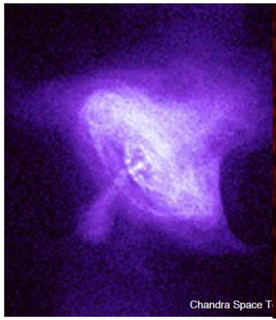
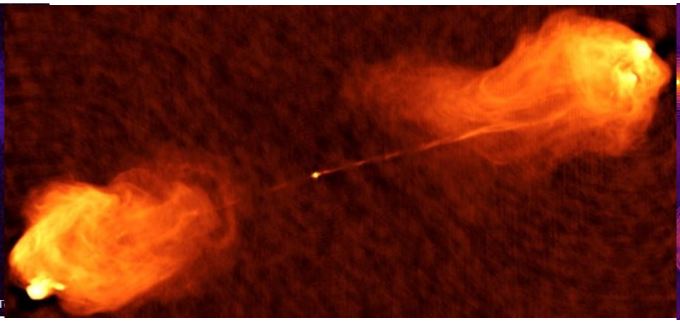
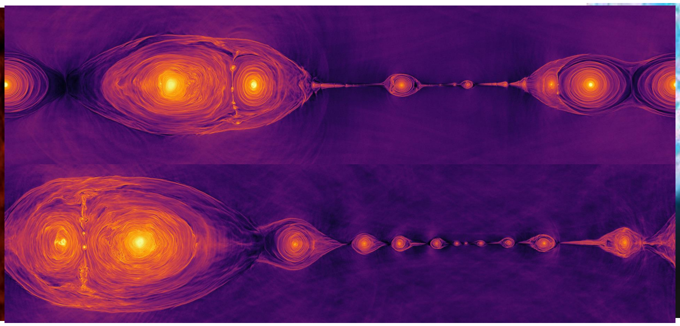
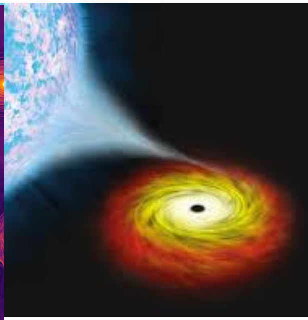
   

# *Radiative Relativistic Magnetic Reconnection in Extreme Astrophysical Plasmas*


## Dmitri Uzdensky

*University of Oxford*

*(recently relocated from Univ Colorado Boulder)*


***Thanks to my Colorado group:***

G.Werner, M.Begelman, J.Mehlhaff, B.Cerutti, K.Nalewajko, A.Chen, O.French

Recent Review: *Sironi, Uzdensky, Giannios ARAA 2025*

https://arxiv.org/abs/2506.02101

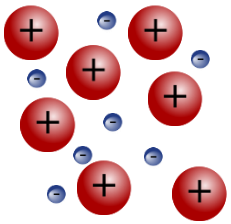

**Work supported by NSF, NASA, DOE**


**ECMRP, June 18, 2025**

# Traditional & Extreme Plasma Physics

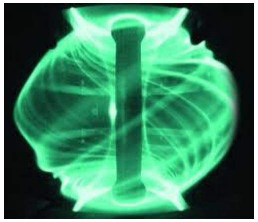
## Traditional Plasmas

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

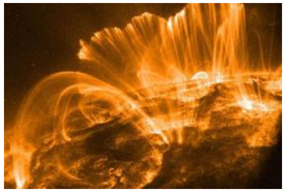


### Applications:

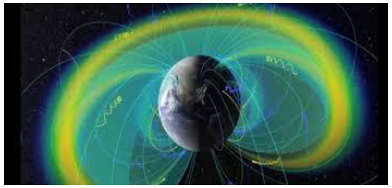
- Most lab plasmas



- Solar corona



- Earth's magnetosphere

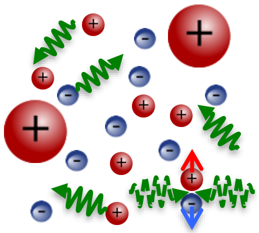


**Based on 19th Century Physics!**

## New: Extreme Plasmas

### "Exotic"* Physics:

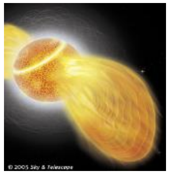
- *e⁻e⁺* pairs (+ ions), photons
- Relativistic (Special & General)
- Radiation (cooling, drag, pressure)
- QED effects (e.g., pair creation)



**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!**

# Radiation in Astrophysical Reconnection

- Conventional reconnection (space/solar/lab): only electrons & ions --- **no photons!**
- Extreme, high-energy ***astrophysical*** reconnection --- radiation is important:
  - Single-particle level: radiation-reaction force: $\boldsymbol{f}_{rad} = -\boldsymbol{\beta}(P_{rad}/c)$
  - Fluid level:

- Radiative cooling
- Radiation pressure
- Radiative drag on reconnection outflow
- Compton-drag resistivity

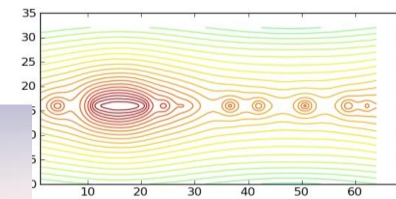
Two main (classical) radiation mechanisms:

- Synchrotron: in magnetic energy density $U = B^2/8\pi$
- Inverse-Compton (IC) scattering (Thomson limit): ambient bath of soft photons of energy density $U$.

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

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

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



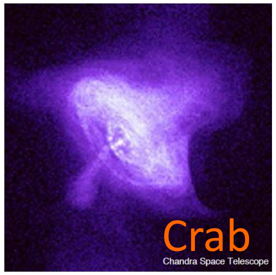

*How does reconnection layer look like, literally?*
*What are the prompt **radiative signatures** (spectra, light-curves) seen by an outside observer?*

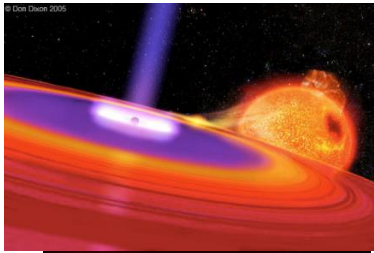
***Radiative magnetic reconnection is a new frontier in plasma astrophysics!***

# Radiative Relativistic Reconnection in Astrophysics

*(Reviews: Uzdensky 2016; Sironi, Uzdensky, Giannios 2025)*

- Pulsar magnetospheres, winds, nebulae



- Black hole accretion disks & coronae
- Active galactic nuclei (AGN/ blazar) jets* powered by supermassive BHs

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

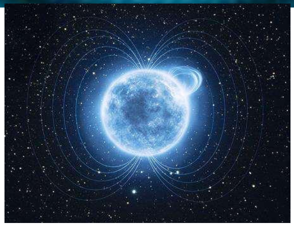


- Gamma-Ray Bursts (GRBs)

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


- Magnetar magnetospheres

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

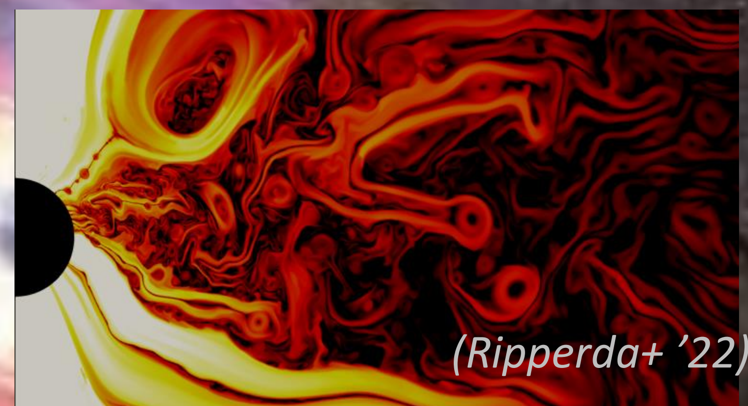


* **Multi-Messenger Astrophysics**

**Reconnection can explain observed properties of high-energy sources:**

- ❖ Nonthermal power-law spectra → ***Nonthermal Particle Acceleration*** **(NTPA)**
- ❖ Intense rapid gamma-ray flares → ***short time variability***

# Reconnection in Accreting Black-Hole Environments (Disks/RIAFs/Magnetospheres/Coronae/Jets)



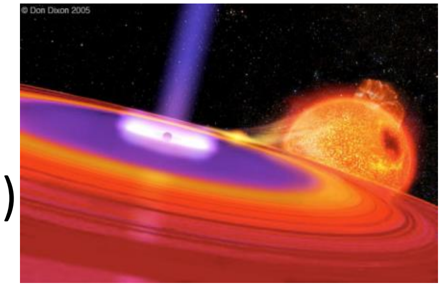

Black-hole accretion disks, flows, coronae, magnetospheres are highly dynamic, complex magnetized plasma environments, so reconnection is generally expected

