

# Investigating the Quiescent State of the TeV-emitting Radio Galaxy 3C 264

Ettore Bronzini<sup>1,2</sup>  
*on behalf of the MAGIC collaboration*

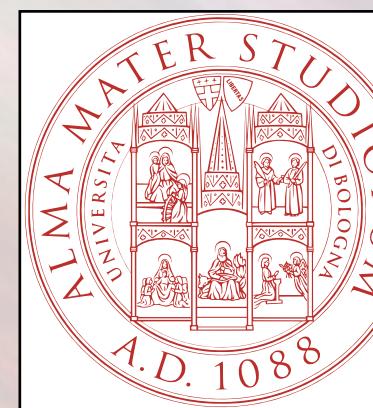
<sup>1</sup>Department of Physics and Astronomy, University of Bologna

<sup>2</sup>INAF, Astrophysics and Space Science Observatory Bologna

[ettore.bronzini@inaf.it](mailto:ettore.bronzini@inaf.it)

E. Torresi, P. Grandi, C. Vignali, R. Zanin, G. Migliori, A. Arbet-Engels, B. Boccardi, L. Di Venere, A. Tramacere  
+ other coll.

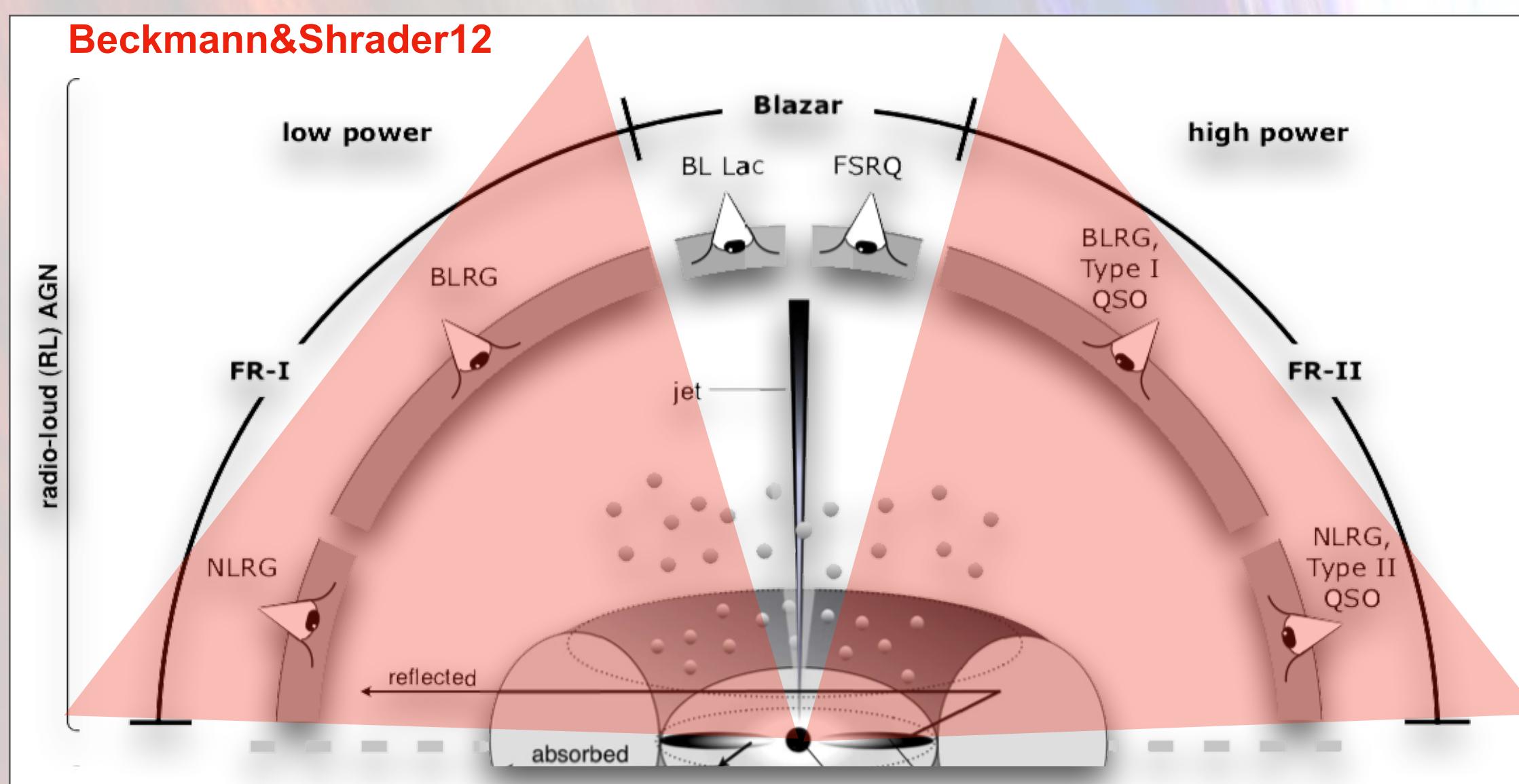
TeVPA 2023, Naples  
Sept. 13, 2023



# Radio Galaxies (I): a general overview

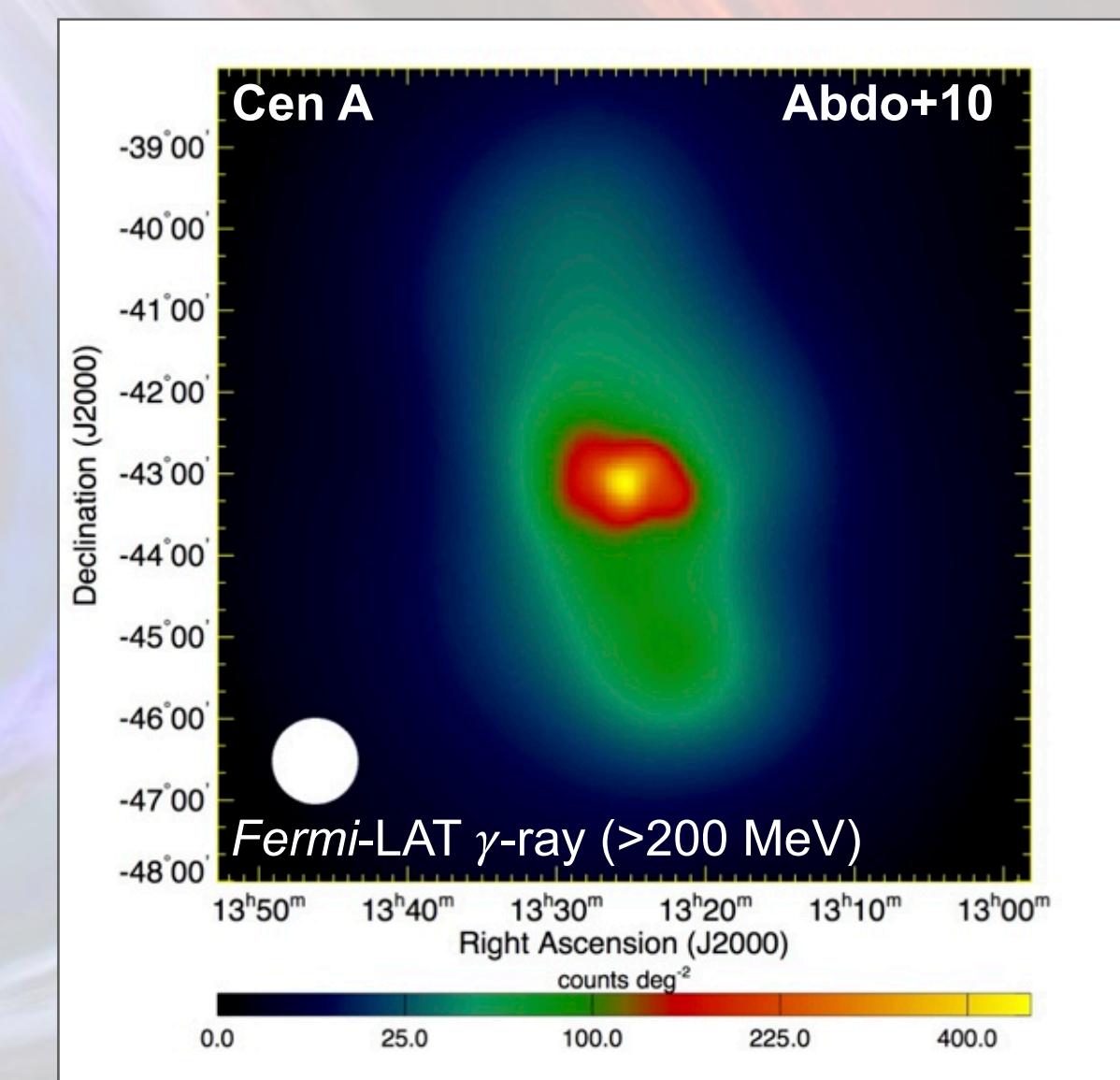
According to Unification Models (Antonucci93, Urry&Padovani+95), jetted AGN are split into two main classes **on the base of the jet angle:**

- blazars
- radio galaxies



## Why radio galaxies?

- **accretion and ejection processes:** less jet-dominated SED in radio galaxies wrt blazars
- radio galaxies complementary to blazars => **unique opportunity to study  $\gamma$ -ray emission processes at different sites from sub-pc up to kpc scales** (e.g., from the radio lobes in Cen A (Abdo+10), Fornax A (Ackermann+16) )

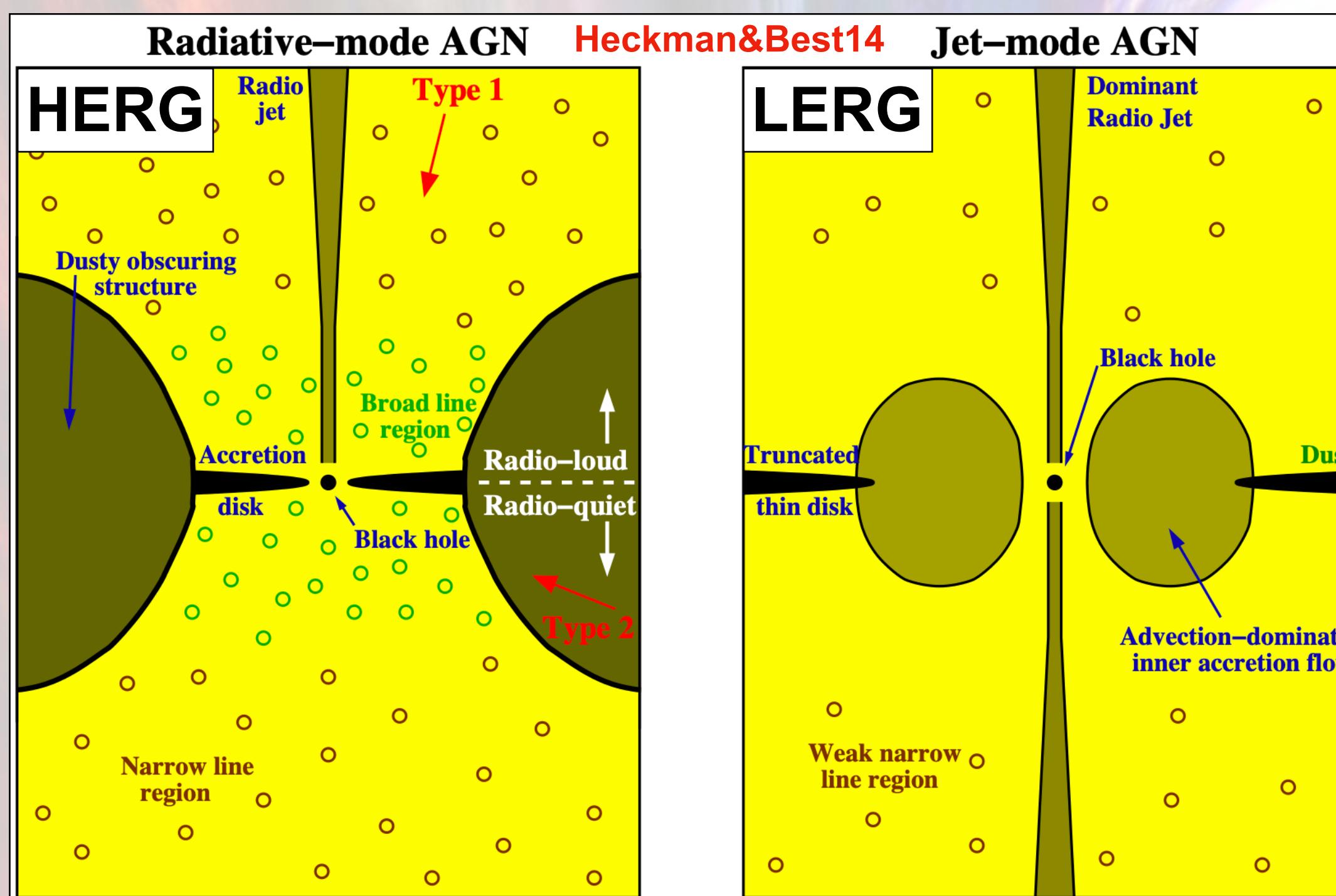


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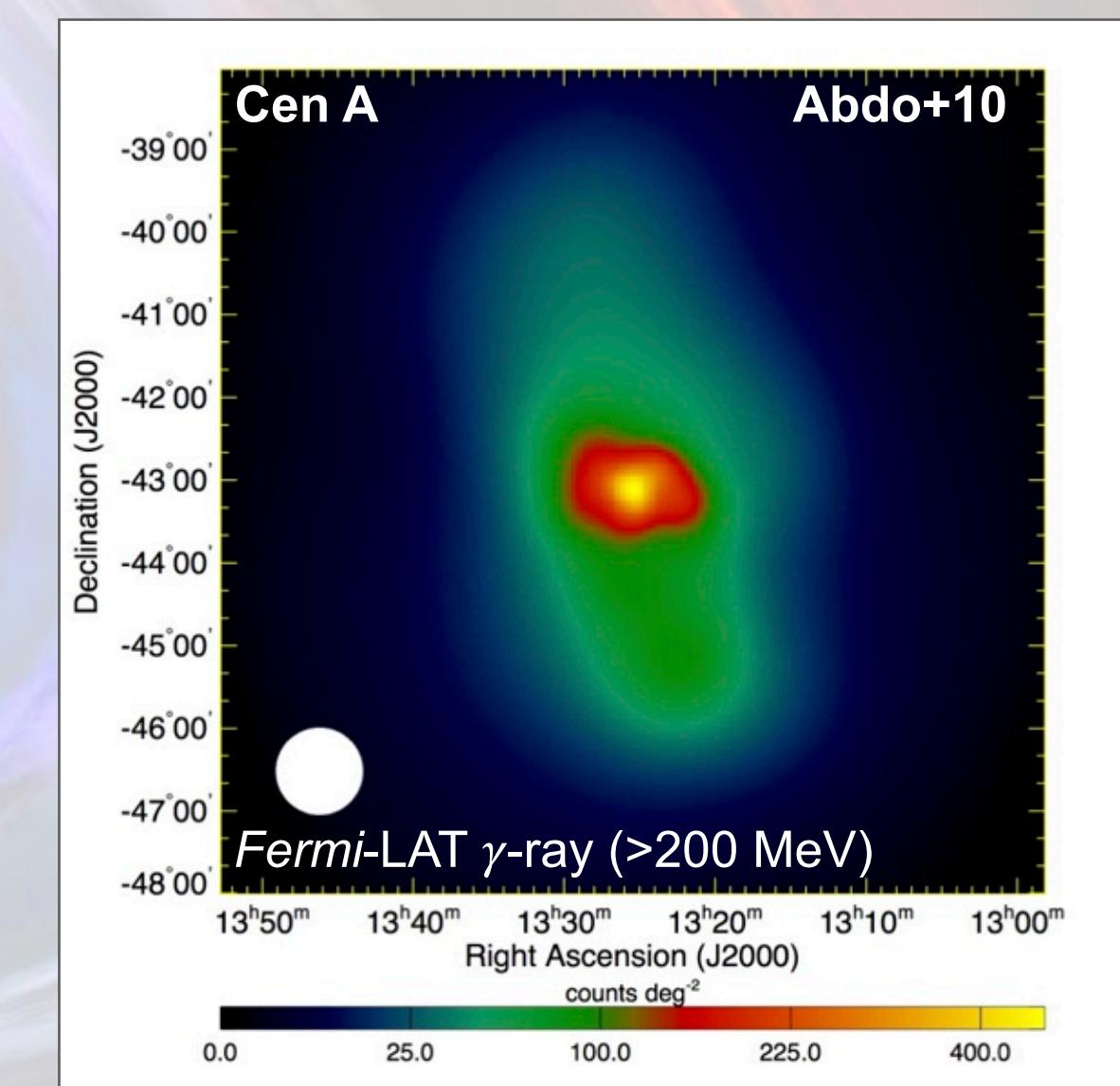
- blazars
- radio galaxies

but.. what about accretion?



## Why radio galaxies?

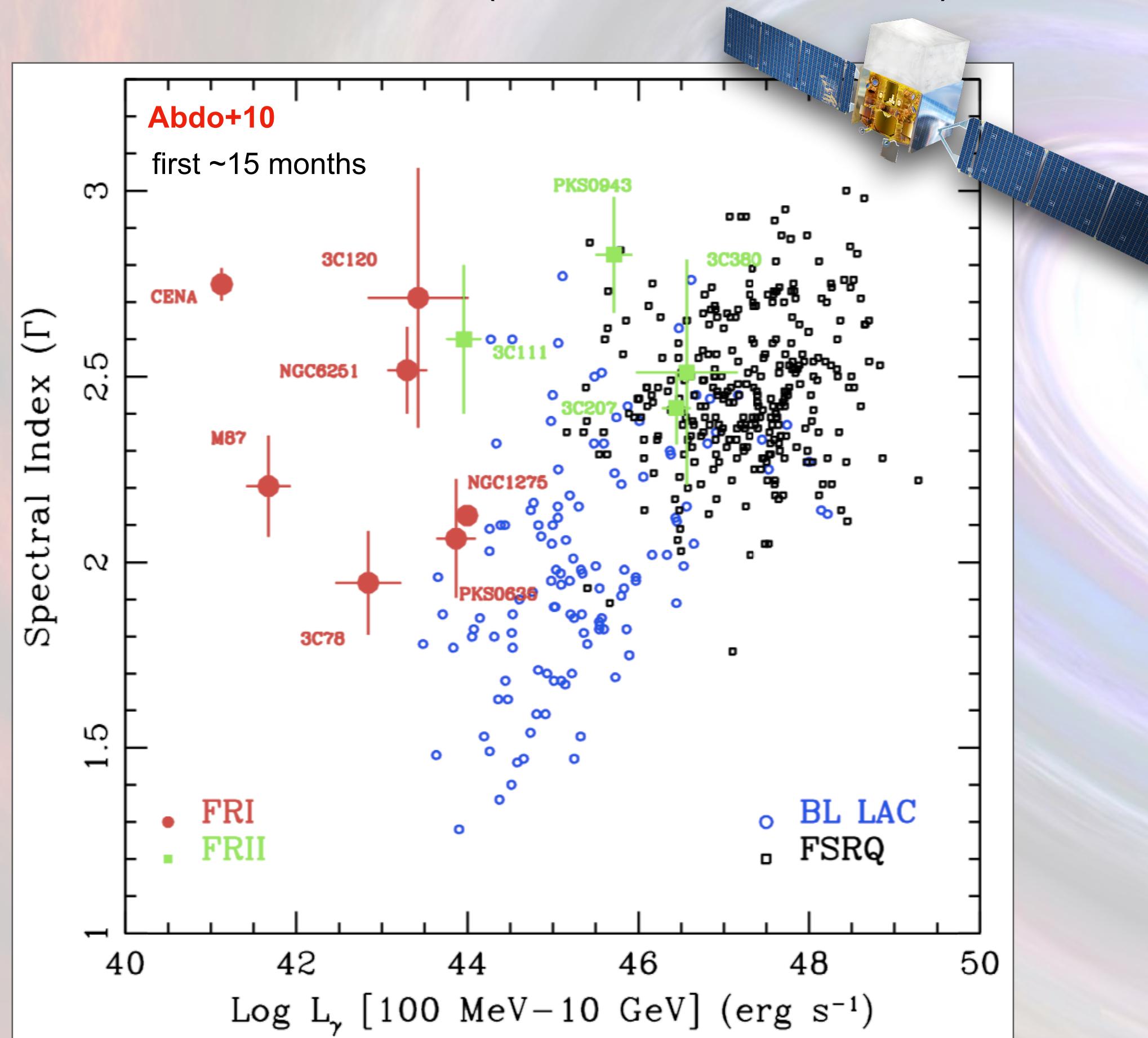
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# Radio Galaxies (II): $\gamma$ -ray view

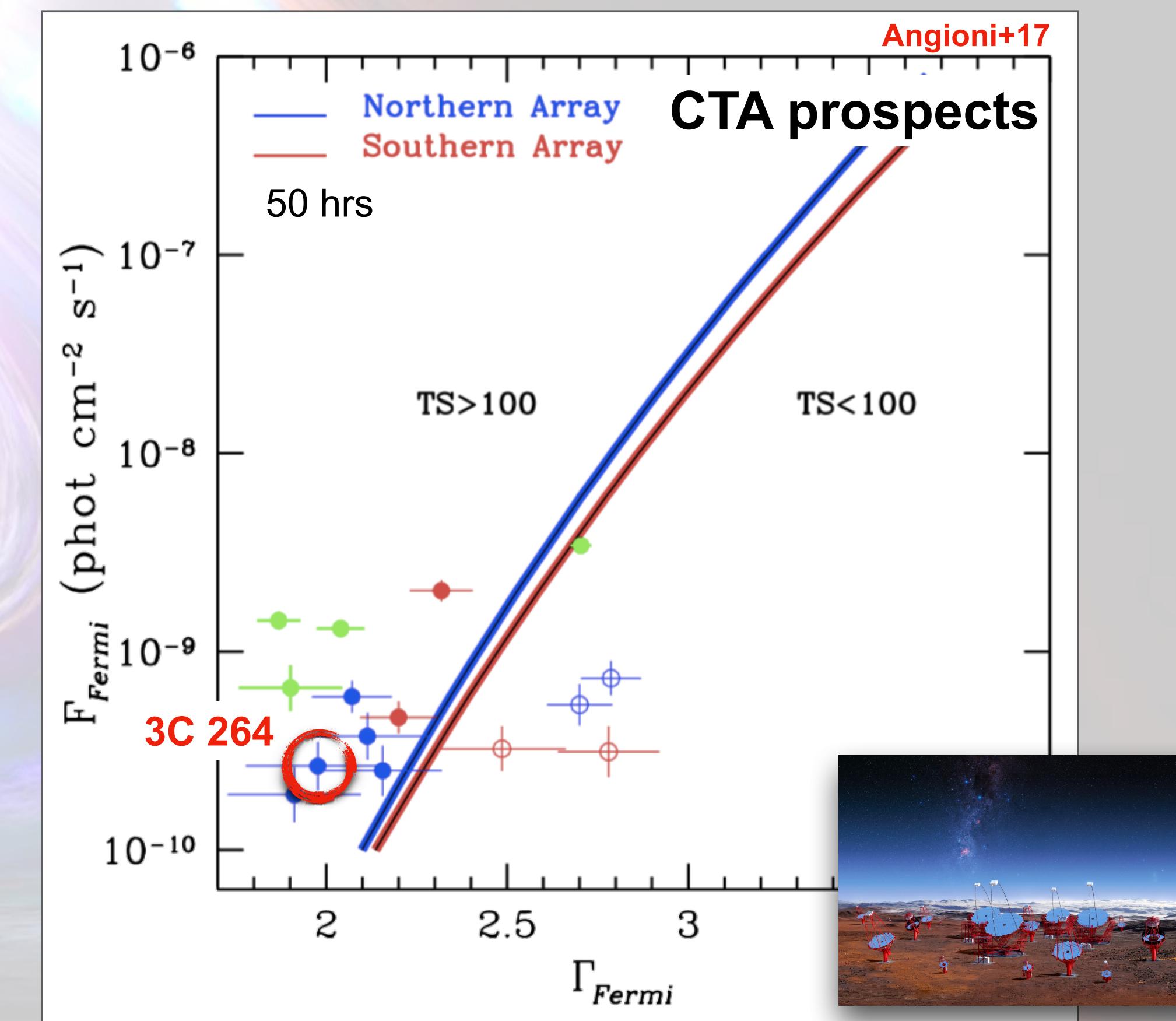
## GeV view

The extragalactic  $\gamma$ -ray sky seen by *Fermi*-LAT is dominated by blazars and radio galaxies represent a small percentage ( $\sim 2\%$ ) of the 4FGL-DR3 (Abdollahi+22) (see also Foschini+22)



