Extreme Electrodynamics
of
Compact Sources

Roger Blandford

Kavli Institute for Particle Astrophysics and Cosmology

Stanford University

SLAC

https://www.simonsceecs.com

KIPAC

THEORY

C. Thompson

S. Meuren

R. Blandford

E. Zweibel

A. Levinson

A. Spitkovsky

A. Philippov

L. Sironi

Y. Yuan

B. Ripperda

SIMULATION

QED

Plasma Physics

General Relativity

S. Gralla

Neutron Stars

EEC

Black Holes

Interior Physics

K. Fang   T. Piran   R. Anantua

Y. Levin   K. Chatziioannou   M. Caplan

N. Globus
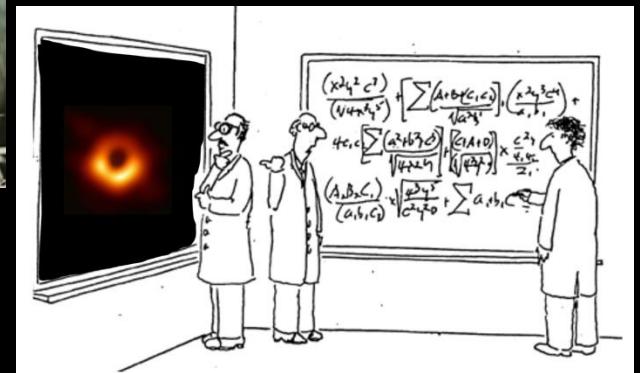
INTERPRETATION

ADVISORY BOARD

A. Arvanitaki
Theoretical Physics

P. Bucksbaum
Photon Science

F. Fiuza
Plasma Physics

F. Harrison
X-ray Astronomy

V. Kaspi
Radio Astronomy

C. Kouveliotou
Gamma-ray Astronomy

S. Reddy
Nuclear Physics

CLASSICAL ELECTRODYNAMICS

$$\nabla \cdot \mathbf{B} = 0; \; \nabla \cdot \mathbf{E} = \rho; \; \partial_t \mathbf{B} = -\nabla \times \mathbf{E}; \; \partial_t \mathbf{E} = \nabla \times \mathbf{B} - \mathbf{j}$$

- Let there be Light
  - And magnetic field
- Maxwell used continuous current
  - Despite kinetic theory, electrolysis!
- Particles, Lorentz force
  - Atomic, nuclear, particle, plasma physics
- New life in old theory

QUANTUM ELECTRODYNAMICS

QED Action

$$S_{\text{QED}} = \int d^4 x \left[-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \bar{\psi} \left(i\gamma^\mu D_\mu - m \right) \psi \right]$$

- Photons are relevant

- Electrons in magnetic field quantized like atoms

- Normal QED is valid when energy jumps are less than rest mass
  - Magnetic field < Schwinger Field ~ 4 GT

- Magnetar field can be 10-30 times larger than this
  - Interior field can be up to a hundred times larger than this!

- Extreme QED needs new approaches including many-body plasma effects

QED

IN   WE TRUST

PHYSICS FRONTIER
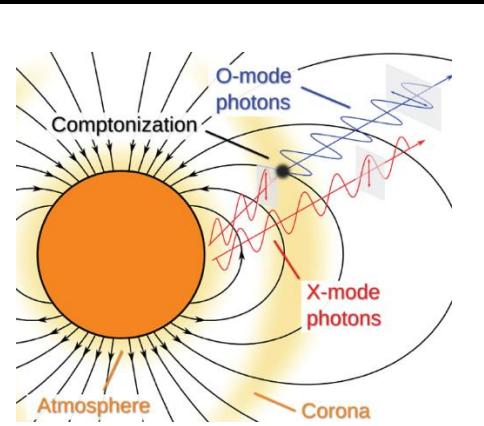
Electromagnetism

Gravity

Gralla, Holz, Wald, 2019
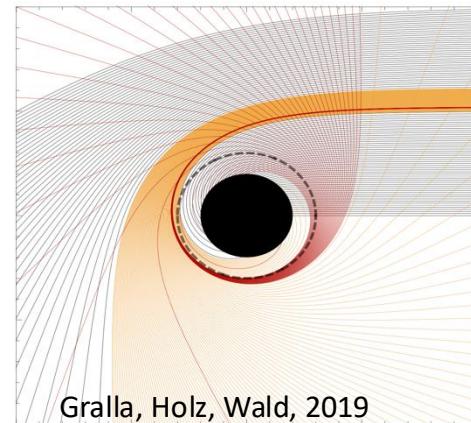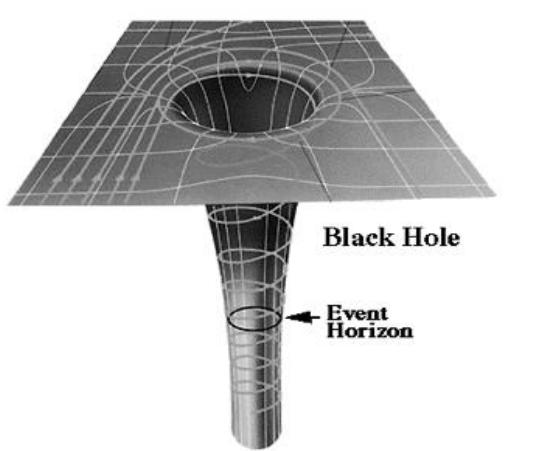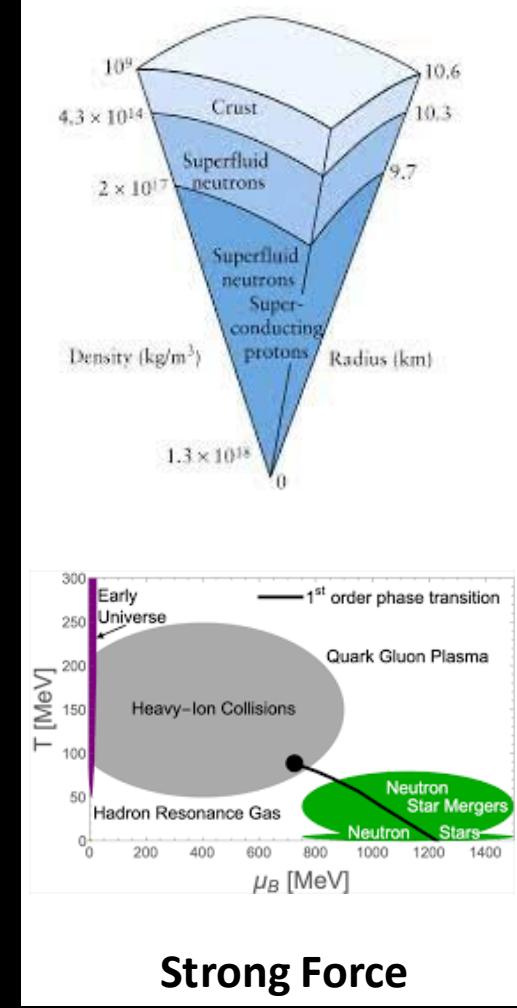
Strong Force
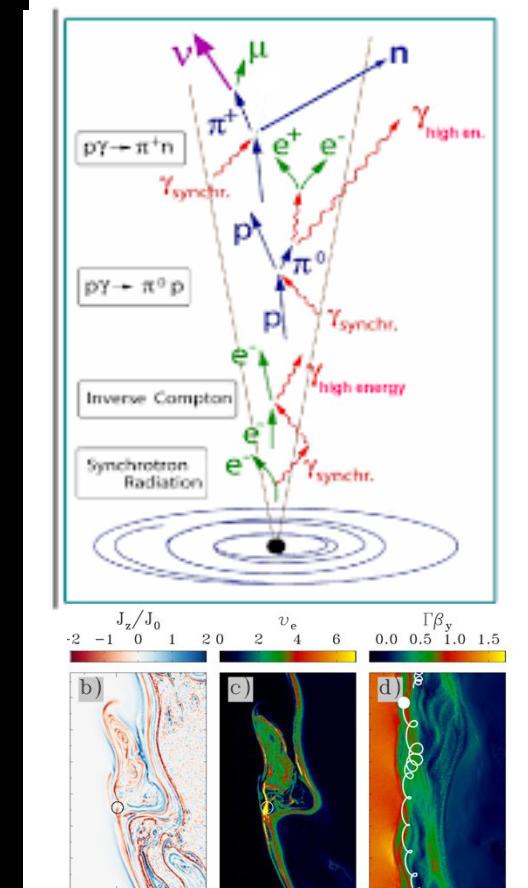
Weak Force

