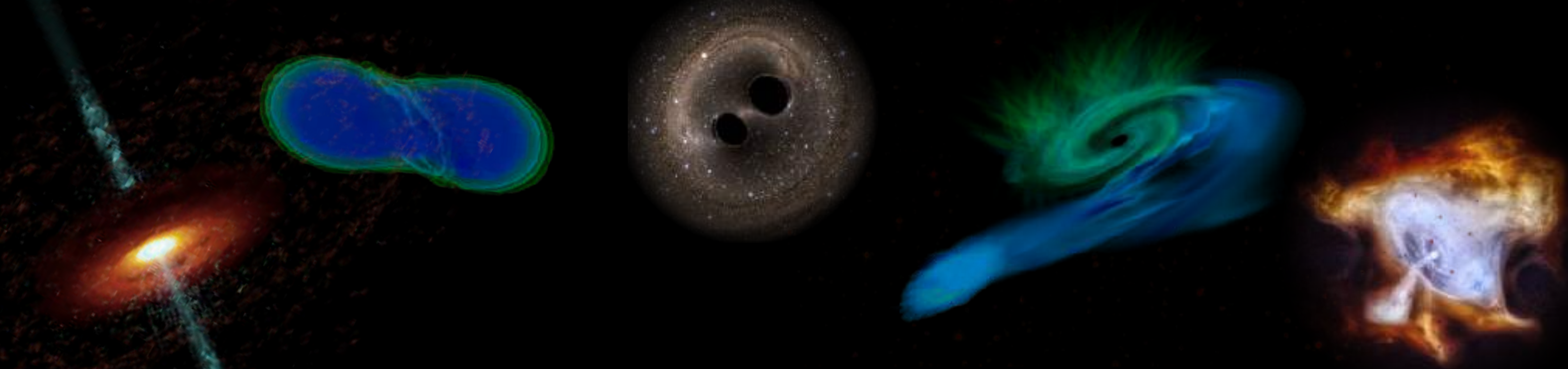

High-energy particles from astrophysical transients

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- **Multi-wavelength (MWL) and multi-messenger (MM) astronomy**: photons, cosmic rays, neutrinos, gravitational waves

ex. Fermi, H.E.S.S. | ex. Auger, TA | ex. IceCube, ANTARES | ex. LIGO-Virgo

High-energy universe and compact sources: emissions, physical processes?

HE - UHE cosmic-rays and neutrinos: sources and production mechanisms?

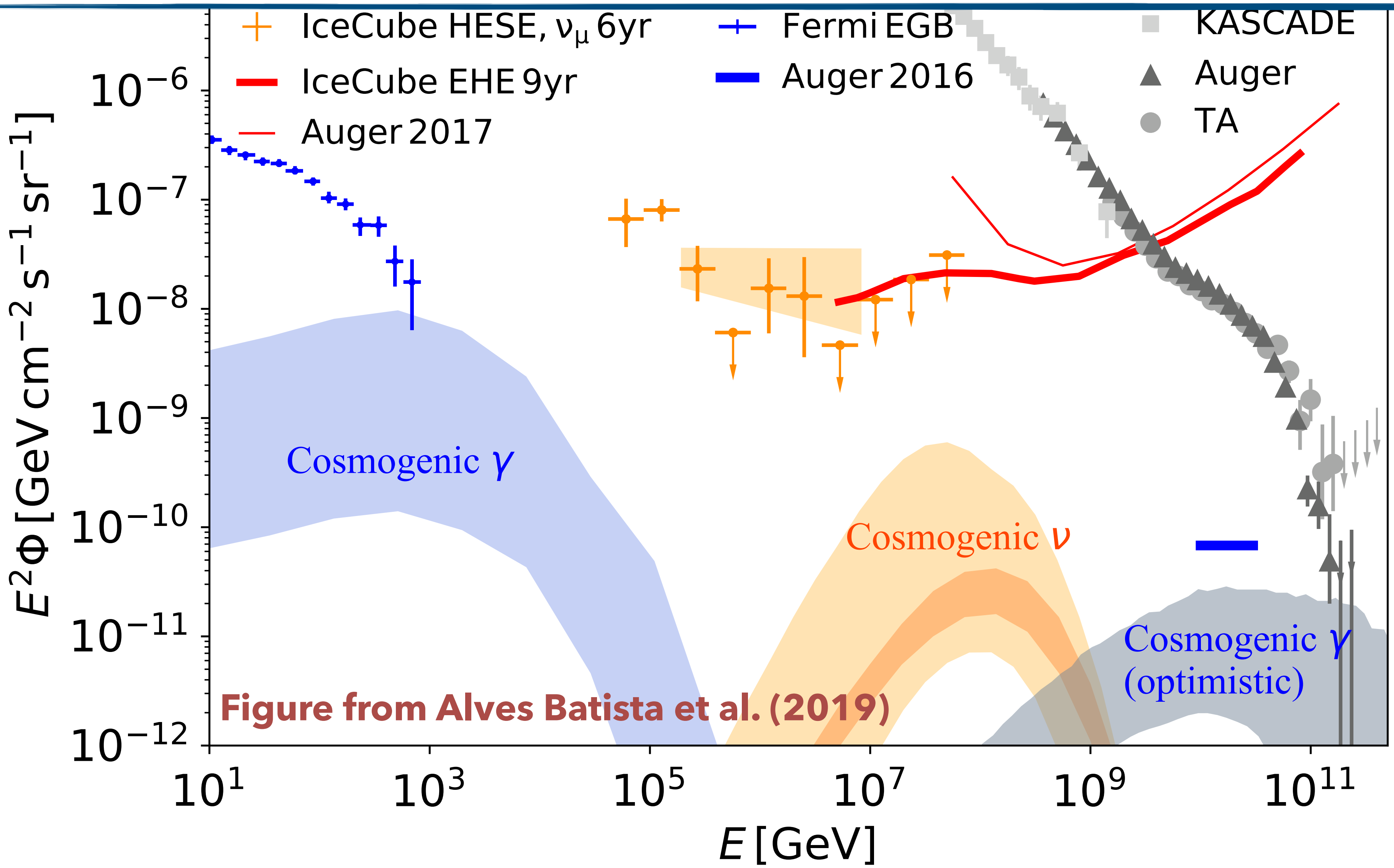

Figure from Alves Batista et al. (2019)

- **HE - UHE neutrinos** (HE $\gtrsim 10^{15}\,\mathrm{eV}$ and UHE $\gtrsim 10^{17}\,\mathrm{eV}$)
  - Undeflected signatures of **hadronic interactions**: sites of **cosmic-ray acceleration**
    → **Identification of HE - UHE cosmic-ray sources?**
  - Rare interactions, no deflections during propagation: deeper **cosmological horizon** than cosmic rays and gamma rays, good potential for **spatial + temporal coincidences**
    → **Identification of neutrino sources?** Advent of HE - UHE neutrino astronomy!
  - Exciting prospects with **future detectors**: many emerging projects

Part of table from: Guépin, Kotera & Oikonomou, Nature Rev. Phys., arXiv 2207.12205

2021 2025 >2030		Peak energy
ANTARES	up(cascade)	$50(100)$ TeV
IceCube	up(cascade)	100 TeV
IceCube-Gen2	up(cascade)	300 TeV
KM3Net ARCA	up(cascade)	$100(100)$ TeV
Baikal-GVD	up(cascade)	$100(100)$ TeV
P-ONE	up(cascade)	100 TeV

2021 2025 >2030	Peak energy
Auger	$0.3-1$ EeV
POEMMA Cerenkov	0.5 EeV
fluorescence	100 EeV
GRAND	0.4 EeV
IceCube-Gen2 Radio	0.3 EeV
Ashra-NTA	0.1 EeV
Trinity	0.1 EeV
TAMBO	10 PeV
RET-N	0.1 EeV

2021 2025 >2030	Peak energy
ANITA	100 EeV
PUEO	20 EeV
ARA	$1-3$ EeV
RNO-G	1 EeV
ARIANNA-200	1 EeV
BEACON	1 EeV

