Title: Physical processes in high energy systems: neutrino fast flavour conversion and efficient magnetic energy dissipation

Speakers: Xinyu Li

Series: Strong Gravity

Date: March 18, 2021 - 1:00 PM

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Abstract: The talk will be based on my latest two papers 2103.02616 and 2103.05700.
In the first part, I will present my GRMHD simulation of a neutron-star post-merger disk with neutrino fast flavour conversion included dynamically. The fast conversion of neutrinos can lead to flavour space equipartition ubiquitously on the time scale as short as 1ns. Due to the reduction of the number density of electron and anti-electron neutrino, the ejecta becomes more neutron rich. The final r-process nucleosynthesis sees an enhanced abundance of heavy elements close to the solar values. A similar effect may allow for increased lanthanide production in collapsars.
In the second part, I will present fast magnetic energy dissipation through the collision of Alfven waves with anti-aligned magnetic fields. The collision produces a current sheet sustained by an electrical field breaking the MHD condition. Particles entering the current sheet are accelerated following a relativistic variation of Speiser orbit and escape with higher energy. This mechanism can dissipate a large fraction of wave energy, nearly 100% when the wave magnetic field equals the background magnetic field. The fast dissipation may occur in various objects, including magnetars, jets from accreting black holes, and pulsar wind nebulae.

Physical Processes in High Energy Systems

neutrino fast flavour conversion and efficient magnetic energy dissipation

Xinyu Li
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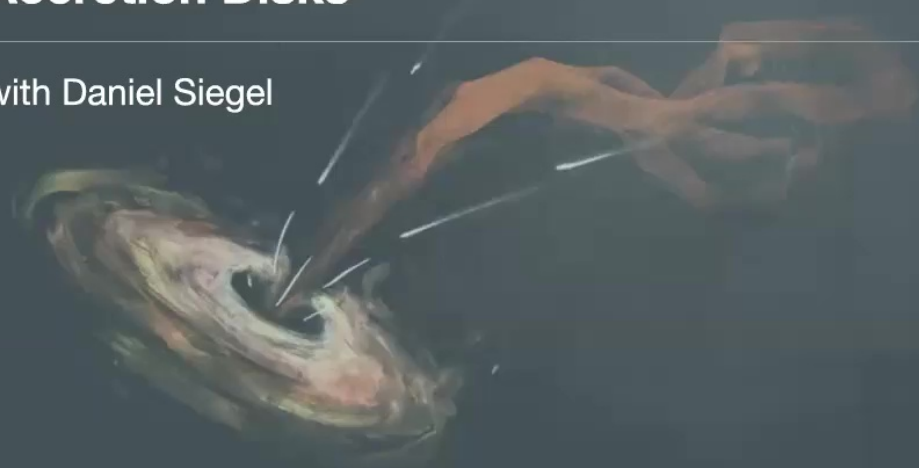
Outline

This talk is based on my two latest papers:

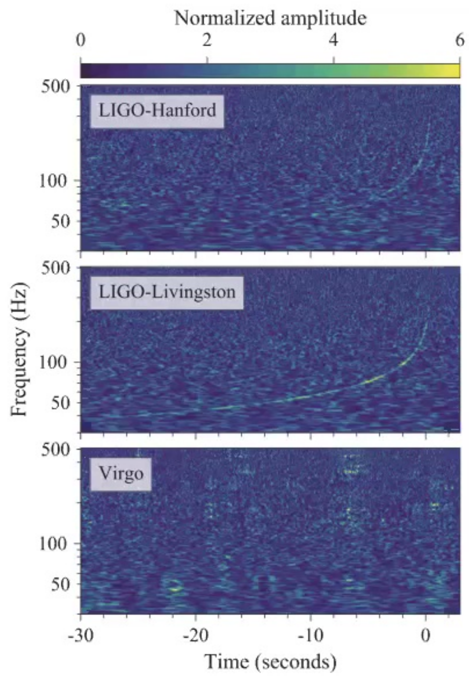
- Neutrino Fast Flavor Conversions in Neutron-star Post-Merger Accretion Disks (arXiv: 2103.02616)
- Fast dissipation of Colliding Alfven Waves in a Magnetically Dominated Plasma (arXiv: 2103.05700)

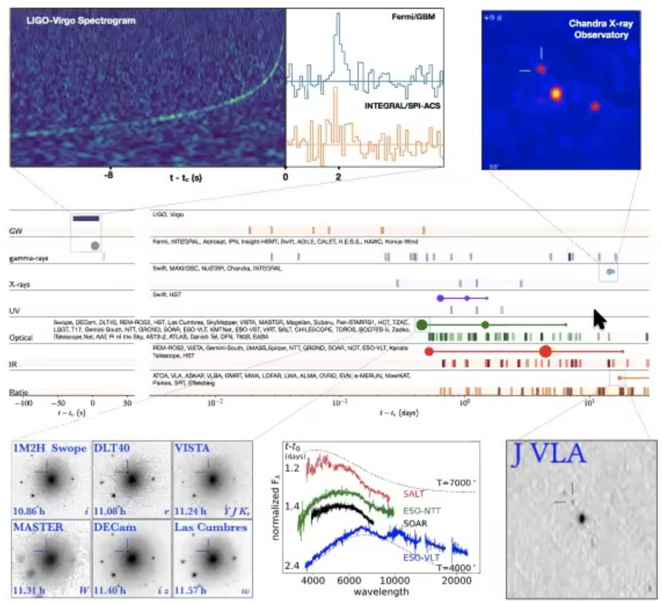
Neutrino Fast Flavor Conversions in Neutron-star Post-Merger Accretion Disks

with Daniel Siegel



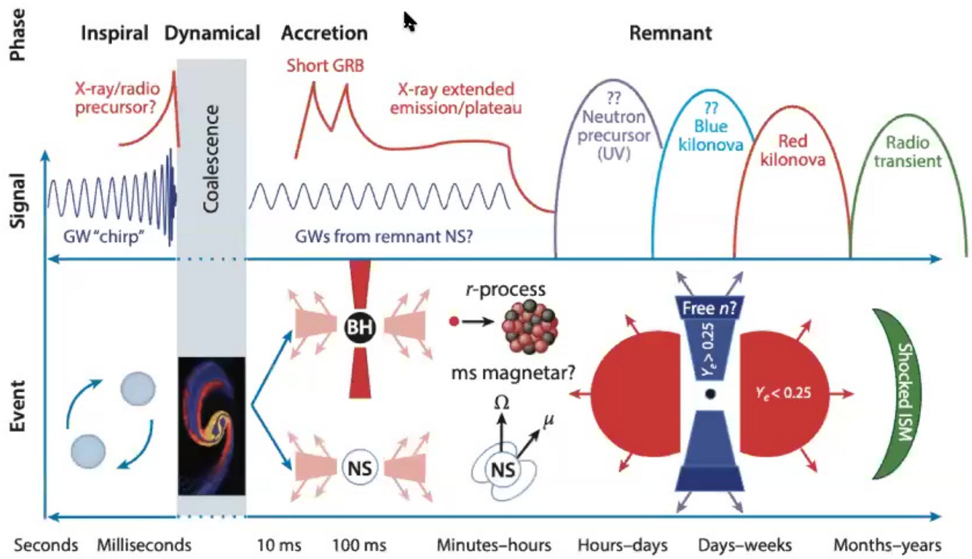
GW170817: The first multimessenger observation with gravitational wave





