FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

INSTITUTO DE ASTRONOMIA, GEOFÍSICA E CIÊNCIAS ATMOSFÉRICAS

# Magnetic Reconnection, and particle acceleration and propagation around Black Holes

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

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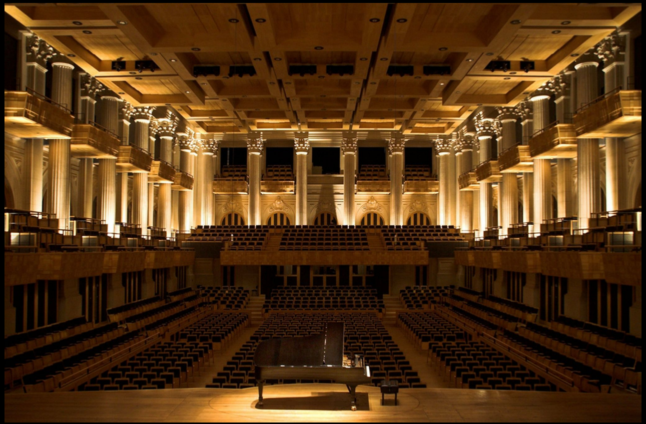

Concert Hall (Sala São Paulo)

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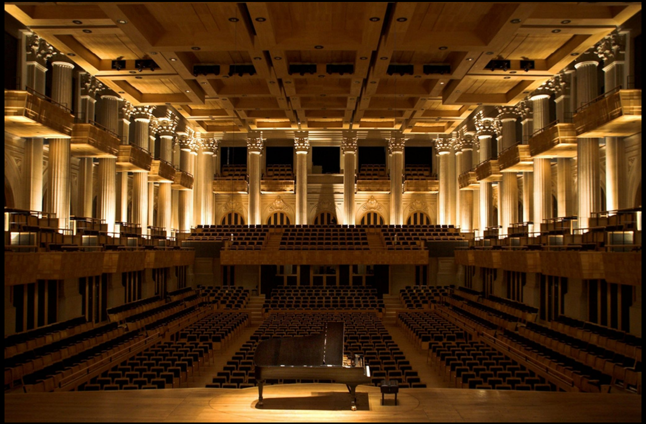

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# Outline

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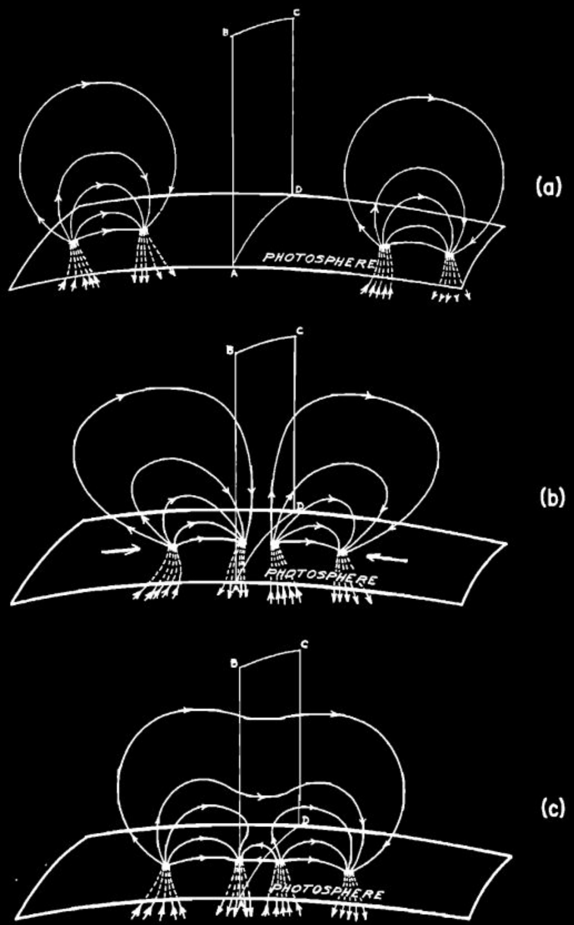
5. Testing theory using numerical MHD simulations

# 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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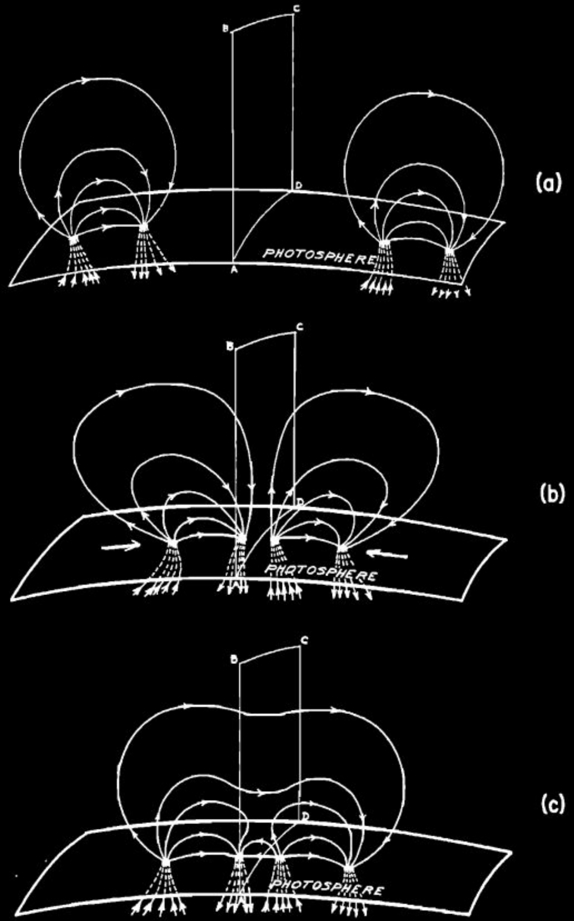


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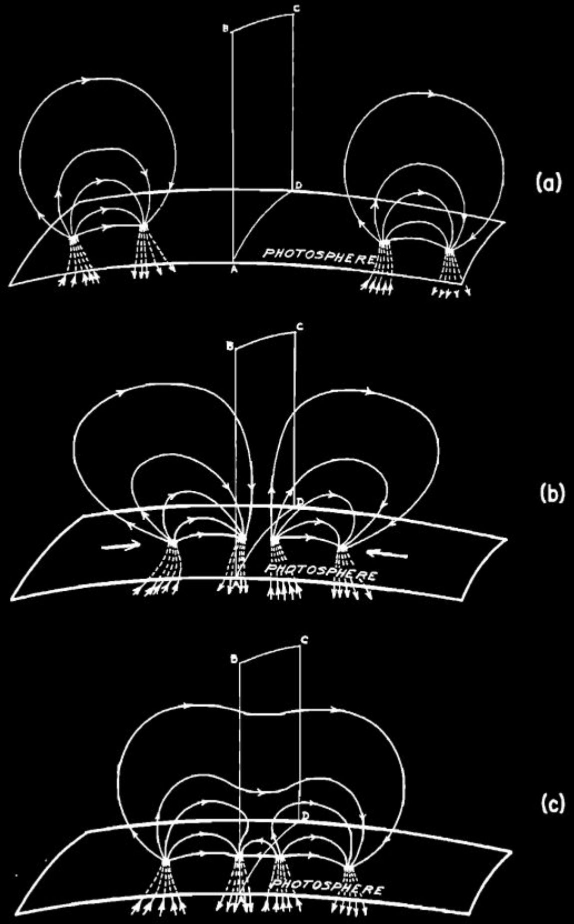


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$$S = \frac{LV_A}{\eta}$$

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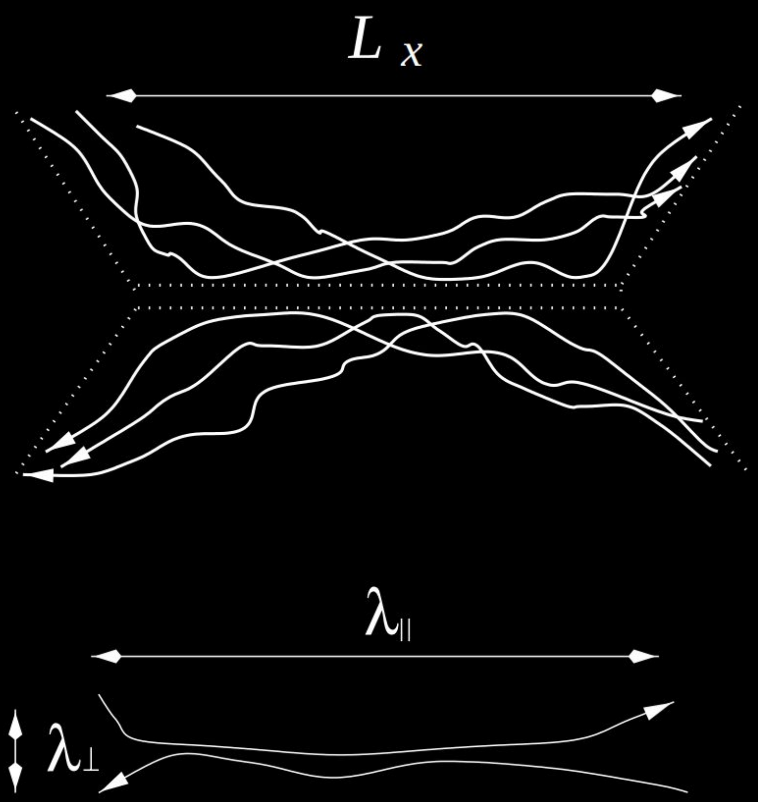
# Turbulent Magnetic Reconnection

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Lazarian & Vishniac, 1999, ApJ

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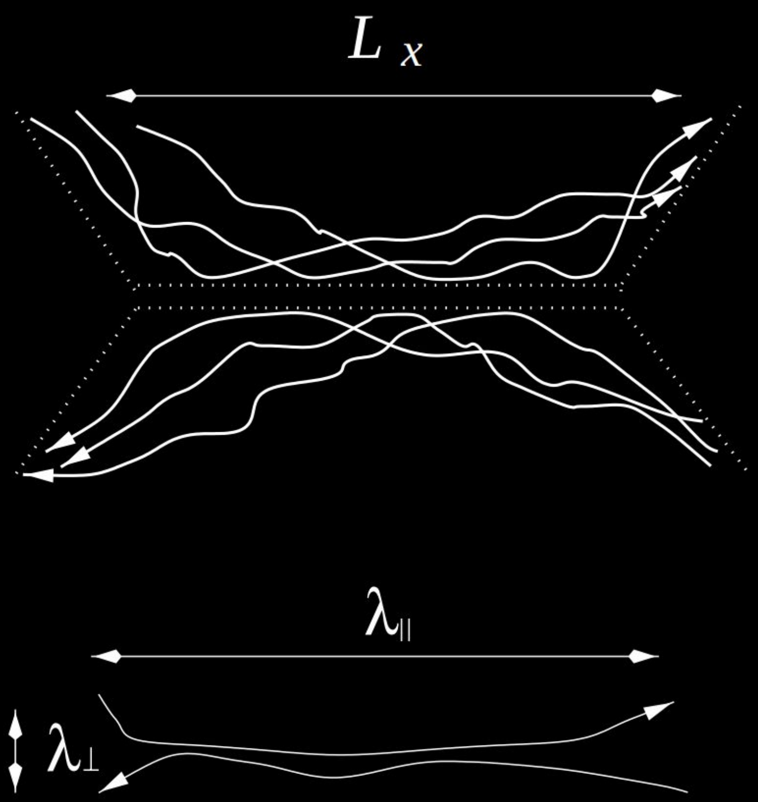


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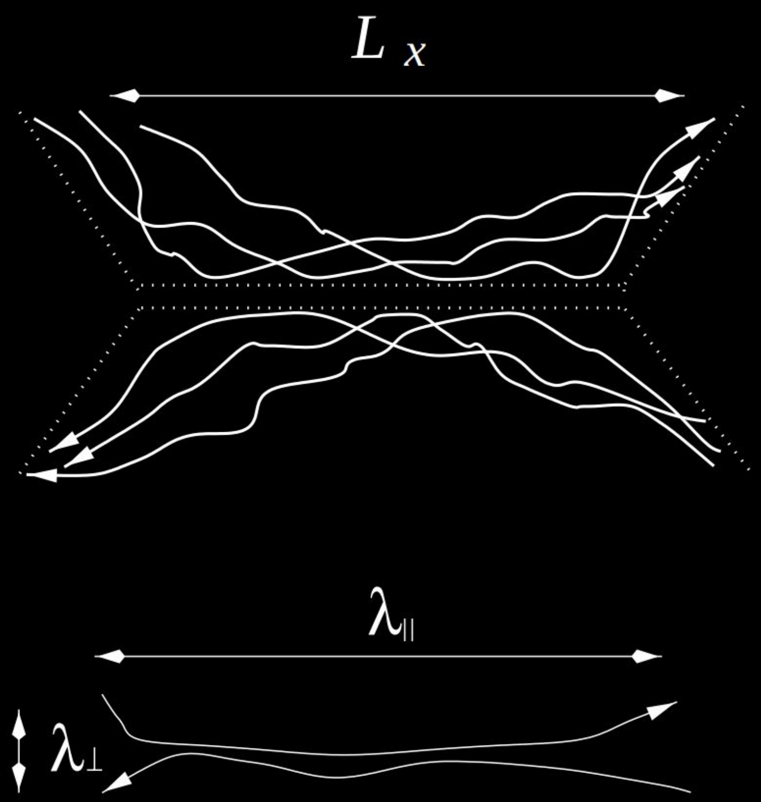


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$$V_{\rm rec} = V_A \left(\frac{\ell_{\rm inj}}{L}\right)^{1/2} \left(\frac{V_\ell}{V_A}\right)^2$$

