JINR-ISU summer school
Bolshie Koty
11-18 July 2023

High Energy Neutrino Astronomy

Lecture 1

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(INR RAS, Moscow)

Plan

- Lecture 1: Introduction to high energy astrophysics
  - Introduction
  - Objects and phenomena under study
- Lecture 2: Neutrino telescopes, Baikal-GVD, experimental results and prospects

Introduction

Astronomy vs. Astrophysics

- Astronomy is the observational study of the universe beyond Earth's atmosphere
- Astrophysics is a science that employs the methods and principles of physics (and chemistry) in the study of astronomical objects and phenomena

What is included in high energy astronomy

- X-ray astronomy
- Gamma astronomy
- High energy neutrino astronomy
- Ultra High Energy Cosmic Ray studies

In this course we focus on energies above 10 GeV

Neutrino as astrophysical messenger

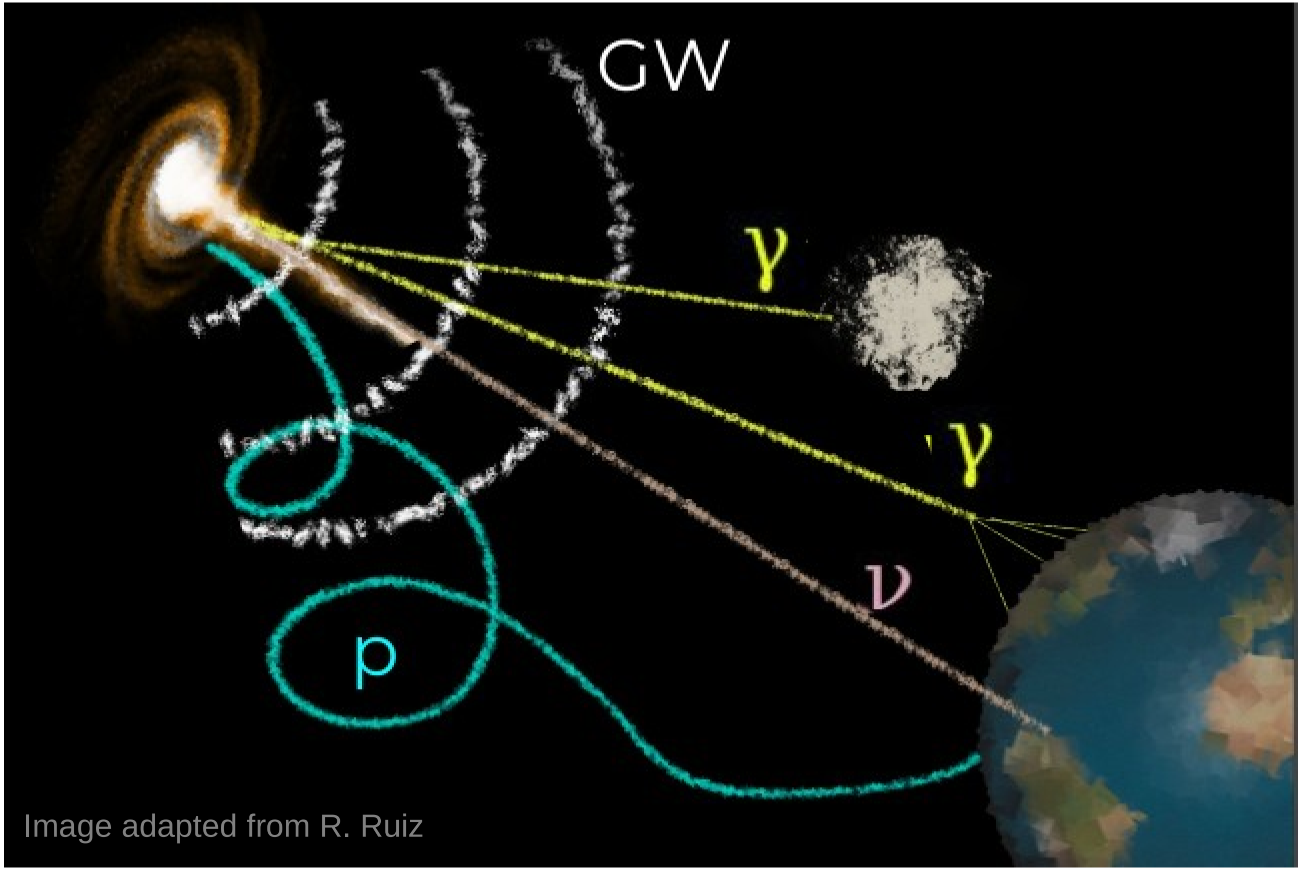
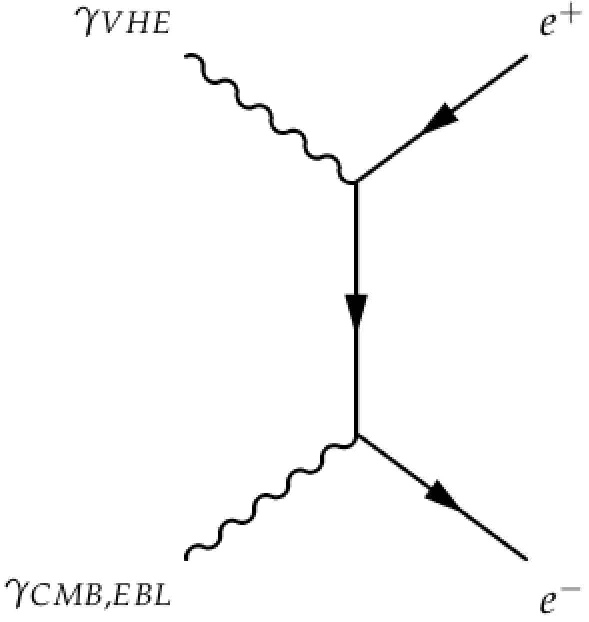


Image adapted from R. Ruiz

- Can escape from dense environments
- Travels unimpeded through gas and dust
- Does not interact with CMB and infrared background
- Stable (no decay)
- Not affected by magnetic fields
- Arrival direction points to the source
- High-energy neutrinos trace production and acceleration sites of cosmic rays

Photon – photon absorption

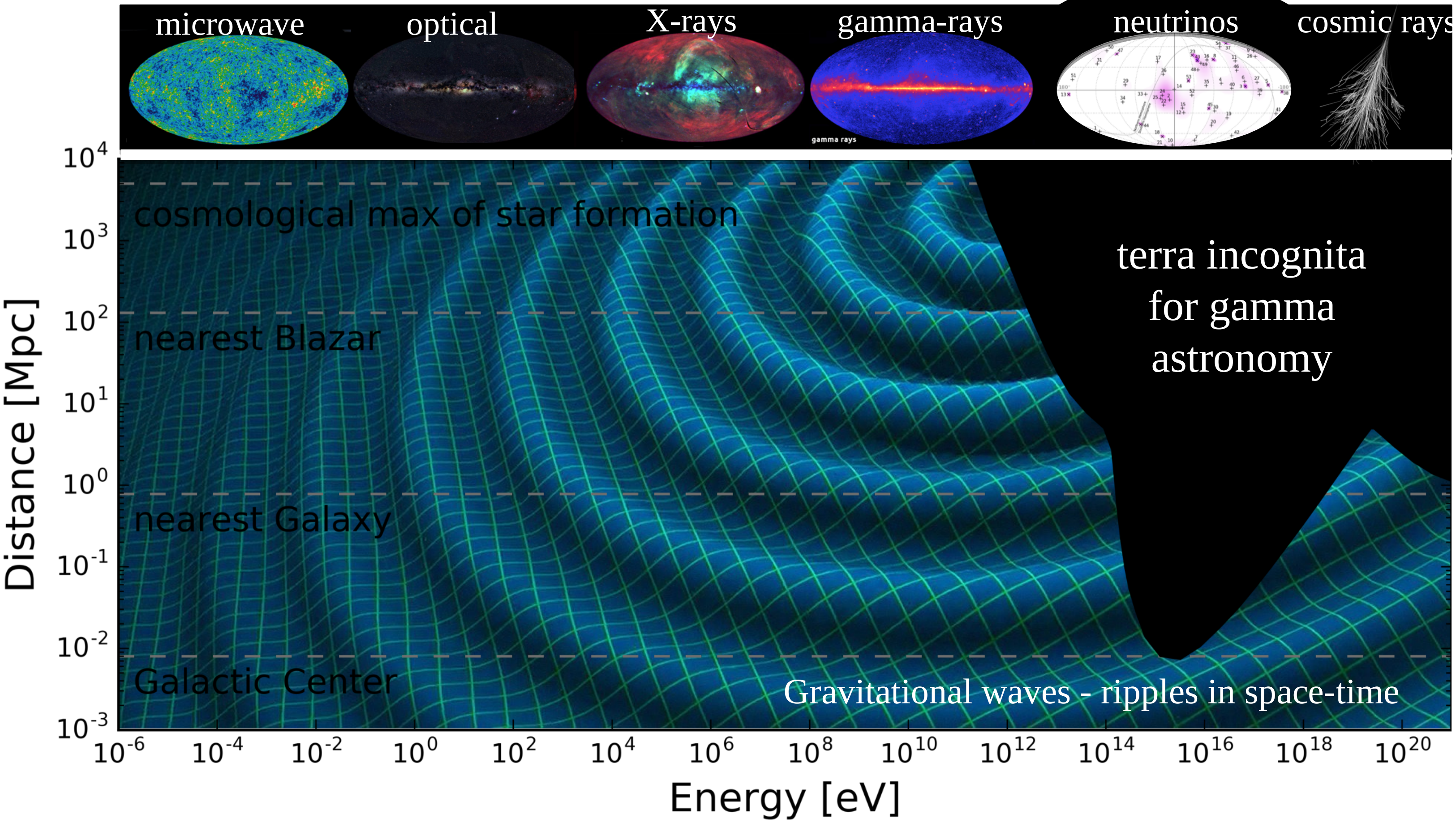


High energy photons scatter off
CMB or EBL photons

CMB = Cosmic Microwave Backgrpound

EBL = Extragalatic background light

Universe is opaque to high energy photons



F. Halzen, Neutrino 2020

Universe is opaque to photons above TeV energies due to interactions on CMB and EBL photons

Distances in astronomy

1 ly = 1 light year
1 pc = 3.26 ly

Nearest star (alpha centauri): 4 ly

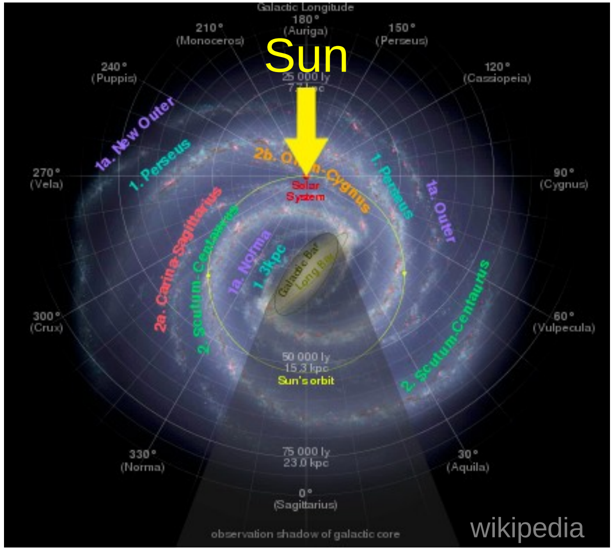
Distance to Milky Way center: 15 kpc (50 kly)

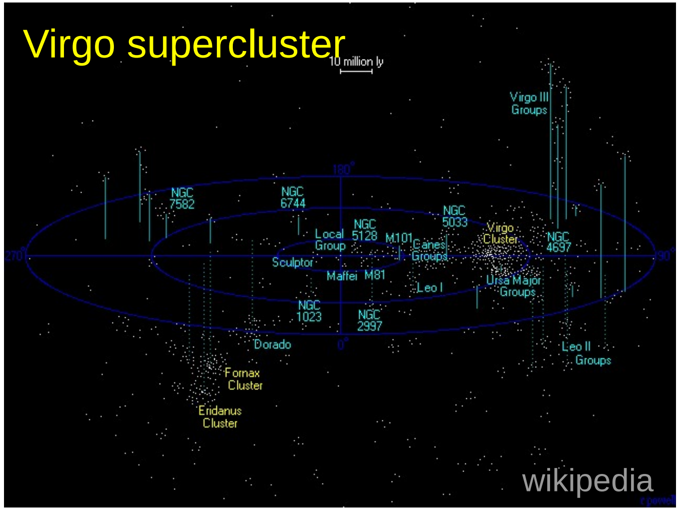
Distance to Andromeda galaxy : 765 kpc (2.5 Mly)

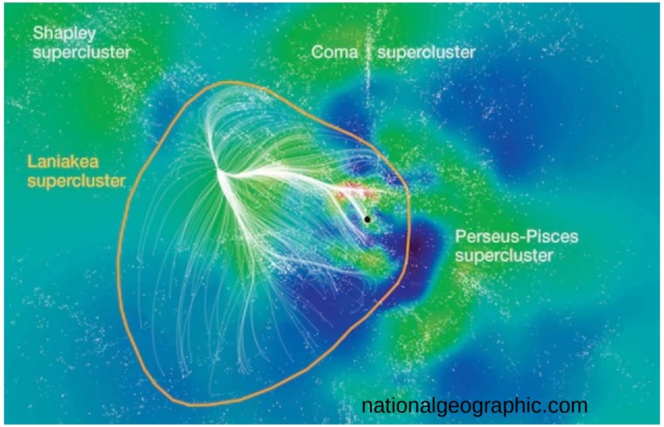
Local Cluster size : 33 Mpc (110 Mly)

Laniakea Supercluster size: 159 Mpc (520 Mly)

Dist. to the most distant known quasar: 13 Gly

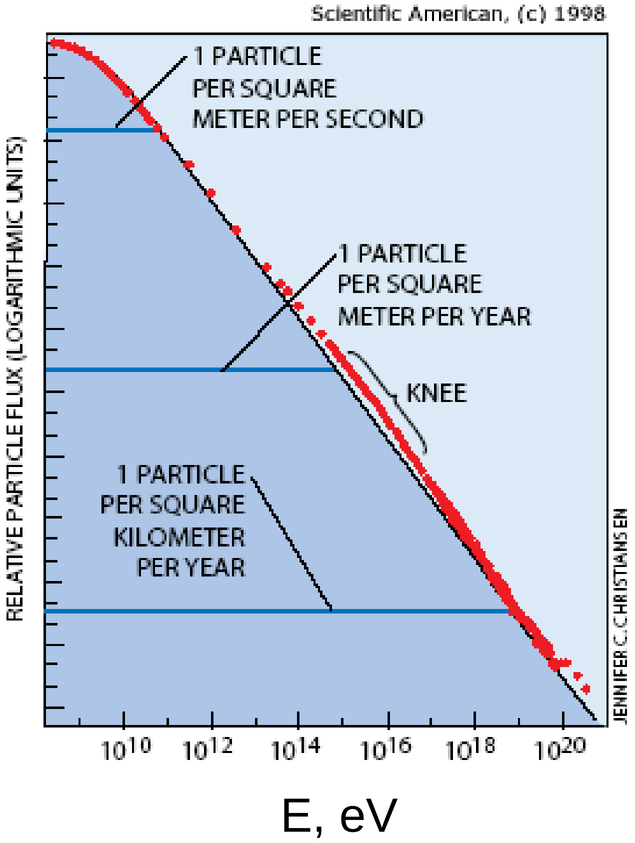






Cosmic Rays

The all-particle energy spectrum of cosmic rays



Protons, α and heavier nuclei

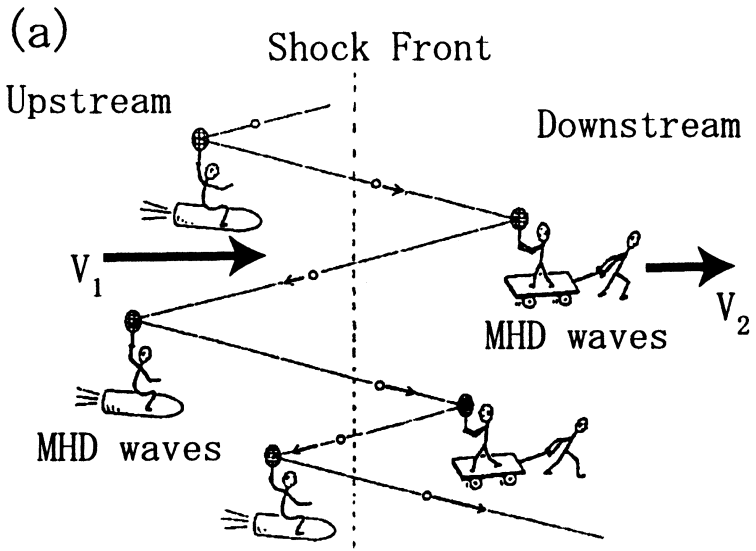
Spectrum spans over 12 decades in energy

