FAPESP
FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

INSTITUTO DE ASTRONOMIA, GEOFÍSICA E CIÊNCIAS ATMOSFÉRICAS

SCIENTIA VINCES

Magnetic Reconnection, and particle acceleration and propagation around Black Holes

PhD student: Giovani Heinzen Vicentin
Advisor: Prof. Elisabete M. de Gouveia Dal Pino

Some facts about me

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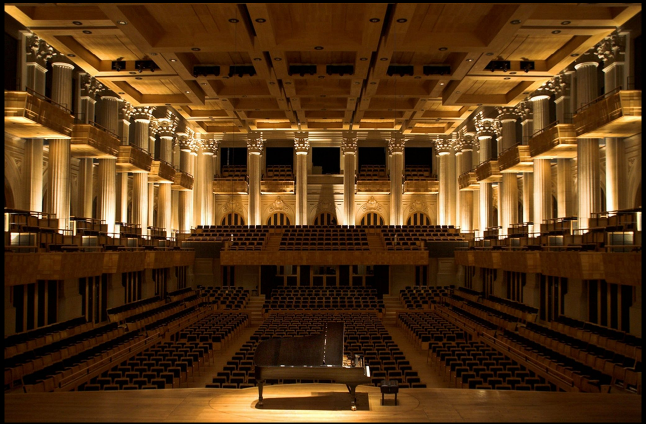

Concert Hall (Sala São Paulo)

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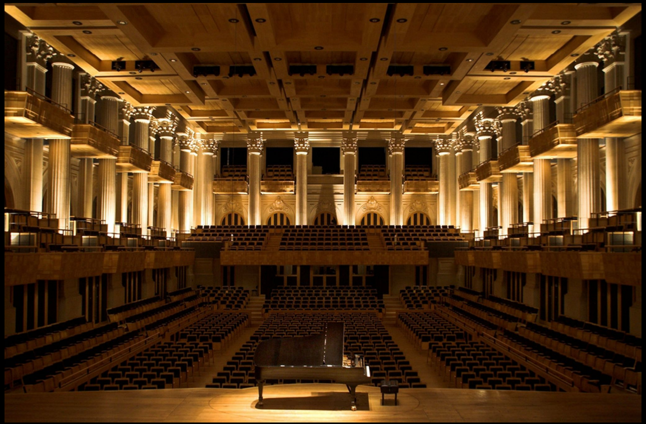

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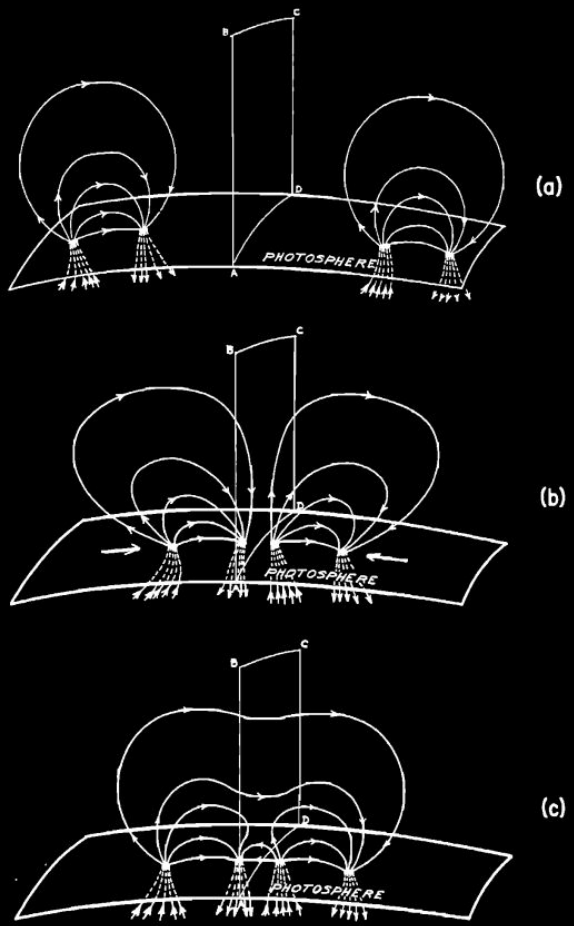
5. Testing theory using numerical MHD simulations
6. Conclusions & take-home message

Sweet-Parker Model for MR

Mechanism for the merging of two oppositely directed magnetic fields in a highly conducting fluid.

- Solar flares;



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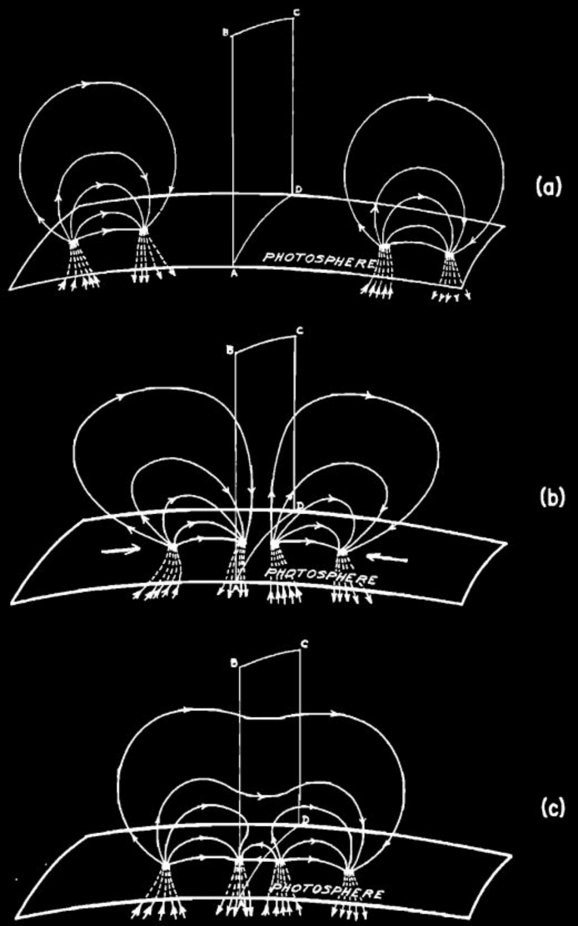

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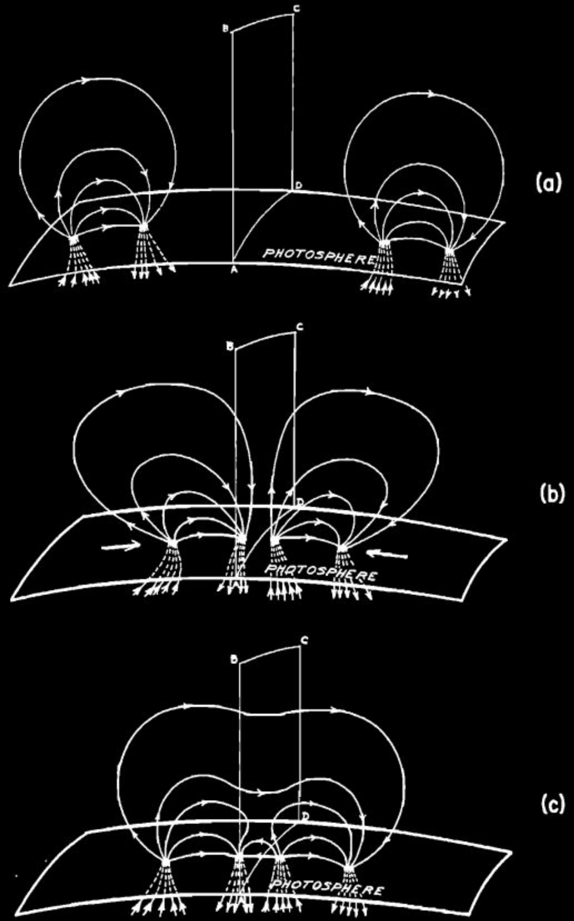

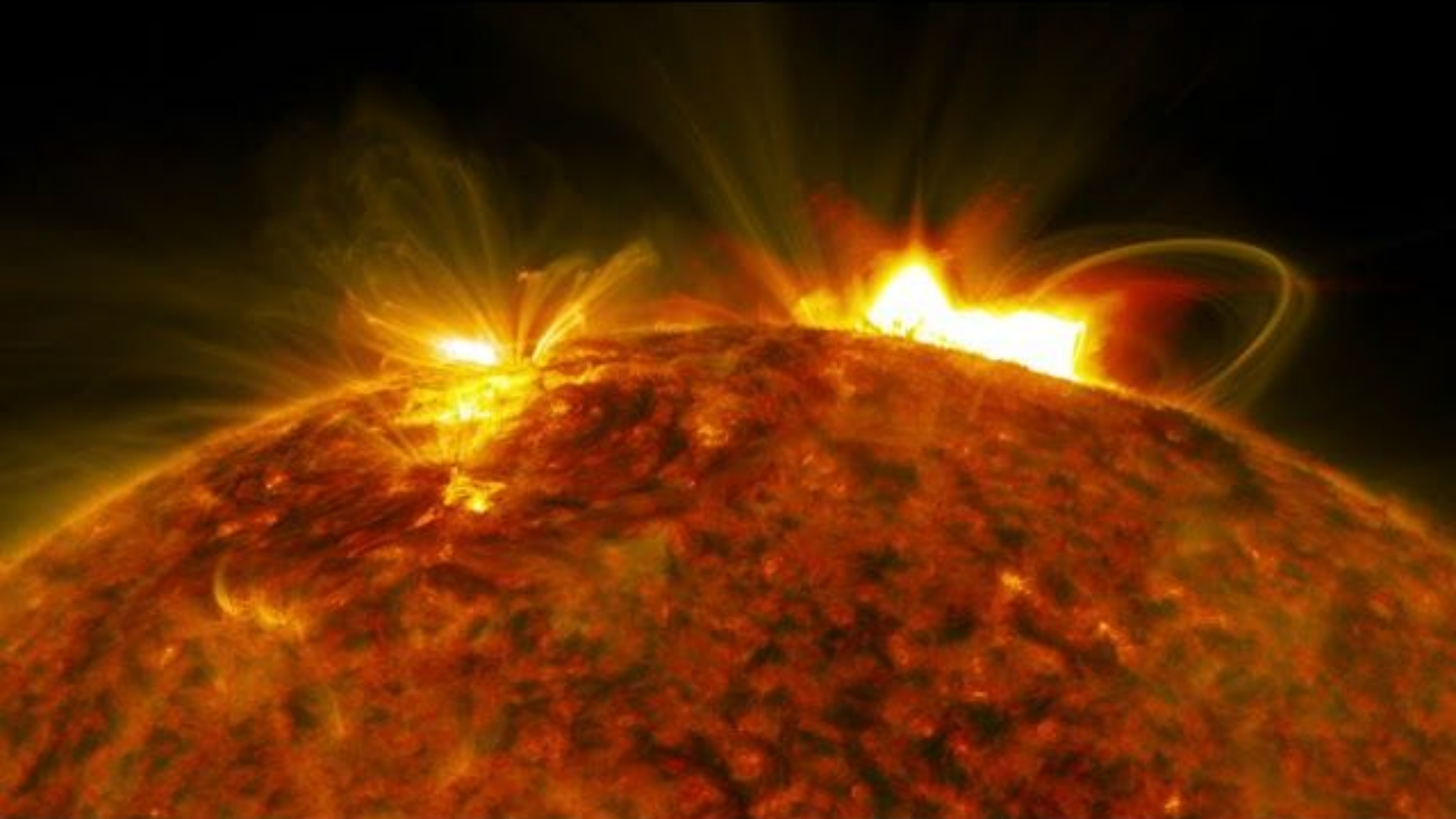

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where the Lundquist number is

$$S = \frac{L V_A}{\eta}$$

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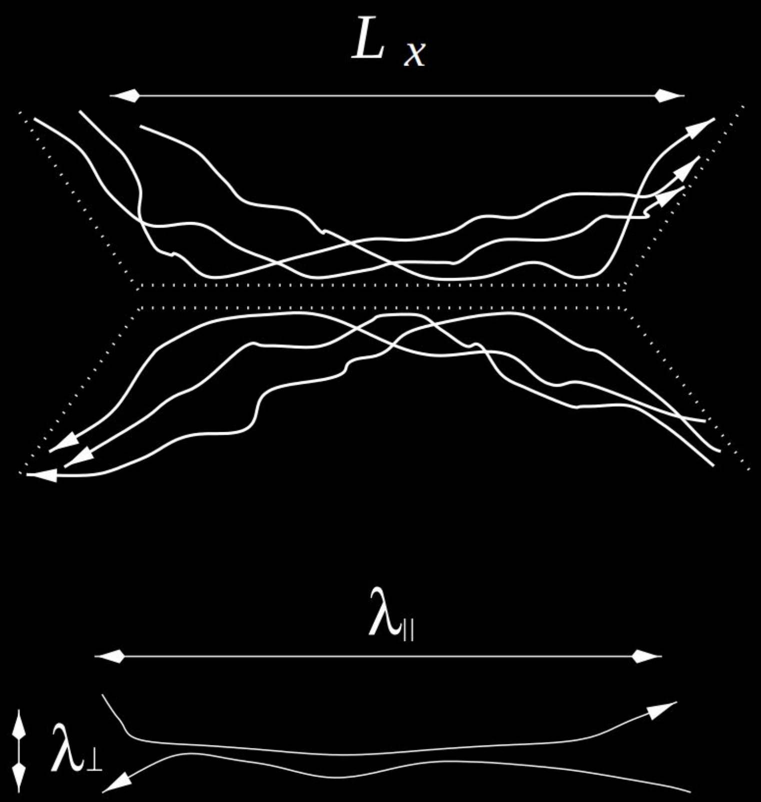
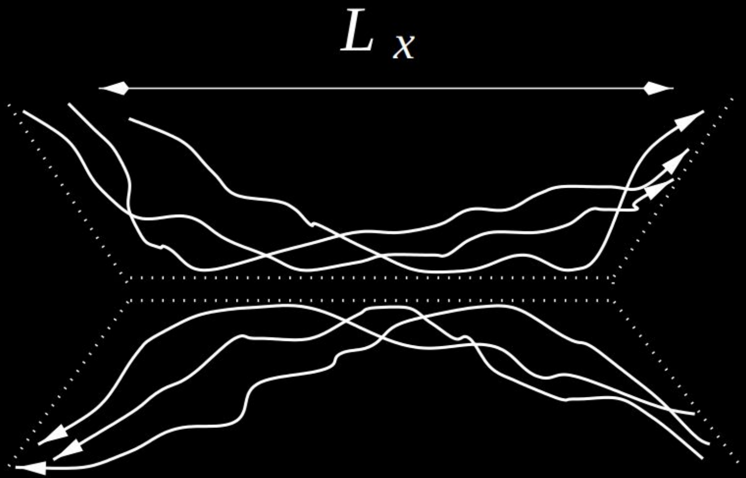
Turbulent Magnetic Reconnection

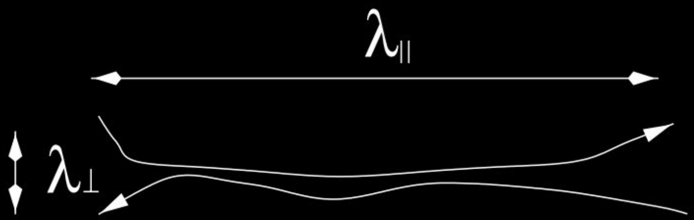


In 1999, Lazarian & Vishniac solve the problem of slow magnetic reconnection rate with...

