Title: QED-mediated plasma processes in compact objects: magnetic reconnection and beyond

Speakers: Hayk Hakobyan

Series: Strong Gravity

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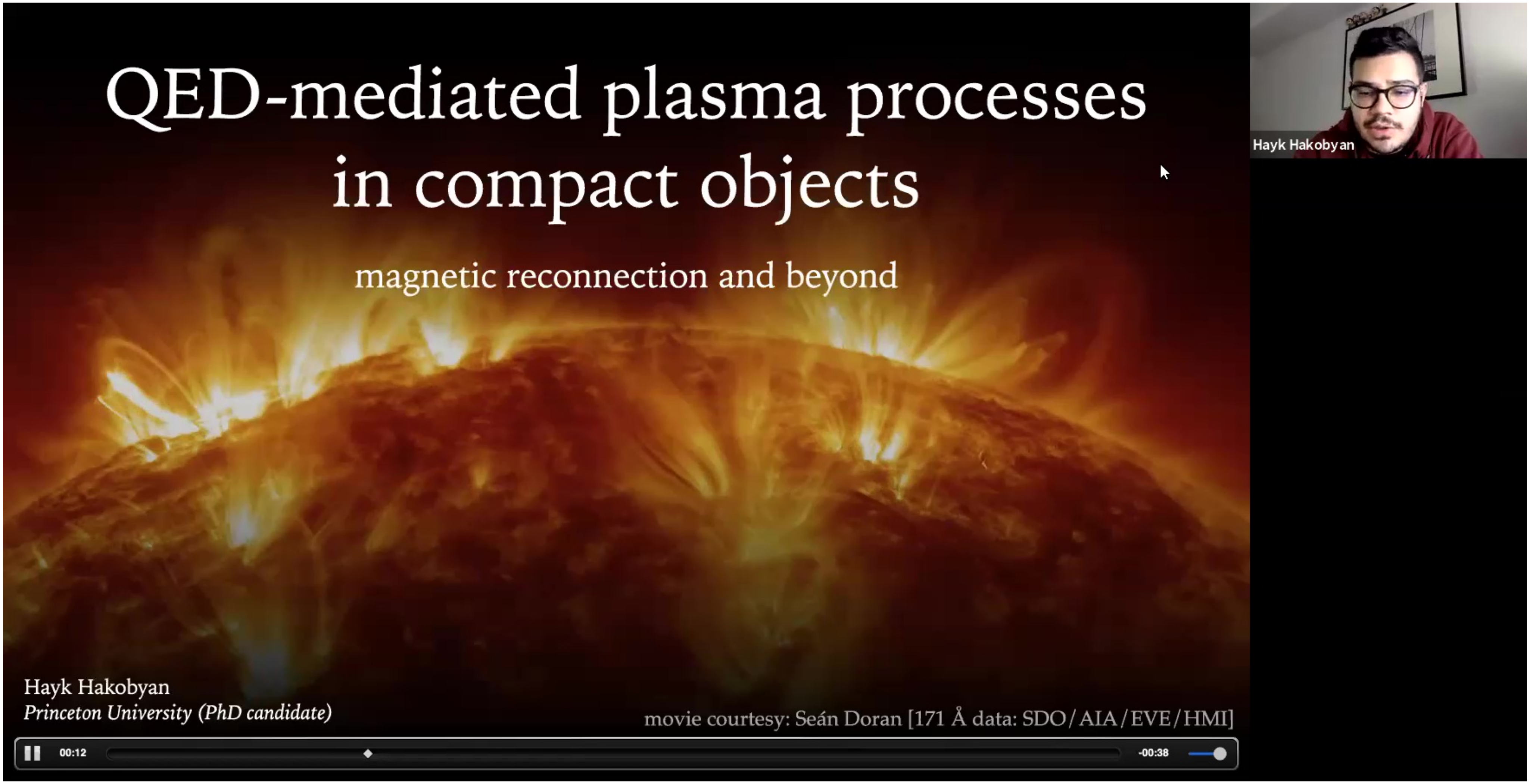
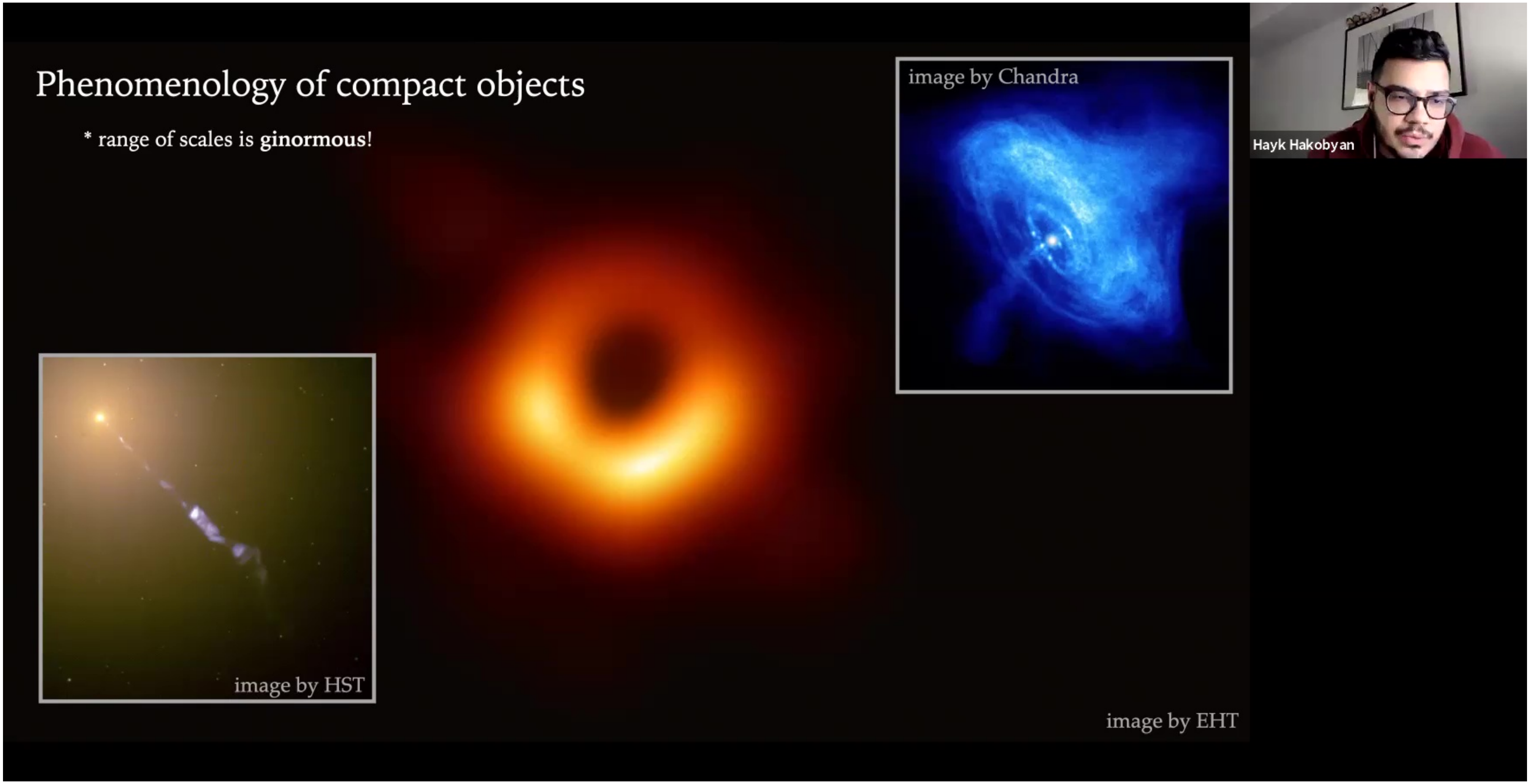
Abstract: In compact astrophysical objects, such as neutron star magnetospheres, black-hole accretion disk coronae and jets, the main energy reservoir is the magnetic field. The plasma processes such as magnetic reconnection and turbulence govern the extraction of that energy, which is then deposited into heat and accelerated particles and, ultimately, the observed emission. To understand what we observe, we first need to describe from first principles how these processes operate in violent regimes applicable to certain classes of compact objects, where radiative drag and pair production/annihilation play a significant role. As a specific example, I will briefly cover our state-of-the-art understanding of one of these processes â€" magnetic reconnection â€" and present the first self-consistent simulations of QED-mediated reconnection in application to neutron star magnetospheres and explain how it helps us understand the observed gamma-ray emission from these objects. I will also talk about the future prospects of this area of research; QED-mediated plasma processes also take place in a variety of other astrophysical objects, such as the accretion disk coronae in X-ray binaries, coalescing neutron stars shortly before their merger, and short X-ray bursts in magnetars.


QED-mediated plasma processes
in compact objects
magnetic reconnection and beyond
Hayk Hakobyan
Princeton University (PhD candidate)
movie courtesy: Seán Doran [171 Å data: SDO/AIA/EVE/HMI]
00:12
-00:38
Hayk Hakobyan

Outline

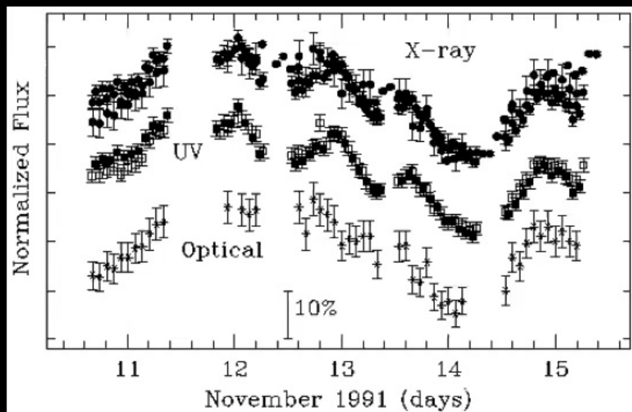
- Phenomenology of compact objects:
  - why kinetic plasma physics and QED effects are important?
- Particle-in-cell algorithms:
  - kinetic plasma simulations with the radiative *and* QED processes.
- Magnetic reconnection:
  - plasmoid (tearing) instability in fast regime;
  - particle acceleration channels.
- Pair-production mediated reconnection in high-energy pulsars:
  - reconnection in global pulsar magnetospheres and high-energy emission;
  - effects of radiative synchrotron cooling and two-photon pair production;
  - observational implications.
- Future prospects for QED mediated kinetic plasma physics.


Phenomenology of compact objects
* range of scales is **ginormous**!
image by Chandra
image by HST
image by EHT
Hayk Hakobyan

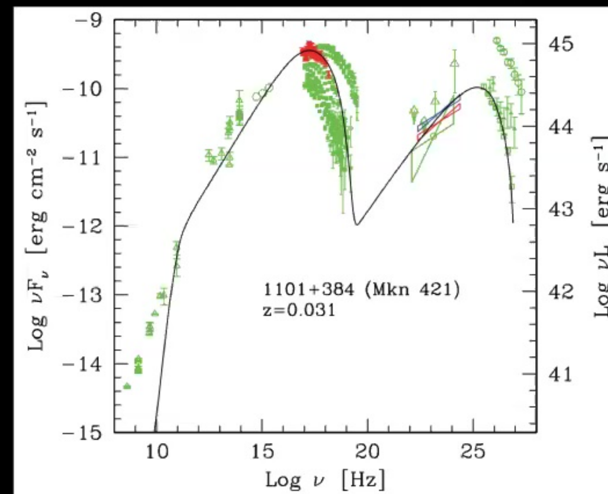
Phenomenology of compact objects

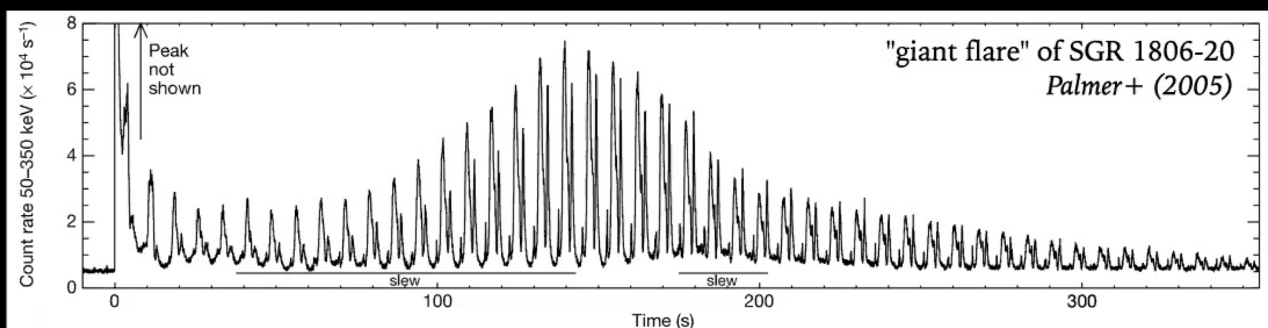
* persistent broadband emission + short/long variability

blazar PKS 2155-304
Edelson+ (1995)



Tavecchio+ (2010)





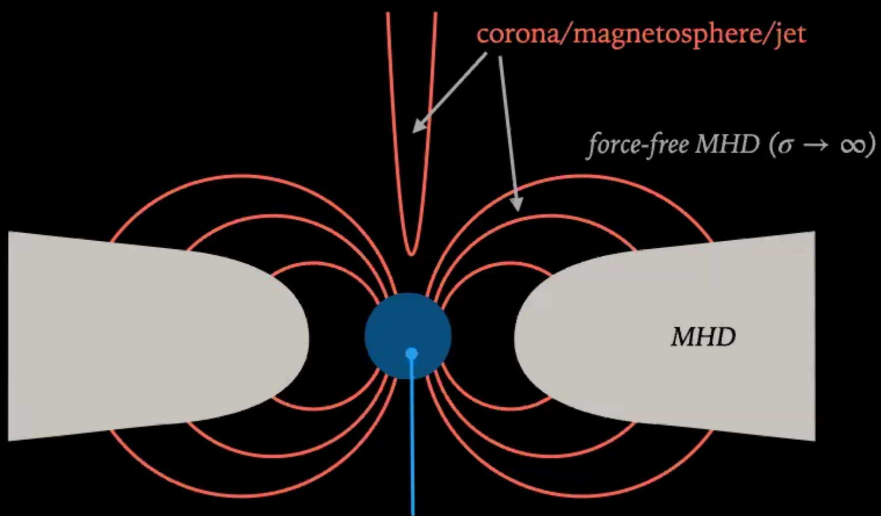
Phenomenology of compact objects

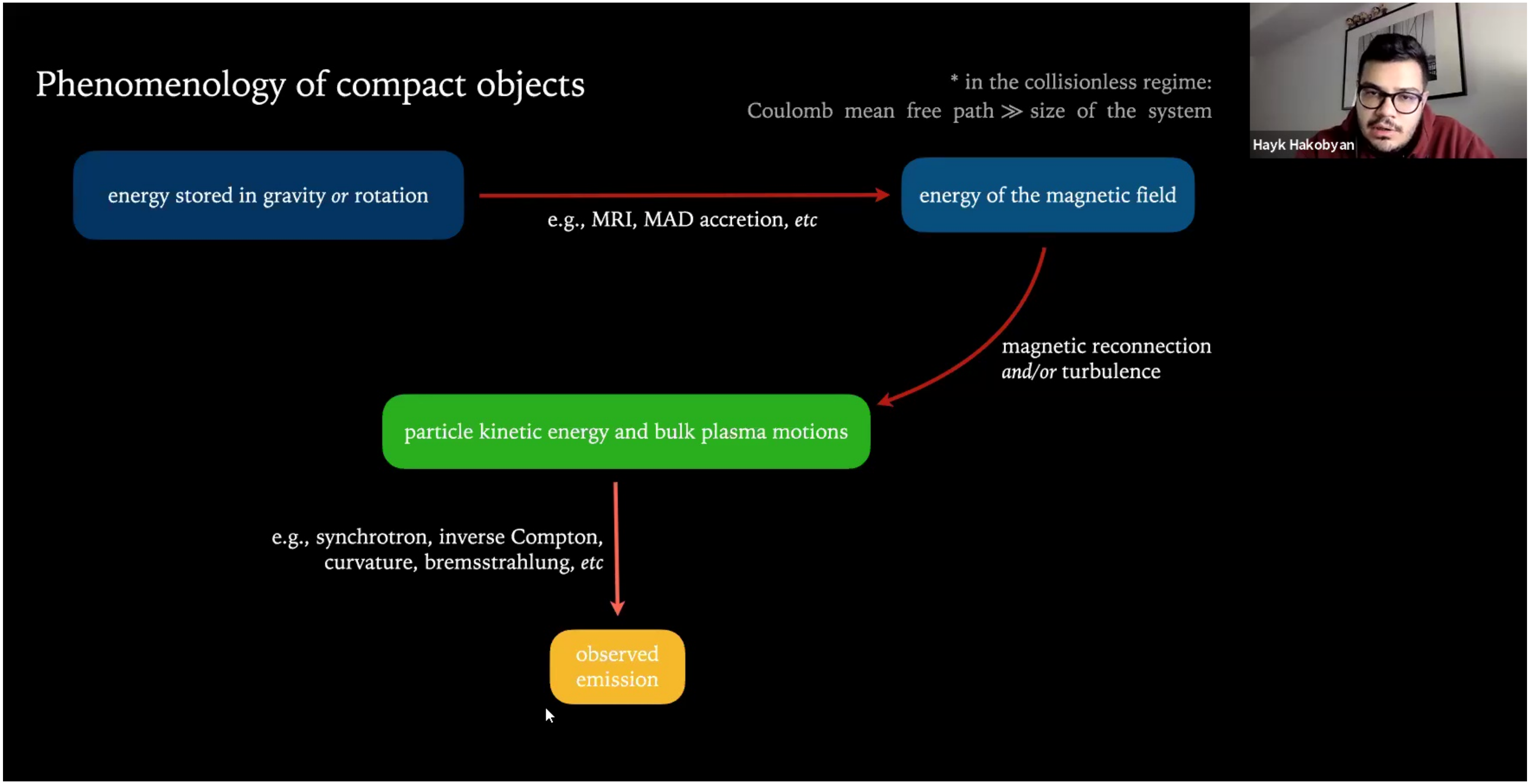
* in the collisionless regime:
Coulomb mean free path $\gg$ size of the system

