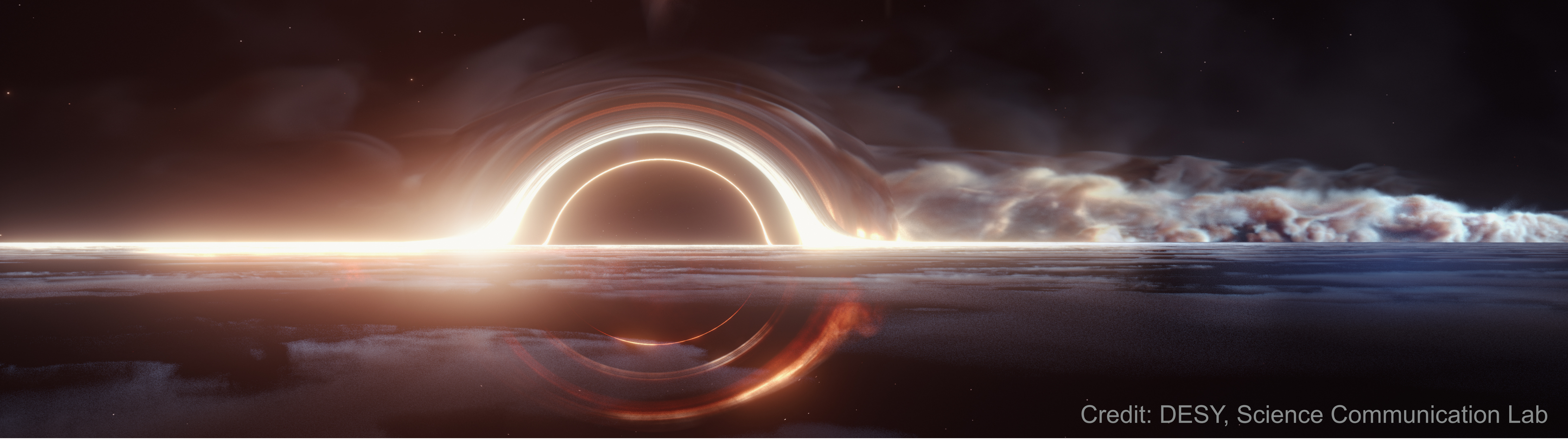

Credit: DESY, Science Communication Lab

Modeling the Hadronic Cascade Emission from Neutrino-Emitting TDEs

Chengchao Yuan

LepHad Workshop, Bochum, 2023/02/28

HELMHOLTZ

Tidal disruption events

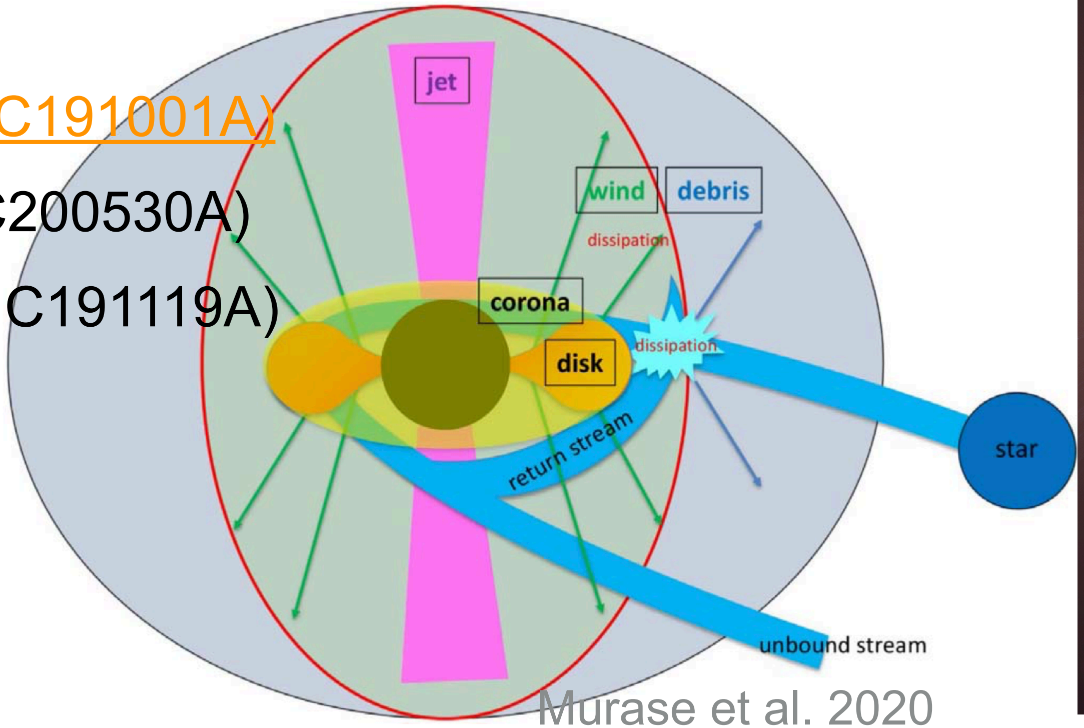
When a massive star passes close enough to a SMBH

- The star can be ripped apart by the tidal force
- ~ half of the star's mass remains bounded by the SMBH gravitational force
- Mass accretion -> months/year-long flare
- Multi-wavelength black body (bb) emissions in optical/ UV (OUV) bands.
- Some TDEs are observed in X-ray and infrared (IR) ranges, e.g., AT2019dsg (Stein et al. 2021)


Credit: DESY, Science Communication Lab

Tidal disruption events

- In addition to the EM signatures, neutrinos might be produced in the accretion disks, disk winds, or jets
- Three TDEs may be associated with IceCube neutrino events
    1. AT2019dsg (IC191001A)
    2. AT2019fdr (IC200530A)
    3. AT2019aalc (IC191119A)

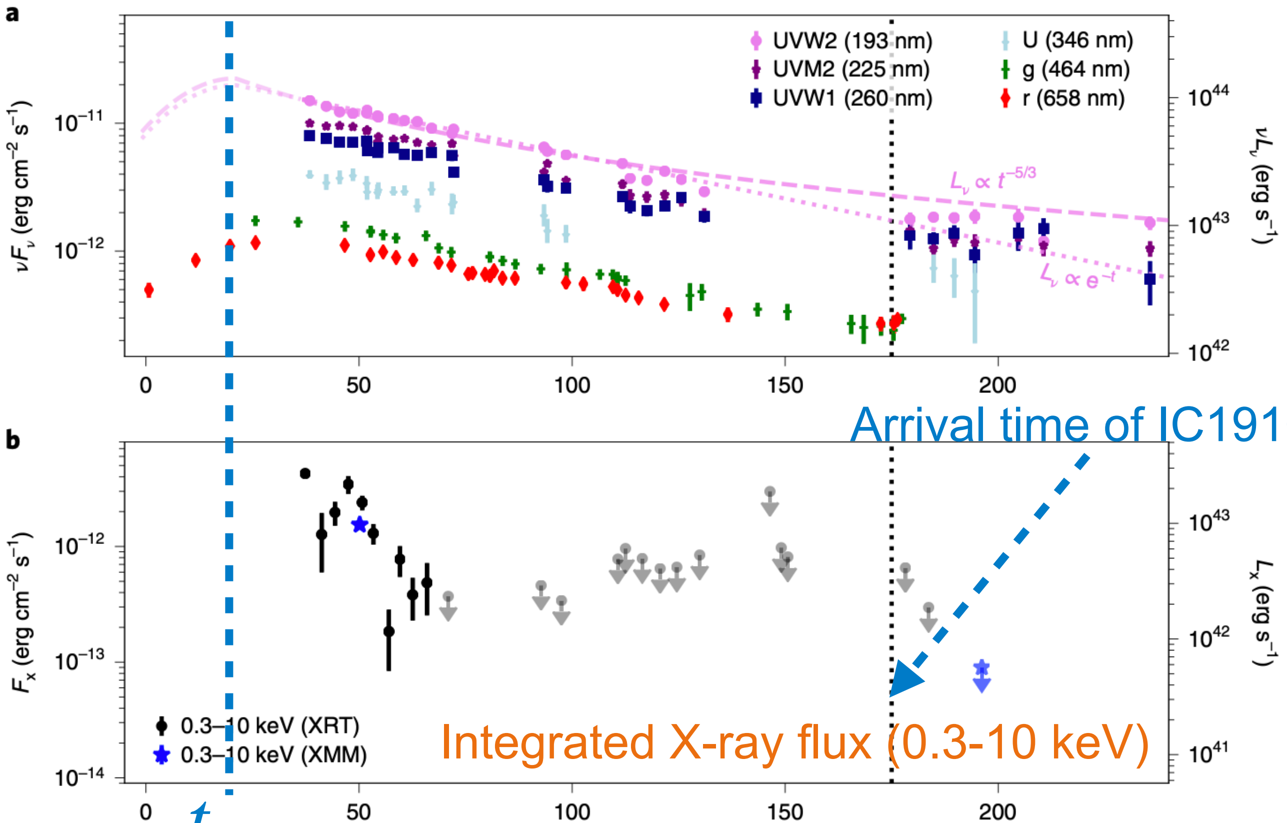


Murase et al. 2020

Credit: DESY, Science Communication Lab

AT2019dsg

- ZTF (optical: g, r) + Swift UVOT (UV)
- Swift-XRT/XMM-Newton: X-ray (0.3-10 keV)
- $z \sim 0.051$, d_L~230Mpc