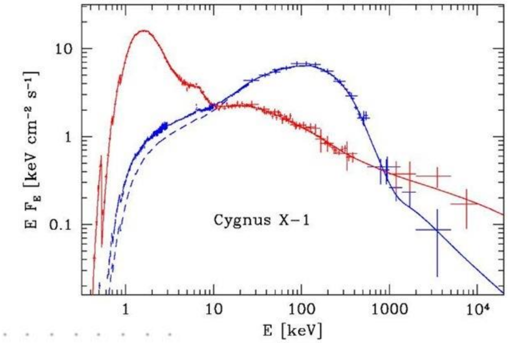
# Reconnection in Black-Hole (BH) Accretion Disk Corona

*Accreting BHs shine brightly by converting gravitational energy into light*

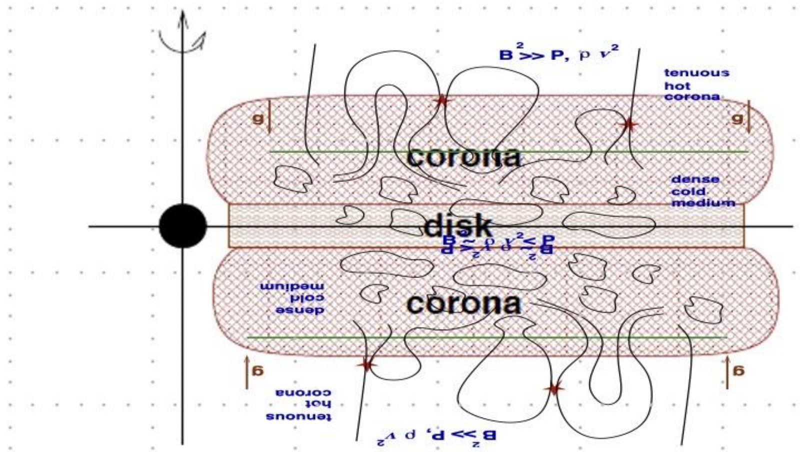
## BH Accretion Disk Corona (ADC):

Hard X-ray ($\varepsilon \gg k_B T_{disk} \sim 1$ keV) emission



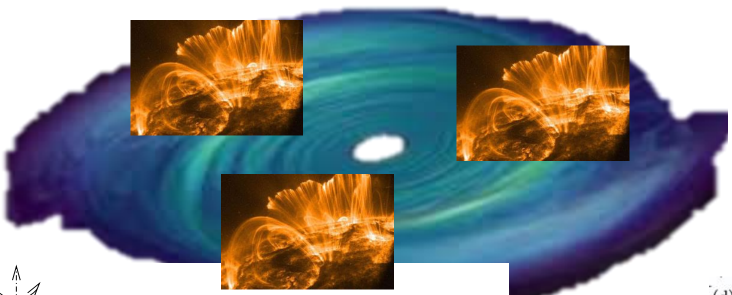



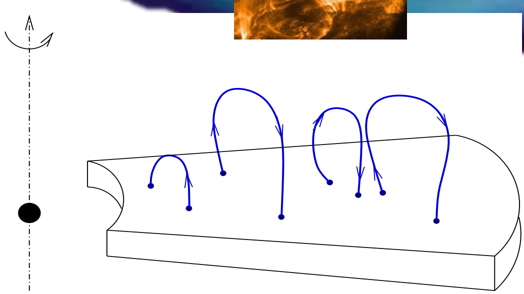

Compton scattering of soft (UV, soft X-rays) disk photons by energetic (~100 keV) electrons in hot, tenuous corona.



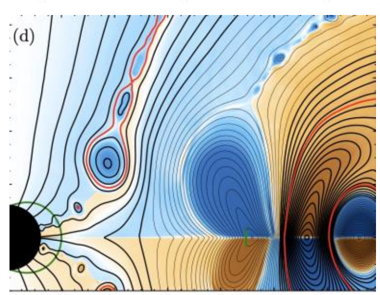

Sandwich Model of ADC

**Solar corona analogy:**
*(Liang & Price 1977; Galeev et al 1979)*

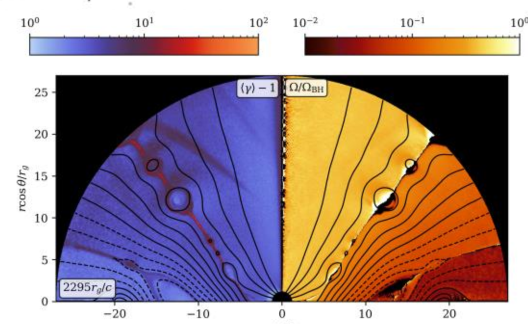




*(Uzdensky & Goodman '08)*




**Rel. force-free sims**
*(Parfrey+'15)*

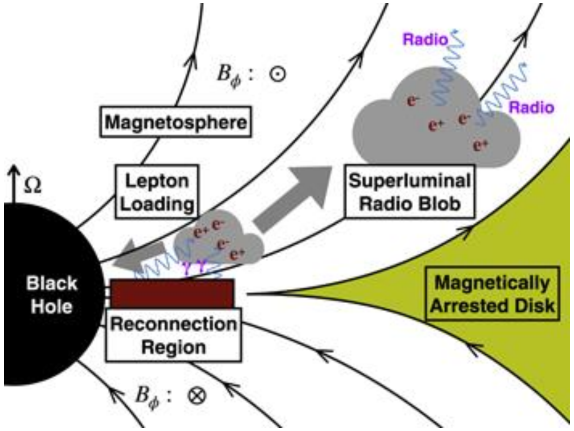



**Relativistic PIC sims** *(Mehlhaff+'25)*

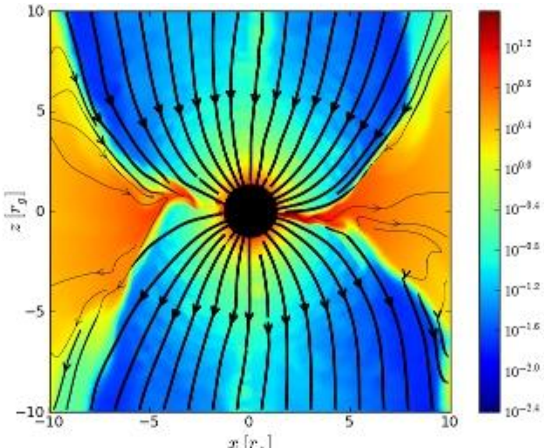
# Reconnection in Accreting Black-Hole Magnetospheres

Radiatively-Inefficient Accretion Flows (RIAFs) onto low accretion rate supermassive BHs like *EHT*'s (*Event Horizon Telescope)* targets M87* and Sgr A*


Equatorial current sheet in the plunging region/ergosphere

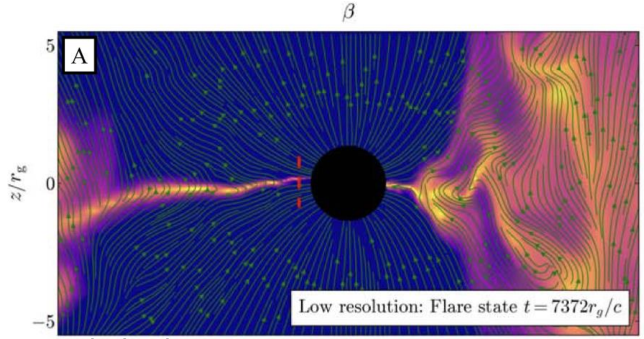



*(image: Kimura+ '22)*



Global GRMHD sims

*(McKinney '12, Dexter+ '20, Ripperda+ 21, Scepi+'21)*




Global resistive GRMHD sims

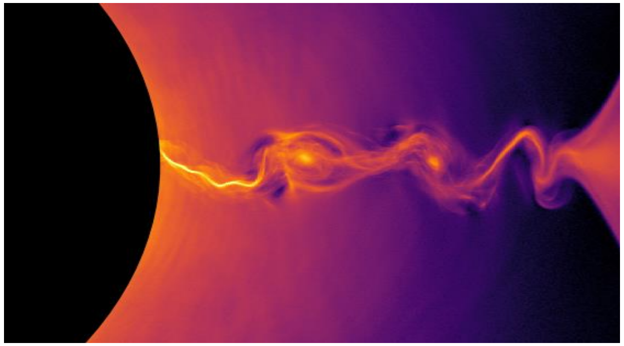
*(Ripperda+ '22)*

***Reconnection creates its own plasma!***

*(Chen+ '23, Hakobyan+ '23)*

Reconnection is a leading mechanism to explain observed SMBH **flares**:

- NIR/ X-ray flares in Sgr A*
- GeV-TeV gamma-ray flares in M87



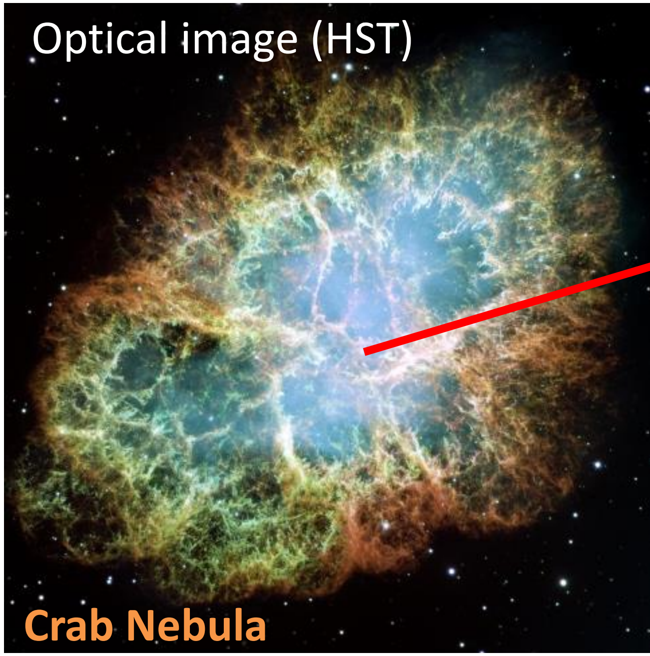
Global radiative GR-PIC sims of BH magnetospheres