energy stored in gravity *or* rotation → energy of the magnetic field

e.g., MRI, MAD accretion, *etc*

high magnetization $\sigma \equiv B^2/4\pi\rho c^2 \gg 1$

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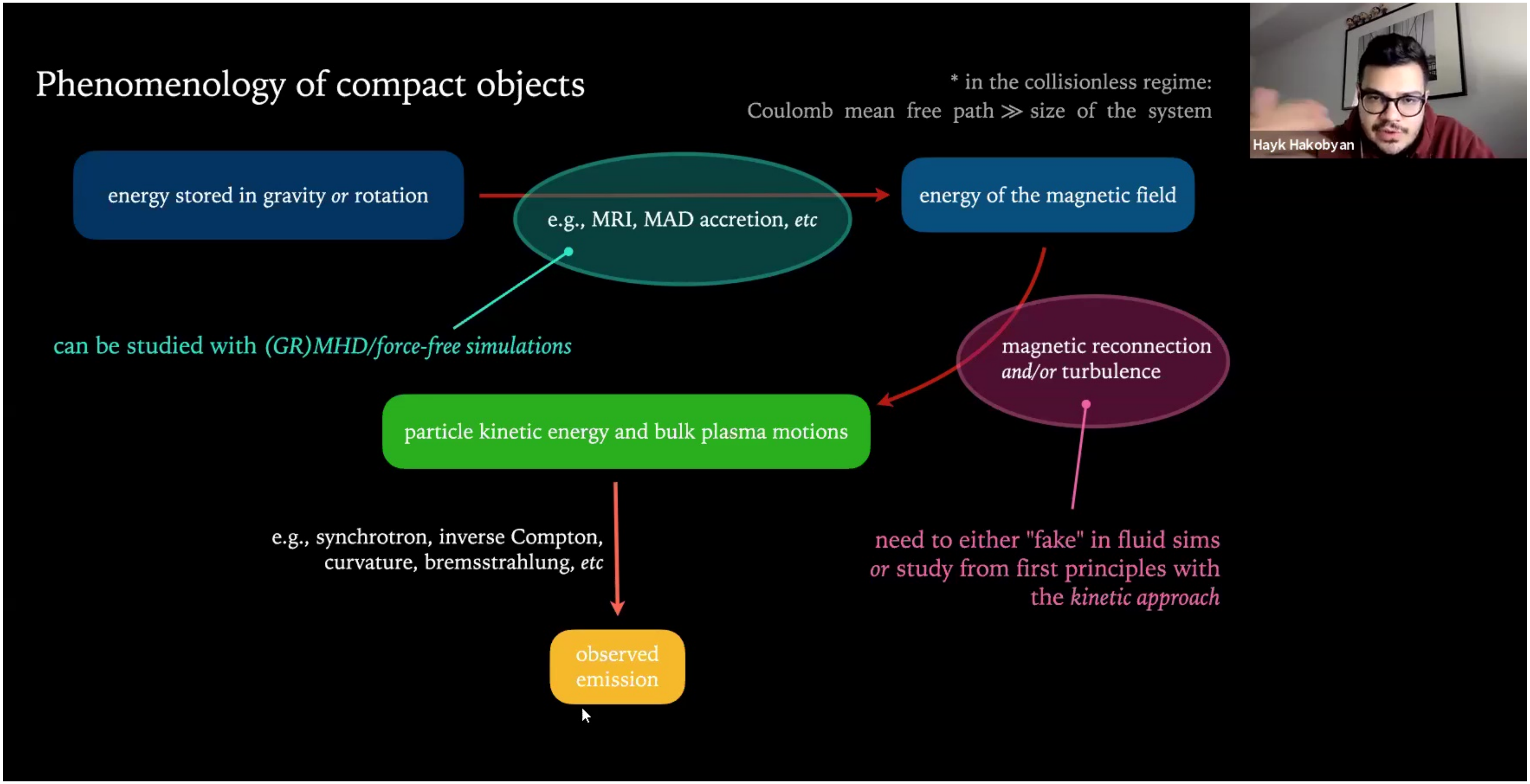
e.g., MRI, MAD accretion, *etc*
energy of the magnetic field
magnetic reconnection
and/or turbulence
particle kinetic energy and bulk plasma motions
e.g., synchrotron, inverse Compton,
curvature, bremsstrahlung, *etc*
observed
emission
Hayk Hakobyan


Phenomenology of compact objects
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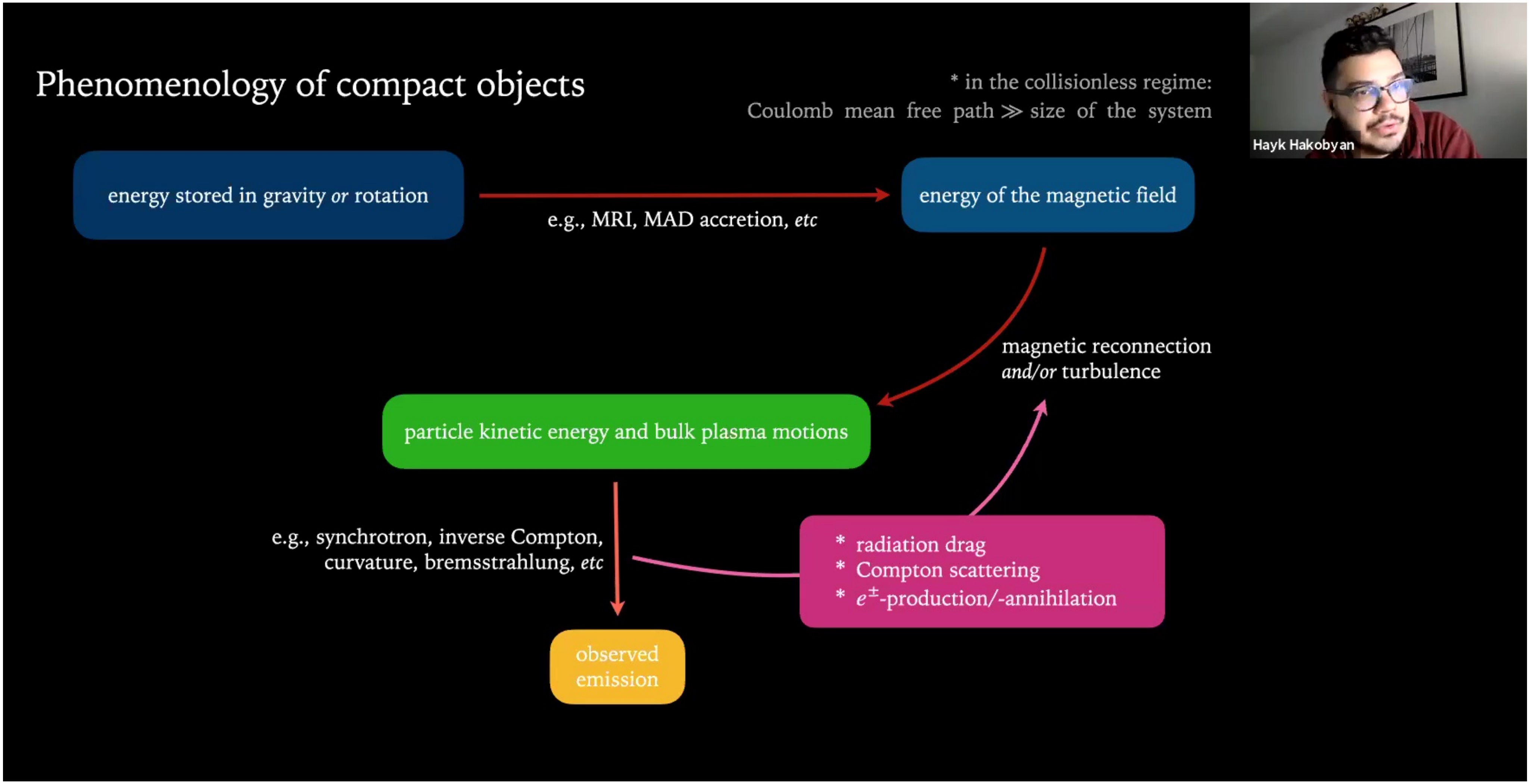
Coulomb mean free path ≫ size of the system
Hayk Hakobyan
energy stored in gravity *or* rotation
e.g., MRI, MAD accretion, *etc*
energy of the magnetic field
can be studied with *(GR)MHD/force-free simulations*
magnetic reconnection
and/or turbulence
particle kinetic energy and bulk plasma motions
e.g., synchrotron, inverse Compton,
curvature, bremsstrahlung, *etc*
need to either "fake" in fluid sims
or study from first principles with
the *kinetic approach*
observed
emission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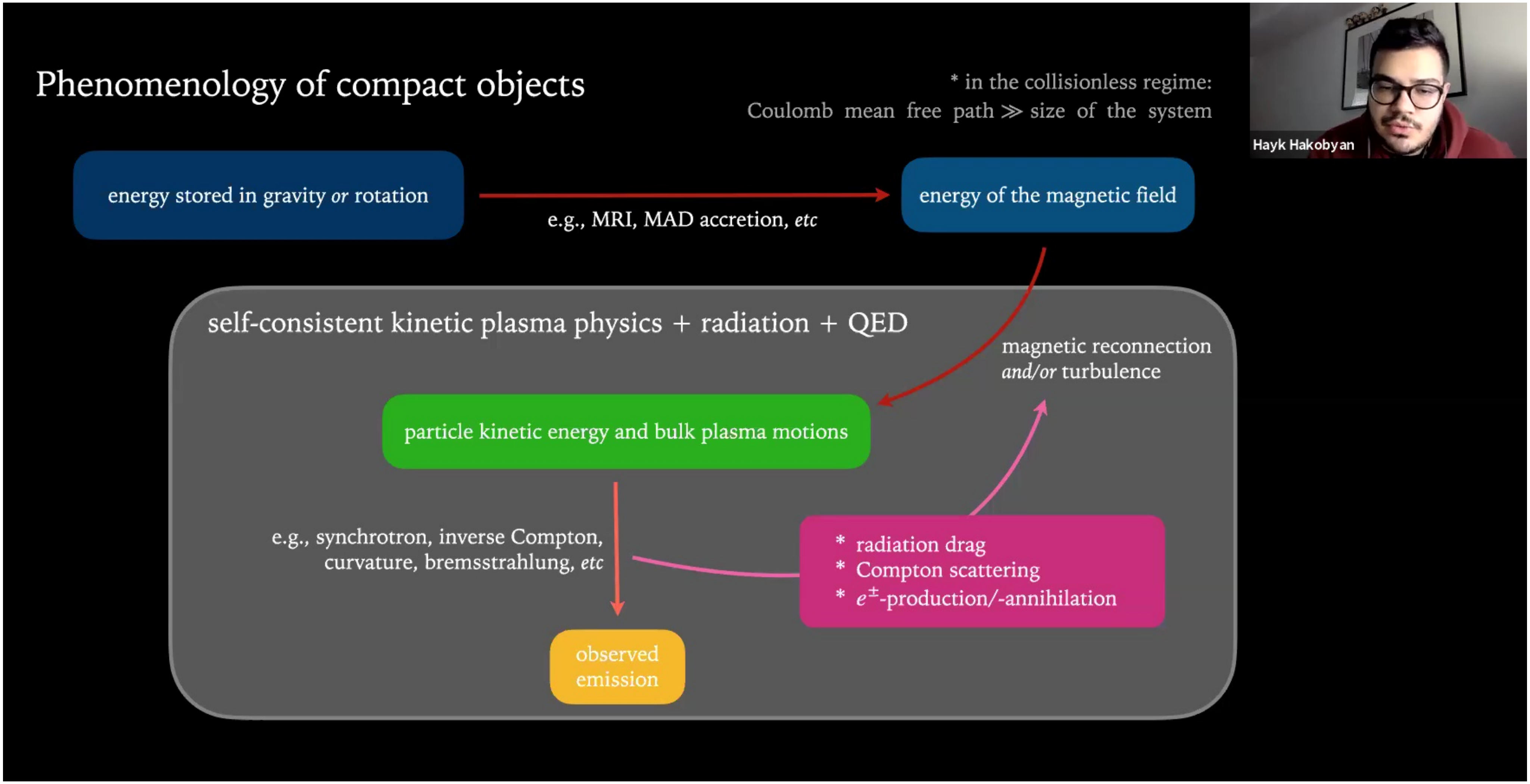
* radiation drag
* Compton scattering
* $e^{\pm}$-production/-annihilation
observed
emission


