

New Directions in Extreme Electrodynamics of Compact Sources

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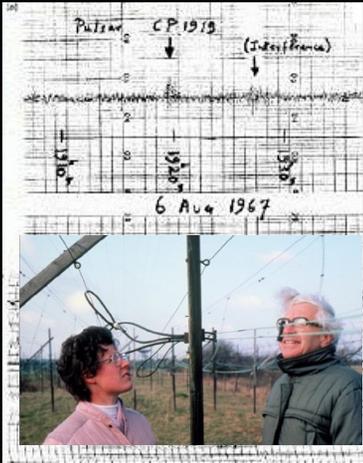
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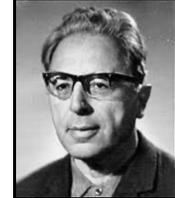
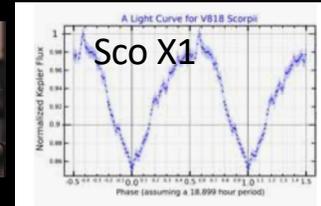
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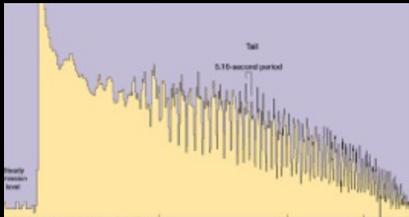
NEUTRON STARS



Pulsars

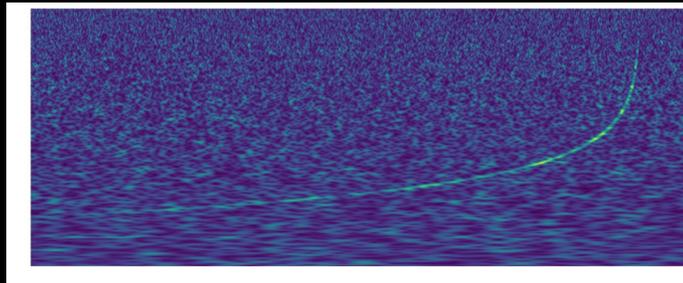


Neutron Star Binary Sources



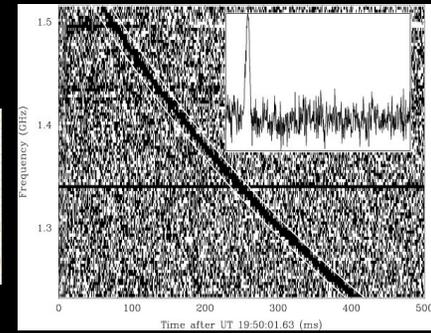
Soft Gamma Repeaters
Magnetars

6/01/2026



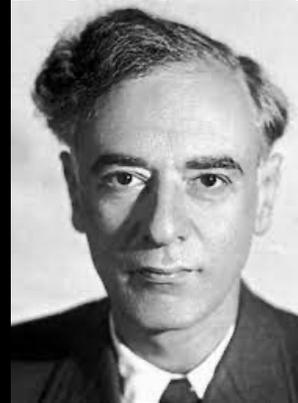
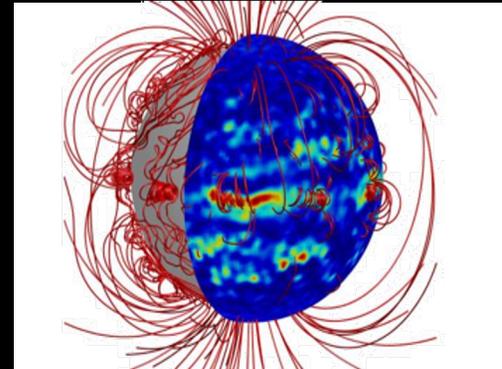
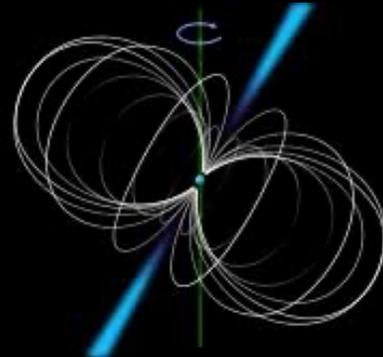
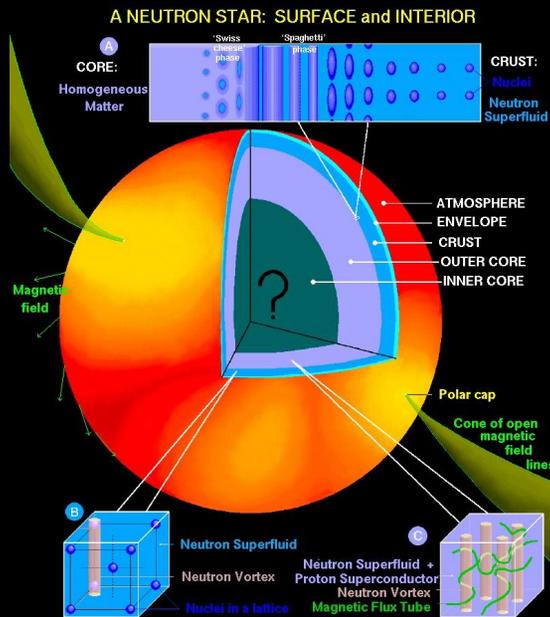
Neutron Star Mergers
Short Gamma Ray Bursts

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Fast Radio Bursts
Magnetars?

NEUTRON STARS



Neutron Star
 Mass $\sim 1 - 2.5 M_{\text{sun}}$
 Radius $\sim 10 \text{ km}$
 Density $\sim \text{Nuclear}$
 Magnetic Field $< 10 \text{ TT}$

All physics?