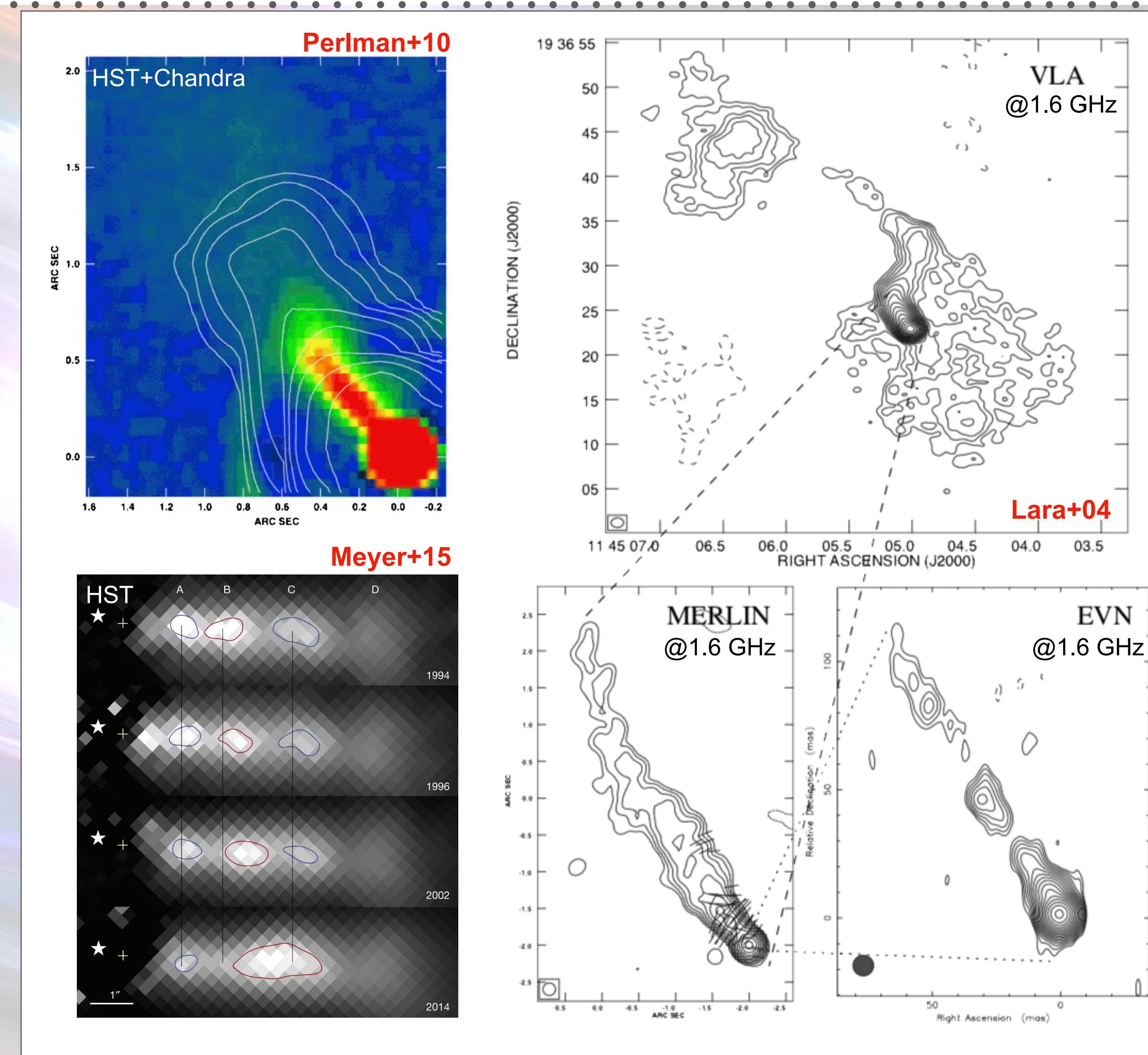
## TeV view

- Only 6 RGs observed at TeV energies (TeVCat): Centaurus A, M 87, NGC 1275, IC 310, 3C 264, PKS 0625-35
- All nearby FR I ( $z \leq 0.05$ )
- 3C 264: VHE-emitter candidate since 2017 (Angioni+17)



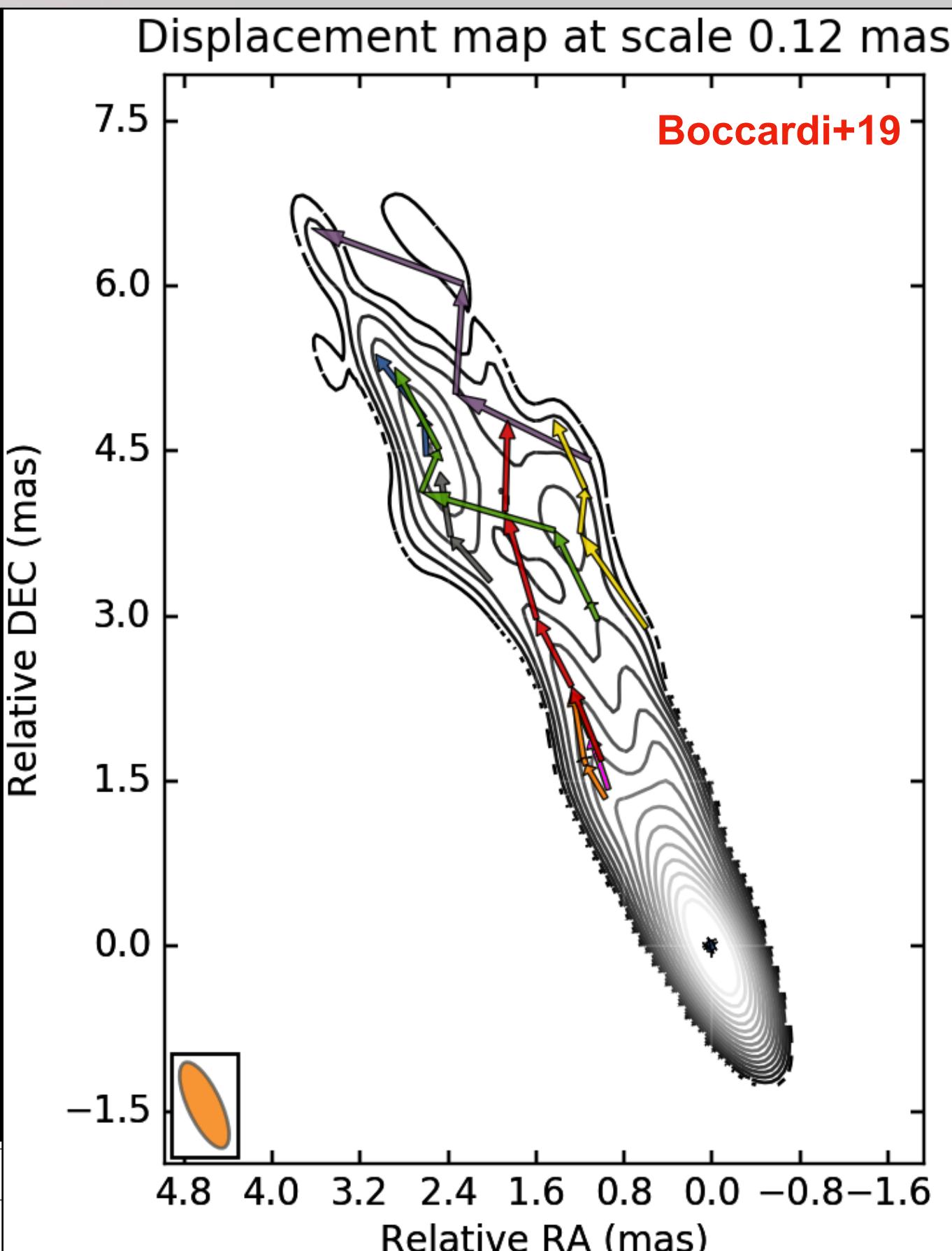
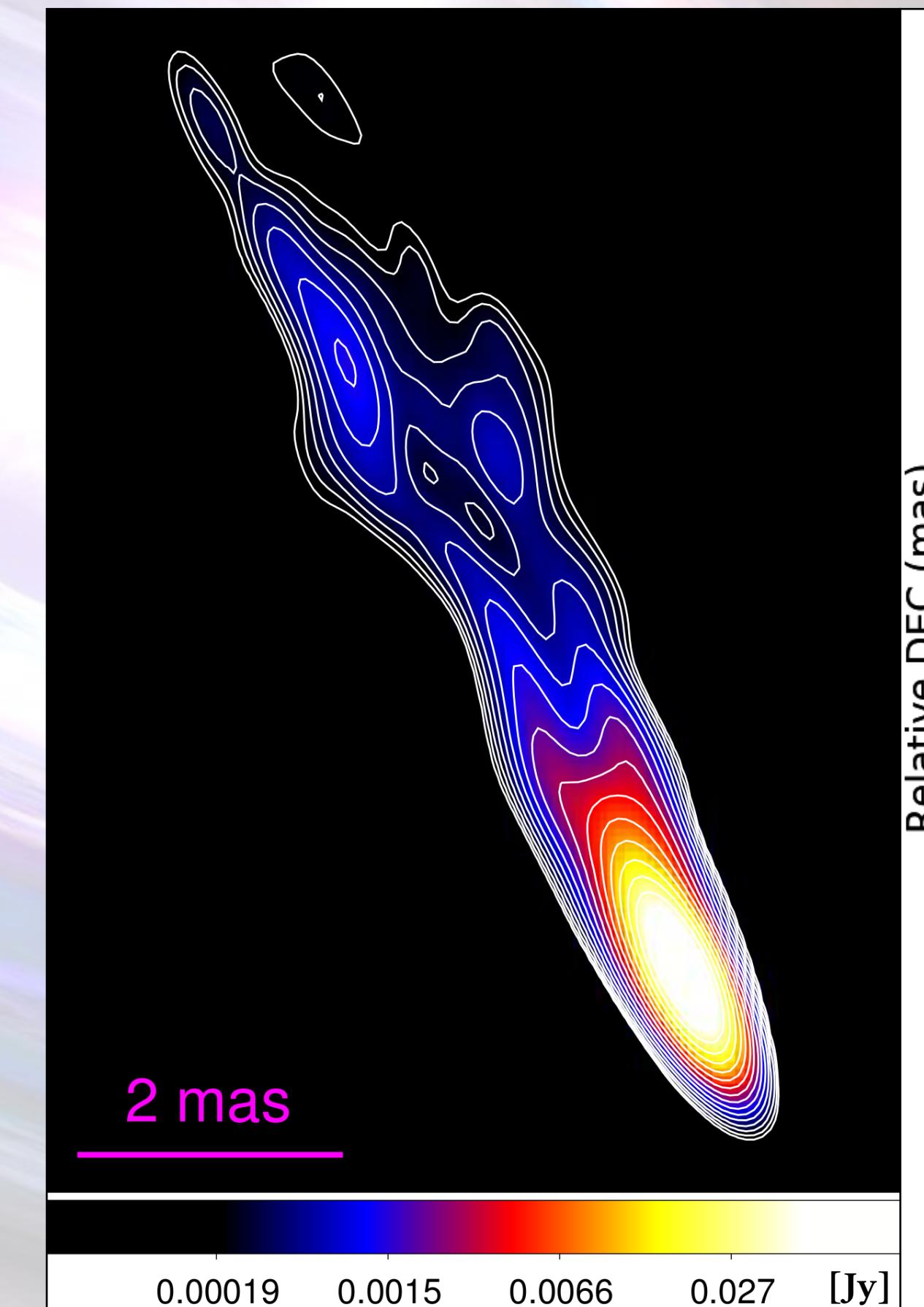
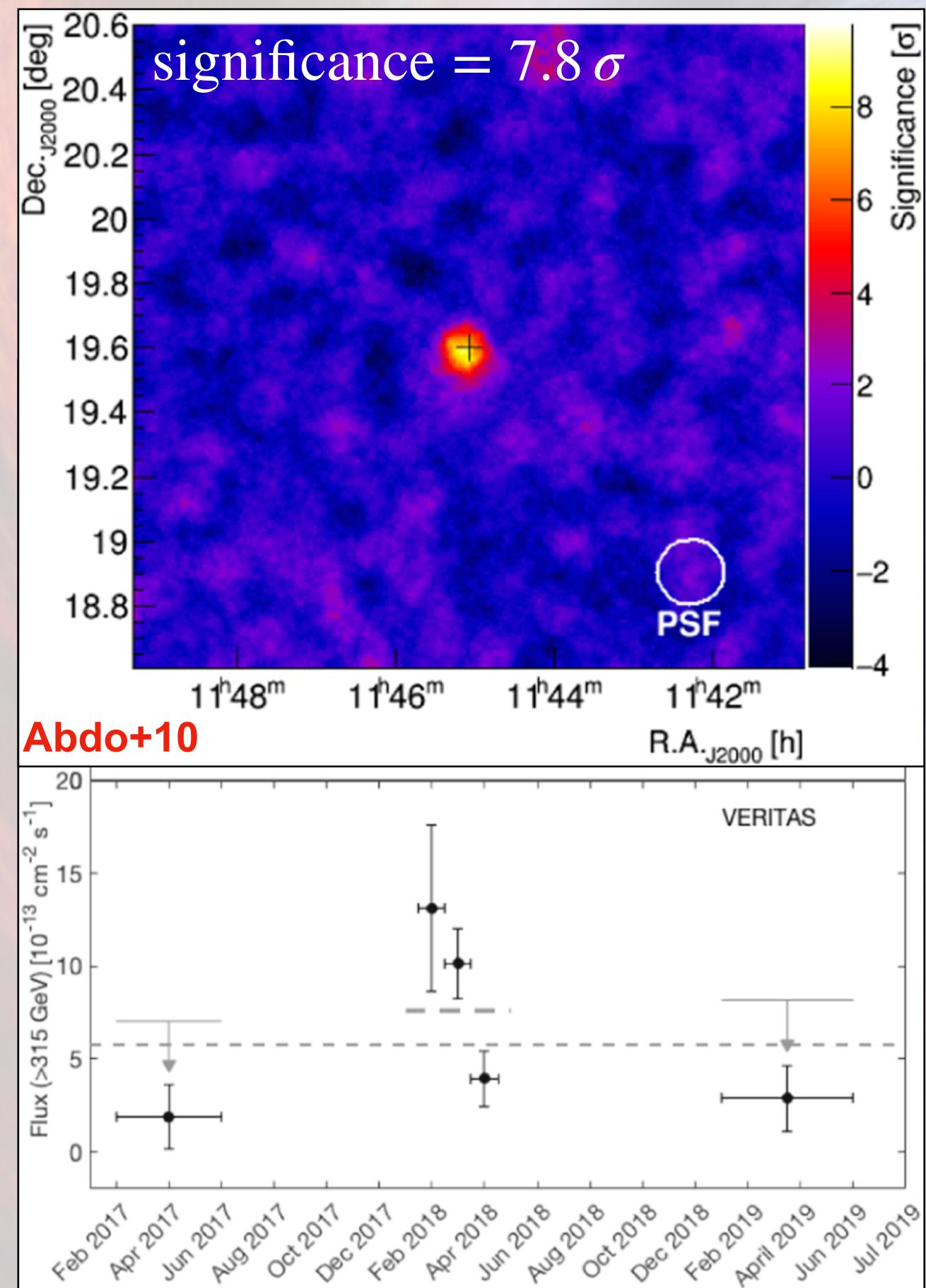
# 3C 264: source properties

- FRI/LERG radio galaxy ( $z=0.0216$ ) in Abell 1367 cluster (RA: 176.27, Dec: 19.61)
- Head-tail kpc structure with extended radio, optical, X-ray jet (Lara+97, Perlman+10, Meyer+15);
- $\gamma$ -ray source:
  - 3FGL J1145.1+1935 (Acero+15)
  - 4FGL J1144.9+1937 (Abdollahi+22)
    - $\Gamma_{\text{LAT}} = 2.02 \pm 0.08$
    - $\text{Flux}_{\text{LAT}} = (2.95 \pm 0.34) \times 10^{-10} \text{ ph s}^{-1} \text{ cm}^{-2}$
- The second most distant TeV-emitting radio galaxy (TeVCat)



# TeV flare

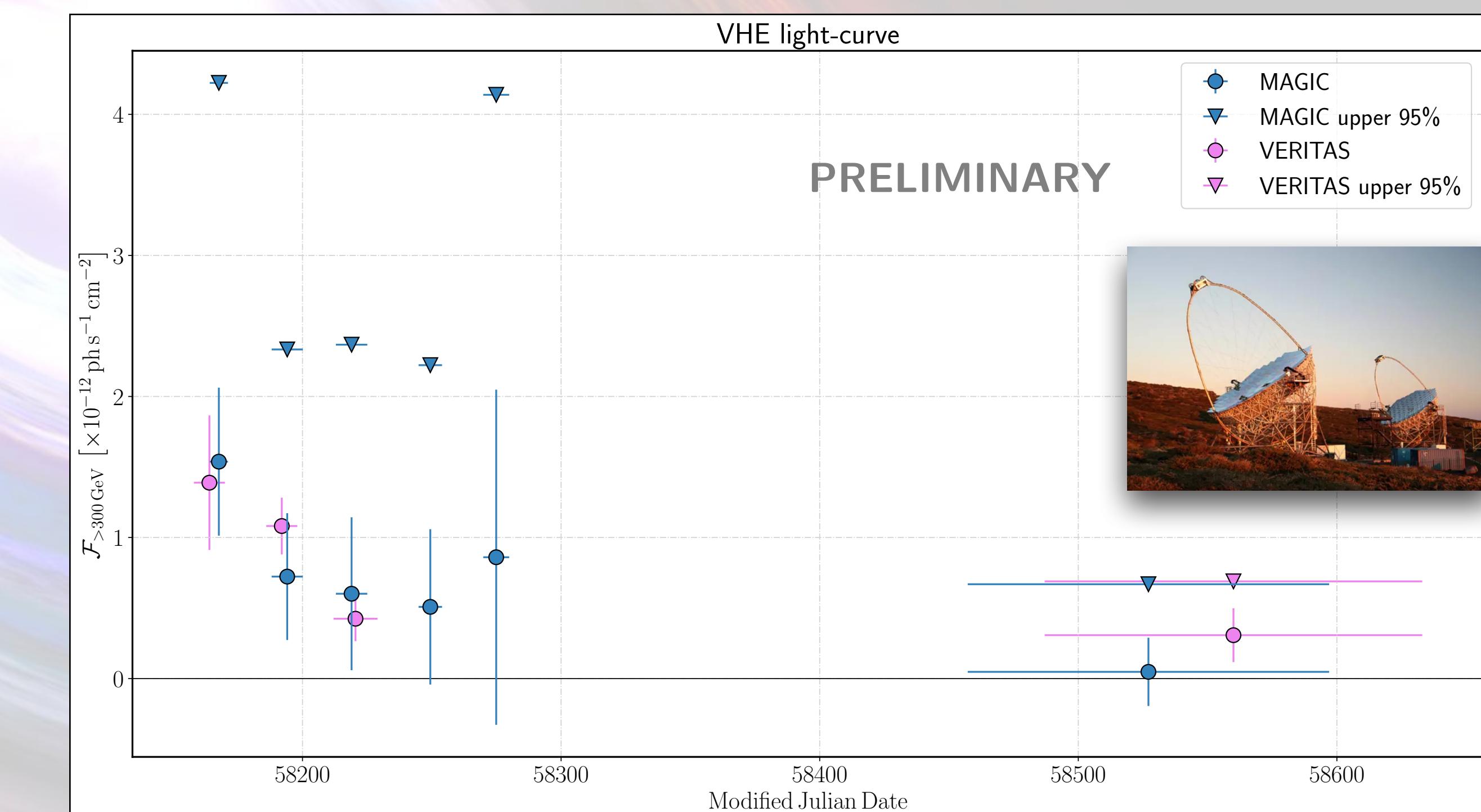
- VERITAS detection (ATel #11436) by **Mukherjee18**
- VERITAS paper by **Archer+20**
- Paper by **Boccardi+19**:
  - unprecedented **VLBI study of the jet components** of 3C 264
  - **X-ray high state contemporary to TeV enhanced activity**



# MAGIC campaign

After 8 days from VERITAS start, MAGIC observed the source

- Period: Feb to Jun 2018; Dec 2018 to Apr 2019 ( $\sim 82$  hrs)
- Significance =  $4.4\sigma$
- $F_{\text{MAGIC}} = (1.5 \pm 0.5) \times 10^{-12} \text{ ph s}^{-1} \text{ cm}^{-2} \sim F_{\text{VERITAS}}$
- $\Gamma_{\text{MAGIC}} = 2.37 \pm 0.39 \sim \Gamma_{\text{VERITAS}}$

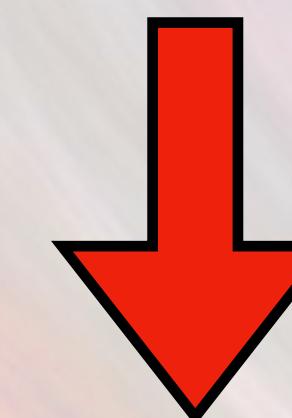


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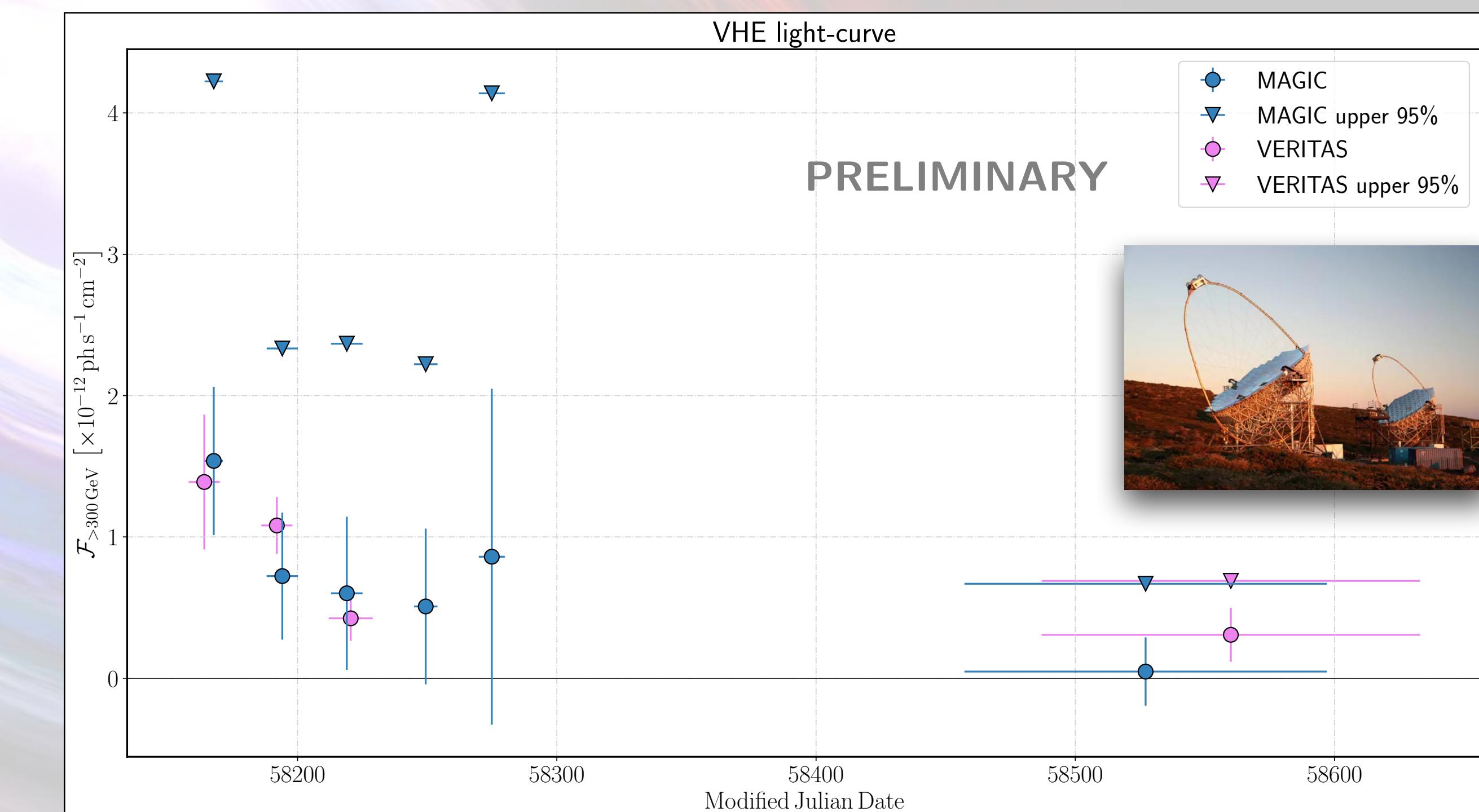
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**SIMILAR FADING TREND AS OBSERVED BY  
VERITAS**