Phenomenology of compact objects
* in the collisionless regime:
Coulomb mean free path ≫ size of the system
Hayk Hakobyan
energy stored in gravity *or* rotation
e.g., MRI, MAD accretion, *etc*
energy of the magnetic field
self-consistent kinetic plasma physics + radiation + QED
magnetic reconnection
and/or turbulence
particle kinetic energy and bulk plasma motions
e.g., synchrotron, inverse Compton,
curvature, bremsstrahlung, *etc*
* radiation drag
* Compton scattering
* $e^{\pm}$-production/-annihilation
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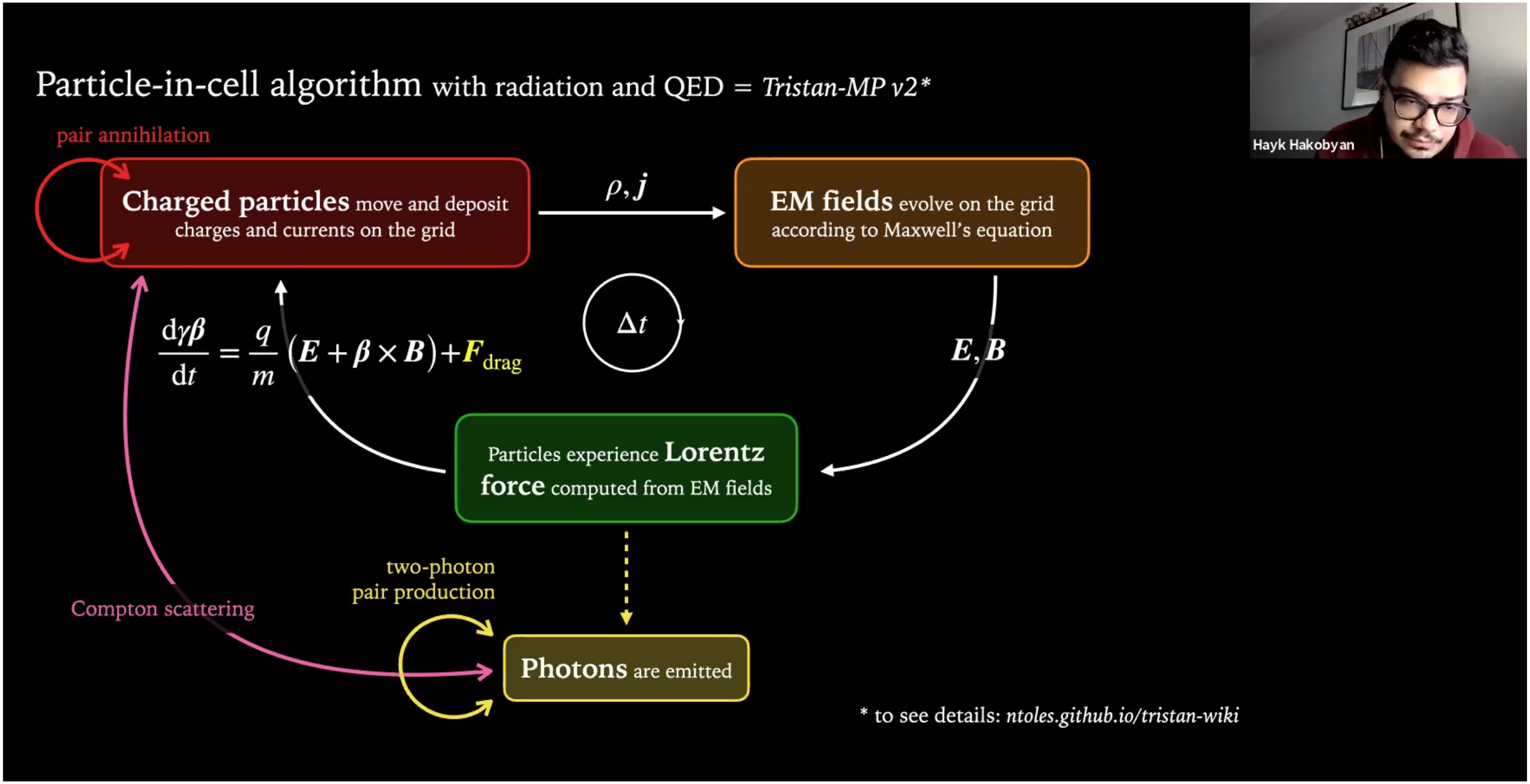


Particle-in-cell algorithm with radiation and QED = Tristan-MP v2*
pair annihilation
Charged particles move and deposit charges and currents on the grid
ρ, j
EM fields evolve on the grid according to Maxwell's equation
Δt
E, B
$\frac{d\gamma\beta}{dt} = \frac{q}{m}(E + \beta \times B) + F_{drag}$
Particles experience Lorentz force computed from EM fields
two-photon pair production
Compton scattering
Photons are emitted
* to see details: ntoles.github.io/tristan-wiki
Hayk Hakobyan

Takeaways so far

- To reliably reproduce energy dissipation and emission from compact objects we need kinetic plasma approach.
- Radiative and QED effects may significantly influence this process (examples in a moment).
- Particle-in-cell (PIC) algorithm for kinetic plasma simulations can be (and has been) coupled with QED (radiative QED-PIC :)).

Takeaways so far

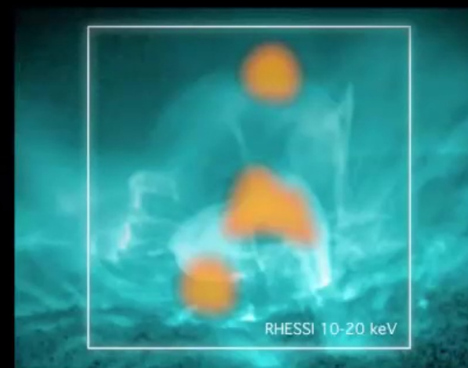
- To reliably reproduce energy dissipation and emission from compact objects we need kinetic plasma approach.
- Radiative and QED effects may significantly influence this process (examples in a moment).
- Particle-in-cell (PIC) algorithm for kinetic plasma simulations can be (and has been) coupled with QED (radiative QED-PIC :)).

Next:

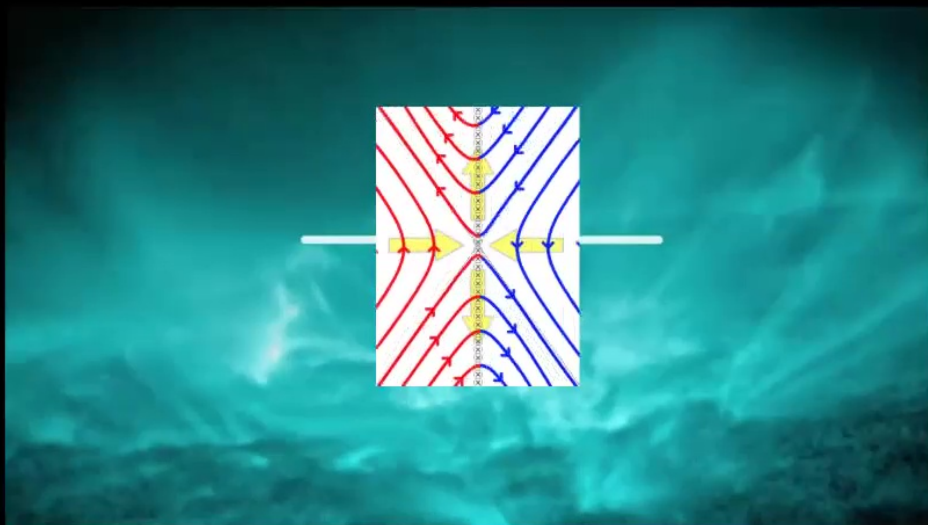
- Examples of what kinetic physics enables us to study.
- Demo of QED-PIC power for modeling pulsars.

Magnetic reconnection

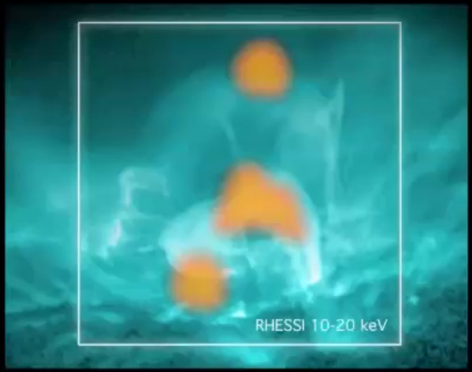
NASA [SDO 131 Å]

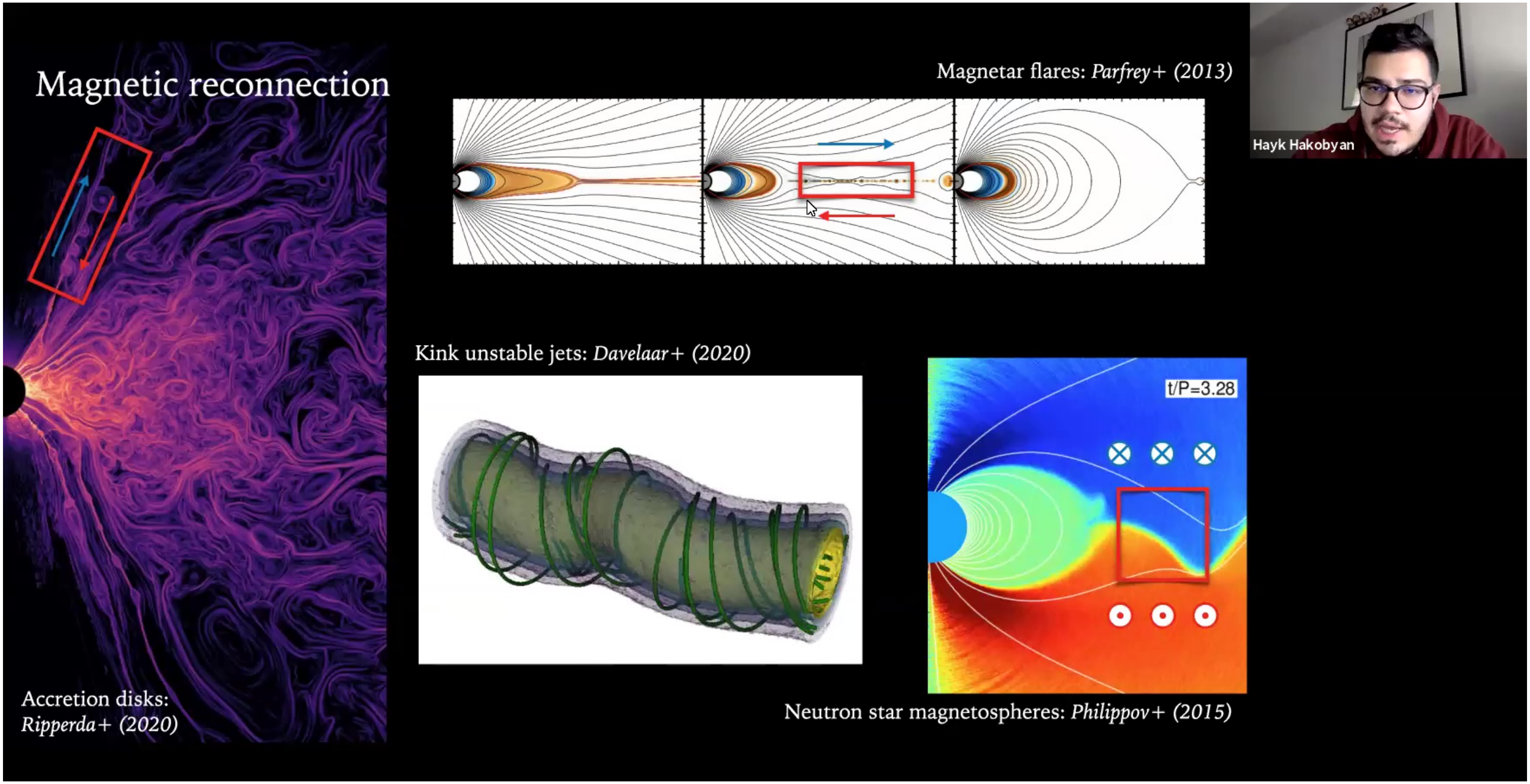


Magnetic reconnection



NASA [SDO 131 Å]

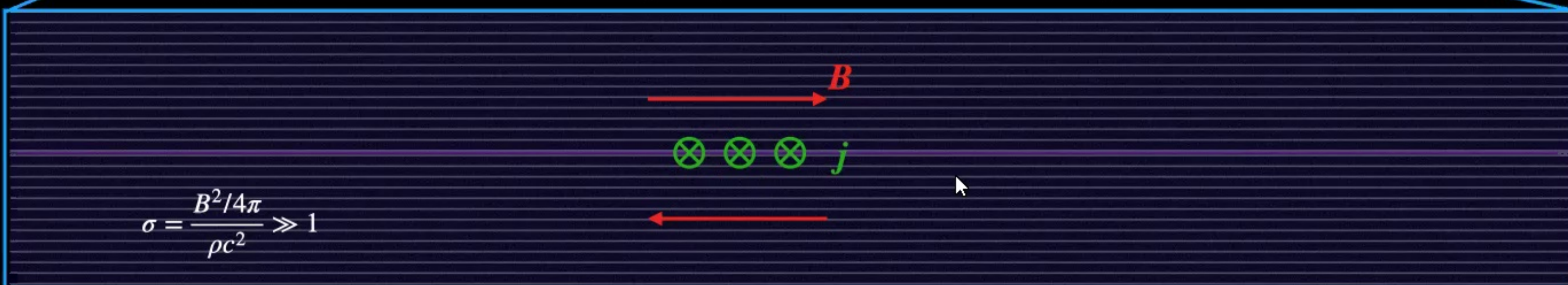



Magnetic reconnection
Magnetar flares: *Parfrey+ (2013)*
Hayk Hakobyan
Kink unstable jets: *Davelaar+ (2020)*
t/P=3.28
Accretion disks:
Ripperda+ (2020)
Neutron star magnetospheres: *Philippov+ (2015)*

Magnetic reconnection

Ripperda+ (2020)

to properly capture kinetic scales we typically simulate localized reconnecting current sheet



$$\sigma = \frac{B^2/4\pi}{\rho c^2} \gg 1$$

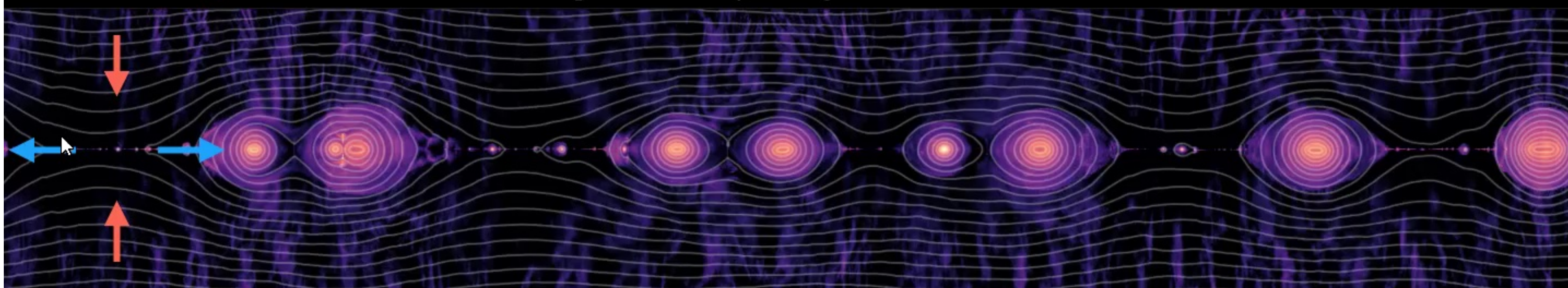
Magnetic reconnection

plasma density + magnetic fieldlines

Magnetic reconnection

$$v_{\mathrm{in}} \sim \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2} c \sim 0.1c$$

plasma density + magnetic fieldlines

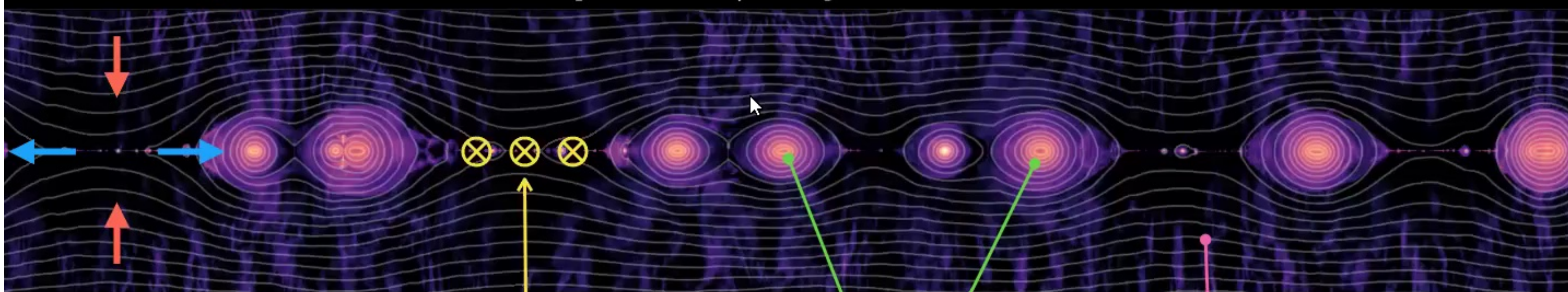


$$v_{\mathrm{out}} \sim v_A \sim c$$

Magnetic reconnection

$v_{\rm in} \sim \frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2}c \sim 0.1c$

