Relativistic Magnetospheres: Major Challenges and Opportunities

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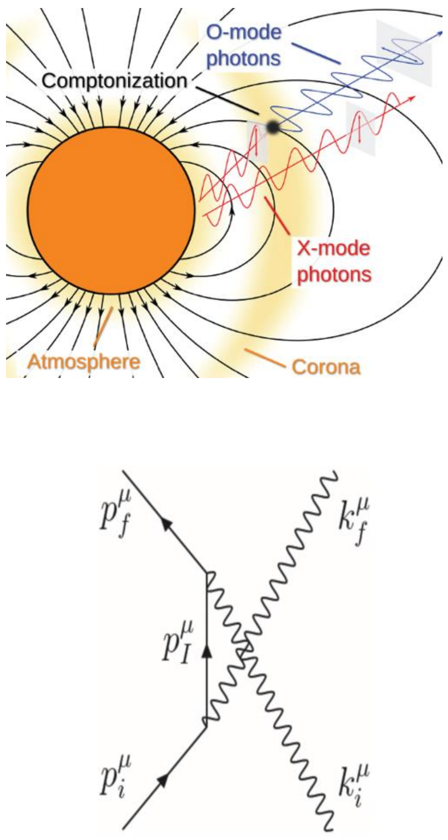
Topics

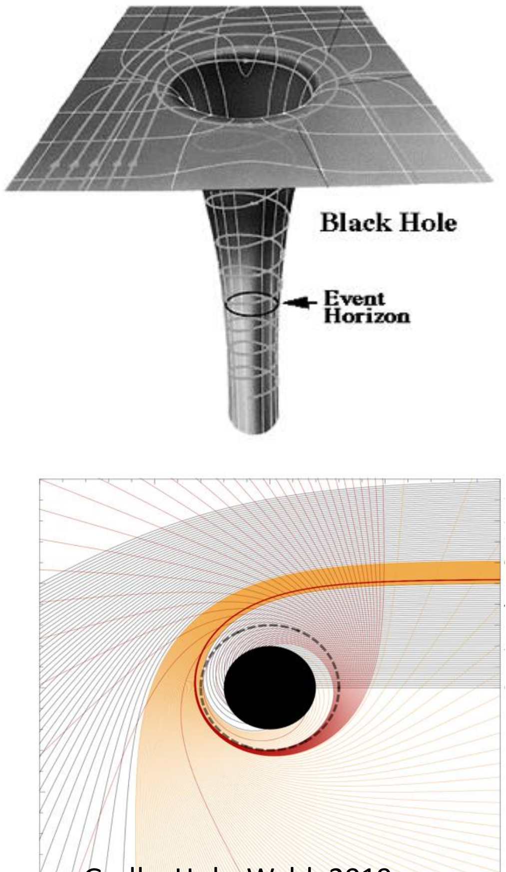
- Frontier Physics
- Neutron Star Magnetospheres
- Fast Radio Bursts
- Black Hole Magnetospheres
- Relativistic Jets
- UHE Cosmic Rays
- Relativistic Reconnection
- Magnetic Turbulence
- Electric Field
- Nonrelativistic Magnetospheres

Frontier Physics

P H Y S I C S   F R O N T I E R

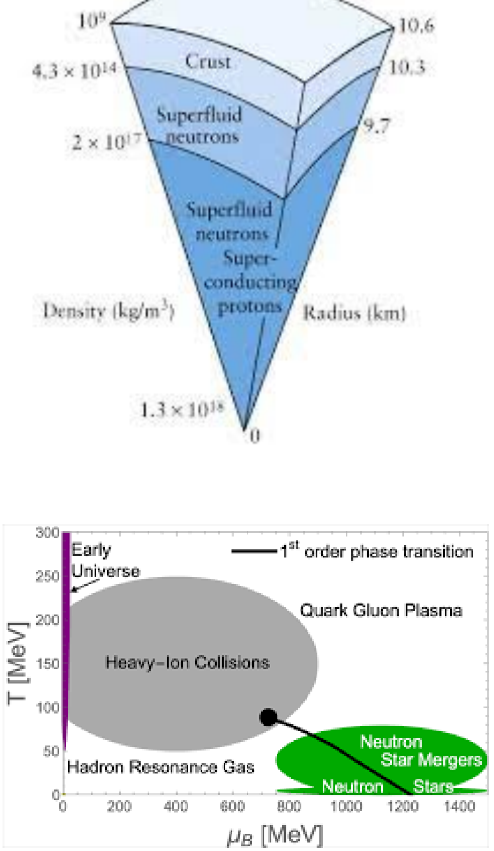


Electromagnetism

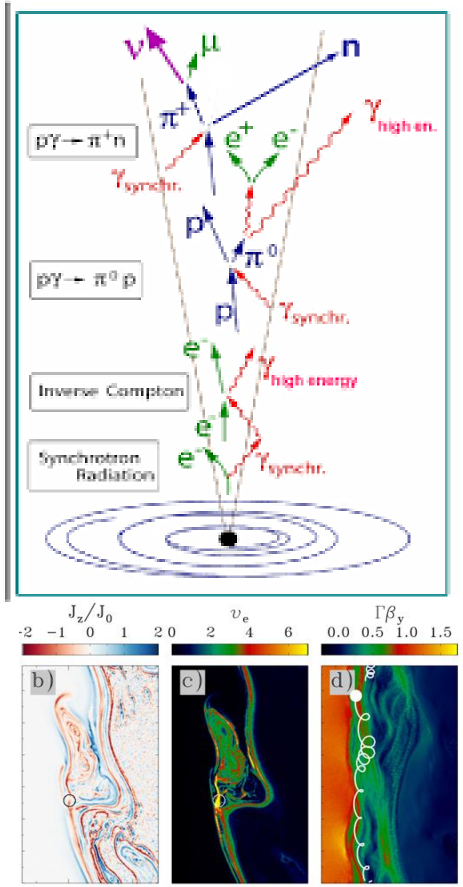


Gralla, Holz, Wald, 2019

Gravity



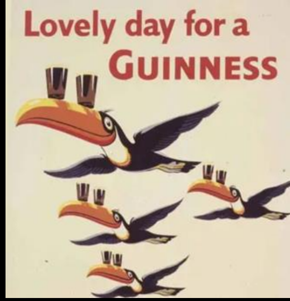
Strong Force



Sironi et. al., 2022

Weak Force

P O W E R   F R O N T I E R



Black Hole Merger

10^{49} W

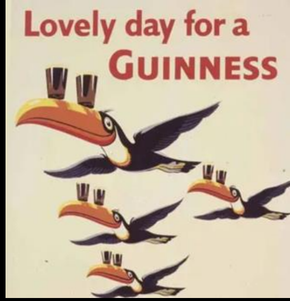
Gamma Ray Burst

10^{45} W

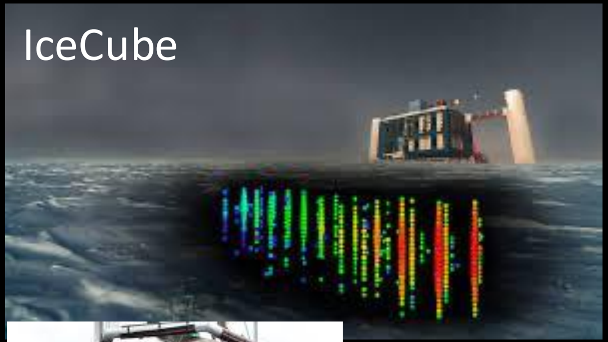
Active Galactic Nucleus

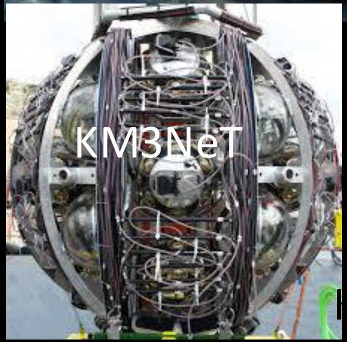
10^{39} W

E N E R G Y   F R O N T I E R



>PeV neutrinos
200 PeV neutrino?

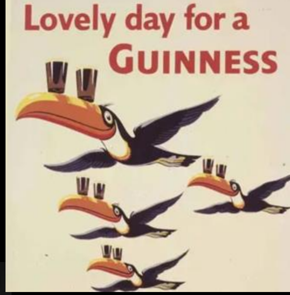




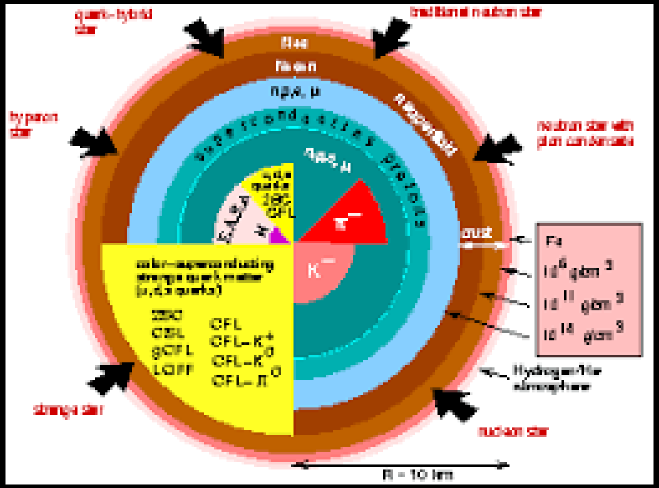
$10^{14\text{-}15}$ eV Gamma Rays

$10^{18\text{-}20.5}$ eV Cosmic Rays

Multi-messenger Observations
Time-domain Astronomy



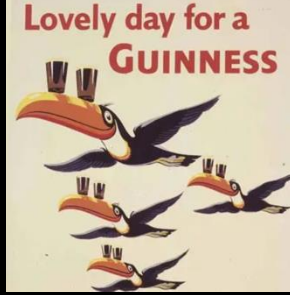
T H E R M A L F R O N T I E R

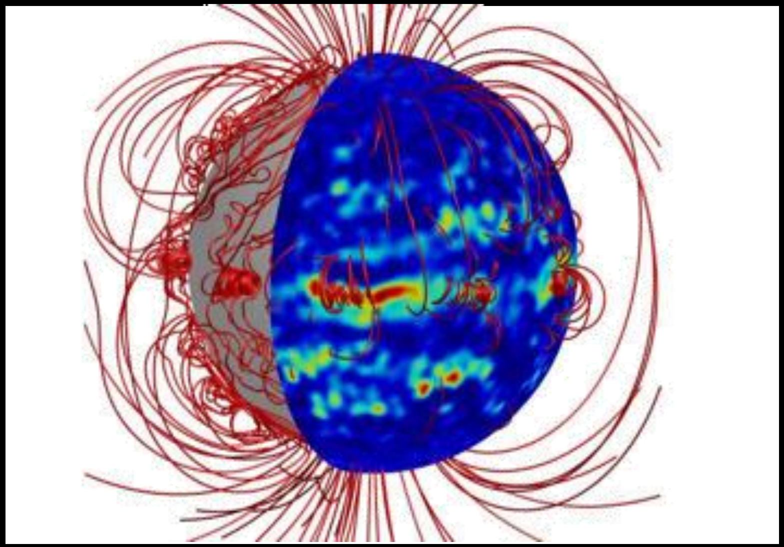


Superconducting protons
Superfluid neutrons
$T_c \sim 10^{10}$ K

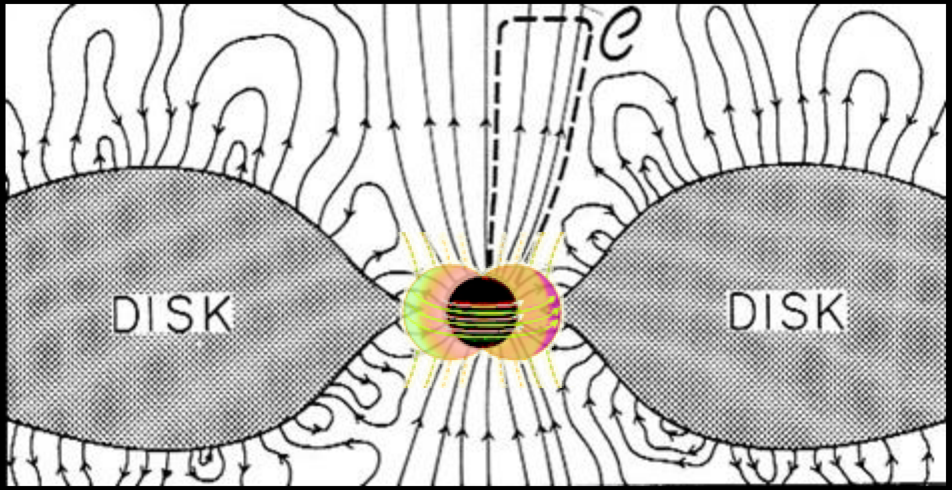
Effective Temperature T
Energy in $d^3x\, d^3k/(2\pi)^3$ is k_B T
Conserved along ray
T ~ 10^{40} K
Similar to a tsunami!

E L E C T R O M A G N E T I C   F R O N T I E R



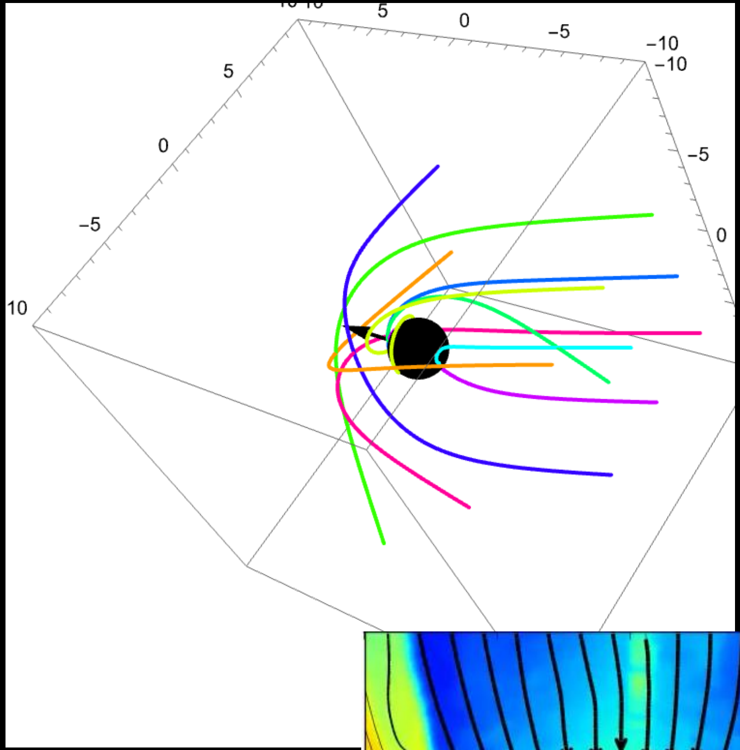


Neutron Star Magnetic Field Strength
Pulsars 10^{12} G
Magnetars 10^{15} G ~ 30 B_{QED}
Neutron Star Interiors < 10^{17} G



Spinning Black Hole EMF (ergosphere)
M87 10^{19} V
Quasar 10^{20} V
GRB, Magnetar, 10^{23} V, 10^{21} A

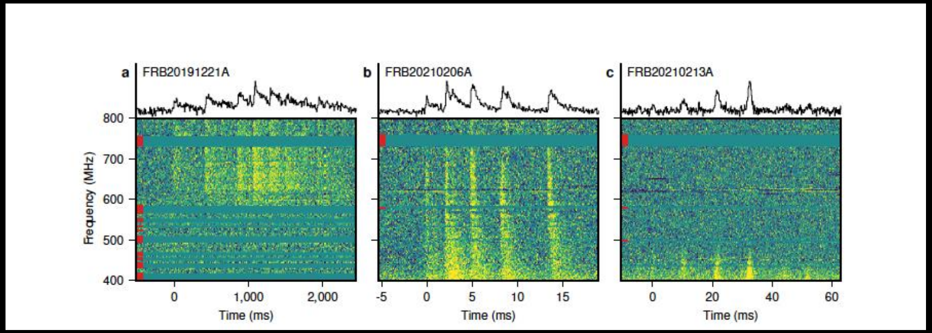
R E L A T I V I T Y   F R O N T I E R

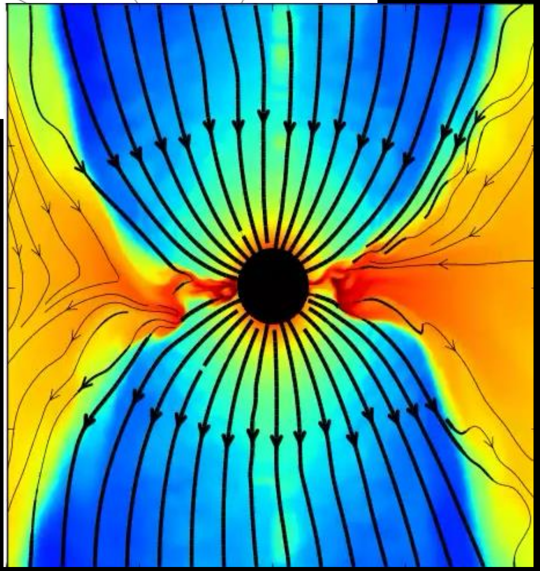


- Kerr spacetime; $m=GM/c^2=1$; $-1 < a < 1$
- Boyer-Lindquist coordinates $\{t,r,\theta,\phi\}$

$$ds^2 = -\alpha^2 dt^2 + \varpi^2 (d\phi - \omega dt)^2 + \rho^2 \left(\frac{dr^2}{\Delta} + d\theta^2\right)$$

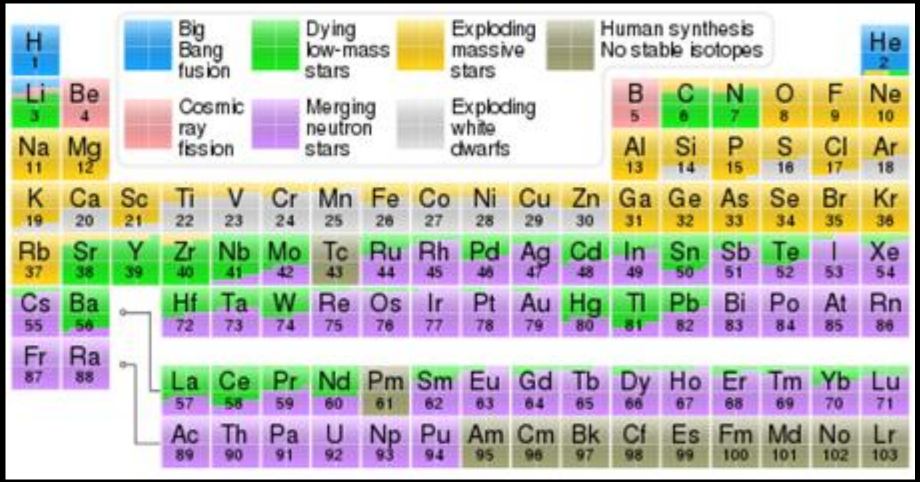
- Paths: $\frac{d\vec{x}}{d\zeta} = \vec{k}$; $\vec{k}$ null; ζ affine
- Symmetry => constants: E =1, (L, K) -> sky vector **X**
- Black hole shadow, not Firewall!
- Complements BH mergers
- Extractable spin energy
- Maxwell + Einstein -> Jets…
- Also neutron stars?
- M(R) tests TOV as well as GR
- “Nastroseismology”?



