Title: Radiation of Extreme Plasmas near the Neutron Stars and Black holes

Speakers: Alexander Philippov

Collection/Series: Colloquium

Subject: Other

Date: March 26, 2025 - 2:00 PM

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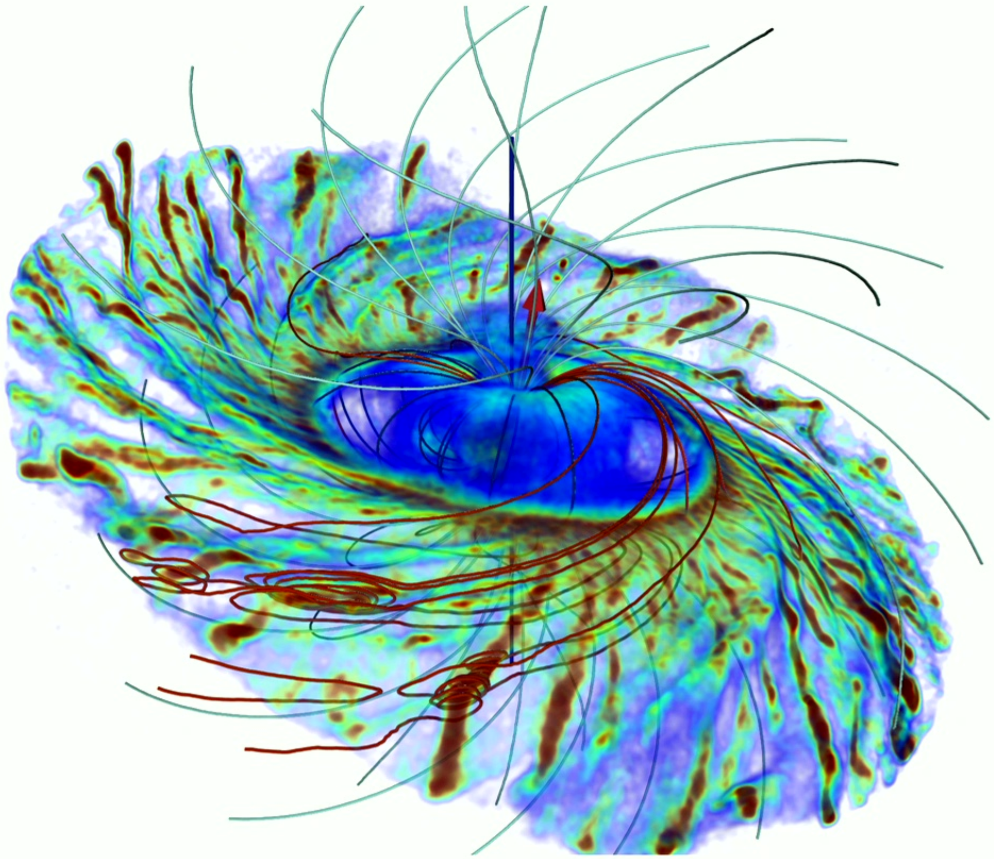
Abstract:

Astrophysical compact objects, neutron stars, and black holes are powerful sources of non-thermal electromagnetic emission spanning many orders of magnitude in photon energy, from radio waves to multi-TeV gamma rays. Despite multiple groundbreaking observational discoveries done in recent years, our understanding of the dynamics of relativistic plasmas that produce these emission signatures remains limited. In this talk, I will describe a few successful examples of modeling the observed light coming from these remarkable astrophysical laboratories using various numerical approaches. I will focus on advances in understanding coherent radio emission of rotating neutron stars, pulsars, and multi-wavelength flares from accreting black holes.

Radiation of Extreme Plasmas around Neutron Stars and Black Holes



Philippov & Kramer, 2022 (Annual Reviews of Astronomy & Astrophysics)

NSF

SIMONS FOUNDATION

Sasha Philippov (Maryland)

with:

Ashley Bransgrove (Princeton)
Benoit Cerutti (Grenoble)
Koushik Chatterjee (UMD)
Sasha Chernoglazov (IAS)
Benjamin Crinquand (Toulouse)
Alisa Galishnikova (Flatiron)
Hayk Hakobyan (Columbia)
Amir Levinson (Tel Aviv)
Matthew Liska (Georgia Tech)
Jens Mahlmann (Dartmouth)
Elias Most (Caltech)
Eliot Quataert (Princeton)
Bart Ripperda (CITA)
Sophia Sanchez-Maes (Harvard)
Siddhant Solanki (UMD)
Anatoly Spitkovsky (Princeton)
Libby Tolman (Flatiron)
Andrey Timokhin (Zielona Gora, Poland)
Dmitri Uzdensky (Oxford)
Yajie Yuan (Washington U., St Louis)
Shuzhe Zeng (UMD)
Vladimir Zhdankin (Wisconsin)

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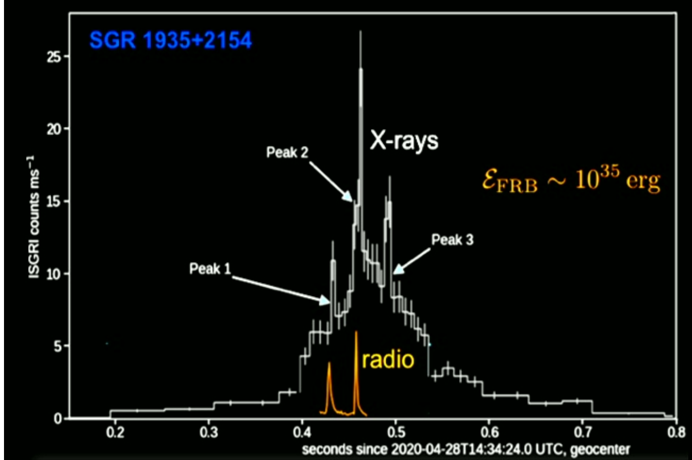
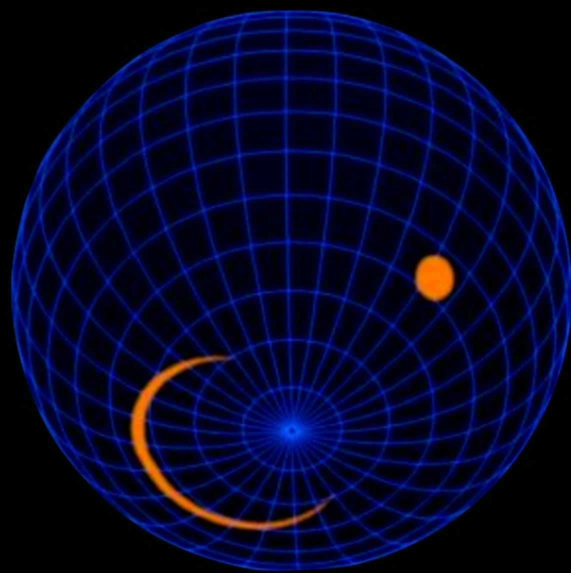
Why Now? (Neutron Stars)

EXCITING, UNPRECEDENTED MULTI-WAVELENGTH OBSERVATIONS

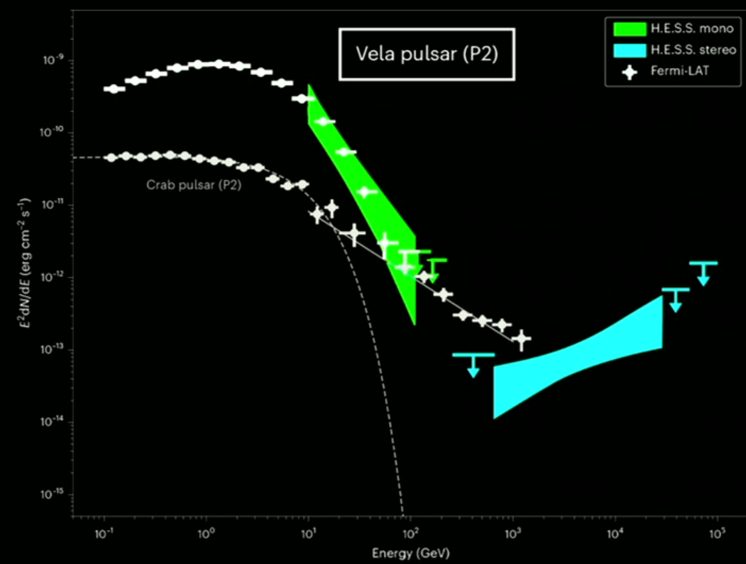
April 2020: Fast Radio Burst from a local magnetar



FRB from galactic magnetar (2020)



"Aurora" on a millisecond pulsar by NICER (2019+)

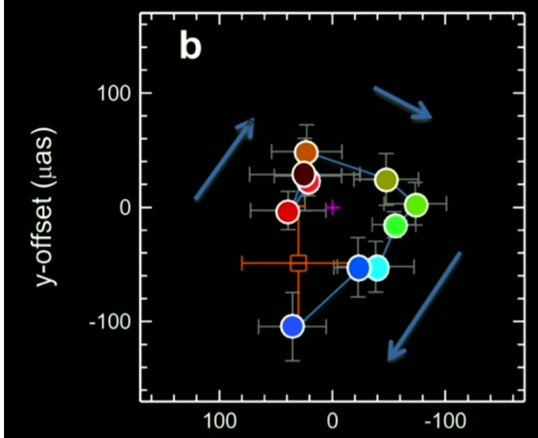


Multi-TeV pulsed emission from Vela (2023)

Understanding the behavior of collisionless relativistic plasmas is a key!

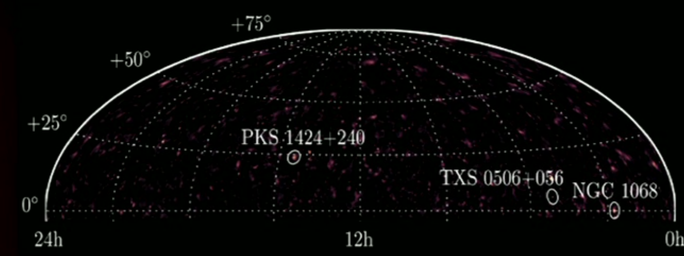
WHY NOW? (BLACK HOLES)

EXCITING, UNPRECEDENTED MULTI-WAVELENGTH OBSERVATIONS



Orbiting "hotspots" by Gravity (2018+)

BH shadow by EHT (2019+)



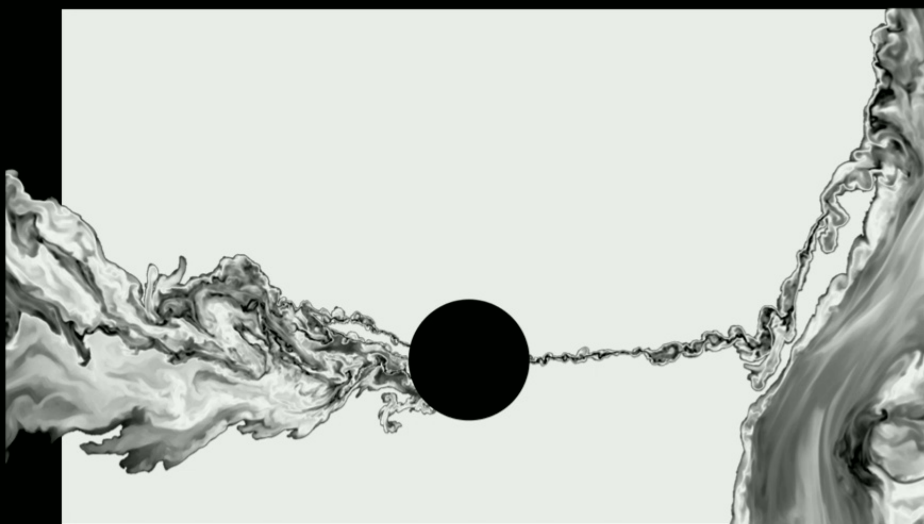
Tentative IceCube neutrino sources (2022+)

Understanding the behavior of collisionless relativistic plasmas is a key!