Sironi et. al., 2022

Plasma Physics Required

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

A NEUTRON STAR: SURFACE and INTERIOR
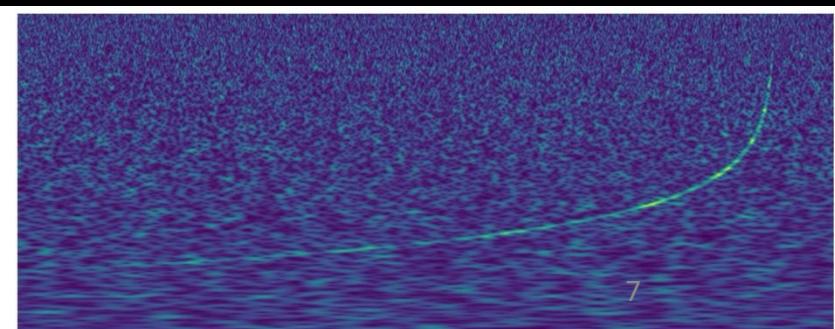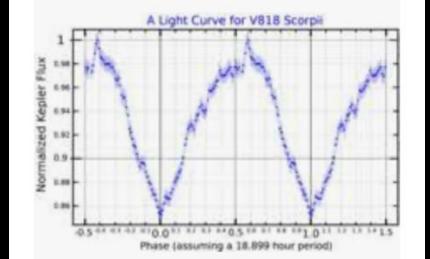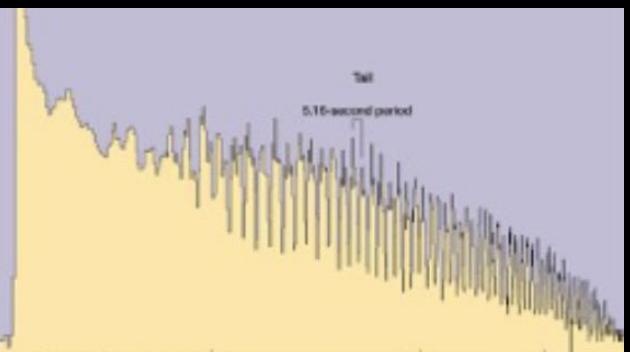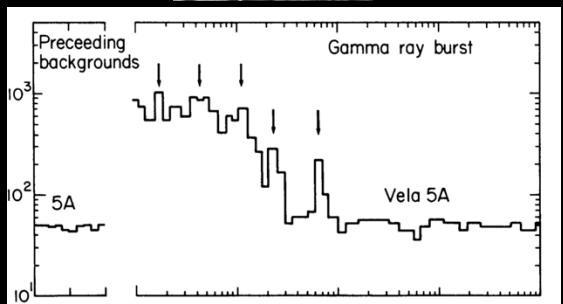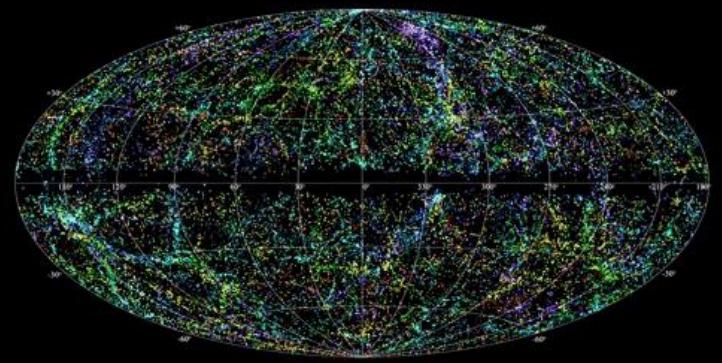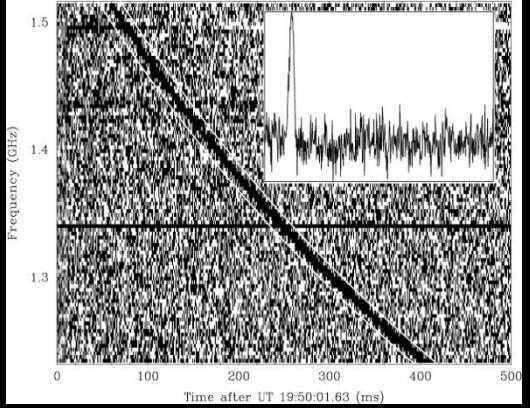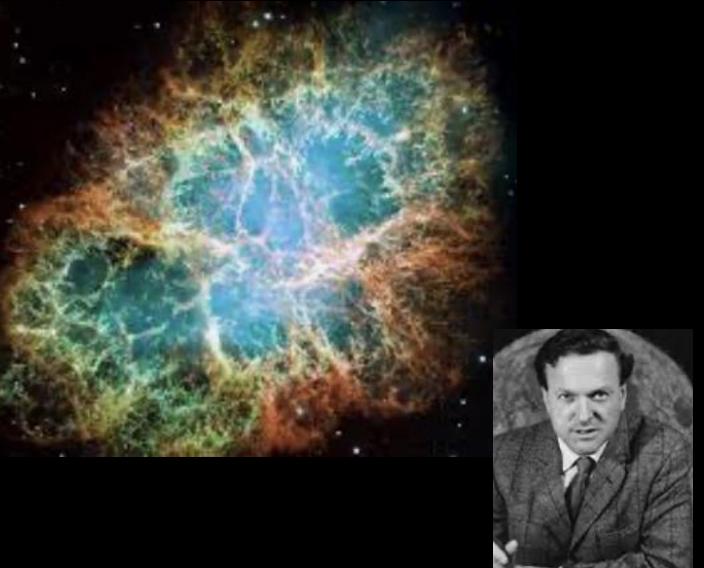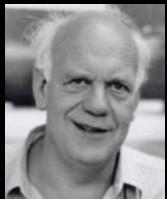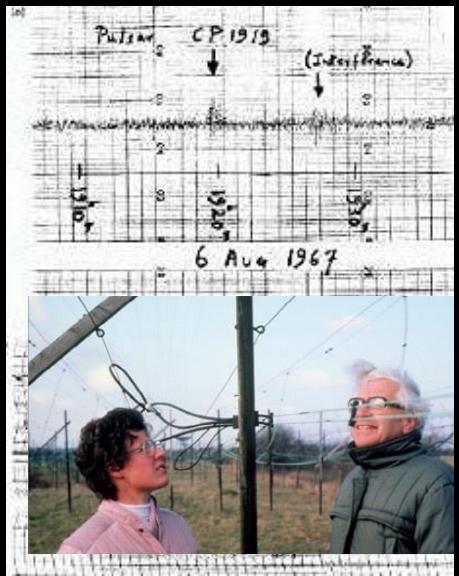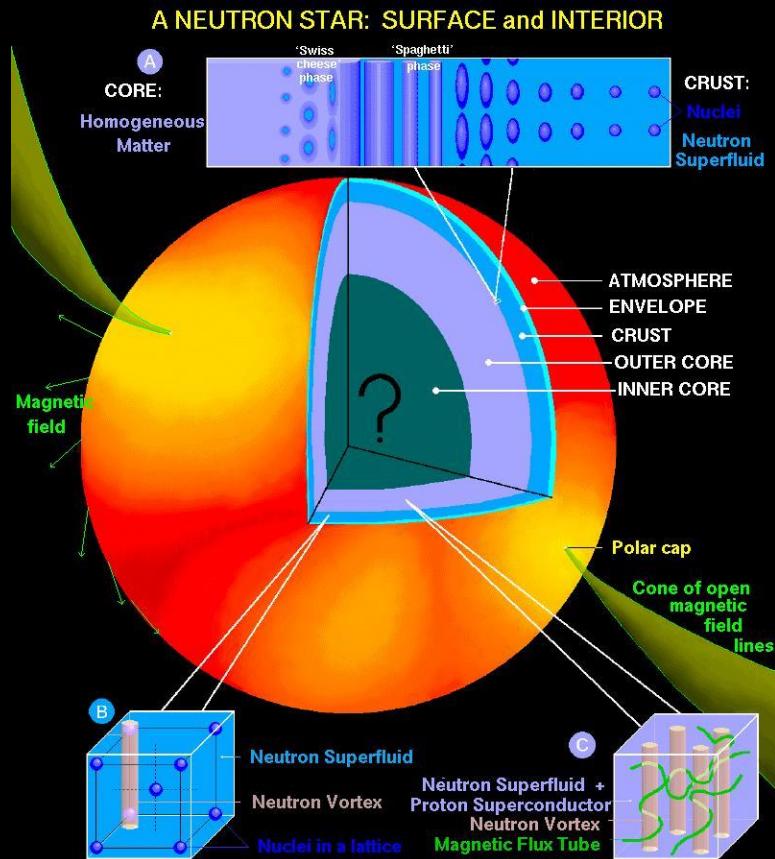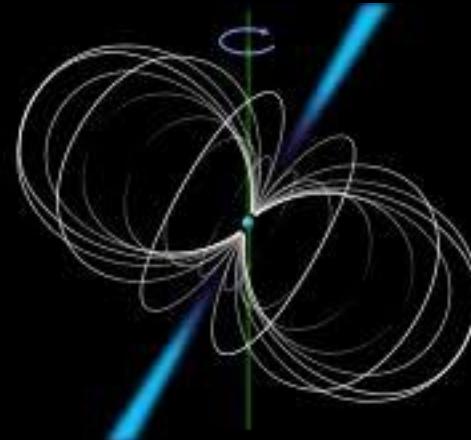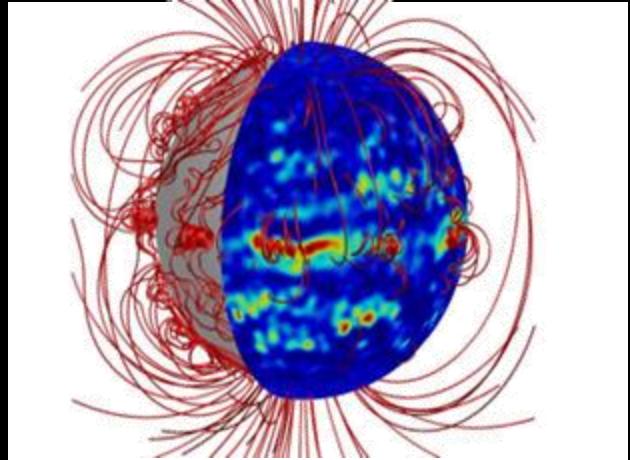
Neutron Star
Mass ~ 1 -2.5 M_{sun}
Radius ~ 10 km
Density ~ Nuclear

Magnetic Field
Pulsars 10^{12} G
Magnetars 10^{15} G ~ 30 $B_{Schwinger}$
Neutron Star Interiors < 10^{17} G
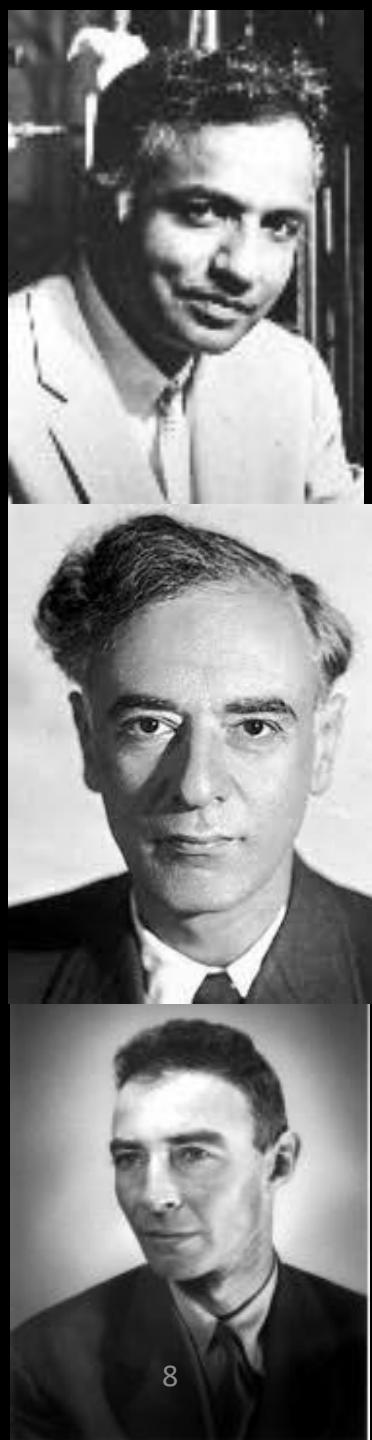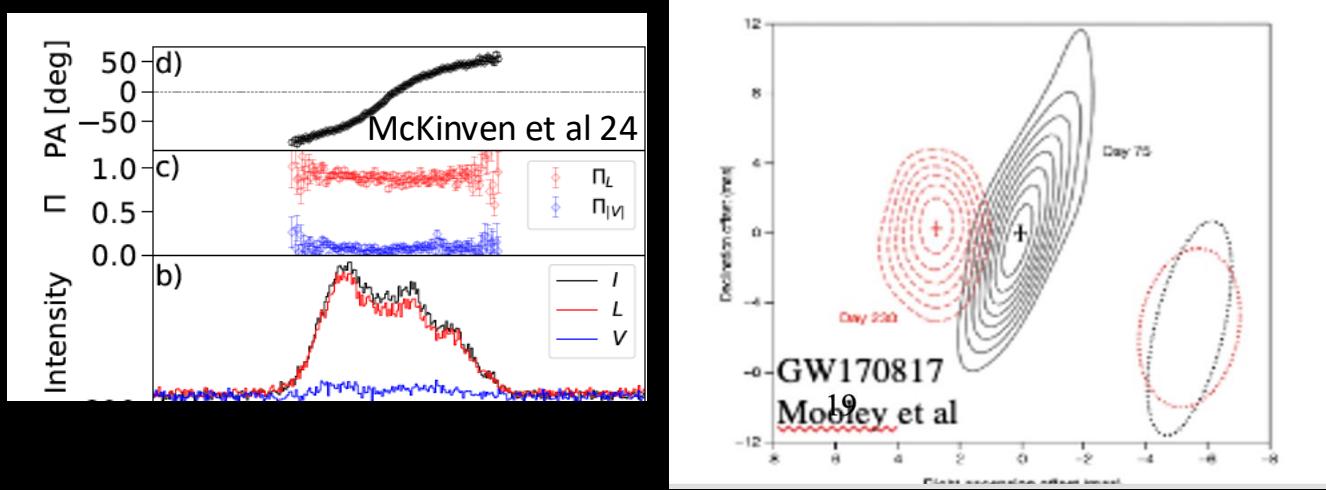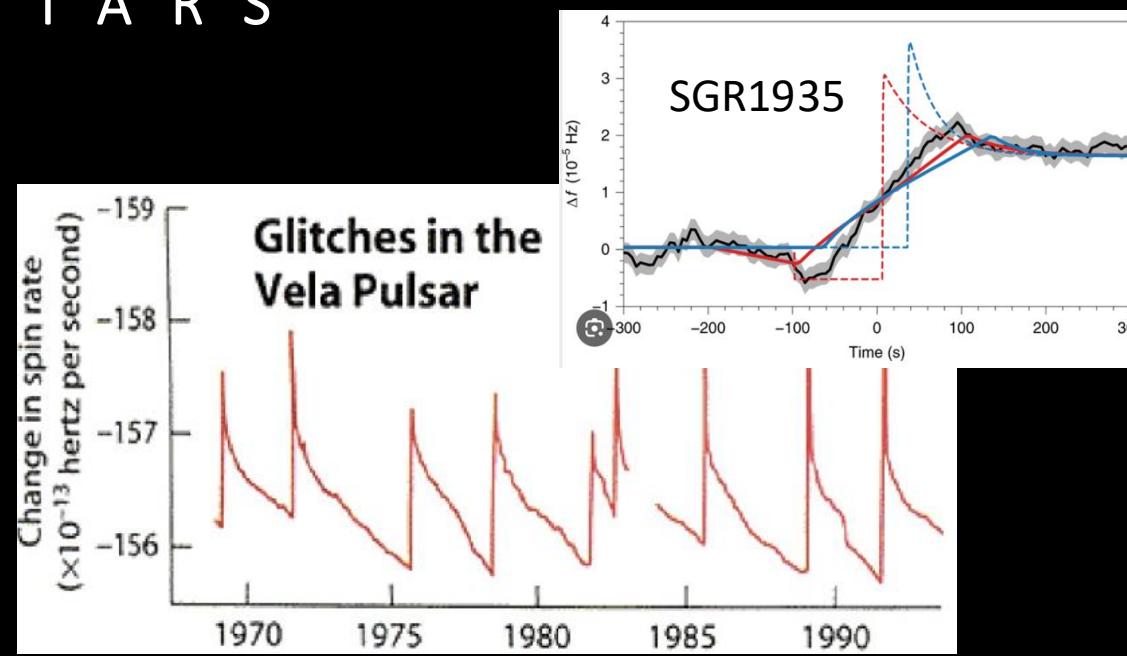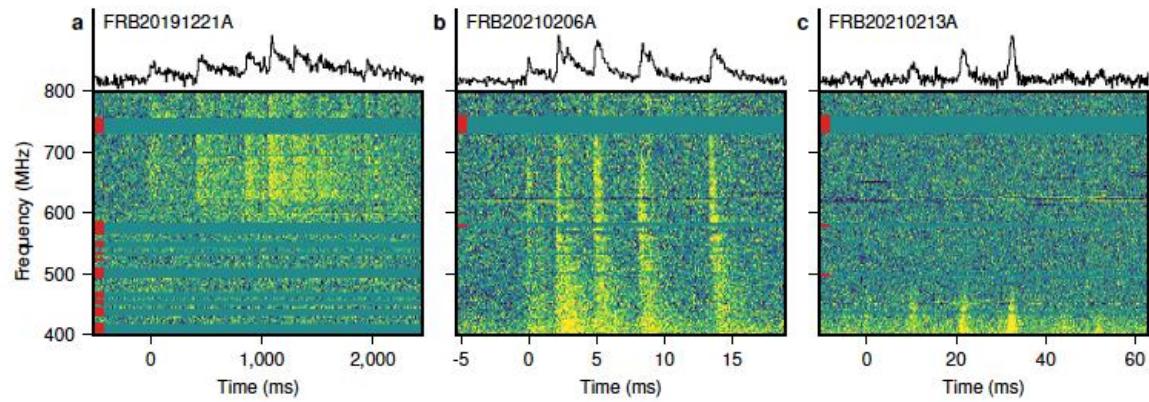
All Physics?

