leptonic and hadronic models with CRPropa: the case of Sgr A*

Rafael Alves Batista

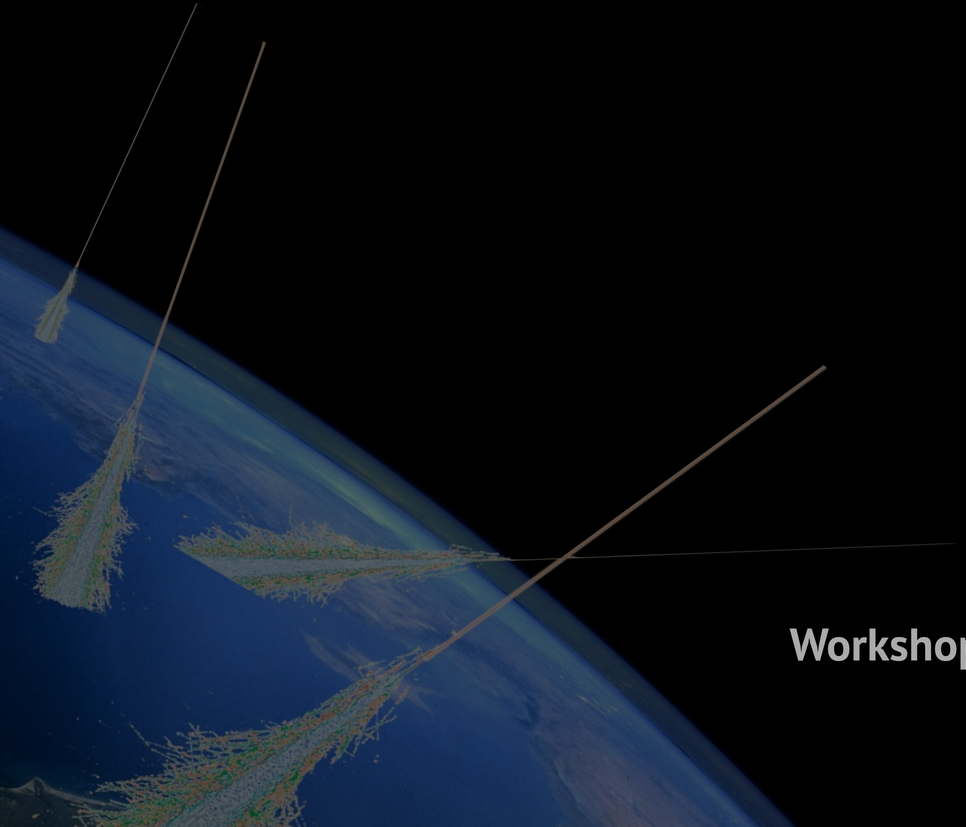
Instituto de Física Teórica (IFT UAM-CSIC)

