HIGH-ENERGY TRANSIENTS AND THE MULTIMESSENGER CONTEXT

A course for the Bachelor and Master Degree Programs

Prof. Elisabetta Bissaldi
Dipartimento Interateneo di Fisica «M. Merlin» - Politecnico di Bari
INFN Bari

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OUTLINE

1. Introduction and overview of High-energy and Multimessenger astrophysics
2. Cosmic rays in Our Galaxy
3. **Galactic and Extragalactic Accelerators, Acceleration Mechanisms**
4. The sky seen in Gamma-Rays
5. Gamma-Ray Bursts
6. Gravitational Wave observations
7. HE neutrino observations
8. The TeV sky and multiwavelength observations

3. GALACTIC AND EXTRAGALACTIC ACCELERATORS AND ACCELERATION MECHANISMS

STANDARD MODEL OF CR ACCELERATION

- In order to explain the features observed in experimental data, CRs must be accelerated by nonthermal processes
  - Theoretical models must consider **sources and processes able to accelerate particles up to 10^{20} eV** (much higher than the thermal energies found in astrophysical environments)
  - Nonthermal" emission = Continuum emission that **cannot be originated by blackbody radiation or thermal bremsstrahlung**

- In ground accelerators, particles are **accelerated by electric fields** and **deflected in circular orbits by magnetic fields**
  - Magnetic fields also ensure that the particles **remain confined** in the acceleration regions

- In most astrophysical environments, **static electric fields cannot be maintained**, because the **matter is in the state of a plasma**
  - Plasma = state of matter described as an electrically neutral and completely ionized medium of positive and negative particles

STANDARD MODEL OF CR ACCELERATION

Standard model of CR acceleration

- **CRs accelerated in recursive stochastic mechanisms**
  - Low-energy particles reach high energies after a **large number of interactions with a shock wave**

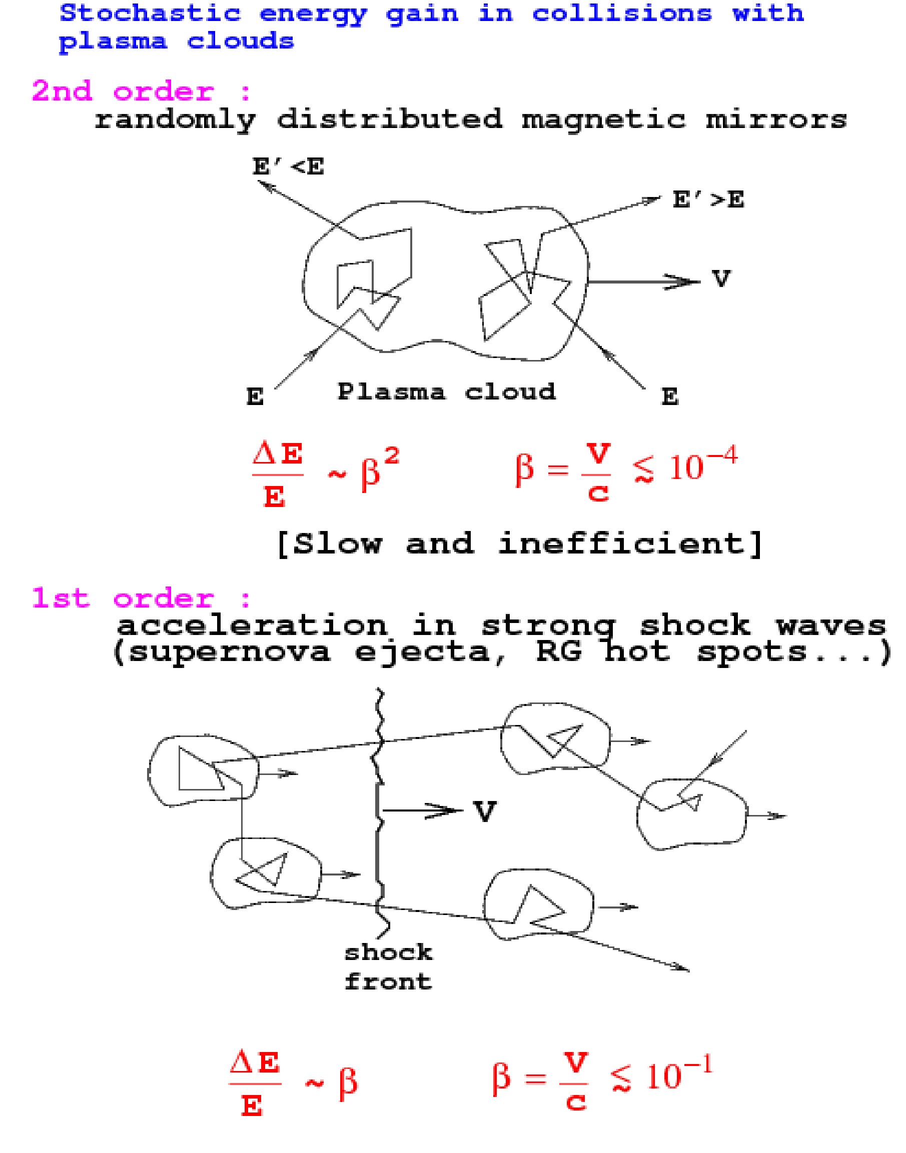
- **Limitations of the model**
  - Fails to describe the flux above the knee

- Suggested alternative models
  - Particle acceleration through electromagnetic mechanisms associated with **time-varying magnetic fields** or due to **peculiar galactic objects**

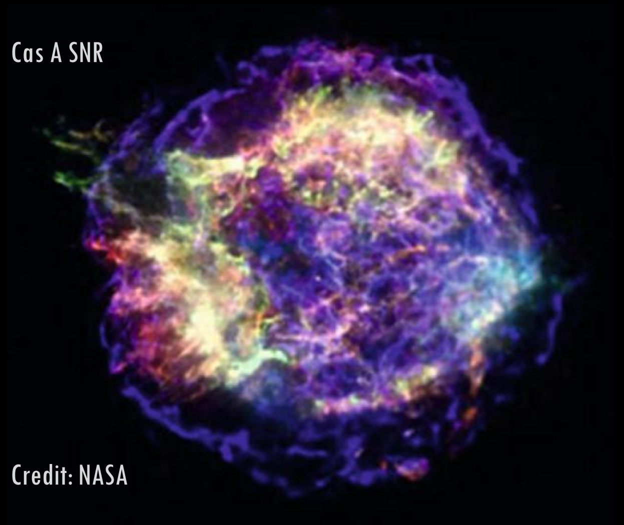
➔ At present, no firm experimental proof is evident for any point-like source of CRs

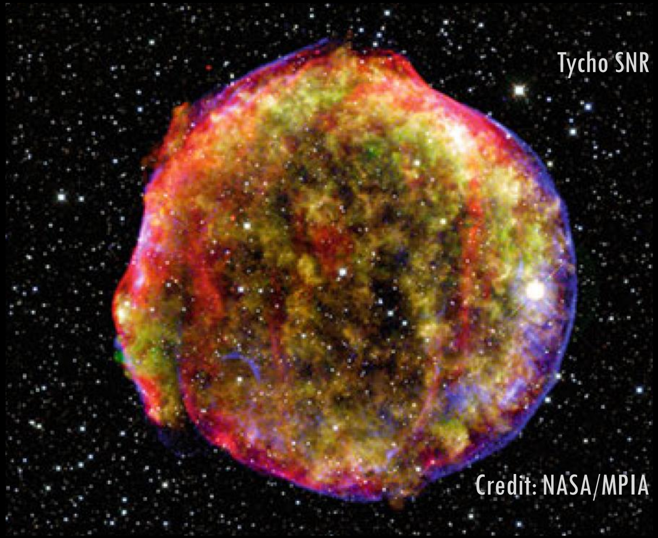
- Acceleration mechanism of charged particles in regions where **very strong inhomogeneous magnetic fields exist**
  - Scattering of the particle by magnetic field irregularities (magnetic mirrors) also called **collisionless shocks**
    - Defined as shock wave in which the scattering occurs on a **length scale much smaller** than the mean free path necessary for a particle collision
    - Particles interact with each other not through collisions, but by emission and absorption of collective excitations of the plasma (plasma waves)
  - In astrophysical situations, the intense magnetic field is provided by a "frozen" cloud of interstellar matter, with a density much higher than that of the surrounding material
    - Scattering between a **particle (with mass m)** and the **magnetic cloud (with mass M >> m)** can be considered as elastic in the reference frame in which the cloud is at rest

SECOND- AND FIRST-ORDER FERMI ACCELERATION MECHANISMS



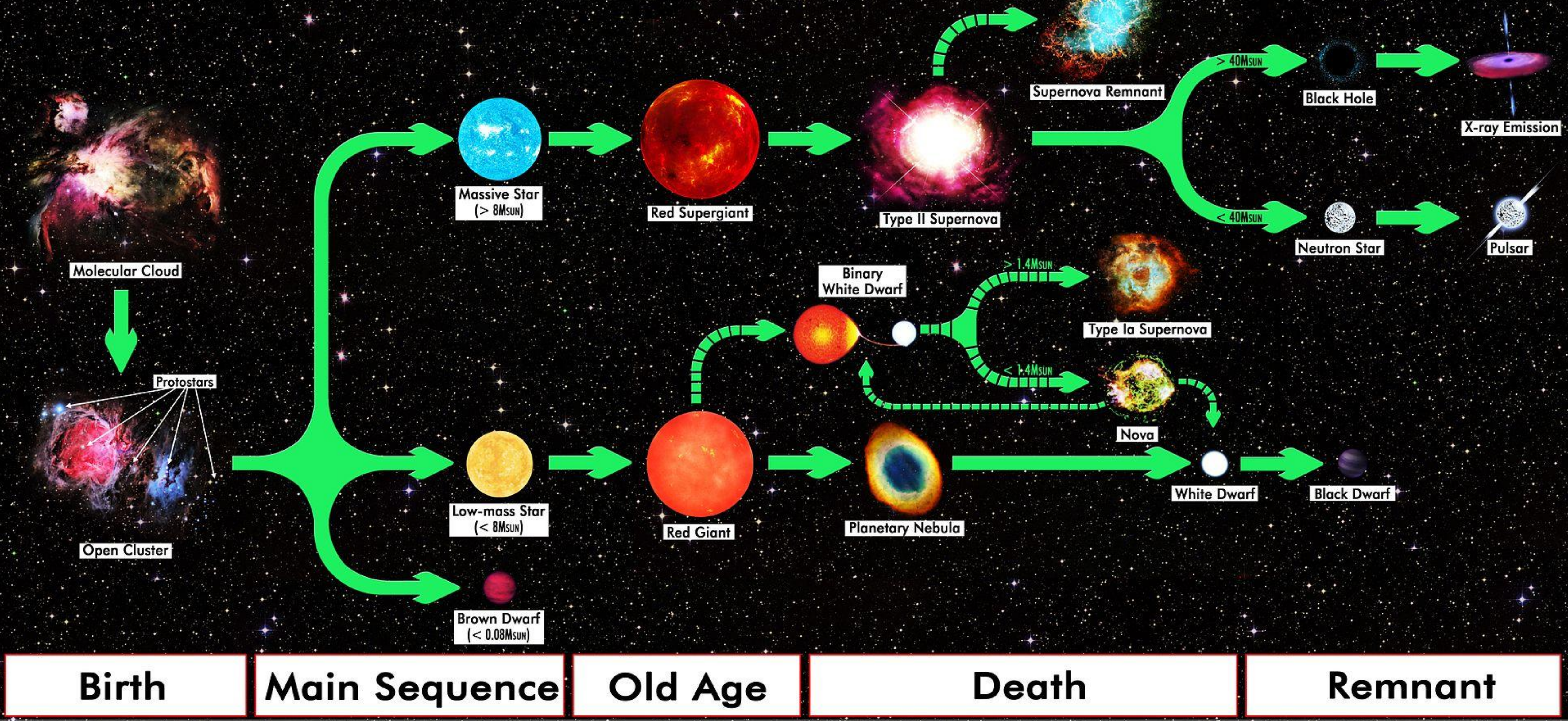
- Supernova Remnants (SNRs) are commonly recognized nowadays as responsible for most of the high-energy CRs, through Fermi first-order acceleration mechanisms





