VHE emissions from pulsars

Insight from analytic approaches

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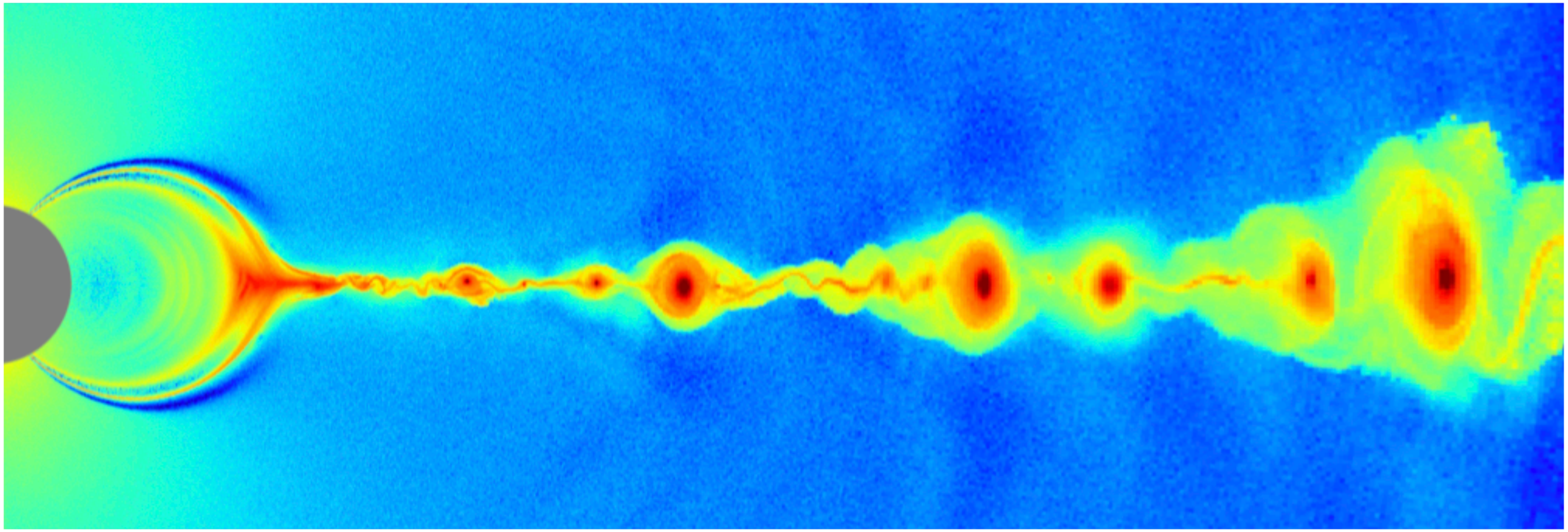


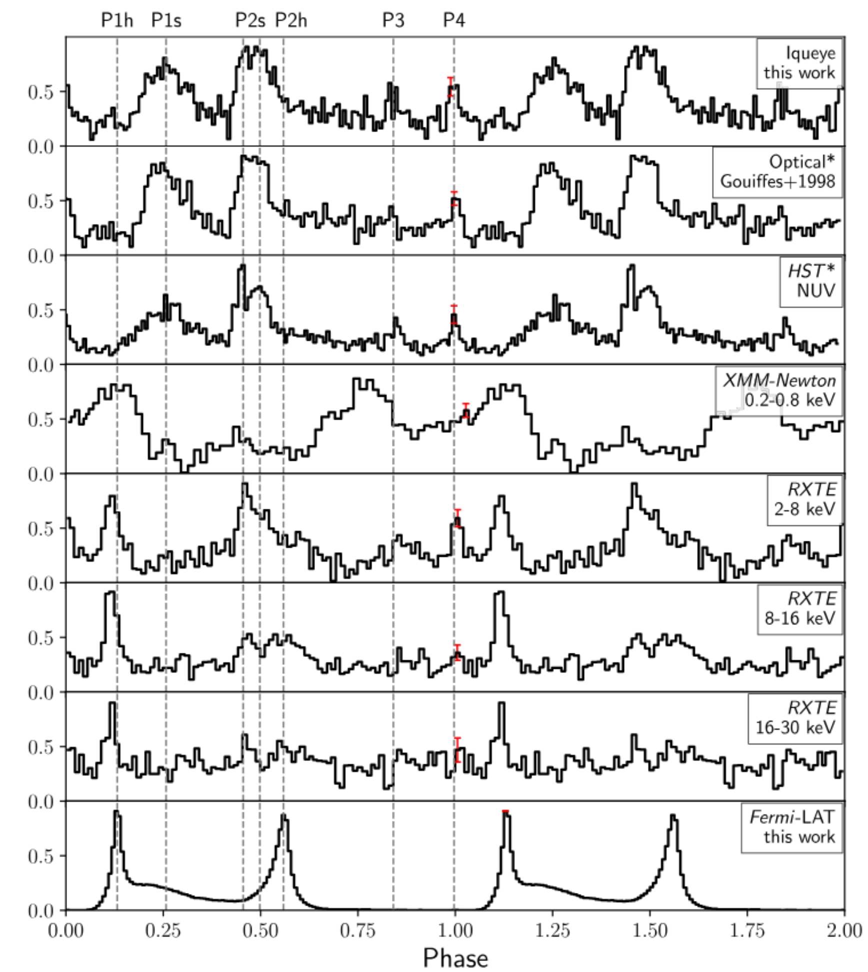
HONEST
HOT TOPICS IN HIGH ENERGY ASTROPHYSICS
3 The high end of Pulsar spectra

Observations to adjust/predictions

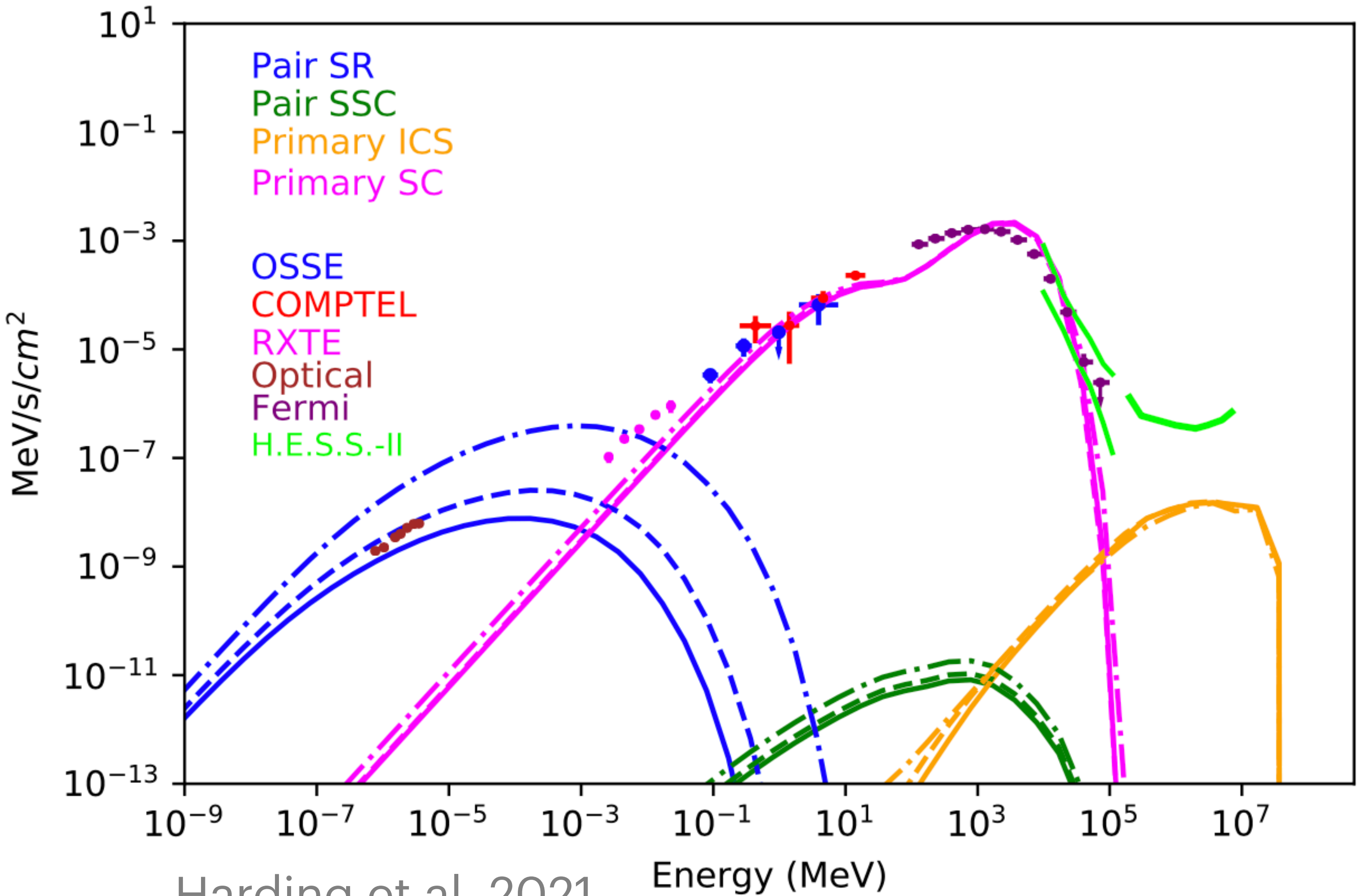
- Light curves, Multi-wavelength spectra

Physics to probe

- Magnetosphere and wind morphology / geometry
- Interplay between particles and electromagnetic fields: propagation, acceleration, radiation, interactions