Approximately a power-law (index ~ 2.7)

Particle acceleration mechanisms

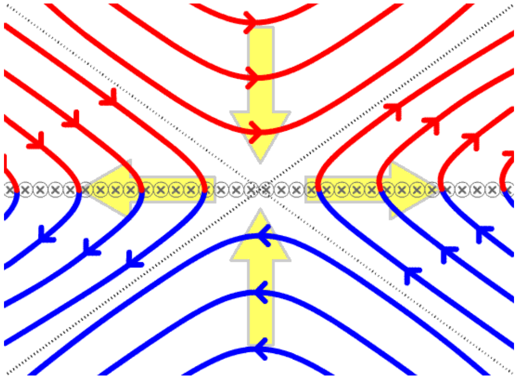
In shocks

Diffusive shock acceleration
a.k.a. 1-st order Fermi acceleration



Picture adapted from M. Hoshino,
https://doi.org/10.1143/PTPS.143.149

during magnetic reconnection



Fermi acceleration by contracting or merging magnetic islands

See, e.g., F.Guo et al, doi:10.1063/5.0012094

Produces power-law spectrum
~ E^{-s}, s ≈ 2
(s depends on conditions)

Hadronic production mechanism: photons and neutrino

1) Accelerate protons (or ions)

2) Have them interact with medium or radiation

In photon-reach environments: p γ → π
In proton-reach environments : p p → π

3) Decay pions

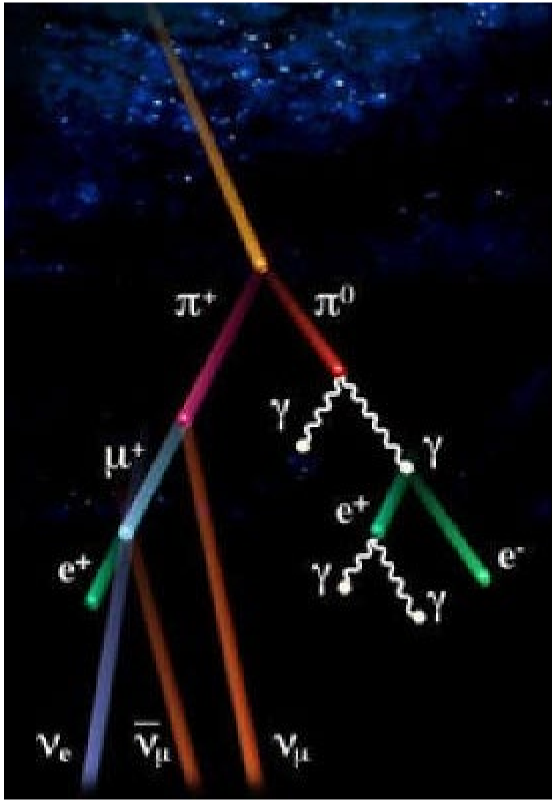
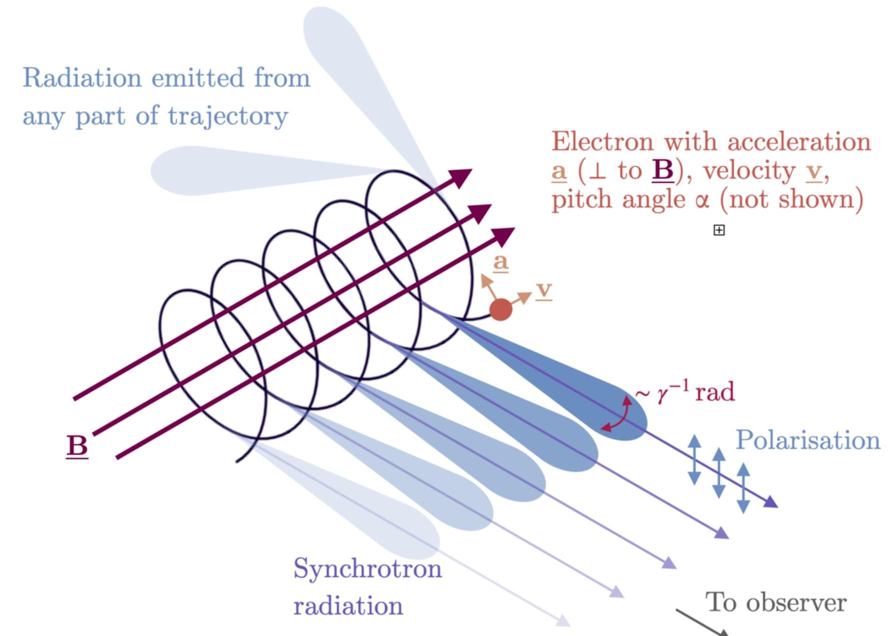


Figure from Relner et al, PRD (2008)

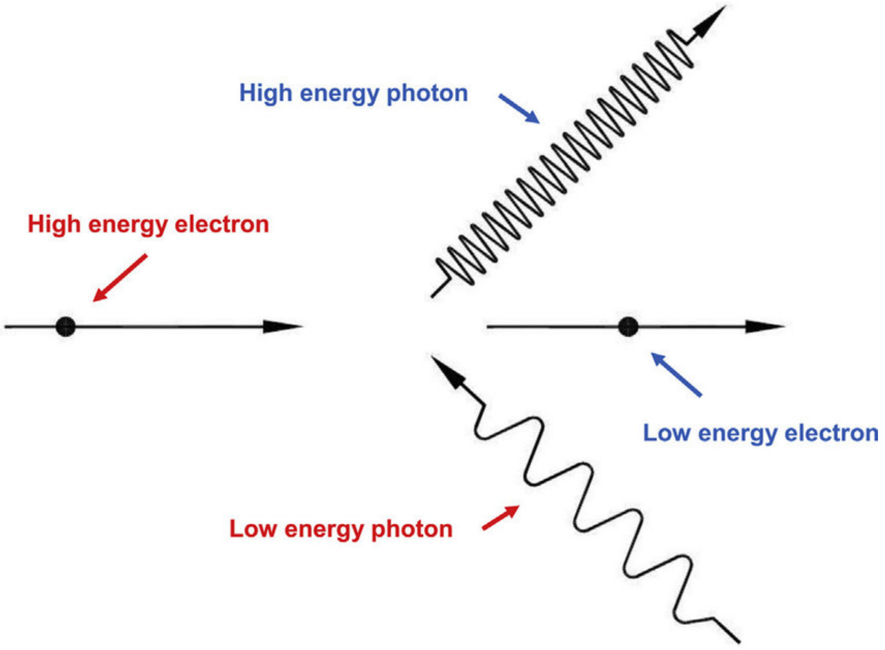
Примеры нетеплового излучения («лептонные процессы»)

Synchrotron radiation



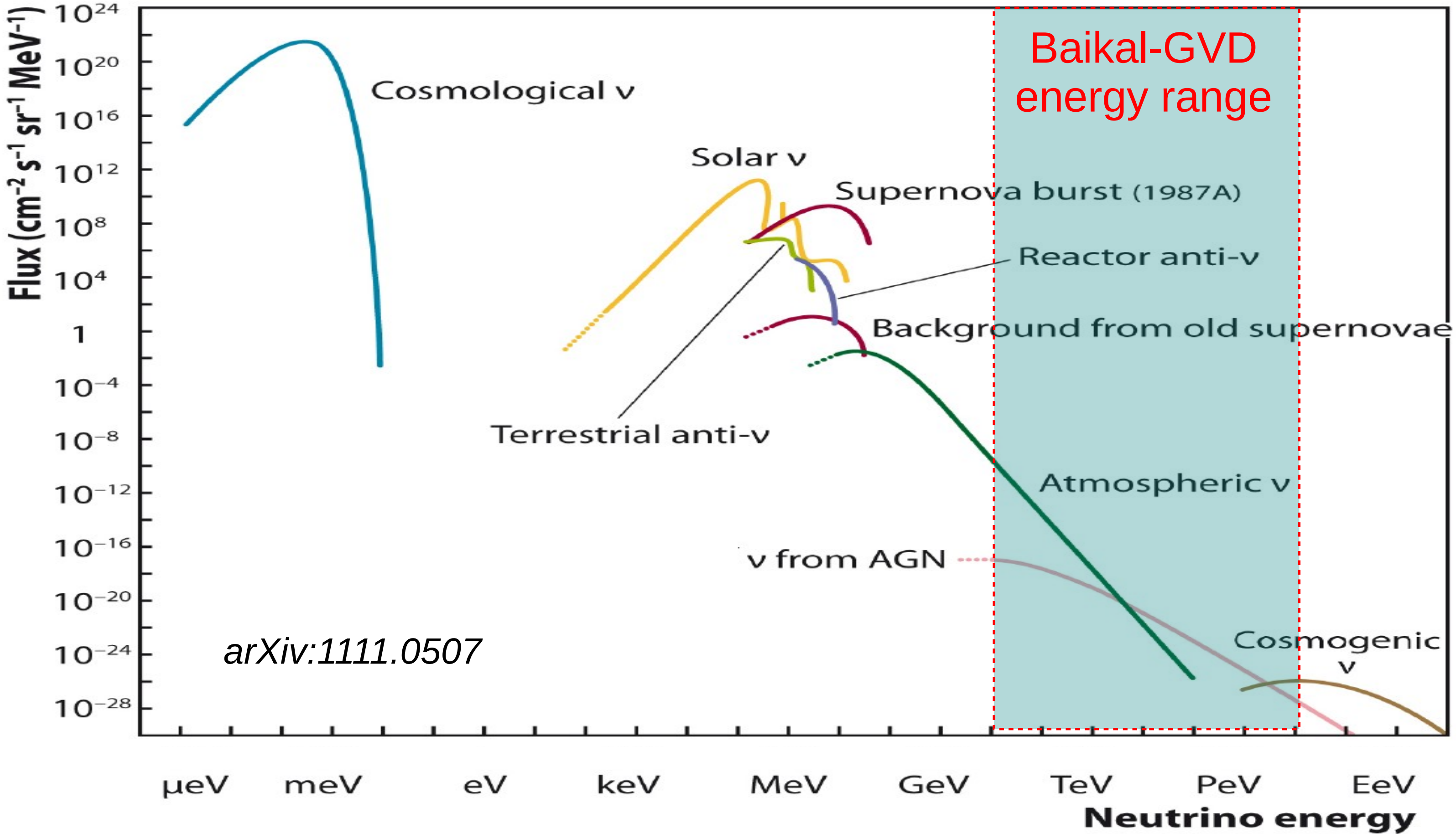
Adapted from wikipedia

Inverse Compton scattering



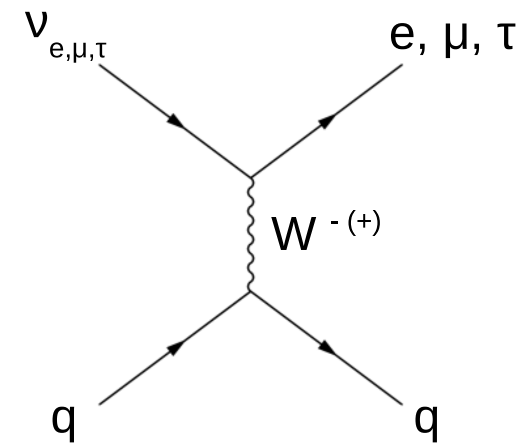
Picture adapted from DOI:10.1016/j.ejmp.2015.04.003

Neutrino energy scale

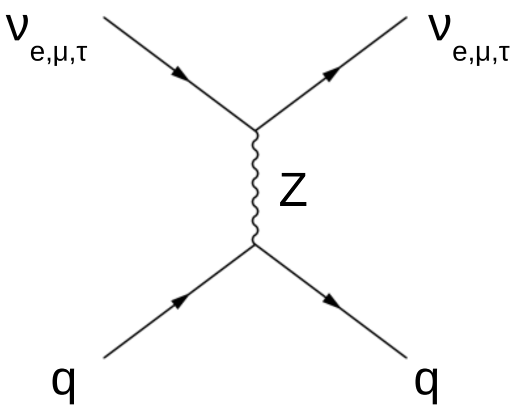


Neutrino interactions at high energy

Charged current (CC)

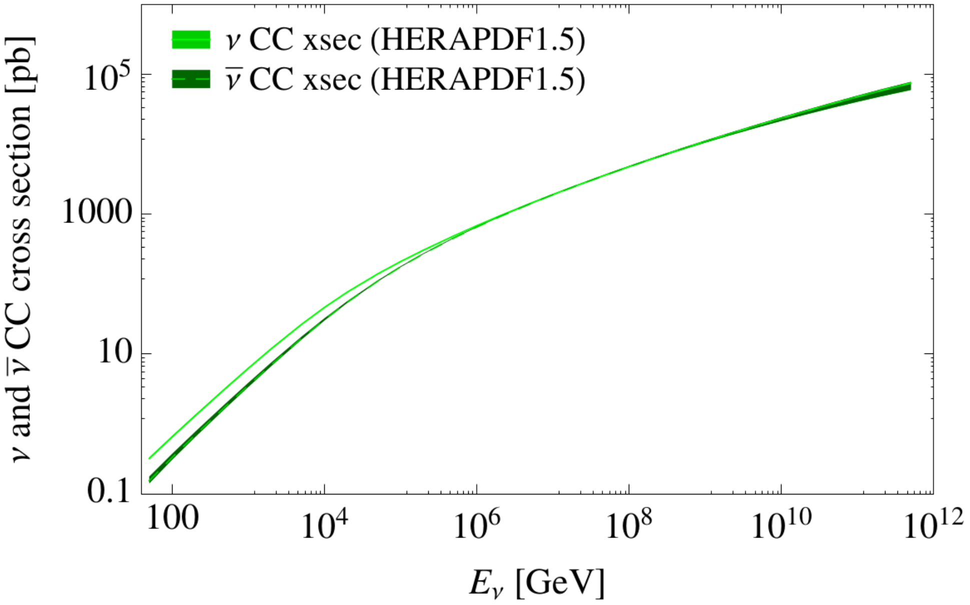


Neutral current (NC)



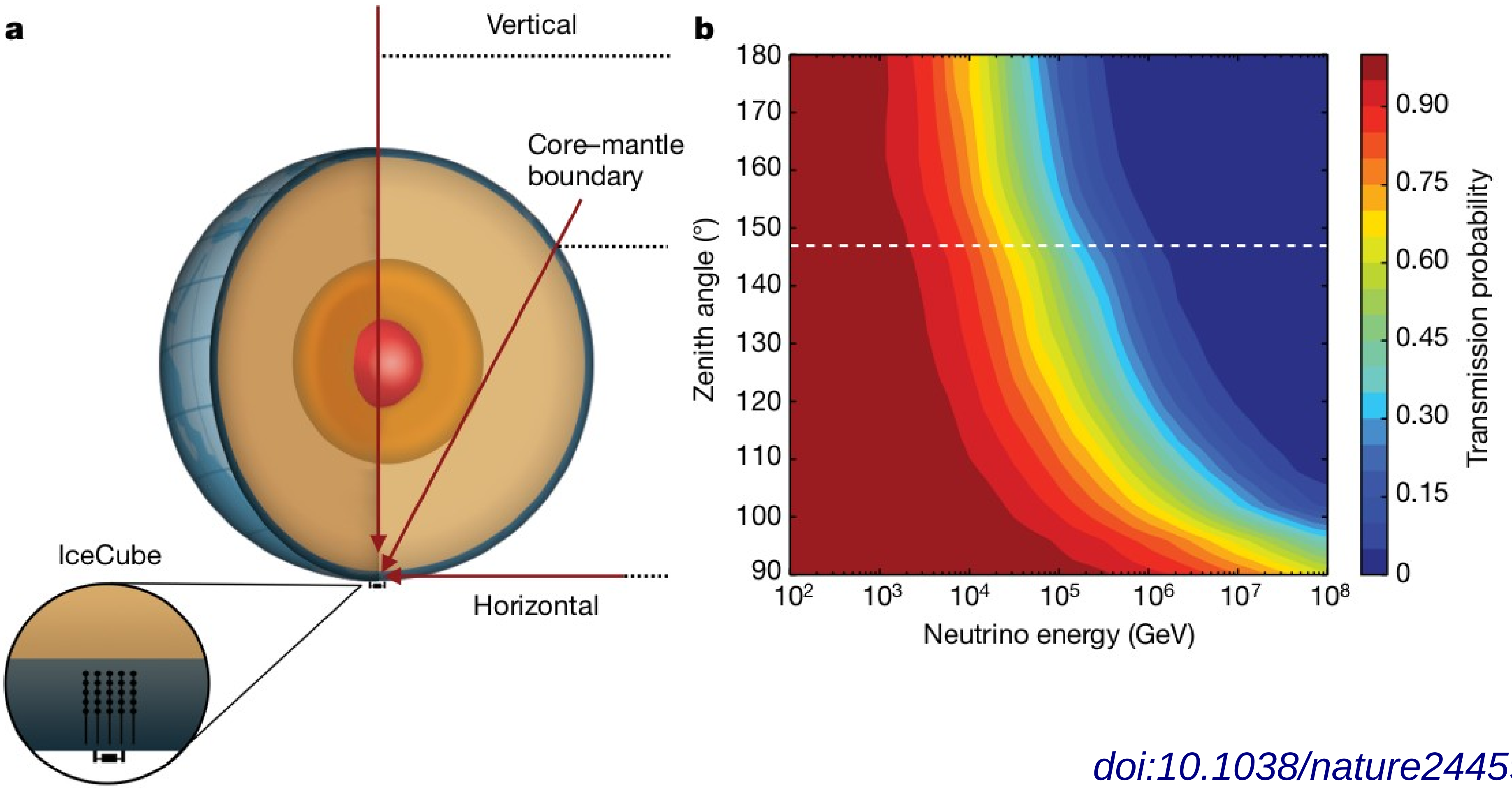
At high energies, the dominant process is deep inelastic scattering on quarks

