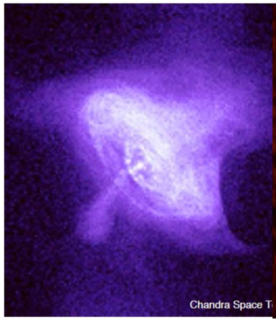
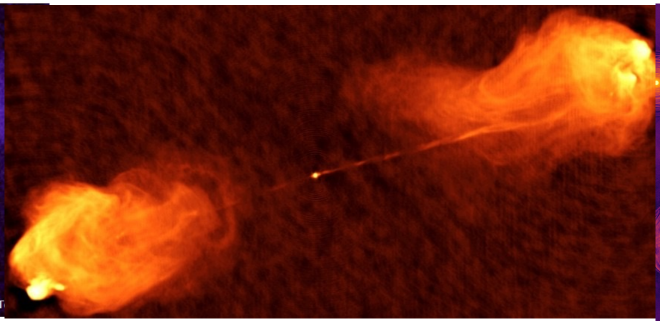
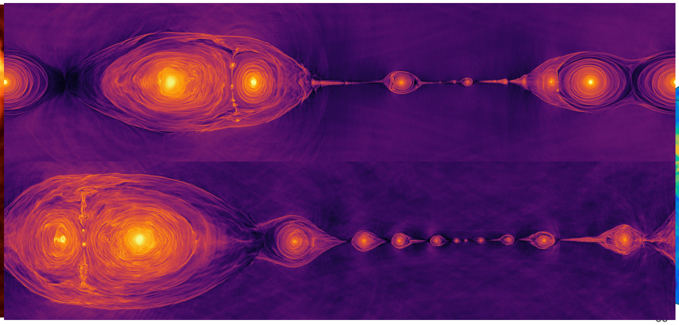
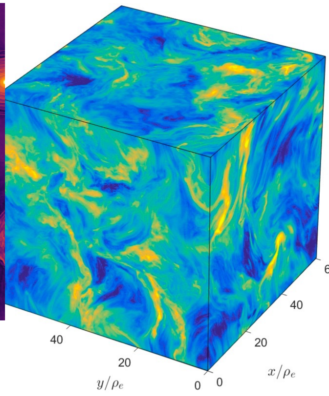








Extreme Plasma Astrophysics: a Shining New Frontier

Dmitri Uzdensky

University of Colorado Boulder

<u>Theorerical Plasma Astrophysics at Colorado</u>:

G. Werner, M. Begelman, A. Chen, F. Bacchini, J. Dexter, N. Scepi

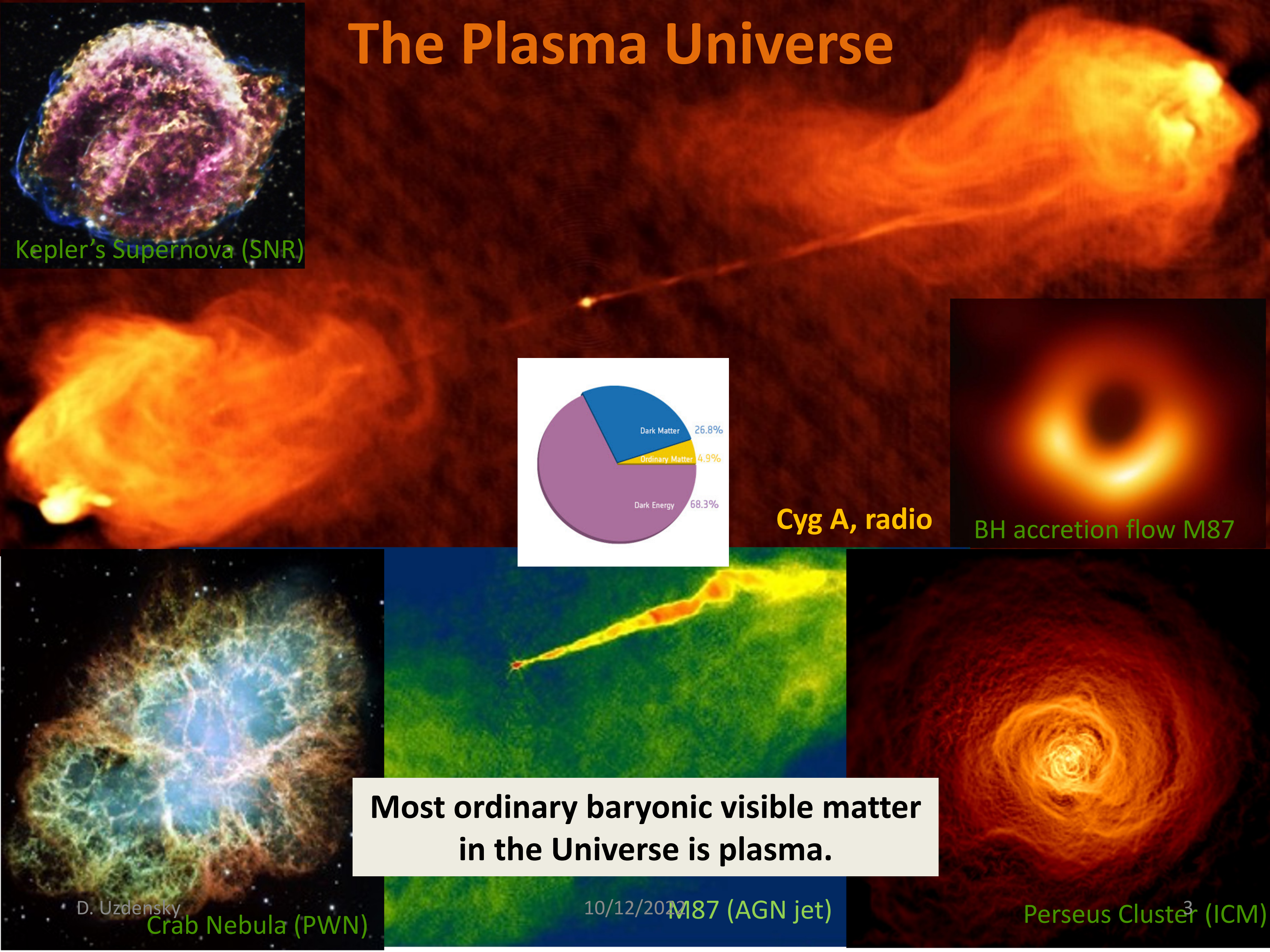
grad students: (John Mehlhaff), Kai Wong, Lia Hankla, Omar French

Work supported by NSF, NASA, DOE; INCITE, XSEDE

MIPSE Plasma Seminar, October 12, 2022

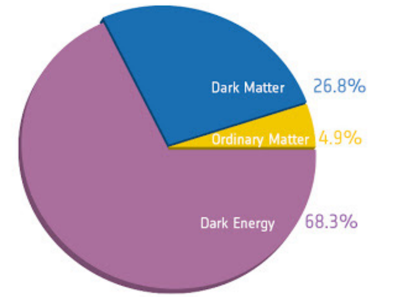
OUTLINE

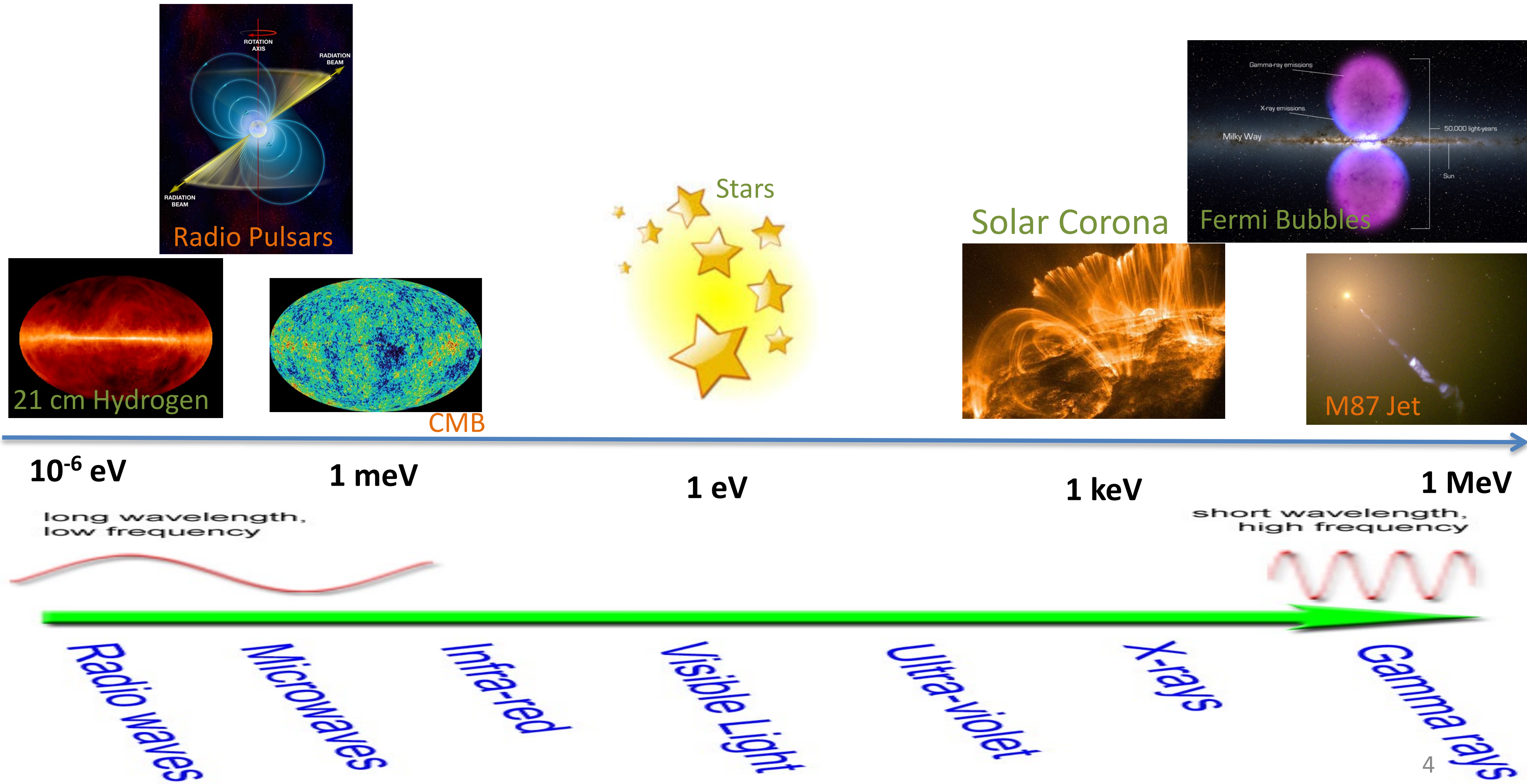
- Introduction:
  - The Plasma Universe
  - What is ***Plasma Astrophysics***?
  - What is ***Extreme Plasma Astrophysics***?
- Examples of Recent Radiative-PIC Numerical Studies of Extreme Plasma Processes:
  - Radiative Relativistic Magnetic Reconnection;
  - Radiative Relativistic Kinetic Turbulence.
- Future Outlook:
  - What can laser experiments do?
- Summary


The Plasma Universe
Kepler's Supernova (SNR)
Dark Matter 26.8%
Ordinary Matter 4.9%
Dark Energy 68.3%
Cyg A, radio
BH accretion flow M87
Most ordinary baryonic visible matter in the Universe is plasma.
Crab Nebula (PWN)
M87 (AGN jet)
Perseus Cluster (ICM)