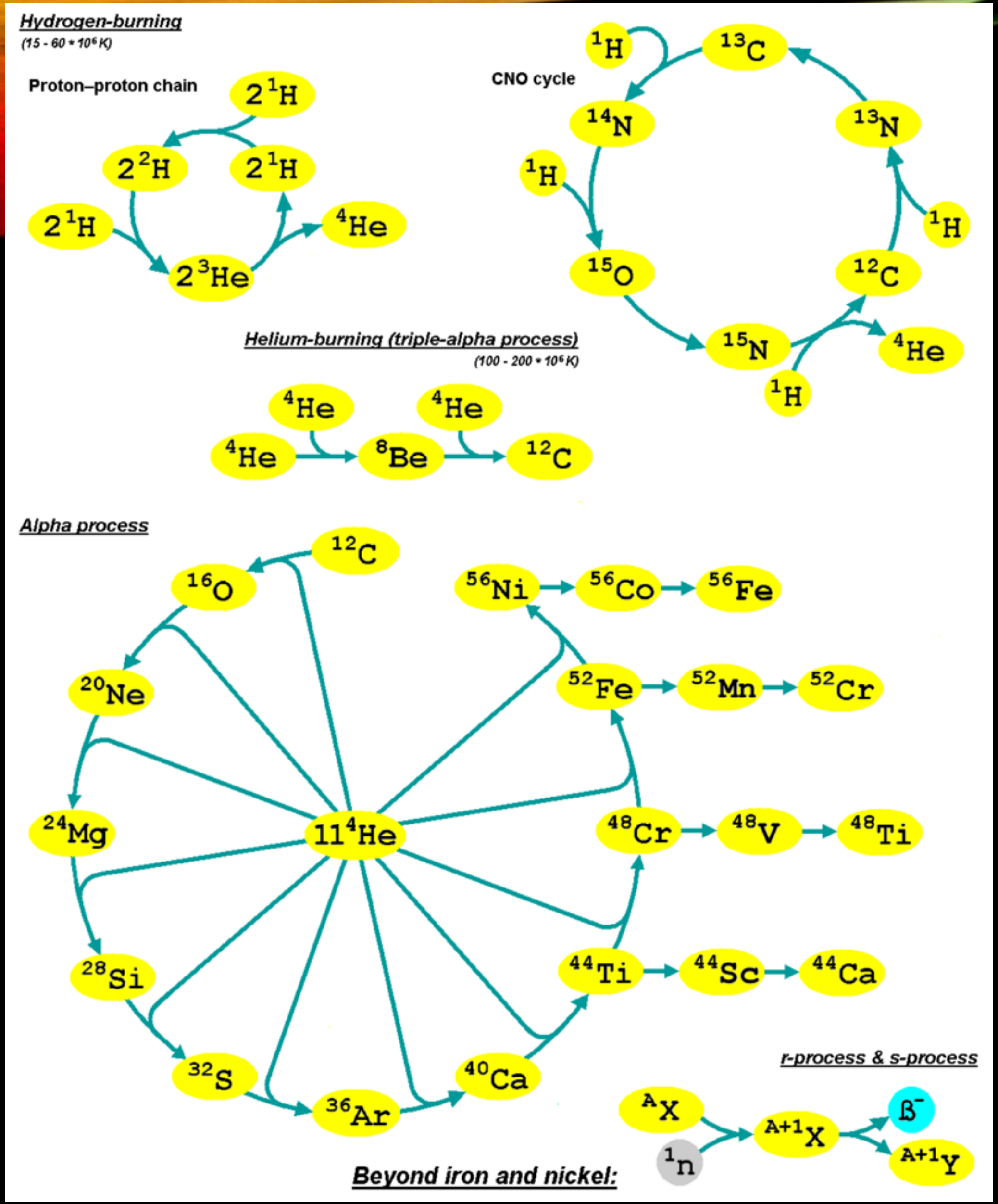
- However, the proof that this mechanism can accelerate CRs all the way up to the knee region is still missing