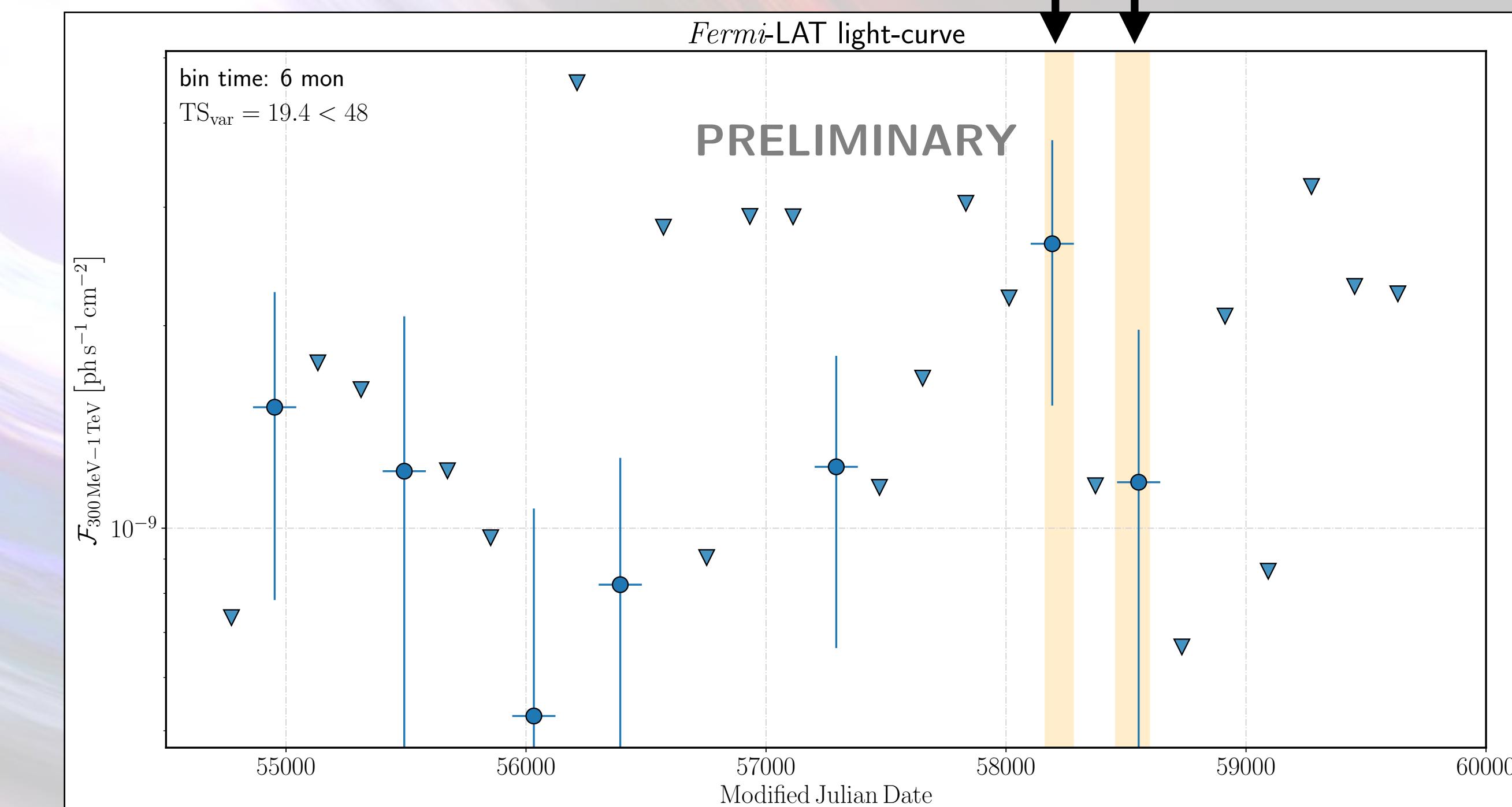
**TRIGGER FOR MULTI-WAVELENGTH VARIABILITY  
ANALYSIS**



- Period: 2008-2022
- Energy range: 300 MeV - 1 TeV
- TS = 168
- $F_{\text{300 MeV}-\text{1 TeV}} = (7.6 \pm 1.3) \times 10^{-10} \text{ ph s}^{-1} \text{ cm}^{-2}$
- $\Gamma = 1.92 \pm 0.09$

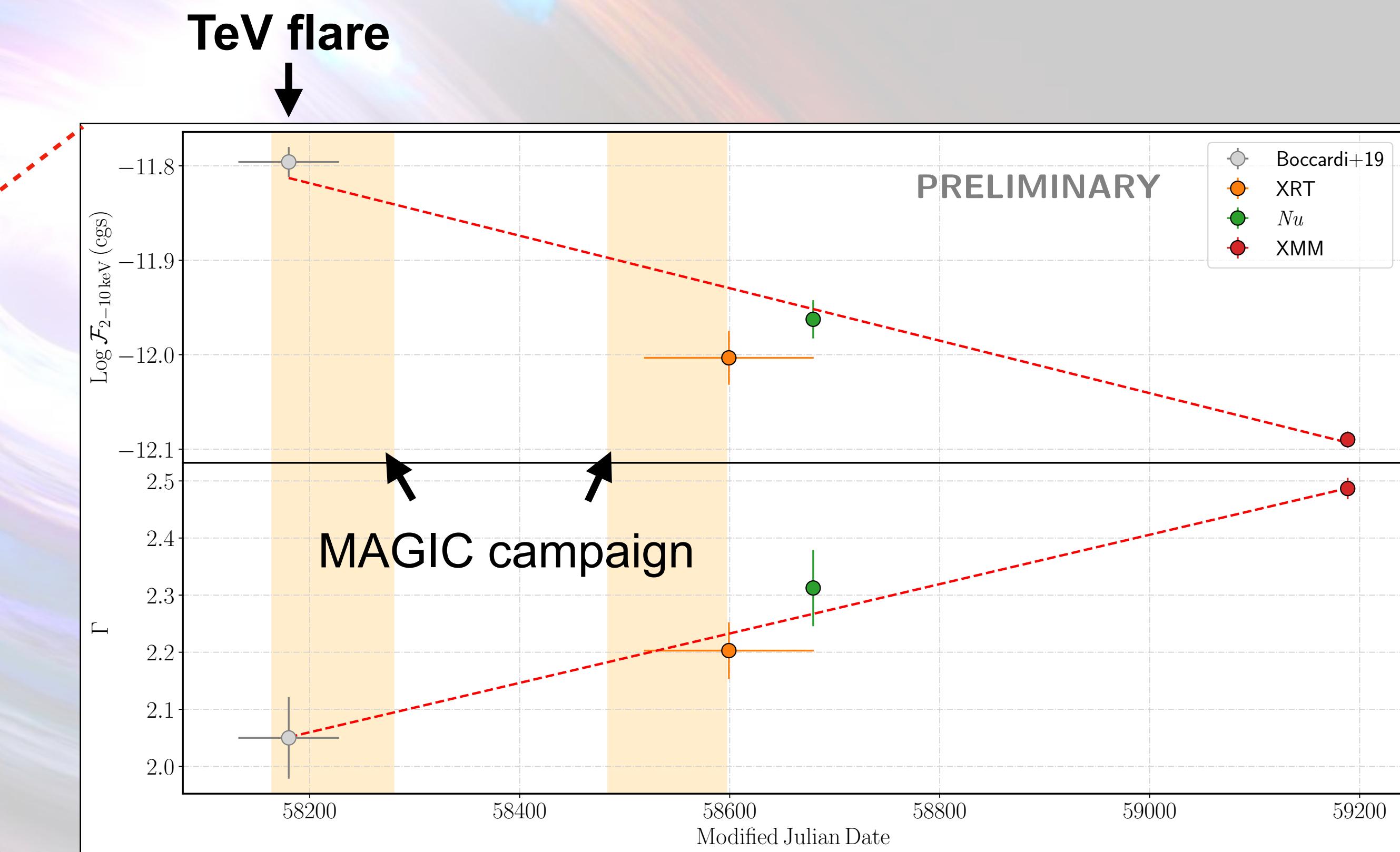
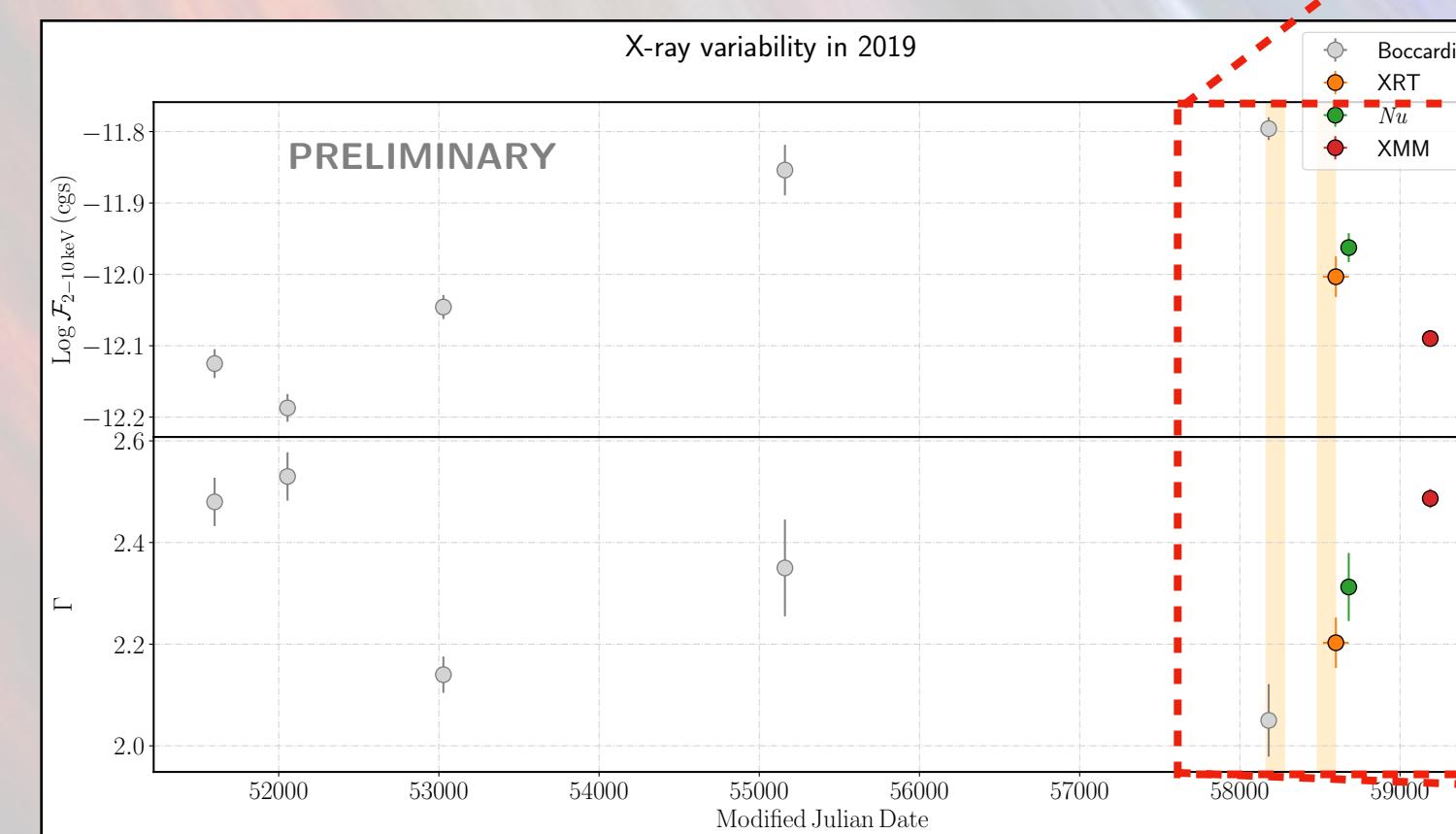
**NO STATISTICALLY SIGNIFICANT GeV-VARIABILITY**

MAGIC campaign



# 3C 264: X-ray

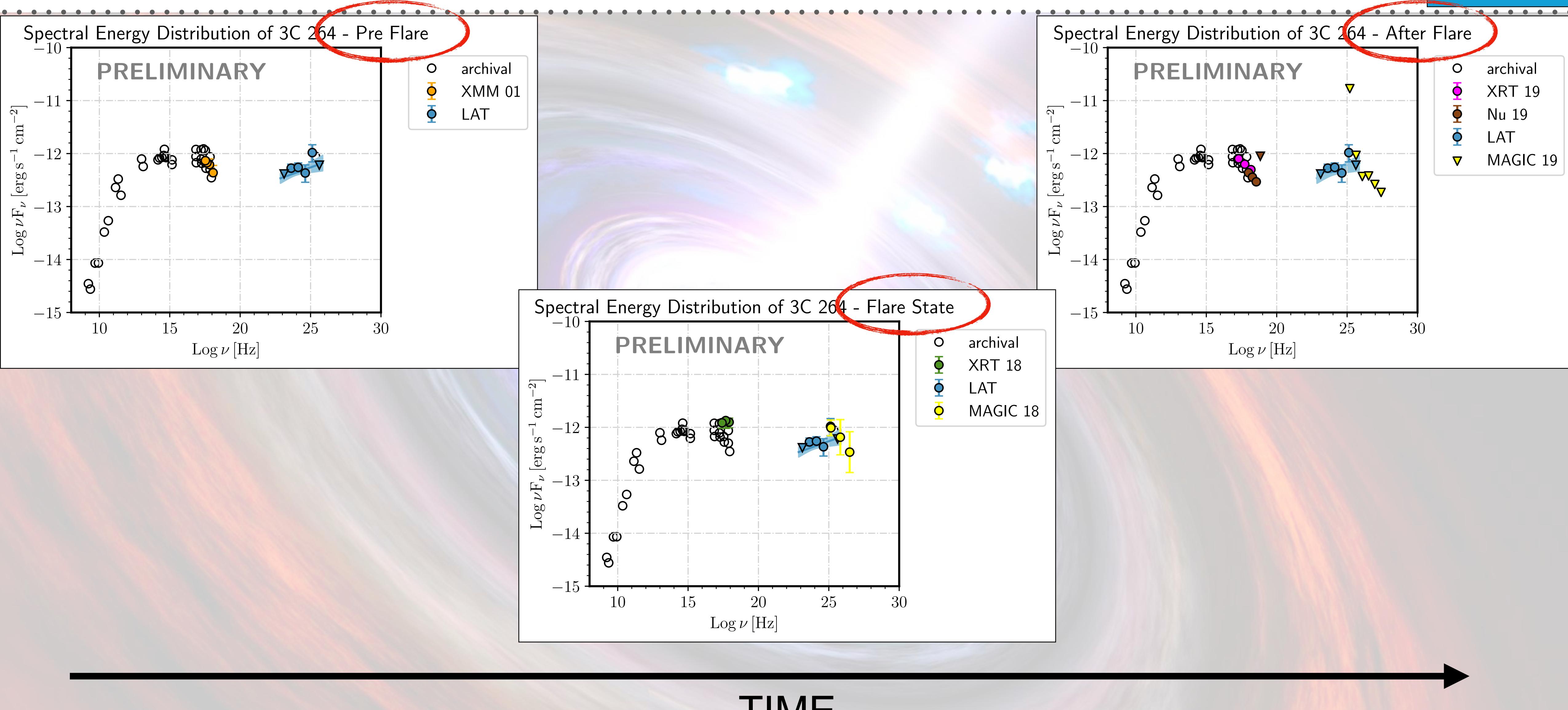
- Lightcurve from 2000 to 2020
- New data from XMM-Newton, *Swift*, *NuSTAR*  
(15 new obs)
- Flux decrease from 2018 to 2020 of a factor of  $\sim 2$
- “Softening when fading” trend after 2018



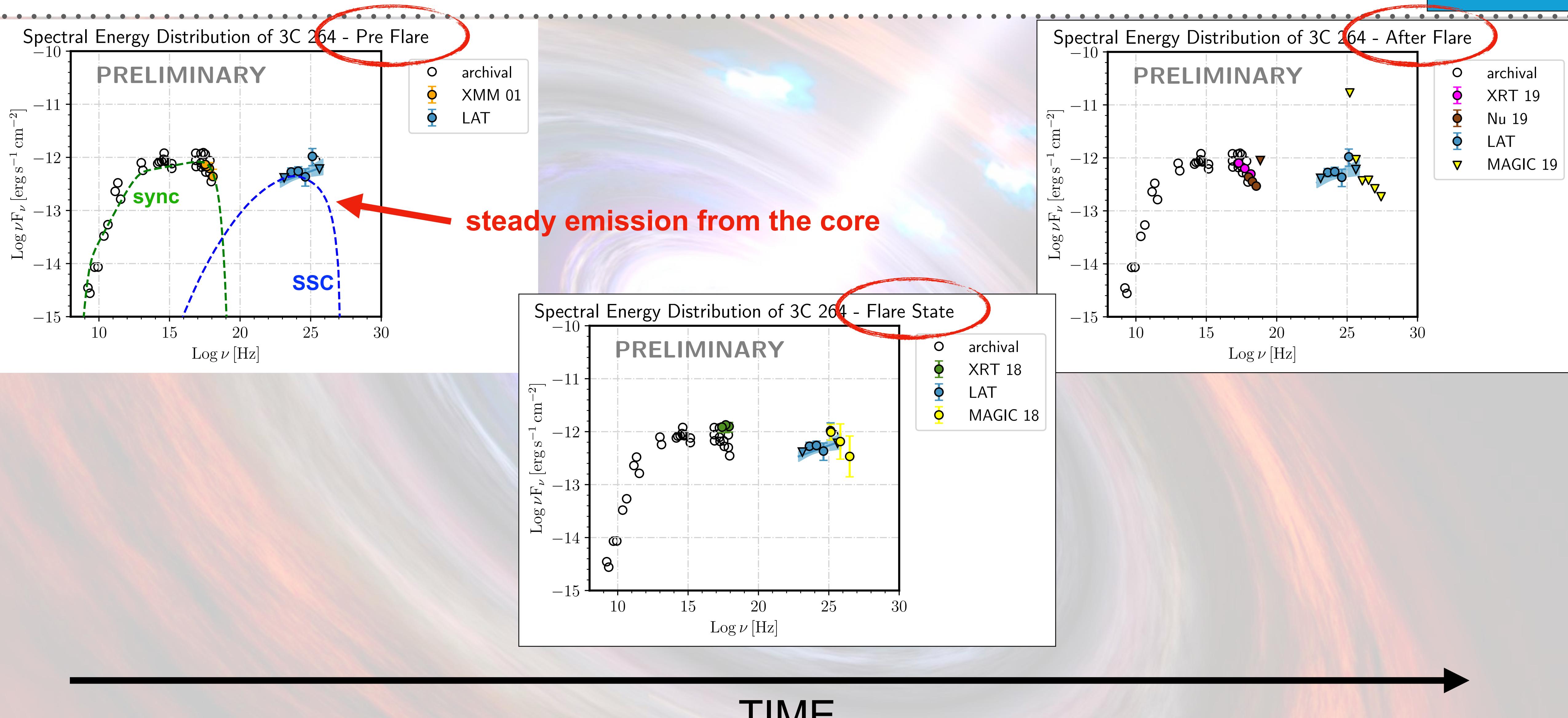
# Observational results

- ✓ 3C 264 detected by MAGIC and VERITAS in a “flaring” state
- ✓ X-ray high state contemporary to TeV flare (2018)
- ✓ No statistically significant variability in GeV band
- ✓ **Softening when fading trend in X-ray after 2018**

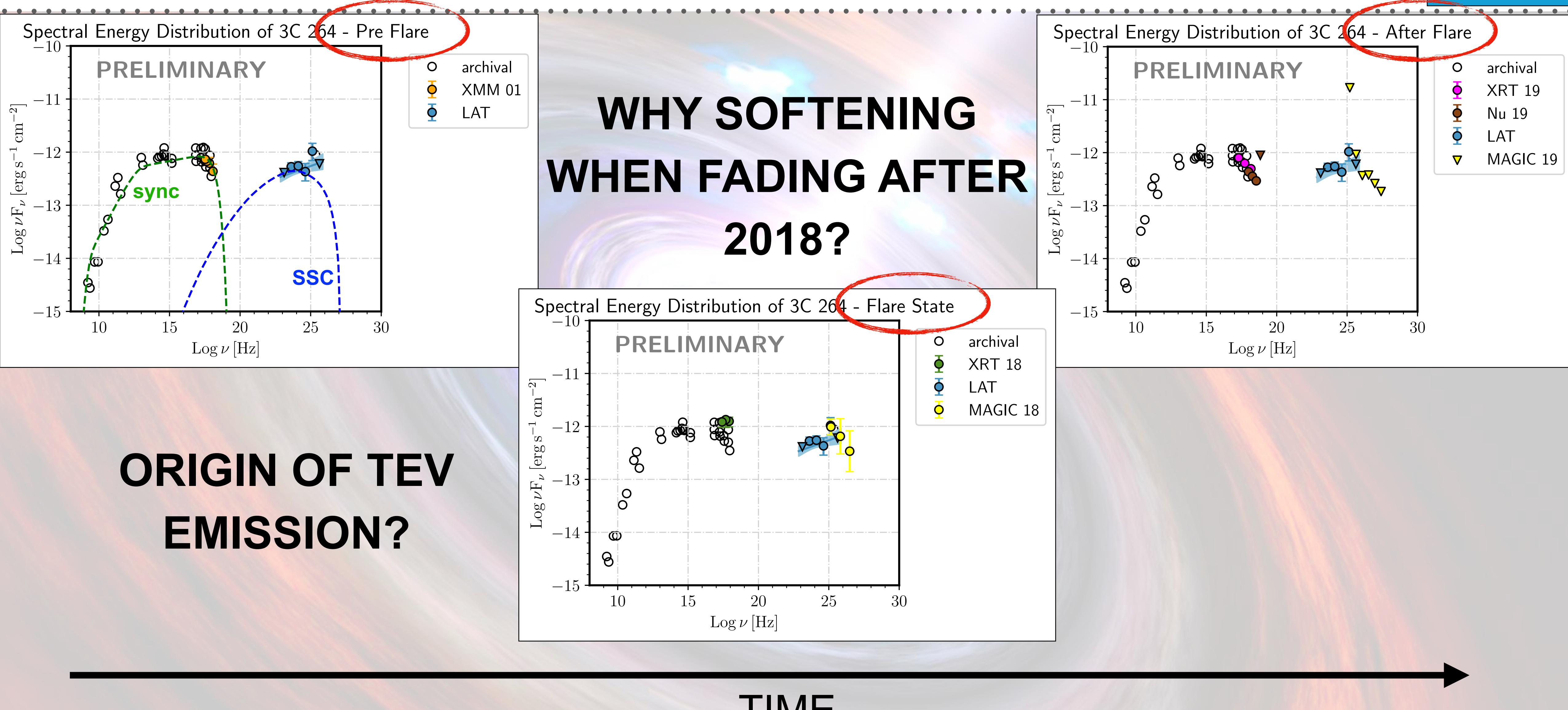
# SED modelling



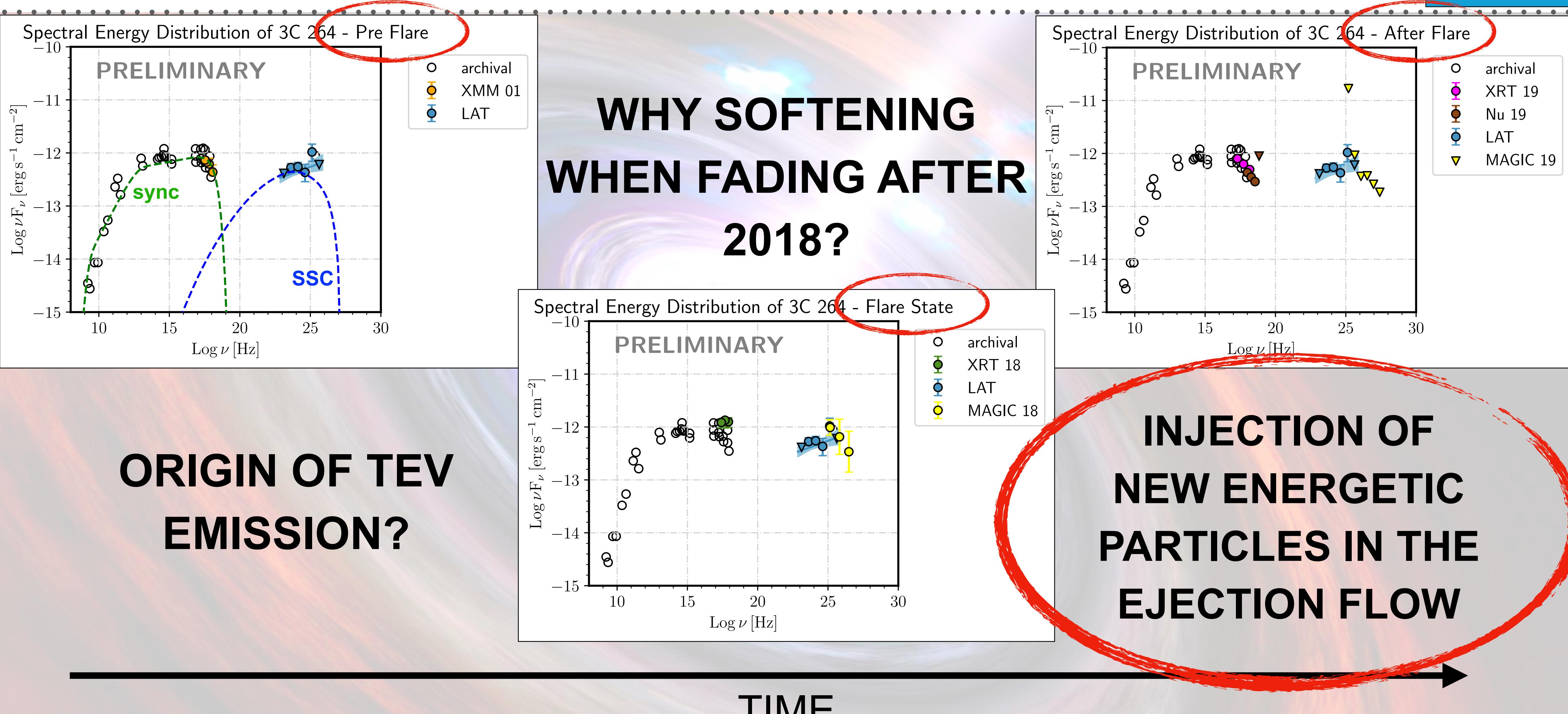
# SED modelling



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# Temporal model of the additional component