The Shining Universe

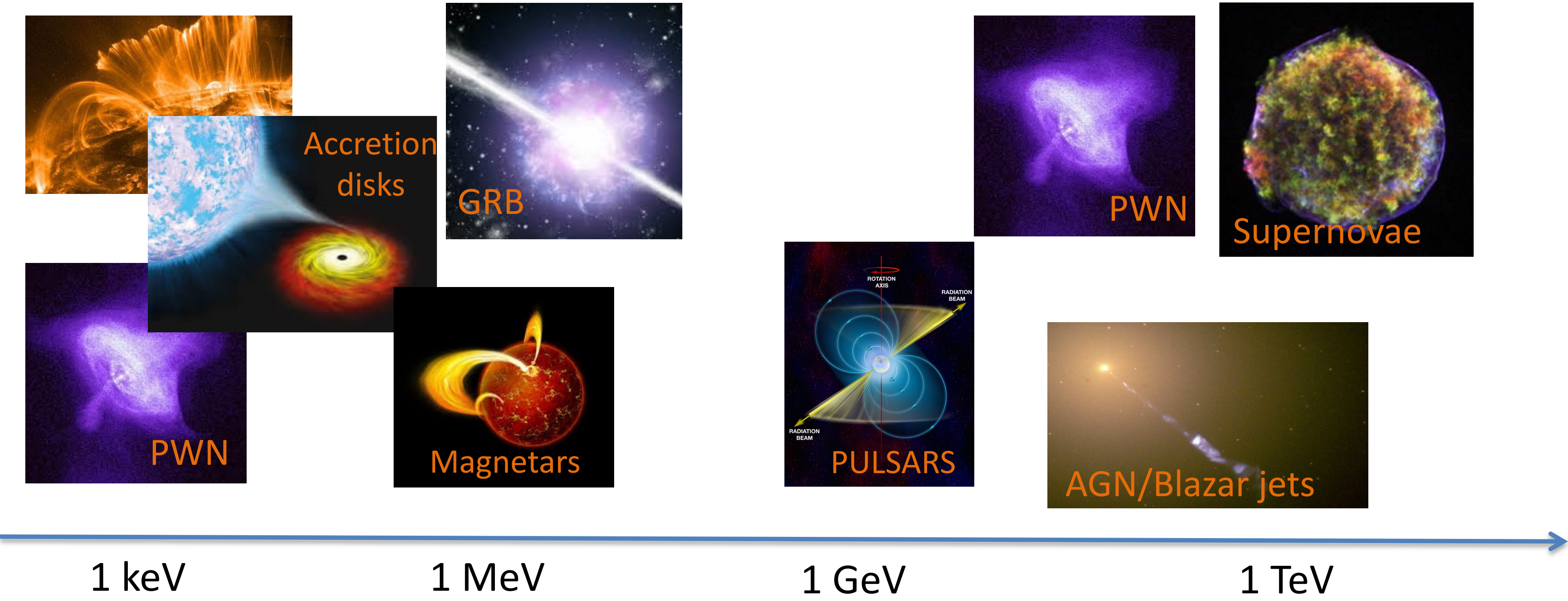
- Universe consists of 68% dark energy, 27% dark matter and only 5% of ordinary baryonic matter.
- But baryonic matter makes 100% of the light we see!





High-Energy Universe

- 6 orders of magnitude in photon energy from CMB (1 meV), through IR, visible, UV, to X-rays (keV).
- High-energy astronomy: γ-rays alone cover > 6 orders: **MeV – TeV**
- X-ray and γ-radiation is often nonthermal and variable (flaring)
- High-energy universe is very rich and diverse.



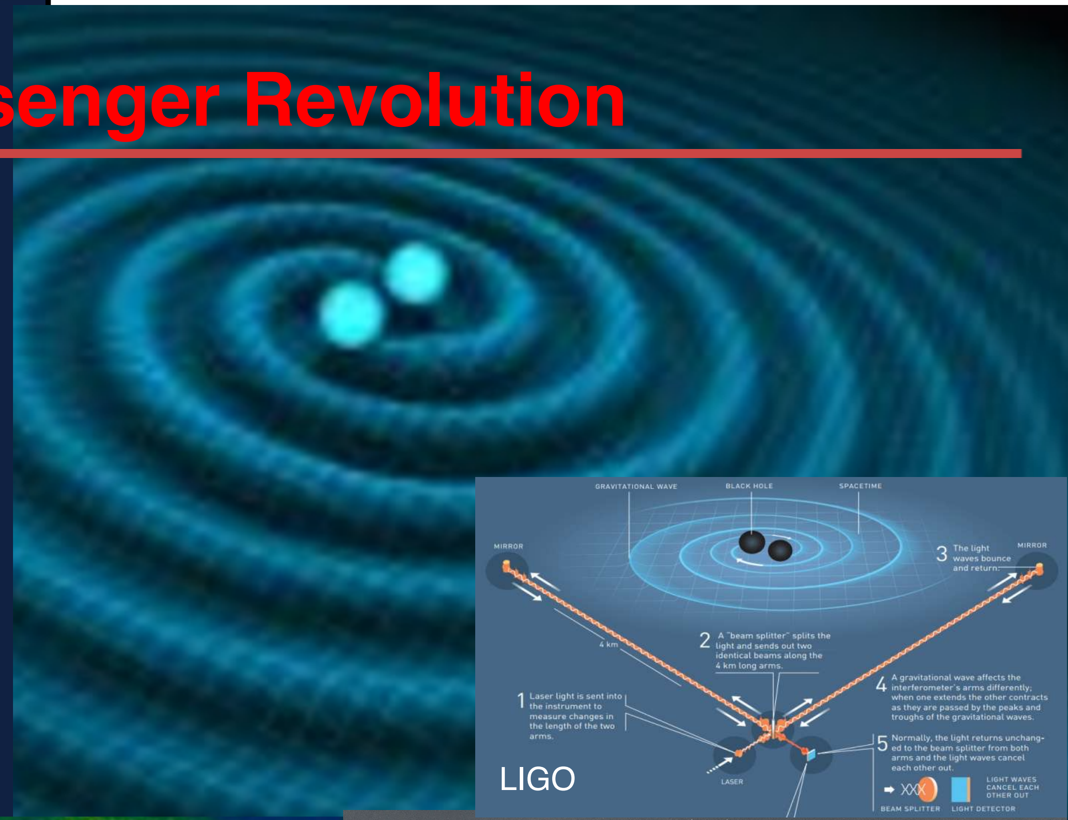
Multi-Messenger Revolution

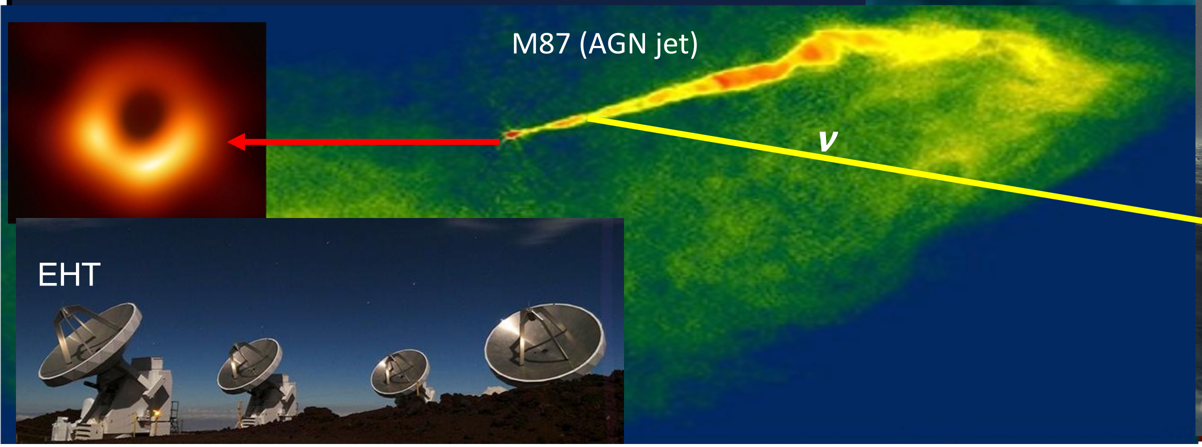
Recent multi-messenger Discoveries:

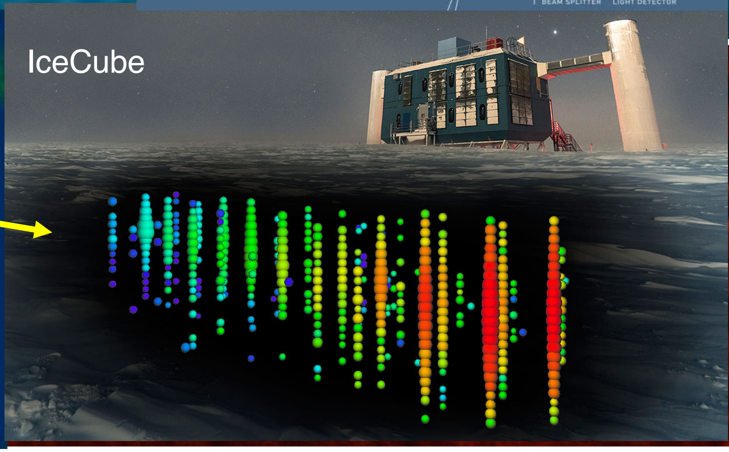
- ✓ GWs from merging BHs and NSs (LIGO)
- ✓ PeV neutrinos from BH jets (IceCube)
- ✓ Ultra-High Energy (10^{20} eV) Cosmic Rays
- ✓ Black Hole shadow in M87 (EHT)
- ✓ Fast Radio Bursts (VLA, Arecibo)

Physical understanding lags behind observations.

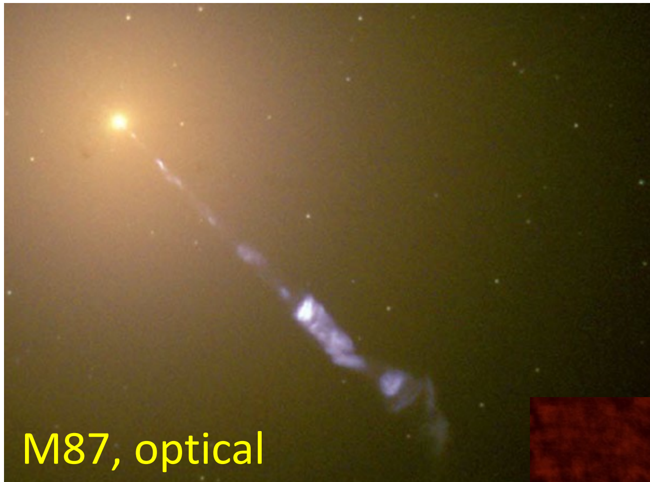
Understanding EM & particle signals requires Plasma Physics

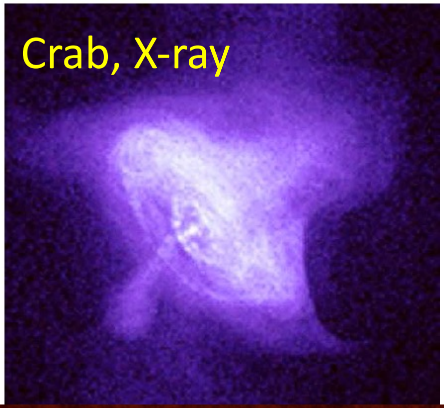


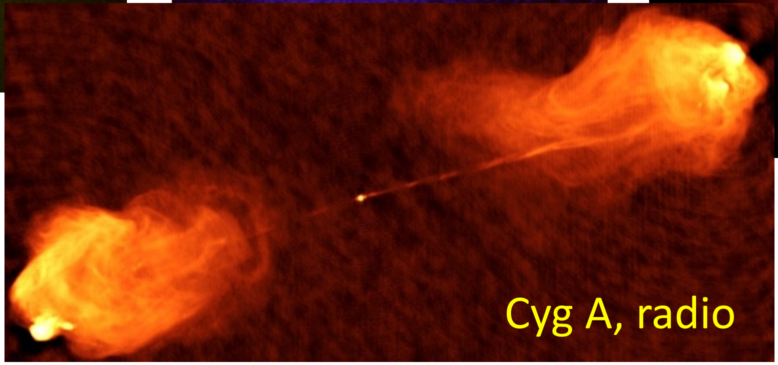




High-Energy Particle Acceleration and Emission in Astrophysical Plasmas







- Astrophysical plasmas ***shine***.
- Extremely ultra-relativistic particles pervade the Universe and emit high-energy gamma-rays
- Produced by powerful cosmic explosions (supernovae, Gamma-Ray Bursts) or by relativistic objects: Neutron Stars, Black Holes and their relativistic outflows: jets, winds.
- Radiative cooling time << travel time from central engine → *in-situ particle acceleration.*

Dissipation/Acceleration Mechanisms

In Astrophysics particles are accelerated by complex nonlinear ***collective plasma processes***.