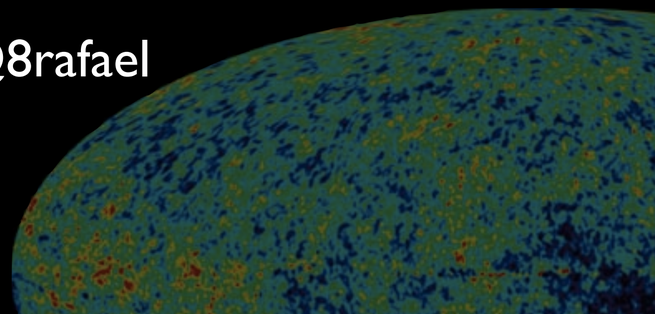
Universidad Autónoma de Madrid

rafael.alvesbatista@uam.es

www.8rafael.com

@8rafael



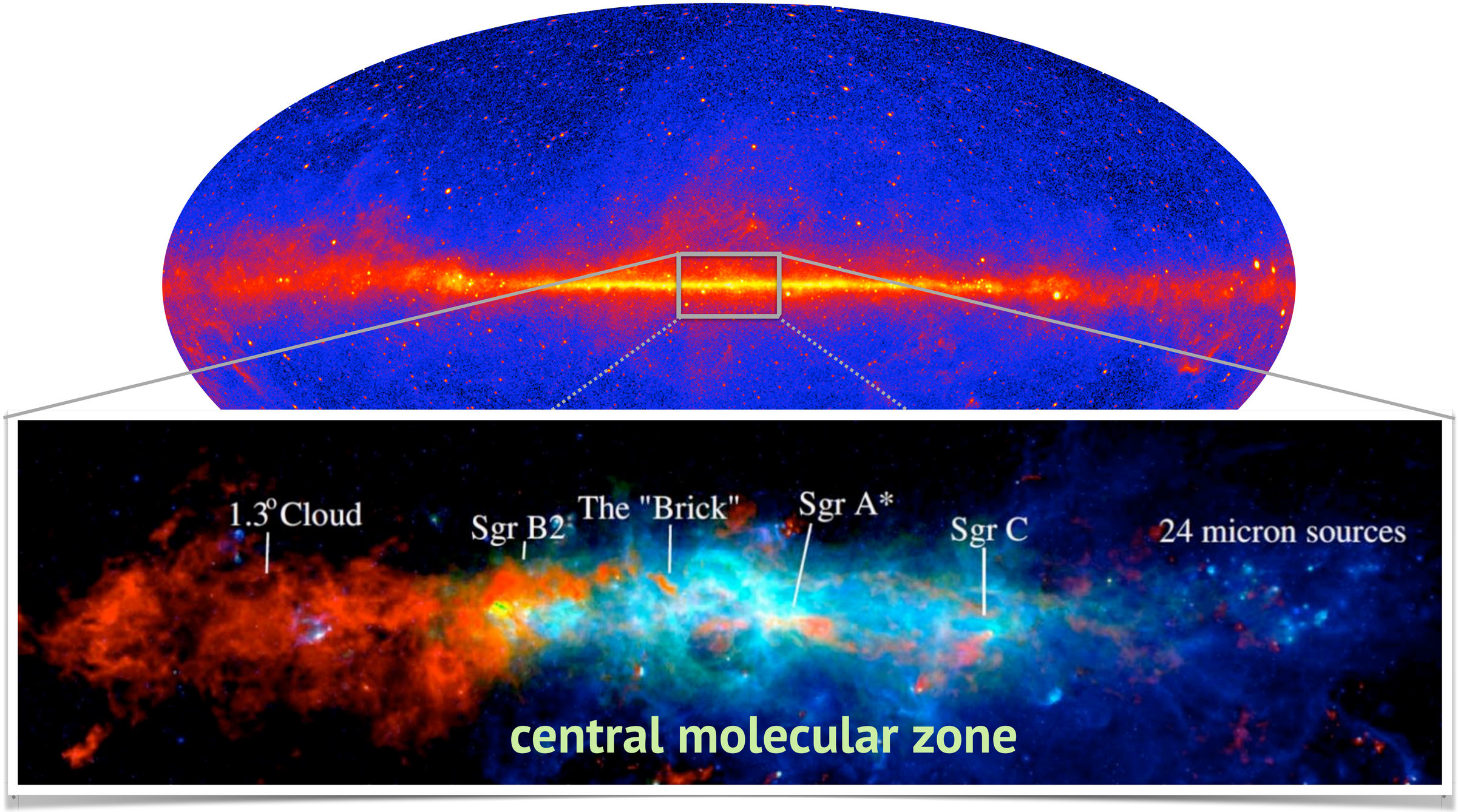


Workshop on Numerical Multimessenger Modelling

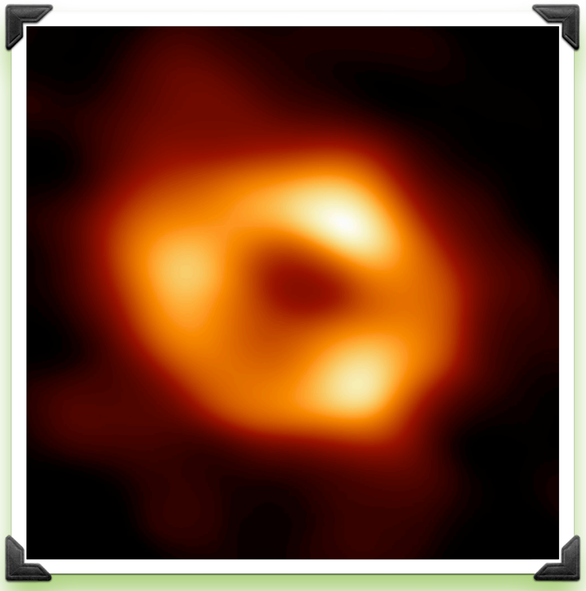
27 February 2023

Bochum

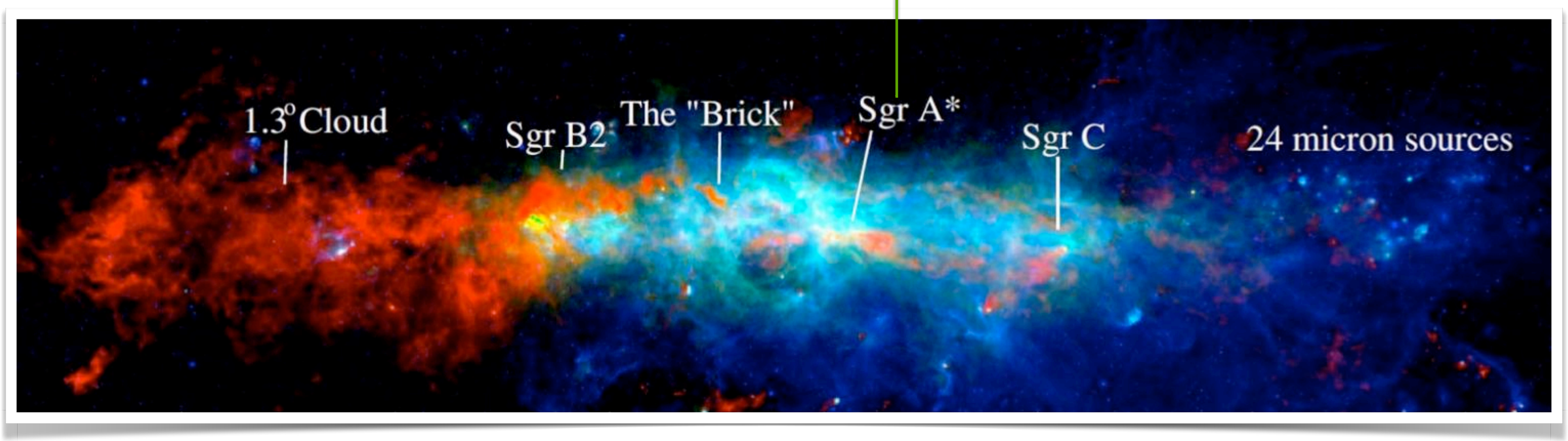
the galactic centre region



SgrA*: the black hole



the central SMBH

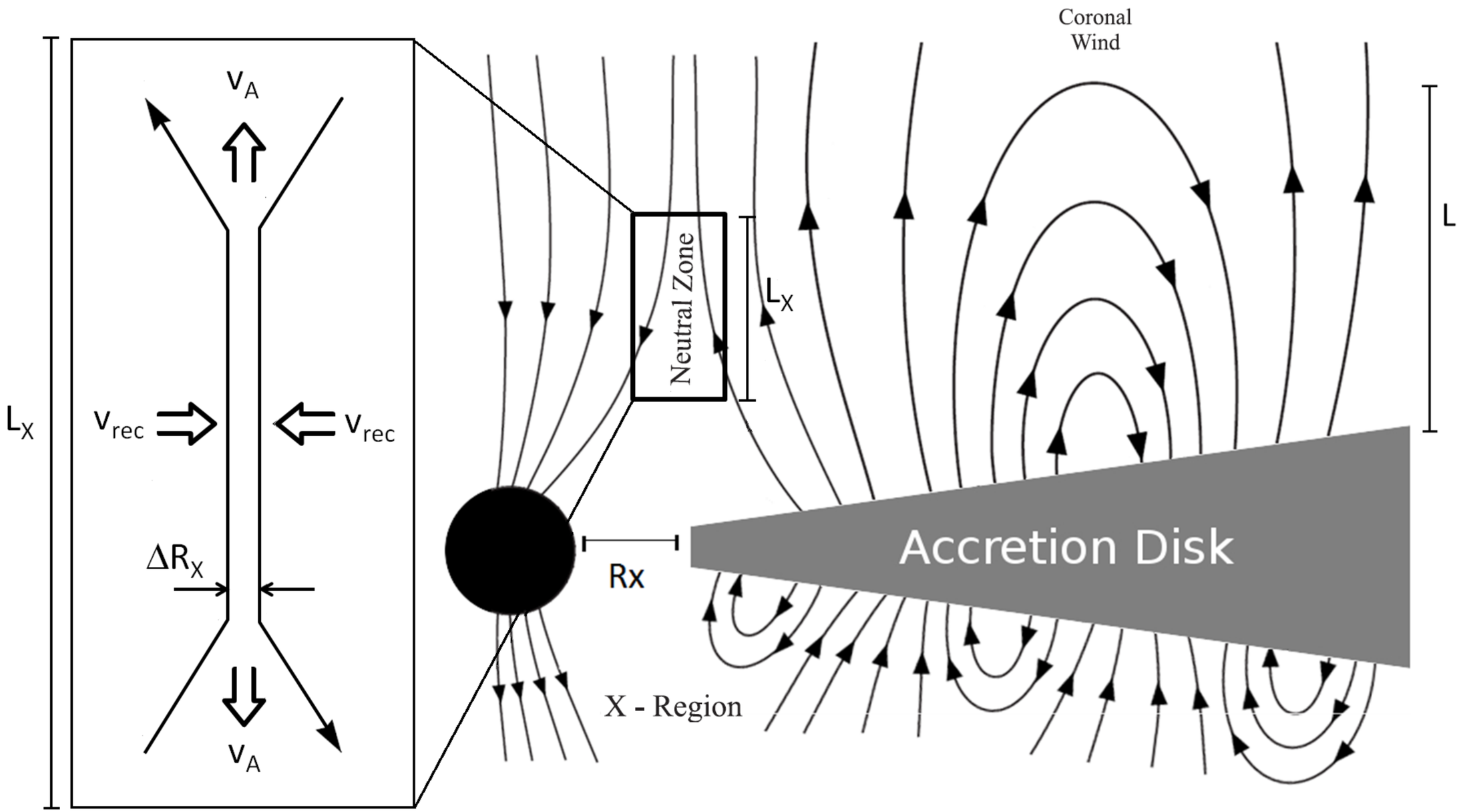


a glimpse into SgrA*

particle acceleration via magnetic reconnection

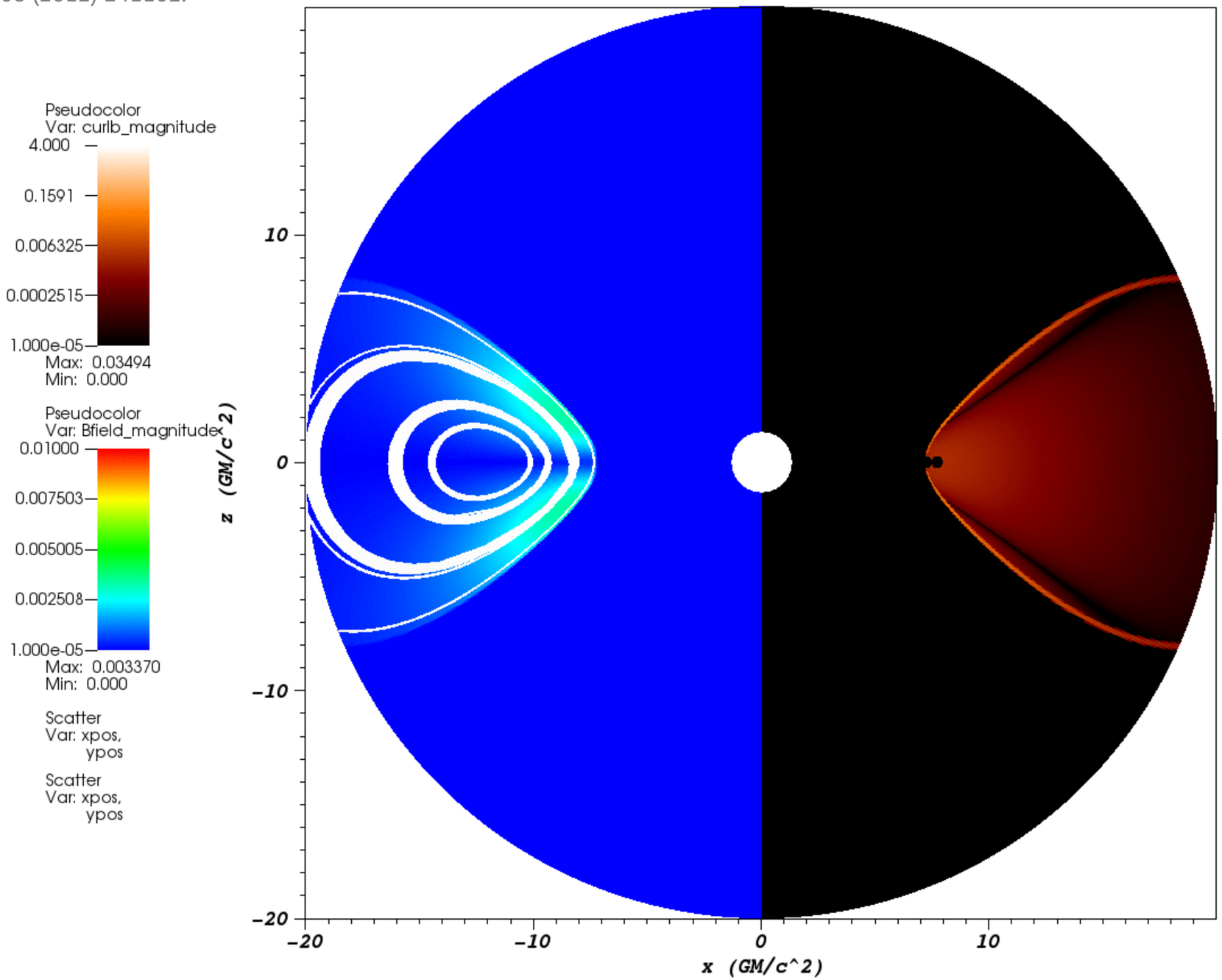
magnetic reconnection in accreting systems

Khiali, de Gouveia Dal Pino, Sol. Phys. Rev. Lett. 108 (2012) 241102.



magnetic reconnection in accreting systems

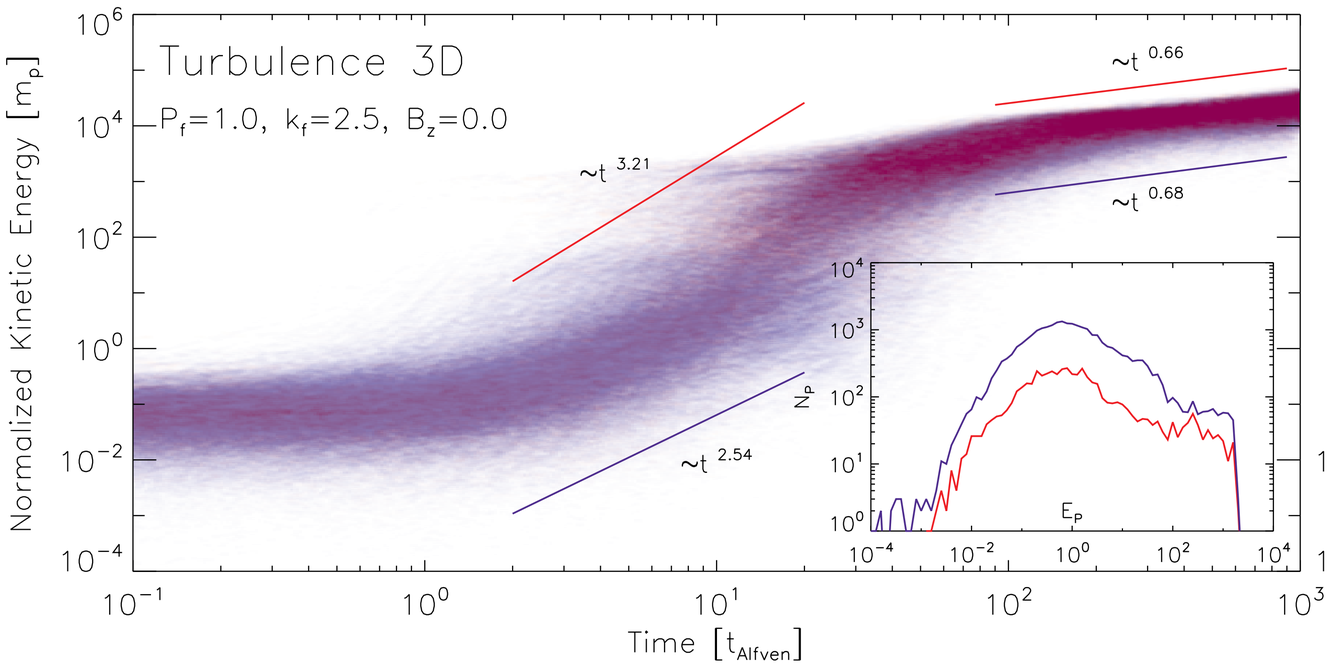
Kowal et al. Phys. Rev. Lett. 108 (2012) 241102.



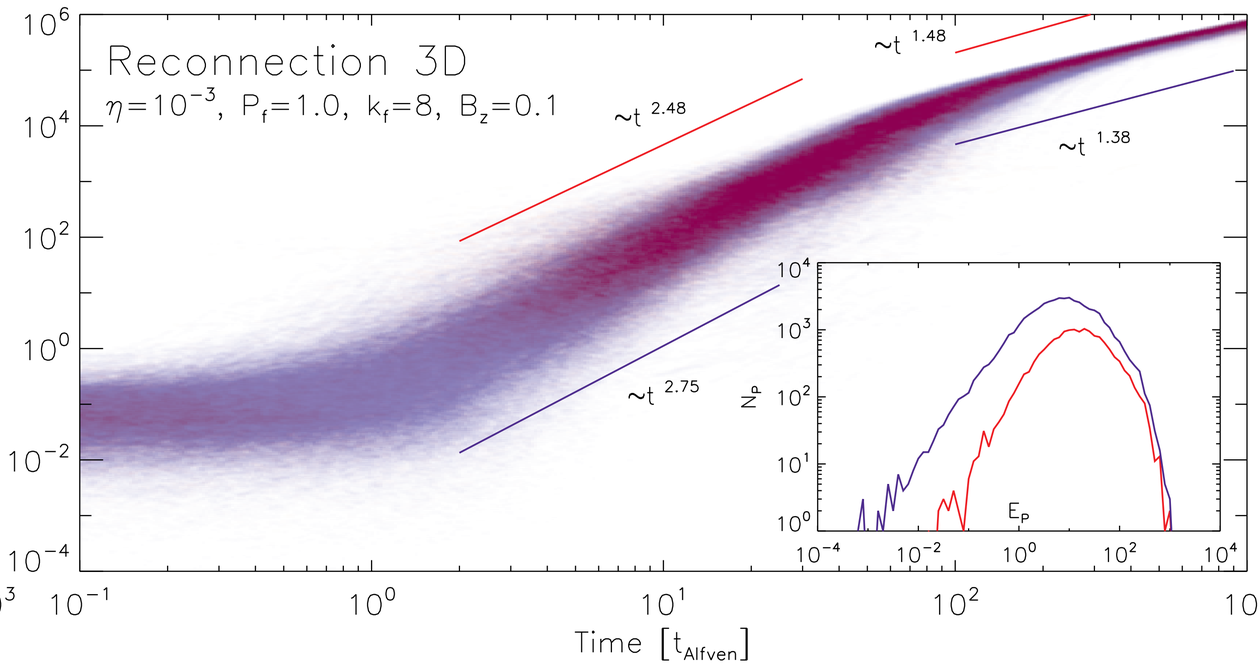
particle acceleration via magnetic reconnection

Kowal, de Gouveia Dal Pino, Lazarian. Phys. Rev. Lett. 108 (2012) 241102.

2nd order Fermi

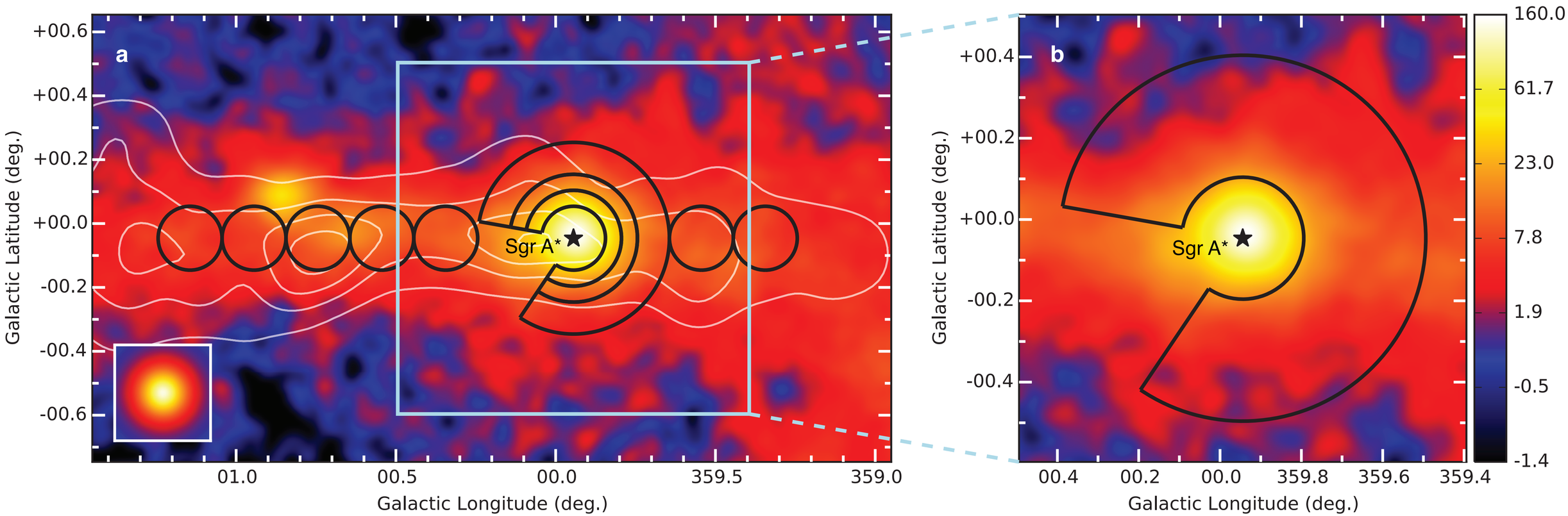


1st order Fermi



a gamma-ray view of the galactic centre

H.E.S.S. Collaboration. Nature 531 (2016) 476.



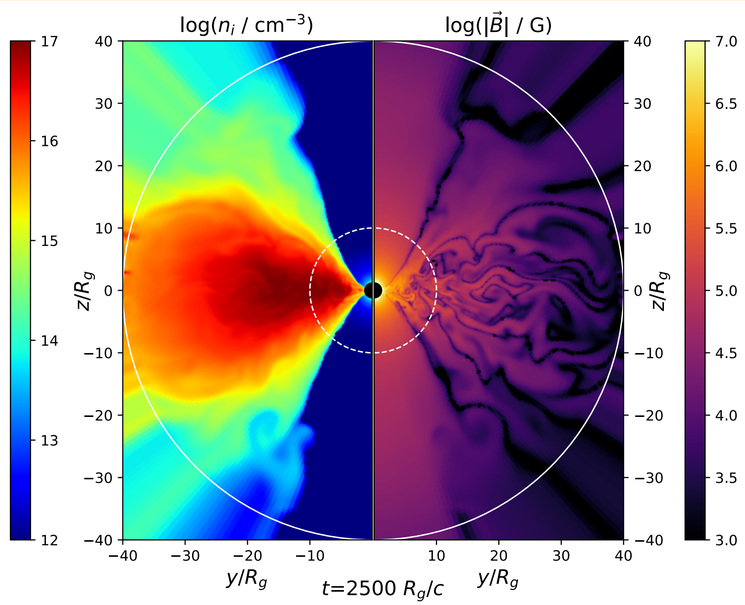
model building: high-energy emission by Sgr A*

simulation of the environment
particle propagation

"multi-zone" lepto/hadronic models

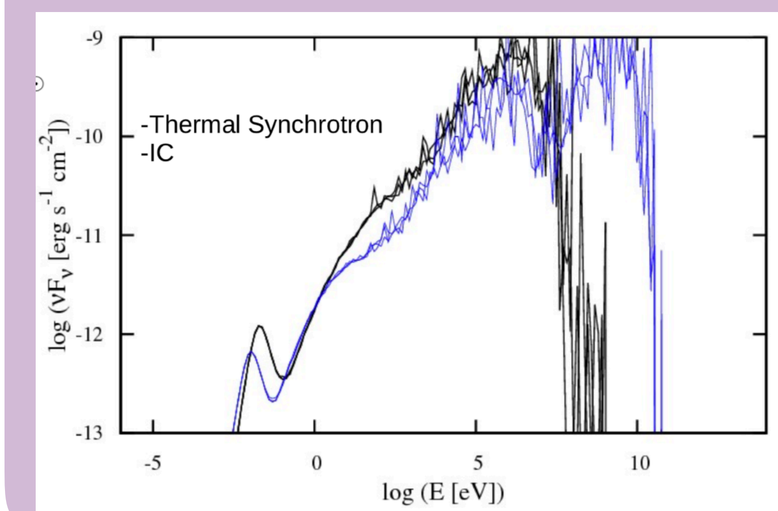
gas density & magnetic fields

- general-relativistic MHD simulation
- HARM code



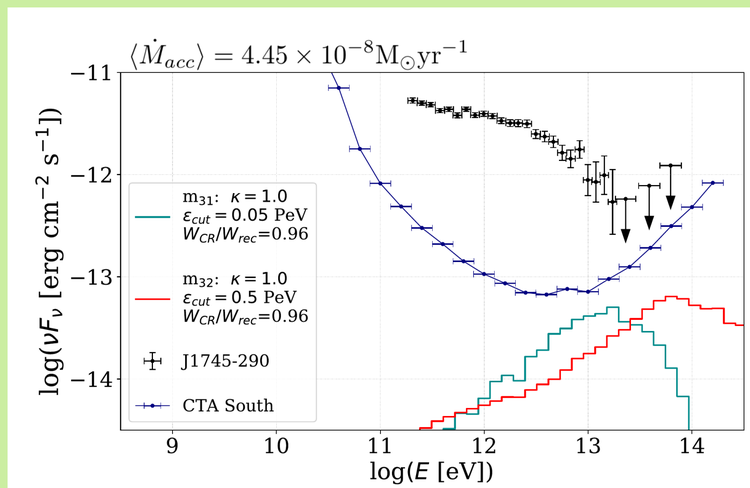
radiative transfer

- provides the photon background: synchrotron, IC, leptonic emission
- grmonty code