Lazarian & Vishniac, 1999, ApJ

# … and turbulence is everywhere

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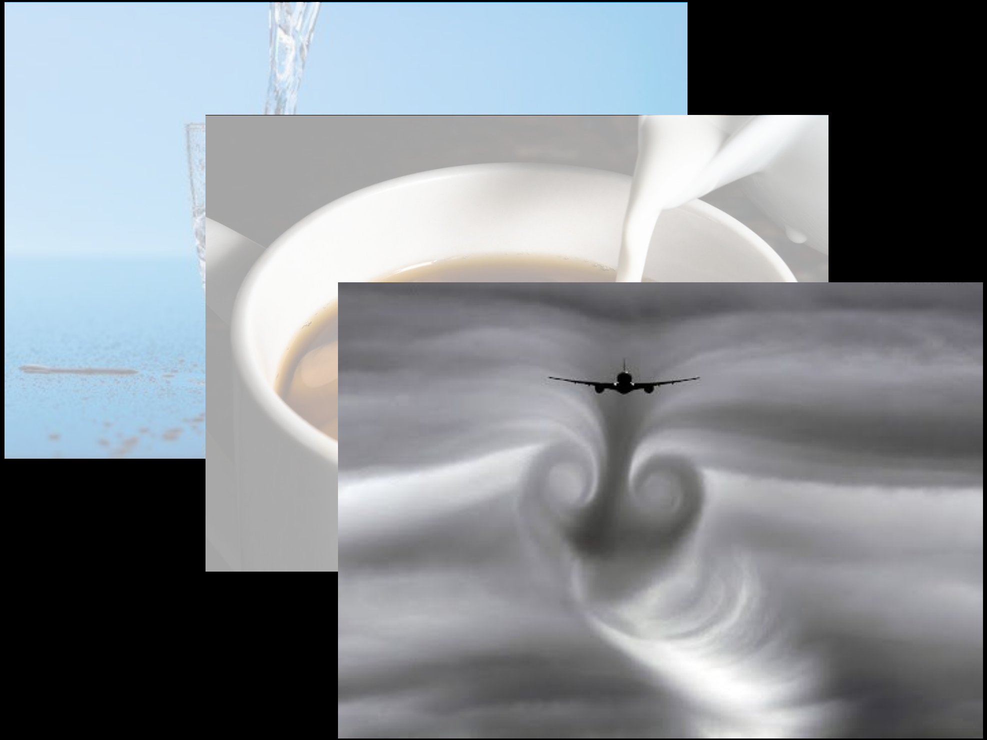

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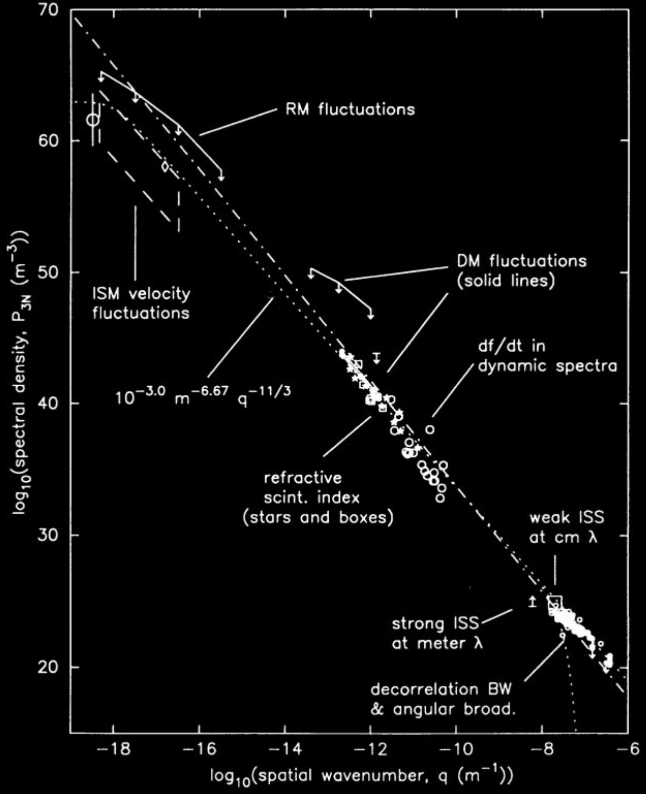
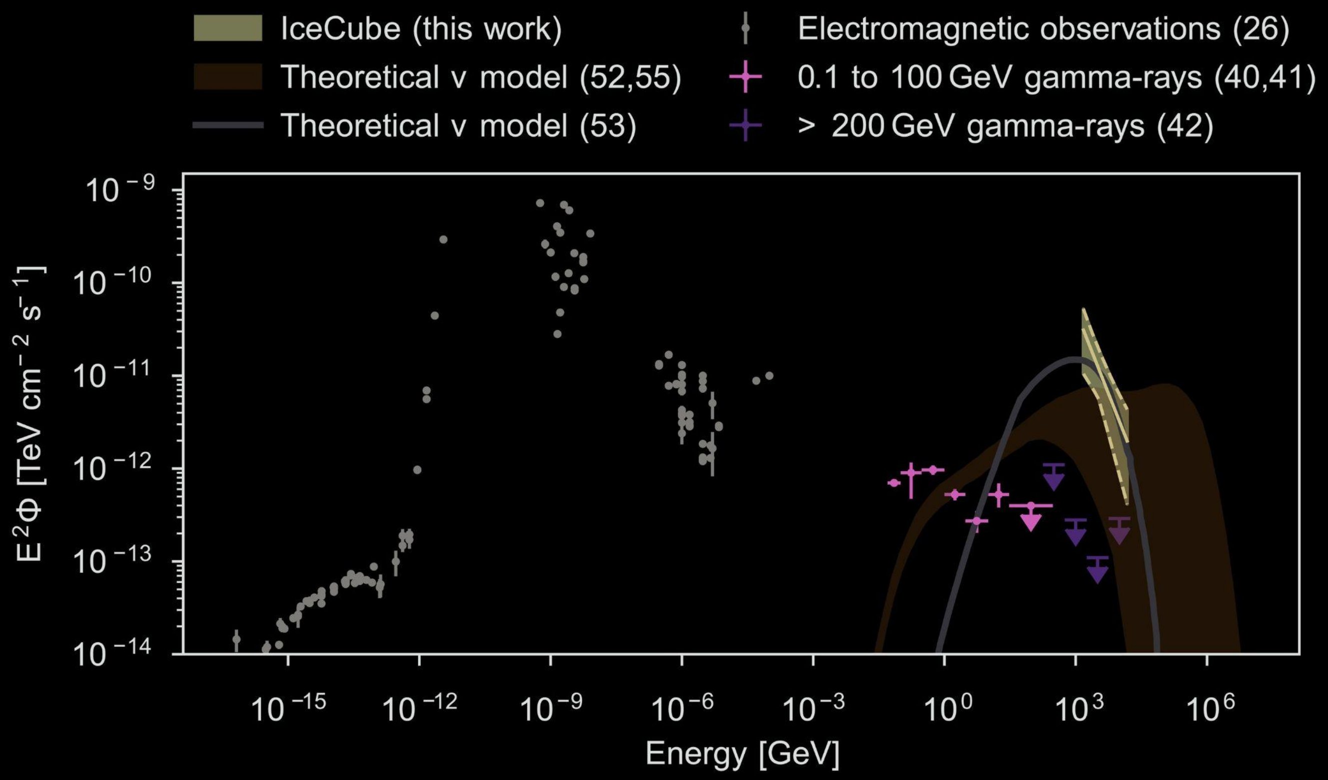



(Armstrong, Rickett & Spangler, 1995, ApJ)

# Neutrino VS gamma-ray flux from NGC1068




(IceCube Collaboration, 2022, Science)

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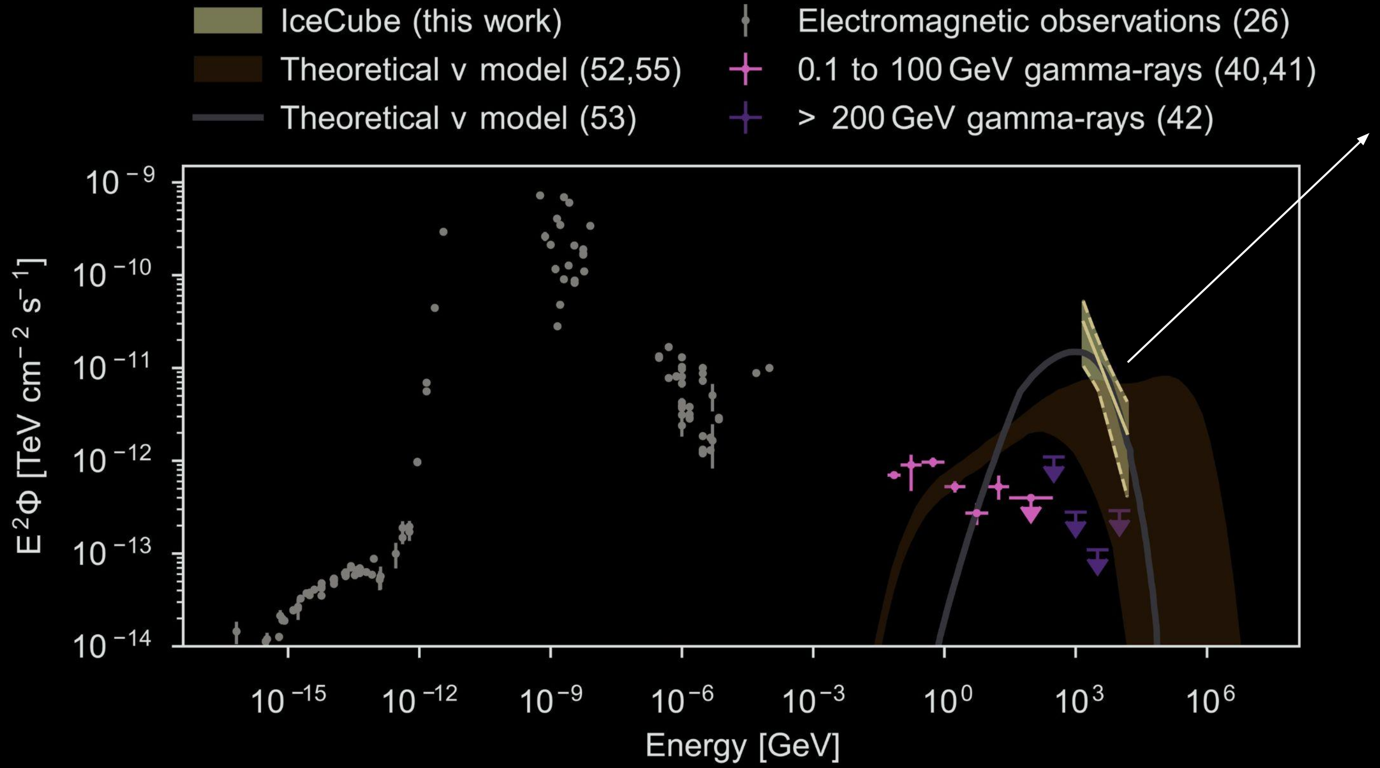


Neutrinos, a clue for the acceleration of protons to relativistic velocities

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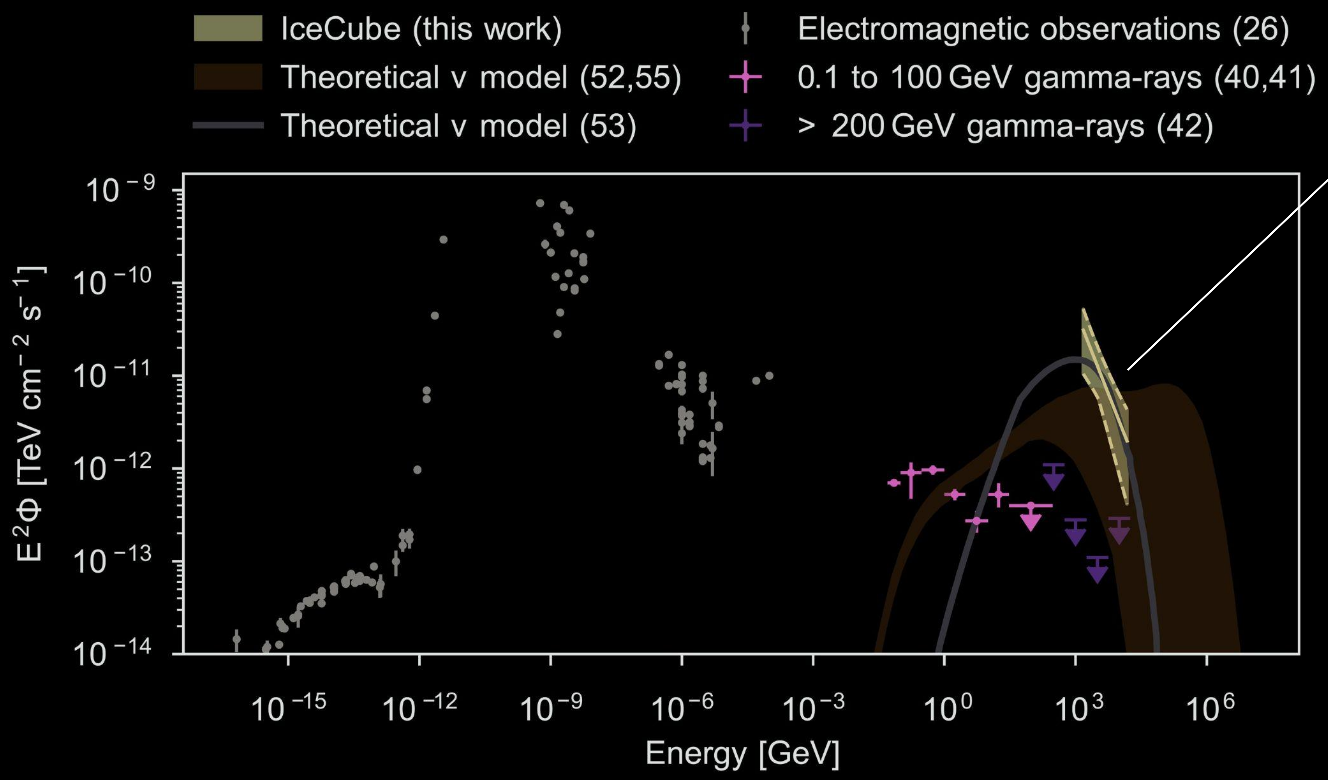