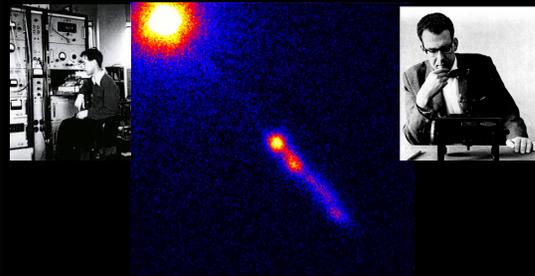
6/01/202p

Pulsar
 Magnetic Field $\sim 100 \text{ MT}$
 Rotation-powered

Magnetar
 Magnetic Field $\sim 100 \text{ GT}$
 $\sim 30 B_{\text{Schwinger}}$
 Magnetically-powered

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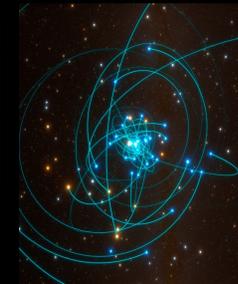
BLACK HOLES



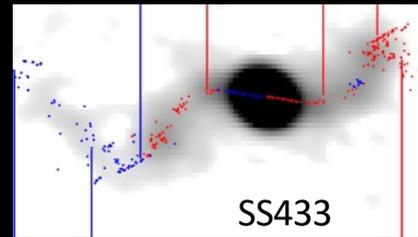
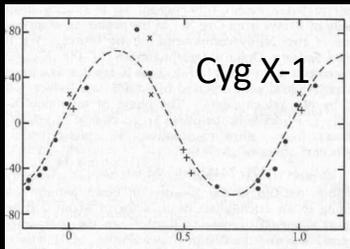
Quasars



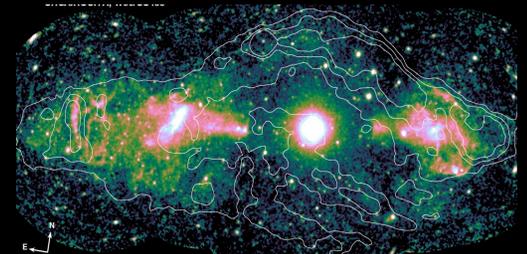
M87



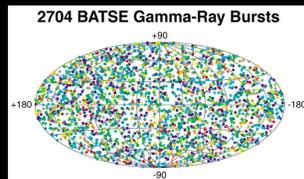
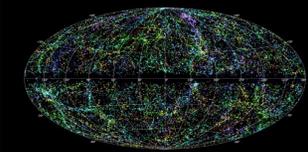
Galactic Center



Black Hole Binary and Triple Sources



GW 150914



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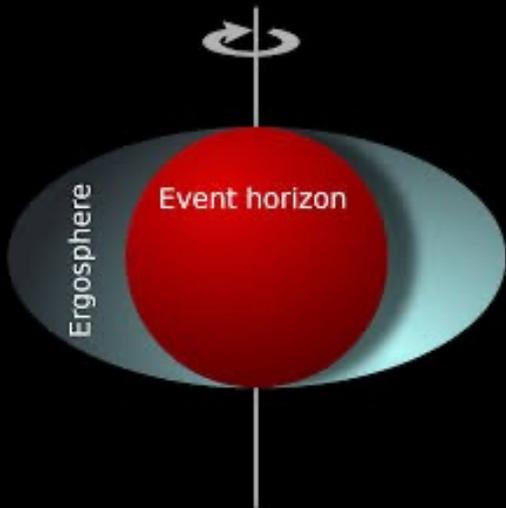
Merging Black Holes