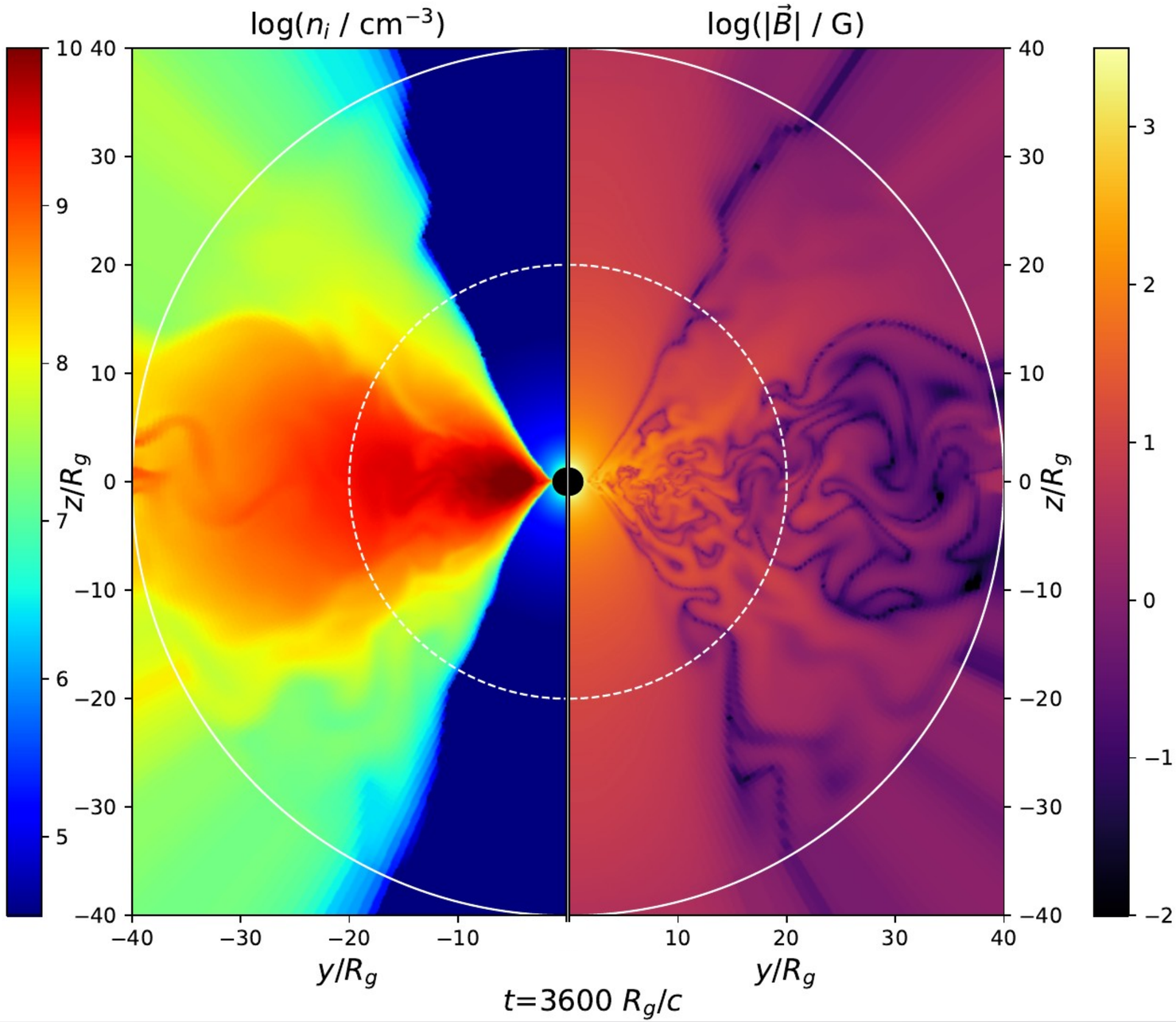
pp & pγ interactions

- CRs accelerated via magnetic reconnection
- interactions with environment
- CRPropa code



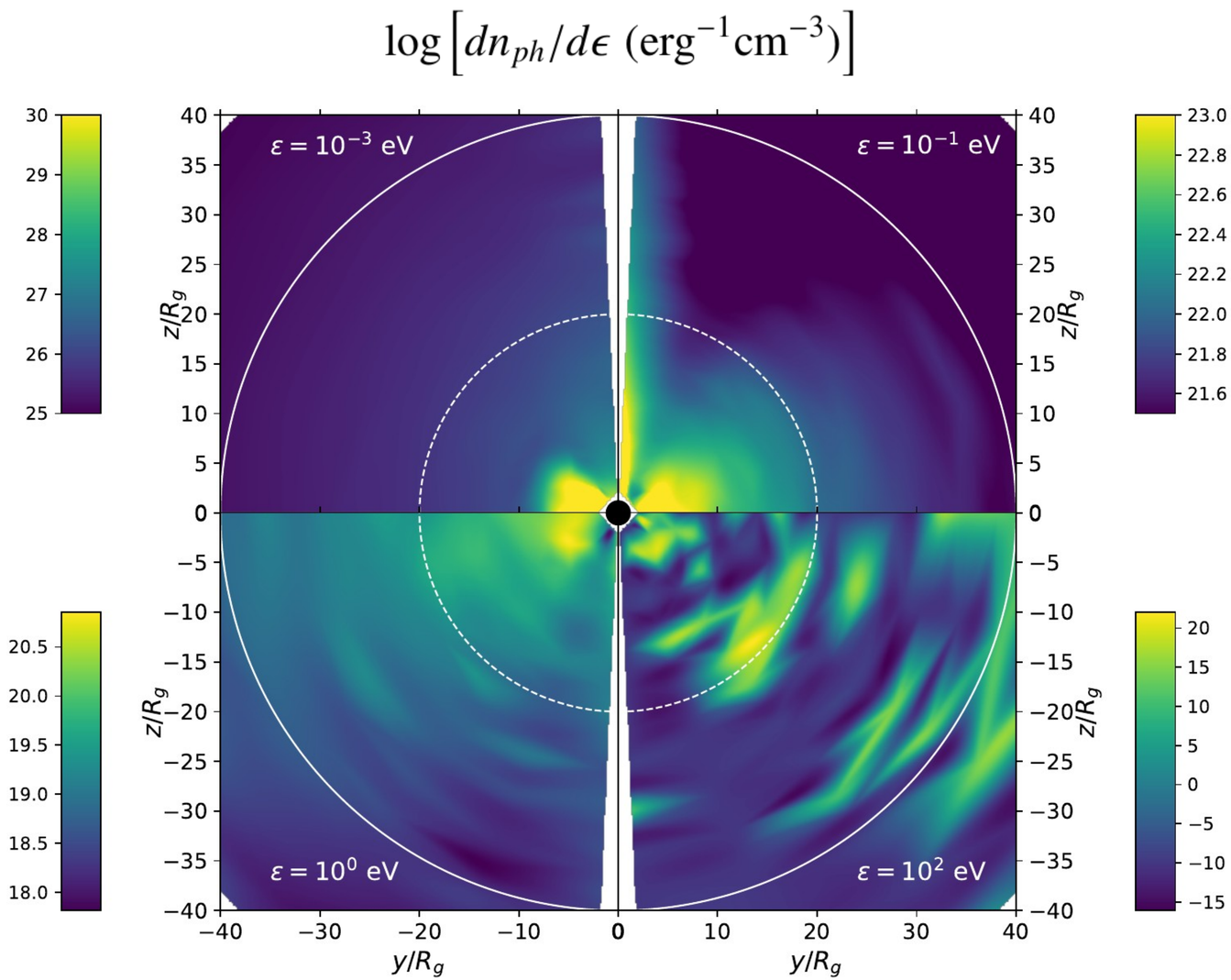
GRMHD simulations of the accretion flow

Rodríguez-Ramírez, de Gouveia Dal Pino, Alves Batista. ApJ 879 (2019) 06. arXiv:1904.05765

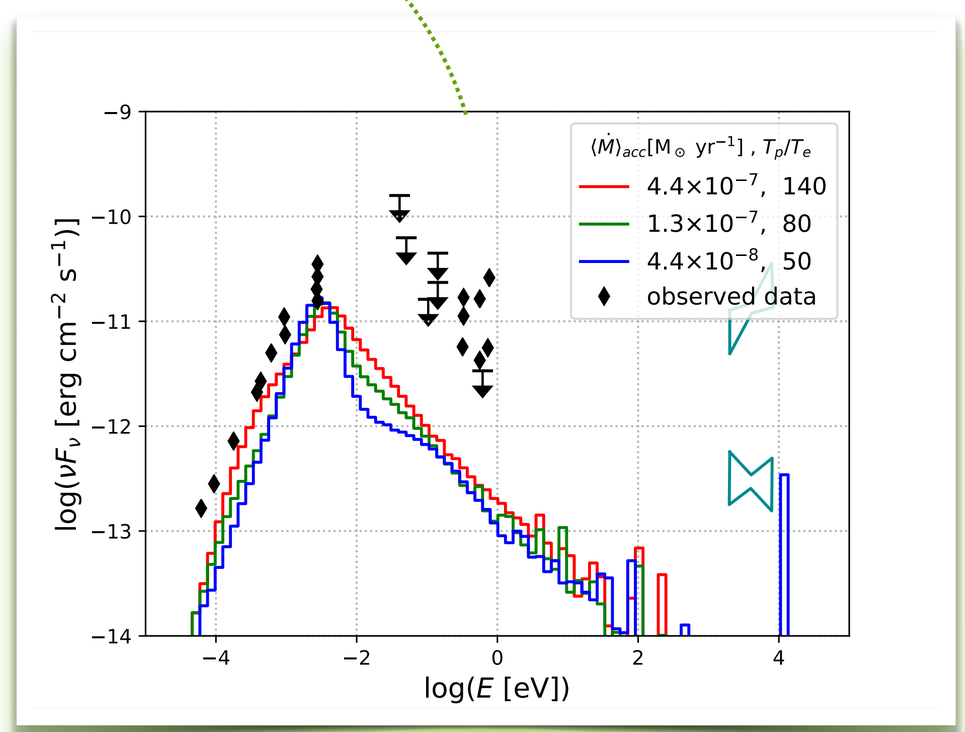


- GRMHD simulation with the harm code
- torus: inner radius = $6R_g$; outer radius = $12R_g$
- thermal-to-magnetic pressure of the plasma flow: β=50
- spin parameter: a = 0.94
- gas specific heat ratio: γ=4/3
- grid: 256x256 (axisymmetric)