STELLAR LIFE CYCLE



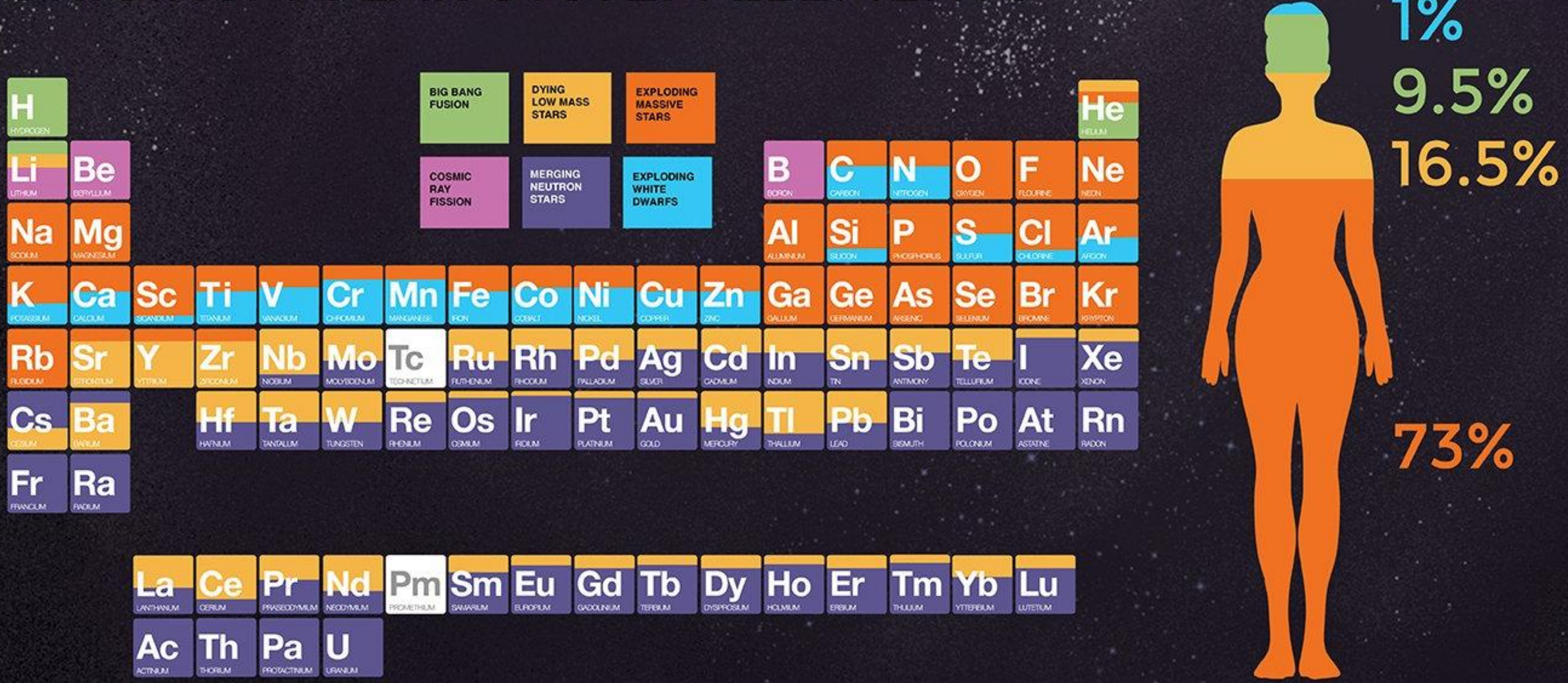
Credit: R.N. Bailey, WikiCommons

STELLAR NUCLEOSYNTHESIS



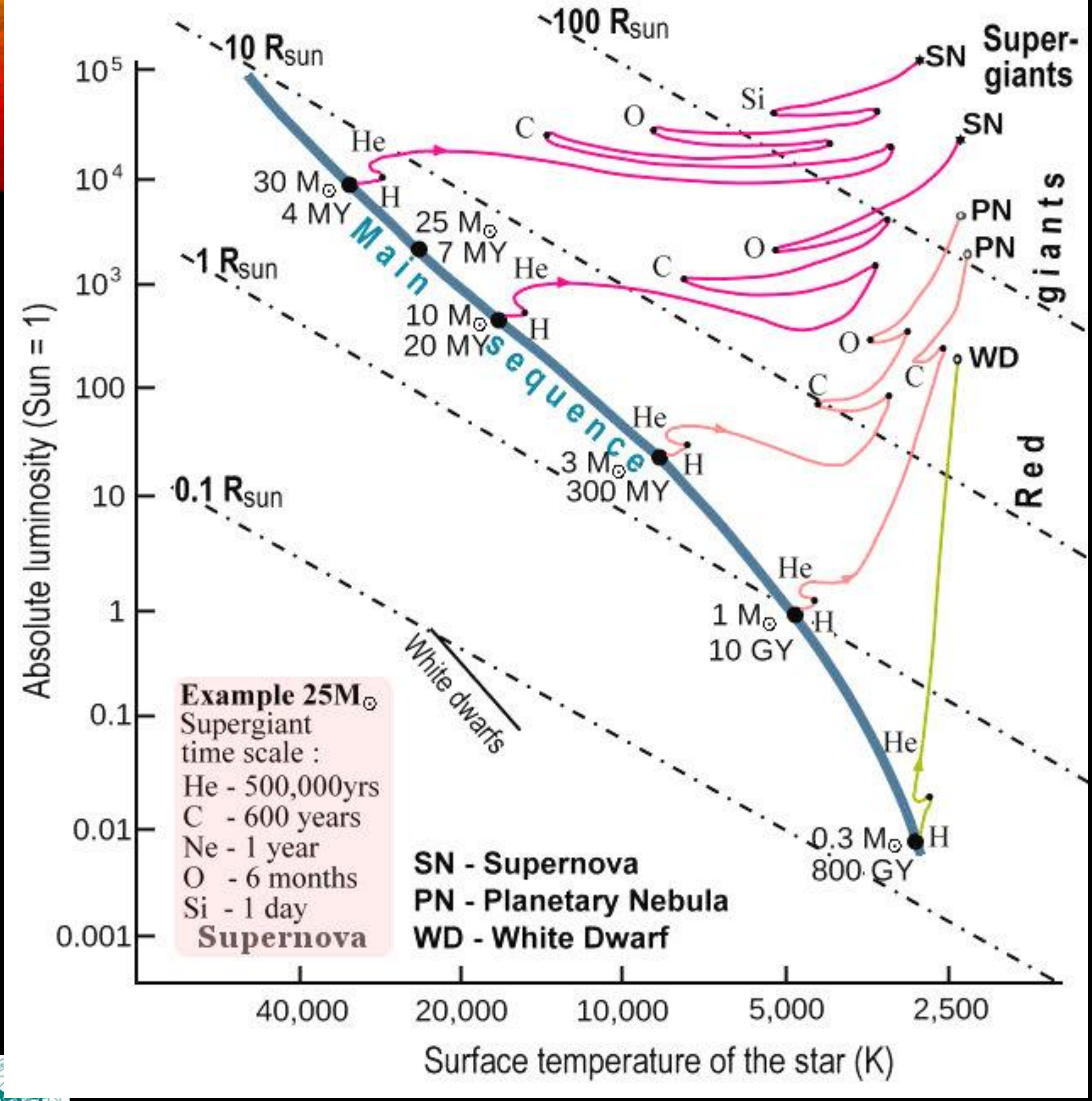
$$ {}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{16}_{8}\mathrm{O} + \gamma\,, \quad E = 7.16\ \mathrm{MeV} $$
$$ {}^{16}_{8}\mathrm{O} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{20}_{10}\mathrm{Ne} + \gamma\,, \quad E = 4.73\ \mathrm{MeV} $$
$$ {}^{20}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{24}_{12}\mathrm{Mg} + \gamma\,, \quad E = 9.32\ \mathrm{MeV} $$
$$ {}^{24}_{12}\mathrm{Mg} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{28}_{14}\mathrm{Si} + \gamma\,, \quad E = 9.98\ \mathrm{MeV} $$
$$ {}^{28}_{14}\mathrm{Si} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{32}_{16}\mathrm{S} + \gamma\,, \quad E = 6.95\ \mathrm{MeV} $$
$$ {}^{32}_{16}\mathrm{S} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{36}_{18}\mathrm{Ar} + \gamma\,, \quad E = 6.64\ \mathrm{MeV} $$
$$ {}^{36}_{18}\mathrm{Ar} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{40}_{20}\mathrm{Ca} + \gamma\,, \quad E = 7.04\ \mathrm{MeV} $$
$$ {}^{40}_{20}\mathrm{Ca} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{44}_{22}\mathrm{Ti} + \gamma\,, \quad E = 5.13\ \mathrm{MeV} $$
$$ {}^{44}_{22}\mathrm{Ti} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{48}_{24}\mathrm{Cr} + \gamma\,, \quad E = 7.70\ \mathrm{MeV} $$
$$ {}^{48}_{24}\mathrm{Cr} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{52}_{26}\mathrm{Fe} + \gamma\,, \quad E = 7.94\ \mathrm{MeV} $$
$$ {}^{52}_{26}\mathrm{Fe} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{56}_{28}\mathrm{Ni} + \gamma\,, \quad E = 8.00\ \mathrm{MeV} $$

ORIGINS: SOLAR SYSTEM ELEMENTS



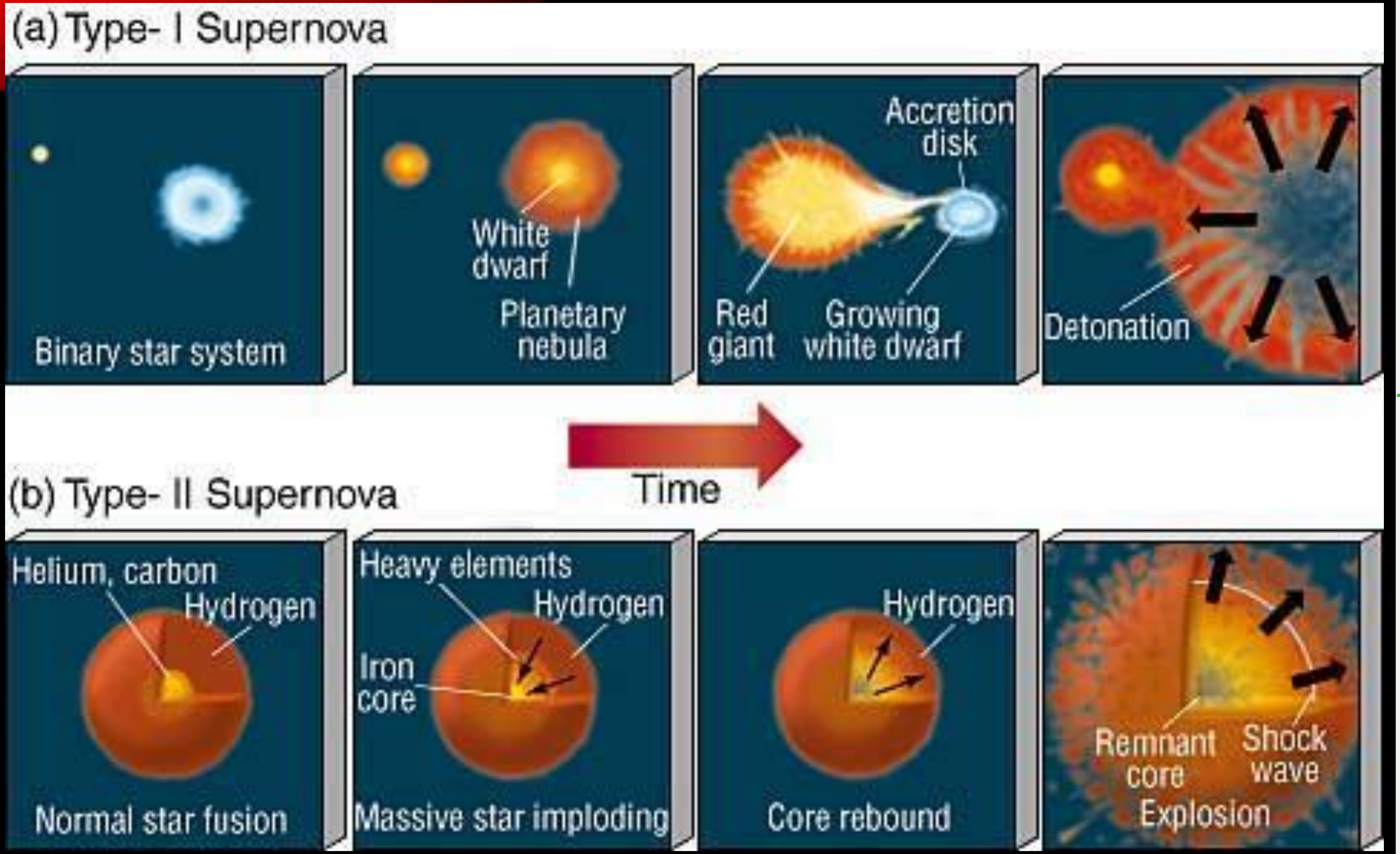
Credit J.Johson/ESA/NASA/AASNova
https://blog.sdss.org/2017/01/09/origin-of-the-elements-in-the-solar-system/

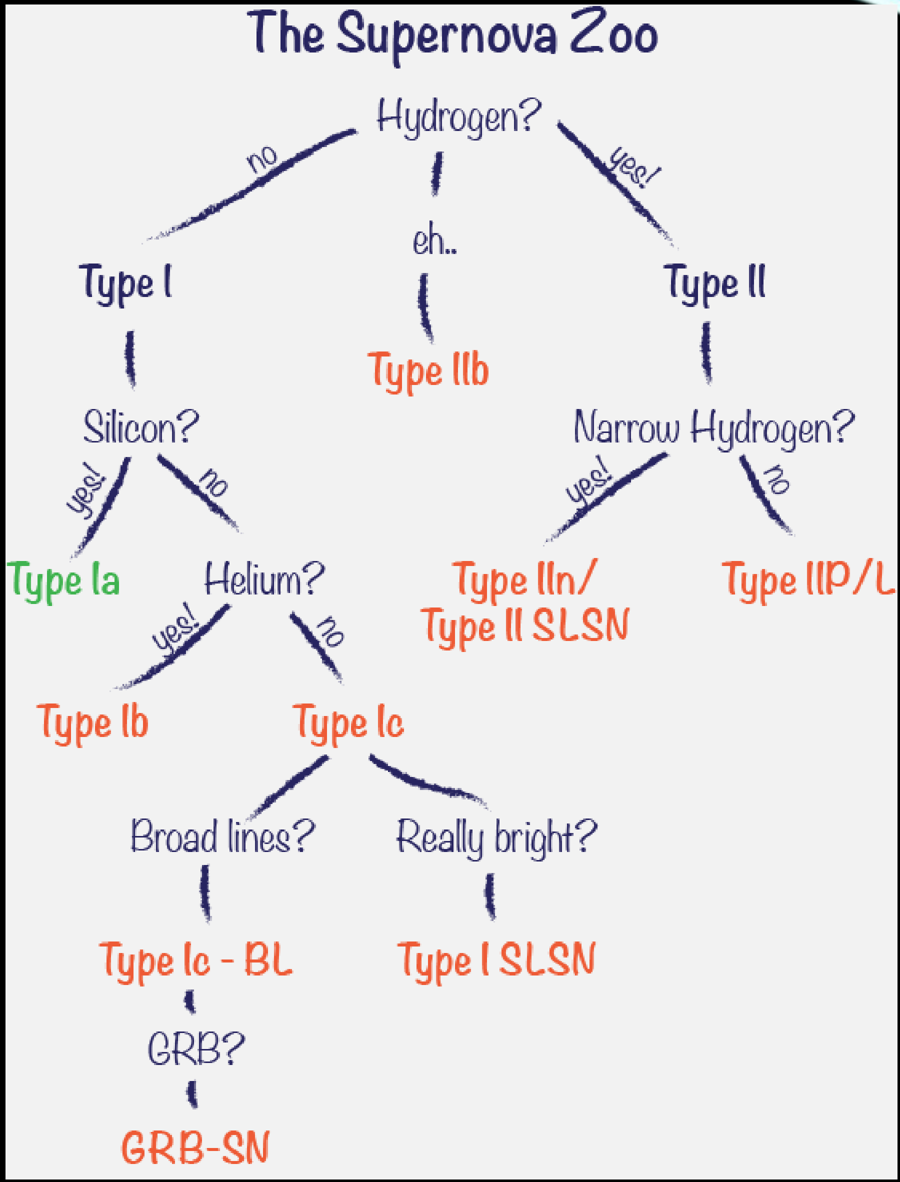
*Tc, Pm + elements beyond U don't have long-lived or stable isotopes → ignored



