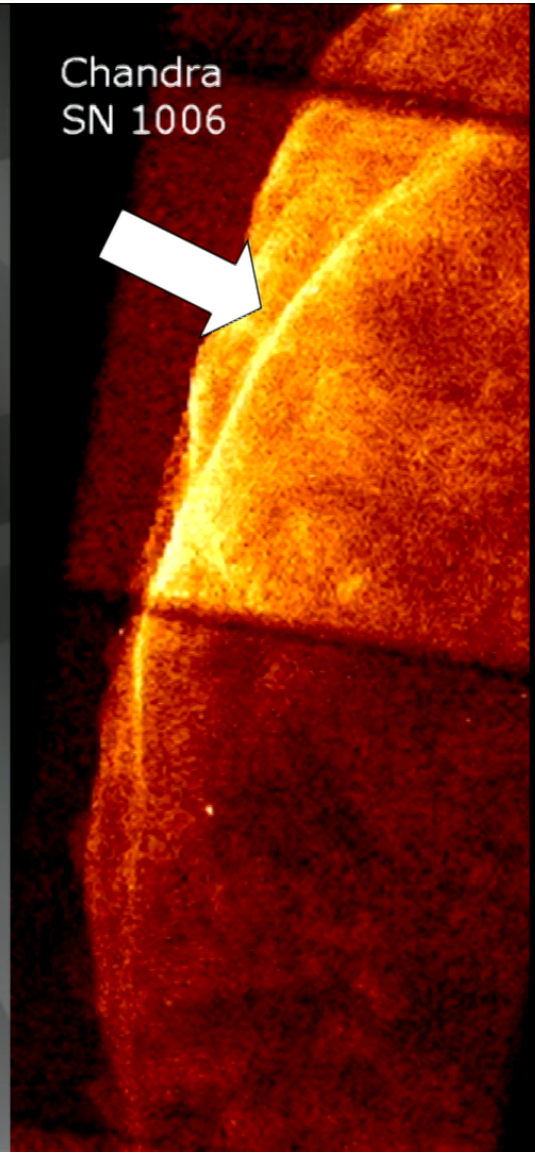
coronal mass
ejection
09 Mar 2000

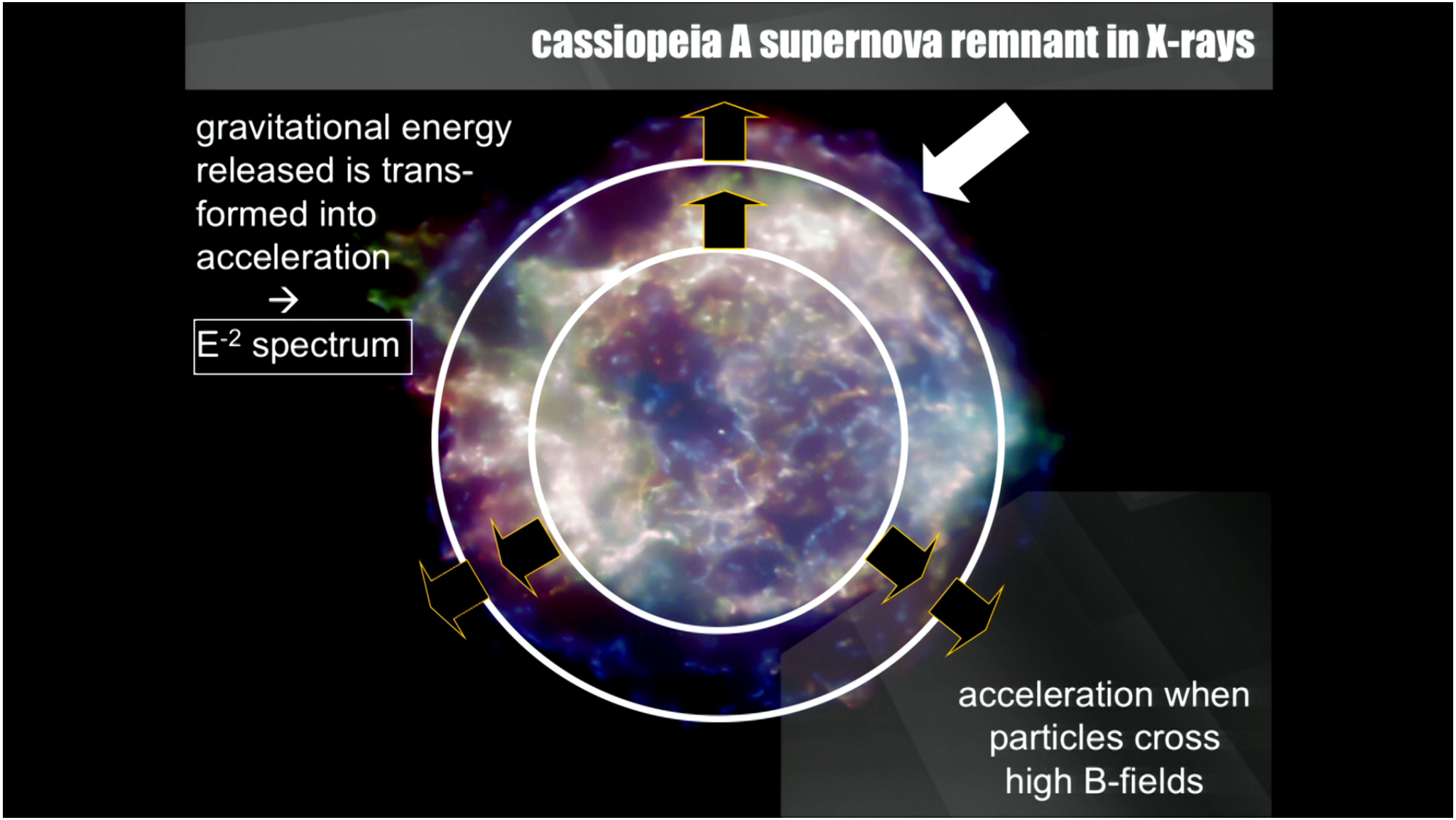
fraction of the graviatational energy released is transformed into the acceleration of particles