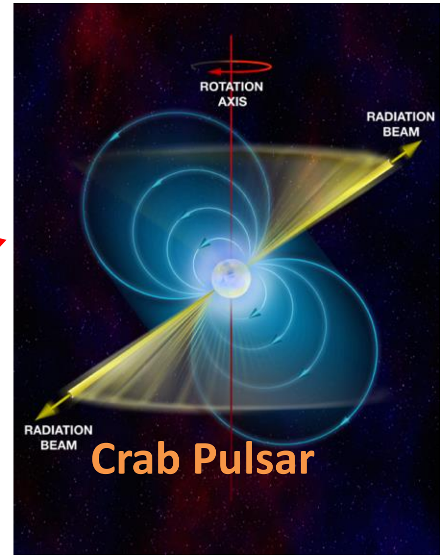
*(Parfrey+'19, Crinquand+'20)*

# Reconnection with Synchrotron Cooling in Pulsar Magnetospheres

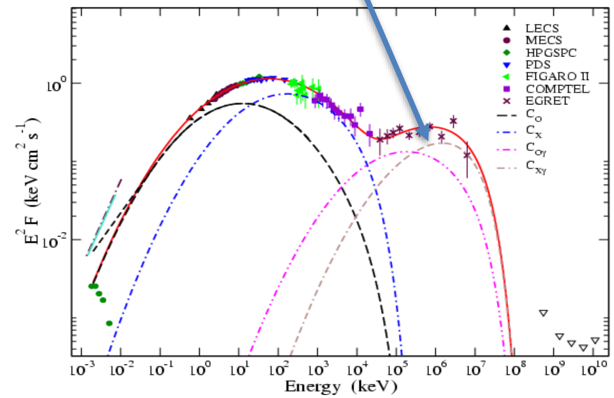
**Crab Nebula**

# Relativistic Reconnection in Pulsar Magnetospheres



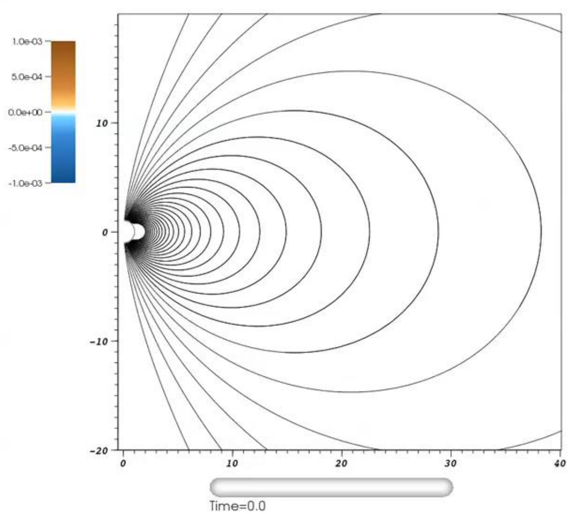

Powerful pulsed emission across EM spectrum, incl. GeV gamma-rays




**Crab pulsar:**

- magnetized ($B \sim 10^{12}$ G
- spinning (33 msec)

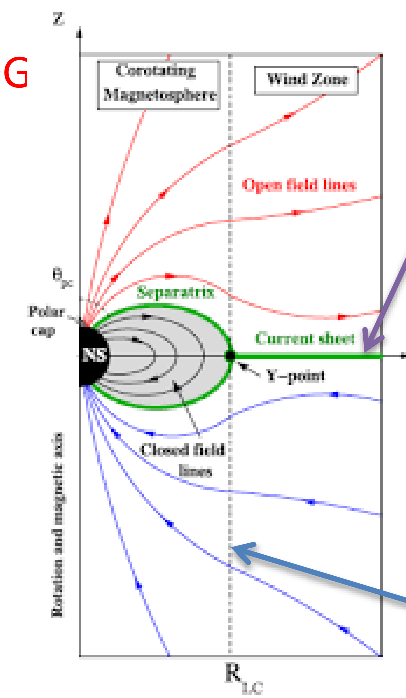
**Neutron Star.**




$R_{NS} \approx 10$ km

$R_{LC} = c/\Omega \approx 1000$ km

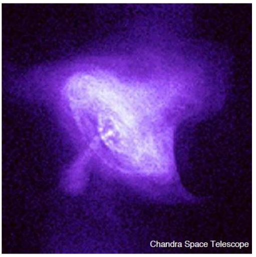
$B_{LC} \approx 10^6$ G



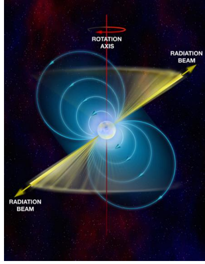

equatorial current sheet

Light Cylinder

*force-free sims: Parfrey & Beloborodov 2012*

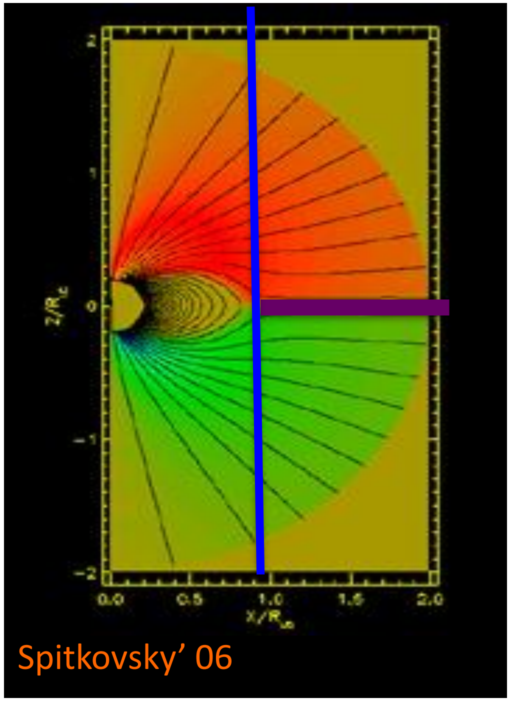



# Reconnection in Pulsar Magnetospheres



E.g.: Crab pulsar: $B \sim 10^6$ G at $R_{LC} \sim 1000$ km

## Why Reconnection?




Spitkovsky' 06

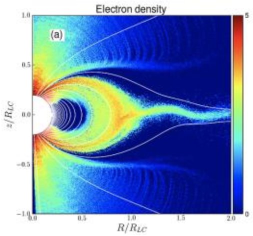
Equatorial **current sheet (CS)** beyond **Light Cylinder**

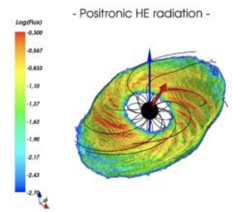
## Why Radiative?

- Strong $B_{LC} \sim 10^6$ G --> strong ***synchrotron cooling*** in reconnecting current sheet outside Light Cylinder (LC) *(Lyubarsky '96, Uzdensky & Spitkovsky '14)*
- Power pulsed emission:
  - γ-ray GeV (synchrotron)
  - VHE (>100 GeV; Compton)
  - Radio (coherent motions) *(Uzdensky & Spitkovsky '14)*
- γγ pair production upstream of reconnection layer *(Lyubarsky '96, Hakobyan+ '19)*

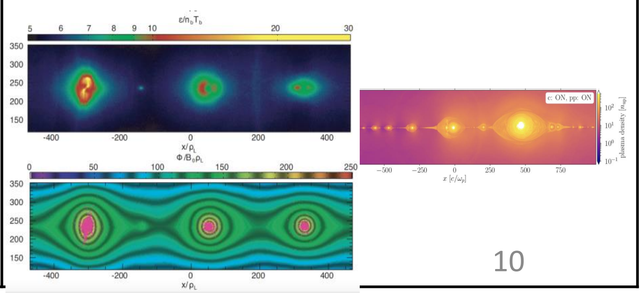
## What is being done?

