Quantum Astrophysics and Cosmology

Roger Blandford

KIPAC

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MULTI-MESSENGER ASTRONOMY

Wavelength

Electromagneti

c

Frequency

Waves

Particles
Photons

Cosmic Rays

Gravitational Radiation

Neutrinos

1zeV ~ 10^{-40} J

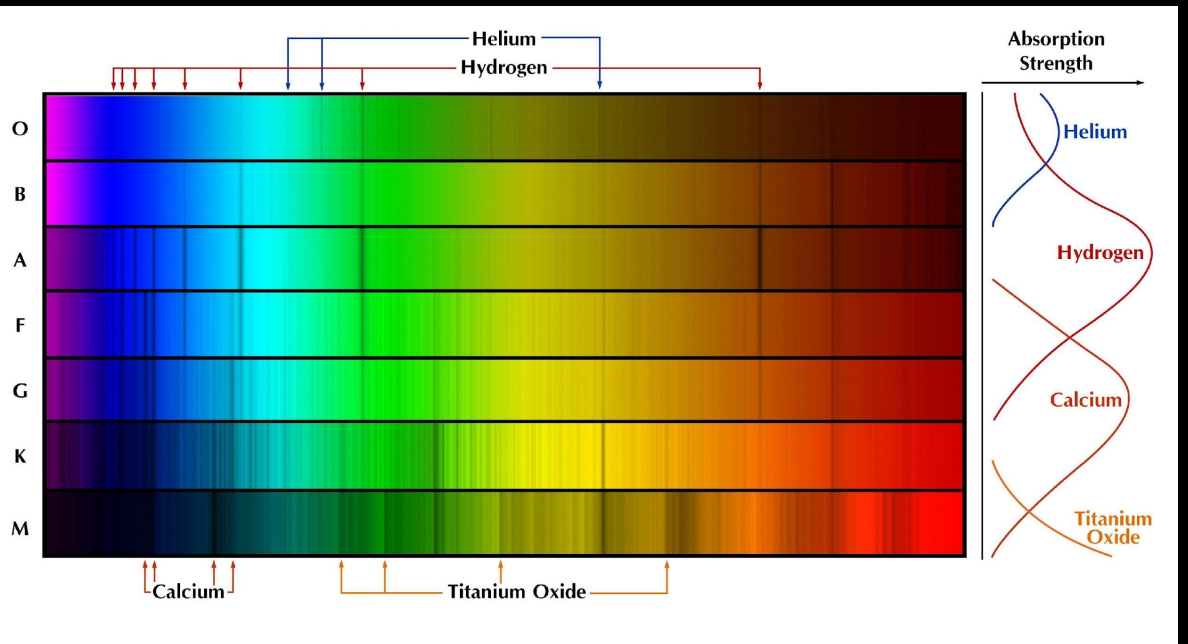
1eV ~ 10^{-19} J

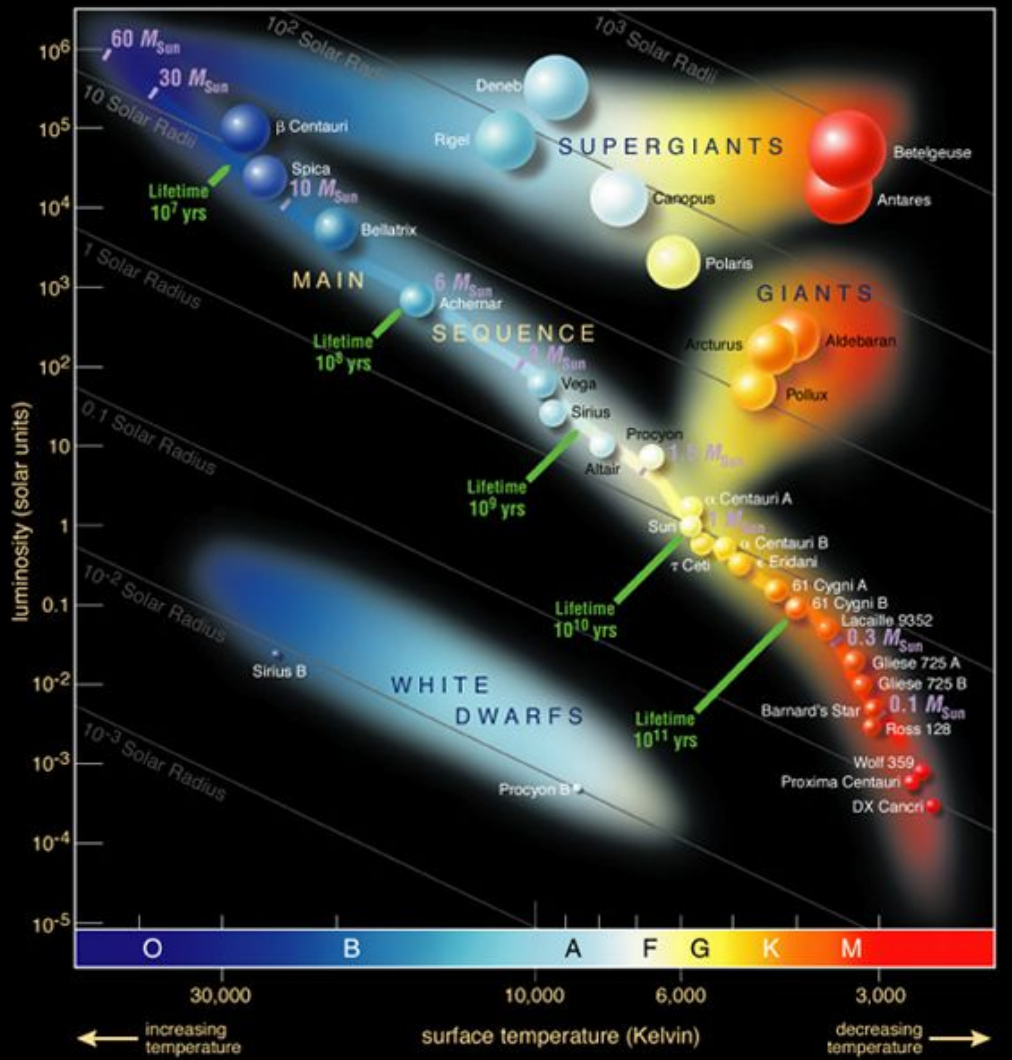
1ZeV ~ 100 J

140 Octaves being Explored

Atomic Astrophysics: Stellar Spectra

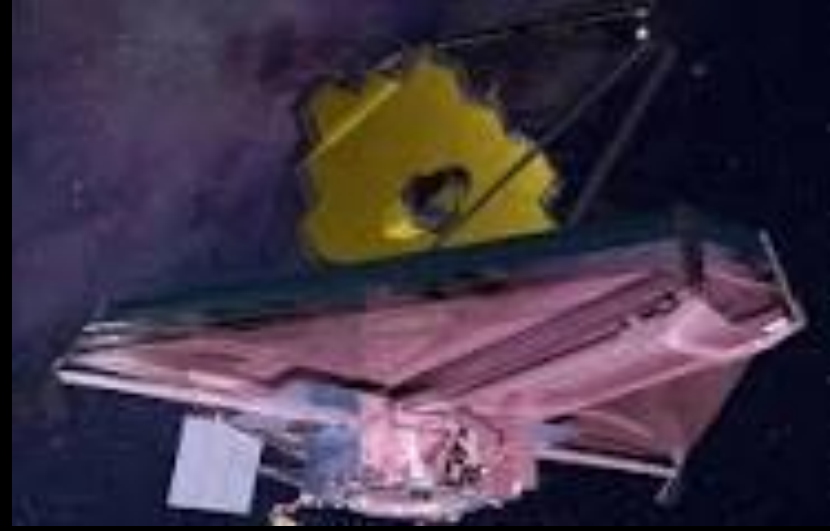
- Fraunhofer lines, including He,
- Understanding of wavelengths, cross sections
- Organization of stellar spectra
- Implementation in stellar atmospheres