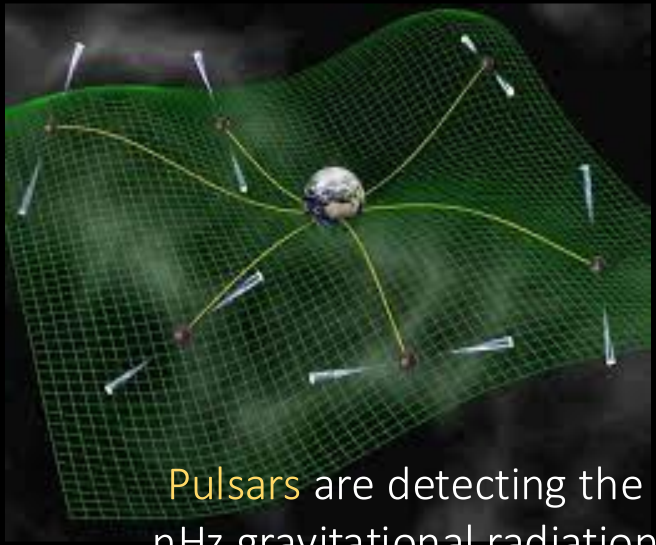


McKinney+RB2009

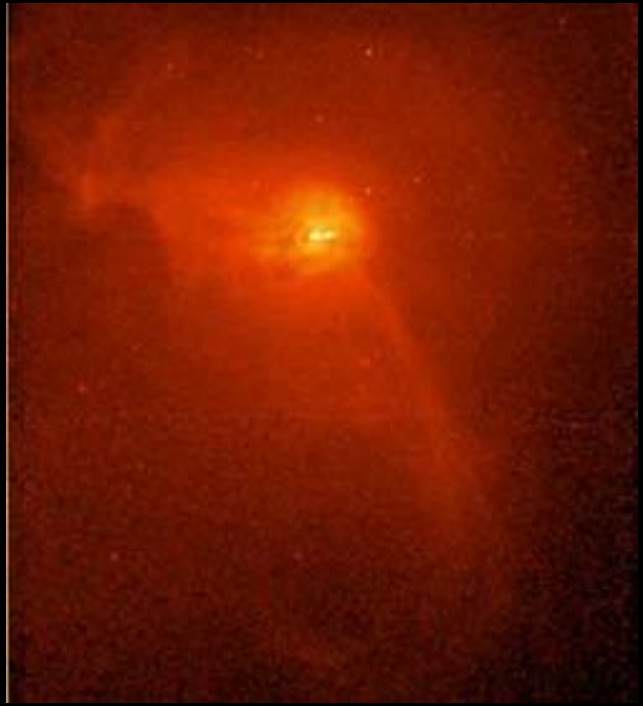
C O S M O L O G I C A L   F R O N T I E R



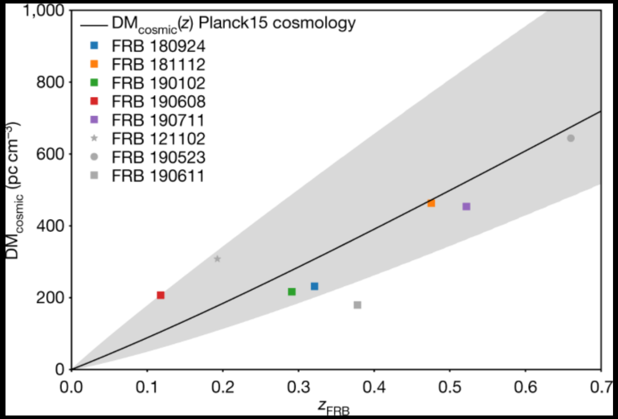
Supernovae and Kilonovae
form the elements



Pulsars are detecting the
nHz gravitational radiation
background

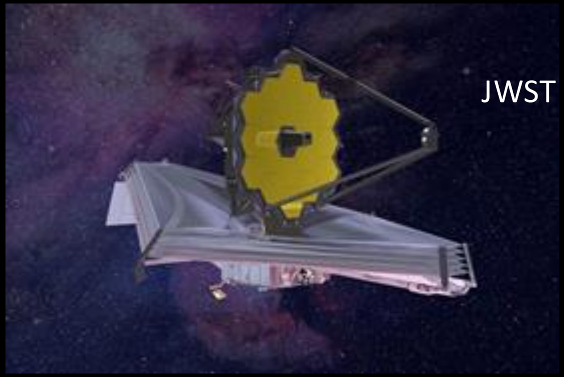


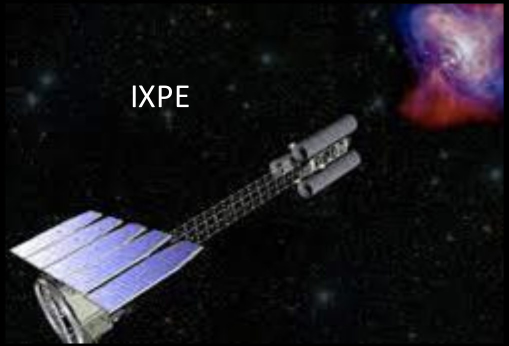
Active Galactic Nuclei (AGN)
mediate the formation
and evolution of galaxies

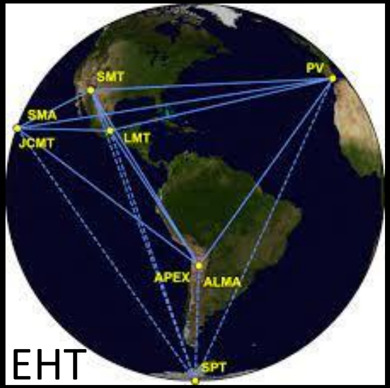


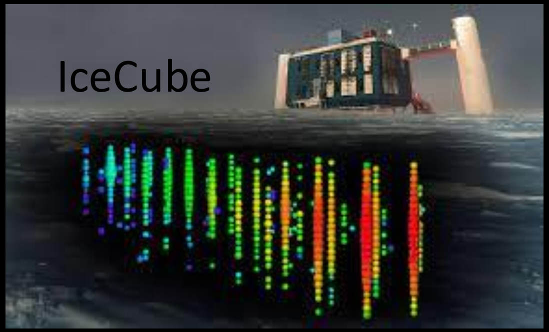
Fast Radio Bursts (FRB)
measure the baryons

O B S E R V A T I O N A L   F R O N T I E R

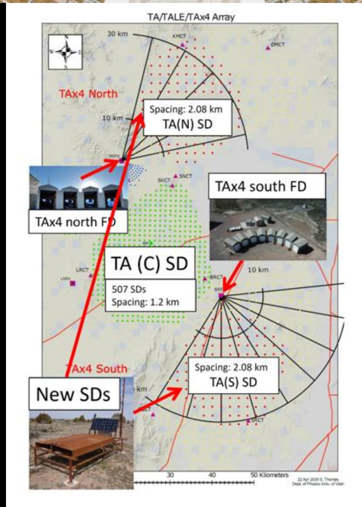






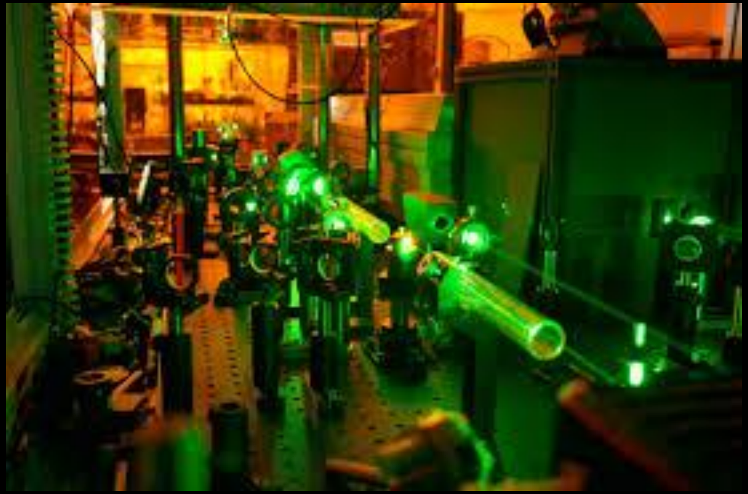


LHAASO



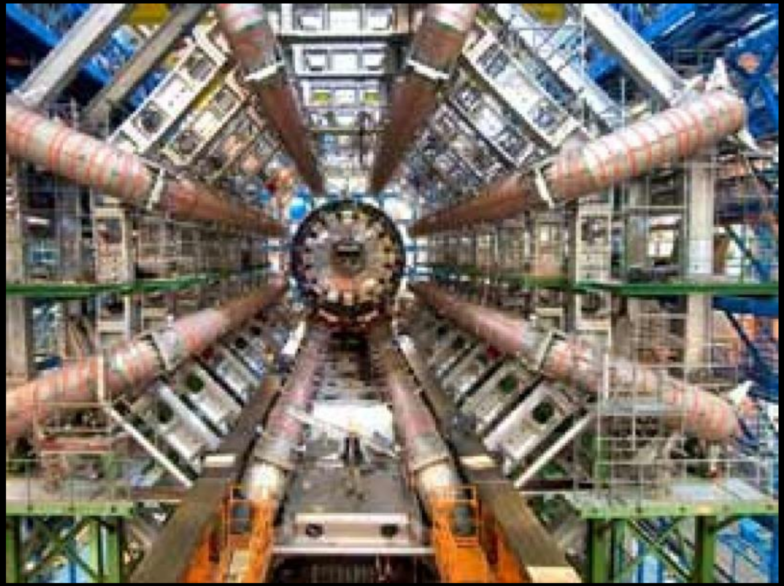
EXPERIMENTAL FRONTIER

PSI



IPFN

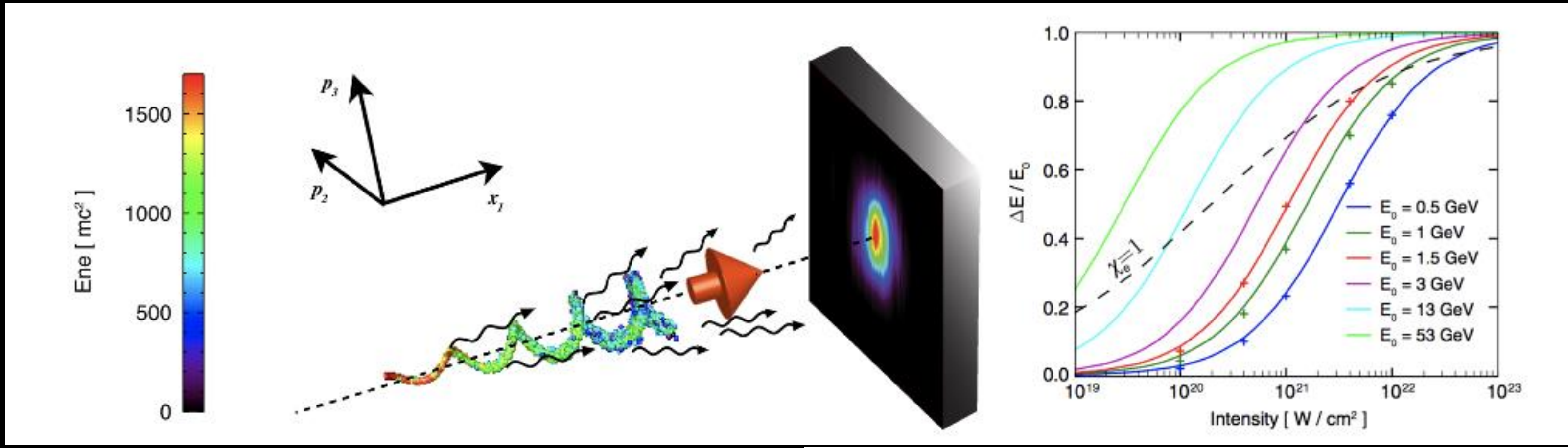
NIF

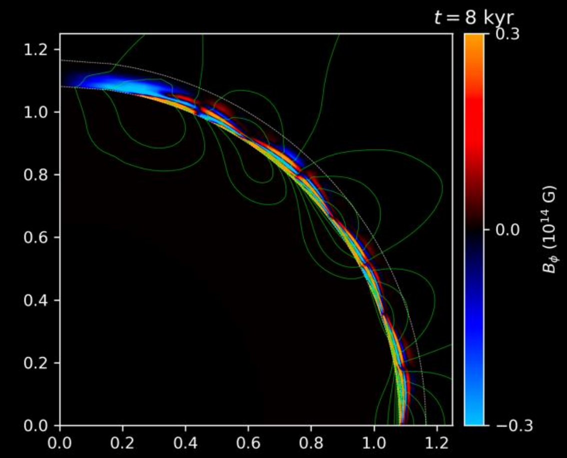


LHC

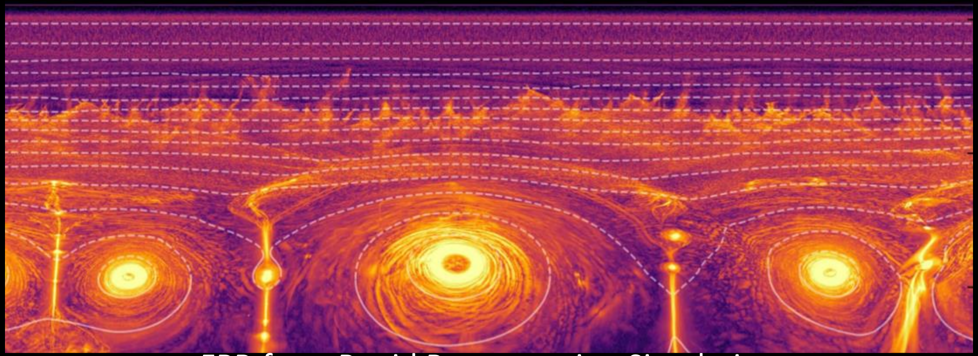
C O M P U T A T I O N A L   F R O N T I E R

Magnetohydrodynamics + +
Particle in Cell codes + +
Molecular dynamics codes + +

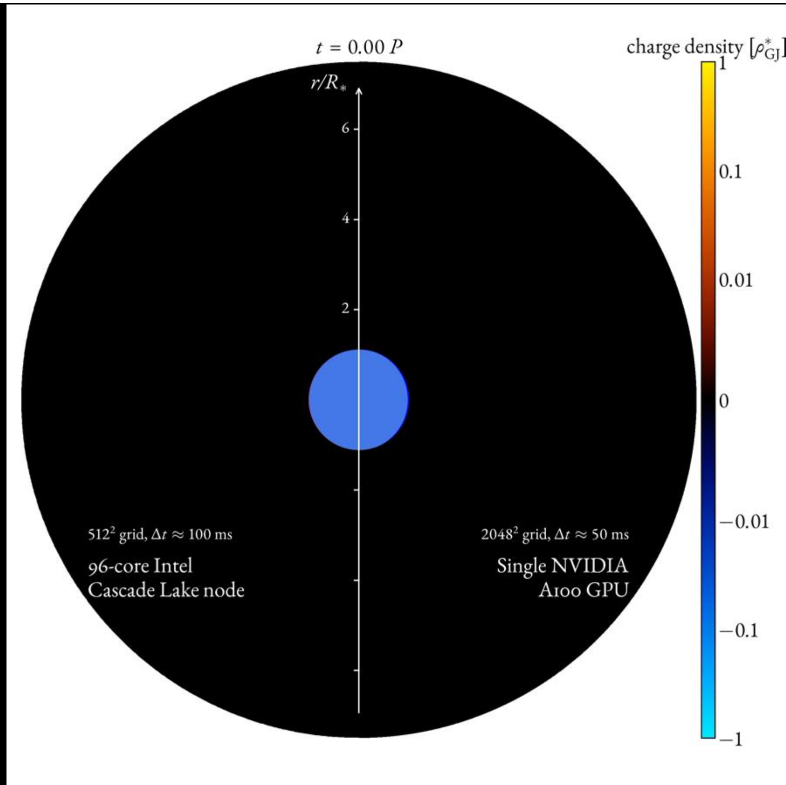




Hall Drift in Crust
Bransgrove, Belaborodov, Levi



FRB from Rapid Reconnection Simulation
(Mahlmann, Philippov, Levinson, Spitkovsky, Hakobyan; 2022)