ARTISTIC VIEW BY A NON-ARTIST

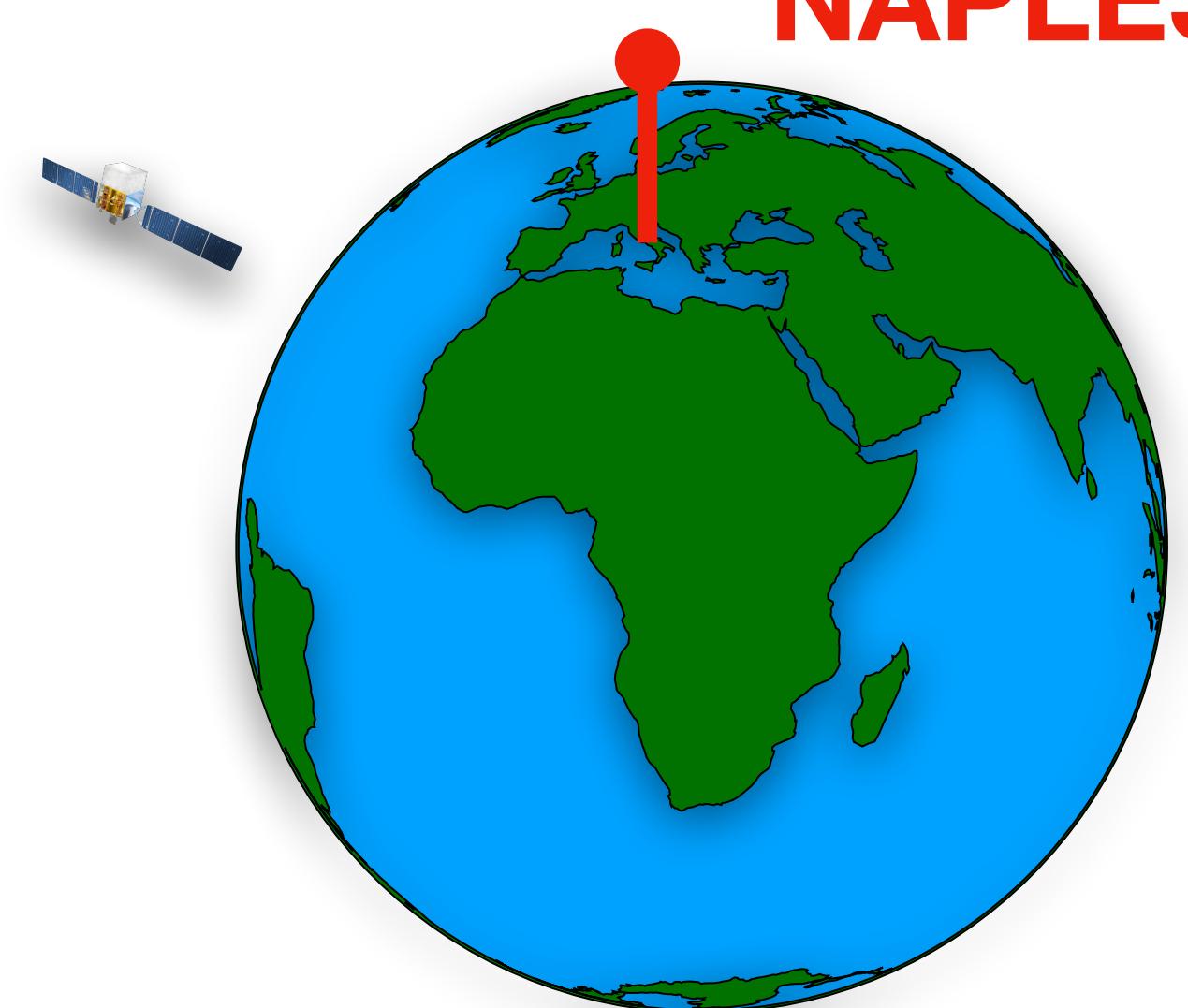
accretion  
flow

injection  
base

BH

jet

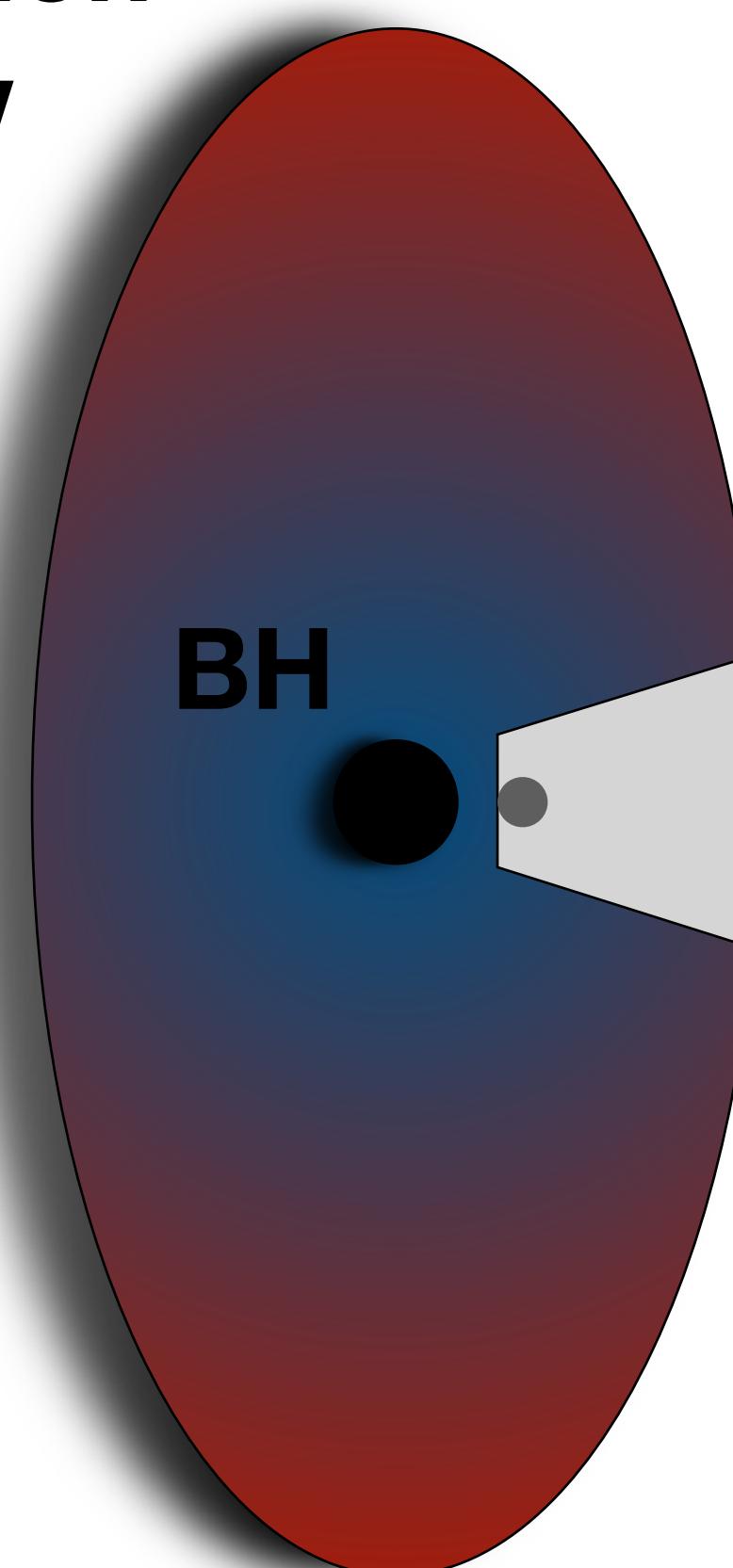
steady emission from  
the core not shown!



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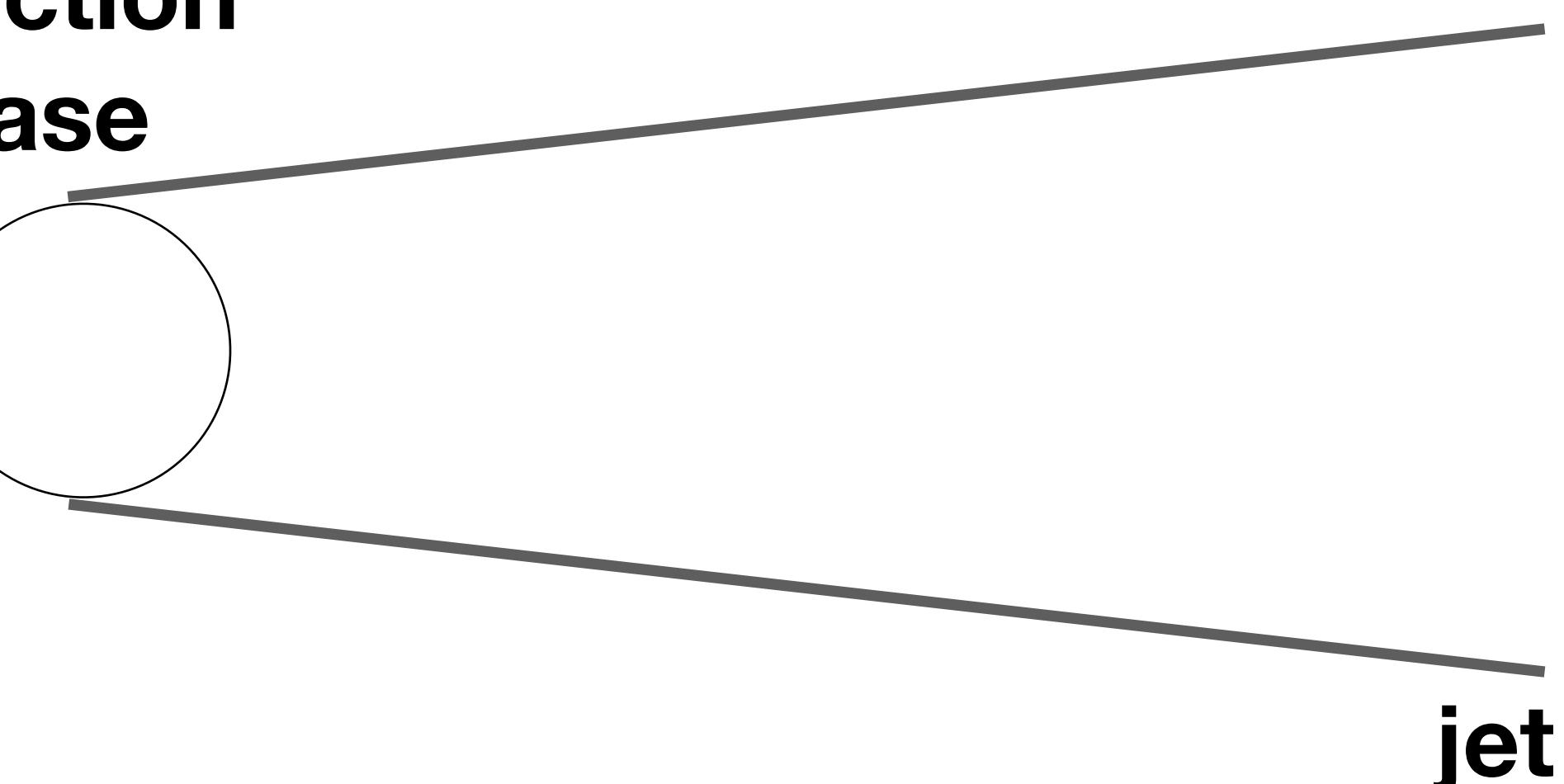
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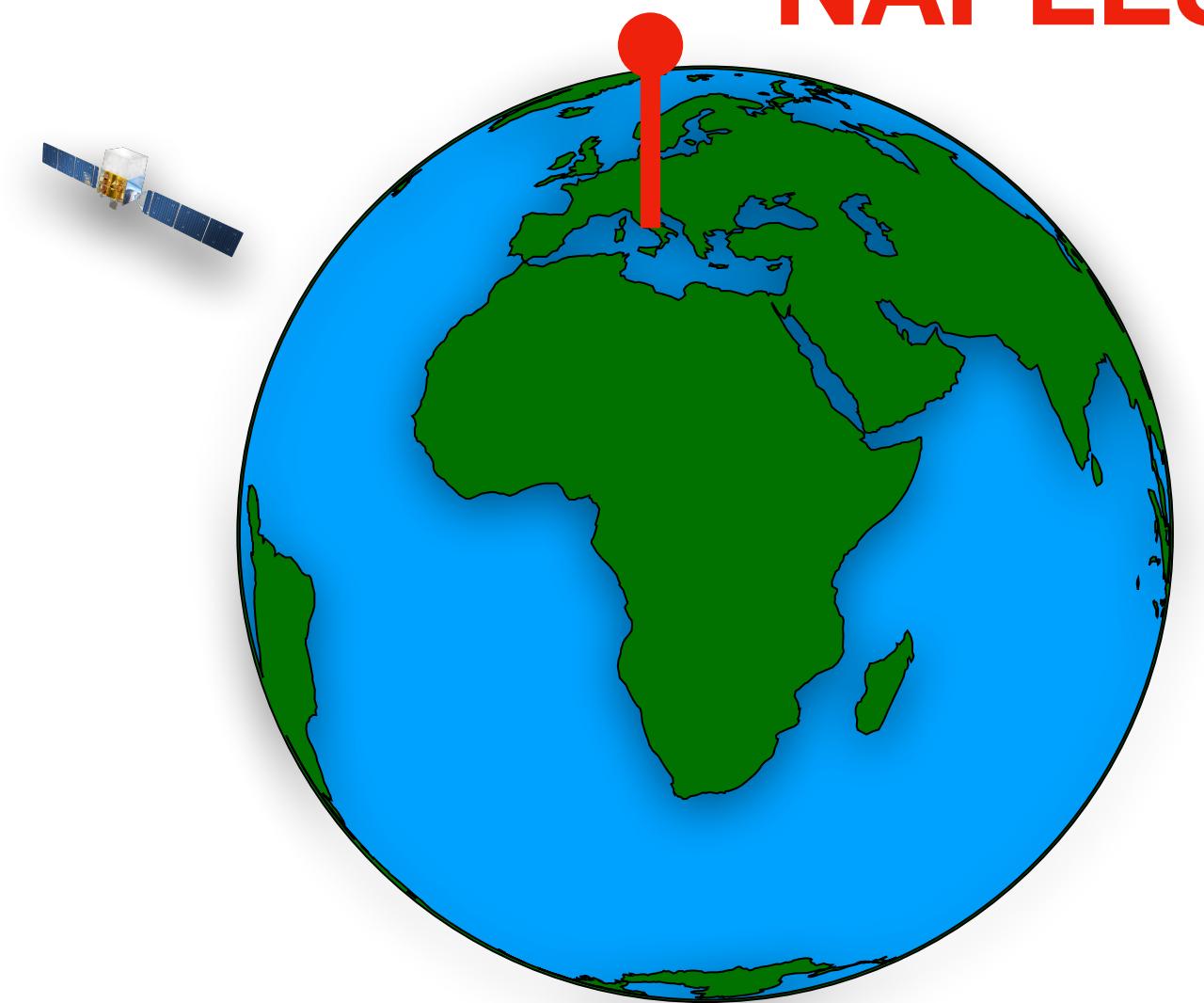


$t = t(\text{start injection})$

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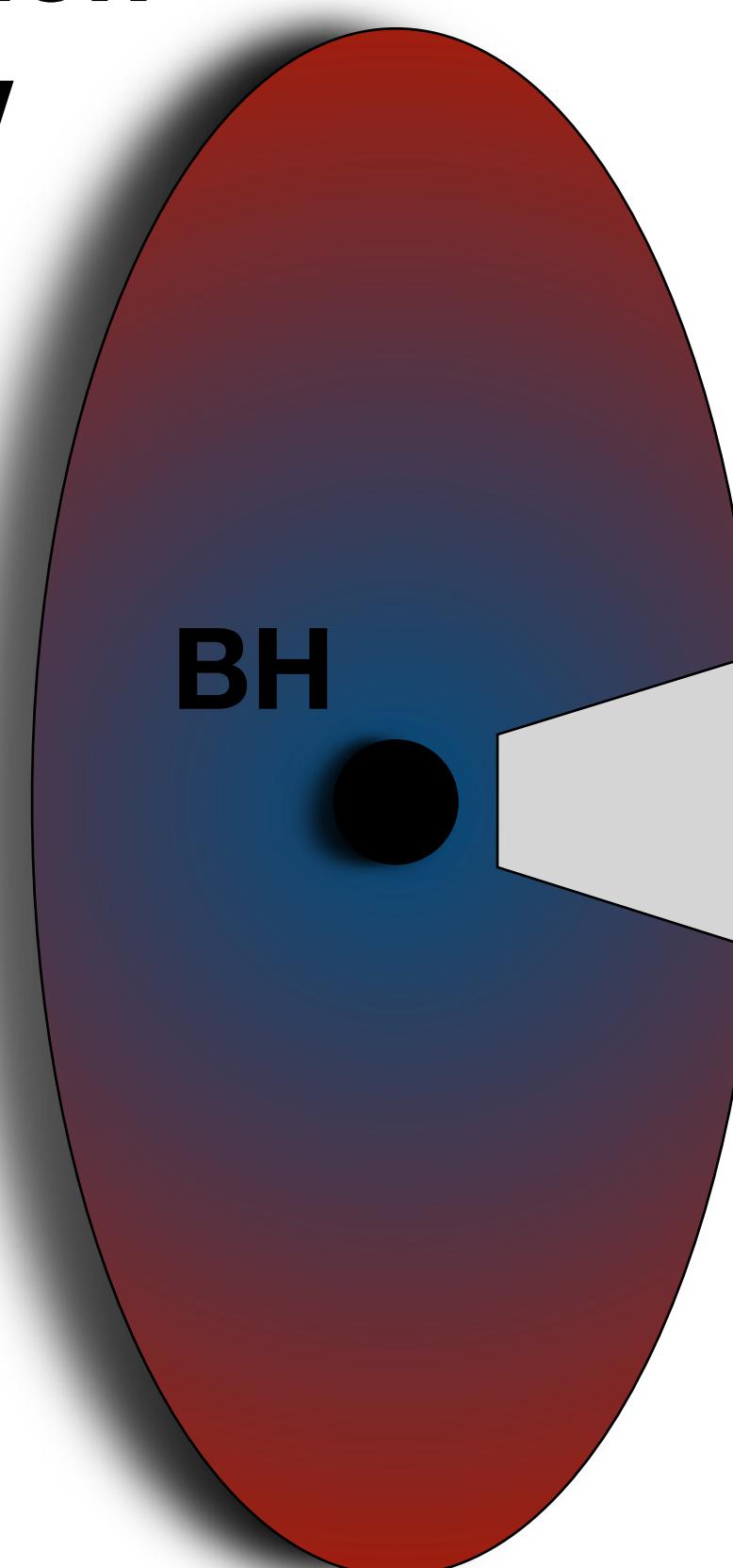


NAPLES

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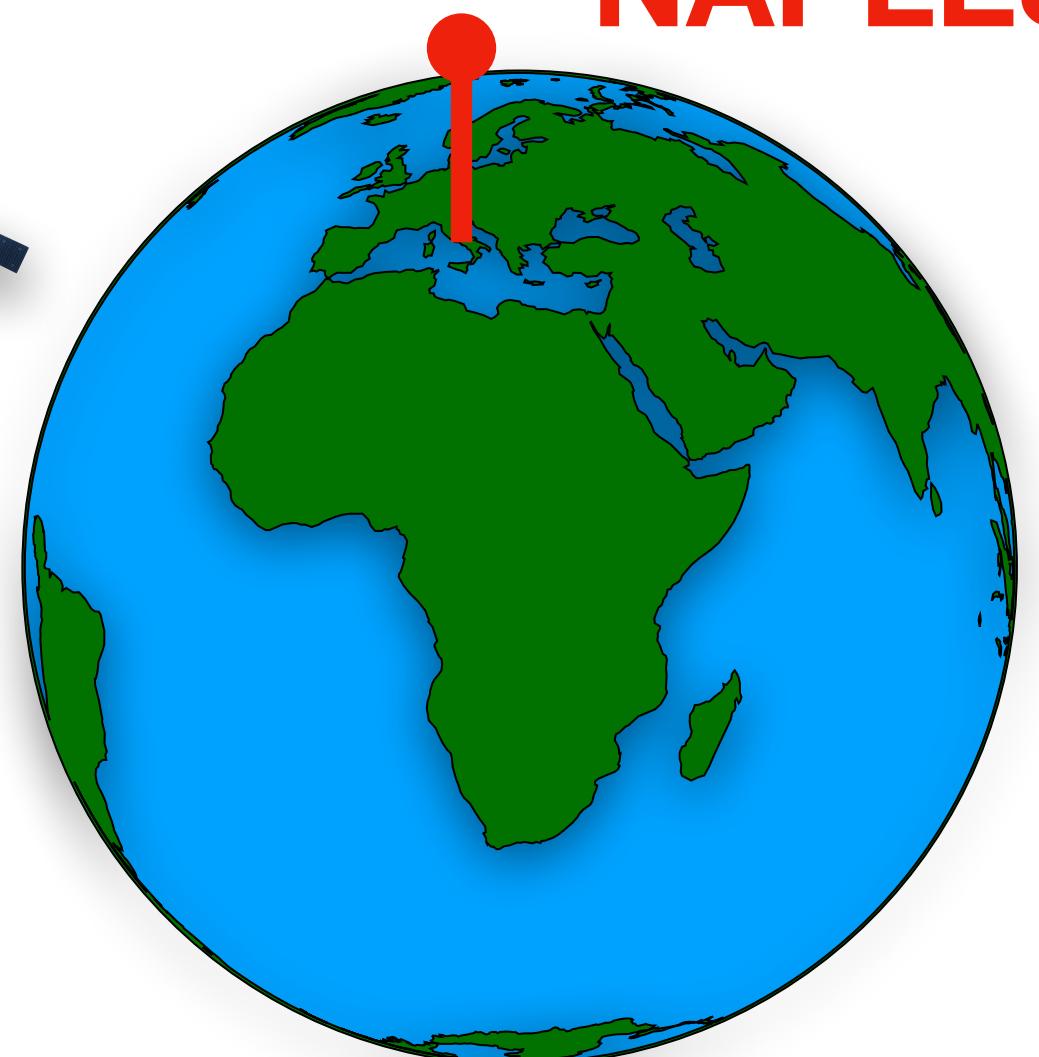