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Gamma Ray Bursts

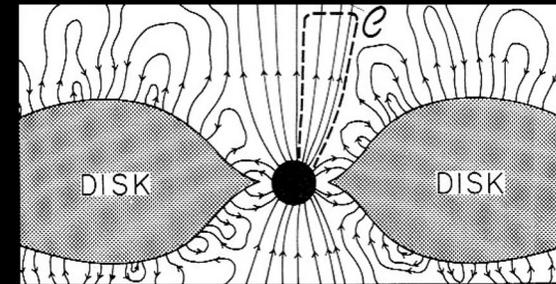
BLACK HOLES



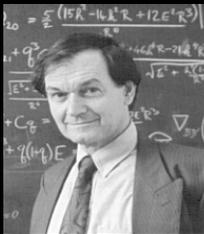
Kerr Black Hole



Accretion Disk
Gravity -powered

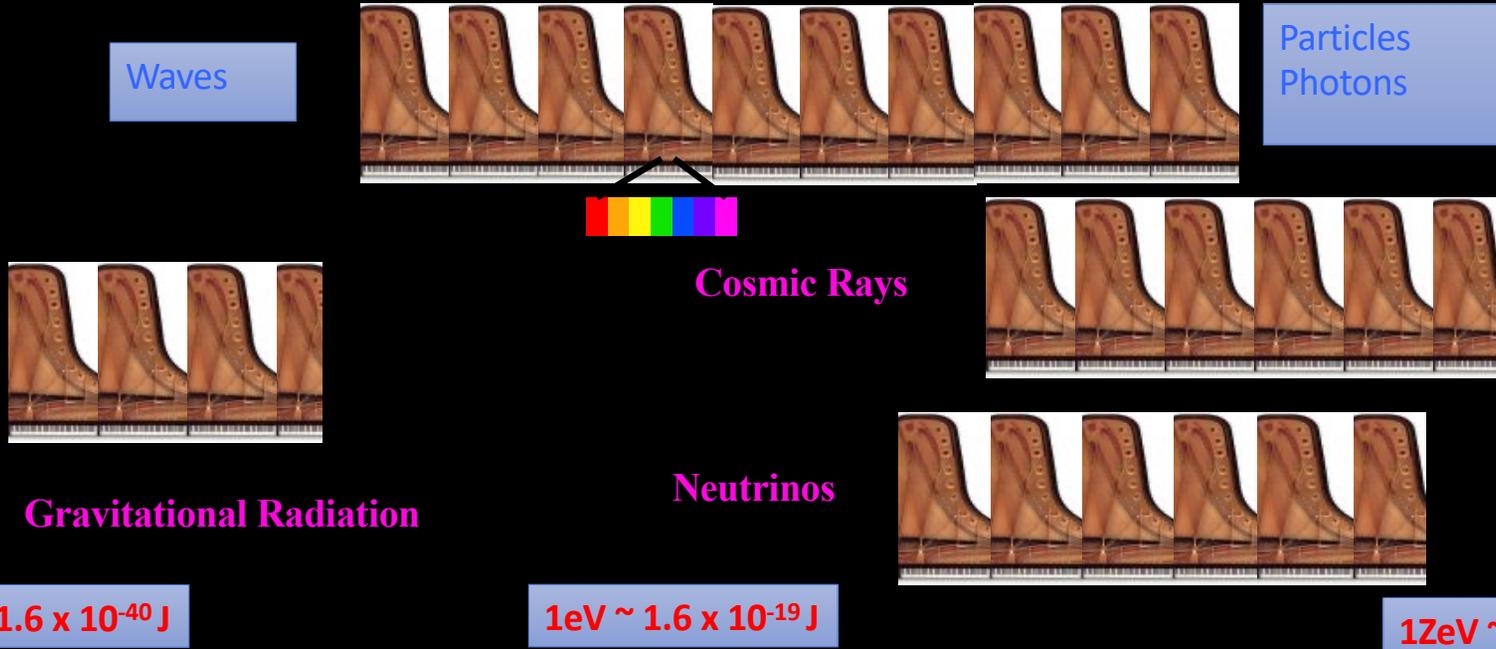


Magnetized Black Hole
Spin-powered



MULTI-MESSENGER ASTRONOMY

Wavelength ← **Electromagnetic** → Frequency



140 Octaves being Explored

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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
 - Special relativity
- Maxwell used continuous current (1860s)
 - Despite kinetic theory, electrolysis!
 - MHD
 - Force-free electrodynamics
 - Energy – Poynting (1885)
- Particles, Lorentz force (1889)
 - Atomic, nuclear, particle, plasma physics



Q U A N T U M E L E C T R O D Y N A M I C S

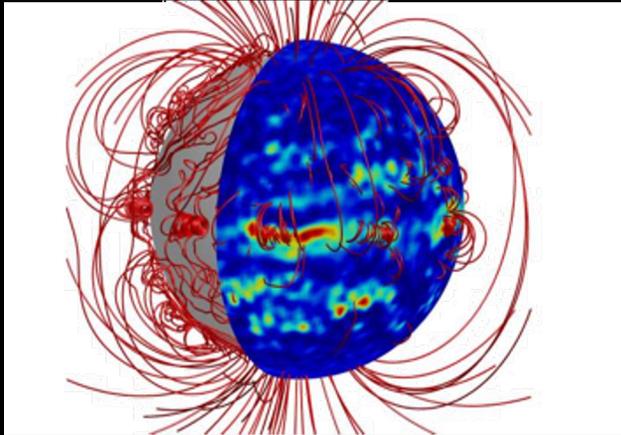
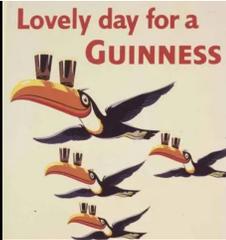
QED Action

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

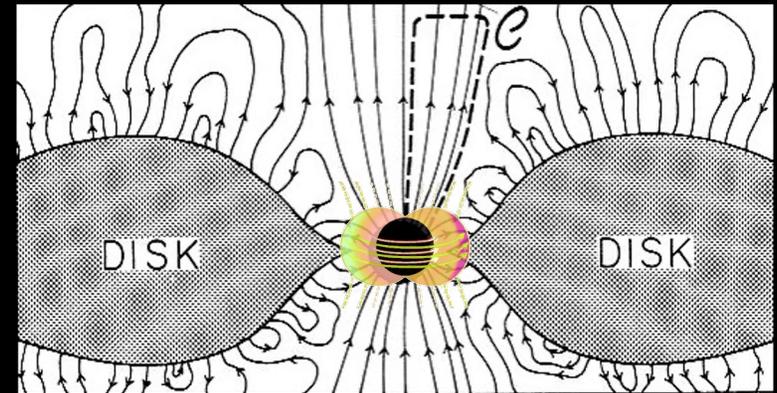
- Photons are relevant
- Electrons in magnetic field quantized like atoms
- Normal QED is valid when energy jumps are less than rest mass
 - Magnetic field < Schwinger Field $\sim 4 \text{ GT}$
- Extreme QED needs new approaches
 - Many-body plasma effects



ELECTROMAGNETIC FRONTIER

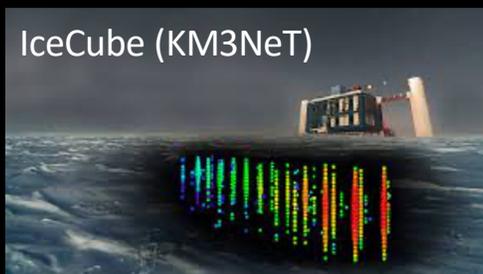
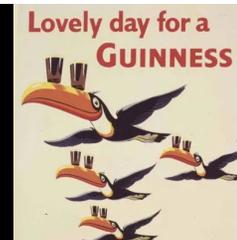


Magnetar Flare
EMF ~ 100 ZV
Axions



Spinning Black Hole
M87 ~ 10 EV , 100 PA
Quasar ~ 100 EV, 1 EA
GRB ~ 100 ZV, 1 ZA

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



IceCube (KM3NeT)