- 2D & 3D global radiative PIC sims with recn. beyond LC *(Chen+Beloborodov'14; Philippov, Cerutti, Spitkovsky '15-18)*




- Local rad.-PIC sims of rel. pair recn. with synchrotron radiation and pair creation *(Schoeffler+'19-23, Hakobyan+ '19-23)*



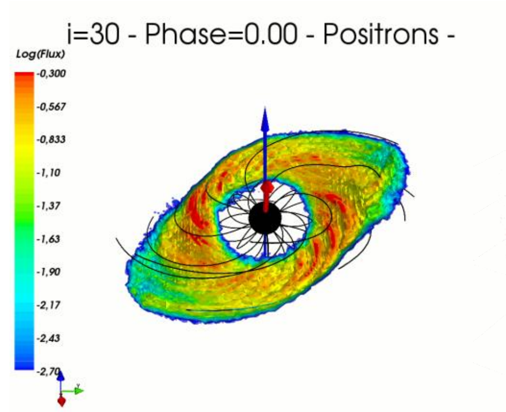
# Global Relativistic Kinetic Plasma (PIC) Simulations of Pulsar Magnetospheres

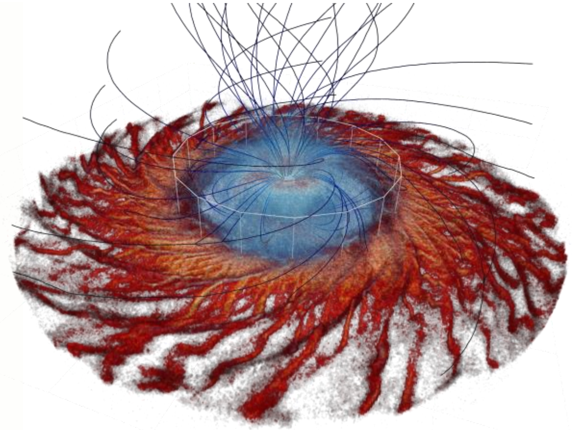
*(Chen & Beloborodov 2014; Philippov, Cerutti, Spitkovsky 2015-2018; Hakobyan et al. 2023)*

2D (axisymmetric) and 3D (oblique) global PIC simulations of pulsar magnetospheres:

- non-radiative
- radiative

(even with GR effects)

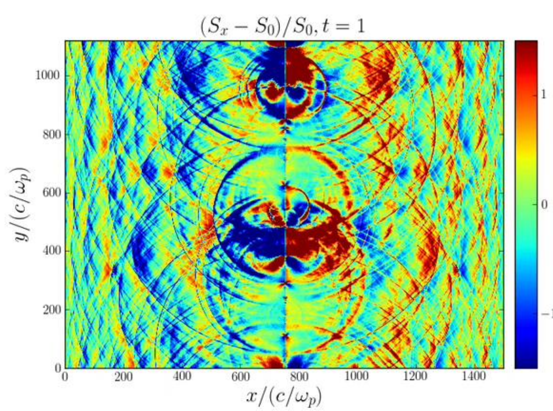


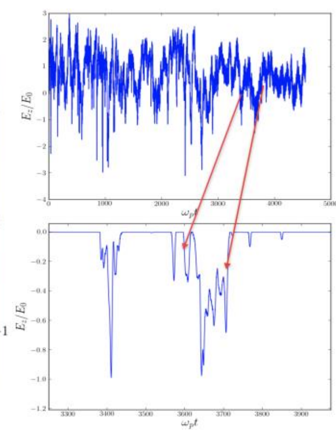



Self-consistent, first-principles modeling of pulsed γ-ray emission!

PIC simulations of dynamic plasmoid-mediated reconnection in equatorial current sheet explain Crab's main radio pulses, including extremely intense nanoshots!

*(Philippov, Uzdensky, Spitkovsky, Cerutti '19; Uzdensky & Spitkovsky '14; Lyubarsky '19)*



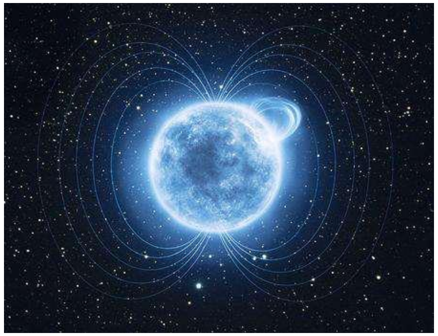



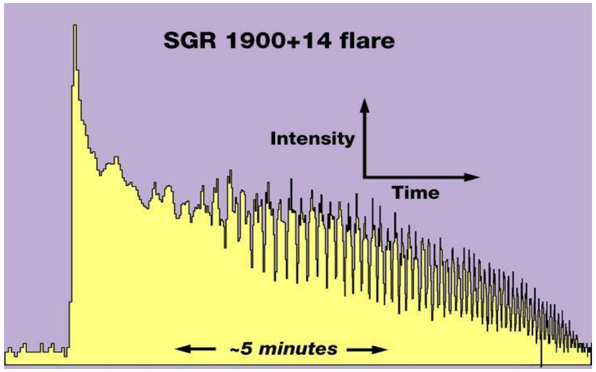
# MAGNETAR FLARES

# QED Reconnection in Magnetar Magnetospheres

- Magnetars: isolated neutron stars with $10^{15}$G magnetic fields.
- Soft Gamma Repeaters (SGRs): magnetars showing powerful

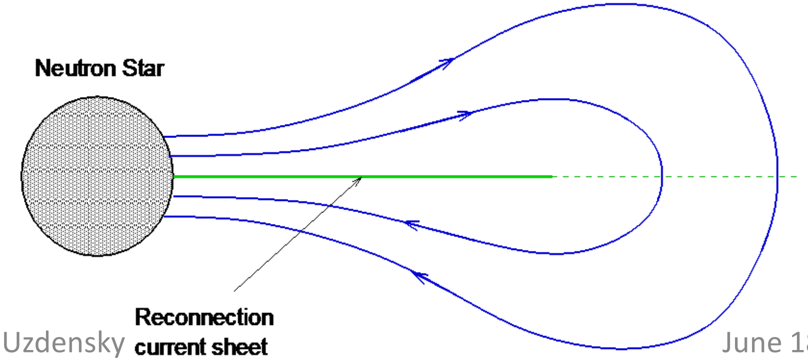
**γ-ray flares** ($10^{44} - 10^{46}$ ergs in ~ 0.3 sec).

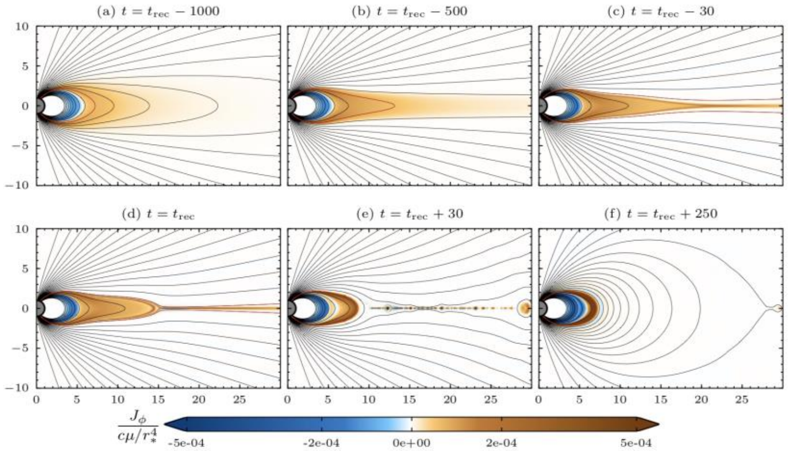





## Magnetic Reconnection Interpretation:

*(Thompson & Duncan'01; Thompson et al.'02; Lyutikov '03, '06; Uzdensky '11; Parfrey et al. 2013; Uzdensky & Rightley '14)*



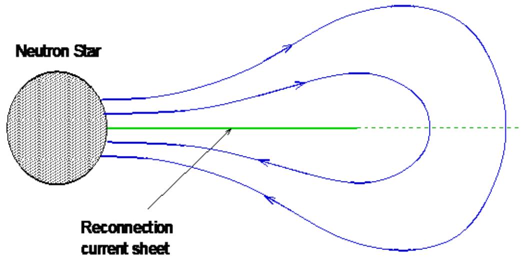




*Axisym. rel. force-free sims: Parfrey et al. 2013*

*Recent 3D sims: Yuan, Chen, Mahlhmann*

*Also: Fast Radio Bursts (FRBs)!*

# Magnetic Reconnection Powering Magnetar Flares




*(Uzdensky '11)*

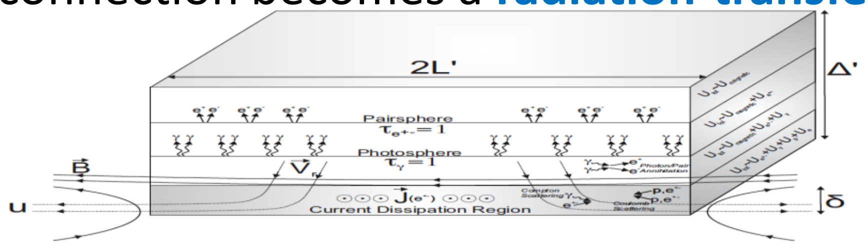
**But how does magnetic reconnection happen in $10^{15}$ G magnetic fields?**