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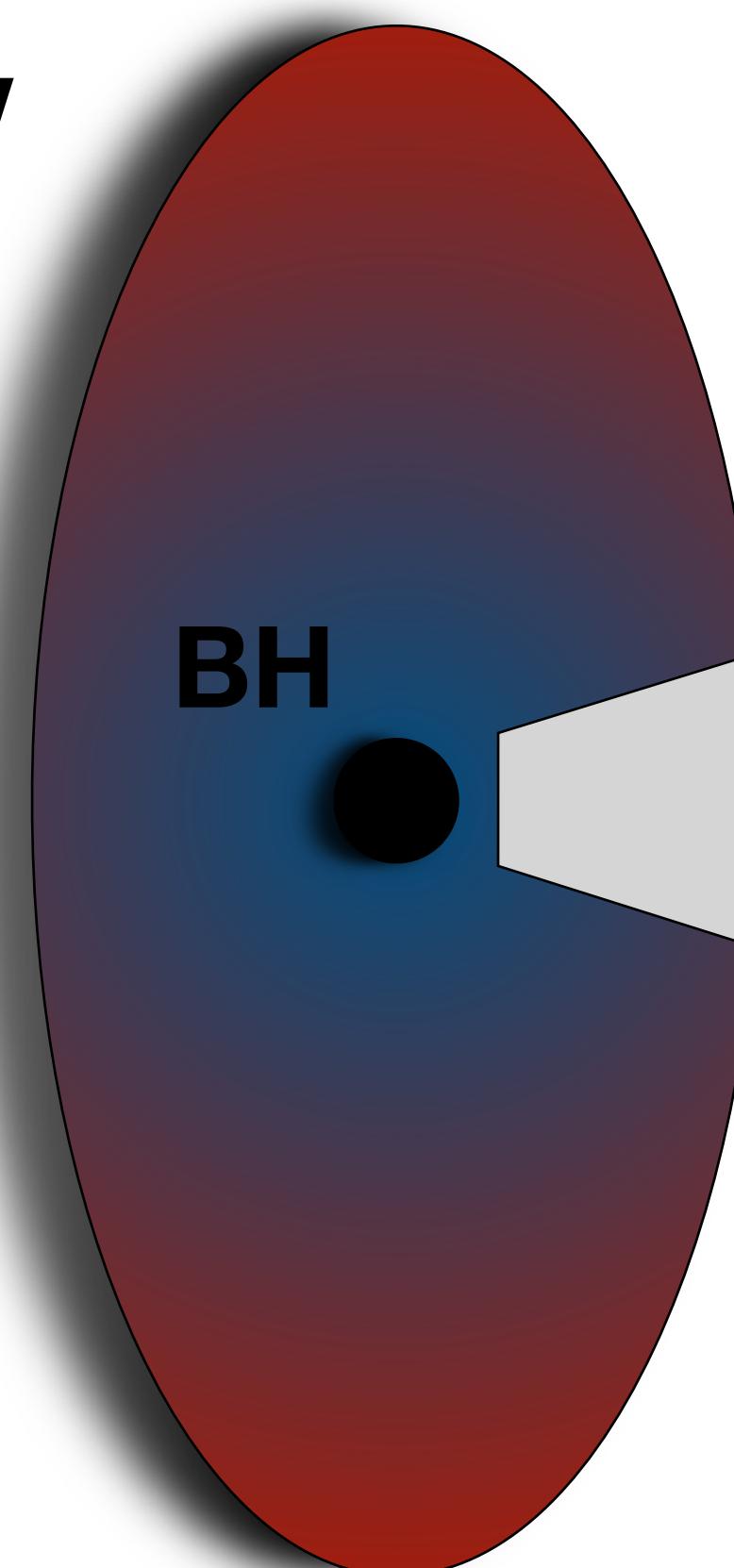
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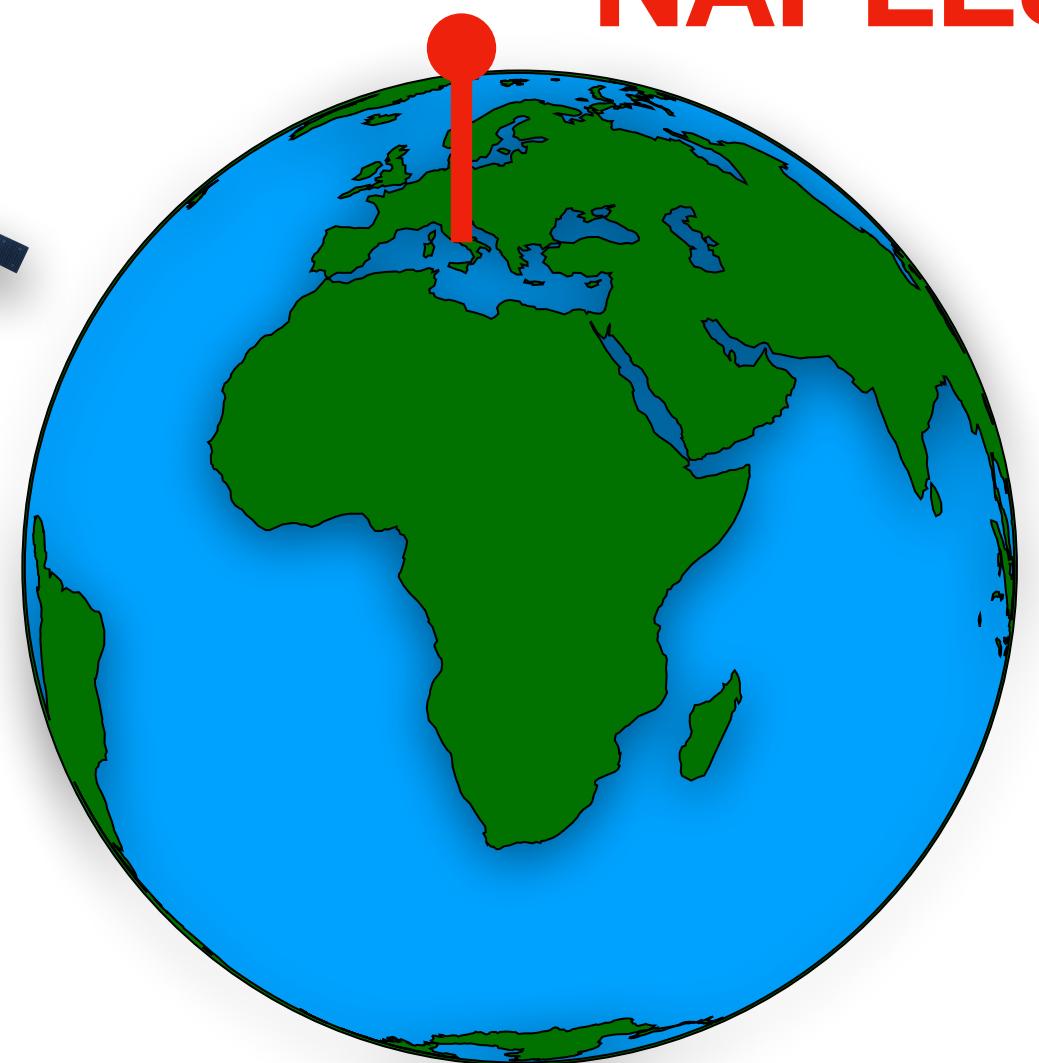


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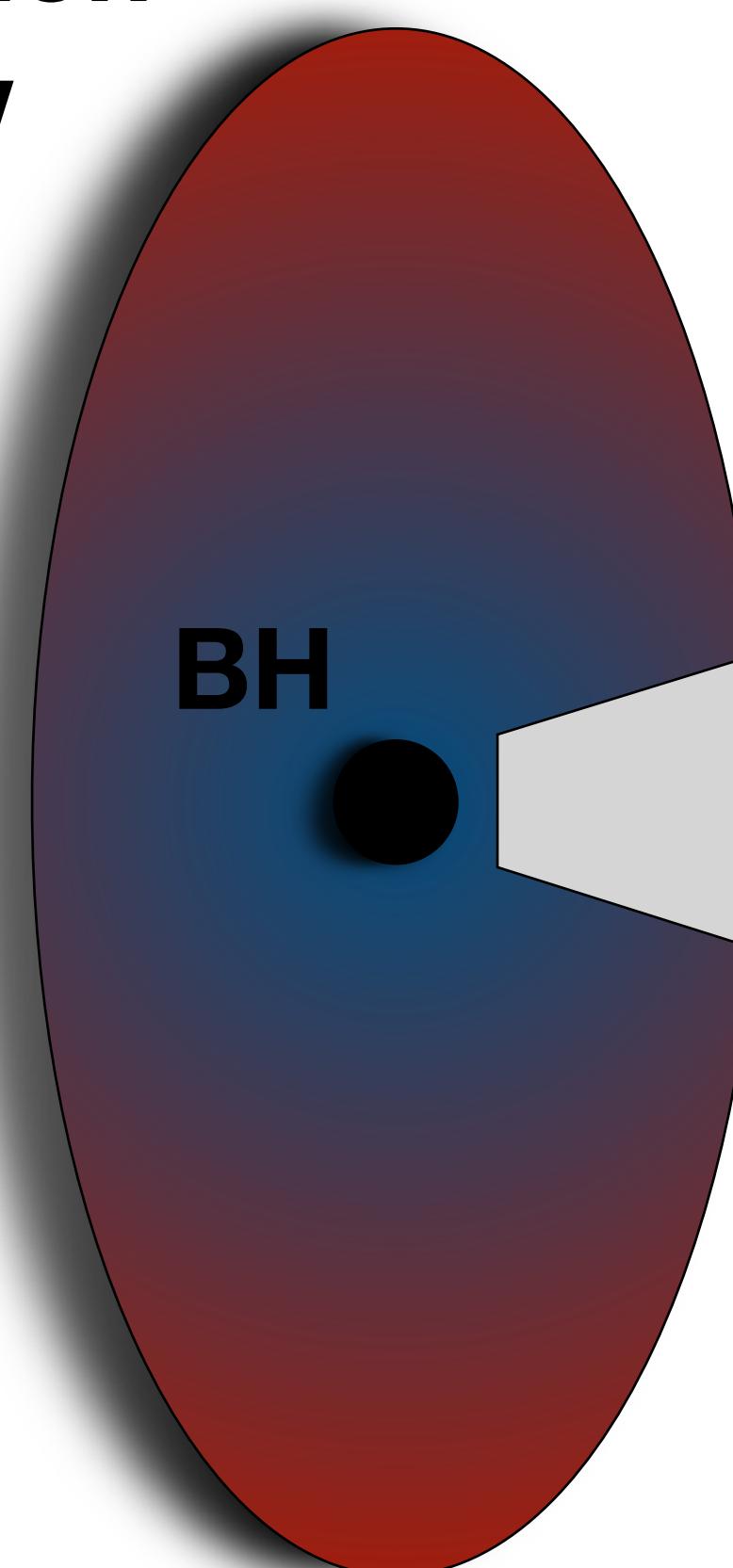