> 1-100?? PeV Neutrinos



LHAASO

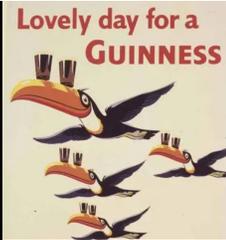
~ 1-3 PeV Gamma Rays



Auger/TA

~ 0.3 ZeV Cosmic Rays

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



Black Hole Merger

10^{49} W



Gamma Ray Burst

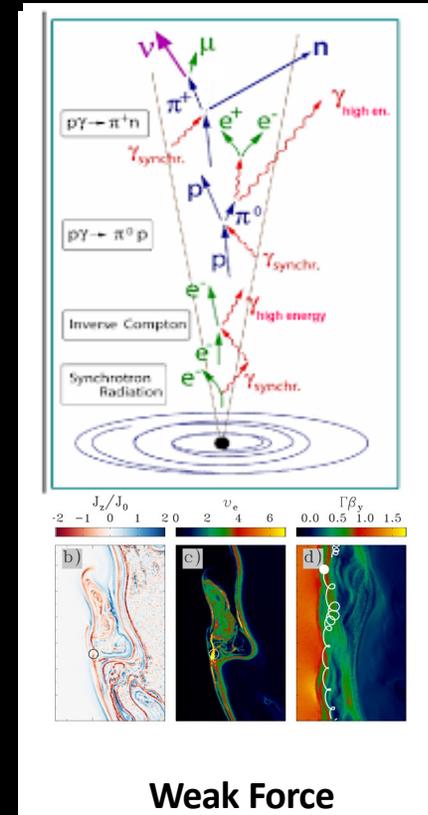
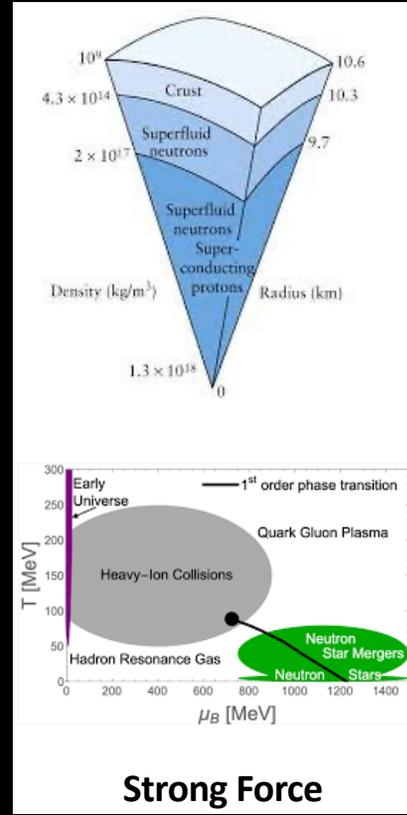
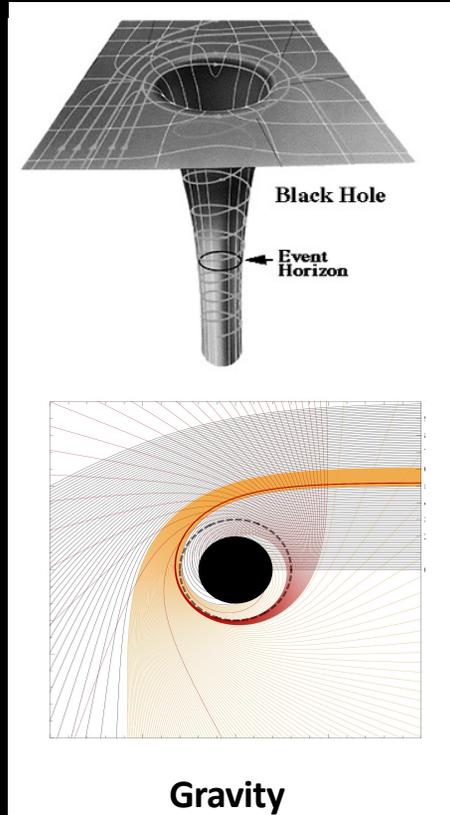
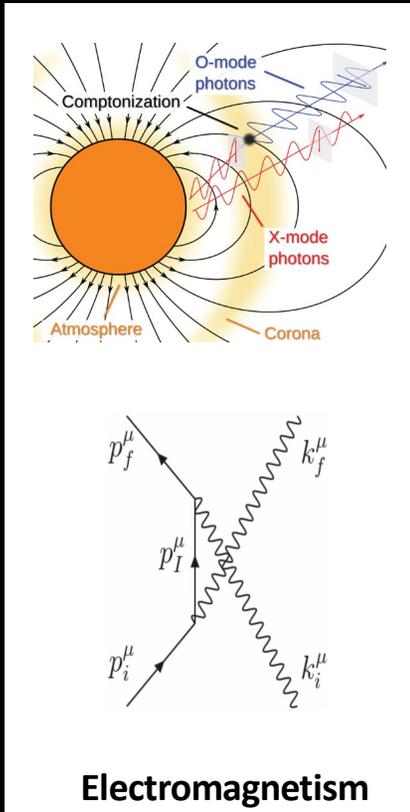
10^{45} W