SGR1935

Glitches in the Vela Pulsar

McKinven et al 24

GW170817
Mobley et al

BLACK HOLES

Cyg X-1

2704 BATSE Gamma-Ray Bursts

Preceeding backgrounds
Gamma ray burst
5A
Vela 5A

SLAC

1/24/2025

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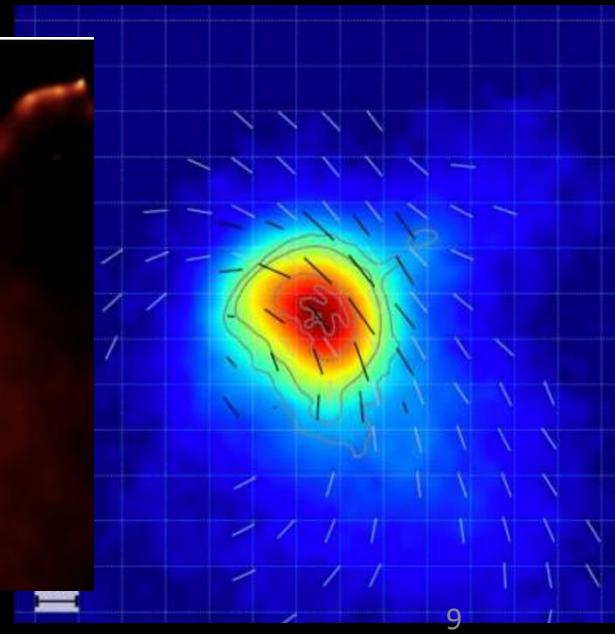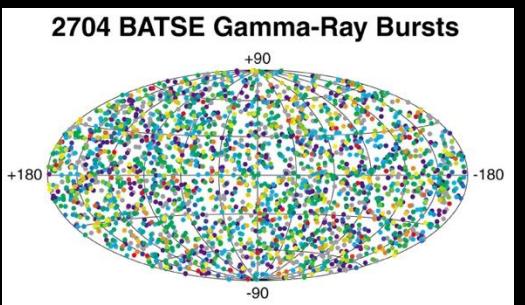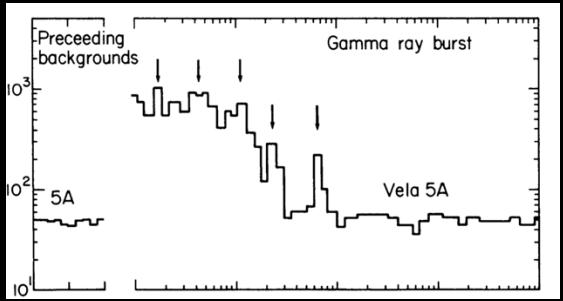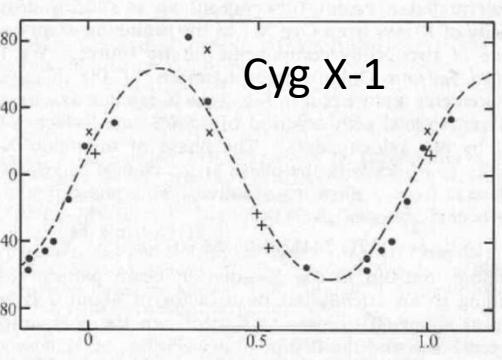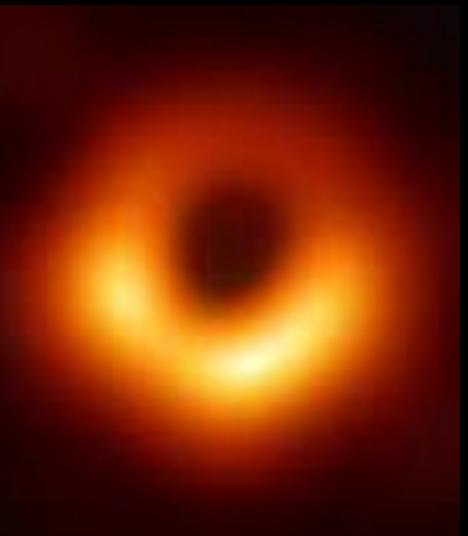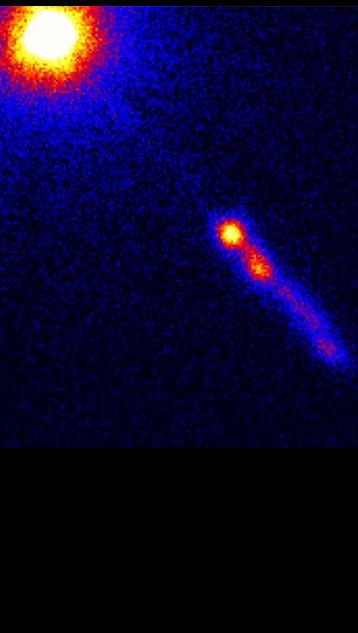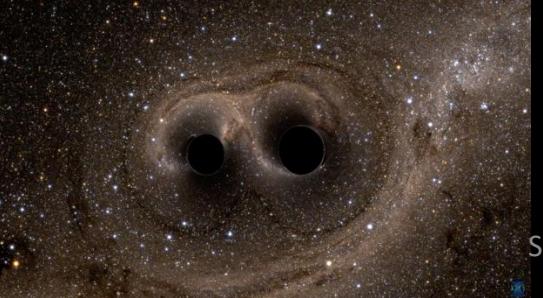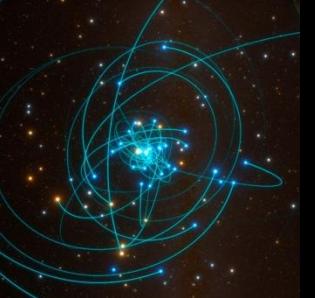
B L A C K   H O L E S

Kerr Black Hole

Accretion Disk
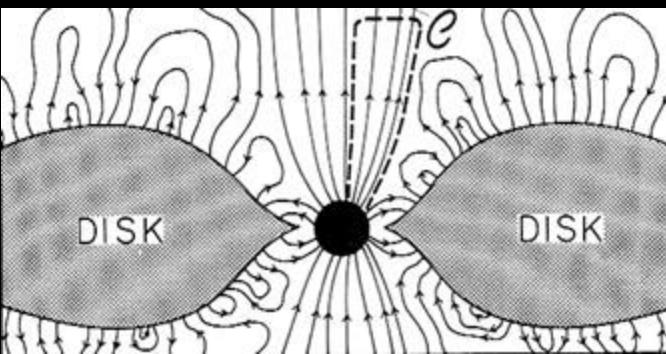
Spinning Black Hole

Described by Mass and Spin
Gravity and Rotational Power

SS 433 – TeV γ!

TXS 0506+056
~ PeV ν ?

Arp 229B
Mattila et al

1 pc
D
2005
2012
2013
2015
8.4 GHz

Amaterasu cosmic ray
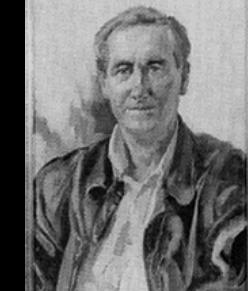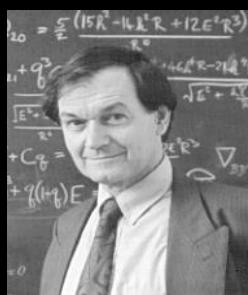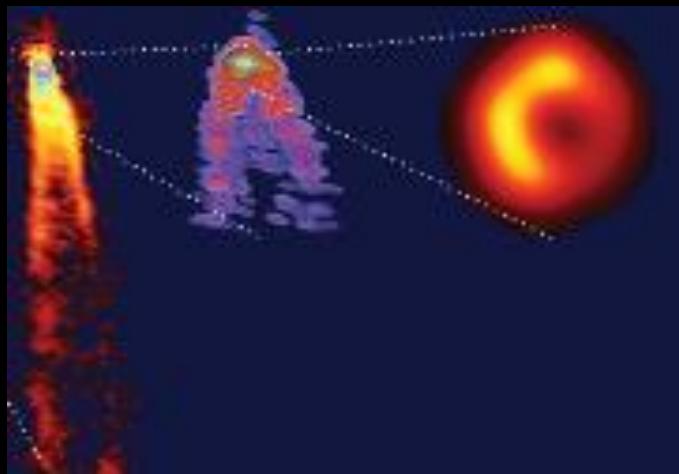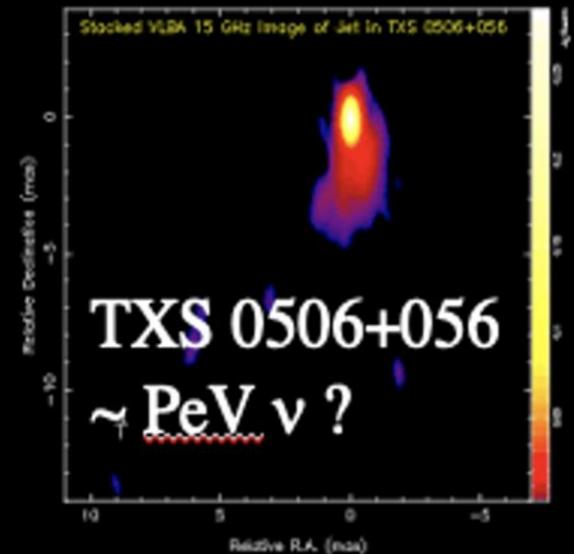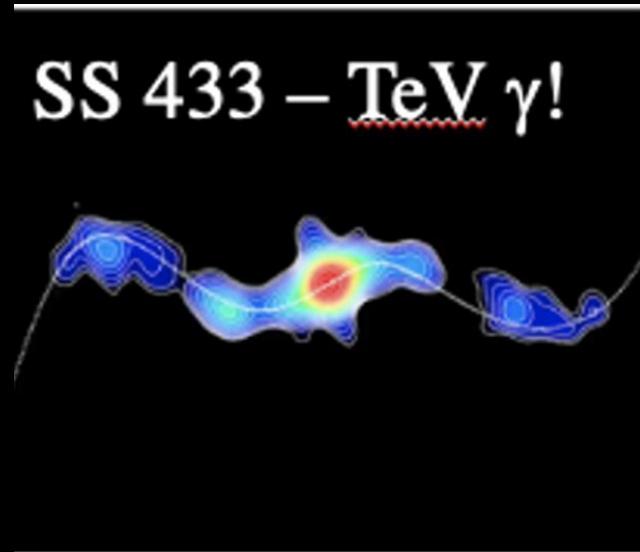
NANOGrav
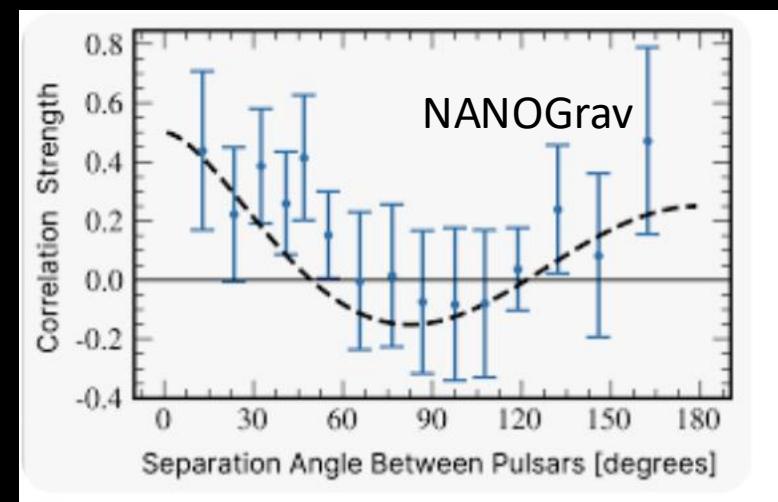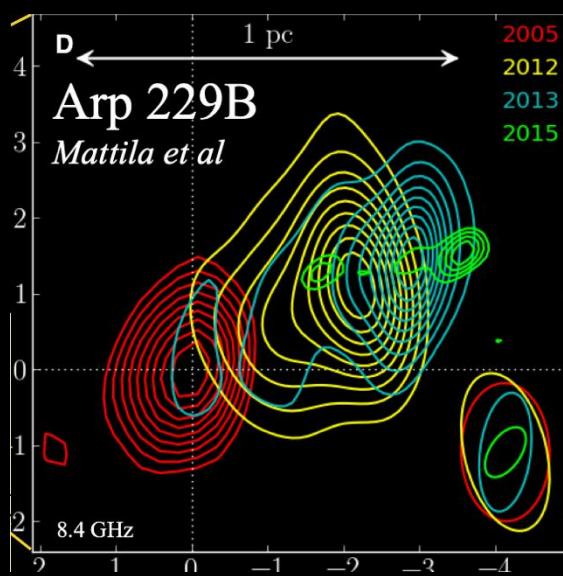
GAMMA RAY BURSTS
A CASE HISTORY

- >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

Soft Gamma Repeater

Magnetar

Long gamma-ray burst (>2 seconds' duration)

A red-giant star collapses onto its core...

...becoming so dense that it expels its outer layers in a supernova explosion.

Torus Jet Gamma rays

Short gamma-ray burst (<2 seconds' duration)

Stars* in a compact binary system begin to spiral inward...

...eventually colliding.

The resulting torus has at its center a powerful black hole.

*Possibly neutron stars.

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

Electromagnetic

Wavelength

Frequency

Waves

Particles
Photons

Cosmic Rays

+ Dark Matter!