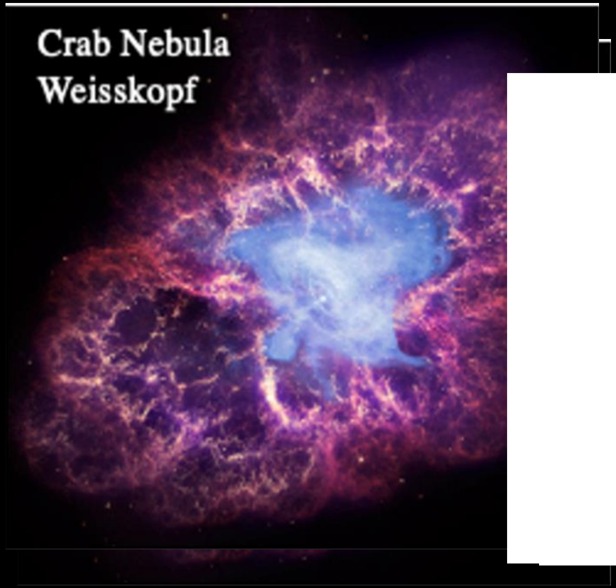


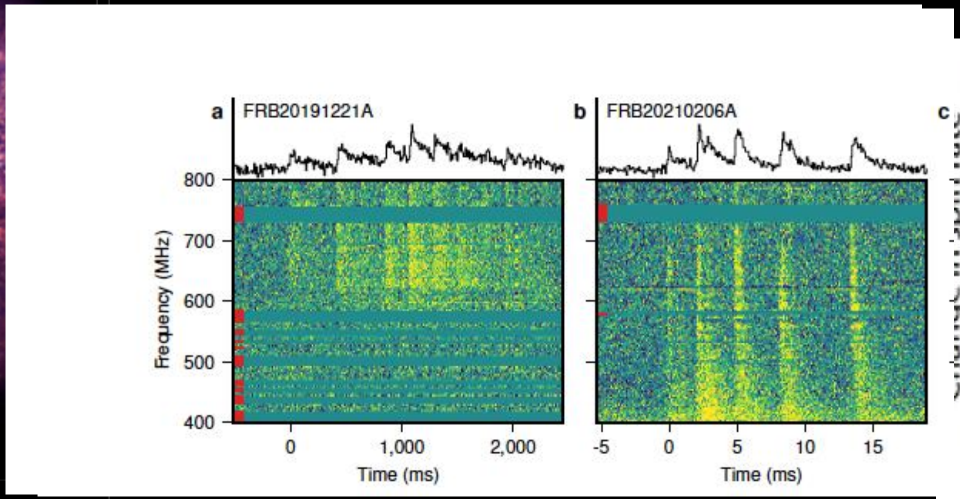
Frontier Physics

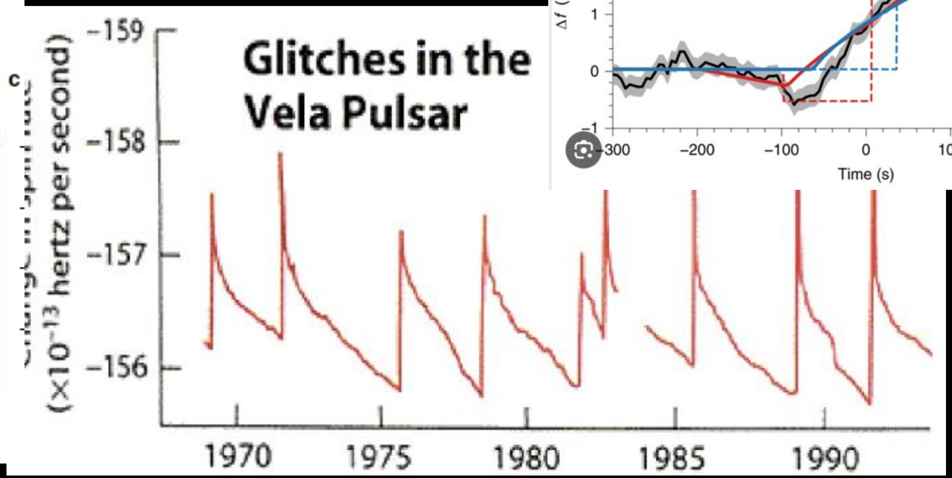
Will we learn new fundamental physics?

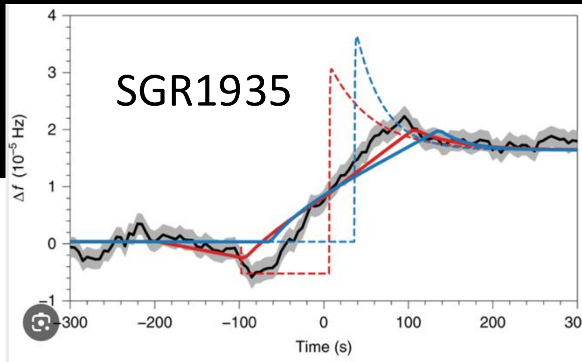
Neutron Star Magnetospheres

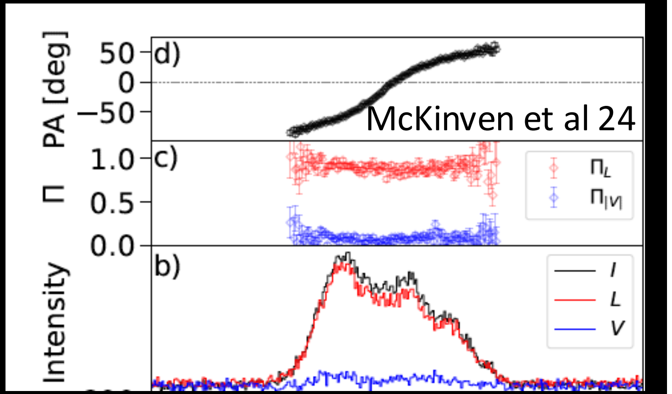
N E U T R O N S T A R S

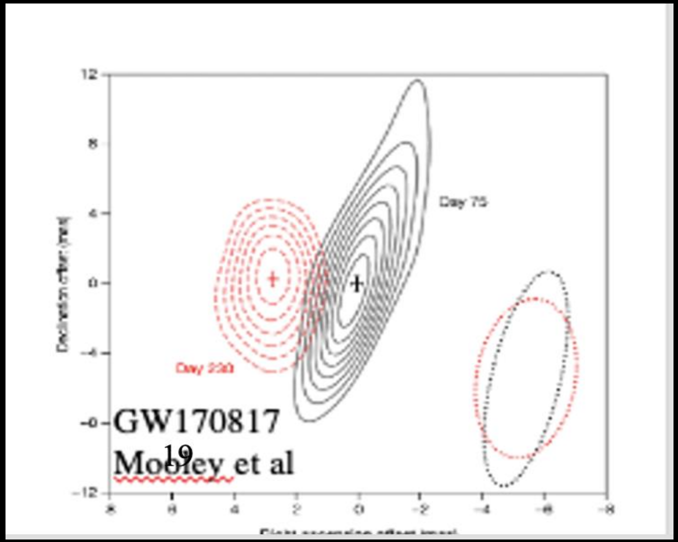


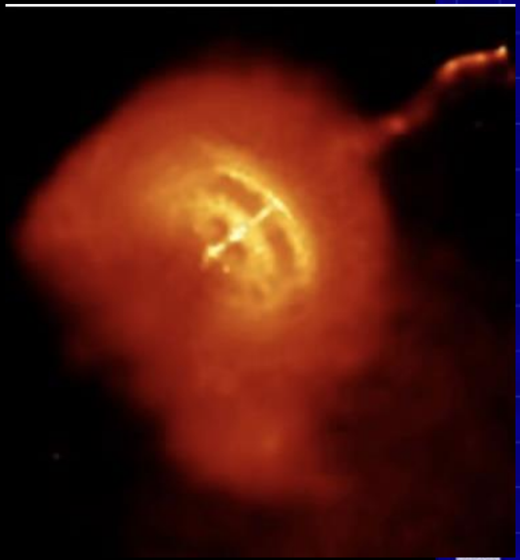


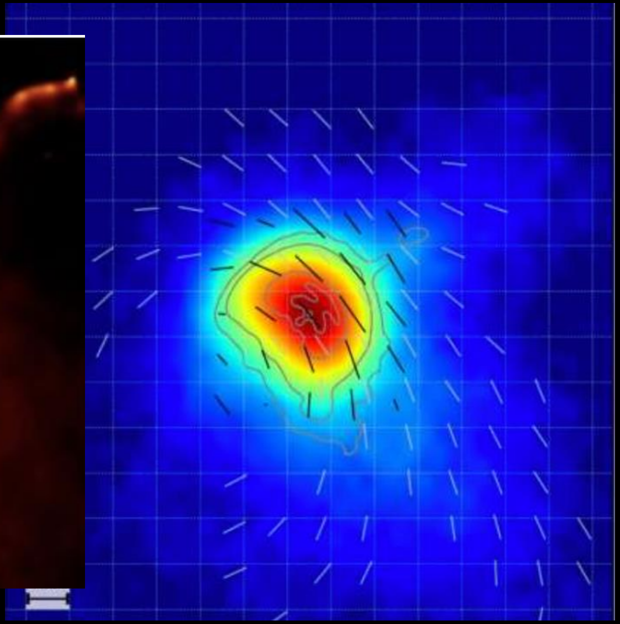








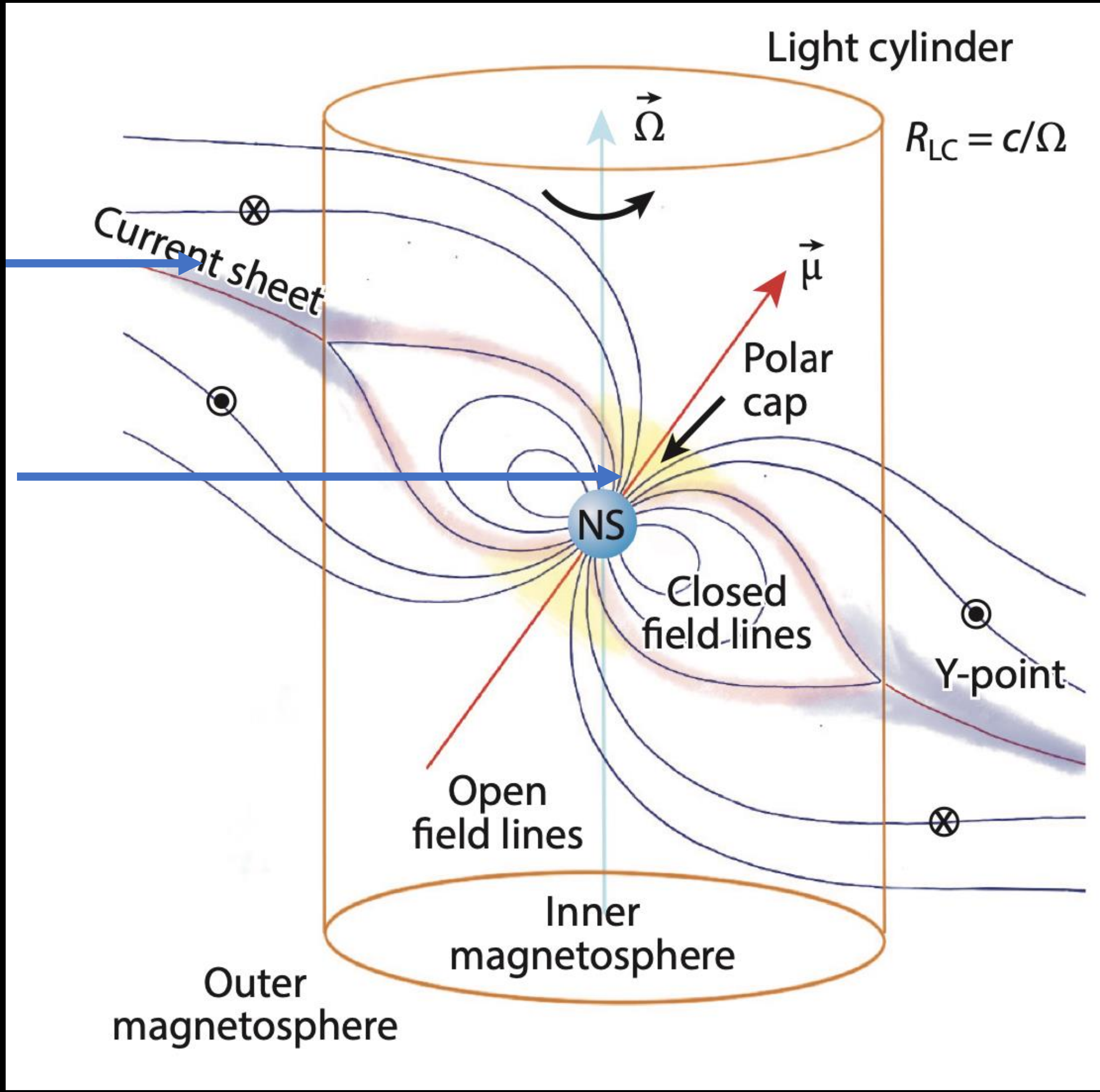




Pulsar Magnetosphere

Gamma rays

Radio



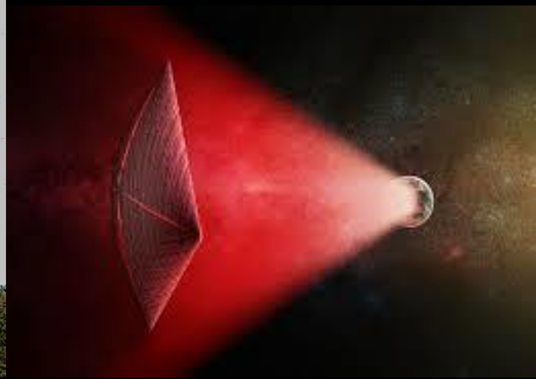
Many talks

Neutron Star Magnetospheres

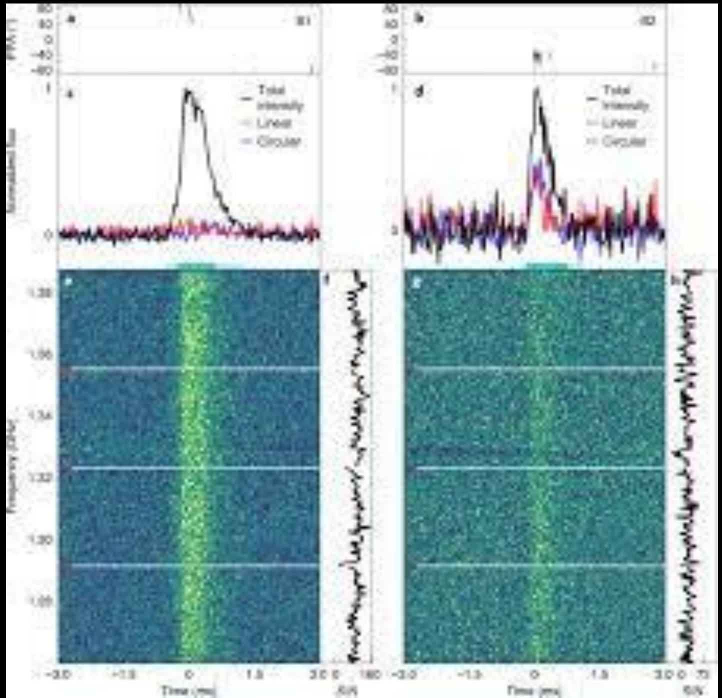
Where and how do they shine?

Fast Radio Bursts

FAST RADIO BURSTS
HISTORY REPEATING ITSELF?