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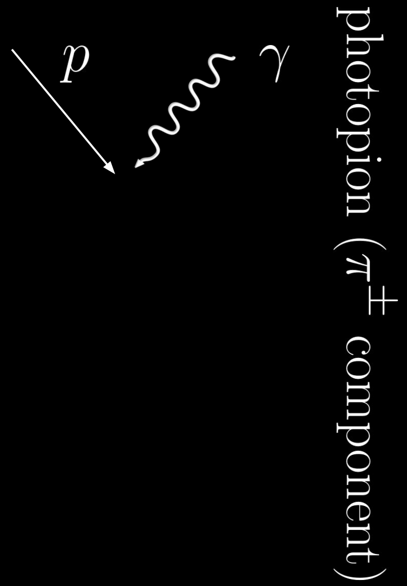


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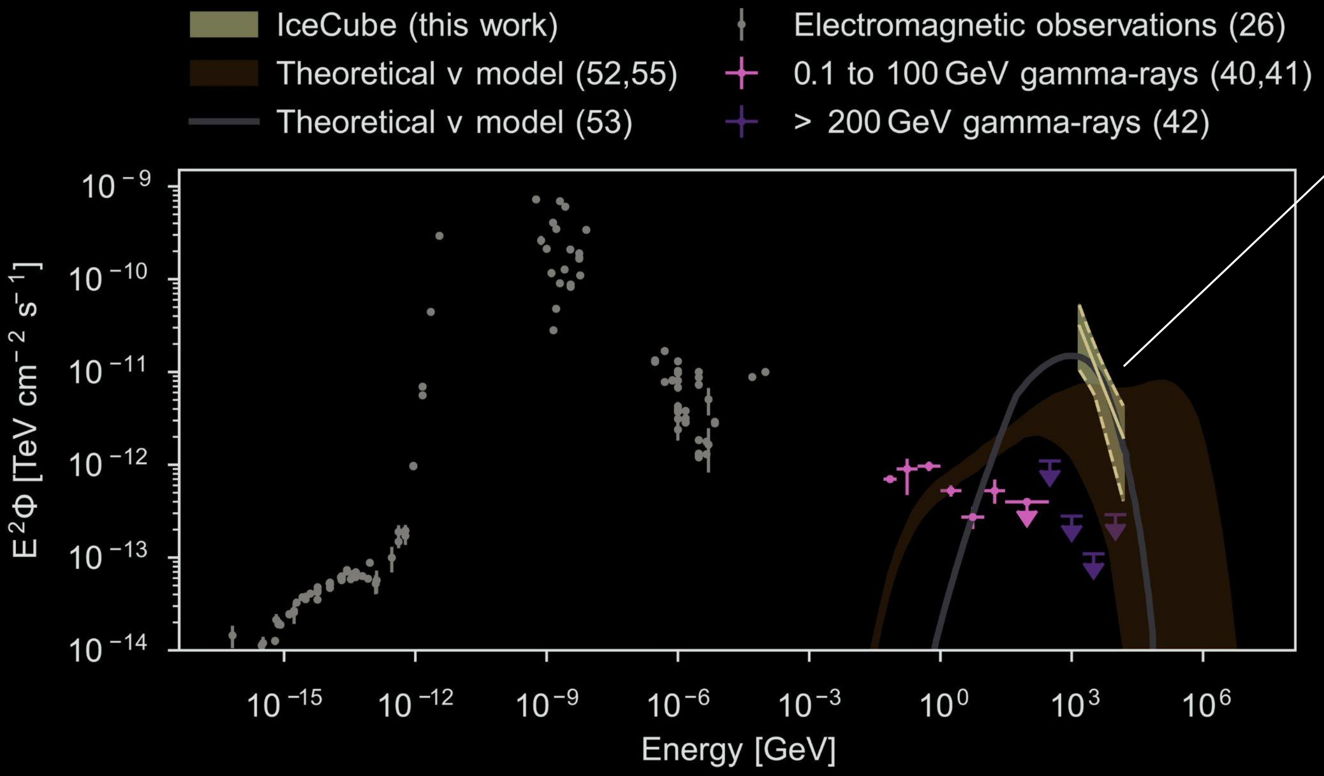


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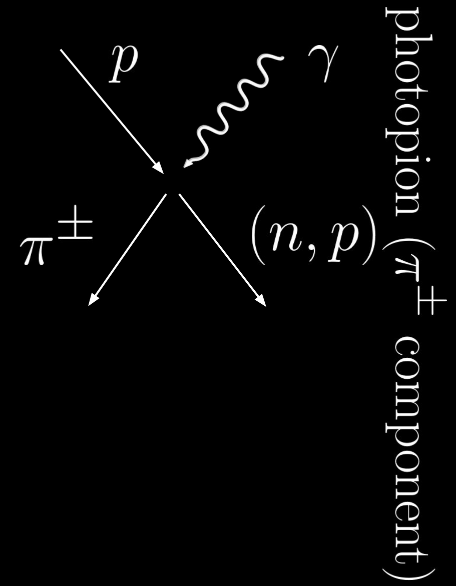


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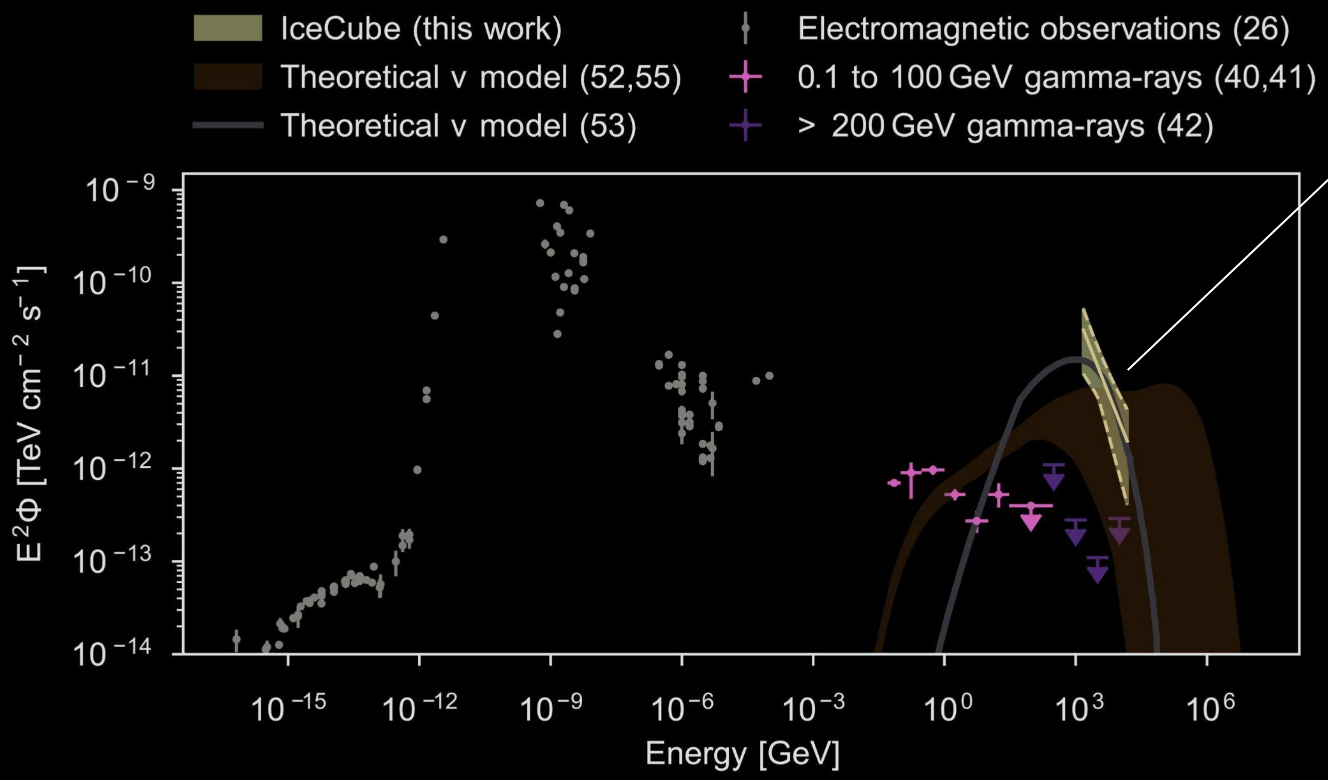


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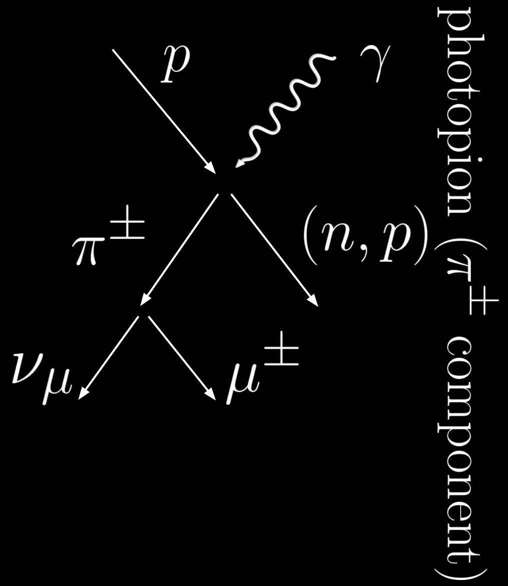


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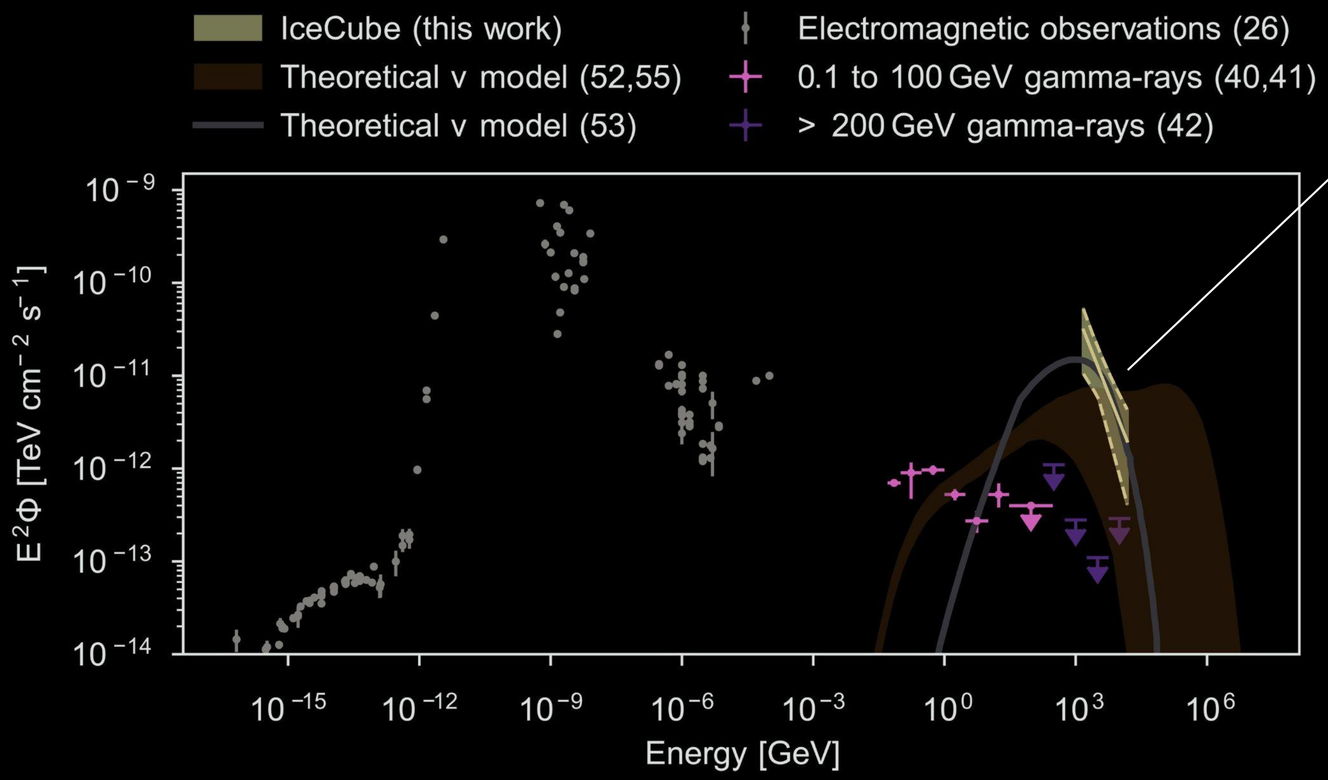


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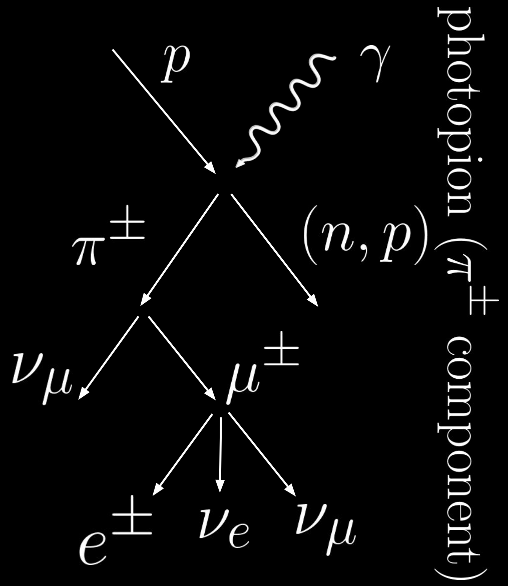