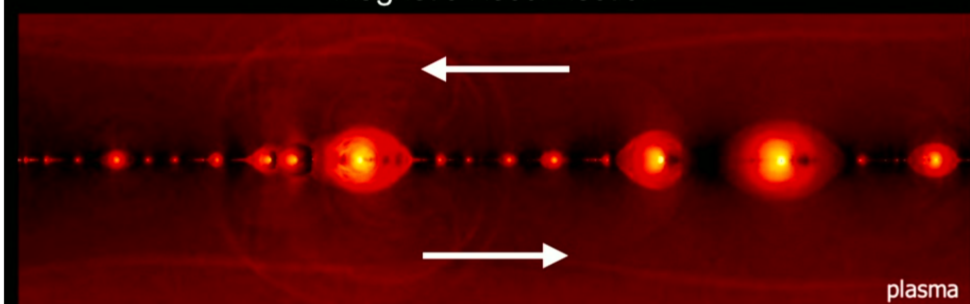
3

Theoretical Approaches

Black Hole Accretion Flow



Magnetic Reconnection



Force-free electrodynamics

Plasma without the plasma

- ✓ OK in highly magnetized regions
- \- breaks when the plasma is not a given, and in reconnection
- • typical apps: NS magnetospheres, jets

Magnetohydrodynamics

Plasma as an ideal collisional fluid

- ✓ e.g., no thermal conduction, pressure is same in all directions. OK as a first approximation for global dynamics
- \- does not describe non-thermal particles
- • typical apps: accretion flows

Kinetic physics

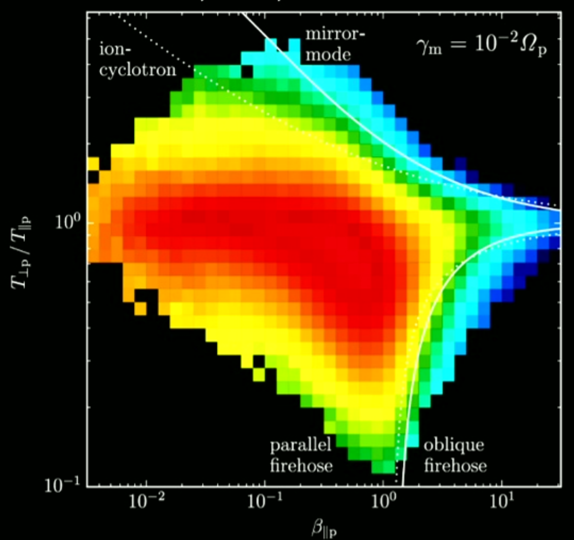
First-principles description

- ✓ includes non-ideal effects (e.g., pressure is different along and across magnetic field, heat flux), describes particle acceleration
- \- expensive and usually allows limited dynamic range
- • typical apps: plasma instabilities, magnetospheres

Why Do We Need Kinetic Physics?

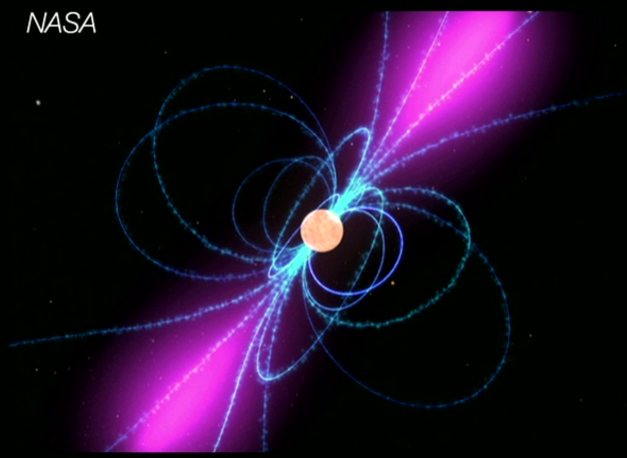
practical answer: need to explain and predict observables, i.e., non-thermal radiation ("power-laws")
theoretical answer #1: collisionless plasmas do not always behave as ideal fluids
theoretical answer #2: small scales can affect large scales

Bale et al., 2009, PRL



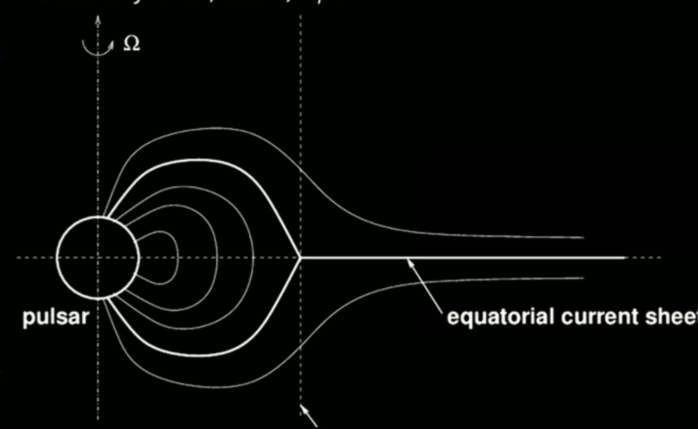
Small-scale plasma instabilities control the plasma-fluid characteristics

NASA



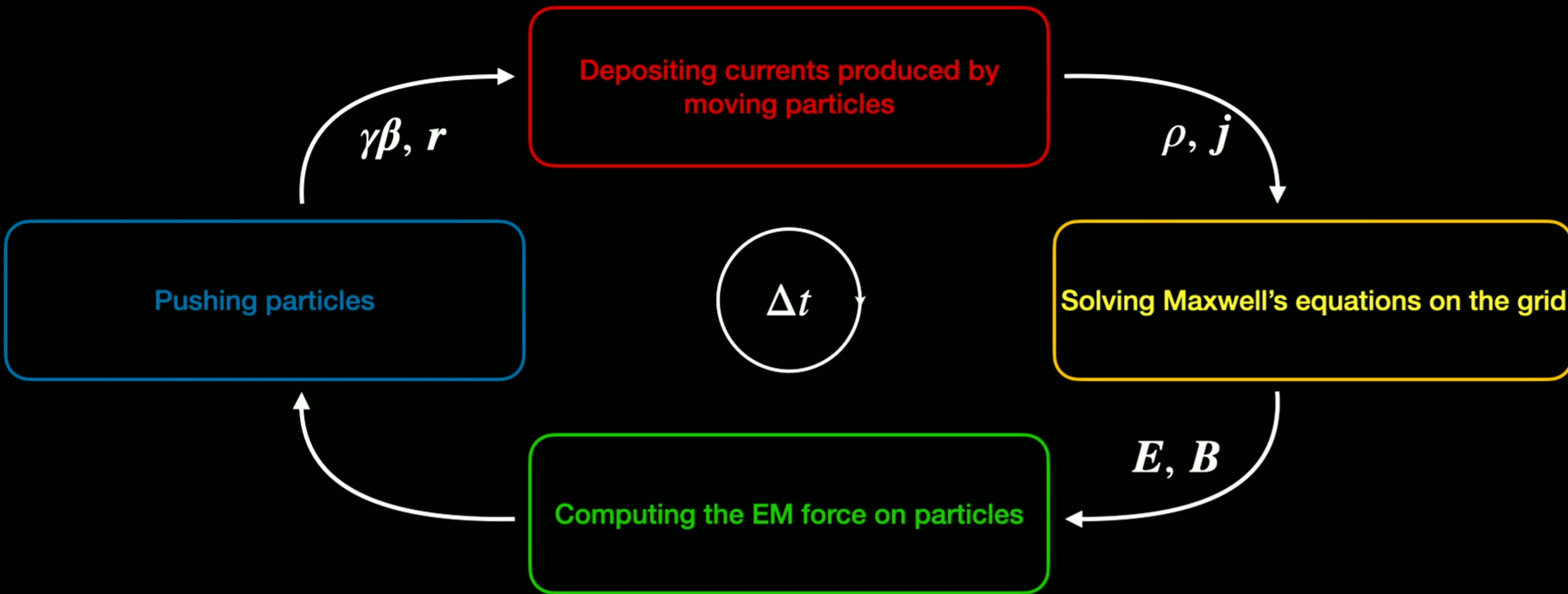
Rate of pair creation controls the shape of the NS magnetosphere