plasma density + magnetic fieldlines



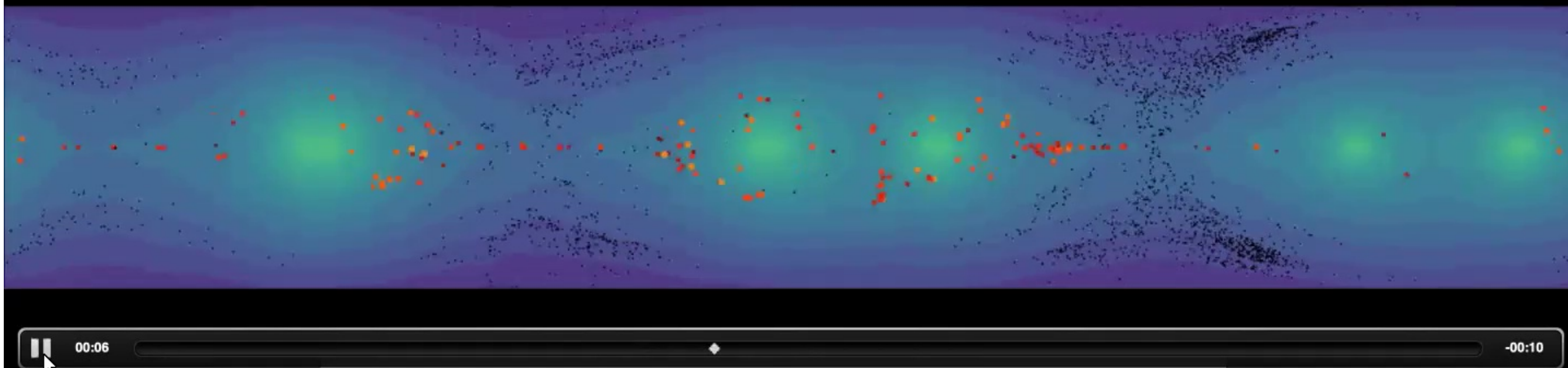
$v_{\rm out} \sim v_A \sim c$

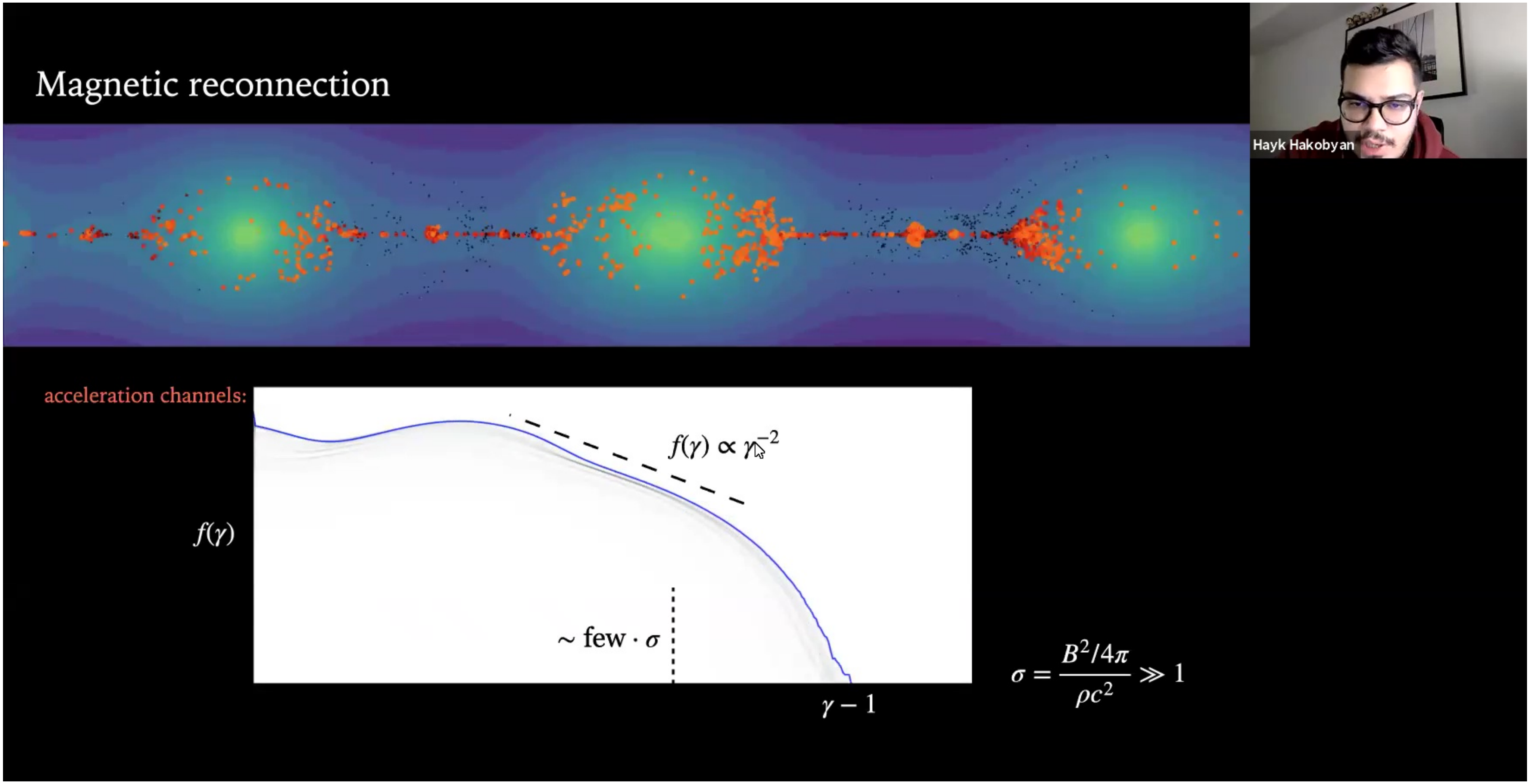
in-plane *resistive* ***E*-field** which accompanies the dissipation of ***B***-field (x-points)

plasmoids that grow, merge and carry away the energized plasma (o-points)

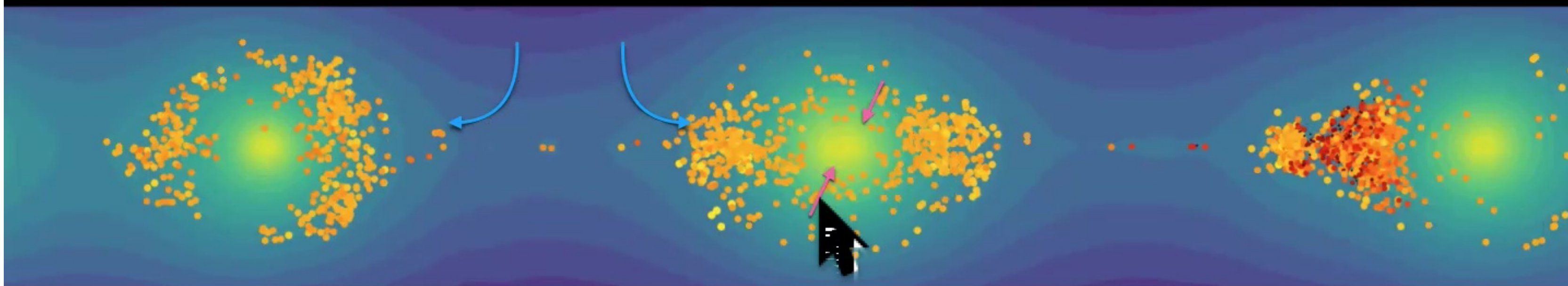
magnetization $\sigma = \frac{B^2/4\pi}{\rho c^2} \gg 1$

Magnetic reconnection




Magnetic reconnection
Hayk Hakobyan
acceleration channels:
$f(\gamma) \propto \gamma^{-2}$
$f(\gamma)$
$\sim$ few $\cdot\ \sigma$
$\gamma - 1$
$\sigma = \frac{B^2/4\pi}{\rho c^2} \gg 1$

Magnetic reconnection



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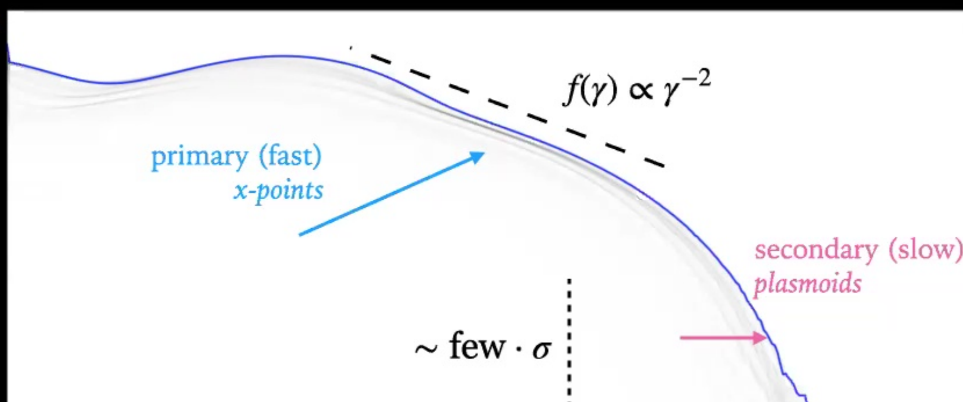
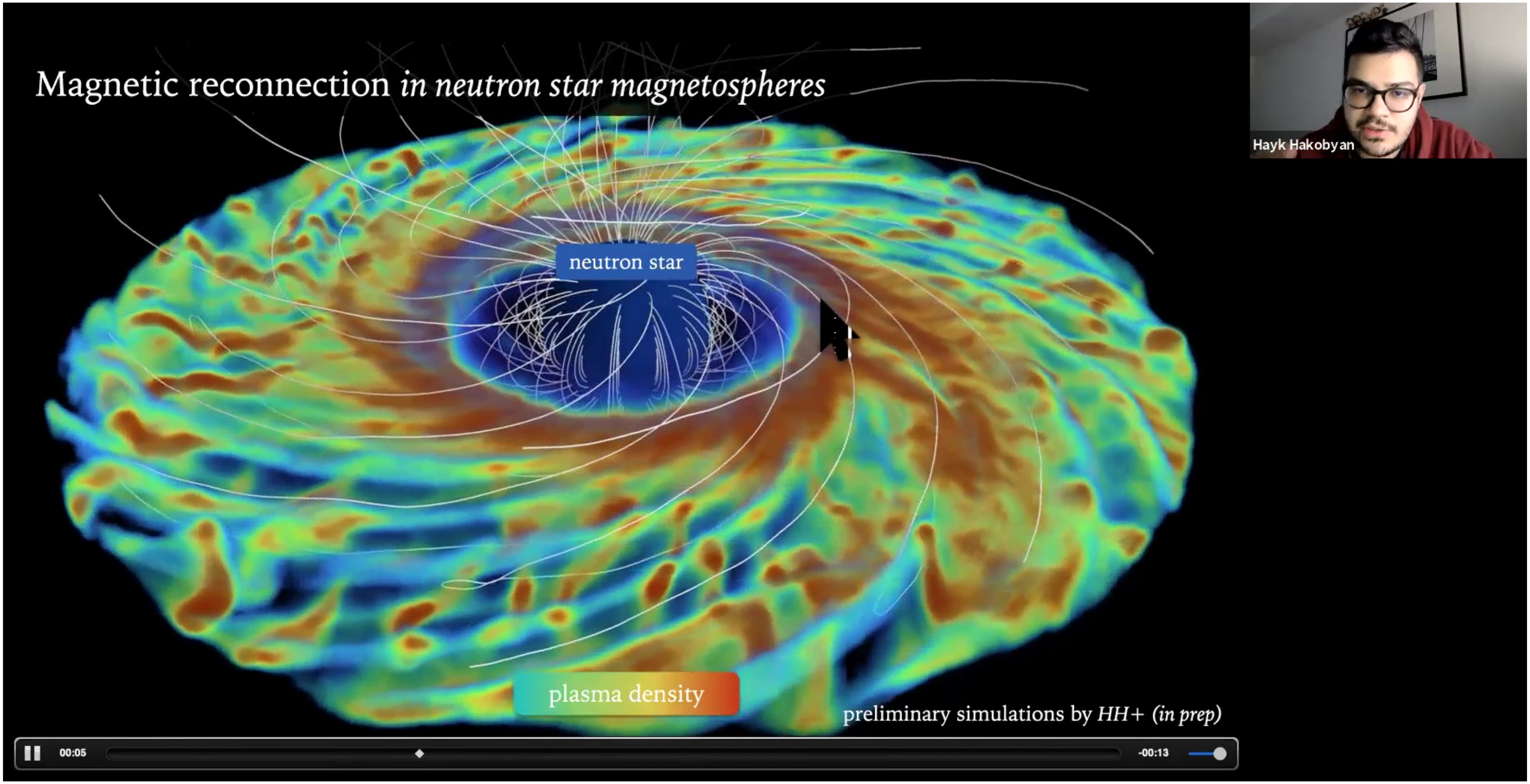


$f(\gamma)$

$\gamma - 1$

$$\sigma = \frac{B^2/4\pi}{\rho c^2} \gg 1$$

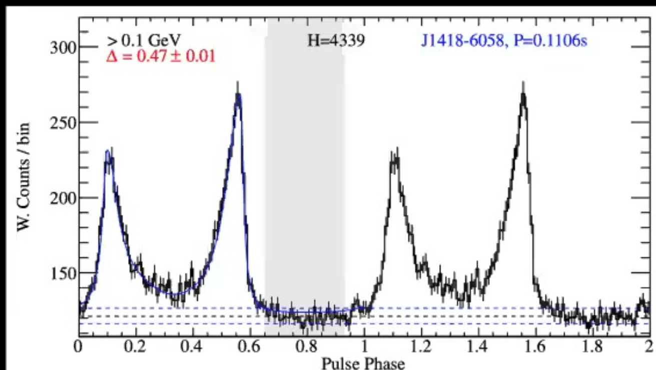
primary: *Sironi & Spitkovsky (2014)*, secondary: *HH+ (2020)*


Magnetic reconnection *in neutron star magnetospheres*
neutron star
plasma density
preliminary simulations by *HH+ (in prep)*
00:05
-00:13
Hayk Hakobyan

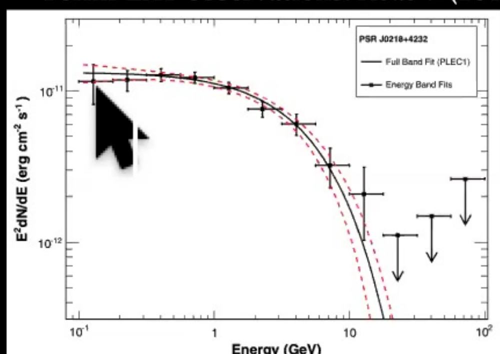
Magnetic reconnection *in neutron star magnetospheres*

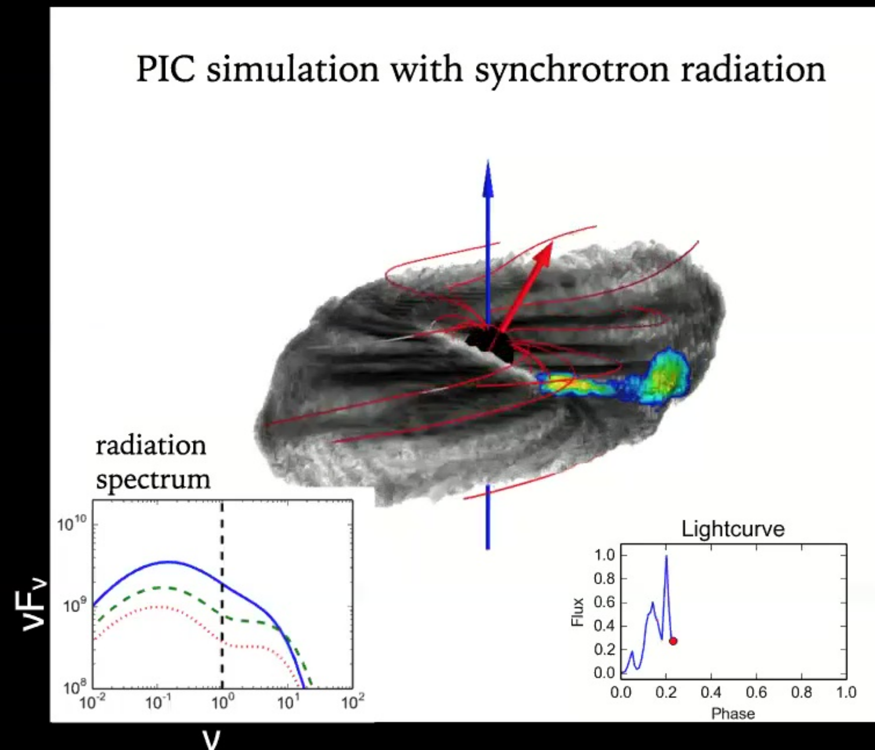
- magnetic reconnection in pulsar magnetospheres powers their γ-ray emission