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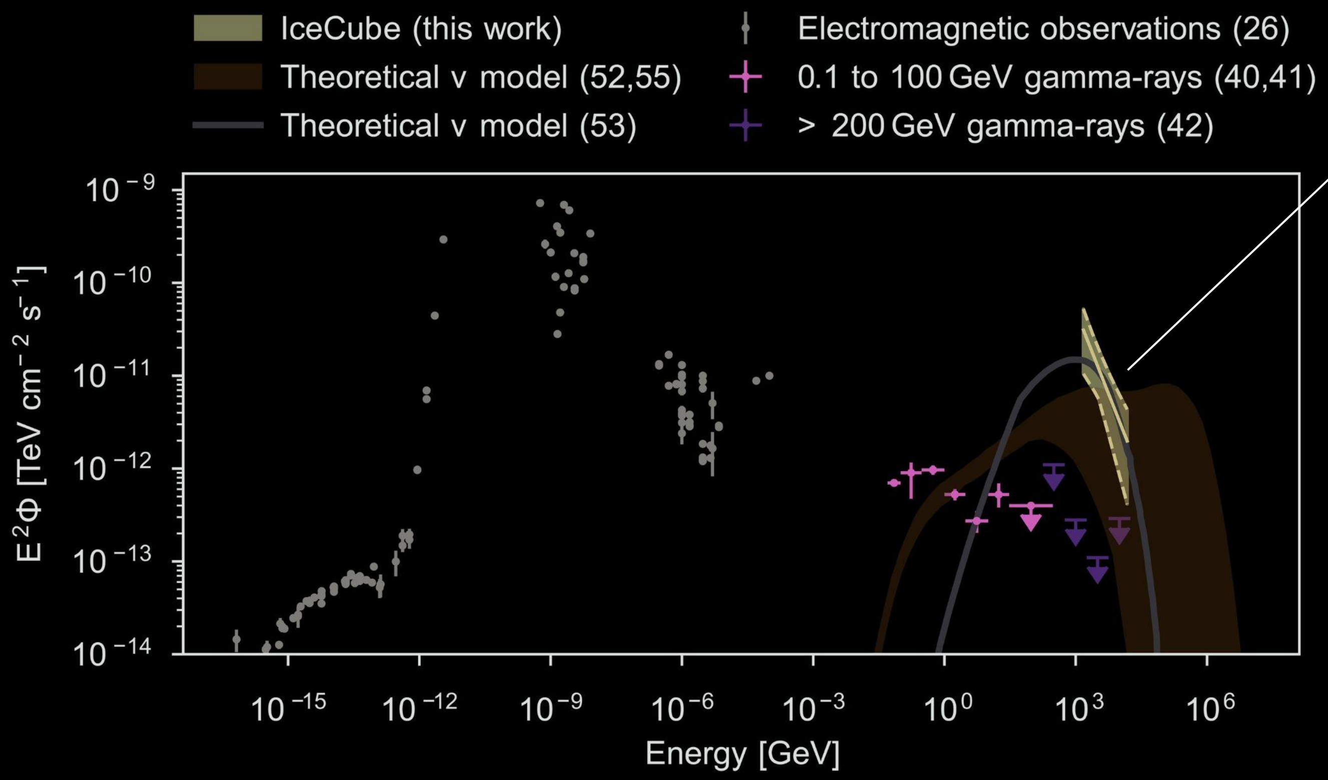


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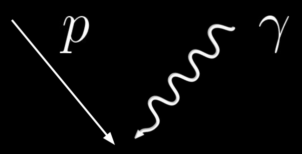


photopion ($\pi^0$ component)

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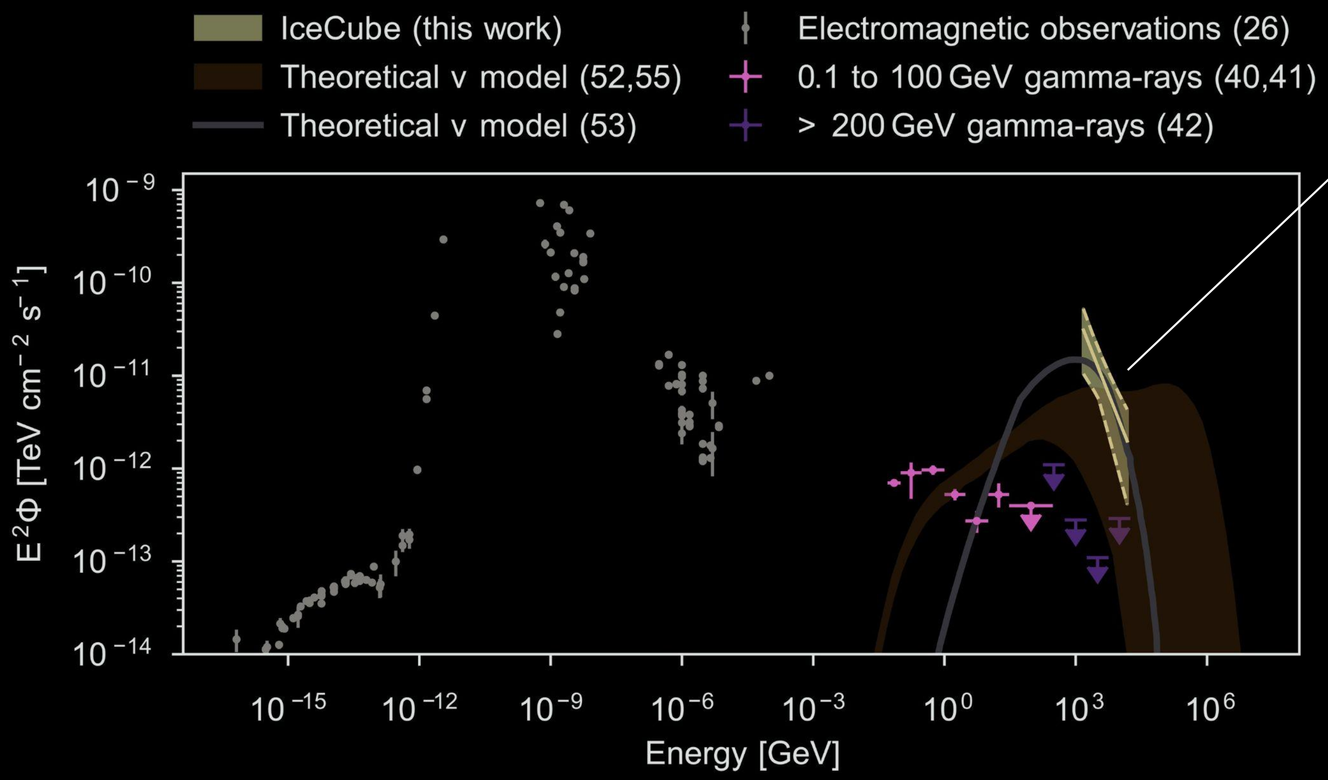


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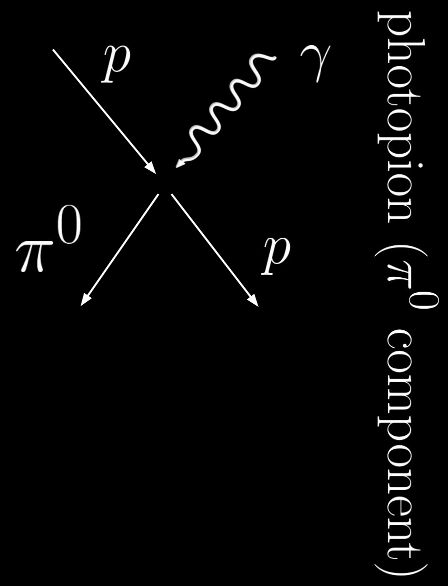

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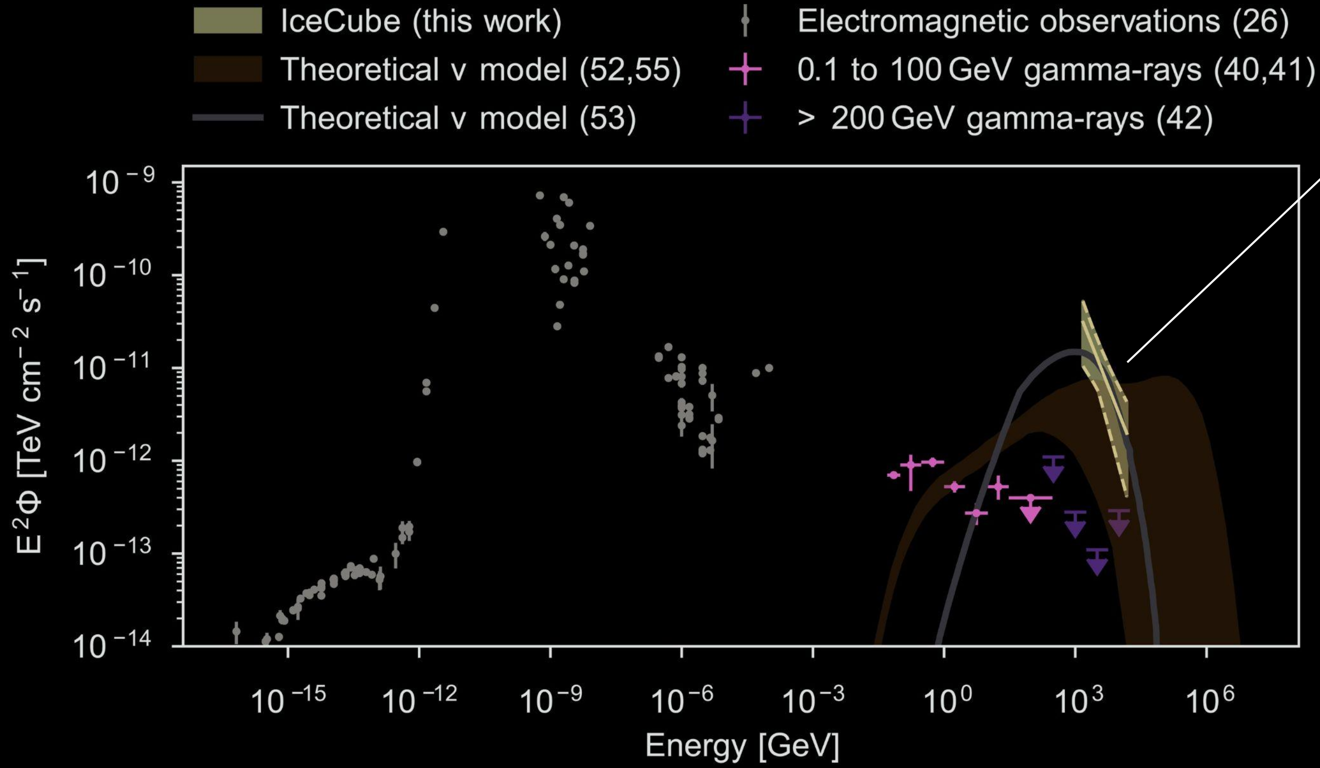


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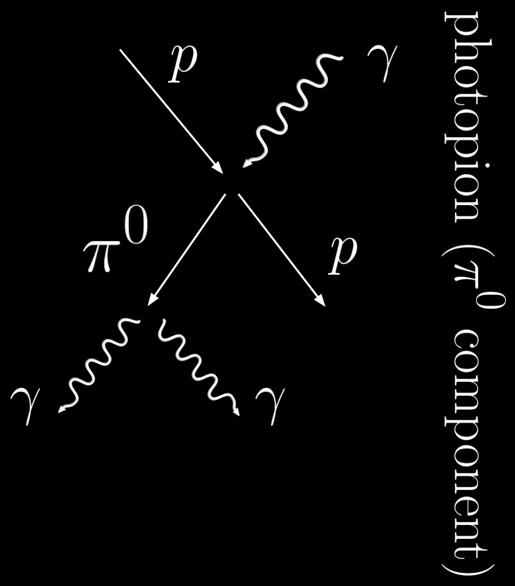


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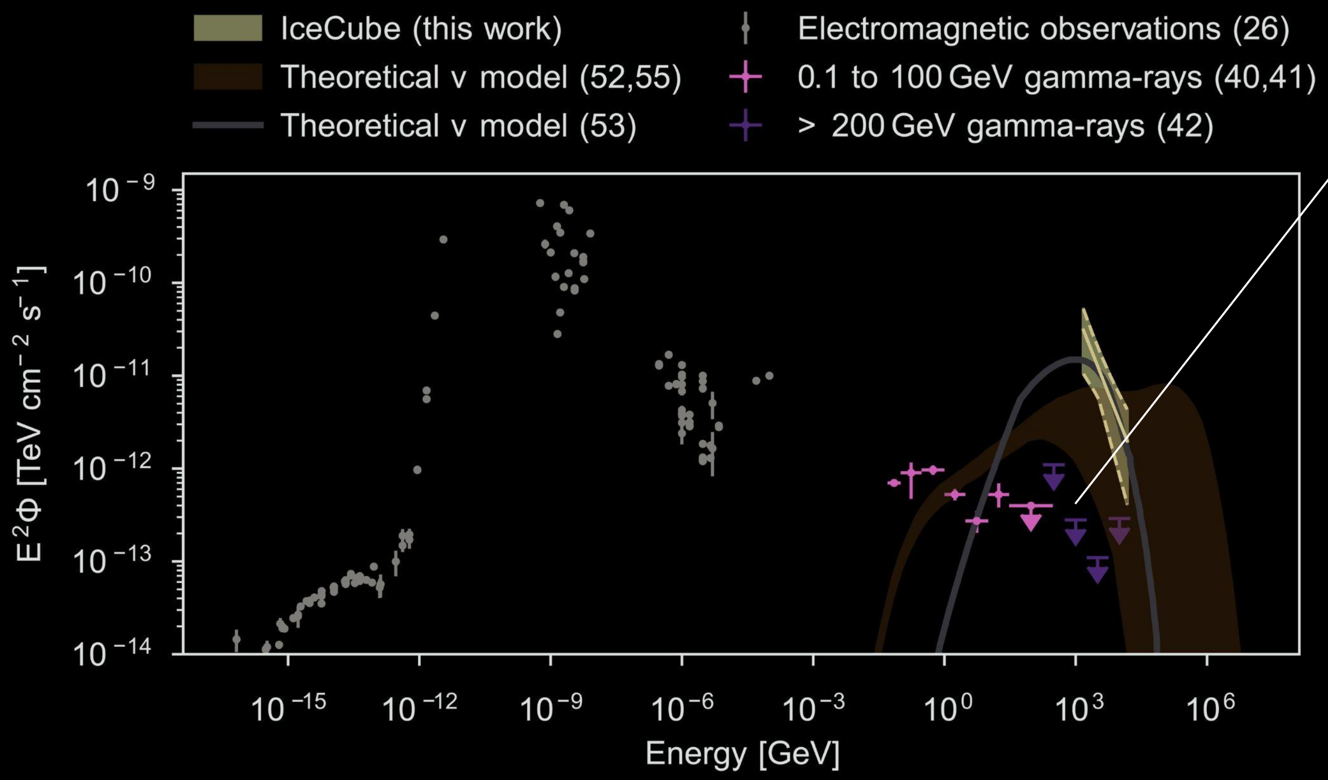