defining the target photon field for the simulations



normalise to observations



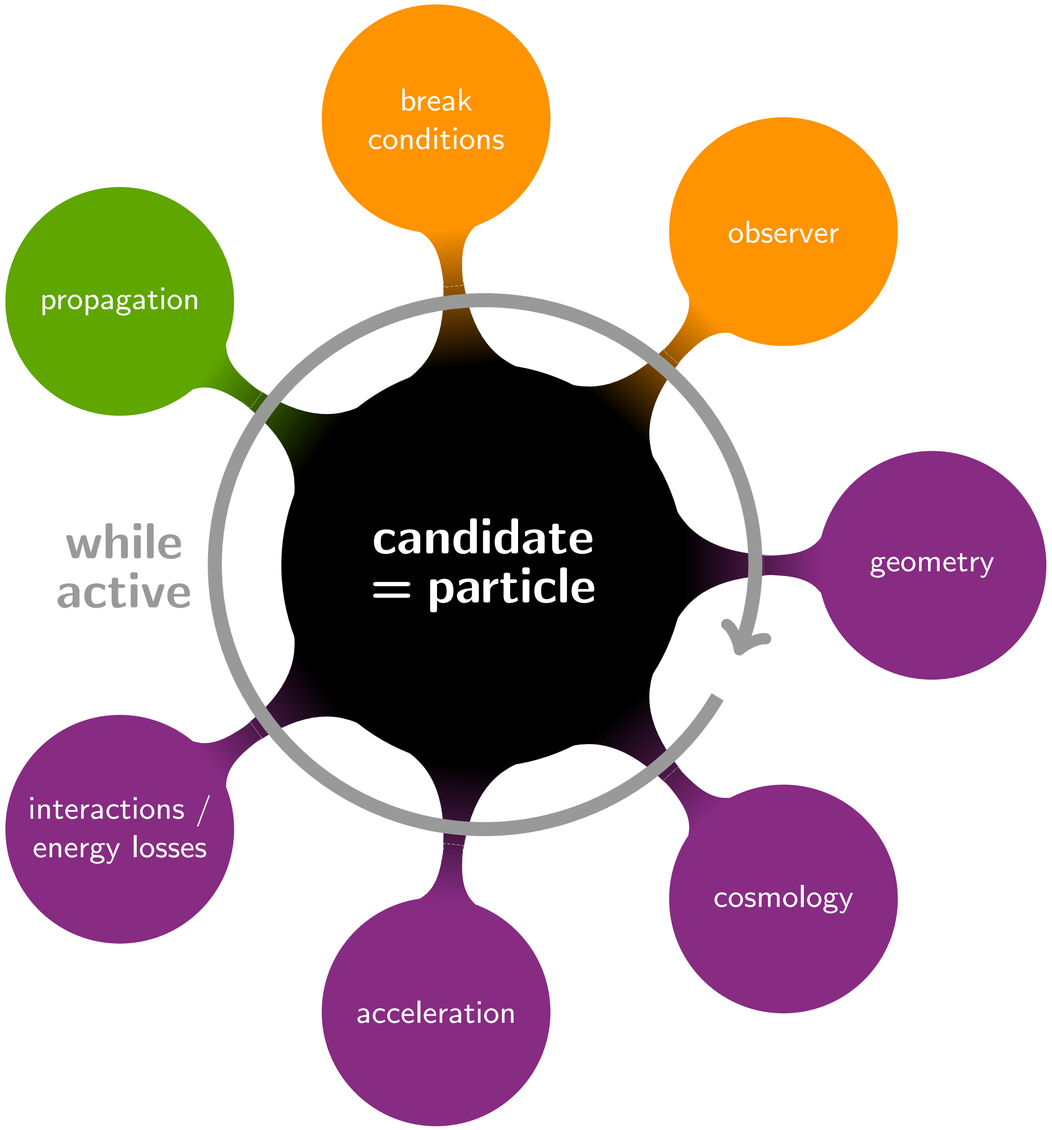
CRPropa

the CRPropa multimessenger framework

the CRPropa framework

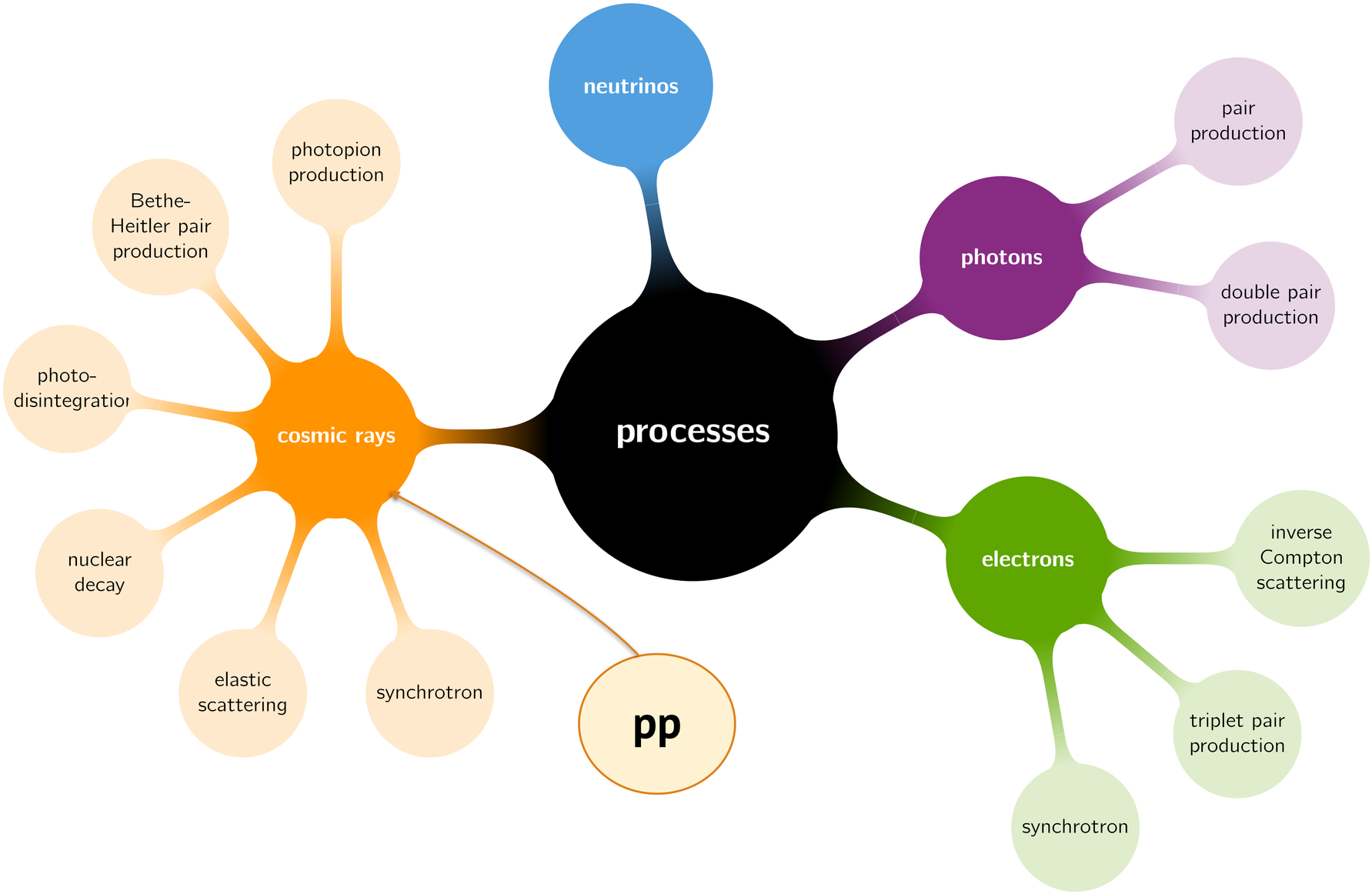
Alves Batista et al. JCAP 05 (2016) 038. arXiv:1603.07142
Alves Batista et al. JCAP 09 (2022) 035. arXiv:2208.00107

- publicly available Monte Carlo code
- propagation of high-energy cosmic rays, gamma rays, neutrinos, and electrons
- Galactic and extragalactic propagation
- modular structure
- parallelisation with OpenMP
- development on Github: https://github.com/CRPropa/CRPropa3



crpropa.desy.de

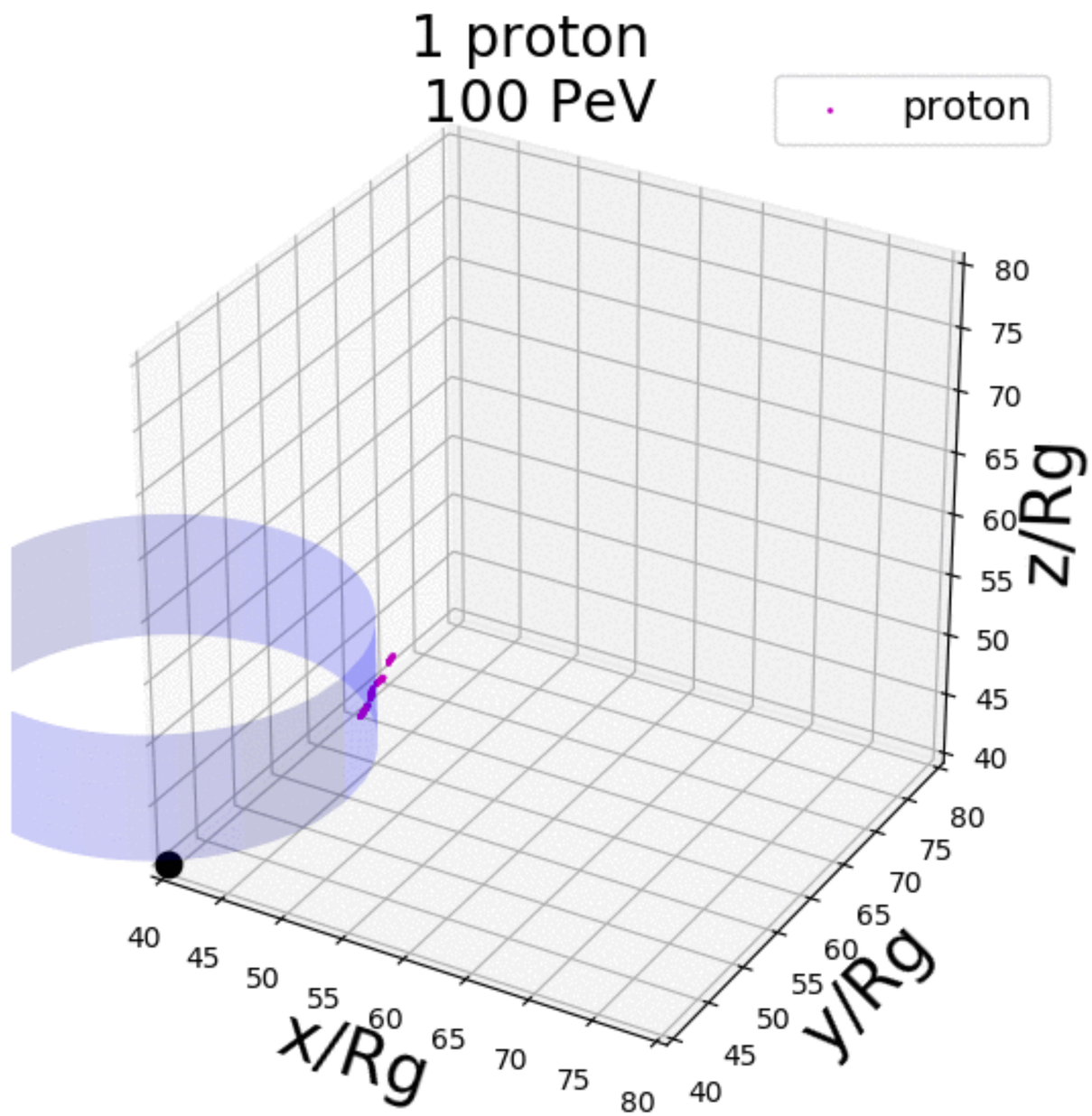
the CRPropa framework: interactions



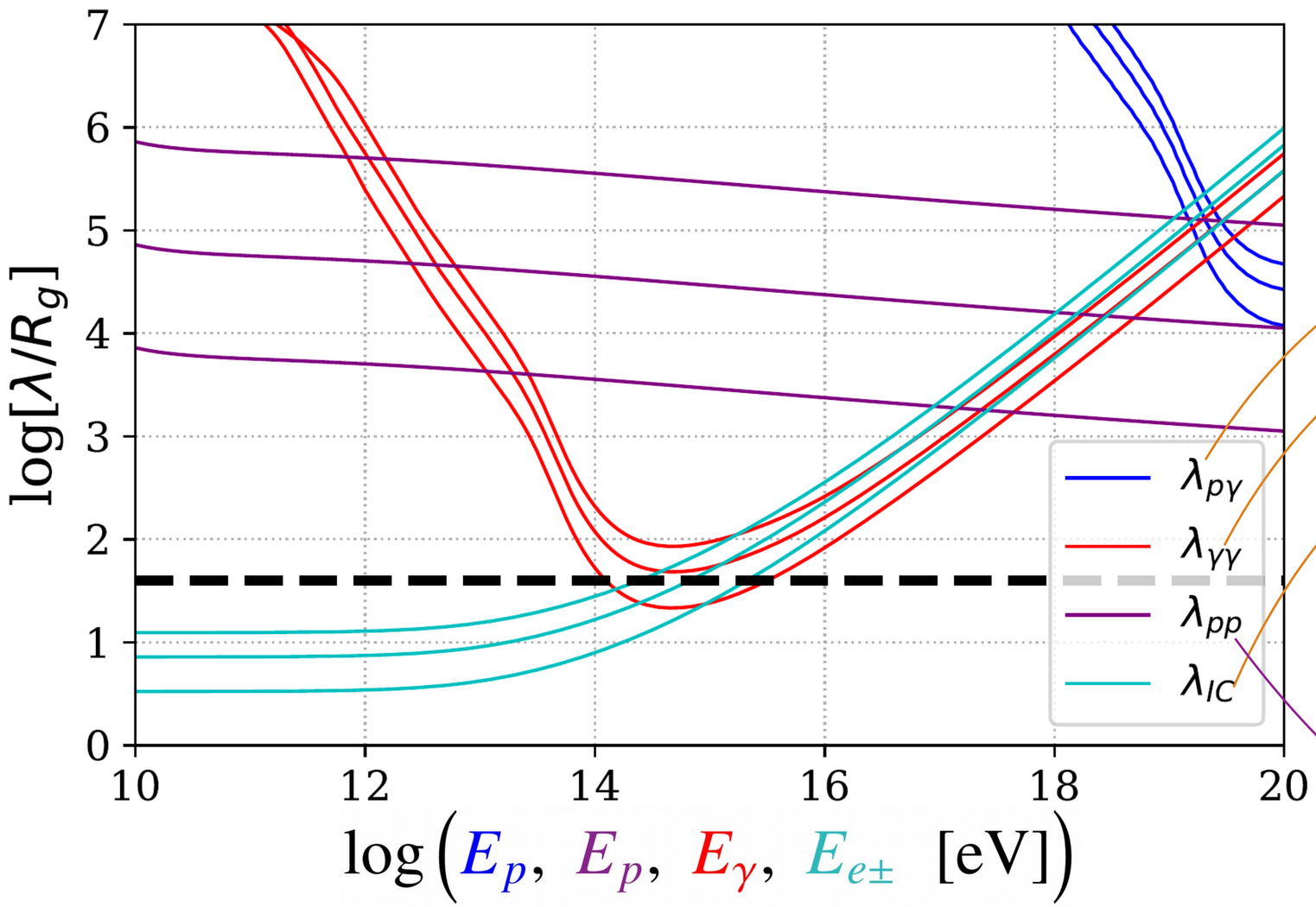
towards a unified framework for (ultra-)high-energy multimessenger studies