Lazarian & Vishniac, 1999, ApJ

Turbulent Magnetic Reconnection





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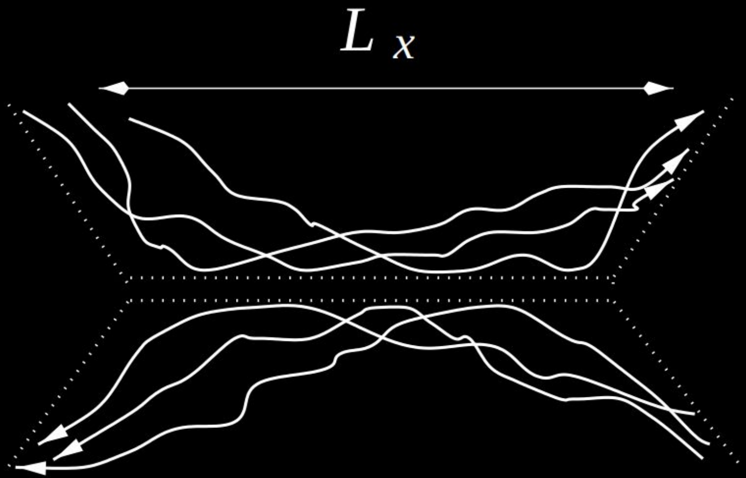

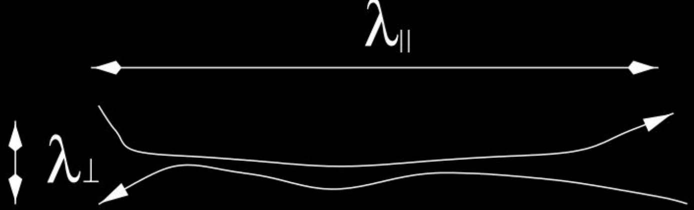

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$$V_{\text{rec}} = V_A \left(\frac{\ell_{\text{inj}}}{L}\right)^{1/2} \left(\frac{V_\ell}{V_A}\right)^2$$

Lazarian & Vishniac, 1999, ApJ

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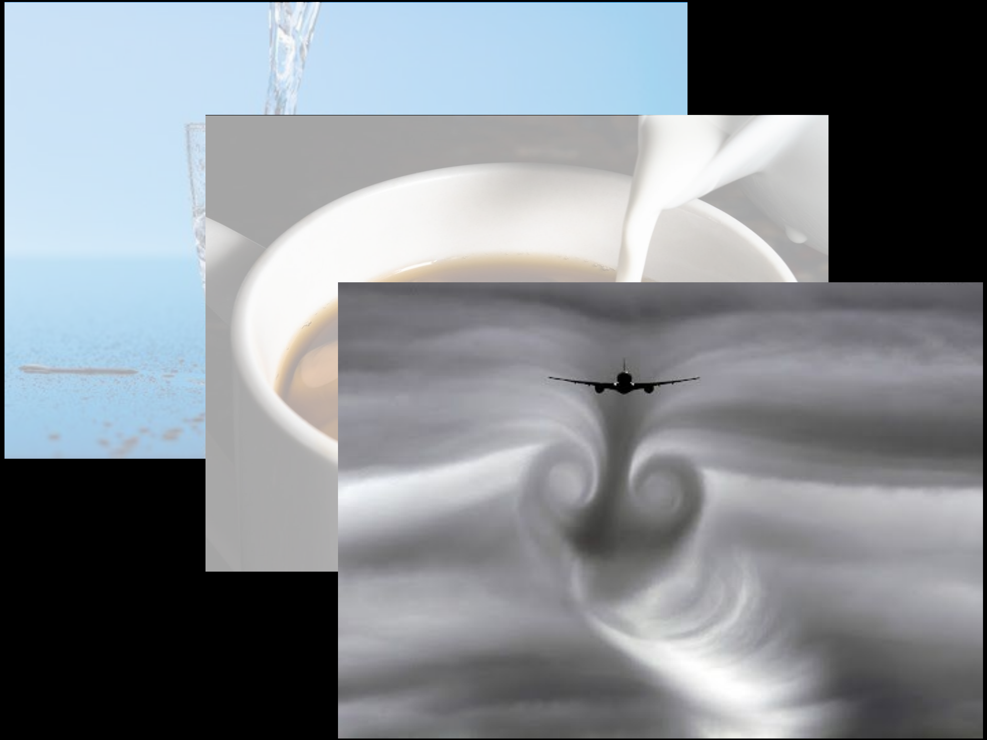

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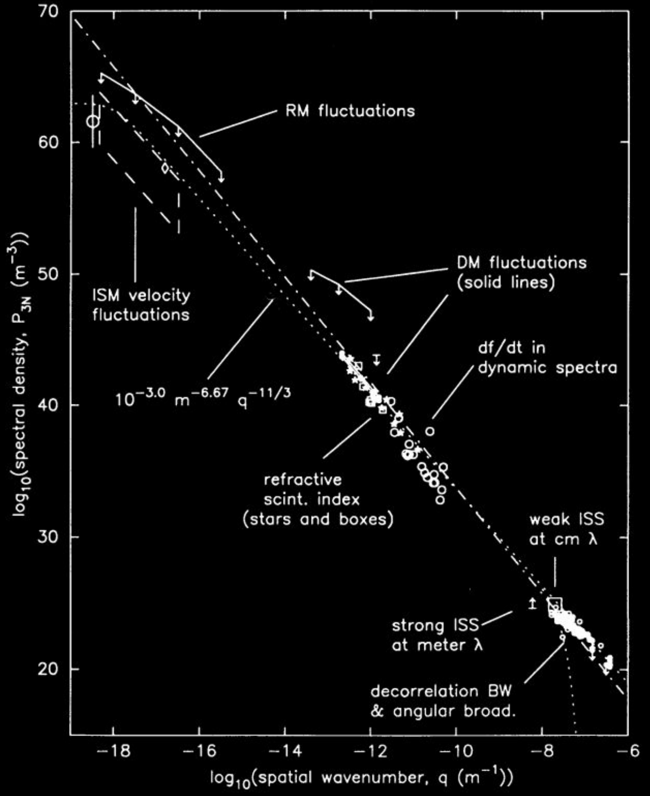
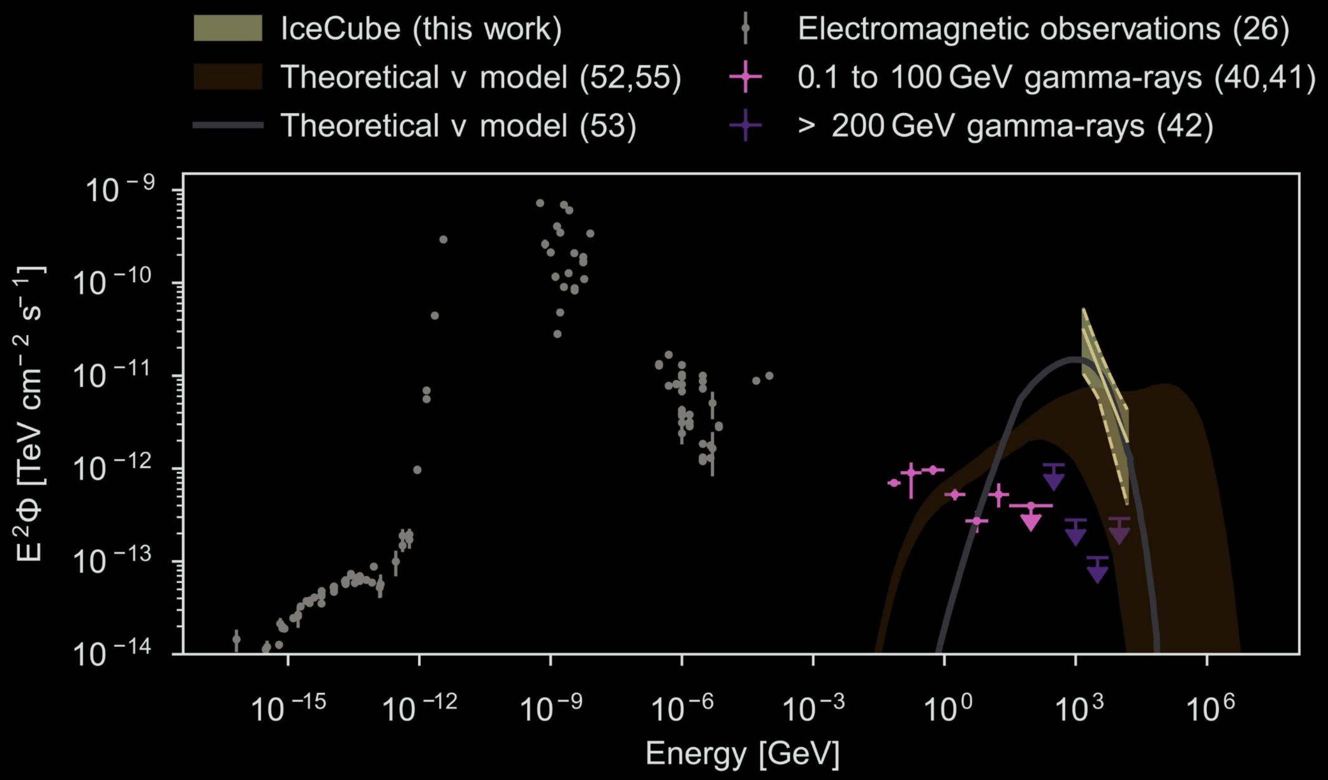


"Big power law in the sky" (ISM)

(Armstrong, Rickett & Spangler, 1995, ApJ)

Neutrino VS gamma-ray flux from NGC1068



(IceCube Collaboration, 2022, Science)

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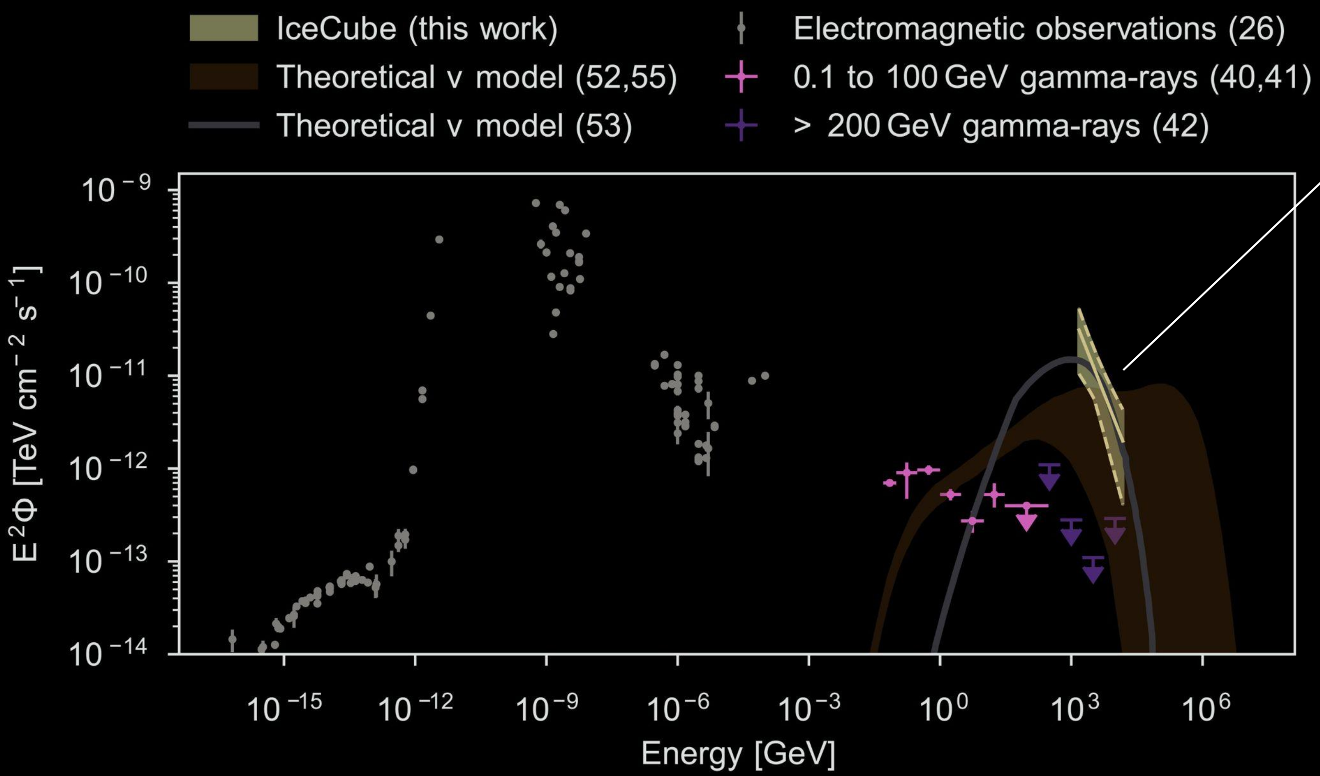