Uzdensky et al., 2014, ApJ



Rate of reconnection controls dissipation in the NS magnetosphere

Plasma Physics on a computer: (GR)(R)PIC

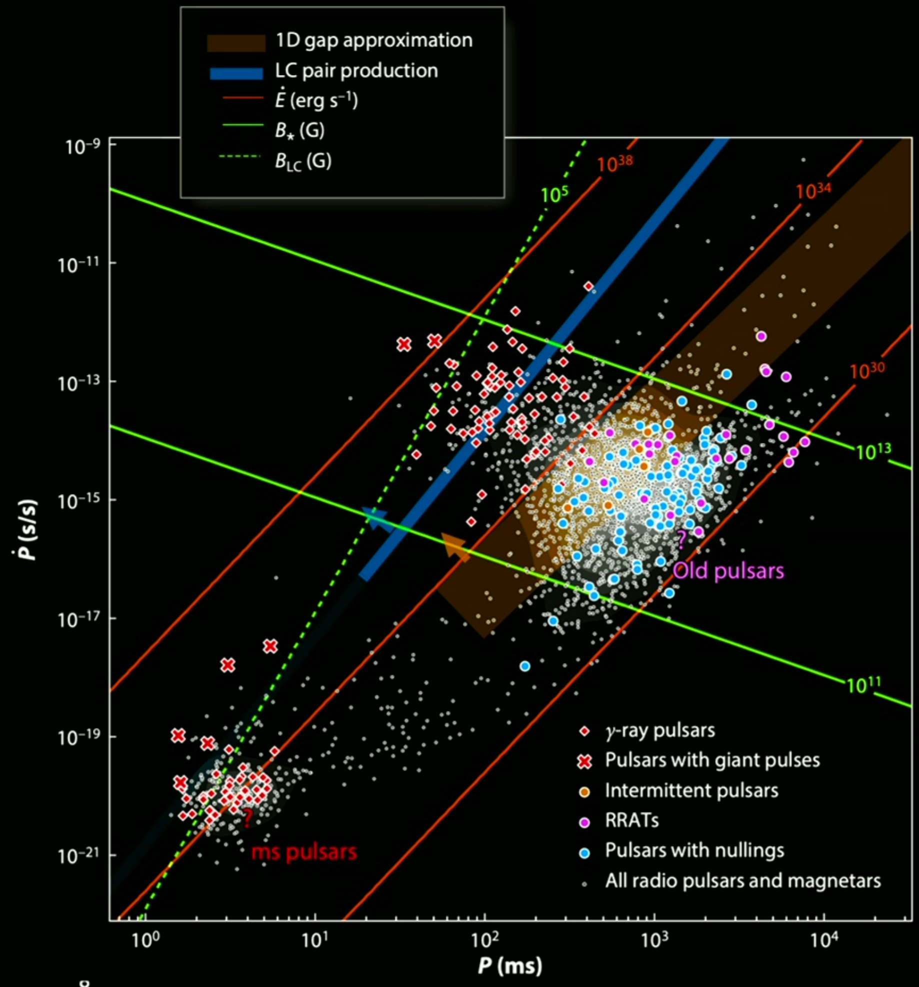


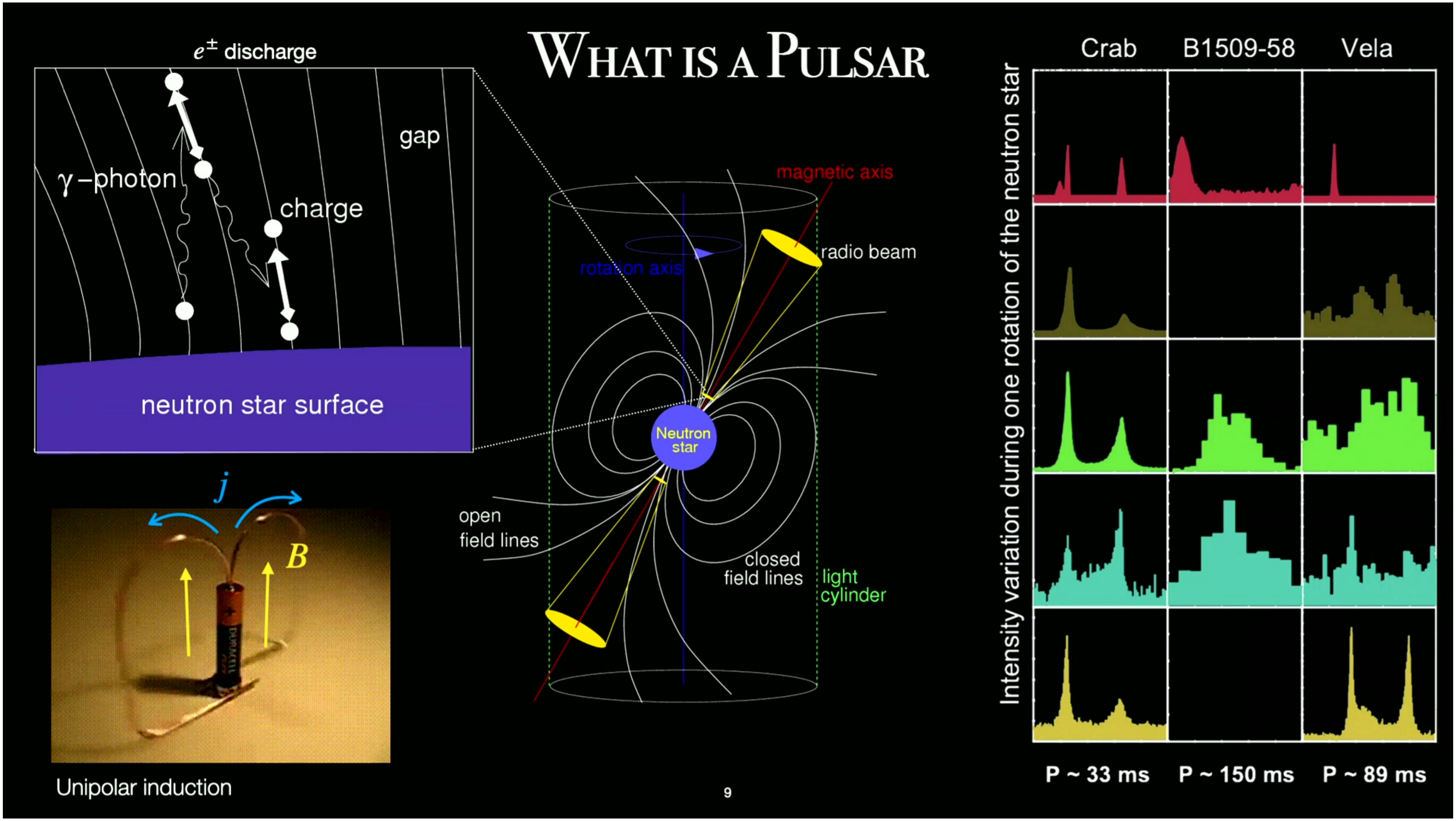
(GR) = general relativistic
(R) = radiation reaction force, photon emission, multiple pair production mechanisms
PIC = particle-in-cell

Black Holes:
SgrA* and M87*

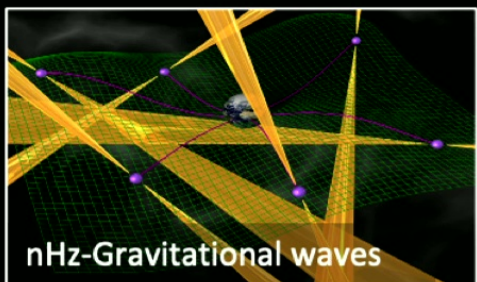
Neutron Stars

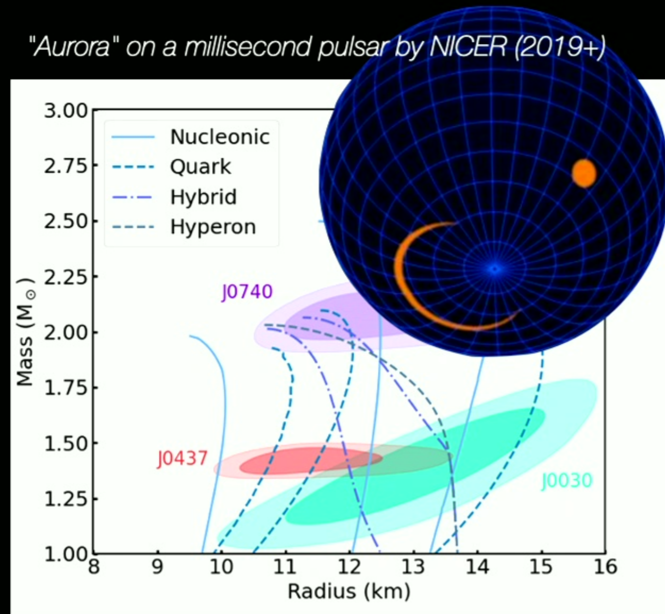
- Almost perfect clocks: measure period.
- Measure magnetic fields from the observed spin down.
- Rotation powered: pulsars.
- Magnetically powered: magnetars.
- Millisecond pulsars: spun up by accretion.
- Broad-band electromagnetic emitters: from radio to gamma-rays.

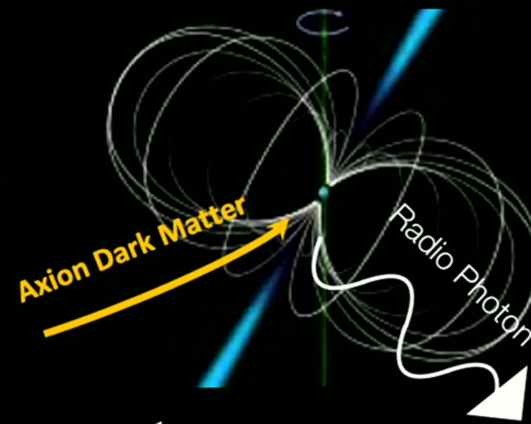



What is a Pulsar
$e^{\pm}$ discharge
gap
γ –photon
charge
neutron star surface
j
B
Unipolar induction
magnetic axis
radio beam
rotation axis
Neutron star
open field lines
closed field lines
light cylinder
9
Crab
B1509-58
Vela
Intensity variation during one rotation of the neutron star
P ~ 33 ms
P ~ 150 ms
P ~ 89 ms

Probes of Fundamental Physics







$$L_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} a =$$

$$= -\frac{1}{4} g_{a\gamma\gamma}(\vec{E}\cdot\vec{B})a$$

Detection of the gravitational wave background

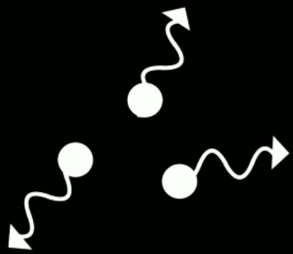
Equation of state of nuclear matter

Physics Beyond Standard Model: e.g., axions

Many more important examples: probes of cosmological baryons (FRBs), effects of superconductivity in the core and superfluidity in the crust, strong field QED-plasma interactions.

YET WE DO NOT KNOW HOW THEY ACTUALLY SHINE!