Spolon et al. 2019



Harding et al. 2021

Setup - morphology magnetosphere & wind

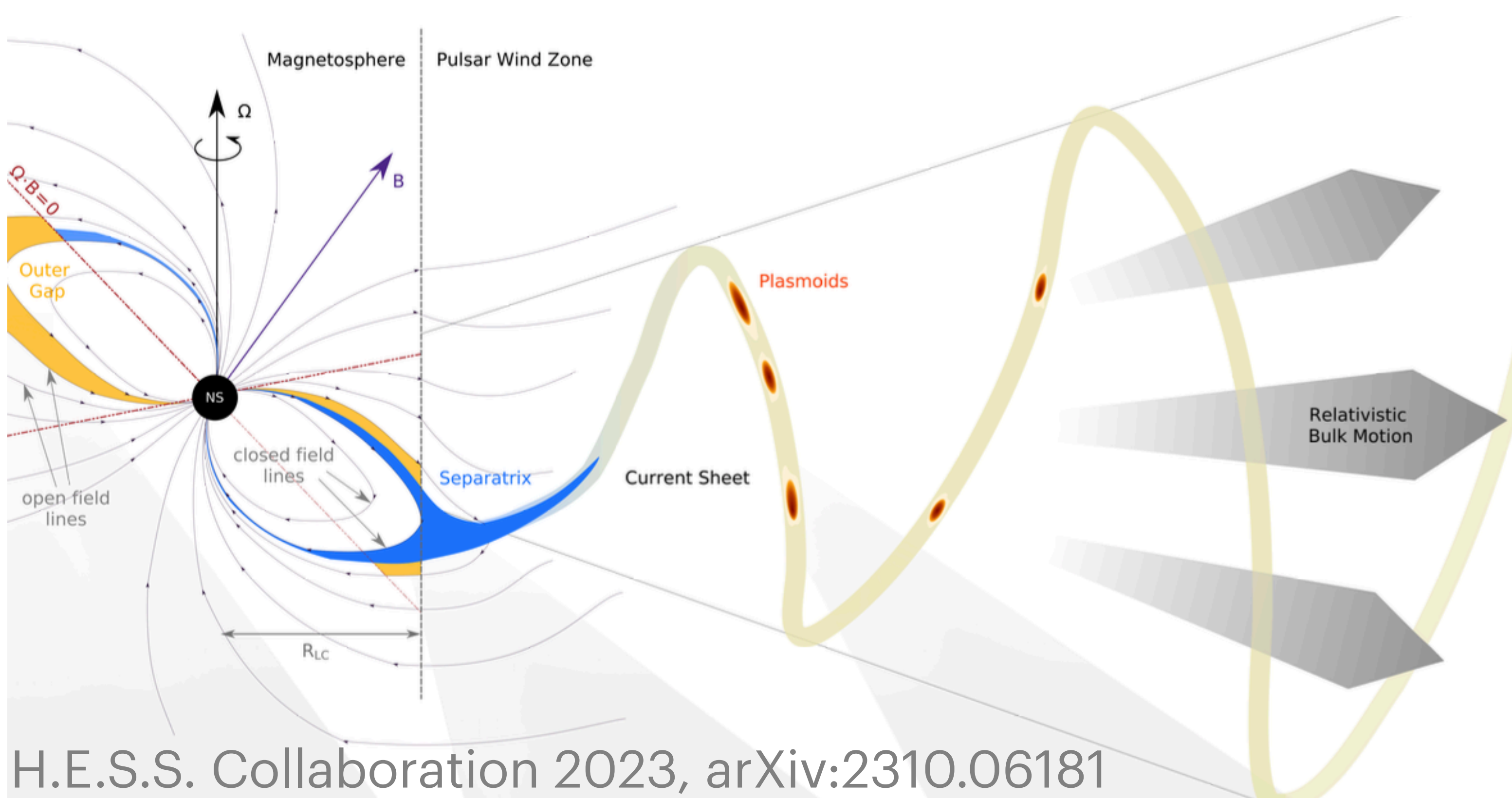
General properties

- Vacuum: Deutsch55. Plasma? Aligned rotator e.g. Goldreich&Julian69, Michel73
- Inclination? Simulations e.g. Force-Free, MHE, PIC, Machine Learning
- *General benchmark solutions*: uncertain properties, closed field lines, current sheet thickness, dissipation?
- Acceleration: gaps, separatrix, current sheet e.g. Bogovalov99, Petri16, Vigano+19

Information about fields and plasma + acceleration and radiation regions

Gamma-ray light-curves: geometry of radiation regions

→ constraints ex. inclination angle, ex. Iniguez-Pascual et al., arXiv:2404.01926



H.E.S.S. Collaboration 2023, arXiv:2310.06181

Setup - particles and processes

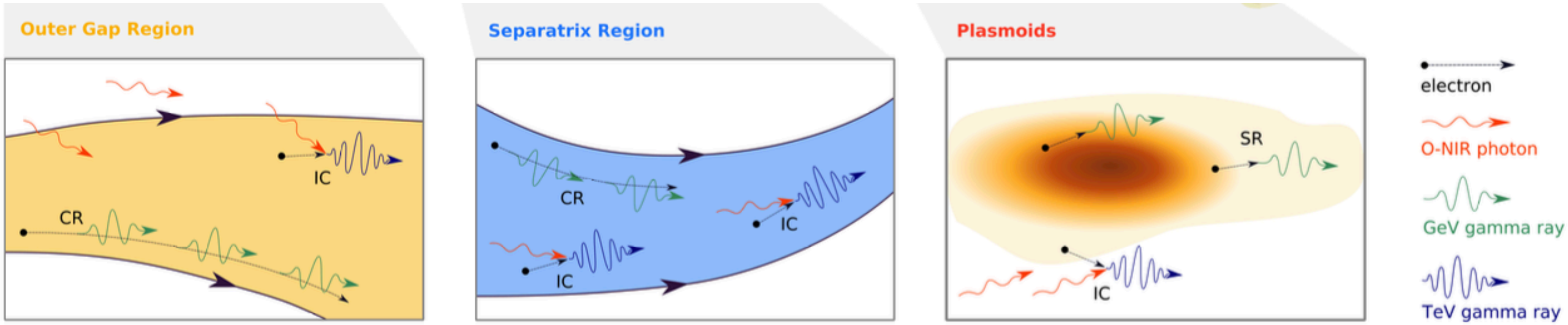
Primary particles

- Electrons, photons. [Protons or nuclei]
- Propagation from the NS surface, acceleration by unscreen parallel electric field, or magnetic reconnection

Secondary particles

- Electrons & positron pairs, photons. [Neutrons, pions, muons, etc.]
- Pairs expected to be produced by cascades close to the NS surface

Radiative/interaction processes: synchro-curvature, inverse Compton, pair production, photo-hadronic



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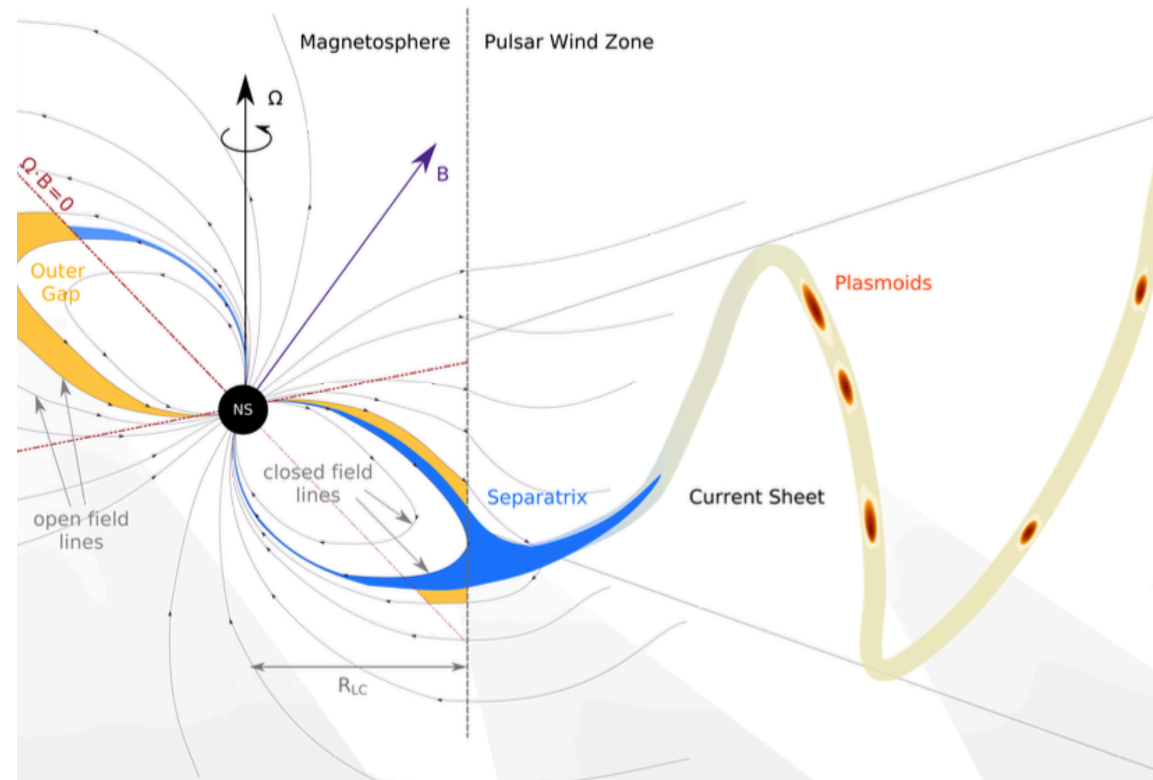
Modeling VHE emission

Model for GeV-TeV emissions

In general, γ rays: **current sheet**

- GeV emission Synchro-Curvature
- TeV emission Inverse Compton (IC)



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IC required <u>target photon field</u>

- hypothesis: accelerated primaries interact with soft photons produced by secondary electron and positron pairs

Multi-wavelength & multi-zone model

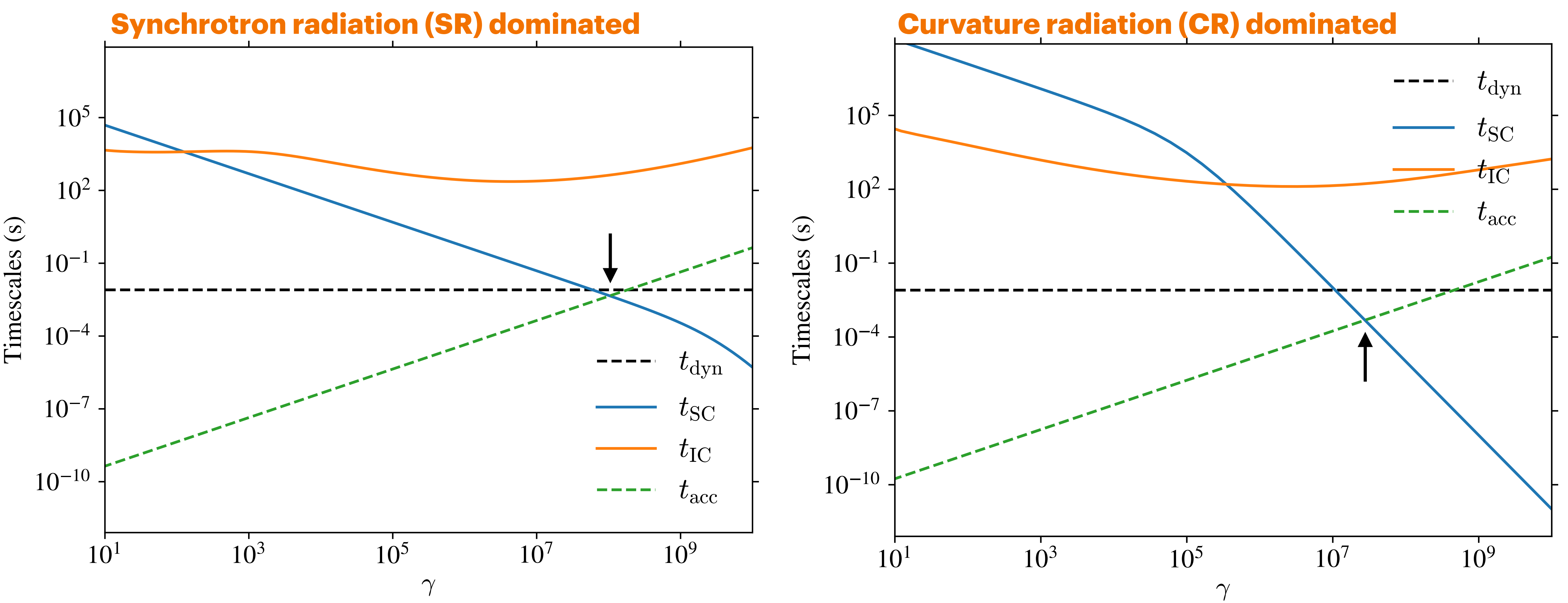
- ex. Petri24: radio emission polar caps, X-rays separatrix, γ rays current sheet

Insight from analytic estimates?