Neutrinos, a clue for the acceleration of protons to relativistic velocities

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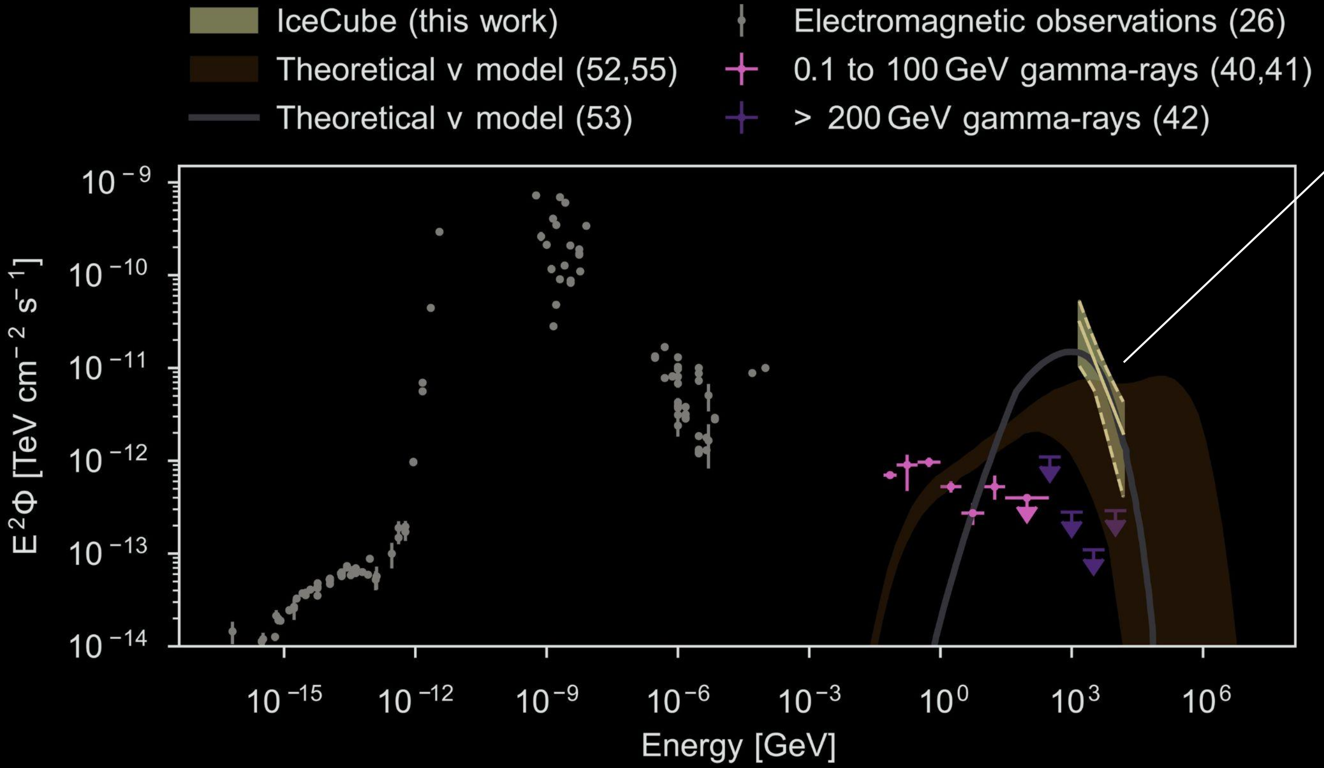

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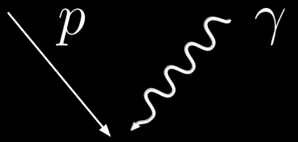

photopion ($\pi^{\pm}$ component)

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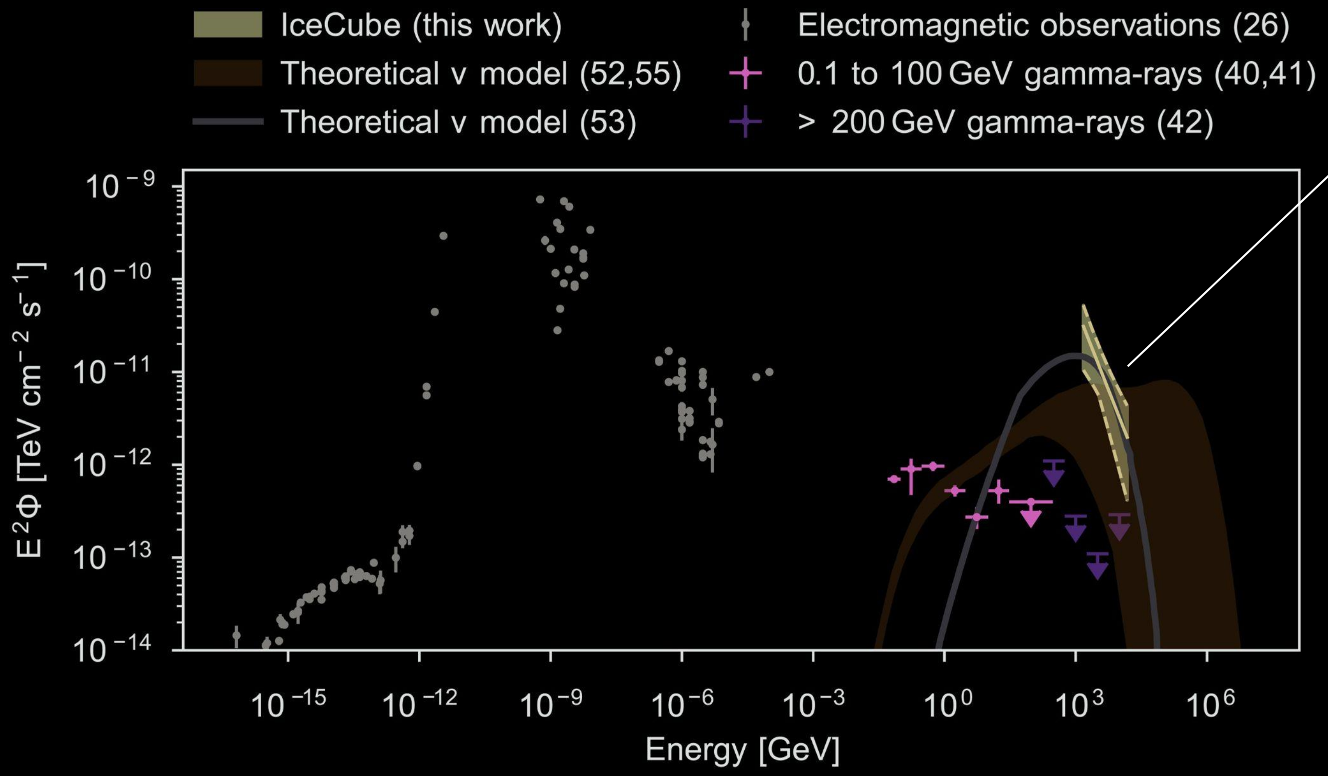

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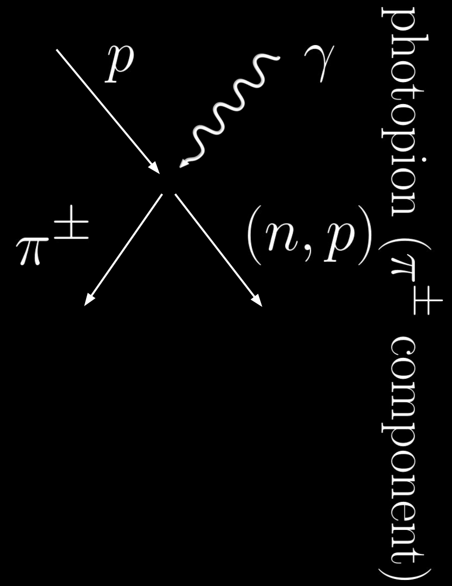

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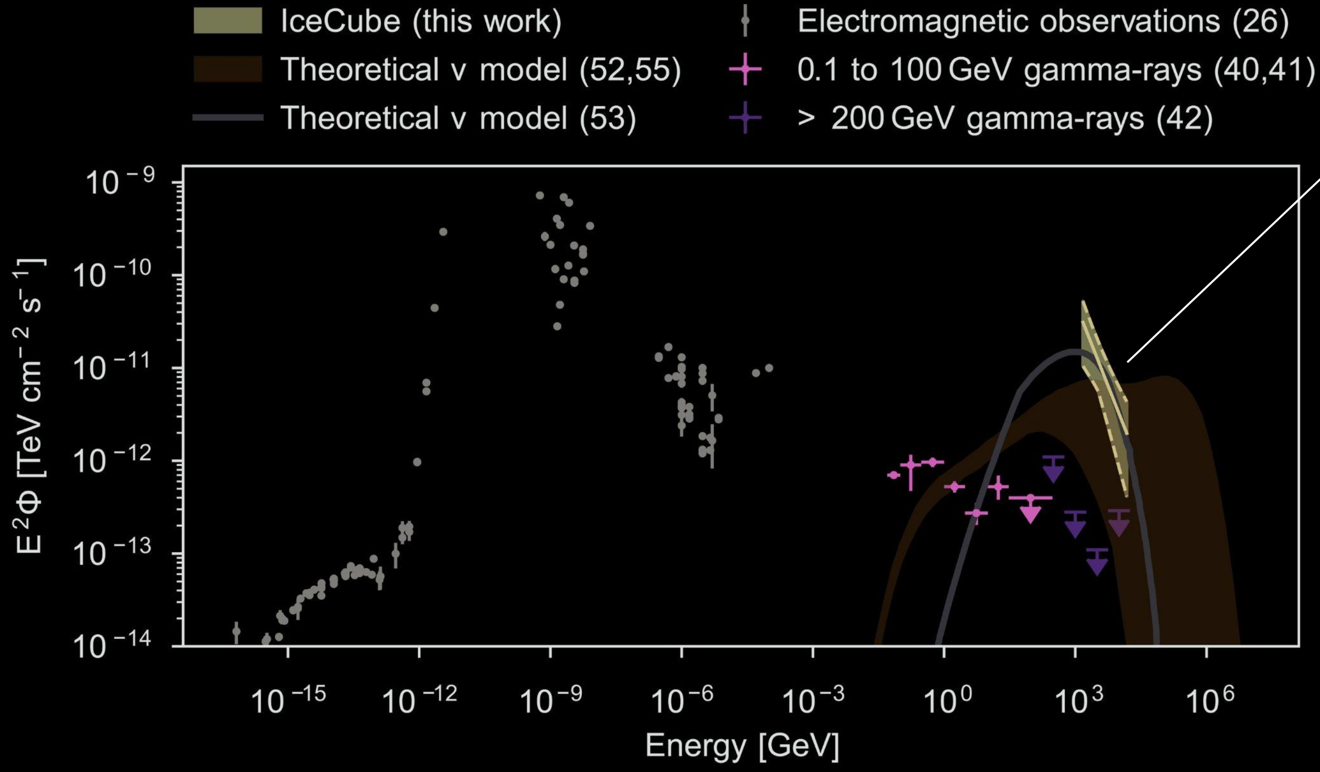

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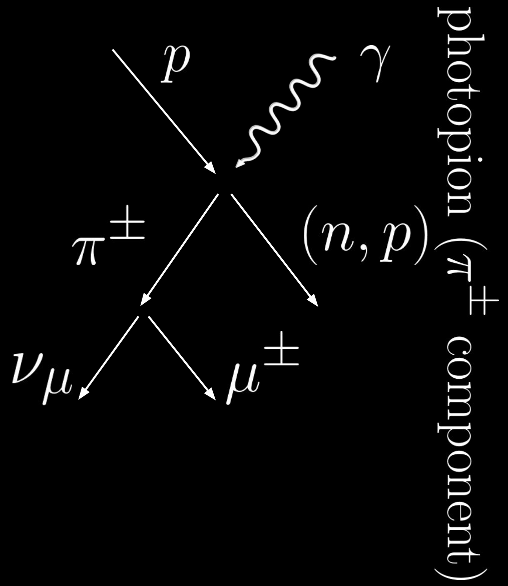

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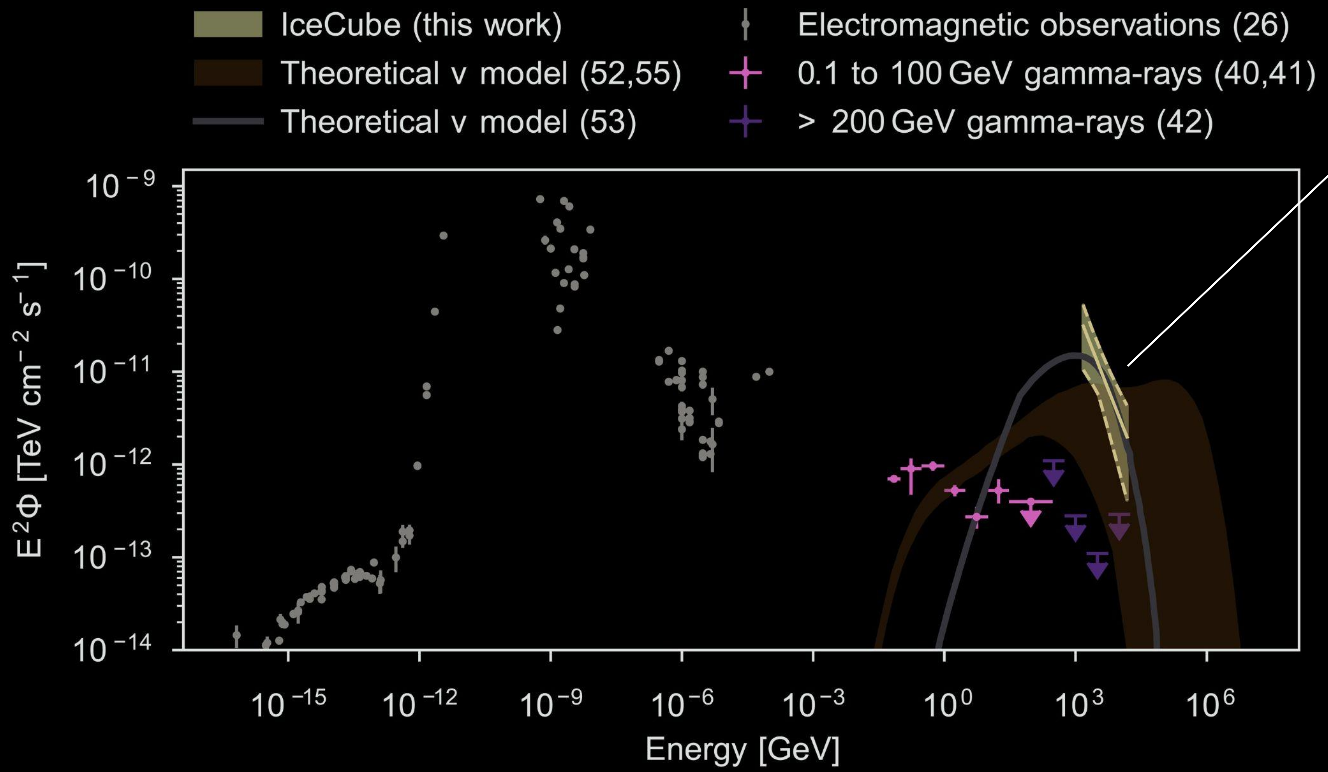

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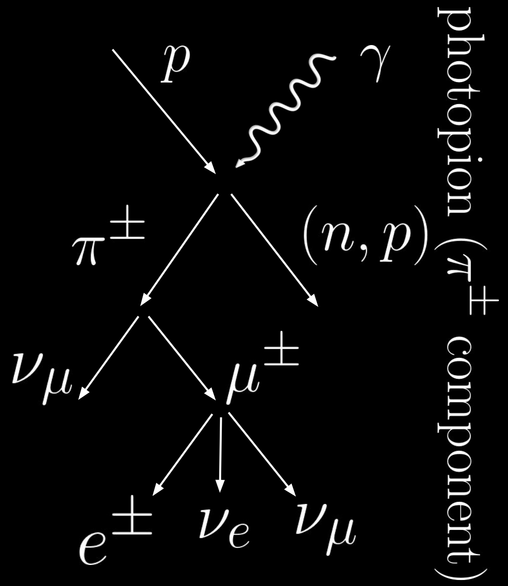