STELLAR EVOLUTION

- Stellar structure kept in **equilibrium** through **balance of gravity** (tendency to contract) and **radiation pressure** (tendency to expand)
- When the star has exhausted its hydrogen fuel, it cools off and collapses until the pressure has risen sufficiently to ignite helium and other types of nuclear burning
  - Process of re-igniting fuel burning with different nuclear species represented by zigzag paths
- Eventually, all the available fuels are consumed, there is no more source to supply the thermal pressure necessary to stop further collapsing


(a) Type- I Supernova
Binary star system
White dwarf
Planetary nebula
Accretion disk
Red giant
Growing white dwarf
Detonation
Time
(b) Type- II Supernova
Helium, carbon
Hydrogen
Normal star fusion
Heavy elements
Hydrogen
Iron core
Massive star imploding
Hydrogen
Core rebound
Remnant core
Shock wave
Explosion


The Supernova Zoo
Hydrogen?
no
yes!
eh..
Type I
Type II
Type IIb
Silicon?
Narrow Hydrogen?
yes!
no
yes!
no
Type Ia
Helium?
Type IIn/
Type II SLSN
Type IIP/L
yes!
no
Type Ib
Type Ic
Broad lines?
Really bright?
Type Ic - BL
Type I SLSN
GRB?
GRB-SN

SUPERNOVA REMNANTS

- Galactic CRs are related to one or more types of supernova explosion
  - Acceleration process is mainly due to diffusive transport in the neighbourhood of strong shocks formed as a consequence of these explosions
  - Main candidate: **shock waves** produced by Type II "core collapse" supernovae (SNe)

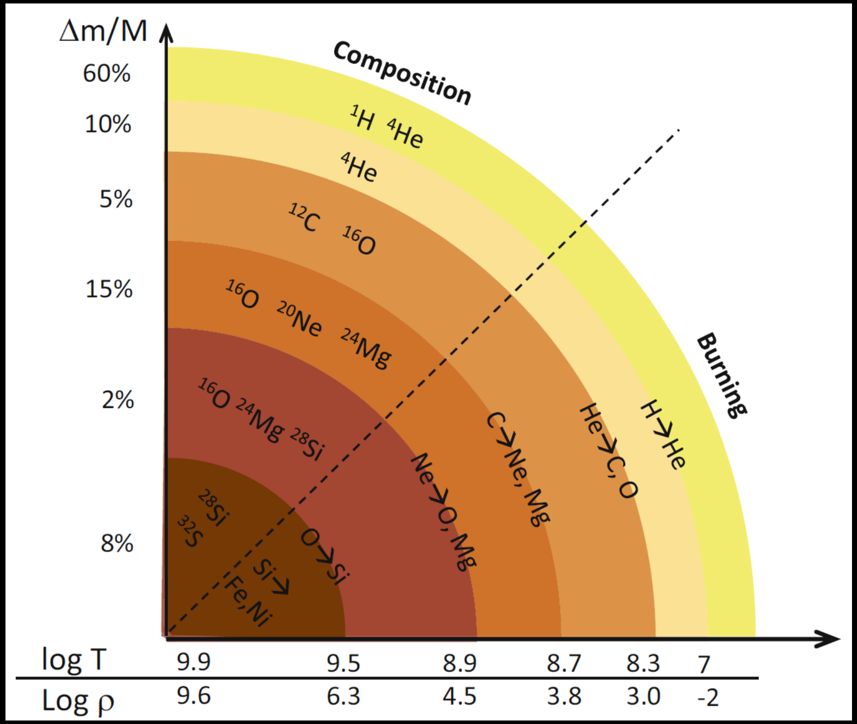
Type II SNe

- End of fusion process in **very massive stars (M ≥ 8 M⊙)**
  - Onion-like structure with a degenerate Fe core
  - After the core is completely fused to iron, no further processes releasing energy are possible
  - Photo-disintegration destroys the heavy nuclei

$$\gamma + {}^{56}Fe \rightarrow 13\ {}^{4}He + 4n$$

→ star collapses, density increases, free electrons and protons are forced to form neutrons via inverse beta decay

- Neutron star forms in the core, with a density that equals that of nuclear matter

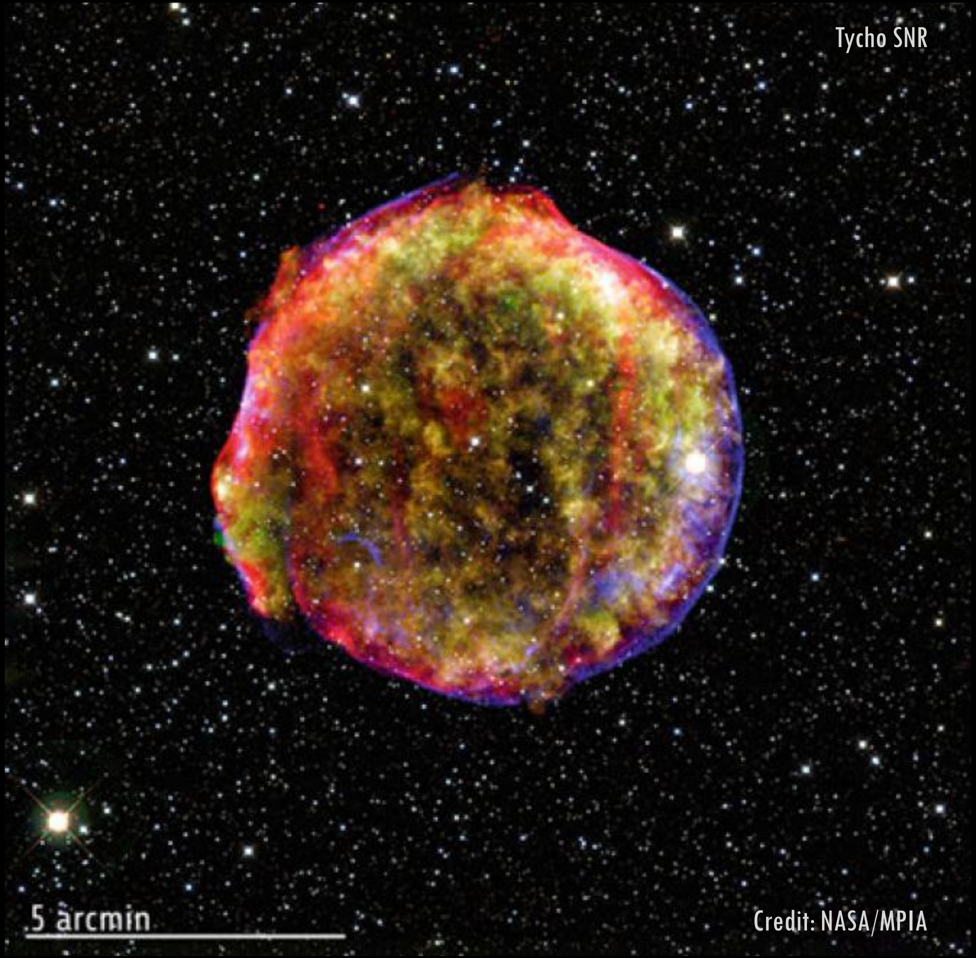


SUPERNOVA REMNANTS

- The in-falling material of outer layers is reflected from the nuclear core

  ➔ A shock wave propagates outwards heated by <u>neutrino emission</u> from the neutron star

- The energy outfall from a supernova explosion is simply evaluated as the **released gravitational binding energy ~(2−4) x 10^{53} erg per explosion**
  - 99% of this energy emitted as neutrinos
  - Only 1% (~10^{51} erg) transferred into kinetic energy of the expulsed material forming the shock wave
  - Energy emitted as electromagnetic radiation is even less, about 1% of the kinetic energy



Maximum Energy Attainable in the Supernova Model

- Maximum energy that a charged particle can reach in the acceleration process due to the diffusive shock mechanism from a supernova explosion

$$E_{CR,max} \sim Z\,e\,\beta\,B\,R_{SN} \sim 300\,Z\,TeV$$

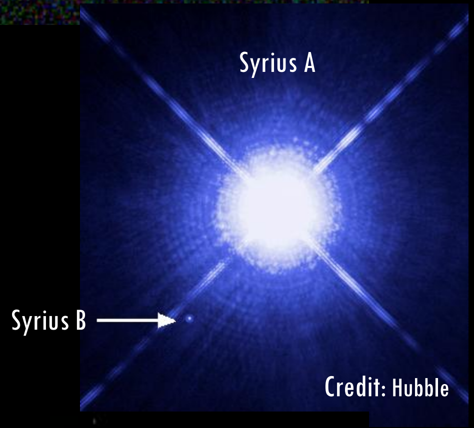
  - Ze: Charge of the particle
  - R_{SN}: Size of the accelerating region
  - B: Magnetic field permeating the region
  - $\beta = V/c$: speed of the shock in unit of light speed

→ Simplified relation, not accounting for radiative losses

- Derived considering the energy increase by a magnetically confined particle with Larmor radius $r_L = pc/ZeB \sim E/ZeB$ and a characteristic period T_{cycle} of the process

- The diffusive shock acceleration mechanism explains:
  - Maximum rigidity $R = pc/Ze \sim E/Ze$ associated with acceleration effects
  - Spectrum of CR protons up to a few hundred TeV (~10^{14} eV, knee region)

WHITE DWARFS



- **Small star made of electron-degenerate matter**
  - The gravitational pressure is counterbalanced by the pressure resulting from the electron degeneracy
    - Electron degeneracy pressure is a quantum-mechanical effect arising from the Pauli exclusion principle!
  - Material no longer undergoes fusion reactions
    - Star has **no source of energy**
- The physics of degeneracy yields a **maximum mass for a non-rotating white dwarf**, the Chandrasekhar limit:

$$\boldsymbol{M_{WD} = M_{ch} \sim 1.44\, M_\odot}$$

  - Derived making energetic considerations involving the critical density of matter for degenerate atomic electrons in the relativistic limit
  - Typical radius of a white dwarf: $\boldsymbol{R_{WD} \sim 5 \times 10^6\, m}$
- A white dwarf is very hot when it forms, but will gradually cool as it radiates its energy → cold black dwarf