<u>Parameter space exploration</u> for Vela-like properties

Timescales

- dynamical: link to typical size
- acceleration: ex. $t_{acc} \simeq \gamma_e m_e c^2 / ce\eta B$
- synchro-curvature: synchrotron radiation (SR) and curvature radiation (CR)
  - local magnetic field, pitch angle & effective curvature
- inverse Compton (IC): requires description photon background
  - IC vs SR or CR: potentially cooling before IC, lower cutoff



Maximum energies

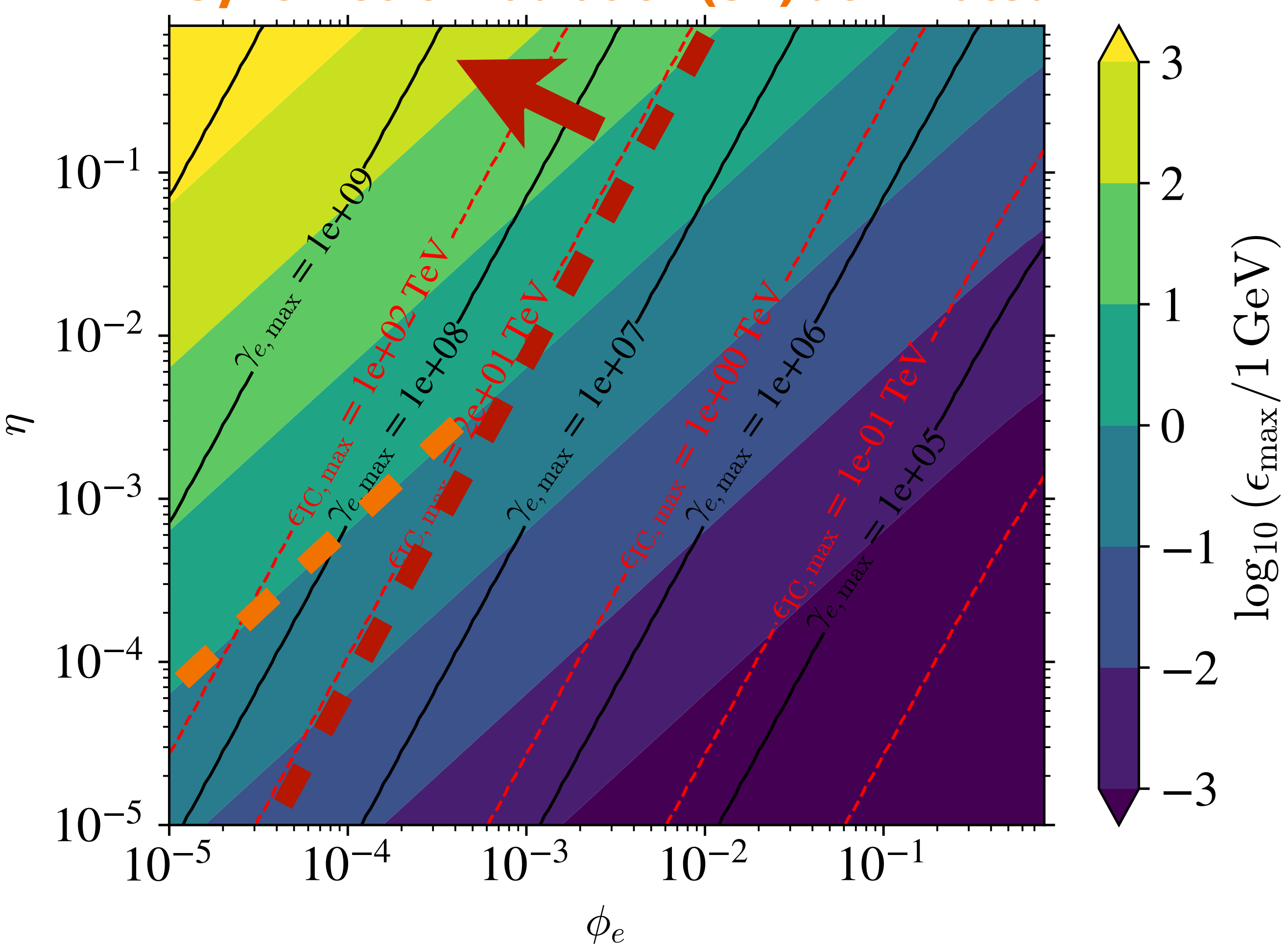
Example: see H.E.S.S. Collaboration 2023, arXiv:2310.06181

Maximum Lorentz factor -> maximum radiated energy & maximum IC energy

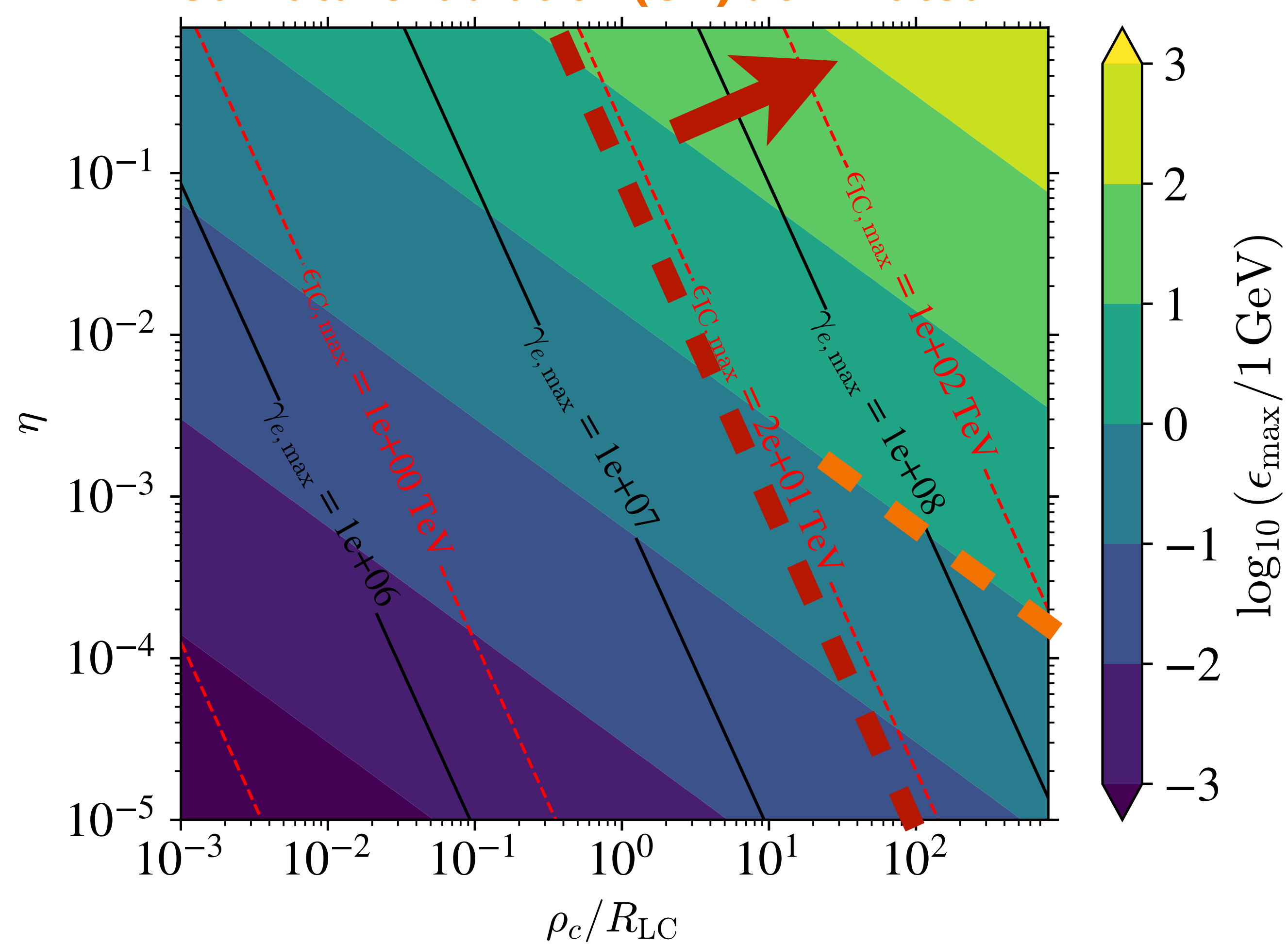
- parameters of Vela pulsar
- for dominant synchrotron radiation (left) or curvature radiation (right)