Abbot et al. 2017

Kilonova emission



- Blue component: neutron-poor (Ye>0.3) ejecta.
- Red component: low velocity (0.1-0.2c) neutron rich (Ye<0.3) ejecta.

Neutron-star post-merger disk

- Hot dense environment with density up to 10^{12} g/cc.
- Neutrinos are produced and are optically thick close to the central object with luminosity up to 10^{52-53} erg/s.
- Neutrinos can change nucleosynthesis through weak interactions.
- Previous simulations use simple approximation, e.g. leakage scheme (Siegel 2018).
- Only Monte-Carlo transport by Miller et al. (2019).

Neutrino fast flavour conversion

- Neutrino density matrix with flavour eigenstates as the bases

$$\varrho_\nu = \frac{f_{\nu_e} + f_{\nu_X}}{2} I + \frac{f_{\nu_e} - f_{\nu_X}}{2} \begin{pmatrix} s & S \\ S^* & -s \end{pmatrix}$$

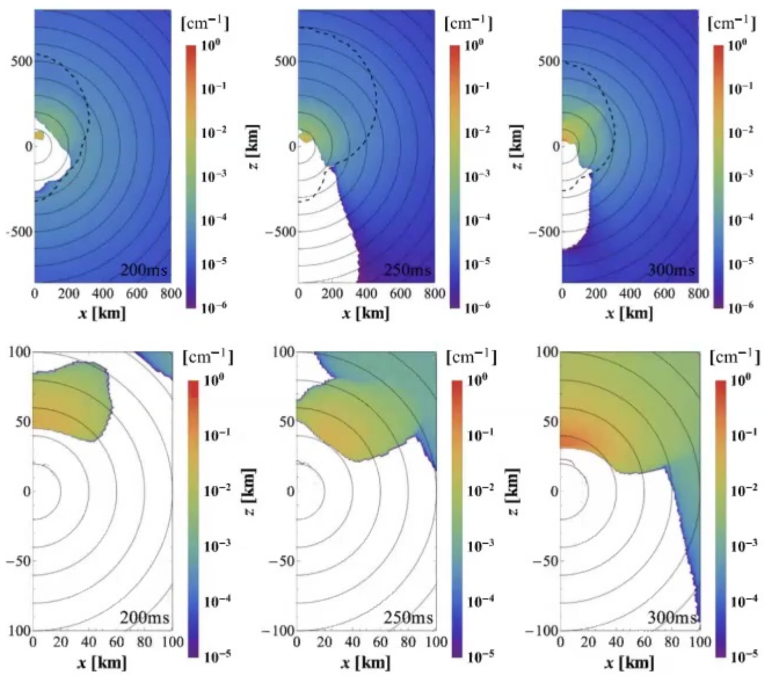
- Hamiltonian

$$H = \frac{M^2}{2E} - v^\nu \Lambda_\nu \frac{\sigma_3}{2} - \frac{\sqrt{2}}{(2\pi)^3} G_F \int v^\nu v_\nu \rho_\nu E^2 \, \mathrm{d}E \mathrm{d}\Omega$$

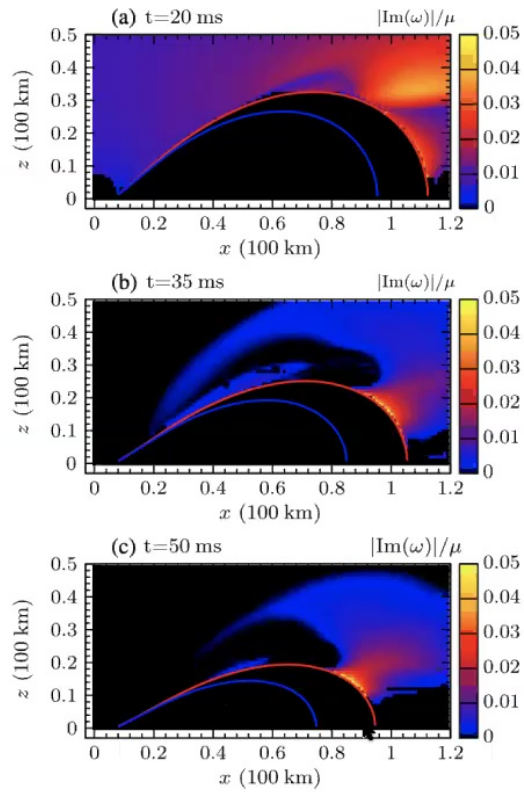
- The self-interaction term induces the exponential growth of the off-diagonal term (flavour conversion) with growth rate

$$\Phi_0 = \sqrt{2} G_F n_\nu / \hbar = 1.92 \times 10^9 \left(\frac{n_\nu}{10^{31} \mathrm{cm}^{-3}} \right) \mathrm{s}^{-1}$$

- ~ns time in the neutron star post-merger disk!



Collapsar (Nagakura et al. 2019)



NS merger remnants (Wu et al. 2017)

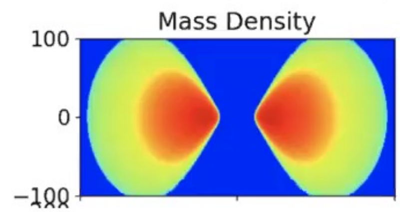
GRMHD simulation: neutrino radiation transport

- Include neutrino transport using the general relativistic M1 method (Shibata et al. 2011, Roberts et al. 2016).
- We trace 4 species with 6 energy bins between 0-60MeV.
- In the fluid dynamics equations, the evolution of the nth moment depends on the (n+1)-th moment (closure problem).
- The M1 scheme treats the radiation field as a fluid and assumes the second moments given by a proposed analytical relation from the first moments.