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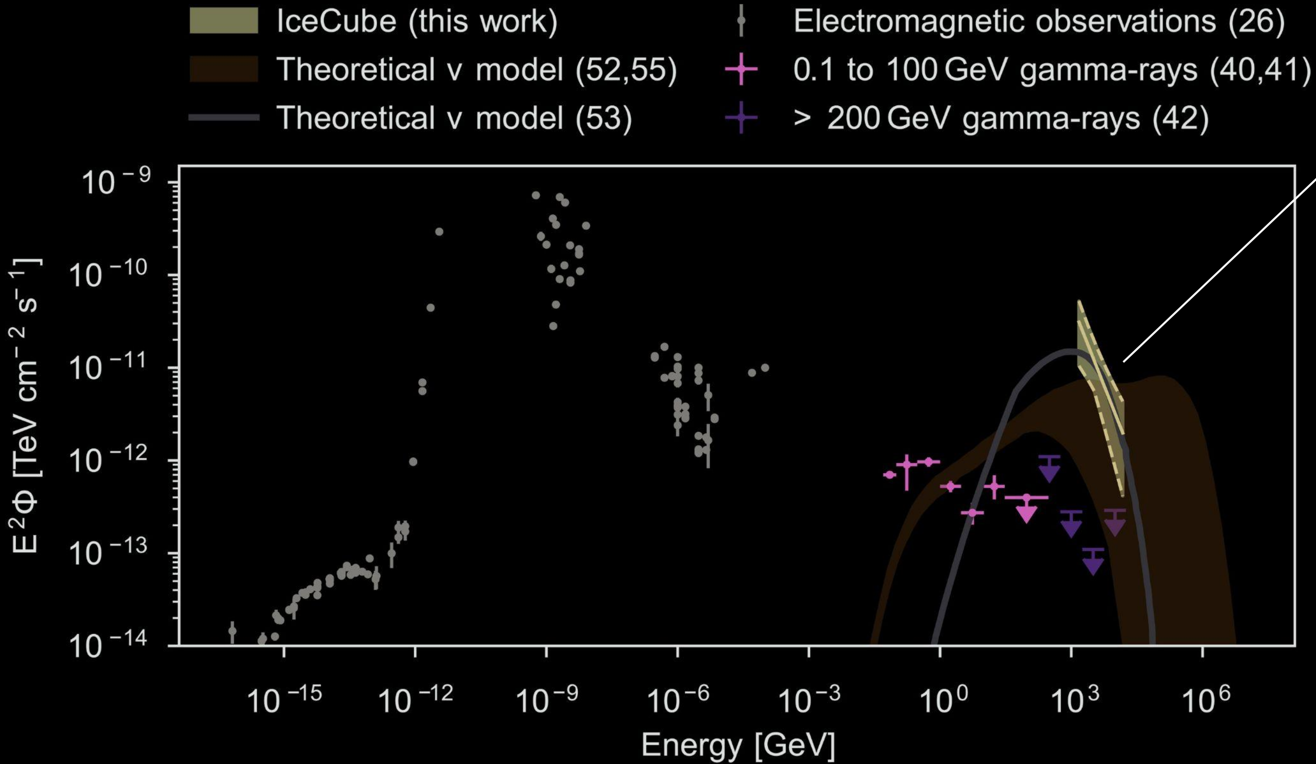

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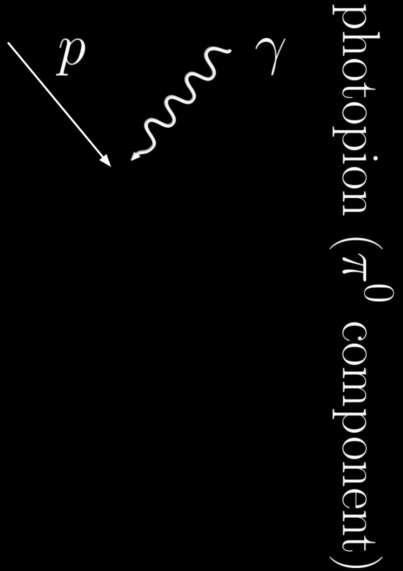

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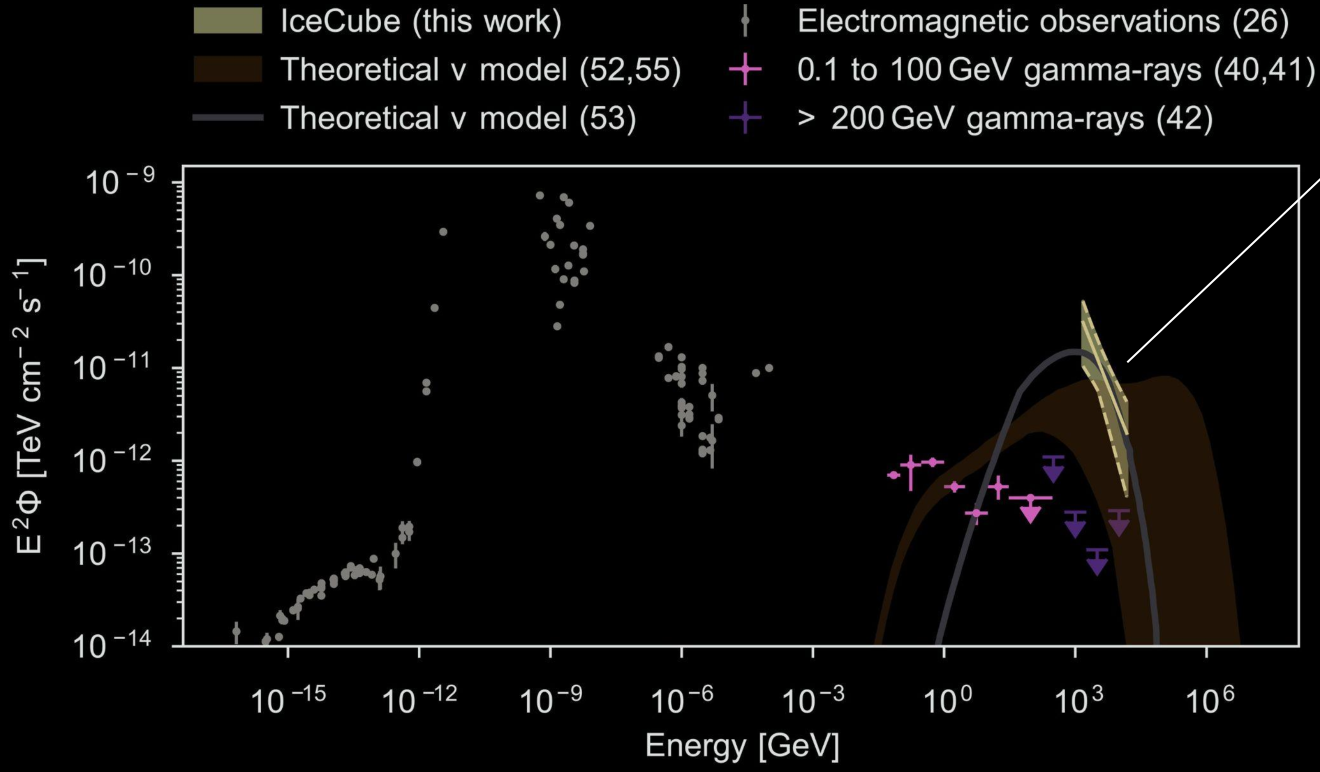

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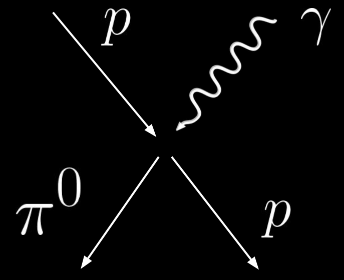

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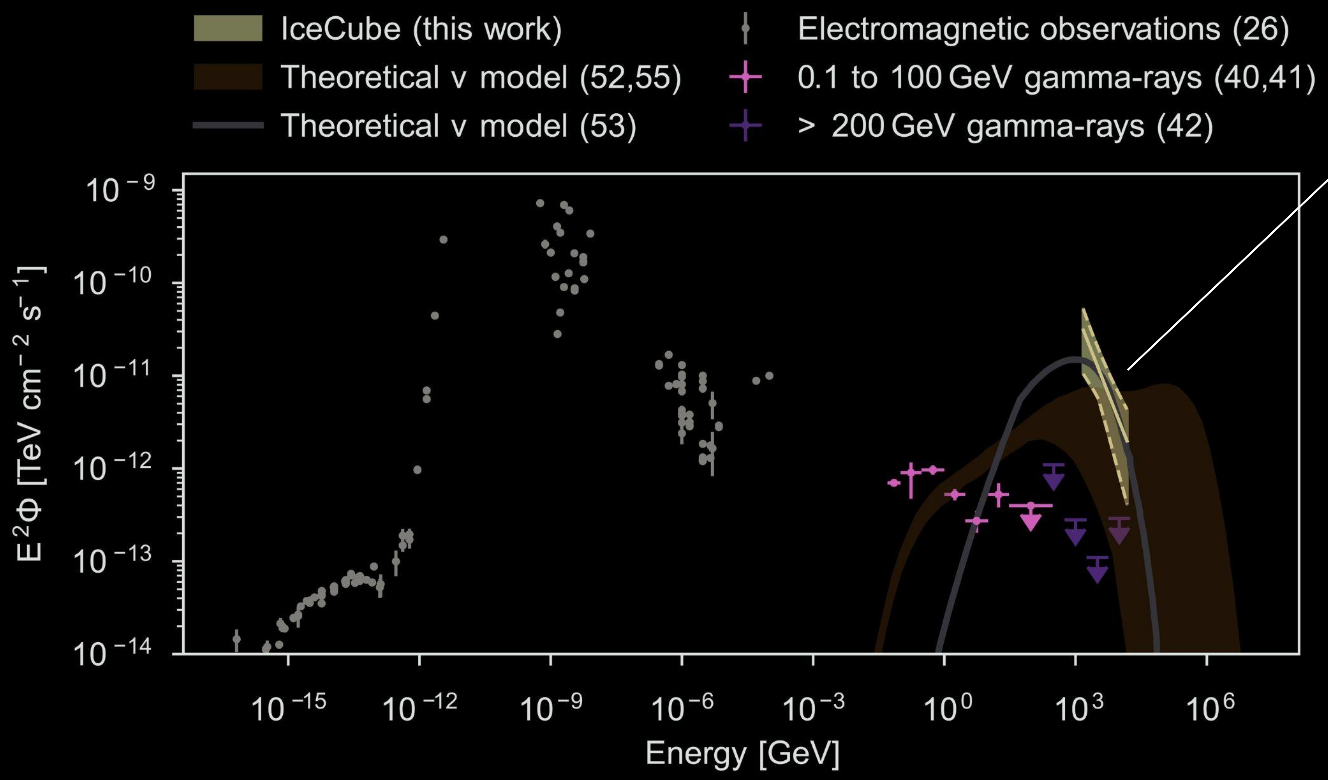

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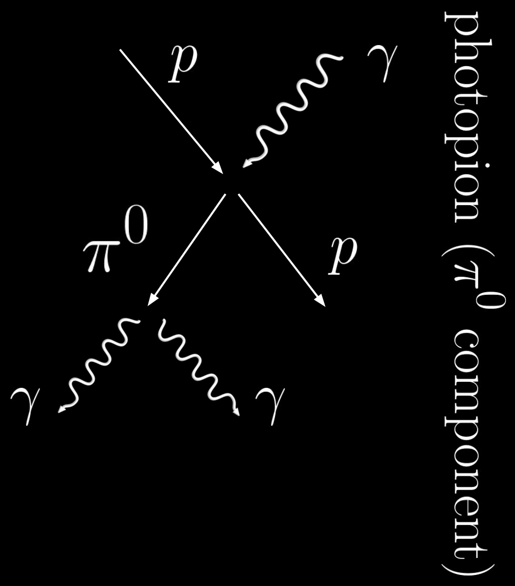

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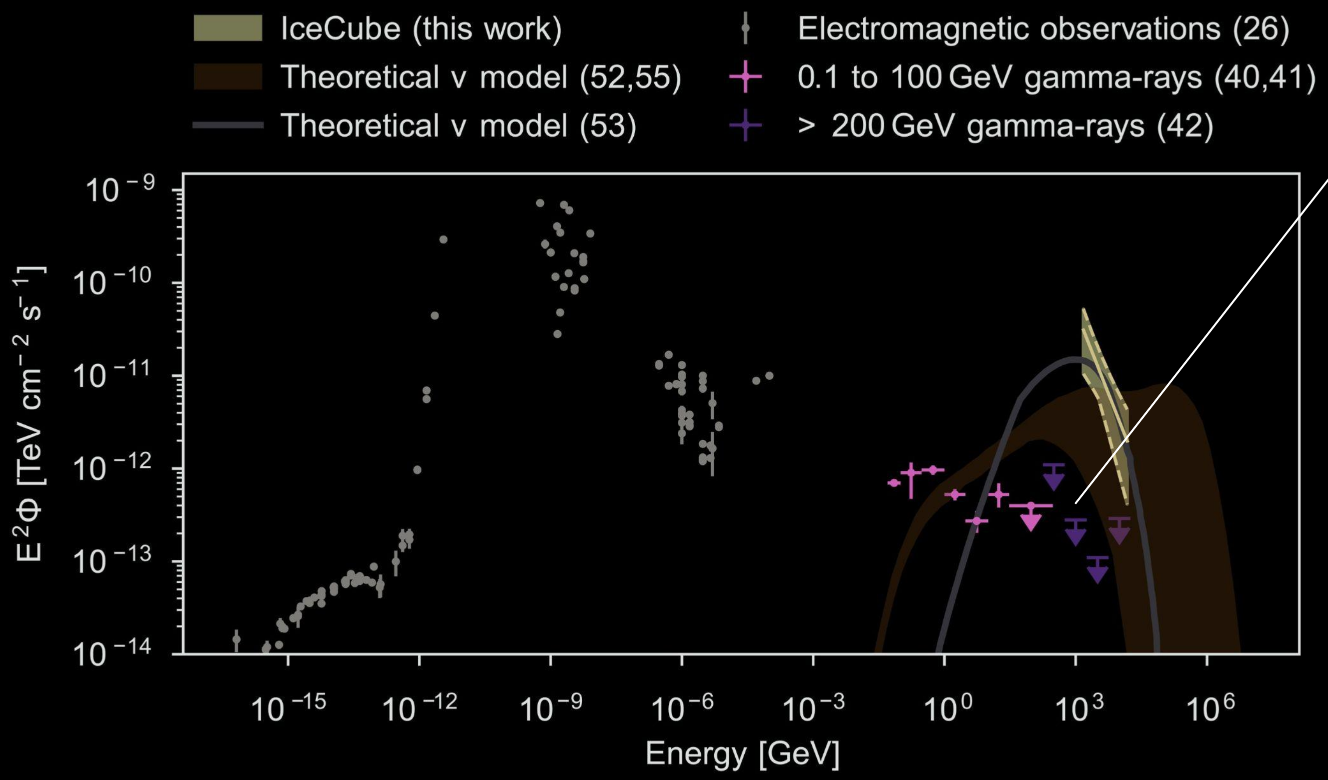