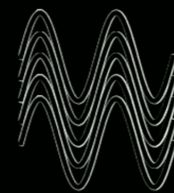
Incoherent vs Coherent Radiation



$N \times$ single particle emission

Examples:
Multiple synchrotron, inverse Compton radiation sources in astrophysics

Cause:
Accelerated charged particles



$$T_b = \frac{S_\nu c^2}{2 k_B \nu^2}$$

$N^2 \times$ single particle emission **high brightness temperatures**

Examples:
radio emission of Io-Jupiter, solar radio bursts, EMP, laboratory (e.g., free electron laser)

Cause:
Plasma instabilities, collective motions

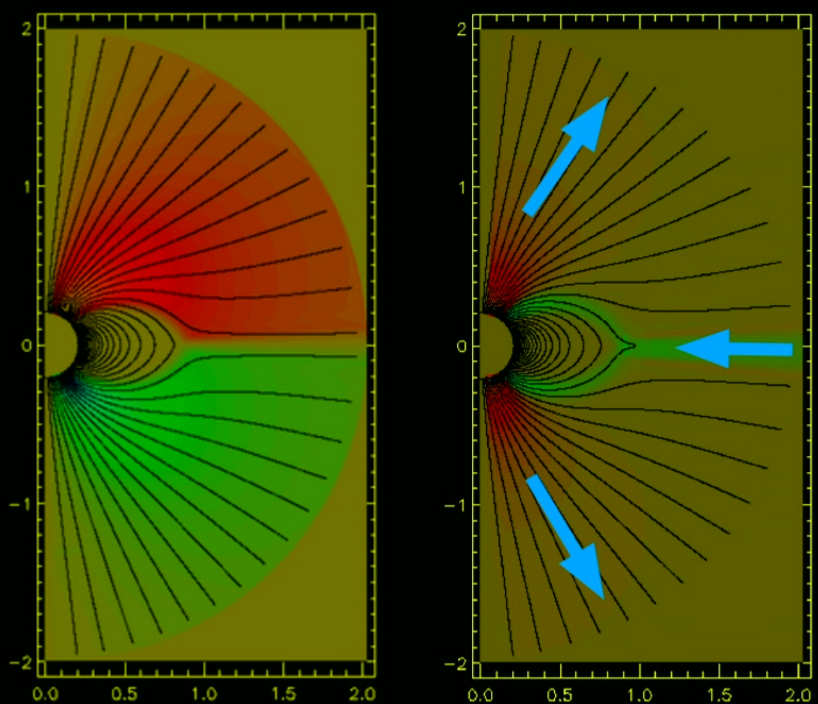
STANDARD PULSAR

Force-free paradigm

$$\rho_c \boldsymbol{E} + \boldsymbol{j} \times \boldsymbol{B} = \cancel{\frac{d\rho_m \boldsymbol{u}}{dt}} + \cancel{\text{pressure}}, \text{ and } \boldsymbol{E} \cdot \boldsymbol{B} = 0$$

+ Maxwell's equations

$$\Rightarrow \quad \boldsymbol{j} = \boldsymbol{j}(\boldsymbol{E}, \nabla \times \boldsymbol{E}, \nabla \cdot \boldsymbol{E}, \boldsymbol{B}, \nabla \times \boldsymbol{B})$$



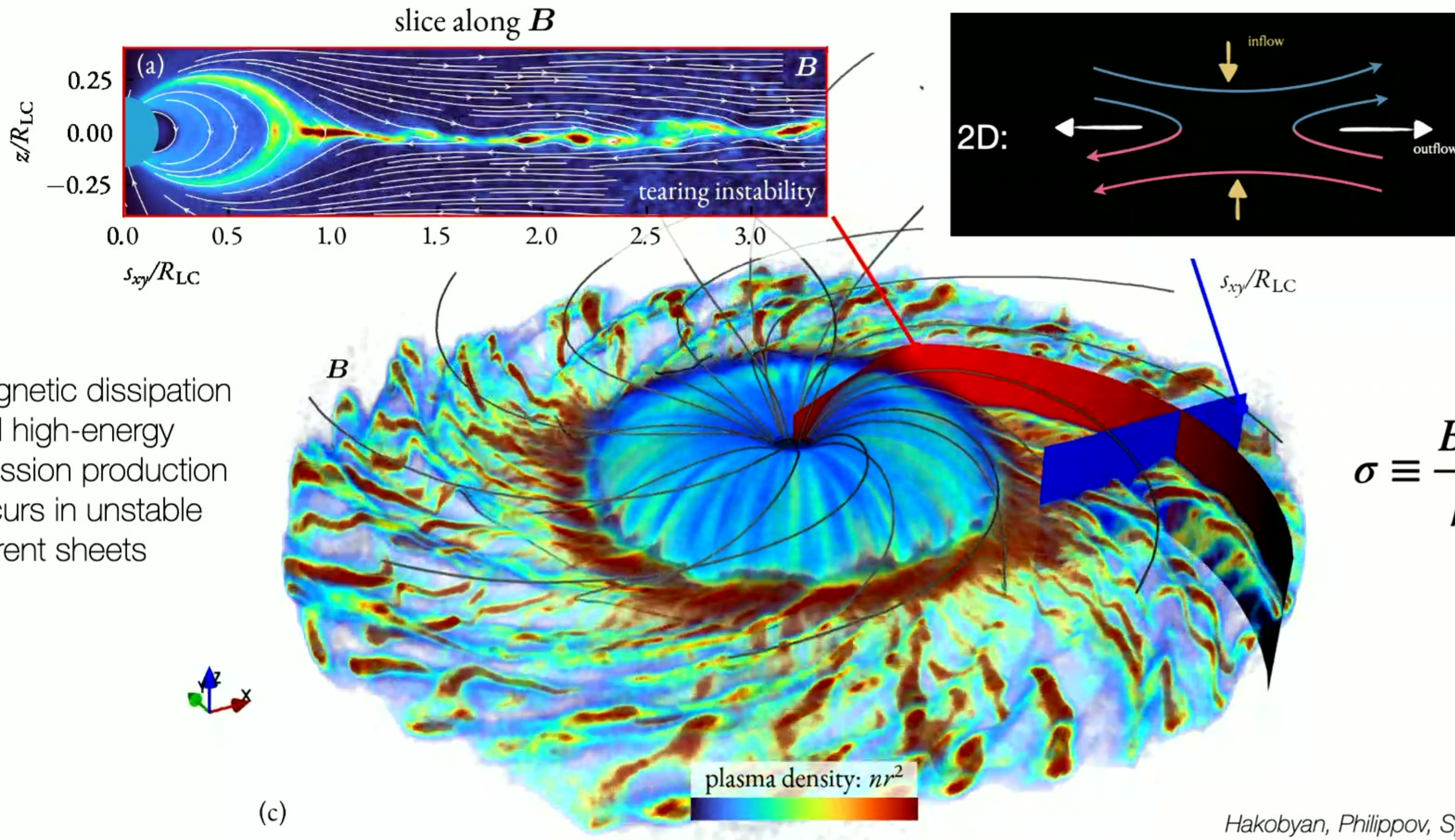
- closed-/open-field-line regions
- equatorial current sheet
- field lines are asymptotically radial
- predicts the spin-down law

$$L_{\rm PSR} = k_1 \frac{\mu^2 \Omega^4}{c^3} \left(1 + k_2 \sin^2 \alpha\right)$$

- can not predict: particle acceleration, plasma supply, non-thermal radiation

Contopoulos+ (1999), Spitkovsky (2006), Kalapotharakos (2009), Petri (2012), Tchekhovskoy+ (2014) (MHD)

Three-Dimensional Magnetospheres



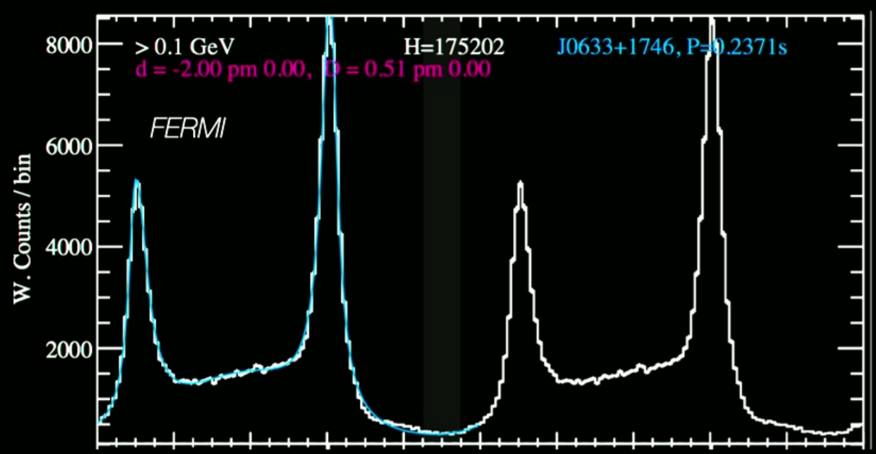
(c)

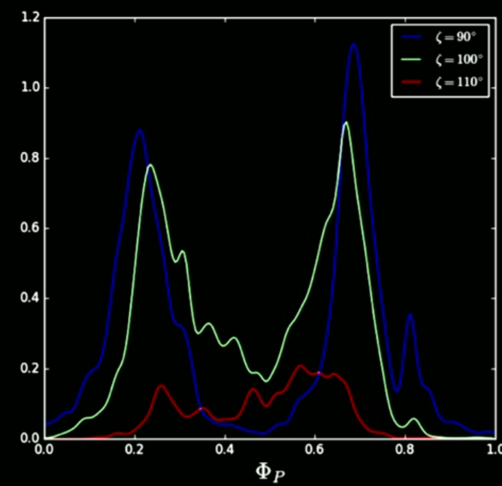
Magnetic dissipation and high-energy emission production occurs in unstable current sheets

$$\sigma \equiv \frac{B^2/4\pi}{\rho_\pm c^2} \gg 1$$

Hakobyan, Philippov, Spitkovsky, 2023 (ApJ)

High-Energy Emission Modeling



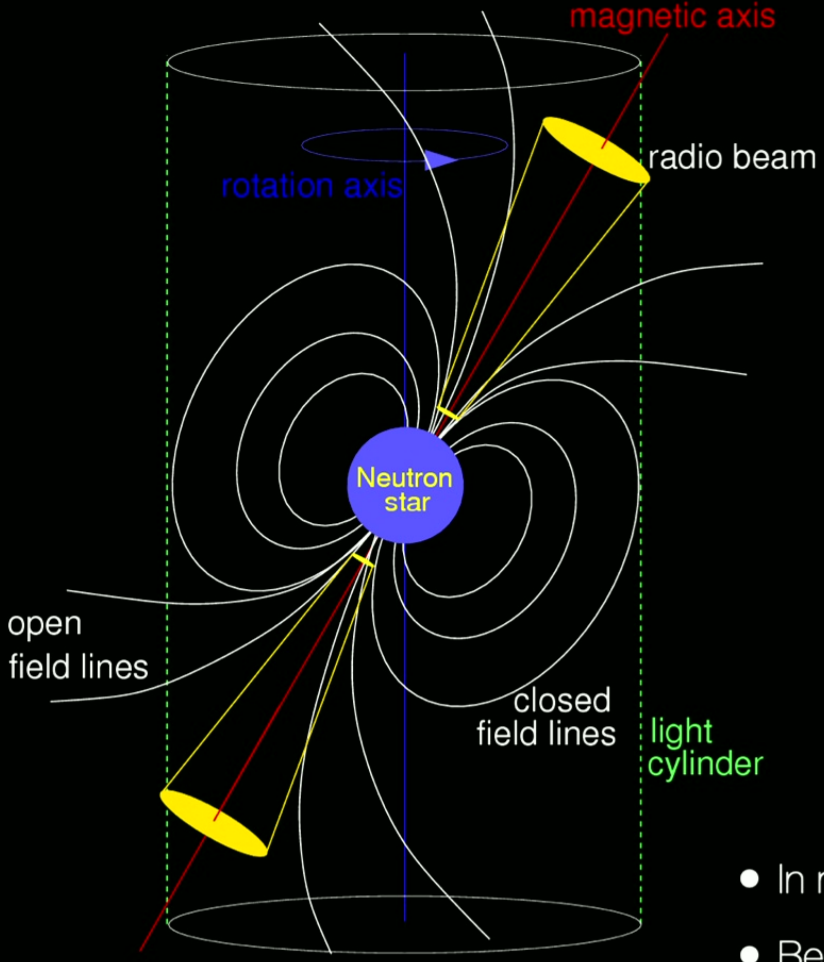


Philippov, Spitkovsky, 2018 (ApJ)