GRMHD simulation: fast flavour conversion

- Calculate the maximum growth rate ω for each grid following Izaguirre et al. (2017): set flavour equipartition among neutrinos and anti-neutrinos separately if $1/\omega < 10^{-7}$s.

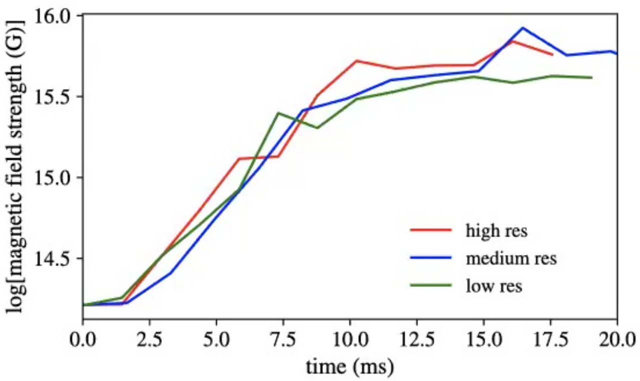
- Start with an equilibrium torus of 0.07Msun around a 3Msun black hole with spin 0.8, Ye=0.1 and evolve to 400ms.

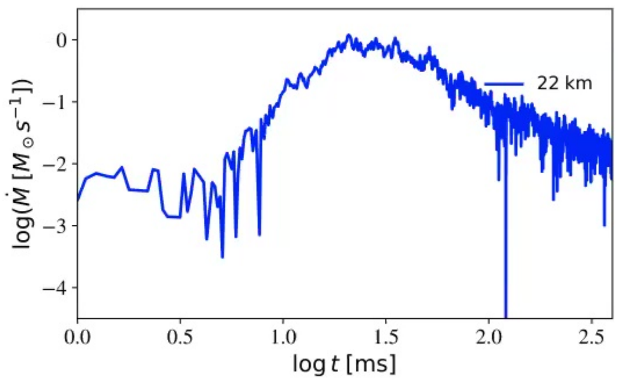


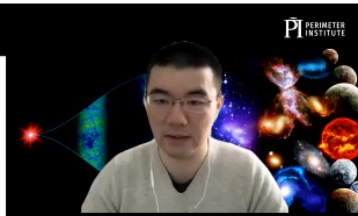
- We compare two simulations with (FC) and without (NFC) fast flavour conversion.

Disk evolution

- After an initial stage of relaxation, the disk relaxes into a quasi-steady turbulent state with accretion rate ~1Msun/s above the r-process threshold.







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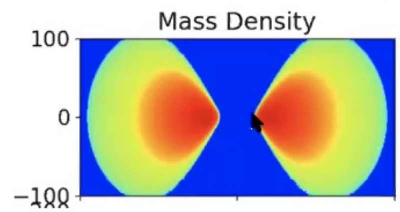
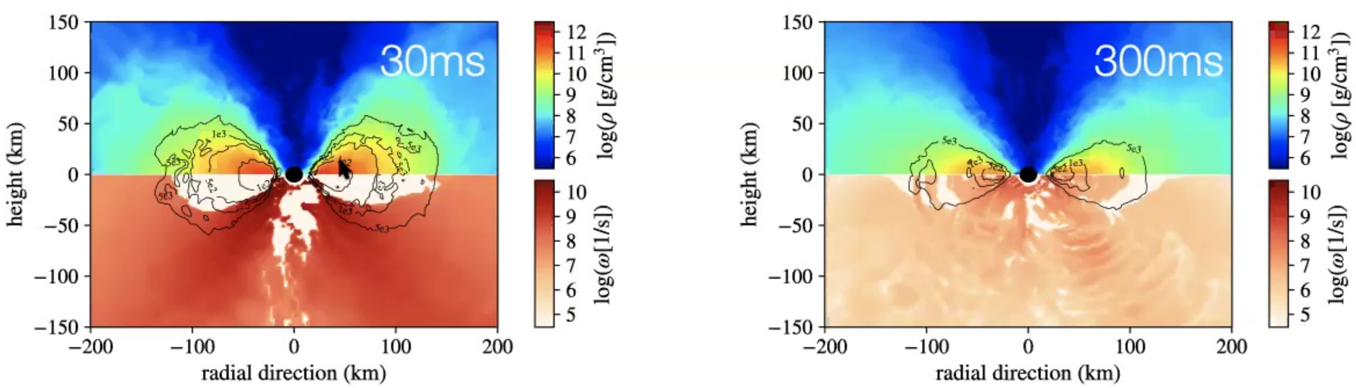


- We compare two simulations with (FC) and without (NFC) fast flavour conversion.

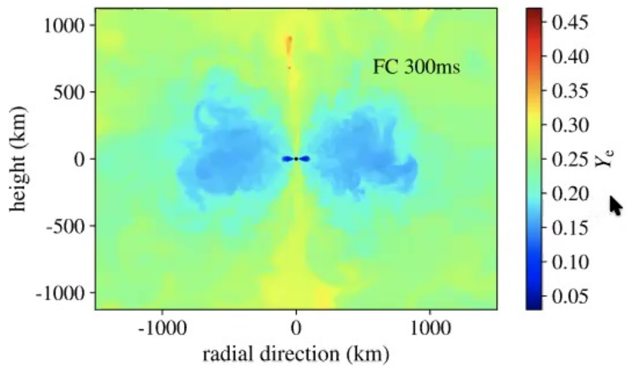
Disk evolution

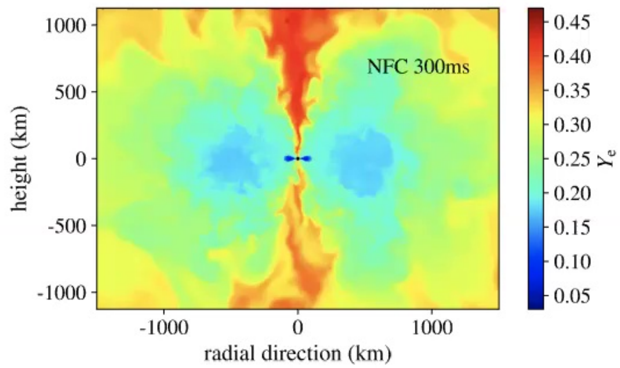
- At early stage, fast flavour conversions emerge where neutrinos stream freely.
- Later, fast flavour conversion becomes ubiquitous with smaller growth rate.