Neutrinos

Gravitational Radiation

1zeV ~ 10^{-40} J

1eV ~ 10^{-19} J

1ZeV ~ 100 J

140 Octaves being Explored
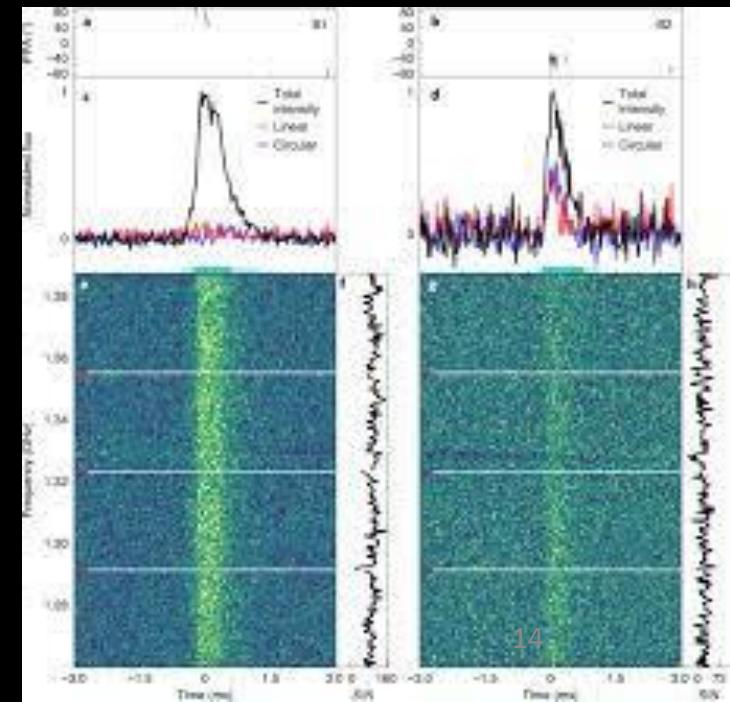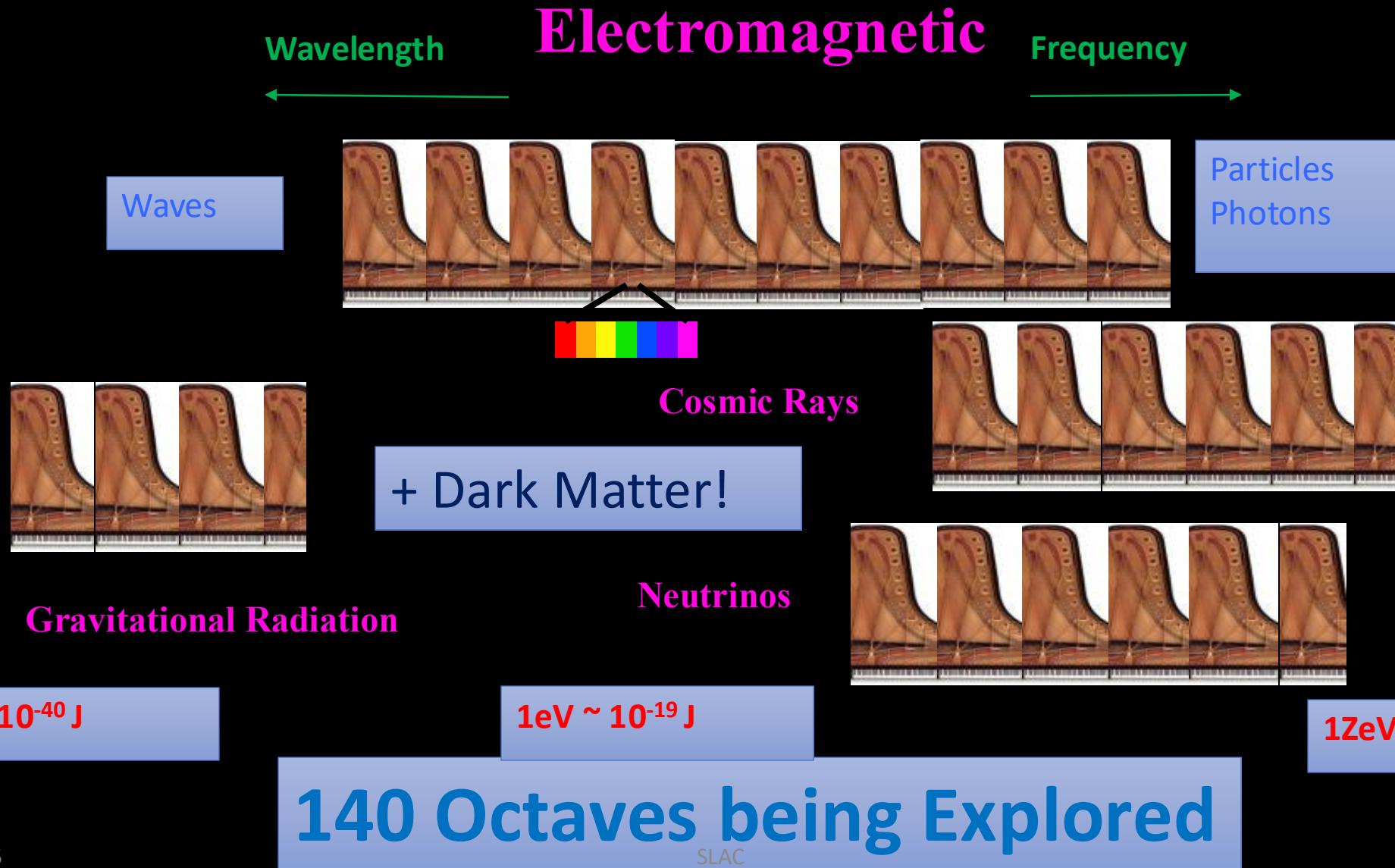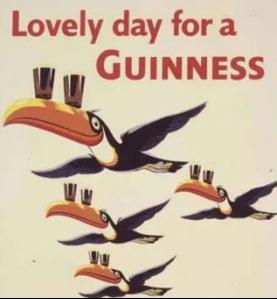
Black Hole Merger

10^{49} W

Gamma Ray Burst

10^{45} W

Active Galactic Nucleus

10^{39} W

ENERGY FRONTIER
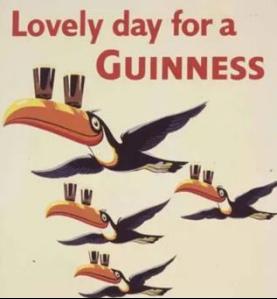
$>10^{15}$ eV Neutrinos
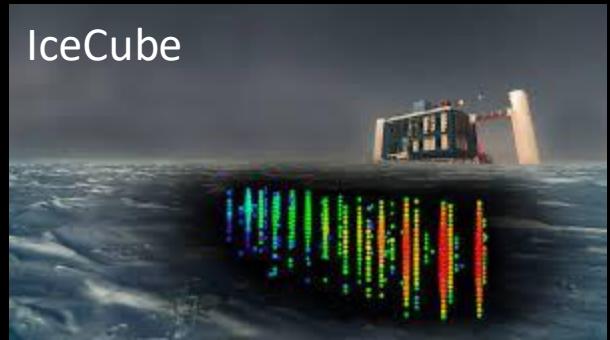
$10^{14\text{-}15}$ eV Gamma Rays

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

IceCube

LHAASO

Auger/TA

Multi-messenger Observations
Time-domain Astronomy
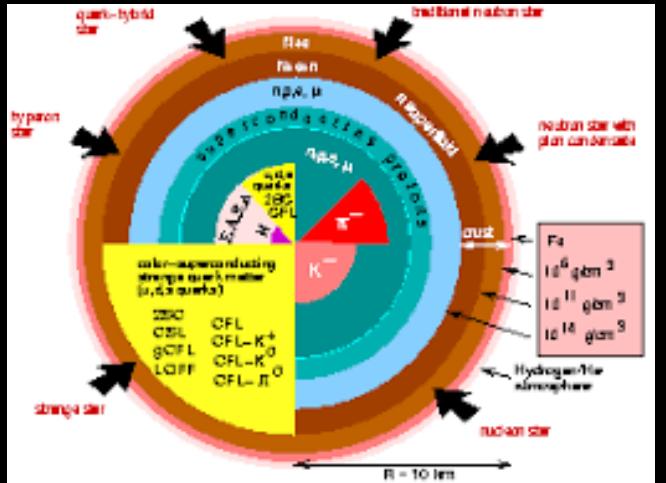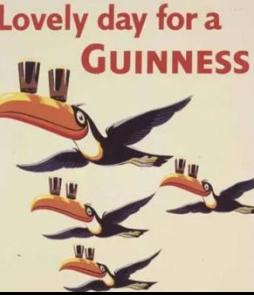
Superconducting protons
Superfluid neutrons
$T_c \sim 10^{10}$ K
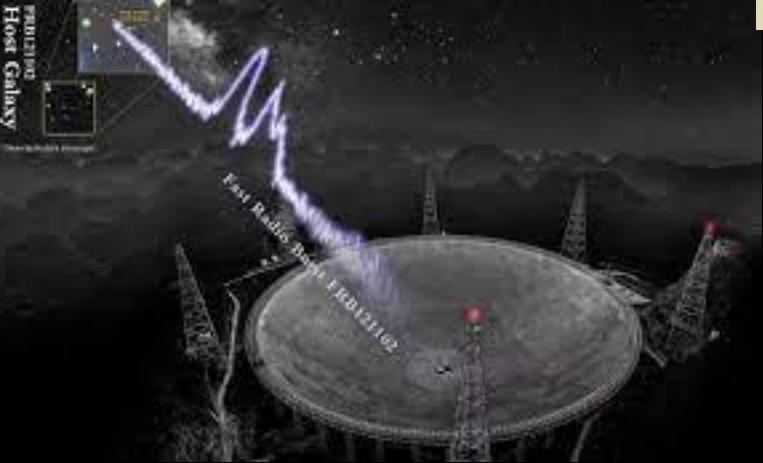
Effective Temperature T
Energy in $d^3x \, d^3k/(2\pi)^3$ is k_B T
Conserved along ray
$T \sim 10^{40}$ K

OBSERVATIONAL FRONTIER
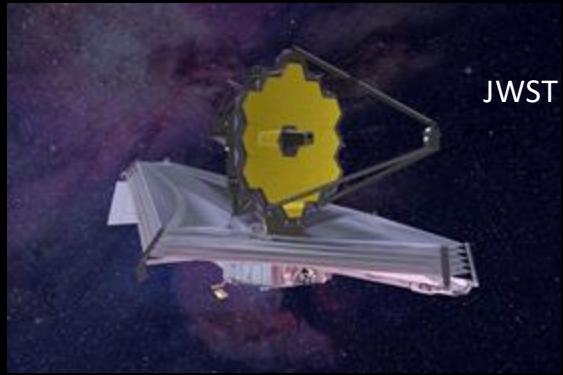
JWST
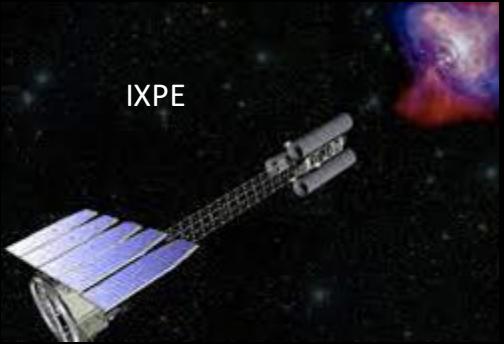
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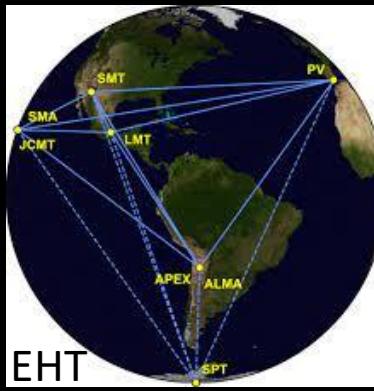
EHT
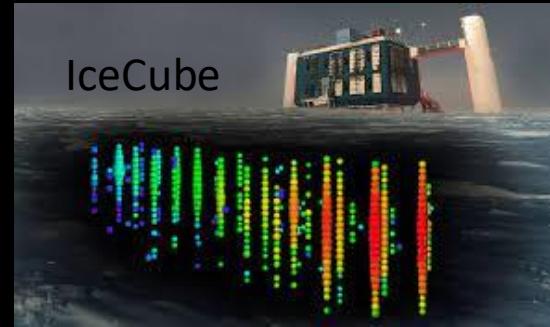
IceCube

Vera Rubin Observatory (2024)

CHIME, DSA2000...