The absence of γ rays indicates auto-absorption due to a dense photon field

(IceCube Collaboration, 2022, Science)

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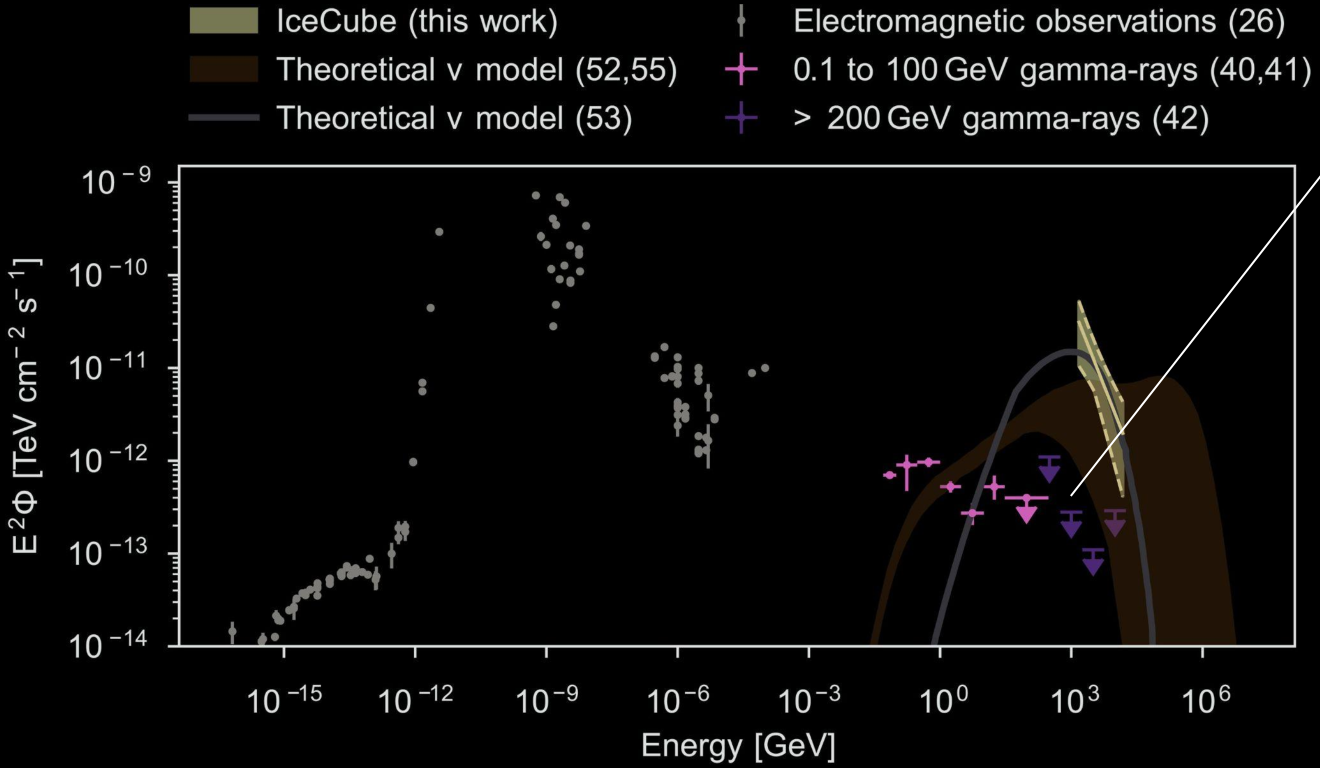

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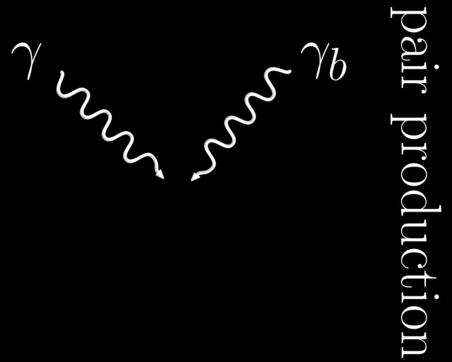

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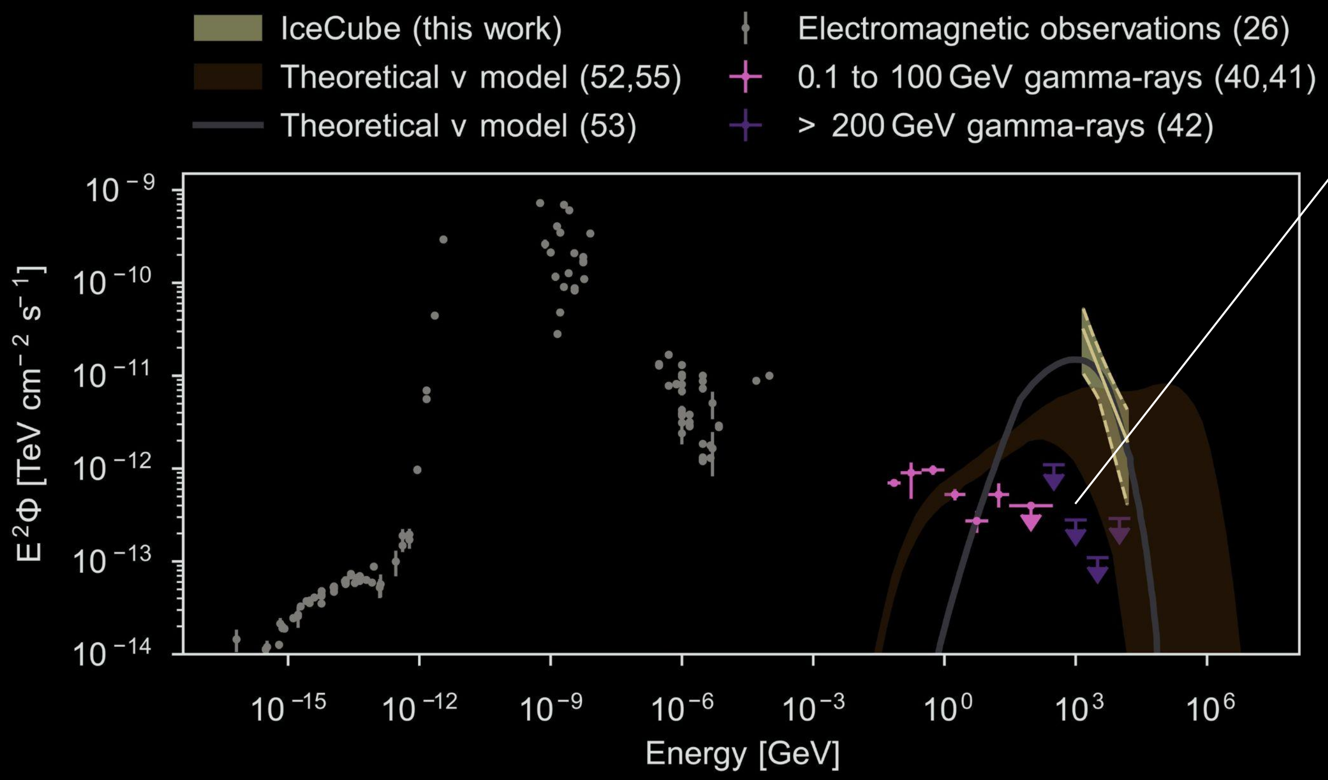

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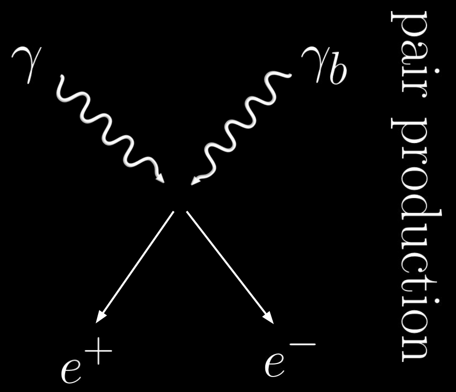

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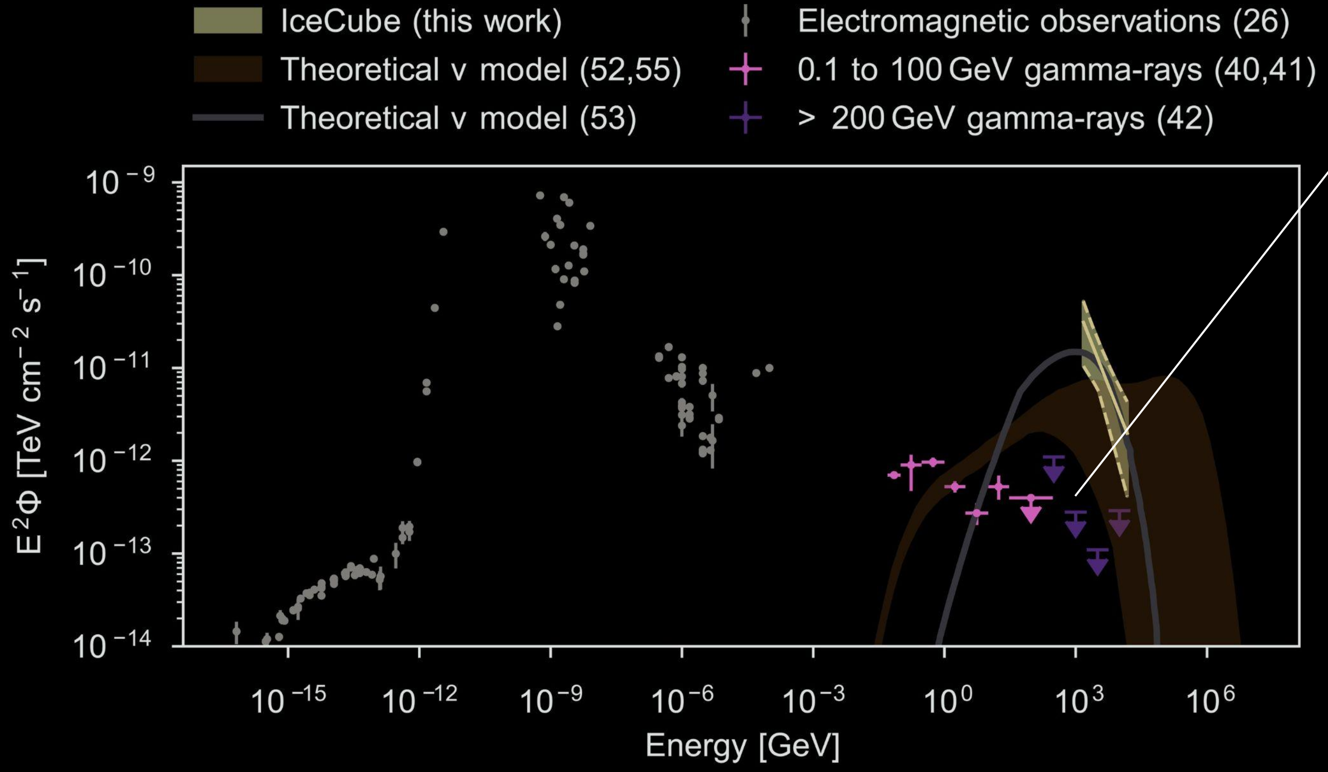

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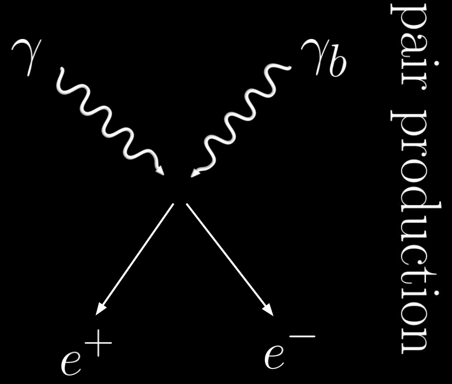
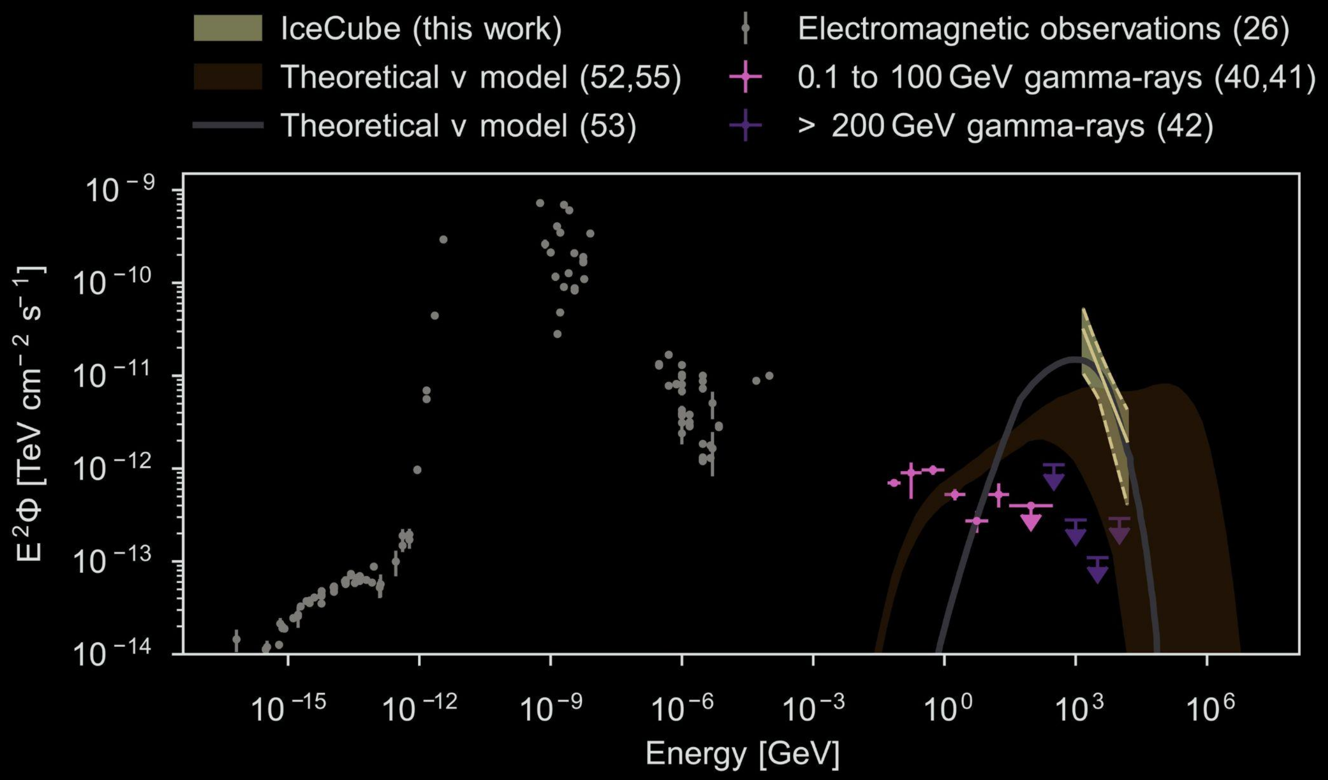


$\therefore$ The emission may become from the inner part of the AGN!