Chandra
Cassiopeia A



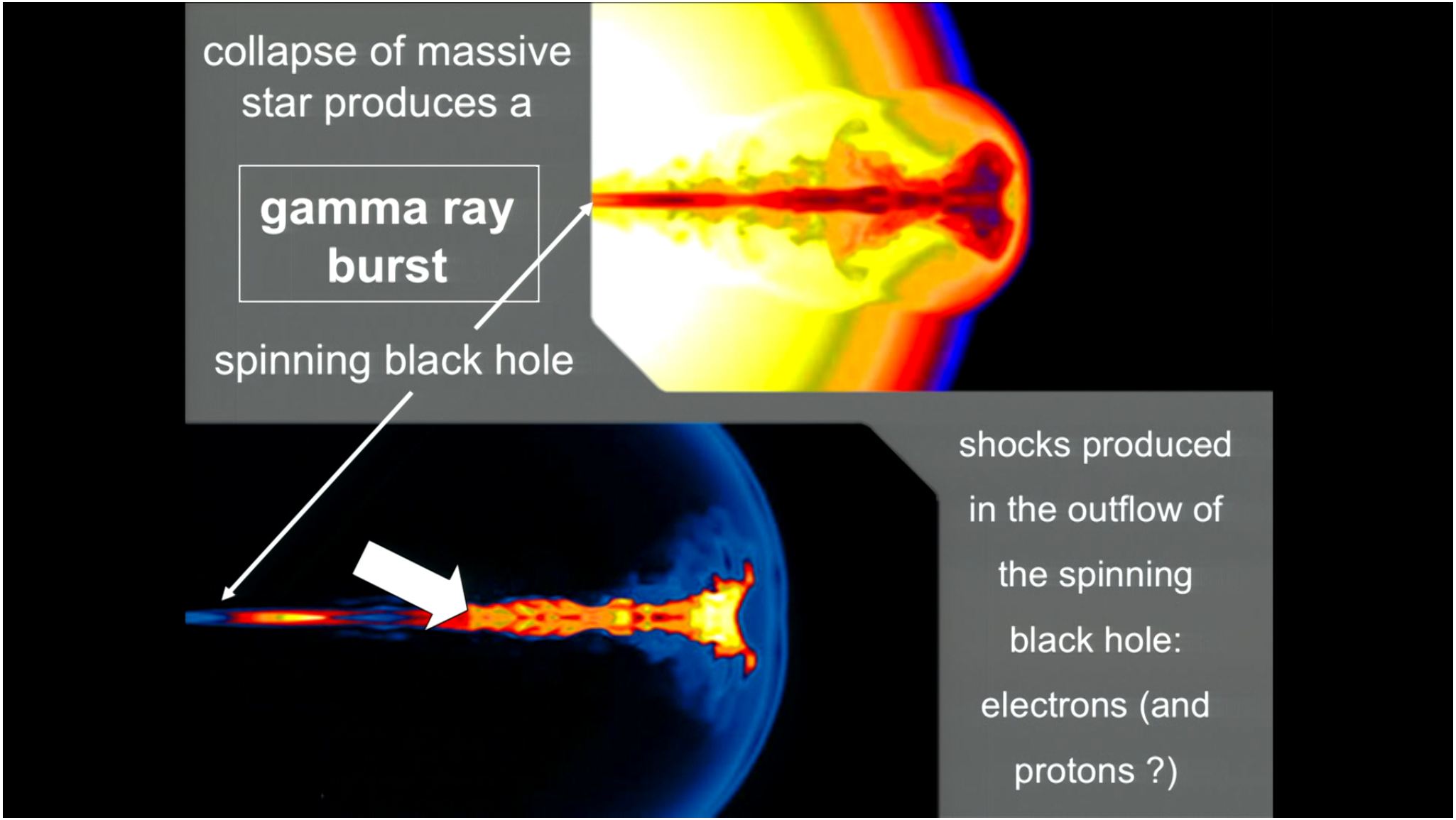
Chandra
SN 1006




cassiopeia A supernova remnant in X-rays
gravitational energy released is trans-formed into acceleration
→
E-2 spectrum
acceleration when particles cross high B-fields

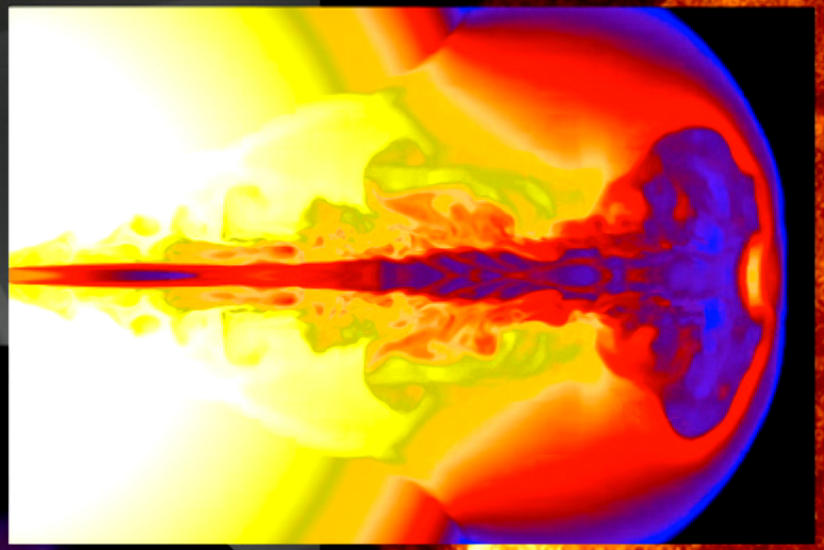
and if the star collapses to a black hole …

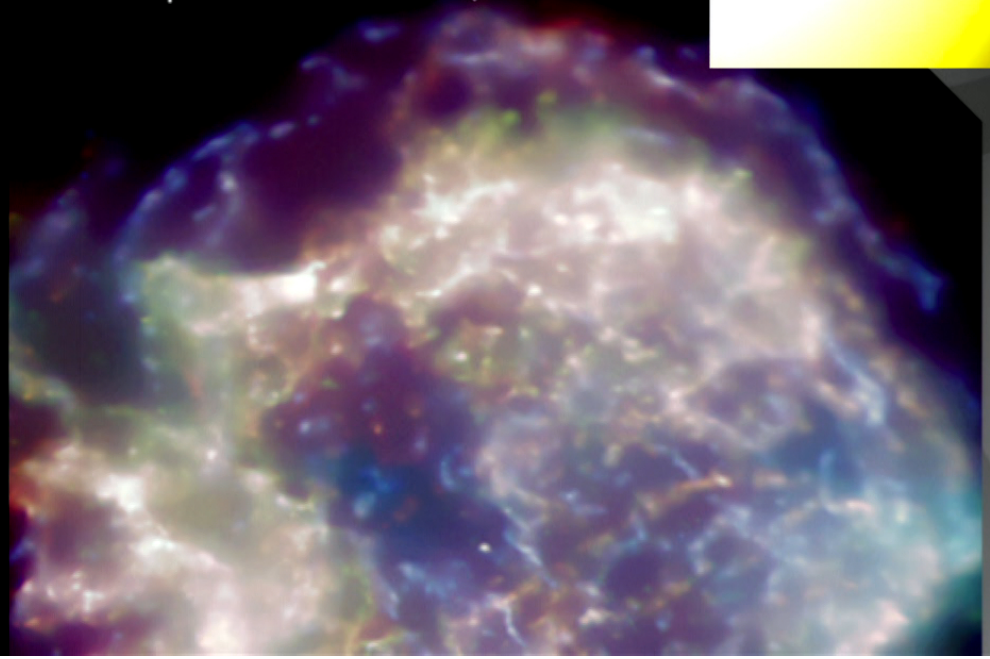
→ happens in seconds not thousands of years
→ beamed not spherical
→ simulation not image


collapse of massive star produces a
gamma ray burst
spinning black hole
shocks produced in the outflow of the spinning black hole: electrons (and protons ?)