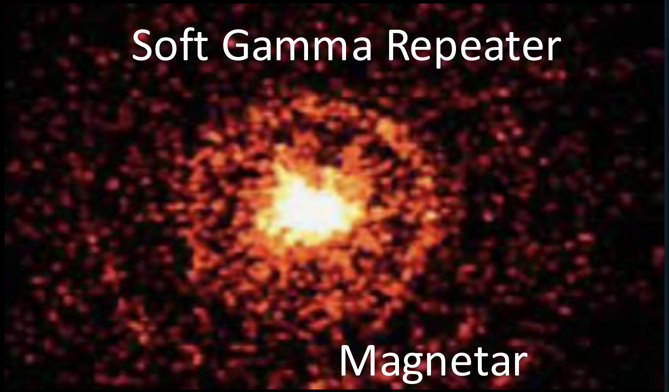


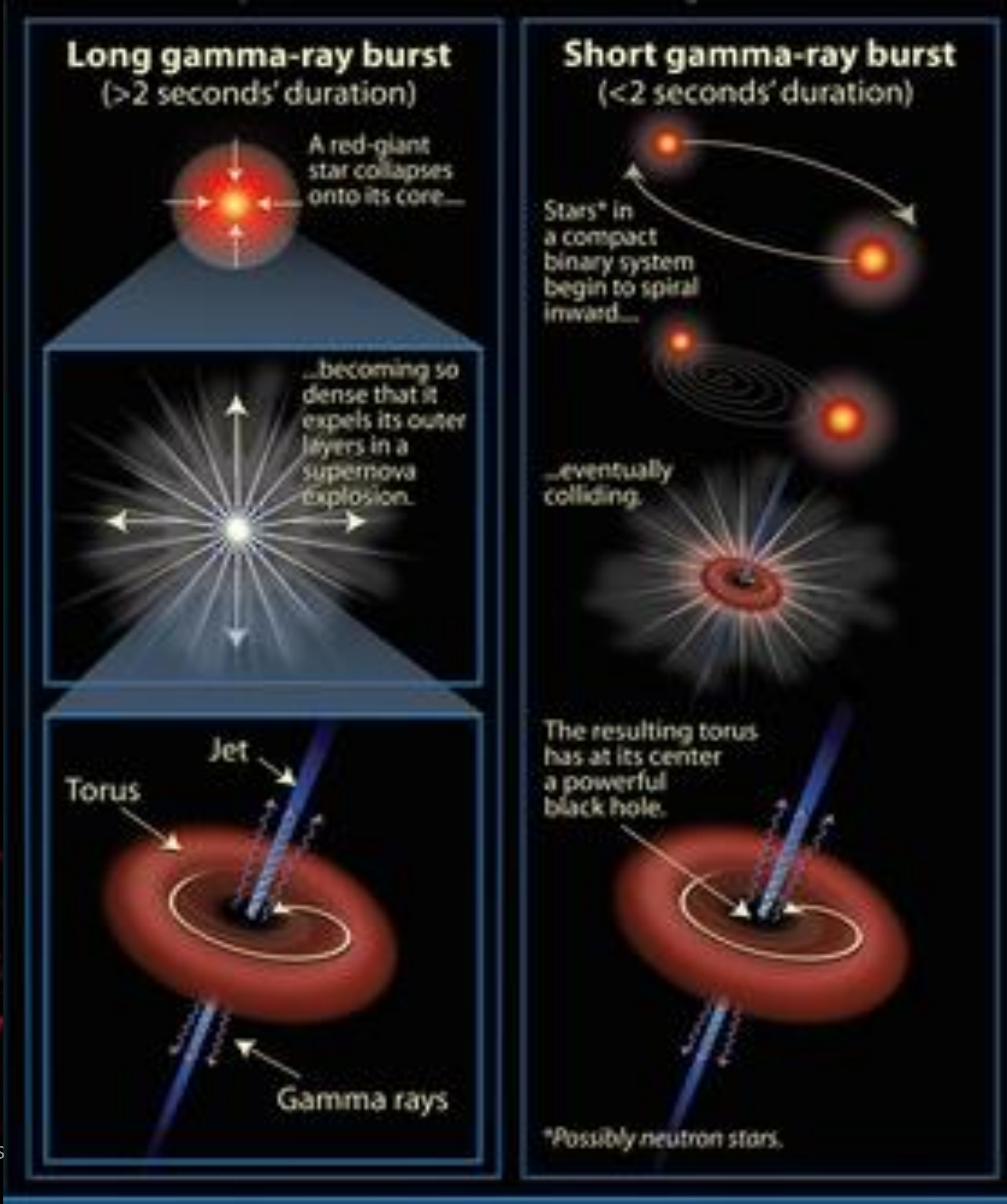
- Radio Interference, microwave ovens
- Alien light sails, strings, white holes, Primordial Black Holes, entangled molecules, large superconducting dipoles, axions quark nuggets, ball lightening, strange stars…
- Active Galaxies, Supernovae, Merging Neutron Stars, Black Holes
- Pulsars – giant pulses
- Magnetars



GAMMA RAY BURSTS
A CASE HISTORY

- >100 Published "Explanations"
  - "For theorist who may wish to enter this broad and growing field, I should point out that there are a considerable number of combinations , for example comets of antimatter falling onto white holes, not yet claimed" (Ruderman 1972)
- Soft Gamma Ray Repeaters
  - Young, magnetized neutron stars
  - Magnetars
- Long (>~ 2 sec.) Gamma Ray Bursts
  - Massive star supernova explosions
  - Black hole formation
- Short (<~ 2 sec.) Gamma Ray Bursts
  - Neutron star mergers
  - Black hole formation





E A R T H ,   A I R ,   F I R E   A N D   W A T E R

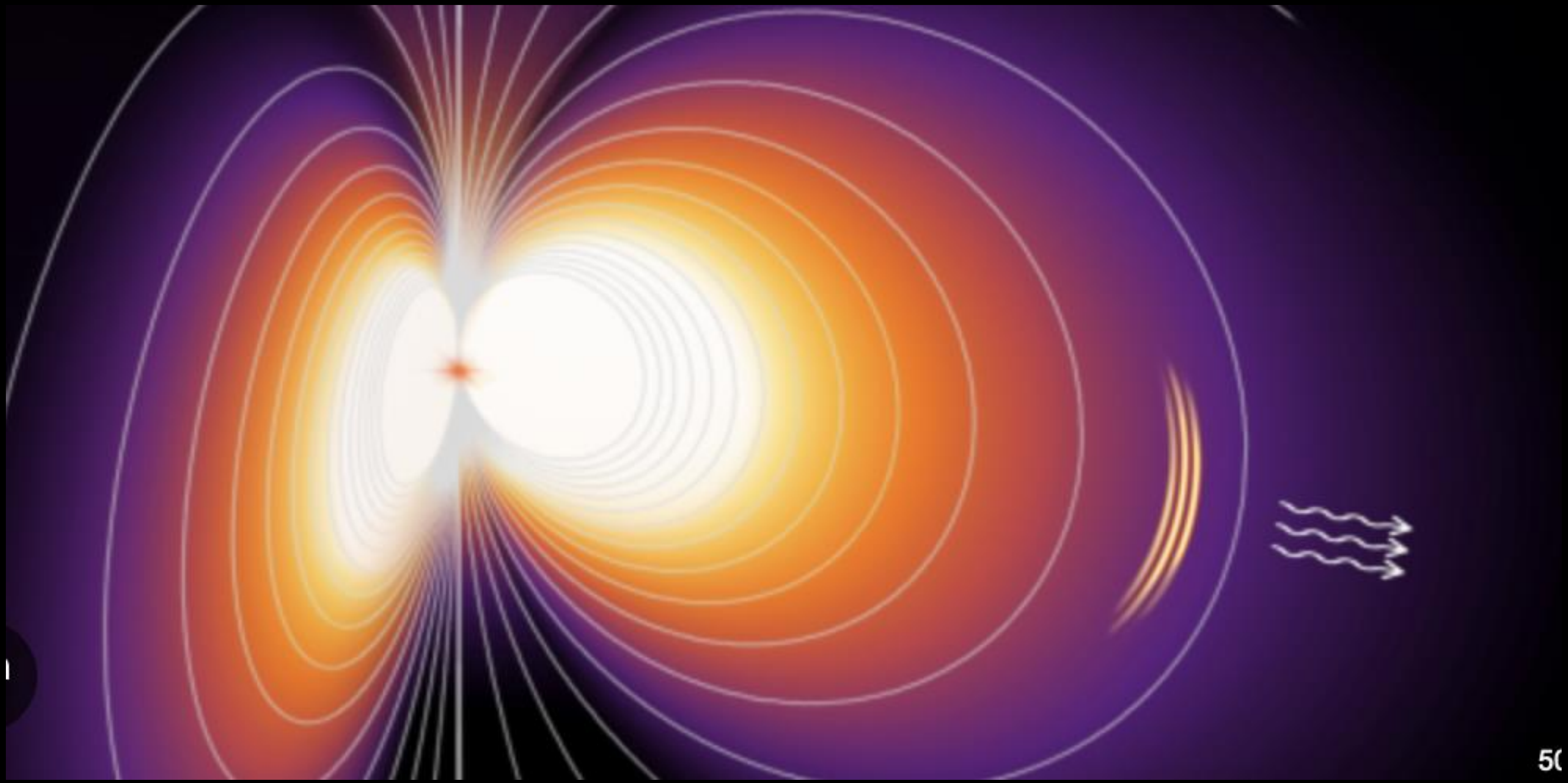
Starquakes?

Magnetic Waves?

Lightening?

Electromagnetic Tsunamis?

Monster Shocks



Radio absorption by cyclotron, ICS, SRS, SBS?

Fast Radio Bursts

How many types?
Where do they originate?

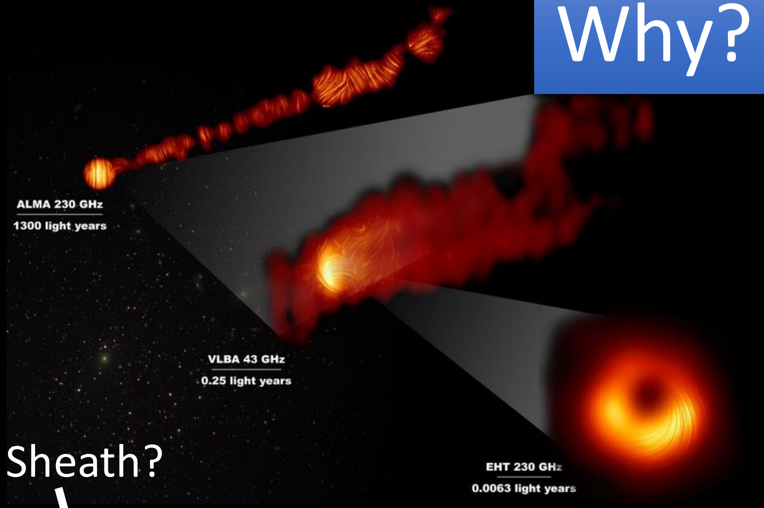
Black Hole Magnetospheres

M 8 7

- Mass
  - $M \sim 6.5 \times 10^9\ M_{sun}$
    - Unit of length, Gm/c^2, time, Gm/c^3
    - $\sim 10^{10}$ km, ~ 8 hr
    - $P_{orb} \sim$ I month at $r \sim 6$
- Spin
  - Treat as 3-vector **a**
    - Fiducial model $|\mathbf{a}| = 0.9$, $\theta_0 = 163^o$ (Walker)
  - Rotational energy $\sim 2 \times 10^{56}$ J
    - Good for 10^{12} y
- $L_{jets} \sim 6 \times 10^{36}$ W
  - $\sim 600\ L_{ring} > 100\ L_{disk} \sim 10^{-4}\ L_{edd}$
- Mass supply rate $\sim 10^{22}$ kg s^{-1}? >> mass accretion rate

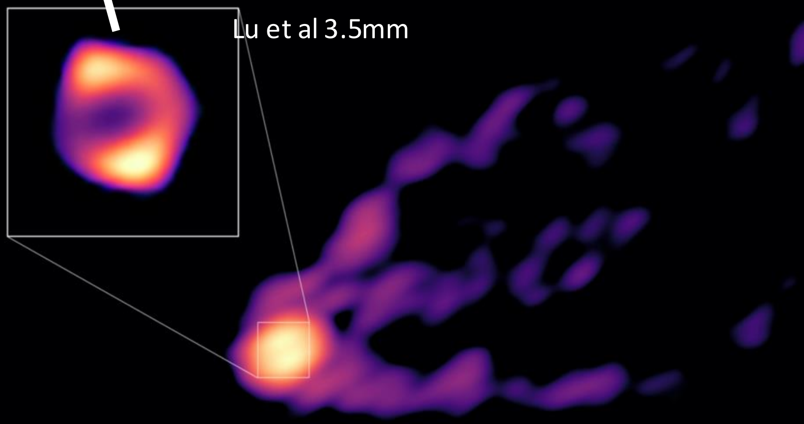
Why?

Why?



Why?

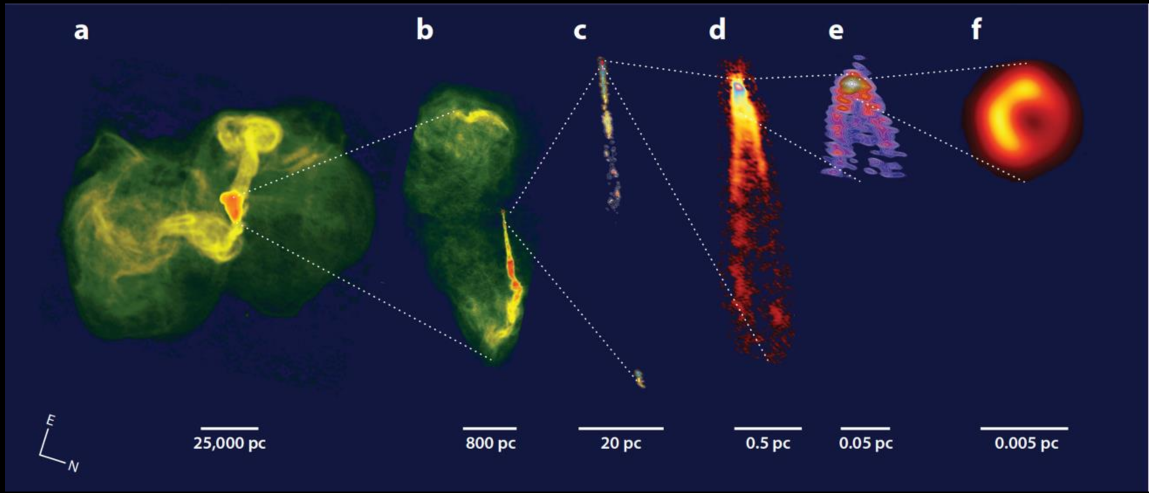
Sheath?

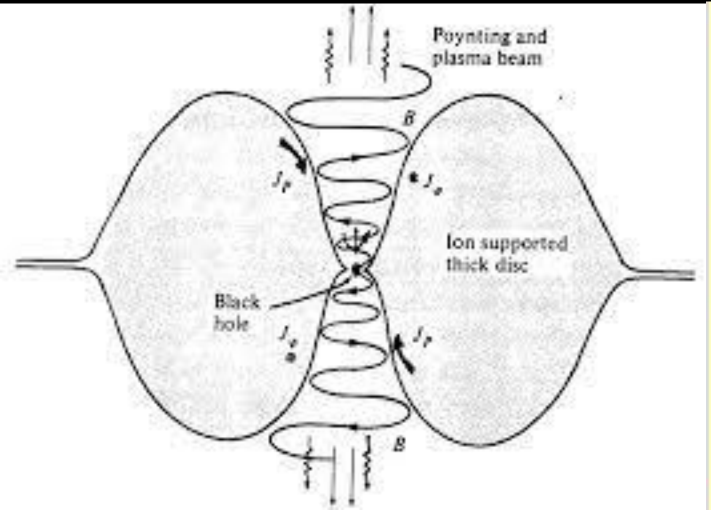


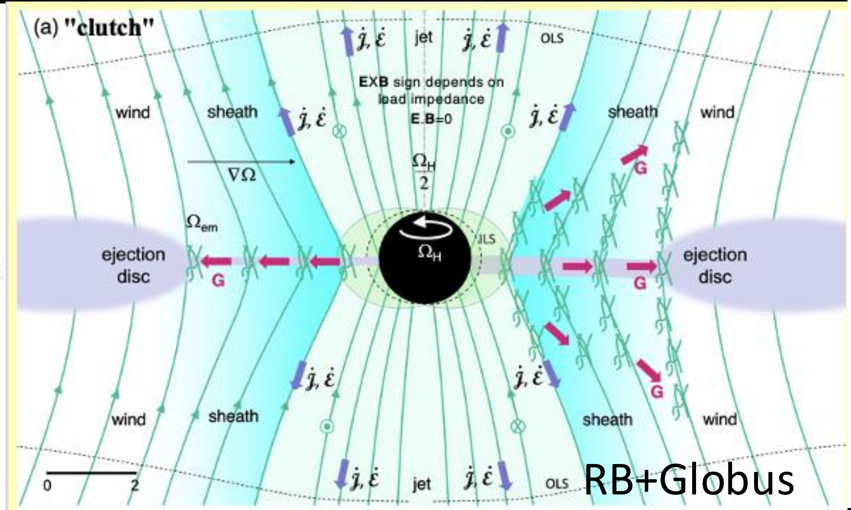
Ergomagnetospheres – Nature and Nurture

- $L_{jet} \sim 100\ L_{disk}$; mass accretion << mass supply; Collimate to $>10^4$m
- Ejection Disk: spin not gravity power
- Infall collimates MHD wind
- MHD wind collimates jets
- Current sheet/boundary layer
- Magnetic clutch/capstan; EM governor
- r_L /m , $j/|n|ec \sim 10^{-11}$