Limitations: parameter space constrained, SR dominated requires suppression CR

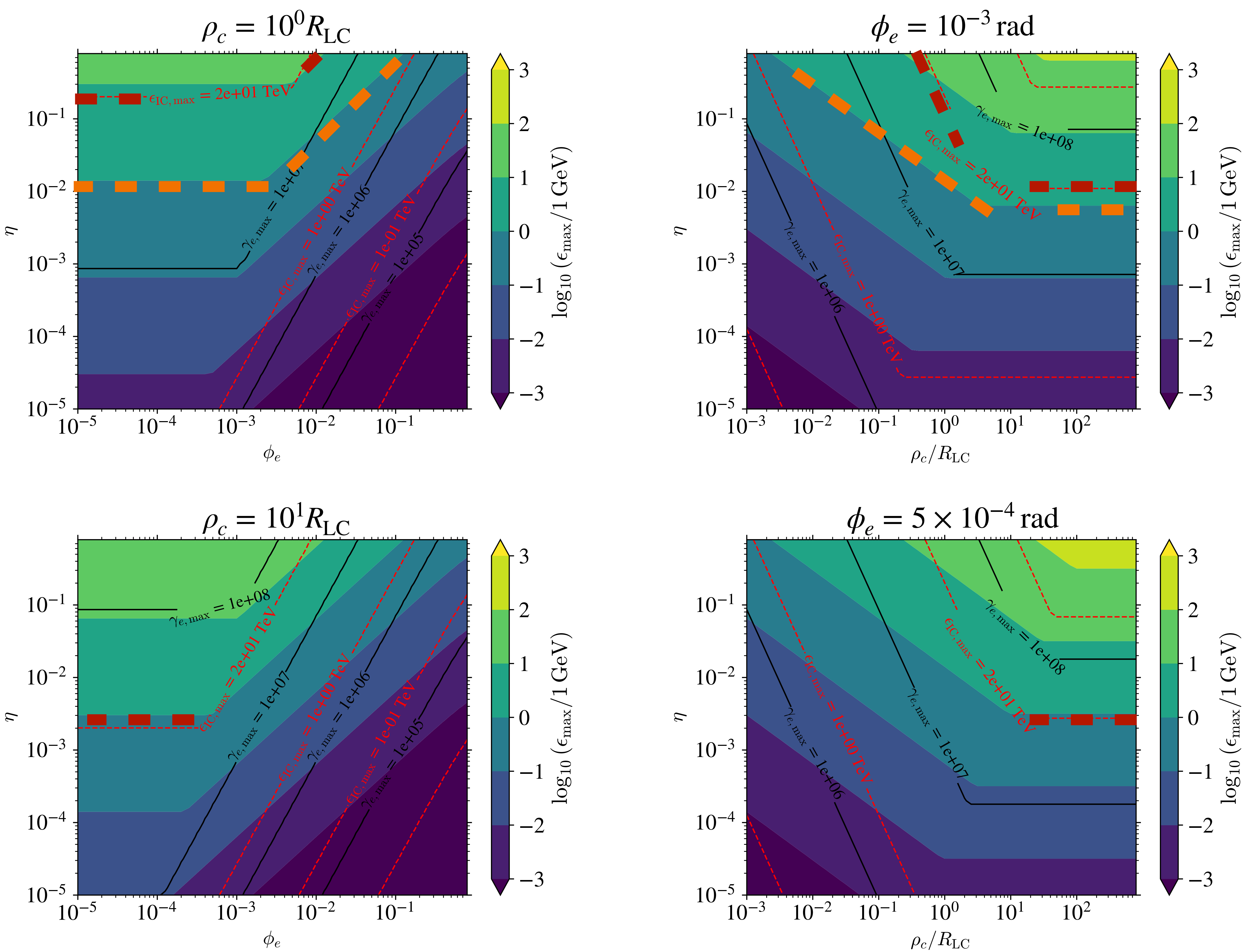
Synchrotron radiation (SR) dominated



Curvature radiation (CR) dominated



Maximum energies



Radiated power and spectra

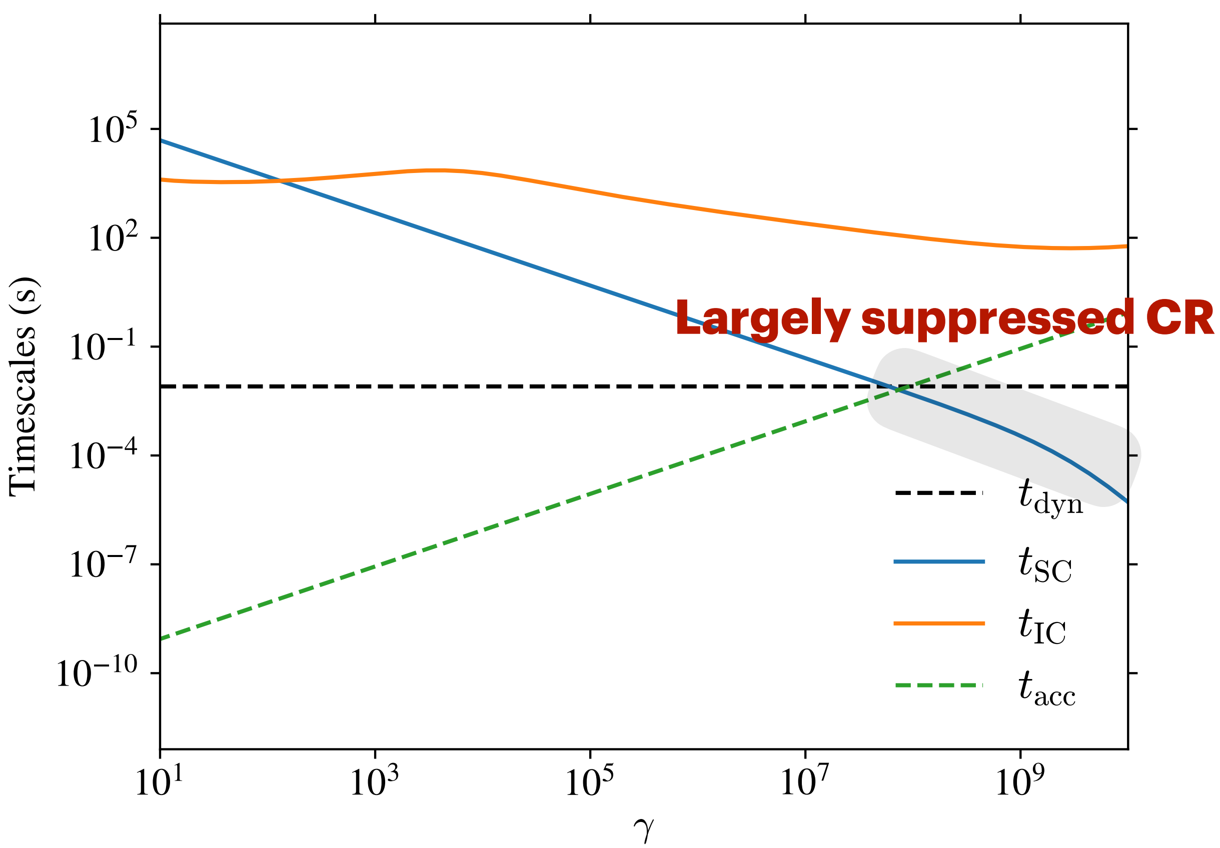
Inputs: observed luminosities & energy loss rates for SR or CR
Assumptions: photon field, typical magnetosphere properties, ex. Goldreich Julian particle densities and pair multiplicies
Estimates: emitting volumes, number particles contributing to HE & VHE emissions

Spectral modeling

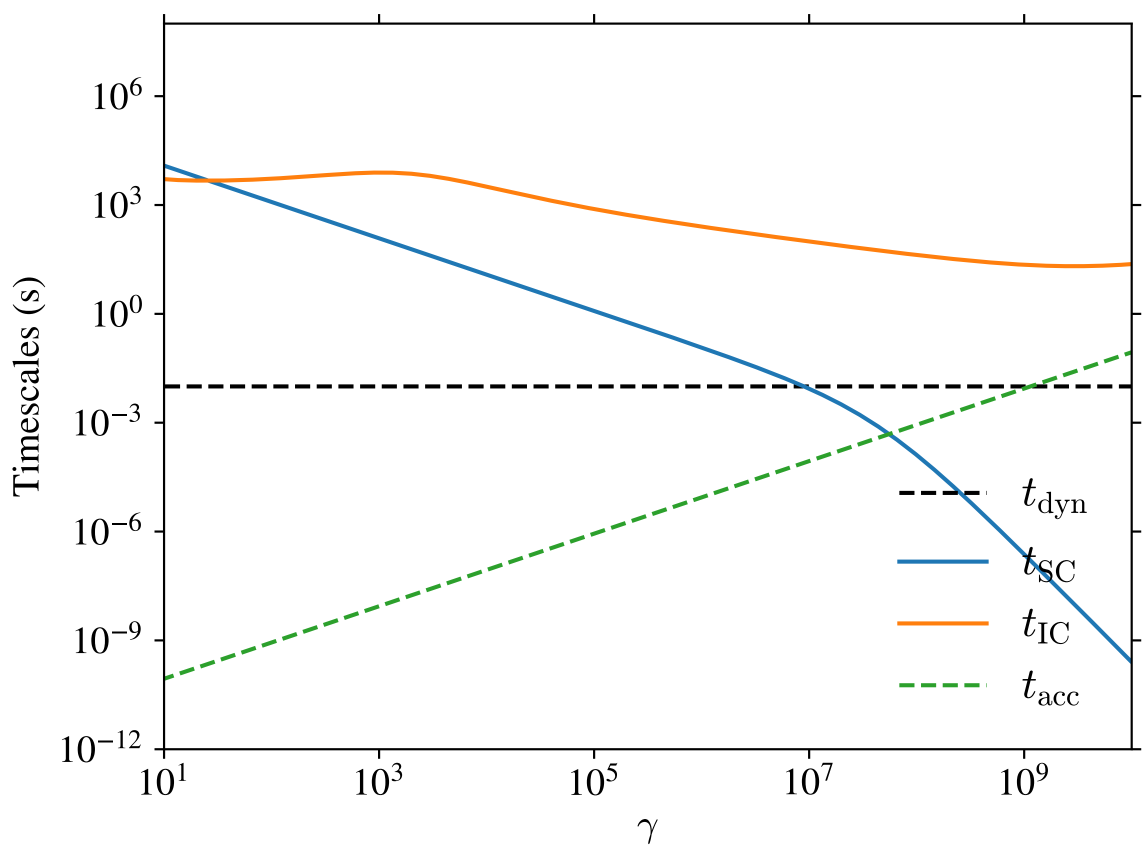
Ex. semi-analytic approach for PDE resolution

- evolution of particle distribution with losses, parametrized photon background
- particle distribution cooling (no reacceleration), typical timescale $t_{\rm dyn} \sim R_{\rm LC}/c$

Synchrotron radiation (SR) dominated



Synchro-curvature



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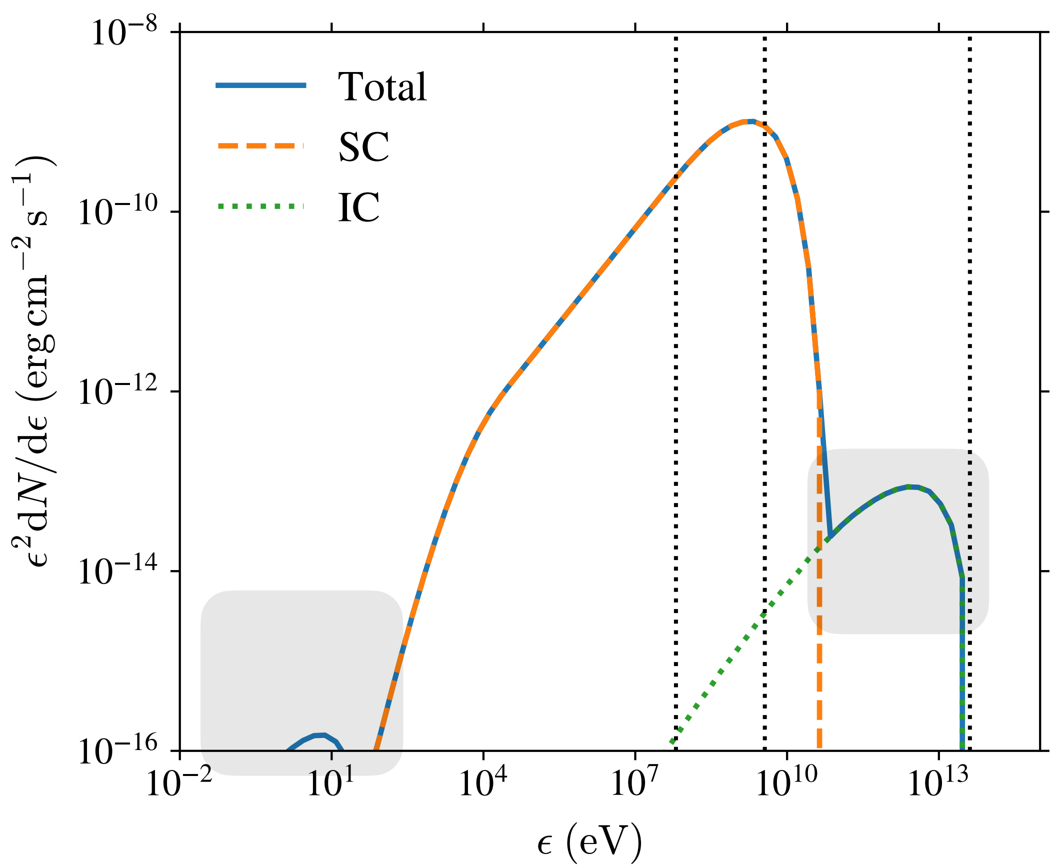
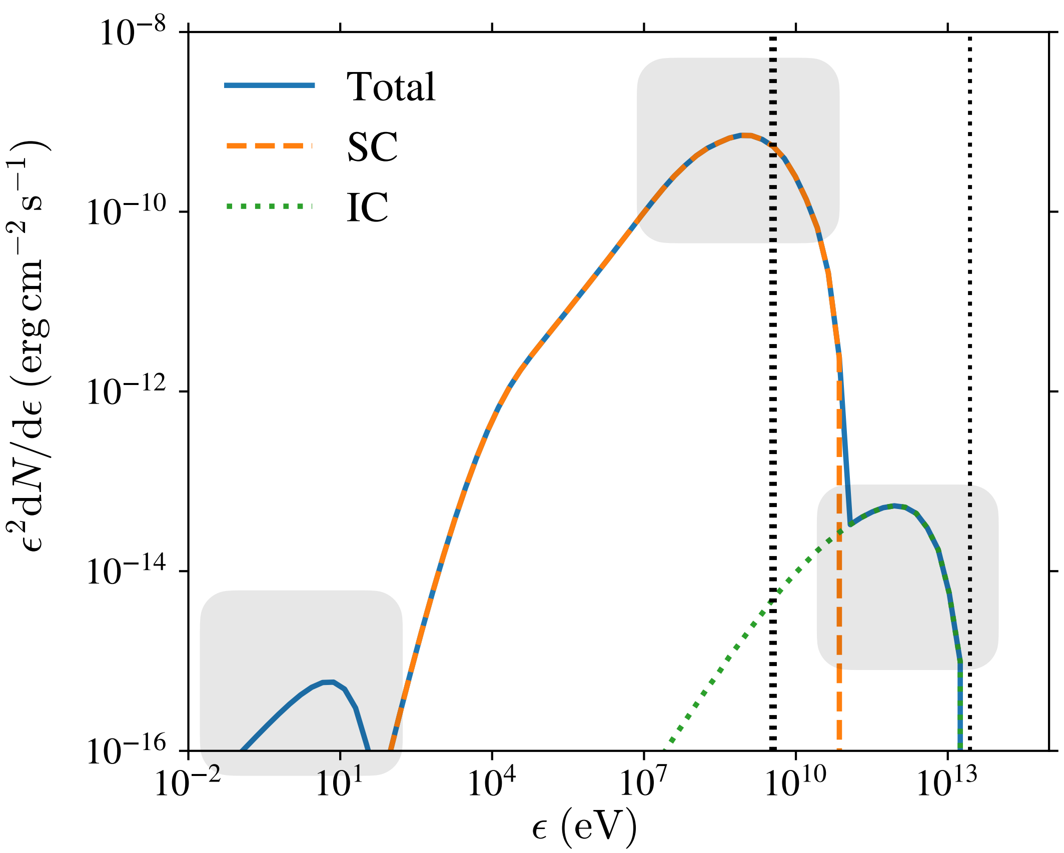