Philippov & Spitkovsky 2014-2018
Cerutti+ 2016



Fermi-LAT observations: *Abdo+ (2013)*





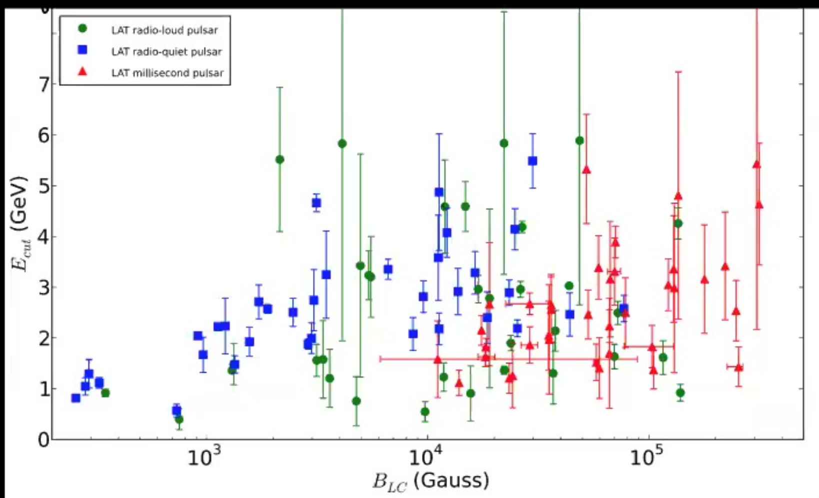
Magnetic reconnection *in neutron star magnetospheres*

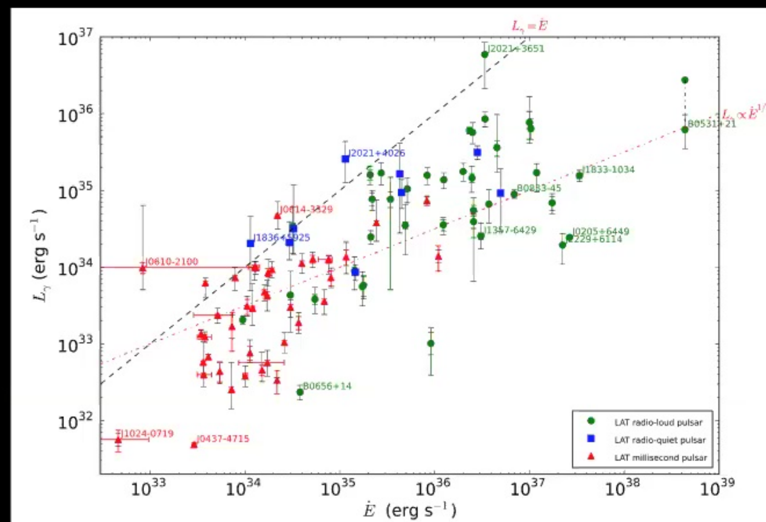
* LC = light cylinder

Problem #1: when extrapolated to the population of γ-ray pulsars this model predicts strong scaling of $E_{\rm cut}(B_{\rm LC})$:

$$\gamma_{\rm cut} \sim \sigma \propto B_{\rm LC}^2/\rho_{\rm LC} \propto B_{\rm LC} \quad \Rightarrow \quad \nu_{\rm cut} \propto \gamma_{\rm cut}^2 B_{\rm LC} \propto B_{\rm LC}^3\,;$$

Problem #2: reconnection model predicts that the ~constant fraction of the Poynting-flux $\dot{E}$ is converted to radiation L_γ.





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Problem #2: reconnection model predicts that the ~constant fraction of the Poynting-flux $\dot{E}$ is converted to radiation L_γ.

1. strong synchrotron drag (can disable secondary acceleration):

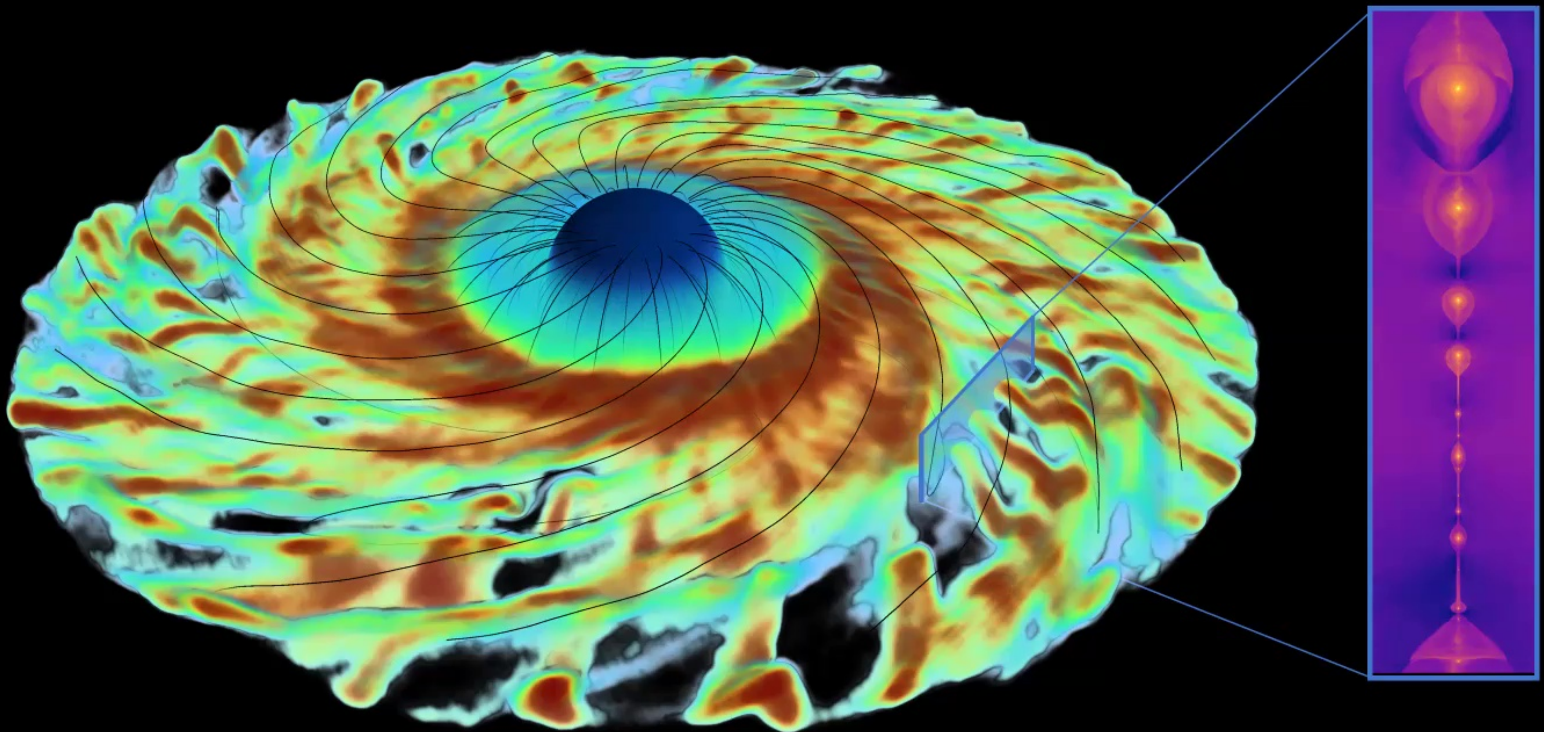
$$eE_{\rm rec}c \ll 2\sigma_{\rm T}U_B\gamma^2 \quad (\text{for } \gamma \lesssim \sigma)$$

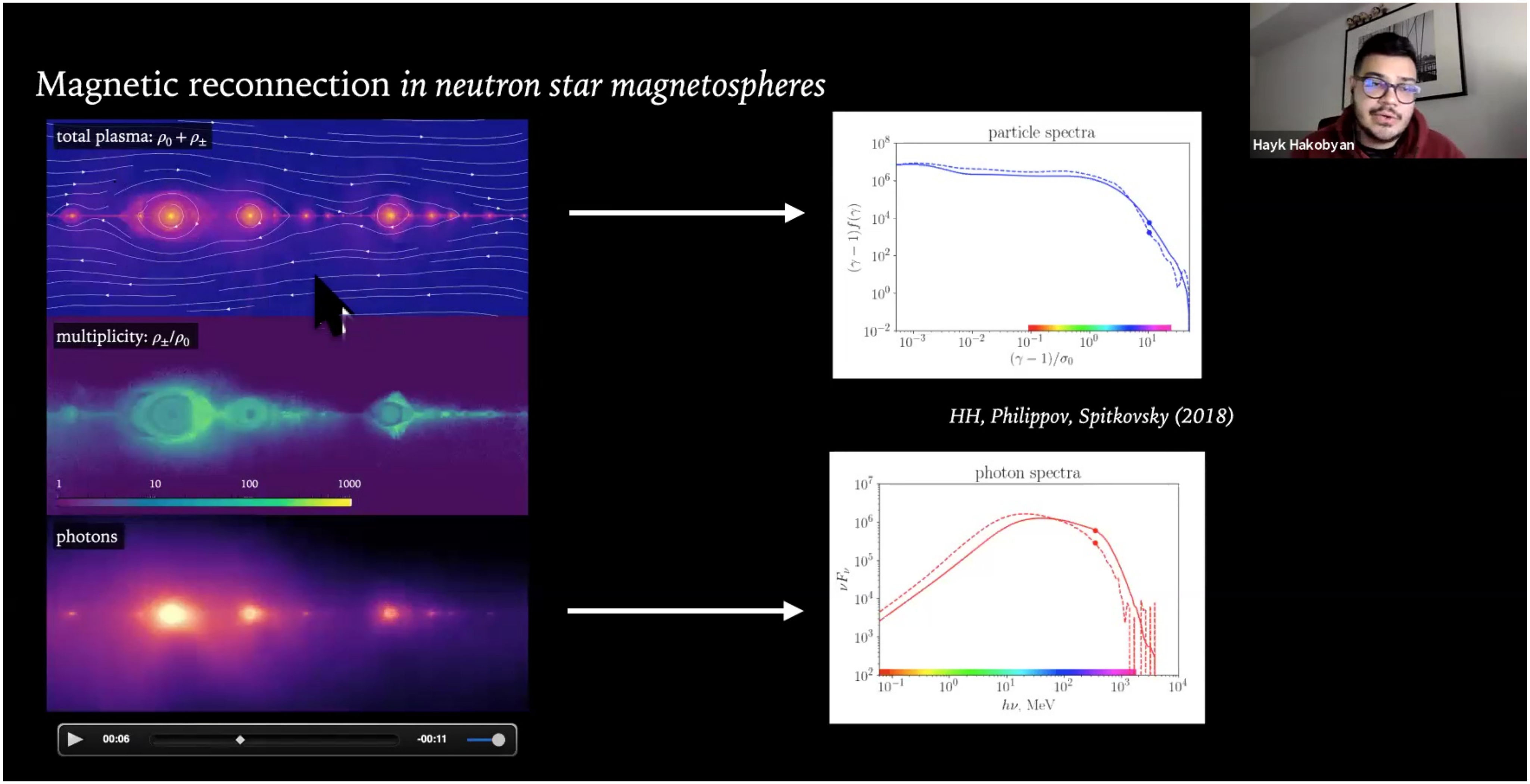
2. two-photon pair production ($\gamma\gamma \rightarrow e^{\pm}$) (can drop the effective magnetization → suppress acceleration):

$$\eta \equiv \frac{\text{secondary plasma}}{\text{primary plasma}} \sim 10^2 \left(\frac{B_{\rm LC}}{10^5\ {\rm G}}\right)^{5/2} \quad (\text{even though } \tau_{\gamma\gamma} \ll 1)$$

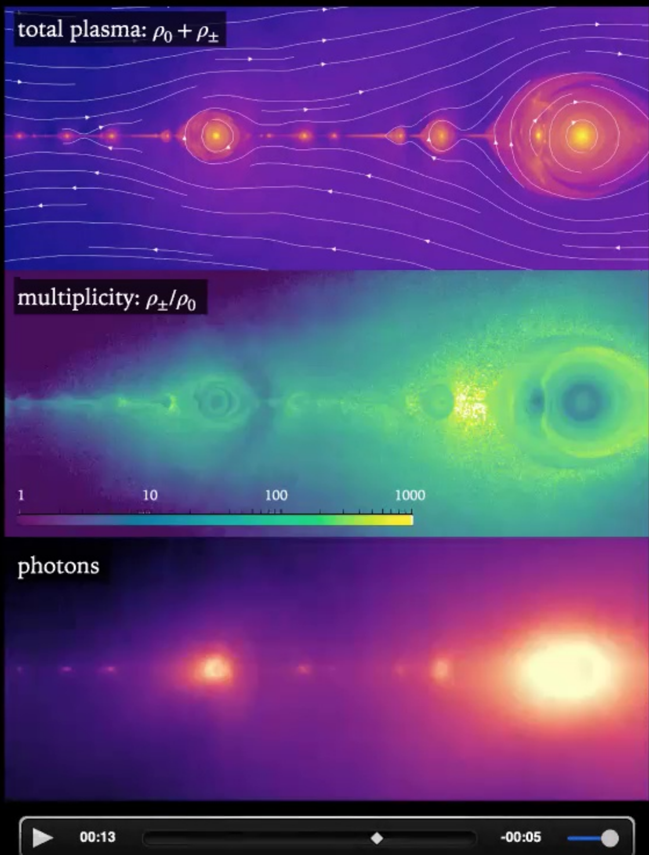
HH, Philippov, Spitkovsky (2018)

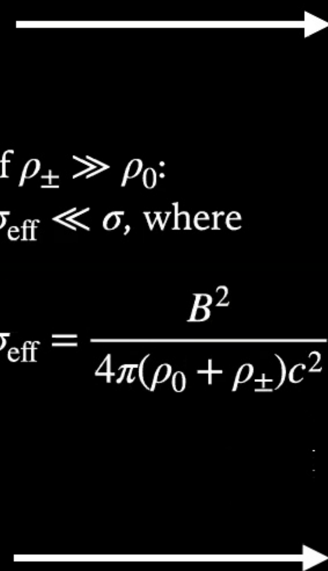
Magnetic reconnection *in neutron star magnetospheres*




Magnetic reconnection *in neutron star magnetospheres*
total plasma: $\rho_0 + \rho_\pm$
multiplicity: $\rho_\pm / \rho_0$
1
10
100
1000
photons
00:06
-00:11
particle spectra
$(\gamma - 1) f(\gamma)$
$(\gamma - 1)/\sigma_0$
HH, Philippov, Spitkovsky (2018)
photon spectra
νF_ν
$h\nu$, MeV
Hayk Hakobyan

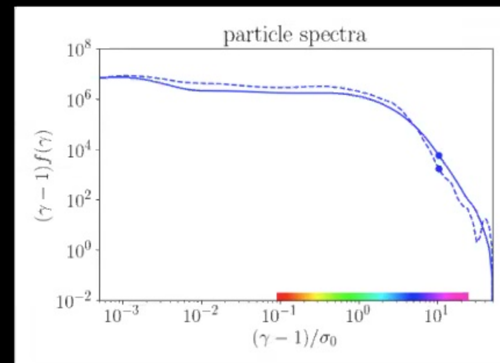
Magnetic reconnection *in neutron star magnetospheres*