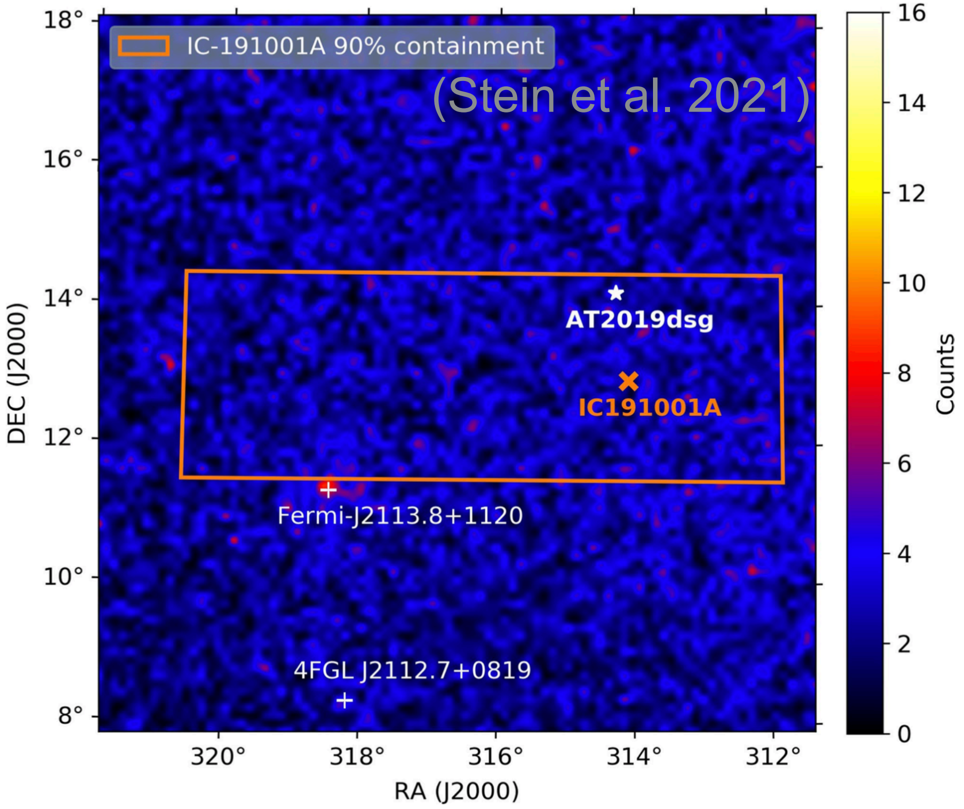


Arrival time of IC191001A

Integrated X-ray flux (0.3-10 keV)

$t_{\rm peak}$

(Stein et al. 2021)



(Stein et al. 2021)

Measured black body spectra:

- X-ray: $T_X = 72$ eV, from hot accretion disk
- OUV: $T_{\rm OUV} = 3.4$ eV, from photosphere (nearly constant)

Dust Echo: infrared (IR) emission

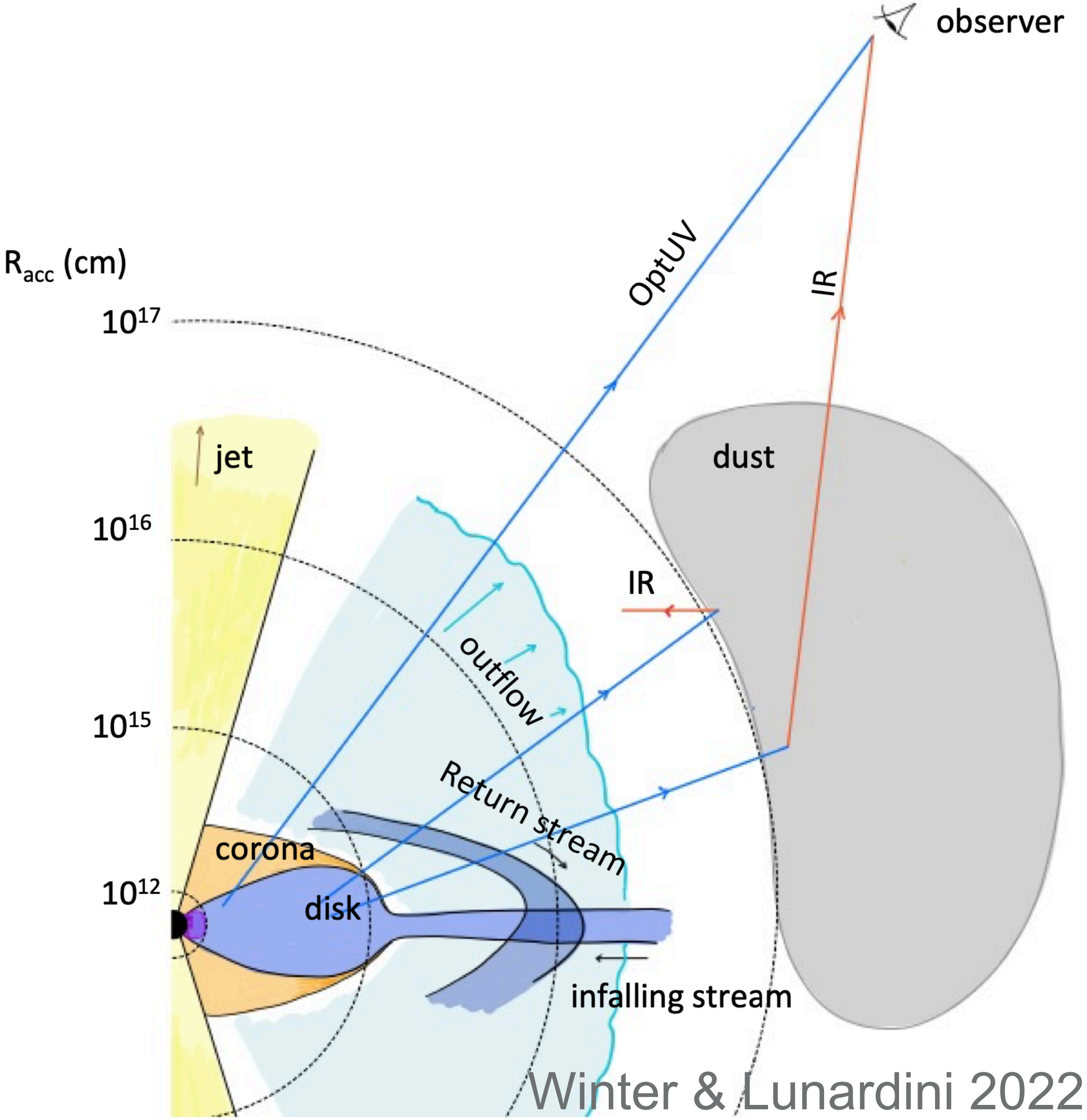
X-ray/OUV photons heat the dust torus

-> thermal IR emission

- could be detected as the delayed IR emission
- feeds IR photons back to the wind/outflow envelope
- temperature $T_{\rm IR} \lesssim 0.16~{\rm eV}$ (Reusch et al. 2022)
- IR luminosity can be obtained by convolving $L_{\rm OUV}$ with a box function $B(T)$, e.g.,

  (Reusch et al. 2022, Winter & Lunardini 2022)

$$L_{\rm IR}(t) \propto \int L_{\rm OUV}(t')B(t-t')dt'$$



Winter & Lunardini 2022

Proton injection

Four parameters: $E_{p,\min} \sim 1\ \mathrm{GeV},$ spectra index $p = 2$, $E_{p,\max}$ (free-param), normalization factor

AT2019dsg: $M_{\mathrm{SMBH}} \simeq 5 \times 10^6 M_\odot$ (van Velzen et al. 2021)

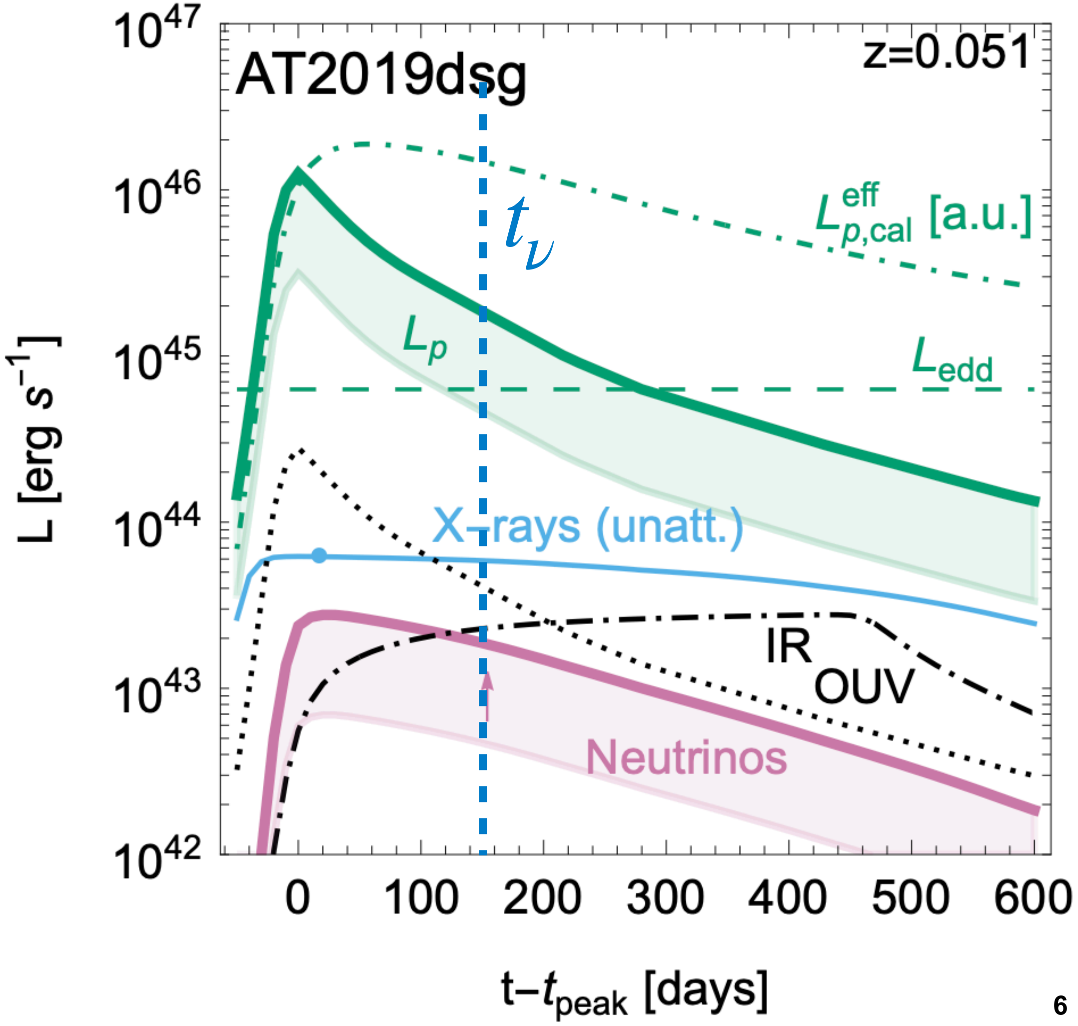
We use four parameters to determine the proton injection (do not specify the accelerator)

- Normalization $\int dE_p E_p \dot{Q}(E_p) = L_p/(4\pi R^3/3)$
- $L_p(t) = \varepsilon_{\mathrm{diss}} \dot{M}_\star(t) c^2$

Assumptions

- $\dot{M}_\star(t)/L_{\mathrm{OUV}}(t) = \mathrm{const}$
- $\dot{M}_{\star,\mathrm{peak}}/L_{\mathrm{Edd}} = 100$
- Proton diffusion in Bohm regime $D = R_L c$