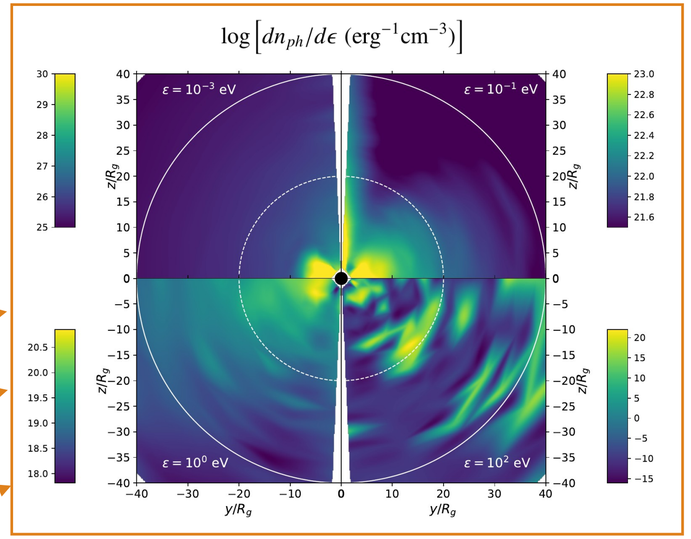
simulating the propagation of particles

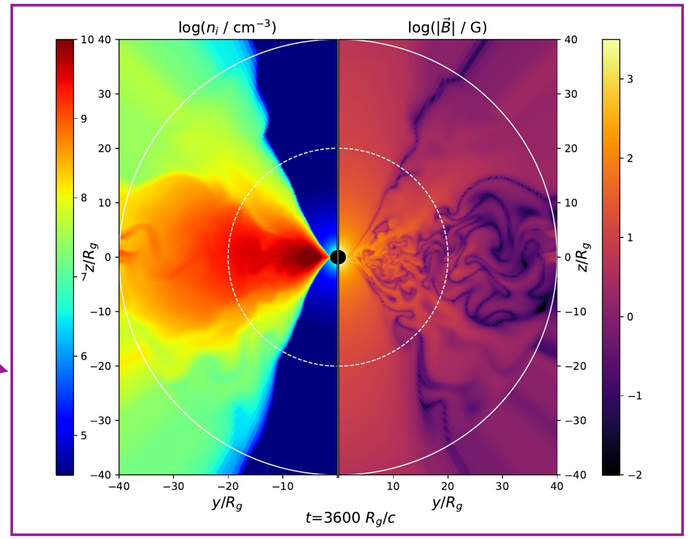
neutrino and gamma-ray emission


1 proton
100 PeV
proton
x/Rg
y/Rg
z/Rg
40
45
50
55
60
65
70
75
80

propagation ingredients: interactions







CR injection model

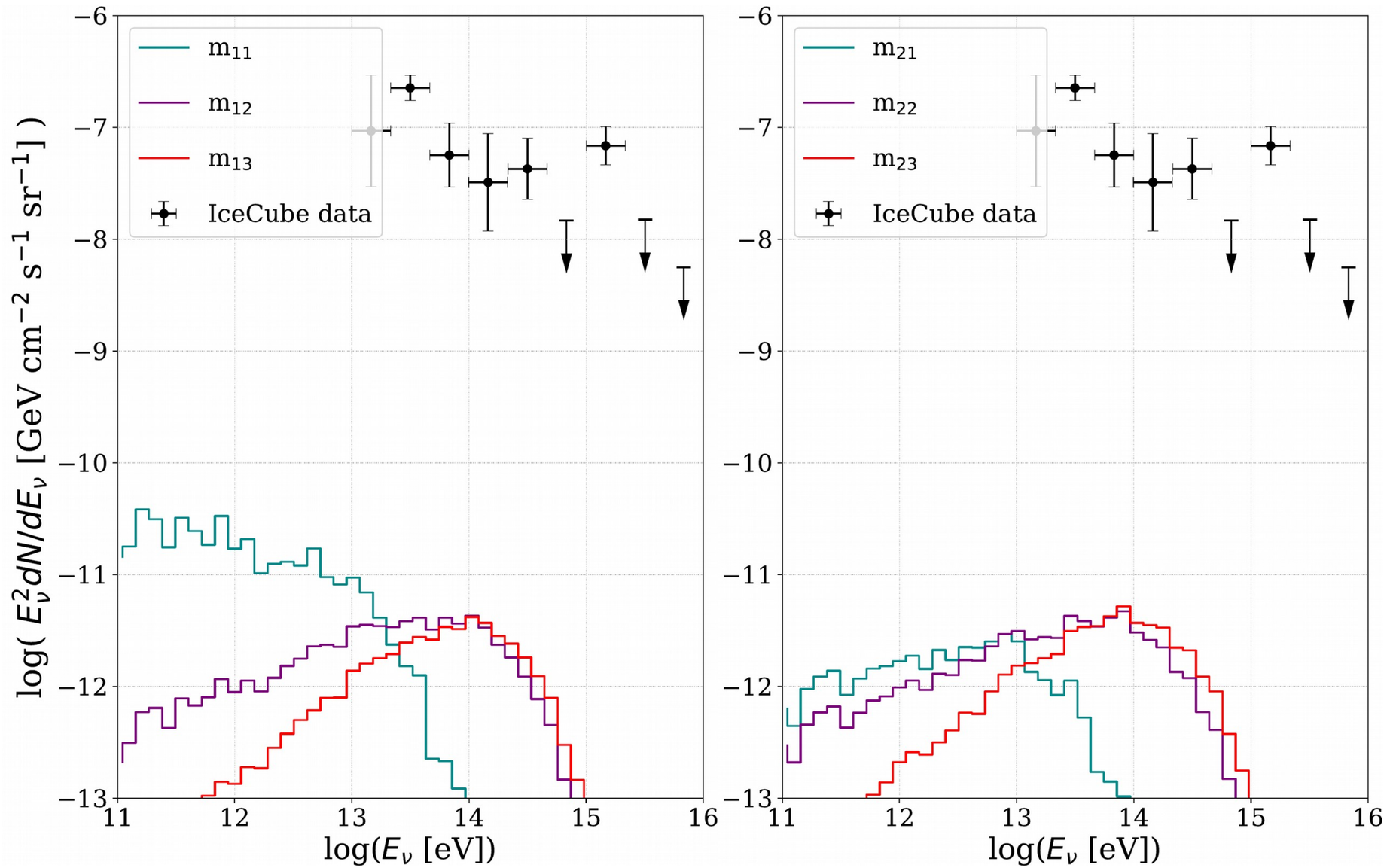
- injection spectrum: $\frac{dN}{dE} \propto E^{-\alpha} \exp\left(-\frac{E}{E_{\text{cut}}}\right)$
- reconnection model by Singh et al. 2015
- magnetic reconnection power: $W = 1.5 \times 10^{42} f \left(\frac{\langle \dot{M}_{acc} \rangle}{M_\odot \, \text{yr}^{-1}}\right) \left(\frac{T_p}{T_e}\right) \text{ erg s}^{-1}$

  where f depends on the Lorentz factor, Alfvén velocity, and viscosity

Model	$\langle \dot{M}_{\rm acc} \rangle \times 10^{-7}$ ($M_\odot$ yr^{-1})	T_p/T_e	$W_{\rm CR} \times 10^{37}$ (erg s^{-1})	$W_{\rm CR}/W_{\rm rec}$	κ	$\epsilon_{\rm cut}$ (PeV)
m_{11}	4.452	140	30	0.8	2.4	0.05
m_{12}	4.452	140	2	0.05	1.8	0.5
m_{13}	4.452	140	0.8	0.02	1.3	0.5
m_{21}	1.335	80	6.5	1.0	1.8	0.05
m_{22}	1.335	80	6	0.92	1.8	0.5
m_{23}	1.335	80	3	0.46	1.3	0.5
m_{31}	0.445	50	1.3	0.96	1.0	0.05
m_{32}	0.445	50	1.3	0.96	1.0	0.5

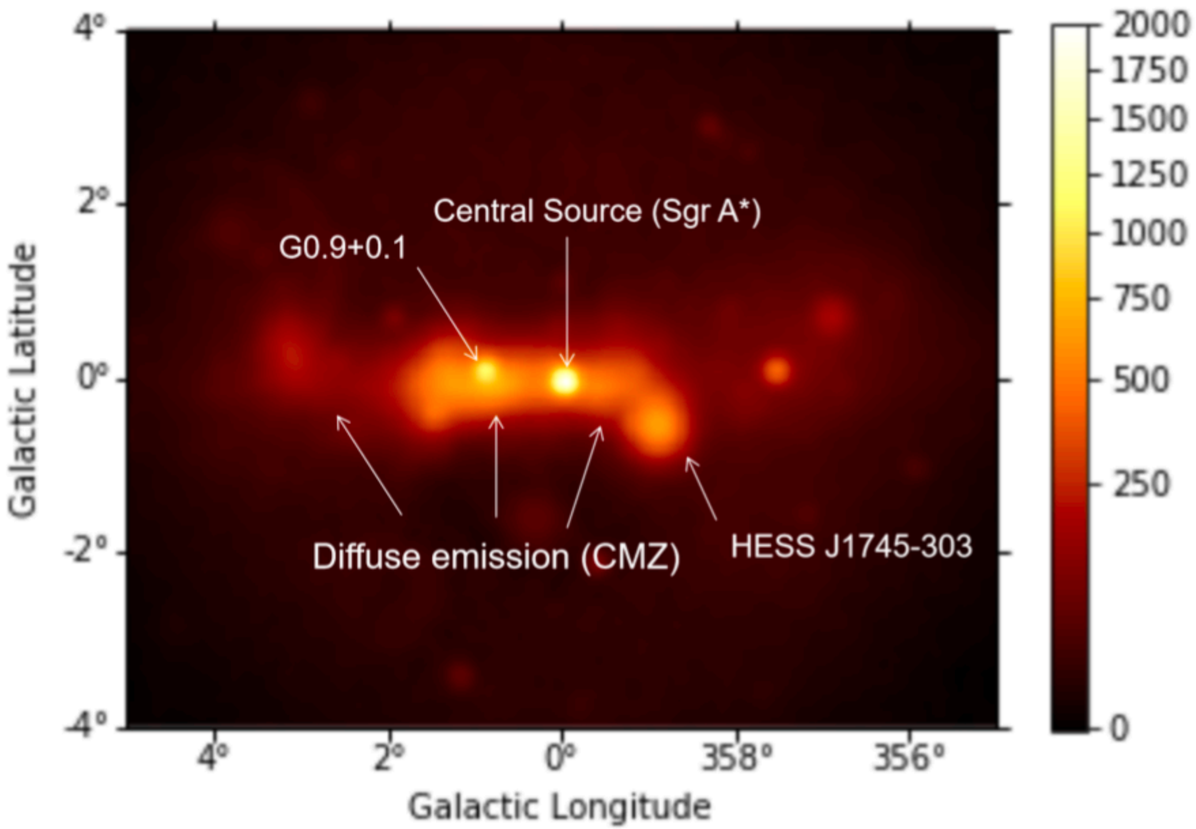
neutrino emission from SgrA*

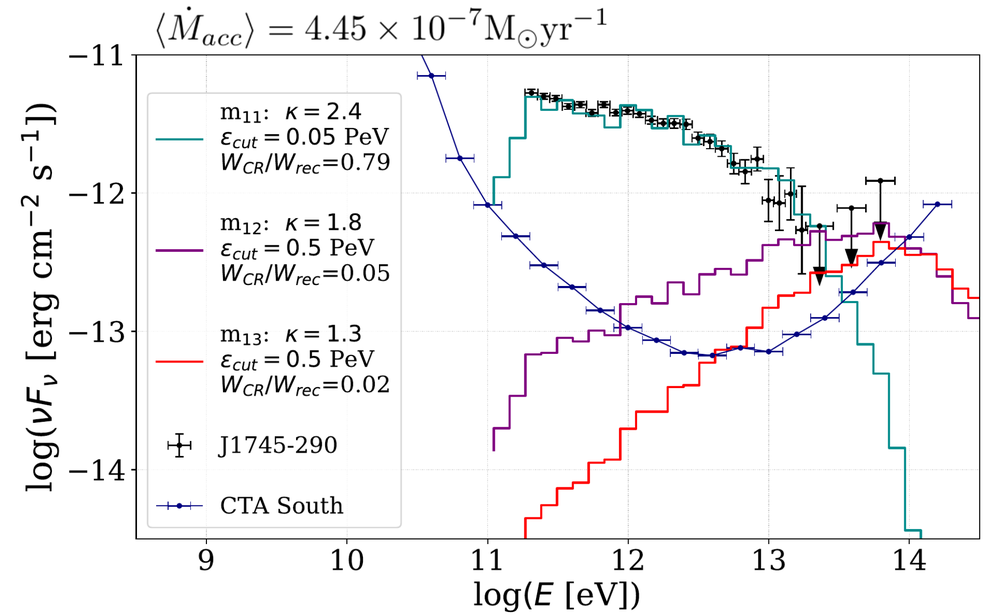
Rodríguez-Ramírez, de Gouveia Dal Pino, Alves Batista. ApJ 879 (2019) 06. arXiv:1904.05765

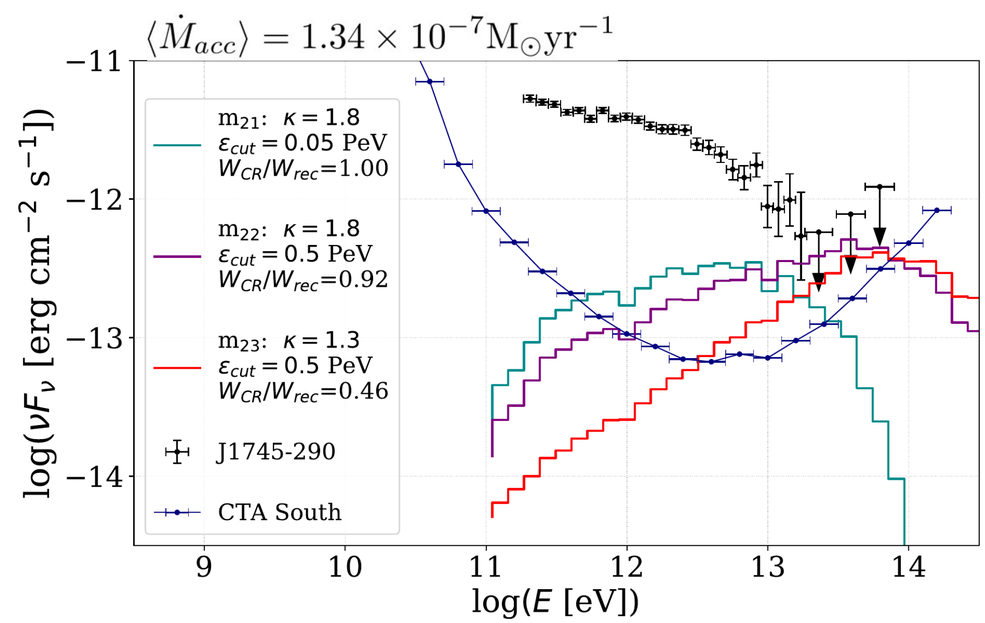


gamma-ray emission from SgrA*

Rodríguez-Ramírez, de Gouveia Dal Pino, Alves Batista. ApJ 879 (2019) 06. arXiv:1904.05765