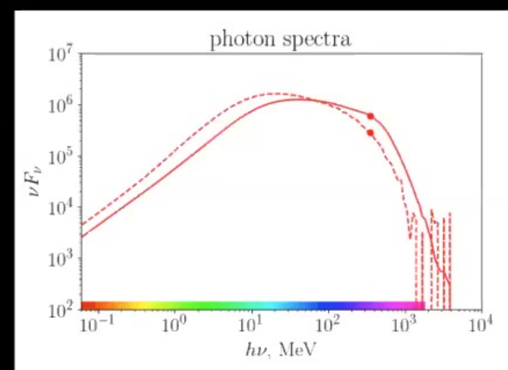


if $\rho_\pm \gg \rho_0$:
$\sigma_{\text{eff}} \ll \sigma$, where

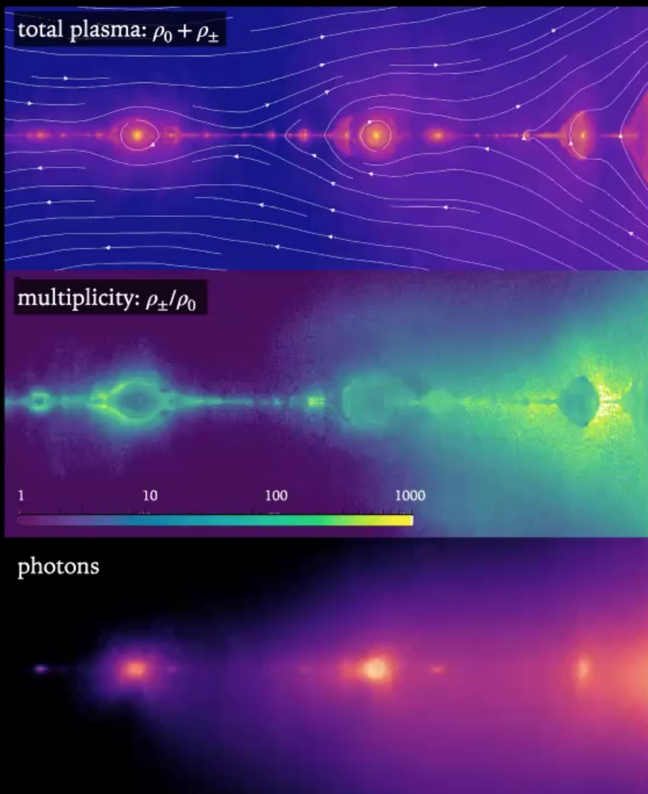
$$\sigma_{\text{eff}} = \frac{B^2}{4\pi(\rho_0 + \rho_\pm)c^2}$$

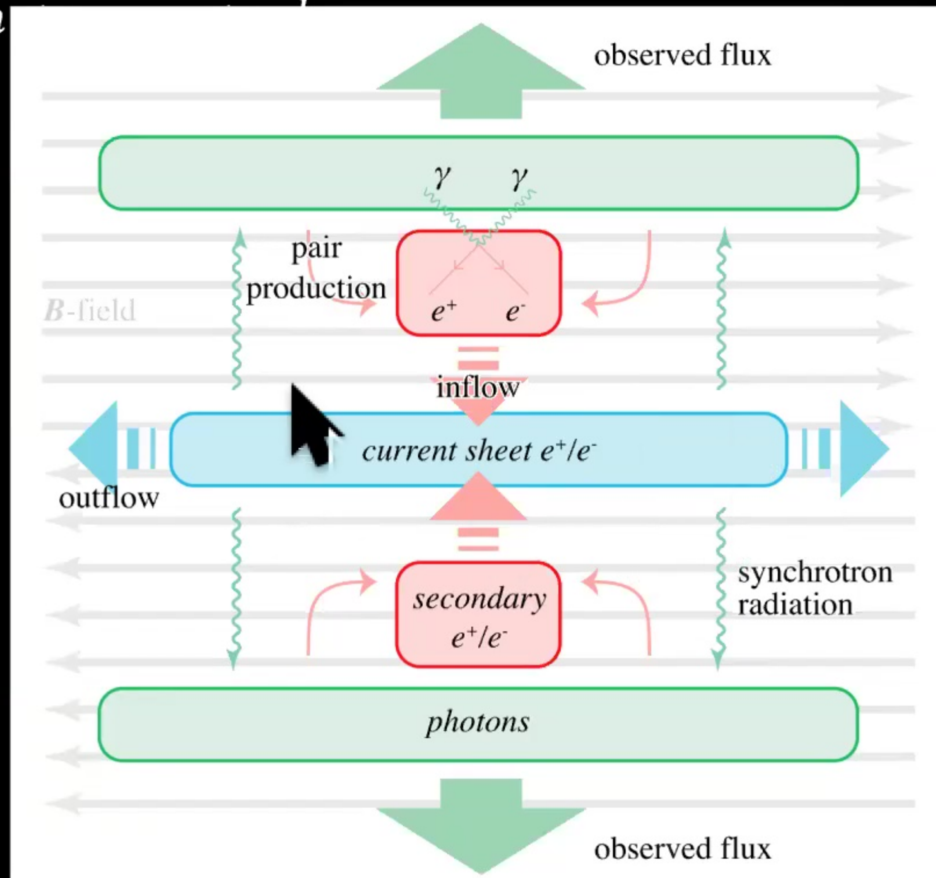


HH, Philippov, Spitkovsky (2018)

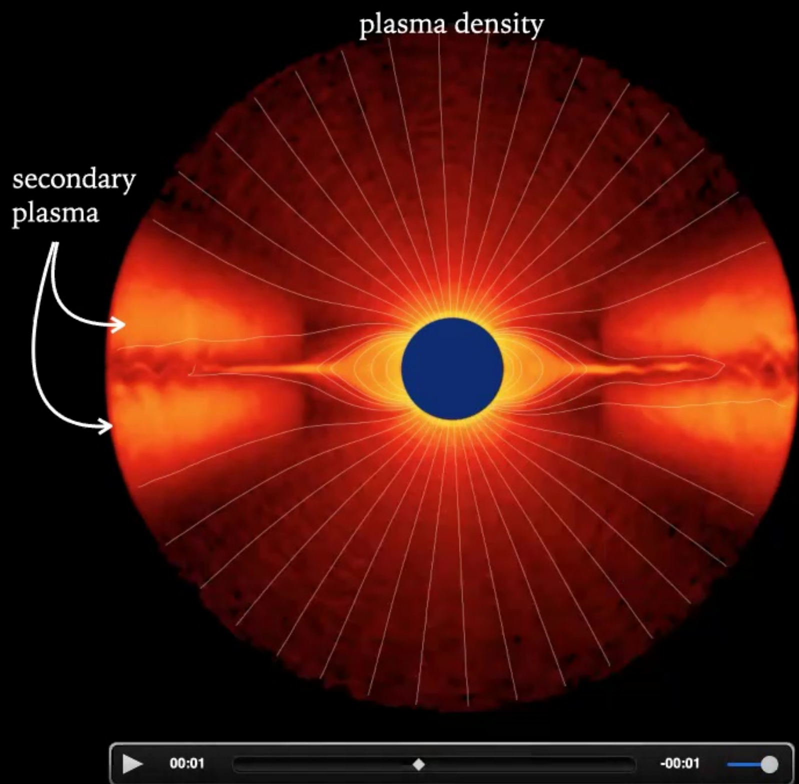


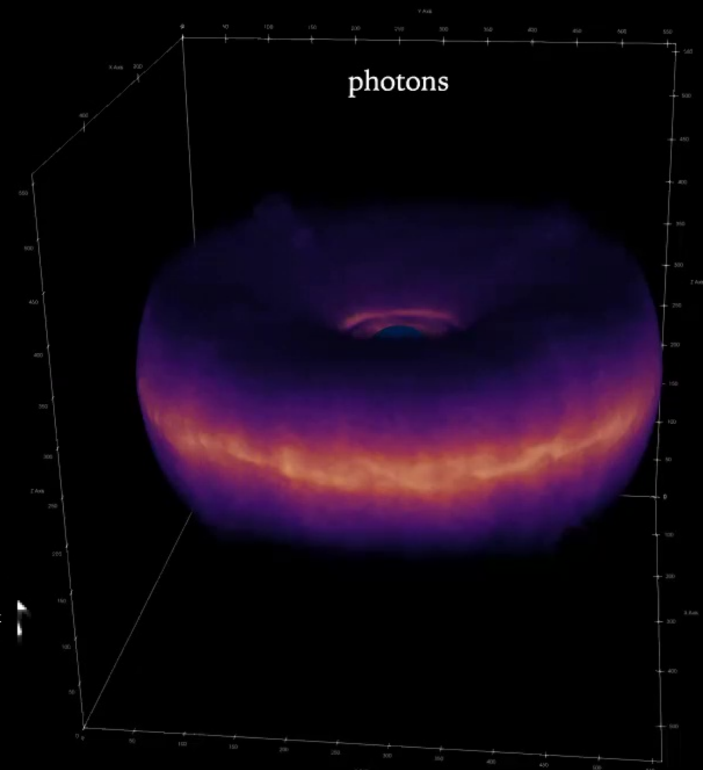
Magnetic reconnection *in neutron*





Magnetic reconnection *in neutron star magnetospheres*





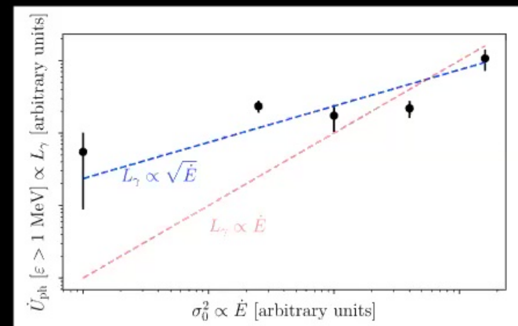
preliminary simulations by *HH+ (in prep)*

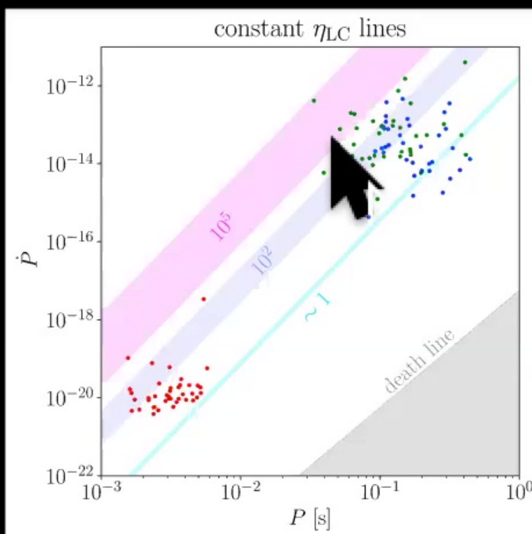
Magnetic reconnection *in neutron star magnetospheres*

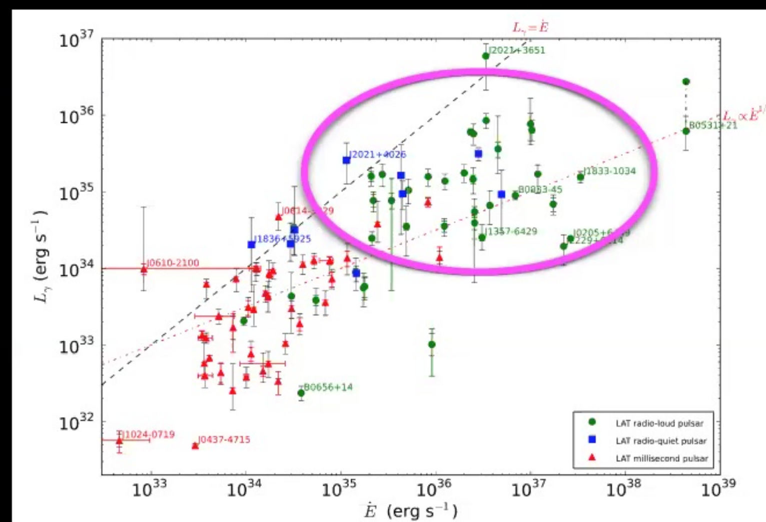
see *HH, Philippov, Spitkovsky (2018)* for local 2D simulations
global 3D — soon

because of the violent two-photon pair production:

- magnetization drops ⇒ reconnection is suppressed
- $E_{\rm cut} \sim$ const
- γ-ray luminosity is suppressed







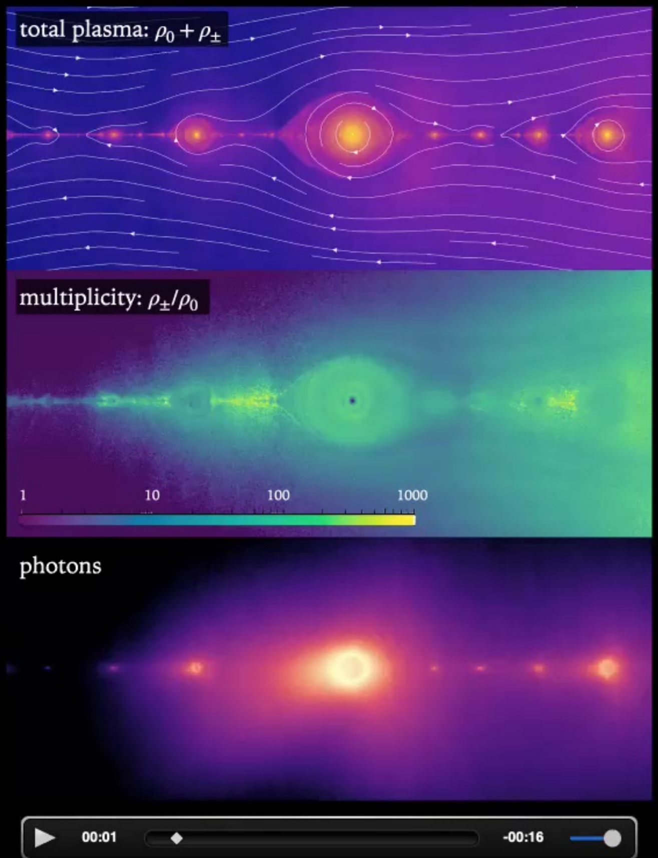
Takeaways so far

- Reconnection is a powerful mechanism for fast magnetic energy dissipation and particle acceleration.
- Reconnection powers the high energy emission in γ-ray pulsars.
- Strong synchrotron cooling and two-photon pair production not only impact, but often dominate this process in some of the youngest pulsars.

Next:

- Other extreme systems where kinetics with QED effects are important.