- Astrophysical **transients**: short ($\lesssim$ few months) and irregular emissions
  - Powerful plasma outflows, but variety of observational characteristics, structure and evolution. Ex. supernovae, gamma-ray bursts, mergers, blazar flares, tidal disruption events, etc.
  - Improved instrumental sensitivity, time resolution, wide-field instruments
    → more observations, new categories of luminous transients discovered
  - **Associations photons + HE neutrinos**: **first hints** (background, model dependent)
    - Challenges: models require high proton luminosities

Neutrino event	Possible coincidence	90% area (sq. deg.)	Signalness
IC170922A	blazar flare TXS 0506+056	1.3	56%
IC190730A	blazar flare PKS 1502+106	5.41	67%
IC191001A	TDE AT2019dsg	25.53	59%
IC191119A	possible TDE AT2019aalc	61.1	45%
IC200107A	blazar flare 3HSP J095507.9+355101	7.62	-
IC200530A	possible TDE / Type IIn SLSN AT2019fdr	25.3	59%

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  - Searches for coincidences for various individual sources and population of sources
    → No dominant source population identified yet
    - Important multi-wavelength (MWL) and multi-messenger (MM) observing effort

Part of table from: Guépin, Kotera & Oikonomou, Nature Rev. Phys., arXiv 2207.12205

2021 2025 >2030	Band Width	ν foll. rate [% alerts] *examples*
LHAASO	100 GeV−1 PeV	?
CTA	20 GeV−300 TeV	20 h/yr (2016)
HAWC	100 GeV−100 TeV	[90% IC Gold alerts]
H.E.S.S.	30 GeV−100 TeV	60−70 h/yr
MAGIC	50 GeV−50 TeV	60 h/yr, 15% ToO
VERITAS	85 GeV−30 TeV	45 h/yr
Fermi LAT	20 MeV−300 GeV	[100% IC alerts]
Fermi GBM	10 keV−25 MeV	[60% IC alerts]
INTEGRAL IBIS	15 keV−10 MeV	[all ANTARES
INTEGRAL SPI-ACS	100 keV−2 MeV	and GCN IC alerts]
XMM-Newton	0.2−12 keV	*PKS 1502+106, Kloppo*
Athena-WFI	0.1−15 keV	[5 ToO/month]
Swift BAT	15−150 keV	
Swift XRT	0.2−10 keV	50% ToO
Swift UVOT	0.16−0.62 μm	

2021 2025 >2030	Band Width	ν foll. rate [% alerts] *examples*
SVOM ECLAIRs	4−150 keV	first 3 yrs:
SVOM MXT	0.2−10 keV	15% ToO
SVOM VT	0.4−1 μm	then: 40% ToO
ASAS-SN	380−555 nm	[70−80% all IC GCN alerts]
ATLAS	420−975 nm	[no ν alert yet]
Pan-STARRS	400−900 nm	[6 follow ups]
ZTF	400−650 nm	[74% IC Gold alerts]
Vera Rubin Obs. (LSST)	0.3−1 μm	-
MASTER-II(VWF)	400−800 nm	[99% GCN neutrino alerts]
TAROT	350−980 nm	<3% obs. time [70% GCN alerts]
GEMINI (GMOS)	0.36−1.03 μm, spec	*SN PTF12csy*
GTC (OSIRIS)	0.365−1.05 μm, spec	*TXS 0506+056*
Keck (LRIS)	0.32−1 μm, spec	*SN PTF12csy*
VLT (X-shooter)	0.3−2.4 μm, spec	*TXS 0506+056, IC190331A*
VLA	1−50 GHz	*TXS 0506+056, ANTARES events*
MWA	80−300 MHz	[30% IC Gold, >30% ANTARES]
SKA1(2)-MID	350 MHz−15.3 GHz	?

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    - Important MWL/MM modeling effort

      Database for transient neutrino models: https://www.lupm.in2p3.fr/users/guepin

High-energy universe and compact sources: emissions, physical processes?

HE - UHE cosmic-rays and neutrinos: sources and production mechanisms?

Advances of multi-wavelength/multi-messenger and transient astronomy

Modeling propagation and interaction of various messengers in the source vicinity

→ **Why is it important?**

- Distinction between source classes.
  - Ex. various classes of SNe, FBOT, TDE
- Use of spatial & temporal properties
  - Ex. describe radiation/acceleration regions, predict SED & lightcurves
- Link between observations and physical processes in sources, ex. plasma physics, particle interactions, jet or wind properties.
  - Ex. identify hadronic & leptonic emissions with VHE particles, or with X-rays/gamma rays from cascaded gamma rays
  - Ex. identify MM signatures for various hadronic components: interaction of cosmic rays, production of secondary nucleons, nuclei, neutrinos?

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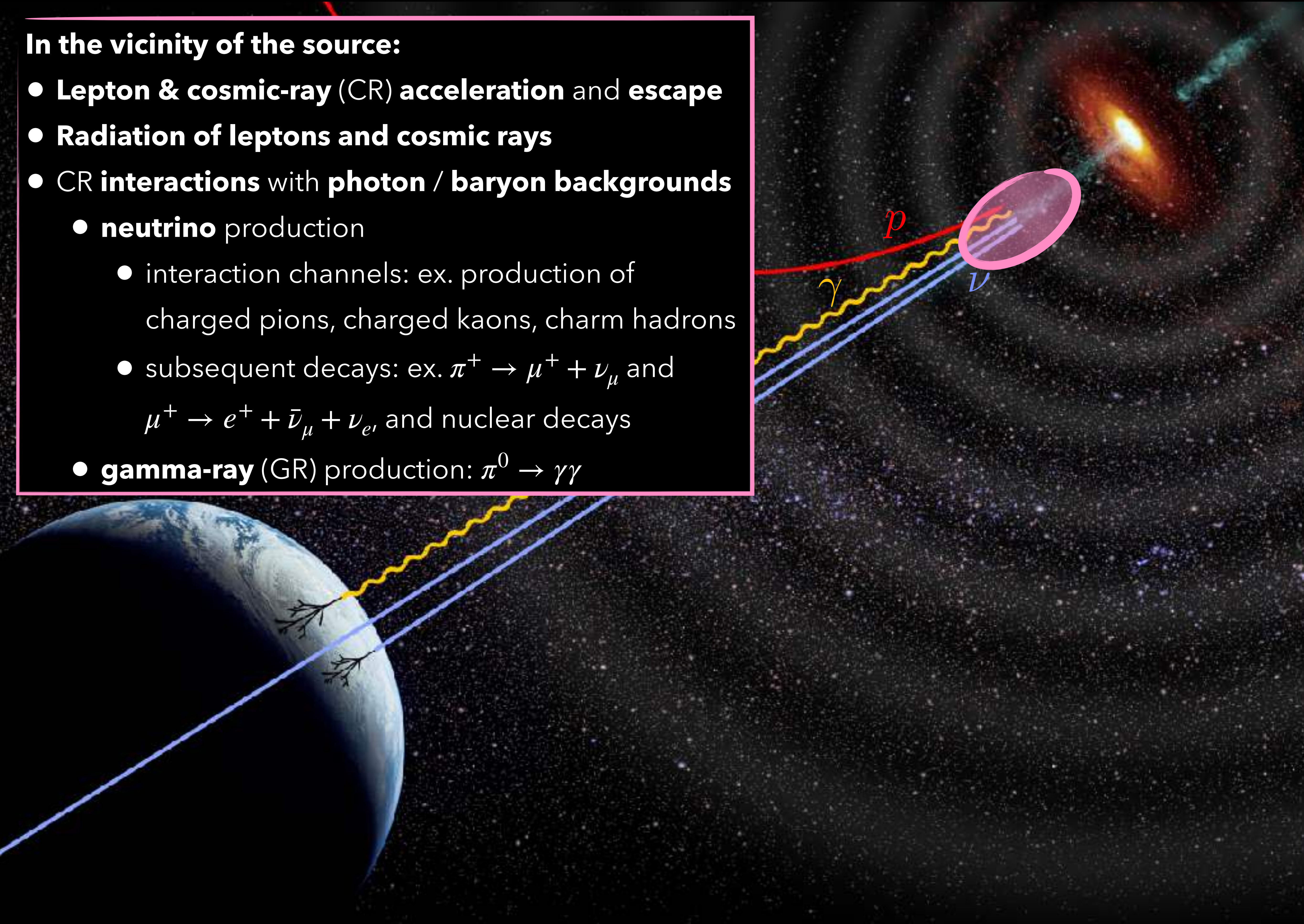
Modeling propagation and interaction of various messengers in the source vicinity