The absence of $\gamma$ rays indicates auto-absorption due to a dense photon field

(IceCube Collaboration, 2022, Science)

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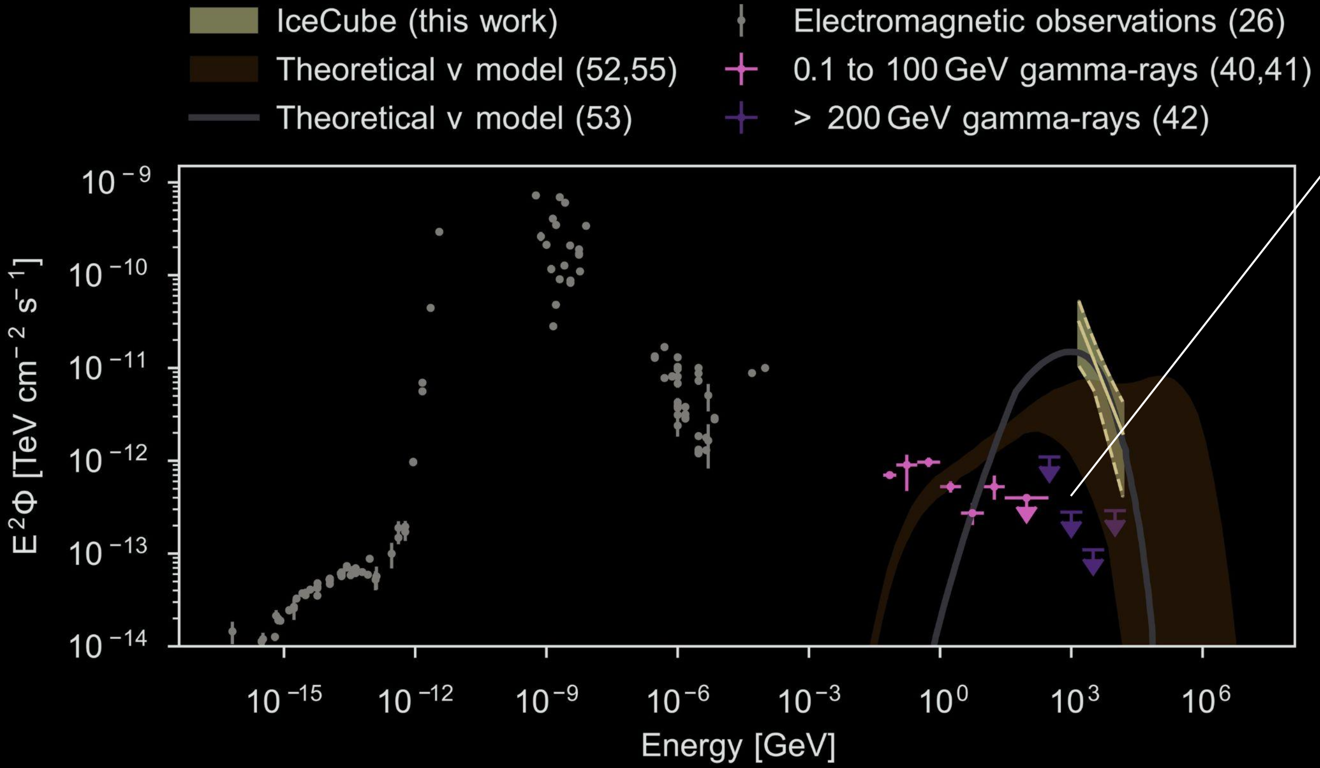


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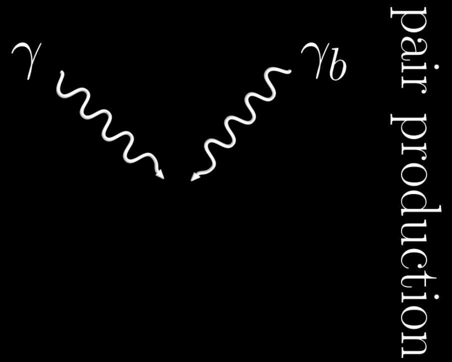


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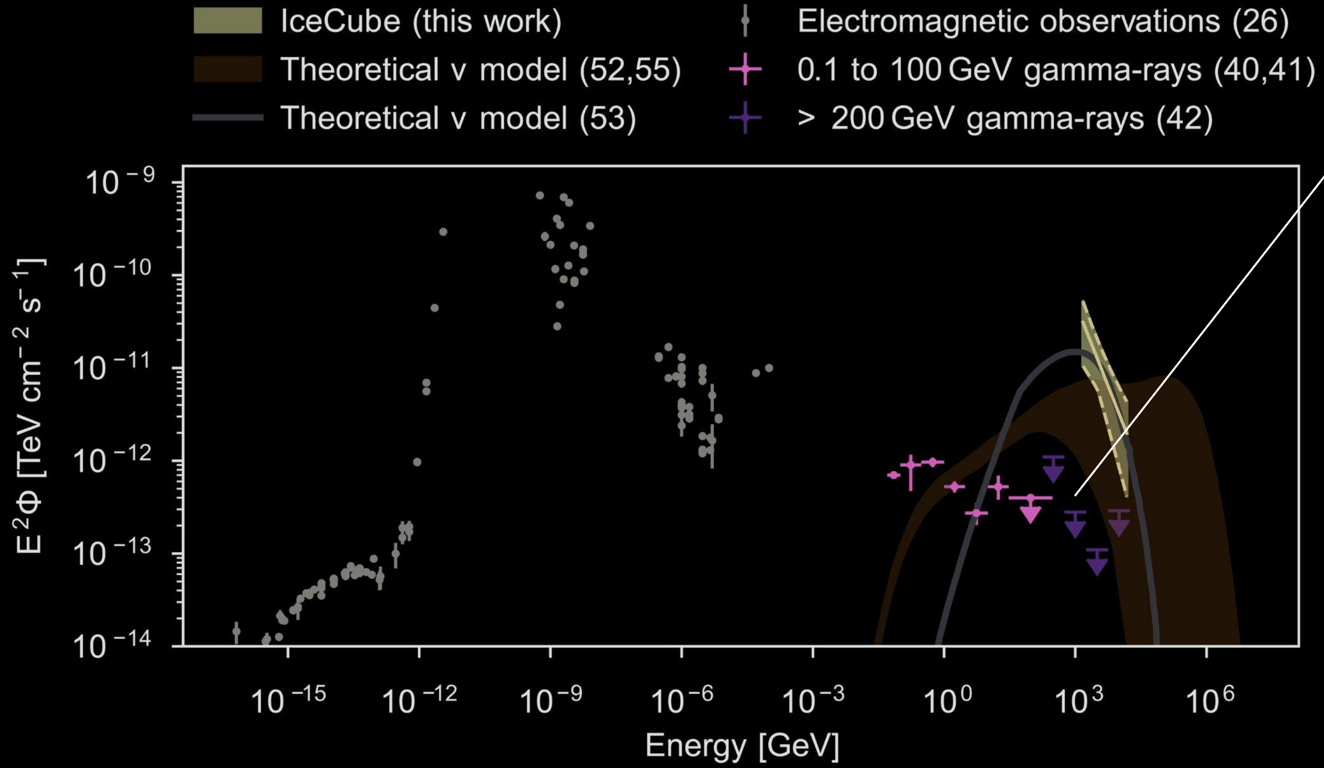


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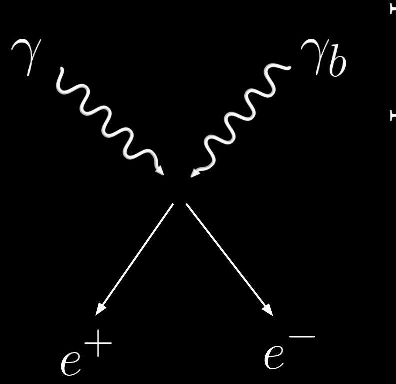


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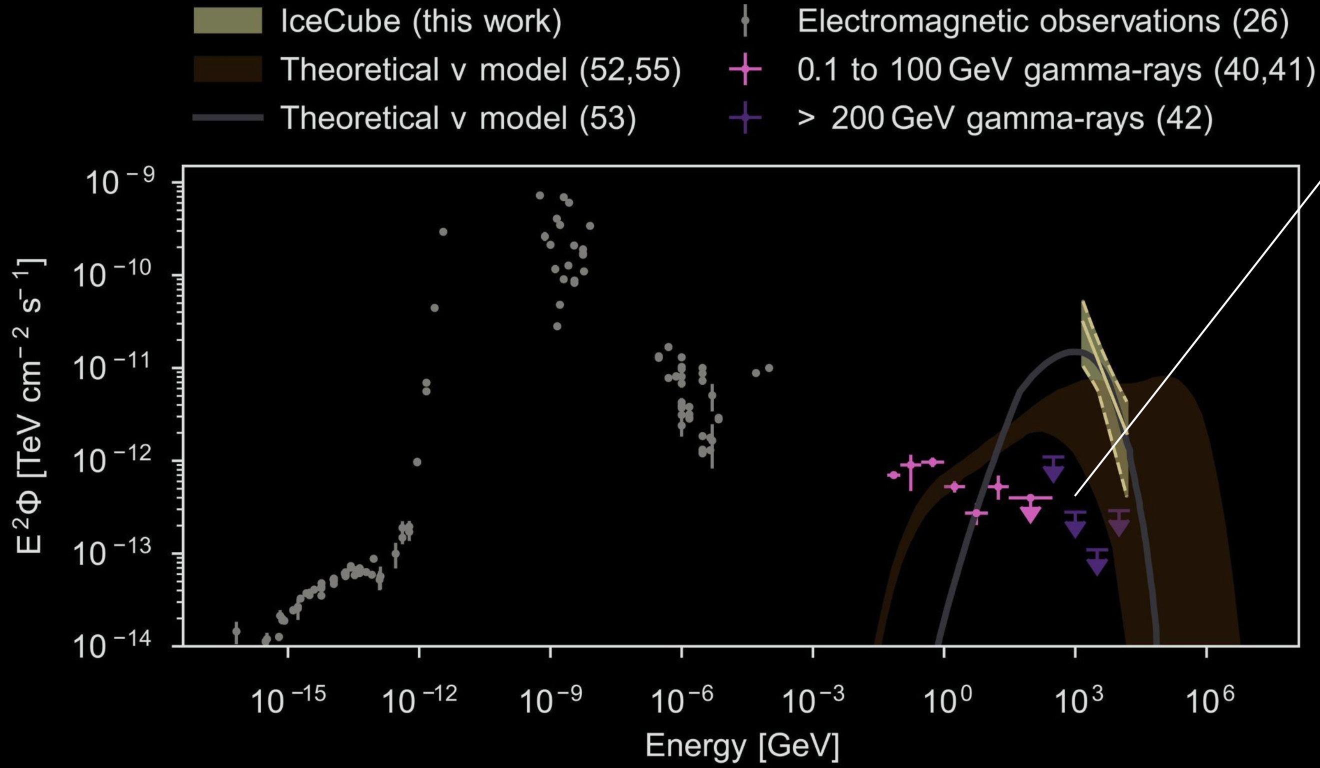


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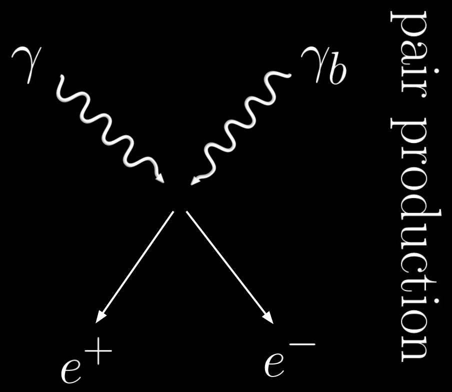


$\therefore$ The emission may become from the inner part of the AGN!