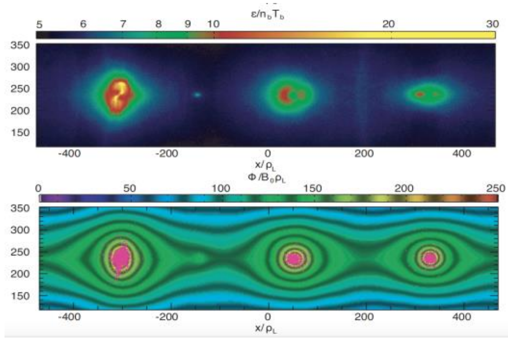
- Critical Quantum Magnetic Field: $\hbar\Omega_e = m_e c^2 \Rightarrow \quad B_* \equiv \frac{m_e^2 c^3}{\hbar} \simeq 4.4\times 10^{13}\,\mathrm{G}\,.$
- Magnetic Energy Density: $\frac{B_*^2}{8\pi} = \frac{1}{8\pi}(m_e c^2)^4\,\alpha^{-1}\,(\hbar c)^{-3} \simeq 8\times 10^{25}\,\mathrm{erg\ cm^{-3}}\,.$
- Pressure balance and/or energy conservation determine $T_0$:

$$P_{\rm magn} = \frac{B_0^2}{8\pi} = P_{\rm rad} = \frac{a}{3}T_0^4 \quad \Rightarrow \theta_e \equiv \frac{T}{m_e c^2} \simeq 2.2\, b^{1/2}$$

$\rightarrow$ **relativistically-hot plasma:** $T \sim m_e c^2$ **!**
$(b \equiv B_0/B_*.)$

- Copious **pair production**: equilibrium pair density: $n_e \sim 10^{30}$ cm$^{-3}$
- Reconnection layer is dressed in **optically-thick pair coat!**
- Reconnection becomes a **radiation-transfer problem**



Plasmoids: optically thick, dense, bright photo-leptonic ***fireballs!*** (*cf. Schoffler et al. 2019*)

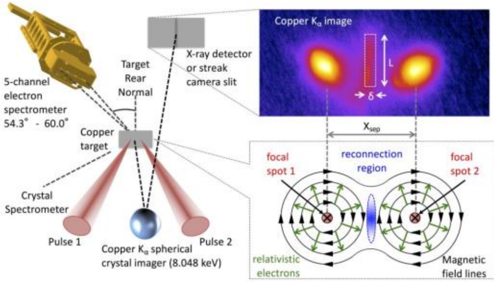
# Prospects for Experimental Studies

*High-intensity lasers provide* ***Experimental Branch*** *of* ***Extreme Plasma Physics,*** *including for relativistic/radiative reconnection studies.*

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

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

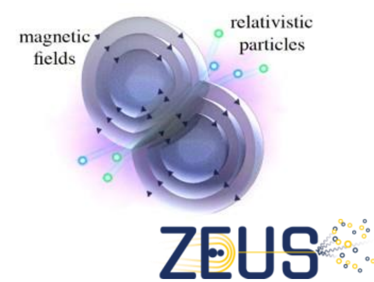
- Relativistic ions are difficult, but we can make rel. electrons!




*Raymond et al. 2018*

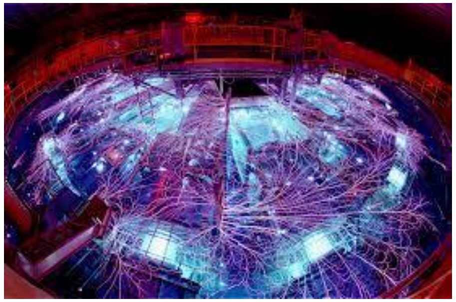
## Possible routes:

- Current: Relativistic *electron-only reconnection* (slow ions) with high-intensity ($10^{18}$ W/cm$^2$) lasers (e.g., Omega-EP)
- Near Term (PW): (ZEUS, BELLA EP-OPAL, ELI) → relativistic pair plasmas
- Long Term: Next-generation 10-100 PW kJ-class lasers will create **macroscopic (*L* ≳ $10^2$ $d_e$, $\lambda_D$, $\rho_L$) relativistic pair plasma**, providing an experimental platform for studying relativistic collective processes!




Lab studies of non-relativistic **Radiative Reconnection**:

- Pulsed-power expts (e.g., double wire arrays):
  Magpie (Imperial), Puffin (MIT), Z-Machine (Sandia)
- Laser expts (NIF, Omega EP, ZEUS)



# SUMMARY

- Magnetic Reconnection in high-energy relativistic environments of black holes and neutron stars is often in radiative regime.
- Key radiative processes in high-energy relativistic astrophysics:
  - Synchrotron (due to magnetic field)
  - Inverse-Compton (due to soft ambient radiation)
- Radiation back-reaction effects:
  - Fluid level: radiative cooling, drag on bulk flows, eff. resistivity, radiation pressure;
  - Kinetic level: suppresses nonthermal particle acceleration
- Most extreme regime: QED radiative reconnection (pair creation, Klein-Nishina)
- Radiation is our only direct diagnostic of astrophysical reconnection.
- Active theoretical and numerical (radiative-PIC) exploration is rapidly advancing our physical understanding of radiative relativistic reconnection.
- Pioneering experimental (lasers, pulsed-power) studies have recently begun.

**Radiative Relativistic Reconnection is an exciting frontier**

**-- open for exploration!**

Thank you!

# EXTRA SLIDES

# Magnetization σ parameter

- Physical parameters of upstream background plasma:
  - Particle density $n_b$; Temperature $\theta_e = T/m_e c^2$
  - Reconnecting magnetic field $B_0$; Guide magnetic field $B_g$
- Key dimensionless parameter: upstream **magnetization $\sigma$**:
  - **"Cold" sigma: $\sigma = B_0^2/(4\pi\, n_b\, mc^2)$**

  (roughly available magnetic energy per particle);
  - **"Hot" sigma: $\sigma_h = B_0^2/(4\pi\, h)$**,

  where $h = n_b \langle\gamma\rangle mc^2 + p_b$ = relativistic enthalpy density (including rest-mass)

  -- governs Alfven velocity and thus how relativistic plasma motions are.

$$V_A = c\beta_A = c\frac{\sqrt{\sigma_h}}{\sqrt{1+\sigma_h}}$$

  - Relativistically-cold plasma ($T \ll m_e c^2$): **$\sigma_h \approx \sigma$**.
  - Ultrarelativistically-hot plasma ($T \gg m_e c^2$): $h \approx 4 n_b \theta_e\, mc^2 \rightarrow$

    **$\sigma_h \approx \sigma/4\theta_e$** $= B_0^2/(16\pi\, n_b\, \theta_e\, mc^2) = 1/(2\beta)$

# Collisionless Relativistic Reconnection --- Efficient Nonthermal Particle Accelerator

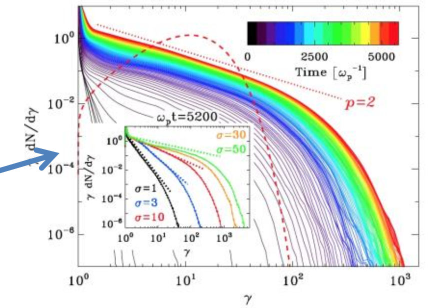
Important early PIC work: *Zenitani & Hoshino '01-'08, Jaroschek+'04, Lyubarsky & Liverts '08, Bessho & Bhattacharjee'07-08, Liu+'11, Cerutti+'13-14, …*

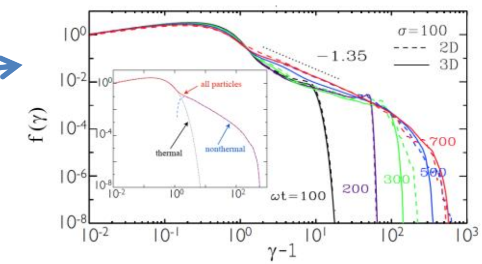
$\gamma = \varepsilon/mc^2$

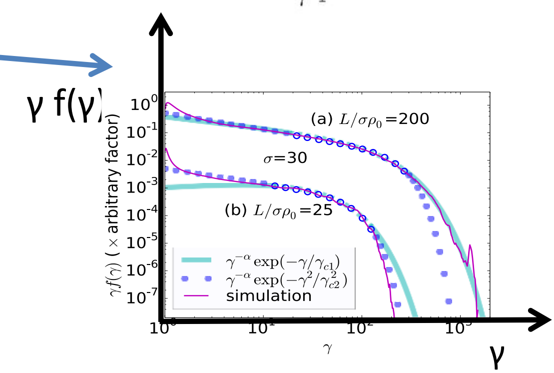
Recent (>2014) PIC simulations:

***robust nonthermal particle acceleration in 2D and 3D (non-radiative) relativistic reconnection!***

- Columbia/Princeton: *Sironi et al.*
- Los Alamos: *Guo et al.*
- Colorado: *Werner et al.*




Great progress on mapping out nonthermal parameters:
spectral index *p,* high-energy cutoff $\gamma_c$, injection energy $\gamma_{inj}$
as functions of system parameters:
magnetization σ, system size *L*, composition, guide field $B_g$.