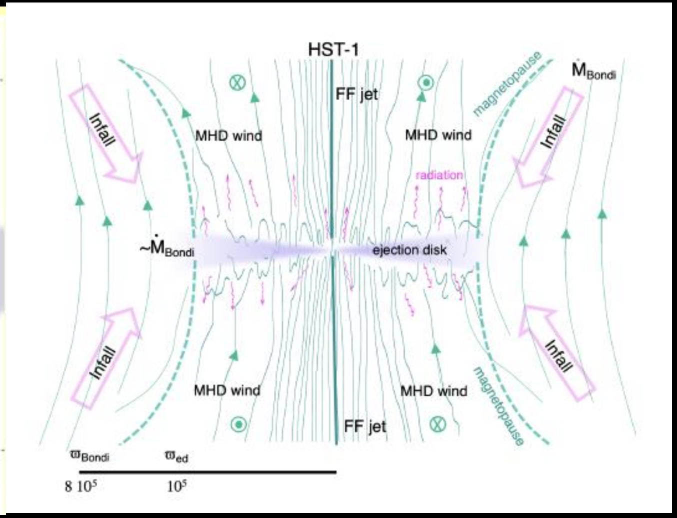
M87/EHT



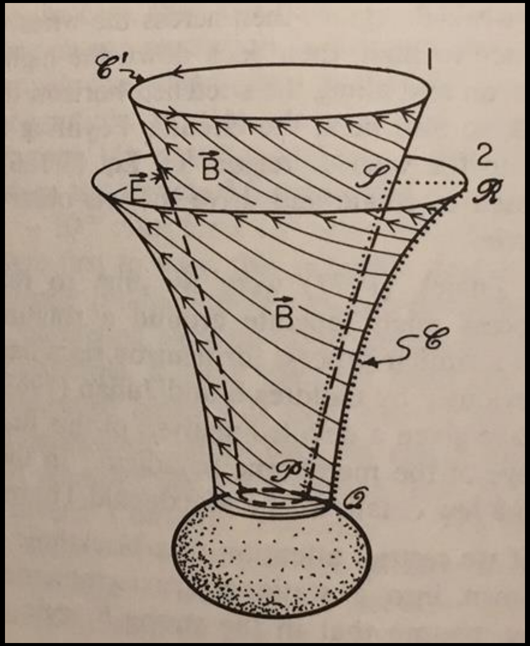




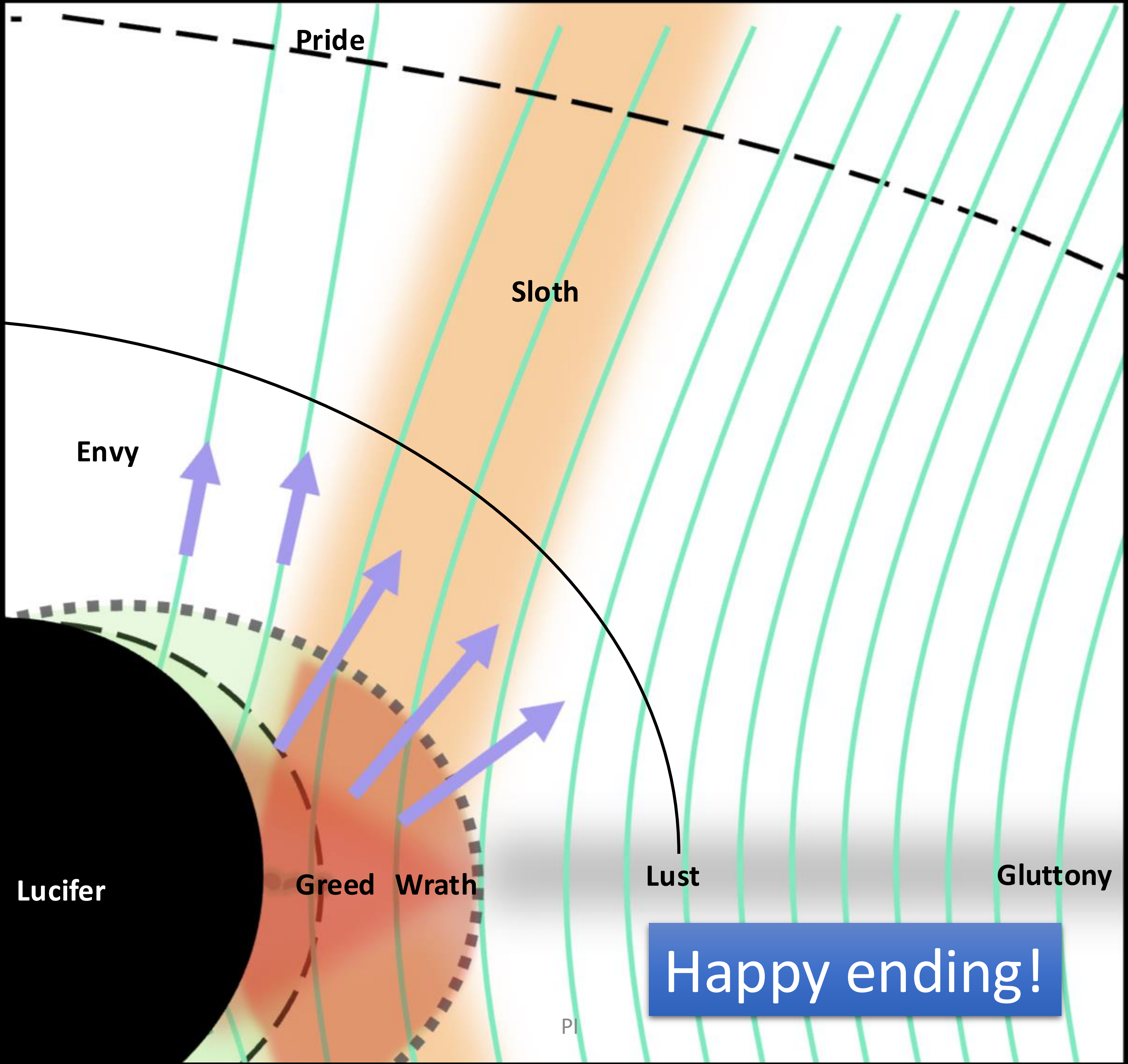
RB+Globus



- Kerr spacetime
  - B frame: symmetry -> conservation laws
  - Z frame: frame dragging; ergosphere
  - M frame: E=0 locally; define emission
  - Inner and Outer Light Surfaces
- Force-free => ρ E + j x B=0
  - Equipotential, Flux Surfaces: $V(\Phi)$
  - Angular velocity: $\Omega(\Phi) = 2\pi dV/d\Phi$
  - Current: $I(\Phi) \Rightarrow B_\phi$
  - Angular momentum: $d\mathcal{J}'_B(\Phi) = I\, d\Phi / 2\pi$ along flux surfaces
  - Energy: $d\mathcal{E}'_B = I\, dV = \Omega\, d\mathcal{J}'_B$; $d\mathcal{E}'_Z = (\Omega - \Omega_H) d\mathcal{J}'_B < 0$; $d\mathcal{E}'_M = 0$
  - Use variational principle with functional: $B_p^2 - E_p^2 - B_\phi^2$ in Z frame



Extract rotational energy as invisible Poynting flux
Dissipation happens "behind the curtain" and remotely in jet



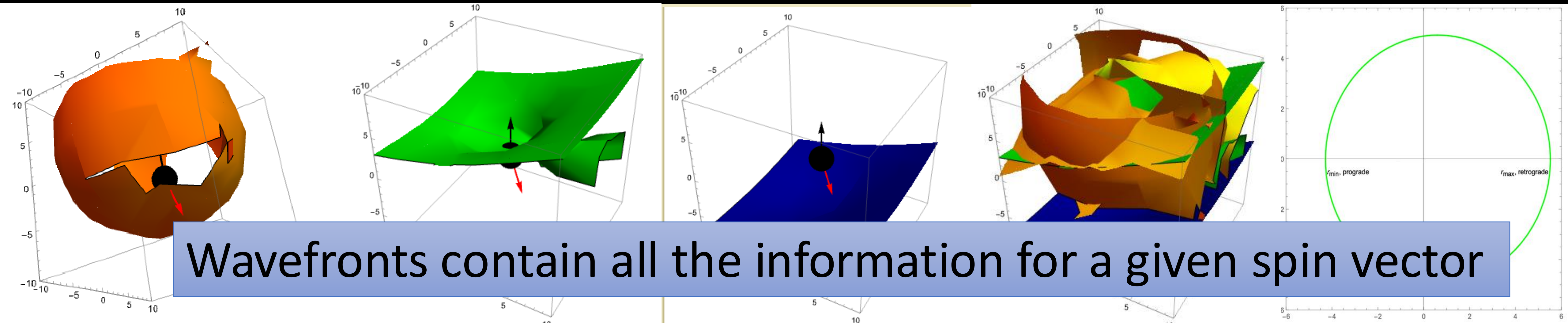
Pride
Sloth
Envy
Lucifer
Greed
Wrath
Lust
Gluttony
Happy ending!

Hole-Energised, Magnetically-Mediated, Ejection Disk

- EHT observations are magnificent accomplishment
  - MAD model has thick torus supported by hot ions
    - Weak field; quasi-steady emission
  - HEMMED model has ergomagnetosphere/ejection disk/magnetopause
    - Strong field, strong variability
    - SNAP: reconnection, magnetoluminescence: flares and sparks
    - CRACKLE : Varibility: arrow of time, whistlers, echoes, polarization
    - POP: caustic crossings: rapid spikes; visibilities
    - Seeking in public data

RELATIVISITIC WAVE OPTICS

- Ray $\frac{d\vec{x}}{d\zeta} = \vec{k} = \vec{\nabla}\psi$
- Escaping, ambivalent and curious photons; photon sphere: r ~ 3 => |**X-ΔX**| ~ 5
- Hessian (inverse magnification): H(ζ; **X**) = $\left[\frac{\partial x_\perp}{\partial X}\right]$; gravitational rotation of E-vector
- **Compute wavefronts that converge on $\mathcal{O}$ using ψ = t(x), once!**
- Source Doppler shift: $\mathcal{D}$ = -$(\vec{u} \cdot \vec{k})^{-1}$; Intensity ~ $\mathcal{D}^3$



Wavefronts contain all the information for a given spin vector

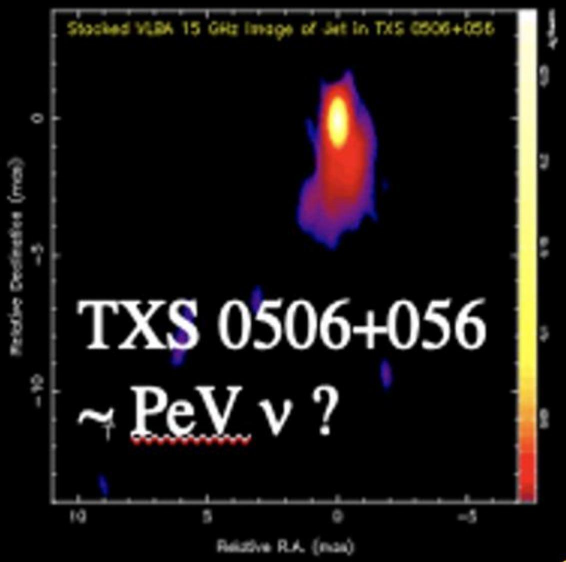
Black Hole Magnetospheres

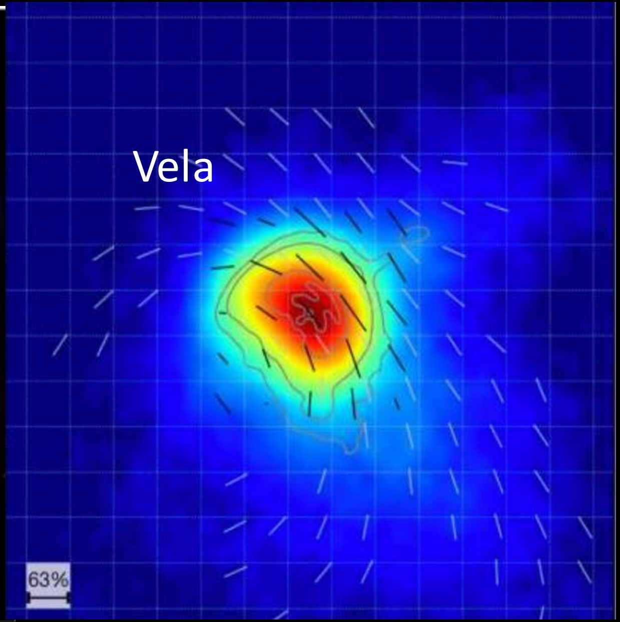
How are they powered?