LHAASO
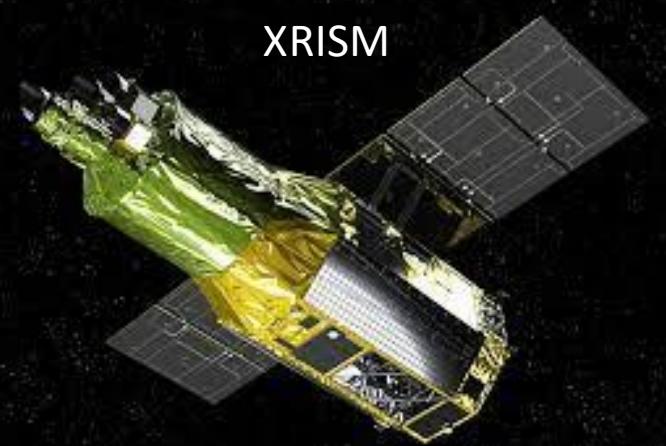
XRISM
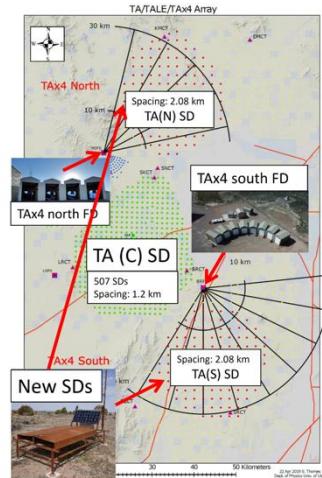
SVOM

The Origin of the Solar System Elements
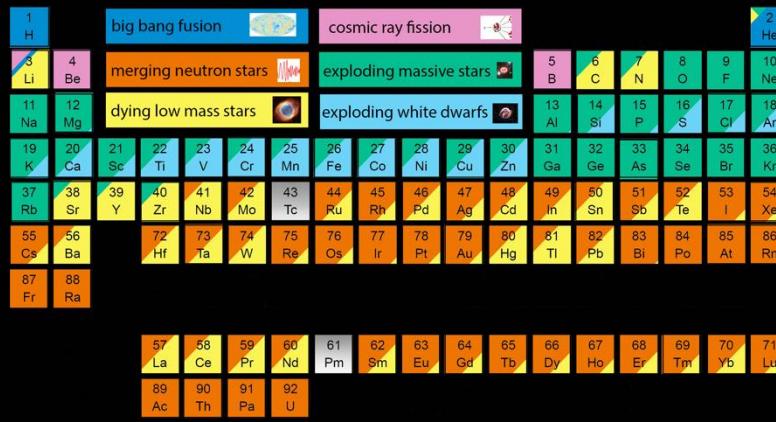
Graphic created by Jennifer Johnson

Astronomical Image Credits: ESA/NASA/AASNova

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
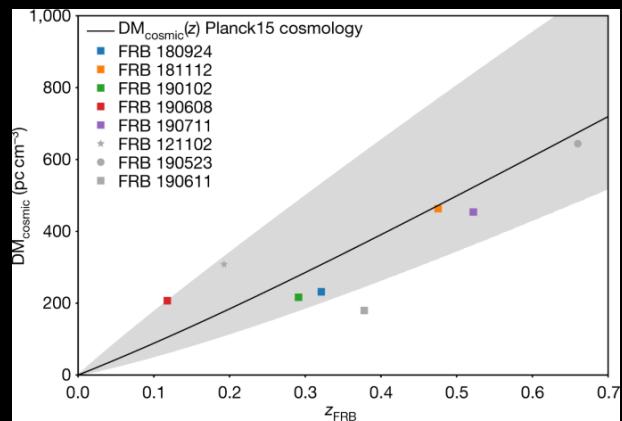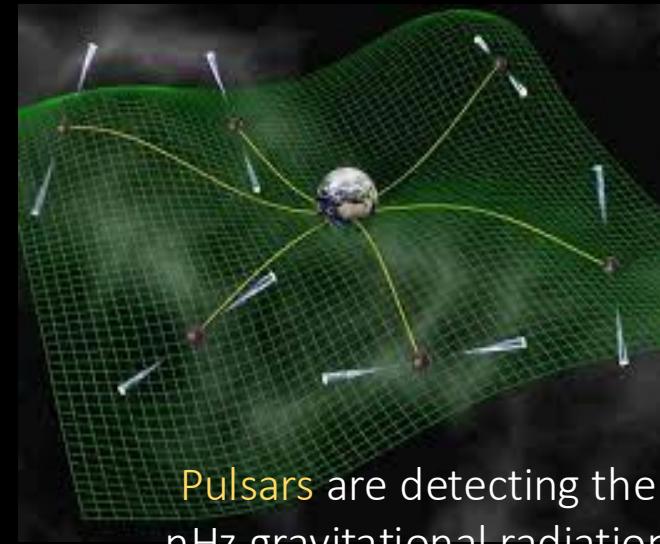
Fast Radio Bursts (FRB) measure the baryons

opaque to cosmic rays

opaque to photons; transparent to cosmic-rays and neutrinos

SLAC
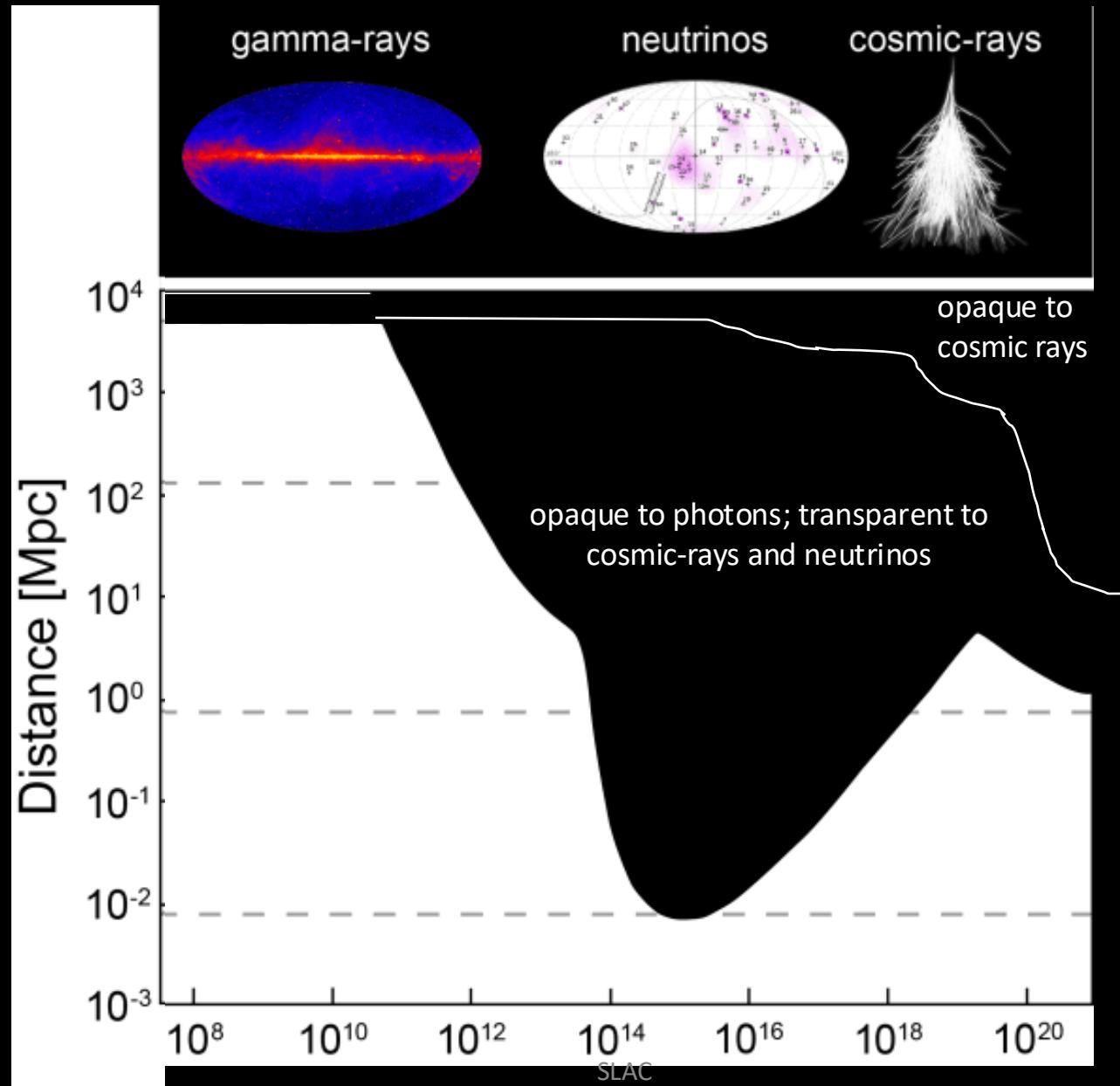
Magnetohydrodynamics ++
Particle in Cell codes ++
Molecular dynamics codes ++
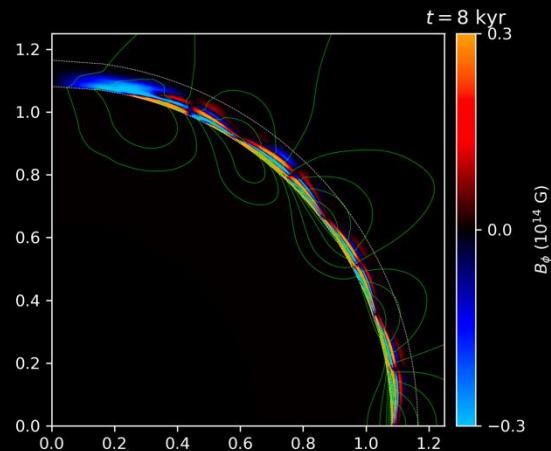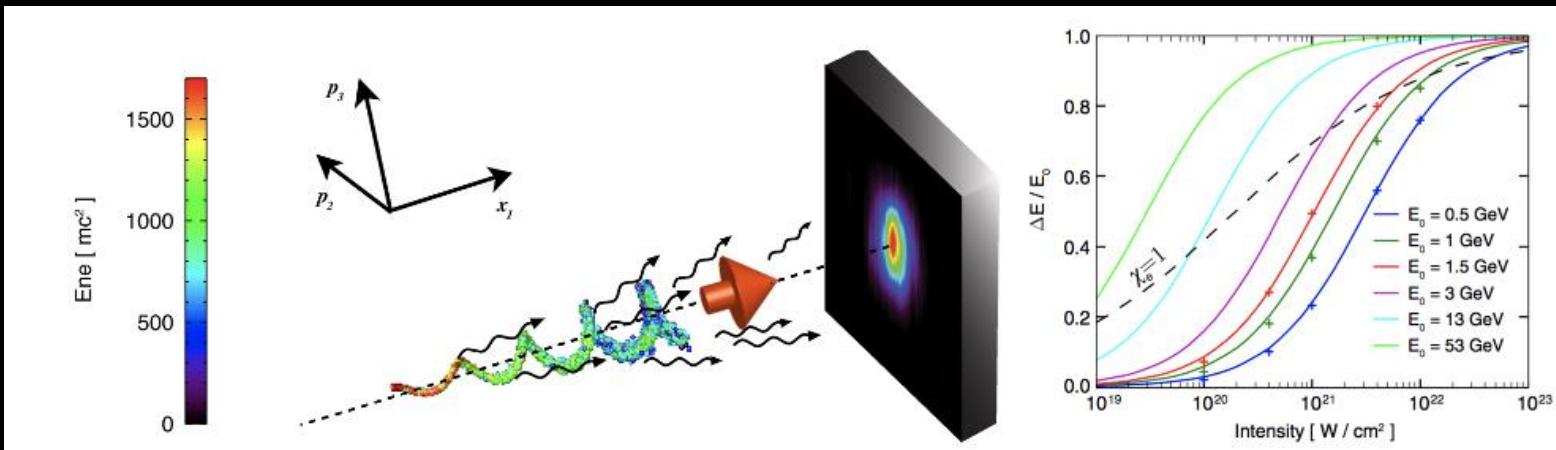
Hall Drift in Crust
Bransgrove, Belaborodov, Levi
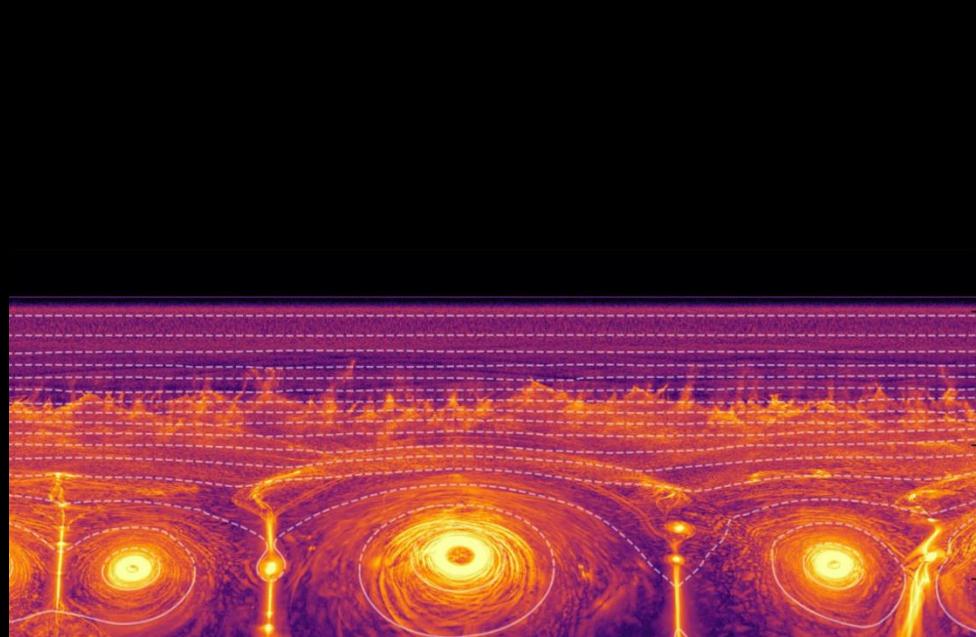
FRB from Rapid Reconnection Simulation
(Mahlmann, Philippov, Levinson, Spitkovsky, Hakobyan; 2022)