Winter & Lunardini 2022



Radiation processes

Particle cooling:

$p \rightarrow p'$

$(e^{\pm}) \rightarrow (e^{\pm})' \rightarrow (e^{\pm})''$

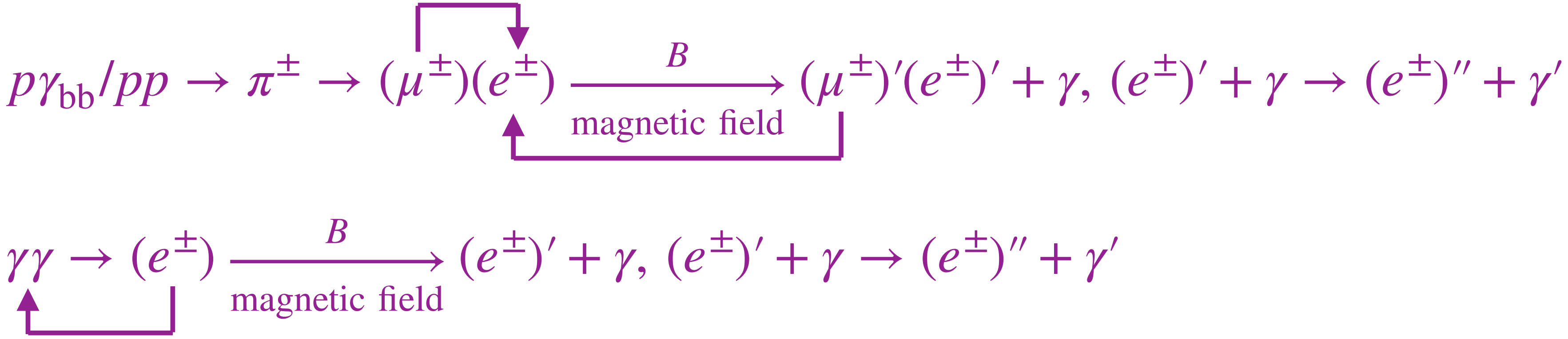
$(\mu^{\pm}) \rightarrow (\mu^{\pm})'$

Neutrino production: $p\gamma/pp \rightarrow \pi^{\pm} \rightarrow \nu_e\bar{\nu}_e\nu_\mu\bar{\nu}_\mu$

synchrotron/SSC: $(e^{\pm}) \xrightarrow[\text{magnetic field}]{B} (e^{\pm})' + \gamma, \;\; (e^{\pm})' + \gamma \rightarrow (e^{\pm})'' + \gamma'$

Proton synchrotron: $p \xrightarrow[\text{magnetic field}]{B} \gamma + p'$

Cascade processes: $\pi^0 \rightarrow 2\gamma$



$$p\gamma_{\rm bb}/pp \rightarrow \pi^{\pm} \rightarrow (\mu^{\pm})(e^{\pm}) \xrightarrow[\text{magnetic field}]{B} (\mu^{\pm})'(e^{\pm})' + \gamma, \; (e^{\pm})' + \gamma \rightarrow (e^{\pm})'' + \gamma'$$

$$\gamma\gamma \rightarrow (e^{\pm}) \xrightarrow[\text{magnetic field}]{B} (e^{\pm})' + \gamma, \; (e^{\pm})' + \gamma \rightarrow (e^{\pm})'' + \gamma'$$

$$p\gamma_{\rm bb} \rightarrow p'(e^{\pm}) \xrightarrow[\text{magnetic field}]{B} (e^{\pm})' + \gamma, \; (e^{\pm})' + \gamma \rightarrow (e^{\pm})'' + \gamma'$$

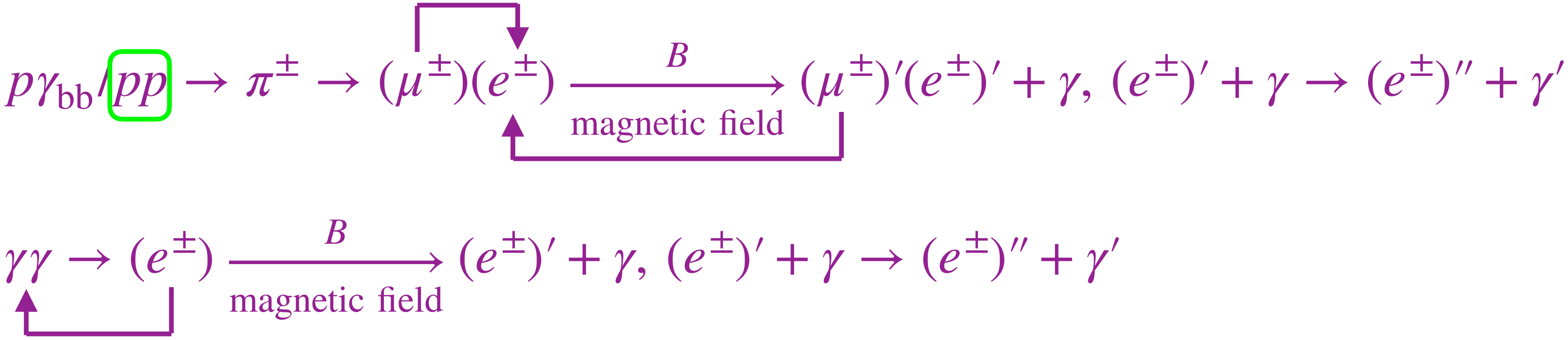
Radiation processes

Neutrino production: $p\gamma/\boxed{pp} \rightarrow \pi^{\pm} \rightarrow \nu_e\bar{\nu}_e\nu_\mu\bar{\nu}_\mu$

synchrotron/SSC: $(e^{\pm}) \xrightarrow[\text{magnetic field}]{B} (e^{\pm})' + \gamma, \quad (e^{\pm})' + \gamma \rightarrow (e^{\pm})'' + \gamma'$

Proton synchrotron: $p \xrightarrow[\text{magnetic field}]{B} \gamma + p'$

Cascade processes: $\pi^0 \rightarrow 2\gamma$



$$p\gamma_{\rm bb}/\boxed{pp} \rightarrow \pi^{\pm} \rightarrow (\mu^{\pm})(e^{\pm}) \xrightarrow[\text{magnetic field}]{B} (\mu^{\pm})'(e^{\pm})' + \gamma, \ (e^{\pm})' + \gamma \rightarrow (e^{\pm})'' + \gamma'$$

$$\gamma\gamma \rightarrow (e^{\pm}) \xrightarrow[\text{magnetic field}]{B} (e^{\pm})' + \gamma, \ (e^{\pm})' + \gamma \rightarrow (e^{\pm})'' + \gamma'$$

$$p\gamma_{\rm bb} \rightarrow p'(e^{\pm}) \xrightarrow[\text{magnetic field}]{B} (e^{\pm})' + \gamma, \ (e^{\pm})' + \gamma \rightarrow (e^{\pm})'' + \gamma'$$

Particle cooling:

$p \rightarrow p'$

$(e^{\pm}) \rightarrow (e^{\pm})' \rightarrow (e^{\pm})''$

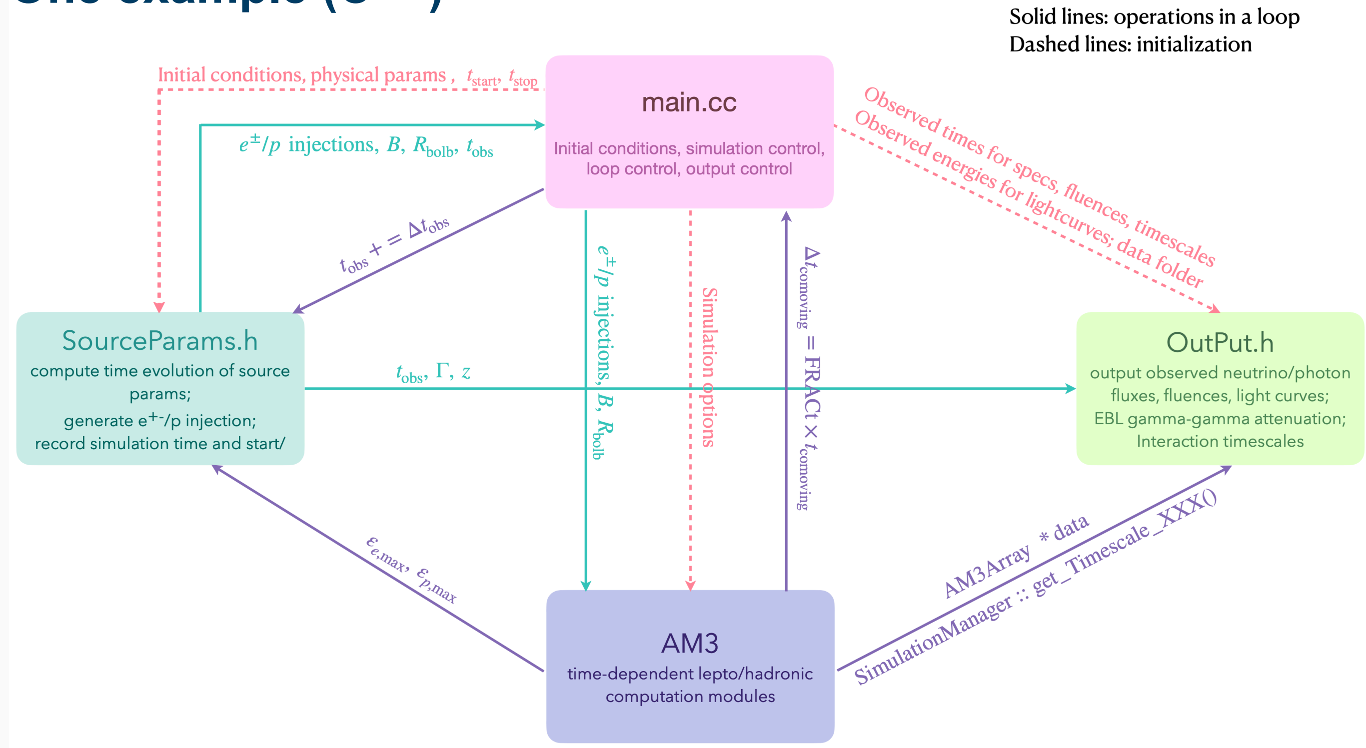
$(\mu^{\pm}) \rightarrow (\mu^{\pm})'$

AM3: a time-dependent LepHad code

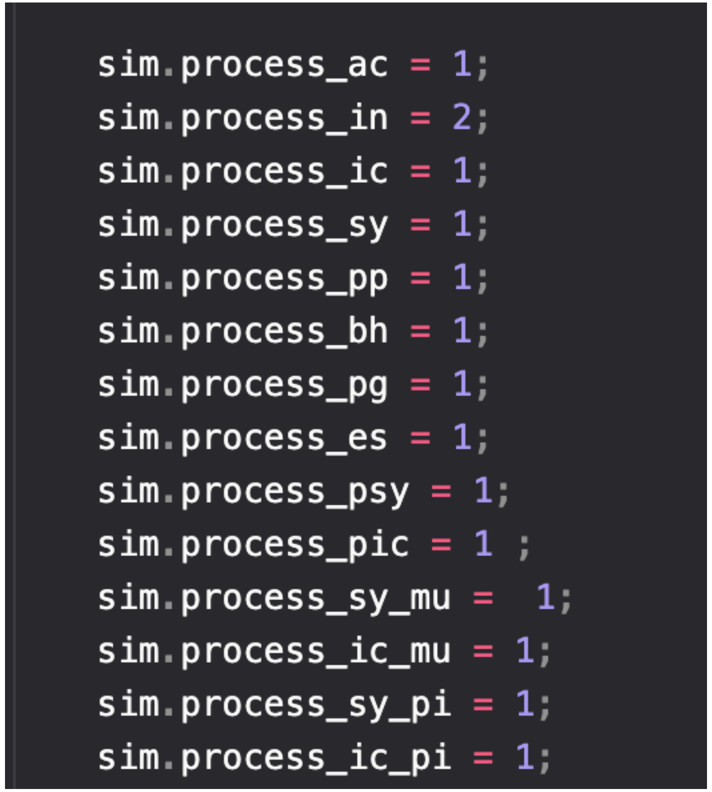
Numerically solving the coupled PDEs for electron, proton, and photon distributions. (Gao et al. 2017)

$$\partial_t n(\gamma,t) = -\partial_\gamma\{\underbrace{\dot{\gamma}(\gamma,t)n(\gamma,t)}_{\text{Cooling}} - \underbrace{\partial_\gamma[D(\gamma,t)n(\gamma,t)]/2}_{\text{Diffusion}}\} - \underbrace{\alpha(\gamma,t)n(\gamma,t)}_{\text{Escape/Advection}} + \underbrace{Q(\gamma,t)}_{\text{Injection}}$$

One example (C++)



To turn on/off each process:



```
sim.process_ac = 1;
sim.process_in = 2;
sim.process_ic = 1;
sim.process_sy = 1;
sim.process_pp = 1;
sim.process_bh = 1;
sim.process_pg = 1;
sim.process_es = 1;
sim.process_psy = 1;
sim.process_pic = 1 ;
sim.process_sy_mu =  1;
sim.process_ic_mu = 1;
sim.process_sy_pi = 1;
sim.process_ic_pi = 1;
```

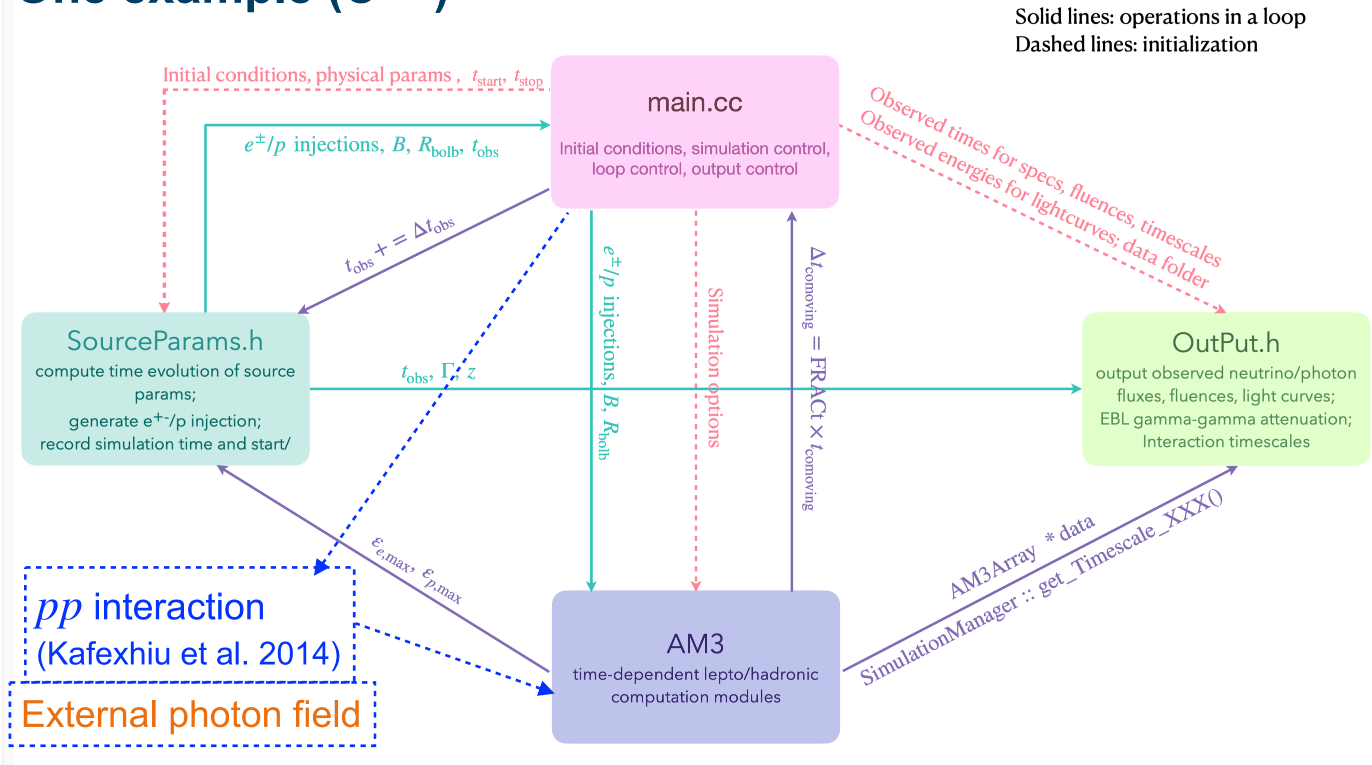
AM3: a time-dependent LepHad code

Numerically solving the coupled PDEs for electron, proton, and photon distributions. (Gao et al. 2017)

$$\partial_t n(\gamma, t) = -\partial_\gamma\{\dot{\gamma}(\gamma, t)n(\gamma, t) - \partial_\gamma[D(\gamma, t)n(\gamma, t)]/2\} - \alpha(\gamma, t)n(\gamma, t) + Q(\gamma, t)$$

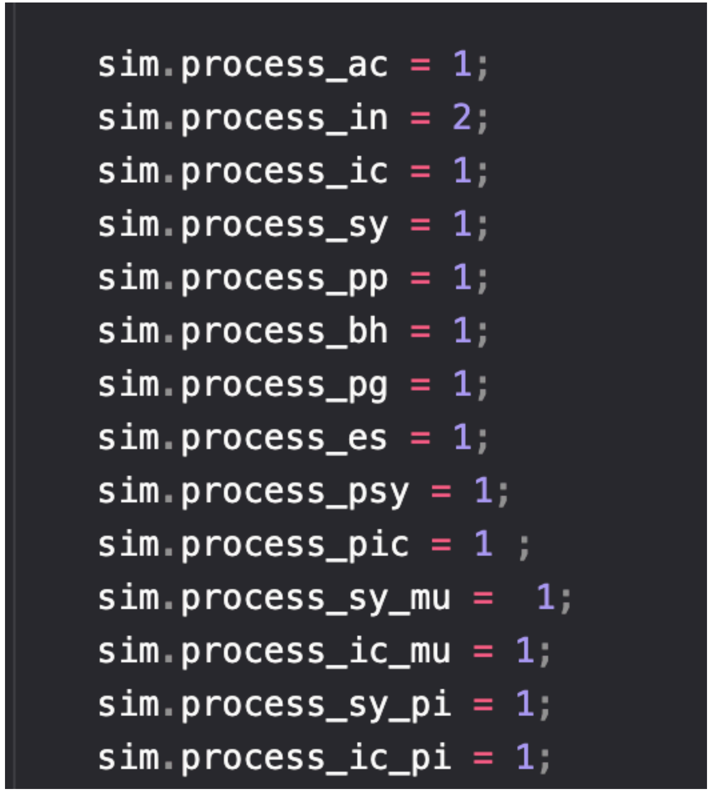
Cooling **Diffusion** **Escape/Advection** **Injection**

One example (C++)



Solid lines: operations in a loop
Dashed lines: initialization

To turn on/off each process:



```
sim.process_ac = 1;
sim.process_in = 2;
sim.process_ic = 1;
sim.process_sy = 1;
sim.process_pp = 1;
sim.process_bh = 1;
sim.process_pg = 1;
sim.process_es = 1;
sim.process_psy = 1;
sim.process_pic = 1 ;
sim.process_sy_mu =  1;
sim.process_ic_mu = 1;
sim.process_sy_pi = 1;
sim.process_ic_pi = 1;
```