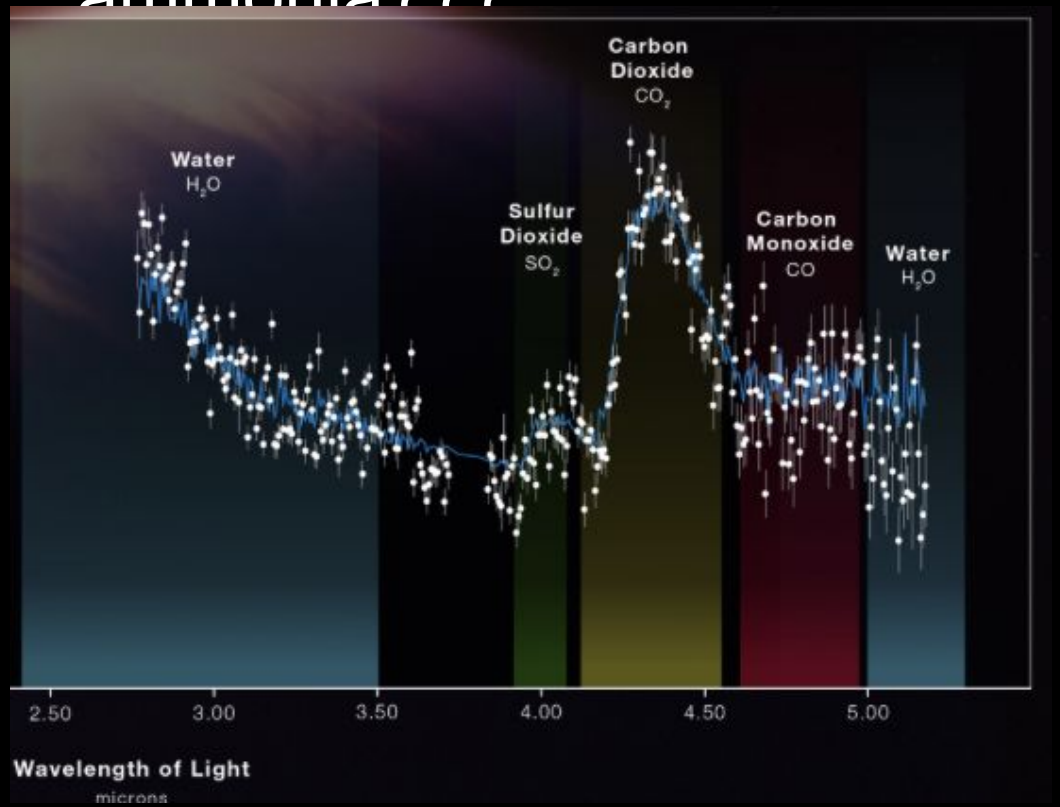


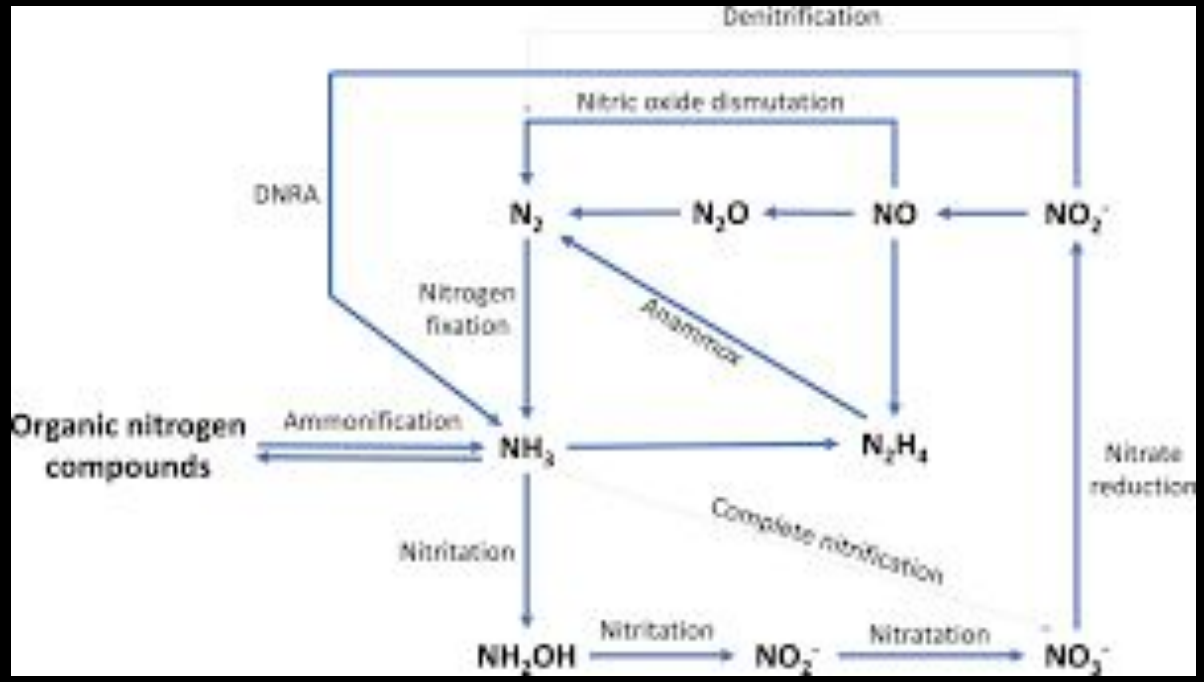


Exoplanet Spectra

- Emission and transmission
- Search for “biosignatures”
- Carbon dioxide, water, methane, ammonia???

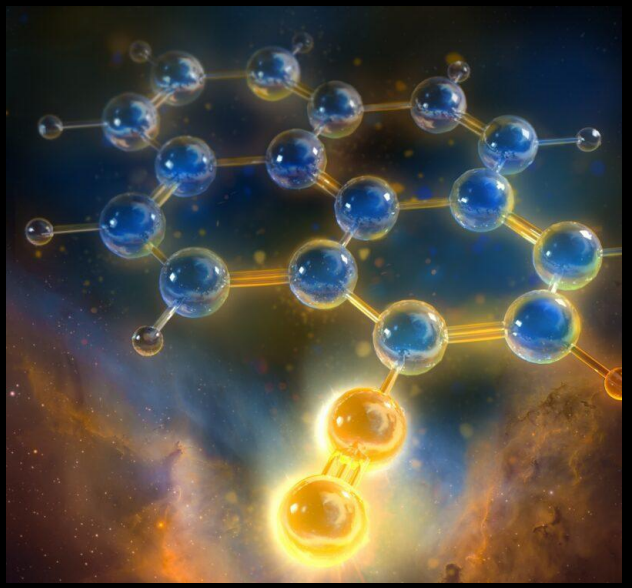


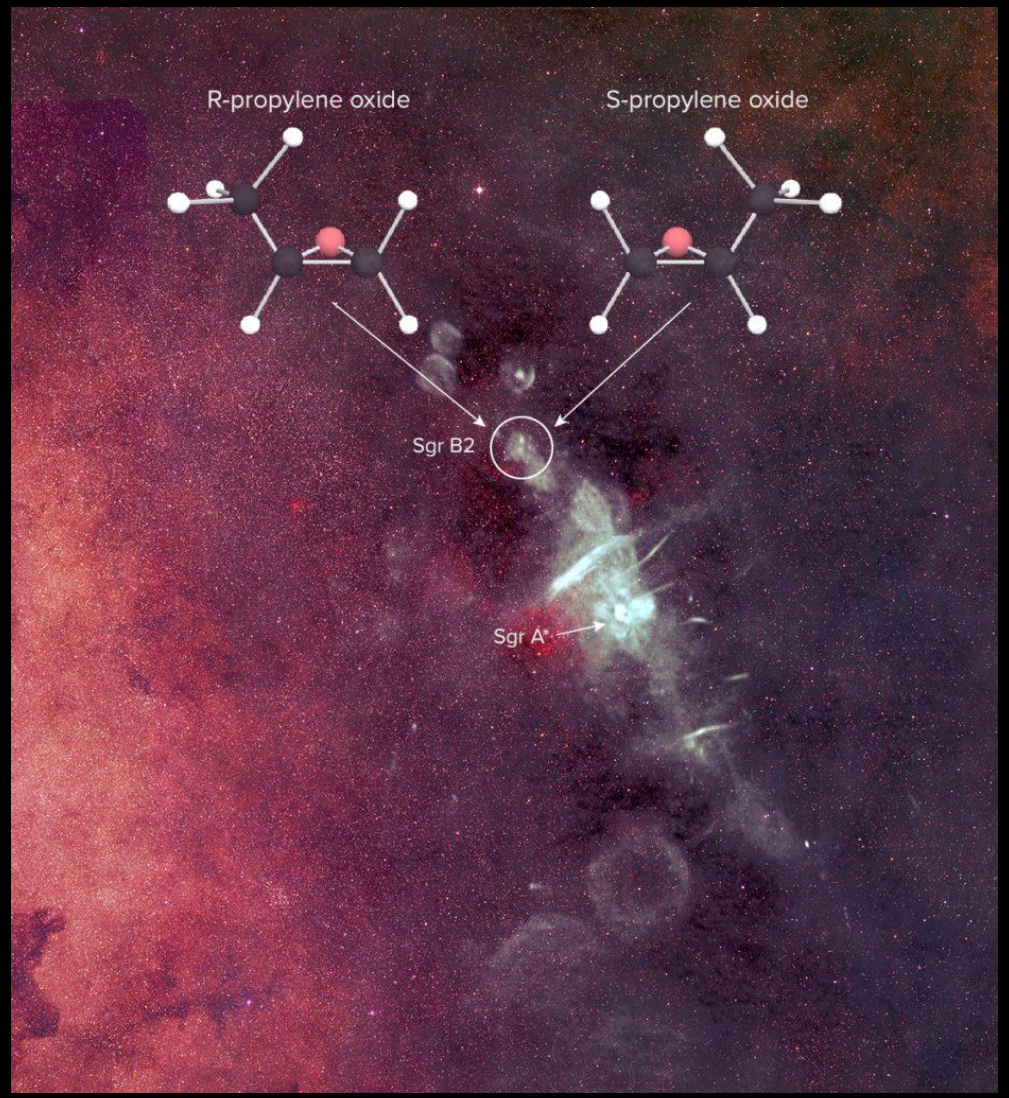




Interstellar Spectra

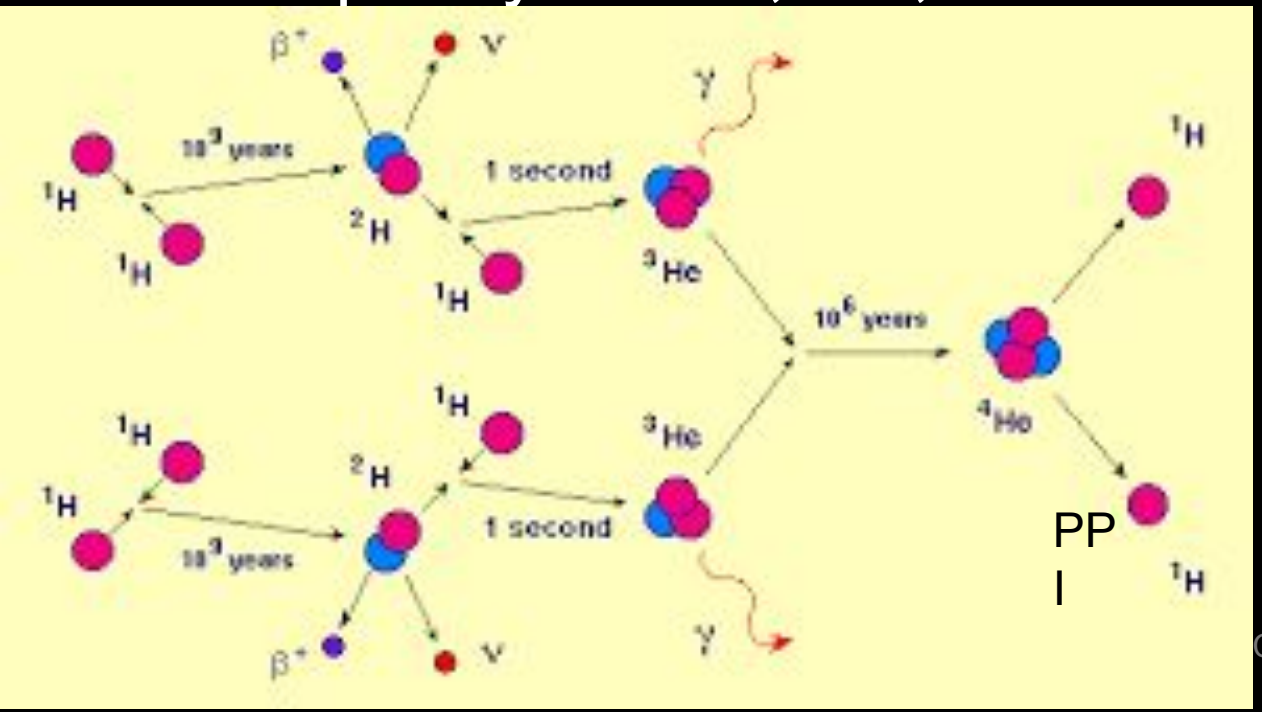
- Unique molecules
- Cyanopyrene
- Propylene oxide
- Chemistry on dust
- Diffuse interstellar bands
- Molecular hydrogen