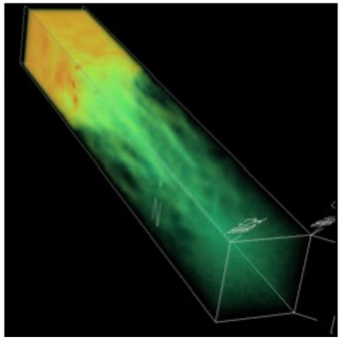
AVAILABLE FREE ENERGY

Bulk Kinetic

Magnetic (Poynting flux)

- longitudinal:

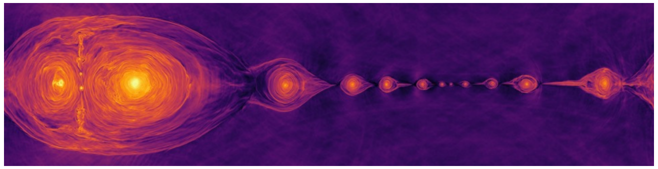
shocks



SINGULAR STRUCTURE

current sheets:

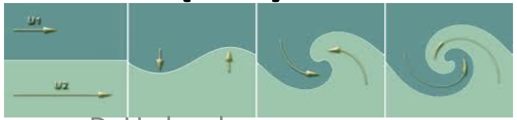
Magnetic reconnection

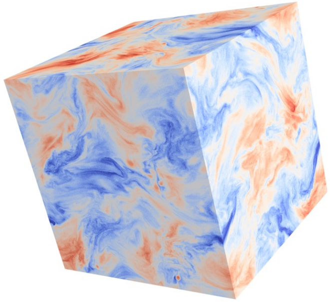


TURBULENCE

- transverse:

shear (KH) instability





Space and Astro plasmas are complex, multi-component systems

Thermal gas/plasma

Nonthermal particles (CRs)

Magnetic field

These components are often in energy equipartition:
e.g., ISM in our Galaxy: $U_{gas} \sim U_{magn} \sim U_{turb} \sim U_{CR} \sim U_{rad}$

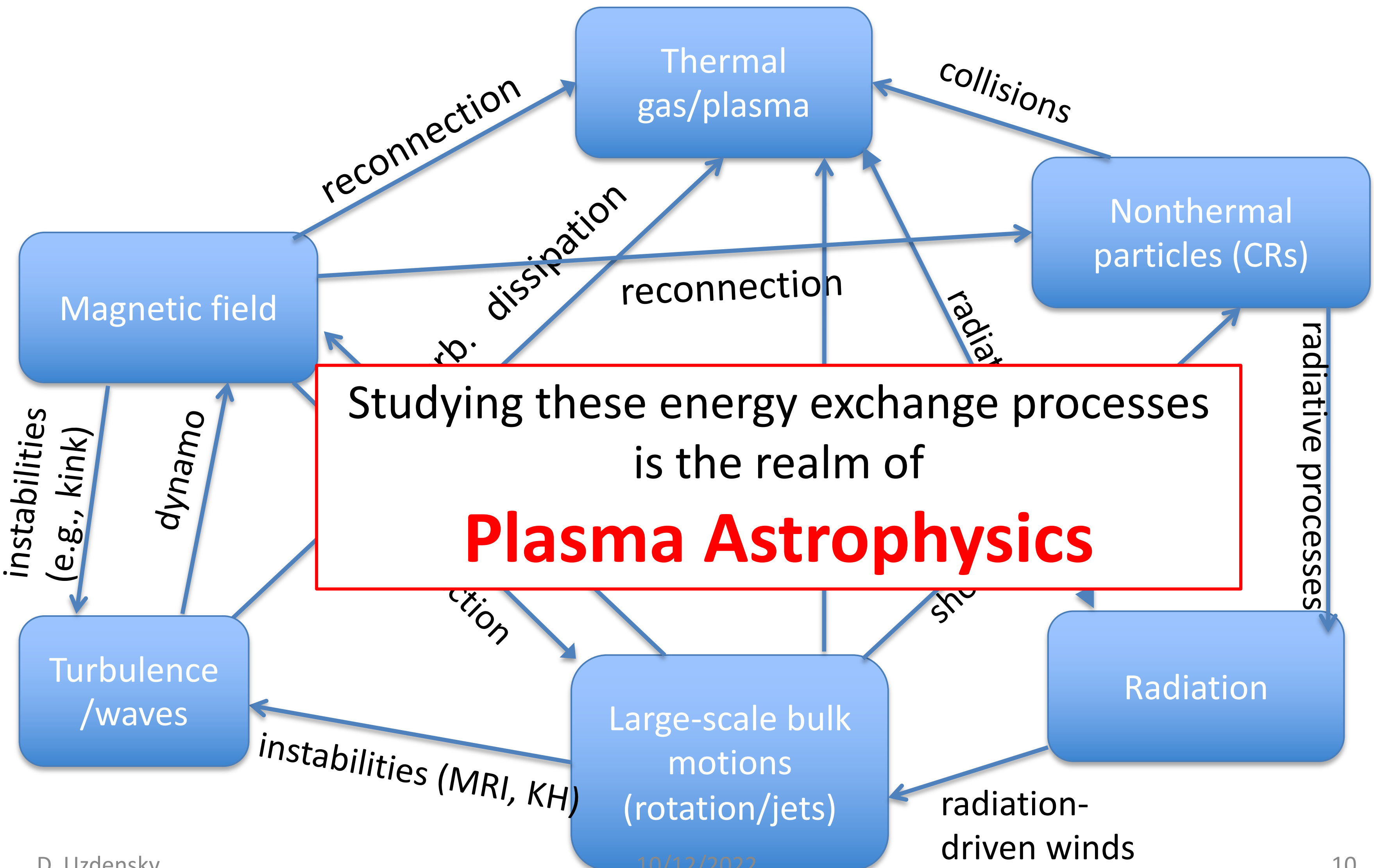
Turbulence /waves

Large-scale bulk motions (rotation/jets)

Radiation

Components and Processes

Energy Exchange between plasma components: collective plasma **processes.**



- Plasma physics is mature.
- Extensive knowledge base of collective plasma processes built over decades of theoretical, computational, experimental research.

We can apply this rich traditional plasma knowledge to high-energy astrophysical plasmas!

OR CAN WE ??

Not so fast!

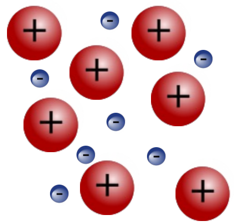
… would be warranted if these plasmas were governed by the same physics, same equations….

But this is not always the case!

Traditional & Extreme Plasma Physics

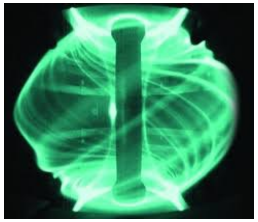
Traditional Plasmas

- Electrons and ions
- Non-relativistic
- Non-radiating

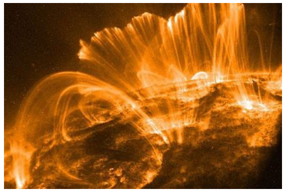


Applications:

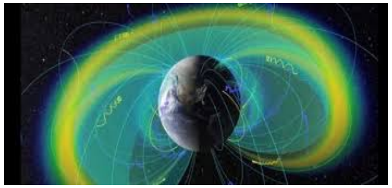
- Most lab plasmas



- Solar corona



- Earth's magnetosphere

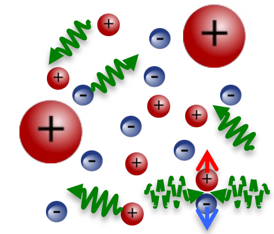


Based on 19th Century Physics!

New: Extreme Plasmas

"Exotic"* Physics:

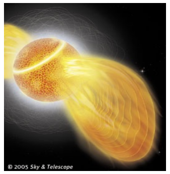
- e^-e^+ pairs (+ ions), photons
- Relativistic (Special & General)
- Radiation (cooling, drag, pressure)
- QED effects (e.g., pair creation)



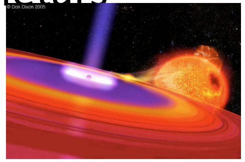
**These effects may be exotic for traditional plasma physicists, but not for high-energy astrophysicists.*

Applications:

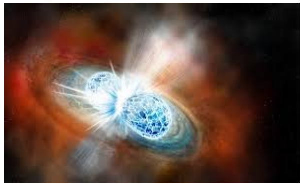
Neutron Stars (NSs) & Black Holes (BH):



- Magnetospheres of pulsars, magnetars
- NS and BH accretion disks, jets



- Cosmic blasts (SNe, GRB)
- NS-NS mergers



- Early Universe

and soon…

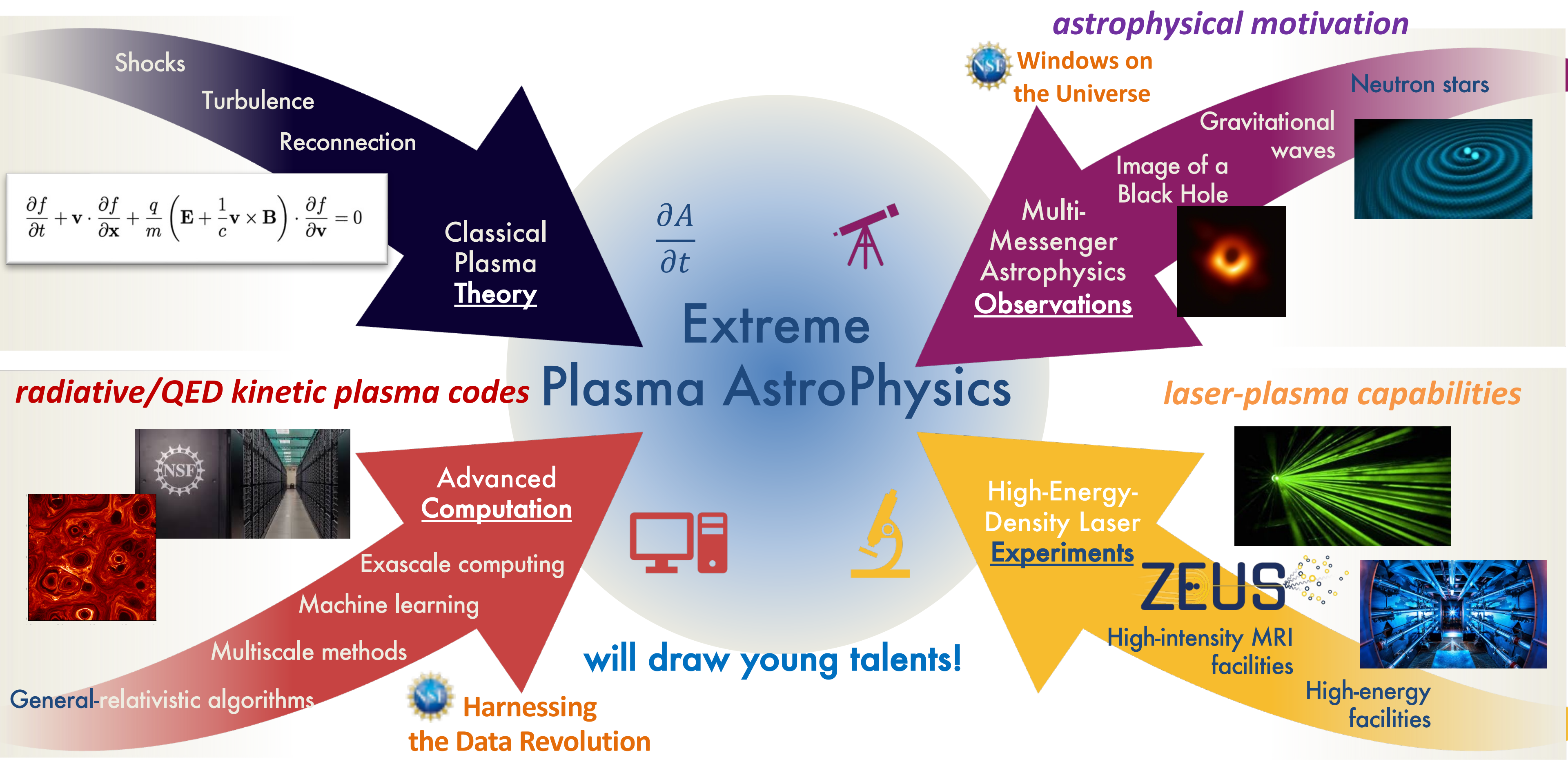
- **Laser-plasma lab experiments!**

Based on 20th Century Physics!

Extreme Plasma (Astro)Physics

This calls for development of ***Extreme Plasma Astrophysics:***
systematic inclusion of these *"exotic"* physical effects into kinetic plasma framework.