**Frontier: Kinetic-level Interplay of Relativistic Collisionless Reconnection & Radiation!**

# Astrophysical Radiation Processes

- **Synchrotron** radiation by relativistic particles spiralling in magnetic field:
  - $\varepsilon \sim \gamma^2 \hbar \boldsymbol{\Omega}_c$   $P_{sync} \sim c\, \sigma_T\, \gamma^2\, U_{magn} \sin^2\alpha$   $U_{magn} = B^2/8\pi$
  - classical regime: $\chi \sim \gamma B/B_Q << 1$ --- continuous radiation drag force
- **Inverse-Compton (ICy)** scattering of soft seed photons:
  - either External IC (prescribed ambient seed photon bath)
  - or Synchrotron-Self-Compton (SSC)
  - Classical Thomson regime: $\gamma \varepsilon_{seed} << m_e c^2$:   $\varepsilon_{IC} \sim \gamma^2\, \varepsilon_{seed}$   $P_{IC} \sim c\, \sigma_T\, U_{rad}\, \gamma^2$
  - Quantum Klein-Nishina (KN): $\gamma \varepsilon_{seed} > m_e c^2$

- QED: 2-photon ($\gamma\gamma$) and 1-photon ($\gamma$-$B$) **pair production**

*Many of these processes are now implemented in **radiative-PIC codes***

# Particle Energy Scales

*Reconnection parameter-space landscape is governed by several key energy scales*

## Non-radiative energy scales:

- Proportional to **system size *L*** (Hillas, extreme acceleration):
  - Electric potential drop along reconnection layer:

    $\varepsilon_{max} \approx e\, E_{rec}\, L \approx e\, \beta_{rec}\, B_0\, L$ where $\beta_{rec} = v_{rec}/c = E_{rec}/B_0 \approx 0.1$

    $\Rightarrow \gamma_{max} \approx \varepsilon_{max}/m_e c^2 = \beta_{rec}\, L/\rho_0$ where $\rho_0 = m_e\, c^2/eB$

    Larmor radius: $\rho_{L,max} = \varepsilon/eB_0 \sim 0.1\, L$ --- comparable to system size
- Proportional to **"cold" magnetization sigma:** $\sigma = B_0^2/(4\pi\, n_b\, mc^2)$ **:**
  - Average particle energy $<\gamma> \approx \sigma/4$
  - "Natural" or "4-sigma" high-energy cutoff: $\gamma_c \approx (4\text{-}10)\sigma$
  - Injection energy $\gamma_{inj} \approx 0.15\text{-}0.3\, \sigma$

  (power-law dynamic range: $R=\gamma_c/\gamma_{inj} \sim 25\text{-}50$, photon spectrum extent $\sim 10^3\text{-}10^4$)

## Radiative particle energy scales (classical, controlled by U):

- Radiation-reaction limit $\gamma_{rad}$: $\mathbf{e\, E_{rec} = f_{rad} = P_{rad}/c} = \sigma_T\, \gamma_{rad}^2\, U$

  $U = U_{rad}$ (for IC) or $U = U_B \sin^2\alpha = (B^2/8\pi) \sin^2\alpha$ (for synch.)

  $$\gamma_{\rm rad}^{\rm IC} = \left[\frac{3}{4}\, \frac{eE}{\sigma_T U_{\rm rad}}\right]^{1/2}$$
- Cooling energy: $\tau_{rad}(\gamma_{cool}) = \gamma_{cool}\, m_e c^2/P_{rad} \approx m_e c^2/cU\sigma_T\gamma = L/c$
- Useful relationship: $\gamma_{rad}^2 \approx \gamma_{max}\, \gamma_{cool}$

***Different radiative reconnection regimes are governed by relative ordering of these scales***

# Regimes of Radiative Reconection

*(e.g. Mehlhaff et al. 2021)*

$\gamma_{rad}^2 \approx \gamma_{max}\,\gamma_{cool}$

**Non-Radiative:** $\langle\gamma\rangle < \sigma < \gamma_c < \gamma_{max} < \gamma_{rad} < \gamma_{cool}$

- Radiative losses are not important on macroscopic dynamical timescale L/c
- Passive radiation, emission mostly concentrated in dense plasmoid cores

**Very weakly radiative**: $\langle\gamma\rangle < \sigma < \gamma_{cool} < \gamma_c < \gamma_{rad} < \gamma_{max}$

- Radiation does not affect fast primary particle acceleration ($\gamma_c < \gamma_{rad}$),
- but energetic accelerated particles ($\gamma \sim \gamma_c$) cool on $L/c$ time scale.
- Overall (low-energy) emission from plasmoid cores
- High-energy emission from plasmoid periphery

***Active 2D/3D radiative-PIC exploration of these regimes is ongoing at Colorado, Columbia, Lisbon, Princeton, Maryland, Grenoble, Warsaw!***

**Weakly radiative (aka strong-cooling in Astro):** $\gamma_{cool} < \langle\gamma\rangle < \sigma < \gamma_c < \gamma_{rad} < \gamma_{max}$

- Radiation does not affect fast primary particle acceleration ($\gamma_c < \gamma_{rad}$),
- but even the average energized particles ($\gamma \sim \langle\gamma\rangle$) cool on dynamical $L/c$ time scale.
- Both high- and medium-energy radiation comes from plasmoids periphery

**Moderately radiative:** $\gamma_{cool} < \langle\gamma\rangle < \sigma < \gamma_{rad} < \gamma_c < \gamma_{max}$

- Energetic particles cool in inter-plasmoid elementary current layers as they are accelerated.
- most high-energy radiation comes from these layers and from Y-points;
- Medium-energy radiation comes from plasmoid periphery

**Strongly radiative:** $\gamma_{cool} < \gamma_{rad} < \langle\gamma\rangle < \sigma < \gamma_c < \gamma_{max}$

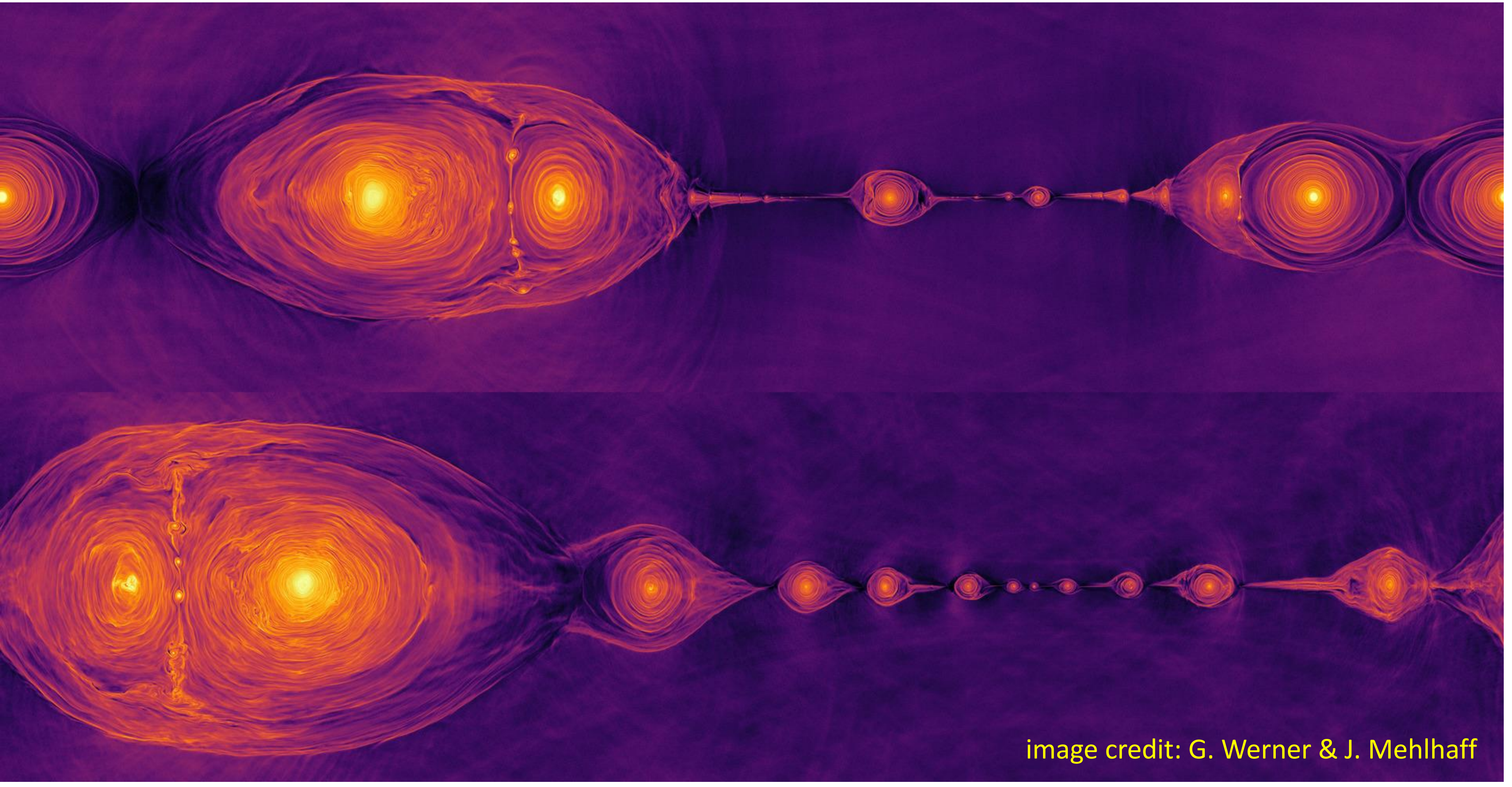
- prompt radiative cooling of bulk energized particles, essentially no power law;
- radiation from inter-plasmoid layers and Y-points.