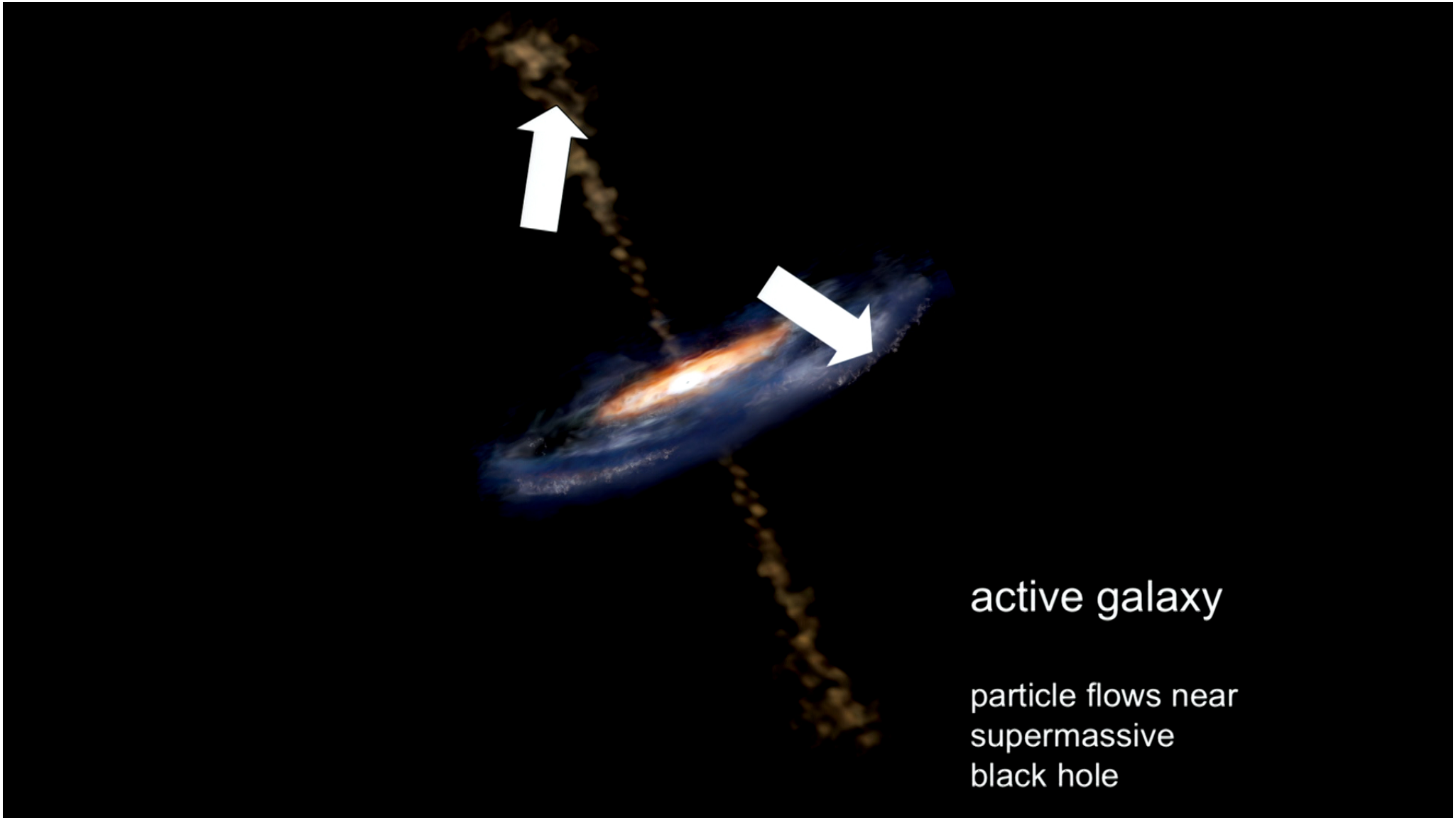
supernova remnants

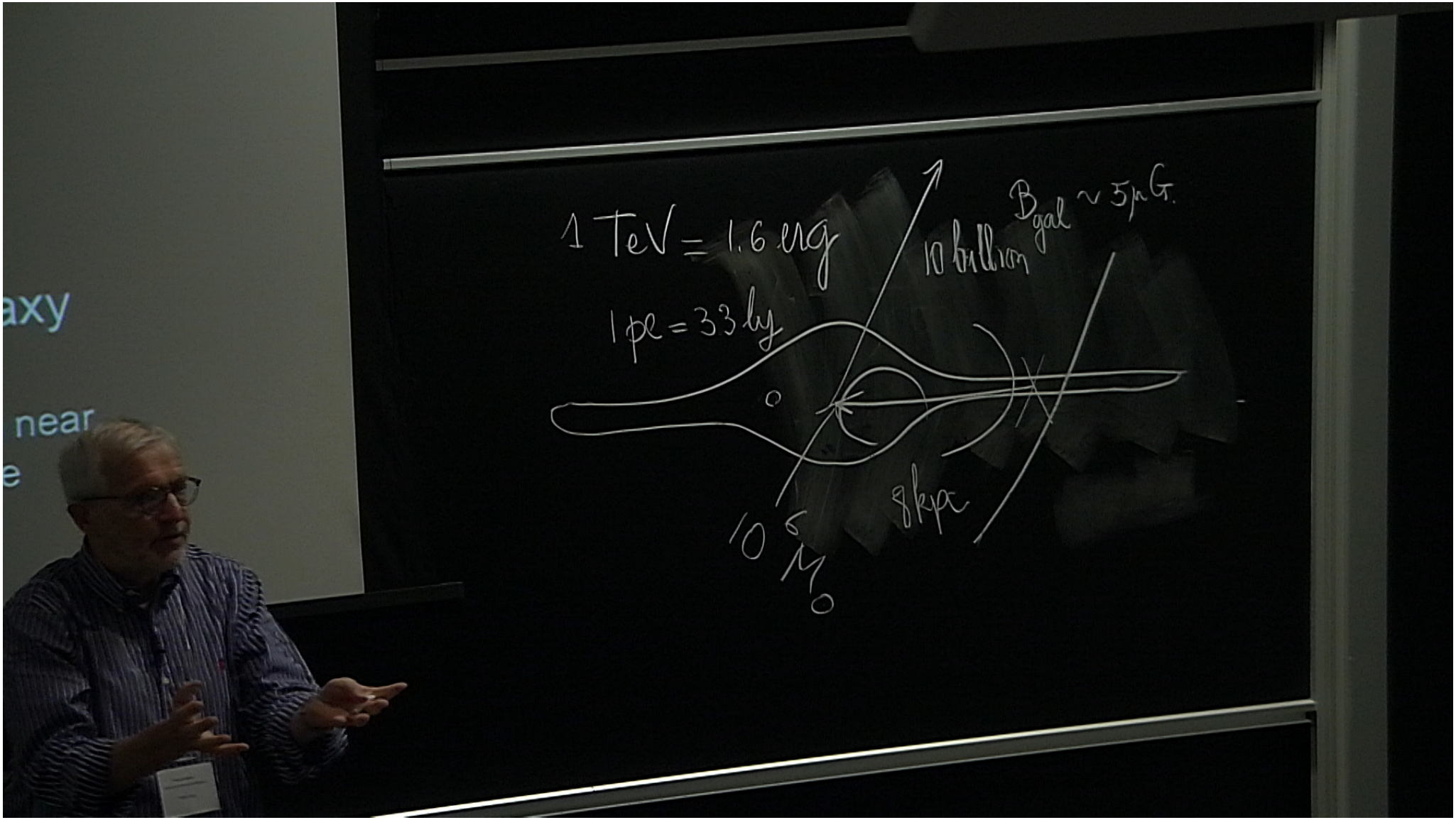
Chandra
Cassiopeia A

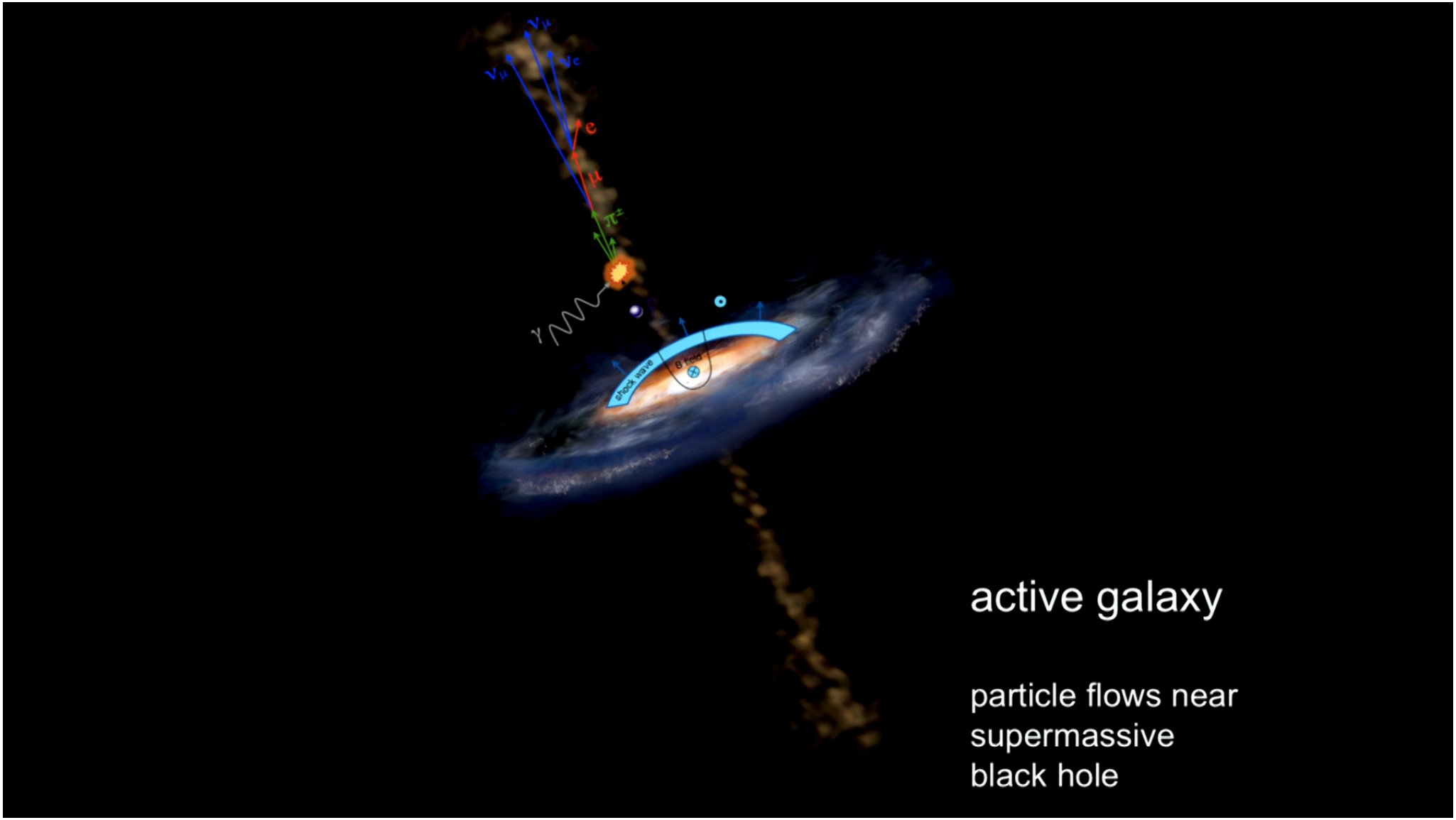


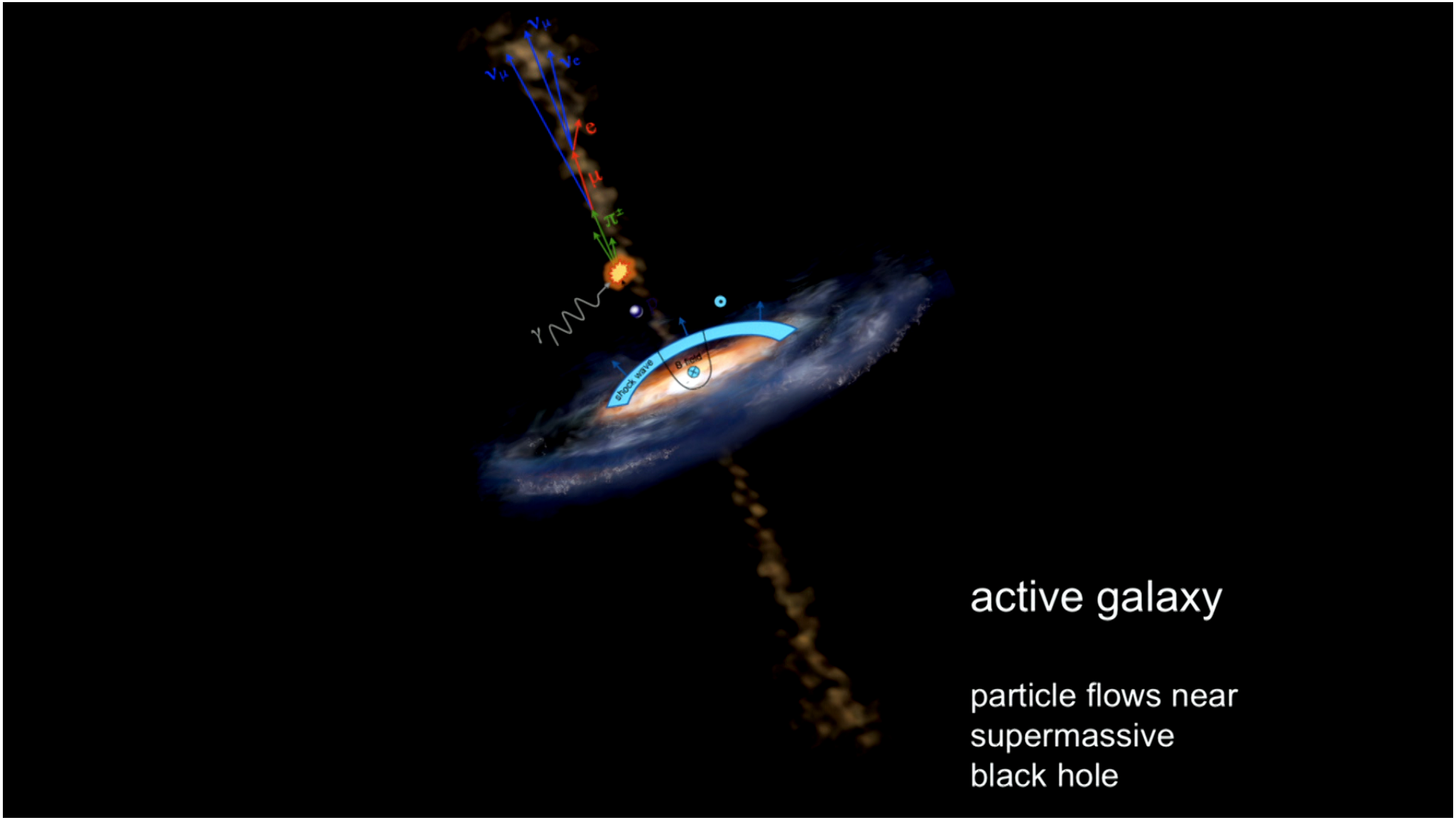


gamma ray bursts


active galaxy
particle flows near
supermassive
black hole