Interaction probability rises with energy



A. Cooper-Sarkar, P. Mertsch, and S. Sarkar, JHEP 2011, 42.

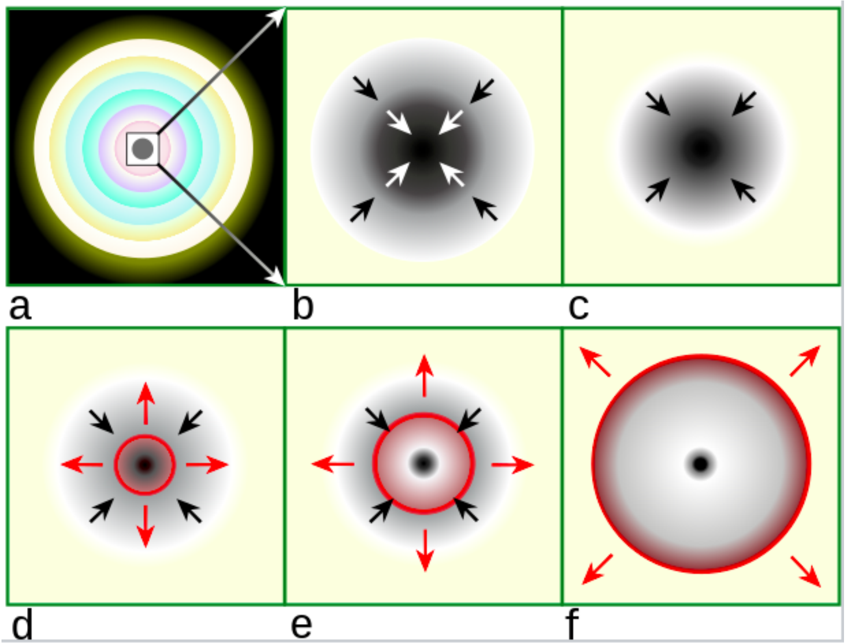
Neutrino absorption in the Earth



doi:10.1038/nature24459

Objects and Phenomena under study in high energy astrophysics

Core Collapse Supernova

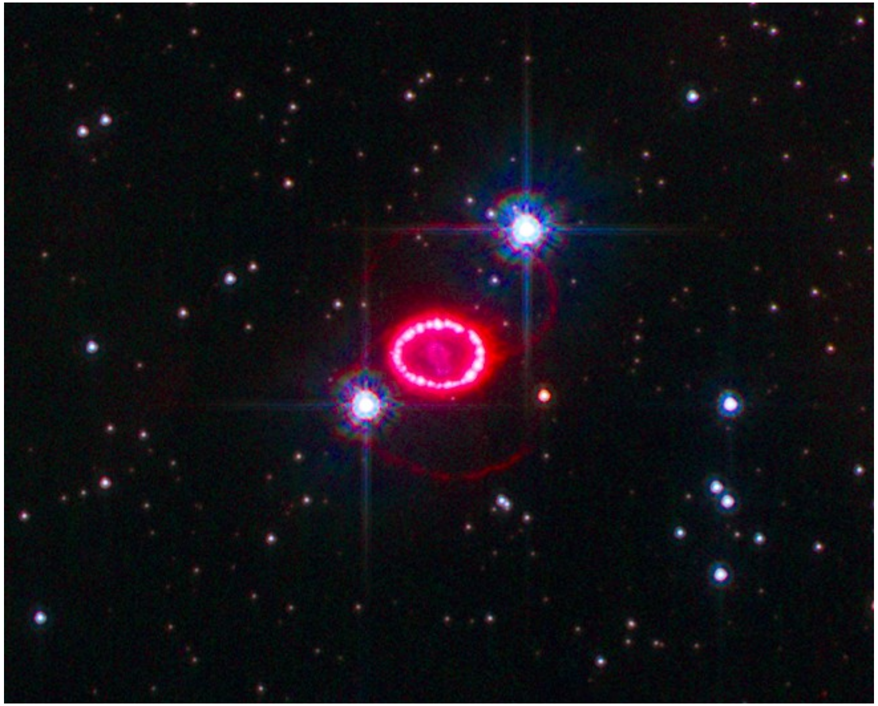


wikipedia

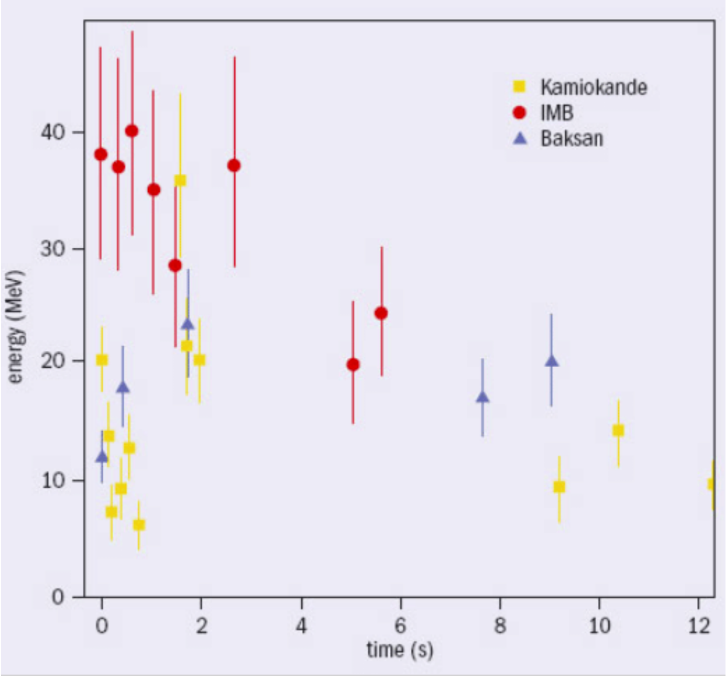
- Collapse of the core of a massive star
- Outer layers are ejected into space
- A compact object (black hole or neutron star) can be formed
- Most of the explosion energy is released with neutrinos of MeV energies

SN 1987A

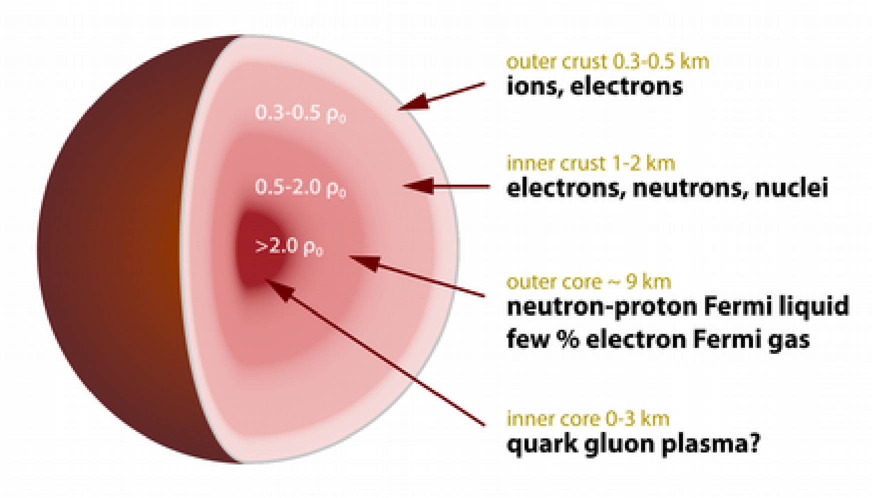
A type II (core-collapse) supernova in Large Magellanic Cloud (51 kpc from us)



MeV neutrinos detected !



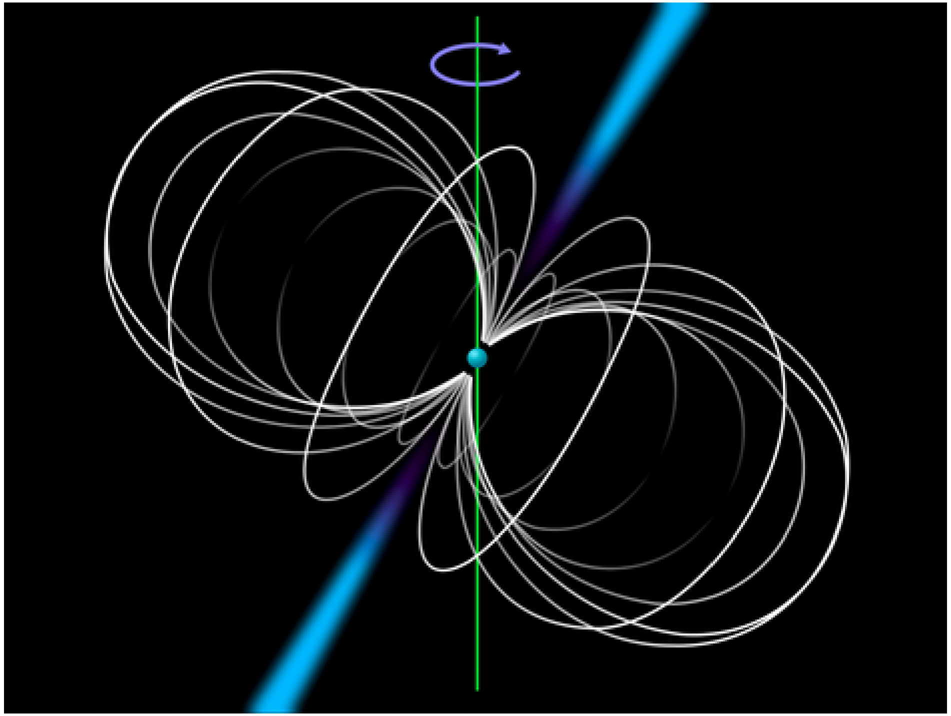
Neutron Star



Wikipedia

- Neutron star is a collapsed core of a massive star
- Supported by neutron degeneracy pressure
- Radius ~ 10 km
- Mass ~ 1.4 M_{sun}

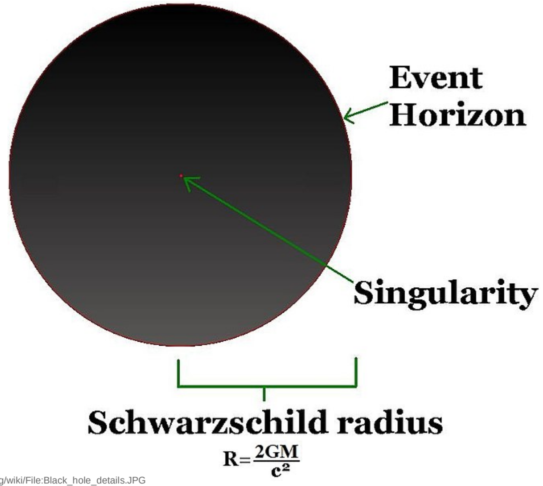
Pulsar



- Highly magnetized rotating neutron star
- Emits beams of electromagnetic radiation
- Rotation period ~ 1 ms to 15 s
- Pulsations can be observed when a beam of emission is pointing toward Earth (once every rotation period)
- Young neutron stars (< 100 Myr) or recycled neutron stars (in binary systems)

Black hole

A non-rotating black hole

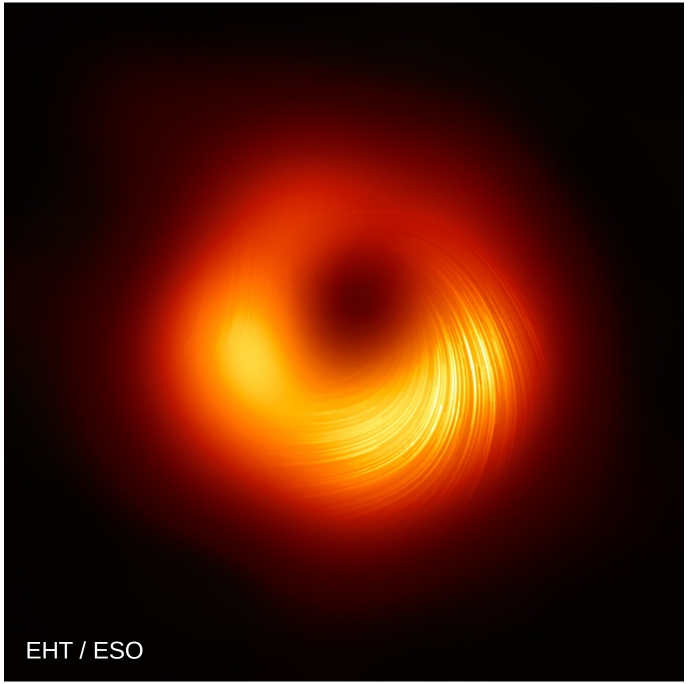


https://commons.wikimedia.org/wiki/File:Black_hole_details.JPG

- Black hole (BH) is a region of spacetime where gravity is so strong that nothing can escape its event horizon
- Black holes can form in collapse of massive stars' cores
- Supermassive black hole (SMBH) are found in centers of galaxies; mass ~ 10^6 ... 10^9 M_{sun}
- A black hole itself is practically invisible, but its interaction with the environment can be spectacular

M87 black hole “shadow”

Black hole shadow (VLBI radio image)

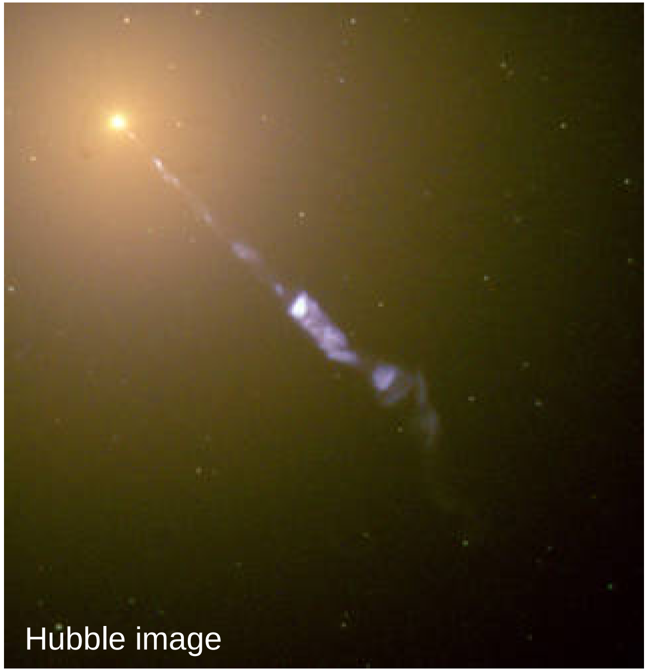


$M_{BH} = 5 \bullet 10^9 M_{sun}$

Black hole diameter ~ 200 a.u.