LCLS II

IPFN

NIF
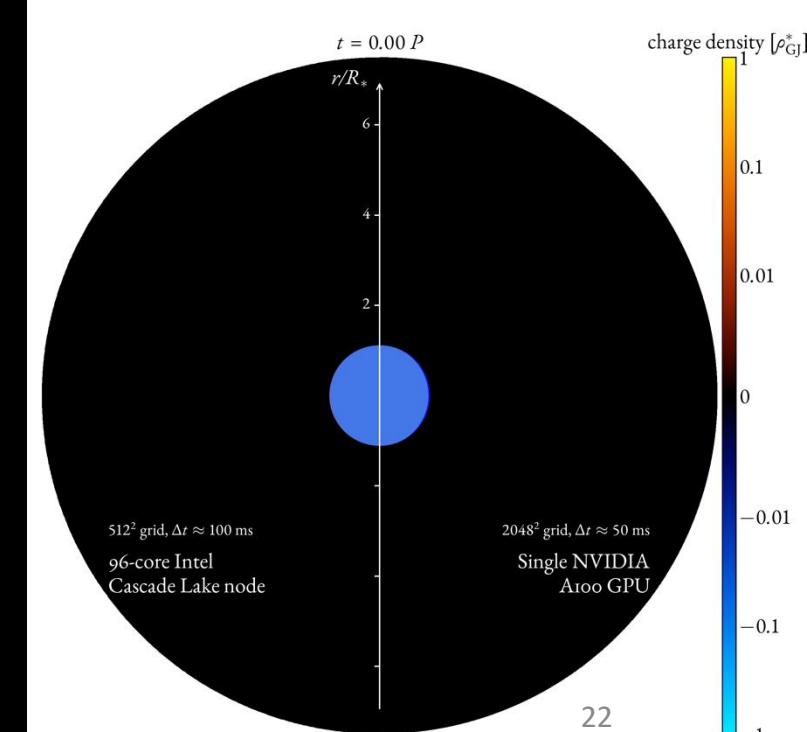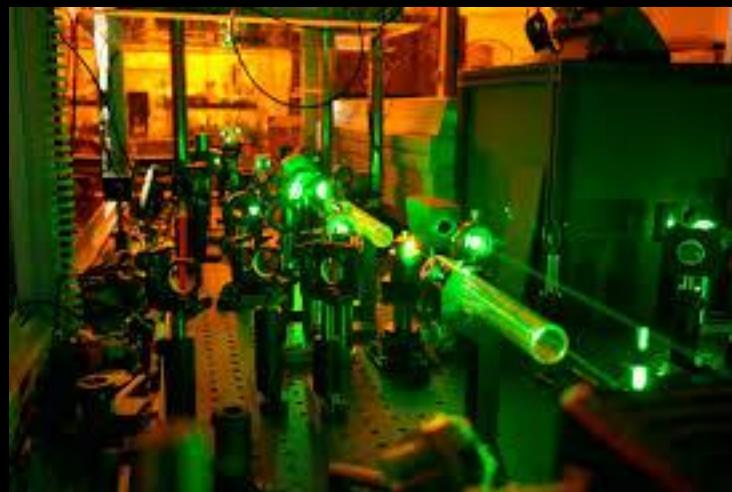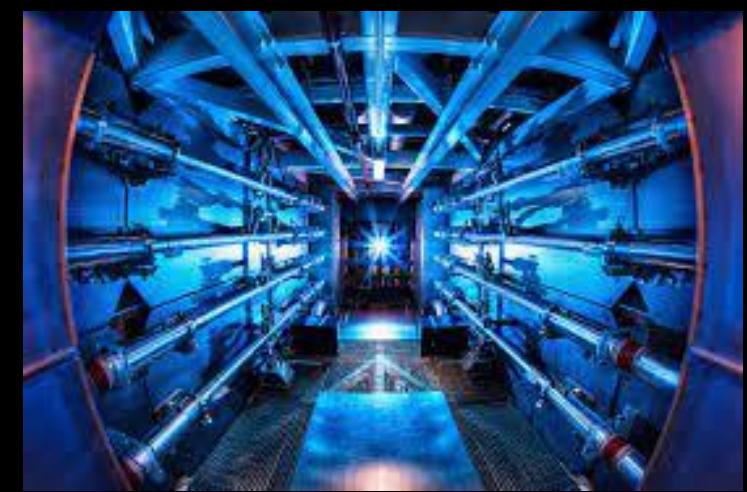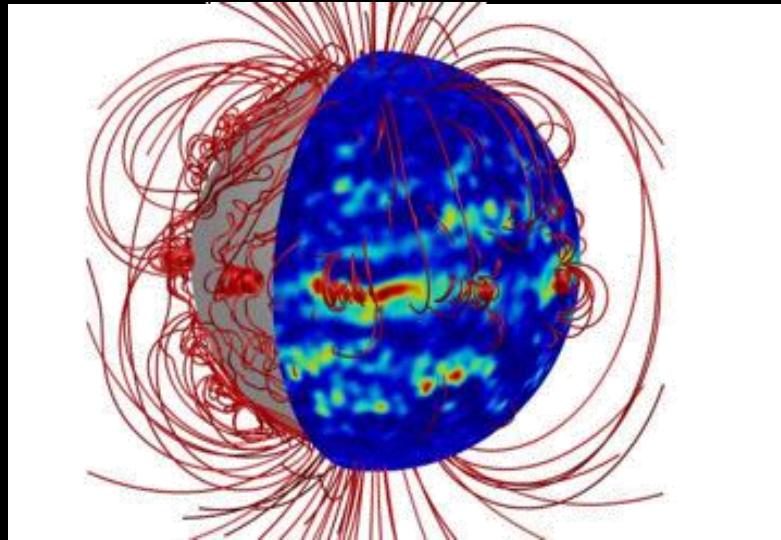
Neutron Star Magnetic Field Strength
Pulsars 10^{12} G
Magnetars 10^{15} G ~ 30 B_{QED}
Neutron Star Interiors < 10^{17} G
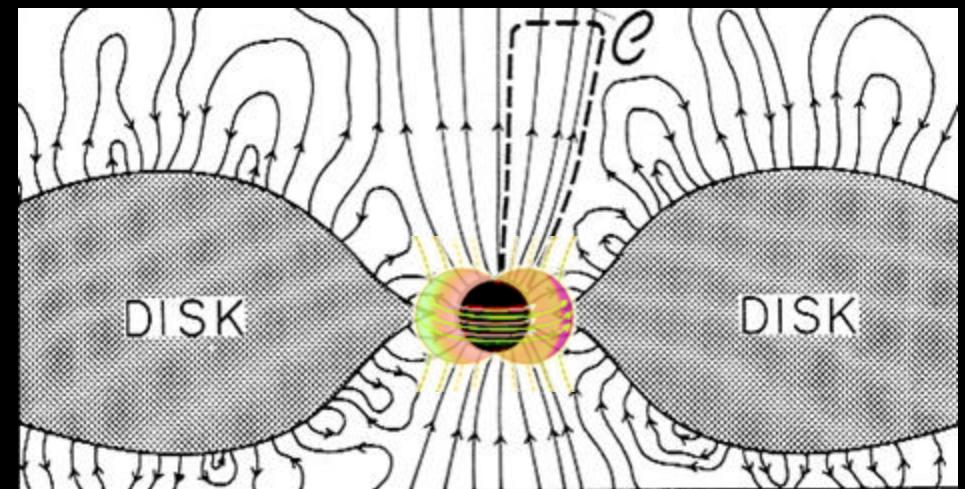
Spinning Black Hole EMF (ergosphere)
M87 10^{19} V
Quasar 10^{20} V
GRB, Magnetar, 10^{23} V, 10^{21} A

Plasma Physics is central to understanding neutron stars and black holes

What are the main "metabolic pathways" of cosmic sources?

- Gravitational
- Rotational
- Electromagnetic
- Neutrino

Mostly understood for pulsars, quasars, SGRs
Big questions for GRB, FRB, AGN...

Where and how are the highest energy particles accelerated?

- ~ ZeV Cosmic Rays
- ~ PeV Neutrinos
- ~ PeV Gamma ray

Direct acceleration, shocks, current sheets, exotic processes

Is there any evidence for physics beyond standard electrodynamics?

- QED when B >> $B_{Schwinger}$
- Axions
- Black Hole Event Horizons

No evidence as yet for any of this

- Is disk magnetically arrested by trapped flux or ejected by ten percent of the jet power derived from the black hole spin?

- Are jets continuously collimated by MHD winds extending over a million decades of radius?

- Polarization and caustics

Parfrey Philippov, Cerutti 2017

RB +Globus

SLAC

Rauch+RB 94

1/24/2025

28
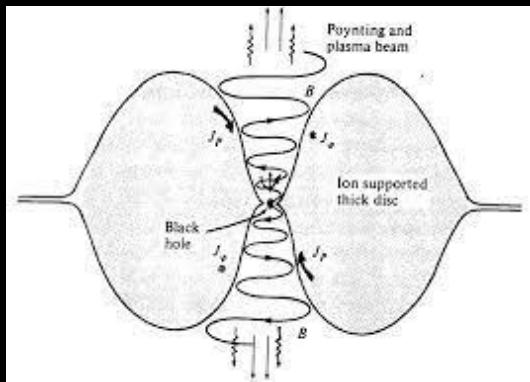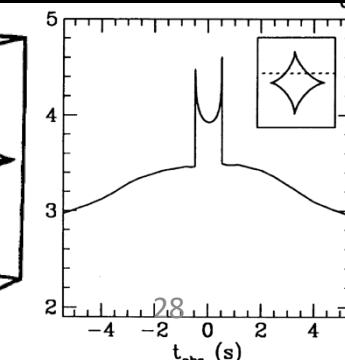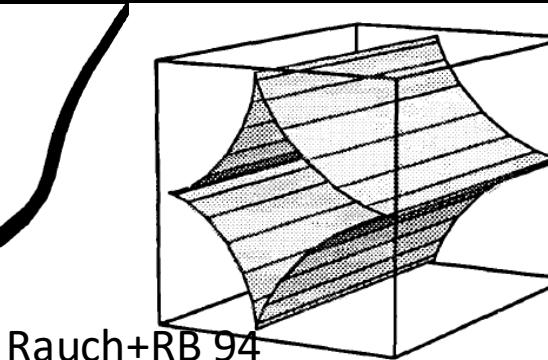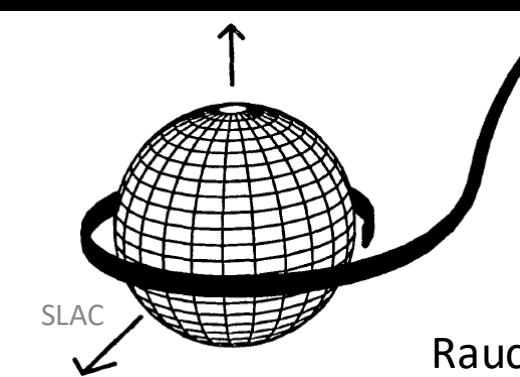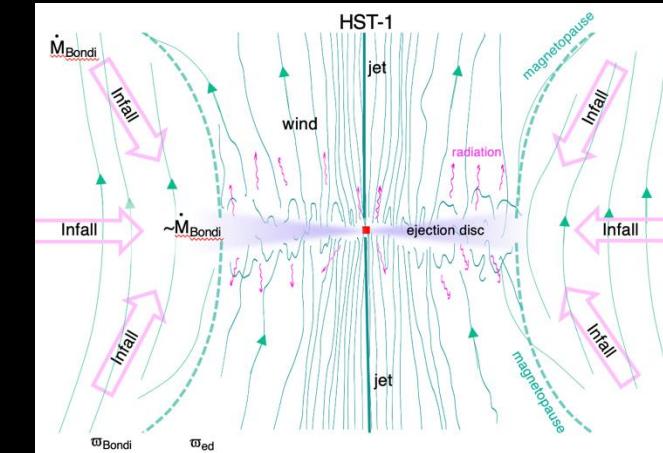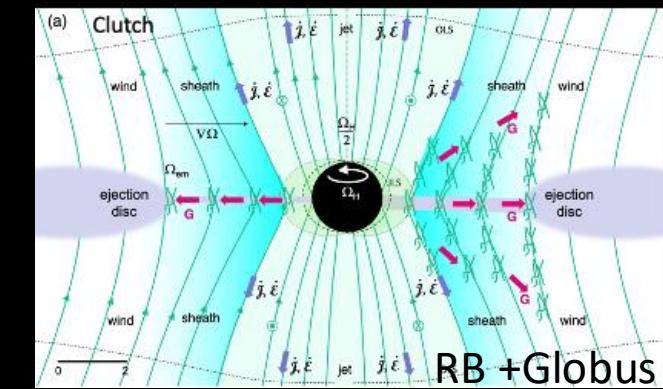
- ## Kerr spacetime
  - B frame: symmetry -> conservation laws
  - Z frame: frame dragging; ergosphere
  - M frame: E=0 locally; define emission

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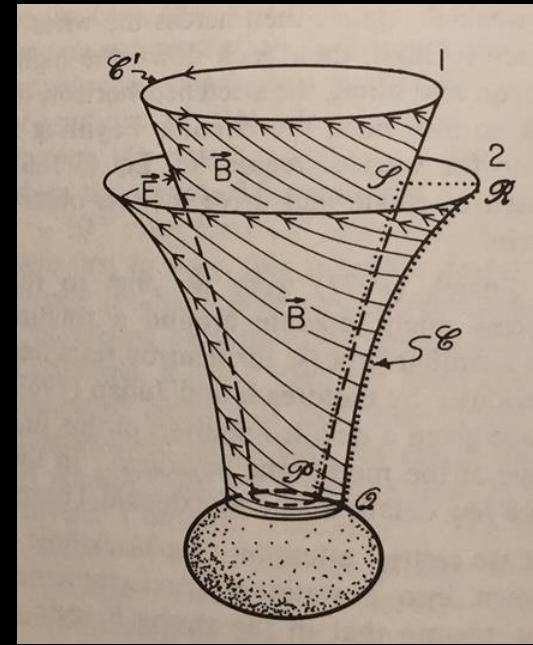
Extract rotational energy as invisible Poynting flux
Dissipation happens "behind the curtain" and remotely in jet