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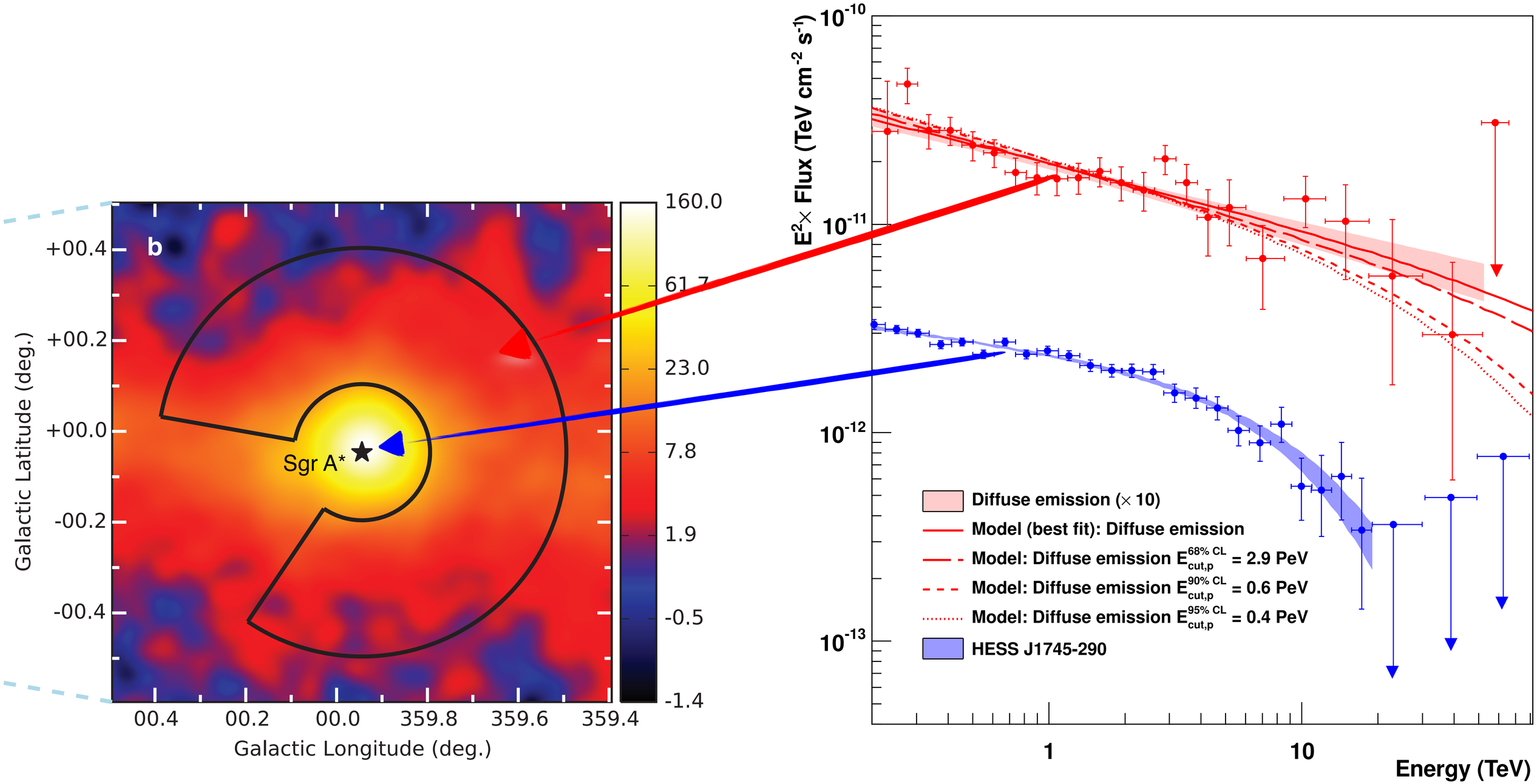
H.E.S.S. Collaboration. Nature 531 (2016) 476.



conclusions and outlook

- we built a multi-zone model for SgrA*
- we assume acceleration via fast magnetic reconnection
- we simulate everything from *first principles*:
  - GRMHD simulation (magnetic field and gas density) → HARM code
  - radiate transfer (photon backgrounds) → GRMONTY code
  - hadronic and leptonic interactions → CRPROPA code
- **CRPROPA**: multimessenger framework for high-energy studies
- for accretion rates > 10^{-7} $M_\odot$/yr we can explain the VHE observations by H.E.S.S. if ~ 0.5 PeV CRs are accelerated
- these models can be readily tested with the Cherenkov Telescope Array once it is operating

thank you

collaborators

Elisabete de Gouveia Dal Pino
Juan C. Rodríguez Ramírez

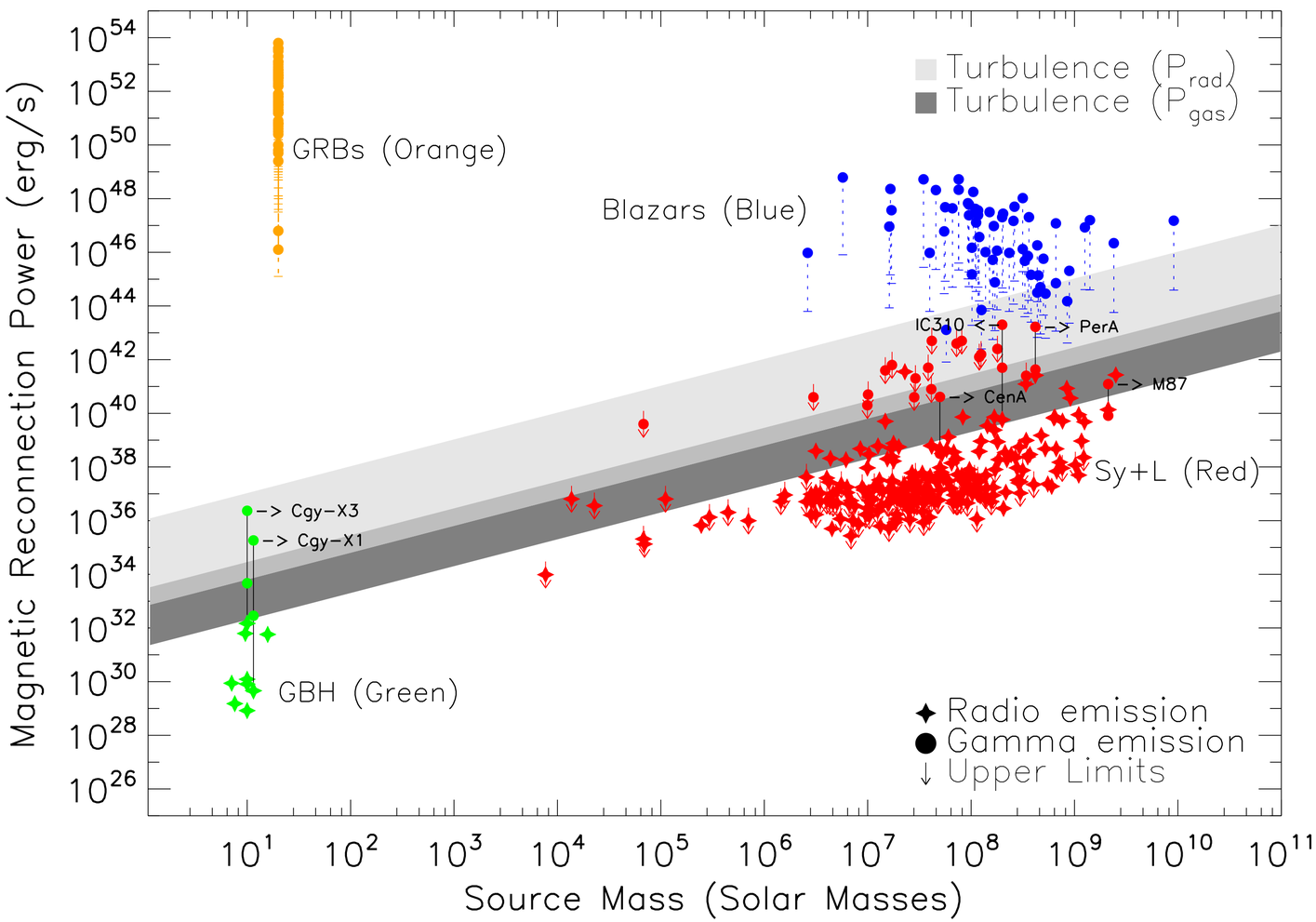
"la Caixa" Foundation

MARIE CURIE ACTIONS

European Commission

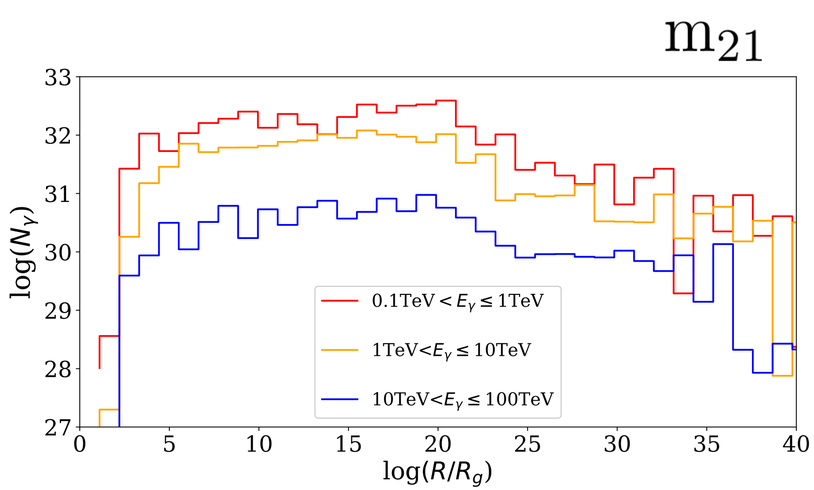
backup

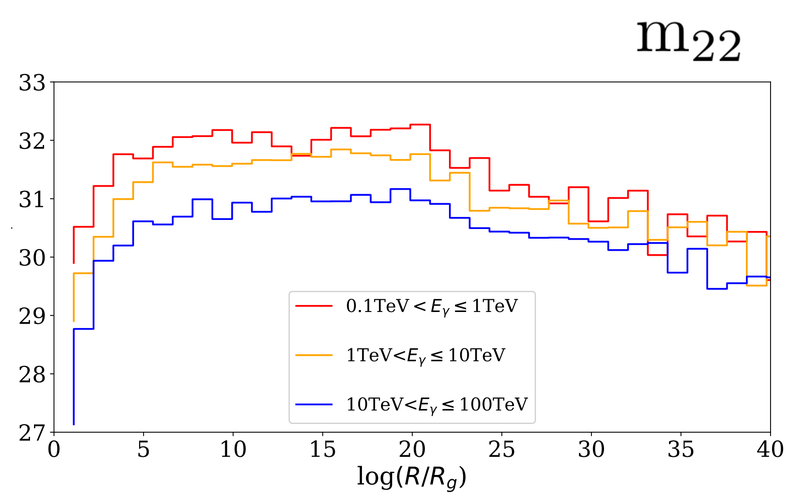
particle acceleration via magnetic reconnection

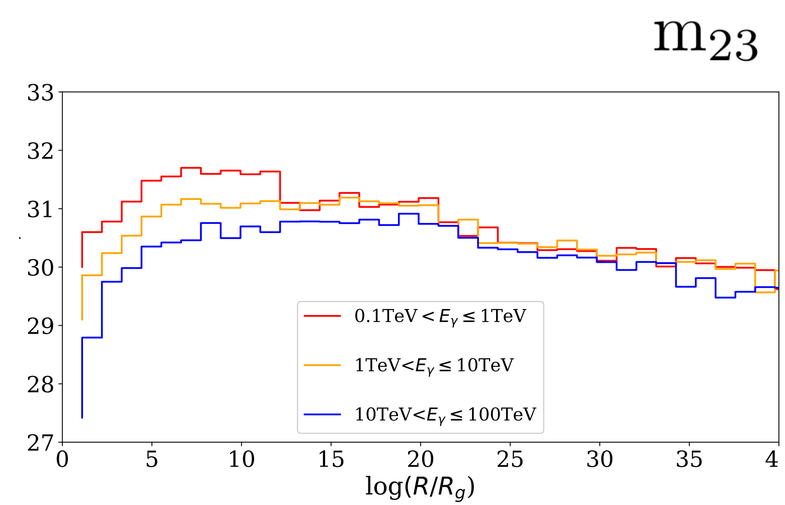


- magnetic reconnection provides a lot of power that can be used for particle acceleration
- may explain high-energy emission in systems with central black holes
- first-order Fermi acceleration is possible in magnetic reconnection sites
- energy gain: $\langle \Delta E/E \rangle \sim v_{rec} / c$
- if the base of AGN jets is magnetically-dominated, then reconnection may take place

gamma-ray emission profiles: curvature effects







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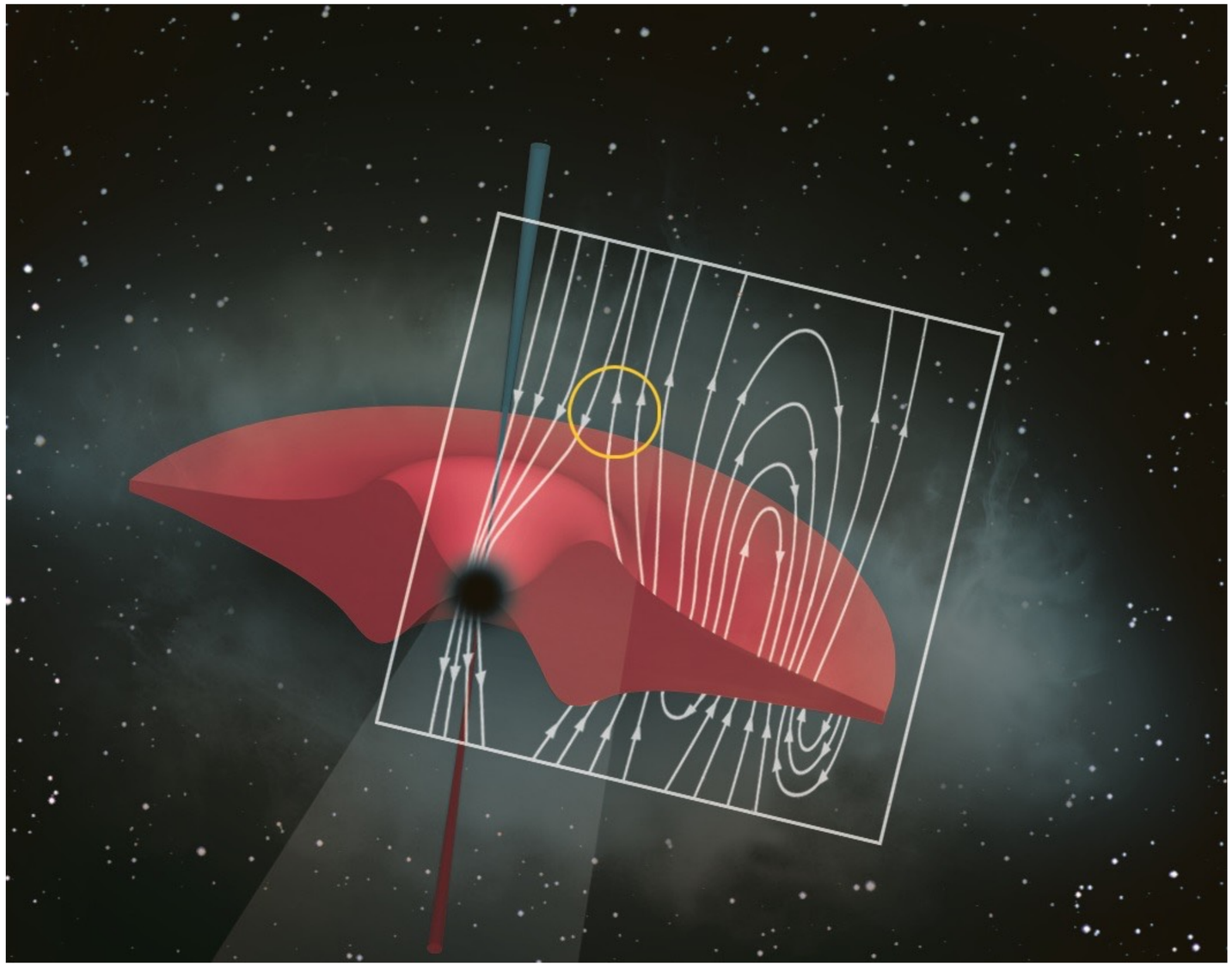
Khiali, de Gouveia Dal Pino, Sol. Phys. Rev. Lett. 108 (2012) 241102.