1 TeV = 1.6 erg
1 pc = 33 ly
10 billion
$B_{gal} \sim 3\mu G$
8 kpc
$10^6 M_\odot$


ν_μ
ν_e
ν_μ
e
μ
$\pi^\pm$
γ
p
shock wave
B field
active galaxy
particle flows near
supermassive
black hole


ν_μ
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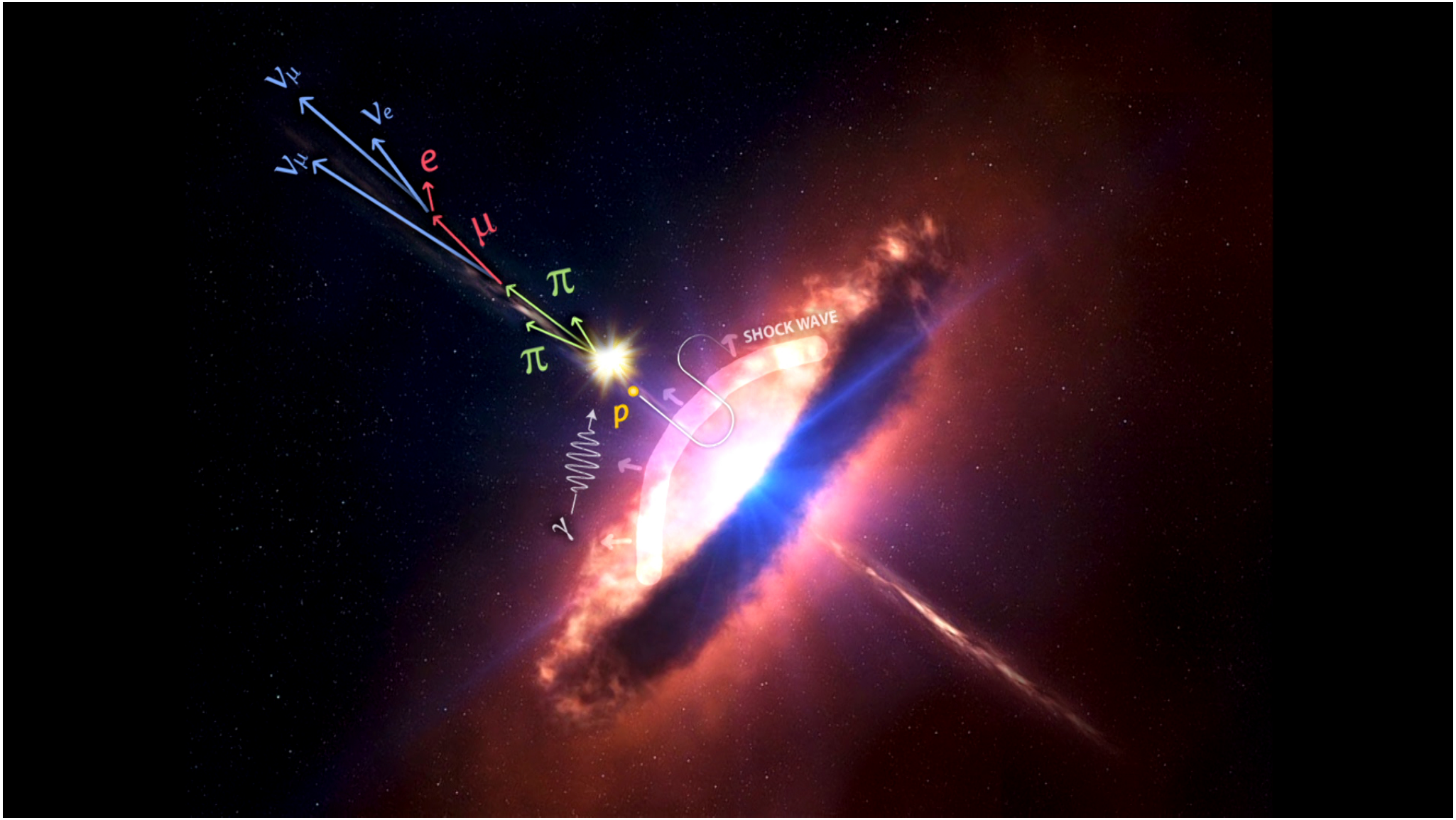