Neutrino VS gamma-ray flux from NGC1068



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What may accelerate these protons in the surroundings of the SMBH?

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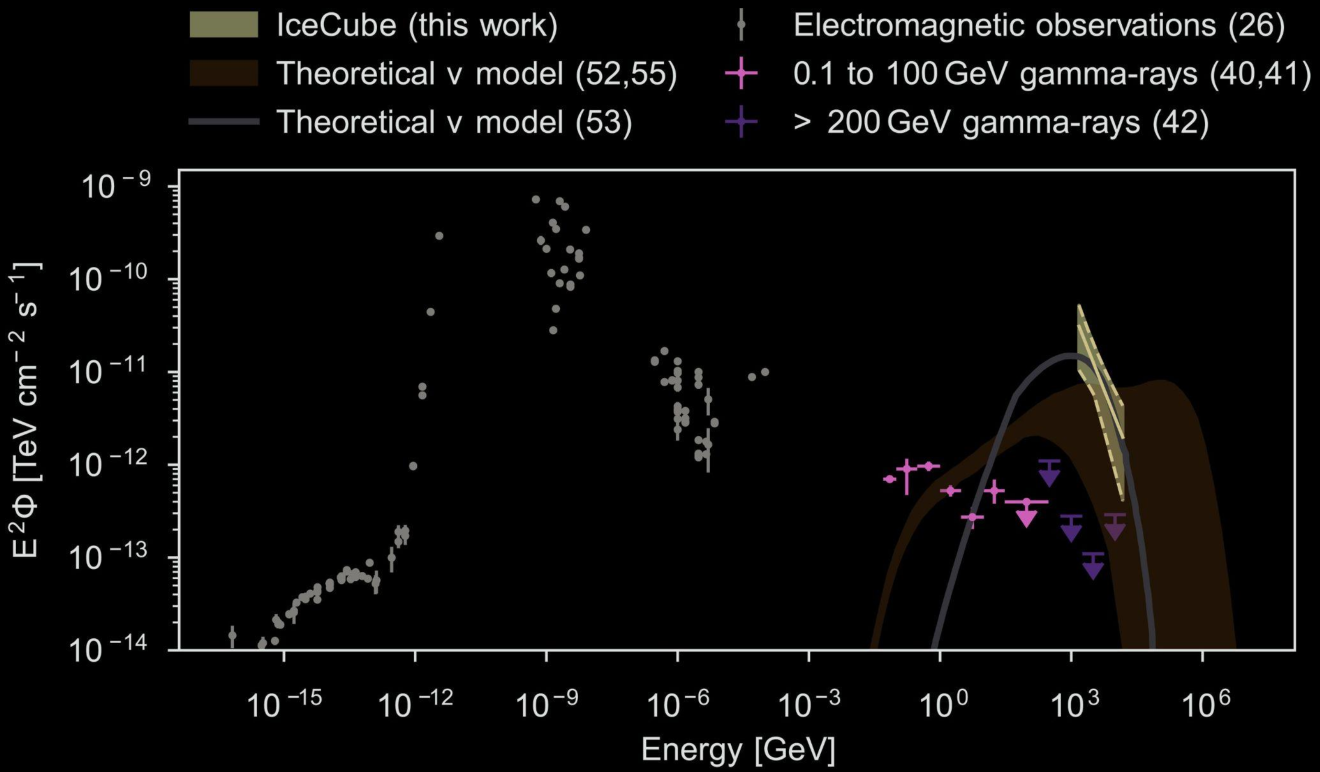

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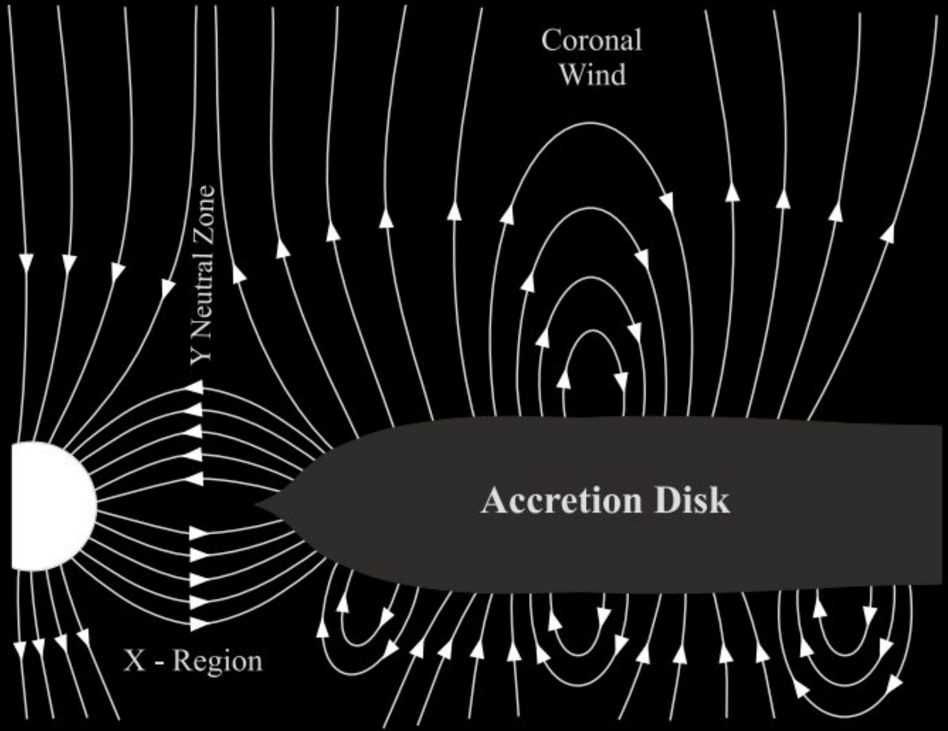
A: Magnetic Reconnection!

(IceCube Collaboration, 2022, Science)

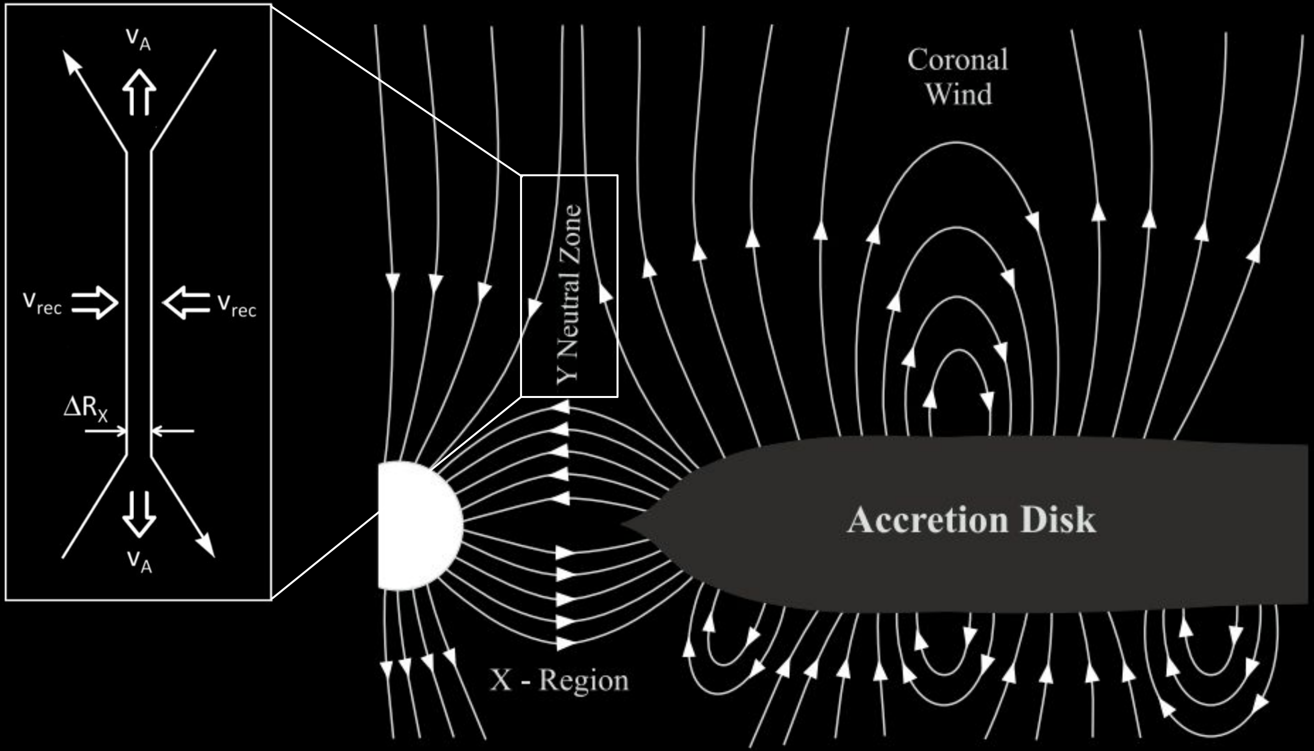
Magnetic Reconnection around Black Holes

Possible configuration of the magnetic field lines for an accretion flow into a black hole



(de Gouveia Dal Pino & Lazarian, 2005, A&A)

Magnetic Reconnection around Black Holes



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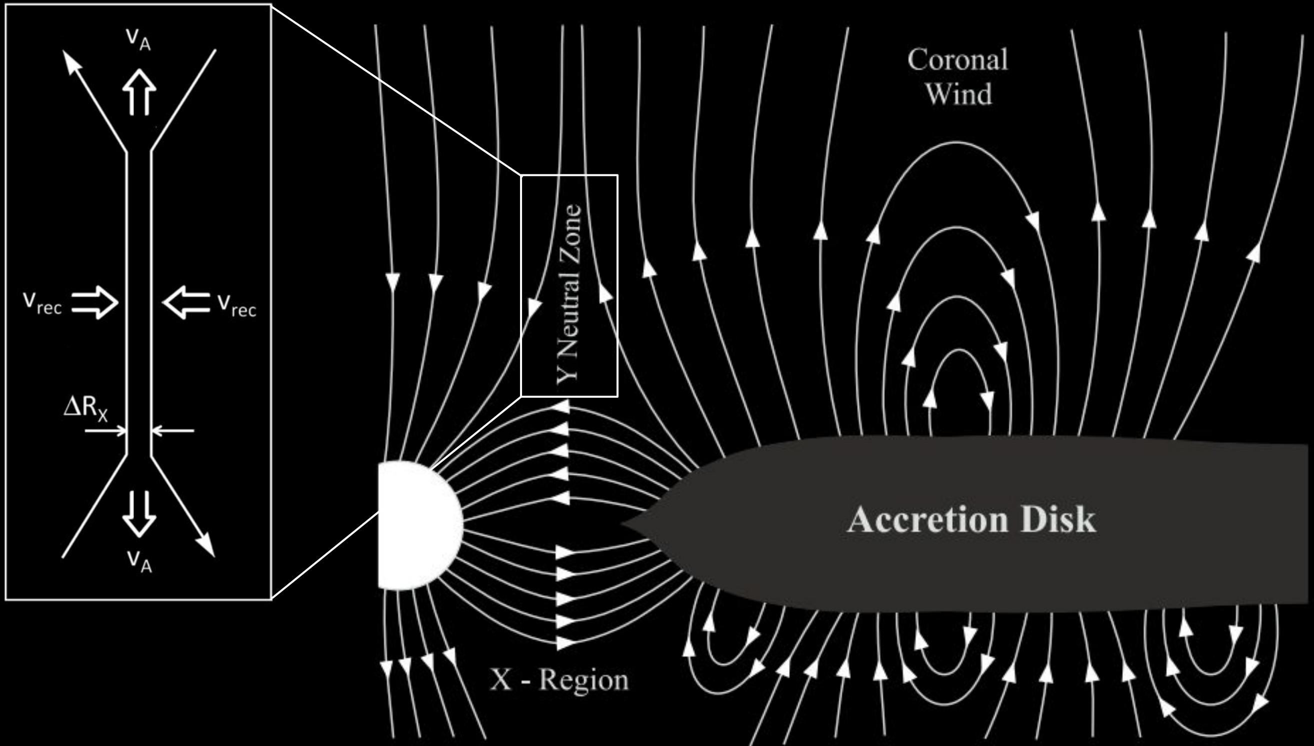
Magnetic Reconnection around Black Holes

Particles can be accelerated in the magnetic discontinuity according to a first-order Fermi process:

$$\left\langle \frac{\Delta E}{E} \right\rangle \sim \frac{V_{\rm rec}}{c}$$



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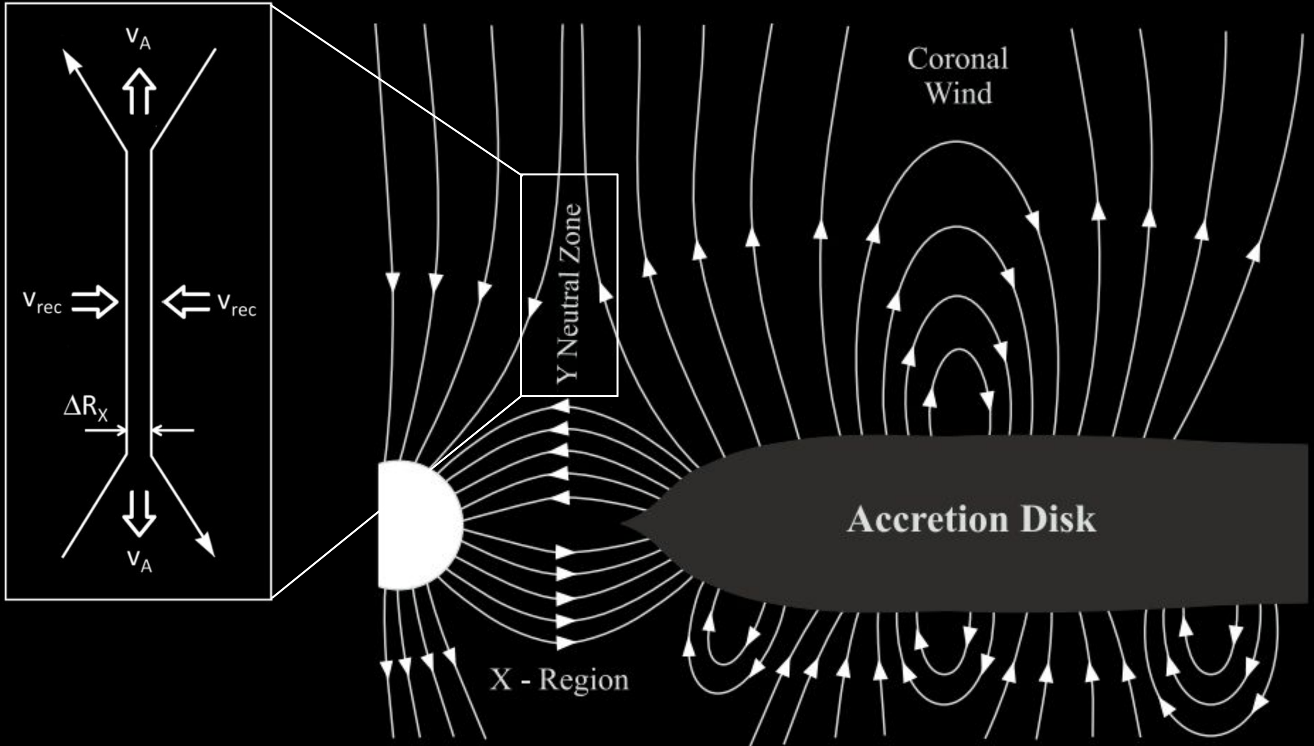
Magnetic Reconnection around Black Holes