→ Various challenges

- Astrophysical transients: variety of observational characteristics, structure and evolution
  - Ex. emission directionality and time-dependence
- Dense environments, test particle approximation not necessarily valid
  - Ex. difficulty of including simplified description of particle acceleration or propagation
- Feedback of particle interactions and radiation on same/other particle distributions
  - Ex. radiation of leptons, interaction backgrounds for hadrons; propagation of photon backgrounds
- Uncertainties related to various modeling aspects
  - Ex. spatial properties mentioned above, but also interaction cross sections and secondary products

In the vicinity of the source:

- **Lepton & cosmic-ray** (CR) **acceleration** and **escape**
- **Radiation of leptons and cosmic rays**
- CR **interactions** with **photon** / **baryon backgrounds**
  - **neutrino** production
    - interaction channels: ex. production of charged pions, charged kaons, charm hadrons
    - subsequent decays: ex. $\pi^+ \to \mu^+ + \nu_\mu$ and $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$, and nuclear decays
  - **gamma-ray** (GR) production: $\pi^0 \to \gamma\gamma$

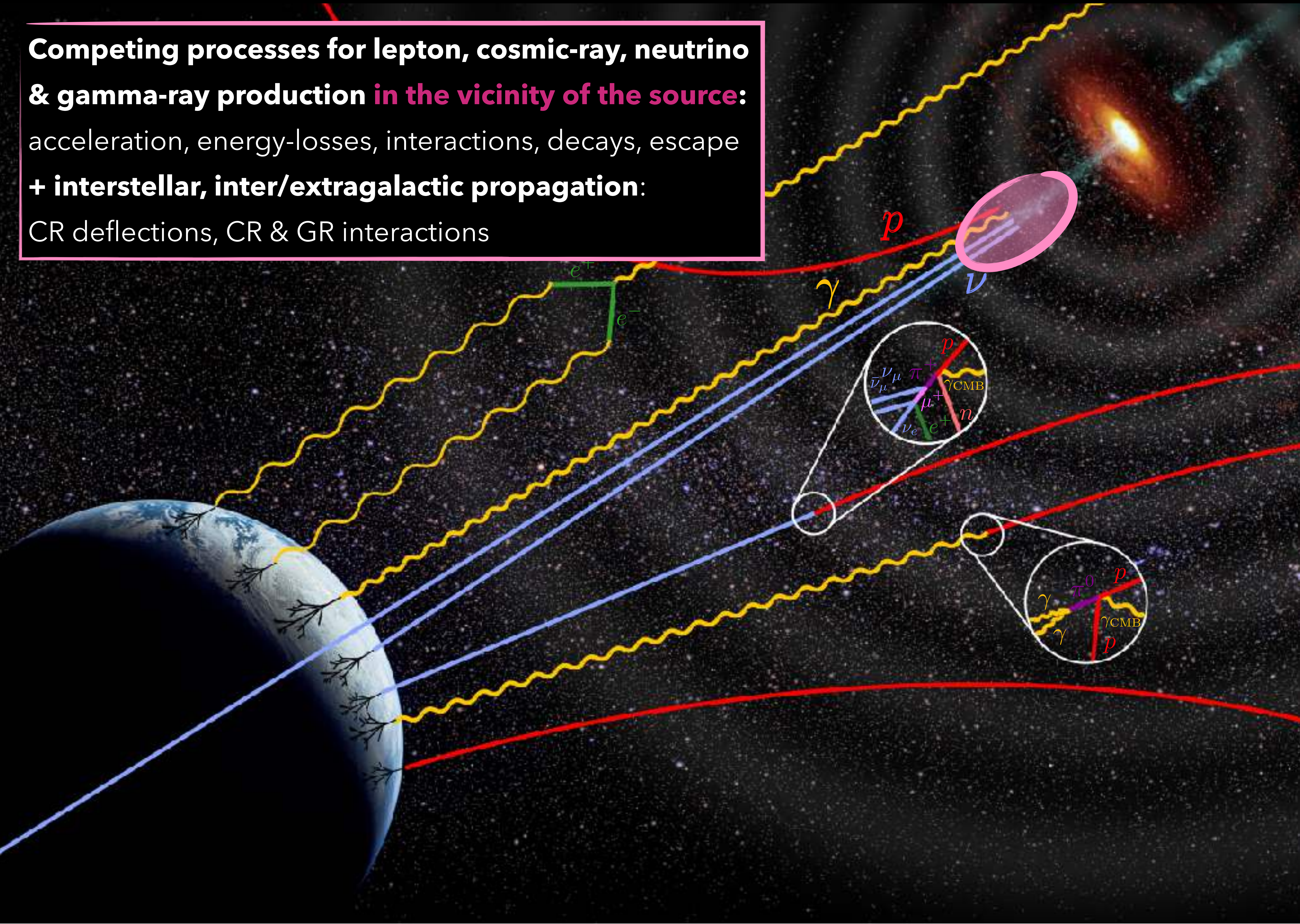


Competing processes for lepton, cosmic-ray, neutrino & gamma-ray production in the vicinity of the source**:**

acceleration, energy-losses, interactions, decays, escape

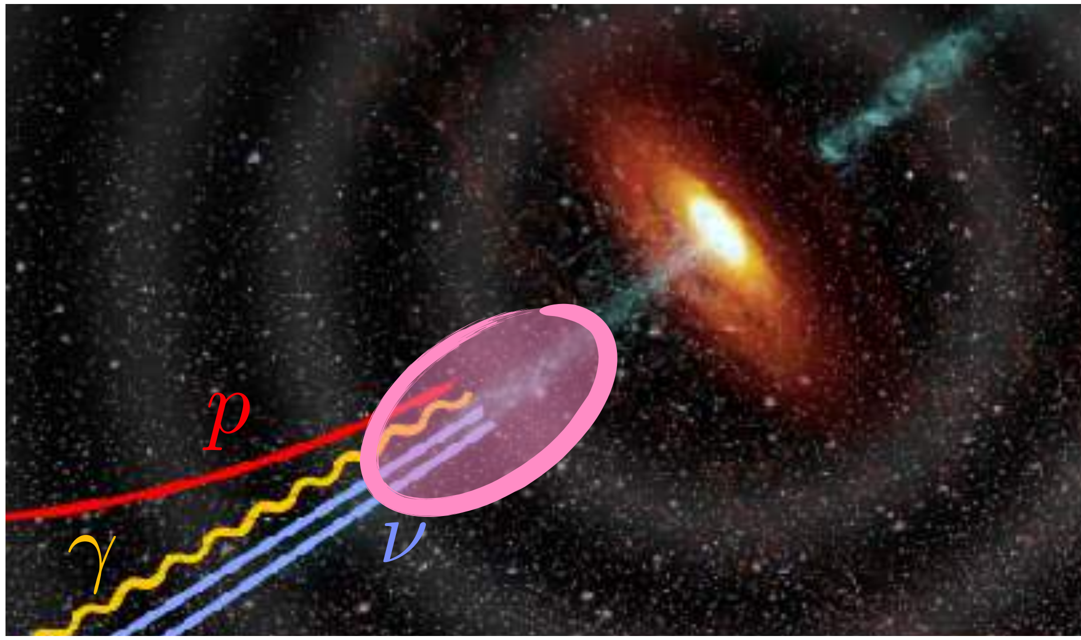
+ interstellar, inter/extragalactic propagation:

CR deflections, CR & GR interactions



Characterizing directionality and time-dependence in the context of MWL/MM emissions

→ account for some **macroscopic characteristics** and some **micro-physics processes**



In the vicinity of the source:

- one zone models, multi-zone models
- when required by multi-wavelength/messenger data: two-zone models: ex. acceleration treated prior to interactions or radiation, or external radiation background

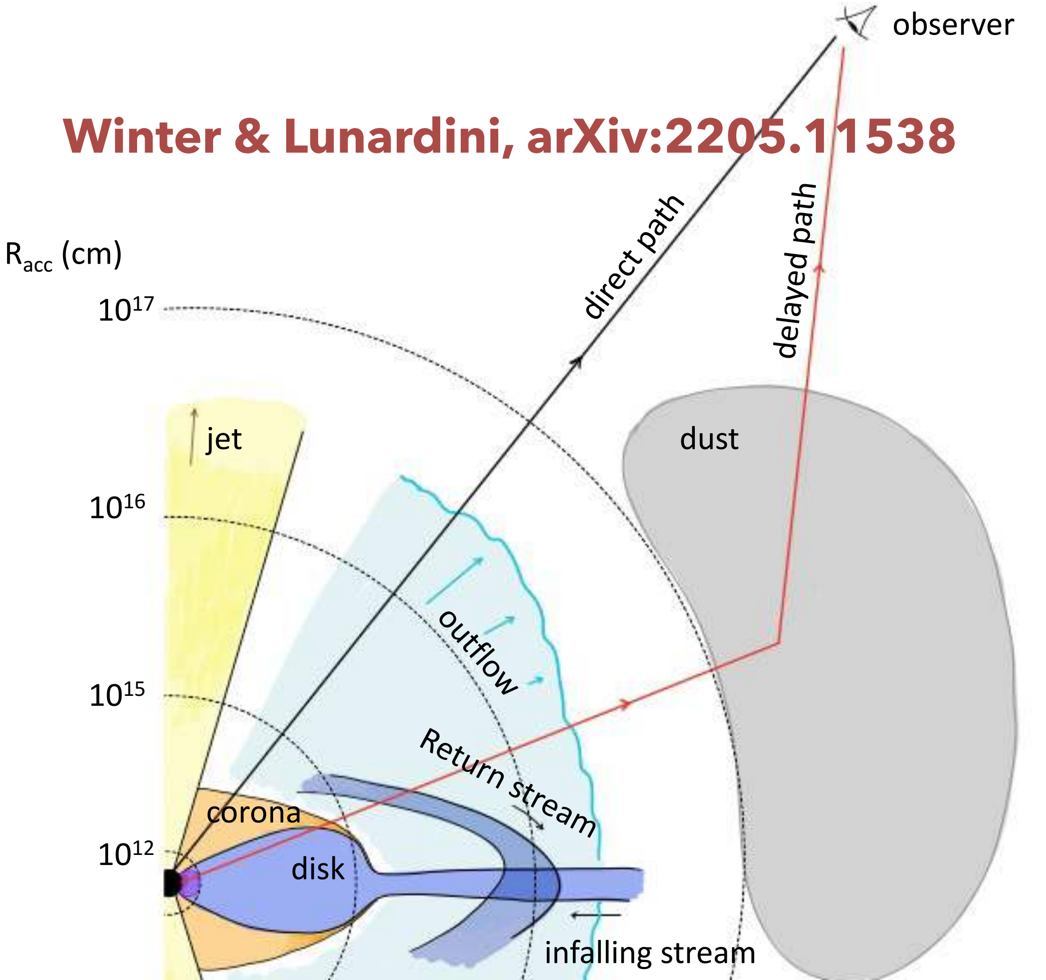
Source geometry and emission directionality:

- disk, corona, outflow, jet
- debris stream, dust clouds

Source evolution and time-dependent emissions, delays:

- outflow expansion, propagation of shock fronts in jets
- propagation of photons
- dilution of background material

Winter & Lunardini, arXiv:2205.11538



Physical processes at play

- **typical timescales** used to compare the effect of various processes, identify dominant processes in the source reference frame, ex. frame comoving with plasma flow

- acceleration: $t'_{\rm acc} = \eta_{\rm acc}^{-1} E'(cZeB')^{-1}$
- evolution of radiation region, confinement: $t'_{\rm dyn} = (1+z)^{-1}\delta\, t_{\rm var}$

- energy-loss timescales: synchrotron radiation, inverse Compton, photopion production, photodisintegration, Bethe-Heitler pair production, pair production, hadronic interactions

  → ex: photopion production, above the pion production threshold $E'_p \simeq 10^{17}\,{\rm eV}\,(1\,{\rm eV}/\epsilon')$

$$t'^{-1}_{N\gamma} = \frac{c}{2\gamma'^2}\int_0^\infty \frac{{\rm d}\epsilon'}{\epsilon'^2}\frac{{\rm d}n'_\gamma}{{\rm d}\epsilon'}(\epsilon')\int_0^{2\gamma'\epsilon'} {\rm d}\bar\epsilon\,\bar\epsilon\,\sigma_{N\gamma}(\bar\epsilon)$$

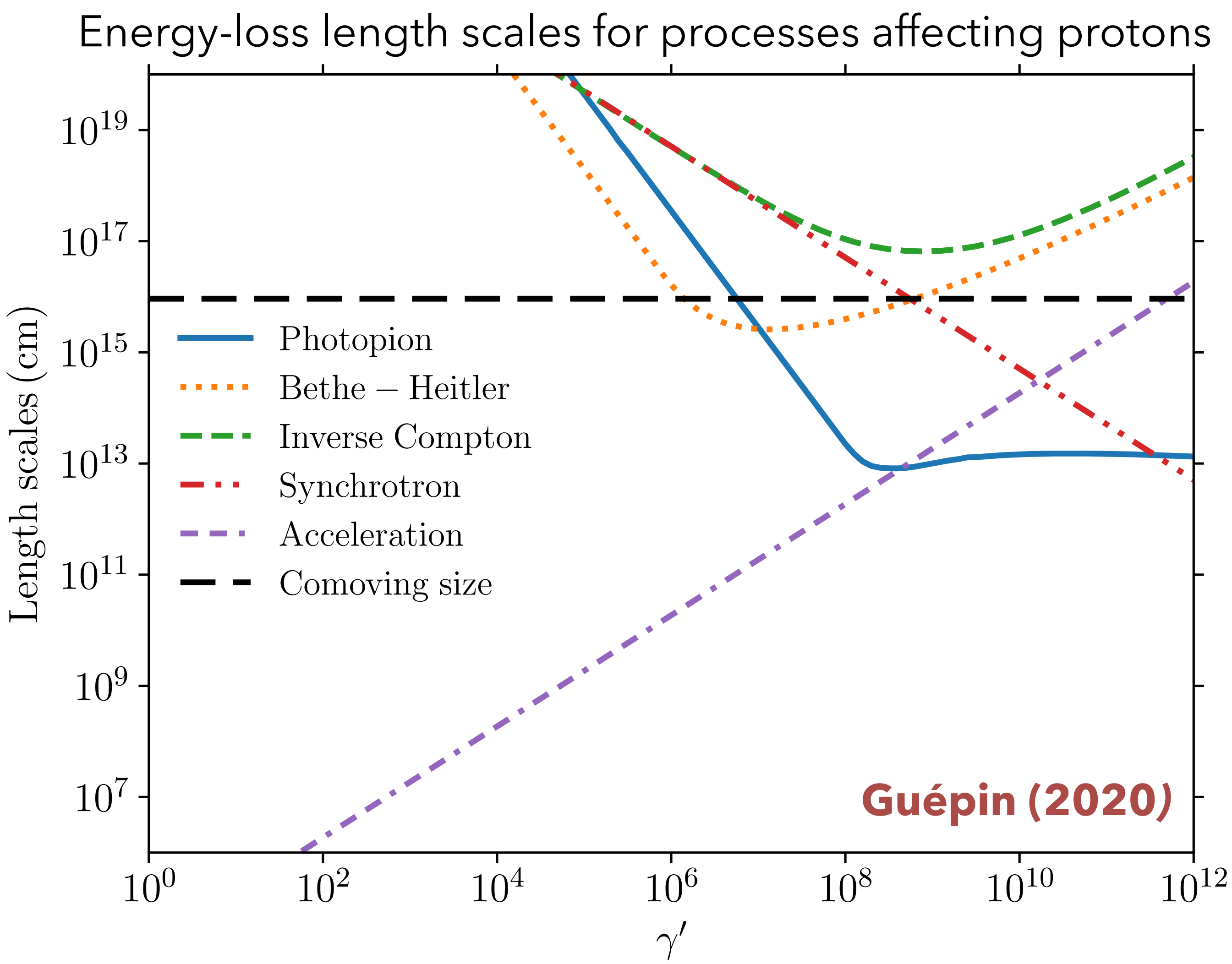
Source and emission properties, notations