- Lorentz invariant $B^2 - E^2$ can change sign
- Magnetars flares, ergomagnetospheres
- Force-free equations become non-evolutionary
- Electromagnetic turbulence with E ~ B
- Tsunamis not masers, not bunches
- Or QED breakdown with electromagnetic energy accounting for most of the energy released.
- Could be relevant for AGN, magnetars,
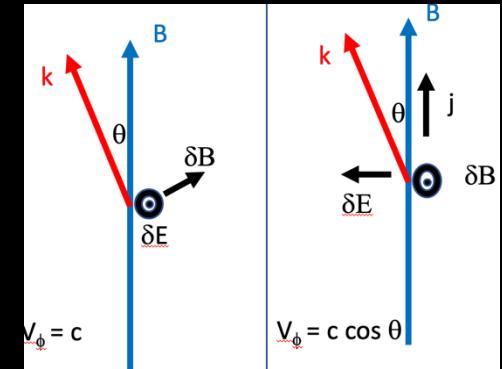
Magnetars

- 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?
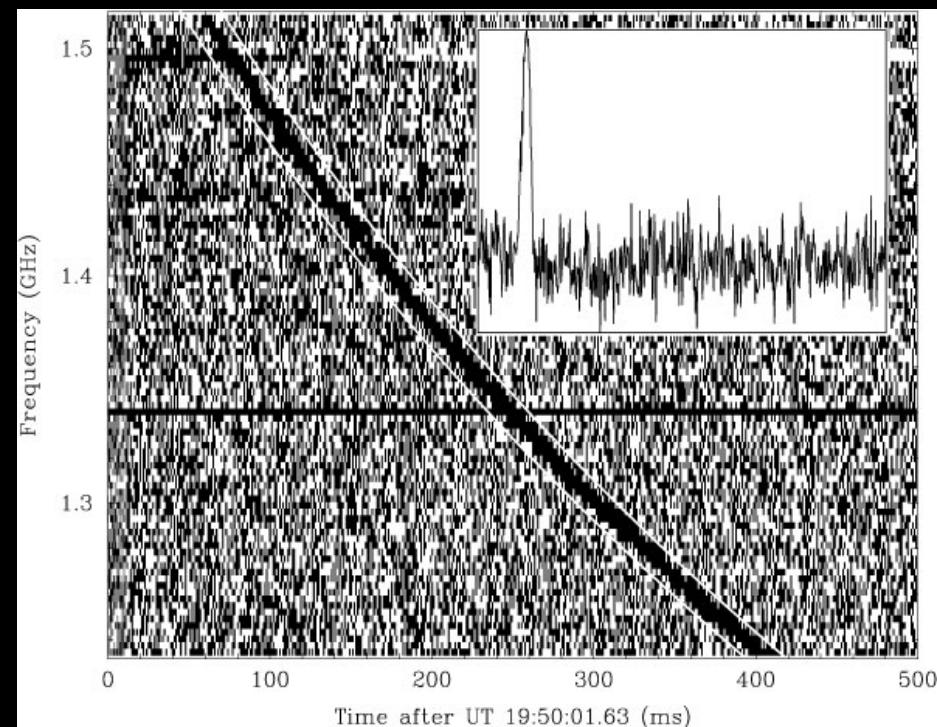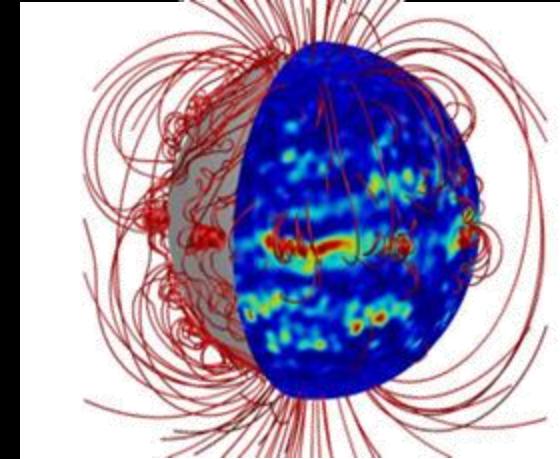
THEORETICAL DEBATE #3
ARE SHOCKS CLEVERER THAN US?

- Gamma Ray Bursts – high Lorentz factors

- Supernova shock fronts may accelerate 3 PeV cosmic rays

- Galactic winds may accelerate 100 PeV cosmic rays

- Cluster shocks may accelerate 300 EeV cosmic rays

- If so, they have to be maximally turbulent

- Most energetic particles escape upstream from spherical shocks

- Can this be sustained?

Spitkovsky
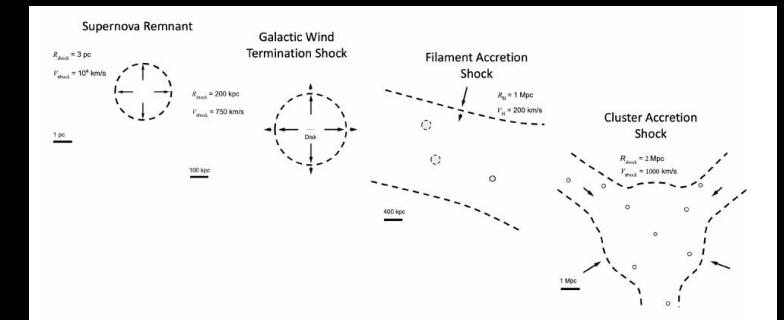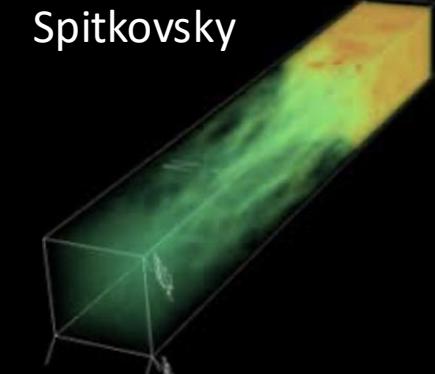
Ultra High Energy Cosmic Rays

- 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

Globus, RB

whole sky
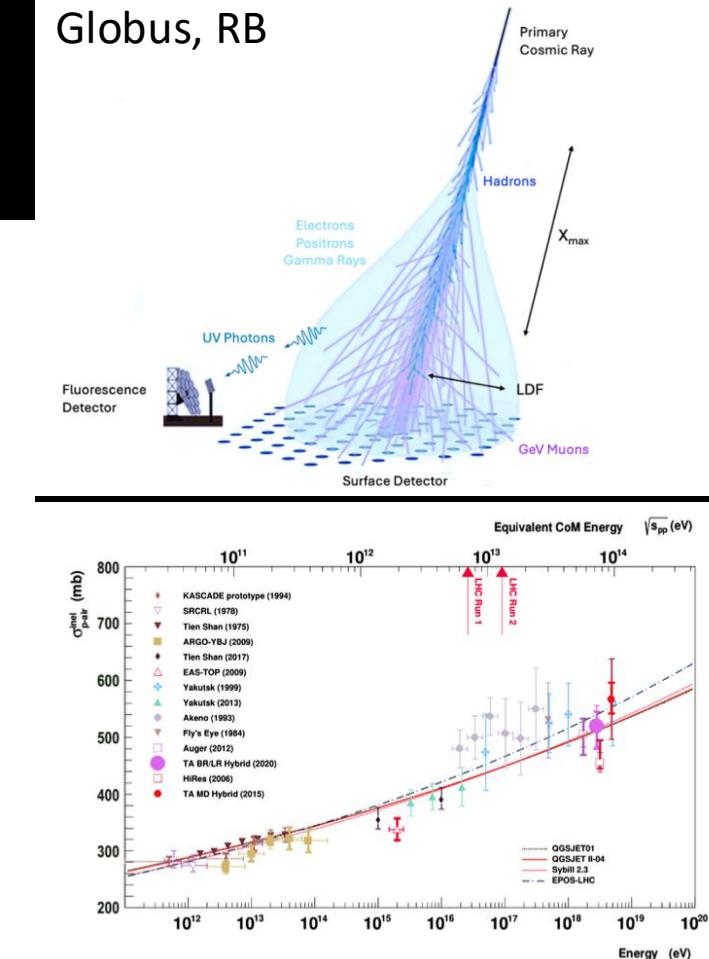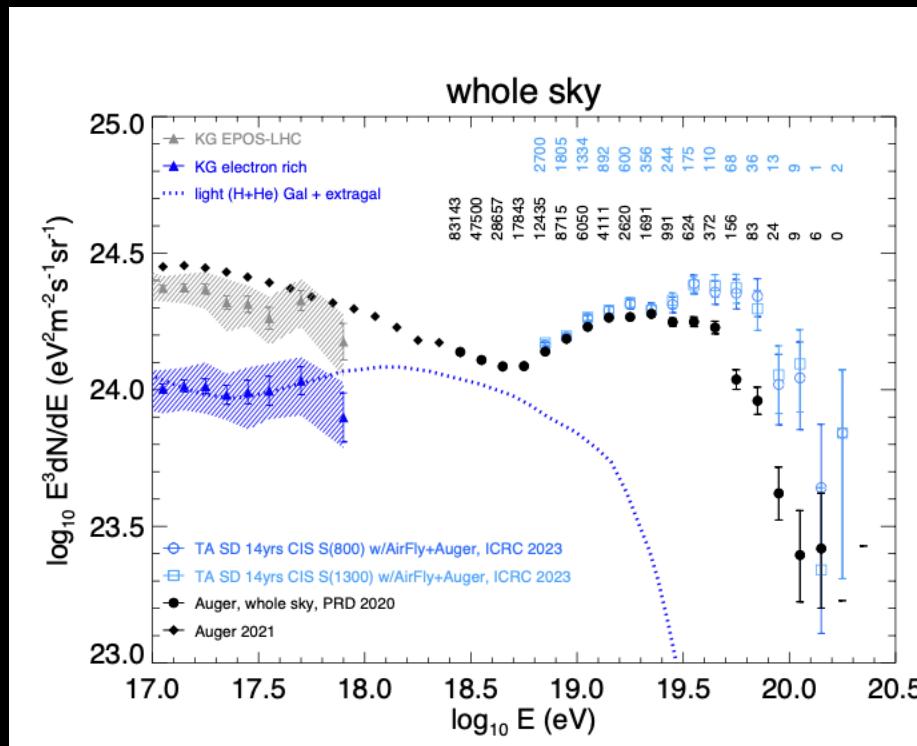
S U M M A R Y

- Remarkable observational discoveries taking CED, QED into extreme regimes
- Multi-messenger astronomy
- Mostly involving neutron stars and black holes
- 10^{40} kg; 100 GT (10 TT?); 10^{23} V; 10^{40} K; 10^{49} W; 1 PeV; 1 PeV; 0.3 ZeV…
- Quasars, Pulsars, GRB, UHECR, Magnetars, FRB, VHE ν, GWB…
- Opportunities for observing new fundamental physics, but nothing so far
- New discoveries-> many explanations
- New facilities-> few explanations-> theory challenges
- Rapid progress: observation, experiment, simulation, theory
- Bottom up and top down

Who knows where it will lead?

M 8 7   B L A C K   H O L E -   F O U R   P U Z Z L E S

- $M_H \sim 6.5 \times 10^9\ M_{sun} \sim 10^{10}$ km
  - Guess: a = 0.9; P_H =7d; $E_{rot} \sim 2 \times 10^{56}$ J
  - Good for > 10^{12} yr
  - Where does this energy go?
- $L_{jets} \sim 6 \times 10^{36}$ W $\sim 600\ L_{ring} > 100\ L_{disk} \sim 10^{-4}\ L_{Edd}$
  - Why is the ring so dim?
  - Average pressure in emitting electrons ~ 10^{-7} magnetic pressure
- Mass supply rate (Bondi) ~ 10^{22} kg s^{-1}?
  - >> Mass inflow rate
  - What drives the mass supplied away with positive energy?
- Jet collimation beyond 10,000 gravitational radii
  - How is this effected?
  - Observe sheaths