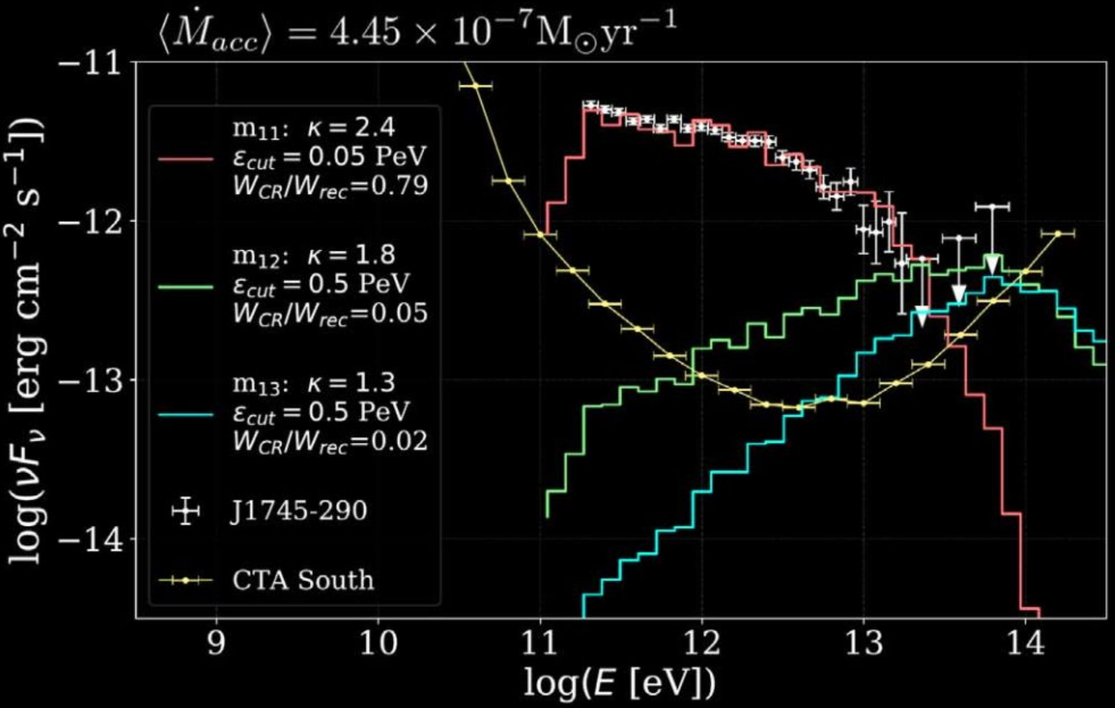
$$\left\langle \frac{\Delta E}{E} \right\rangle \sim \frac{V_{\rm rec}}{c}$$

Implies an exponential growth of the energy with time!



(de Gouveia Dal Pino & Lazarian, 2005, A&A)

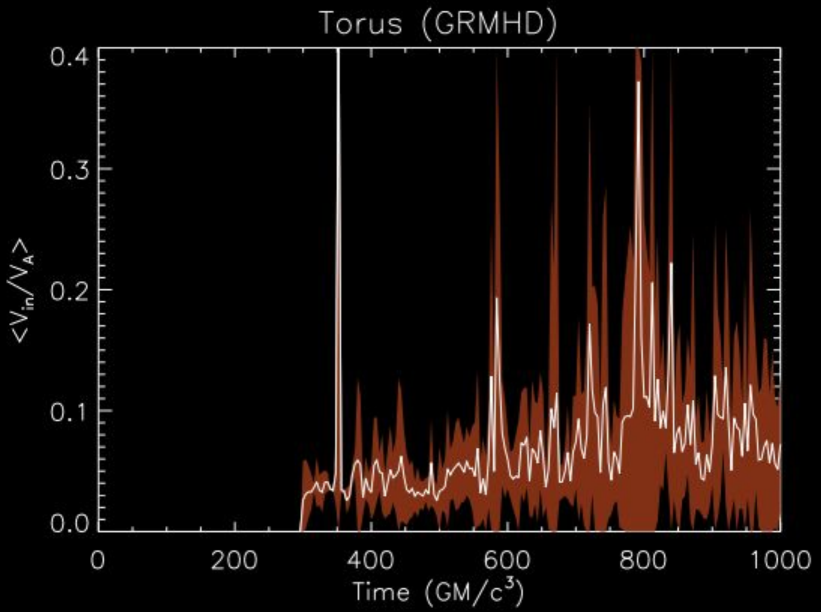
Example of application: SgrA*

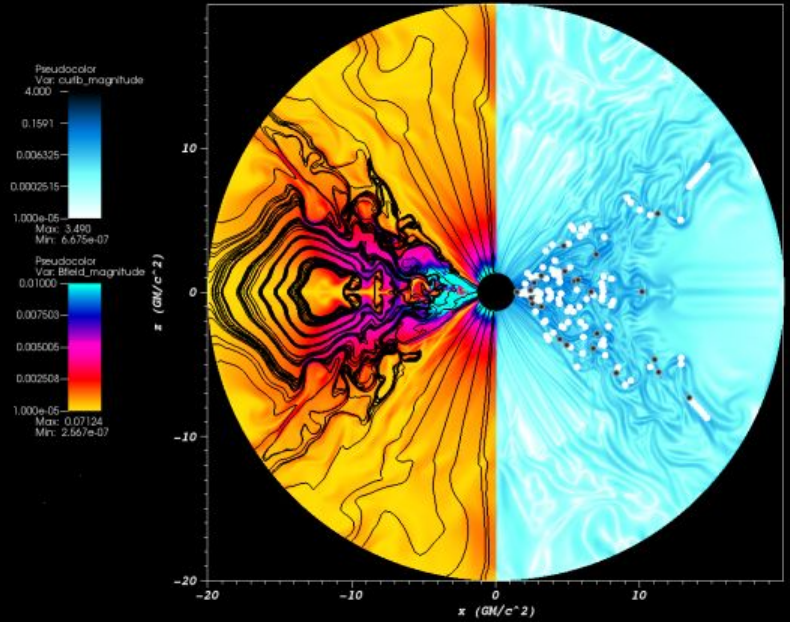


(Rodríguez-Ramírez, de Gouveia Dal Pino & Alves Batista, 2019, ApJ)

Algorithm for search reconnection sites

Search for reconnection sites in 2D & 3D GRMHD simulations of accretion flows





(Kadowaki et al. 2018; de Gouveia Dal Pino et al. 2018)

Testing theory with MHD simulations

In classical regime, we use the AMUN code (Kowal, 2009) to solve the isothermal non-ideal MHD equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0,$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v} \boldsymbol{v} + \left(a^2 \rho + \frac{B^2}{8\pi} \right) I - \frac{1}{4\pi} \boldsymbol{B} \boldsymbol{B} \right] = \boldsymbol{f},$$

$$\frac{\partial \boldsymbol{A}}{\partial t} + \boldsymbol{E} = 0,$$

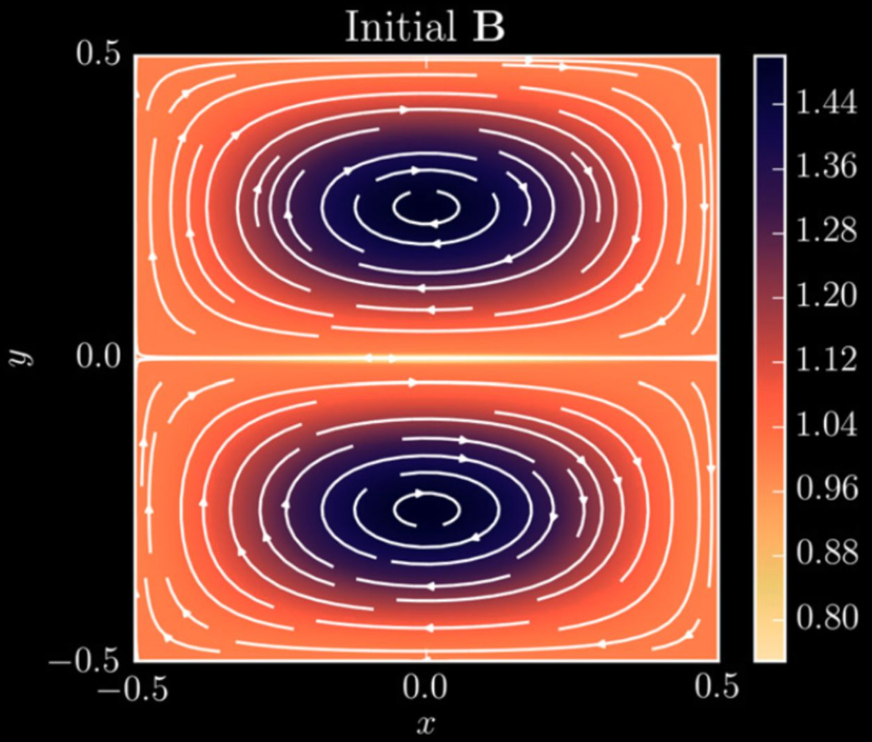
Testing theory with MHD simulations

and the initial magnetic field is given by

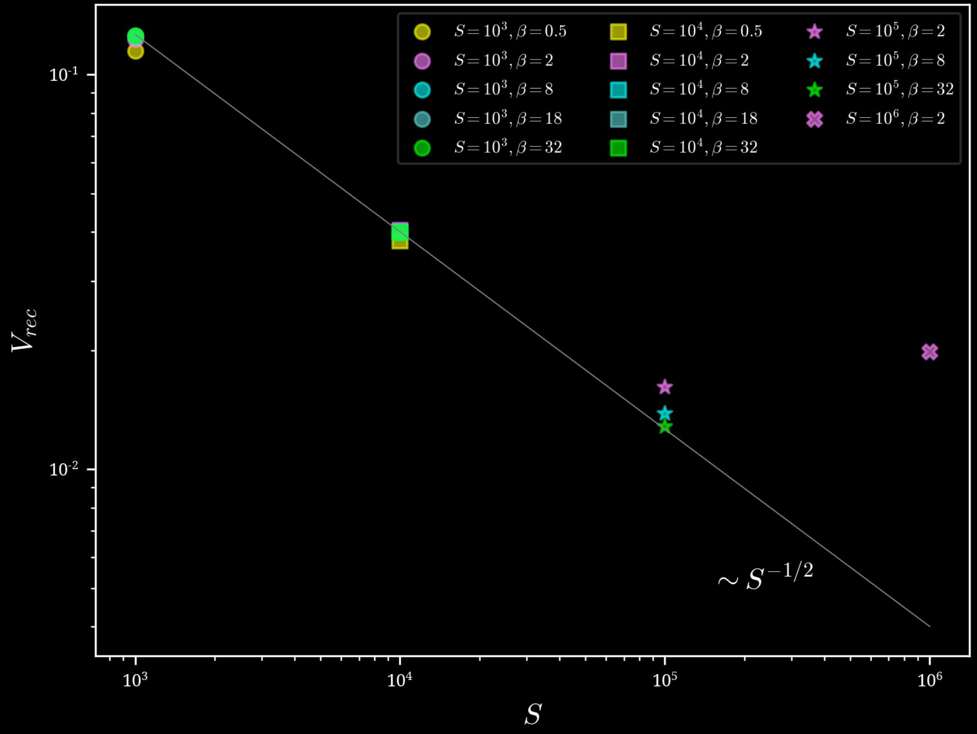
$$\vec{B} = B_z \hat{z} + \hat{z} \times \nabla \psi,$$

where

$$\psi = \frac{1}{2\pi} \tanh\left(\frac{y}{h}\right) \cos(\pi x) \sin(2\pi y)$$



💻 Testing theory with MHD simulations



(Vicentin et al., *in prep.*)

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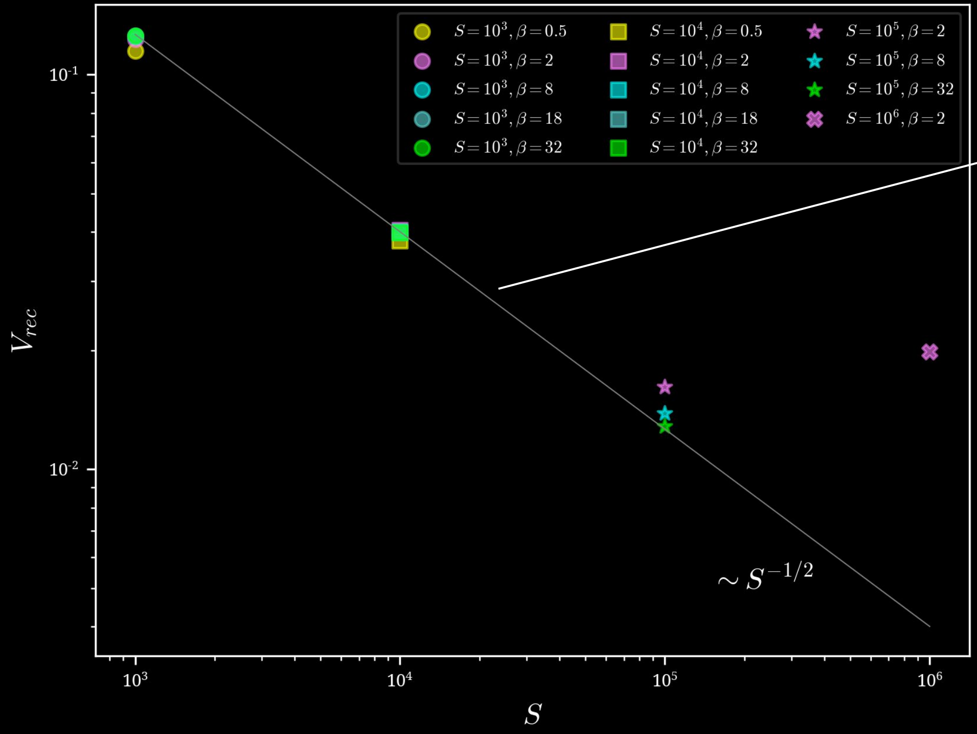

We can recover the Sweet-Parker regime for low-Lundquist numbers!