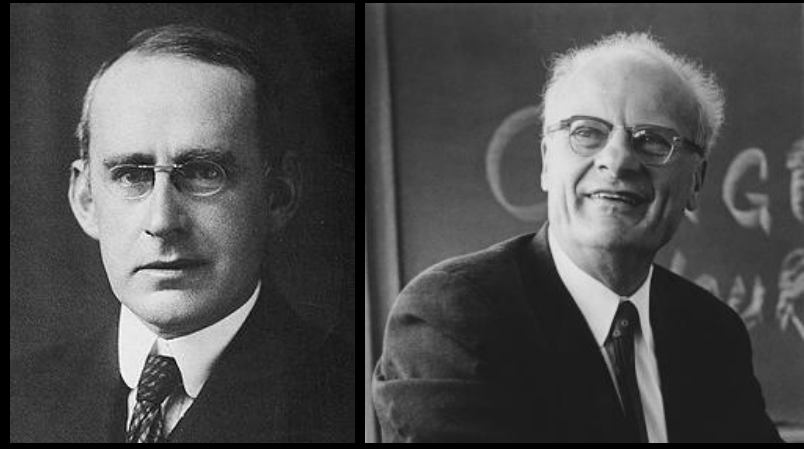


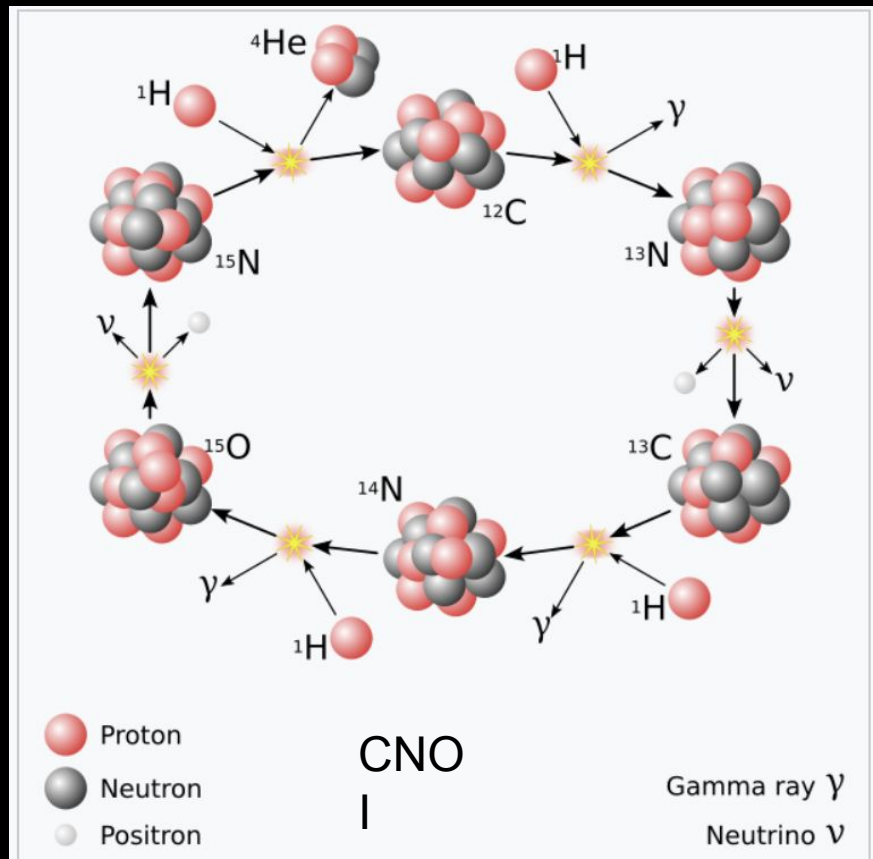
Stellar Power

- Sun (and stars) last for billions of years
- Powered by nuclear fusion H -> He
- PP, CNO chains
- Until you run out of fuel
- Evolve quickly to WD, NS, BH



PP I

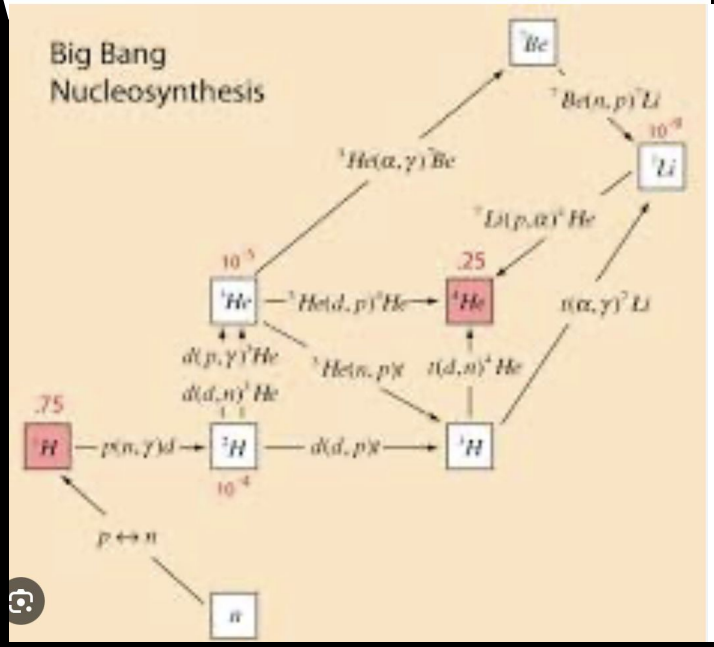


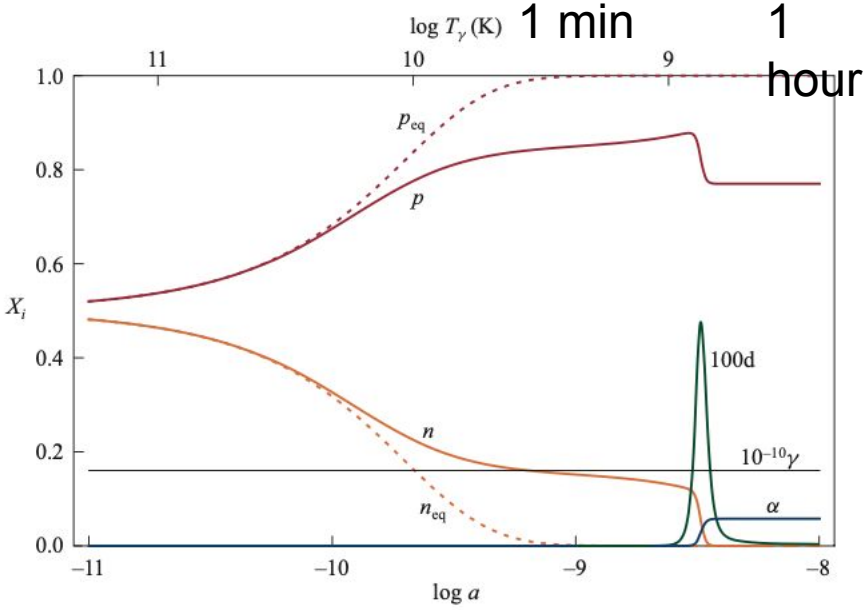


CNO I

Big Bang Nucleosynthesis

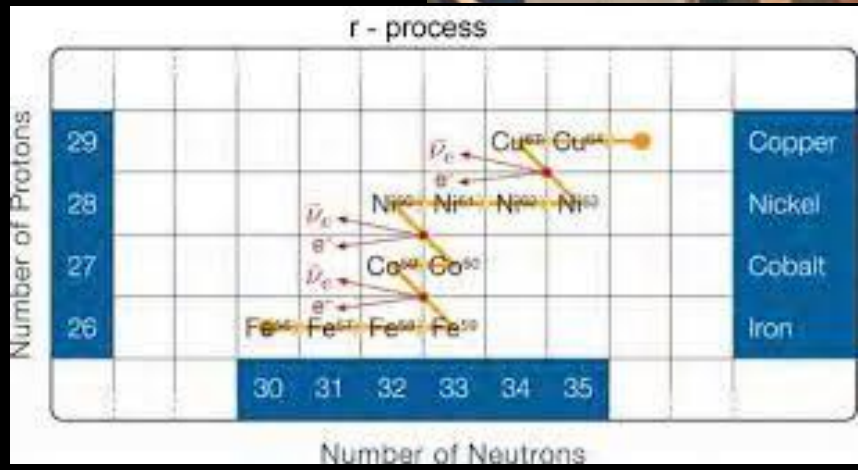
- Hot Big Bang
- Out of equilibrium when expansion rate faster than reaction rate
- Most neutrons -> He
- d and Li
- No stable element with A=5, 8