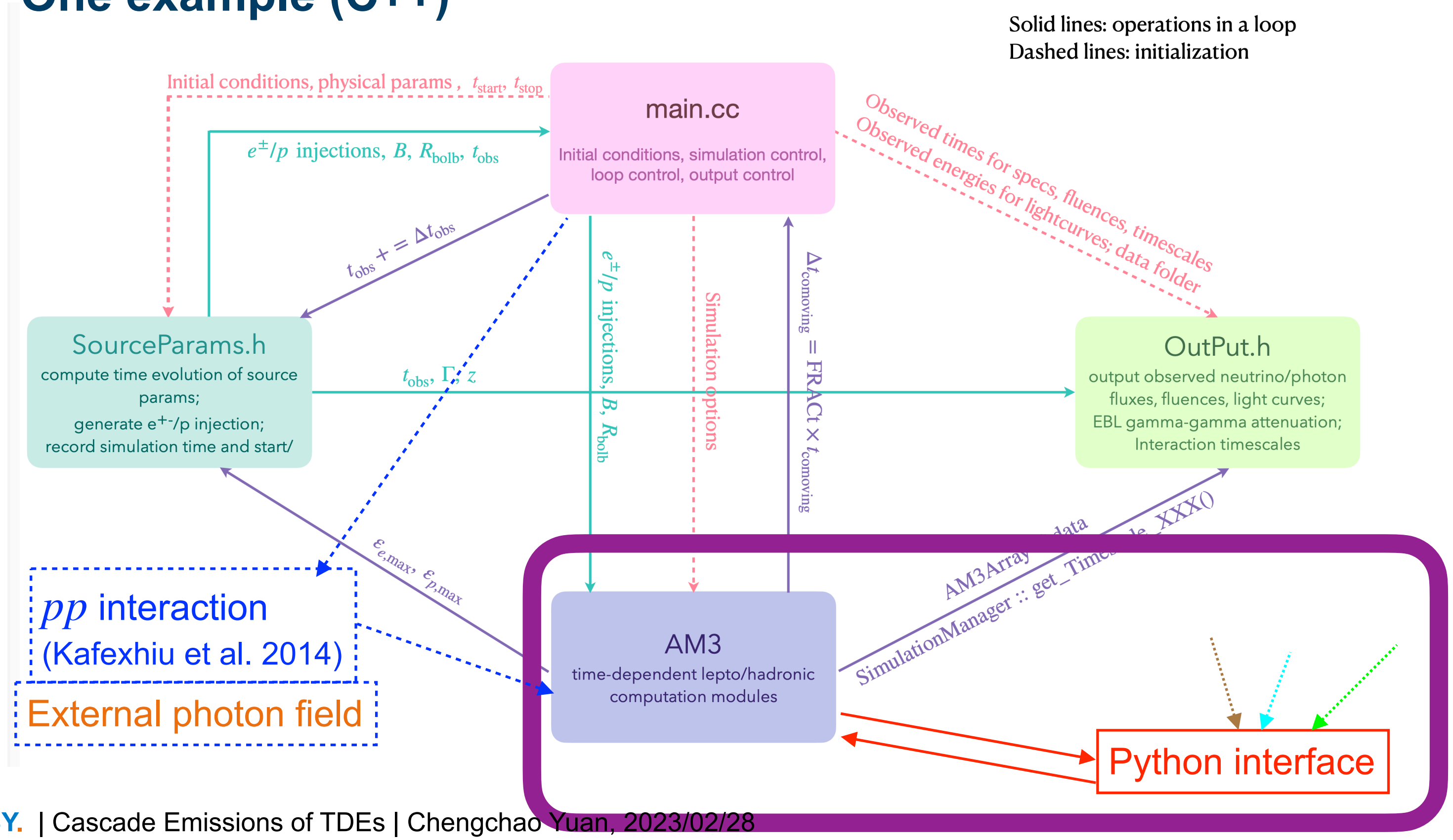
AM3: a time-dependent LepHad code

Numerically solving the coupled PDEs for electron, proton, and photon distributions. (Gao et al. 2017)

$$\partial_t n(\gamma,t) = -\partial_\gamma\{\dot\gamma(\gamma,t)n(\gamma,t) - \partial_\gamma[D(\gamma,t)n(\gamma,t)]/2\} - \alpha(\gamma,t)n(\gamma,t) + Q(\gamma,t)$$

Cooling **Diffusion** **Escape/Advection** **Injection**

One example (C++)



Solid lines: operations in a loop
Dashed lines: initialization

main.cc
Initial conditions, simulation control, loop control, output control

SourceParams.h
compute time evolution of source params;
generate e+-/p injection;
record simulation time and start/

OutPut.h
output observed neutrino/photon fluxes, fluences, light curves;
EBL gamma-gamma attenuation;
Interaction timescales

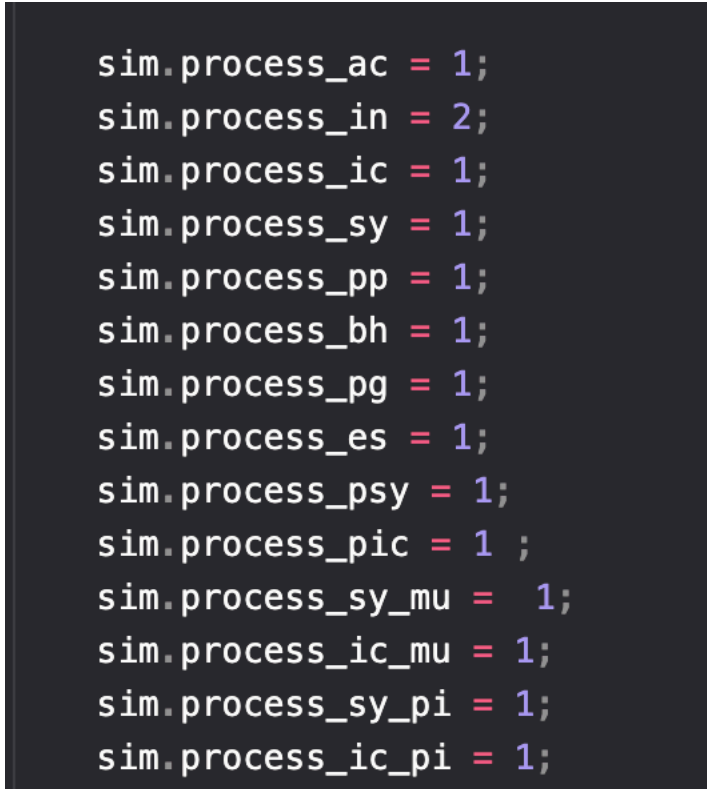
AM3
time-dependent lepto/hadronic computation modules

pp interaction (Kafexhiu et al. 2014)

External photon field

Python interface

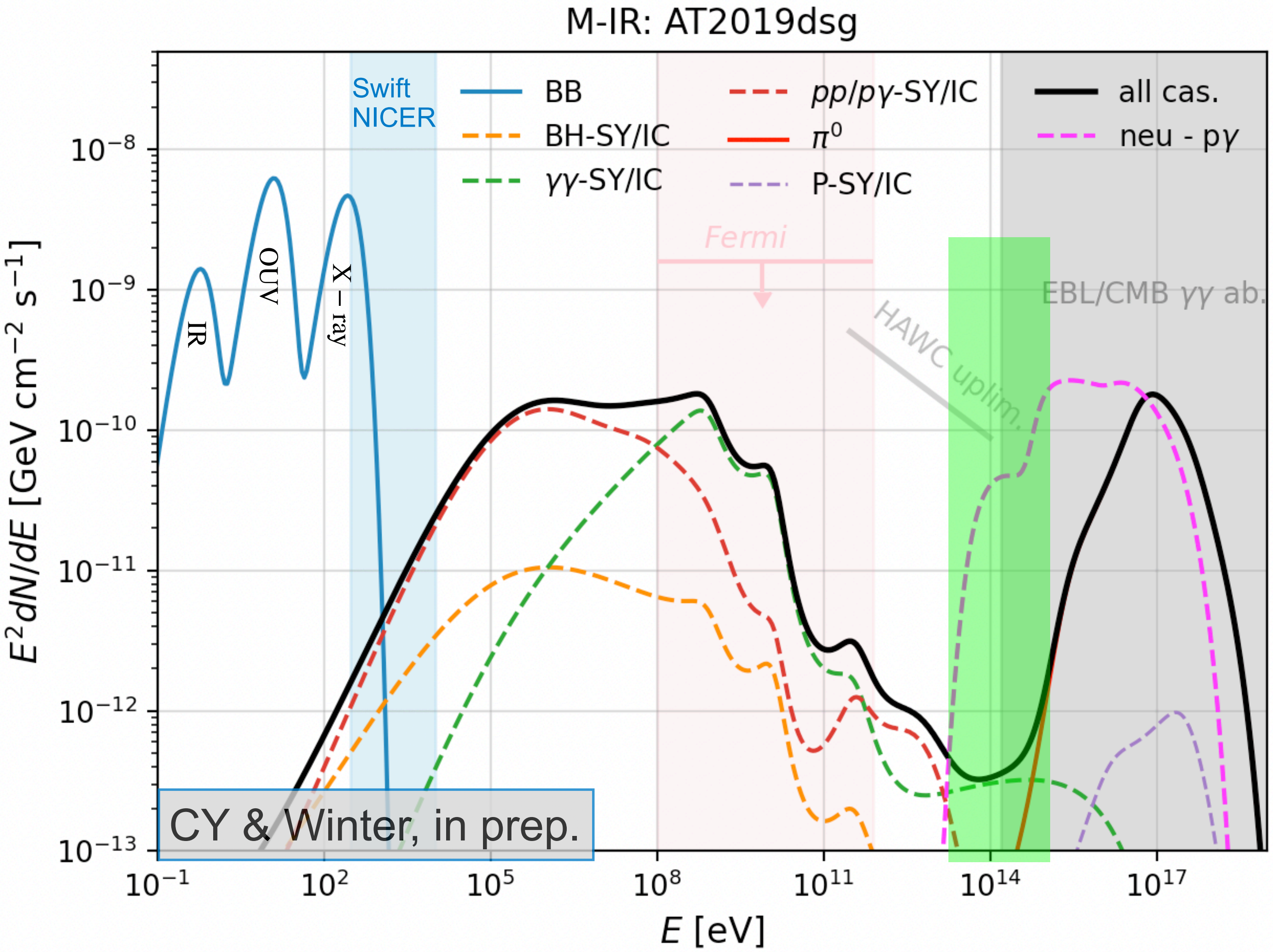
To turn on/off each process:



```
sim.process_ac = 1;
sim.process_in = 2;
sim.process_ic = 1;
sim.process_sy = 1;
sim.process_pp = 1;
sim.process_bh = 1;
sim.process_pg = 1;
sim.process_es = 1;
sim.process_psy = 1;
sim.process_pic = 1 ;
sim.process_sy_mu =  1;
sim.process_ic_mu = 1;
sim.process_sy_pi = 1;
sim.process_ic_pi = 1;
```

Hadronic cascade spectra: M-IR (dust echo)