Distance to M87 : 16 Mpc (53 Mly)

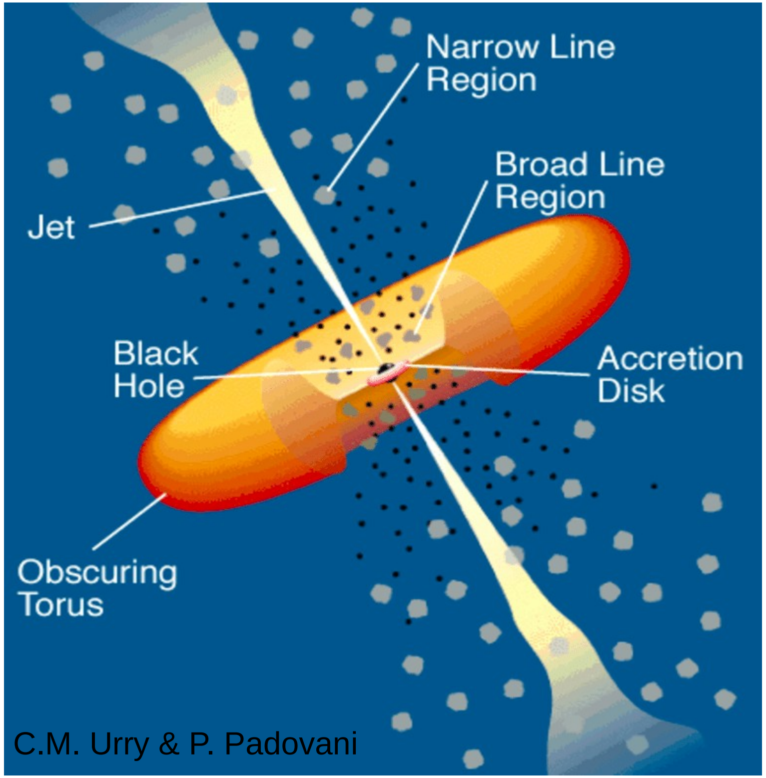
Large-scale jet (optical & IR image)



Credits: NASA and the Hubble Heritage Team (STScI/AURA)

The jet of matter is ejected at nearly speed of light, and stretches 1.5 kpc (5 kly) from the galactic core

Active Galactic Nuclei (AGN)

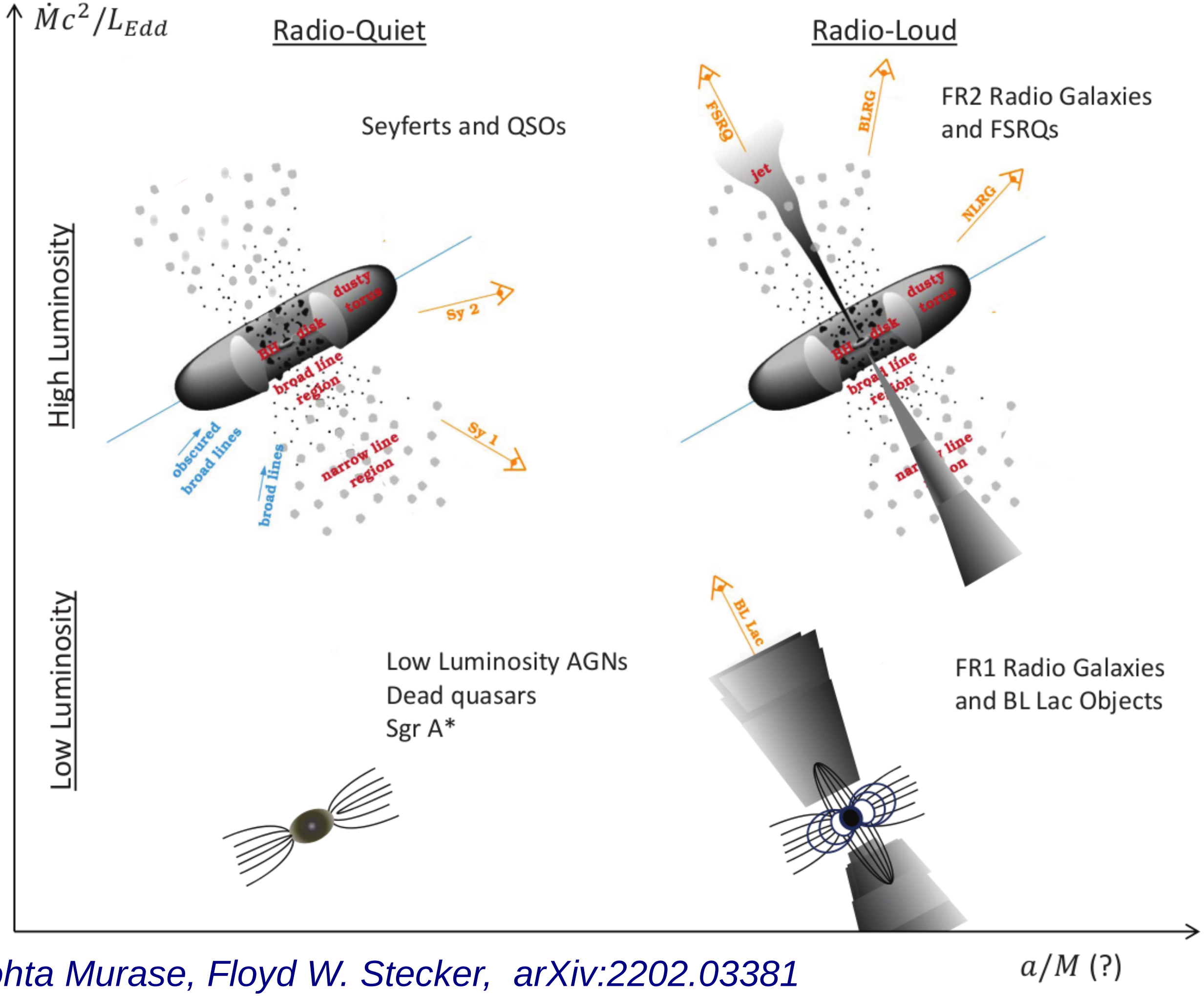


AGN is a compact region
at the center of a galaxy,
with bright electromagnetic emission,
which is not produced by stars

Observed at radio, IR, optical, UV,
X-ray, gamma-ray

Variable emission + flares

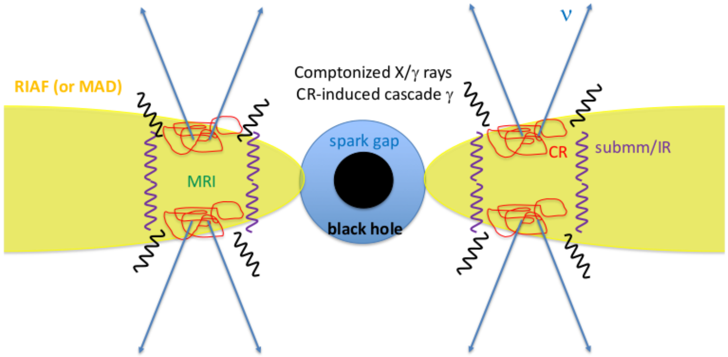
AGN classification



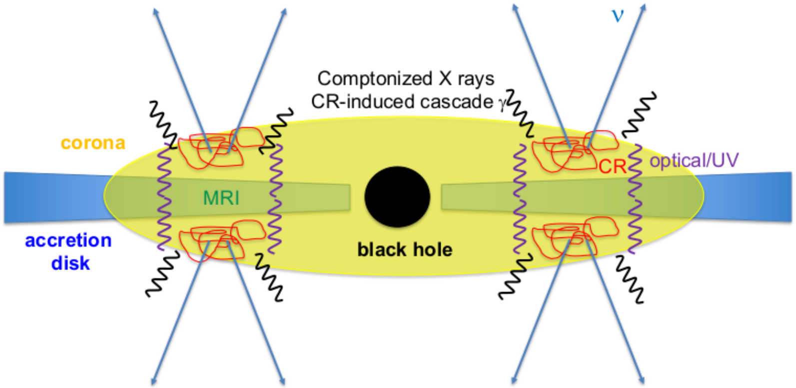
Kohta Murase, Floyd W. Stecker, arXiv:2202.03381

AGN neutrino production models

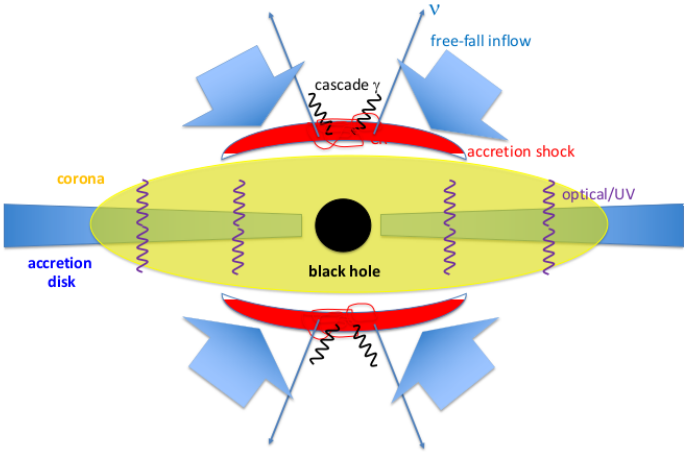
RIAF/MAD model



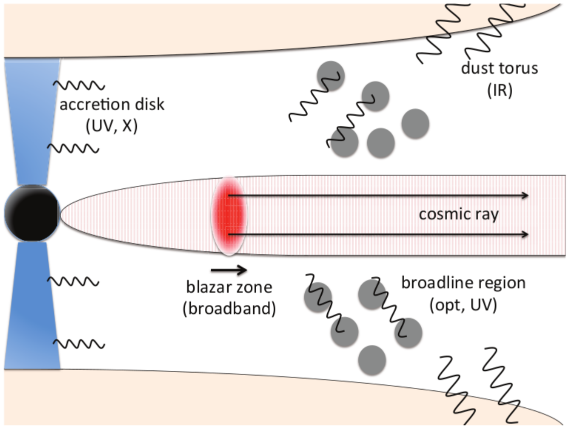
magnetically-powered corona model



accretion shock model

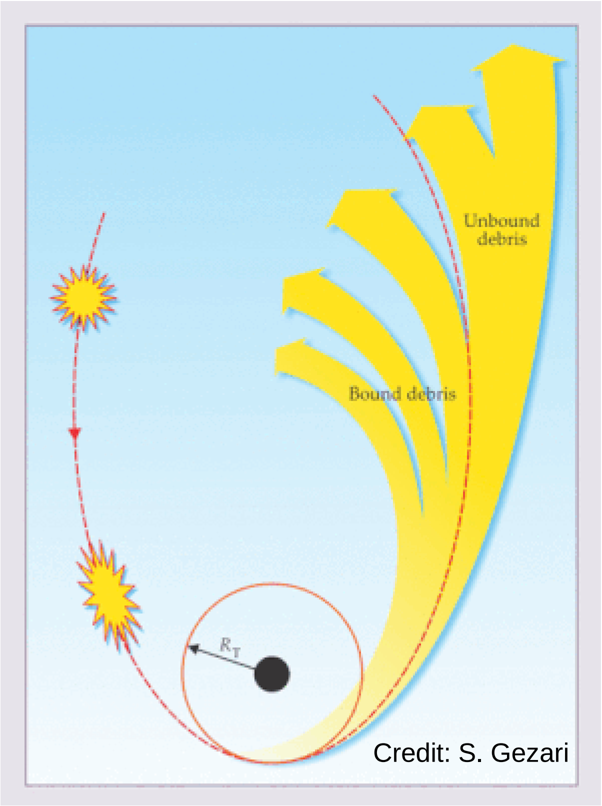


production in the inner jet



Kohta Murase, Floyd W. Stecker, arXiv:2202.03381

Tidal Disruption Events



Long transient (~ 1 yr)

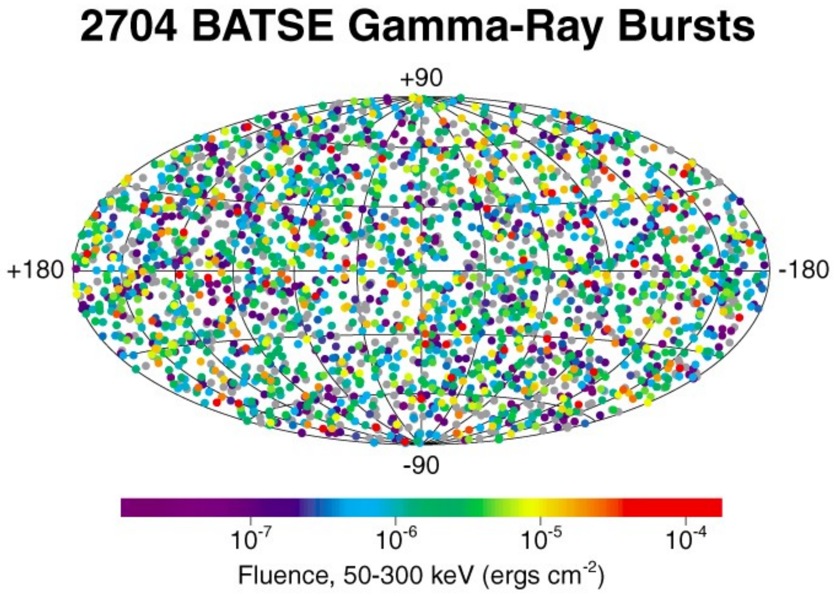
Star disrupted
in gravitational field
of supermassive black hole

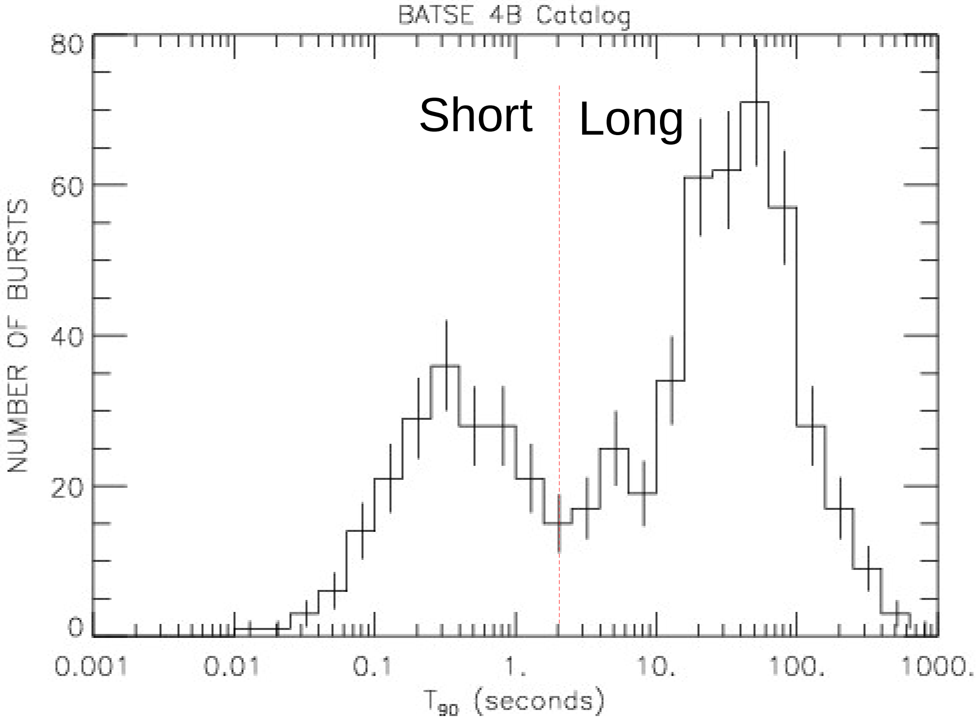
R = Rocher limit

Also see *R. Stein et al., Nat. Astron. 5, 510 (2021)*

Gamma-Ray Bursts (GRB)

Extremely energetic explosions in distant galaxies
First observed in the late 1960s by the U.S. Vela satellites
Duration of prompt phase from ms to ~ 1000 s