ν_μ
ν_e
ν_μ
e
μ
π
π
p
γ
SHOCK WAVE

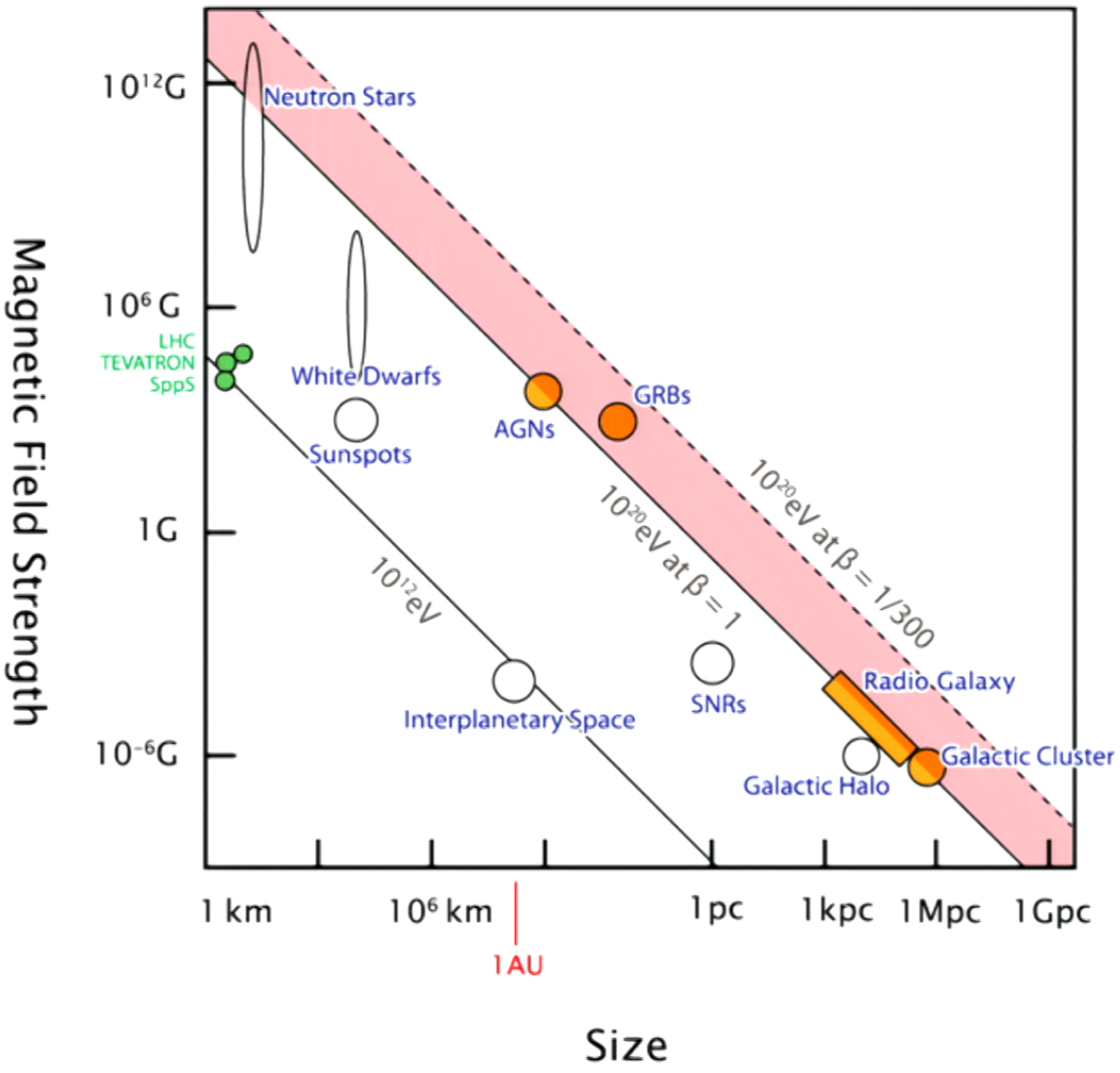
- accelerator must contain the particles

$$R_{gyro}\left(=\frac{E}{\mathrm{v}qB}\right)\leq R$$

$$E \leq \mathrm{v}\, qBR$$

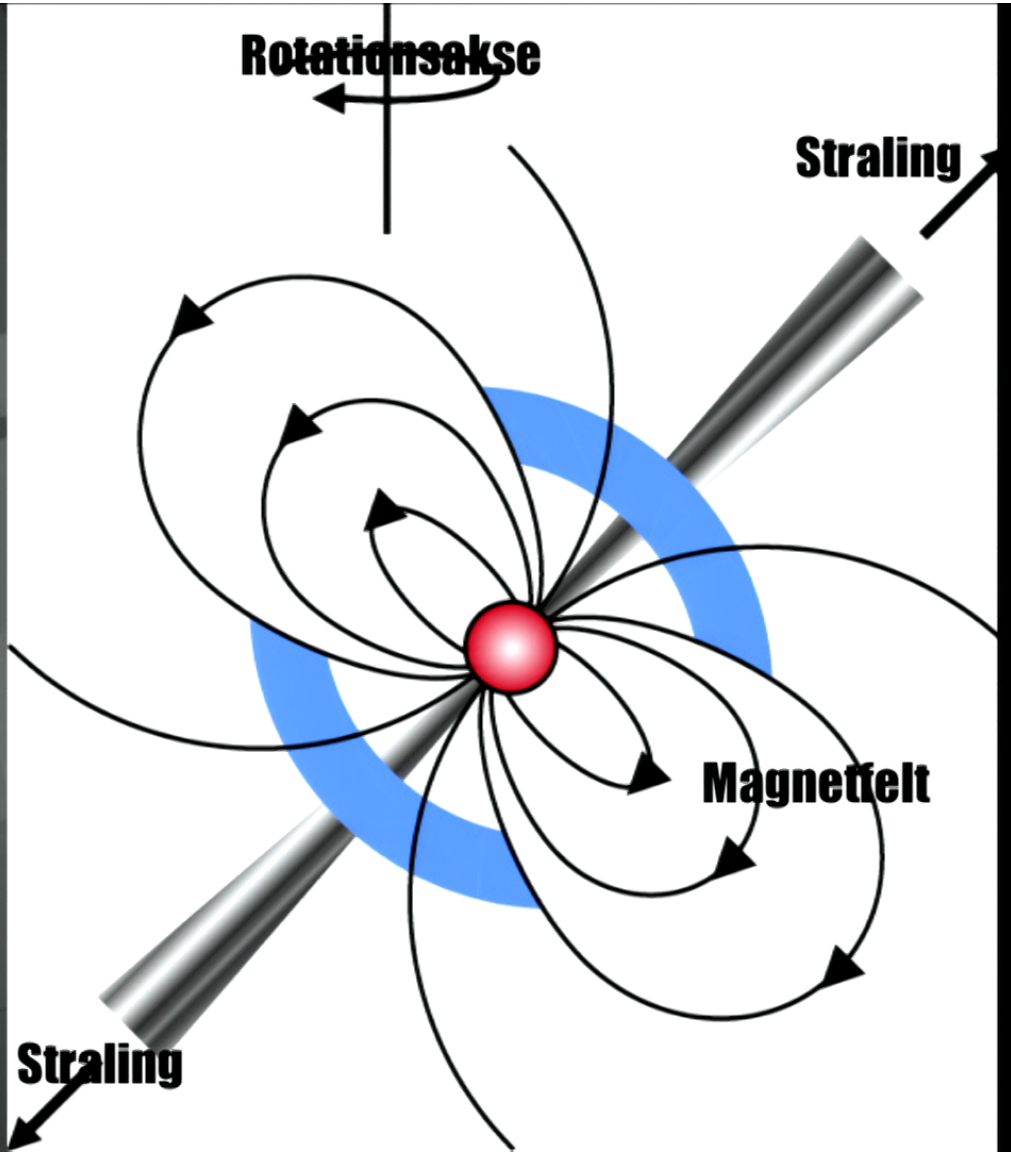
challenges of cosmic ray astrophysics:

- dimensional analysis, difficult to satisfy
- accelerator luminosity is high as well