Magnetic reconnection *in neutron star magnetospheres*



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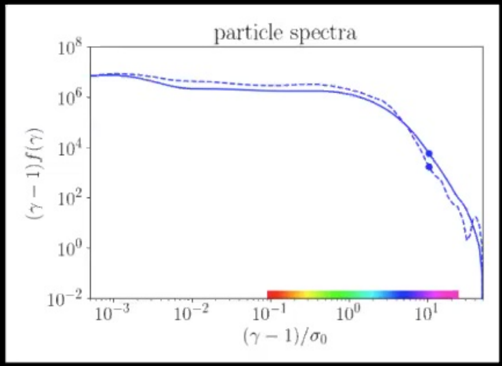
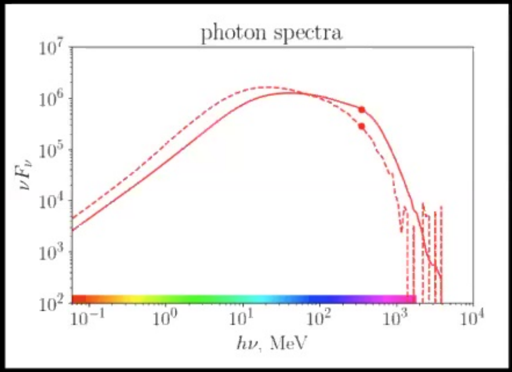
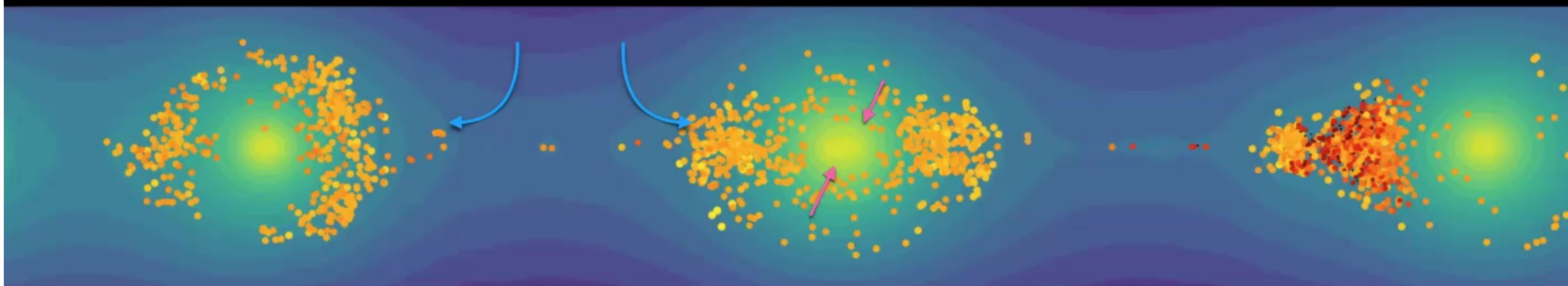
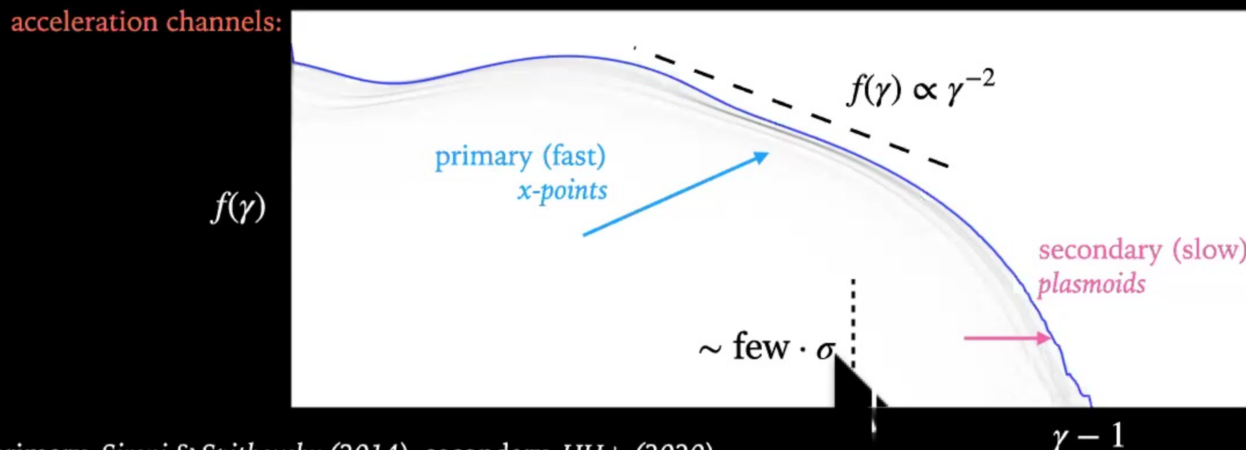


HH, Philippov, Spitkovsky (2018)



Magnetic reconnection

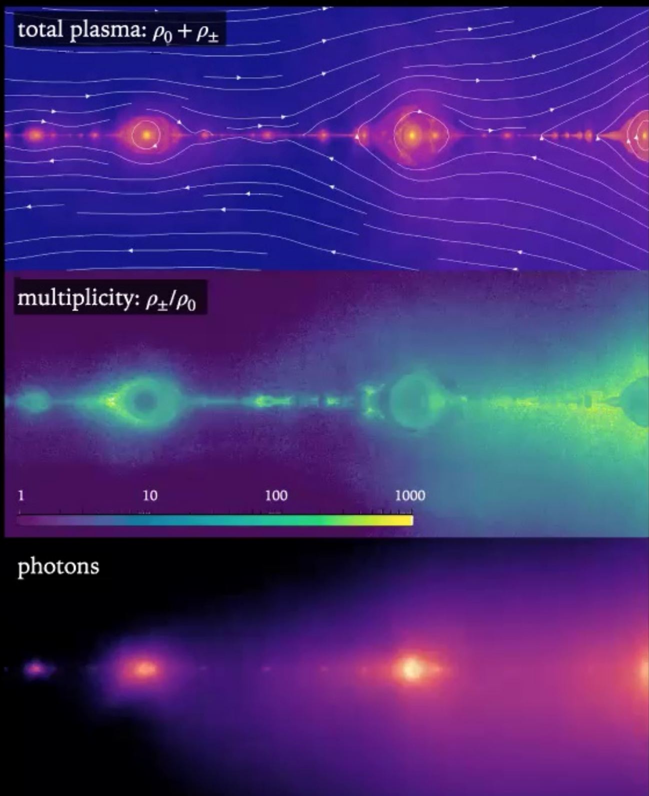


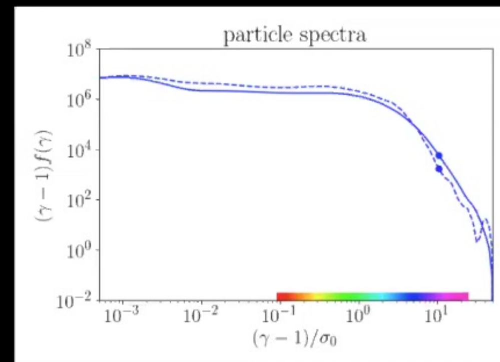


$$\sigma = \frac{B^2/4\pi}{\rho c^2} \gg 1$$

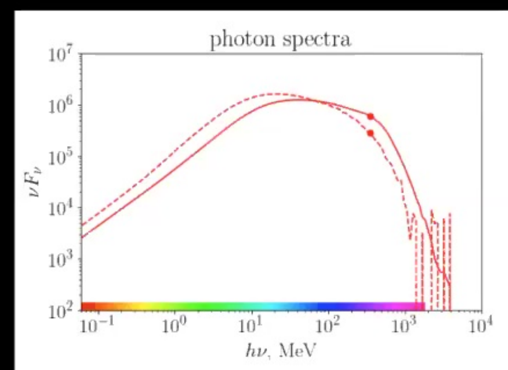
primary: *Sironi & Spitkovsky (2014)*, secondary: *HH+ (2020)*

Magnetic reconnection *in neutron star magnetospheres*





HH, Philippov, Spitkovsky (2018)



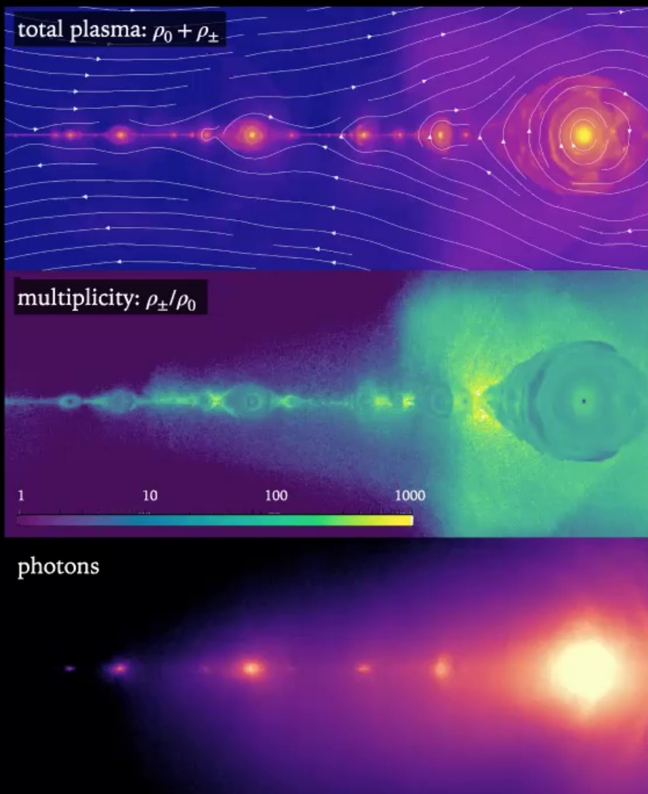
Takeaways so far

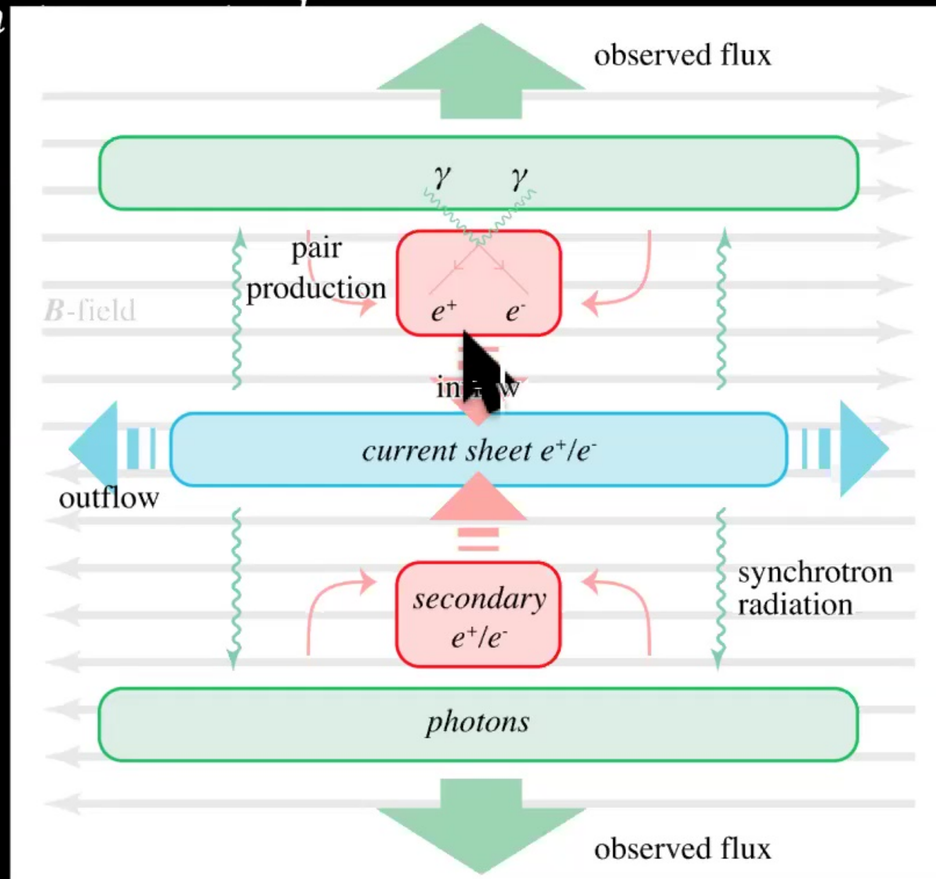
- Reconnection is a powerful mechanism for fast magnetic energy dissipation and particle acceleration.
- Reconnection powers the high energy emission in γ-ray pulsars.
- Strong synchrotron cooling and two-photon pair production not only impact, but often dominate this process in some of the youngest pulsars.

Next:

- Other extreme systems where kinetics with QED effects are important.

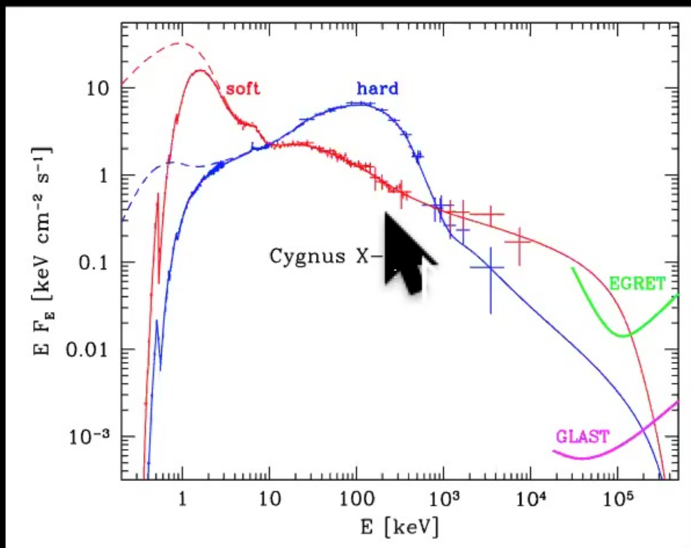
Magnetic reconnection *in neutron*

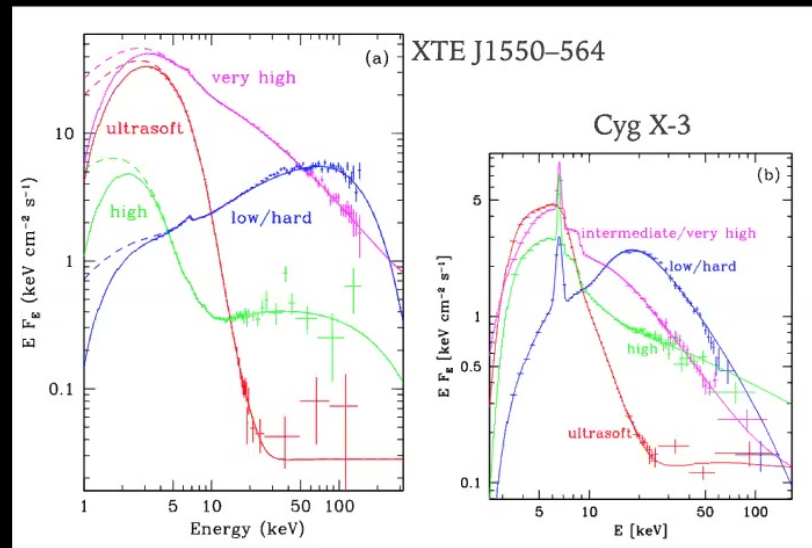




Coronae of x-ray binaries

* Hard state is powered by the IC emission from hot corona. Energization mechanism for corona is an open issue.





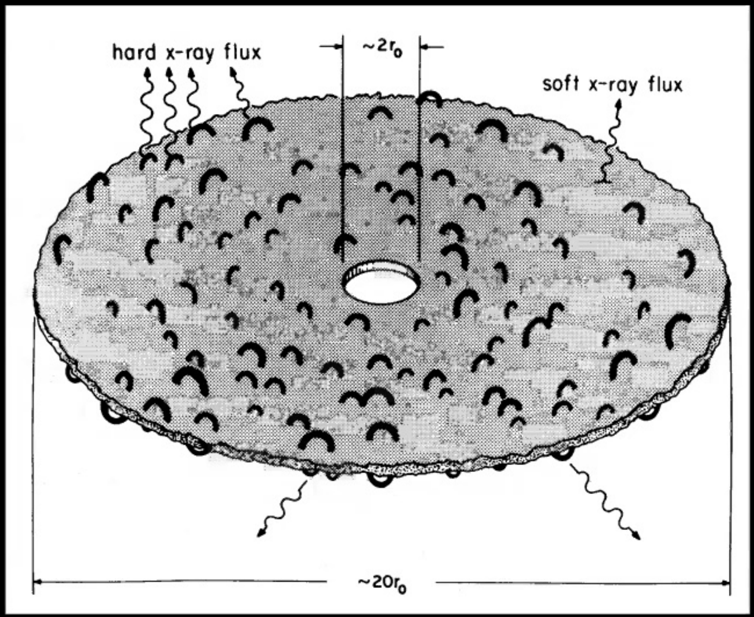
Zdziarski & Gierliński (2004)

* ms-duration strong flares are observed during hard state (Schwarzschild timescale is $t_g \sim 0.1$ ms)

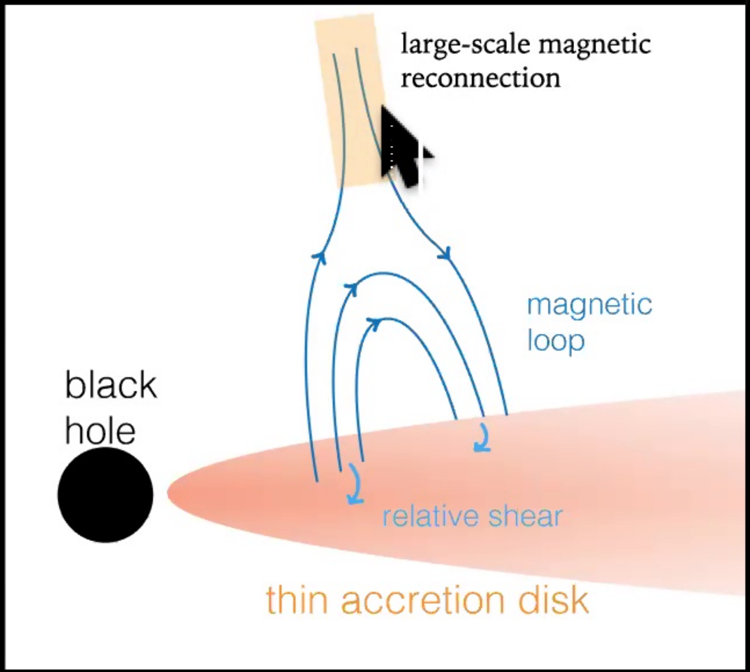
see, e.g., Zdziarski & Gierliński (2003)

Coronae of x-ray binaries

* Magnetic reconnection of the coronal loops is a likely mechanism to power the energization.