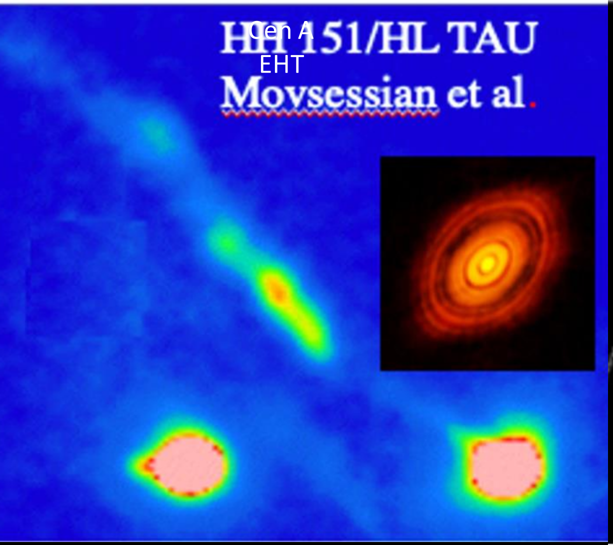
Relativistic Jets

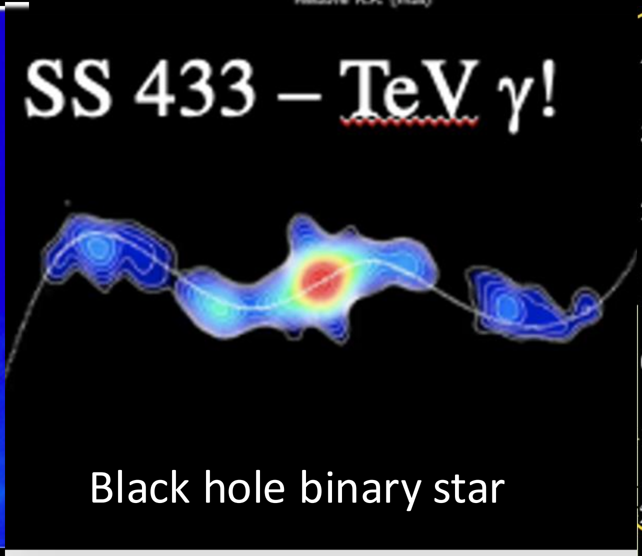
Jets are Everywhere

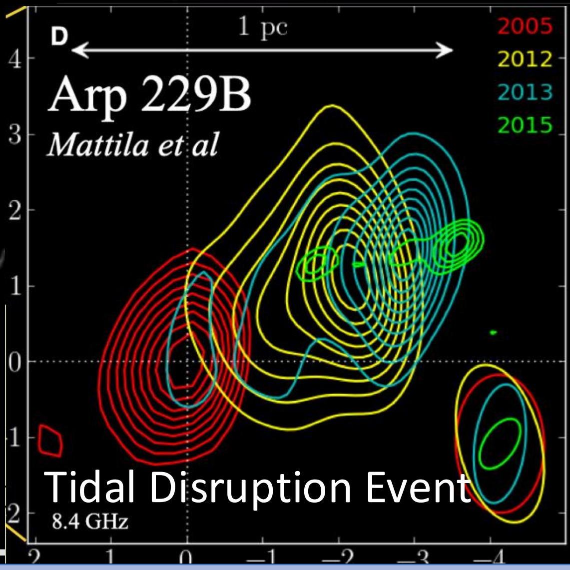
Cen A

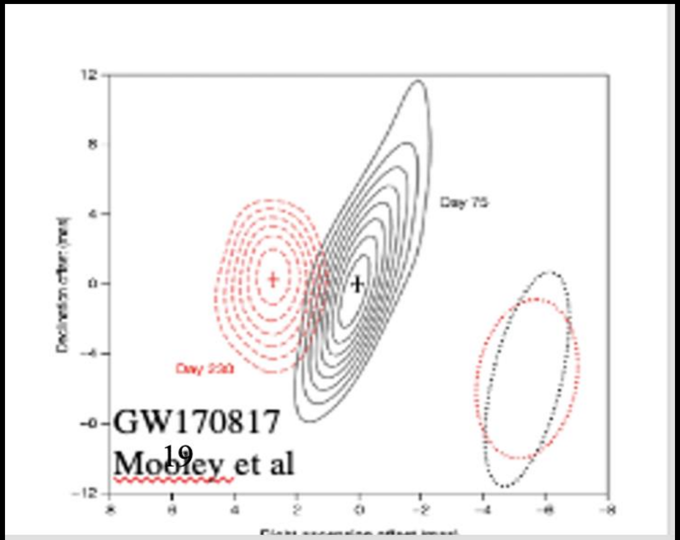






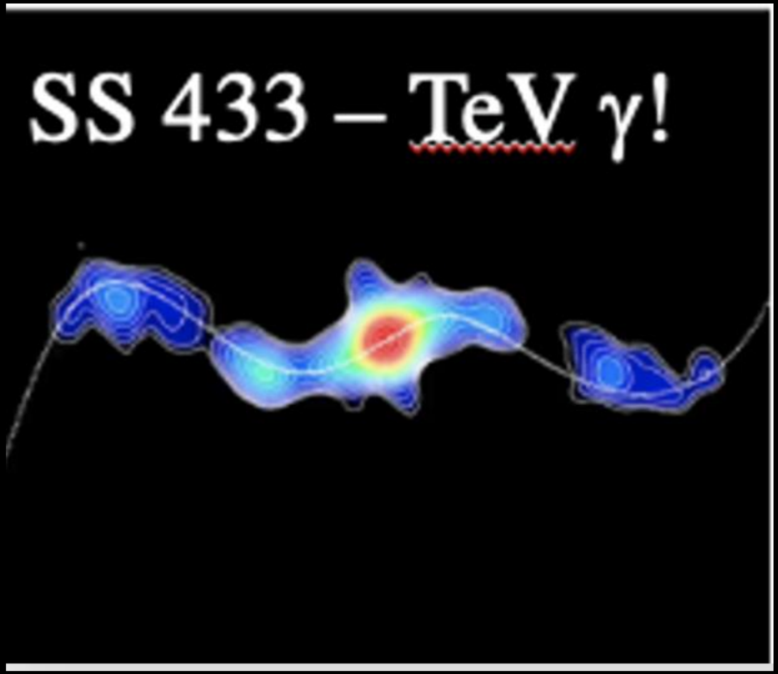




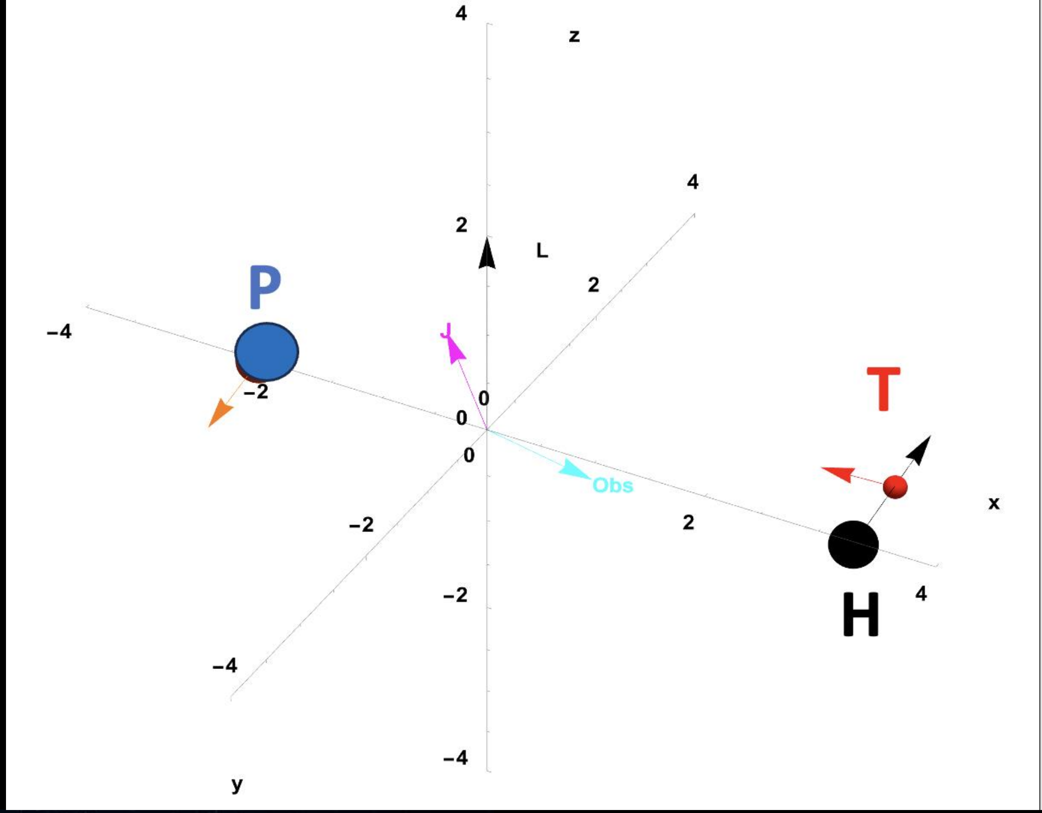


Extreme Electrodynamics?

SS 433

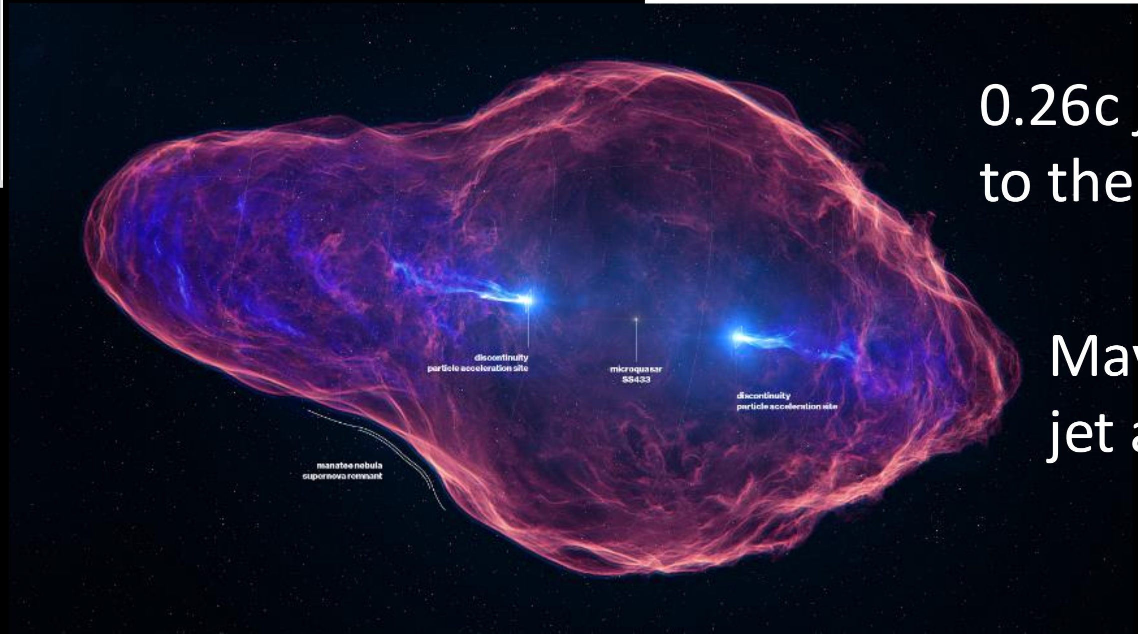


Three body model explains precession and other periodicities



Ejection of “bolides”

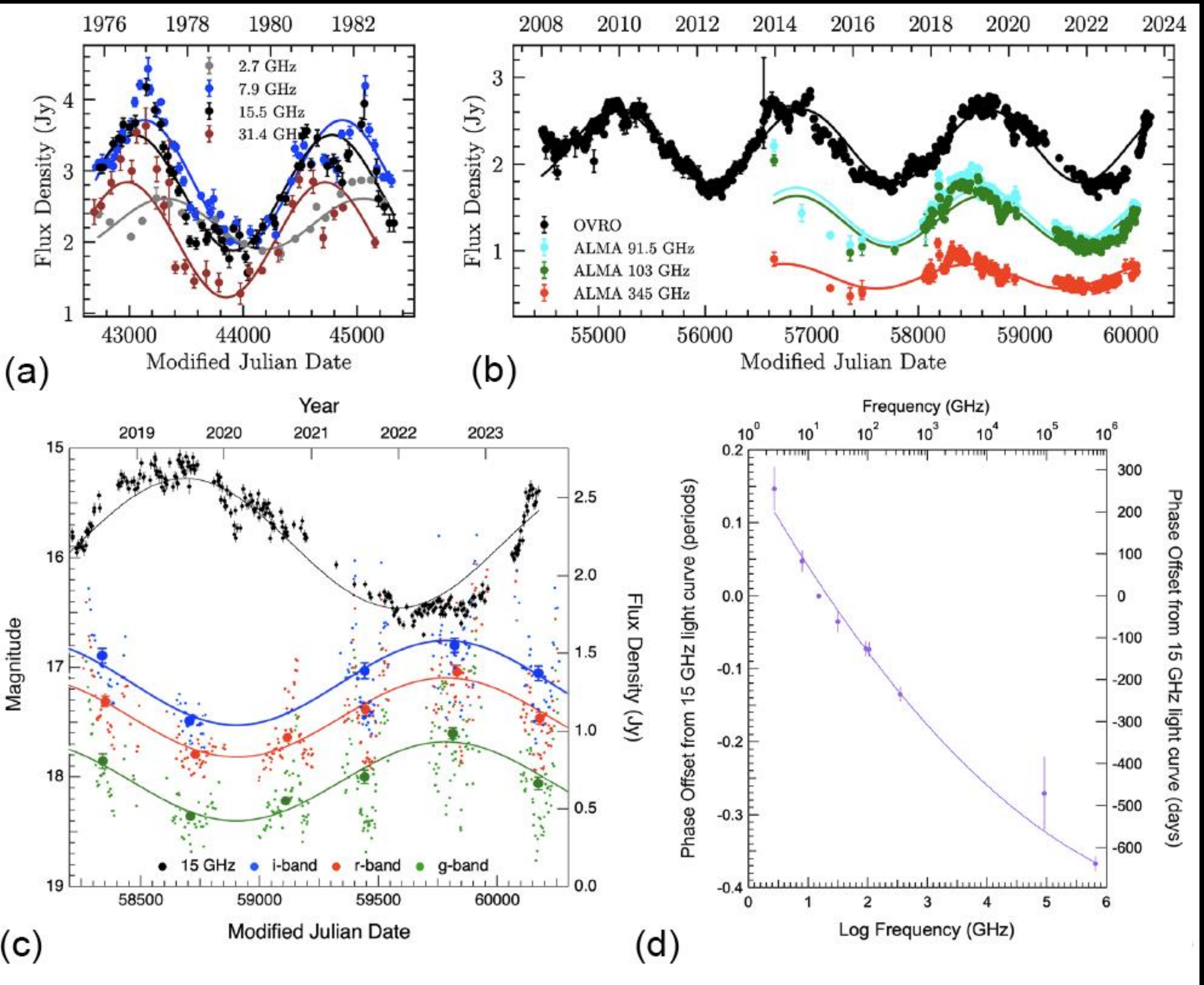
K. Blundell



0.26c jet perpendicular to the H-T orbital plane

May be ultrarelativistic jet as well

Binary Black Holes



Best candidate massive black hole binary
Relativistic blazar with 2.1y rest frame period
Predictive and retrodictive over 9 cycles

Modulation due to aberration observed from orbiting jet.
Requires jet with speed close to orbital speed.
Jet direction might also be perpendicular to the orbital plane.
Momentum dominated by MHD wind
Energy dominated by EM jet?

w Readhead, Sullivan...

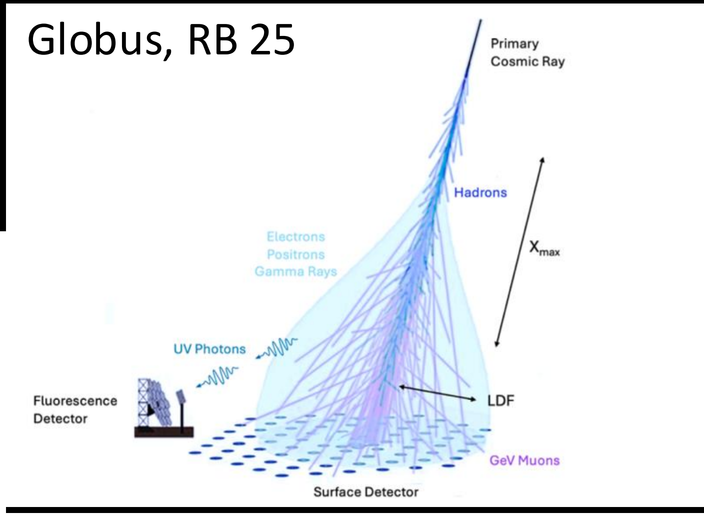
Relativistic Jets

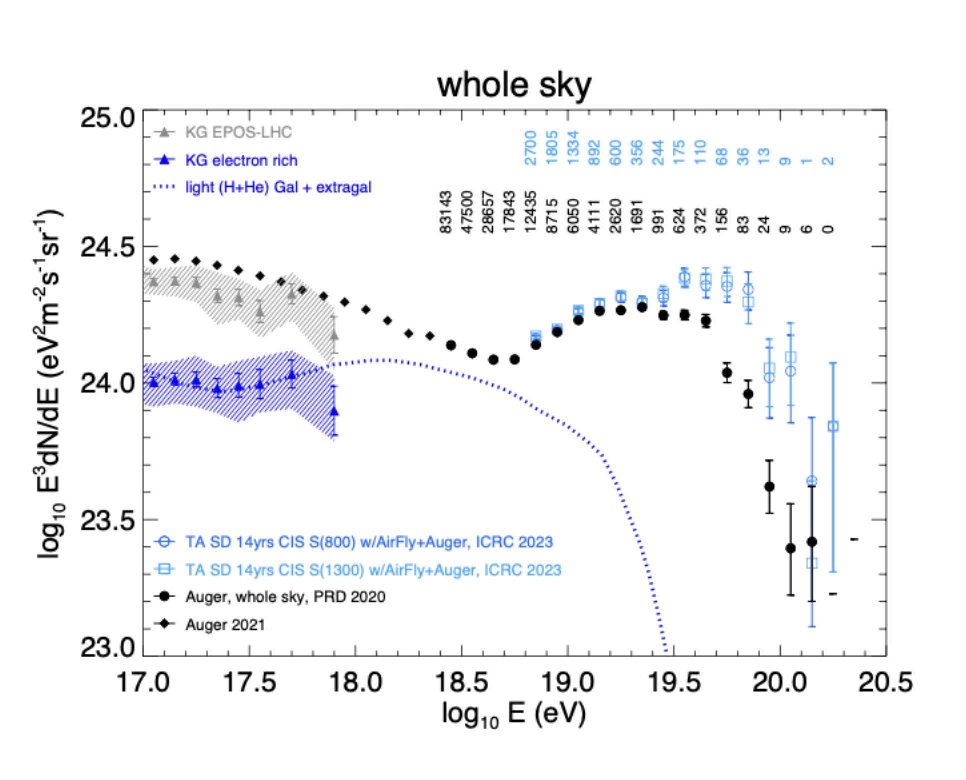
How are they directed?

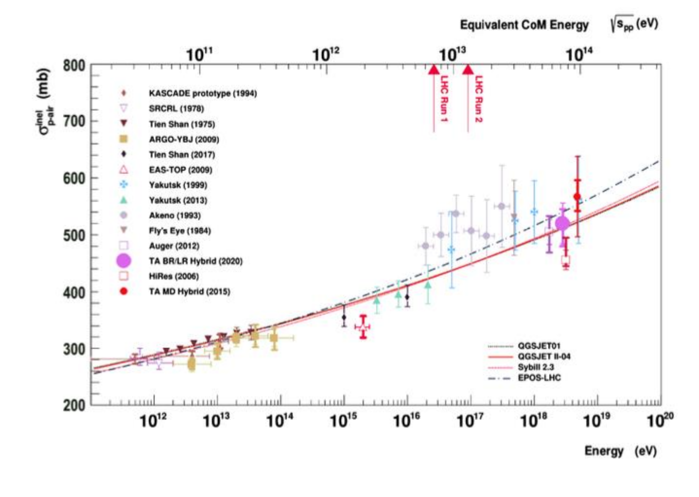
UHE Cosmic Rays

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 magnetospheres
- Individual **n**, R, Z ->sources







Models	Rigidity	Luminosity	Spectral	Injection	Composition	Anisotropy	Background
Top-down	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Clusters	4.3.2	4.3.2	4.3.2, 4.3.3	4.3.2, 4.3.5	4.3.2	2.3	4.3.2
Winds	4.2	4.2	4.0	4.2	4.2	4.2	4.2
Magnetars	4.4.2	4.2	4.0	4.2	4.2	2.3	4.4.2
GRB jets	4.4.3	4.2	4.4.3	4.4.3	4.2	4.2	4.4.3
AGN jets	4.4.3	4.4.3	4.4.3	4.4.3	4.2	4.2	4.4.3
TDE jets	4.2	4.2	4.4.3	4.4.3	4.4.3	2.3	4.4.3

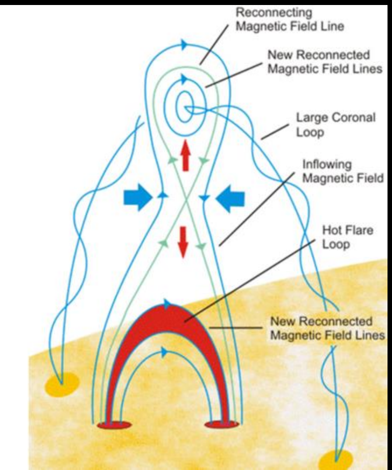
UHE Cosmic Rays

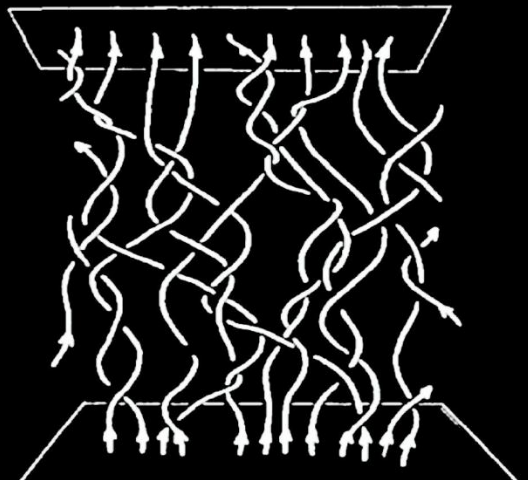
How and where are they accelerated?