NEUTRON STARS

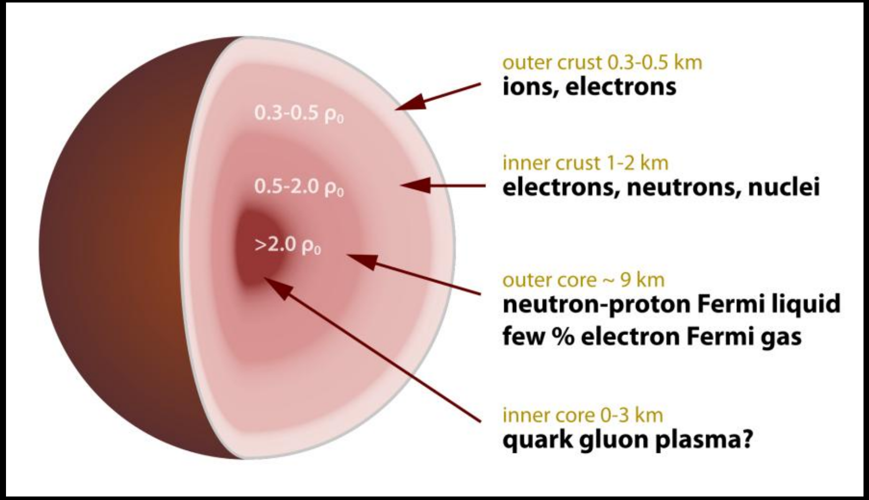
- Stellar remnant that can result from the gravitational collapse of a massive star, with $M > 8\ M_{\odot}$
  - As the core of a massive star is compressed during a SN event, increases in the electron Fermi energy allow **the electron capture reaction** (threshold 1.36 MeV)

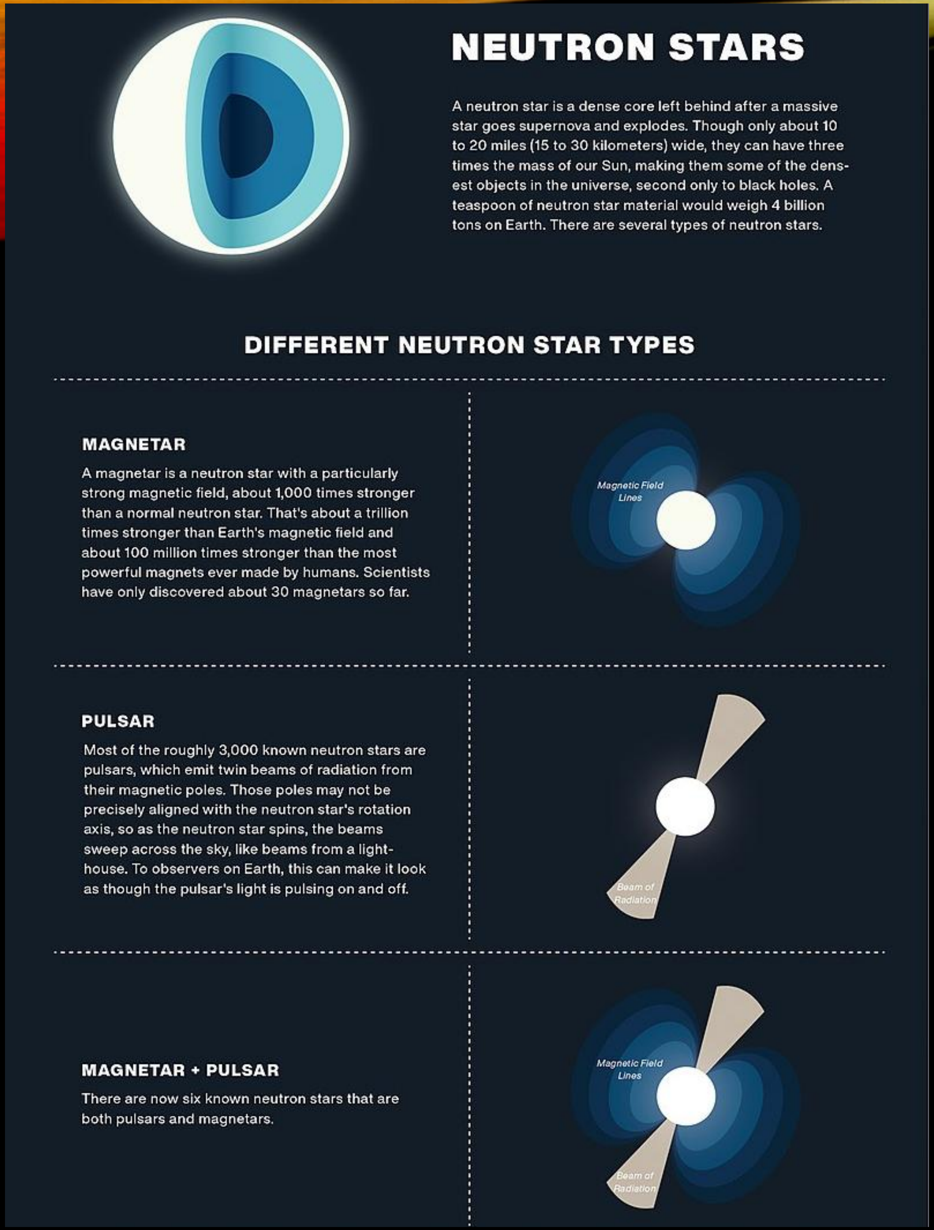
$$e^{-} + p \rightarrow n + \nu_e$$

  - Weakly-interacting neutrinos escape
  - Matter cools down
  - Density increases
  - Nuclei in the center of the star become neutron-enriched
  - Nuclei break into their components
  - Enough neutrons are created → neutron become degenerate
  - **Neutron degeneracy pressure** stops the collapse

  → Equilibrium state is established

- Transition from collapse to equilibrium is very sudden: in-falling material experiences a bounce against the degenerate core, which creates an outward-propagating shock wave (the SN)
  - The shock wave is further boosted by the neutrino pressure from the core





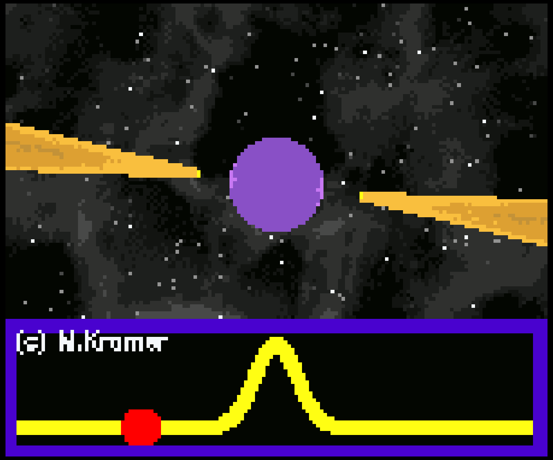
NEUTRON STARS

- The description of the equilibrium state in a neutron star is similar to that of the white dwarf
  - The degenerated fermions are now the neutrons!
  - The mass limit assumes the Oppenheimer-Volkoff mass limit: $\boldsymbol{M_{NS}} = \sim \mathbf{1.6\ - 2.5}\ \boldsymbol{M_\odot}$
  - Since the critical density for relativistic neutrons is $\sim \mathbf{10^3}$ larger than that of electrons, the radius is much smaller than $\boldsymbol{R_{WD}}$:

$$\boldsymbol{R_{NS}} \sim \mathbf{3 \times 10^3}\ \boldsymbol{m}$$

- Estimated number of NS in our Galaxy : $\sim \mathbf{10^8}$
  - Obtained considering stars that have undergone SN explosions
  - Most NS are old and cold
  - NS can only be easily detected if they are young, rotating systems (referred to as pulsars!)

PULSARS



- **Rotating neutron star** that emits a beam of electromagnetic radiation, typically along its magnetic axis

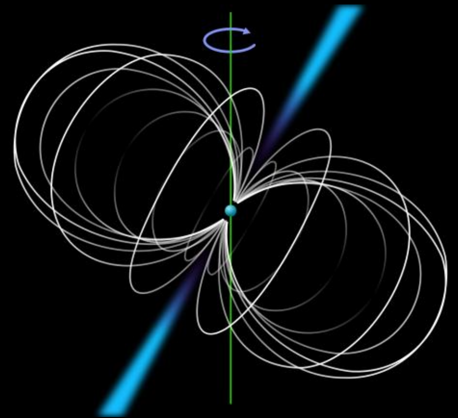
- Discovered in the radio band by **Hewish & Bell in 1967** soon identified with isolated, rotating, magnetized NSs
  - **Key observations:**
    - Very stable, short periods of the pulses
      ➔ Pulses range **from** $\sim \mathbf{1\ ms}$ **to** $\sim \mathbf{10\ s}$
    - Polarized radio emission
    - Radiation can only be observed when axis pointing towards Earth
    - Rotation slows down over time as electromagnetic radiation is emitted

- More than **3170 pulsars** are currently known
  - Visit PSR Catalogue https://www.atnf.csiro.au/research/pulsar/psrcat/