Long GRBs

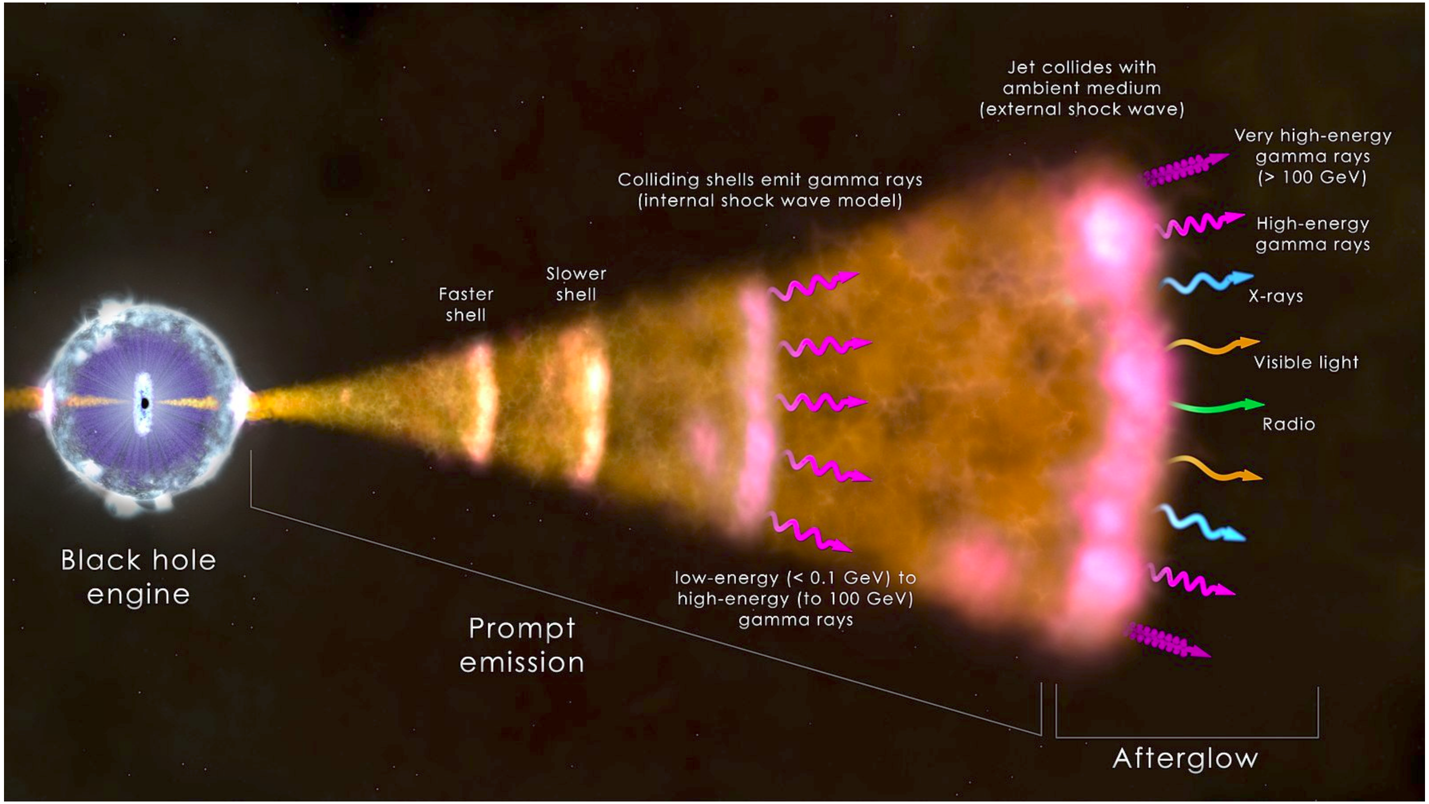
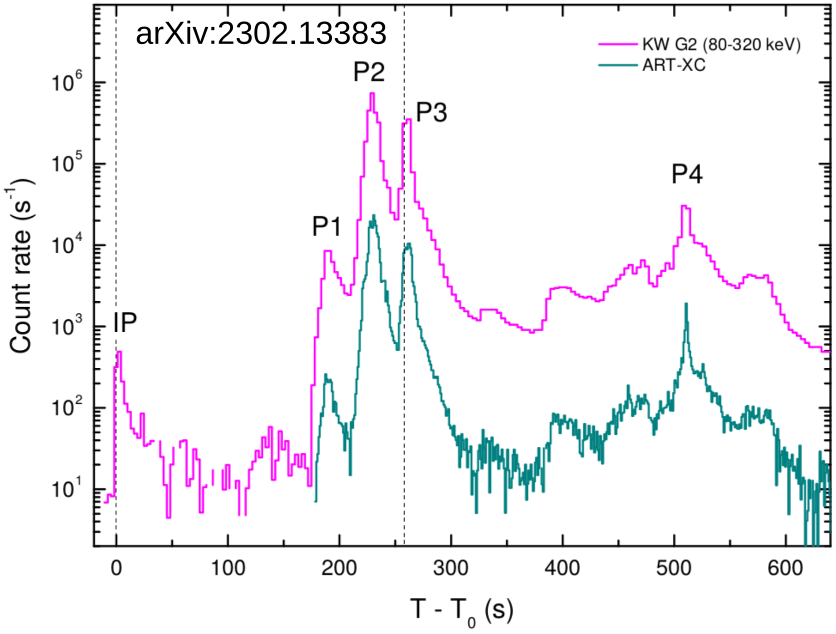


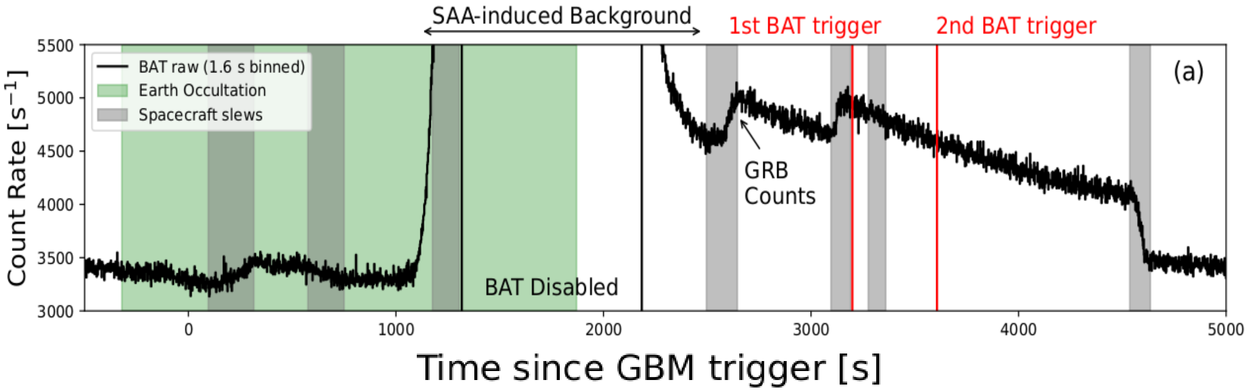
Image credit: NASA/Goddard Space Flight Center/ICRAR

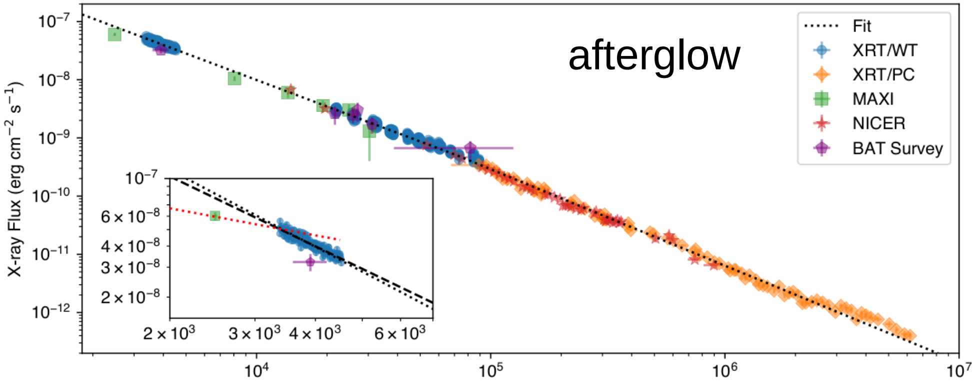
- Long GRBs originate from collapse of massive, rotating stars
- Prompt emission is normally followed by “afterglow” on a time scale from hours (in gamma-rays) to years (in radio)

GRB 221009A

Konus-Wind





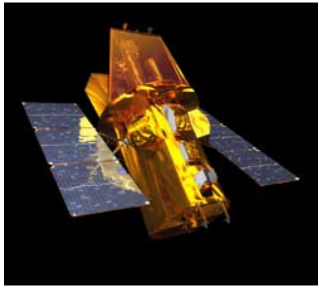


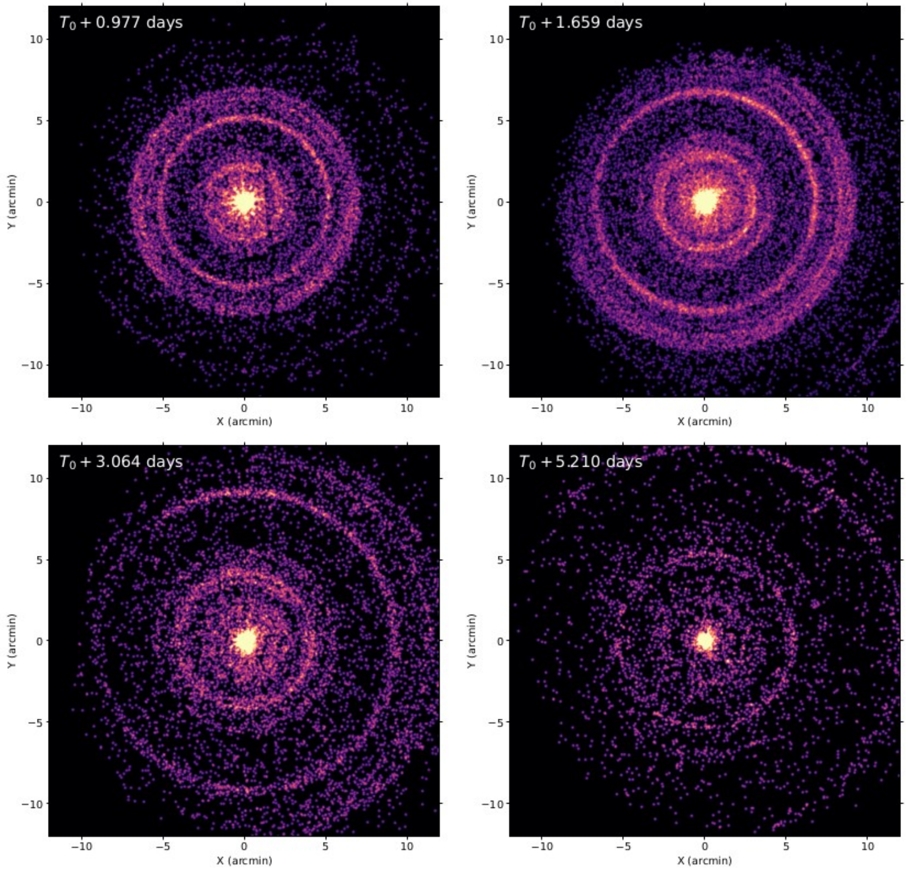
Detected on Oct 9, 2022 by gamma-ray and X-ray satellites

LHAASO ground-based gamma-ray observatory reported detection of gamma-rays with energies up to 18 TeV [GCN circular 32677]

arXiv:2302.03642

Galactic dust echo from GRB 221009A detected by Swift

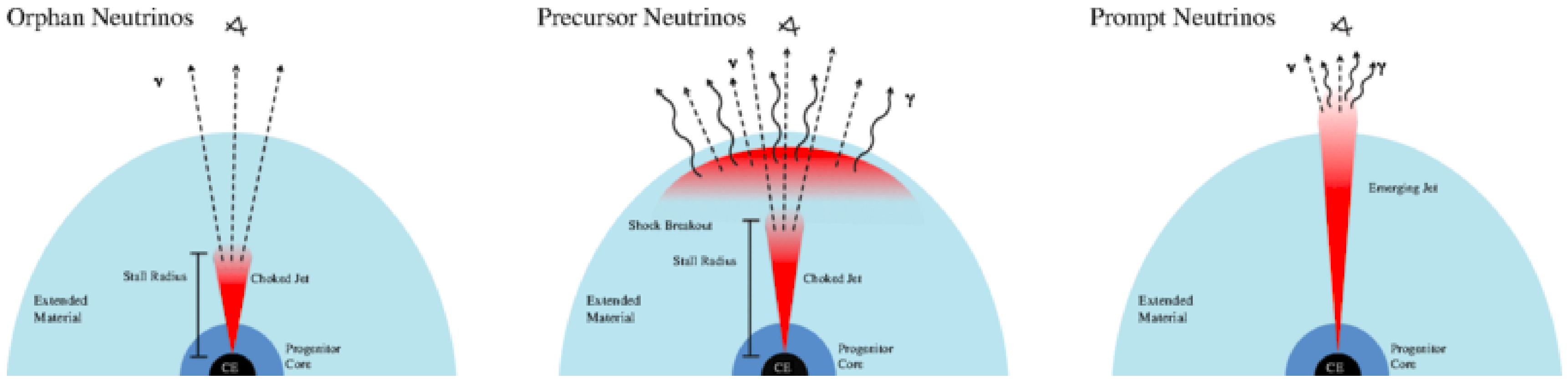




The bright rings form as a result of X-rays scattered from otherwise unobservable dust layers within our galaxy that lie in the direction of the burst

arXiv:2302.03642

Neutrino from GRB / Core-collapse Supernovae ?



N. Senno, K. Murase, and P. Mészáros (2016)

Short transient sources
MeV prompt emission for long GRBs: 2 – 1000 seconds
GRB afterglow: up to a few months

Short GRB: the binary merger model

Artist's impression (wikipedia)