Relativistic Reconnection

SNAP

- Impulsive acceleration in magnetically dominated regions
  - Radiative, relativistic reconnection / magnetoluminescence?
- Emission from local, fast "flares "
  - Radiative and expansion cooling
  - Orbit with electromagnetic angular velocity
- $t_{cool} \sim 1000\ B_2^{-3/2}$ s; $l_{cool} \sim 10^{13}\ B_2^{-3/2}$ cm << r; $L_{mm} < 10^{39}\ B_2^{-1}$ erg s^{-1}; $N_{flares} > 100\ B_2$?
- Absorption – $T_B < 10^{11}\ B_2^{-1/2}$ K
- Strong variable linear/circular polarization
- Faraday rotation mainly from sheath, wind





Local, fast acceleration is a feature

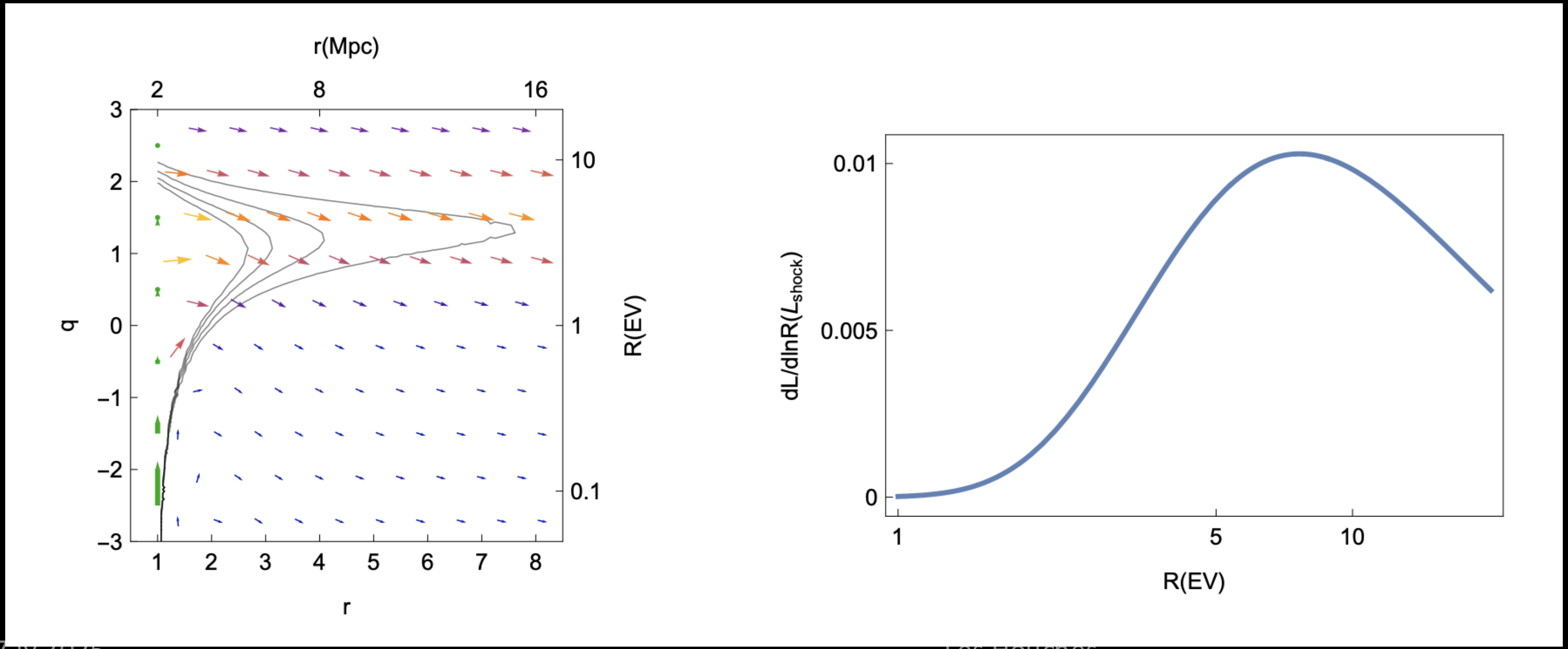
Relativistic Reconnection

How efficient is it?

Magnetic Turbulence

Hierarchical Acceleration

Strong MHD turbulence may be an efficient accelerator.
Important sites include coronae, jet sheaths and strong shocks.
PIC etc codes often lack the dynamic range for the problem.
It may be possible to impose suitable boundary conditions to limit the phase space volume.
e.g. cluster accretion shock



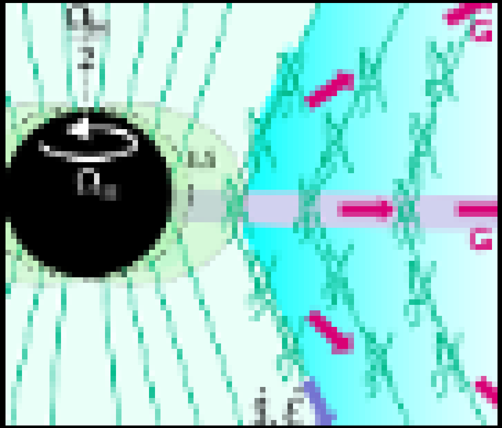
Magnetic Turbulence

Are shocks as effective as observations suggest?

Electric Field

E L E C T R I C   Z O N E S

- $E^2 - B^2 > 0$
  - FRB, Ergosphere
- Force-free equations become non-evolutionary
  - Neighboring initial conditions diverge exponentially
- Conventional view is that massive QED breakdown and remains magnetic
  - However, γ-rays trapped and cannot escape fast enough
- Instead equations remain may valid with dissipative inner scale
  - Electromagnetic "turbulence"?
  - Independent of microphysics
- e.g. Field lines in ergosphere lose angular momentum and become electric
  - Turbulence propagates backward on negative energy orbits into horizon
  - More power extracted
  - Independent of microphysics
- e.g. colliding waves in magnetar.
  - Convert km to cm waves and create a FRB
  - Force free fast waves -> EM waves at larger radii
  - Minimal plasma creation to avoid absorption



RB+Globus

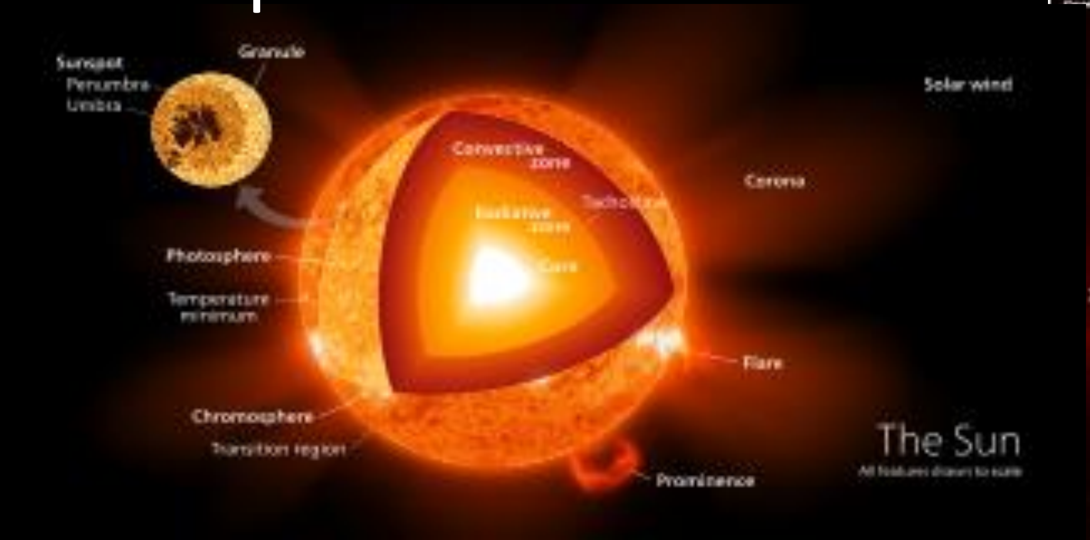
Parfrey Philippov, Cerutti 2017

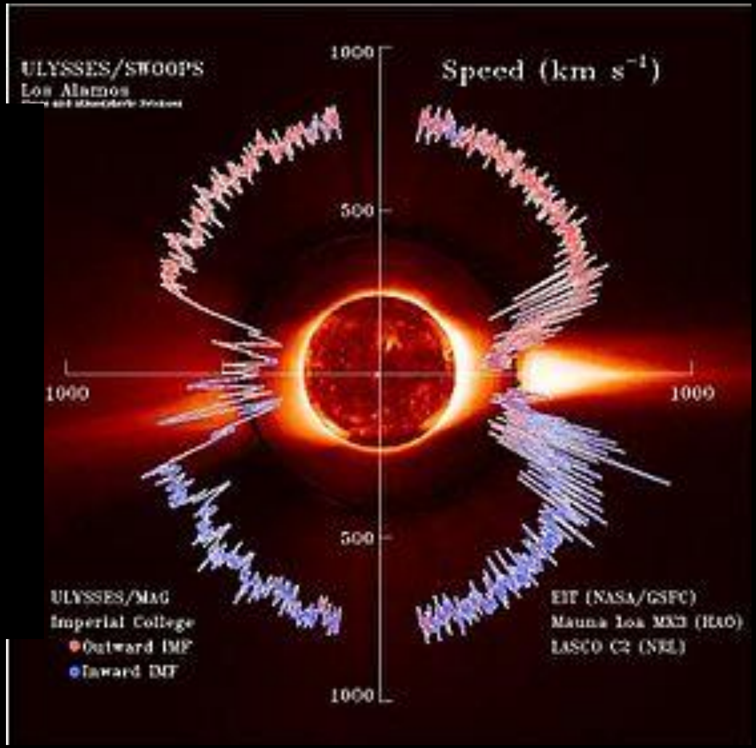
Electric Field

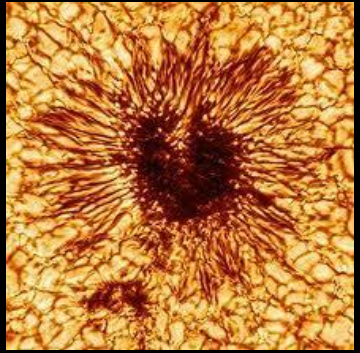
How much pair plasma is made?