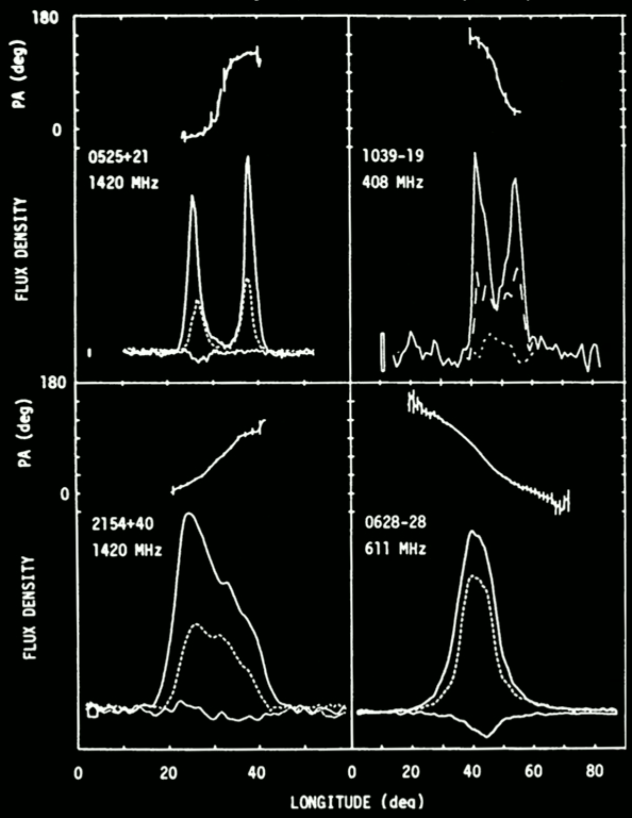
Double-peaked lightcurves are generic

- Spectral modeling from local reconnection simulations suggests that emitting particles have Lorentz factors $\gamma \gtrsim 10^7$ for Vela-like pulsars — consistent with the multi-TeV HESS detection.
  (see Chernoglazov, Hakobyan, Philippov, 2023, ApJ)
- Prediction: CTA will see moderately energetic γ-ray pulsars as multi-TeV sources.
  Chernoglazov, Hakobyan, Philippov, in prep

Polar Radio Emission

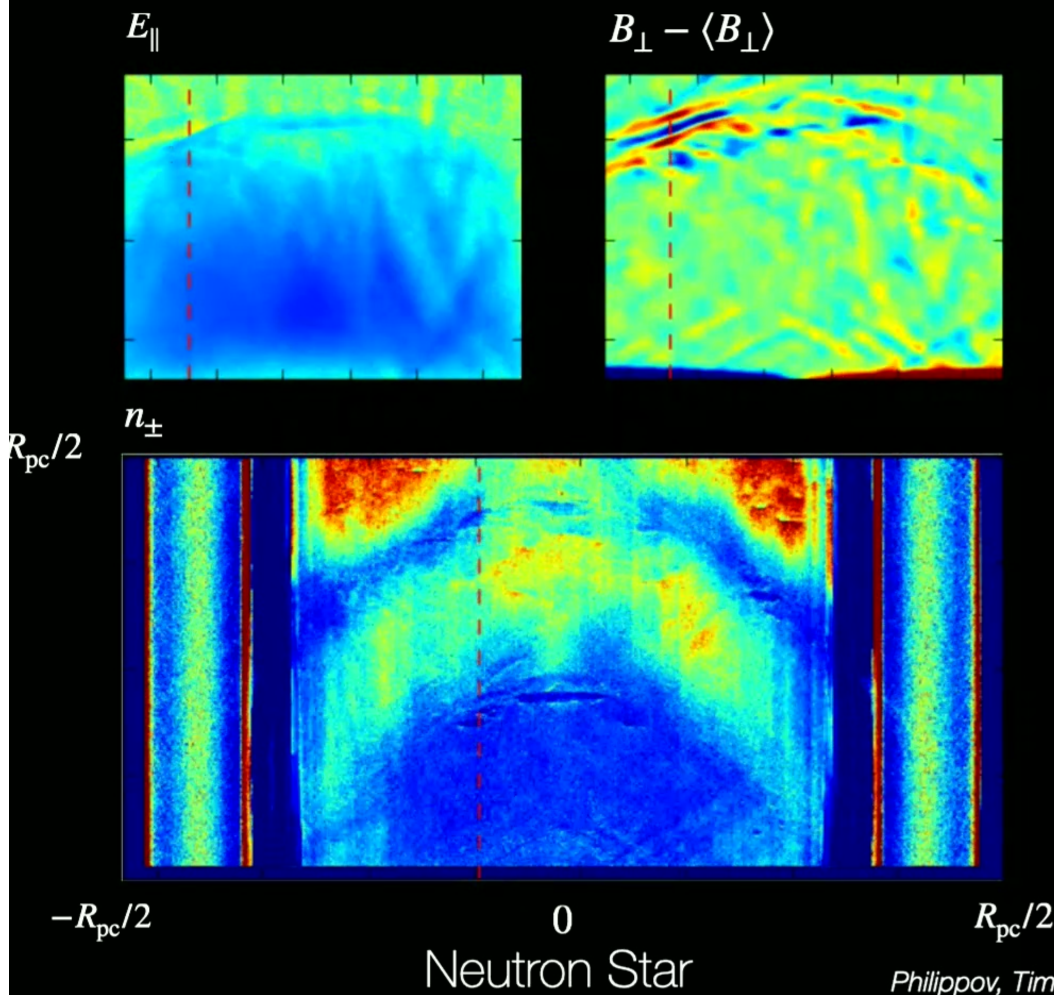


Lyne, Manchester (1988)



- In most cases we see one short pulse per period.
- Beam width is related to the polar cap size.

Local Simulation of 2D Discharge



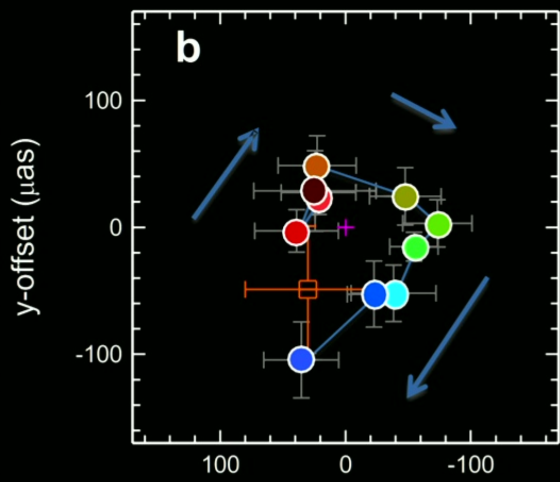
- Intermittency of the discharge results in production of coherent currents that are "screening" the electric field.
- Oblique "screening" waves are electromagnetic and superluminal; thus, can escape from the magnetosphere.
- The power is fixed at $\sim 10^{-4} L_{\rm sd}$ (Tolman, Philippov, Timokhin, 2022).
- Subsequent works explain the core-cone structure of the emission beam.

$$\nu_{\max} \simeq \sqrt{4\pi e^2 \kappa n_{\rm GJ} \langle 1/\gamma^3 \rangle / m_e^3} / 2\pi \sim 50 \sqrt{\kappa_5 B_{12} / r^3 P_{0.1} \gamma_{10}^3} \text{ GHz}$$

Philippov, Timokhin, Spitkovsky 2020 (PRL)

See also *Cruz et. al. 2021, Bransgrove et. al. 2023 (ApJL)*

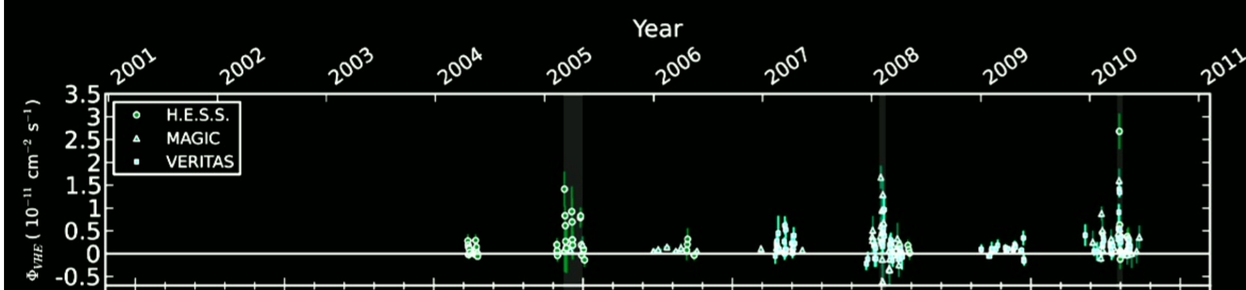
Sgr A* and M87*

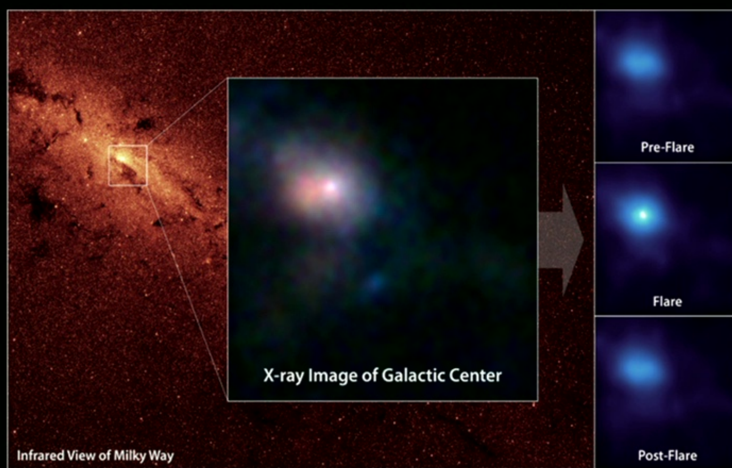


- conditions imply macroscopically collisionless, but strongly magnetized plasma
- large-scale jet is observed for M87*
- Multi-wavelength flares (NIR/X-ray for SgrA*, TeV for M87)

EHT, 2019 (ApJL)

GRAVITY collaboration, 2018 (A&A)