Magnetic Field Strength
10^{12}G
10^{6} G
1G
10^{-6}G
Neutron Stars
LHC
TEVATRON
SppS
White Dwarfs
Sunspots
AGNs
GRBs
10^{20}eV at β = 1/300
10^{20}eV at β = 1
10^{12}eV
Interplanetary Space
SNRs
Radio Galaxy
Galactic Cluster
Galactic Halo
1 km
10^{6} km
1AU
1pc
1kpc
1Mpc
1Gpc
Size

an example pulsars

$$v \rightarrow \frac{2\pi R}{T}$$

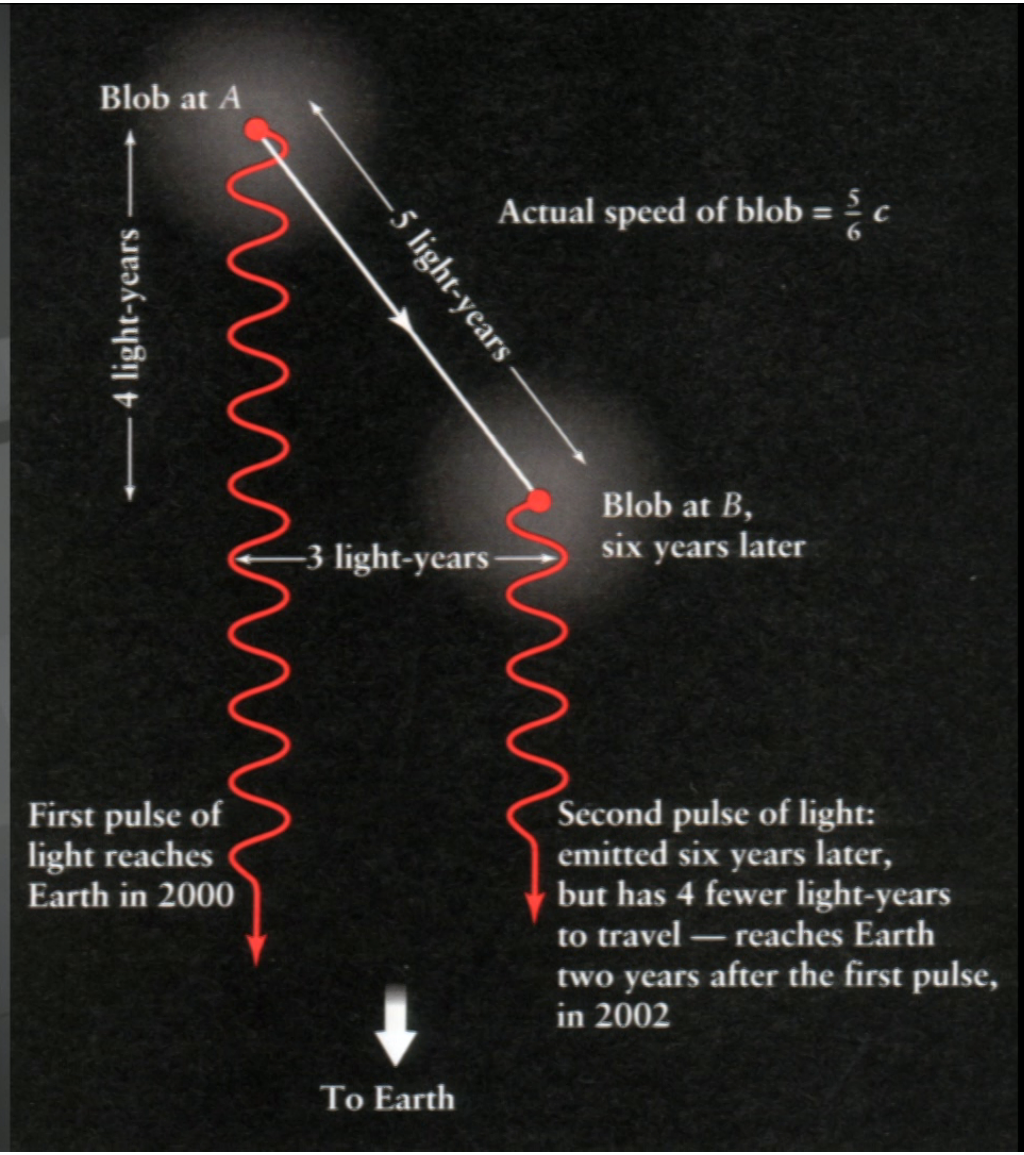


$$E(eV) = B(Tesla)\, R(m)\, \frac{2\pi R}{T}$$

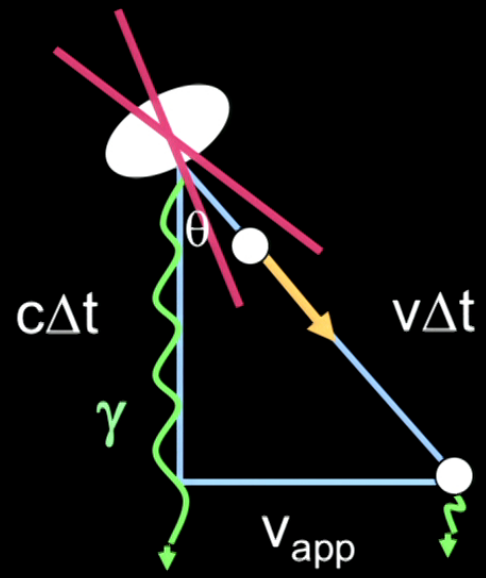
	ms-pulsar	**Fermilab**
R	10 km	km
B	10^8 Tesla	Tesla
T^{-1}	10^3	10^5 (#rev/s)
E	10^7 TeV	10^{12} eV = 1 TeV !

still a very open problem…

superluminal motion



superluminal motion: boosted accelerators



$\beta = v/c \qquad \gamma = (1-\beta^2)^{-1/2}$

$D^{-1} = (1+z)\,(1 - \beta \cos\theta)\,\gamma$

$$E_{\rm obs} = \gamma E'$$
$$\Delta t_{\rm obs} = \gamma^{-1} \Delta t'$$

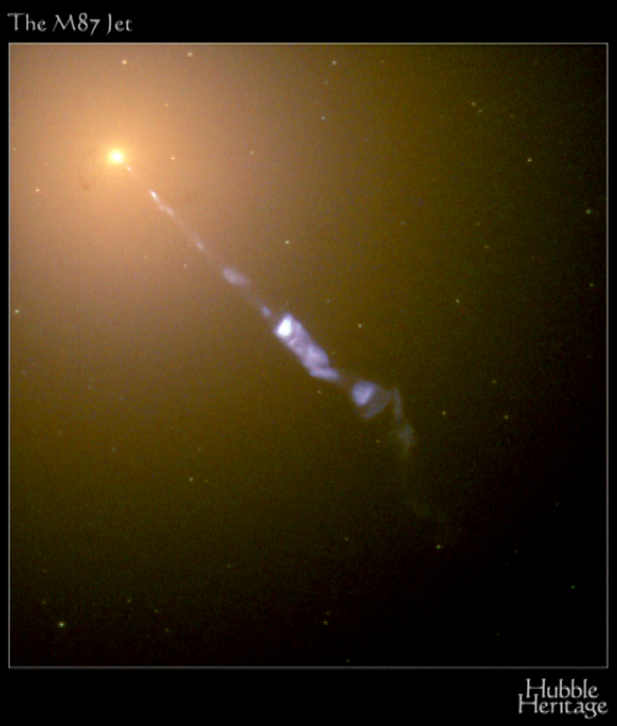
$$v_{app} = \frac{v\Delta t \sin\vartheta}{\frac{c\Delta t}{c} - \frac{v\Delta t \cos\vartheta}{c}}$$

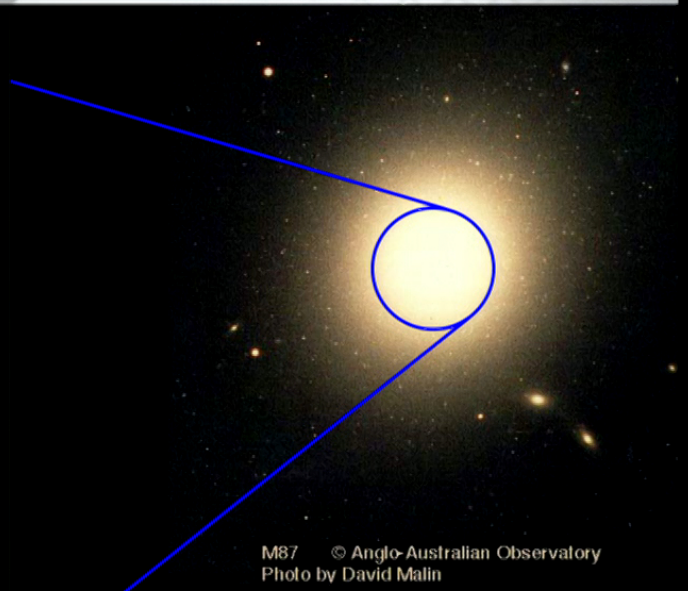
strongest effect :