Comparison between with and without fast flavour conversion

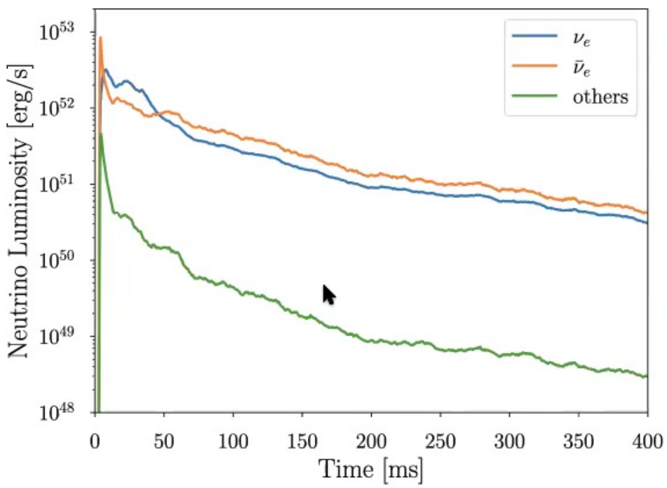
- With fast conversion, the ejecta are more neutron rich.
- The inner part of the disk keeps Ye low through self regularization.
- The Ye gradient is more prominent without fast conversion.





Comparison between with and without fast flavour conversion

- Electron and anti-electron neutrinos are more copiously emitted than other species.
- Fast flavour conversion essentially reduce their densities.



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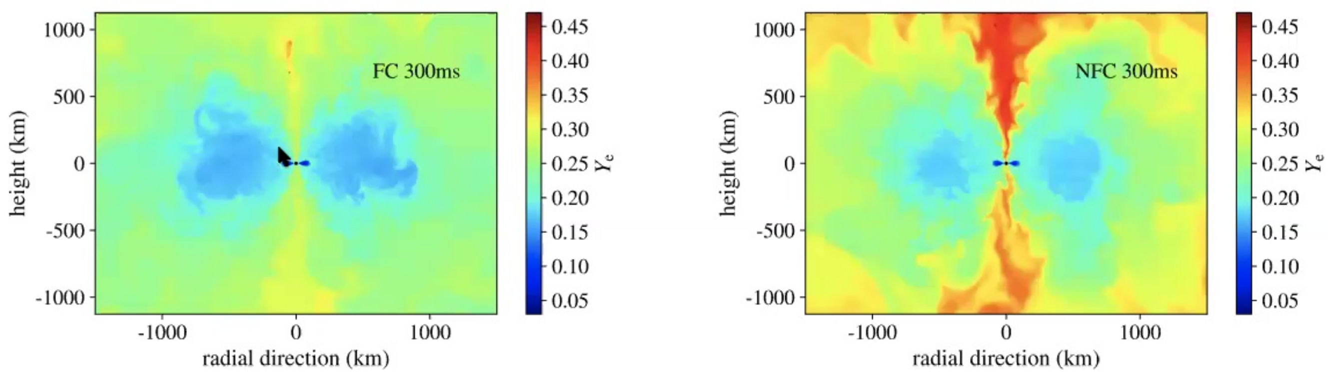
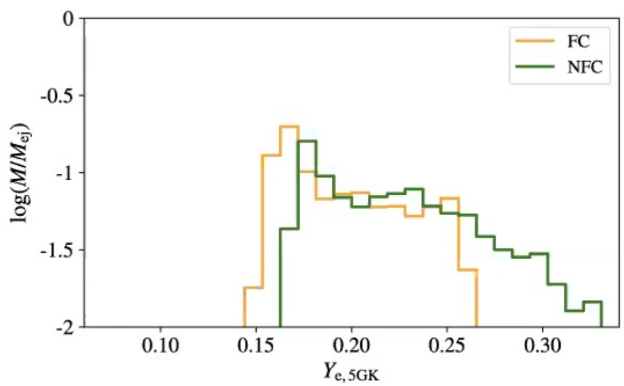
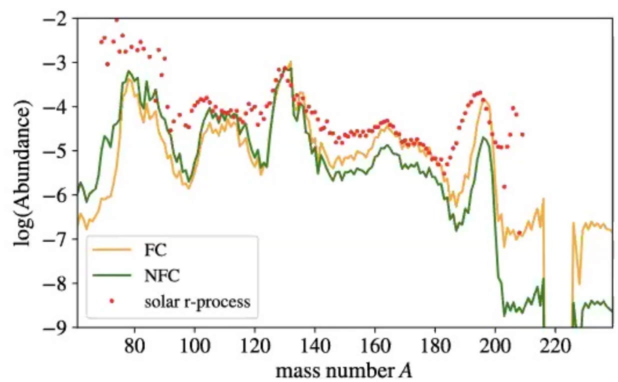