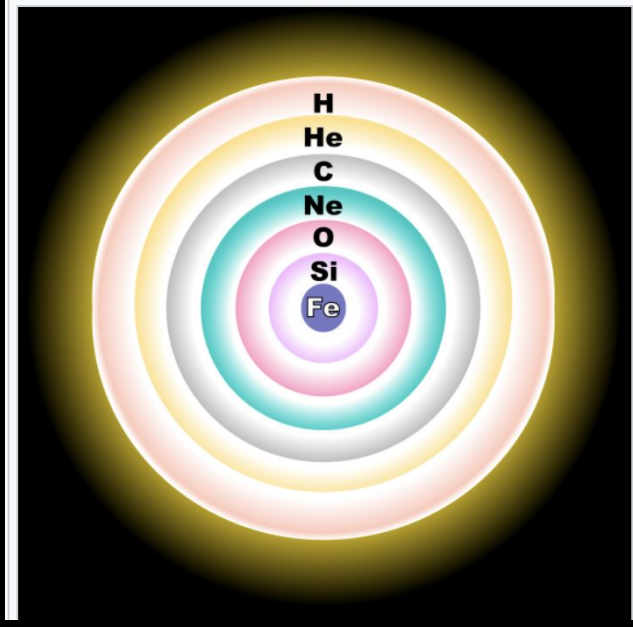




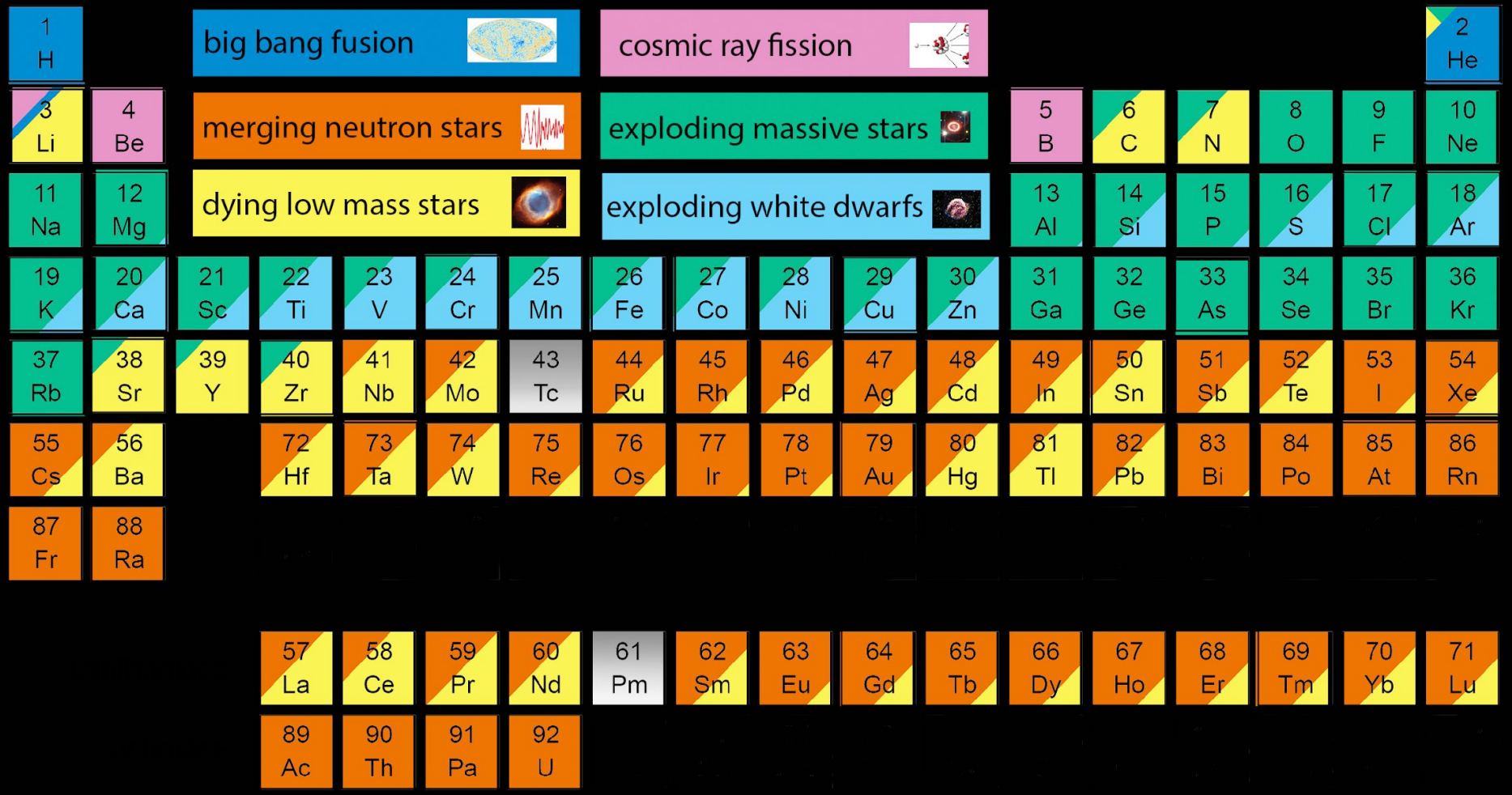
Stellar Nucleosynthesis

- Triple alpha process
  - $\alpha + \alpha$ -> Be; Be + α −>C* -> C
  - C + α −> O −> …. −> Fe
- p process: rapid proton capture
  - Evolving massive stars
- r process: rapid neutron capture
  - Supernovae of massive stars
  - Neutron star mergers; kilonovae
- s process: slow neutron capture
  - Evolving lower mass stars





The Origin of the Solar System Elements



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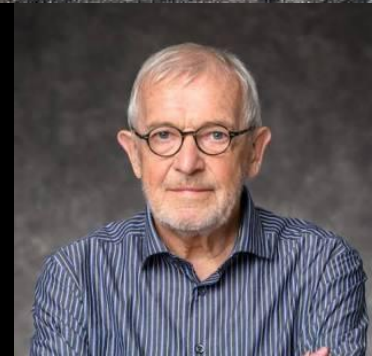
Neutrinos



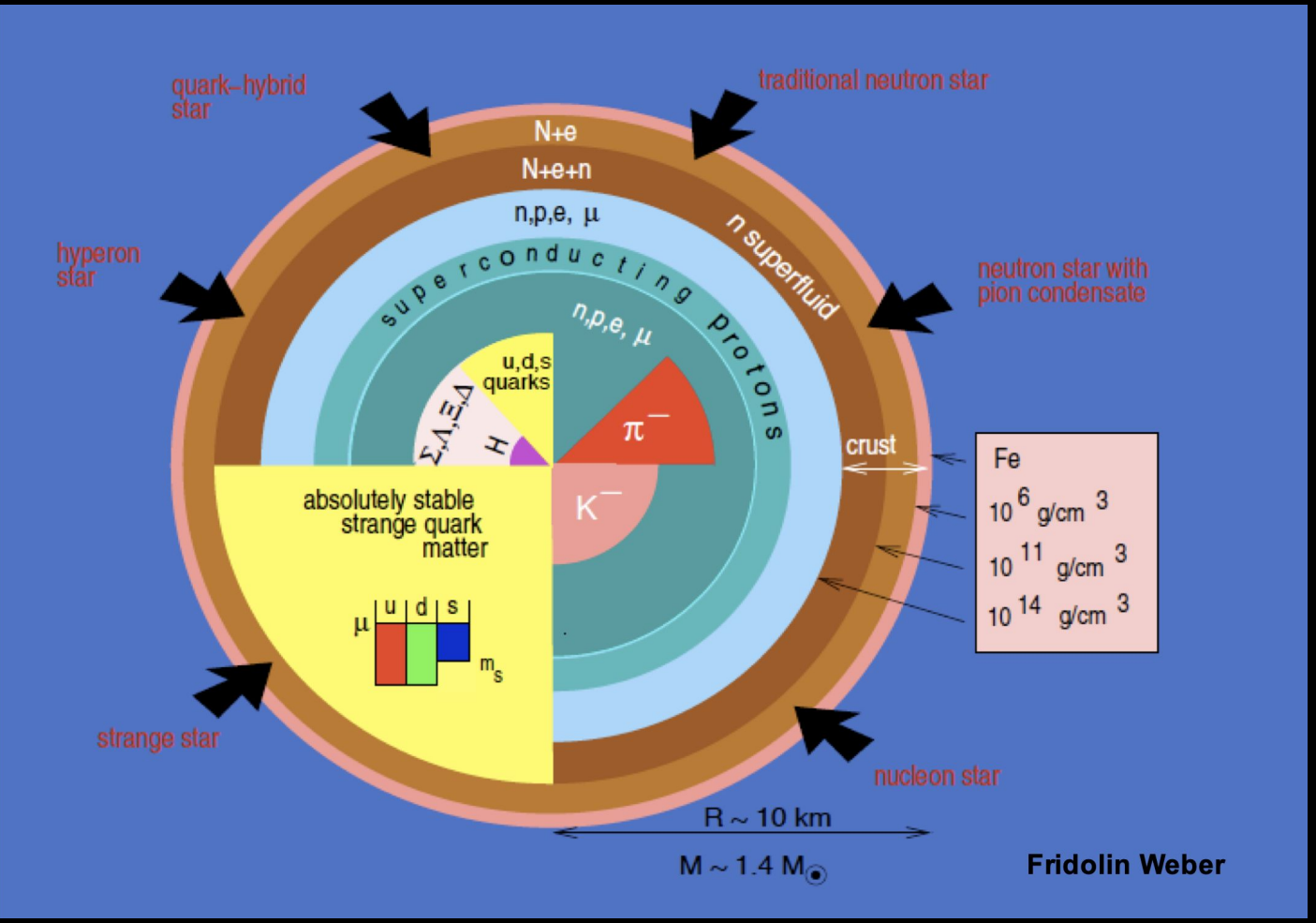

- Solar and supernova neutrinos
  - Solar neutrino “problem”
  - Neutrino oscillations, MSW
  - SN 1987a
- ~PeV neutrinos
  - >~PeV cosmic ray protons +p, γ
  - Local or distant sources?
  - Multi-messenger astronomy
- Cosmological neutrinos

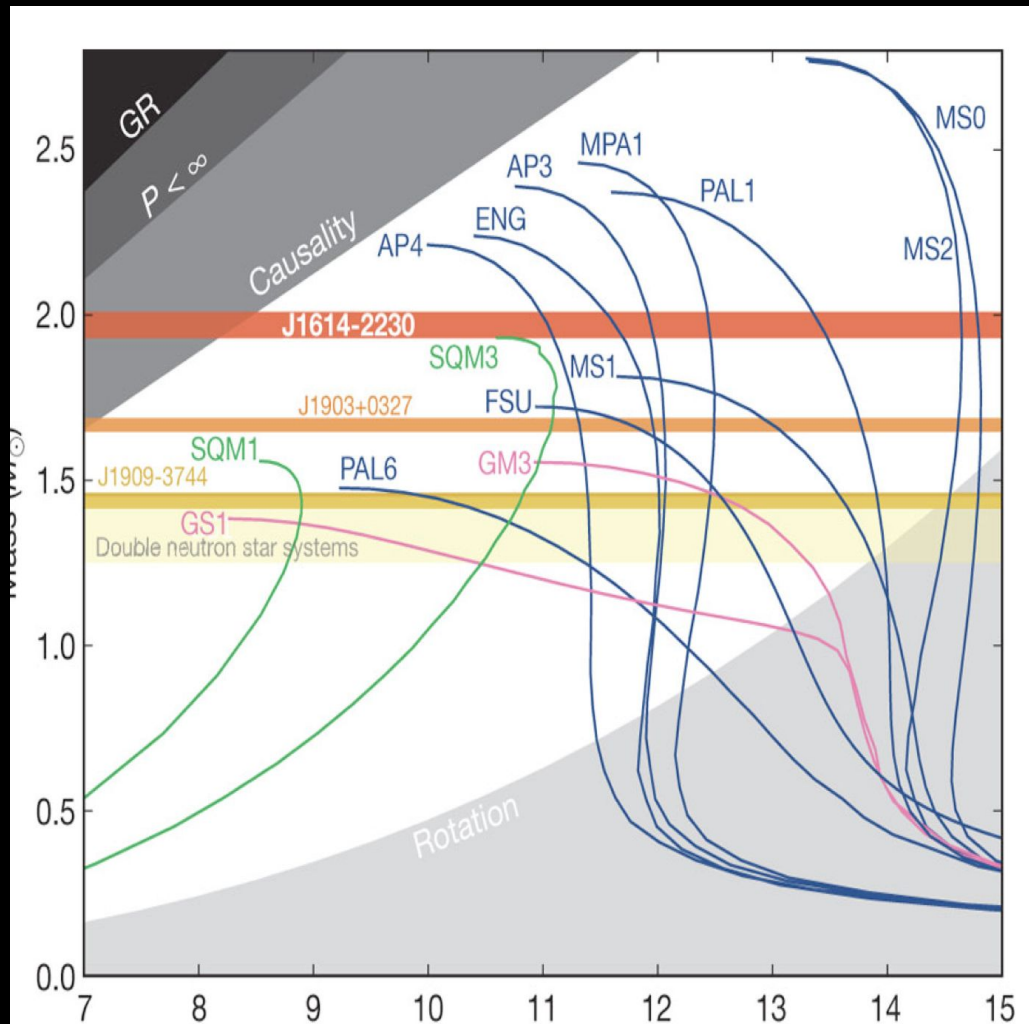


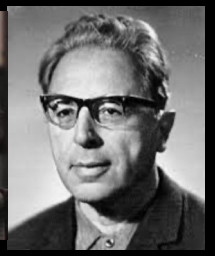
Neutron Stars

- White dwarfs: Fowler, Chandrasekhar 1931
- Chadwick 1932, Baade-Zwicky 1934
- Oppenheimer-Volkoff 1939