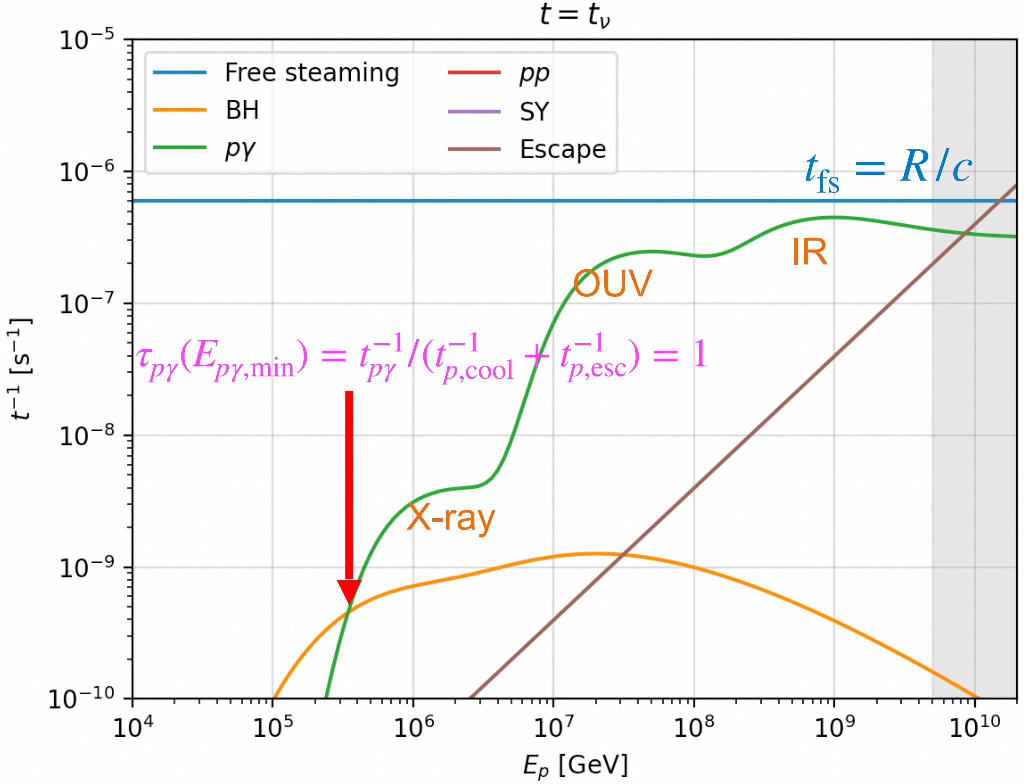
$p\gamma$ optically thin: ($\pi^\pm \rightarrow e^\pm \rightarrow \mathrm{SY/IC}$) + ($\gamma\gamma \rightarrow e^\pm \rightarrow \mathrm{SY/IC}$)



CY & Winter, in prep.

Parameters: $\varepsilon_{\mathrm{diss}} = 0.2$

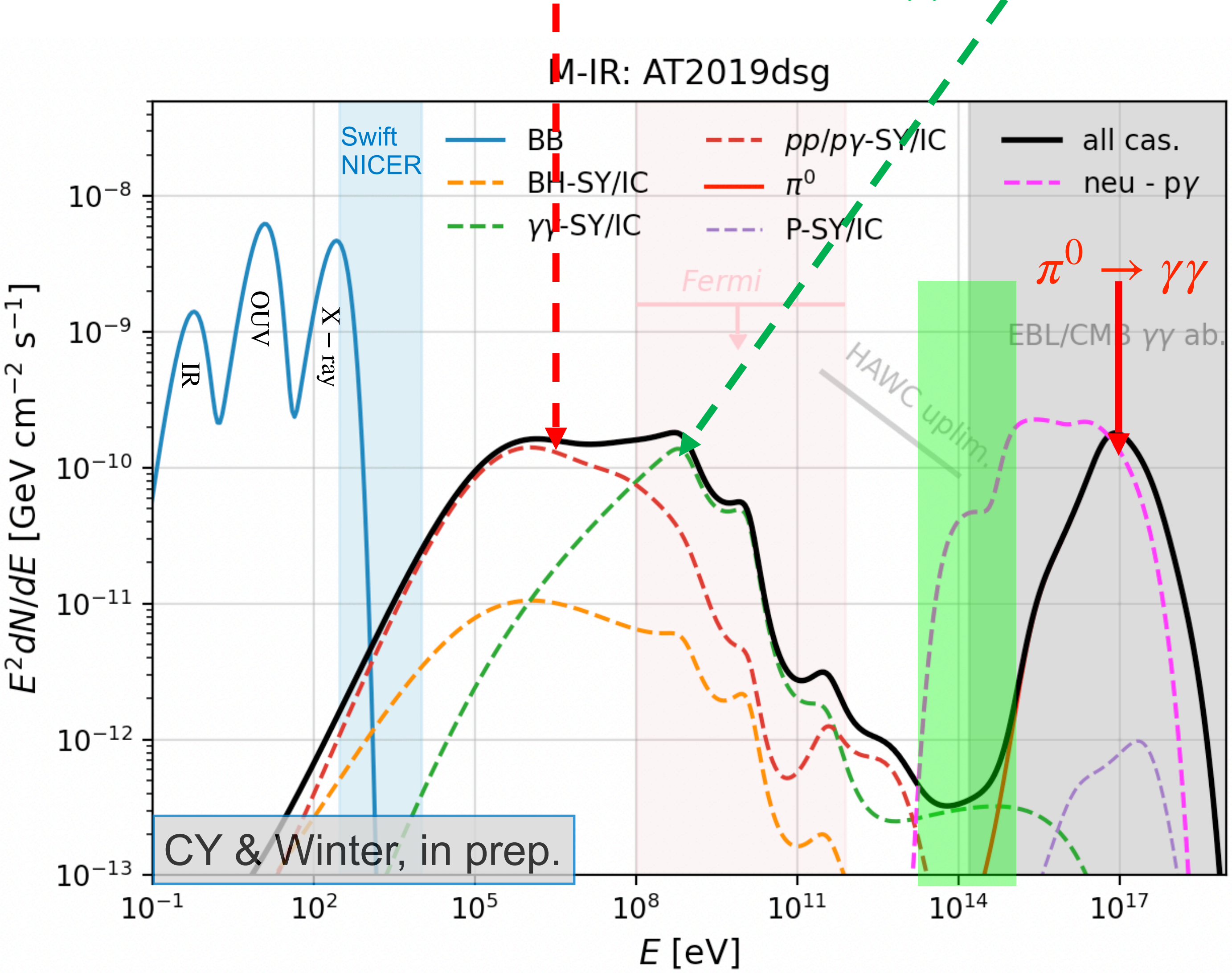
$B = 0.1$ G, $R = 5 \times 10^{16}$ cm, $E_{p,\max} = 5 \times 10^9$ GeV



Neutrino peak energy is significantly higher than the detected energy (green area) ->low N_ν

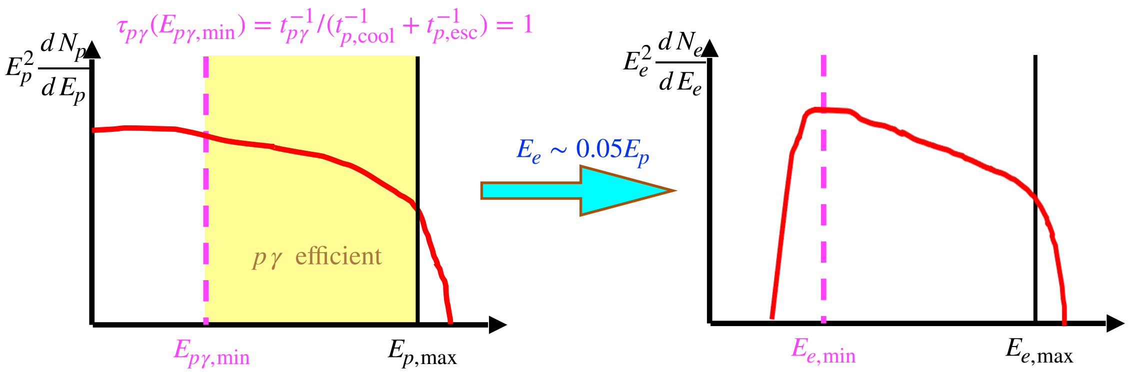
Hadronic cascade spectra: M-IR (dust echo)

$p\gamma$ optically thin: $(\pi^\pm \to e^\pm \to \mathrm{SY/IC})$ **+** $(\gamma\gamma \to e^\pm \to \mathrm{SY/IC})$



CY & Winter, in prep.

$\pi^\pm \to e^\pm \to \mathrm{SY/IC}$



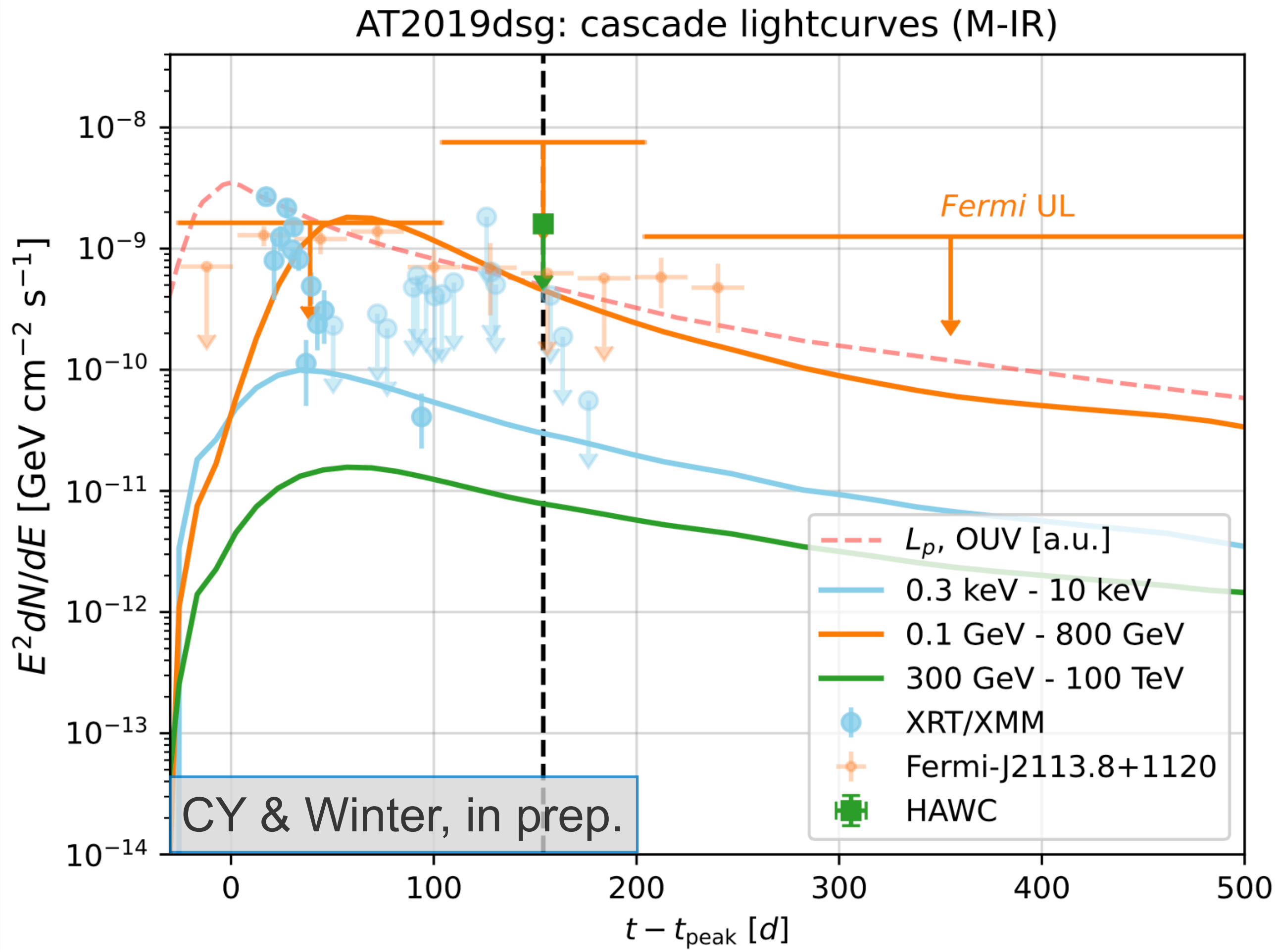
$$E_{pp/p\gamma,\mathrm{SY}} \sim \frac{3}{4\pi} h\gamma_{e,min}^2 \frac{eB}{m_e c}$$
$$\sim 420\ B_{-1}\left(\frac{E_{p\gamma,\min}}{10^5\ \mathrm{GeV}}\right)^2\ \mathrm{keV}$$