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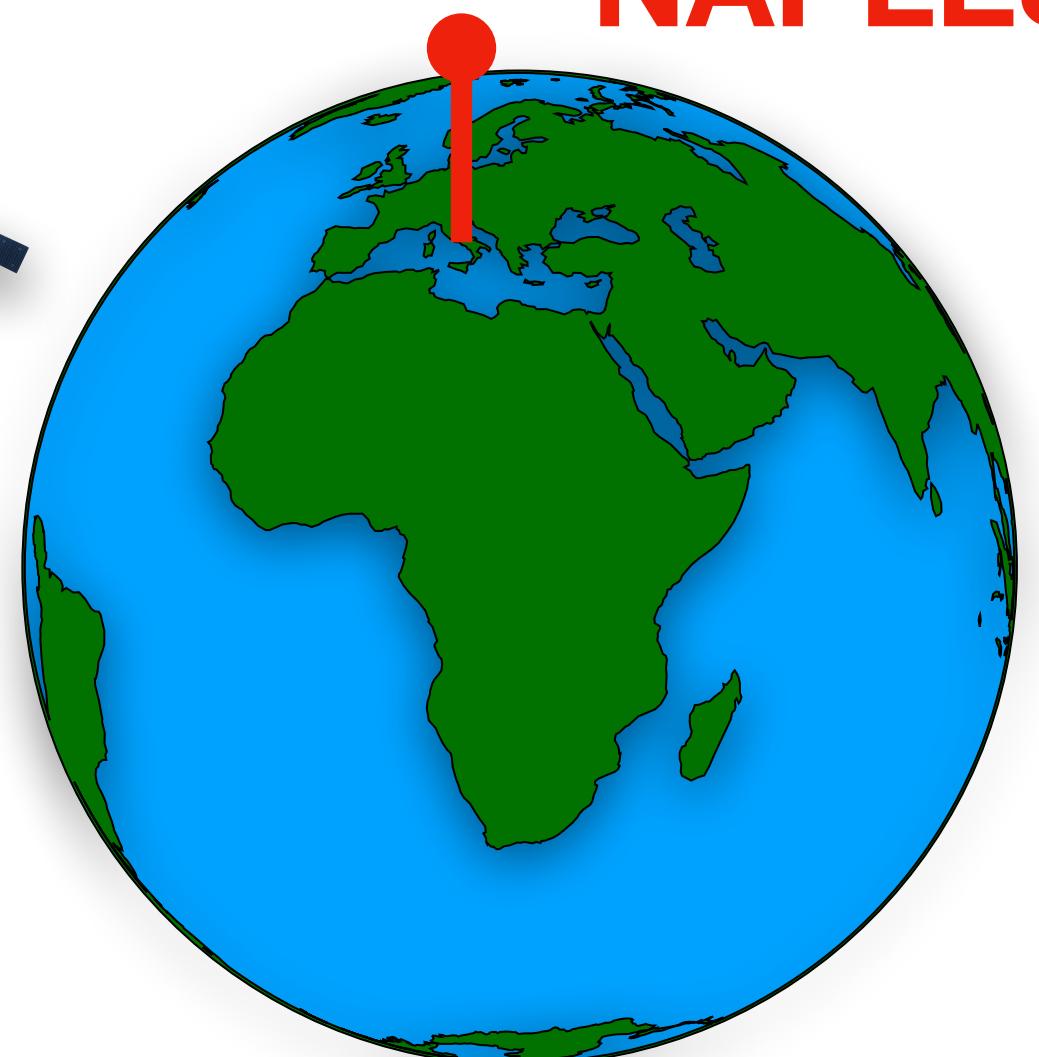
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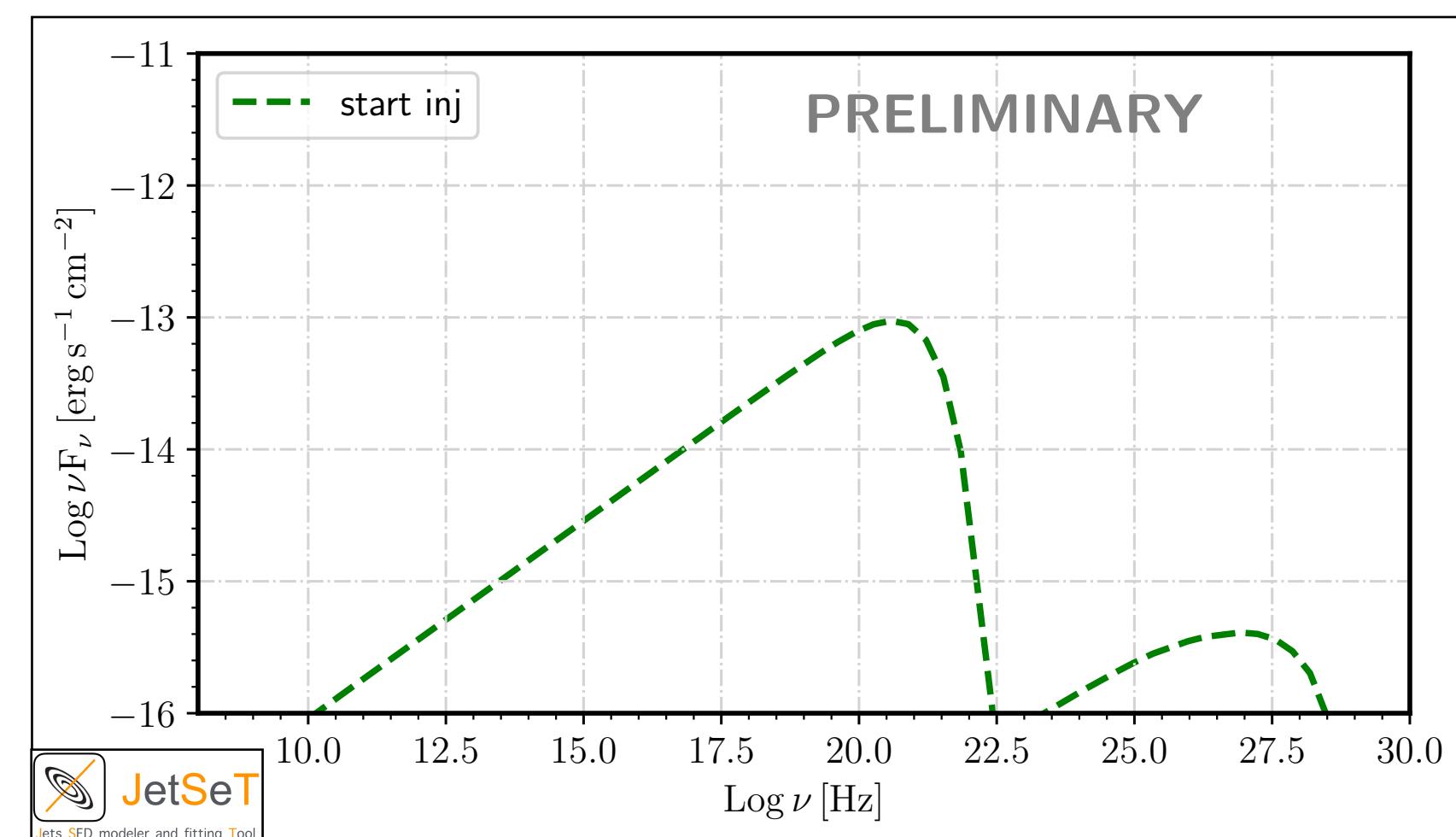
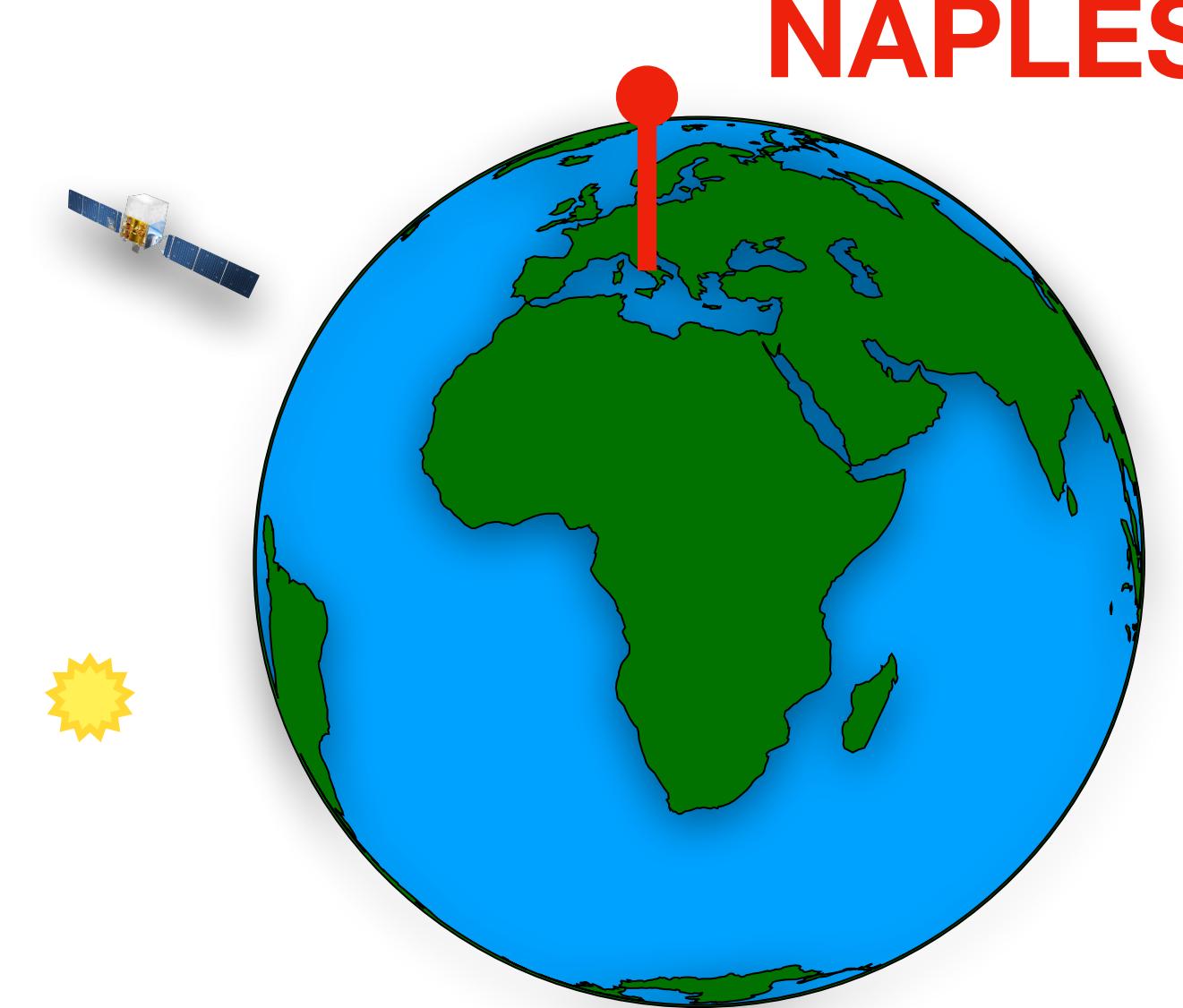
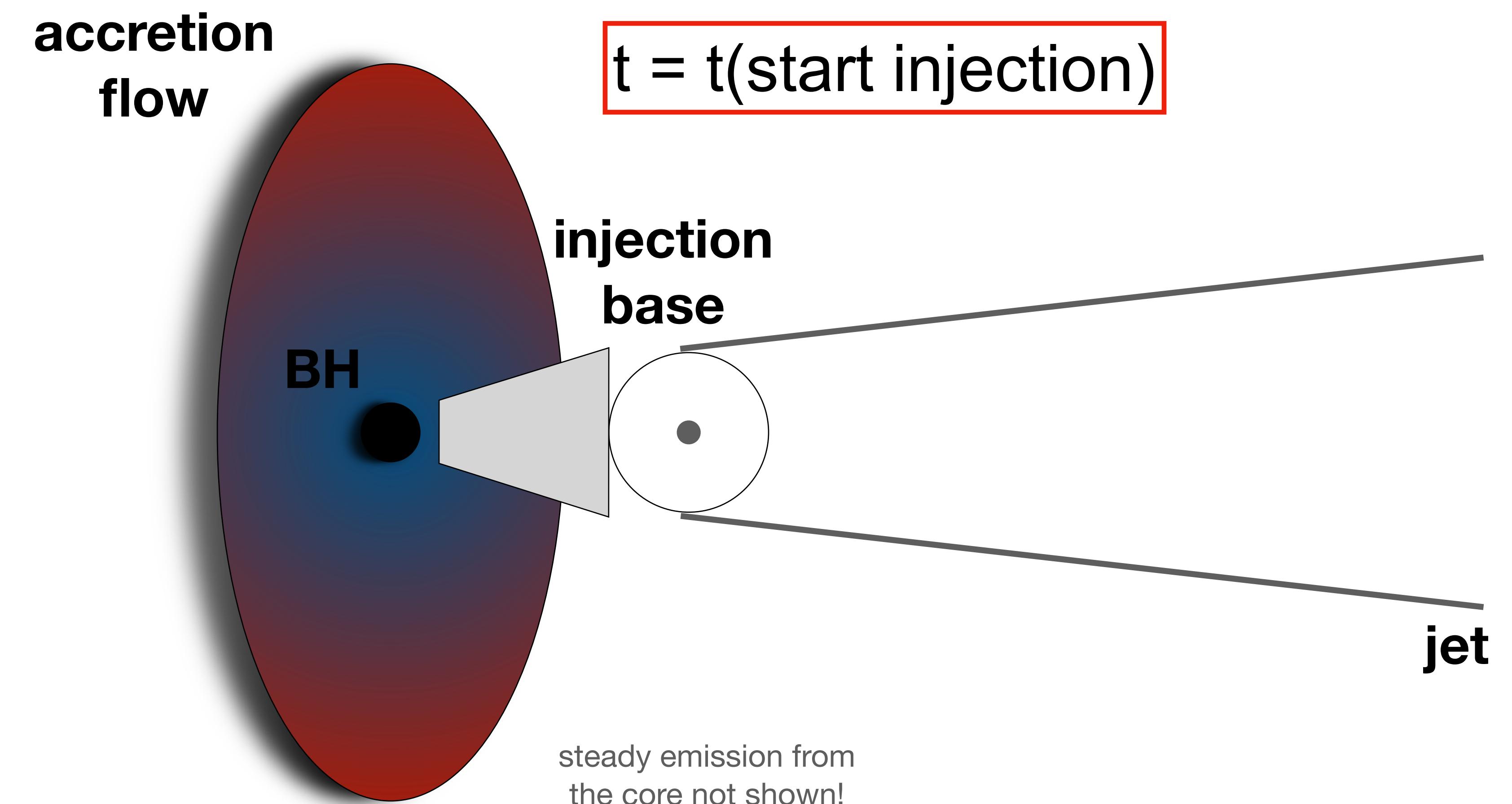
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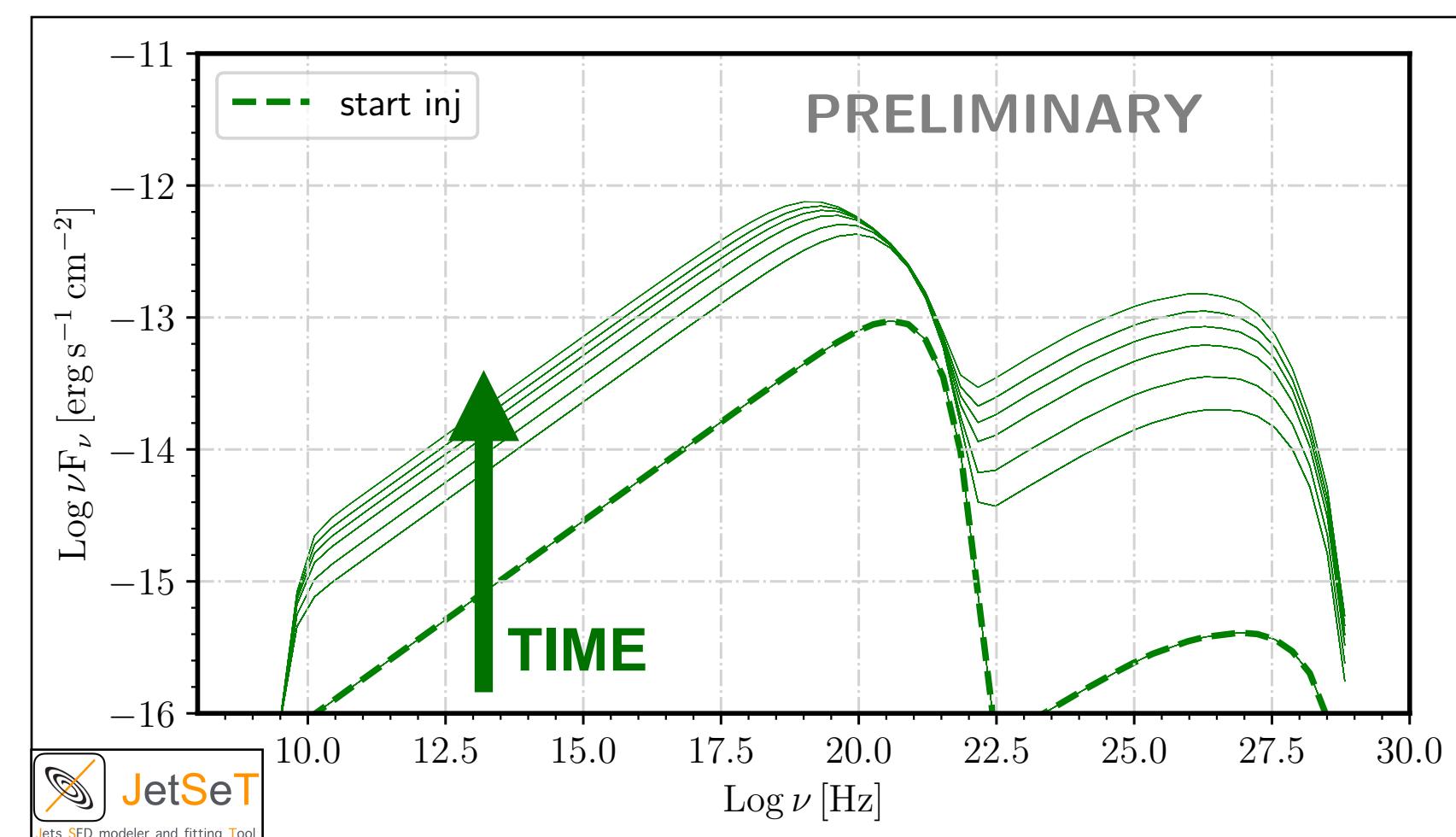
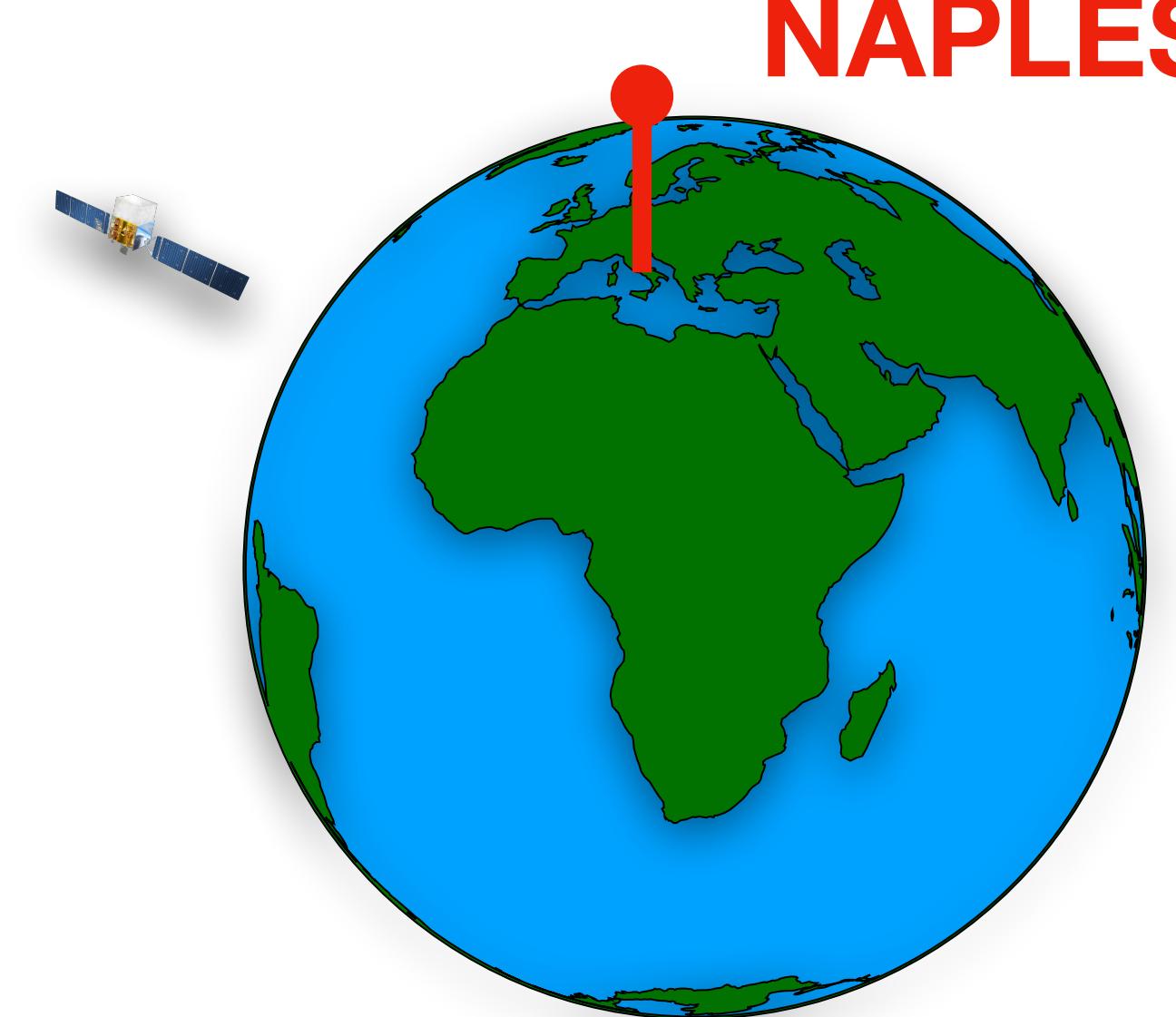
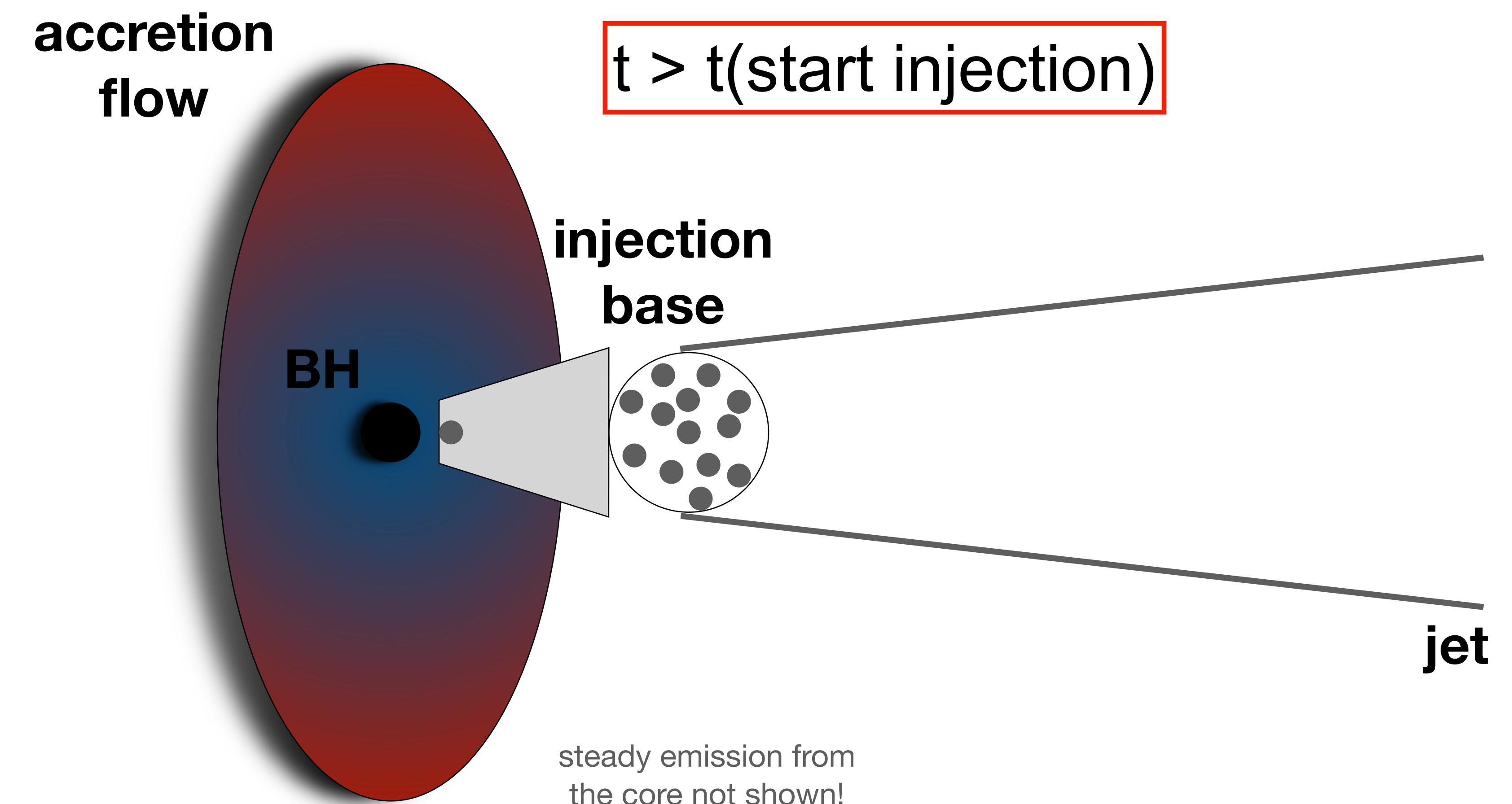