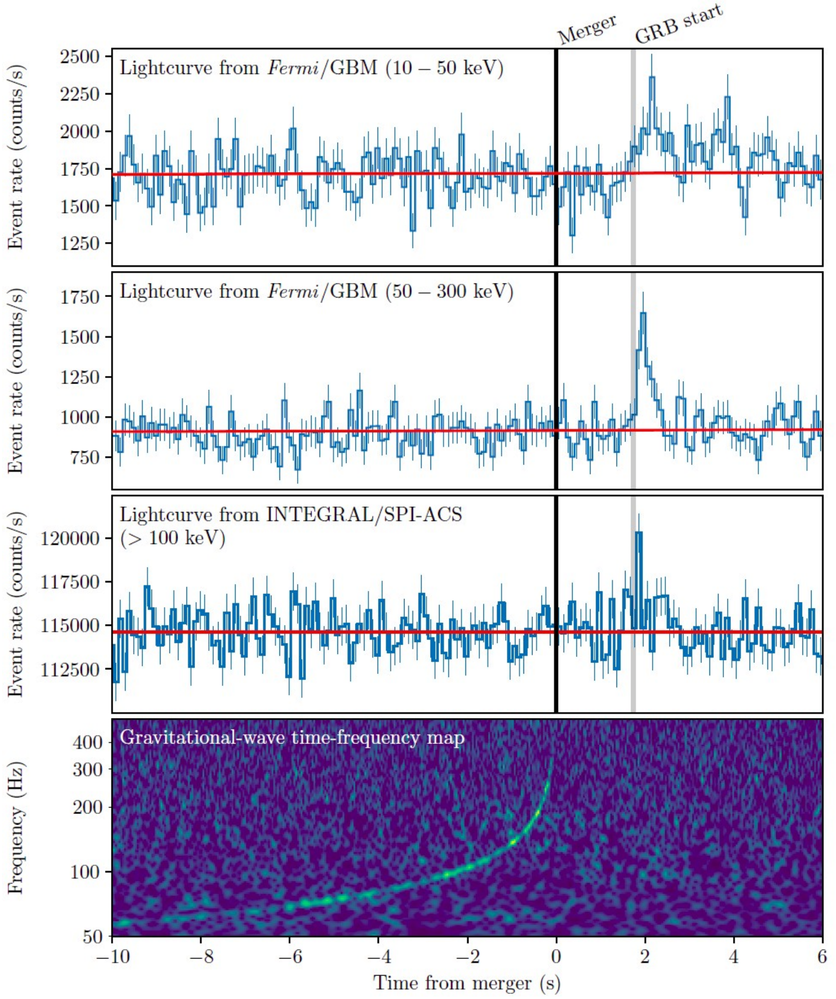
NS-NS or BH-NS

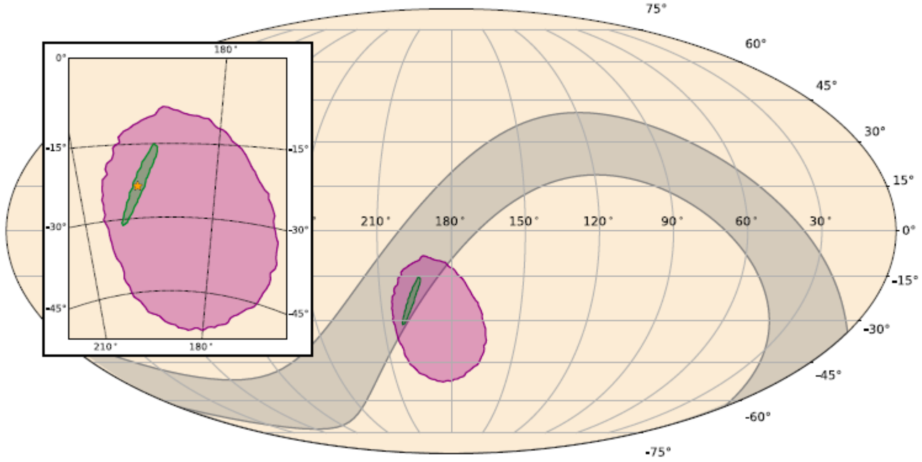
BH = black hole
NS = neutron star

Sources of gravitational waves and high energy radiation

Merger duration: ~ 1 s or shorter
Afterglow may last for months

GW170817 / GRB 170817A

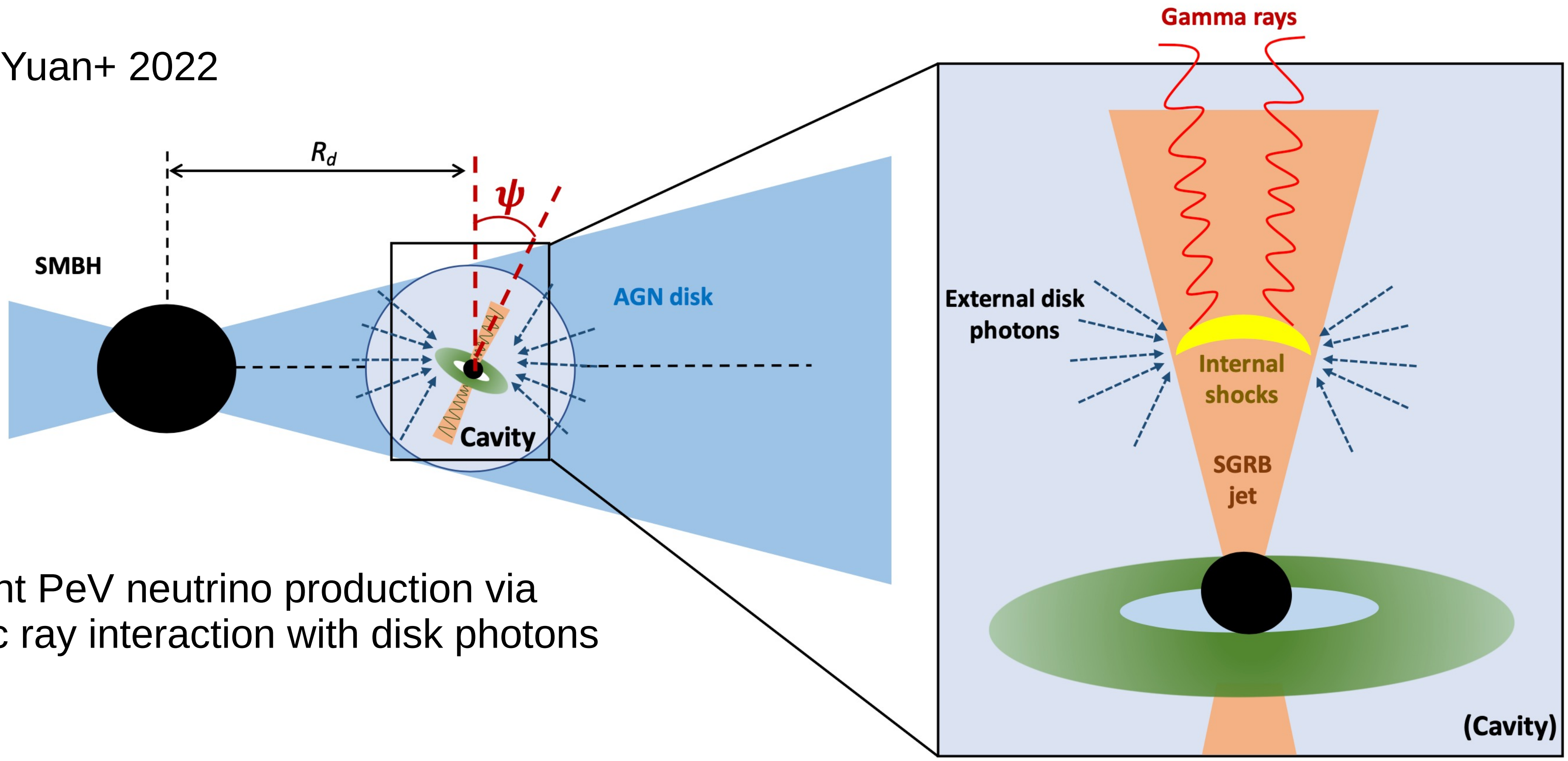




green = LIGO-Virgo
purple = Fermi-GBM
grey = Fermi + INTEGRAL timing information
yellow star = optical transient

Neutron star mergers in AGN disks

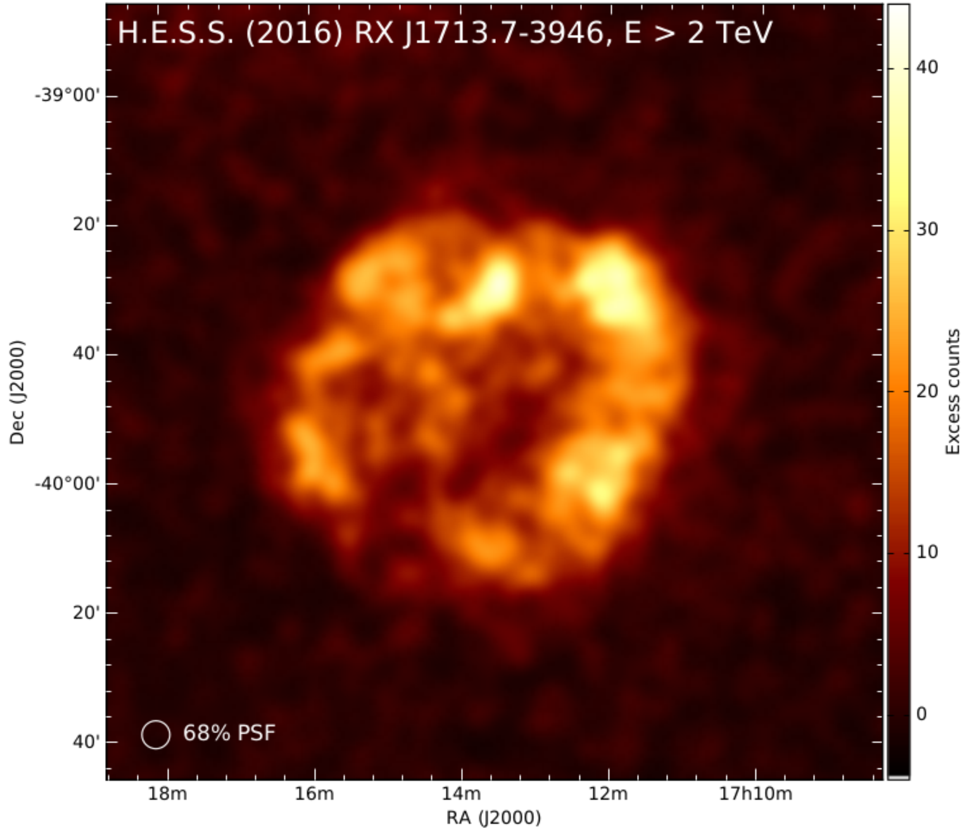
Yuan+ 2022



Efficient PeV neutrino production via cosmic ray interaction with disk photons

Also possible with black hole mergers (Kimura et al., 2021)

Galactic sources : Supernovae Remnants (SNR)



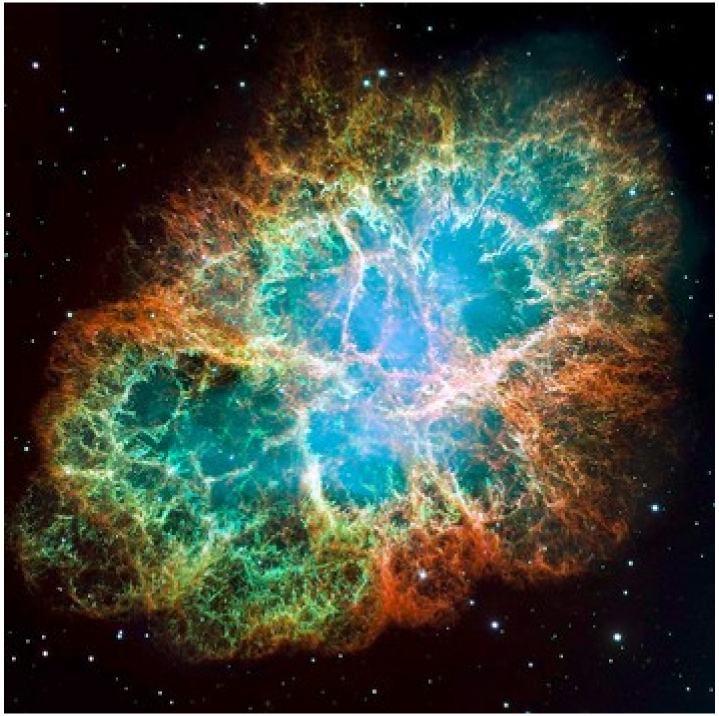
Angular extension : ~ 1 deg (or smaller)

Variability : not expected

Can be hadronic, especially in the case of interacting with a nearby gas cloud

https://doi.org/10.1051/0004-6361/201629790

Pulsar Wind Nebulae (PWN)



Crab Nebula (HST image)

High energy emission
is generally considered
to be of leptonic origin
(not expected to produce neutrinos)

Can be variable
(due to pulsar activity, bright knots, etc)

Related to PWN : “TeV halos”
(not shown here)

* Crab Nubula is also as SNR

Microquasars

Artist’s impression (wikipedia)

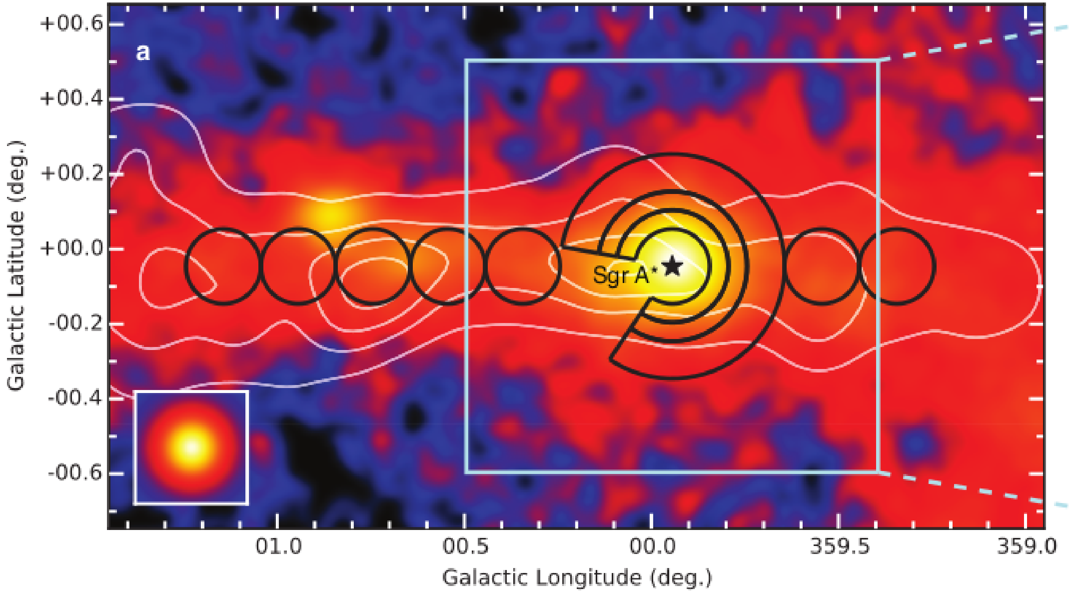
A mini-version of AGN

Stellar-mass black hole
+ a companion star

Variable

Emission likely hadronic

Galactic center

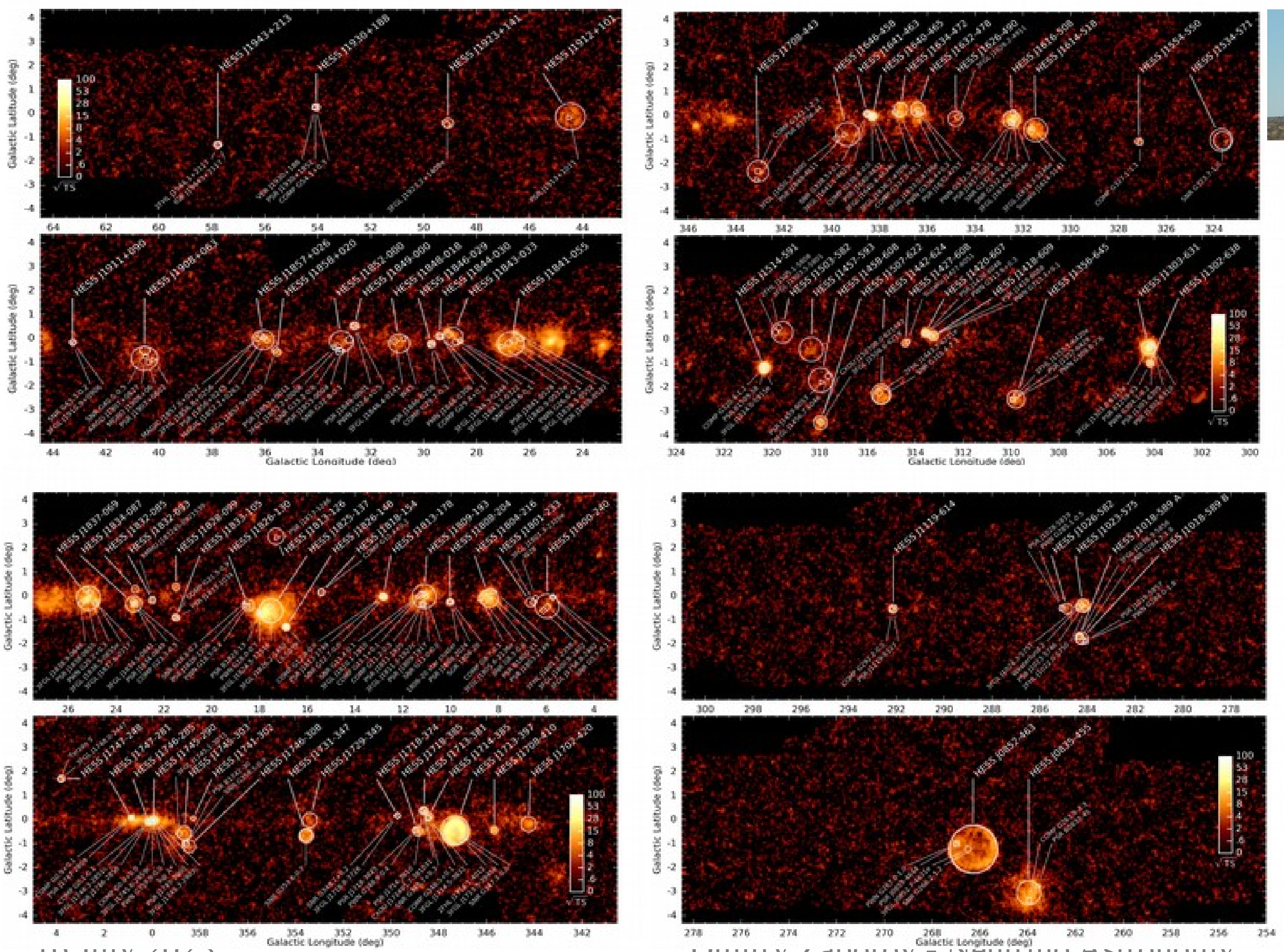


VHE gamma observations suggest that it's a hadronic PeVatron

Past activity of the central black hole might be a major source of PeV cosmic rays in our galaxy

https://doi.org/10.1038/nature17147

H.E.S.S. Galactic plane survey



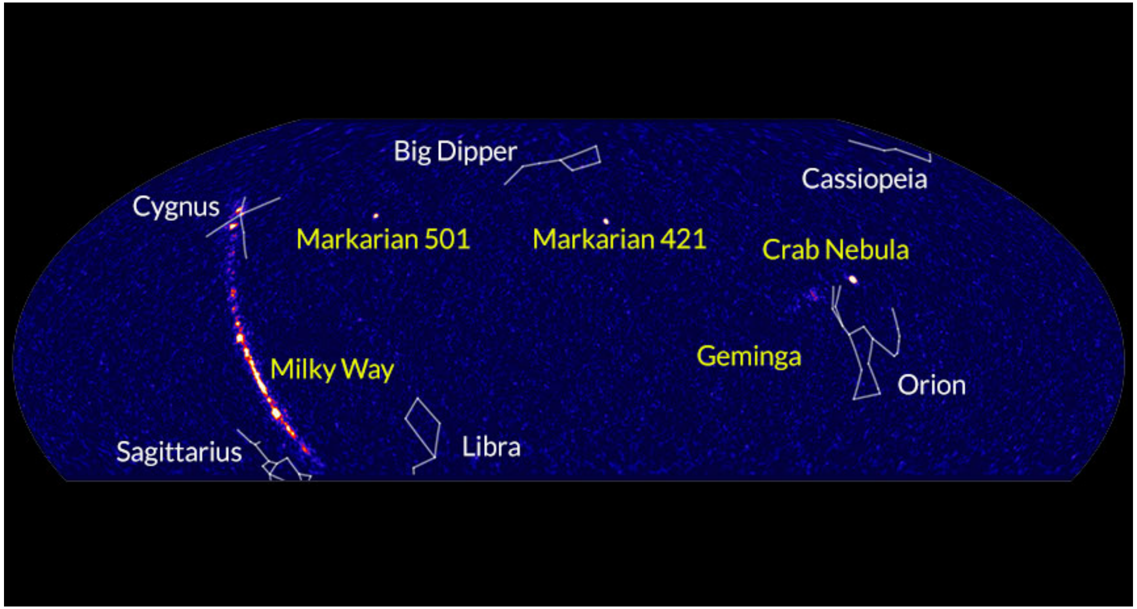
Many TeV sources of different types and sizes are found near the Galactic plane