Synchro-curvature

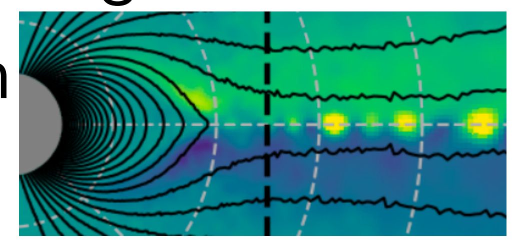


Particle trajectories

Emission along particle trajectory. *Analytic models?*

Propagation regions

- HE particles not trapped in plasmoids
- lower energy pairs in plasmoids, radiating
- evolution of $B, E_{\|}$ during propagation



Particle properties

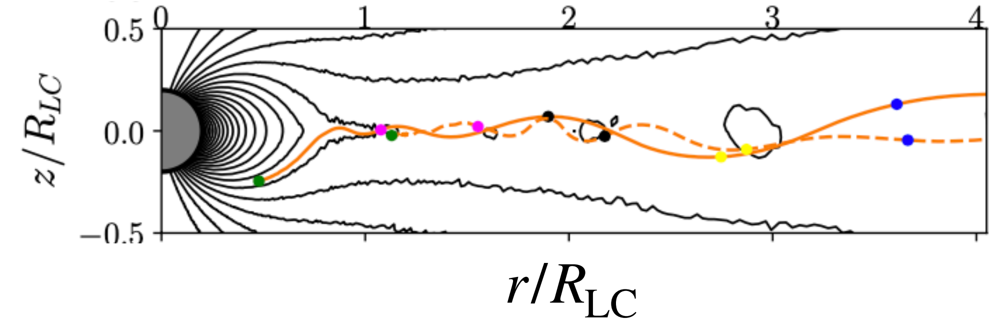
- evolution of effective curvature & pitch angle

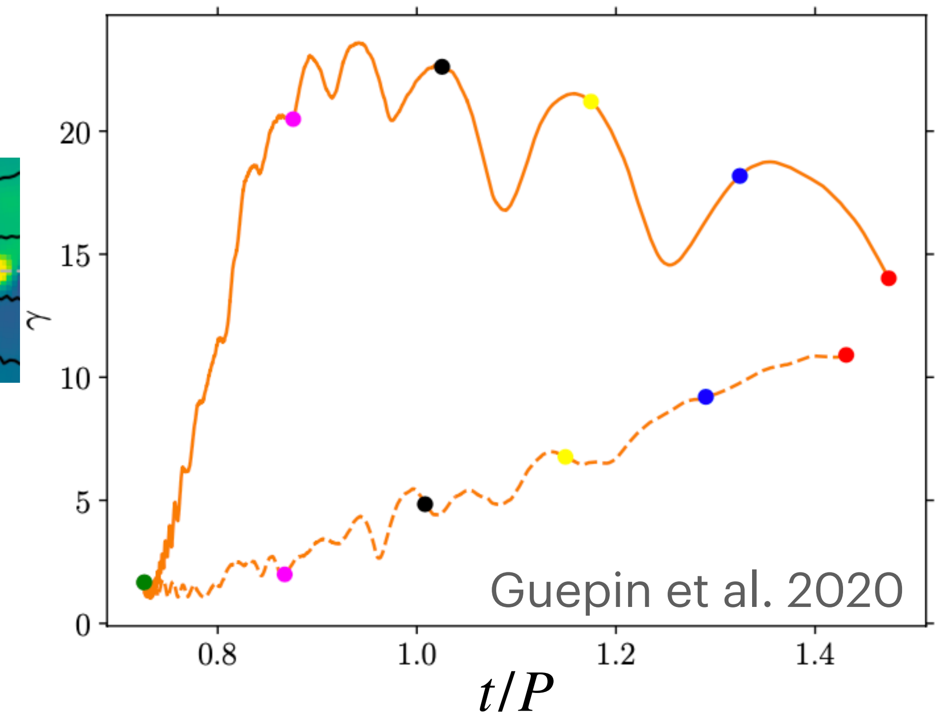
Semi-analytic models / simulations

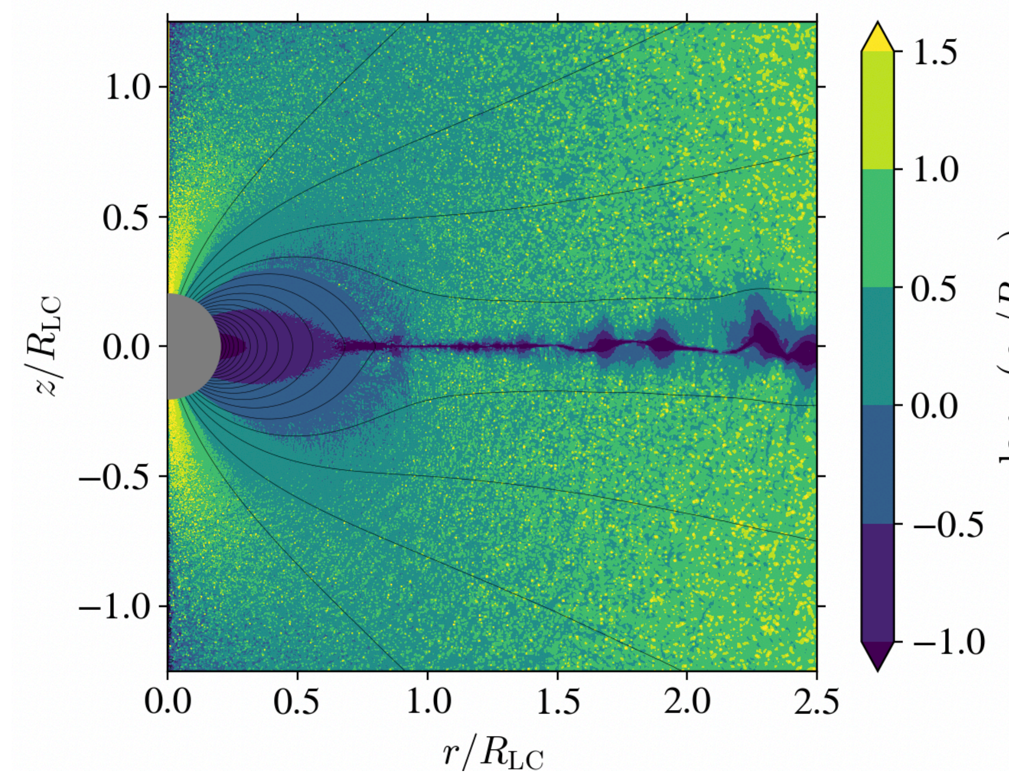
- lorentz factor & pitch angle evolution
- radiation reaction limit, ex. Mestel+85, Petri16

  $q(E + v \times B) = \mathscr{P}\ v/c^2$ (SI)
- momentum evolution along propagation, ex. Hirotani&Shibata99, Vigano+15

Pair production regions







Multi-wavelength constraints

Photon background

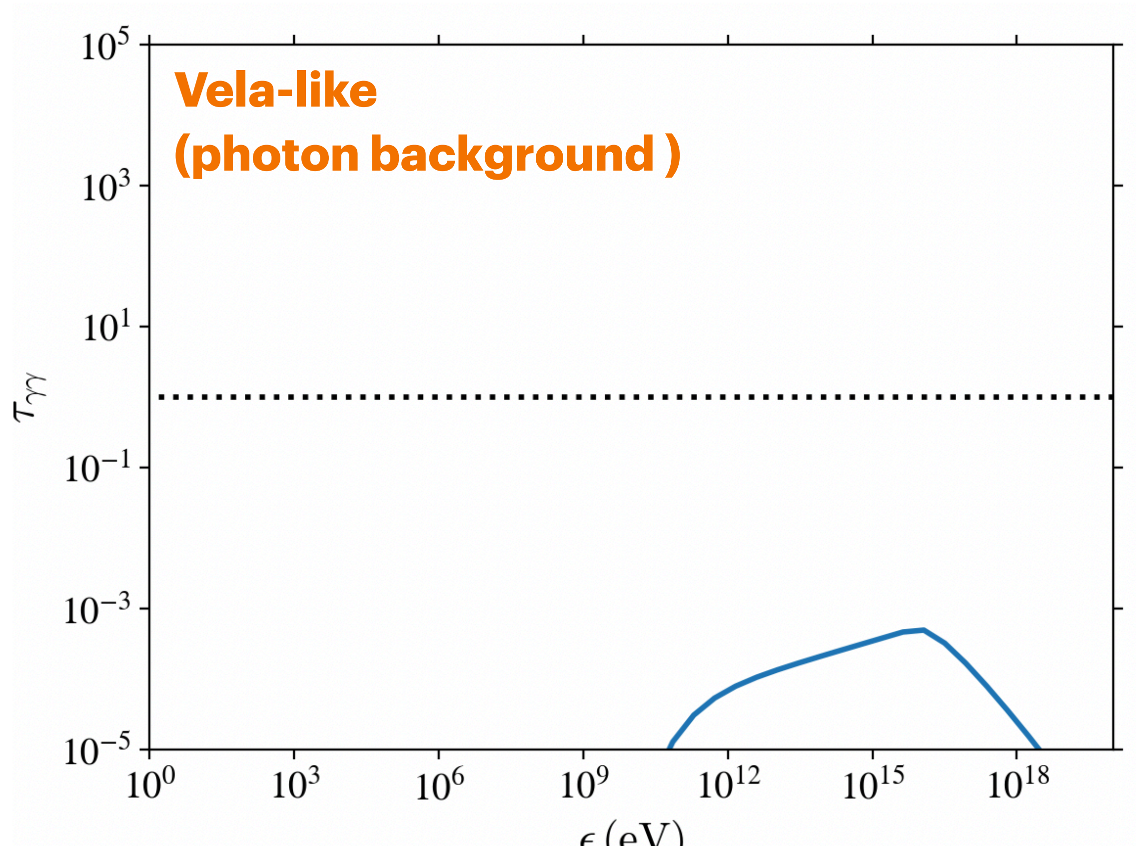
Impact on inverse Compton, pair production, photo-hadronic processes