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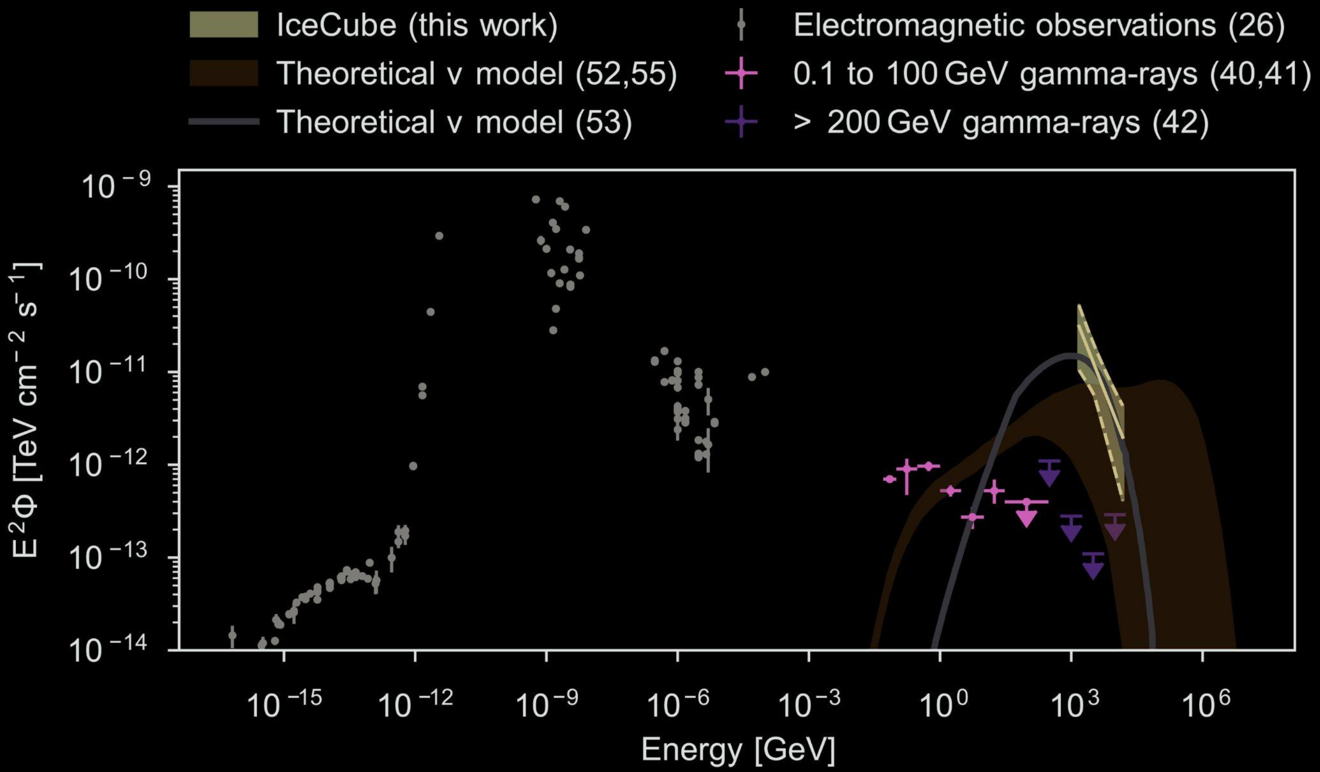


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What may accelerate these protons in the surroundings of the SMBH?

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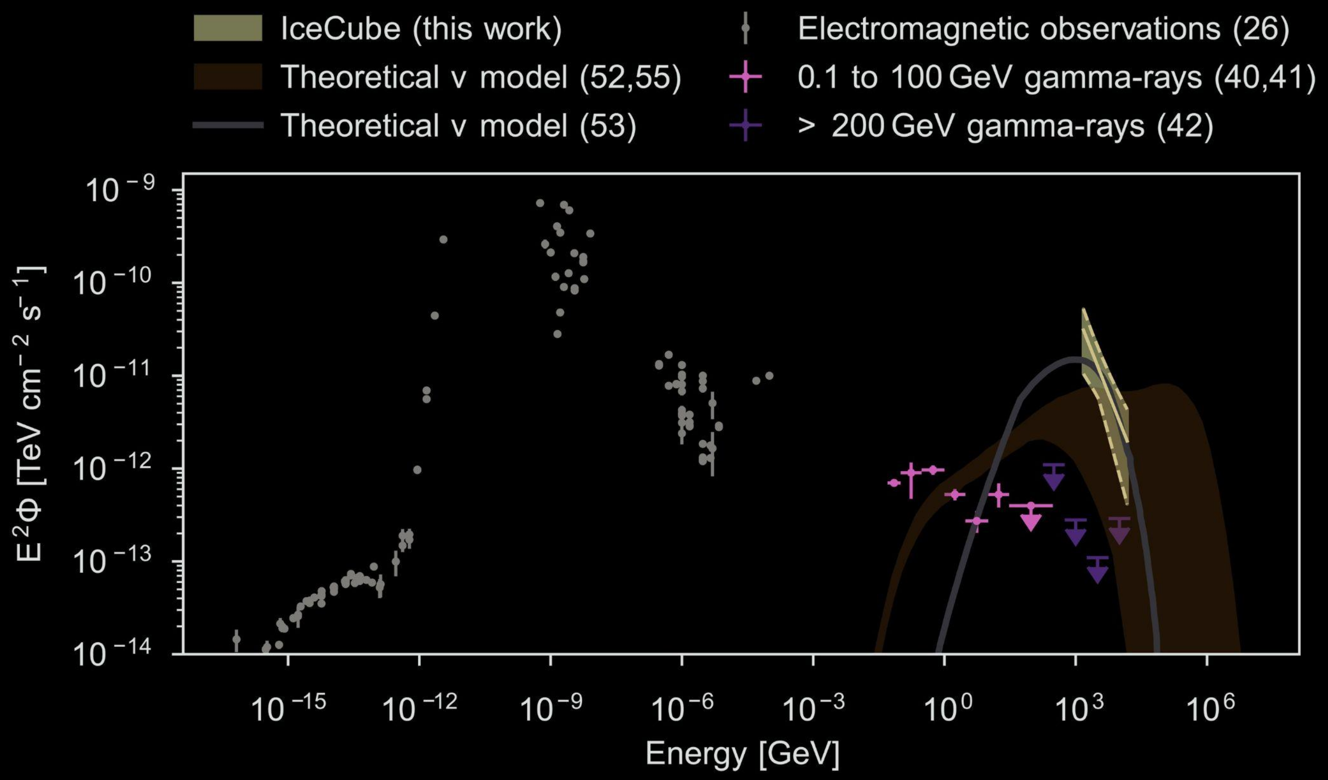


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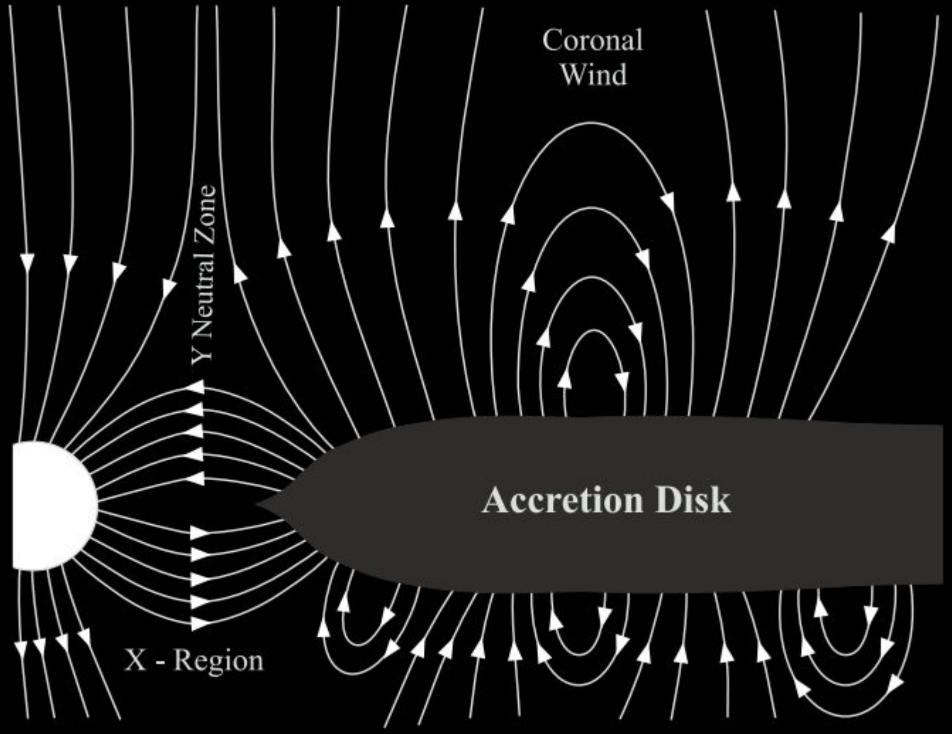
A: Magnetic Reconnection!

# Magnetic Reconnection around Black Holes

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




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

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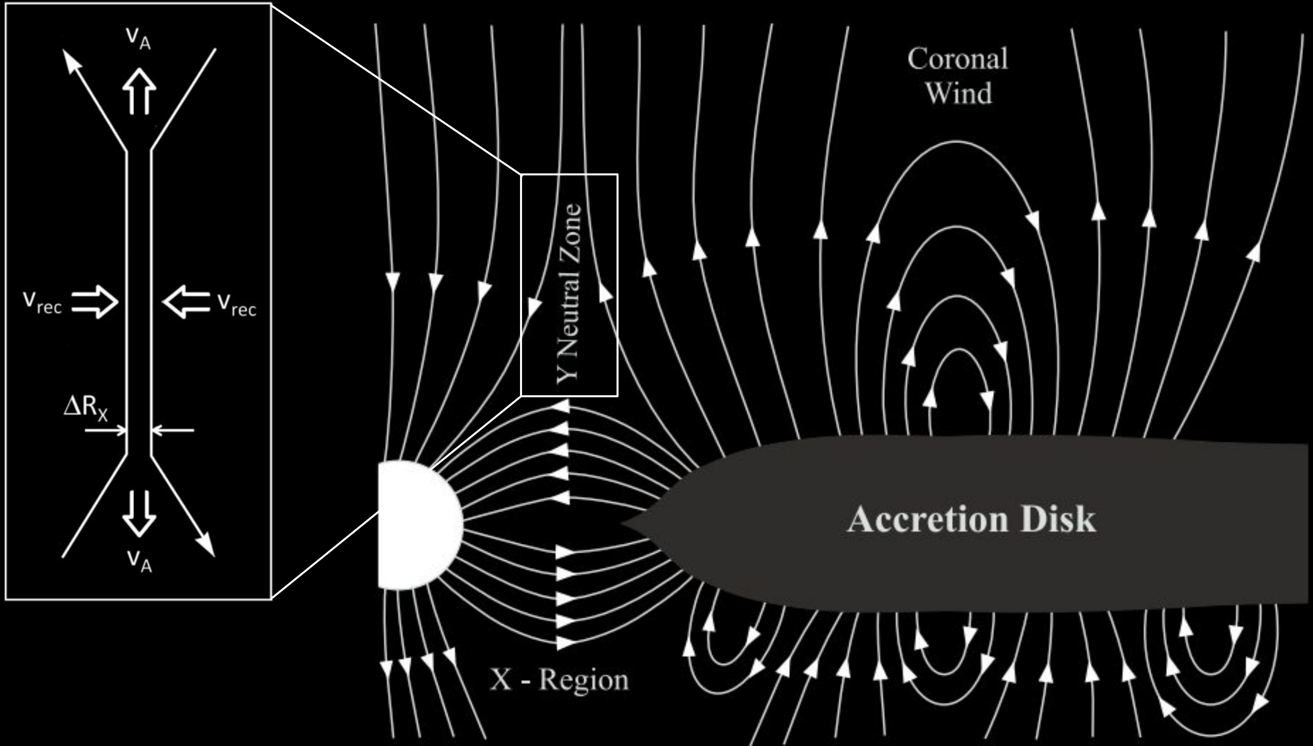


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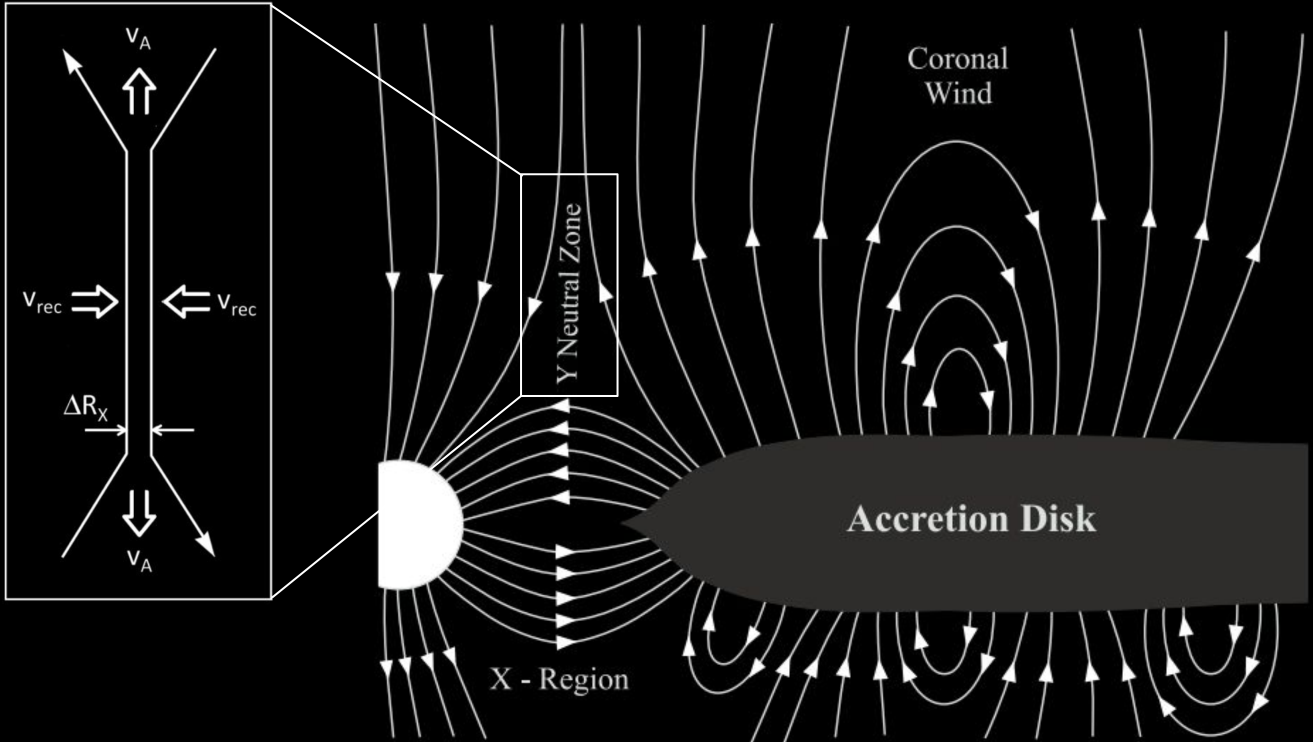
# Magnetic Reconnection around Black Holes