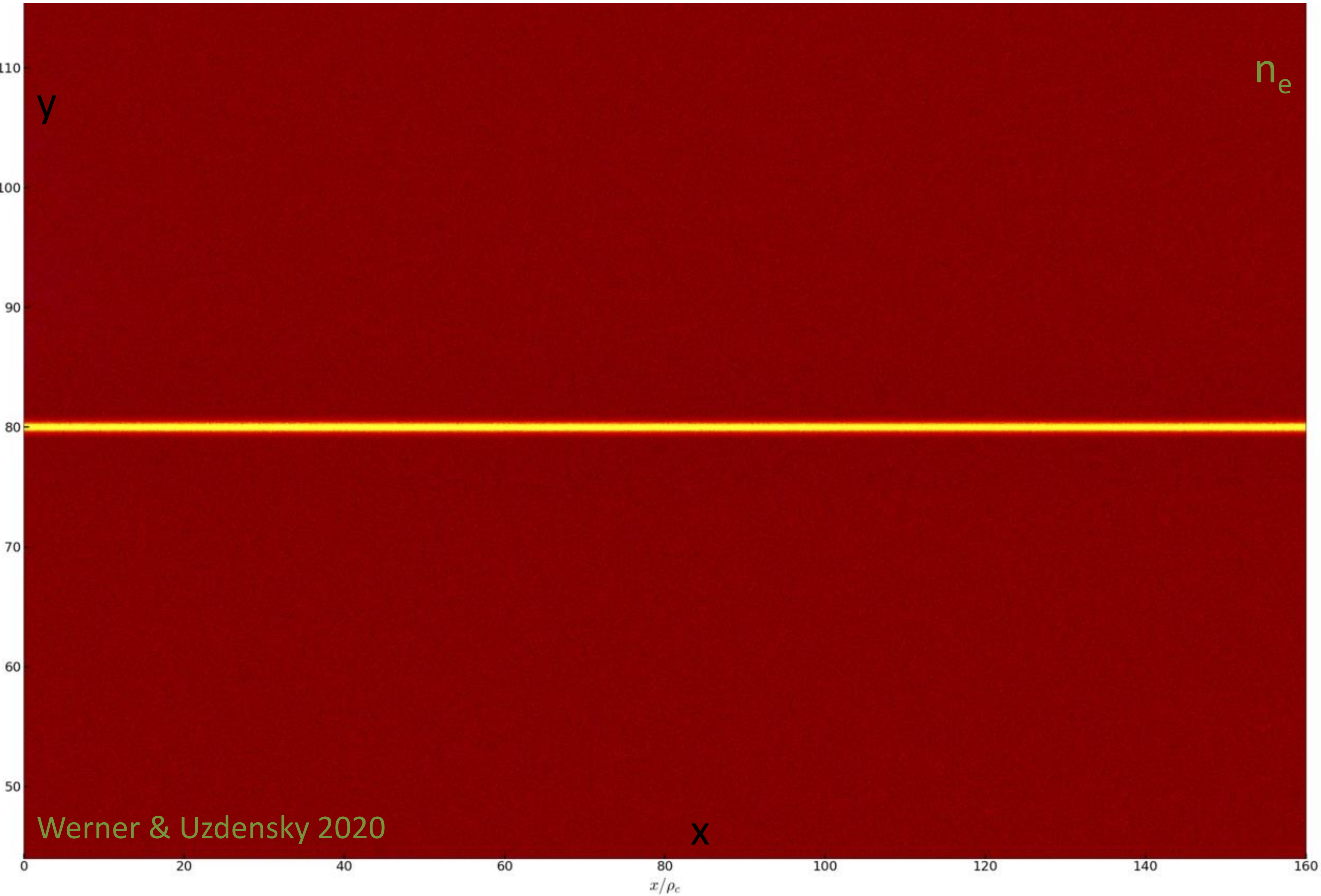
# Beyond Classical Radiaction…

(venturing into the quantum realm)

- **Classical Radiation Reaction:** ultrarelativistic particle ($\gamma \gg 1$) emits many low energy photons ($\varepsilon_{ph} \ll \gamma\, m_e c^2$) beamed along its motion → continuous radiation reaction force: $\boldsymbol{f}_{rad} = -\boldsymbol{\beta}\, P_{rad}/c$, where $P_{rad}(\gamma) \sim \sigma_T\, c\, \mathbf{U} \gamma^2$ is radiated power, and **U** is energy density causing radiation:
  - synchrotron: $U = U_{magn} \sin^2\alpha$
  - inverse-Compton (Thomson limit): $U = U_{seed}$
- But $\varepsilon_{ph} \sim \gamma^2$ (for both IC and synchrotron) =>
  => critical particle energy $\gamma_Q$: $\varepsilon_{ph}(\gamma_Q) \sim \gamma_Q\, m_e c^2$ => *Something's gotta give!*
- Quantum nature of radiation => discrete photons with $\varepsilon_{ph} \sim \gamma\, m_e c^2$
  - synchrotron: $\chi \simeq \gamma/\gamma_Q = \gamma\, b = O(1)$, $b \equiv B/B_Q$ ($B_Q \equiv m_e^2 c^3/e\hbar \simeq 4\text{x}10^{13}$ G – QED field)
  - inverse-Compton: $q \equiv \gamma/\gamma_{KN} \equiv \gamma\, \varepsilon_{seed}/m_e c^2 = O(1)$ (Klein-Nishina regime)
- Quantum regime (both IC & synchrotron): γ-ray photons with $\varepsilon_{ph}(\gamma_Q) \sim \gamma_Q m_e c^2$ can pair-produce on the same agent that causes radiation:
  - synchrotron: 1-photon (γB) pair creation on strong B-field (nonlinear Breit-Wheeler)
  - inverse-Compton: 2-photon (γγ) pair creation on ambient soft photons
- Thus:
  - Classical case: 1 key parameter: energy density U ($U_{magn}$ or $U_{seed}$)
  - Quantum case: 2nd parameter (governs quantum effects, pair production): $b$ or $\varepsilon_{seed}$

# First-Principles Kinetic Numerical Simulations of Radiative Relativistic Magnetic Reconnection





y
$n_e$
Werner & Uzdensky 2020
x
110
100
90
80
70
60
50
0
20
40
60
80
100
120
140
160
$x/\rho_c$

# PIC Simulations of Radiative Recoonnection with ICγ cooling

*(Werner, Philippov, & Uzdensky 2019)*

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

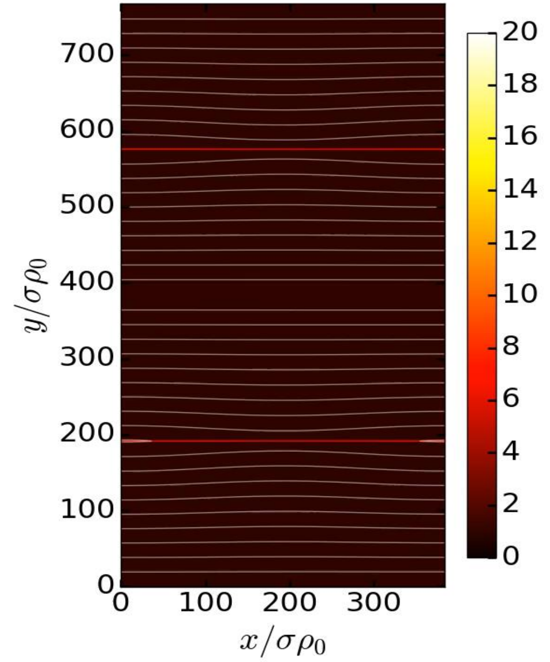
Magnetization:

$$\sigma = \frac{B_0^2}{4\pi n_b mc^2}$$

IC radiaction (radiation reaction) limit:

$$eEc \approx 0.1eB_0c = P_{IC}(\gamma_{rad}) \propto U_{ph}\gamma_{rad}^2$$

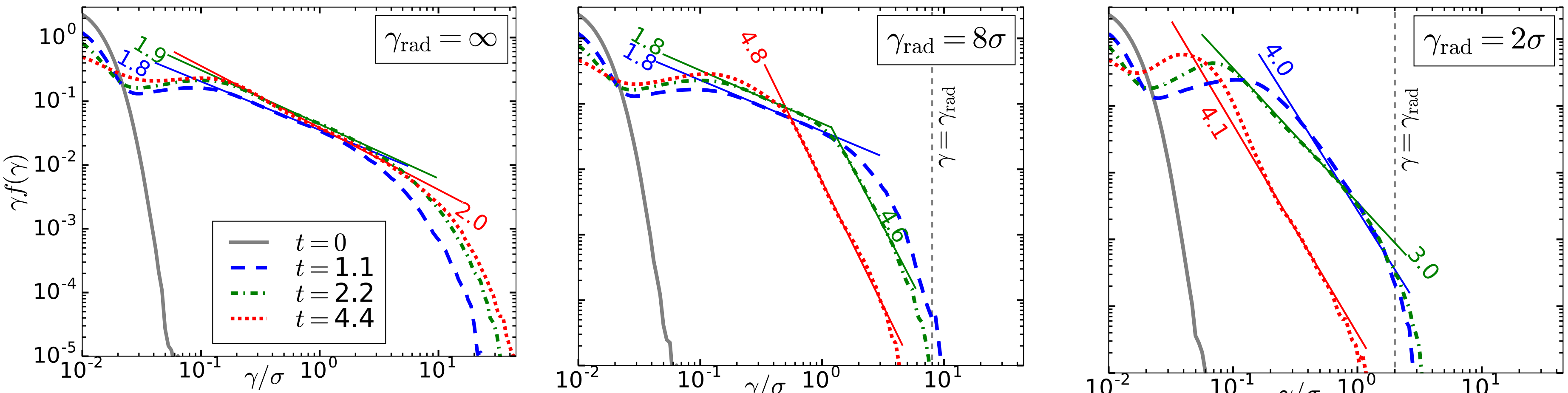
$$\gamma_{\rm rad}^{\rm IC} = \left[\frac{3}{4}\,\frac{eE}{\sigma_T U_{\rm rad}}\right]^{1/2}$$