Comparison between with and without fast flavour conversion

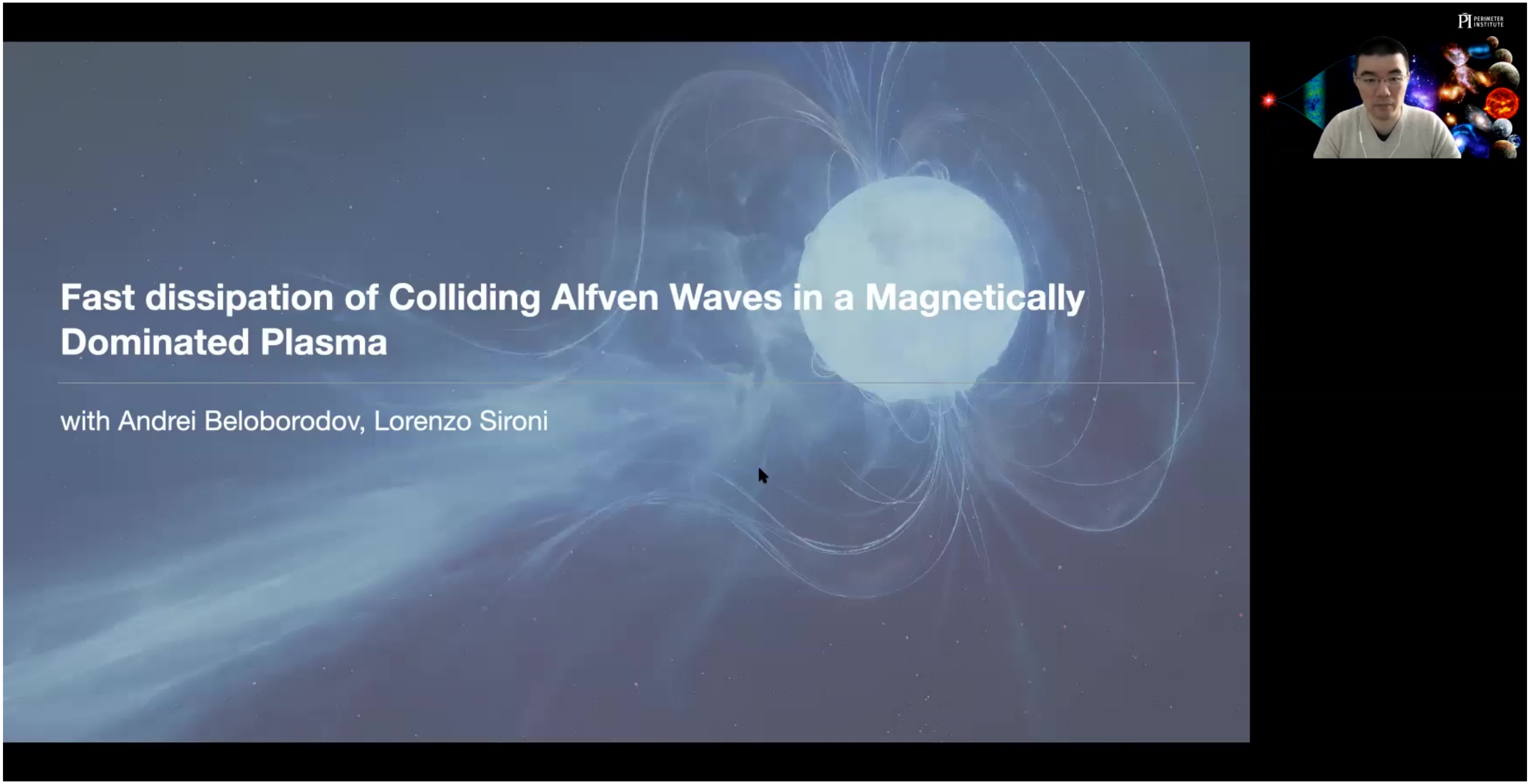
- The unbounded tracer particle is input into SkyNet for r-process calculation
- High energy neutrinos reduce the lanthanide production. Fast conversion can restore the abundance close to solar values.





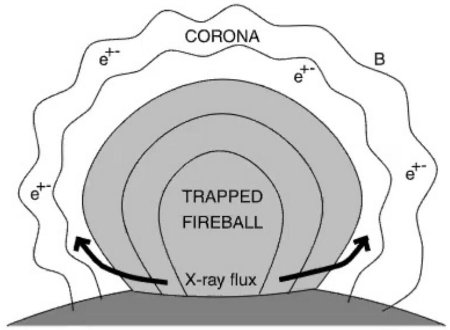
Conclusion

- We performed GRMHD simulations with neutrino fast flavour conversion included dynamically.
- The post-merger disk has high accretion rate ~1Msun/s and shows clear radial gradient of Ye indicating early bluer kilonova emissions turning into redder emissions, similar to GW170817.
- Fast flavour conversion is found to boost the r-process lanthanide abundance close to the solar values.

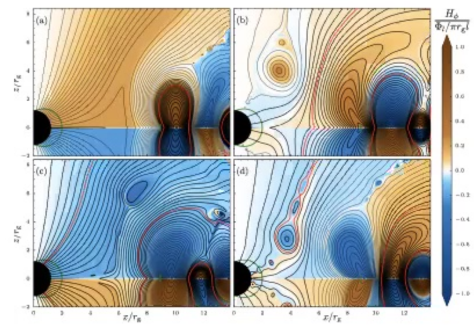

Fast dissipation of Colliding Alfven Waves in a Magnetically Dominated Plasma
with Andrei Beloborodov, Lorenzo Sironi

Strongly Magnetized Systems

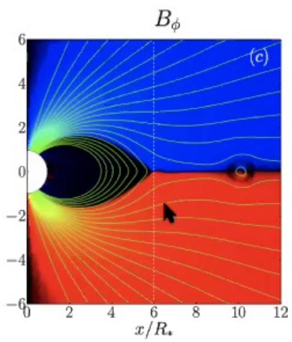
- Many astrophysical systems are thought to be strongly magnetized including magnetars, black hole corona and jets and pulsar wind nebula.
- Perturbations of the magnetic field produce Alfven waves.
- Ultrafast flares from magnetars and black hole coronae require fast dissipation of magnetic energy to particles.
- Previously suggested mechanisms are mainly turbulence and magnetic reconnection.



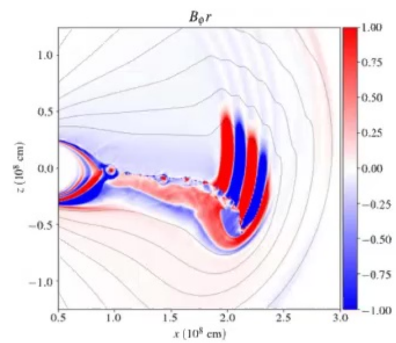
Dissipation of Alfven waves powers the SGR (Thompson & Duncan 2001)



Reconnection in the accreting BH corona (Parfrey et al. 2014))



Pulsar (Philippov & Spitkovsky 2014, Chen & Beloborodov 2017)



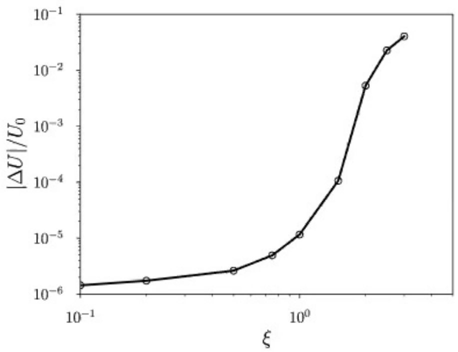
Relativistic ejecta for FRB (Yuan et al. 2020)