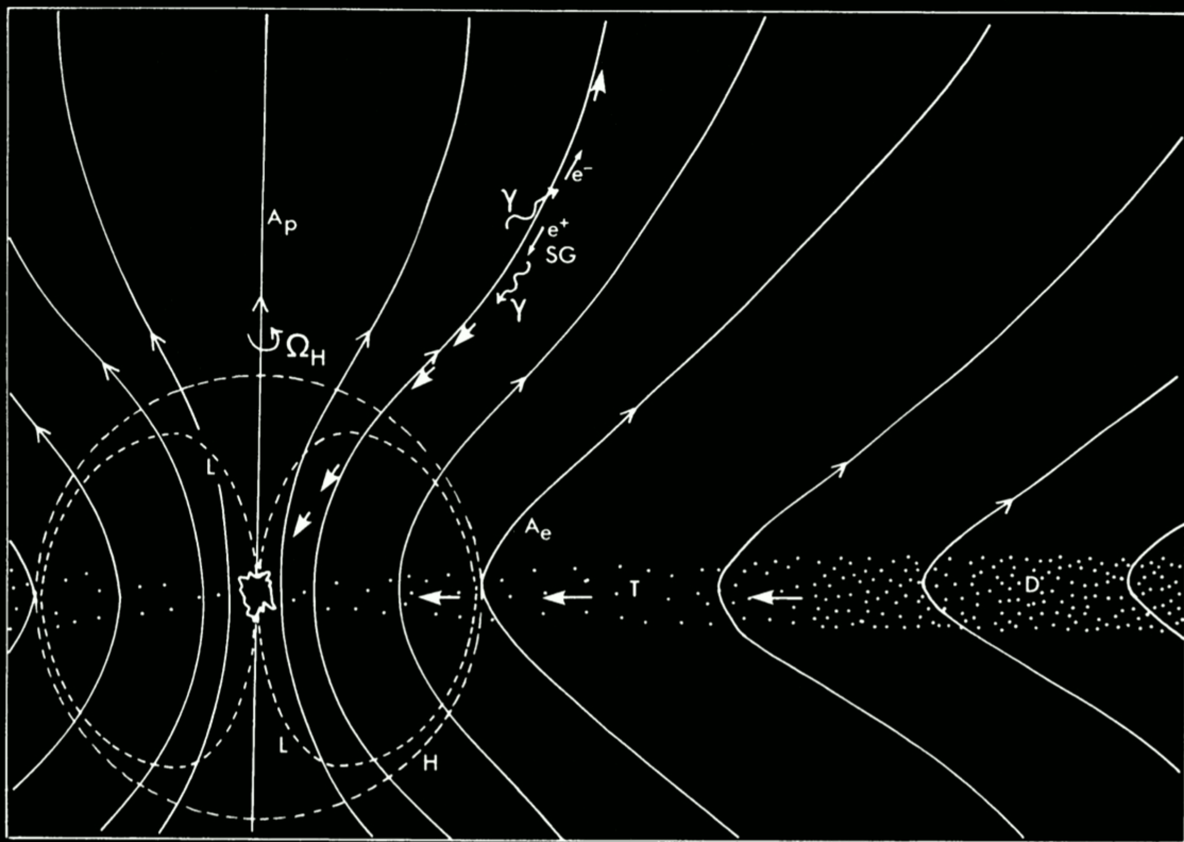




Abramowski et. al., 2012 (ApJ)

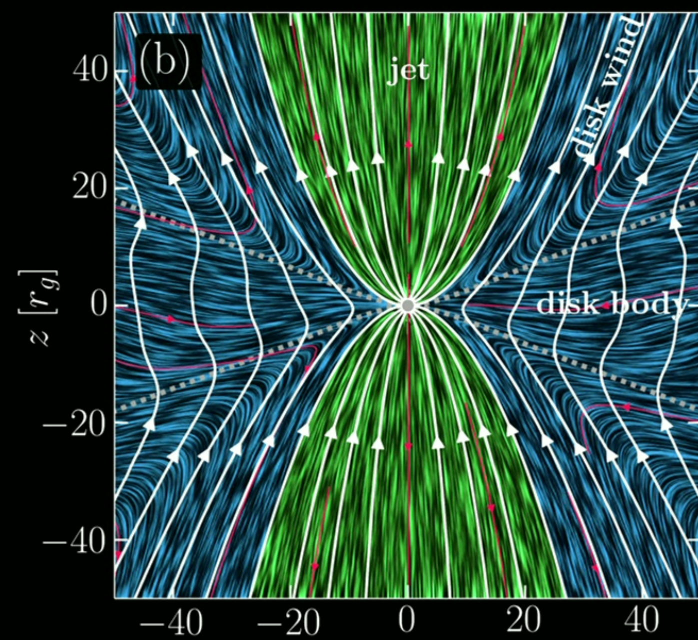
20

Theoretical Scheme: Plasmas around black holes



Blandford, Znajek 1977

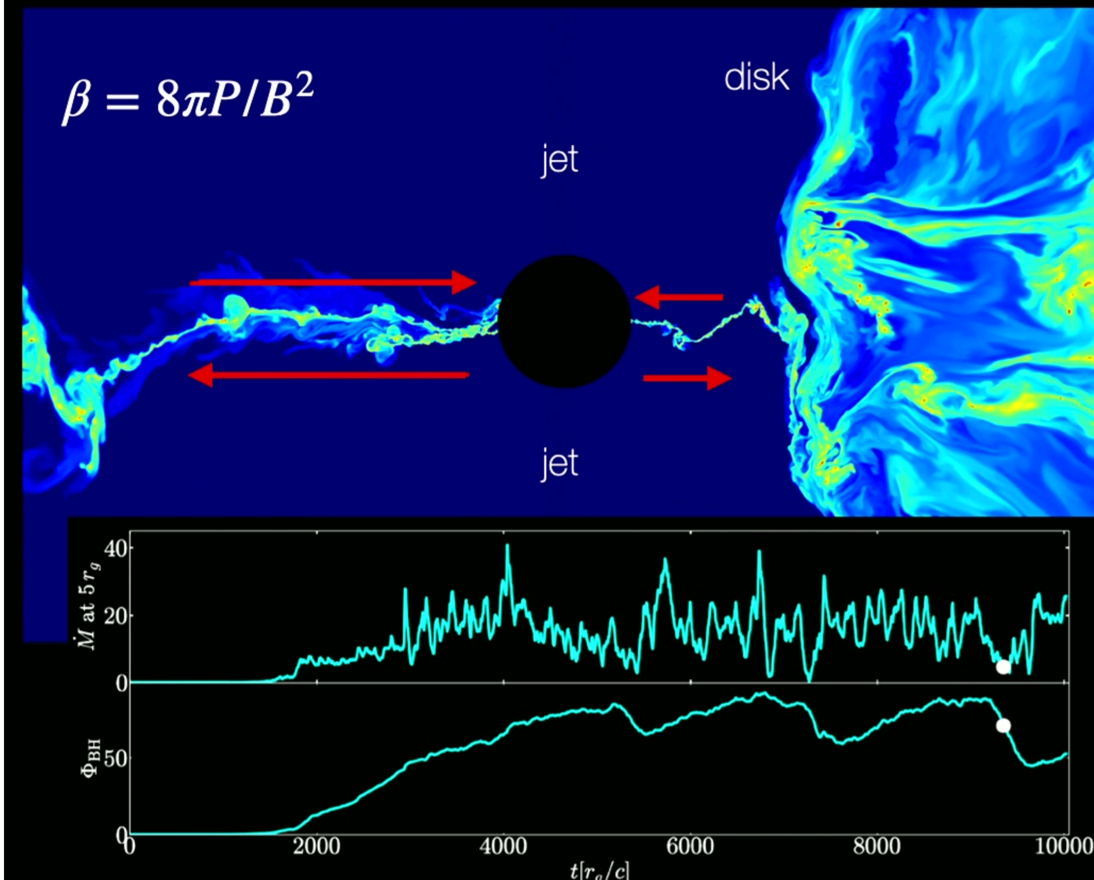
State-of-the-art MHD
(single fluid) model



e.g., Tchekhovskoy 2015

LARGE FLARES

MAGNETIC RECONNECTION NEAR THE EVENT HORIZON



- Increase of the magnetic pressure in the jet leads to creation of intermittent current sheets. At extreme resolution they are plasmoid-unstable.
- Magnetic flux leaves the BH through reconnection ("flux eruption"), and the cycle repeats.
- Alternative picture: "ejection" disk, ergomagnetosphere, FFE turbulence. (Blandford, Globus, 2022).

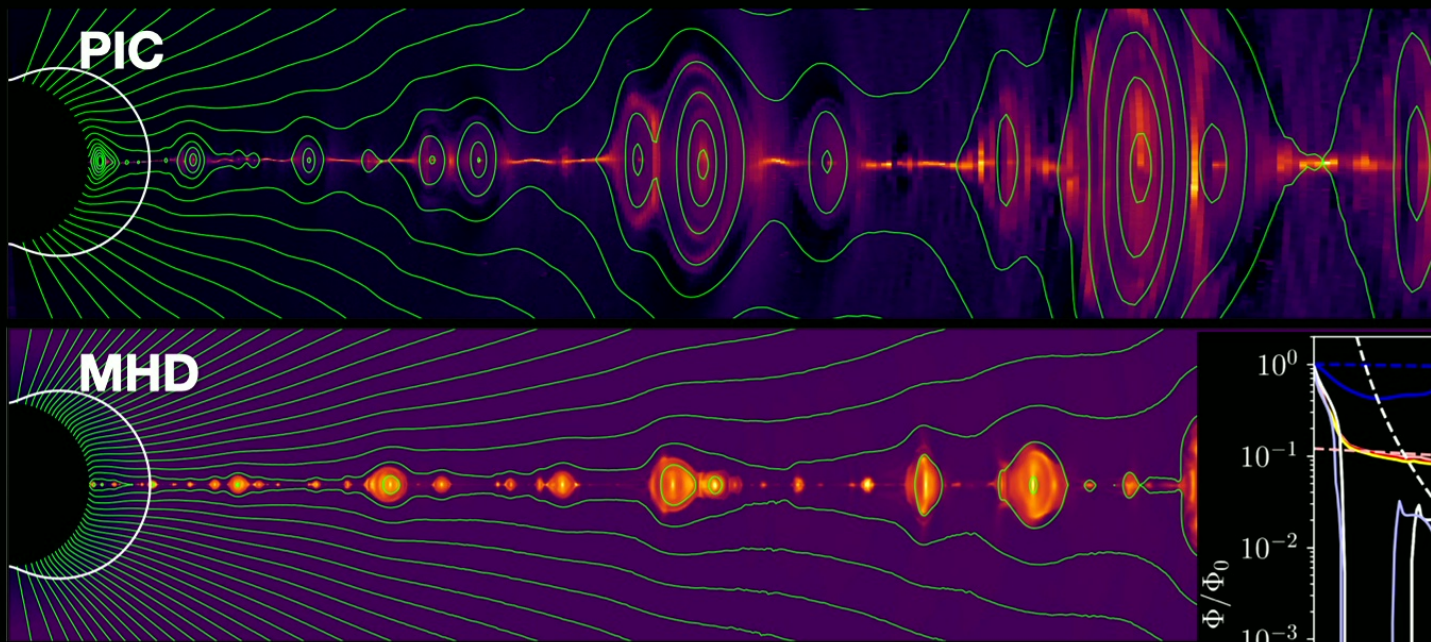
MAD: Bisnovatyi-Kogan, Ruzmaikin, 1974; Narayan, Igumenshchev et al., 2003, Tchekhovskoy, Narayan, McKinney, 2011