- mean magnetic field B', Lorentz boost δ, redshift z,
- variability timescale $t_{\rm var}$, bolometric luminosity $L_{\rm bol}$,
- photodisintegration cross section $\sigma_{N\gamma}$, acceleration efficiency $\eta_{\rm acc}$,
- photon energy ϵ', photon spectrum n'_γ, particle energy / Lorentz factor E'/γ', particle charge Ze

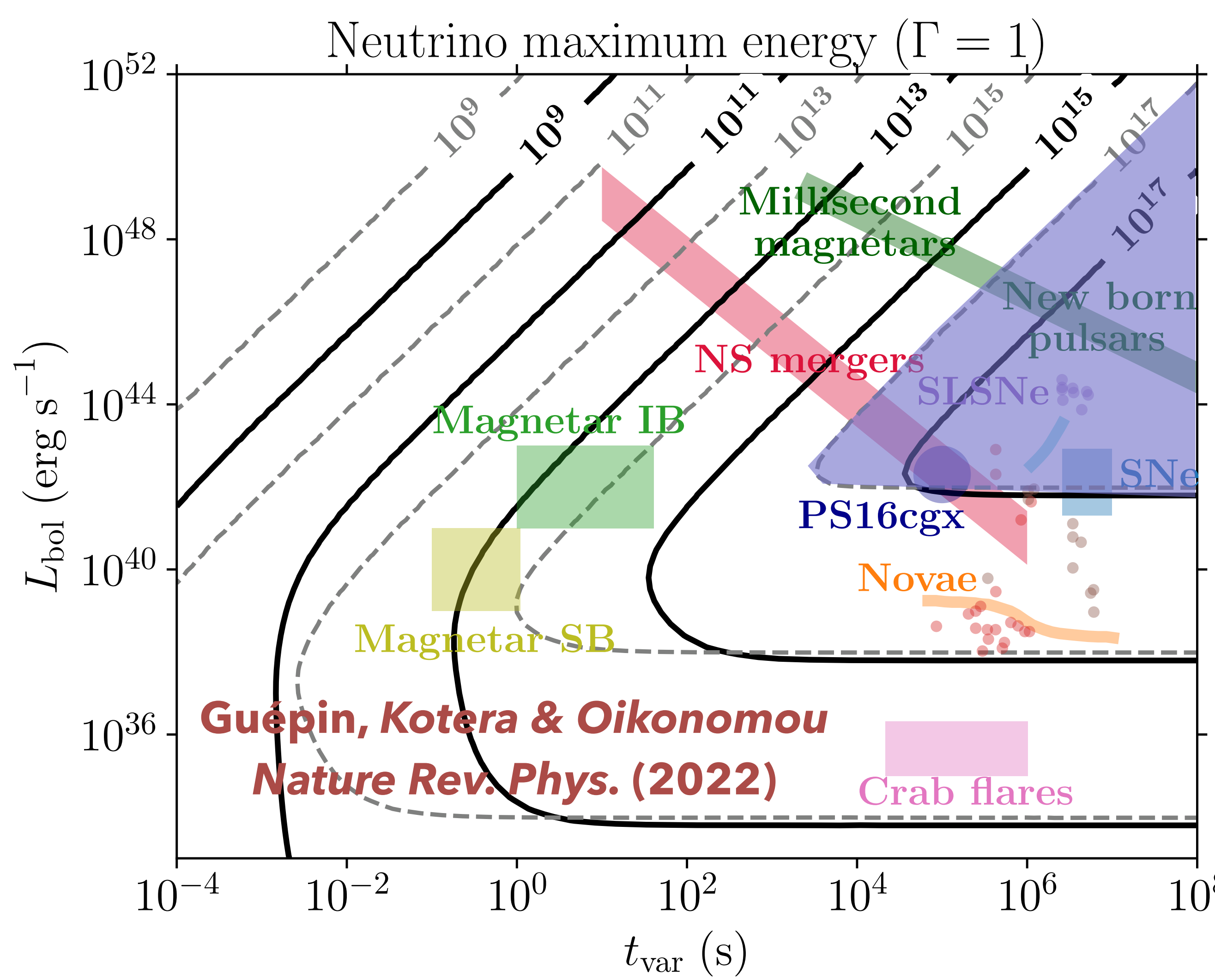
Physical processes at play

- **typical timescales** used to compare the effect of various processes, identify dominant processes in the source reference frame, ex. frame comoving with plasma flow