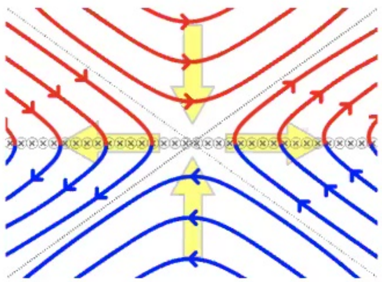
Waves in MagnetoHydroDynamics

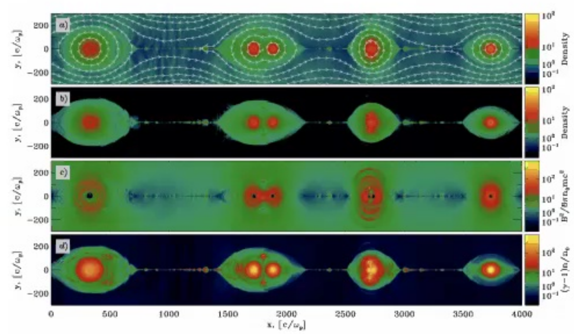
- MHD is applicable when the scale is much larger than the plasma scale
- The equations require two conditions: $E < B$ and $E \cdot B = 0$
- MHD reduces to Force-Free Electrodynamics in the limit of high magnetization
- Waves in MHD: Alfven mode $\omega = |k_z|$ and magnetosonic mode

Dissipation in turbulence and reconnection

- Turbulent dissipation acts on time scales much longer than a single wave crossing time (Li et al. 2019).
- Relativistic reconnection has rate 0.1c, and dissipates ~50% of magnetic energy (Uzdensky et al. 2010, Sironi et al. 2015).

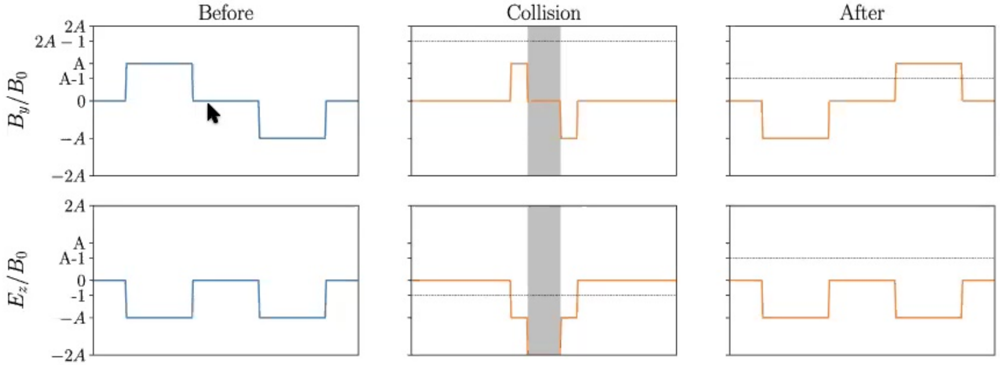






Collision of Alfven waves with anti-aligned magnetic fields

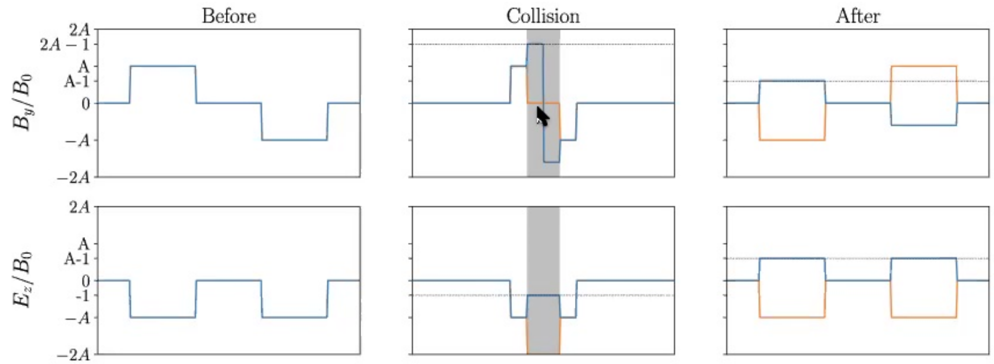
- Uniform $B_x=B_0$ and waves amplitude $A=|B_y|/B_0$. Linear superposition can induce E>B for A>0.5.



- In FFE simulations, one reduces E field by hand and assumes this process reflects the realistic fast dissipation (McKinney 2006, Spitkovsky 2006).

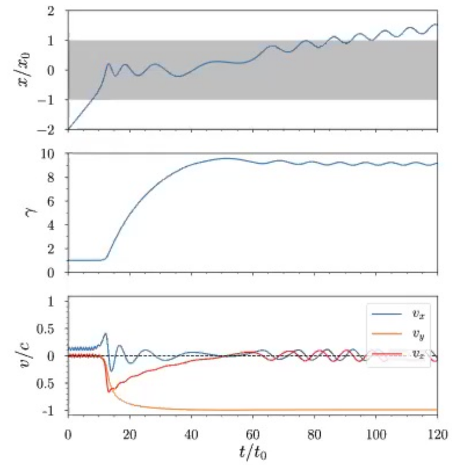
Wave Dynamics in the Presence of Plasma

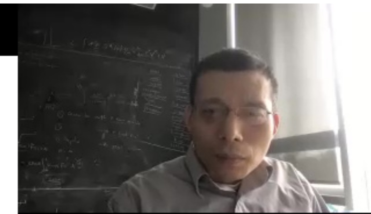
- Particles are accelerated to form a current sheet and reduce the electrical field close to B_0.
- Incoming waves are reflected with amplitude |A-1|. Across the current sheet, By reverses direction with magnitude 2A-1.
- The energy difference between incoming and reflected waves are dissipated to particles with fraction $f = (2A-1)^2/A^2$.



Particle Motion and Acceleration

- The particle follows a relativistic variation of Speiser (1965) orbit in the current sheet of size Δ.
- The particle is first accelerated to develop v_z.
- $F_x = v_z B_y$ points towards the centre, confining the particle.
- $E_z * v_z$ keeps doing positive work, accelerates the particle.
- As the particle finishes half of the gyration, v_z and F_x reverses sign, pushing the particle outward.
- The particle escapes with energy gain $\bar{\gamma} \sim A^2 \sigma_0$.