PULSARS

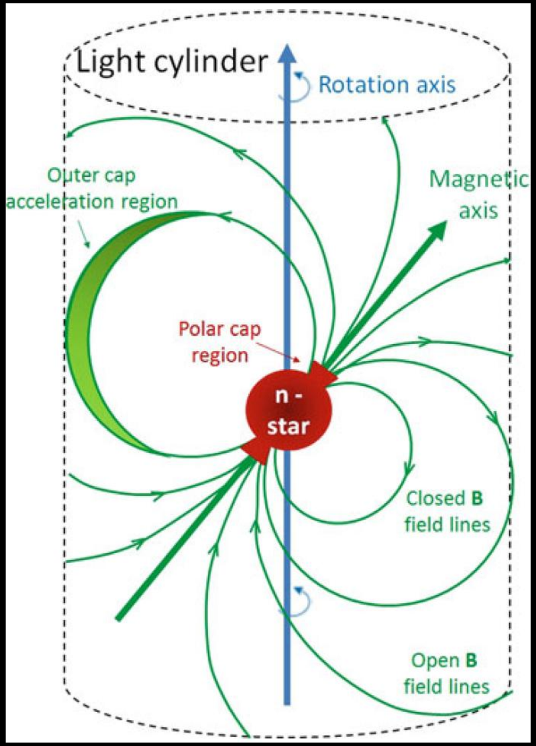
- Stellar magnetic field extremely high near the NS surface, amplied by gravitational collapse:

$$B_{NS} \sim 10^{12}\ G$$



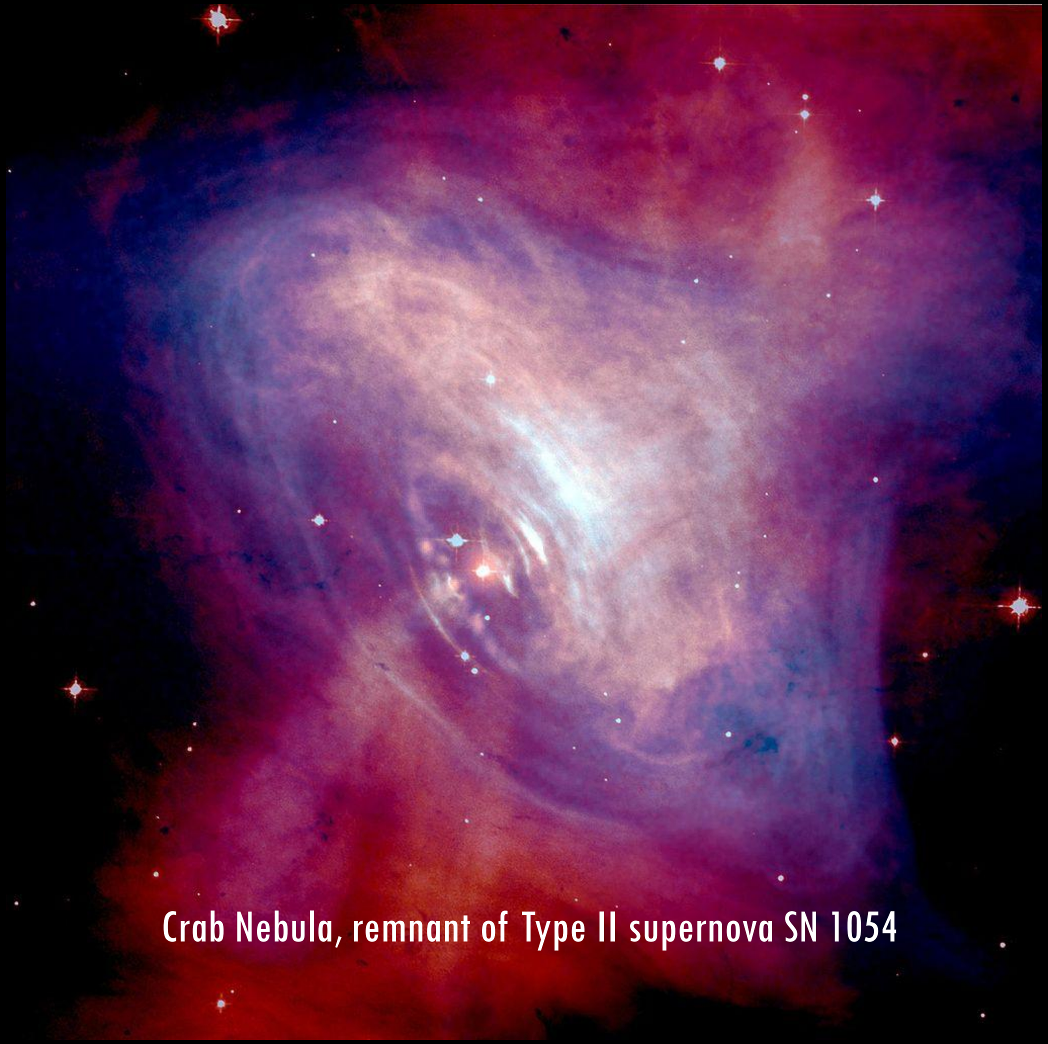
- Pulsars emit e.m. radiation <u>at all wavelengths</u>
  - The pulsed radiation due to misaligned **magnetic and rotation axes**
  - Radio pulses due to **beams of radio emission from the poles of the magnetic field distribution**
    - Charged particles in polar cap **magnetically accelerated** to very high energies along open but curved field lines
    - Acceleration resulting from curvature causing **strongly polarized synchrotron radiation**

    ➔ Photons can reach **energies up to the TeV region**



Vela and Crab pulsars and nebulae

Vela Nebula, remnant of Type II supernova exploded ~11–12 kyrs ago



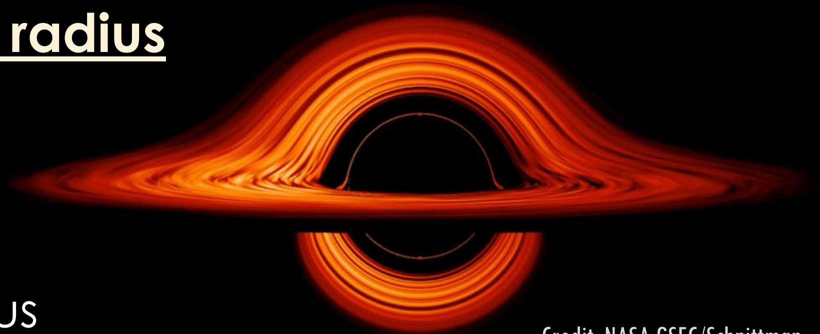
Crab Nebula, remnant of Type II supernova SN 1054

STELLAR-MASS BLACK HOLES

- Final state of the evolution of a massive star
- Massive object exhibiting such strong gravitational effects that nothing (particles nor EM radiation) can escape from inside its boundary = the event horizon
  - In most cases → event horizon equivalent to **Schwarzschild radius**

$$R_{Sc} = \frac{2Gm}{c^2} = 2.95 \left(\frac{m}{M_\odot}\right) km$$

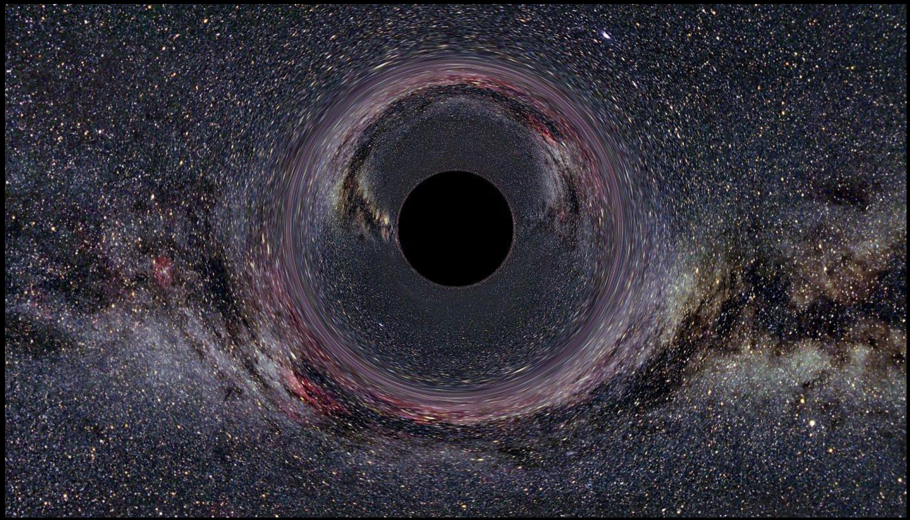
    - R_{Sc} scales linearly with object mass m
    - Correct for non-rotating massive objects that fit inside this radius



Credit: NASA GSFC/Schnittman

  - Obtained from Newtonian considerations, but same conclusion emerges from General Relativity
    - In classical GR, a particle that is inside the event horizon can never emerge outside

    → Black holes are particular solutions to the Einstein field equations

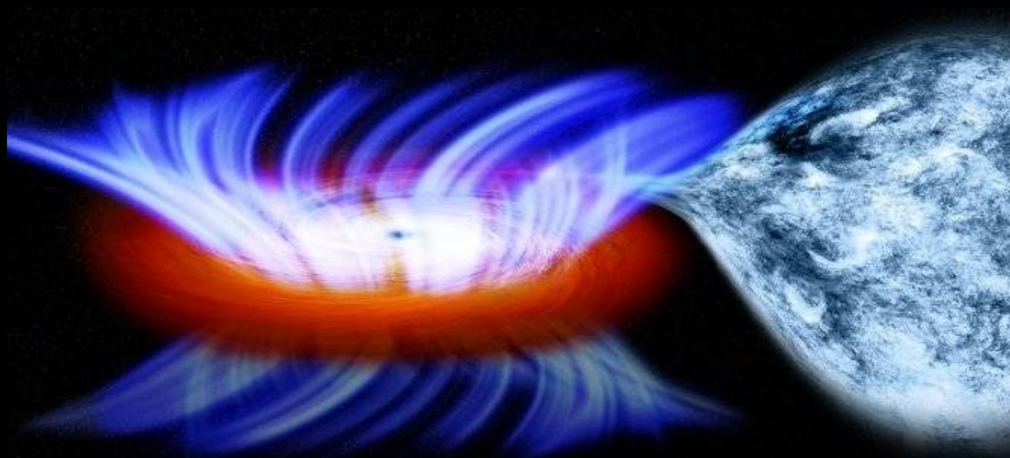


Supermassive black holes (SMBH)

- Formed as BHs **absorb other stars** or **merge with other BHs**
- Can reach ~10^6 M⊙
- Should exist in the **centers of most galaxies**
- Particular active galaxies have hypermassive BHs (~10^{10} M⊙)
  - Good candidates to explain origin of highest energy CRs