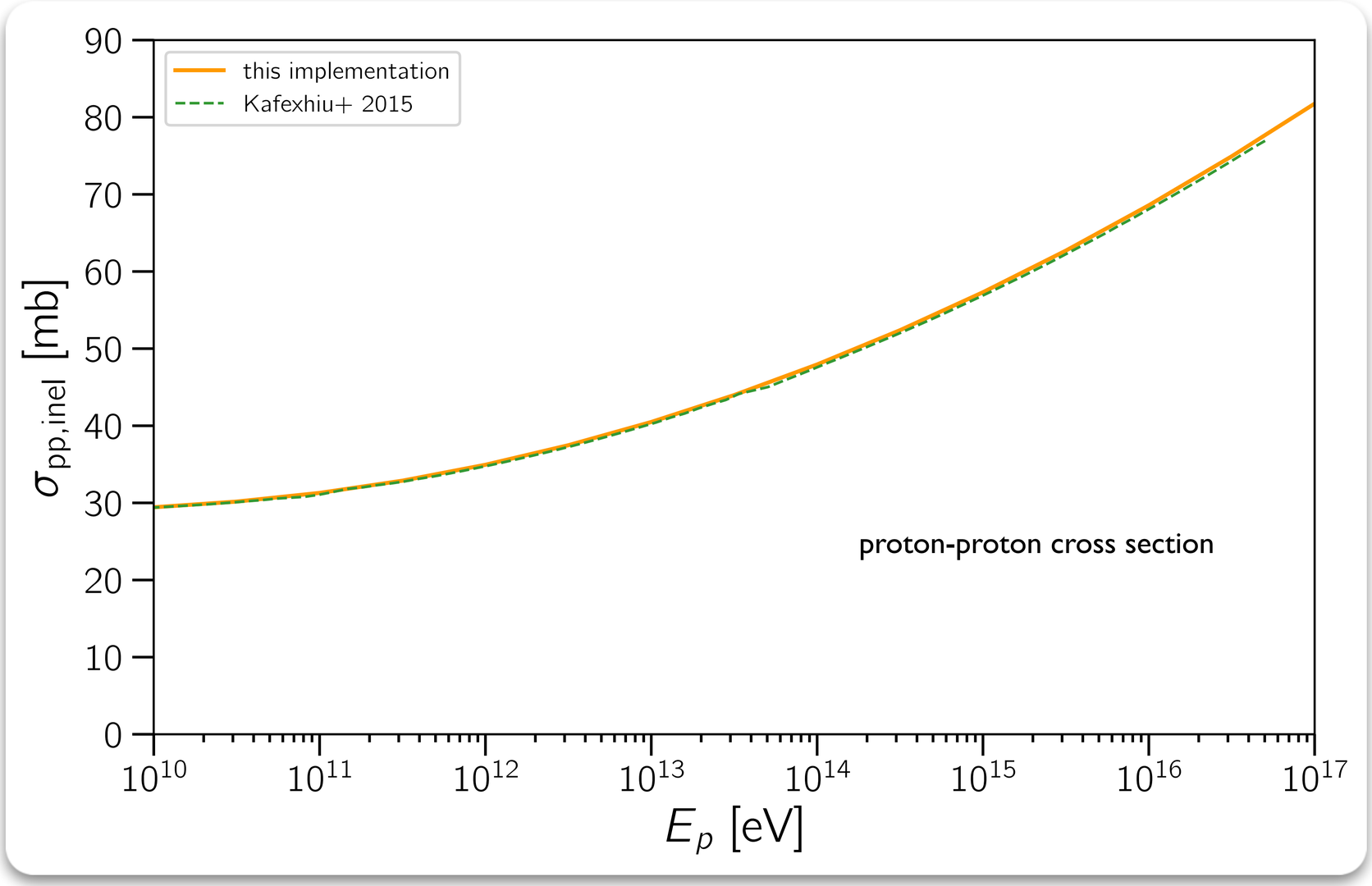
pp interactions: implementation

proton-proton cross section
[Kafexhiu et al. 2014]

pion cross section & multiplicity
[Kafexhiu et al. 2014]

gamma-ray spectrum & multiplicity
[Kafexhiu et al. 2014]

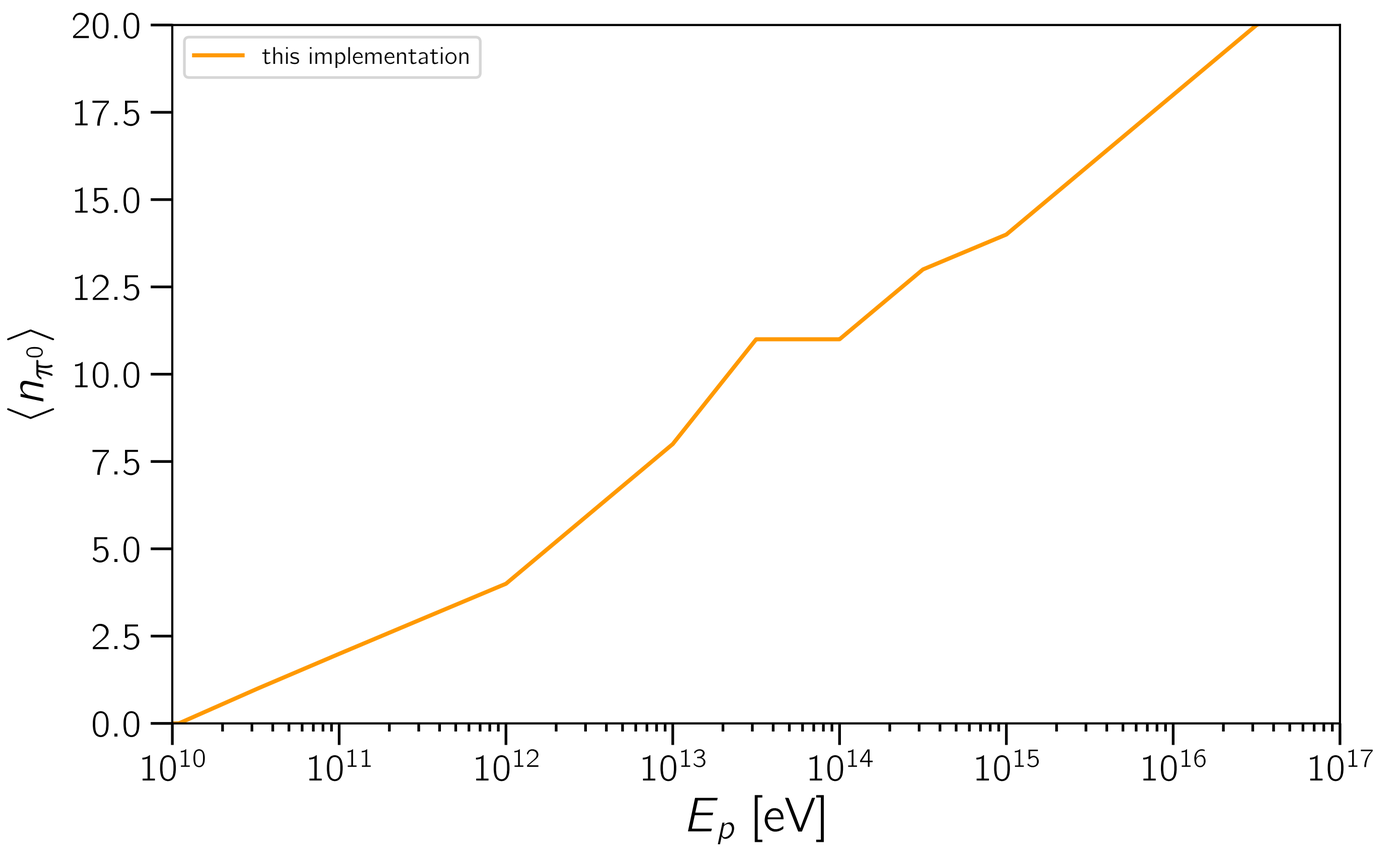
scaling relation for lepton multiplicity
[Kelner et al. 2006]

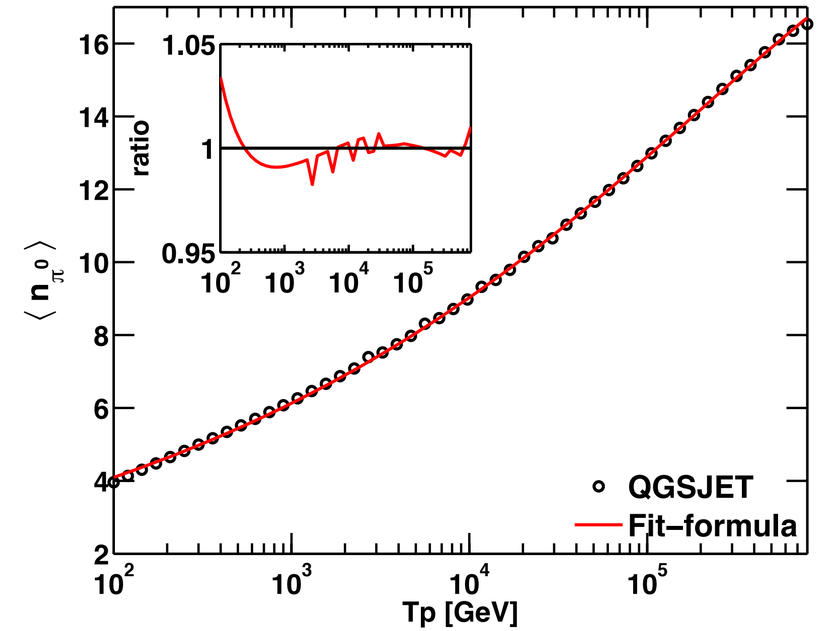


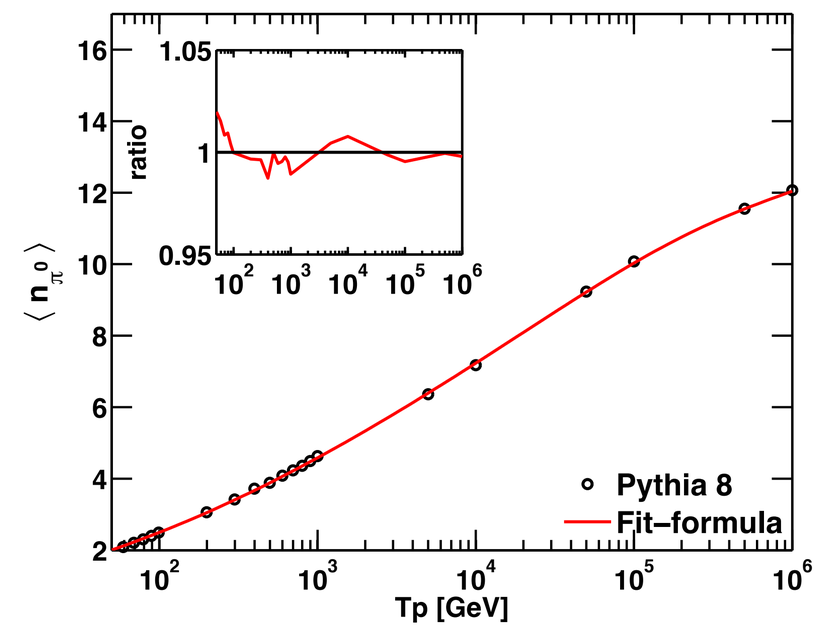
pp interactions: checks

Kafexhiu et al. PRD 90 (2014) 123014

- MANY secondaries are produced per interaction
- secondaries can hardly be tracked on a particle-per-particle basis







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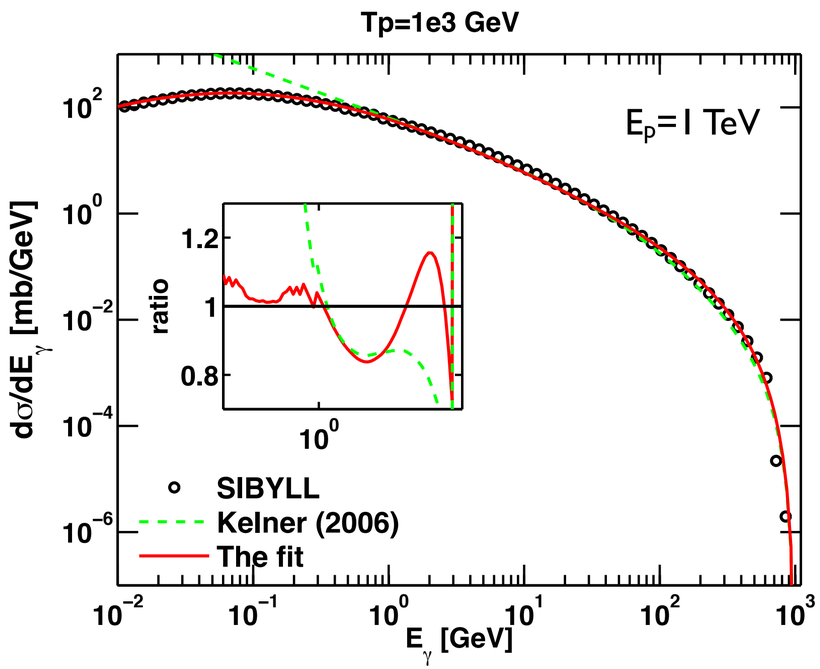