ALMA 230 GHz
1300 light years

VLBA 43 GHz
0.25 light years

EHT 230 GHz
0.0063 light years

3C 84 Radio Astron

1 Light Day

Cen A
EHT
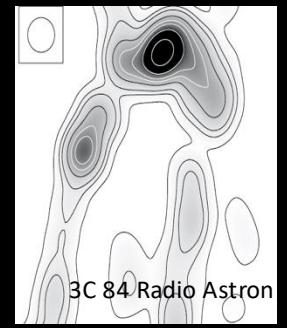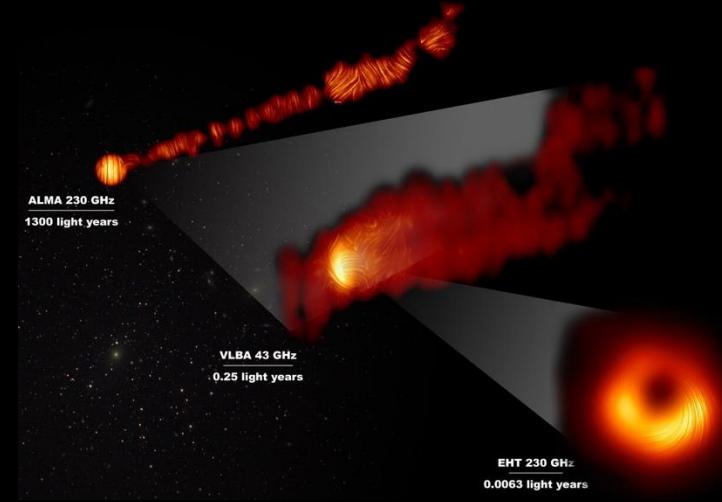
- ~ 0.1 jet power drives off gas
- Collimates jets
- Interacts with infalling gas
- Magnetic Field > 10 mT
- Cooling time < 1000 s
- Observing flares
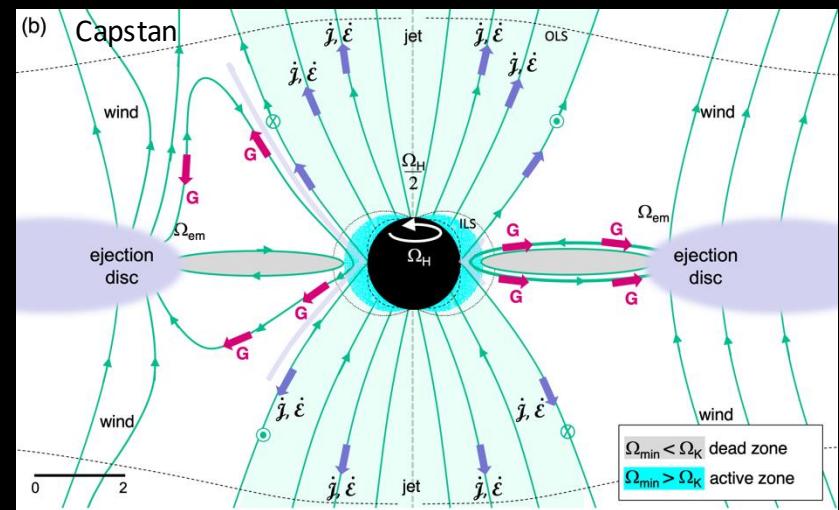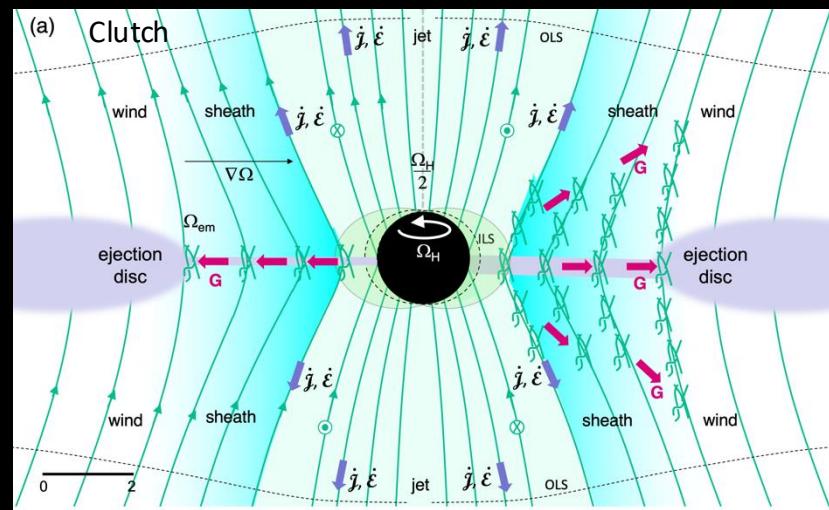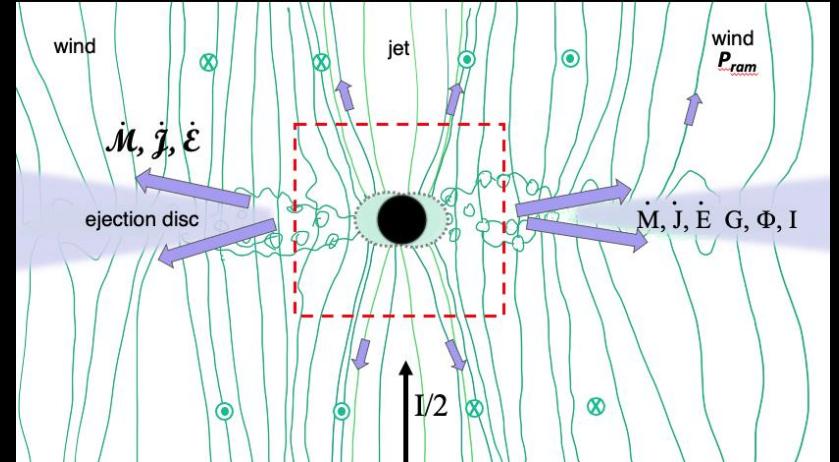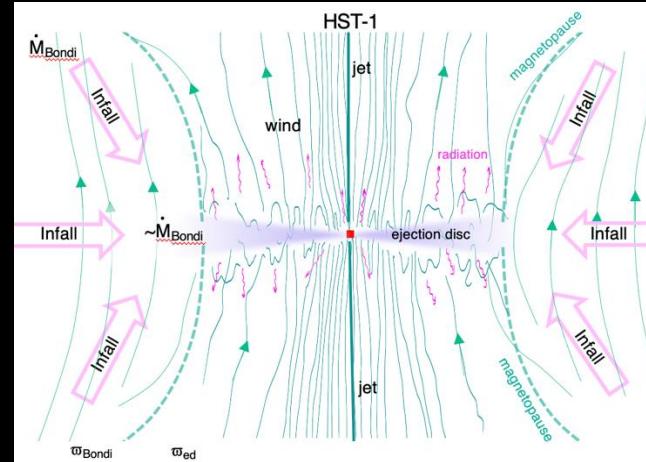
M87 powered by rotational not gravitational energy – Nature not Nurture – cf Stars

RB + Globus

$$\nabla \cdot \mathbf{B} = 0; \ \nabla \cdot \mathbf{E} = \rho; \ \partial_t \mathbf{B} = -\nabla \times \mathbf{E}; \ \partial_t \mathbf{E} = \nabla \times \mathbf{B} - \mathbf{j}$$

$$\partial_t \mathbf{S} + \nabla \cdot \mathcal{T} = \rho \mathbf{E} + \mathbf{j} \times \mathbf{B} = 0, \ \mathbf{j} = \frac{(\nabla \cdot \mathbf{E})(\mathbf{E} \times \mathbf{B}) + (\mathbf{B} \cdot \nabla \times \mathbf{B} - \mathbf{E} \cdot \nabla \times \mathbf{E})\mathbf{B}}{B^2}.$$
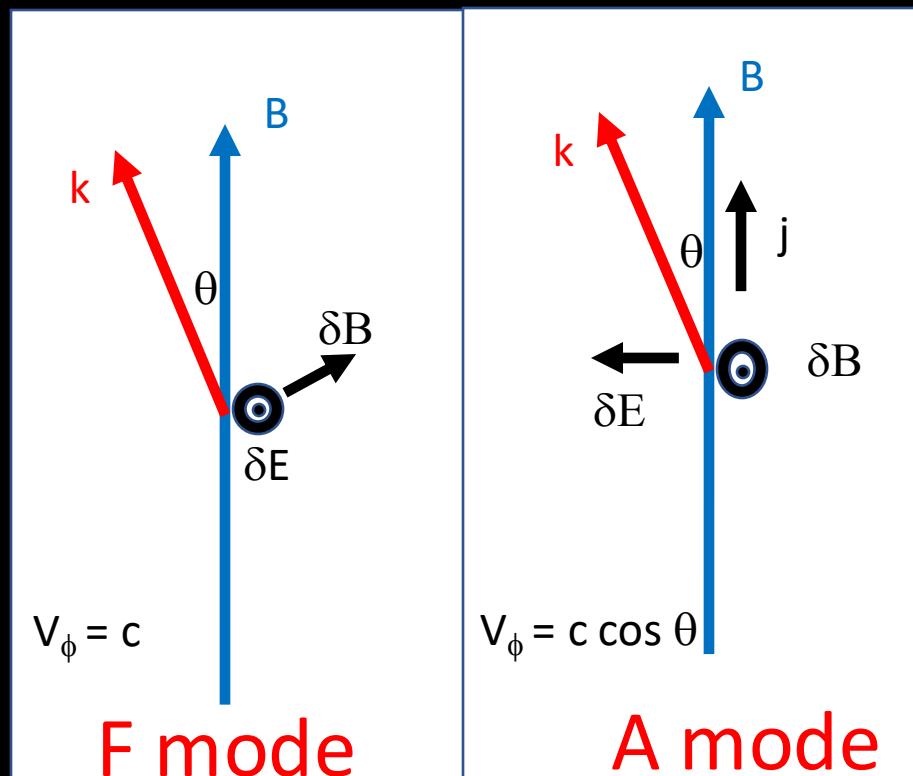
- E.B = 0; ∇(E.B)=0
- Use GR version for black holes
- Add small **E . B**
  - cf viscosity
  - QED so important you can ignore it

F mode — $V_\phi = c$

A mode — $V_\phi = c \cos \theta$

Post-Maxwell, pre-Thomson Electrodynamics

ELECTRIC ZONES

- $E^2 - B^2 > 0$
  - 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 valid with dissipative inner scale
  - Electromagnetic "turbulence"?
  - Independent of microphysics
- 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

Parfrey Philippov, Cerutti 2017

- ## Linear Polarization
  - ### Magnetic Field Direction
- ## Circular Polarization
  - ### Magnetic Field Sign
- ## Caustic Crossing
  - ### Distinctive time signatures
  - ### cf photon rings

Rauch +RB 94

SLAC
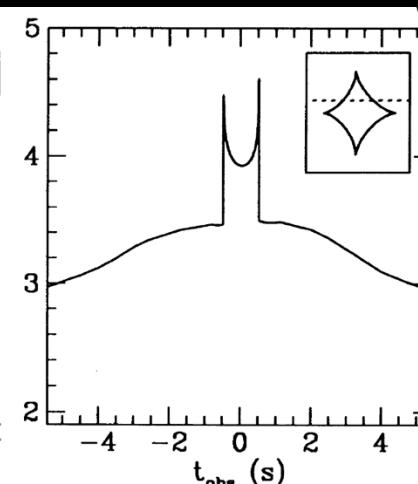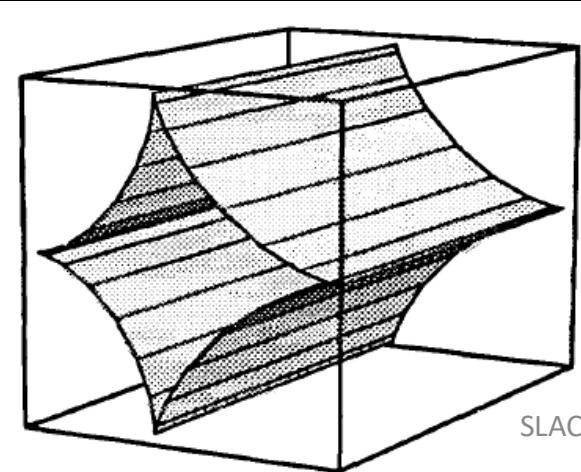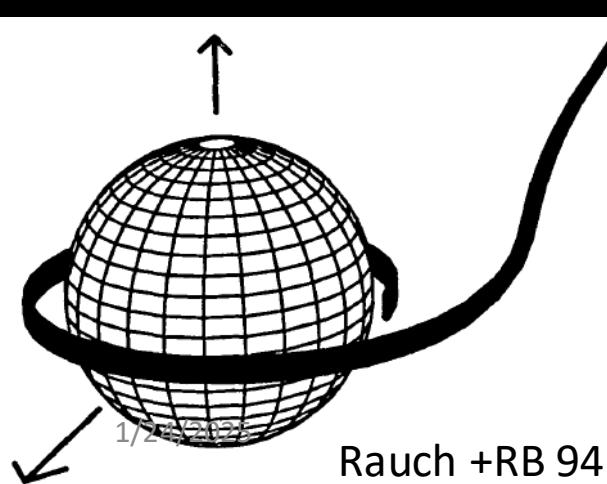
EARTH, AIR, FIRE AND WATER

Starquakes?

Magnetic Waves?

Lightening?

Electromagnetic Tsunamis?

- Magnetic waves created at neutron star surface
- Become nonlinear as B ~ r^{-3}
- Waves can interact
  - F+F modes – transform to head on collision
  - F+A modes – transform to head on, or rear end collision
  - A+A modes – transform to stationary frame – traffic jam
- Can also lead to electric zones
- Creates electromagnetic turbulence which mode converts to radio waves
  - Microphysics unimportant
- Or QED showers

The Future of Relativistic Astrophysicists

- Longstanding, global, existential crises
  - Climate, energy, disease, deforestation, flood, drought, fire, resource, inequality…
- Needs adaptive, corrective, innovative and rapid response
  - Problems are global
  - Space and ground
  - Monitoring requires new instruments and creates large, heterogeneous, datasets
  - Machine learning…
- Solutions will involve many fields of science
  - Atomic, biology, chemistry, computational, engineering, fluid, nuclear, plasma, radiation…
  - Progress at interfaces, requiring boldness to "fail fast" and supply new insight
- Just like relativistic astrophysics!
- We need to become more broadly proficient
  - Learn new fields; resist specialization

We Need to Start Now

Top-Down and Bottom-Up Science

- Reductionist Approach
  - Celestial Mechanics, Stellar Atmospheres
  - EM, Plasma, for Modest Dynamic Range
  - Cosmological Subgrid Modeling?
  - Connect Data with Simulation using Machine Learning?
- Inductive Approach
  - Global Conservation Laws
  - Characteristic Length, Time, Mass, Energy Scales
- Special Sources vs Statistical Sample

SLAC Start with Best Observational Clues on Largest Scales 43

Scientific Discovery is "Logically Unscripted"

- CMB – antenna noise
- Quasars (massive BH) – radio source identifications
- Stellar BHs – X-ray source identifications
- Massive and mutable ν's – checking solar model
- Neutron stars – lunar X-rays
- Pulsars – interplanetary scintillation
- Gamma ray bursts – nuclear weapons monitoring
- Dark matter – galactic and stellar orbits
- Cosmic acceleration – supernova explosions
- Gravitational lenses – quasar follow up
- Gravitational radiation – pulsar timing
- Massive black hole binaries – LIGO….
- Fast Radio Bursts – transients e.g. NSB, PBH

BIG Surprises still Coming