--- intellectually exciting ***Frontier of Fundamental Physics***



Plasma-2020 & Astro-2020 Decadal Surveys whitepaper: ***"Extreme Plasma Astrophysics"***

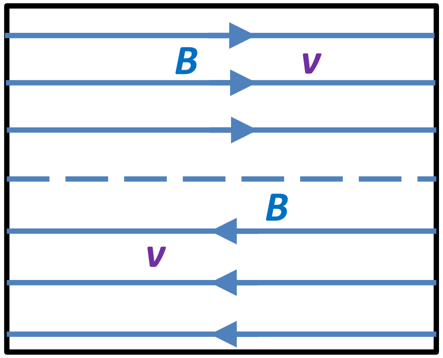
https://arxiv.org/abs/1903.05328

Slide credit: L.Willingale, F.Fiuza

Problems of (Extreme) Plasma Astrophysics

Local:
Collective Plasma Processes

- Waves
- Instabilities
- Reconnection
- Turbulence
- Shocks
- Pair Cascades



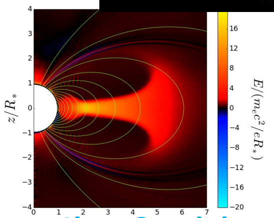
Magnetic Reconnection
Kelvin-Helmholtz Inst.

QUESTIONS:

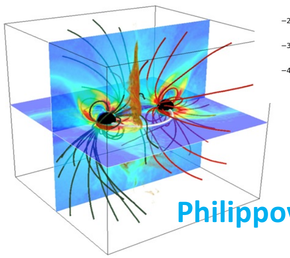
- How is energy dissipated?
- How is it partitioned btw. *e*ns & ions?
- How does nonthermal particle acceleration work?
- What is the spectrum of turbulence?
- What coherent field, flow structures form?
- **What light is produced?**
- **How many e^+e^- pairs are created?**

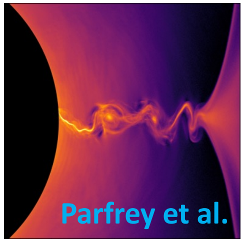
Global:
Astrophysical Systems

- Pulsar Magnetosphere
- Magnetar Magnetosphere
- Merging NSs
- Accreting BH Magnetosphere

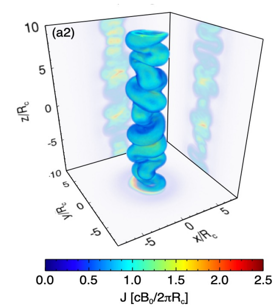


Chen & Beloborodov





Something in between:
Mesoscopic Problems



Alves et al.

Tools of Extreme Plasma Astrophysics

- Analytical Theory

- Massively-parallel simulations:

Radiative GRMHD and Radiative Particle-in-Cell (PIC) (incl. QED-PIC):

– relativistic radiative PIC codes: *Zeltron*, *Tristan-MP, Aperture, OSIRIS, Runko, GRPIC*

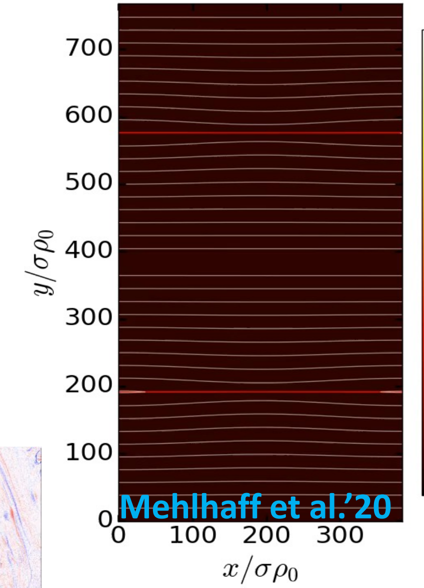
– include radiation reaction on emitting particles

– e^+e^- pair or electron-ion plasma + photons

– Hundreds of billions simulated particles

– $(10^4)^2$-cell (2D) or $(10^3)^3$-cell (3D) grids

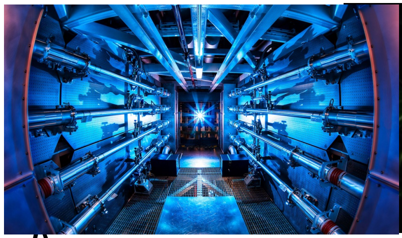
– Run on hundreds of thousands cores



- HED Laboratory Plasma Experiments:

– Laser Plasma (*NIF, LLE, SLAC, Michigan, Rutherford*)

– Pulsed Power (Imperial, MIT, Sandia)



Radiative Plasma Astrophysics

- **Radiaction (= Radiation Reaction)** force on emitting particles is important in many high-energy ***astro*** systems:

$$m_e c \frac{du^\mu}{ds} = -\frac{e}{c} F^{\mu\nu} u_\nu + g^\mu$$

Lorentz 4-force

Radiation reaction 4-force
For relativistic particles:

$$g^\mu \approx -\frac{P_{\rm rad}}{c^2} u^\mu$$

u^μ : **4-velocity**

$F^{\mu\nu}$: **Electromagn. field tensor**

$ds = c\,dt/\gamma_e$: **Relativistic interval**

Two main (classical) radiation mechanisms:

- Synchrotron: in magnetic energy density $U=B^2/8\pi$

$$P_{rad} = 2\sigma_T c U \gamma^2 \sin^2\varphi$$

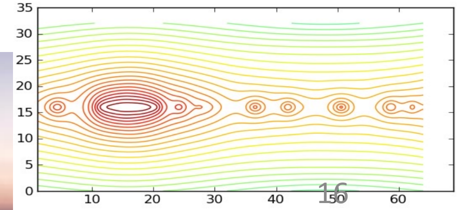
- Inverse-Compton (IC) scattering (Thomson limit): ambient bath of soft photons of energy density U.

$$P_{rad} = \frac{4}{3}\sigma_T c U \gamma^2$$

- ***Fluid-level manifestations***:
  - Radiative cooling;
  - Radiation pressure;
  - Radiative drag on bulk plasma flows;
  - Compton-drag resistivity.

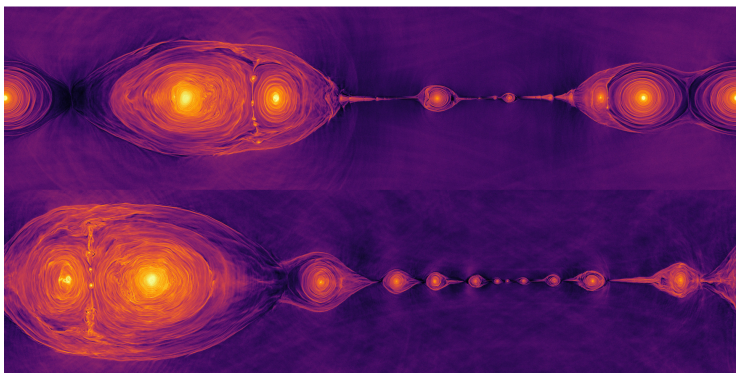
- Radiation is often our only ***observational probe*** into astro systems.

How does, e.g., a reconnection layer look like, literally?
*What are the prompt **radiative signatures** (spectra, lightcurves) seen by an outside observer?*

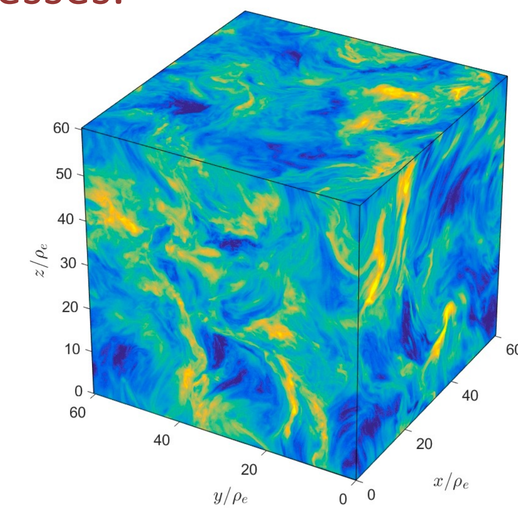


Examples of Recent Radiative-PIC Simulations of Radiative Relativistic Collective Plasma Processes

New radiative-PIC codes and powerful computers enable ab initio simulation studies of extreme astrophysical collective plasma processes.

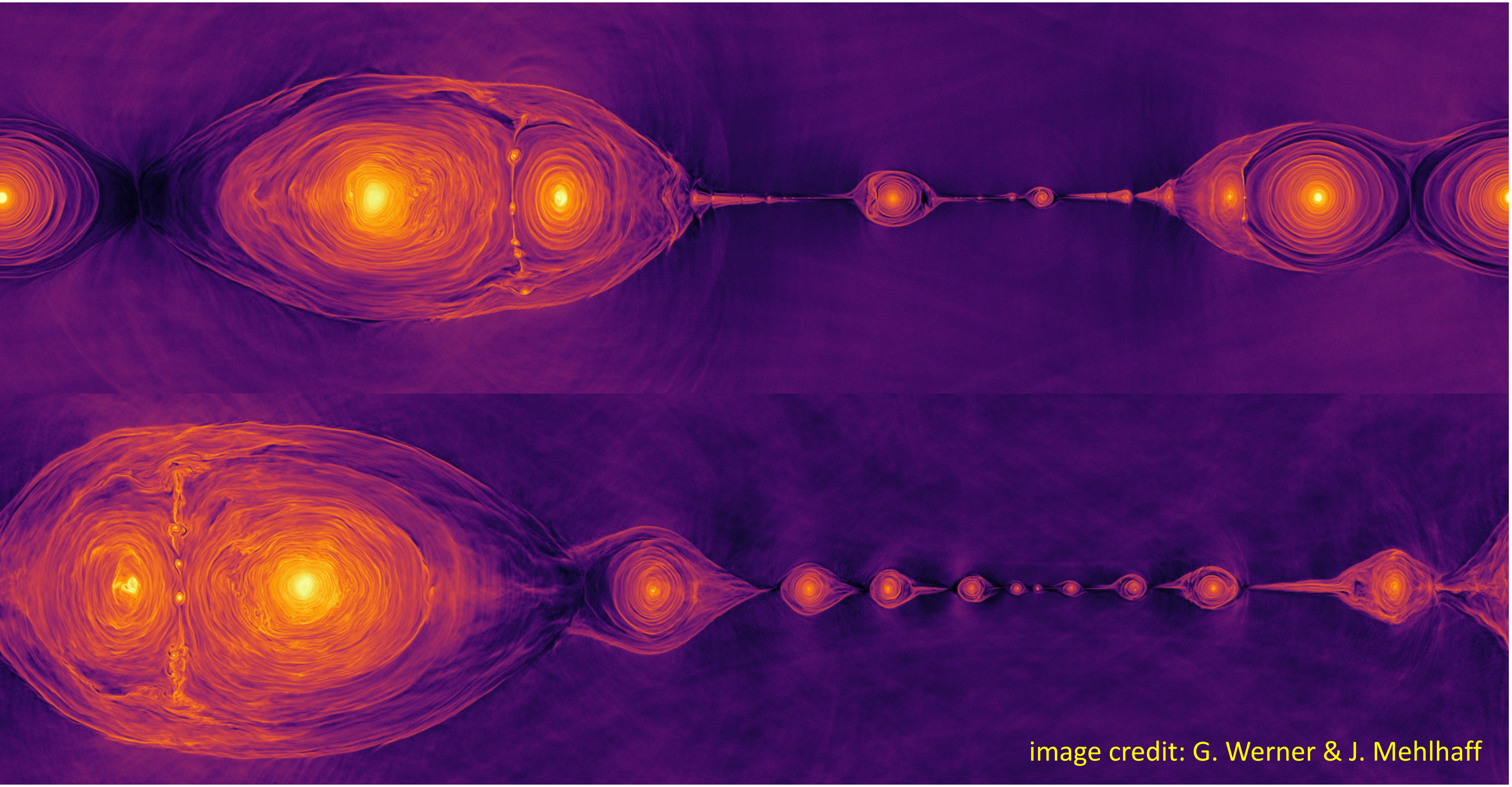


Magnetic Reconnection
(Greg Werner)