Ripperda, Liska, Chatterjee, et. al. (including Philippov), 2022 (ApJL)

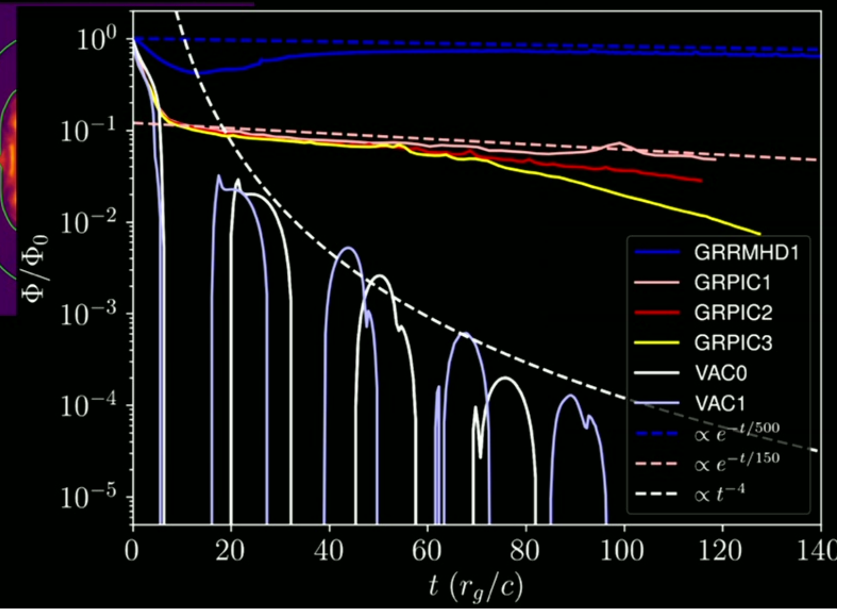
23

Toy Model: ``Balding'' Black Hole

(See also Lyutikov, 2011, PRD)



Bransgrove, Ripperda, Philippov, 2021, (cover of PRL)



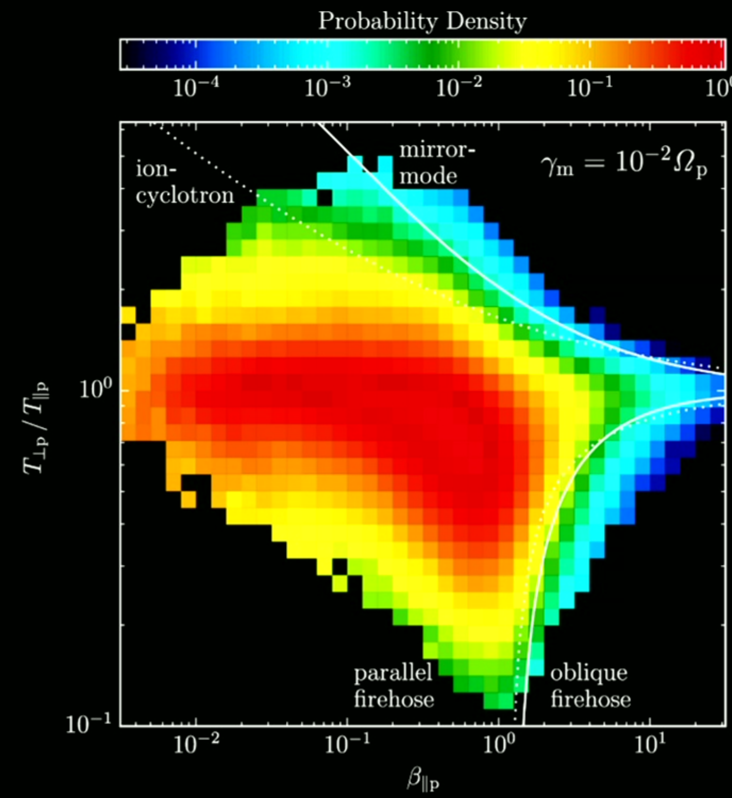
The time for magnetic flux to escape the event horizon is controlled by the plasma physics of magnetic reconnection

EFFECTS OF COLLISIONLESS PHYSICS ON GLOBAL SCALES?

- Self-regulated pressure anisotropies and heat fluxes may have a dynamical effect on the global evolution
  (initial studies by Chandra et. al., 2015, Foucart et. al., 2017)
- Reconnection is faster, $0.1V_A$ vs $0.01V_A$, because E-field is provided by a different effect.

$$E = -v \times B + \frac{1}{ne} j \times B - \frac{1}{ne} \nabla P_e + \frac{m_e}{ne^2} \frac{\partial j}{\partial t} + \eta j$$

Observed anisotropy in the solar wind



Bale et al., 2009 (PRL)

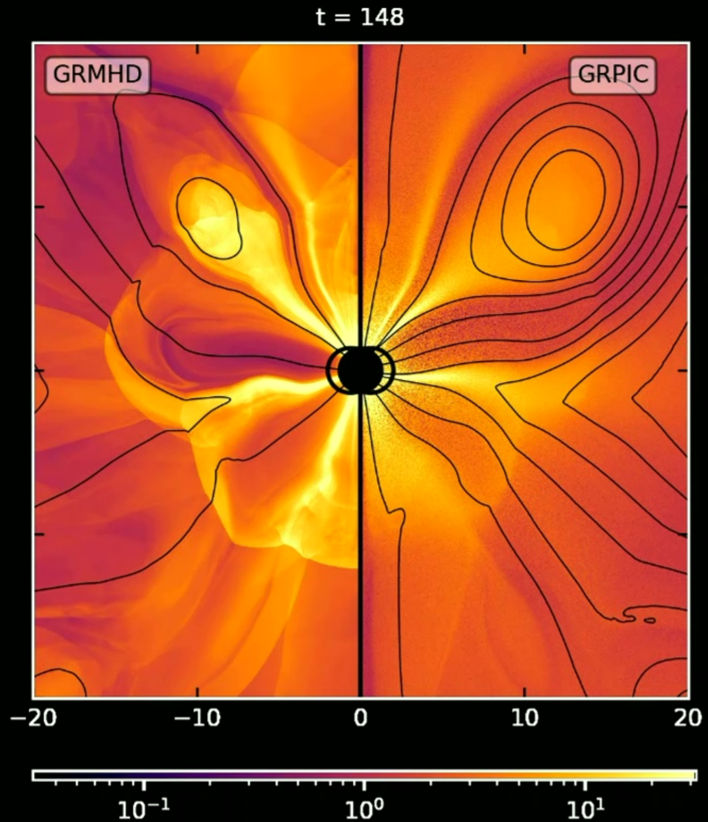
2D "MAD" IN GRPIC

- 2D axisymmetric accretion. Zero angular momentum flow
  Motivated by the stellar-wind fed model; Ressler et. al., 2021. New simulations suggest potential alternation of jet - no jet states in this regime (Galishnikova, Philippov et al., 2025).

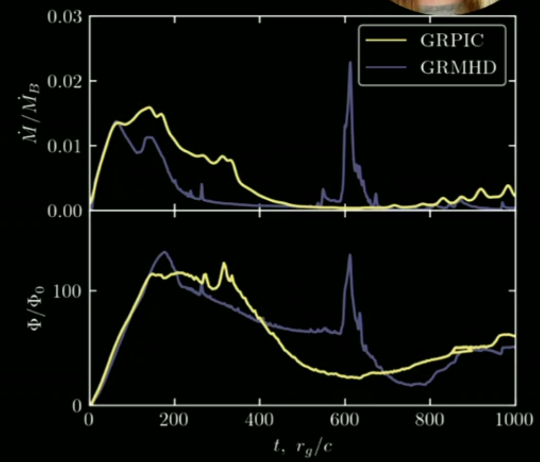
- $\beta_0 = P/P_B = 4$ or 10, and $m_i/m_e = 1...3$

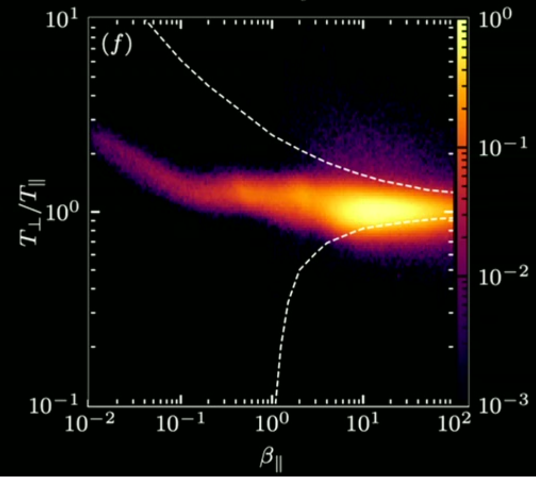
- Major changes in the temperature profile (significant heat flux in highly magnetized regions) and in the rate of eruptions.

- Non-thermal electrons in erupting current sheets.



Galishnikova, Philippov, Quataert et al. PRL, 2023 (cover of PRL)





27

Future Observations

SKA: MSP, old and erratic pulsars

CTA: TeV sources

GEN2

IceCube gen2: robust neutrino sources

DSA-2000: FRBs and (?) precursors to NS mergers

ngEHT: black hole movies; BHEX

LHASSO+: highest-energy photons

X-rays (AXIS?, IXPE+), sensitive MeV mission (COSI, AMEGO-X?), etc.