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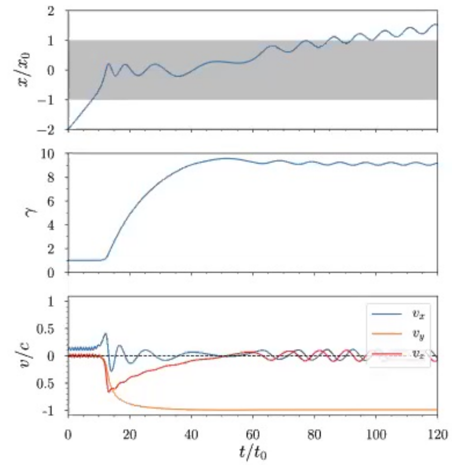
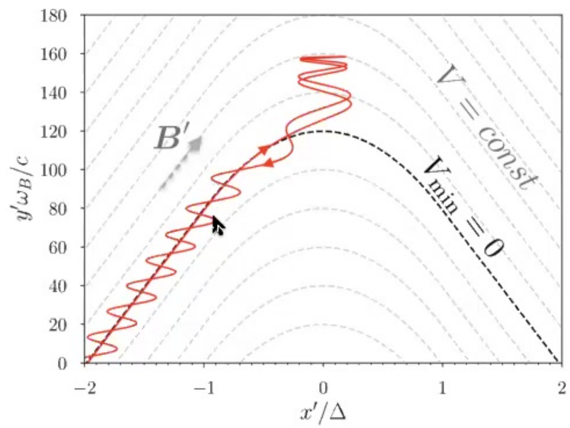


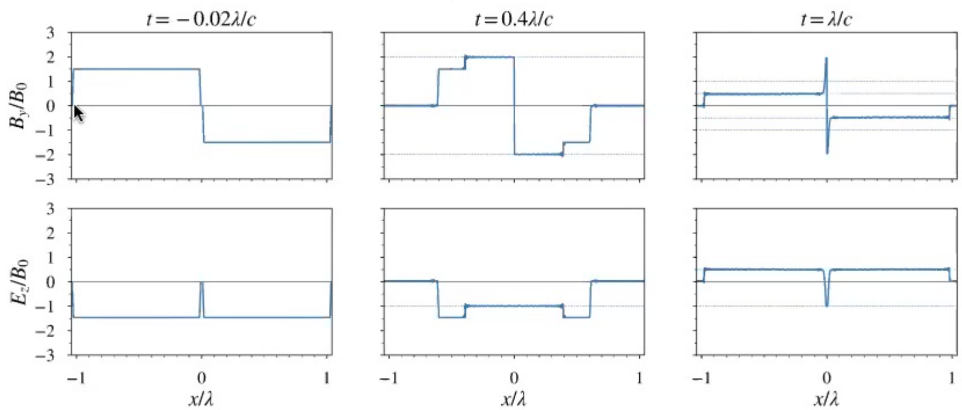
Particle Motion and Acceleration

- Alternatively, the magnetic vector field can be viewed as an effective potential.
- Particles first climb the potential and then return to the origin.
- The current sheet is self-regularized to give $\Delta \sim c/\omega_p$.



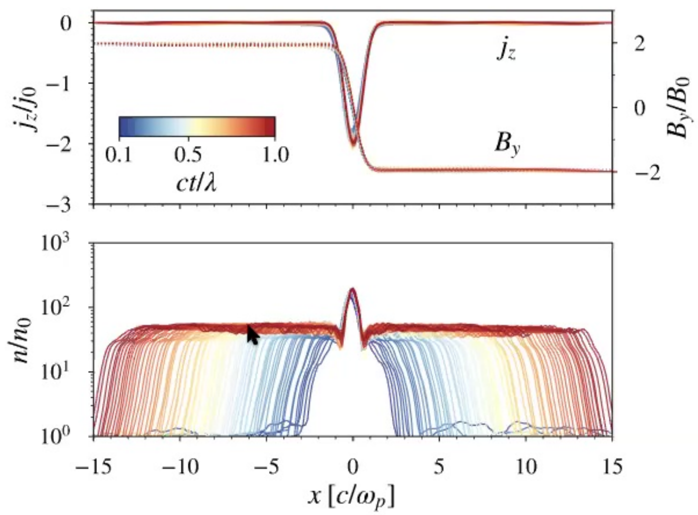
Kinetic Simulations —1D

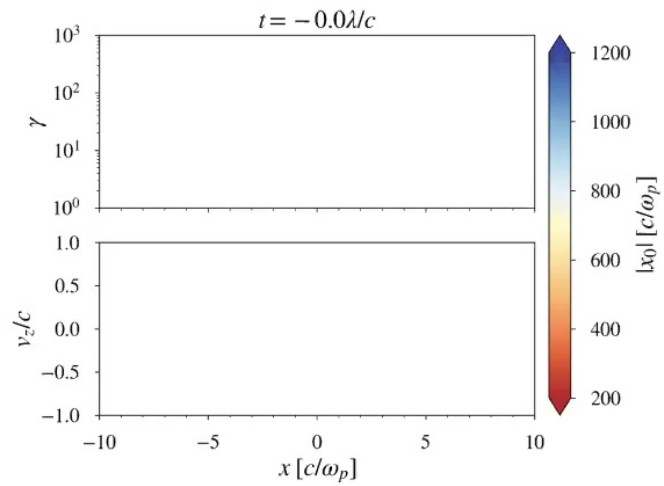
- Particle-In-Cell code TRISTAN-MP.



Kinetic Simulations —1D

- Particles stream into the current sheet and escape, forming a steady state.