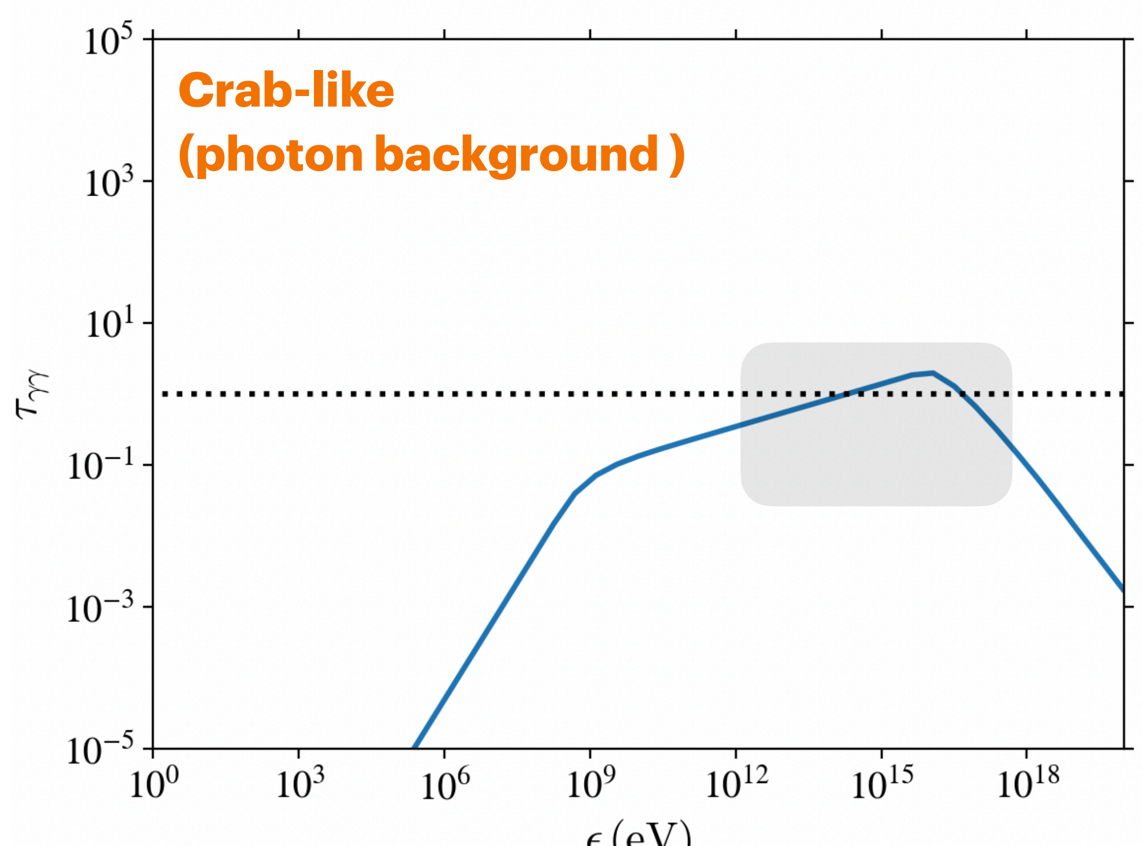
Observations in optical and lower energies limited

- determine from VHE observations, ex. H.E.S.S. Collaboration 2023, arXiv:2310.06181
- information from lightcurves, time coincidence, extended regions emitting
- constraints from pair production models, ex. Harding et al. 2021

Pair production, γB, $\gamma\gamma$

- analytic & (simple) numerical approaches: map potential pair production regions

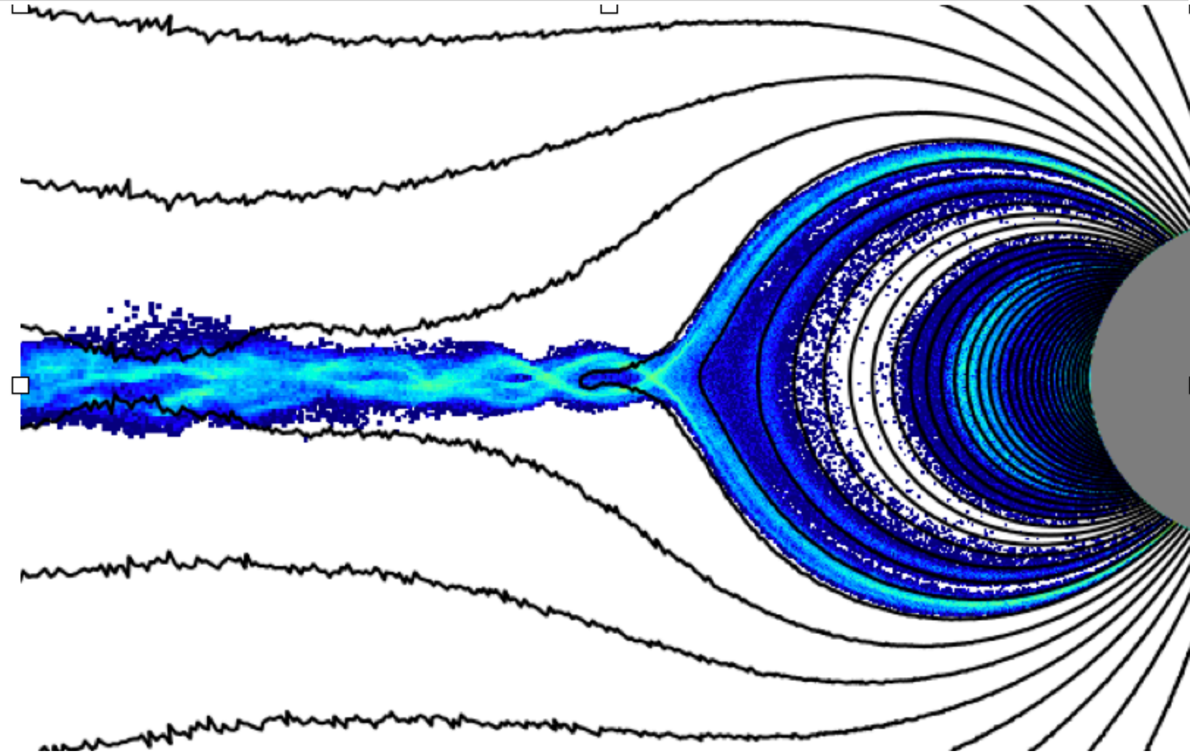




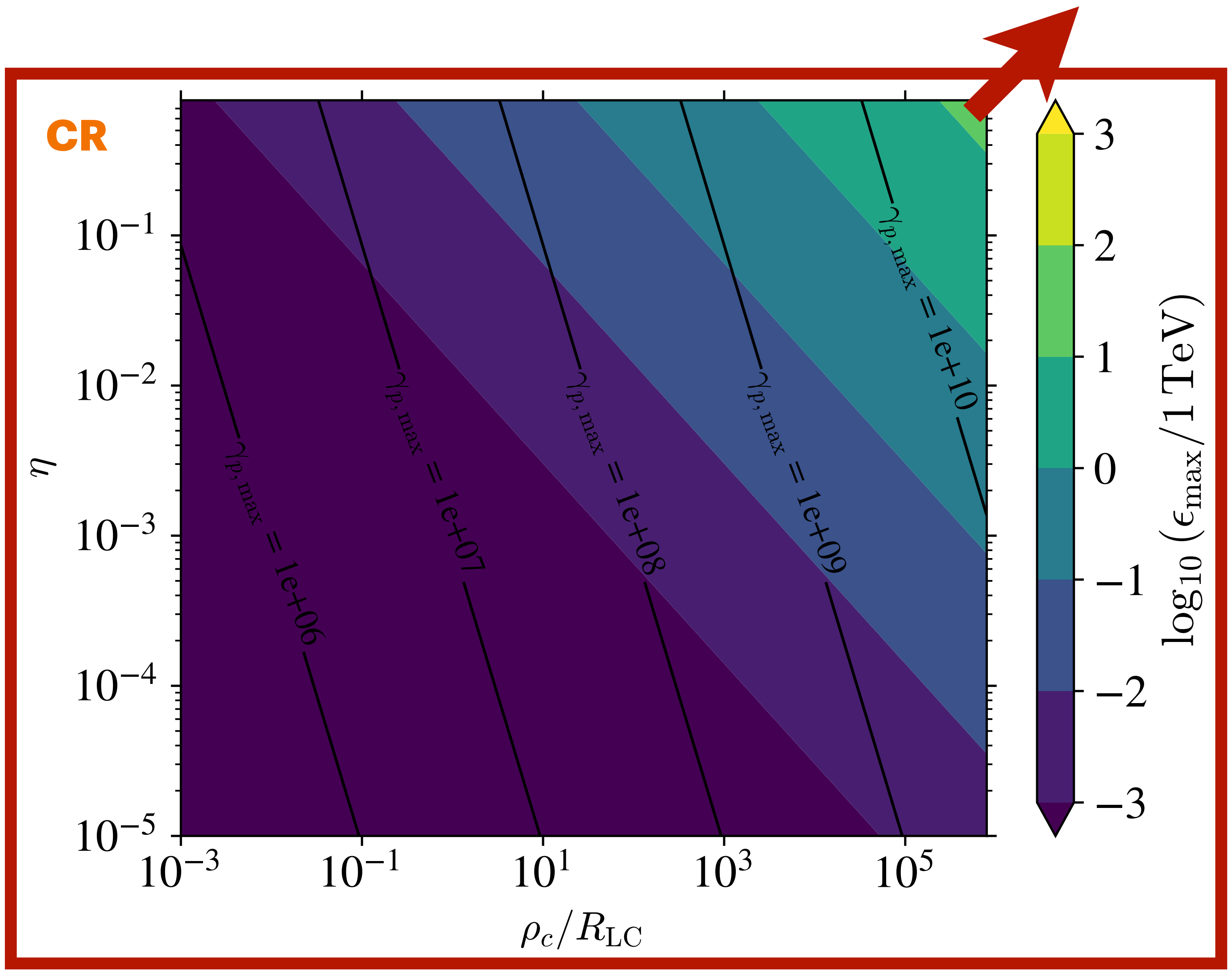
What about protons?