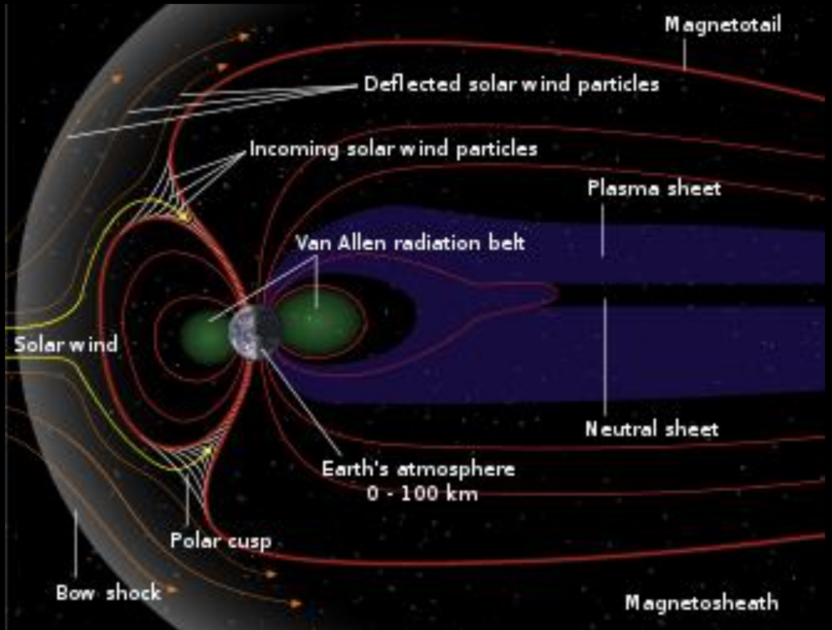
Nonrelativistic Magnetospheres

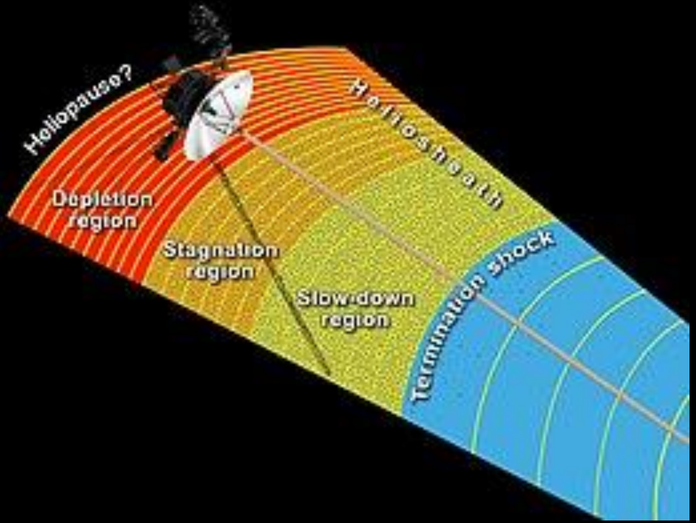
Heliosphere



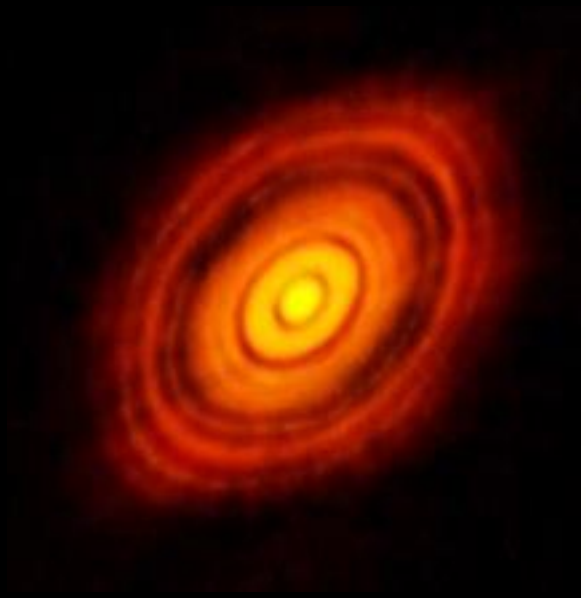


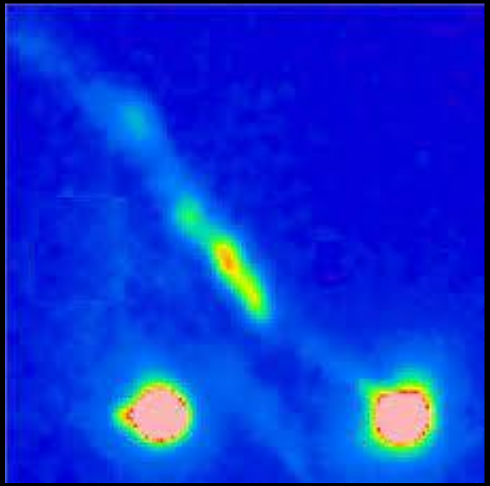


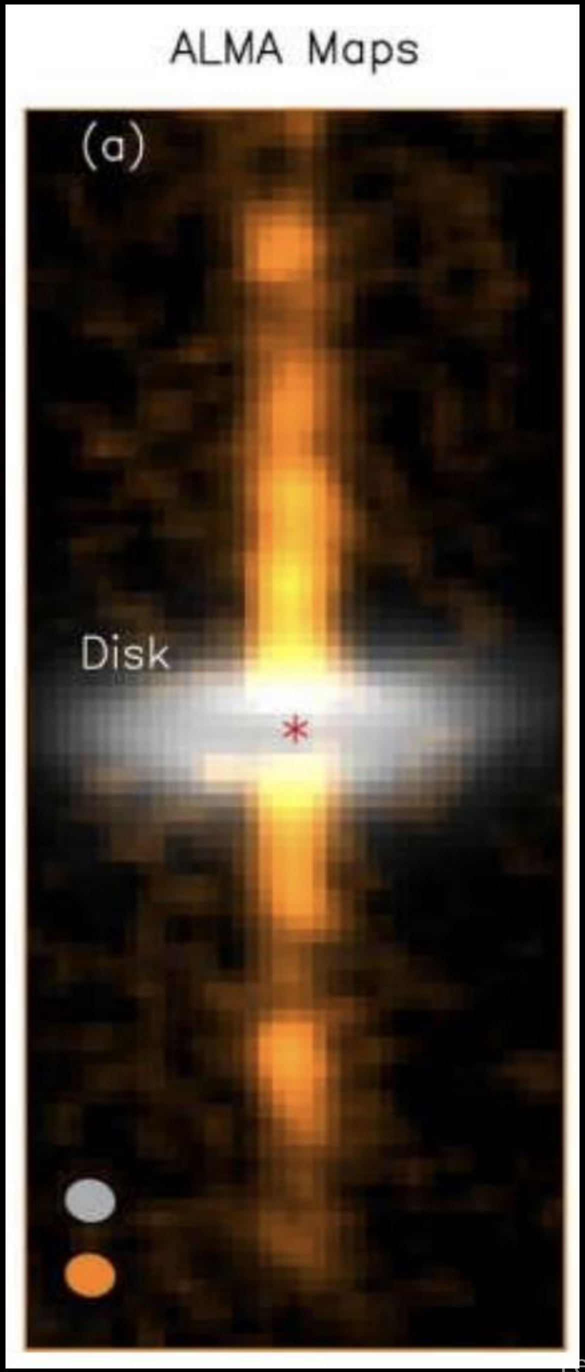


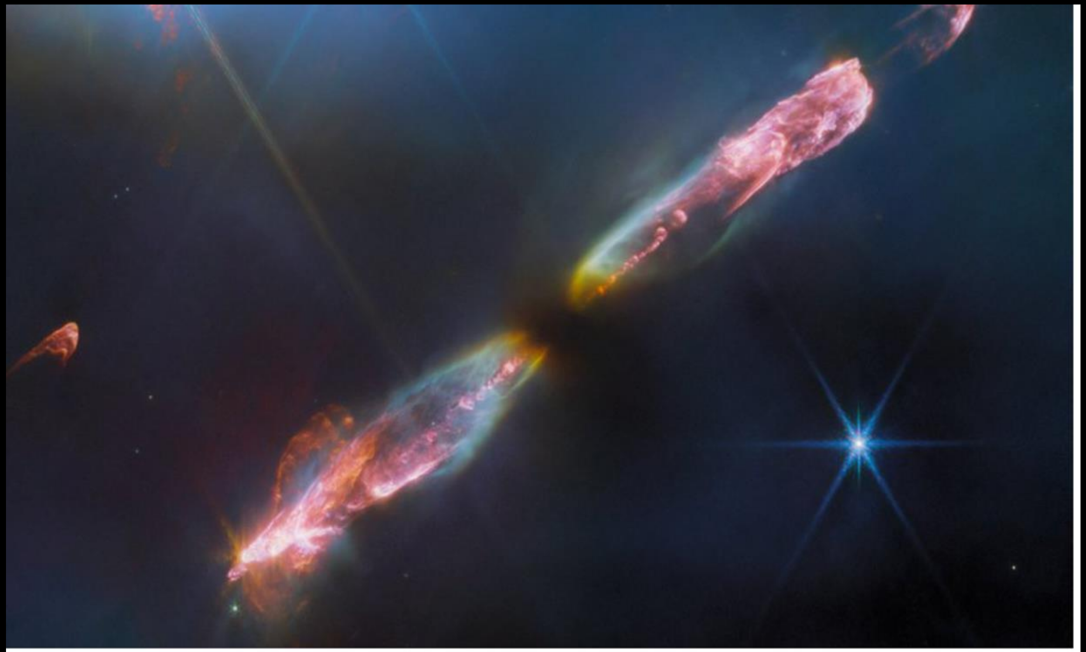


Protoplanets

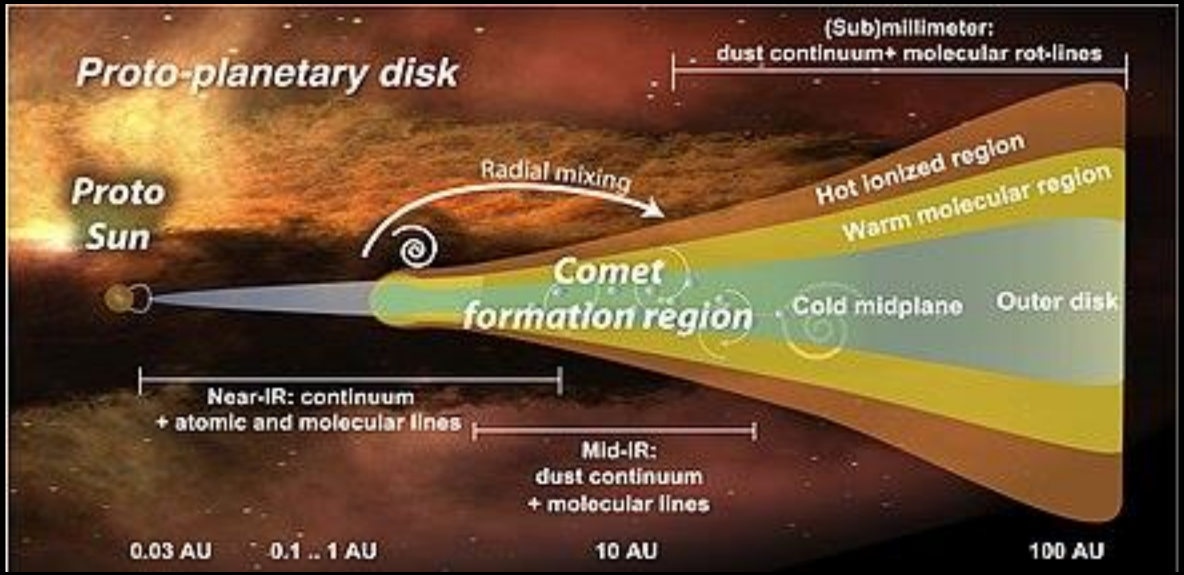




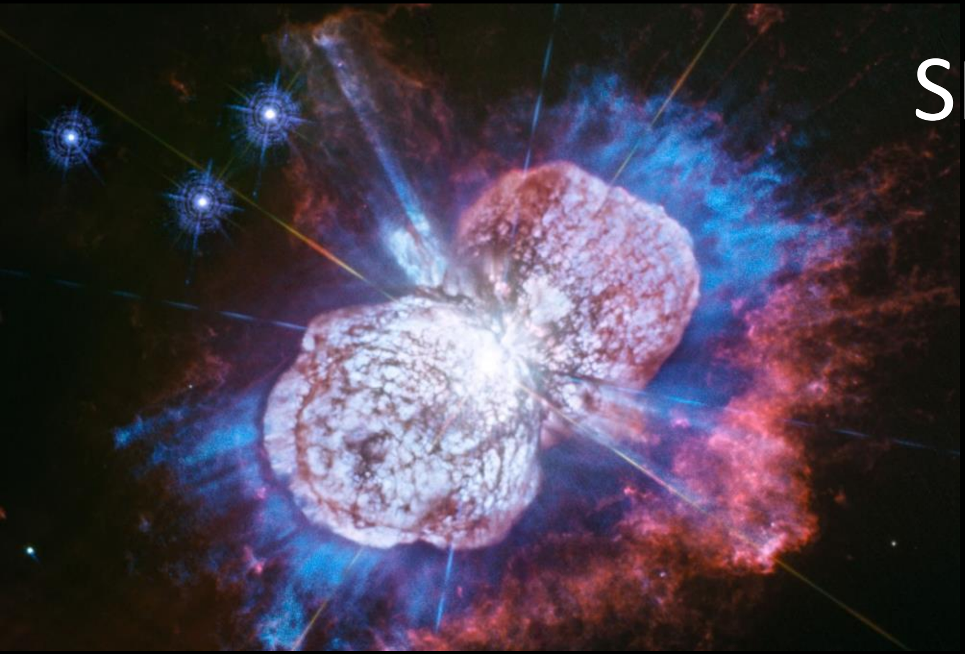


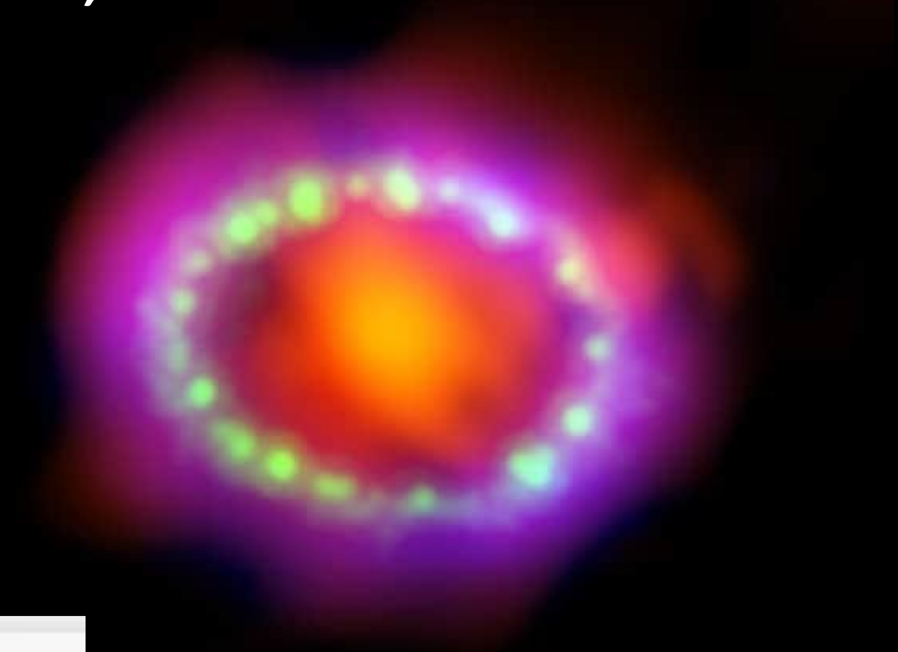


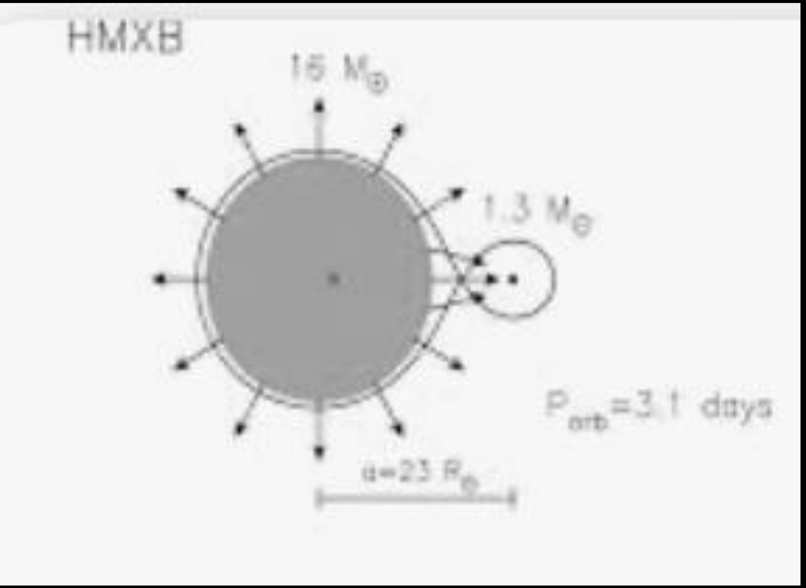
NASA's James Webb Space Telescope's image of Herbig-Haro 211
ESA/Webb, NASA, CSA, Tom Ray

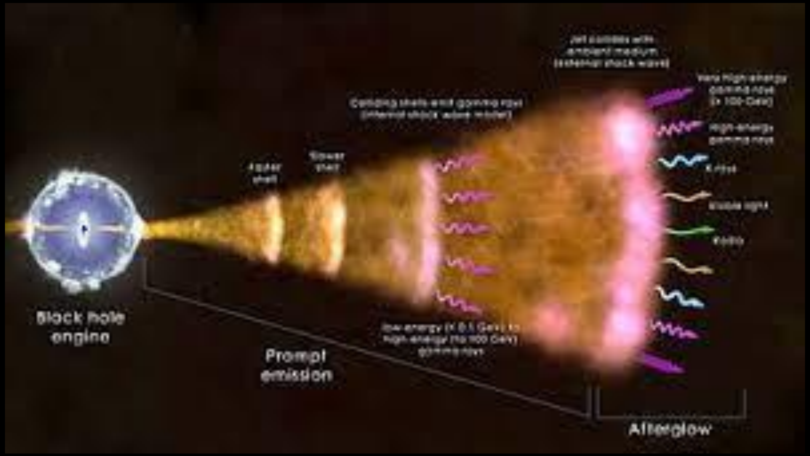


SNR, GRB…

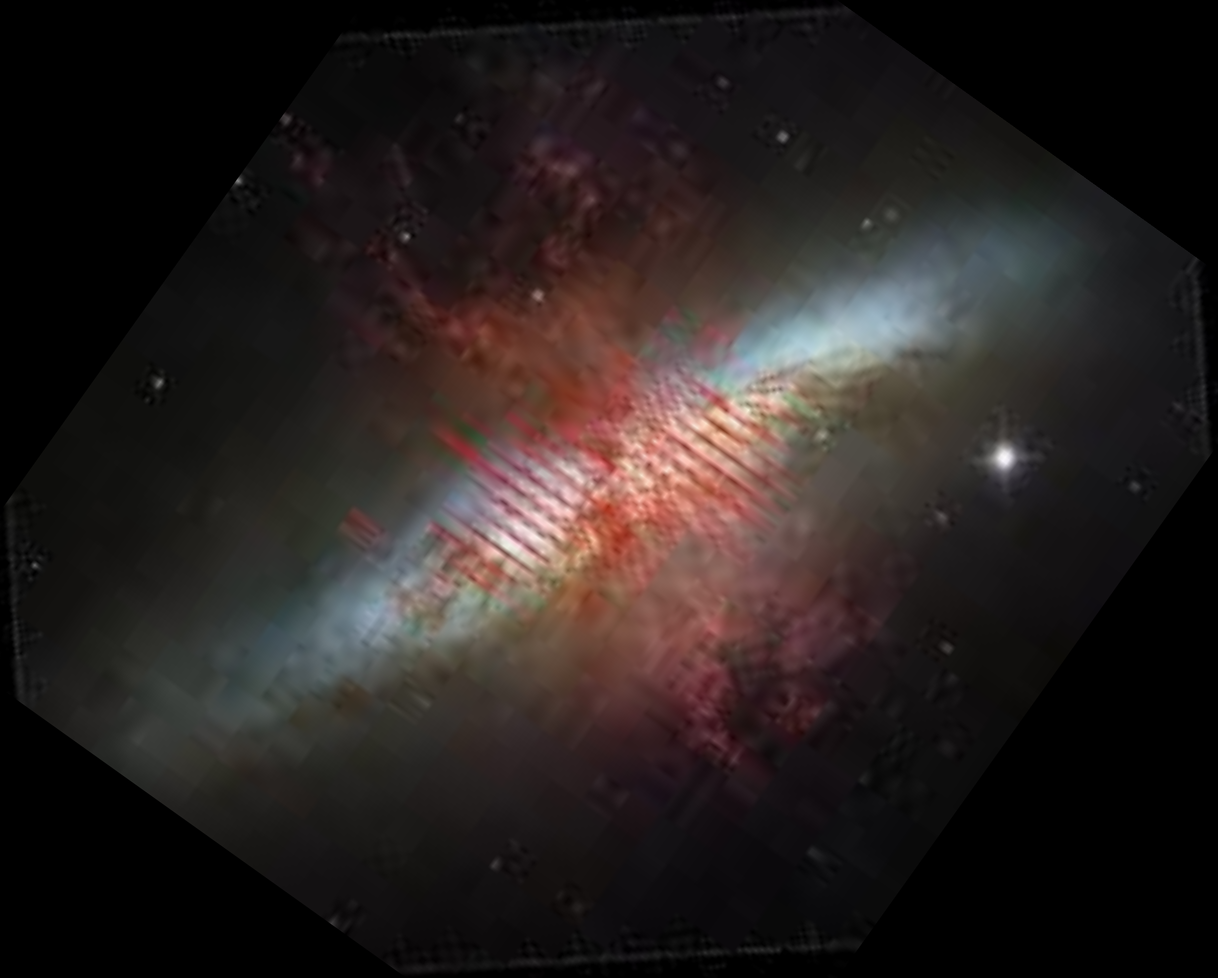





HMXB
16 $M_\odot$
1.3 $M_\odot$
P_{orb}=3.1 days
a=23 $R_\odot$


Black hole engine
Prompt emission
Afterglow

Galactic Winds



Nonrelativistic Magnetospheres

What are the qualitative differences introduced by special and general relativity?

Summary

- Follow the observations; models should predict and be falsifiable
- Focus on the flow of energy, angular/linear momentum, mass, current, flux…
- Rapid variability implies compact sources and/or relativistic kinematics/caustics
- Stress test PIC et al codes and adapt to awkward geometries and flows
- Much can be learned from the sun, SNR, protostars…, experiment
- Golden age of observational/experimental discovery, especially at the frontiers