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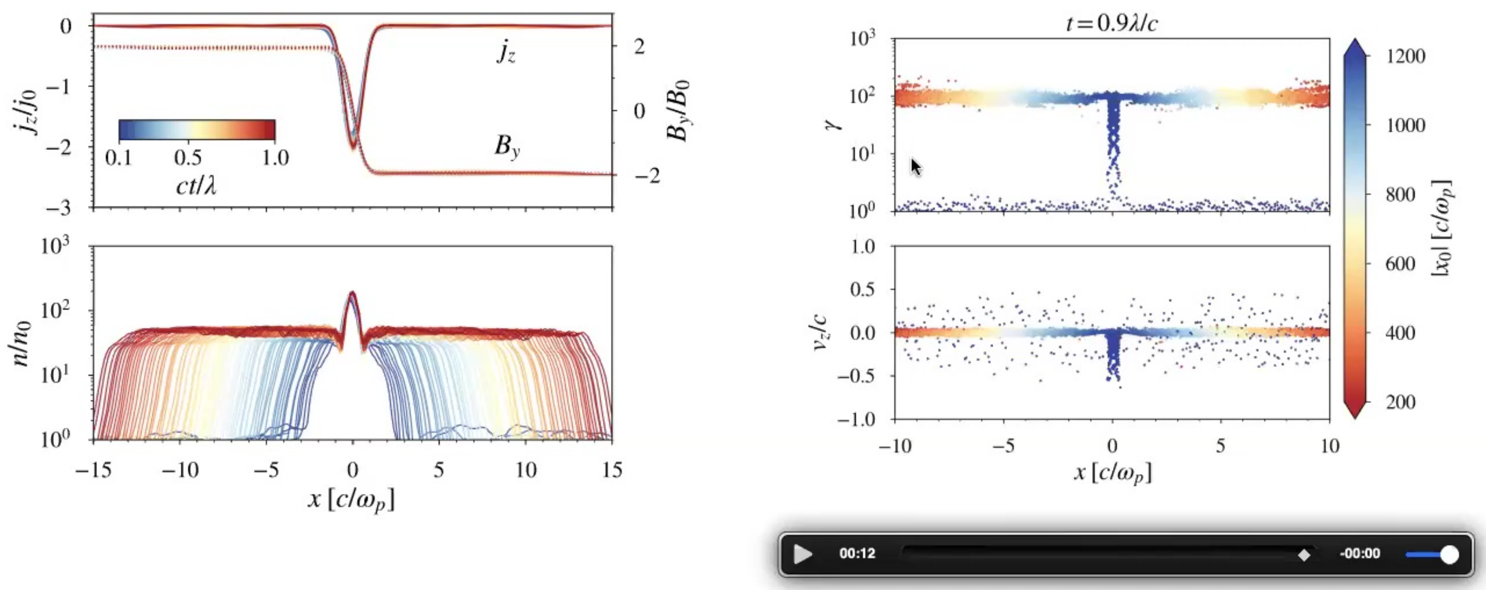
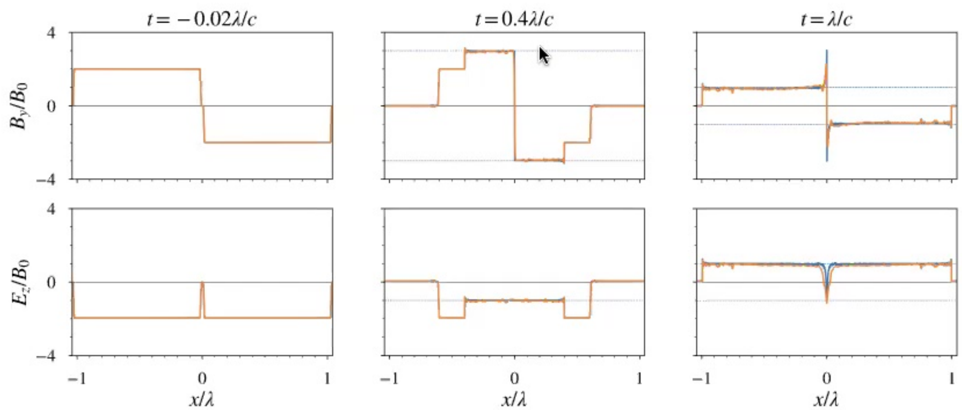


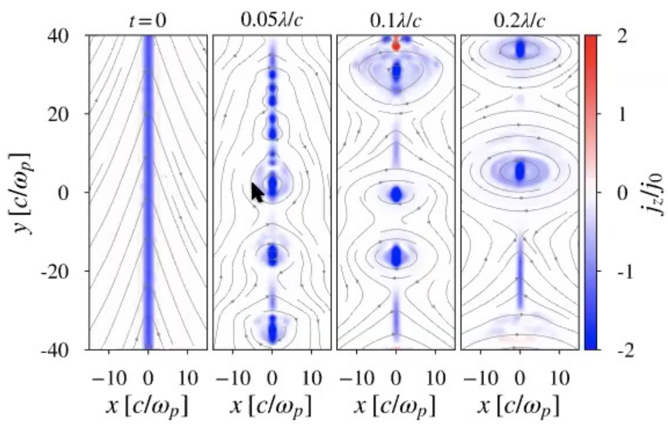
Kinetic Simulations — 2D

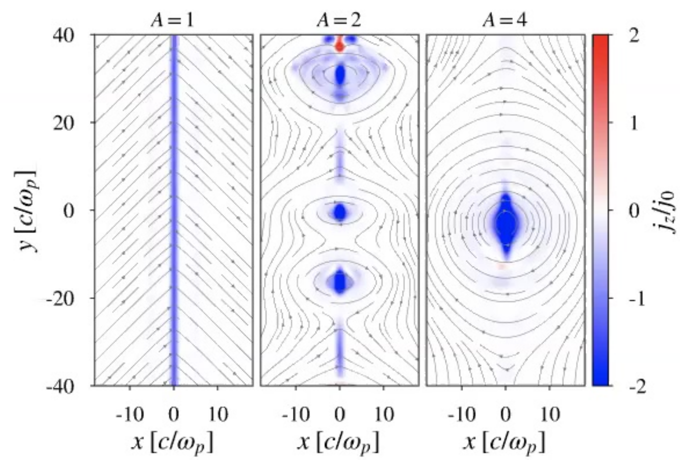
- y direction is along the perturbed magnetic field.



Kinetic Simulations —2D

- Bx stabilizes the current sheet against tearing instability. Magnetic reconnection is activated for $A \geq 2$.

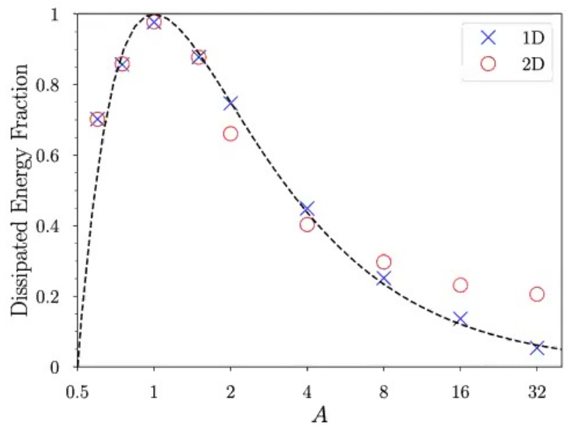




Dissipated fraction

- 1D dissipation agrees with analytical calculations $f = (2A-1)^2/A^2$, ~100% efficiency for A=1.

- 2D, dissipation of large amplitude waves is dominated by normal reconnection with dissipated fraction ~20%.



Conclusion

- We propose a fast dissipation of magnetic energy through the collision of anti-aligned Alfven waves.
- 1D kinetic simulations agree well with analytical calculations. 2D dissipations agree with 1D for small amplitude waves, but are dominated by magnetic reconnection for large amplitude waves.
- This mechanism can operate in strongly perturbed magnetized plasmas around compact objects, including jets from black holes, coronae of accretion disks, magnetospheres of neutron stars, and pulsar winds.
- It occurs significantly faster than magnetic reconnection or the turbulence cascade to a small dissipation scale.

Thank you for your attention!