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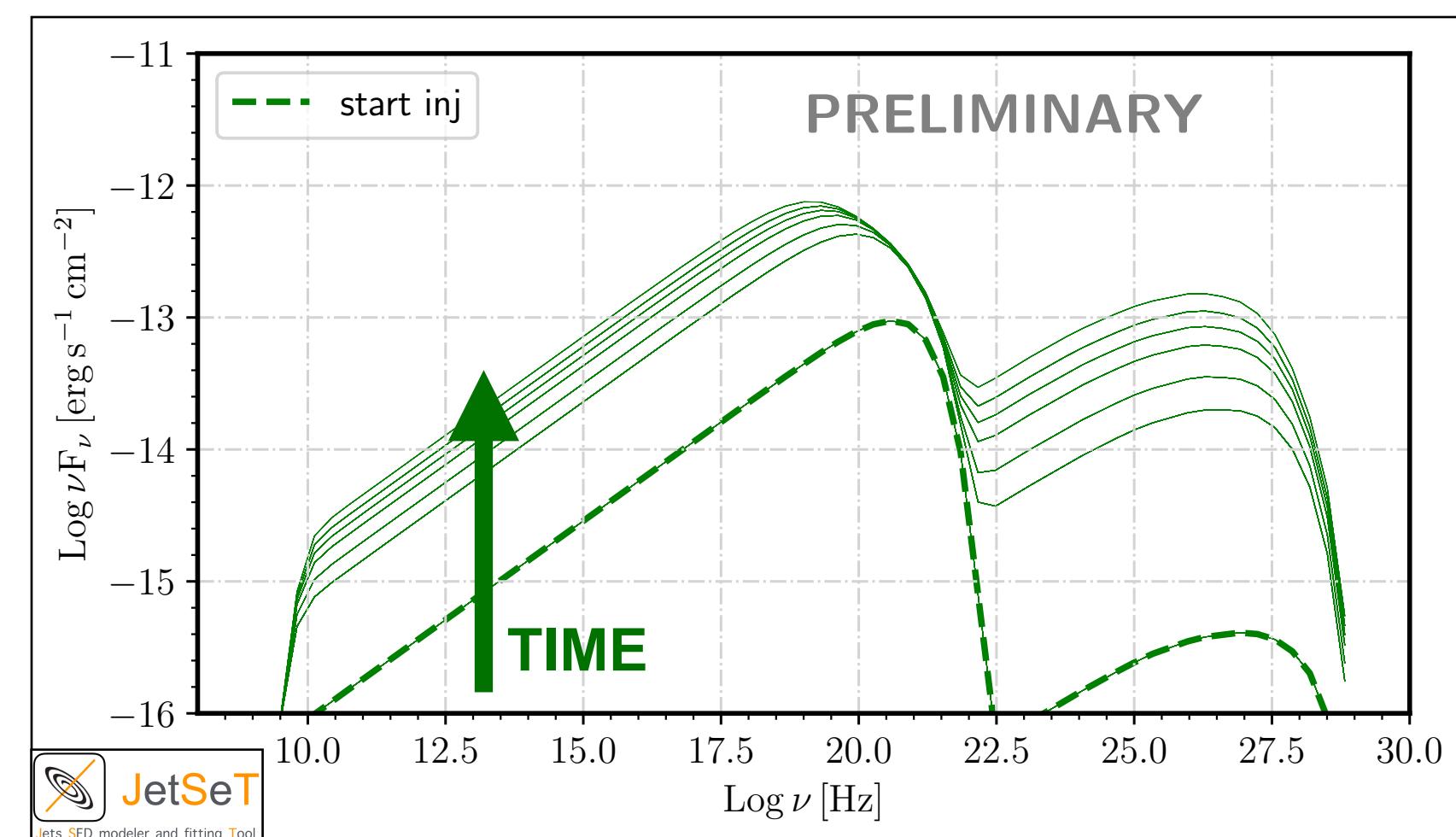
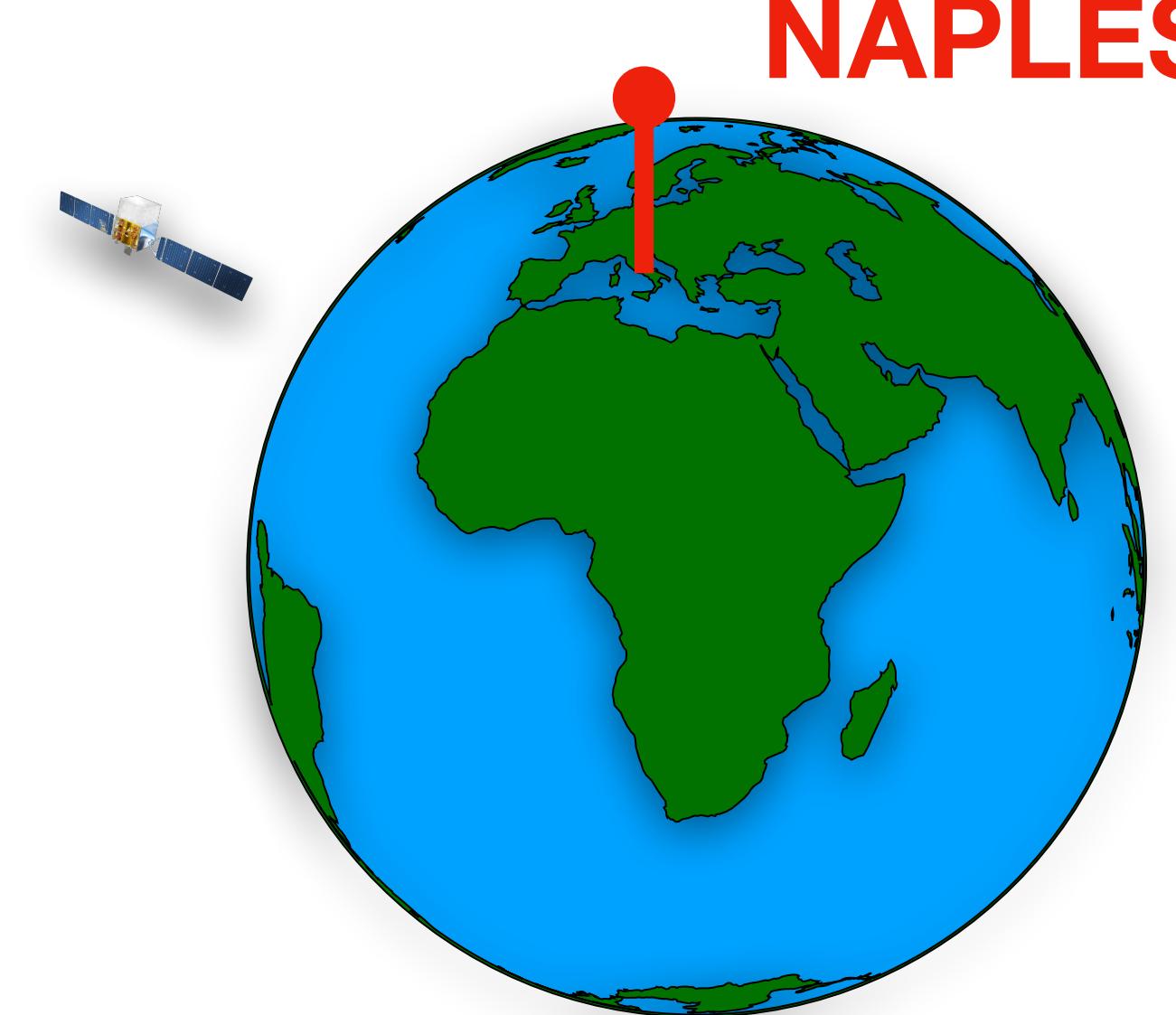
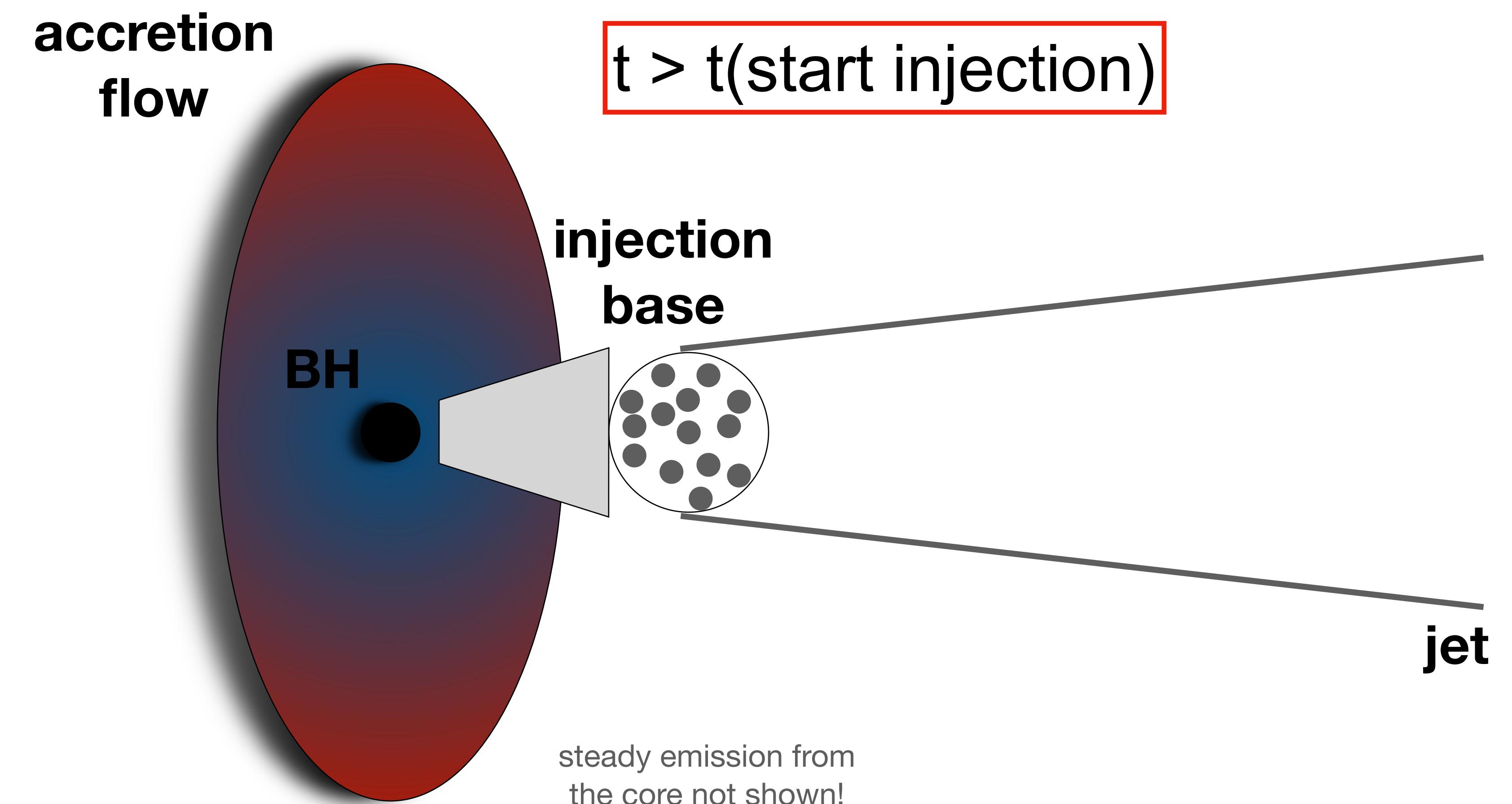
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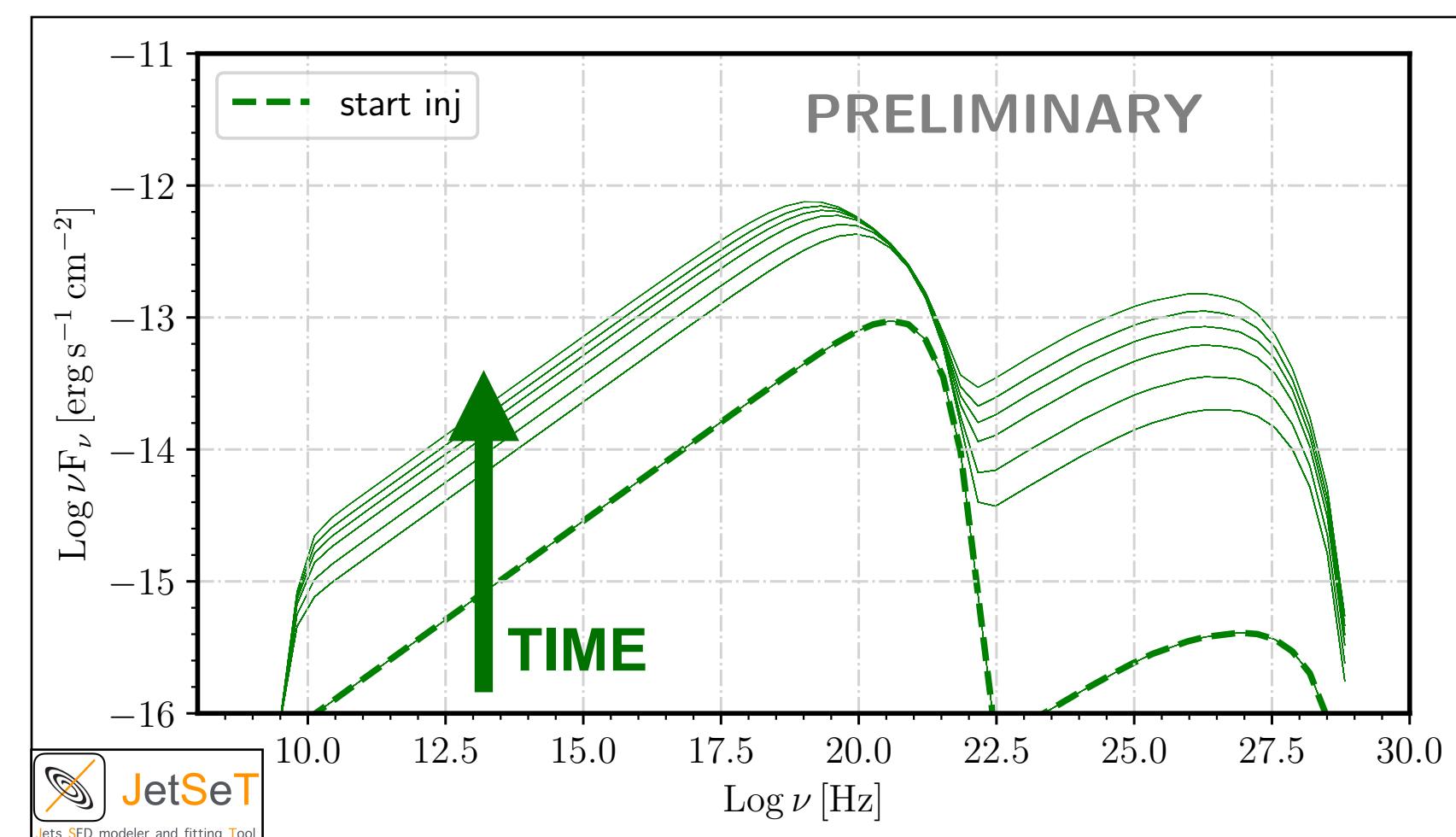
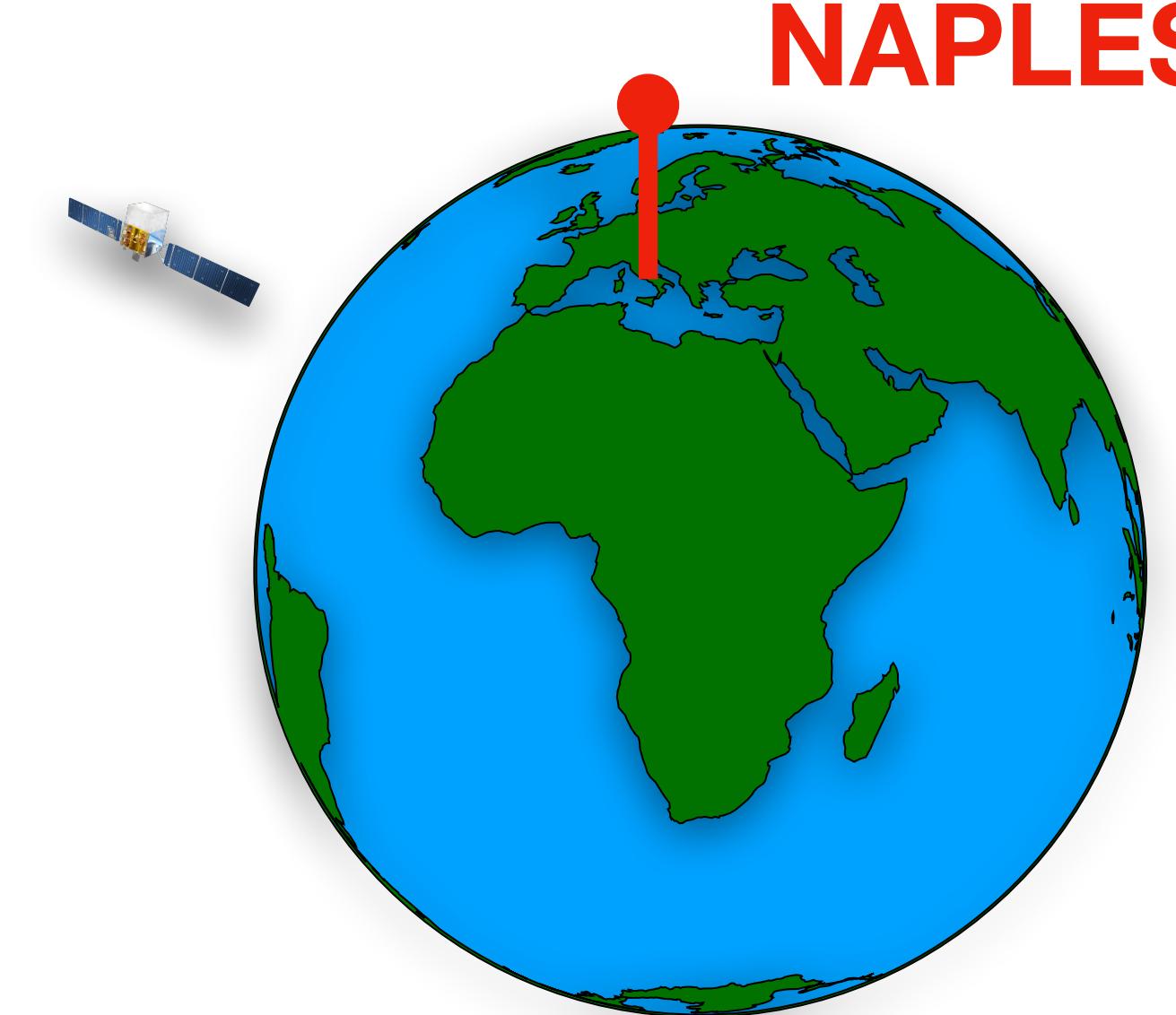
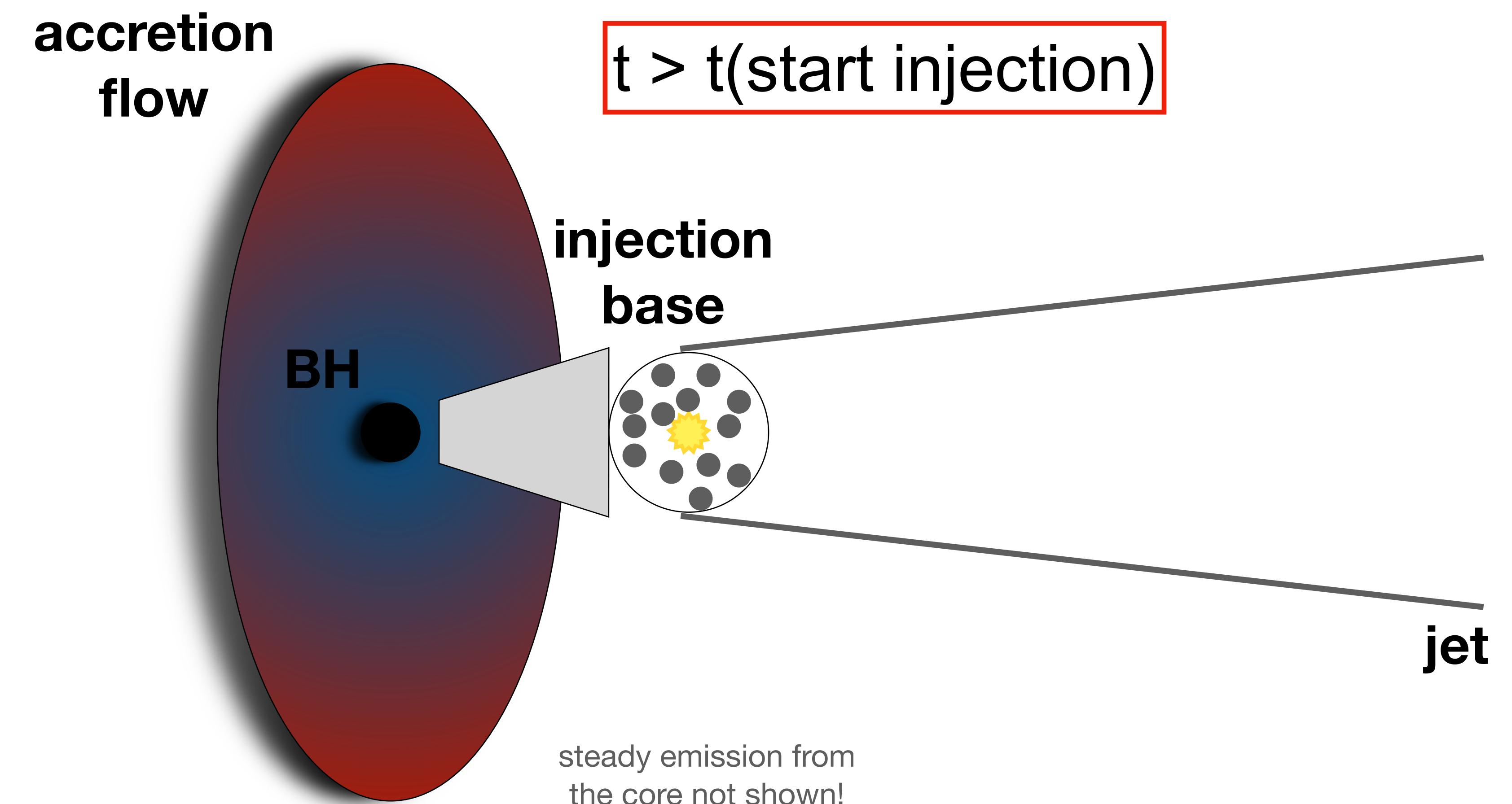
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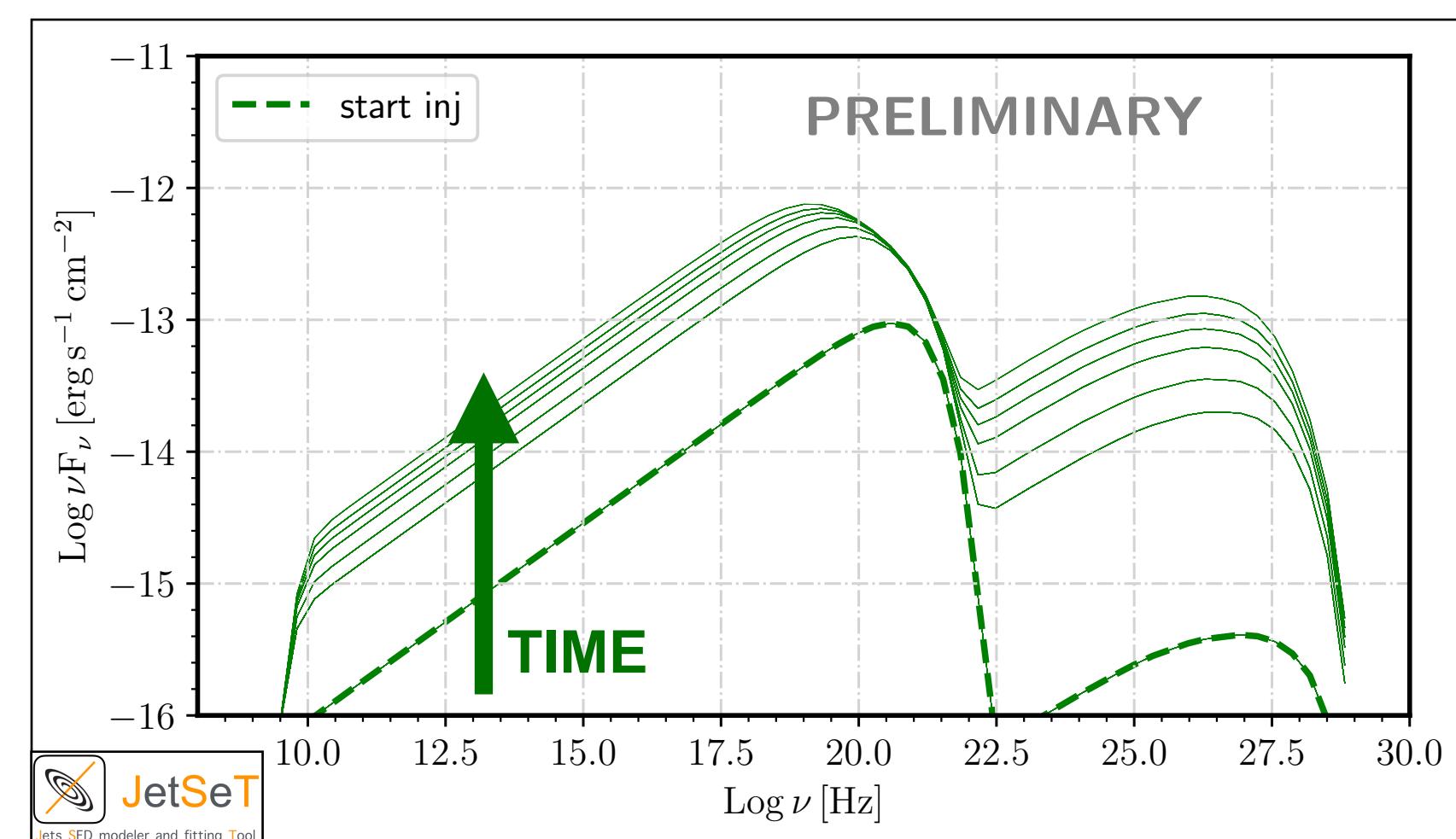
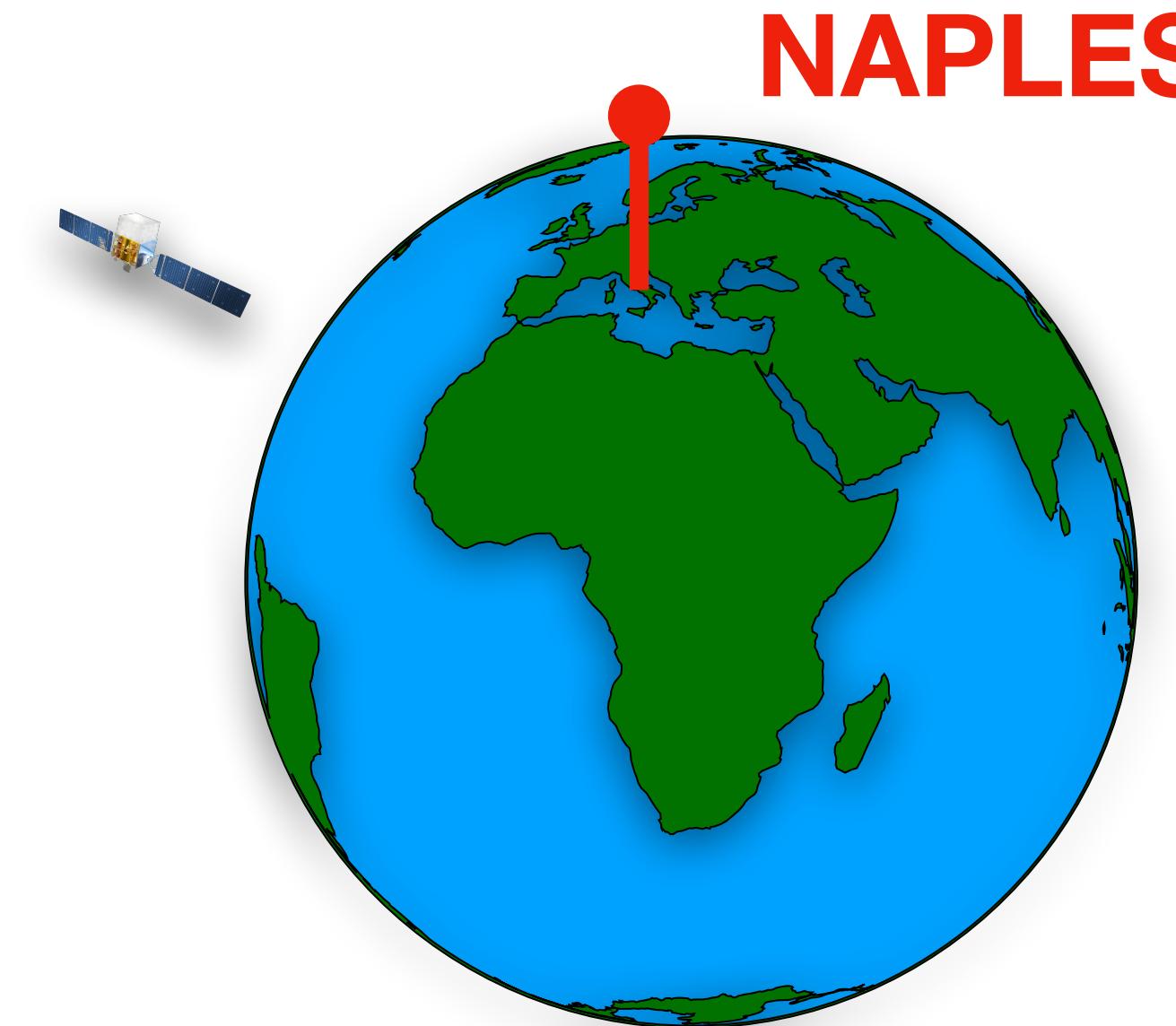