Energy ~ 1 TeV

https://www.mpi-hd.mpg.de/hfm/HESS/hgps/
Figs 35-38

HAWC

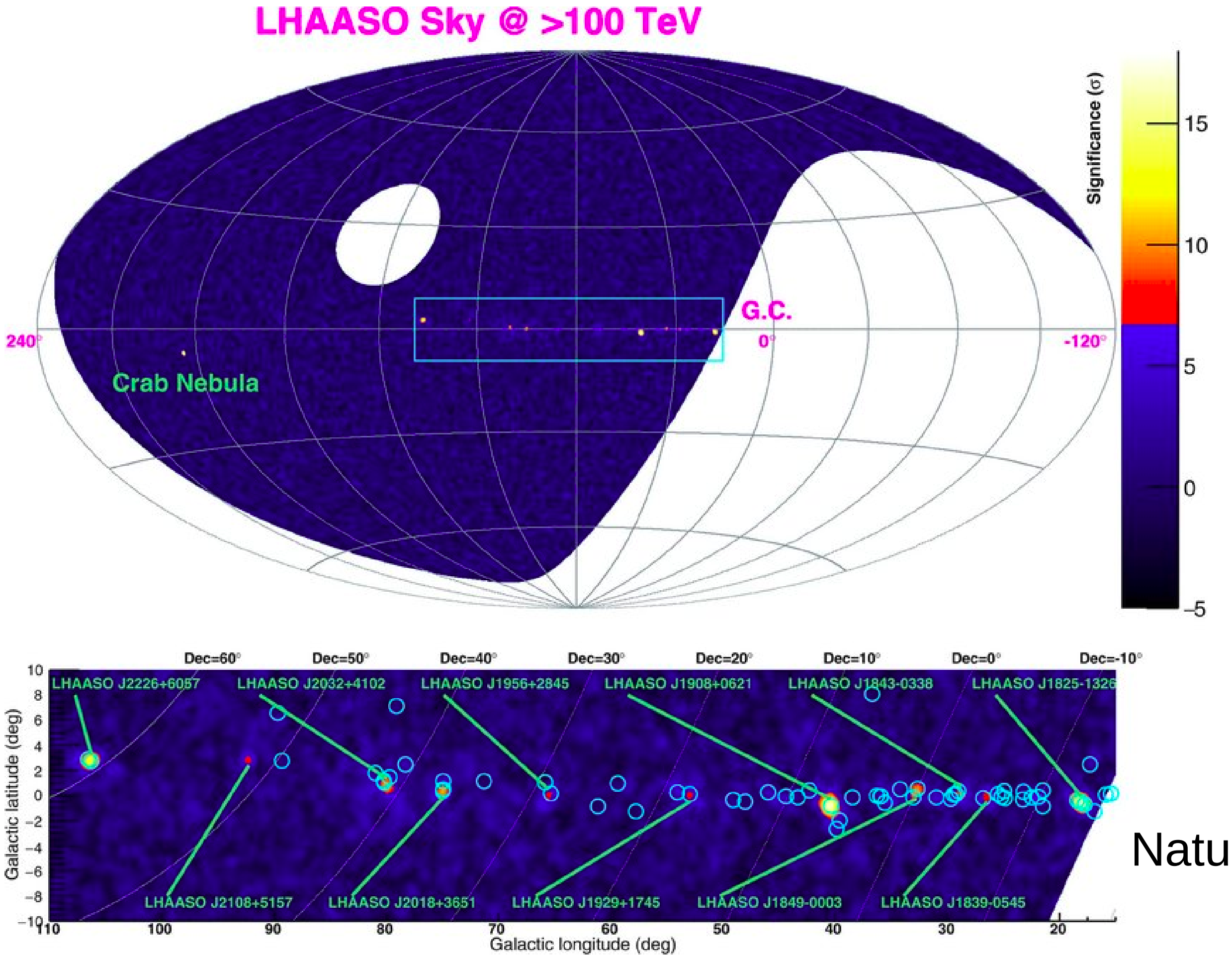
VHE gamma-ray sky map



At TeV energies most emission comes from |b| < 3 deg

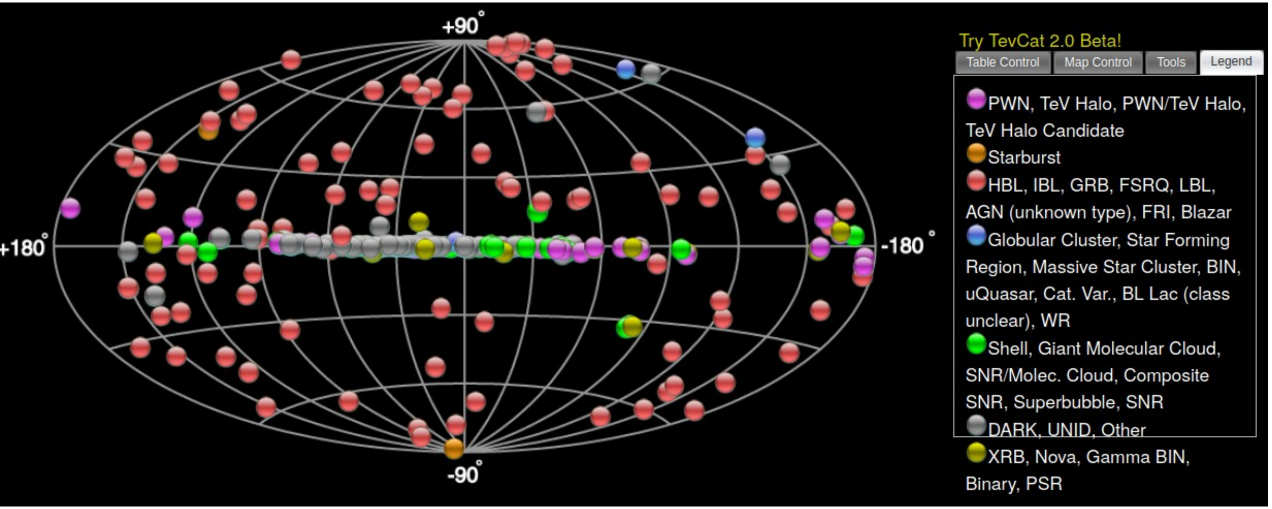
https://doi.org/10.1016/j.nima.2023.168253

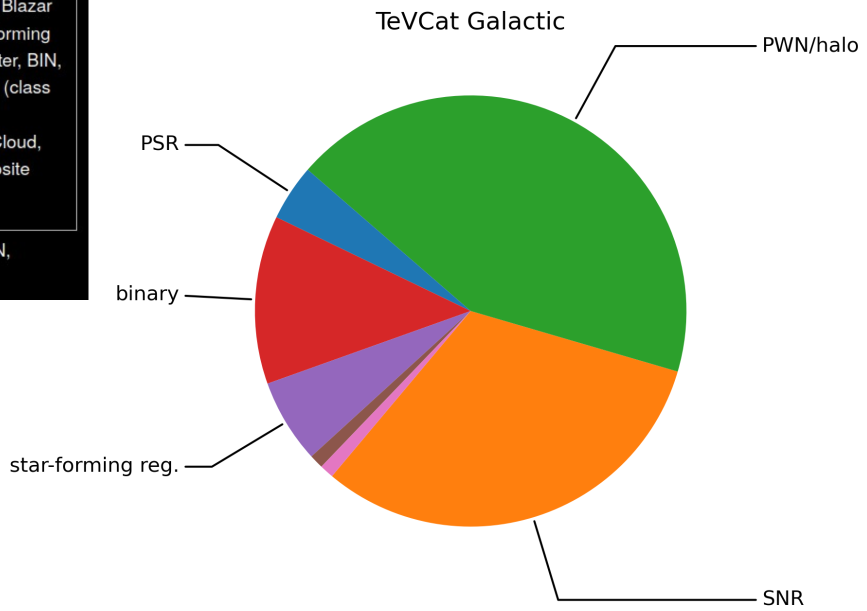
LHAASO observations at E > 100 TeV



Nature 594, 33–36 (2021)

TeVCat source catalog

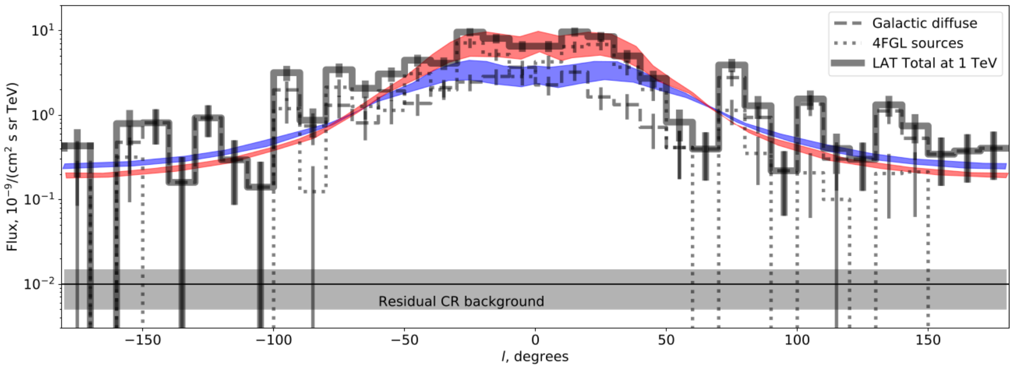




http://tevcat.uchicago.edu/

Galactic diffuse emission

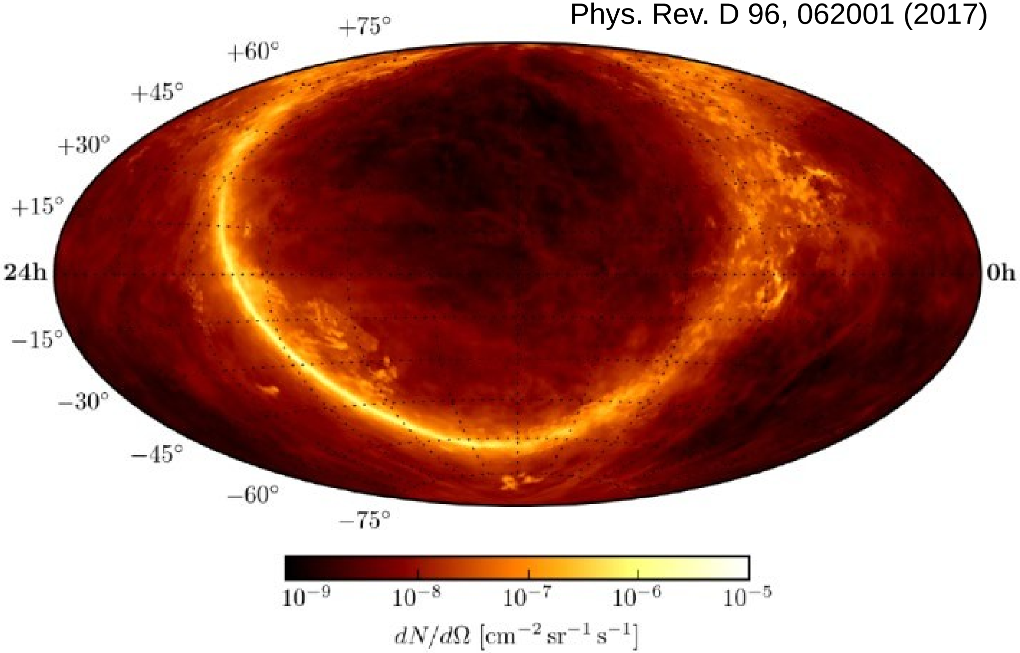
gamma-ray data : latitude profile



A.Neronov, D.V.Semikoz, A&A 633, A94 (2020)

A theoretical model for
galactic diffuse neutrino emission

Phys. Rev. D 96, 062001 (2017)



Product of Cosmic Ray interactions
with gas and photon fields in our Galaxy

Conclusion

- High energy astrophysics provides a unique view of extreme phenomena in the Universe, allowing for tests of fundamental physics laws under conditions not achievable in laboratory
- Neutrino astronomy enables studies of objects hidden from view by classic astronomy tools and is complementary to other branches of astronomy

Backup slides

Why high energy astrophysics is important

- Advance our understanding of the Universe
- Research physics in extreme conditions inaccessible in laboratory (black holes, extreme energy density, ...)
- Possible synergies with applied science, e.g. in the field of plasma physics
  - Example 1: magnetic reconnection is important in nuclear fusion reactors
    Example 2: plasma instabilities are important in detonation engines

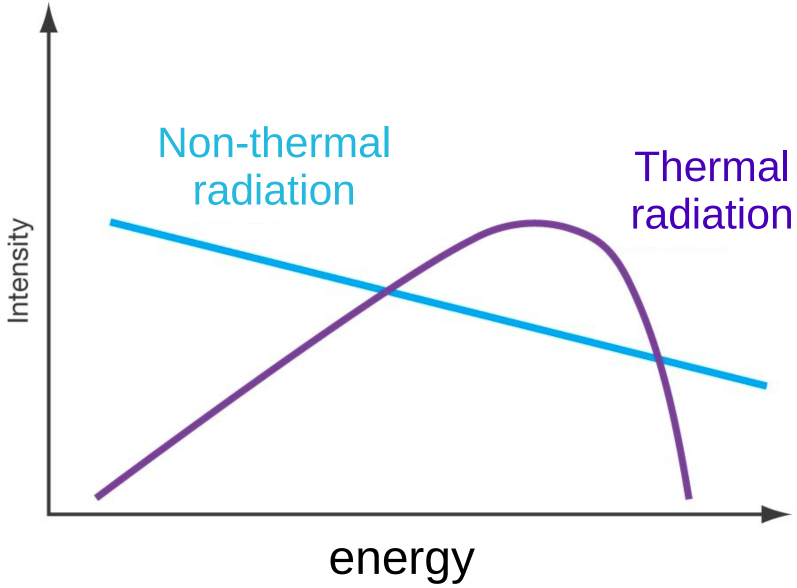
Области физики, необходимые для описания астрофизических объектов и процессов, упомянутых в данной лекции

- Физика частиц
- Физика высоких энергий
- Физика плазмы
- Ядерная физика
- Термодинамика
- Магнитогидродинамика
- Общая теория относительности
- ...