Active Galactic Nucleus

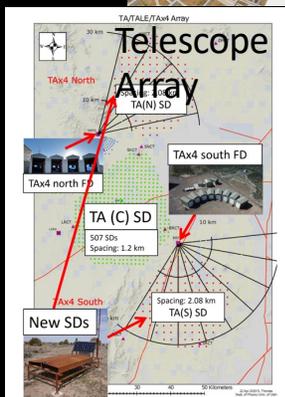
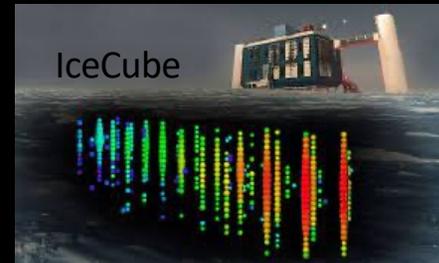
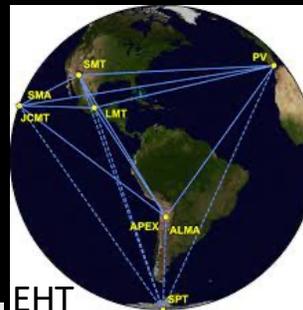
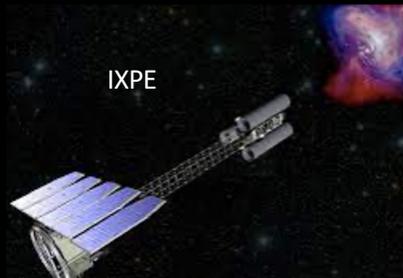
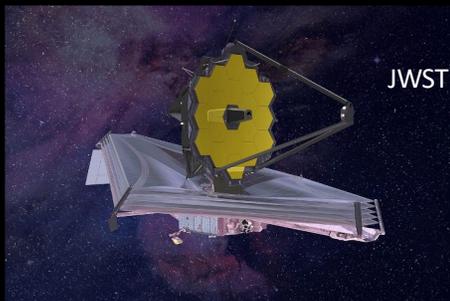
10^{39} W $\sim 10^3$ galaxies

PHYSICS FRONTIER



Plasma Physics Required

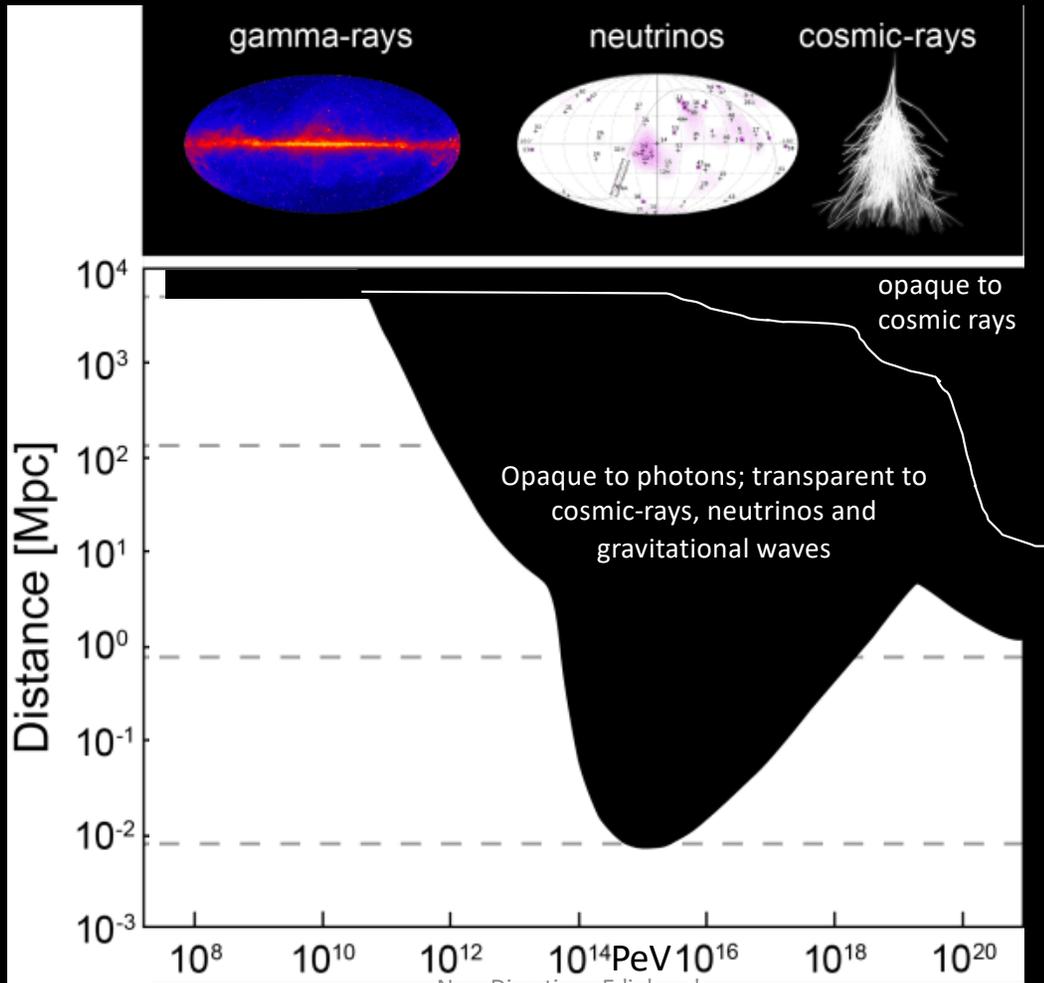
OBSERVATIONAL FRONTIER



OBSERVATION FRONTIER

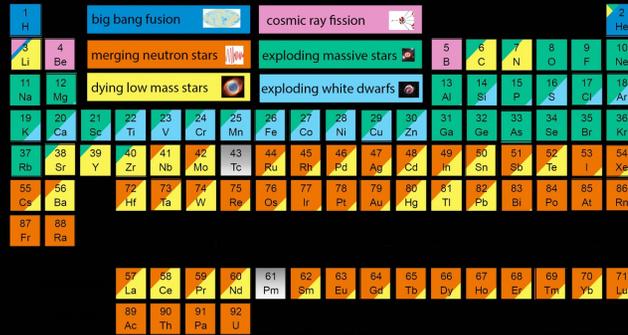
> 100 EeV cosmic ray
Sources within ~ 30 Mpc