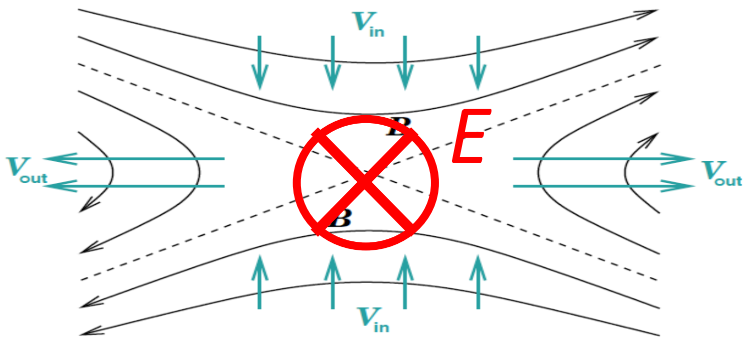
Kinetic Plasma Turbulence
(Vladimir Zhdankin)

Radiative Relativistic Magnetic Reconnection

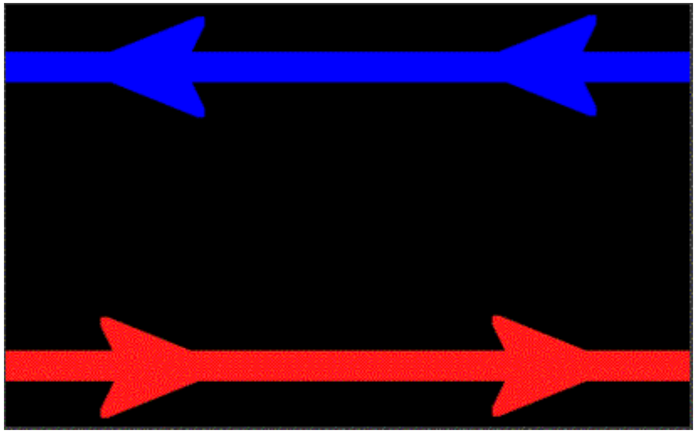


Introduction: Magnetic Reconnection

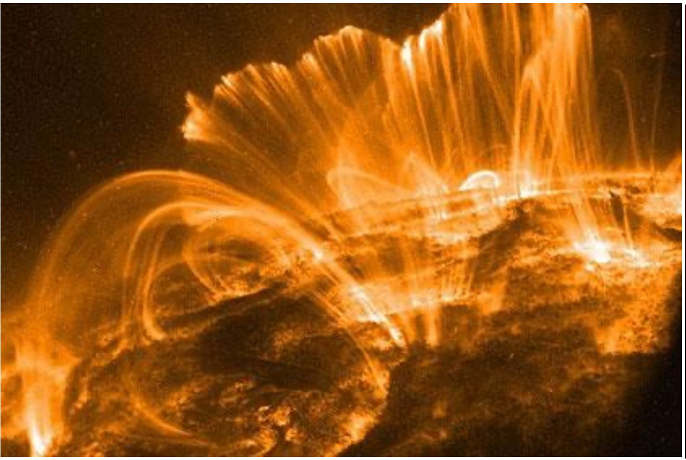
- **<u>Magnetic reconnection</u>** is a rapid rearrangement of magnetic field topology, breaking ideal-MHD.

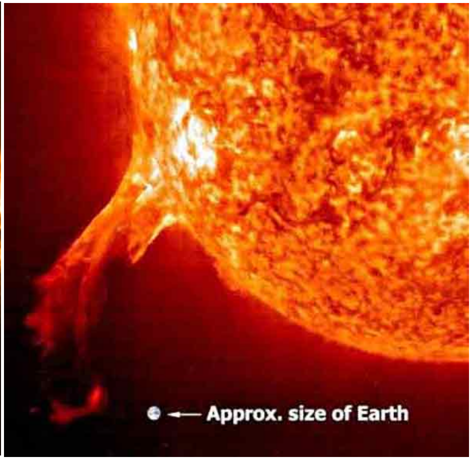


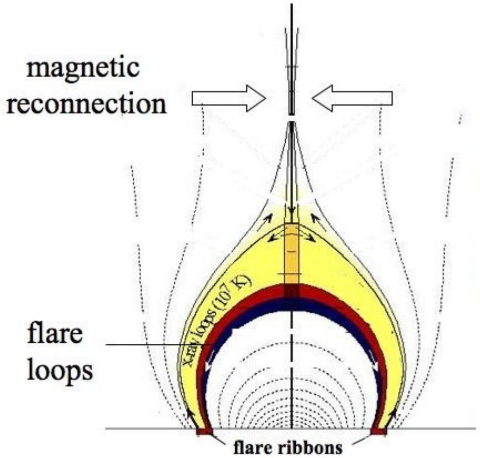
- Reconnection results in a violent <u>release of magnetic energy</u> and its conversion to:
  - electron and ion heating
  - bulk flow kinetic energy
  - non-thermal particle acceleration
  - **radiation**



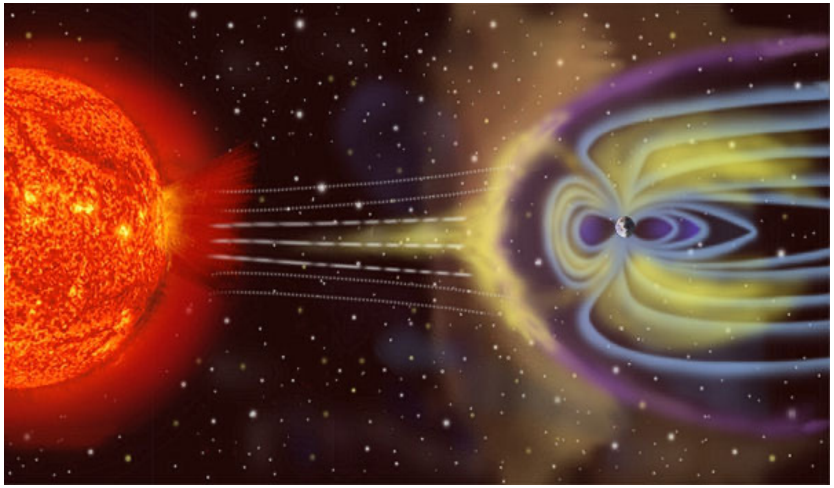
Traditional Magnetic Reconnection in the Solar System

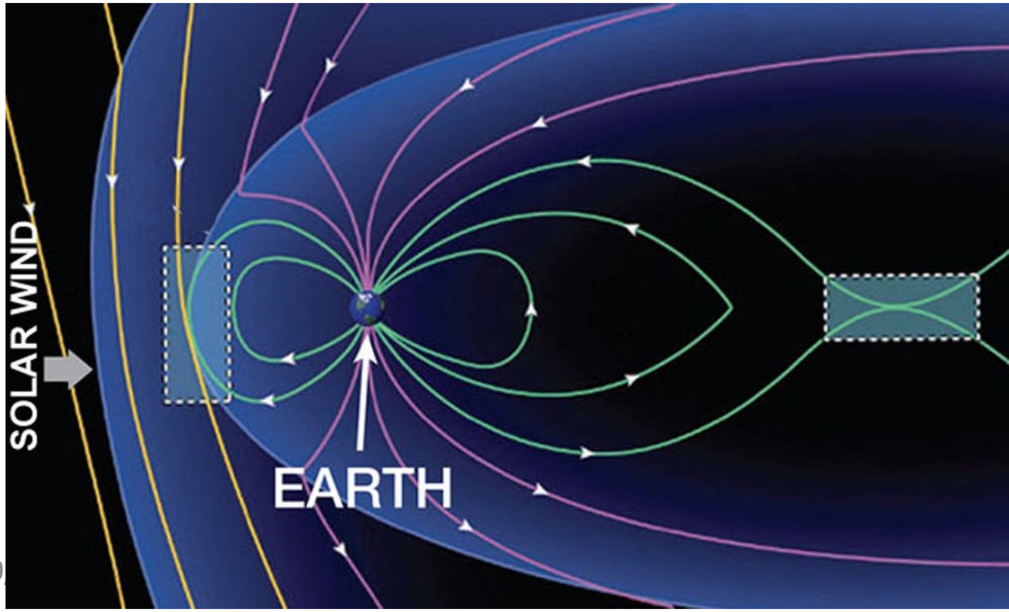






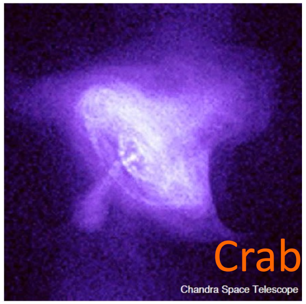
(adapted from Forbes & Acton, 1996)

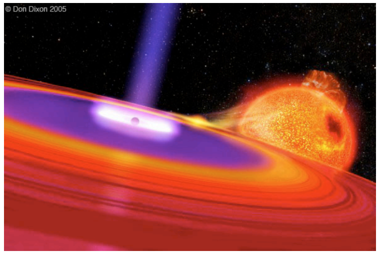




Radiative Reconnection in Astrophysics

(Uzdensky 2016 review)



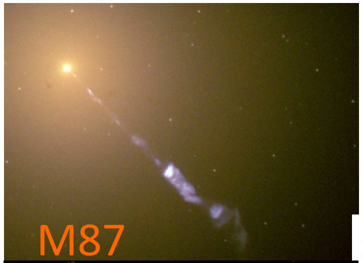


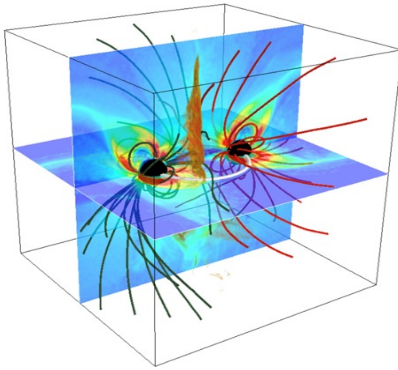
- Pulsar magnetospheres, winds, PWNe

- Black hole accretion disks & coronae

- Active galactic nuclei (AGN/ blazar) jets*
  powered by supermassive BHs

(producing CRs, PeV neutrinos, TeV γ-ray flares)



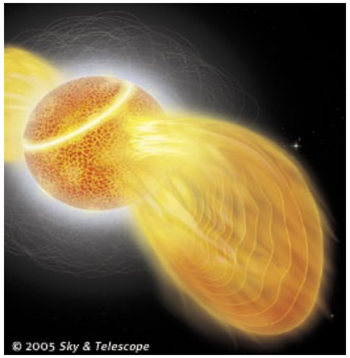


- Gamma-Ray Bursts (GRBs)

exploding massive stars
or NS-NS mergers* - gravitational wave sources

- Magnetar magnetospheres

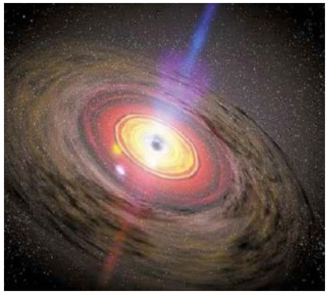
(ultra-magnetized neutron stars: γ-ray flares)