(Vicentin et al., *in prep.*)

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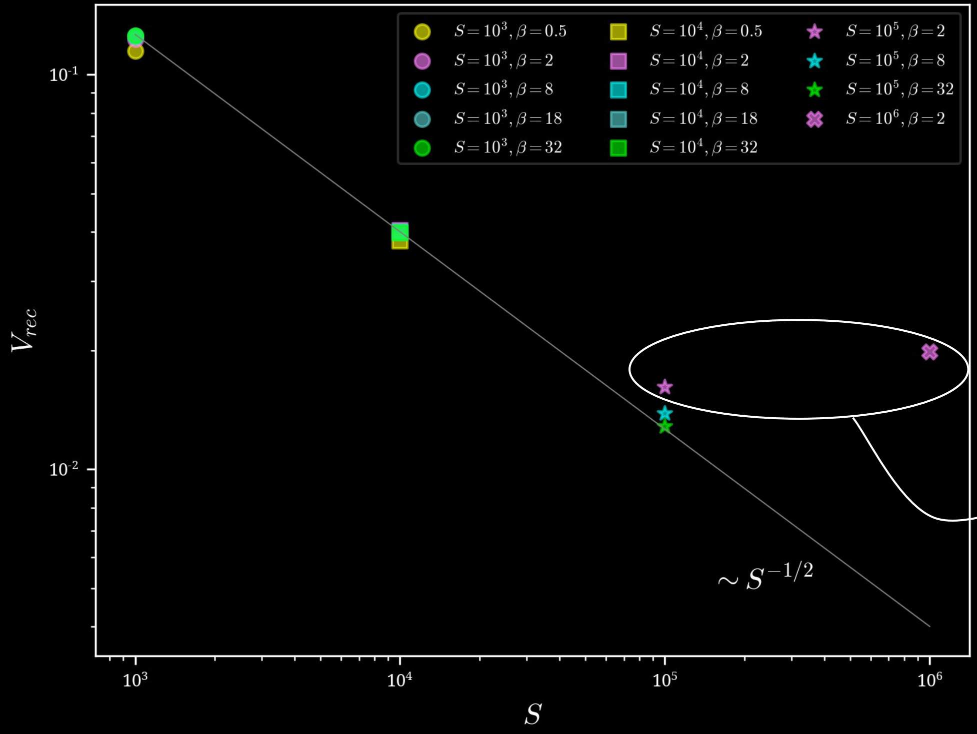
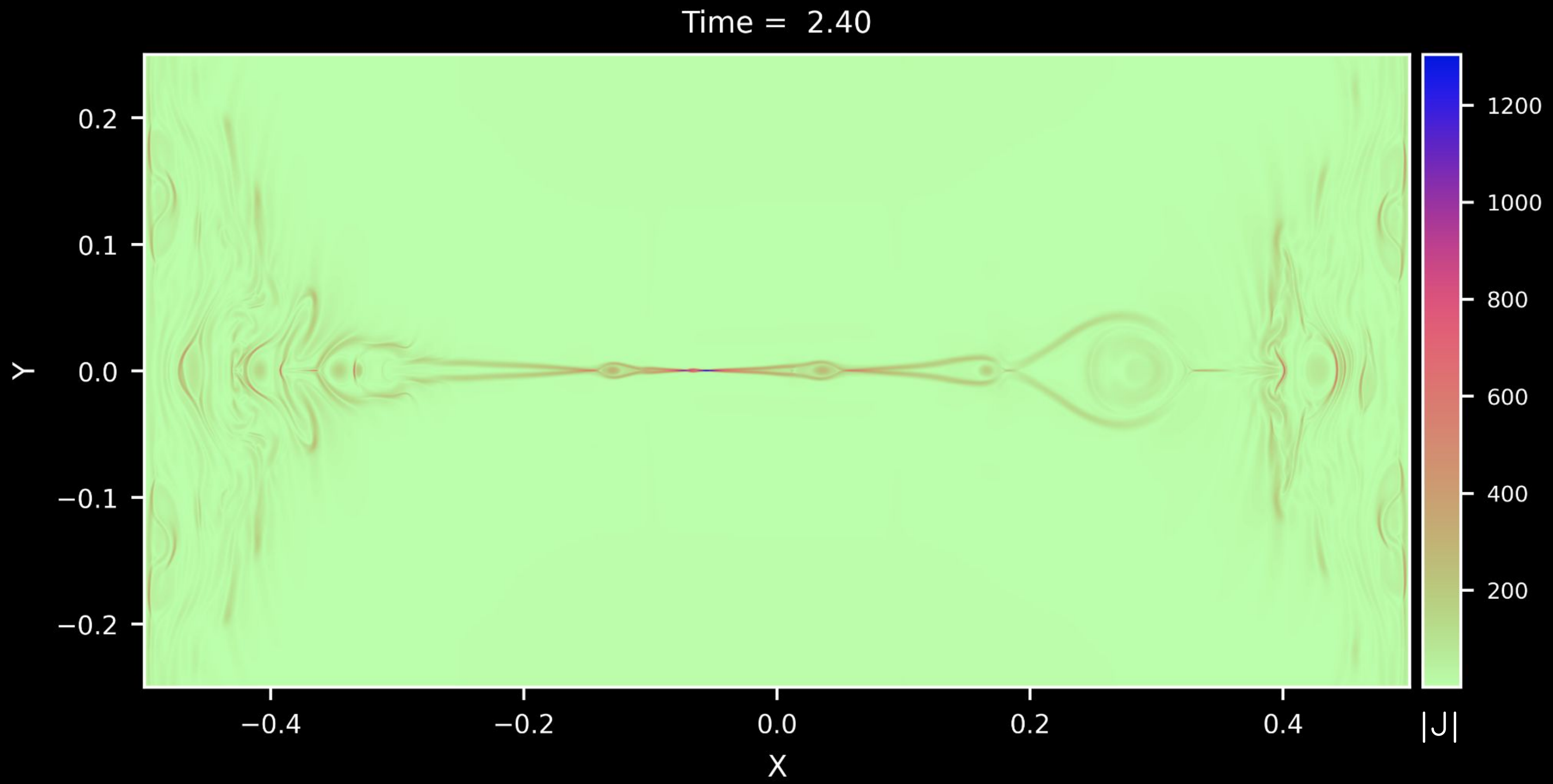


We can recover the Sweet-Parker regime for low-Lundquist numbers!

The reconnection rate starts to deviate from SP for high-Lundquist numbers (plasmoid instability)

(Vicentin et al., *in prep.*)



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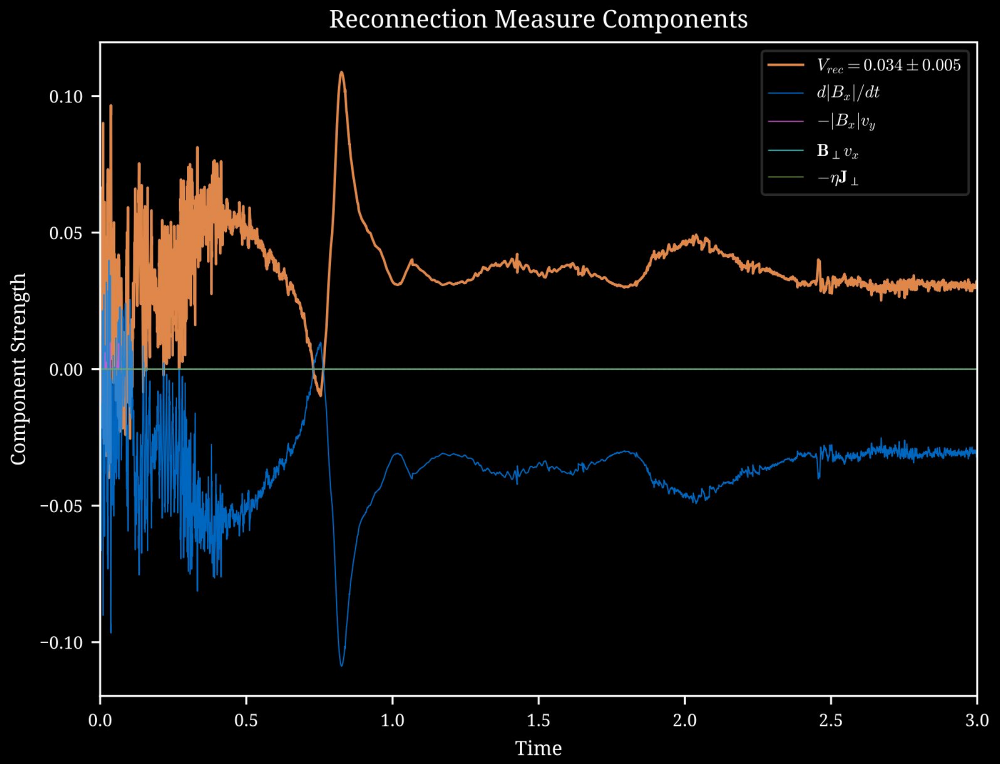
💻 Testing theory with MHD simulations



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$$V_{\rm rec} \sim 0.1\, V_A$$

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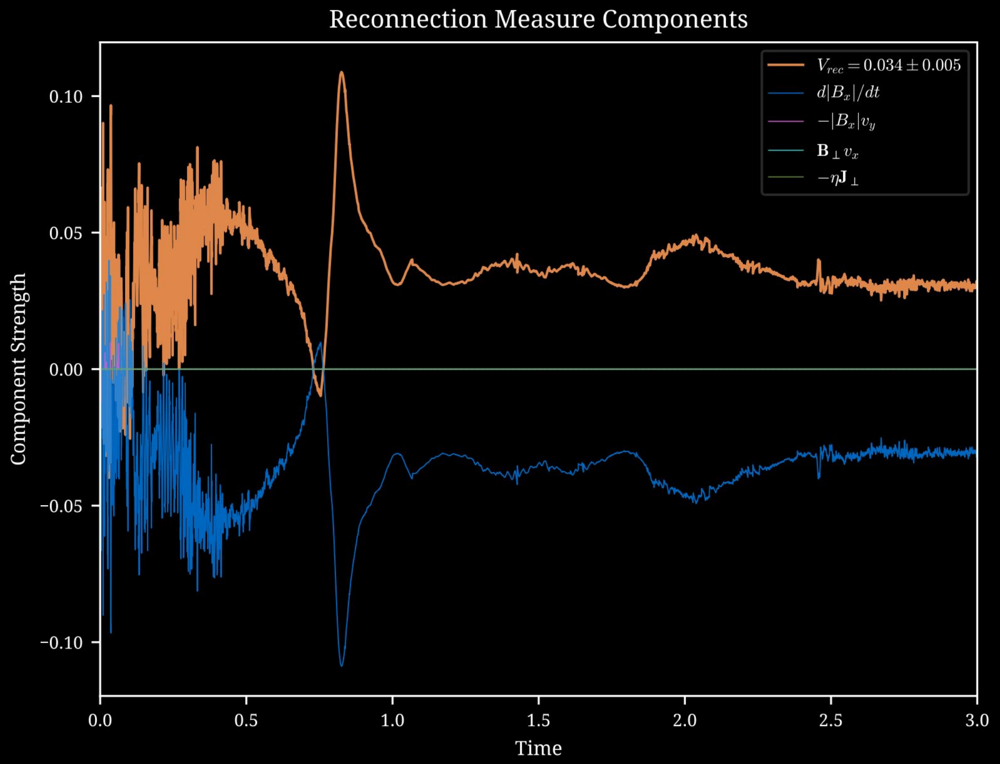

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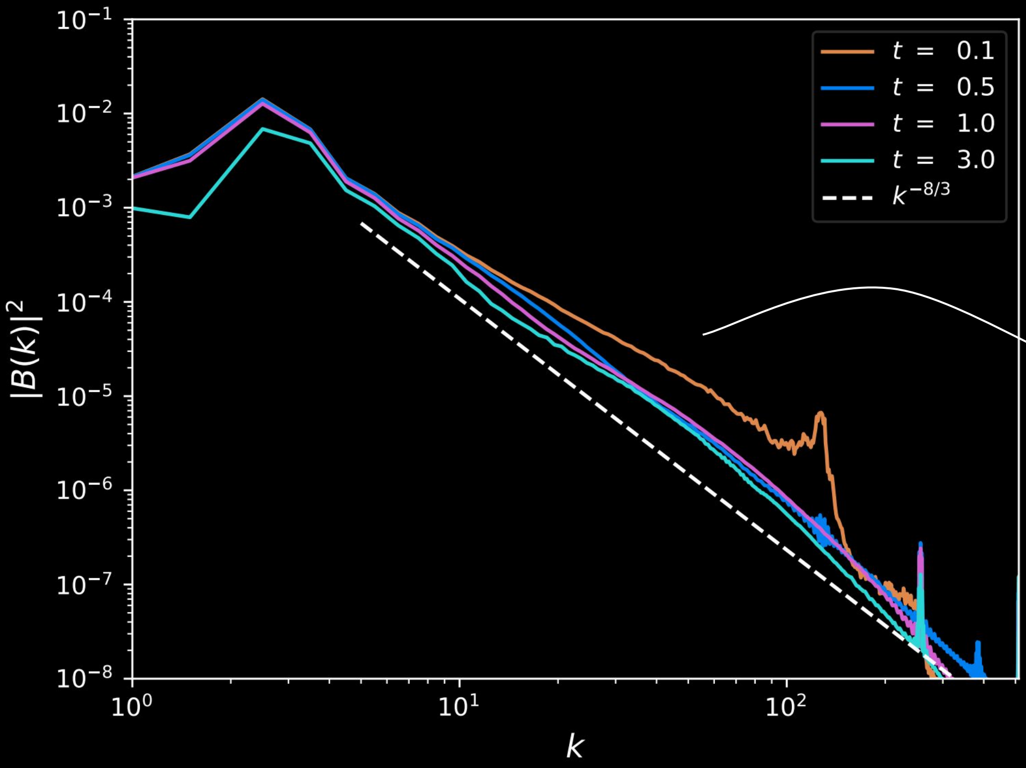
For the case where we inject forced turbulence initially in the domain (up to $0.1\,t_A$), we can reach high values of

$$V_{\rm rec} \sim 0.1\,V_A$$

even after the turbulence injection is stopped.

💻 Testing theory with MHD simulations



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The system remains turbulent longer after the turbulence injection!

Conclusions & take-home messages

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    - Solar flares

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- Turbulent magnetic reconnection around BHs can explain VHE emission from these compact sources
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Conclusions & take-home messages

- Magnetic reconnection is ubiquitous in Astrophysics
  - Solar flares
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  - Independent on S and η
- Turbulent magnetic reconnection around BHs can explain VHE emission from these compact sources
  - from theory and global GRMHD sims.
- Classical MHD simulations have showed that the system remains turbulent even after injection is stopped

Thank you!

Any question?

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