$\gamma\gamma \to e^\pm \to \mathrm{SY/IC}$

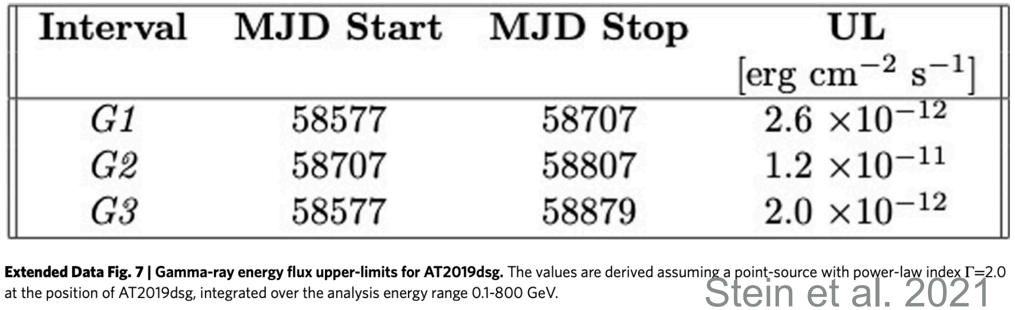
$$E_\gamma \sim m_e^2/E_{\mathrm{bb}} \simeq 2\ \mathrm{GeV}(E_{\mathrm{bb}}/100\mathrm{eV})^{-1}$$

Temporal signatures: M-IR

Dust echo scenario: $\varepsilon_{\rm diss} = 0.2, B = 0.1\ {\rm G}, R = 5 \times 10^{16}\ {\rm cm}, E_{p,\max} = 5 \times 10^{9}\ {\rm GeV}$



Fermi-LAT uplimit $(0.1 - 800\ {\rm GeV})$



Interval	MJD Start	MJD Stop	UL [erg cm^{-2} s^{-1}]
G1	58577	58707	2.6×10^{-12}
G2	58707	58807	1.2×10^{-11}
G3	58577	58879	2.0×10^{-12}

Extended Data Fig. 7 | Gamma-ray energy flux upper-limits for AT2019dsg. The values are derived assuming a point-source with power-law index Γ=2.0 at the position of AT2019dsg, integrated over the analysis energy range 0.1-800 GeV.

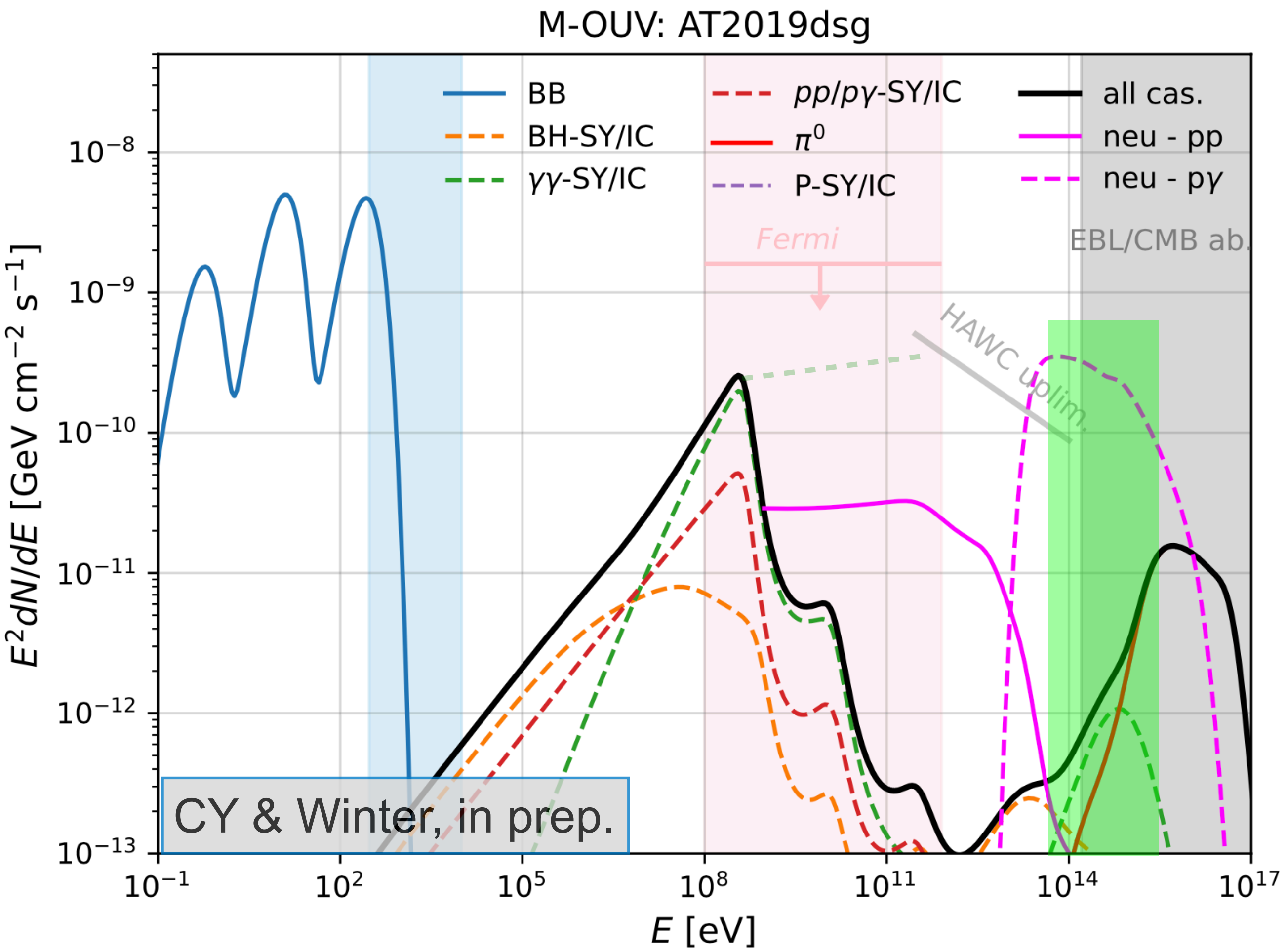
Stein et al. 2021

Consistent with Fermi UL., but predicts a low neutrino number

~50 days time delay is compatible with $p\gamma$ interaction time $t_{p\gamma} \sim 10 - 100\ {\rm d}$

Hadronic cascade spectra: M-OUV

$p\gamma$ optically thick: $(\pi^\pm \rightarrow e^\pm \rightarrow \mathrm{SY/IC})$ + $(\gamma\gamma \rightarrow e^\pm \rightarrow \mathrm{SY/IC})$



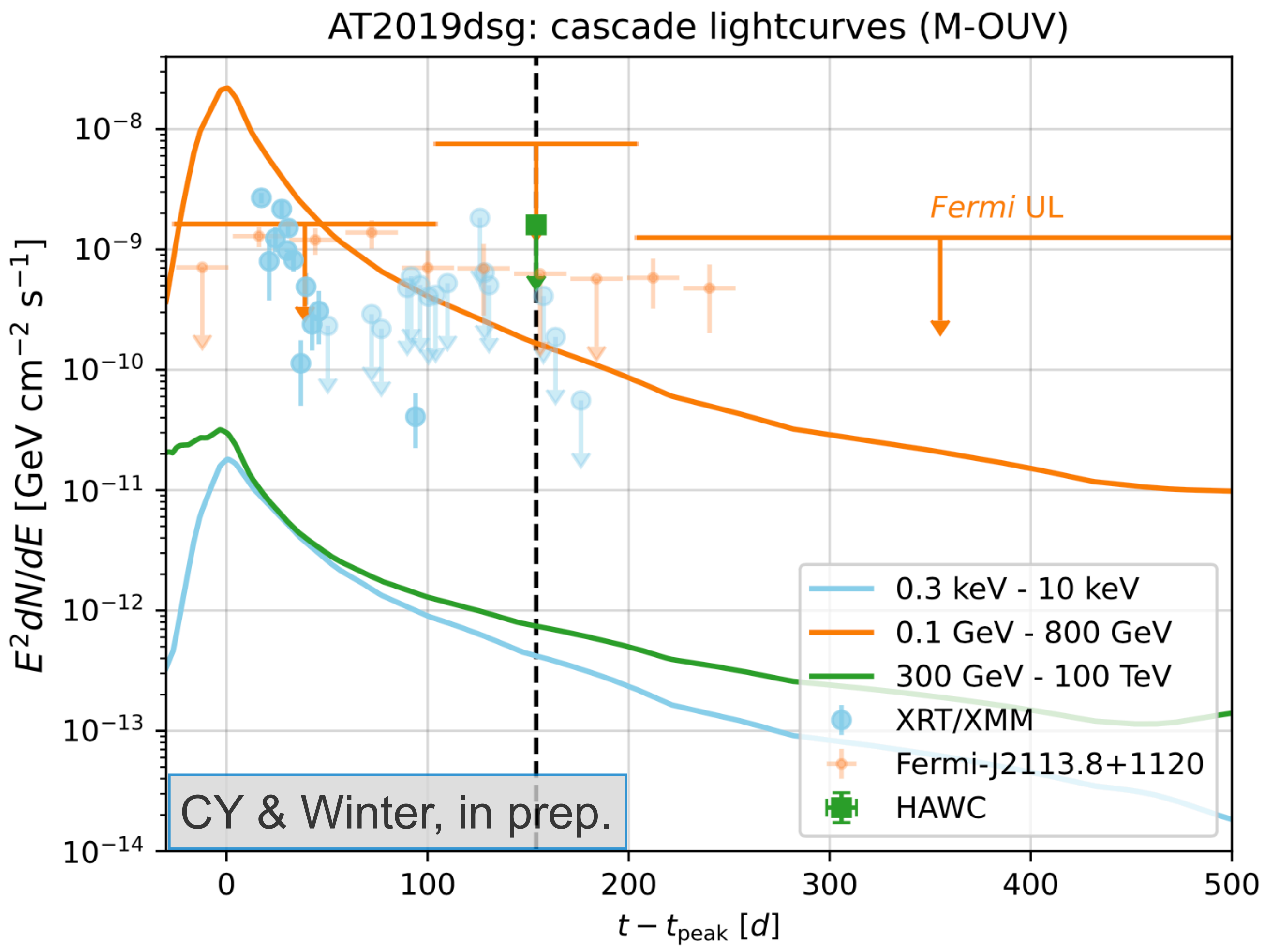
Parameters: $\varepsilon_{\rm diss} = 0.2$