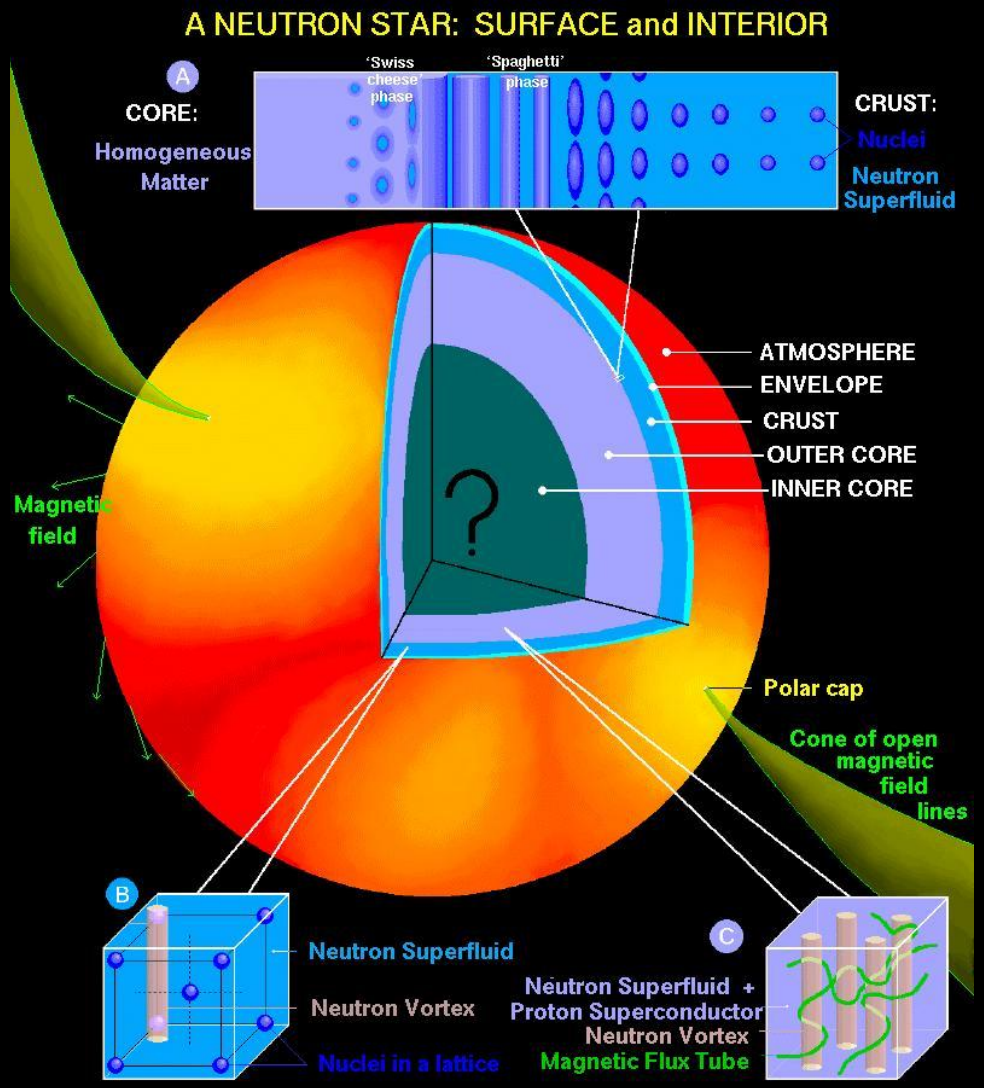




Pulsars

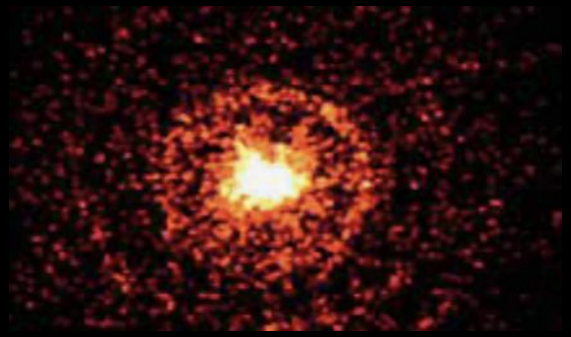


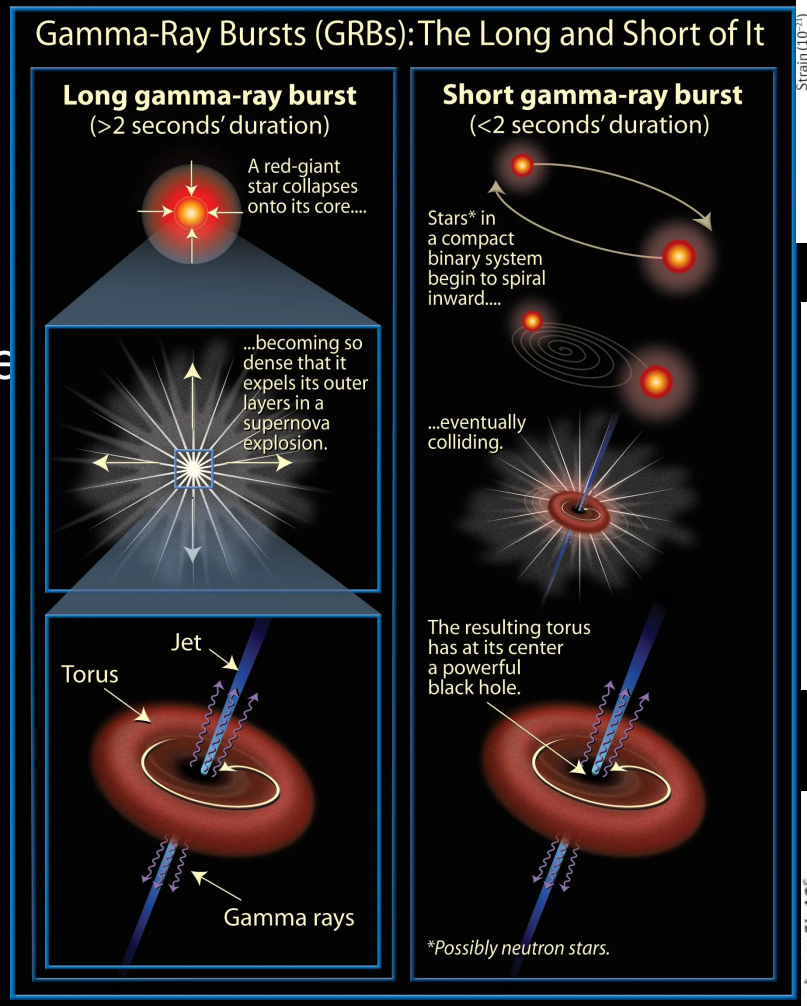
- 1962: X-ray pulsars
  - Accretion-powered
- 1967: radio pulsars
  - Rotation-powered
- Period 1.5 ms – 76 s
- Magnetic field ~ 100 MT
- Linear atoms,
- Strong field QED

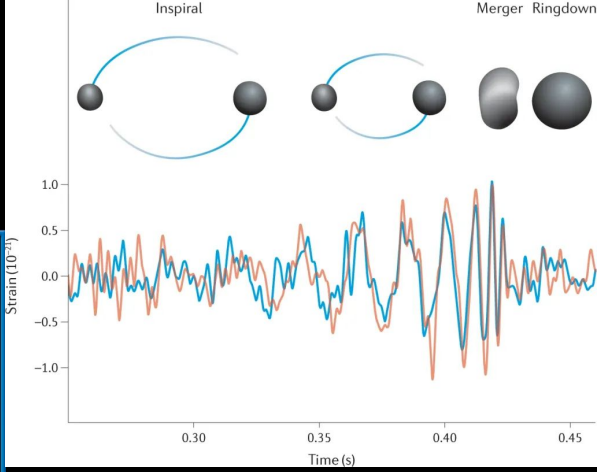


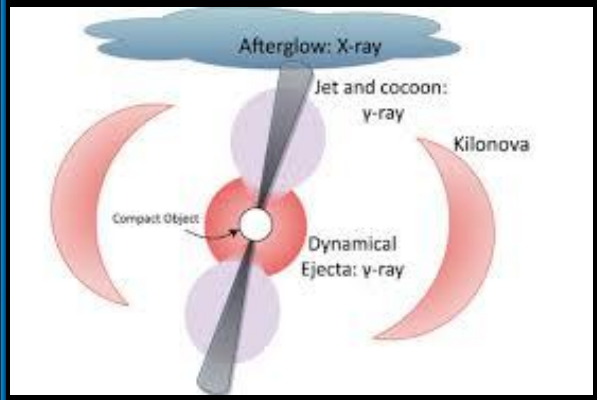
Gamma Ray Bursts

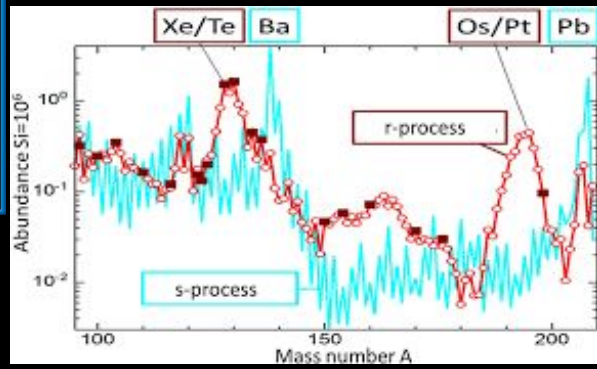
- Observed since1960s
  - Many hundred models
- Cosmological
  - Long
    - Core collapse/massive star supernovae
  - Short
    - Binary neutron star mergers
    - Major source of r-process elements
- Soft Gamma Ray Repeaters
  - Galactic neutron stars