>~ PeV γ -rays Galactic



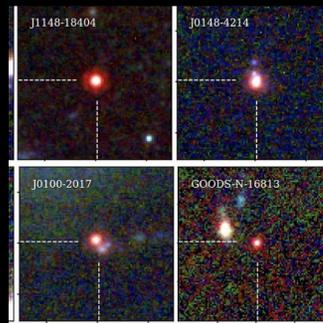
C O S M O L O G I C A L F R O N T I E R

The Origin of the Solar System Elements

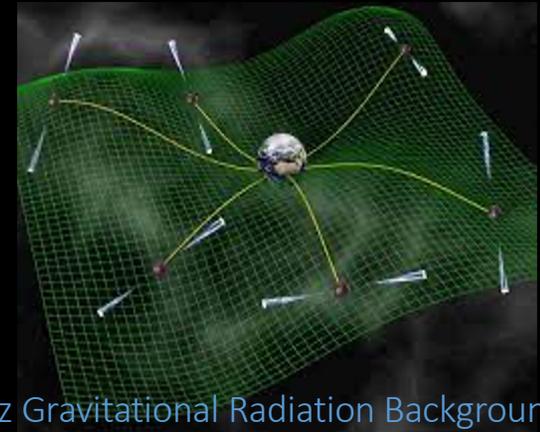


Active Galactic Nuclei (AGN)
Mediate the evolution of galaxies

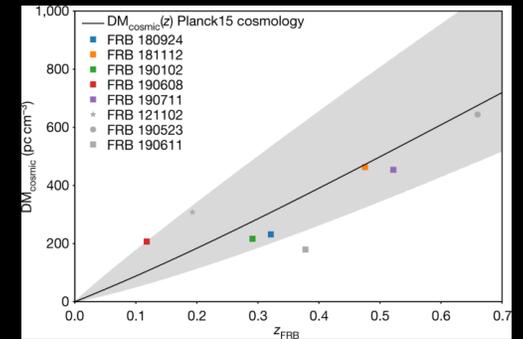
Supernovae, kilonovae Element formation



Little Red Dots
Early galactic nuclei?



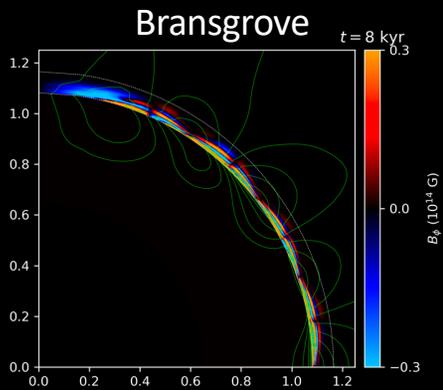
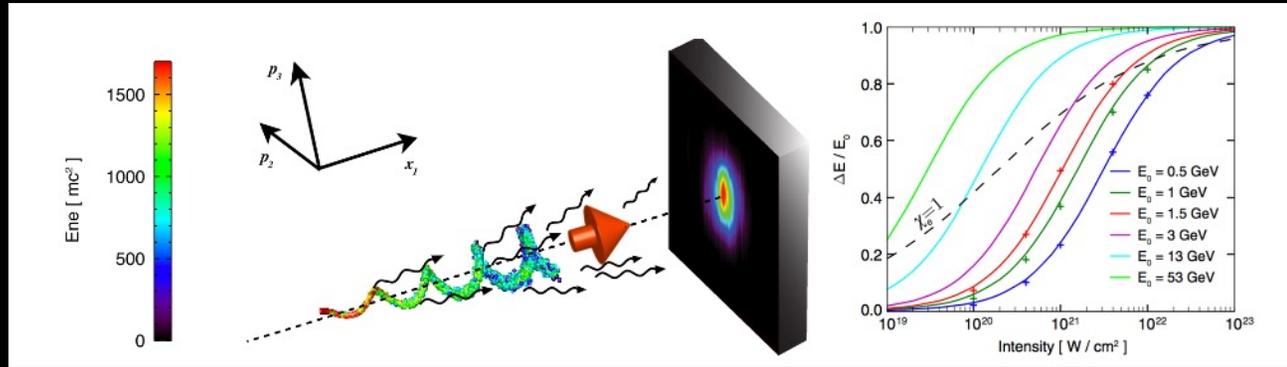
nHz Gravitational Radiation Background
Black hole binaries?