29

Conclusions

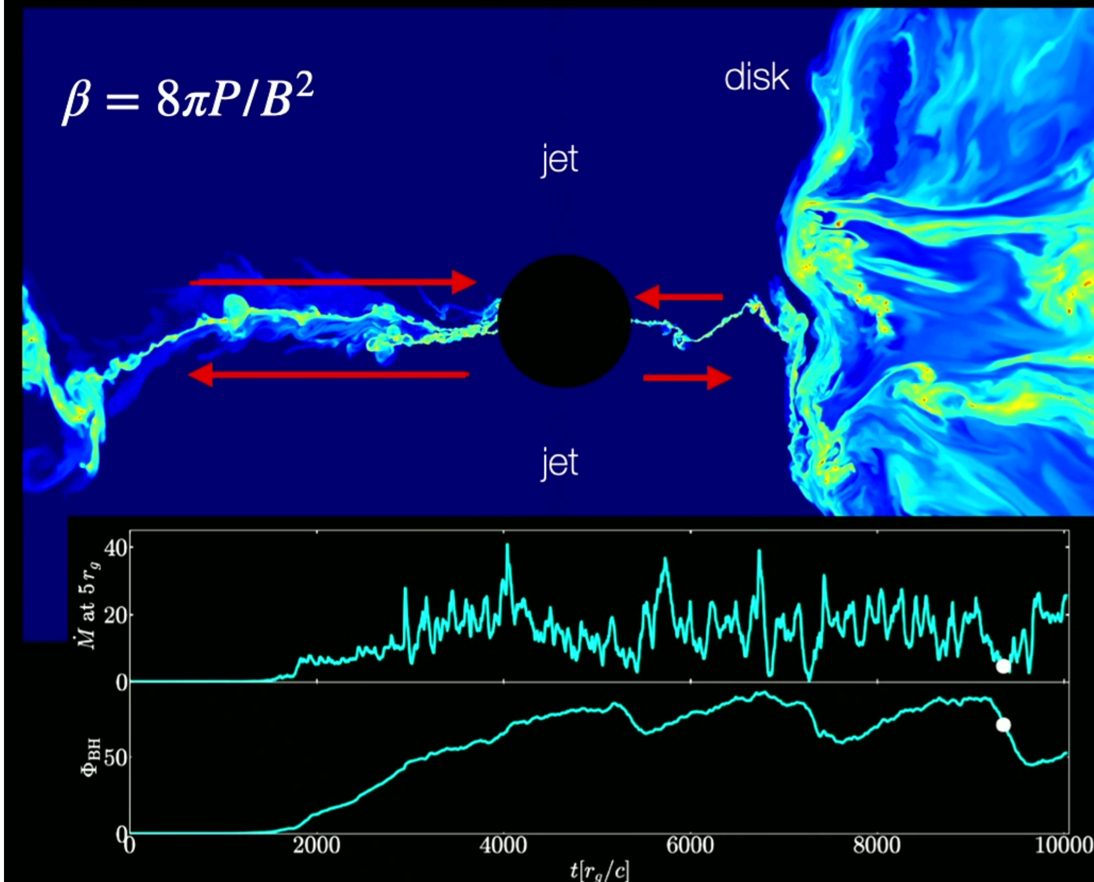
1. Origin of radiation from neutron stars has been a puzzle since 1967. Kinetic simulations are finally addressing this from first principles.

2. Flux eruption in magnetically-arrested accretion flows is accompanied by formation of large-scale reconnecting current sheets that can power multi-wavelength flares.

3. The future of neutron star and black hole observations and relativistic plasma astrophysics is bright!

LARGE FLARES

MAGNETIC RECONNECTION NEAR THE EVENT HORIZON



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Ripperda, Liska, Chatterjee, et. al. (including Philippov), 2022 (ApJL)

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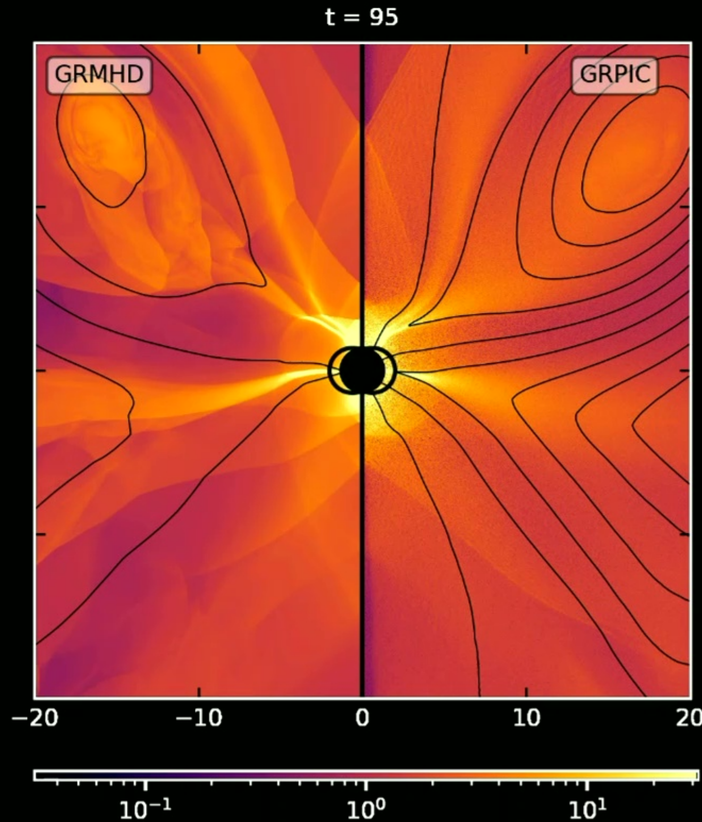
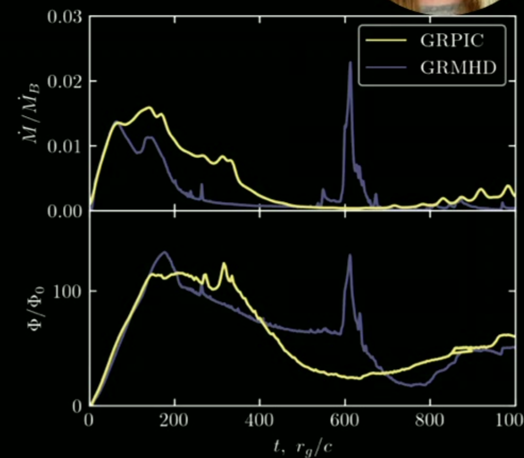
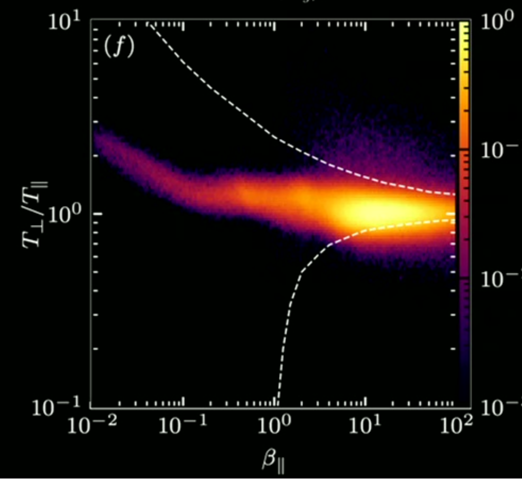


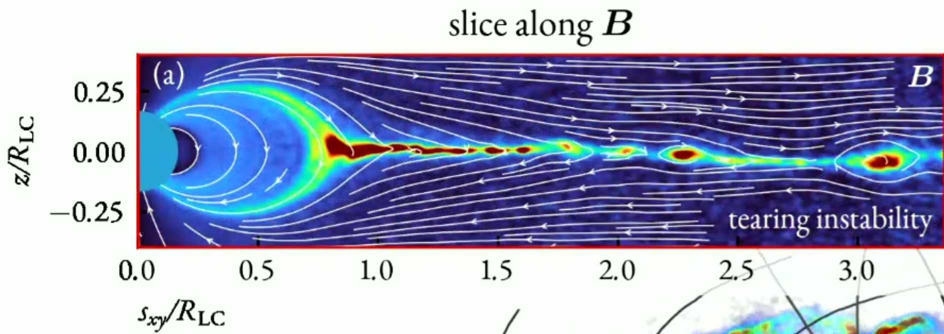
Galishnikova, Philippov, Quataert et al. PRL, 2023 (cover of PRL)

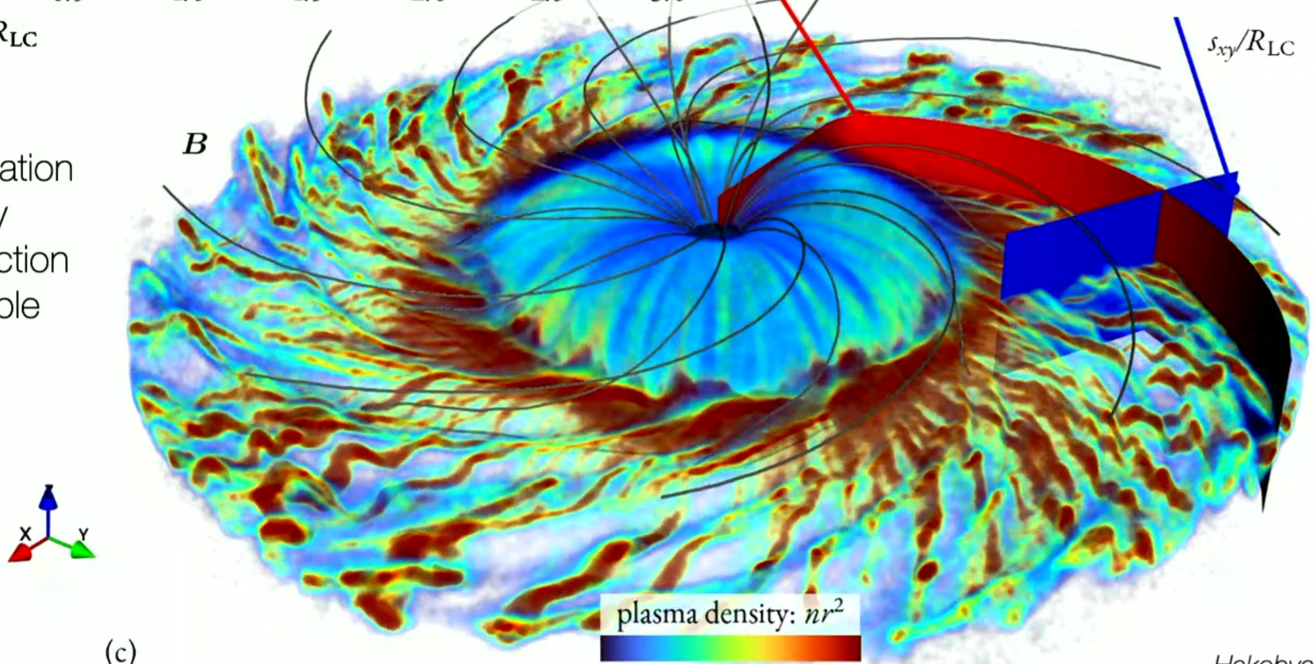


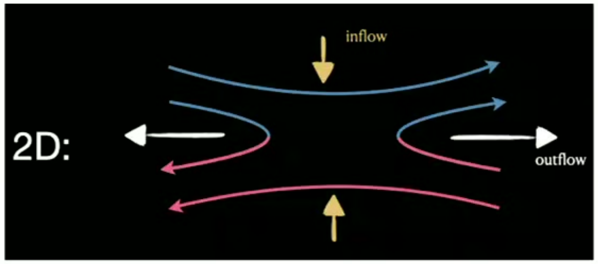


27

THREE-DIMENSIONAL MAGNETOSPHERES







Magnetic dissipation and high-energy emission production occurs in unstable current sheets

$$\sigma \equiv \frac{B^2/4\pi}{\rho_\pm c^2} \gg 1$$

Hakobyan, Philippov, Spitkovsky, 2023 (ApJ)