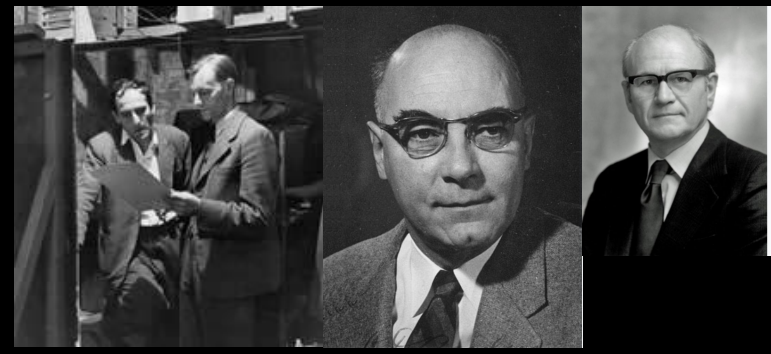


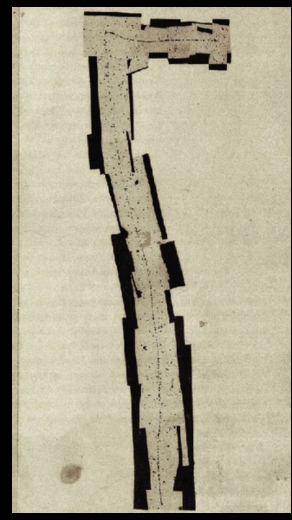


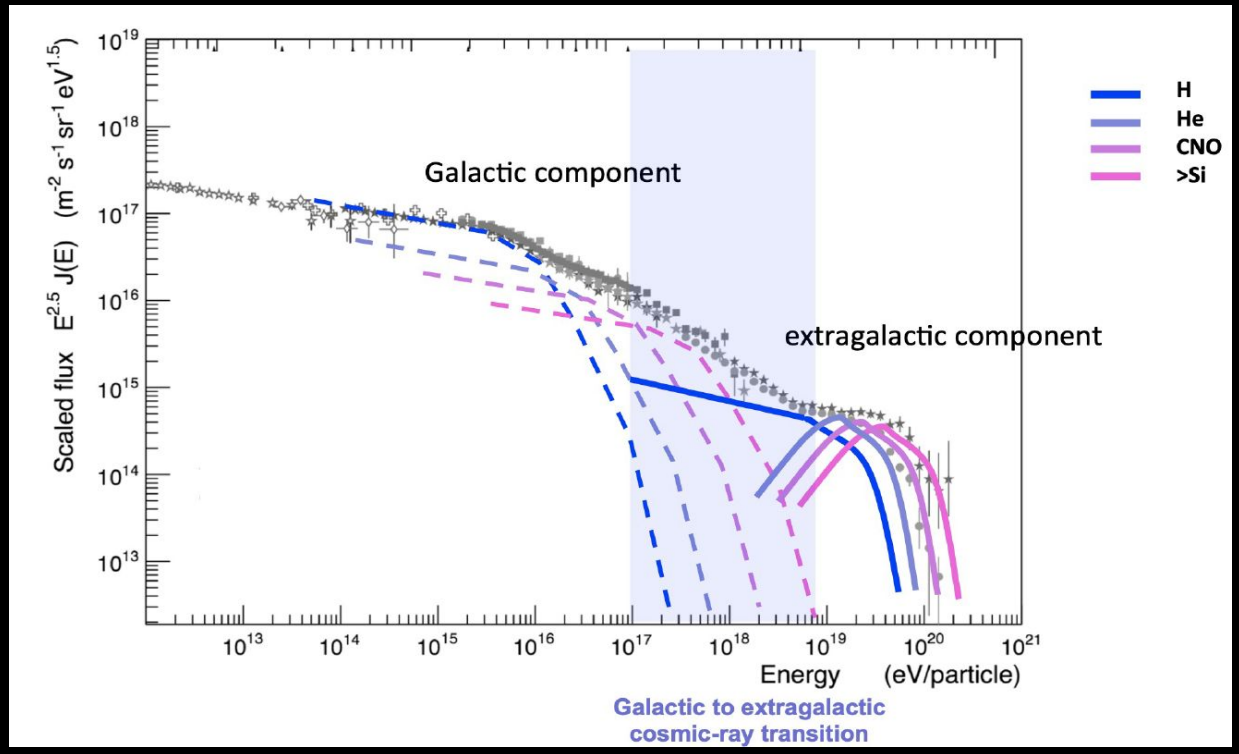


Cosmic Rays

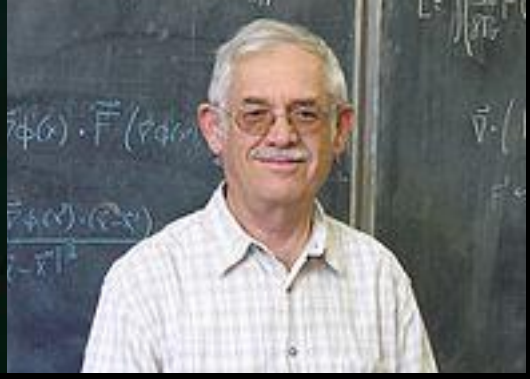
- Positron 1932
- Muon 1936
- Pion 1947
- Kaon 1957
- Observed from ~100 MeV to ~ 0.3 ZeV ~ 50 J



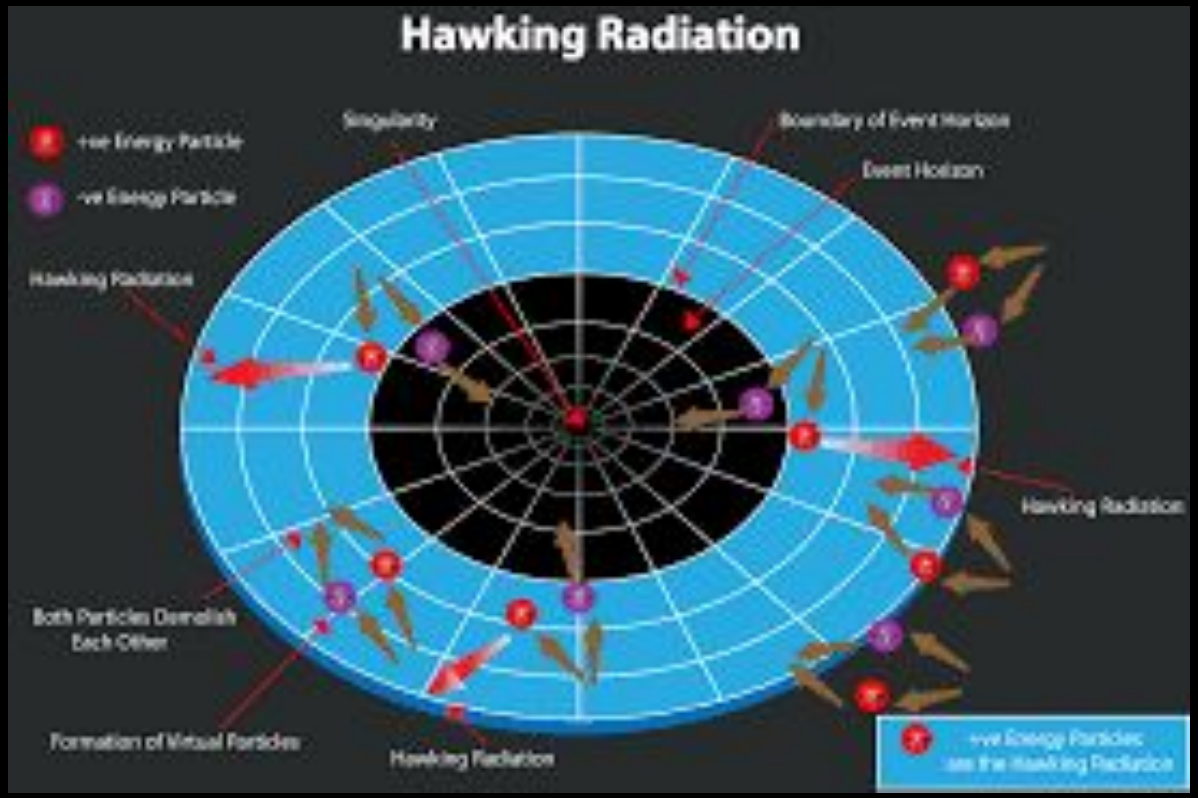




Hawking Radiation

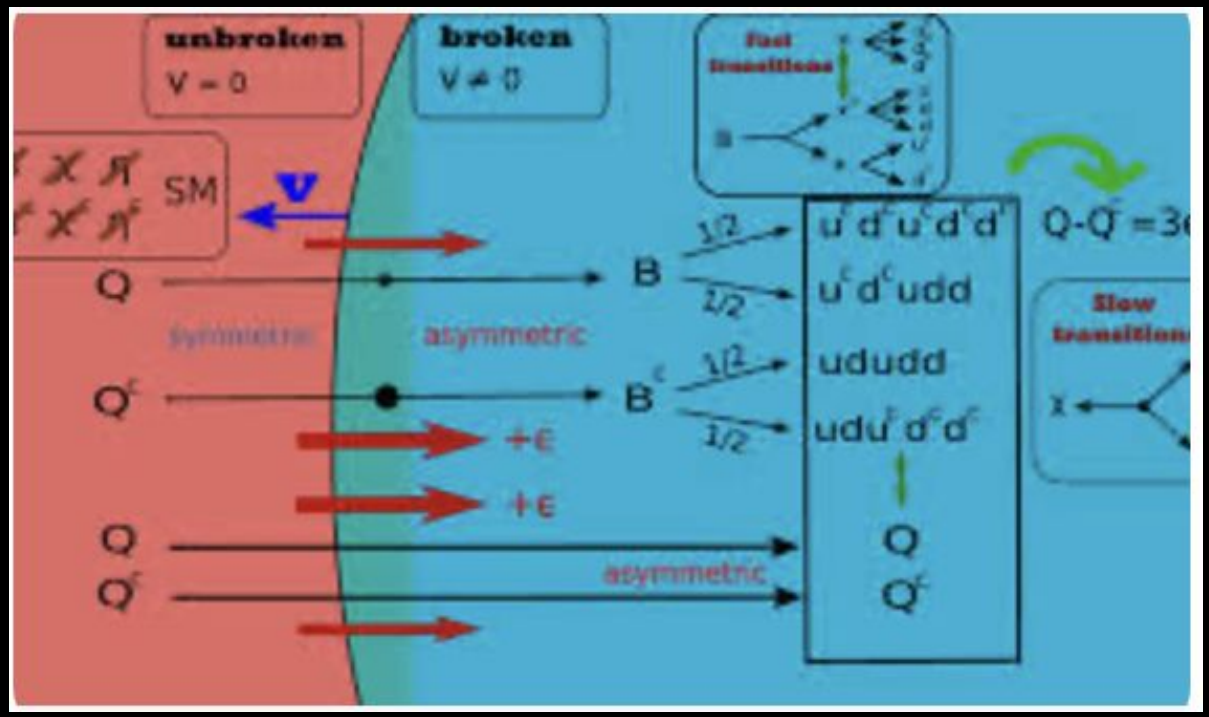


- T =1/(8 π m); S=A/4
- Evaporation
  - M<~ 1 Pg
- Bekenstein entropy ~ area
  - Information
  - Unitarity
  - Firewalls
  - Wormholes
  - …
- Primordial black holes
  - γ-ray, radio upper limits