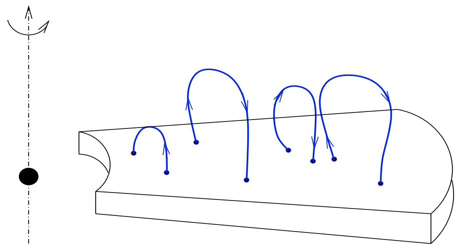


* **Multi-messenger astrophysics**

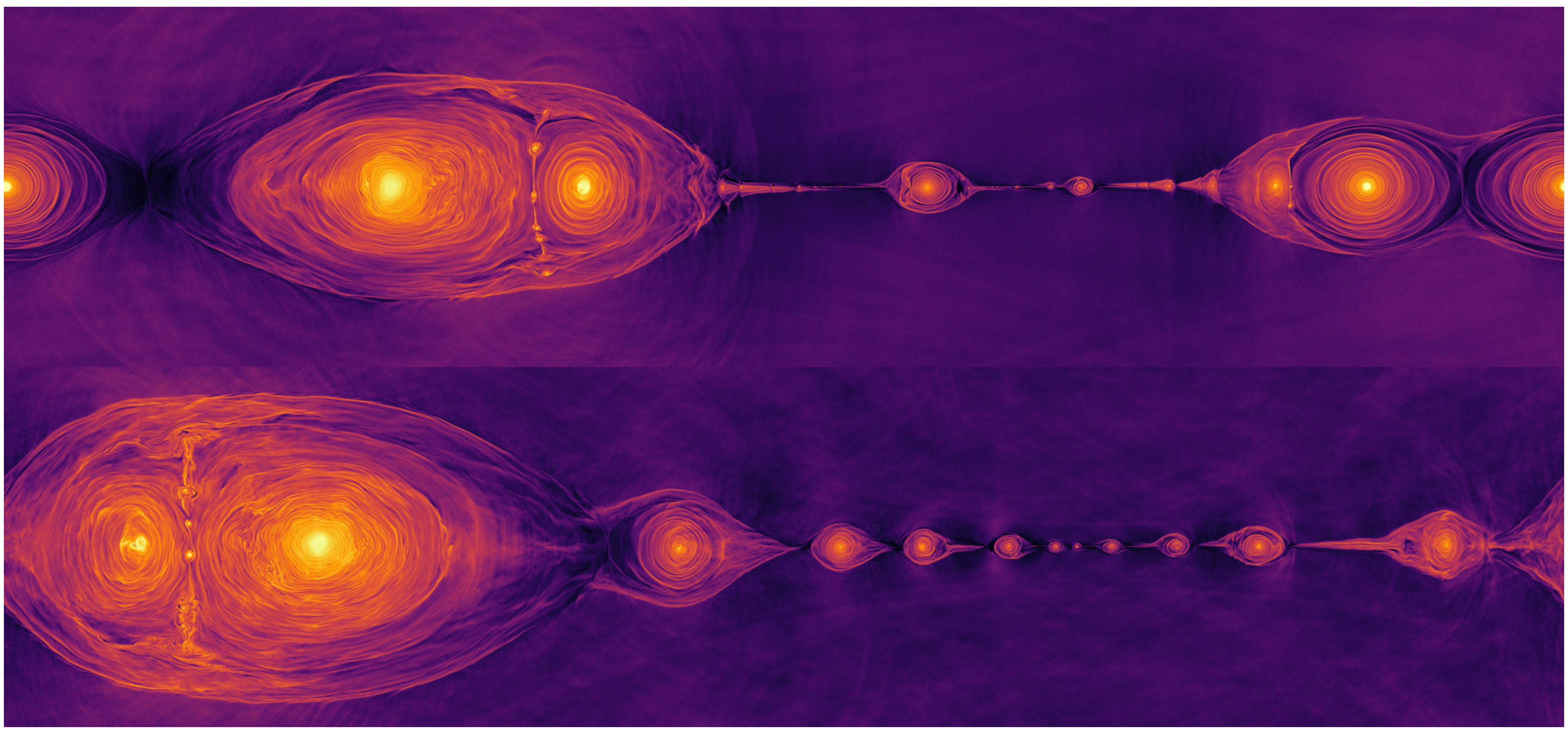
PIC Simulations of Relativistic Magnetic Reconnection with inverse-Compton (ICγ) Radiative Cooling

Werner, Philippov, Uzdensky 2019

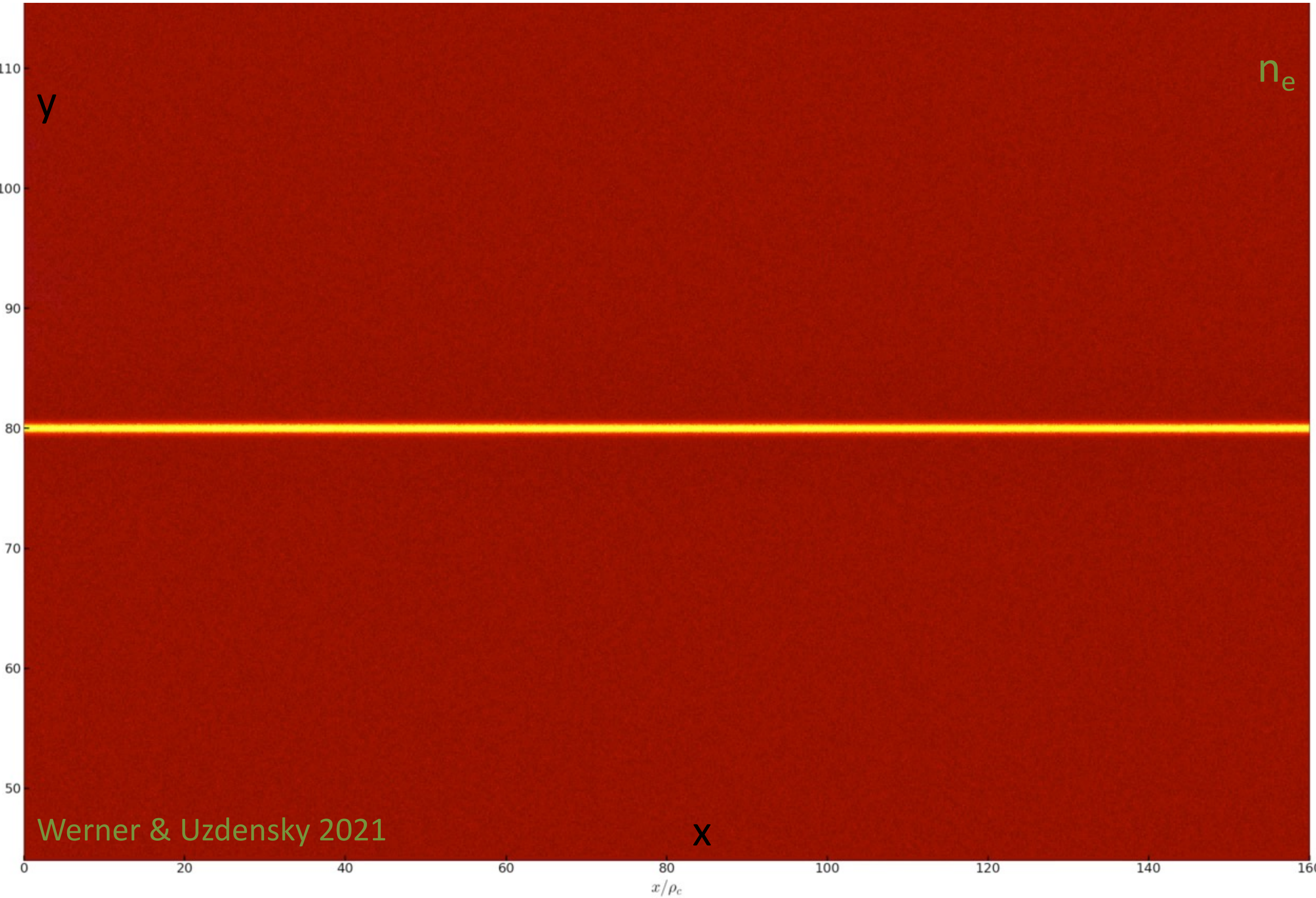




Relevant to coronae of black-hole accretion disks



Also: Sironi & Beloborodov (2020); Ortuño-Macías & Nalewajko (2019); Mehlhaff et al. (2020-21)

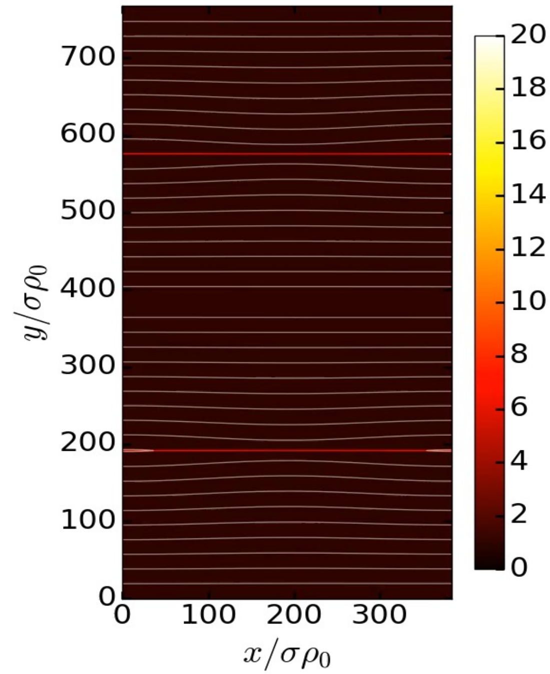


y
n_e
Werner & Uzdensky 2021
x
x/ρ_c

PIC Simulations of Radiative Reconnection with ICy cooling

(Werner, Philippov, & Uzdensky 2019)

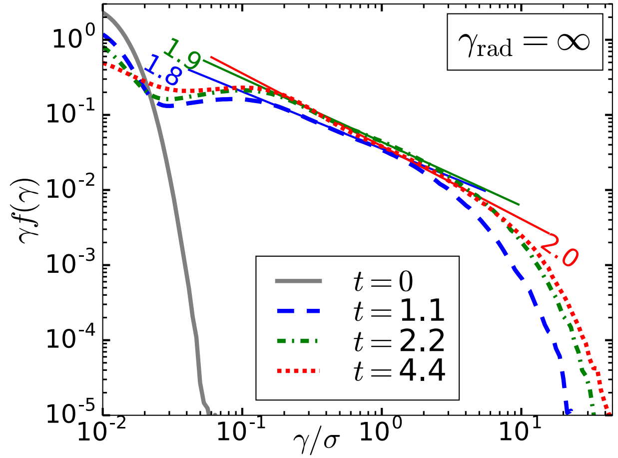
Radiative-PIC (Zeltron) sims of relativistic pair-plasma reconnection with inverse-Compton radiation cooling.



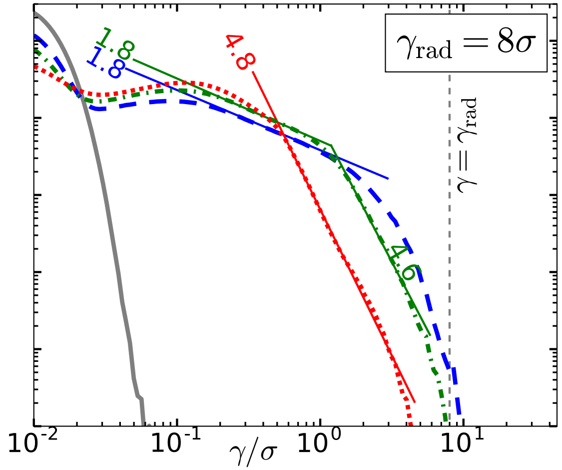
Weak cooling (large γ_{rad}/σ): usual hard power law

Strong cooling (small γ_{rad}/σ): variable steep power law

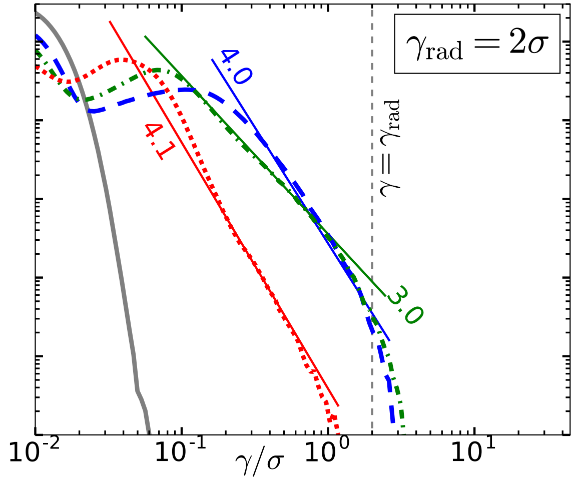
Intermediate (medium γ_{rad}/σ): both power laws



no cooling



medium cooling



strong cooling

Kinetic Beaming of Particles and Radiation

(Mehlhaff, Werner, Uzdensky, Begelman 2020)

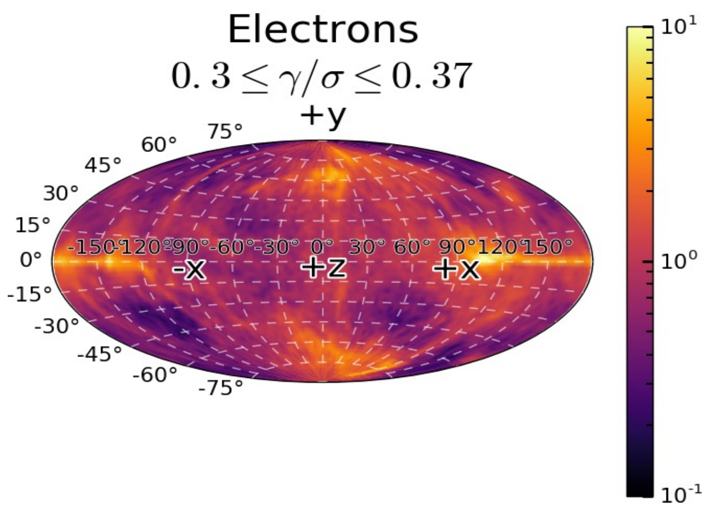
- Relativistic reconnection focuses accelerated particles into narrow beams/fans *(Uzdensky et al. 2011, Cerutti et al. 2012)*
- Focusing is ***energy-dependent*** (higher energy -> stronger collimation):