Example: case study, millisecond magnetar



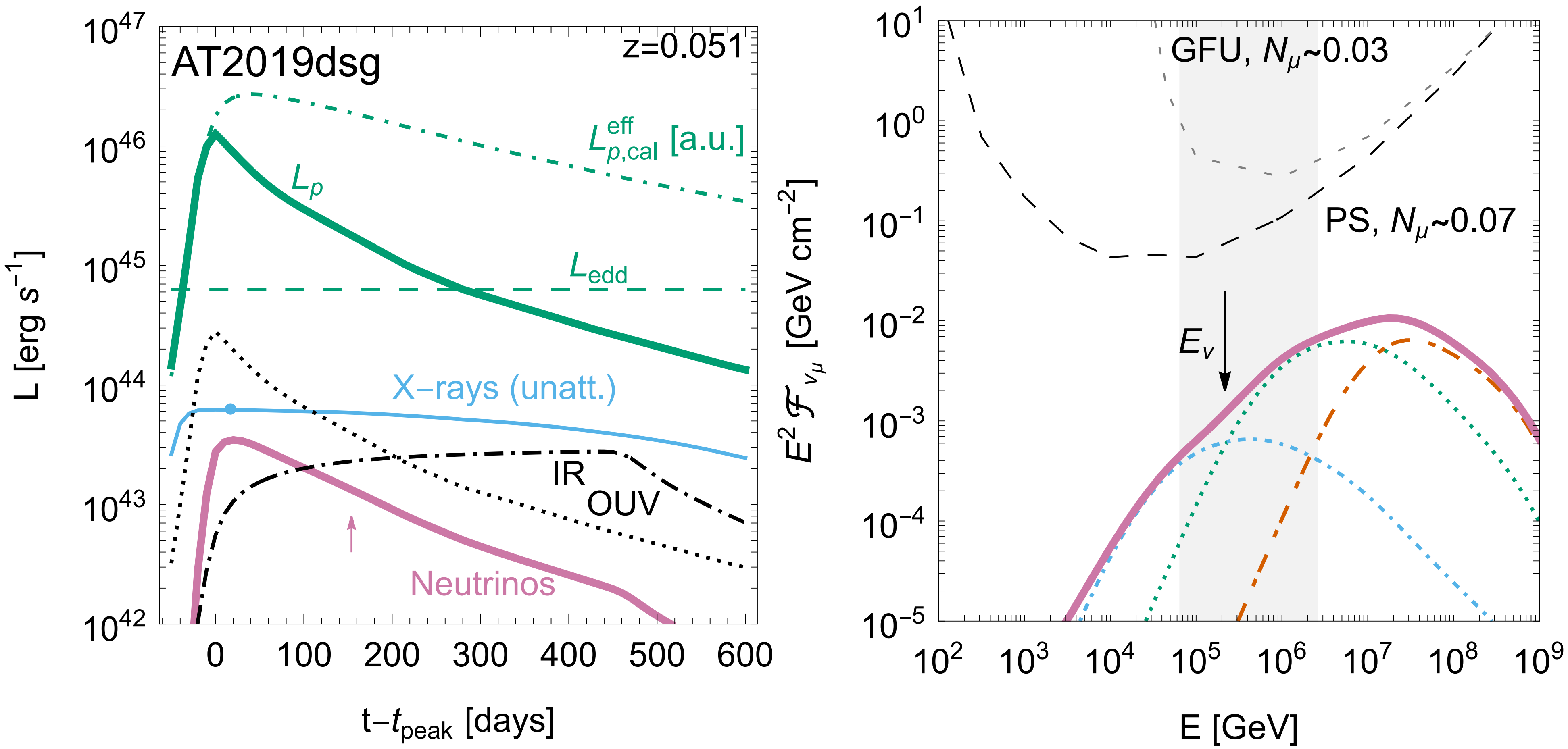
Example: parameter space study



Spatial and time-dependent modeling

- Multi-wavelength (MWL) and multi-messenger (MM) predictions with lepto-hadronic processes + time dependent predictions
- Typical methods: successive steady "snapshots", combination between transport equations and monte carlo / parametric treatment of interactions and production of secondaries
- Extensive follow-up observation campaigns required, account for propagating photons
- Ex. MWL and HE-UHE neutrino lightcurves

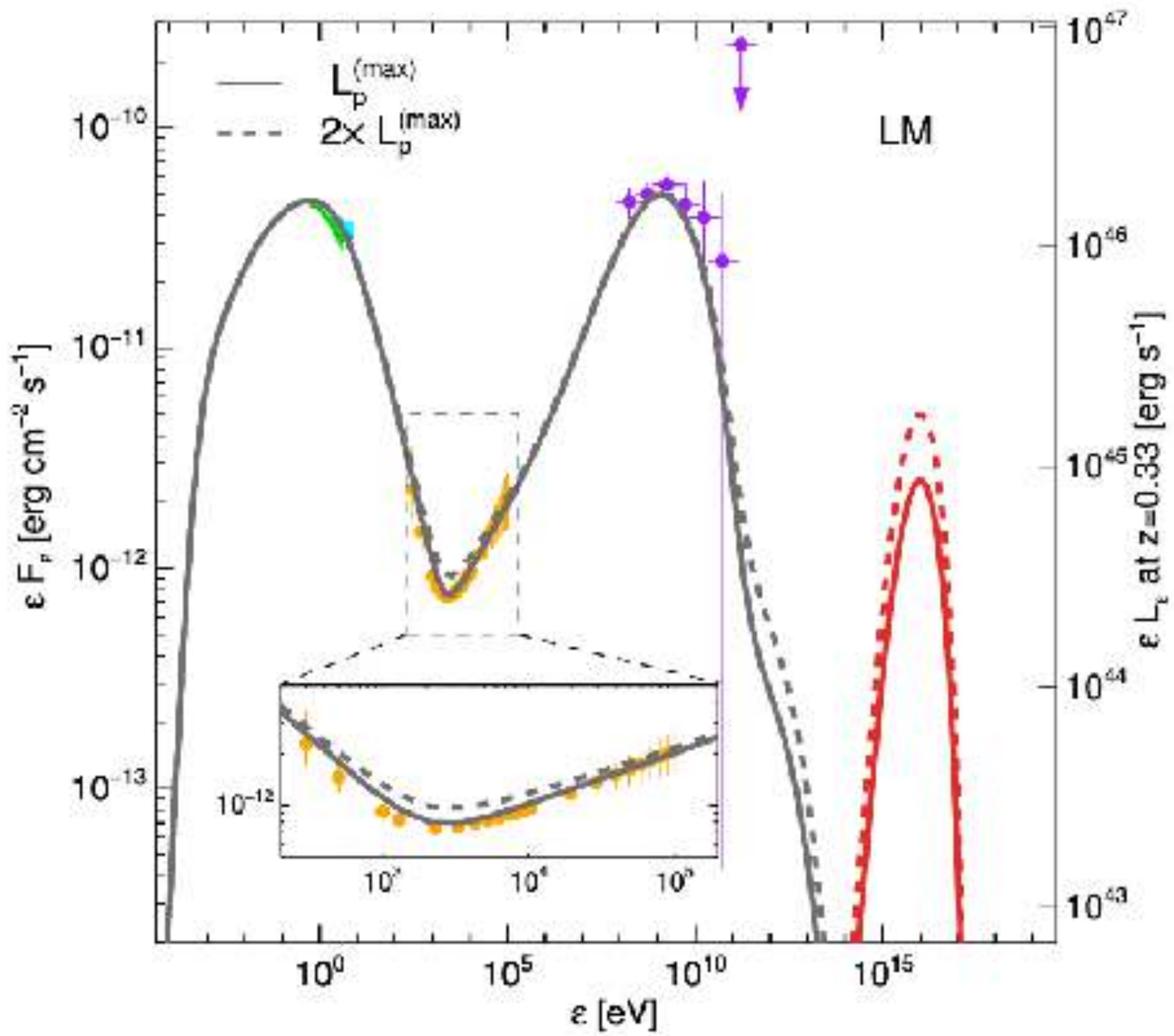
Example: AT2019dsg + IC191001A, Winter & Lunardini, arXiv:2205.11538



More about the physical processes at play

- In general, importance of accounting systematically for leptonic and hadronic processes
  - Account for photon cascades, potential constraints on hadronic components.
  - Ex. gamma rays produced through π^0 decay, and $\gamma\gamma \rightarrow e^+e^-$ cascades

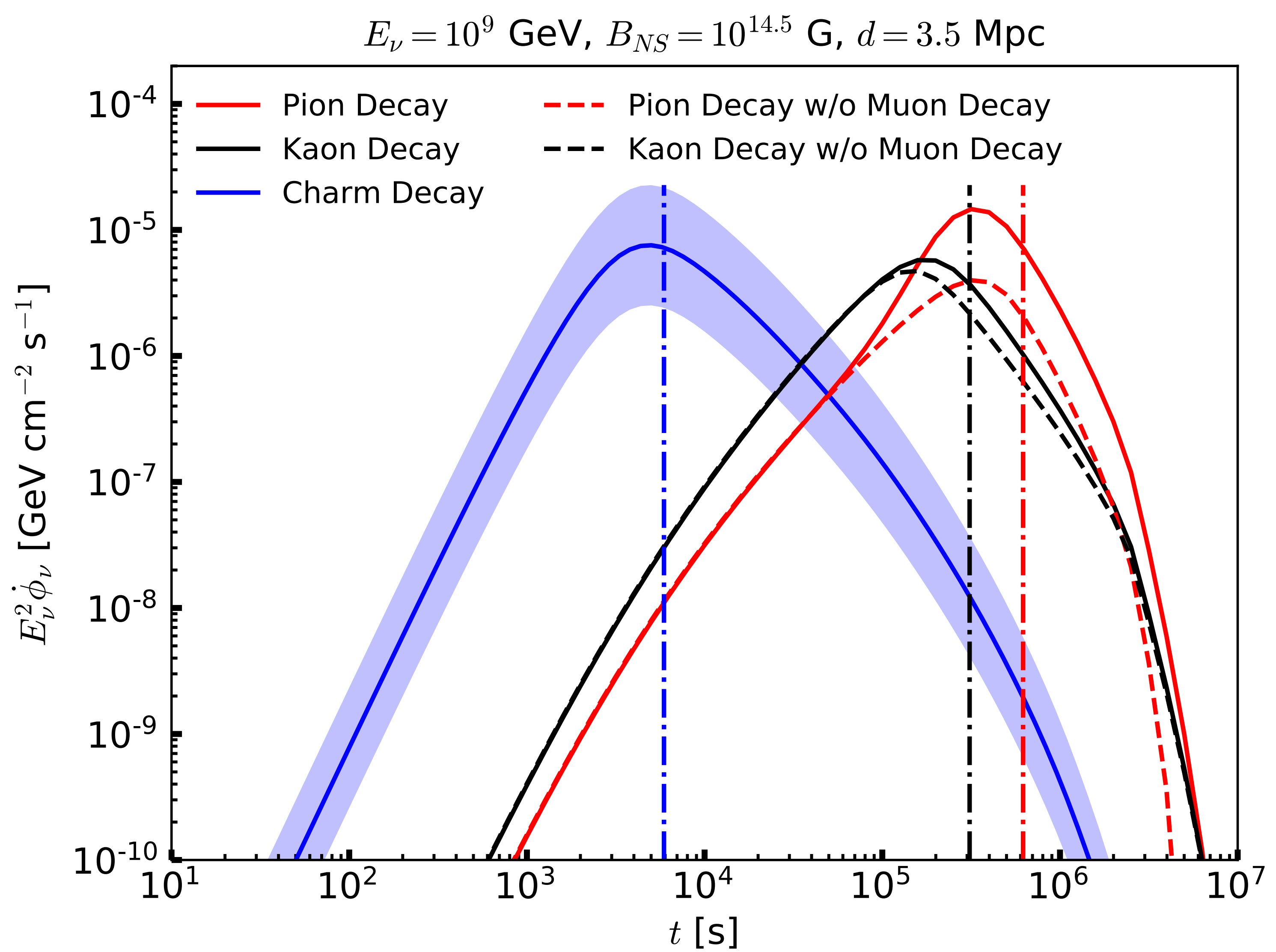
Example: TXS 0506+056 + IC170922A, Keivani et al., arXiv:1807.04537