$B = 0.1$ G, $R = 5 \times 10^{14}$ cm, $E_{p,\max} = 1 \times 10^{8}$ GeV

- Small R leads to fast proton escape
- $E_{p\gamma,\min} \sim 10^{6-7}$ GeV
- Synchrotron peak energy $>$ GeV
- Attenuated before reaching the peak -> spikes
- Promising neutrino emitter in the neutrino energy range

Temporal signatures: M-OUV

Compact region: $\varepsilon_{\rm diss} = 0.2, B = 0.1\ {\rm G}, R = 5 \times 10^{14}\ {\rm cm}, E_{p,{\rm max}} = 1 \times 10^{8}\ {\rm GeV}$



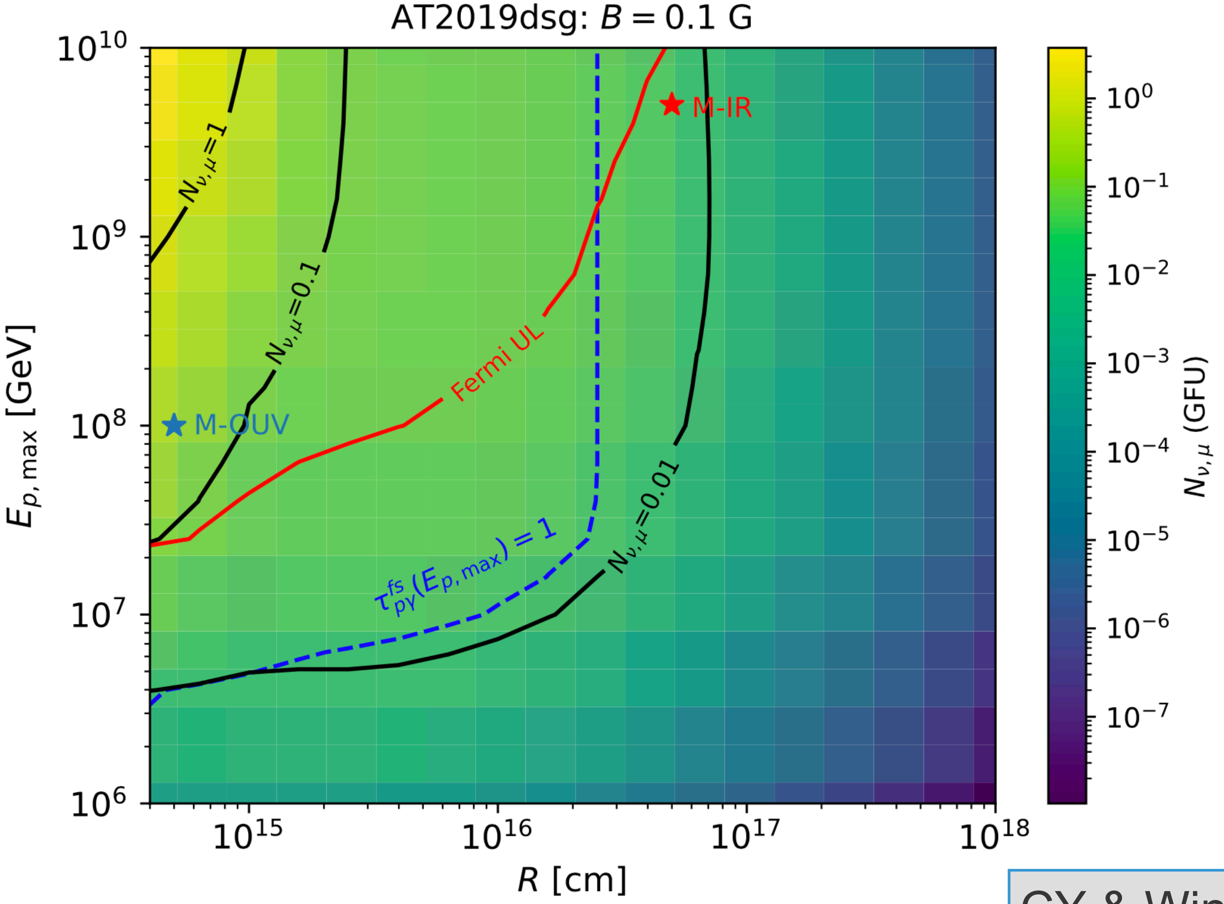
In this compact and dense region, interactions occur very fast

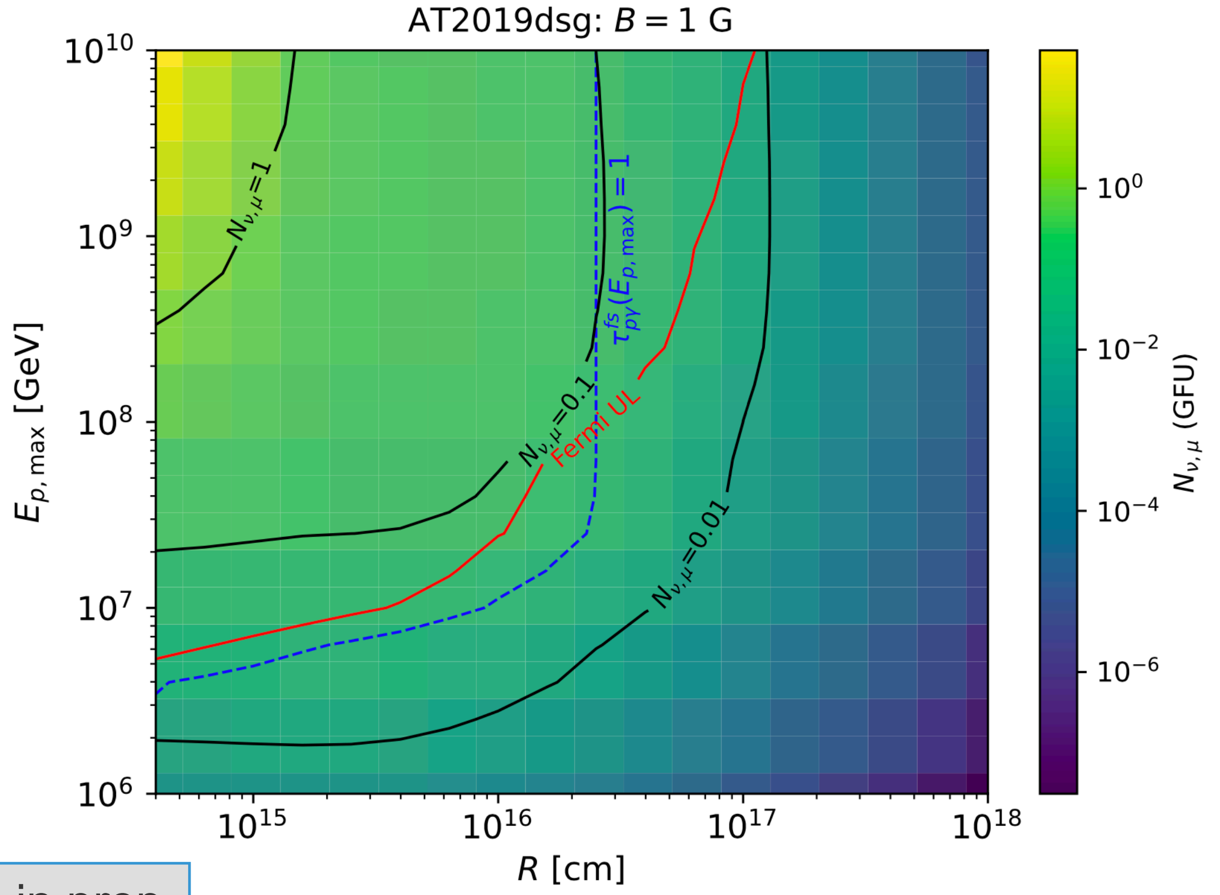
- $p\gamma$ optically thick: $t_{p\gamma}^{-1}/t_{\rm fs}^{-1} > 1$
- no significant time delay
- Cascade emission peaks in LAT energy range -> overshooting the γ-ray limits

Constraints on $E_{p,\max}$ and B

Obscured radiation region may be able to solve the missing γ-ray problem.

CRs are more confined with a stronger magnetic field, which enables a less compact region to be a promising neutrino emitter. (Easier to overshoot γ-ray uplimits)





CY & Winter, in prep.

Summary

- EM/hadronic cascade processes in TDE winds can produce detectable X-ray/γ-ray emissions, e.g., M-IR (dust echo scenario). But so far no γ-ray has been detected!
- Significant (~10-100 days) time delay is expected in the $p\gamma$ optically thin regime.
- To explain the neutrino coincidence, very efficient energy dissipation to CRs and compact/dense radiation region are needed. The accompanying cascade emission will unavoidably overshoot the X-ray/γ-ray constraints.
- γ-ray obscured/hidden models may solve the missing γ-ray problem.
- It might be interesting the explore the time-dependent LepHad cascade signatures in jetted TDEs, e.g., AT2022cmc.
- Collaborations in future TDE projects