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

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

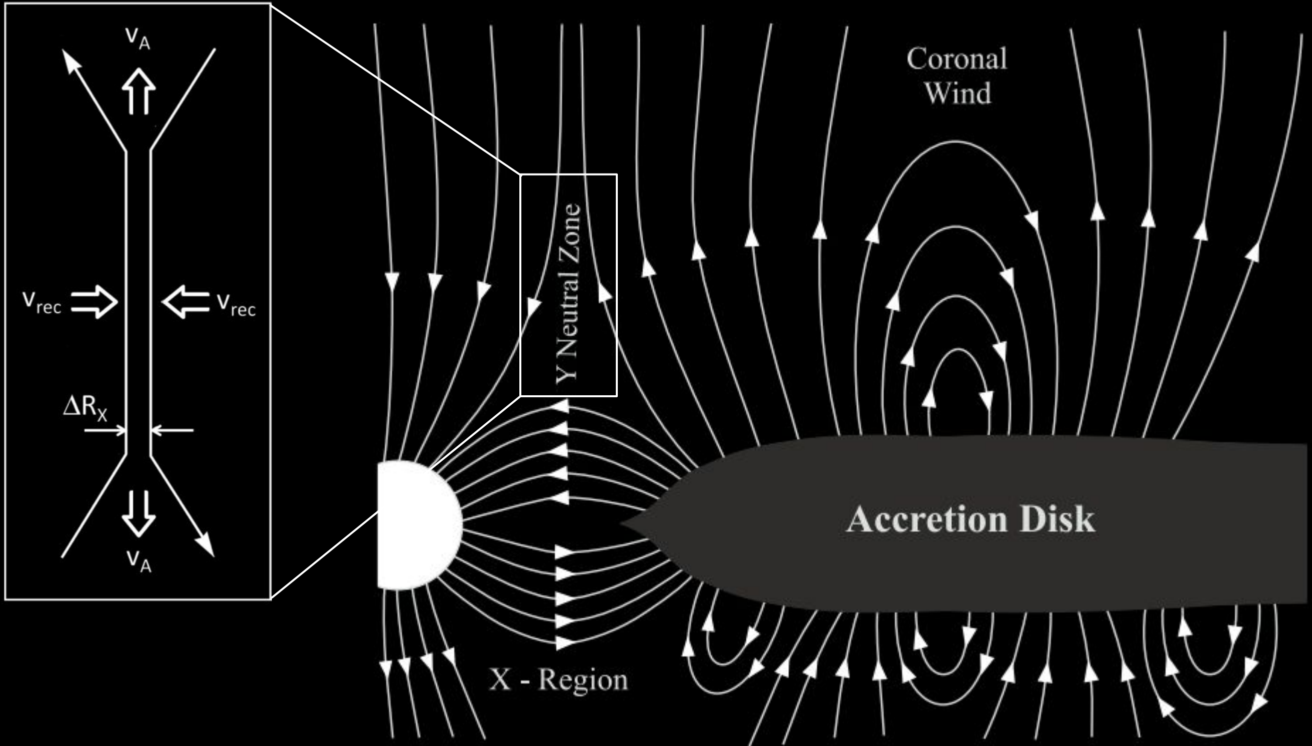



(de Gouveia Dal Pino & Lazarian, 2005, A&A)

# 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!

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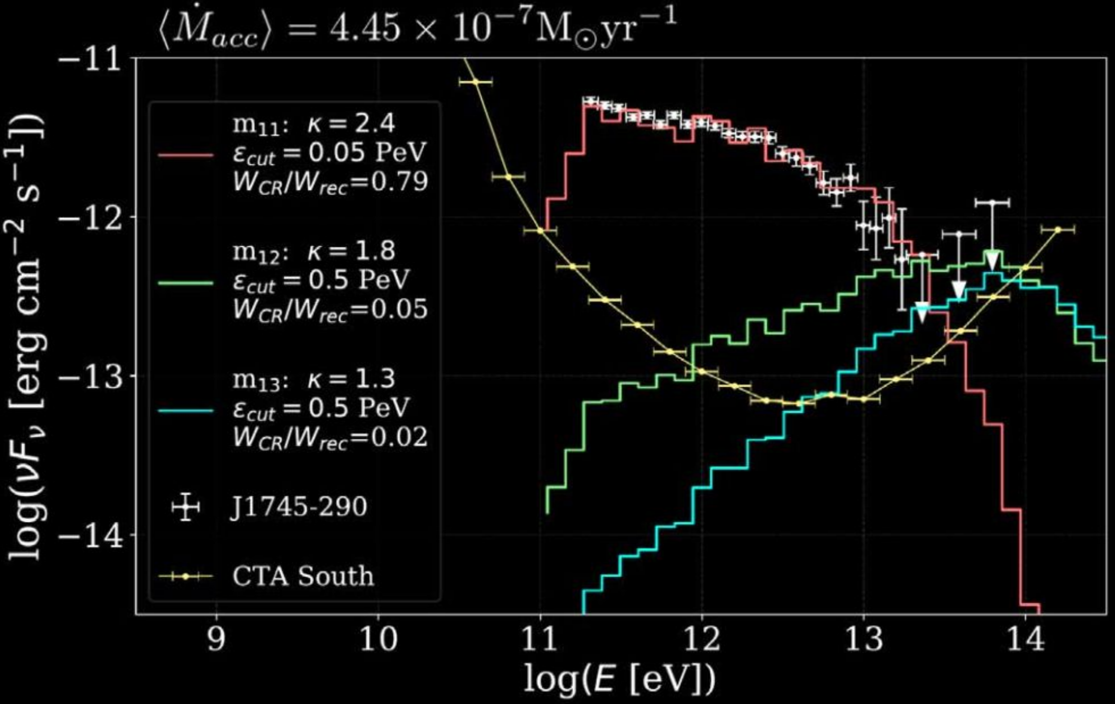
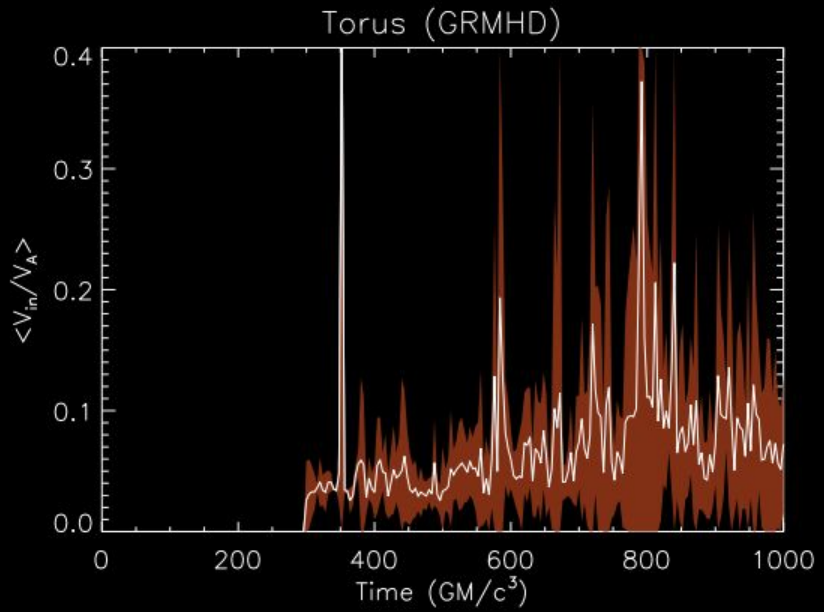
# Example of application: SgrA*

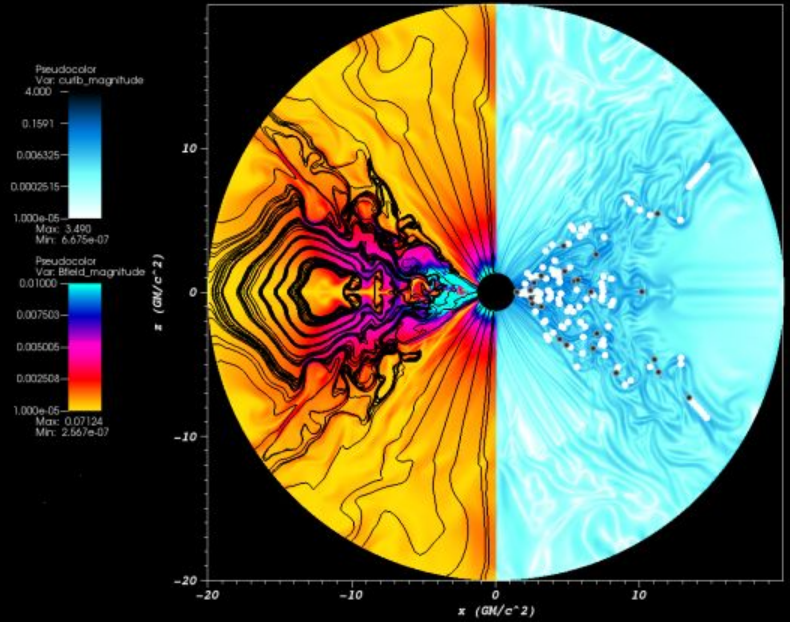



(Rodríguez-Ramírez, de Gouveia Dal Pino & Alves Batista, 2019, ApJ)

# Algorithm for search reconnection sites

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




(de Gouveia Dal Pino, Kowal, Kadowaki et al. 2018)

# Testing theory with MHD simulations

We use the AMUN code (Kowal, 2009) to solve
the isothermal non-ideal MHD equations:

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

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

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

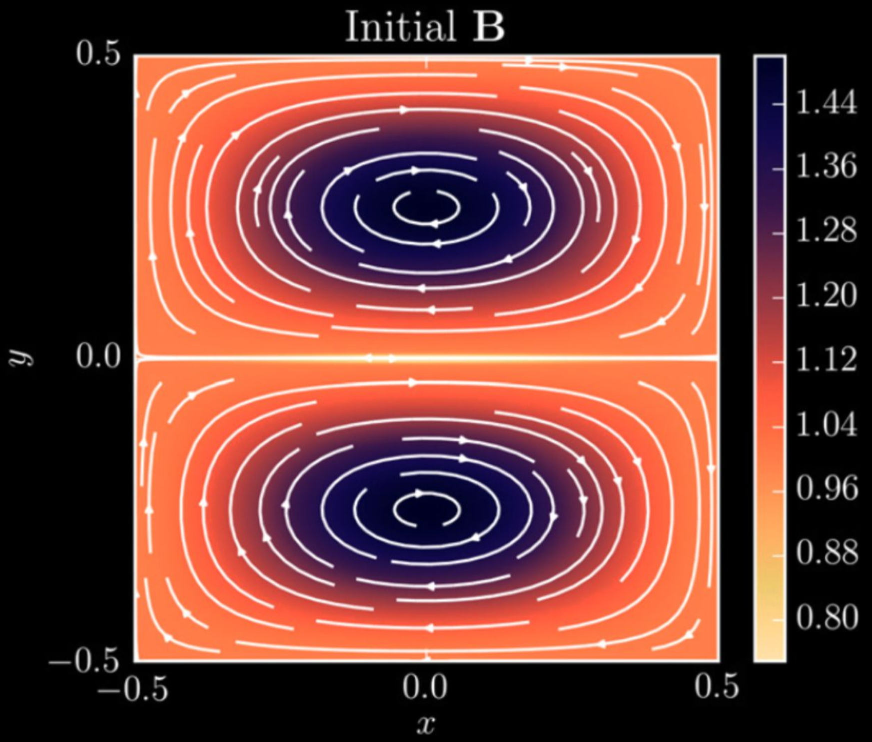
# Testing theory with MHD simulations

and the initial magnetic field is given by

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

where

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



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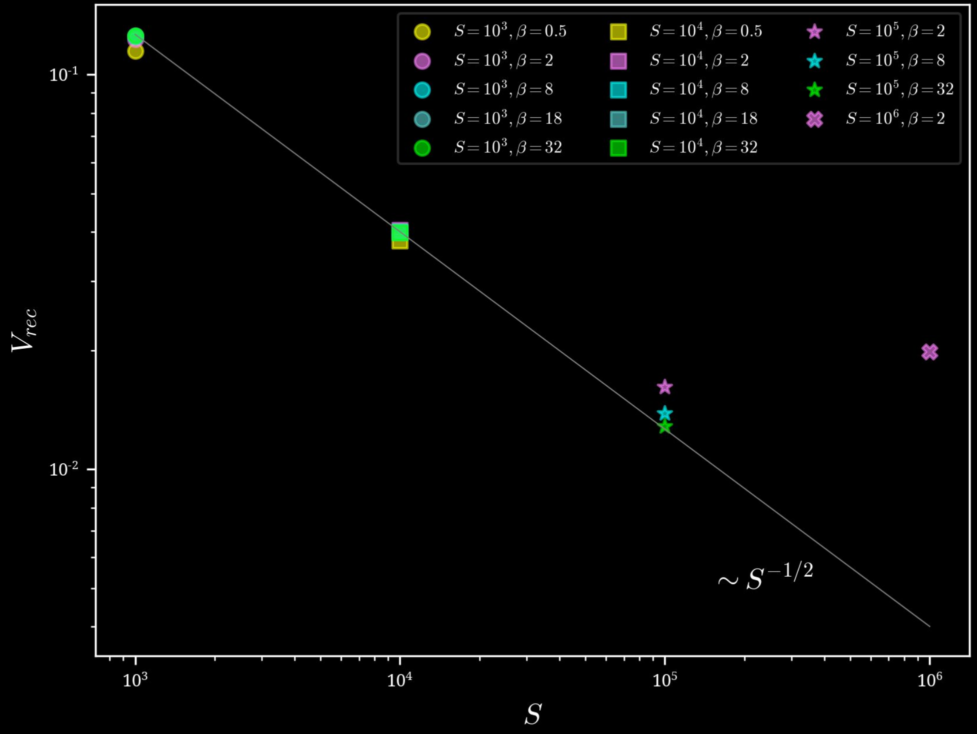