How to spot the presence of a BH

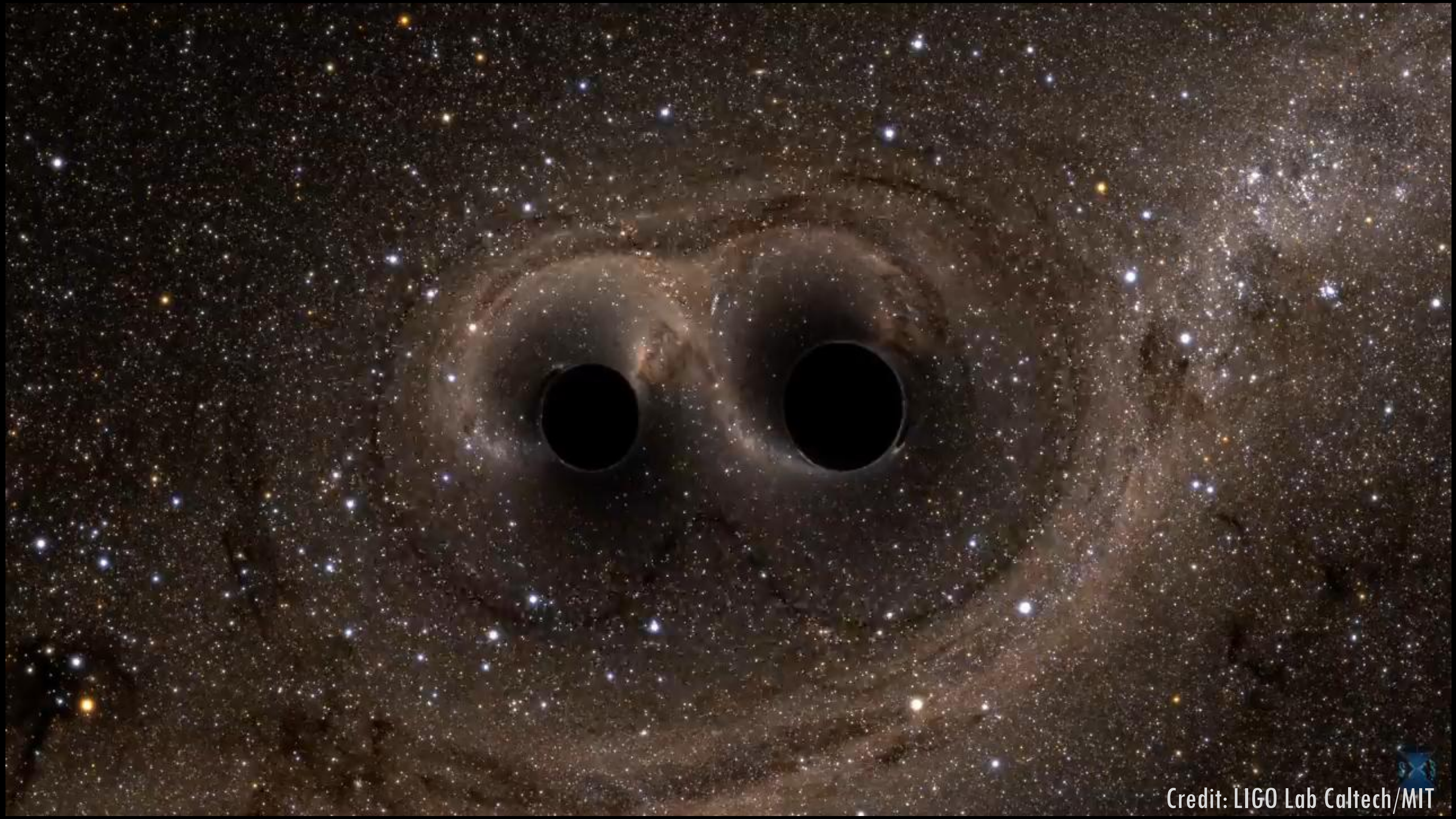
- Clear evidence of a SMBH in our Galaxy, provided by the **proper motions of stars**
- Stellar BHs in **close binary systems** are observable when matter is **transferred** from a companion star to the BH
  - Energy release by matter falling toward the BH is so large that it radiates in X-rays
  - Companion star observed in the optical



Artist's impression of a binary system containing a stellar-mass black hole called IGR J17091-3624. The strong gravity of the black hole, on the left, is pulling gas away from a companion star on the right. This gas forms a disk of hot gas around the black hole, and the wind is driven off this disk. Credit: NASA/CXC/M.Weiss

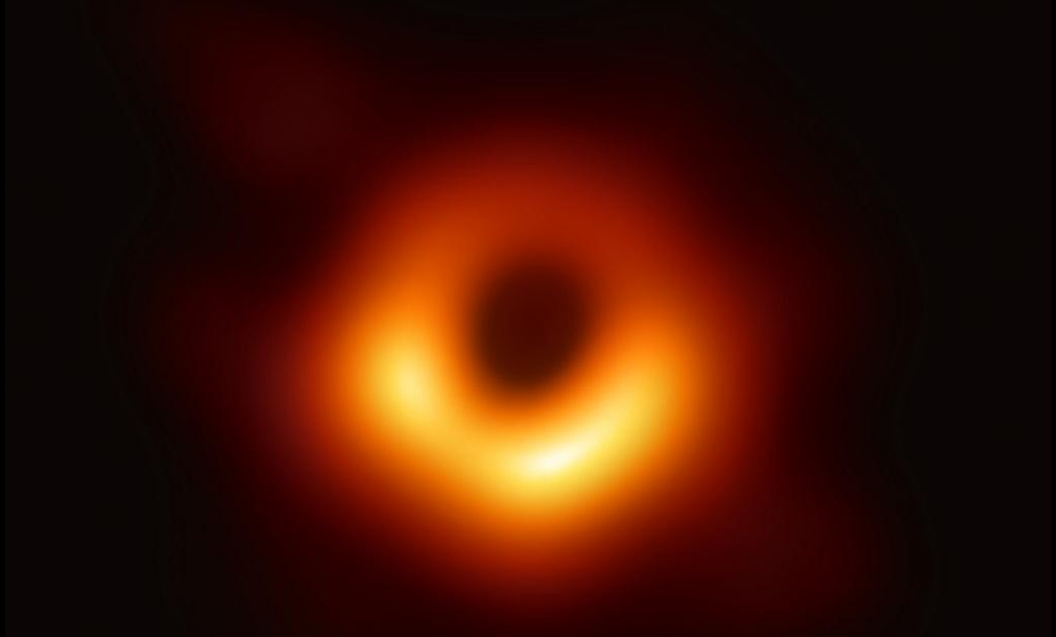
STELLAR-MASS BLACK HOLES

- **GW150914**: First-ever successful observation of gravitational waves
  - Consistent with theoretical predictions for the gravitational radiation produced by merger of 2 BHs (Primary BH ~ 36 M⊙, secondary BH ~ 29 M⊙)
  - Observation provided **first most concrete evidence** for the existence of stellar BH



https://www.youtube.com/watch?v=I_88S8DWbcU

- The famous M87* supermassive black hole
  - Messier 87 (M87/Virgo A/NGC 4486): supergiant elliptical galaxy, Virgo constellation
  - One of the most massive galaxies (~200 x more than Milky Way!) in the local universe (distance = 16.4 ± 0.5 Mpc)

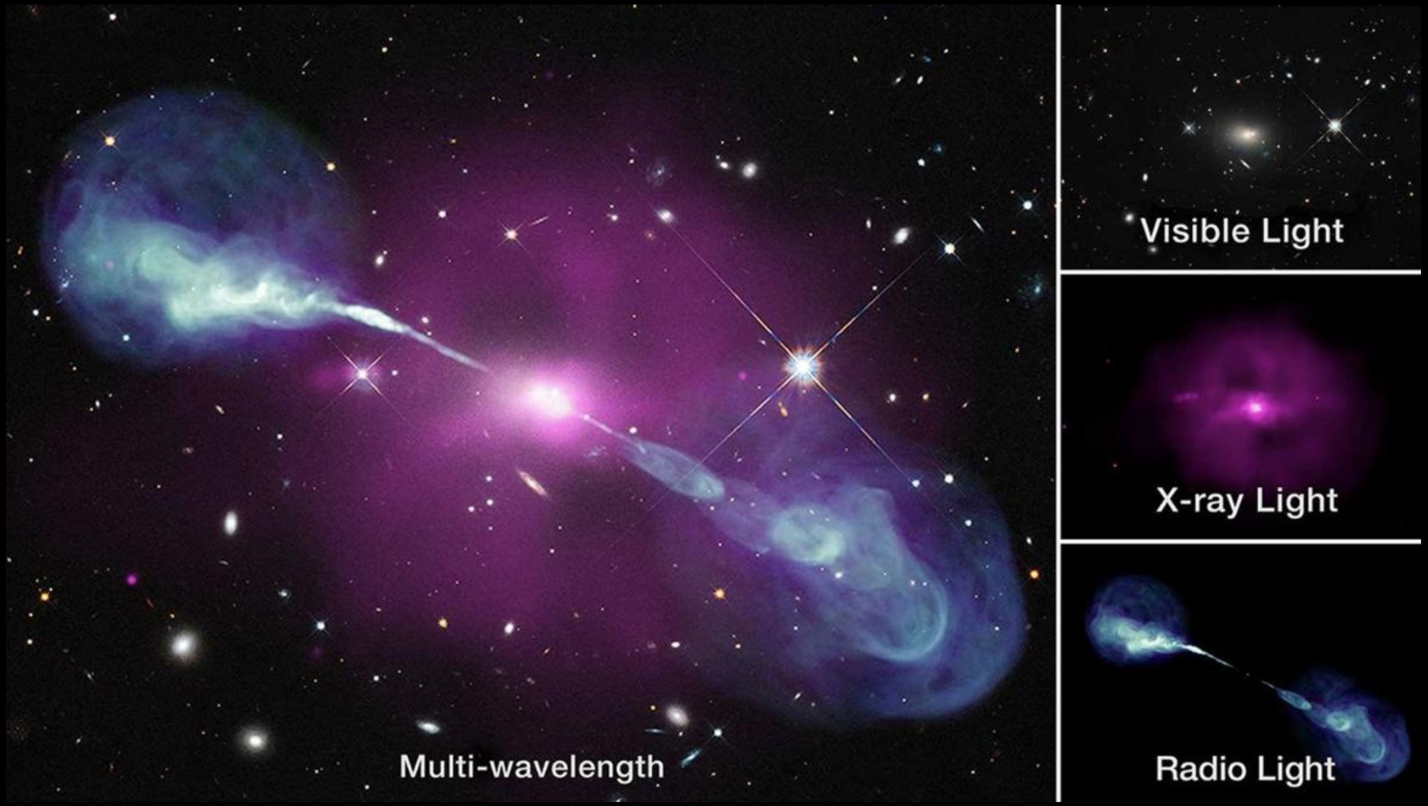


The EHT image of the core of M87 using 1.3 mm radio waves, published on 10 April 2019. The central dark spot is the shadow of M87* and is larger than the black hole's event horizon.
Credit: EHT - https://www.eso.org/public/images/eso1907a/

A view in polarised light, taken by EHT and published on 24 March 2021. The direction of the lines shown over the total intensity mark the direction of the electromagnetic wave electric vector oscillations around the shadow of the BH.
Credit: EHT - https://www.eso.org/public/images/eso2105a/