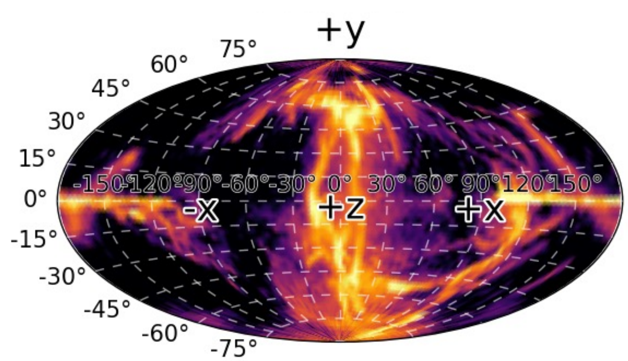
  "kinetic beaming"

- But: beams diverge and isotropize over time...unless radiaction cools them first...

low-energy particles isotropize before radiating away their energy

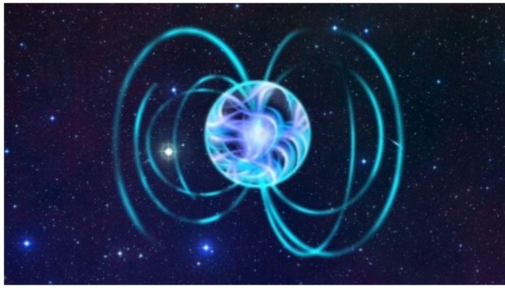
high-energy particles radiate away their energy before isotropizing





Angular distributions of emitted photons

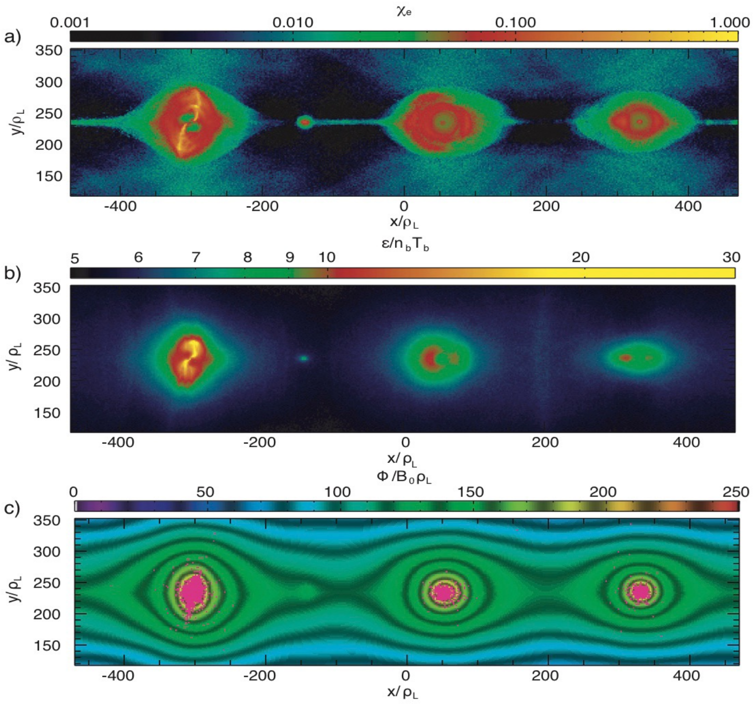
QED-Radiative-Reconnection-Powered Pair Creation in NS & BH Magnetospheres



Rel. PIC Simulations of Reconnection with Synchrotron Radiation and Pair Creation

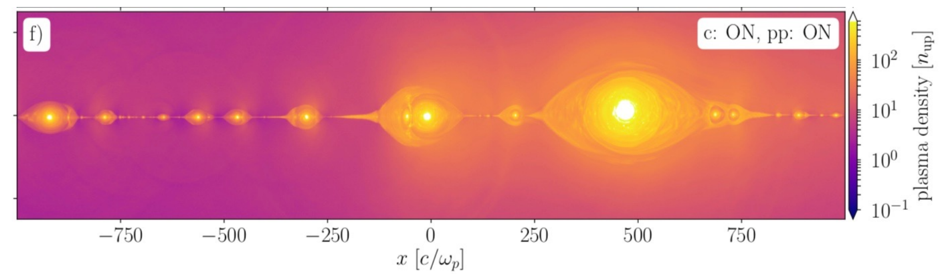
Schoeffler, Grismayer, Uzdensky, Fonseca, Silva '19

- 1-photon in strong-B pair production (OSIRIS)



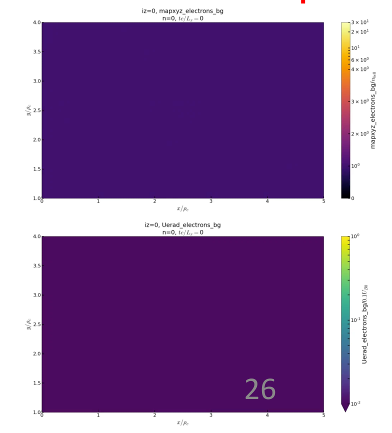
Hakobyan, Philippov, Spitkovsky '19

- 2-photon (γγ) pair production (TRISTAN)

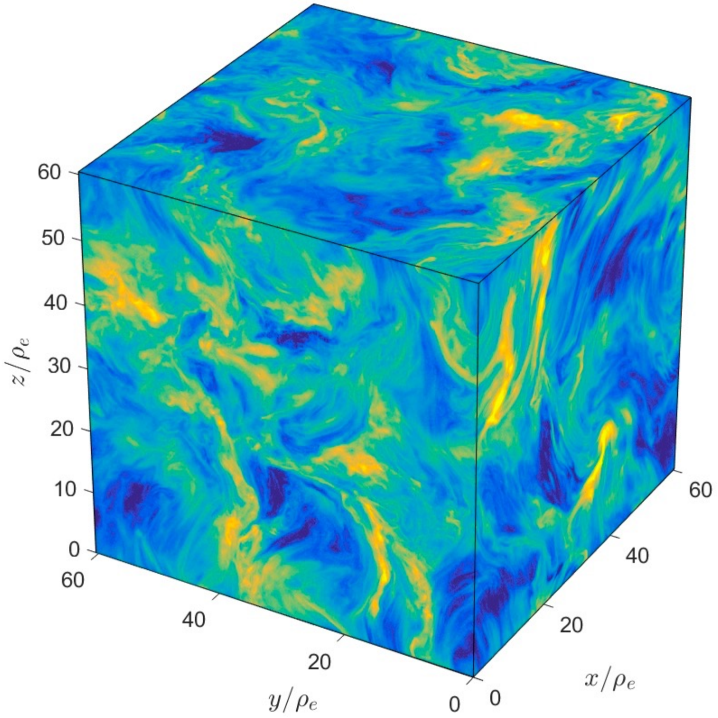


New QED Module for Zeltron (developed by J. Mehlhaff):

- ✓ discrete photon macroparticles
- ✓ Klein-Nishina QED effects
- ✓ (γγ) pair production



Relativistic Radiative Turbulence

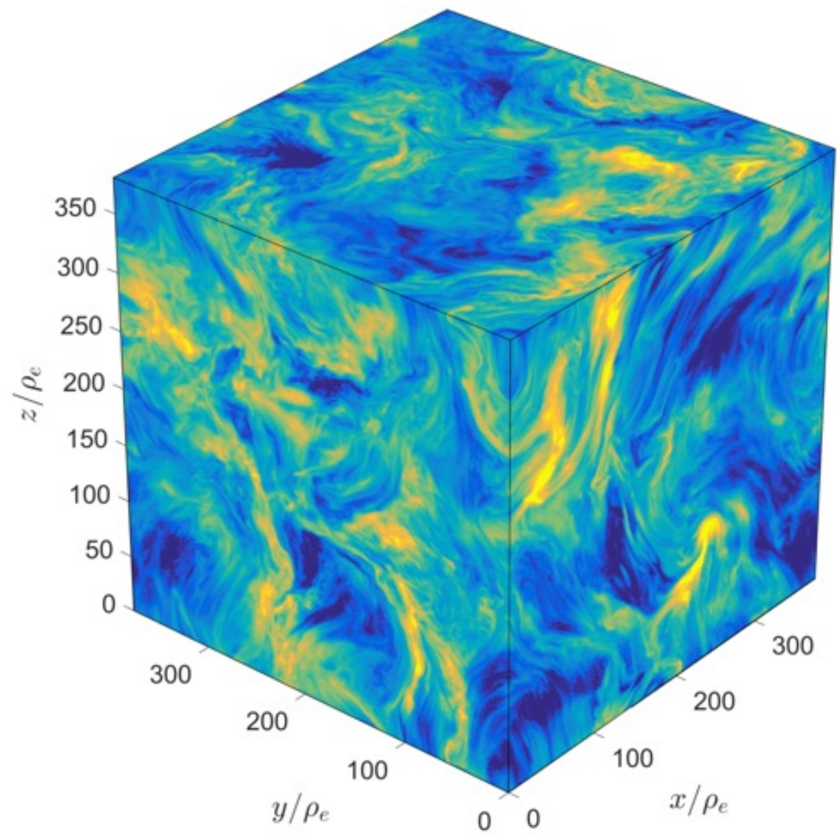


Astrophysical applications:

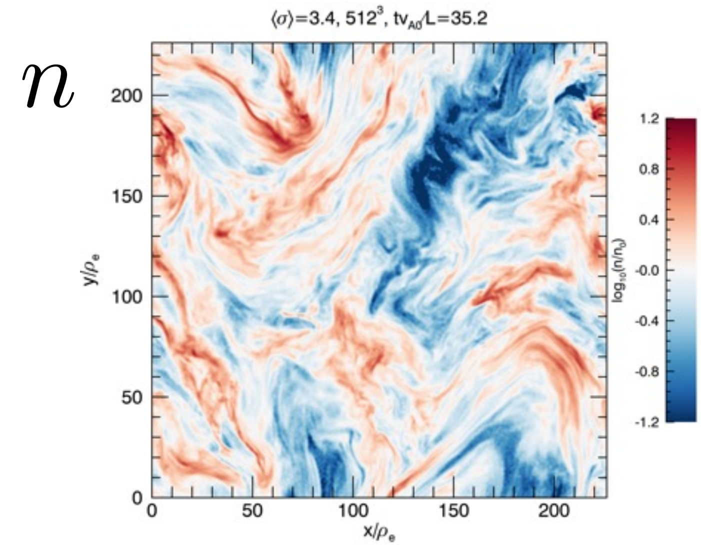
PWN, hot BH accretion flows, AGN/blazar jets, GRBs.