Fast Radio Bursts (FRB)
Measure baryons

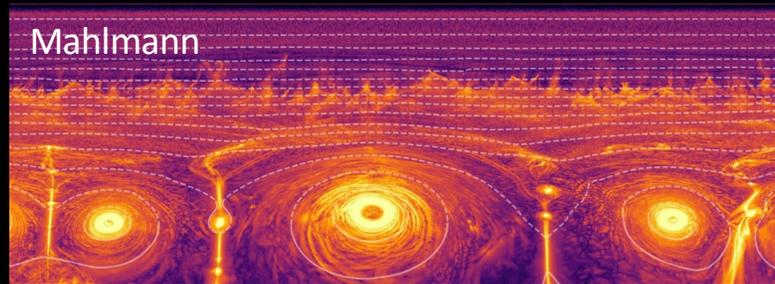
COMPUTATIONAL FRONTIER

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



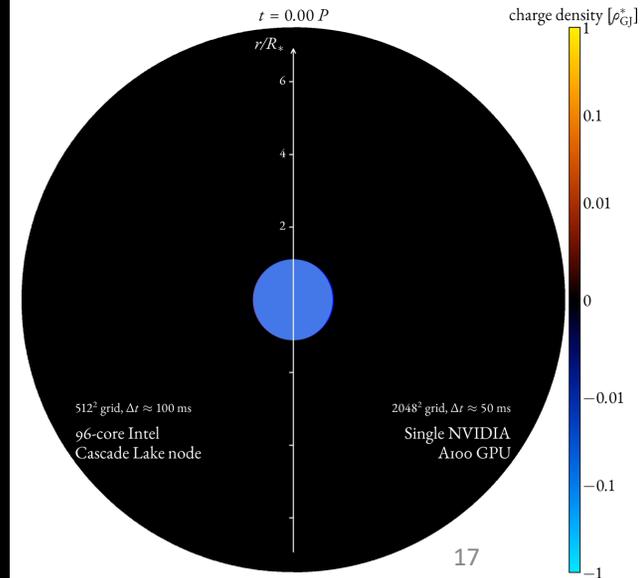
Hall Drift in Crust

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Rapid Reconnection

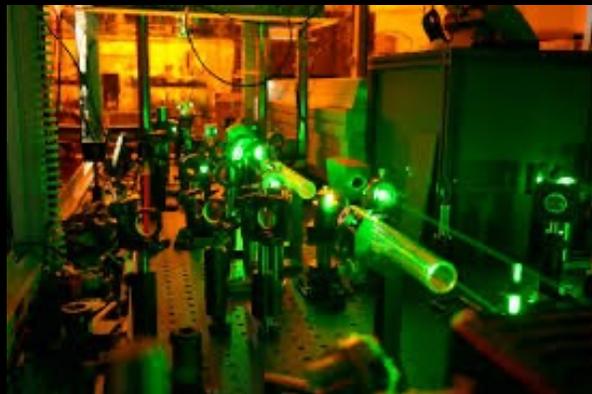
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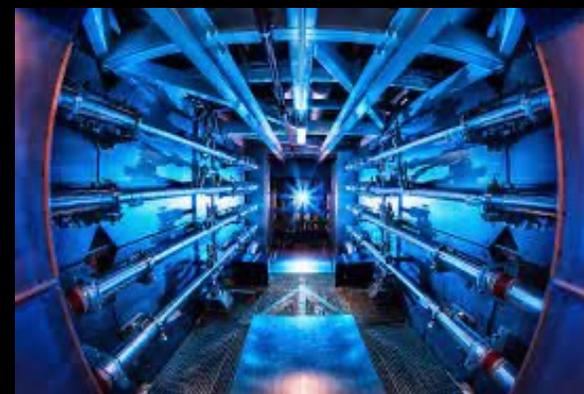
EXPERIMENTAL FRONTIER



LCLS II



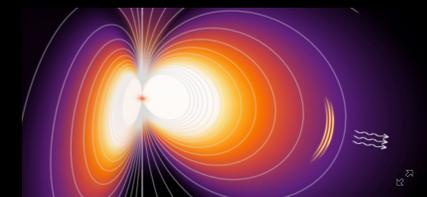
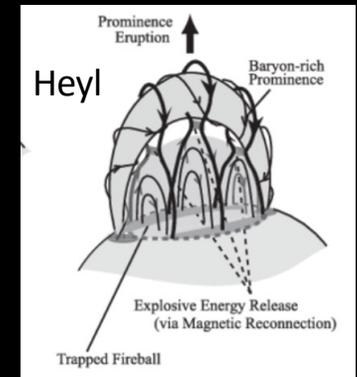
IPFN



NIF

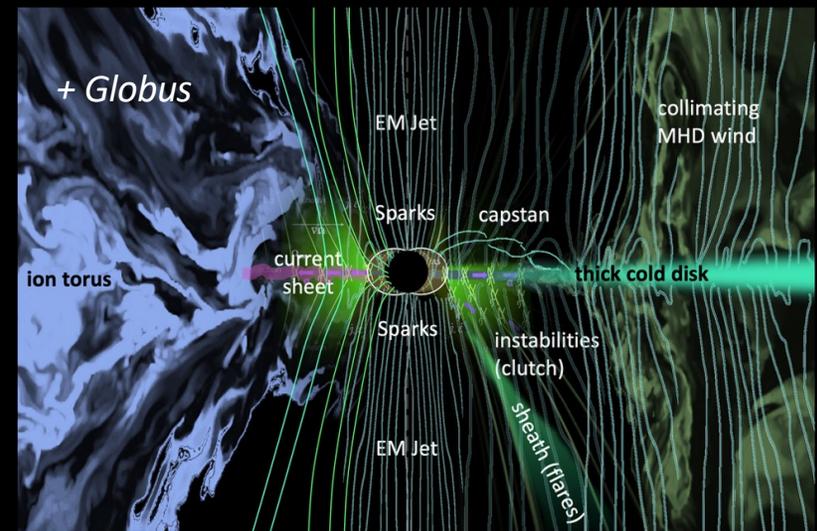
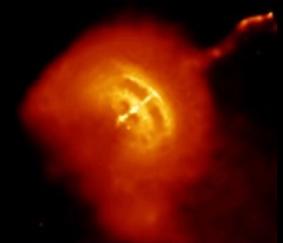
A R E C H A R G E D P A R T I C L E S N E C E S S A R Y F O R F A S T R A D I O B U R S T S ?

- Coherent radio emission; μs pulses
 - Hot as a tsunami
 - Magnetar flares; km \rightarrow cm waves
 - Escape may be challenging
- Kinetic explanations
 - Plasma instabilities; maser emission...
 - Monster shocks, current sheets, sparks form FRB...
 - Outer magnetosphere $B \sim r^{-3}$
- Alternative continuum explanation
 - Force-Free Electrodynamics; Maxwell, $\rho \mathbf{E} + \mathbf{j} \times \mathbf{B} = 0$, evolutionary
 - Max/min plasma density $\sim L / r_L$
 - Fast and Alfvén waves; nonlinear and $E/B \rightarrow 1$, non-evolutionary
 - Electromagnetic turbulence in inner magnetosphere
 - Inner scale determined by charge starvation
 - FFE \rightarrow escaping EM waves at inner scale, not heat