ACTIVE GALACTIC NUCLEI

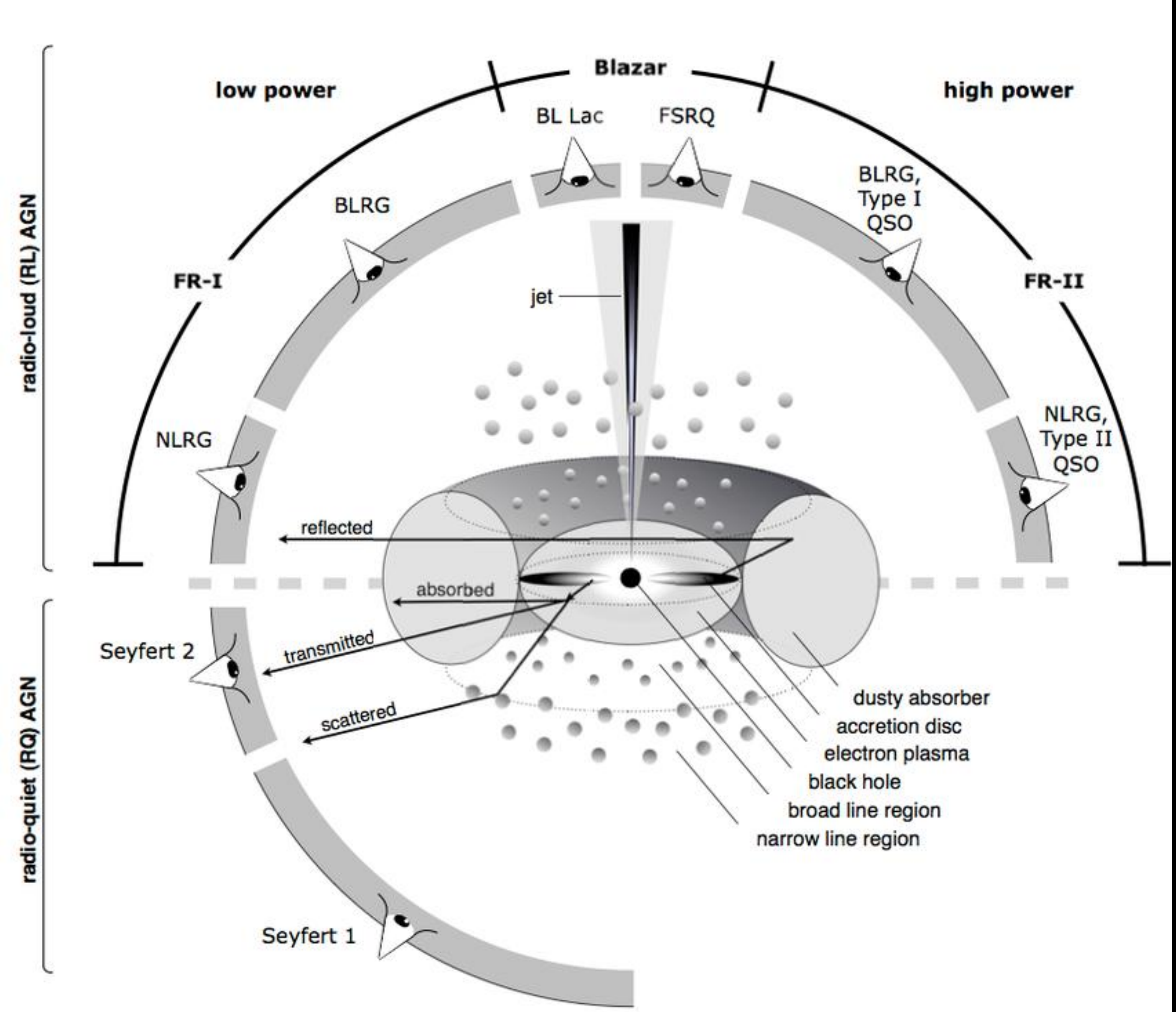
- An AGN is the ultra-bright, **compact core of a galaxy powered by a SMBH**
  - As the black hole rapidly consumes surrounding gas and dust, it creates a blazing, spinning disk that emits massive amounts of energy **across the entire e.m. spectrum**



- **Properties:**
  - **Engine**: SMBH at the center
  - **Accretion Disk**: Gas and dust swirl into the black hole, forming a super-heated disk. The friction and gravitational energy in this disk glow intensely, sometimes outshining the entire galaxy
  - **Jets & Winds**: Strong magnetic fields can shoot some of this material outward into deep space as massive, relativistic particle jets and energetic winds.

Classification:

- **Seyfert Galaxies**: Nearby, spiral galaxies with bright, star-like centers and broad optical lines
  - Type 1: showing both narrow and broad emission lines
  - Type 2: showing only narrow lines
- **Quasars (QSOs)**: Extremely luminous and distant AGN that outshine their host galaxies
  - Discovered in radio → no distance, no redshift, just a continuum;
  - 1960s first optical observations → point sources with luminosity of a galaxy
- **Radio Galaxies**: AGNs that emit massive amounts of energy in the radio spectrum
  - Mostly giant elliptical galaxies with radio, optical and X non-thermal emission
  - Typically featuring colossal, relativistic jets
- **Blazars**: AGNs where one of the relativistic jets is pointed almost directly at Earth
  - Extraordinary brightness and very short variability across all wavelength;
    - FSRQs: very intense emission+absorption lines;
    - BL Laq: no lines



OTHER ACCELERATION SITES

- Following the arguments used for galactic CR sources, the **extragalactic acceleration** mechanisms must provide enough energy to reach the largest observed energies
  - While the presence of plasmas in any real astrophysical condition destroys large-scale electric fields, **magnetic fields are instead almost omnipresent in astrophysical objects**
    - Magnetic field space/time variations imply existence of transient electric fields (Faraday law!) that can supply a consequent amount of energy to charged particles
  - Maximum energy of a CR nucleus of charge Ze accelerated in a region where the magnetic field B changes in a spatial region of size L

$$E_{max} \sim Ze\,\beta\,L\,B$$

    - $\beta = Uc$, where U is the characteristic velocity of magnetic scattering centers
    - **This relation is usually called the Hillas criterion**

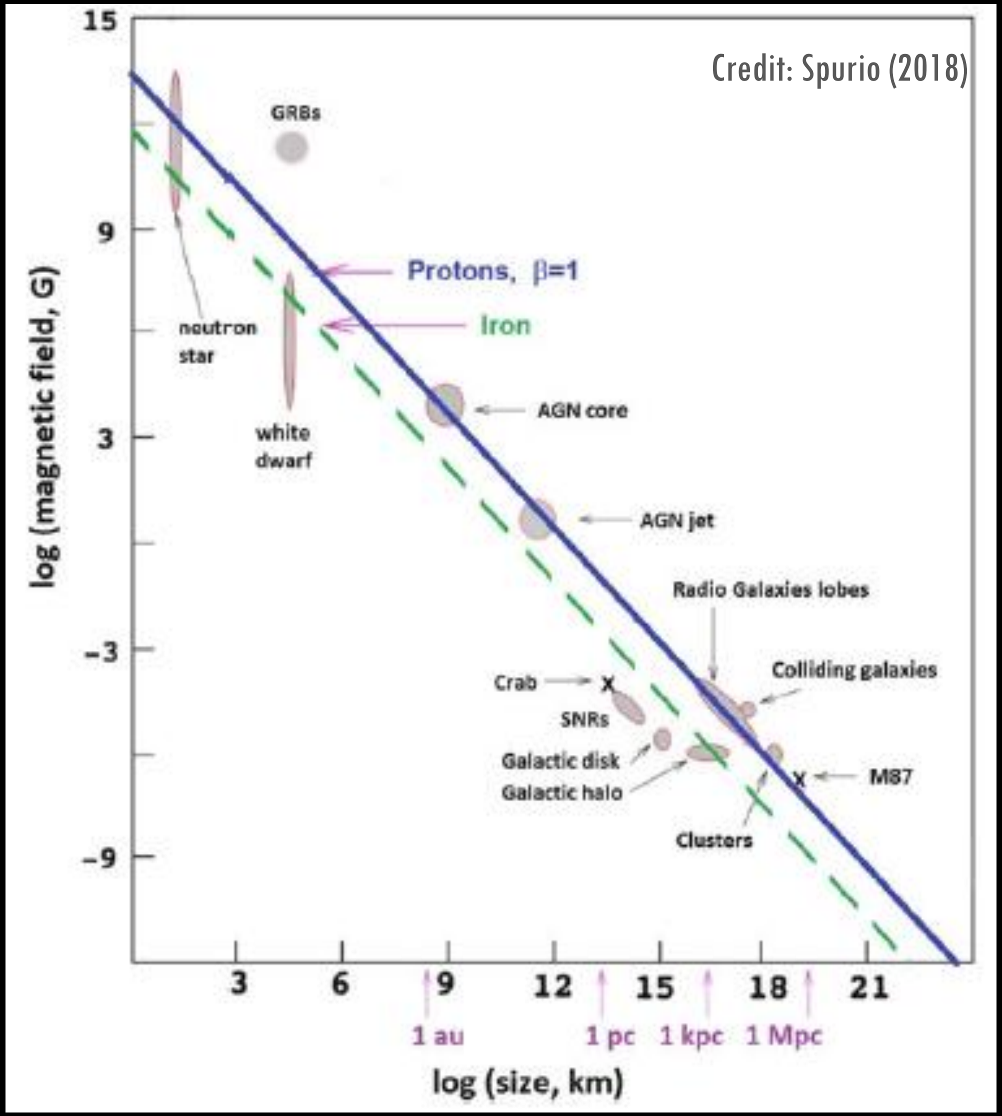
OTHER ACCELERATION SITES

Hillas plot (Hillas 1984, Ostrowski 2002)

- In any accelerator where particles are magnetically confined while being accelerated, their Larmor radius r_L has to be smaller than the system size
- Relation between **magnetic field B** and **size L** of different astrophysical objects representing potential CR accelerators. Acceleration of CR to a given energy requires magnetic fields and sizes above the respective line
  - Regions of roughly $r_L < \beta L$ define the allowed range for sources with the acceleration parameter β
  - Typical values of β go from ~1 in extreme environments such as relativistic shocks, down to ~1/300
- Diagonal lines correspond to values of $E_{CR,max} = 10^{20} eV$ for protons (blu) and iron nuclei (green dashed)

➔A same value of $E_{CR,max}$ can be realized:

- In large acceleration regions with low-B fields
- In compact accelerators with high-B fields



OTHER ACCELERATION SITES

- Values for typical electromagnetic emissions and characteristic lifetimes for different galactic and extragalactic objects
  - Estimates based on multiwavelength observations of objects in e.m. emission
  - The power measured in electromagnetic wavelengths should roughly correspond to the CR power at the source, since e.m. radiation originates from the emission processes of charged particles!

Source class	Electromagnetic output erg/s	Lifetime	Energy range
Galactic sources			
Supernova remnants (SNR)	10^{42}	10^3–10^4 y	$10^{10} \div 10^{15}$ eV
Wind-SNR	10^{44}	1000 y	$10^{10} \div 10^{18}$ eV
X-ray binaries	10^{38}	10^5 y	$10^{14} \div 10^{18}$ eV
Pulsars	10^{37}	10^6 y	$10^{14} \div 10^{18}$ eV
Extragalactic sources			
Galaxy clusters	10^{44}	10^7 y	$10^{18} \div 10^{21}$ eV
AGN	$10^{44} \div 10^{47}$	10^7 y	$10^{18} \div 10^{21}$ eV
GRBs	$10^{49} \div 10^{51}$	1–100 s	$10^{18} \div 10^{21}$ eV