Other topics not covered here

- Other astrophysical phenomena (Novae, binary systems, ...)
- Diffuse flux
- Dark matter
- Magnetic monopoles
- Other exotics

Тепловое и нетепловое излучение

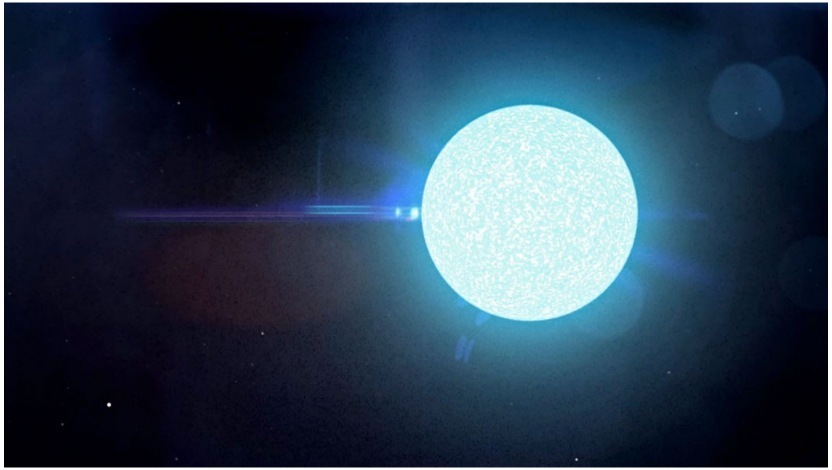


Adapted from https://pages.uoregon.edu/jimbrau/astr123-2015/Notes/Exam1rev.html

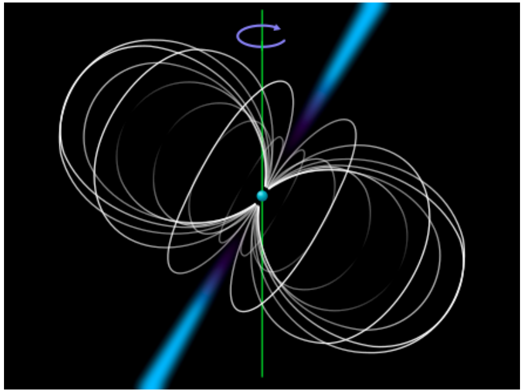
Тепловое излучение = превращение тепловой энергии в электромагнитную

Нетепловое излучение = любое другое излучение

Neutron star

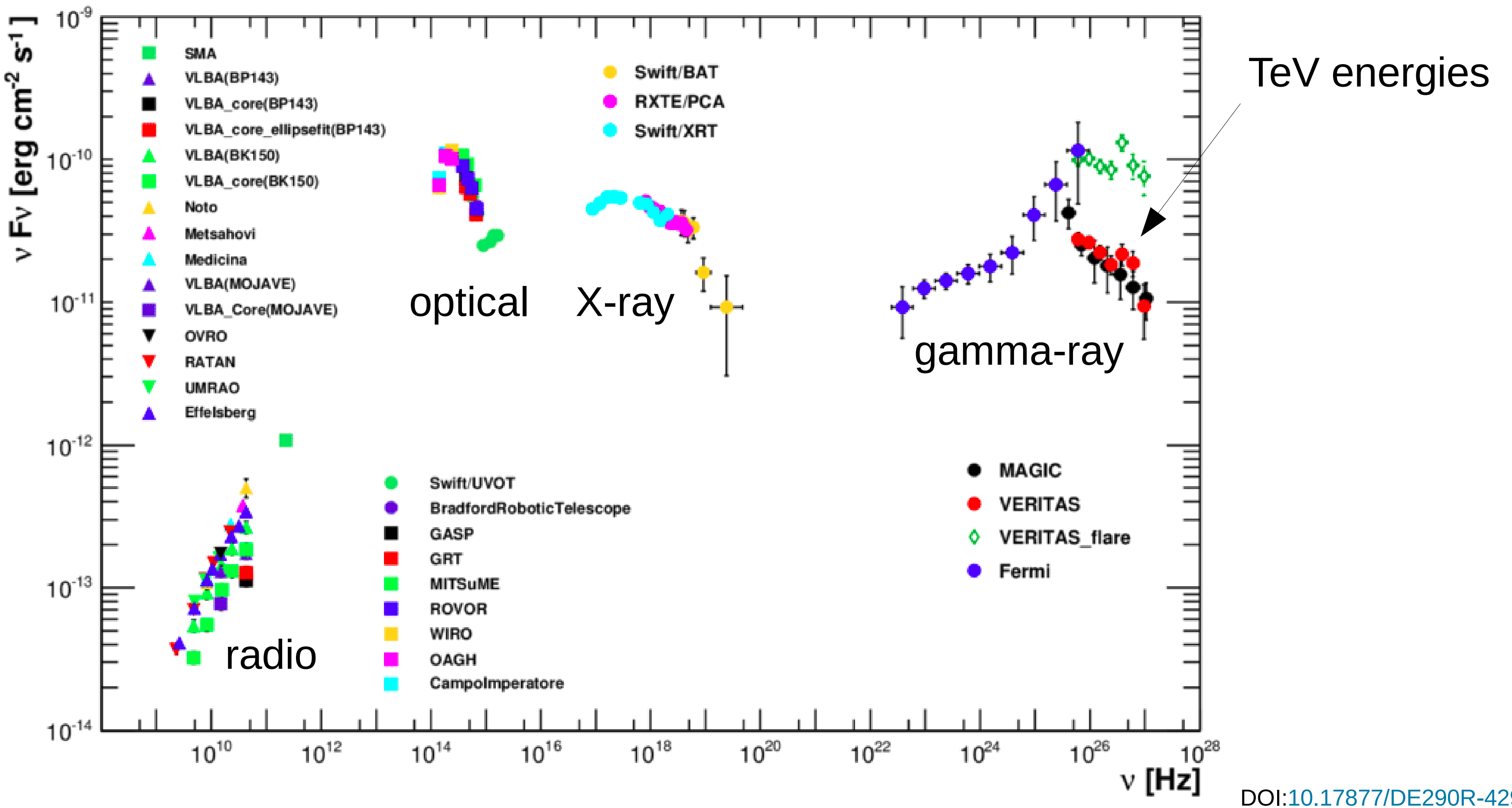


Artist's conception. Image credit: NASA



- A neutron star is a remnant left from core collapse of a supergiant star
- Supported by neutron degeneracy pressure
- Radius ~ 10 km
- Mass ~ 1.4 M_{sun}
- Pulsar is a highly magnetized neutron star, emitting pulses of electromagnetic radiation
- Magnetar is an extremely magnetized neutron star

Example of a broadband spectrum : Mrk 501



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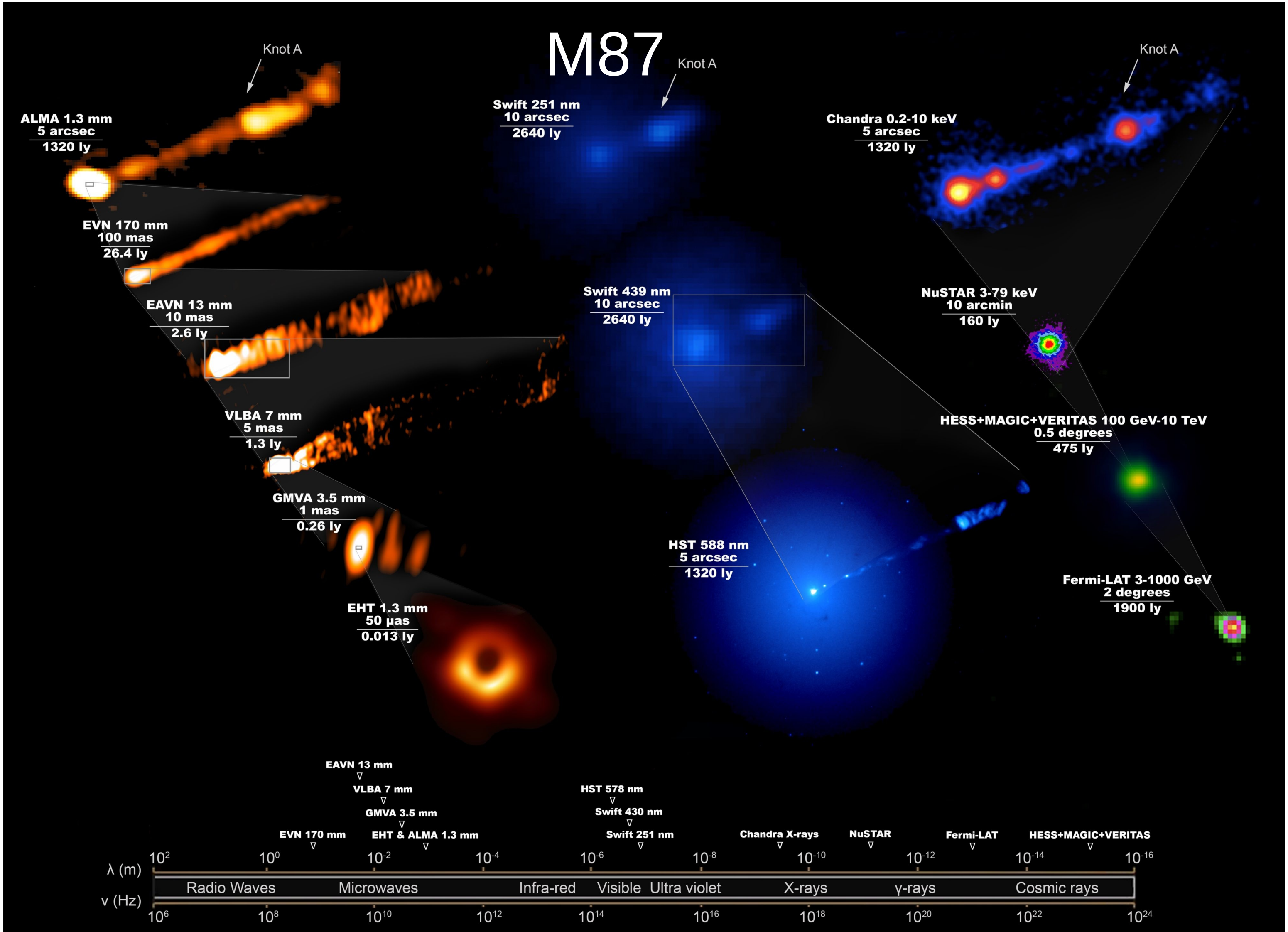
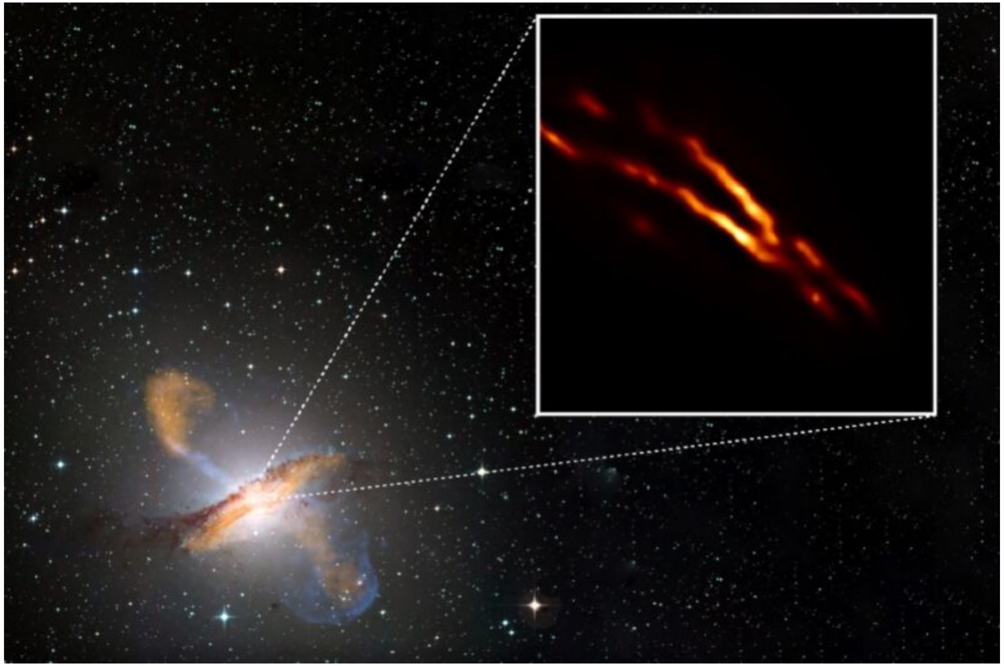


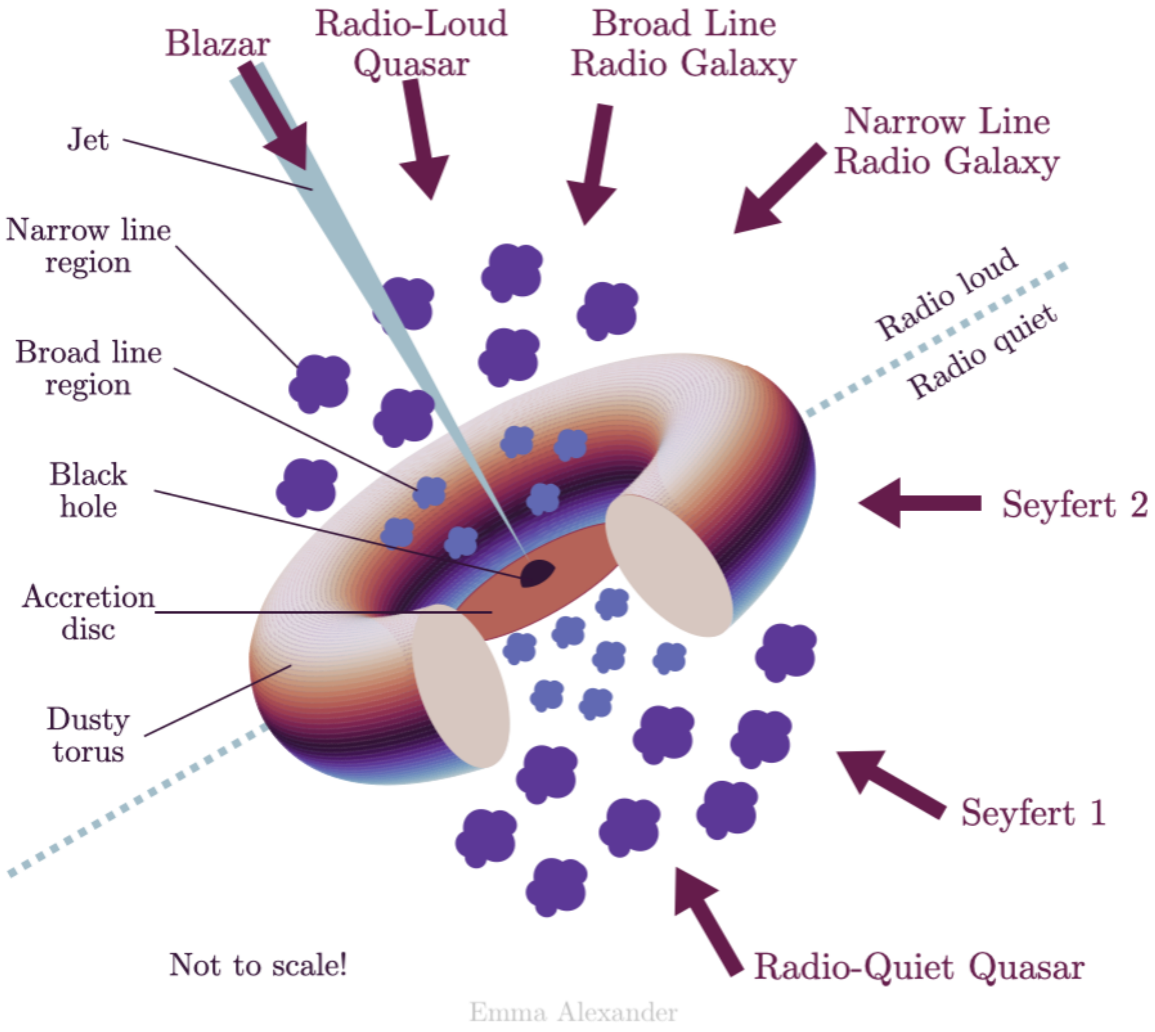
Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

AGN / radio galaxy Centaurus A

Cen A



Optical and radio images of emission from the jet of the jet-loud AGN Cen A.
Credit: Radboud University; ESO/WFI; MPIfR/ESO/APEX/A. Weiss et al.; NASA/CXC/CfA/R. Kraft et al.; EHT/M. Janssen et al.


Blazar
Radio-Loud Quasar
Broad Line Radio Galaxy
Narrow Line Radio Galaxy
Jet
Narrow line region
Broad line region
Black hole
Accretion disc
Dusty torus
Radio loud
Radio quiet
Seyfert 2
Seyfert 1
Radio-Quiet Quasar
Not to scale!
Emma Alexander