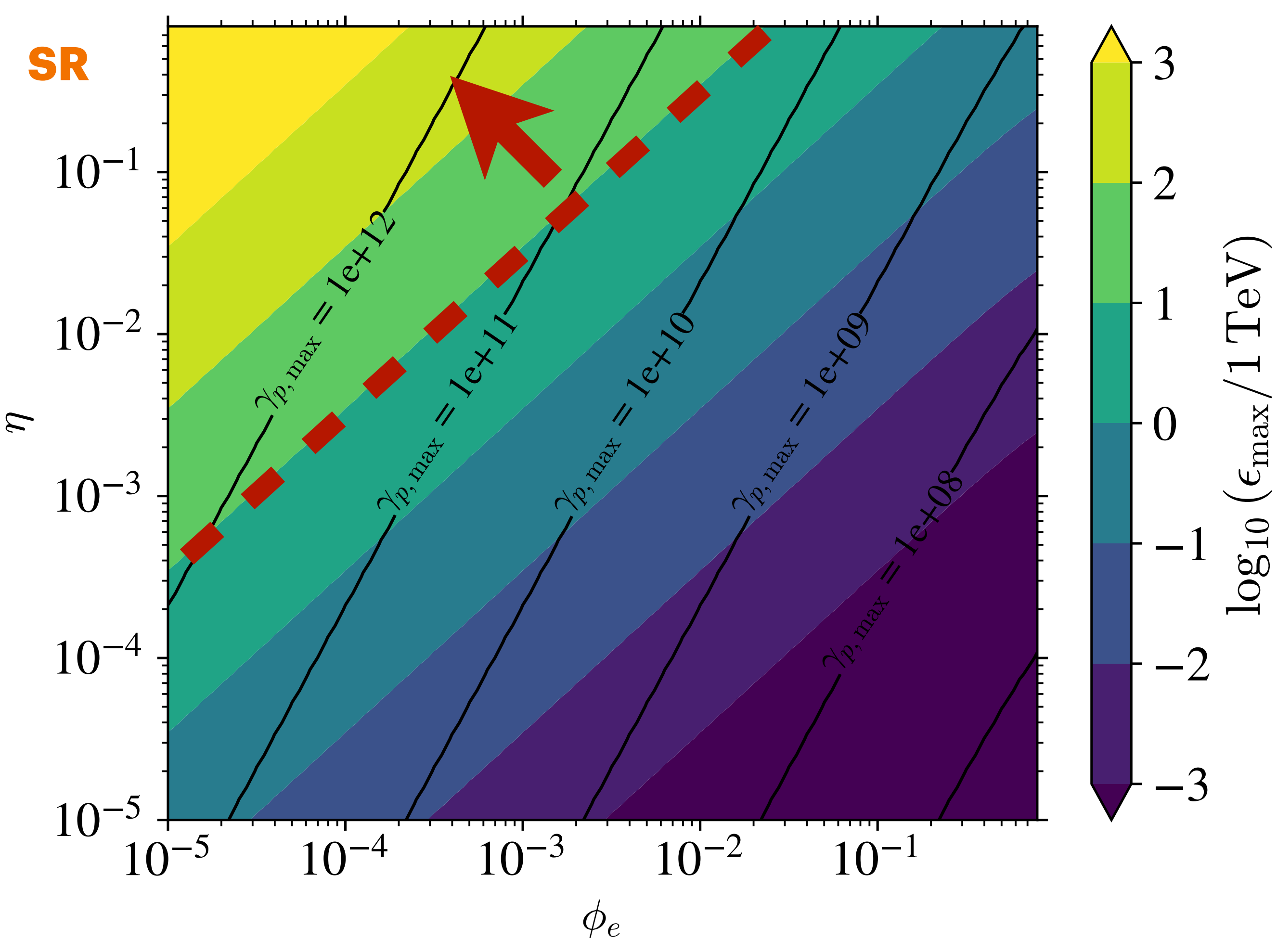
Protons can be:

- injected from the NS surface
- accelerated in gaps / current sheet
- ex. PIC simulations Guepin et al. 2020, arXiv:1910.11387



Contributions to the MWL spectrum, through radiation and interactions?





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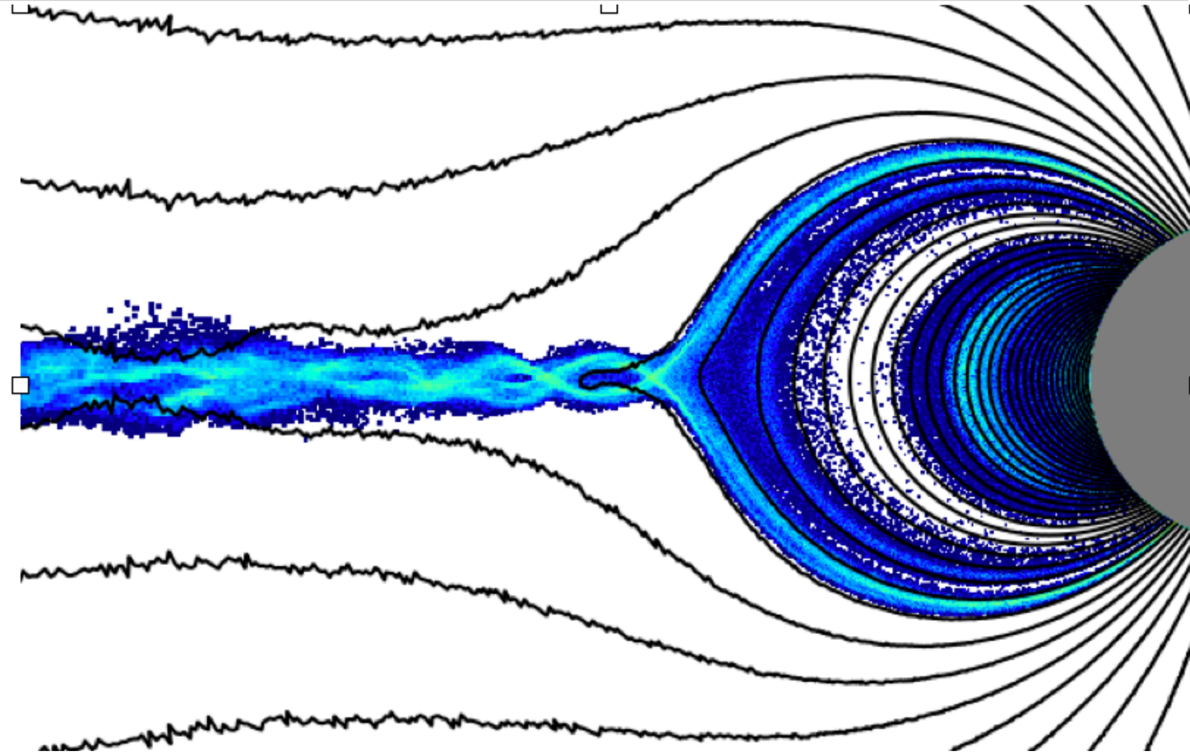
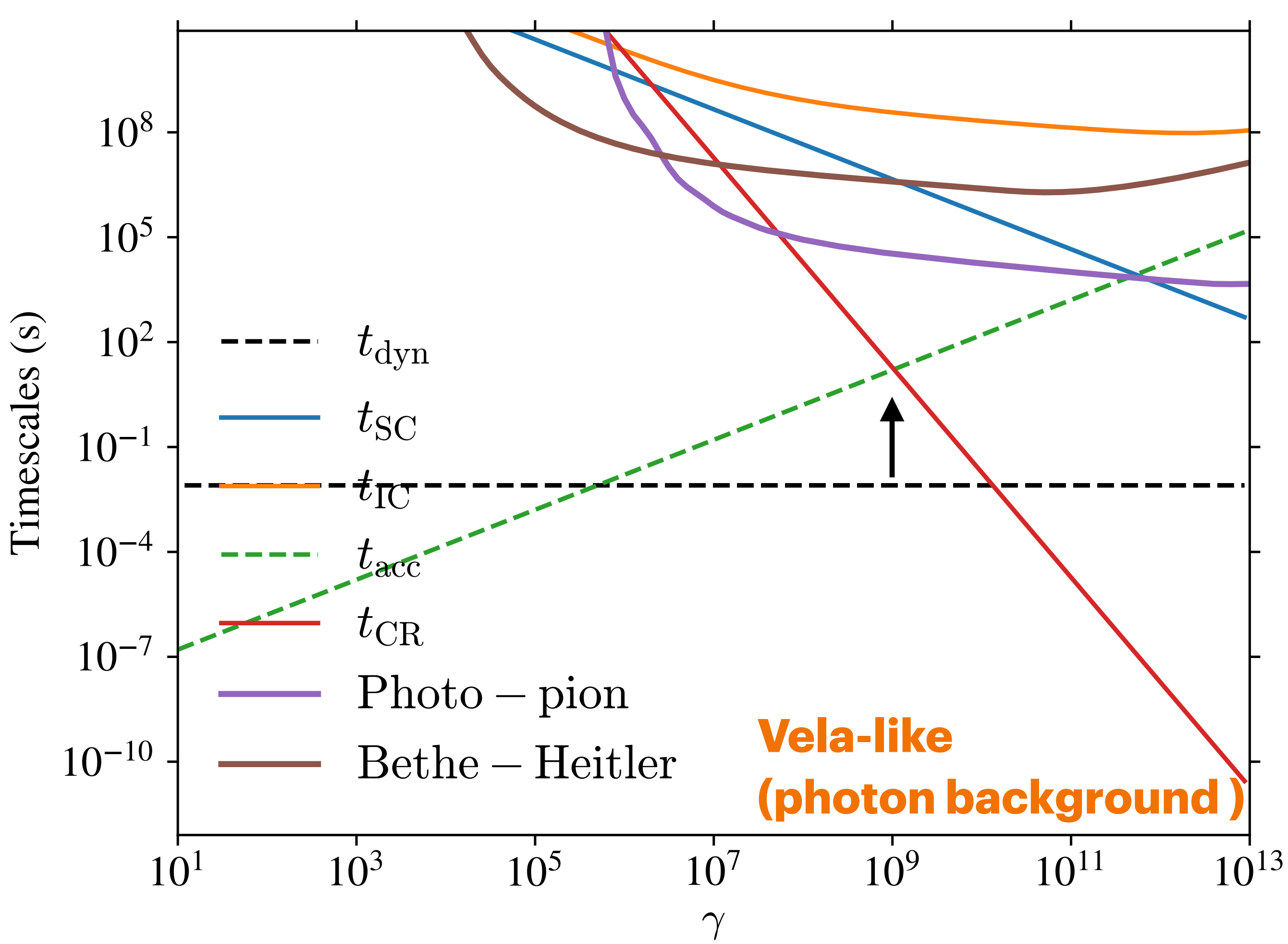


Contributions to the MWL spectrum, through radiation and interactions? Most certainly weak