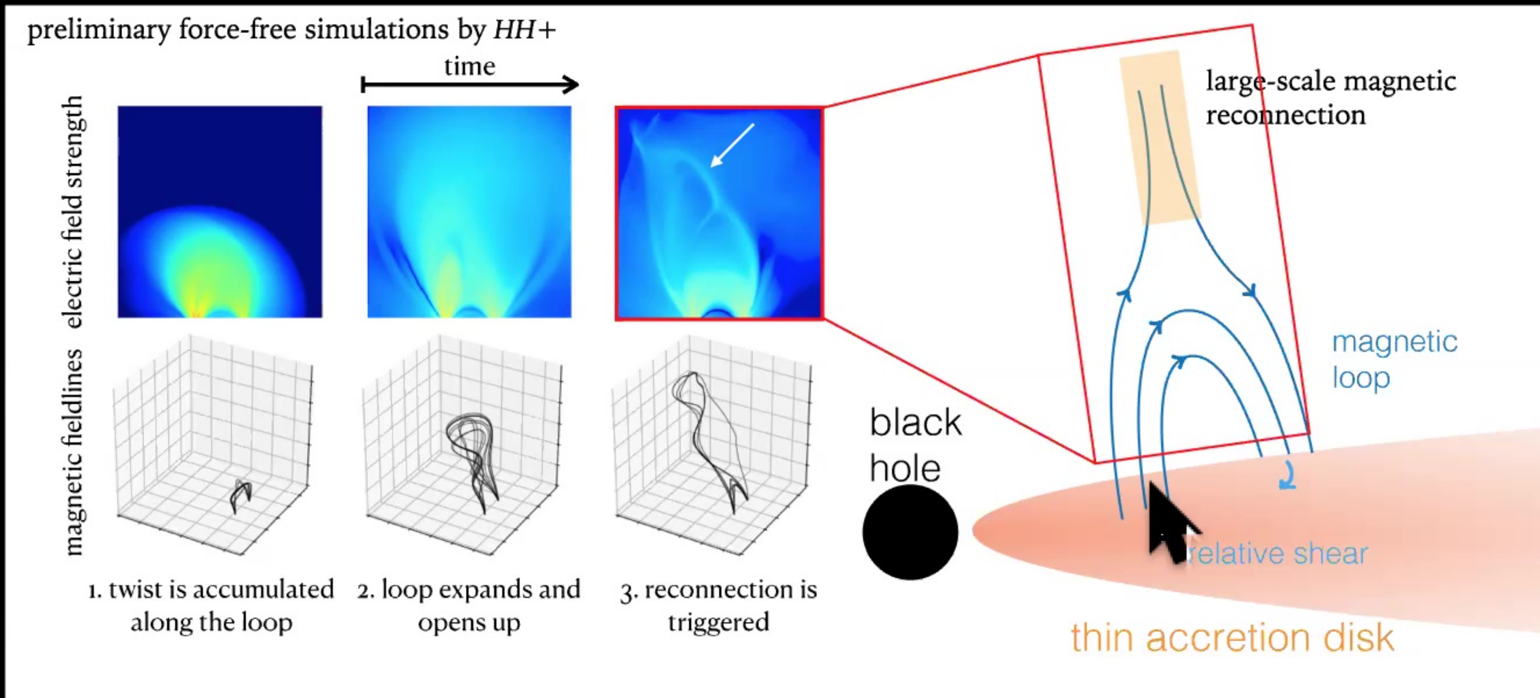


Galeev, Rosner, & Vaiana (1979)



Svensson (1987), Romanova+ (1998), Parfrey+ (2015), Beloborodov (2017)

Coronae of x-ray binaries



* Shear leads to transient reconnection and flare eruptions in force-free. Kinetic properties of these large-scale explosions (mediated by QED effects) have never been studied.

Conditions in XRB coronae (during the hard state)

- $B \sim 10^8$ G , $kT_e \sim 100$ keV , $B^2/4\pi \gg \rho c^2$, $L \sim 3 \cdot 10^{37}$ erg/s

Inverse Compton radiation: *Sironi & Beloborodov (2020)*

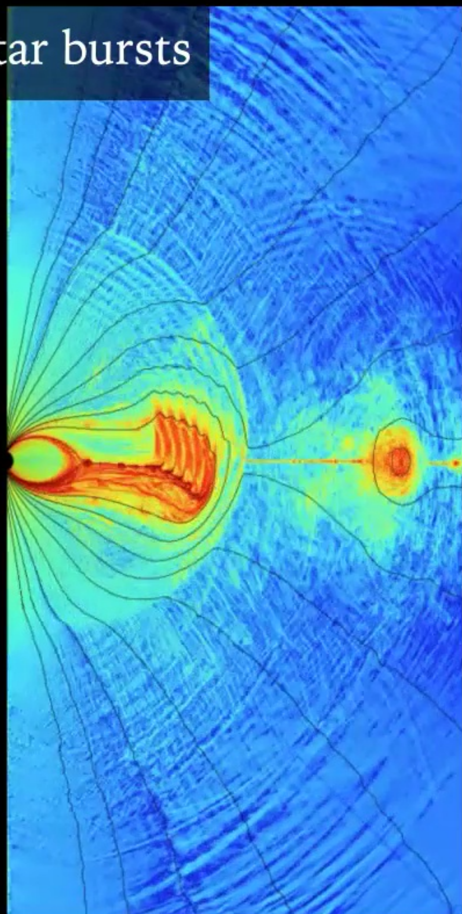
- $t_{\rm IC} \gg t_{\rm acc}$ $\Rightarrow$ moderate IC drag compared to acceleration
- $t_{\rm IC} \ll L/v_A$ $\Rightarrow$ IC drag important on dynamical timescales

Pair production/annihilation: *Beloborodov (2017)*

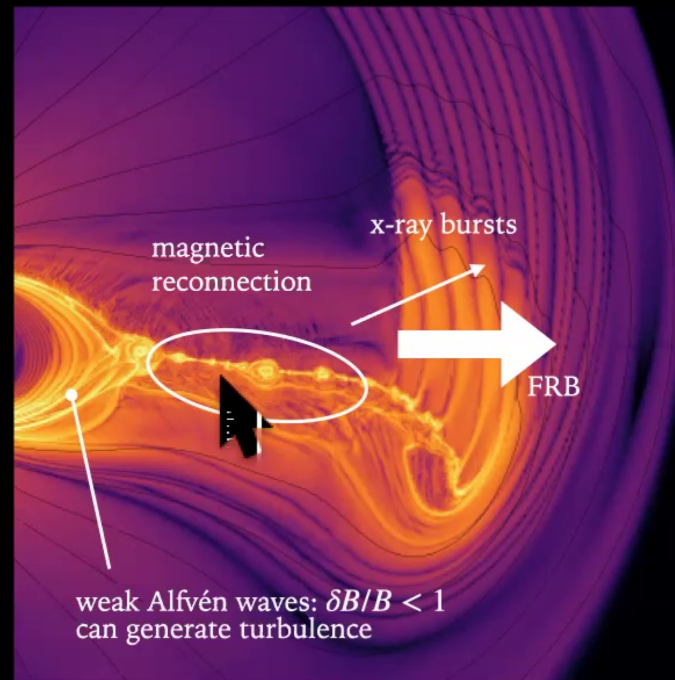
- Compton parameter: $y \sim 4\left(kT_e/m_e c^2\right)\tau_{\rm T}^2 \sim 1 \quad \Rightarrow \quad \tau_{\rm T} \sim 1$
- If only e^-/H^+: $\tau_{\rm T} \ll 1$ $\Rightarrow$ dominated by $e^{\pm}$ plasma
- $\tau_{\gamma\gamma} \sim$ 1-10 $\Rightarrow$ $e^{\pm}$ production/annihilation ($\gamma\gamma \leftrightarrow e^{\pm}$)

movie credit: Seán Doran [171 Å data: SDO/AIA/EVE/HMI]

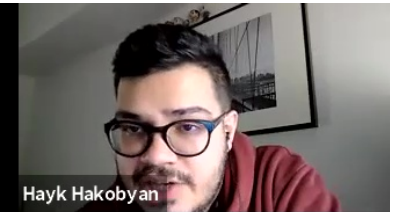
Magnetar bursts



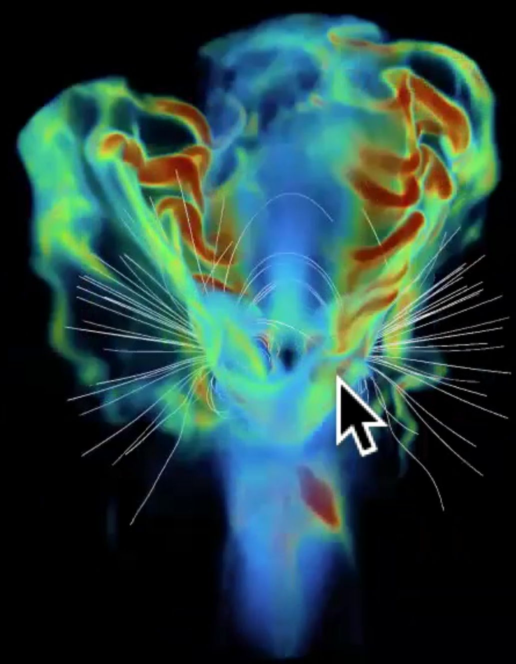
duration ~ 1 s, $L_X \sim 10^{40}$ erg/s, $B \sim 10^{8}$-10^{11} G,
$B^2/4\pi \ggg \rho_e c^2$, $\tau_T \gg 1$, $T_e \sim$ few $\cdot$ 10 keV



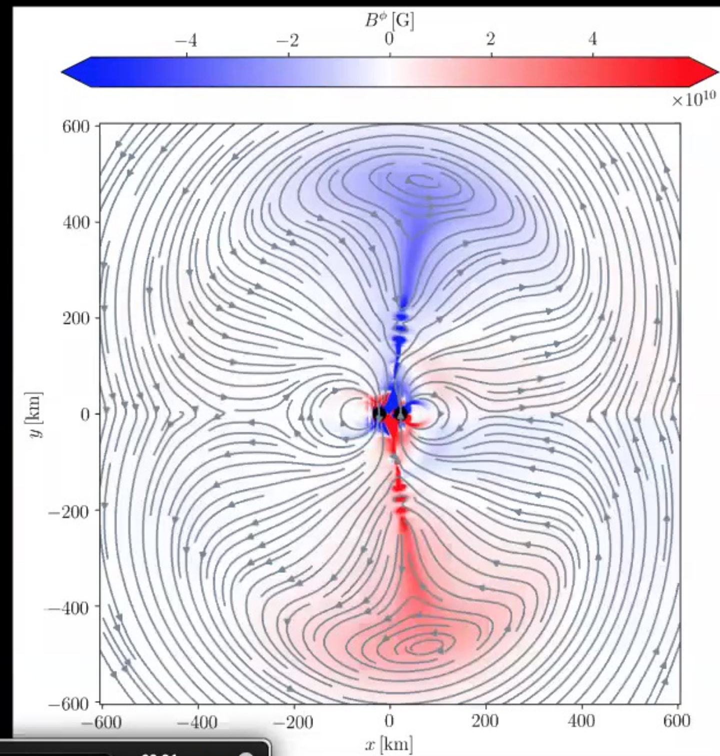
magnetar burst in force-free MHD *(Yuan+ 2020)*
* also see *Parfrey+ (2013)*



EM precursor to gravitational waves



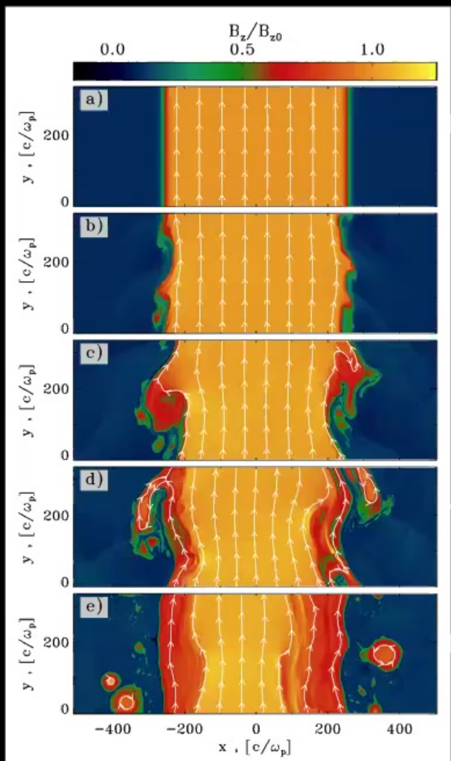
binary neutron star in PIC (preliminary simulation by A. Philippov)
* also see 2D PIC simulations by *Crinquand+ (2019)*



force-free simulation by *Most & Philippov (2020)*

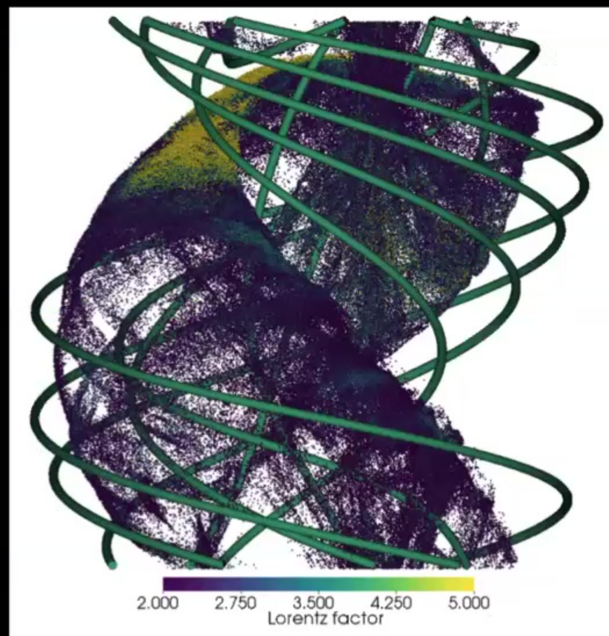
AGN jets

instabilities in jets onset **magnetic reconnection** and generate **turbulence**

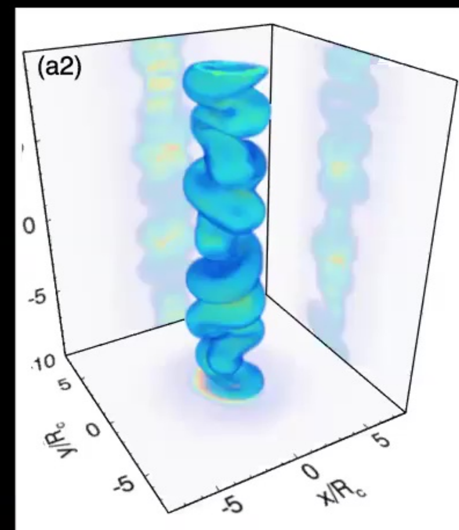


Sironi+ (2020)

time



Davelaar+ (2020)



Alves+ (2018)

Main takeaways

- Magnetic energy dissipation and particle acceleration/heating is dictated by small-scale kinetic plasma processes (*turbulence*, *reconnection*).
  - From kinetic simulations we know that the reconnection (and turbulence) is an efficient mechanism for particle acceleration. These processes cannot be captured with fluid (MHD, force-free) simulations.
- In certain compact objects these processes are mediated by strong *radiation*, *Compton scattering* and $e^{\pm}$*-production/-annihilation*.
  - For instance, in γ-ray pulsars two-photon pair production self-consistently suppresses particle energization, controlling the observed high energy cutoff. To numerically study these effects a novel approach (QED-PIC) is required.
- These QED processes may strongly influence* and sometimes even dominate the energy *dissipation* process, *particle heating/acceleration* and, ultimately, the *emerging emission*.
  - XRB coronae in hard state, binary neutron stars shortly before the merger, magnetar flares, relativistic AGN jets, GRB jets in subphotospheric regime, *etc*.

* ask me for details