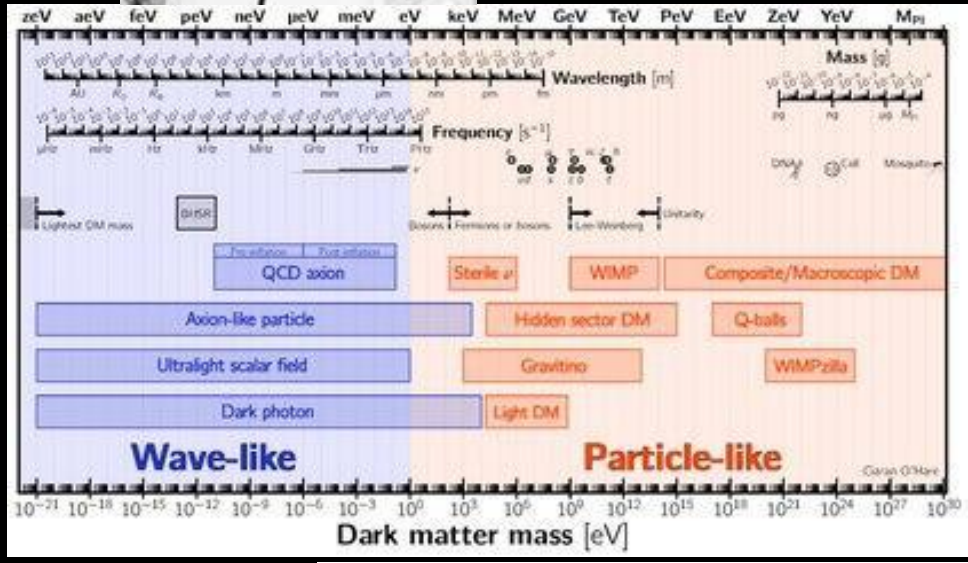
Baryogenesis

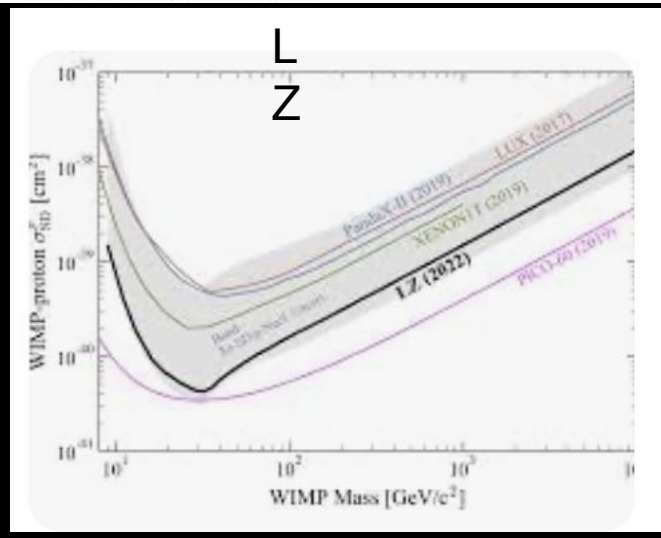
- $n_b / n_\gamma = 6 \times 10^{-10}$
- Why?
- Sakharov violations
  - Baryon number
  - C, CP
  - Thermal equilibrium
- Leptogenesis?



Dark Matter

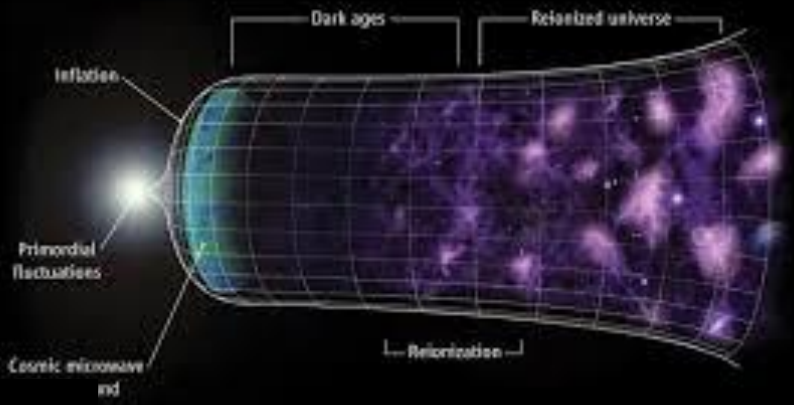
- Clusters of galaxies
- Individual galaxies
- Standard cosmology
- yeV – million solar mass!
  - WIMPs or NIMPs or axions?
- Upper limits
  - Astronomy
  - Cosmology
  - Experiment

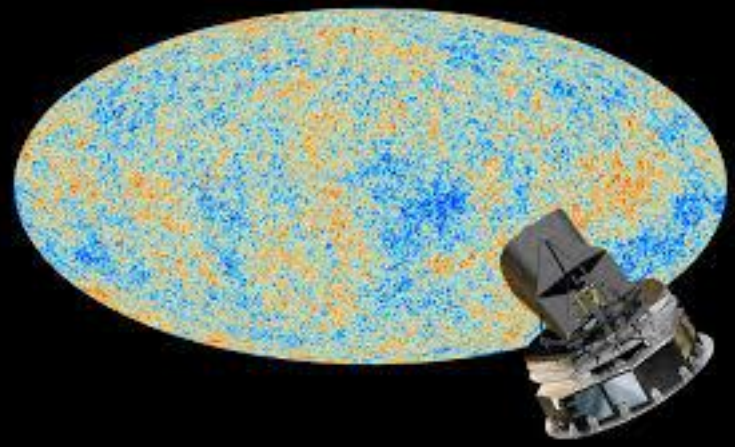


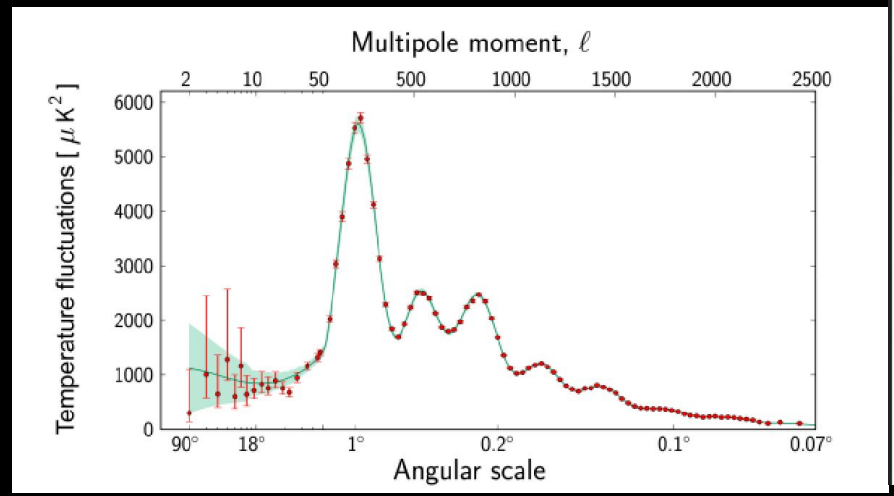


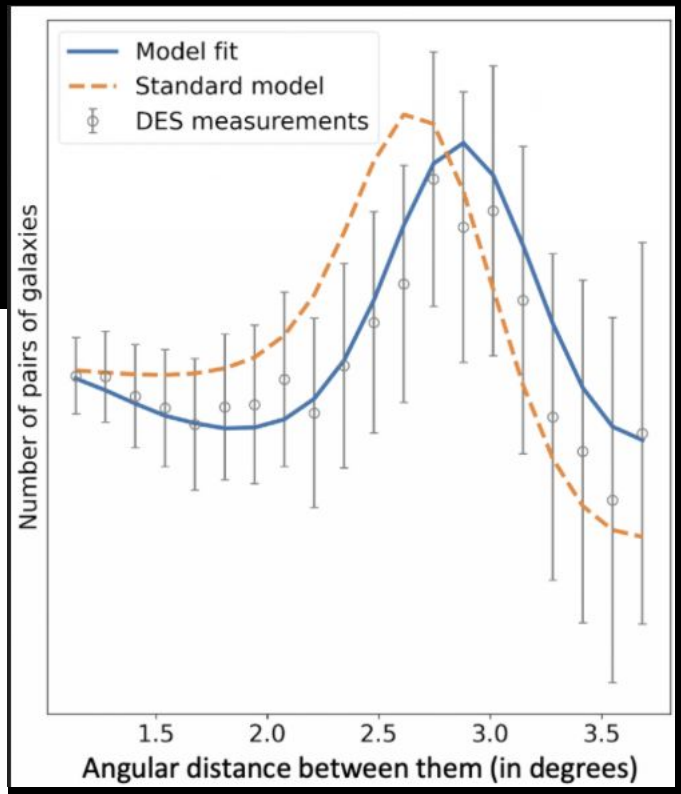
Primordial fluctuations

- Standard Model of Cosmology
  - Cosmological constant
  - Highly successful
  - Tensions
- CMB fluctuations
  - Quantum origin during inflation
  - cf Hawking radiation
  - Scale-free, small tilt
  - Gaussian
- Large Scale Structure
  - Mostly consistent
  - Some tensions
  - New galaxy surveys
  - Galaxy tracers
  - Gravitational lensing