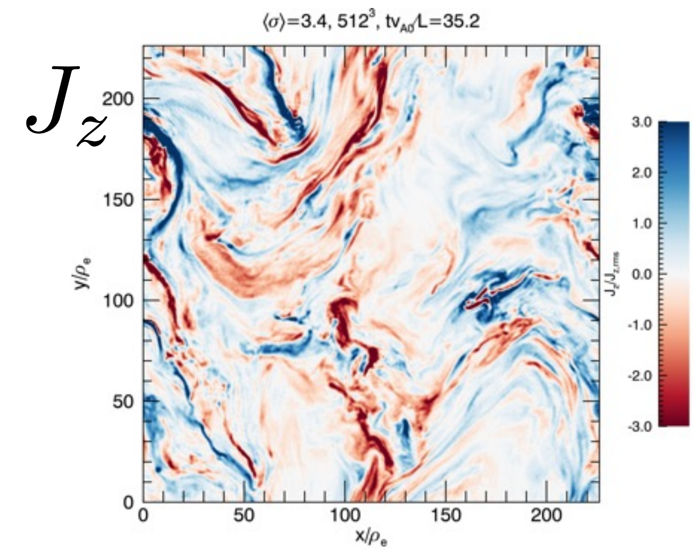
3D PIC Simulations of Relativistic Kinetic Turbulence with External Inverse-Compton Radiative Cooling

(Zhdankin, Werner, Uzdensky, Begelman 2020)



Emissivity

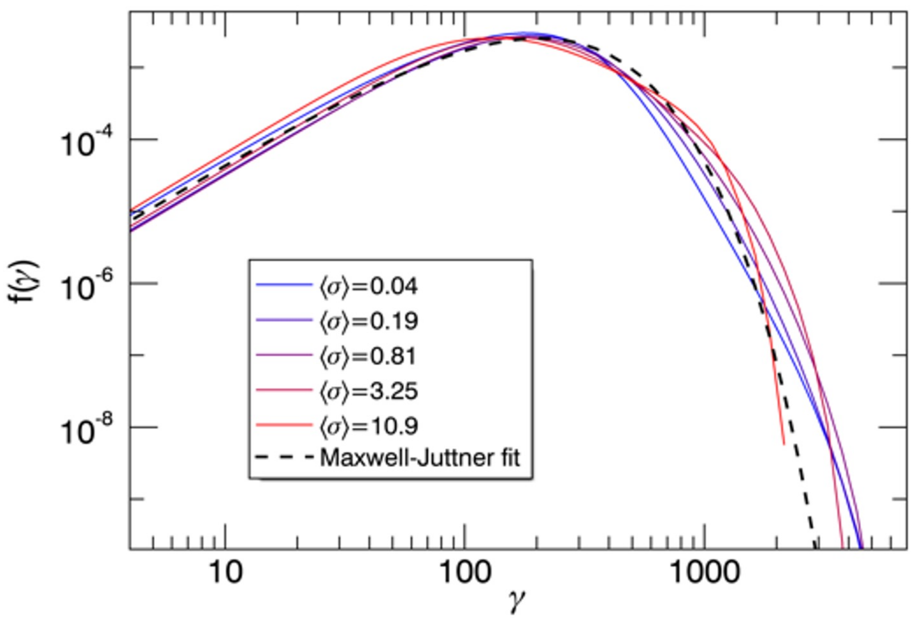


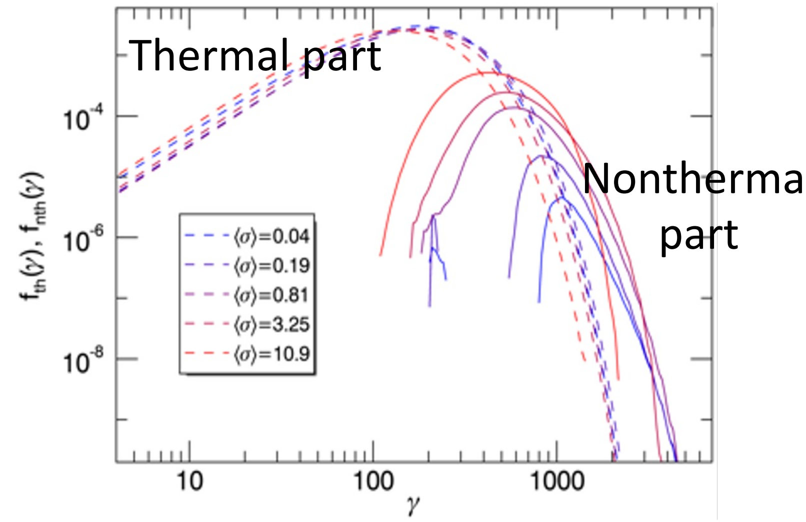


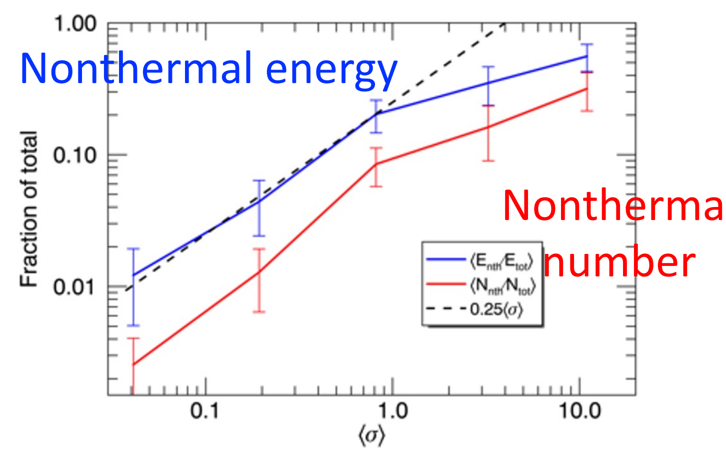
(Also: Comisso & Sironi; Nattila & Beloborodov)

Steady-State Particle Distribution

(Zhdankin, Werner, Uzdensky, Begelman 2020)







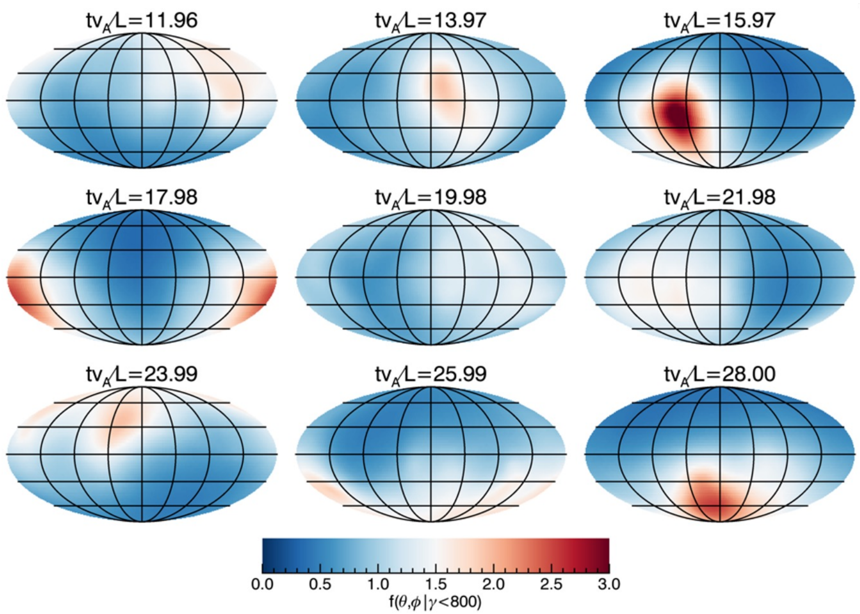
Quasi-thermal particle distribution
Power-law tail quenched by cooling

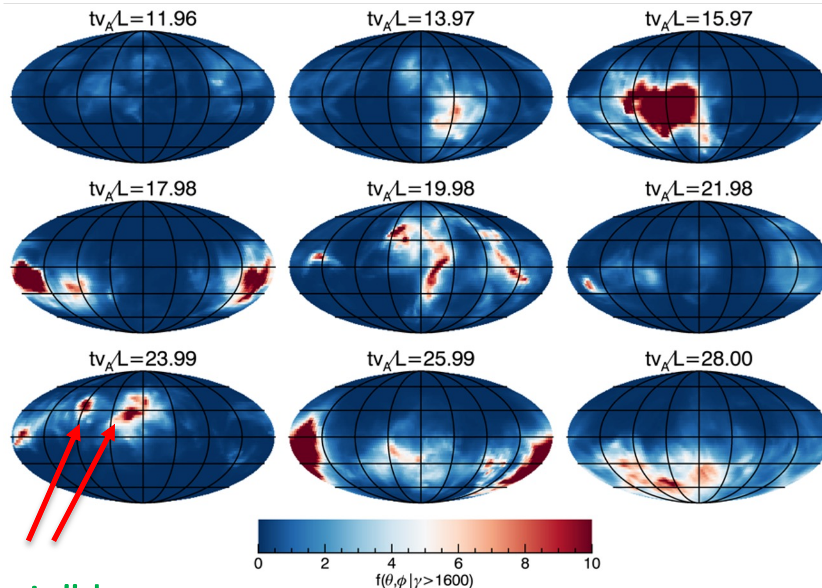
Turbulent Kinetic Beaming

Low-energy particles

$\langle \sigma \rangle = 3.4$

High-energy particles





"Kinetic" beams

Intermittent high-energy beams – Kinetic Beaming!
Similar to magnetic reconnection
(c.f., Cerutti et al. 2012, 2013; Mehlhaff et al. 2020)

Prospects for Experimental Studies

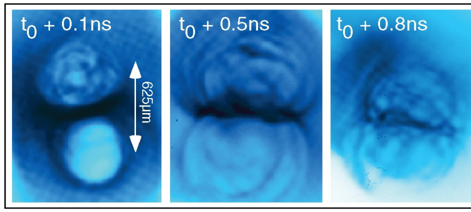
But how do we know that our simulations are correct?

What can lab experiments do?

Powerful, high-intensity lasers such as ZEUS give us the ***Experimental Branch*** *of* ***Extreme Plasma Physics.***

- In Astrophysics, high-energy particles are accelerated by *collective plasma processes (shocks, reconnection, turbulence) in extreme environments* near BHs and NSs.
- Collective plasma processes (and particle acceleration) are already studied in laser-plasma expts, yielding valuable insight.
- PIC simulations + theory: efficient high-energy relativistic nonthermal particle acceleration requires relativistic regime:

$$u \sim V_A \sim c \iff \sigma = \frac{B_0^2}{4\pi n_b m c^2} > 1$$



Vulcan Laser: Nilson et al. 2006

Previous moderate-intensity (10^{14}-10^{15} W/cm^2) laser expts (NIF, Omega, Hercules, Vulcan…) cannot achieve relativistic conditions, are not optimal for studying relativistic plasma dynamics.

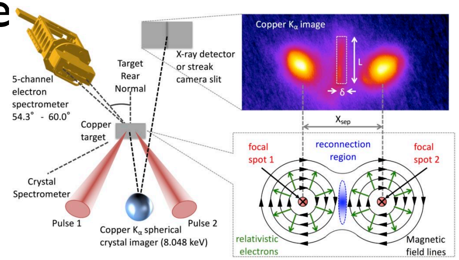
Prospects for Experimental Studies

What can lab experiments do?

- PIC simulations + Theory: efficient high-energy relativistic nonthermal particle acceleration requires relativistic regime:

$$u \sim V_A \sim c \iff \sigma = \frac{B_0^2}{4\pi n_b m c^2} > 1$$

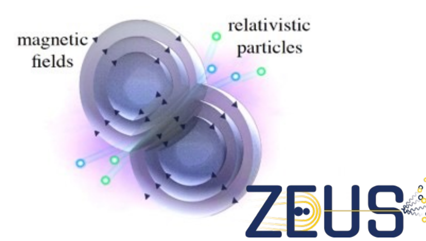
- It is difficult to make bulk ions relativistic but it's possible to make relativistic electron component!



Raymond et al. 2018

Possible routes:

- Current: Relativistic *electron-only reconnection* (slow ions) with high-intensity (10^{18} W/cm^2) lasers (e.g., Omega-EP)
- Near Term: ZEUS (3 PW) → relativistic pair plasmas
- Long Term: Next-generation **multi-PW** kJ-class lasers will create **macroscopic ($L \gtrsim 10^2\, d_e, \lambda_D, \rho_L$) relativistic pair plasma**, providing an experimental platform for studying relativistic collective processes.

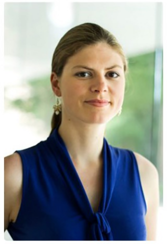


MP3 Multi-Petawatt Physics Prioritization Workshop

April 2022, Sorbonne Univ., Paris, France

Stay tuned for MP3 Workshop Report!

Antonino Di Piazza
Max Planck Institute for Nuclear Physics, Germany



Louise Willingale
University of Michigan, USA

Jon Zuegel
University of Rochester, USA

SUMMARY

- Understanding extreme astrophysical systems --- neutron stars & black holes -- demands ***Extreme Plasma Astrophysics:*** kinetic plasma physics with nontraditional, "*exotic*" physics:
  - special and general relativity;
  - pair plasmas;
  - radiation;
  - pair creation;
  - QED effects in strong magnetic fields.
- Conquering this frontier is now possible, theoretically and computationally: we have developed 1st-principles plasma codes incorporating these effects.
- Rapid progress in laser and pulsed-power technology may soon enable laboratory exploration.

The Future of Extreme Plasma Astrophysics is bright!

But we do need bright young people!