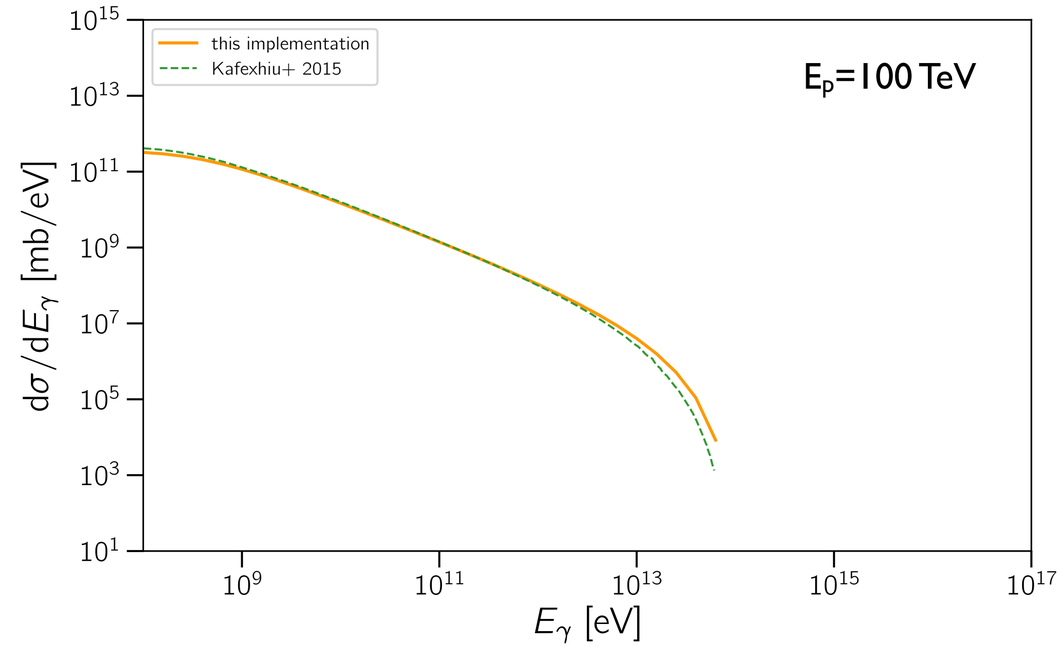

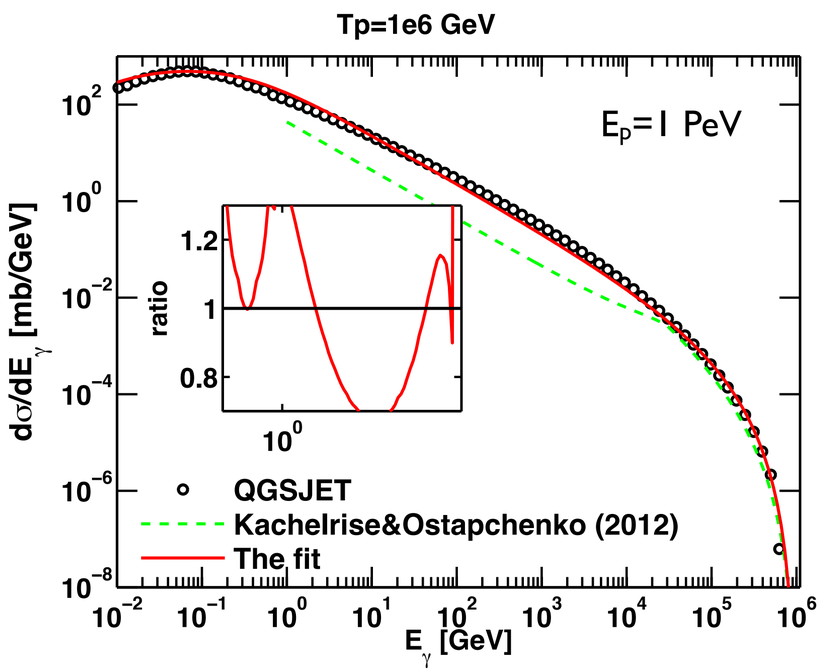

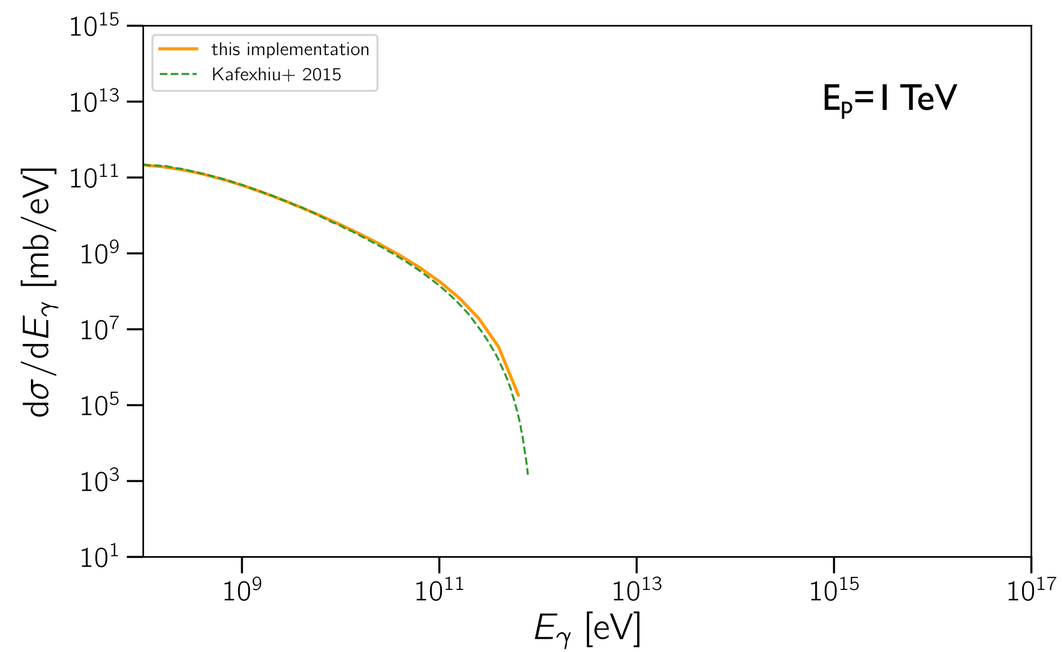

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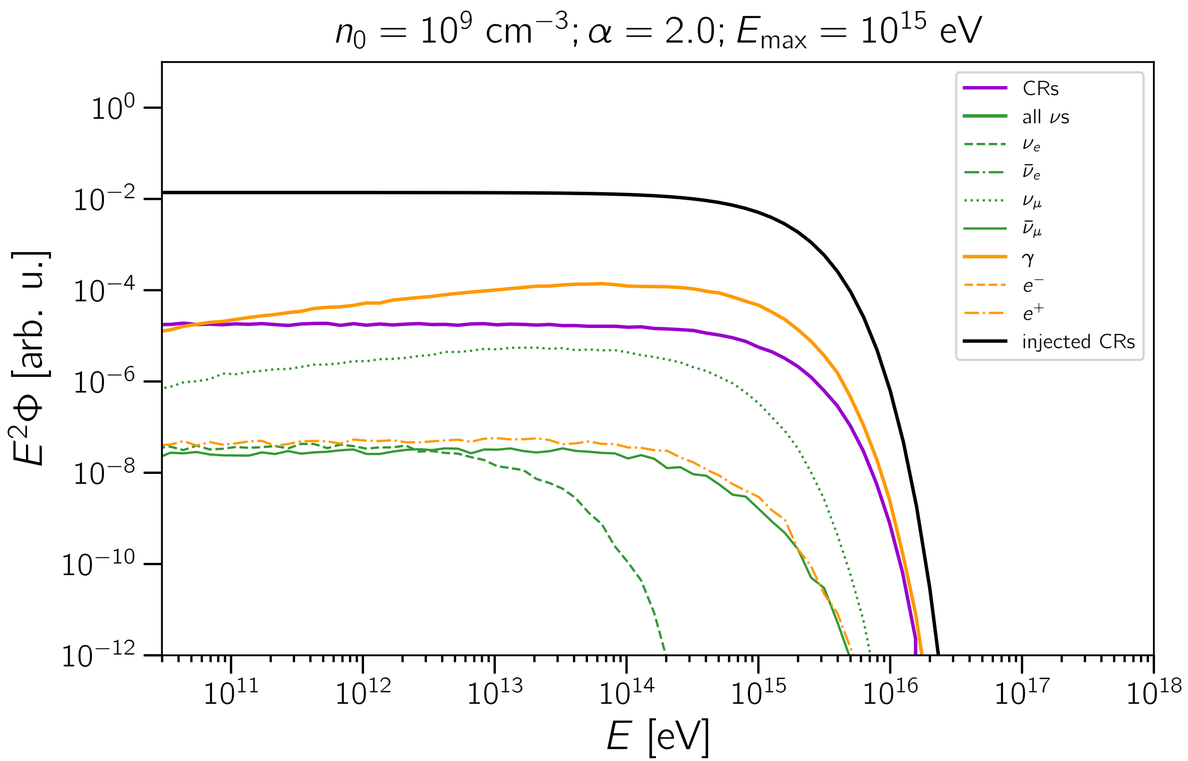
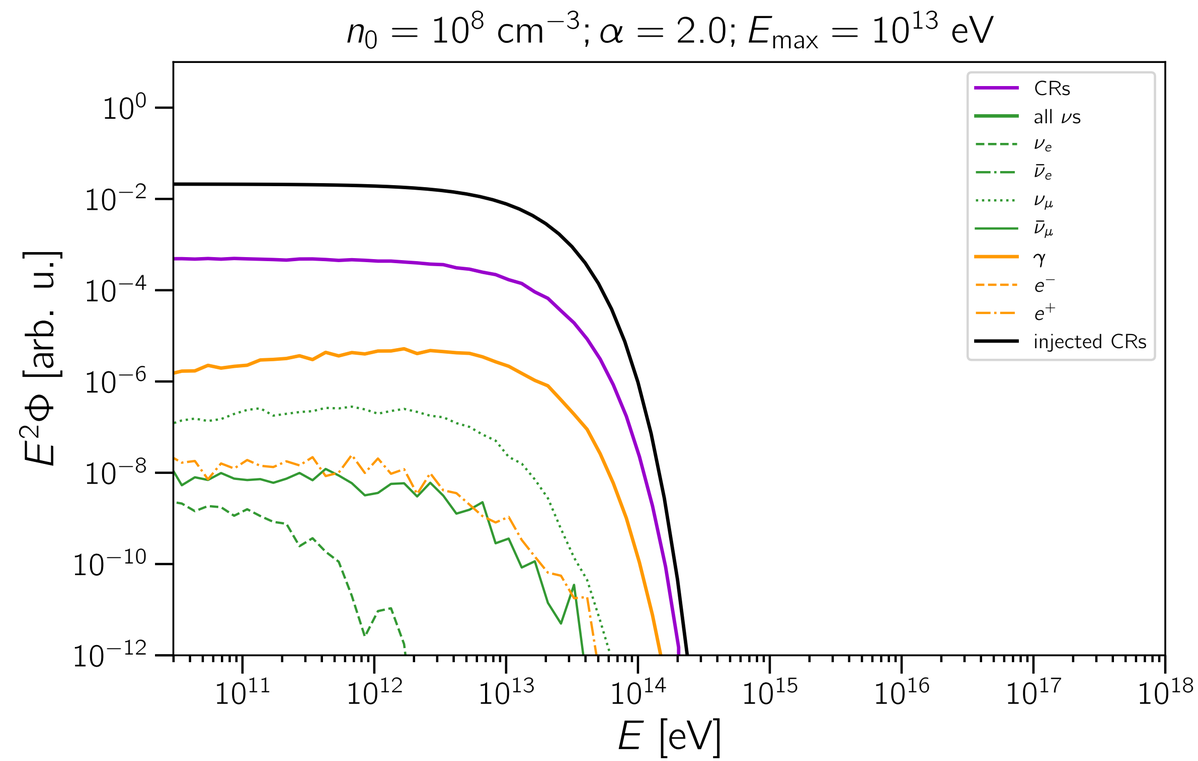
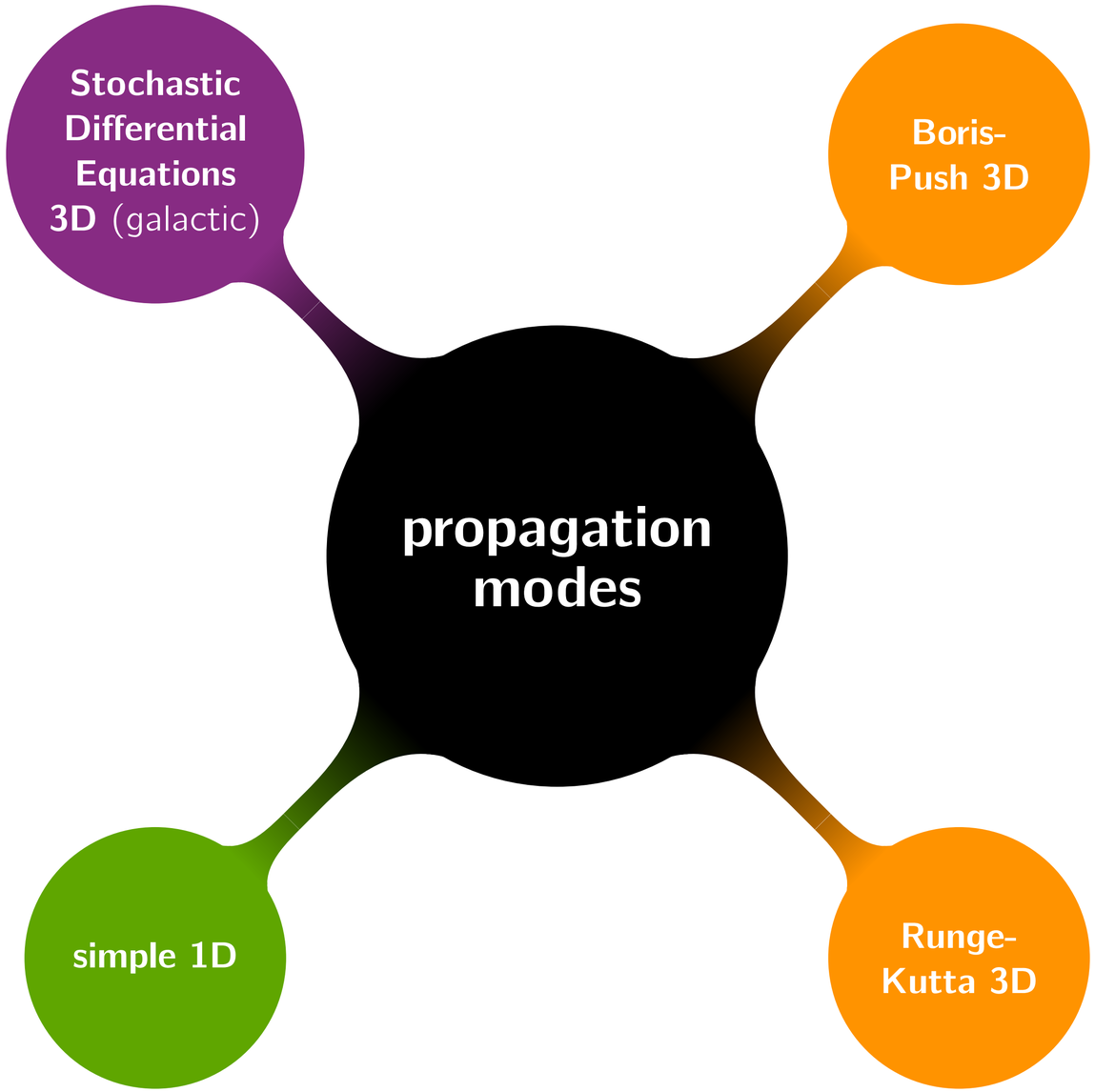




the CRPropa framework:



the CRPropa framework: magnetic fields