Weak cooling (large $\gamma_{rad}/\sigma$): usual hard power law

Strong cooling (small $\gamma_{rad}/\sigma$): variable steep power law

Intermediate (medium $\gamma_{rad}/\sigma$): both power laws




**no cooling** **medium cooling** **strong cooling**

# Kinetic Beaming of Particles and Radiation

*(Cerutti et al. 2012; Mehlhaff, et al. 2020)*

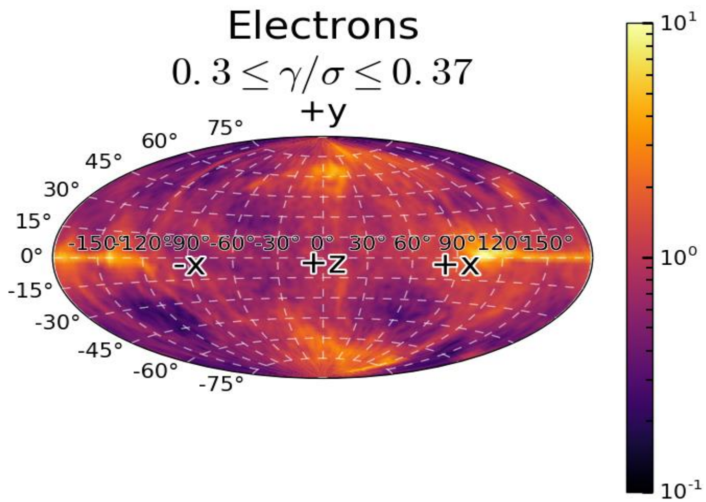
- Relativistic reconnection focuses accelerated particles into narrow beams/fans *(Uzdensky et al. 2011, Cerutti et al. 2012)*
- Focusing is ***energy-dependent*** (higher energy -> stronger collimation):

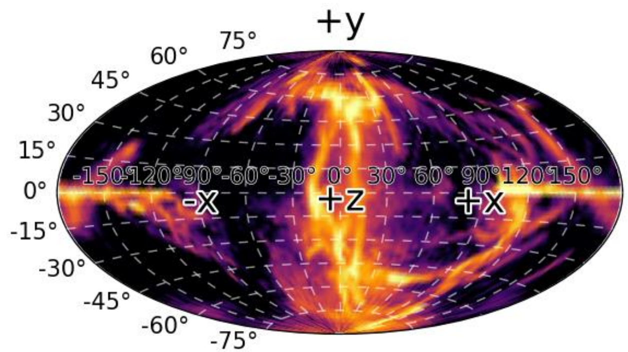
  ***"kinetic beaming"***

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

low-energy particles isotropize before radiating away their energy

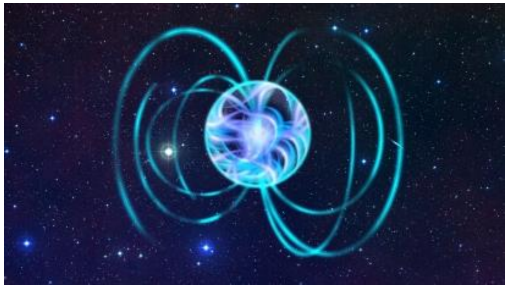
high-energy particles radiate away their energy before isotropizing




Angular distributions of emitted photons

# <u>QED-Radiative-Reconnection-Powered</u>
# <u>Pair Creation in NS Magnetospheres</u>

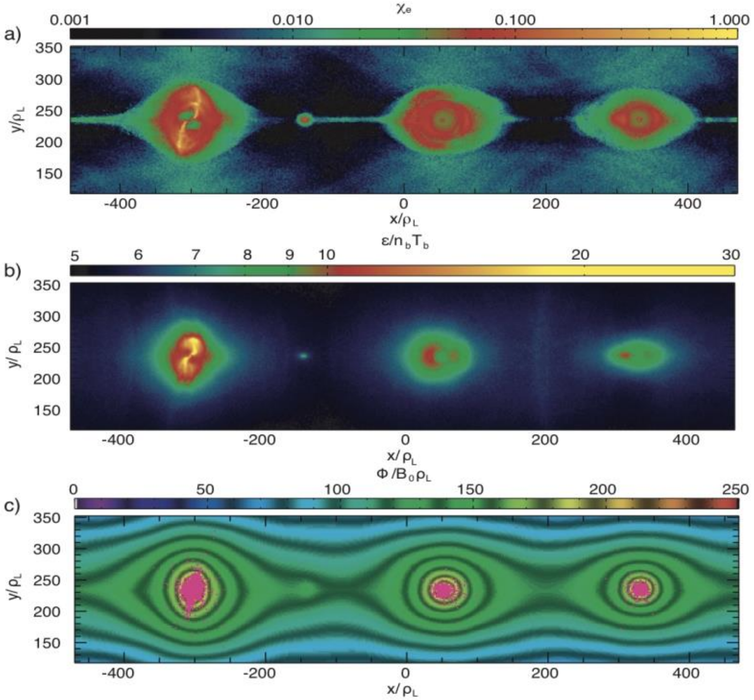


Reconnection-powered γ-ray emission creates pairs
(Lyubarsky 1996; Uzdensky 2011; Hakobyan et al. 2019-22)

## Rel. PIC Simulations of Reconnection with Synchrotron Radiation and <u>Pair Creation</u>

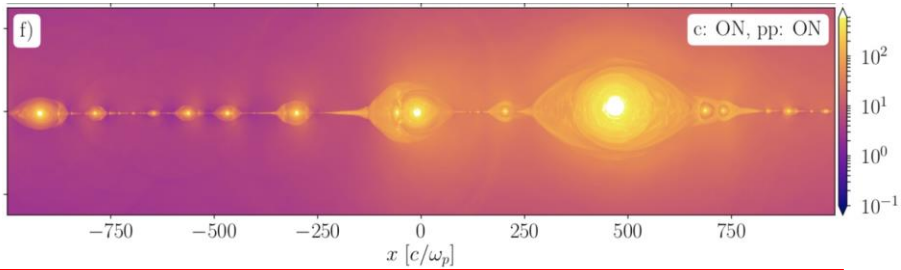
*Schoeffler, Grismayer, Uzdensky, Fonseca, Silva ’19-22*

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



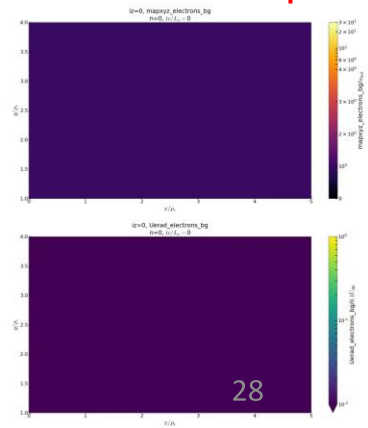

*Hakobyan, Philippov, Spitkovsky ’19-22*

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




**New radiative QED Module for Zeltron** (*Mehlhaff et al. 2024*):

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



# Reconnection in Extreme Astrophysical Plasmas: Challenges and Future Directions

- **New "exotic" physics:**
  - Radiation: KN IC, Synch.-Self-Compton, curvature, synch. self-absorption, bremsstrahlung)
  - Collisions: Coulomb, pair creation/annihilation, hadronic processes
  - QED effects in ultra-strong magnetic fields
- **Numerical Diagnostics:** new ways to extract physical insight from simulations
- **Multi-scale simulation methods:**
  - Adaptive mesh refinement; Implicit PIC
  - Multi-physics embedding (e.g., FFE-MHD-PIC)
- **Interplay with other collective plasma processes:**
  - Instabilities (kink, KH, RT)
  - Turbulence (incl. MRI)
  - Collisionless shocks (merger of Weibel filaments)
- **Self-consistent CS formation and reconnection onset in global astrophysical scenarios**
- **Prospects for Laboratory Experiments:**
  - Magnetically-driven
  - Laser-Plasma
  - Pulsed-power

**THANK YOU!**