(Vicentin et al., *in prep.*)

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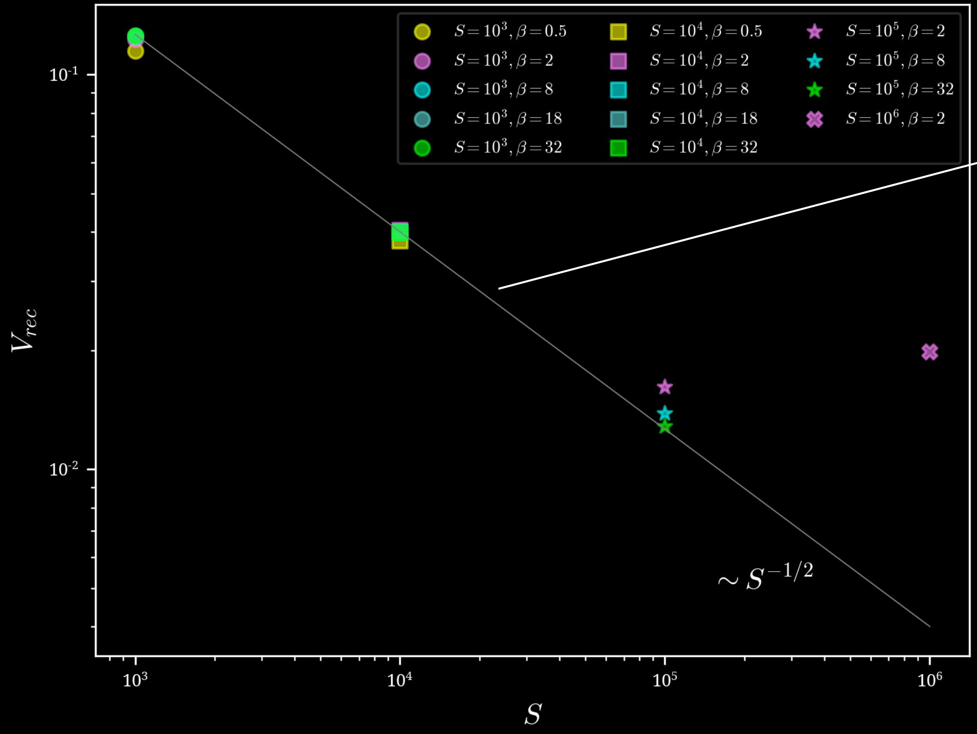


We can recover the Sweet-Parker regime for low-Lundquist numbers!

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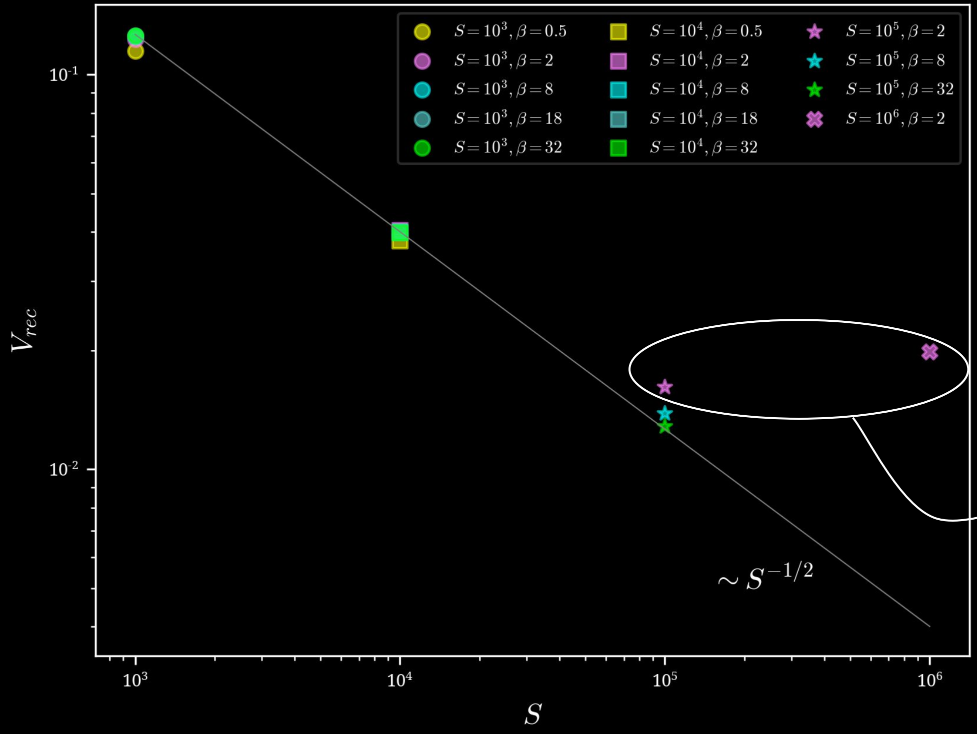
# 💻 Testing theory with MHD simulations

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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)

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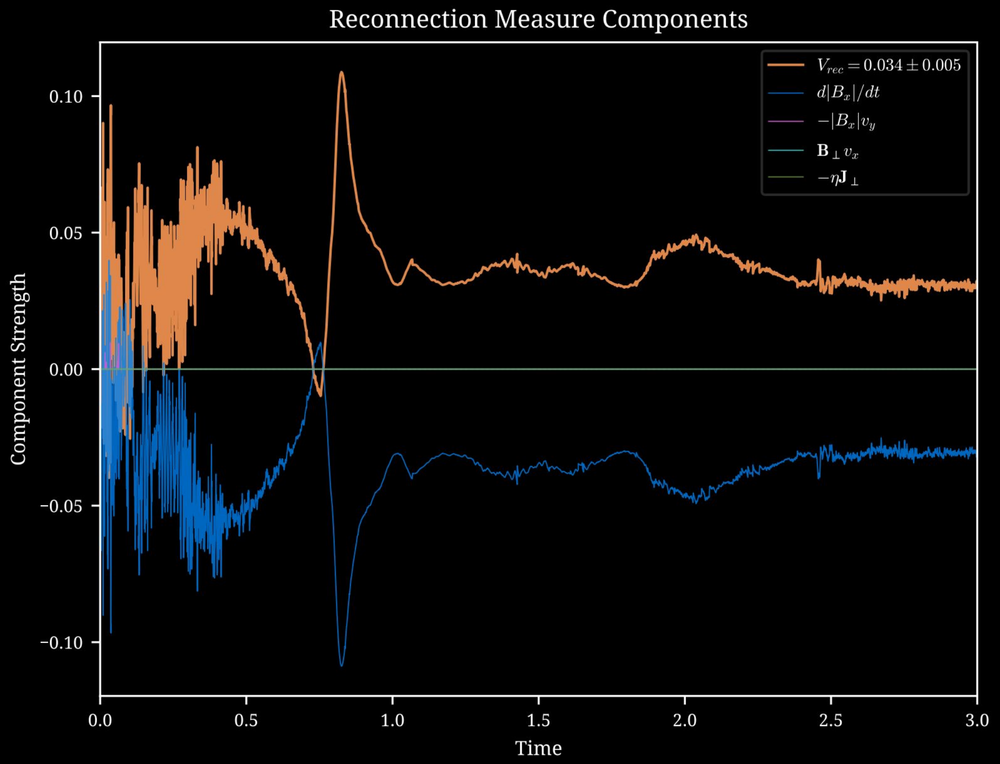


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For the case where we inject forced turbulence initially in the domain (up to $0.1\, t_A$), we can reach high values of

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

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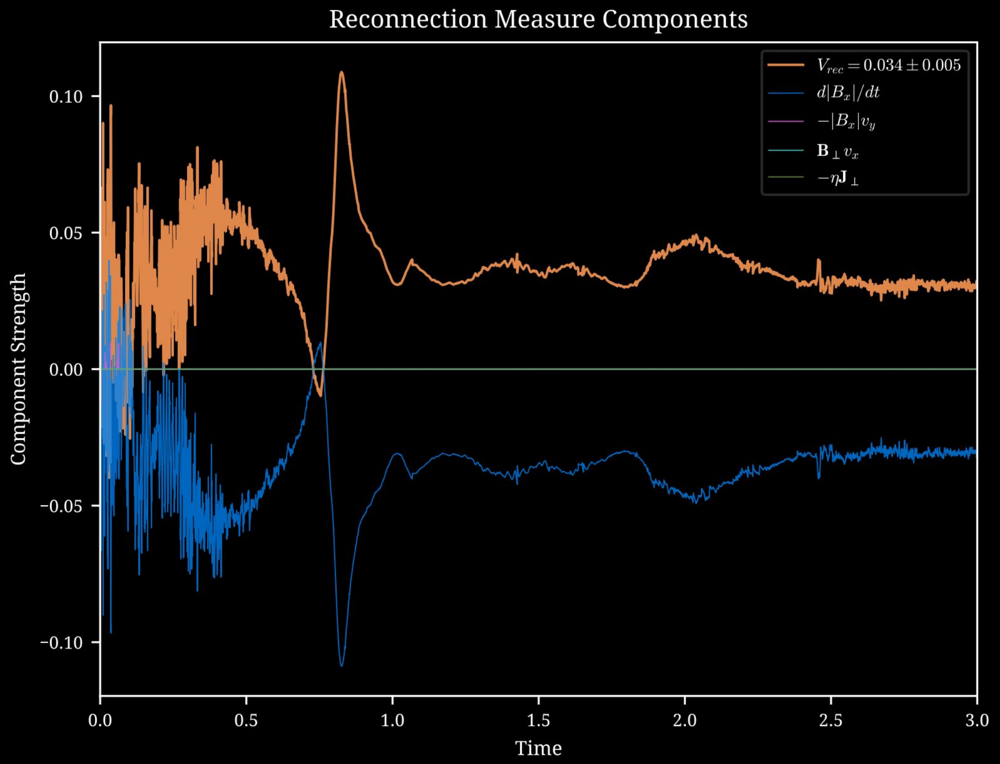


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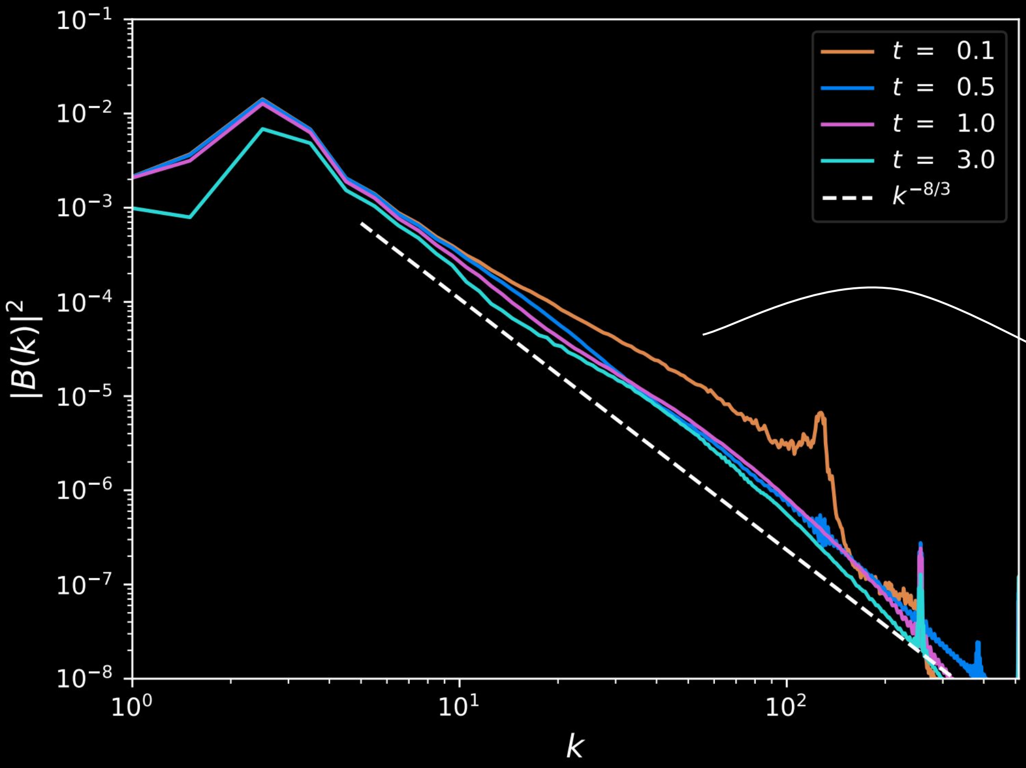
For the case where we inject forced turbulence initially in the domain (up to $0.1\, t_A$), we can reach high values of

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

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!

# Thank you!


Any question?

Giovani H. Vicentin

IAG USP

+55 (11) 98714-5080

giovani.vicentin@usp.br