More about the physical processes at play

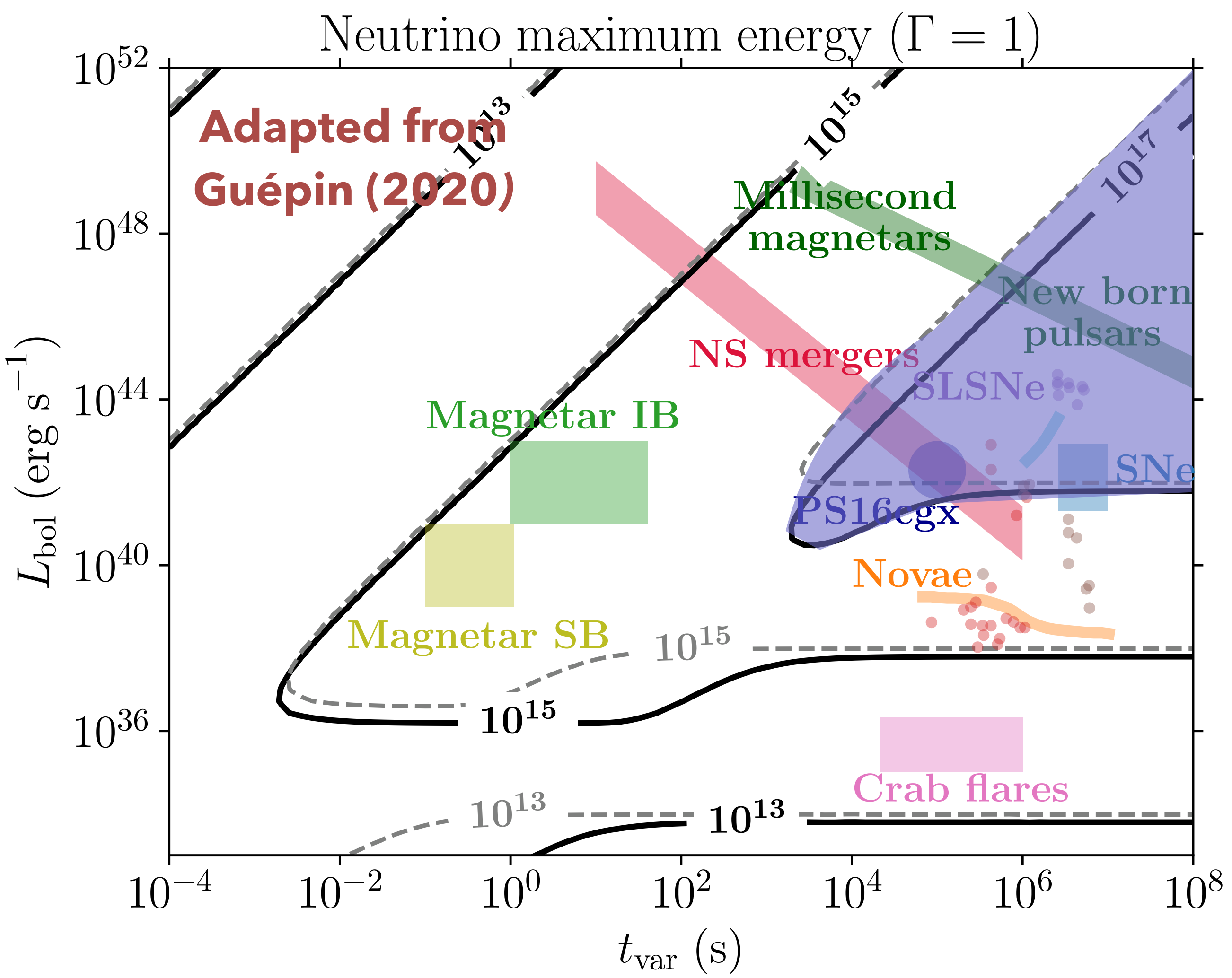
- Account for various interaction channels
  - Ex. HE to UHE neutrino modeling: time-dependence and contribution of charm hadrons
  - Ex. photodisintegration and energy dependence

Example: Charm contribution to UHE neutrinos from newborn magnetars
J.A. Carpio et al. (2020), arXiv:2007.07945