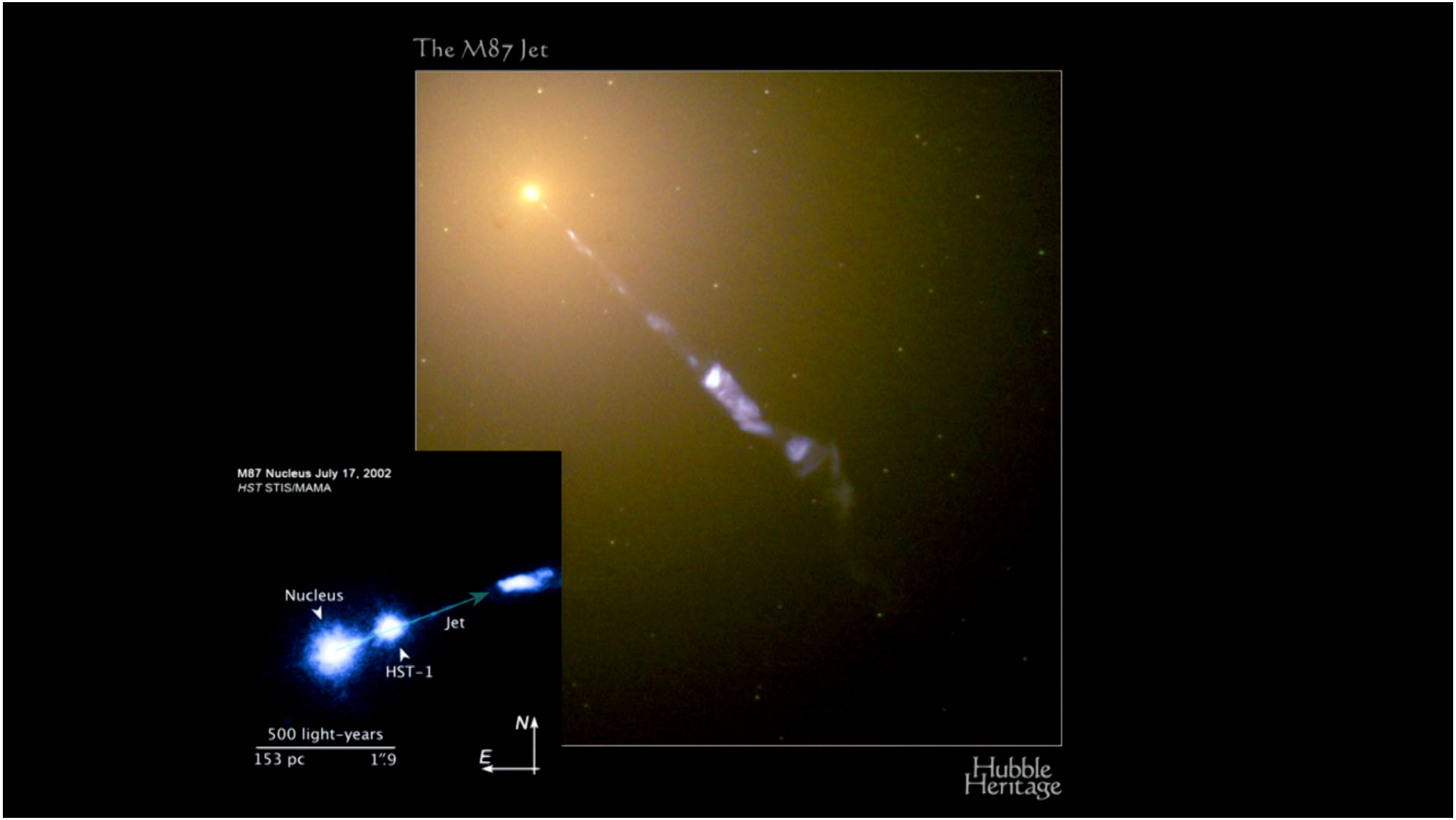
$$\frac{dv_{app}}{d\vartheta} = 0 \; or \; \cos\vartheta = \frac{v}{c} = \beta$$

$$or \; D = \gamma$$

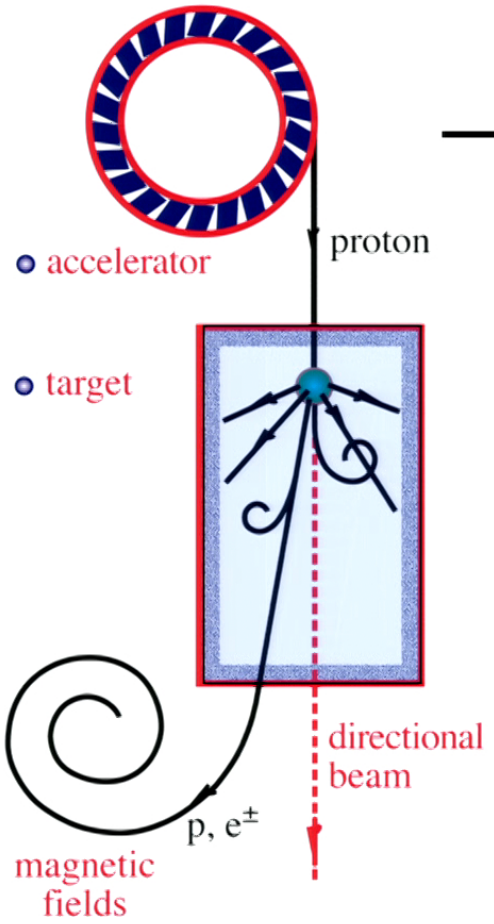
active galaxy M87






The M87 Jet
M87 Nucleus July 17, 2002
HST STIS/MAMA
Nucleus
Jet
HST-1
500 light-years
153 pc
1".9
N
E
Hubble Heritage