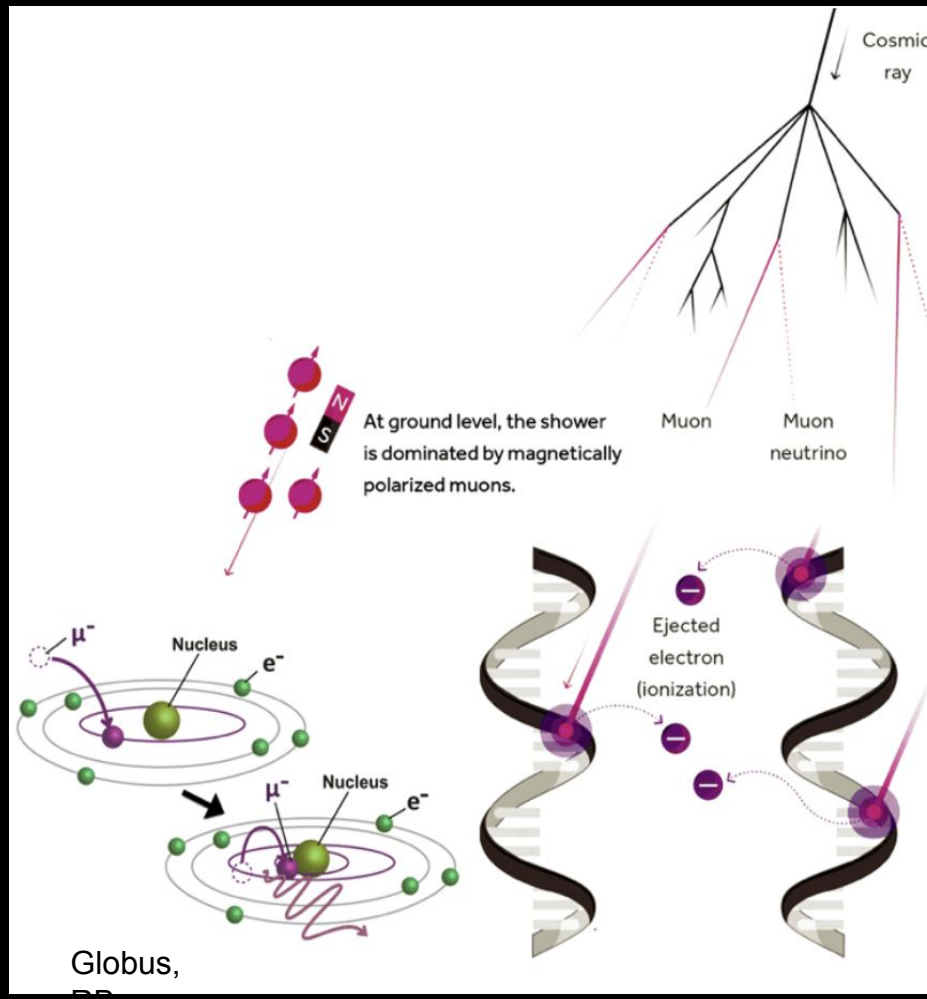






Origin of Life

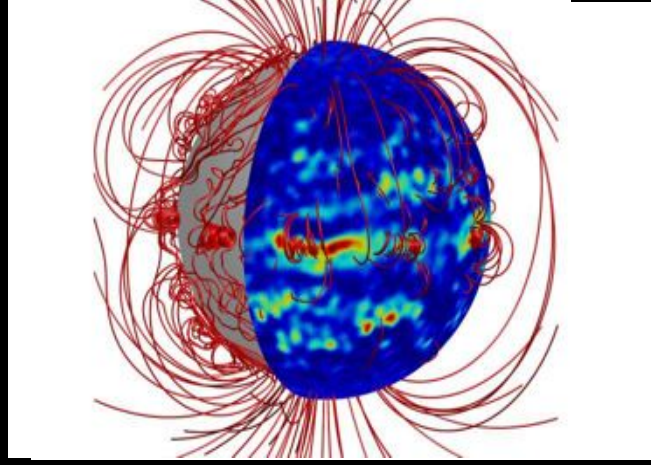
- Life, as we know it, is homochiral
  - Extremophiles, sample returns?
- Could be chance or causal
  - Cosmic ray muons are chiral
  - Retain negative “lodacity”
  - Unlike electrons
- Tiny bias in transbiotic “experiments”
  - How is it expressed?
  - Quantum mechanical
  - General requirements
  - cf baryogensis
- Experiments underway with CP UV, muons
- Panspermia?

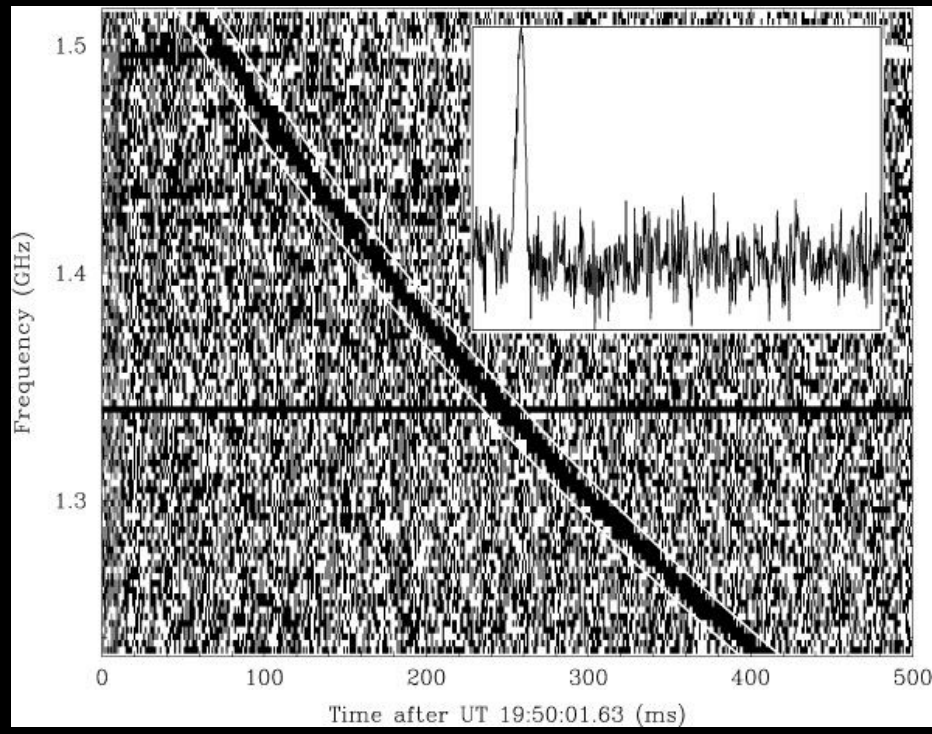


Globus,

Magnetars

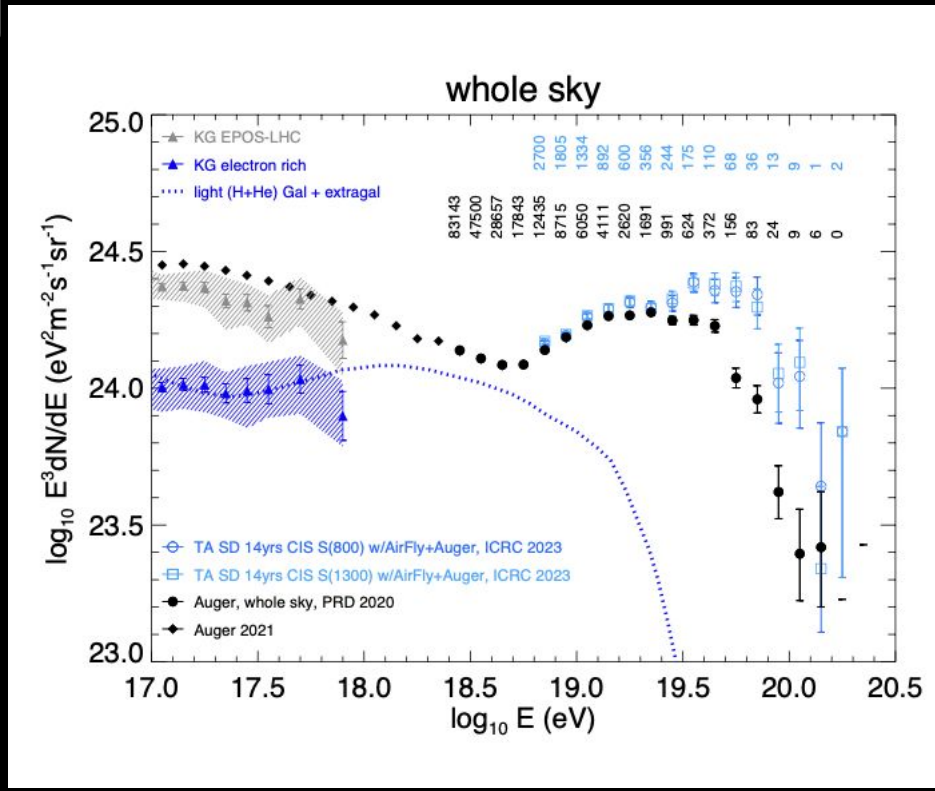
- Soft Gamma Repeaters
  - B~ 100 GT
  - Magnetic-, not accretion-, rotation-powered
  - Young neutron stars?
  - Magnetic flares, starquakes?
  - Interior fields could be 10 TT!
- Fast Radio Bursts
  - ~1 per minute over whole sky
  - T ~ 10^{40} K cf tsunami
  - Induced Compton effect, Stimulated Raman Scattering
  - Tools for cosmology
- 100 GT ~ 30 $B_{Schwinger}$
  - Novel QED processes
  - Many-body problem
  - X- and $\gamma-$ rays
  - ν?
  - Radio?

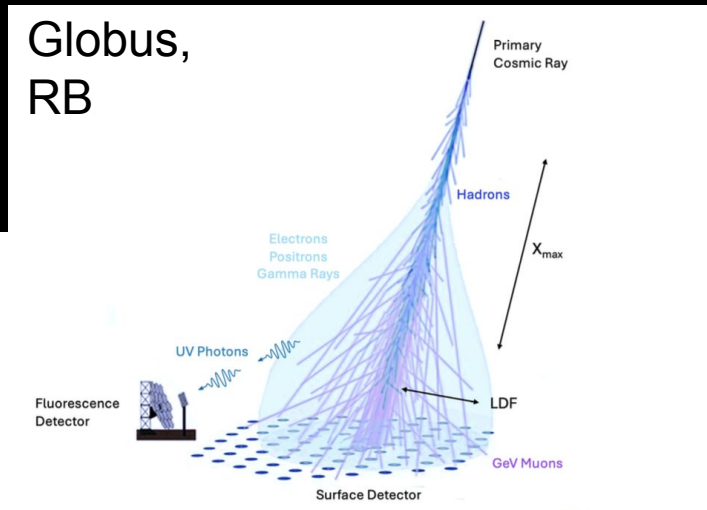


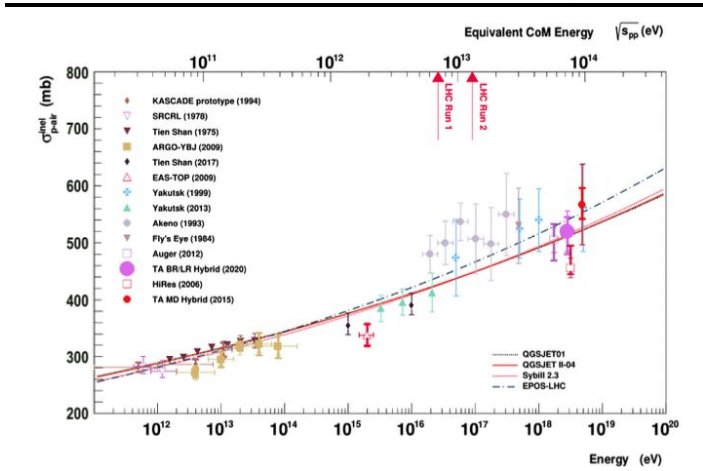


Ultra High Energy Cosmic Rays

- Up to E ~200 EeV = 30 J
  - R ~ 10 EV
  - E_{CM} ~ 10-100 x LHC
  - Muon “puzzle”
- Probably ~ Fe
- Accelerated locally
- Dipole anisotropy
- Few credible sources
  - Relativistic jets?
  - Extragalactic shocks?
- Better shower data and models -> each E, Z, direction -> sources







Quantum Astrophysics and Cosmology

- Symbiotic relationship between QM and astrophysics
  - Experiment and observation
- Application of developing physics, technology to understanding the Universe
  - Atomic, nuclear, particle physics and astrophysics, cosmology
- Excellent questions:
  - Stars and exoplanets: spectra, explosions, environmental impact…
  - Astrobiology: origin, resilience, dissemination…
  - Extreme electrodynamics: UHECR, magnetars, GRB…
  - Cosmology: narrative history, baryogenesis, dark matter, inflation, multiverse…
  - GRQED: axions, black holes, primordial perturbations…
  - Quantum gravity: string theory, Planck time, cosmological constant…