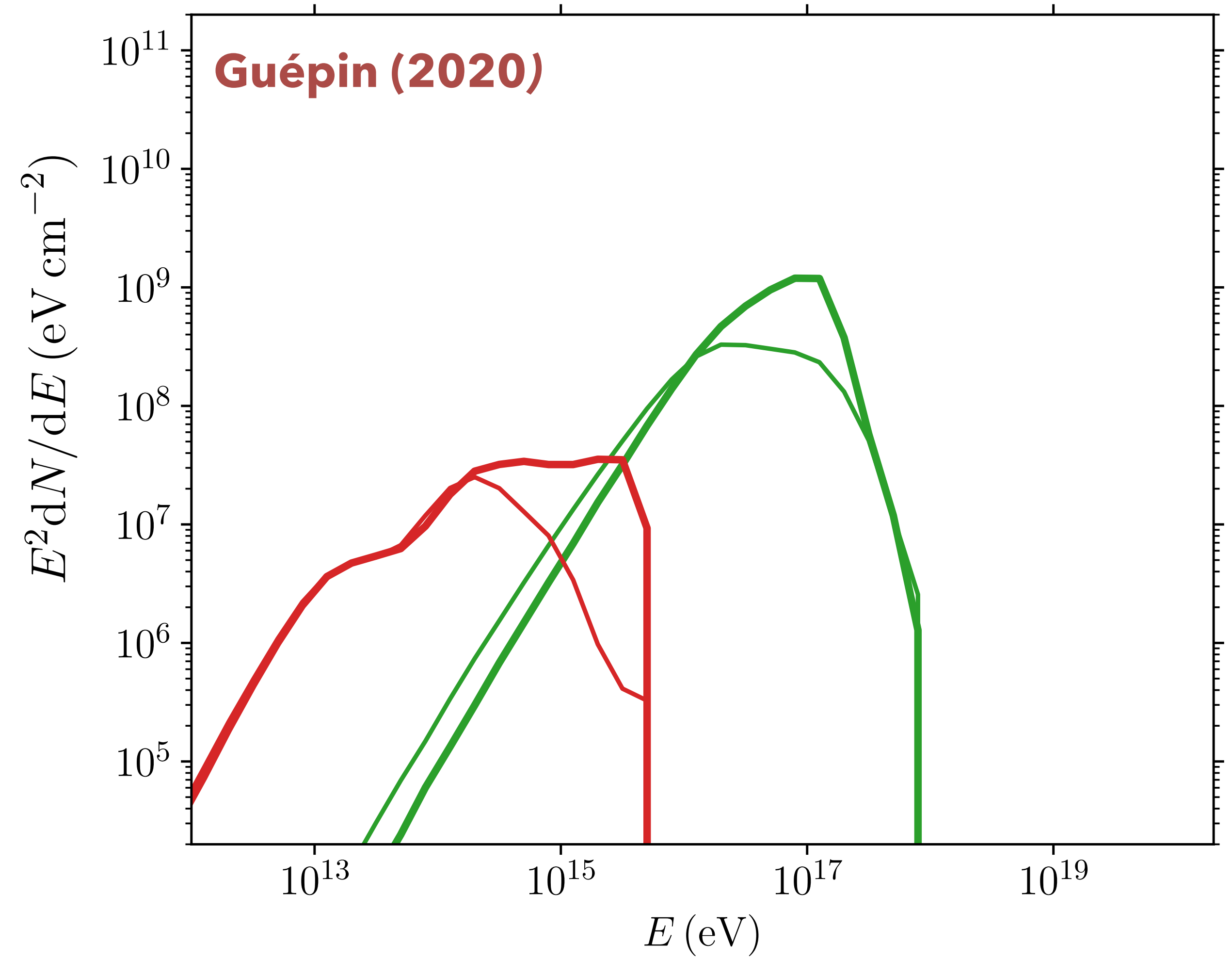


More about the physical processes at play

- Processes affecting primary and secondary particles
  - Ex. HE to UHE neutrino emissions: acceleration of secondary charged pions and muons
  - Ex. photohadronic processes and acceleration of secondary electrons and positrons



Example: millisecond magnetars

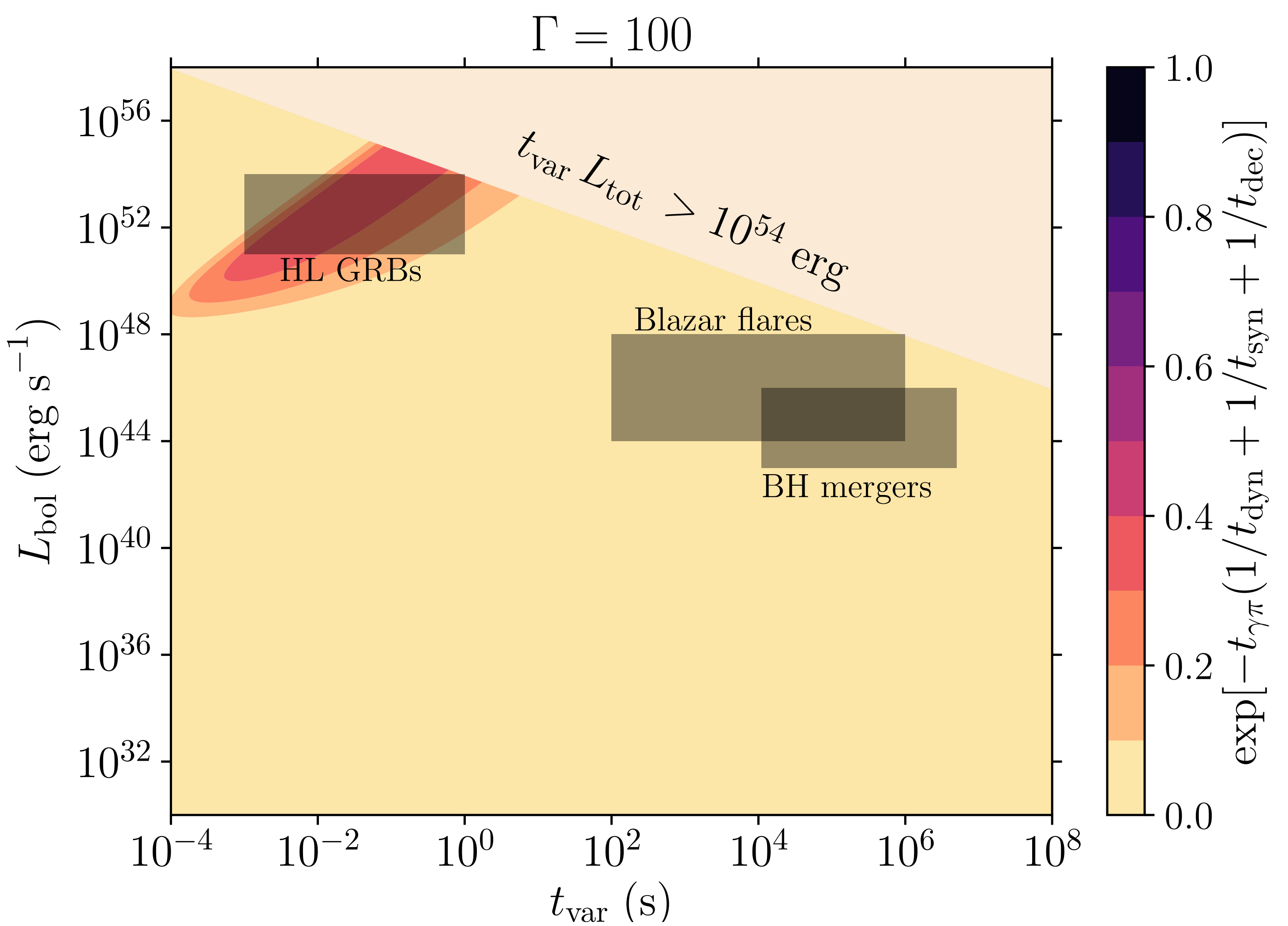


More about the physical processes at play

- Processes affecting primary and secondary particles.
  - Ex. HE to UHE neutrino emissions: charged pion cascades in some dense photon backgrounds. Impact for short GRBs?

Example: parameter space study

Interaction of charged pions with photons, broken power law peaking in X-rays



More about the physical processes at play

- Towards more precise description of **particle distributions**: account for **anisotropies** in distributions (leptons, hadrons, photons) and their impact on radiation and interactions
- Ex. impact or particle distribution on synchrotron radiation (Comisso et al. 2020, arXiv:2004.07315)
- Ex. impact of "external" radiation backgrounds, ex. jet models for active galactic nuclei
  - Frame of emission of "external" radiation background versus comoving frame of jet
  - Small factors affecting photopion production, photopair production or gamma gamma pair production, but potential for cumulative effects

Sources of uncertainties

- Source parameters, degeneracies due to lack of observational constraints
  - Electromagnetic fields: impact on propagation, acceleration, radiation
  - Cosmic-ray luminosity and composition
  - Interaction backgrounds and interaction processes
  - Lorentz boost, collimated or isotropic emissions
- Large-scale propagation and interactions, backgrounds
- Systematic exploration of parameter space, or parameter ranges and uncertainties displayed

Variety of existing tools

- As for modeling, limitations related to the range of spatial and energy scales to be considered

- Self-consistent treatments, evolution of the properties of the particles coupled with the evolution of the electromagnetic fields: ex. PIC simulations; hybrid, MHD-PIC, PIC with Monte Carlo
- Simplifying assumptions: test-particle assumption, Monte Carlo methods and partial differential kinetic equations solvers… Check database, future list of simulation tools (https://www.lupm.in2p3.fr/users/guepin)

- (Historical?) decoupling between codes oriented towards hadronic processes and leptonic processes. First ones tackle well interaction of nuclei and secondaries, second radiation processes and cascades, thus multi-wavelength emissions.

- Efforts underway by several groups to produce coupled versions of cosmic-ray interaction and time-dependent radiative codes

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