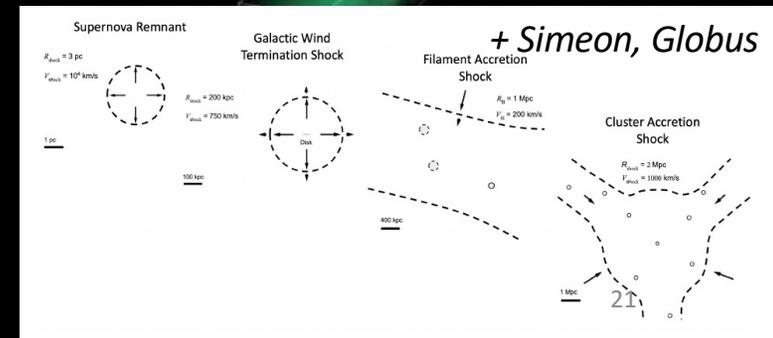
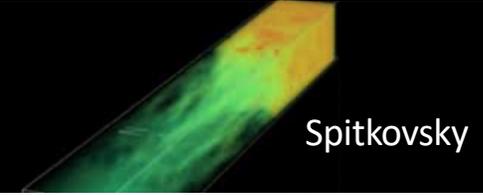
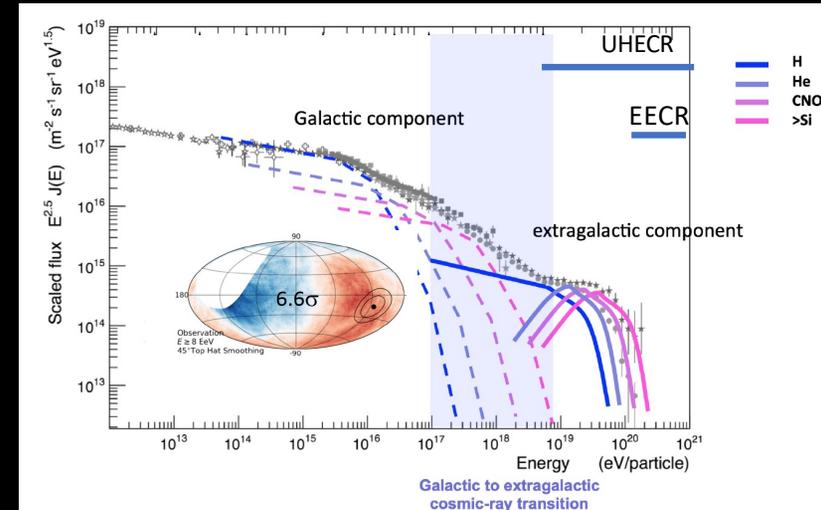
ARE BLACK HOLE SOURCES POWERED BY GRAVITY OR SPIN?

- Jets exhibit large linear polarization
 - AGN, binaries (SS433), GRB, pulsar nebulae
 - Spin powered
 - Black holes (and neutron stars) create giant electrical circuits
- Standard accretion disks have conservative mass inflow
 - Driven by magnetic torque, releases gravitational energy
 - Torque carries energy outward
 - Dissipation -> radiation
 - Intermediate mass supply?
- Alternatively, powered by spinning hole
 - Large magnetic torque at inner radius of disk
 - Capstan, clutch and governor
 - Ejection disk, MHD wind, collimates jets,
 - Low mass supply – M87
 - High mass supply - SS433
- New modes of accretion



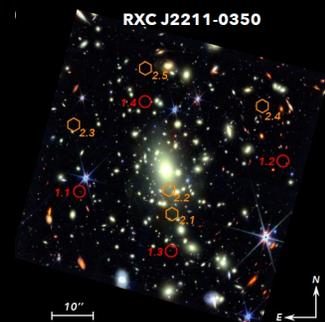
HOW ARE EECR ACCELERATED?

- EECR appear to be heavy
 - 10 EV rigidity and EMF may suffice
 - Sources within ~ 40 Mpc - dipole
 - Other sources contribute to UHECR
- Many possible compact jet/outflow sources
 - AGN, GRB, TDE, NS mergers ...
 - Direct acceleration
- Alternative, diffusive shock acceleration models
 - c/u crossings with $O(u/c)$ relative energy gains
 - Kinetic calculation shows that transmits power law
 - Impressive simulations of linear shock
 - $mfp \sim rigidity$; spherical shocks; upstream escapers
 - Hierarchical model: SNR \rightarrow galactic winds \rightarrow clusters
 - Escapers bootstrap strong magnetic turbulence
 - Are shocks cleverer than us?



LITTLE RED DOTS (OR HERRINGS)?

- JWST (2024); $0.1 < z < 10$ – $10^8?$ on sky
 - Distinct infrared spectra
 - X-ray, radio quiet; few stars
 - Shrouded by ~ 0.01 pc photosphere?; 100 yr variability ; low density of elements with $Z > 2$
- Early phase of general galaxy/nucleus formation lasting ~ 10 My?!
 - Galaxies form from the inside out ?!
- $10^6 M_{\text{sun}}$ “quasistars” – accreting massive holes with compact “stellar” envelopes
 - Fragile? Why no double radio sources?
- Alternative compact nuclear star cluster
 - With low Z stars with $M \sim 100 M_{\text{sun}}$
 - Form $\sim 10 M_{\text{sun}}$ black hole star cluster in collapsed core plus supernovae ejecta
 - Black holes merge to increase their average mass
 - Rotation leads to flattening which may become non-axisymmetric?
 - Make nHz background through coherent emission of gravitational waves?
 - Make high mass LIGO mergers?
 - Evolve eventually to form single massive black hole -> quasar
 - Combined supernova ejecta form standing shock/photosphere arrested by infalling gas
 - Can account for rapid growth of luminous quasars in the early universe



+ Sullivan, Pabari, Choi

S U M M A R Y

- Time of remarkable, unscripted discovery 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; \sim PeV γ ; \sim PeV ν ; 0.3 ZeV CR...
- Quasars, pulsars, GRB, UHECR, Magnetars, FRB, VHE ν , GWB...
- Opportunities for discovering new fundamental physics, but nothing so far
- Calculate using order of magnitude, traditional applied math, fluid, kinetic, PIC simulation
- Many manifestations of “turbulence”
- New discoveries-> many explanations
- New facilities-> fewer explanations-> better defined theory challenges
- Time of rapid progress: observation, experiment, simulation, theory
- Bottom up (reductionist) and top down (phenomenological) approaches both useful
- Falsifiable explanations of more scientific value than “post-modern” interpretations!?

Who knows where this will lead?