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

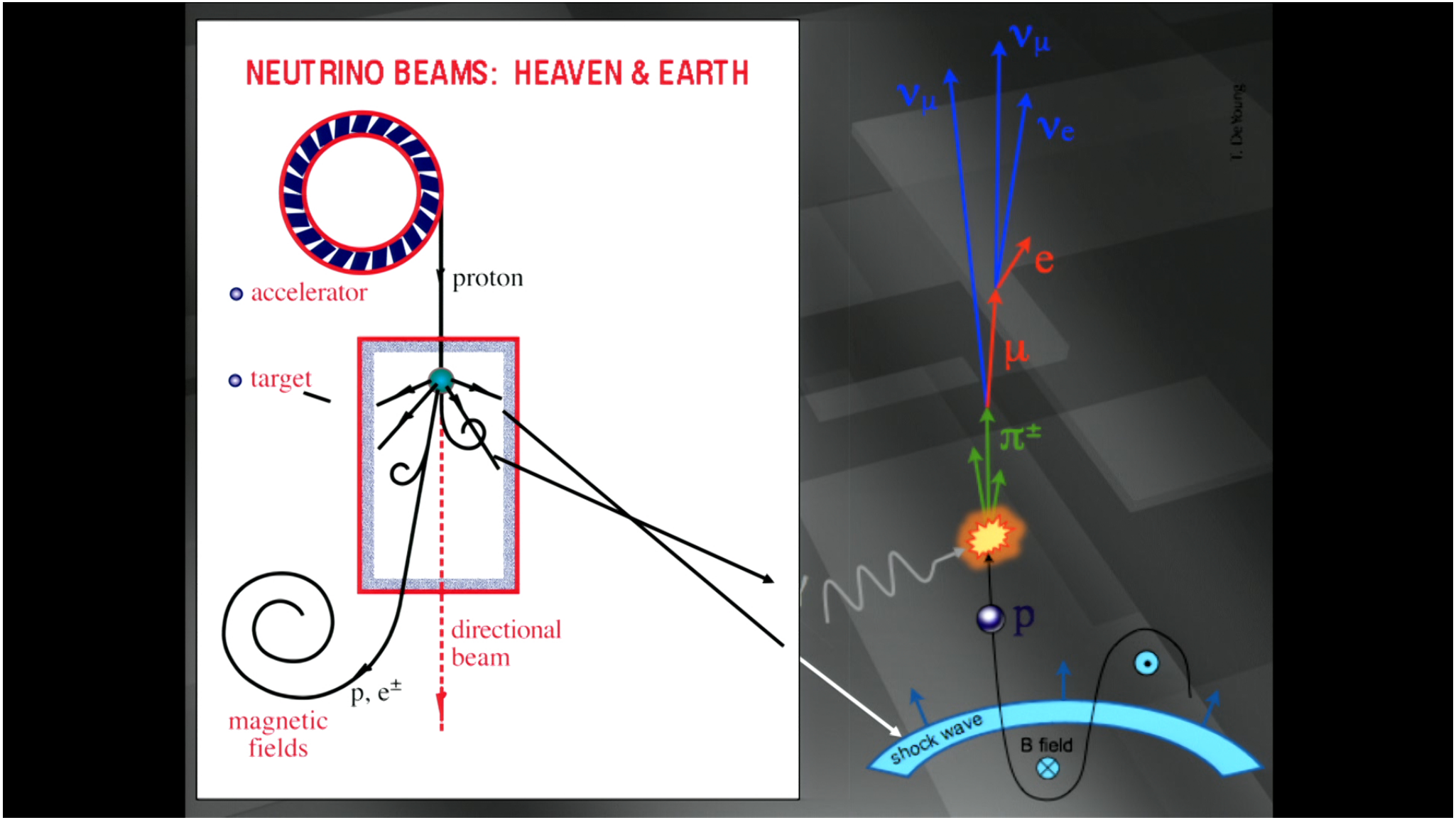
radiation and dust

$p + \gamma \rightarrow n + \pi^+$

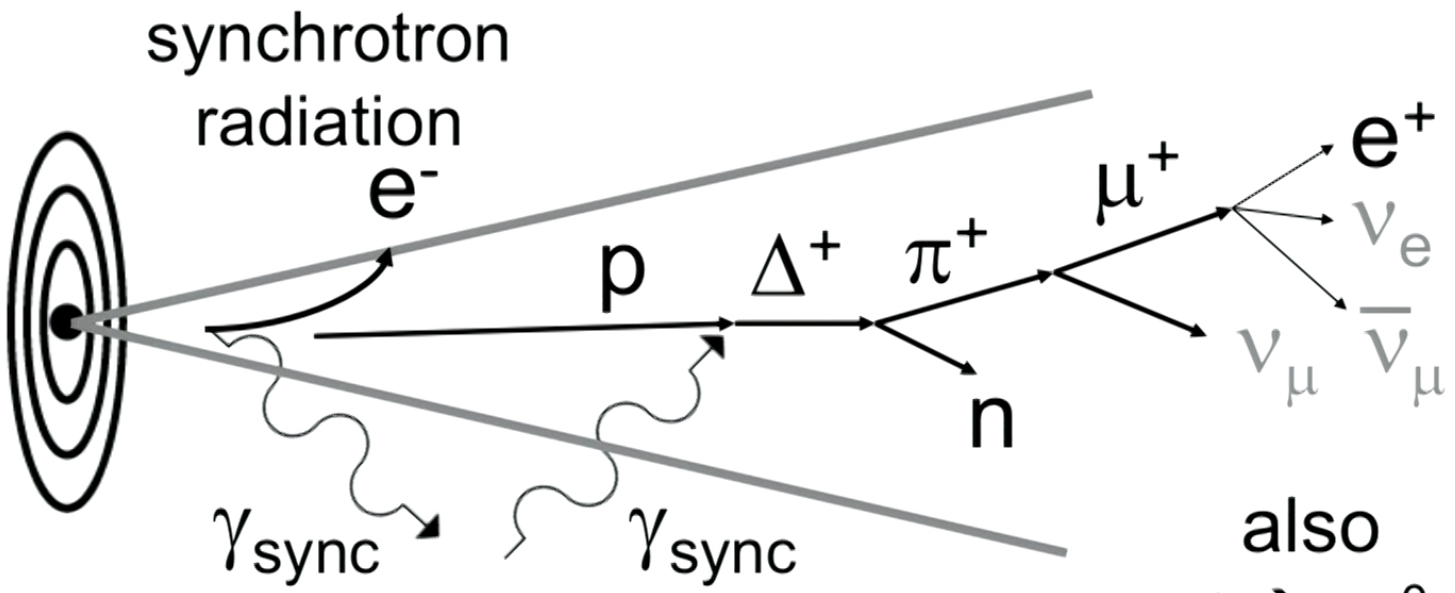
~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma


NEUTRINO BEAMS: HEAVEN & EARTH
accelerator
proton
target
directional
beam
p, e±
magnetic
fields
νμ
νμ
νe
e
μ
π±
p
shock wave
B field

heavenly neutrino beam dump: photons: synchrotron versus $\pi^0 \rightarrow \gamma\gamma$



multi-messenger identification of cosmic ray sources

- **cosmic rays with little magnetic deflection** *(flux very low near 10^{20} eV)*
- **associated pions produced in interactions close to the source and during propagation**

  → **TeV photons:** *difficult to disentangle from those produced by synchrotron radiation and inverse Compton scattering*

  → **neutrinos:** *difficult to detect (→ rationale for kilometer-scale detectors)*

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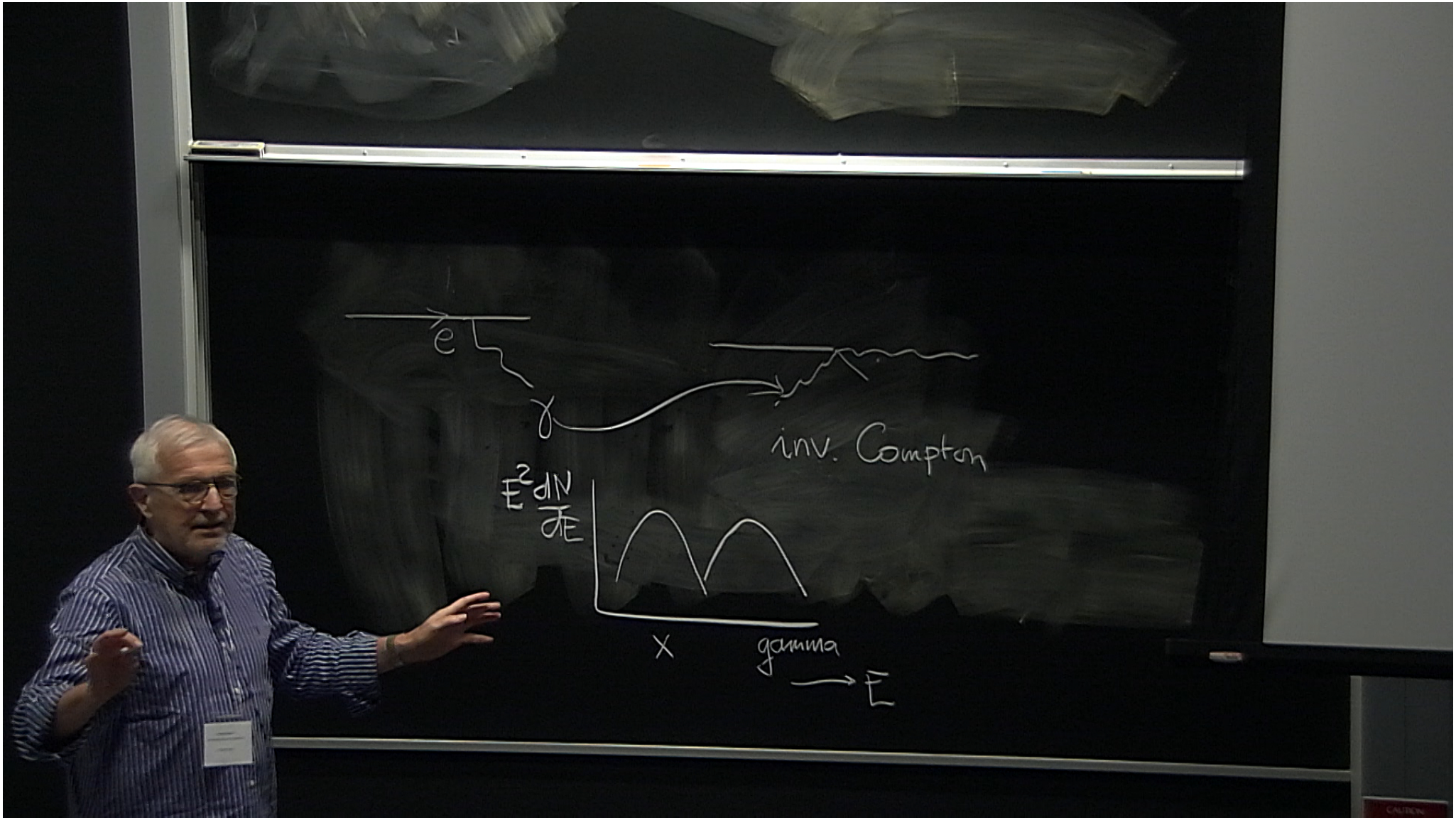
e
γ
inv. Compton
$E^2 \frac{dN}{dE}$
X
gamma
E