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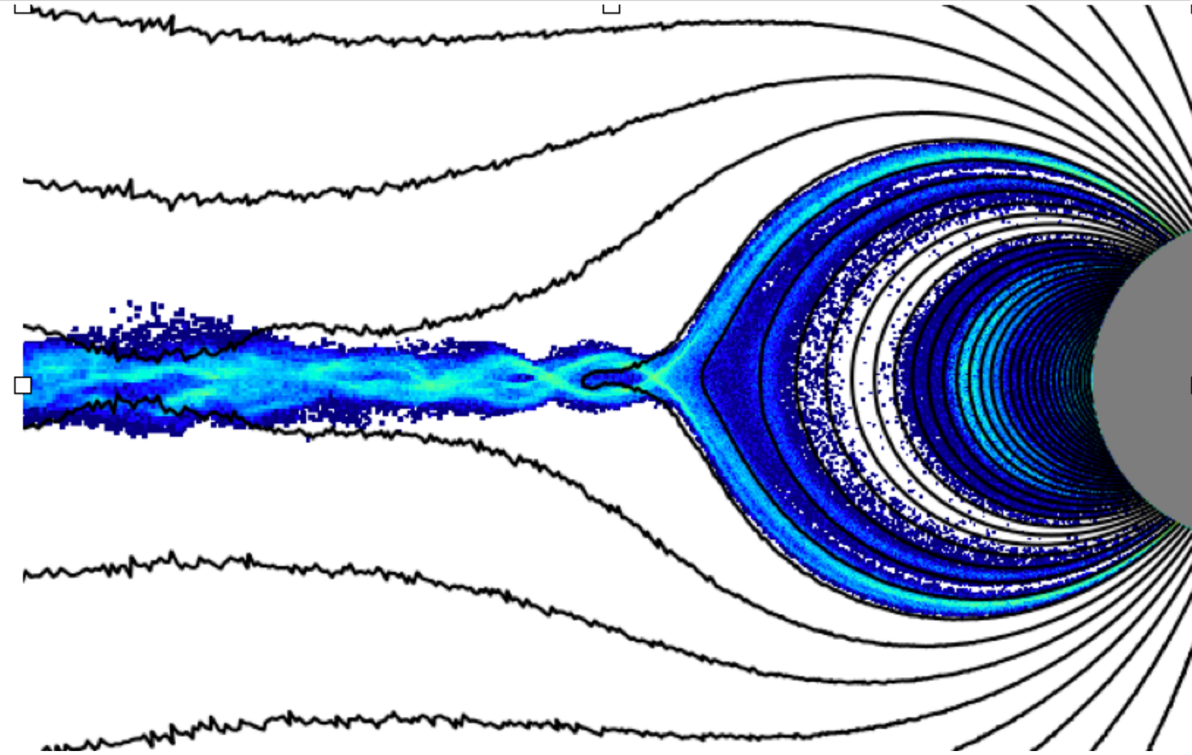

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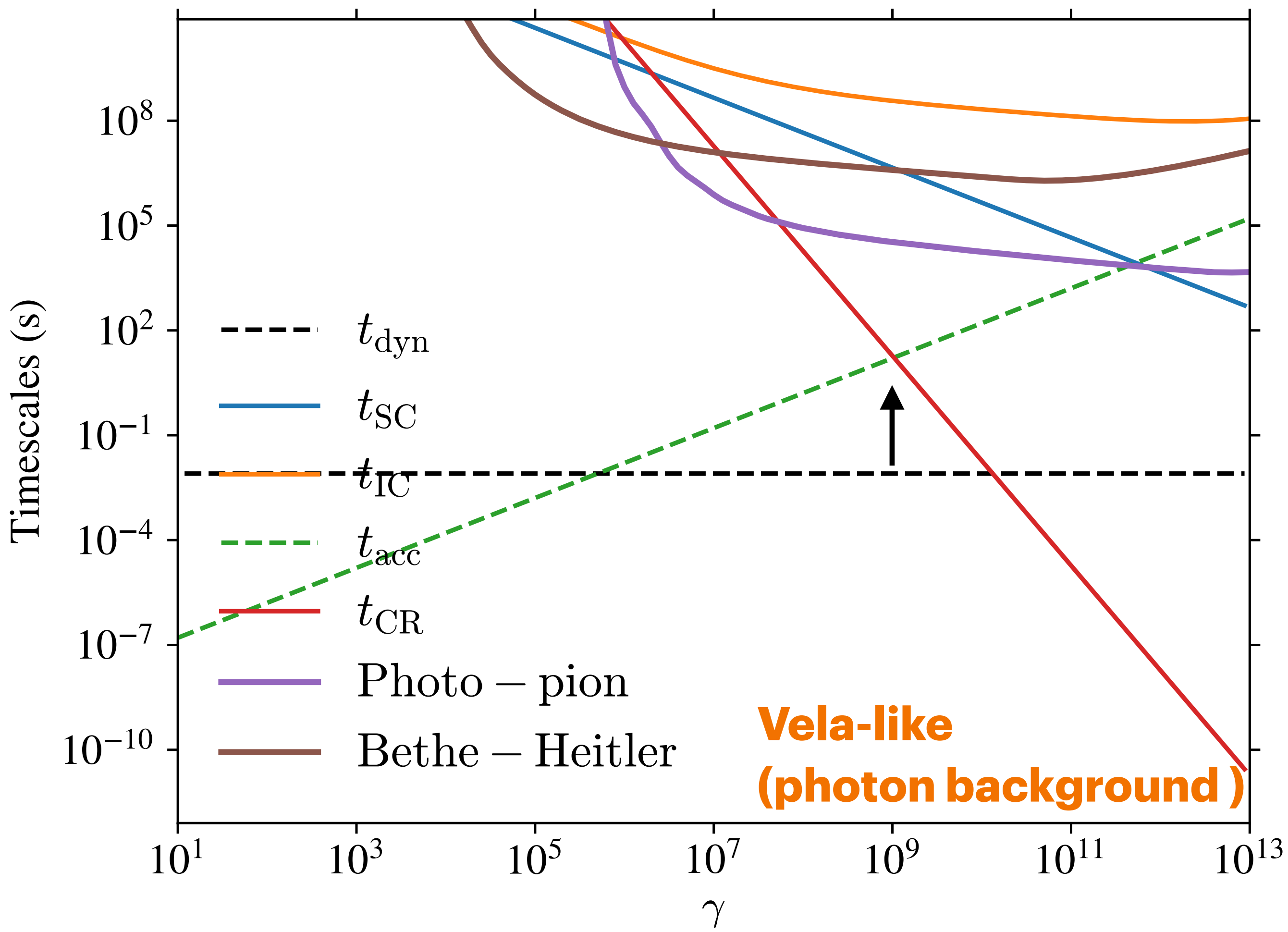

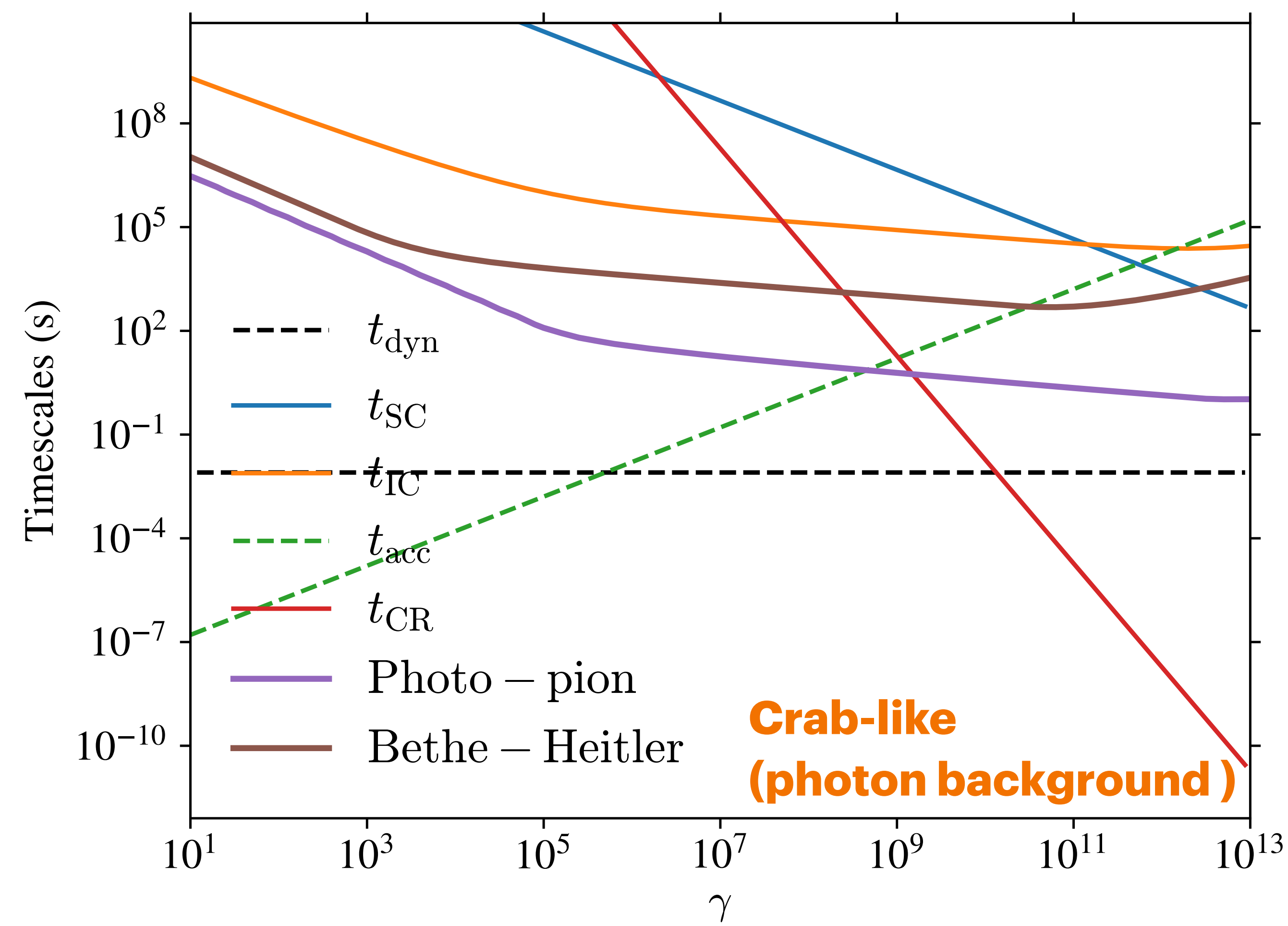

VHE emissions from pulsars - Insight from analytic approaches

Morphology and geometry: early magnetosphere models, numerical simulations

Lightcurves: inclination pulsar-observer, emission regions, particle trajectories

MWL spectrum: particle distributions, acceleration, radiation and interactions
- analysis typical timescales and maximum energies: parameter space exploration
- total energy radiated, uncertainties & degeneracies
- spectral modeling with simple "one zone" models
  - parameter space constrained
  - SR dominated requires suppression CR
  - SC cooling can impact GeV peak and IC cutoff
- further constraints from "multi-zone" models
  - acceleration zones, suppression of SC
  - particle propagation & photon fields predictions

Coupling with photohadronic studies: protons, nuclei, HE neutrinos?
- no impact on MWL spectum expected for Vela parameters
- perspectives: other pulsars with higher optical photons background