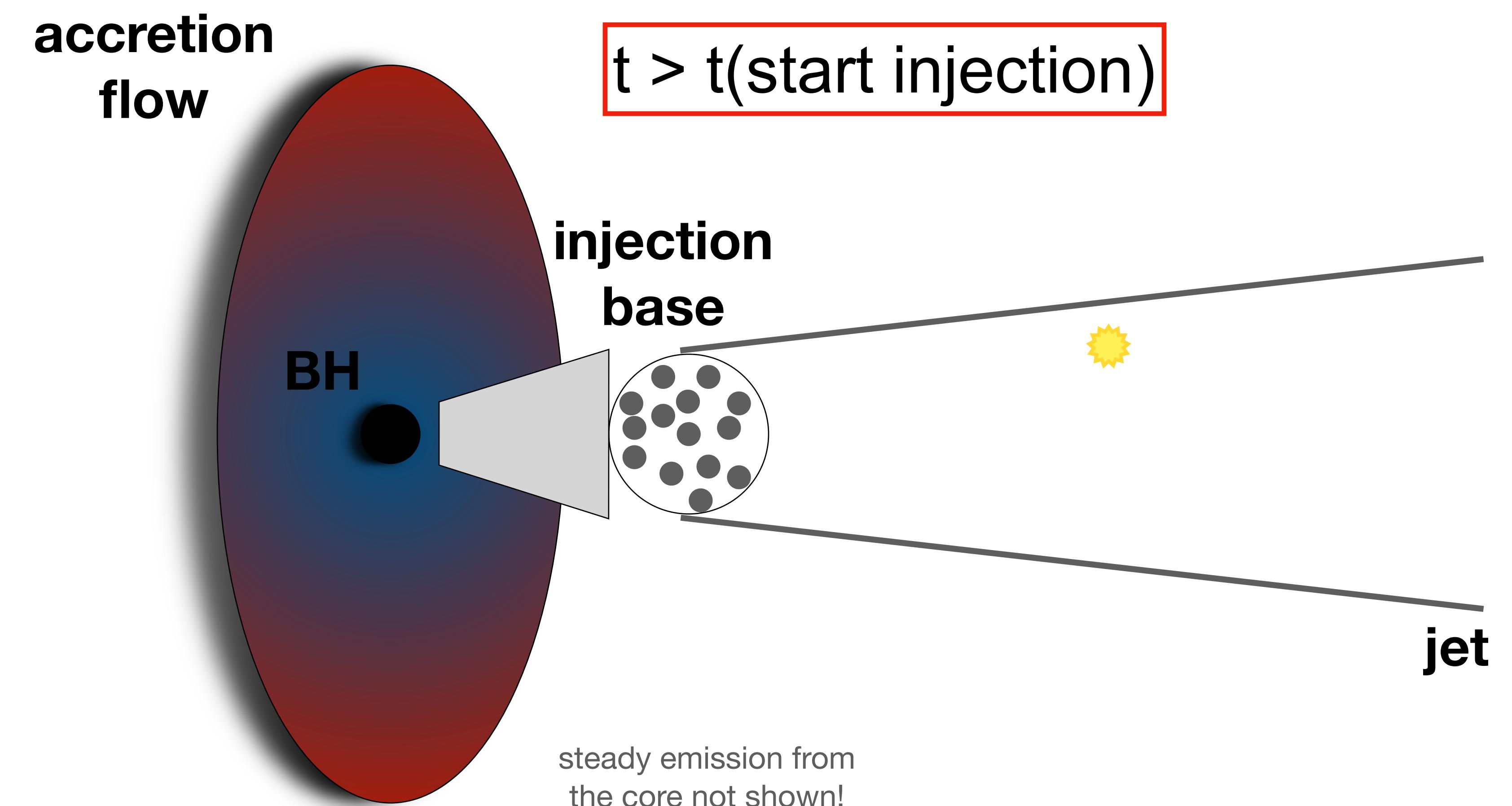
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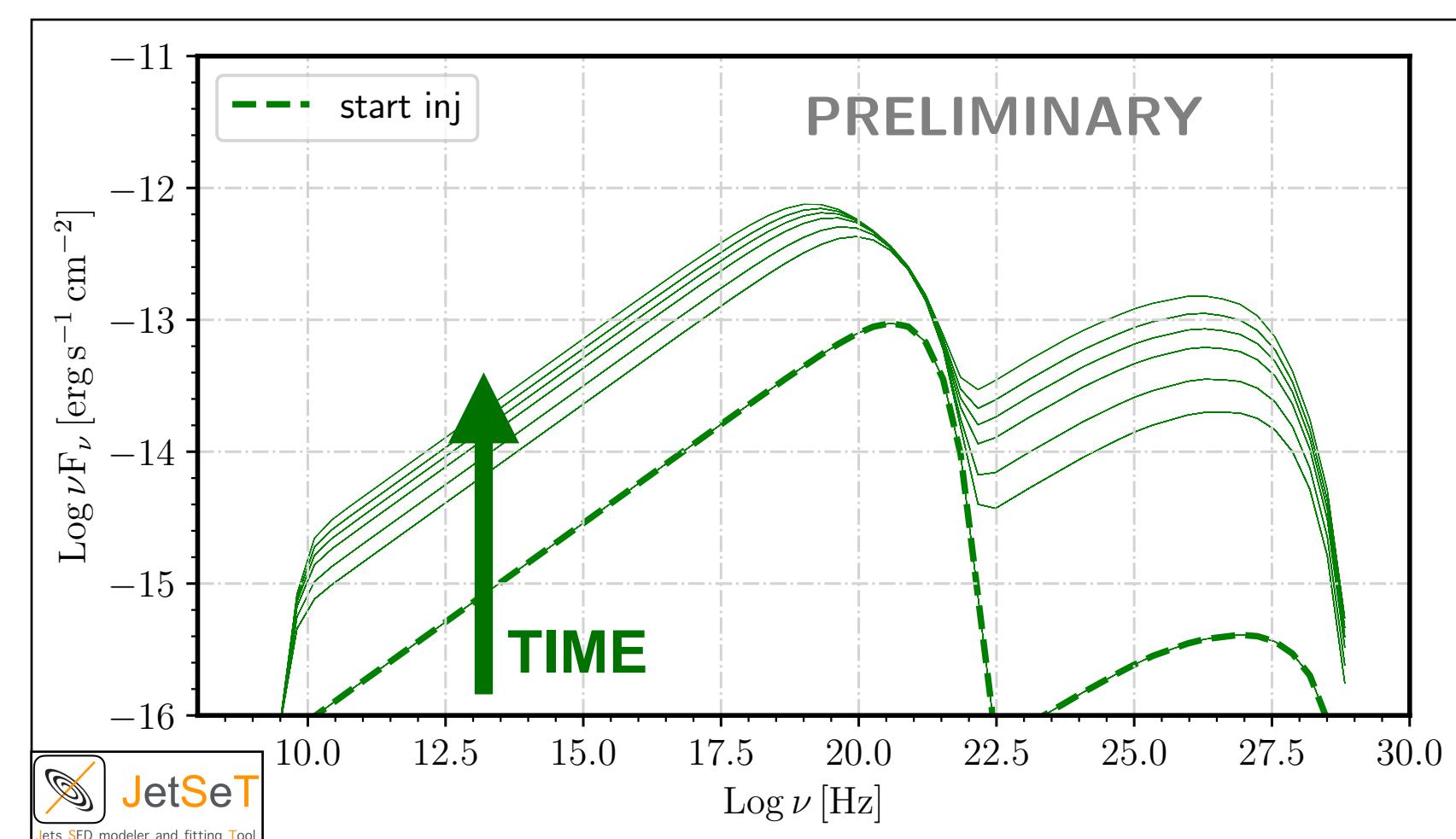
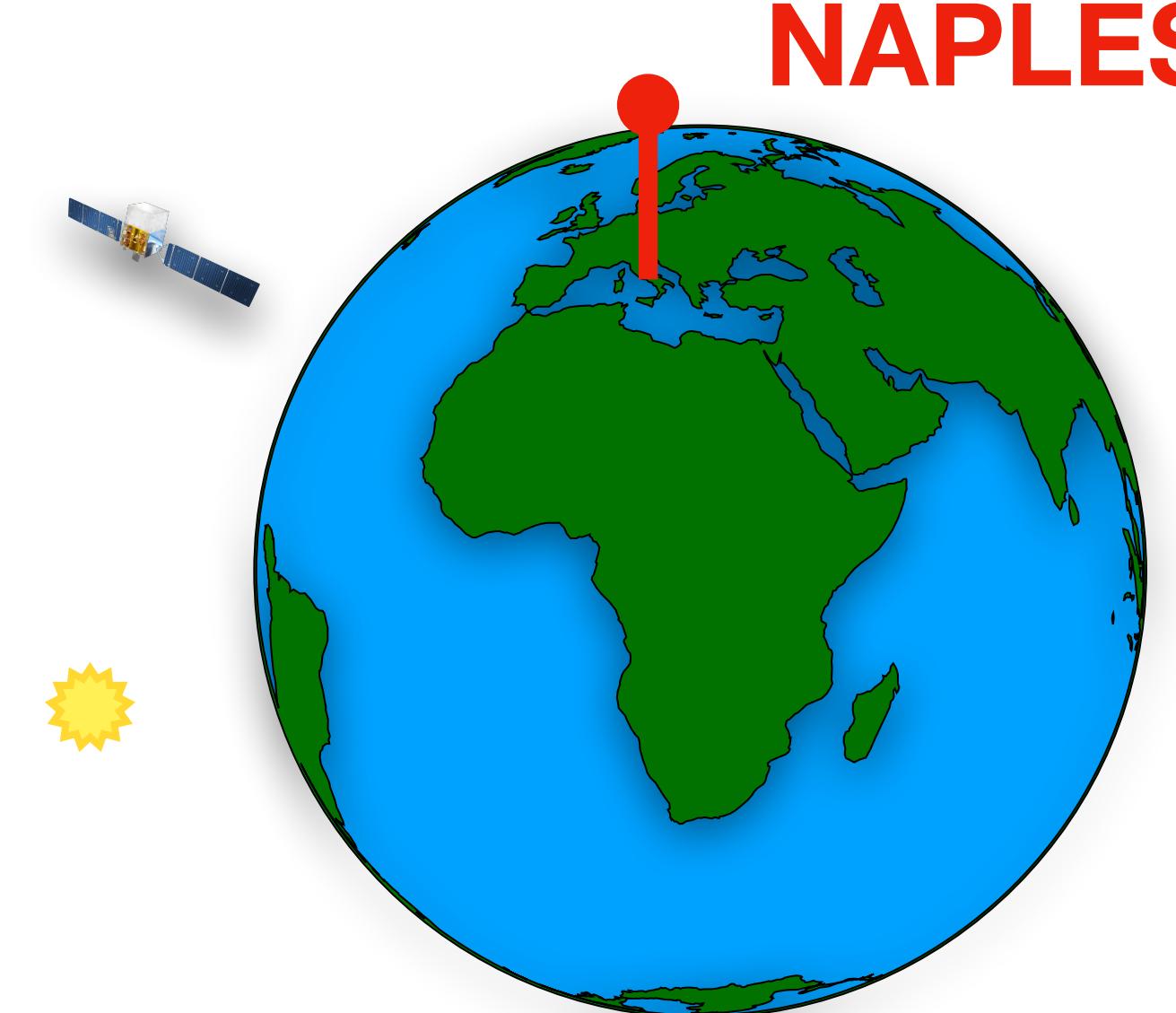
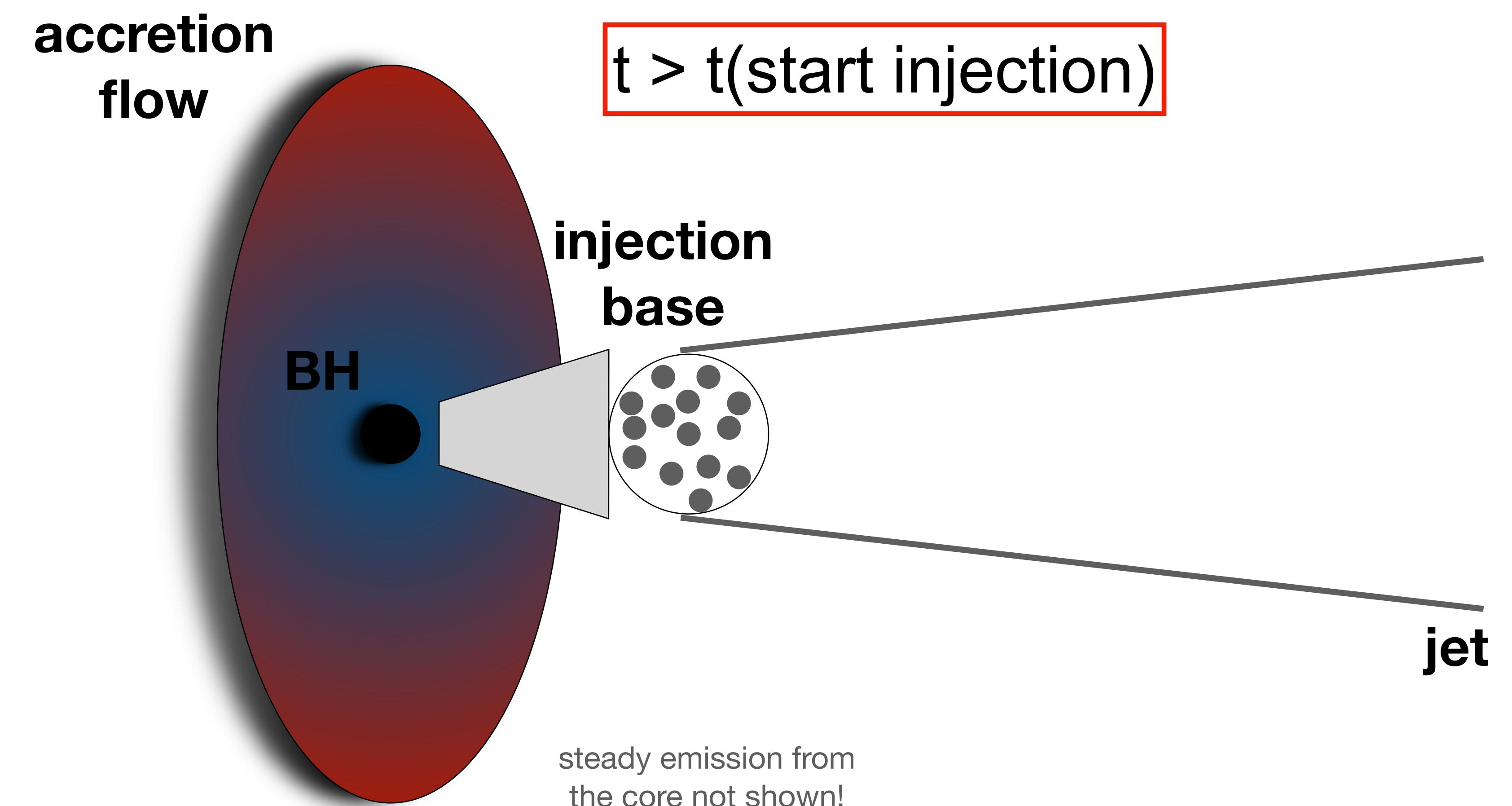
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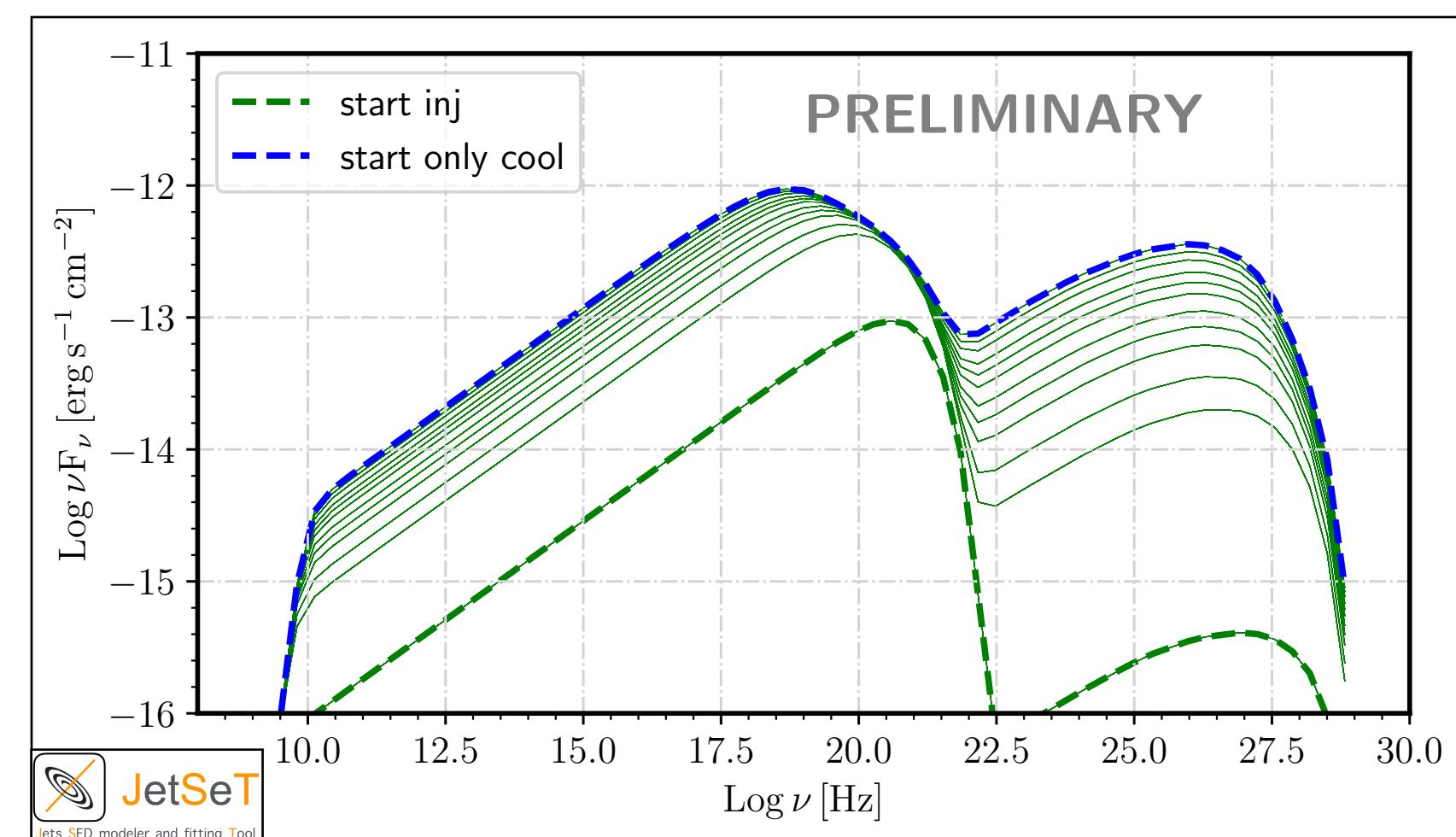
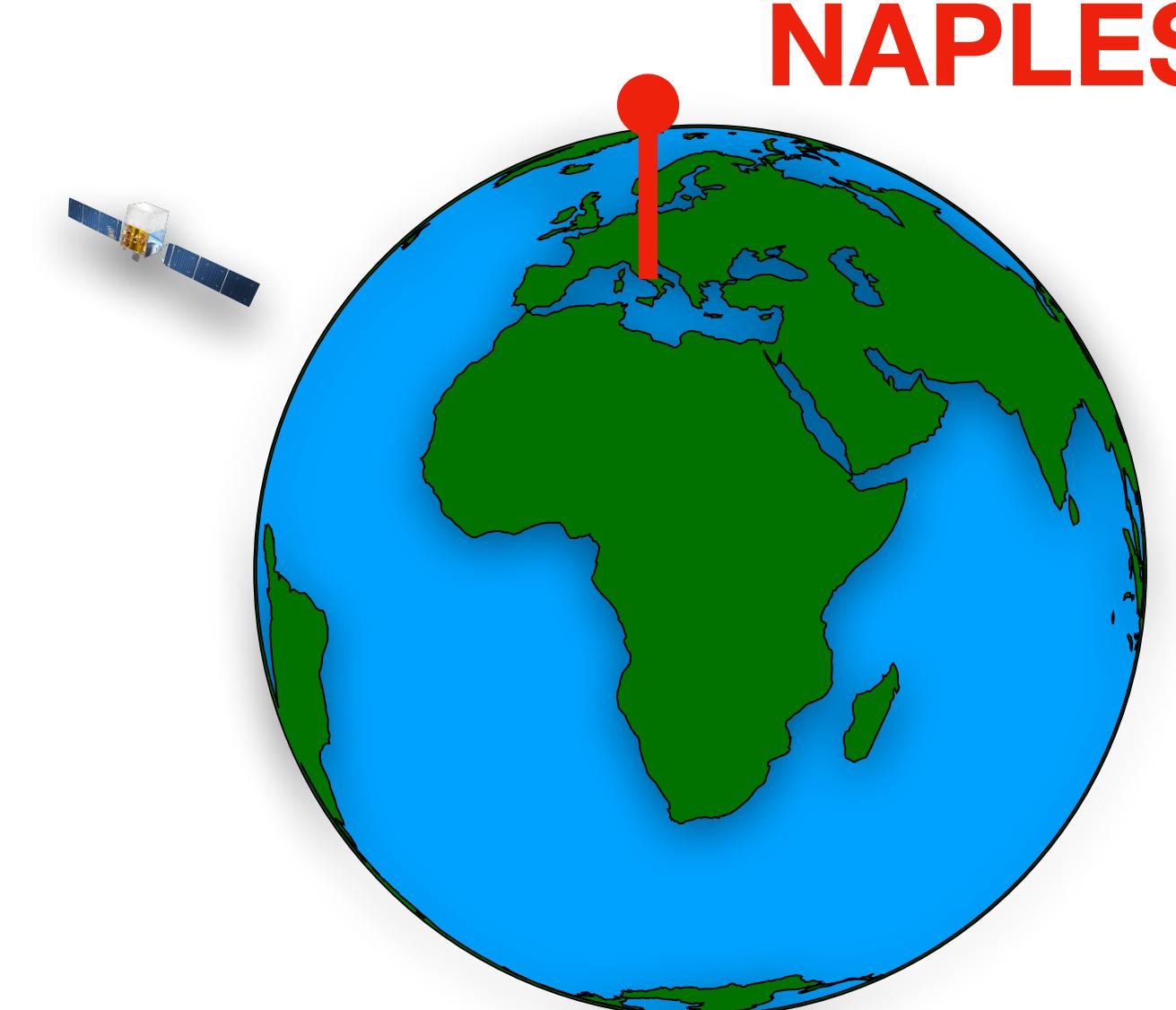
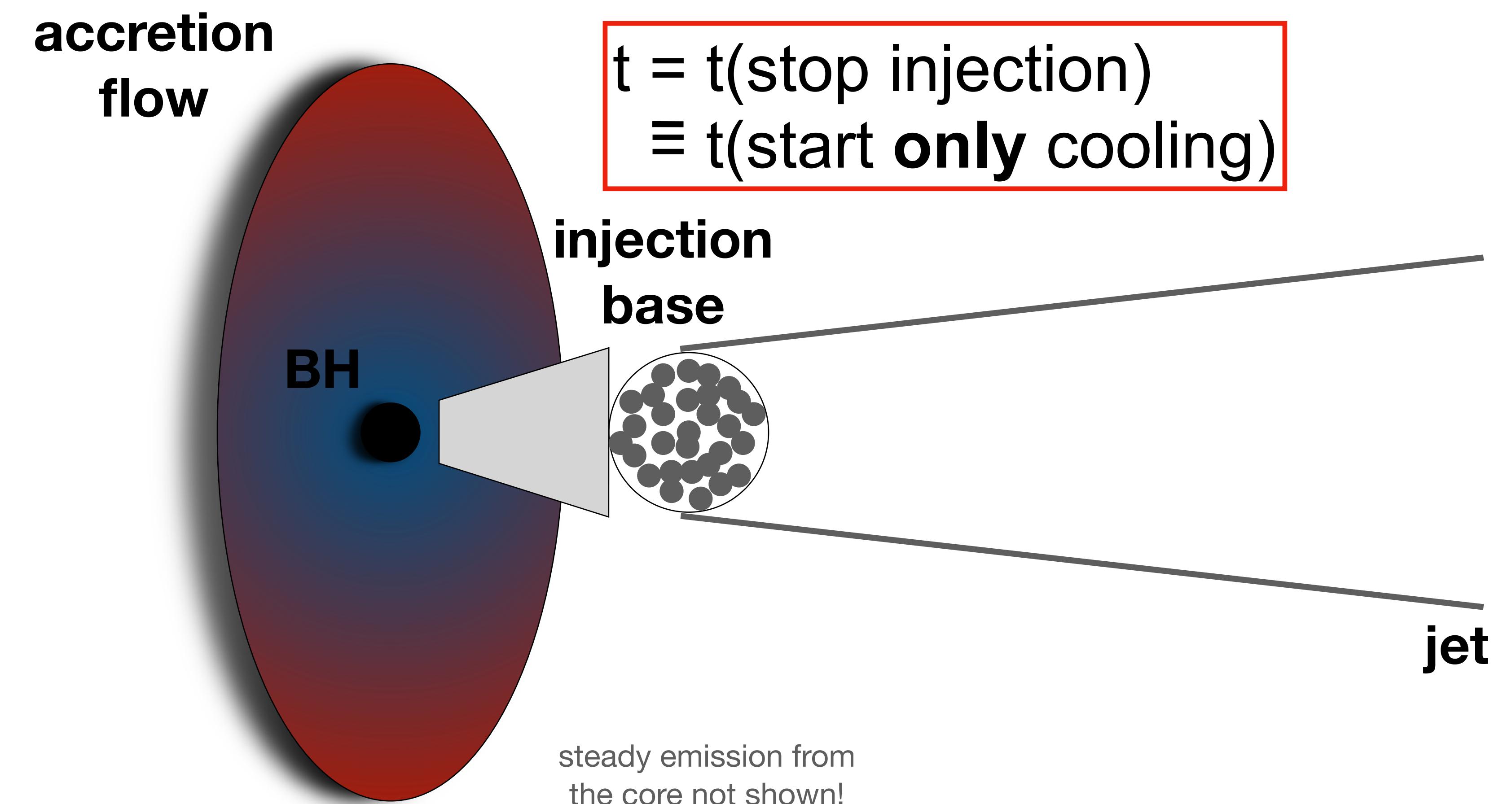
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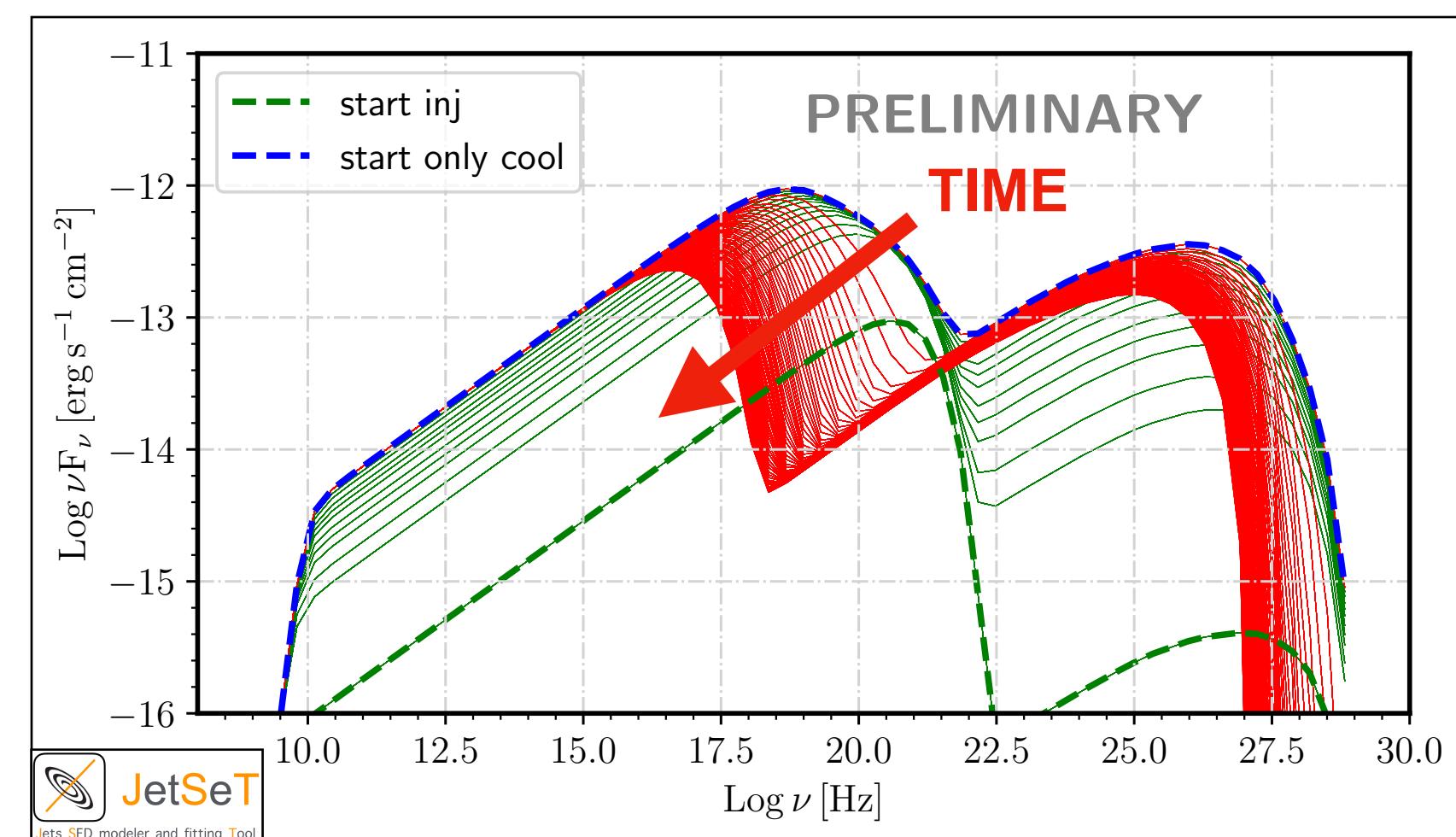
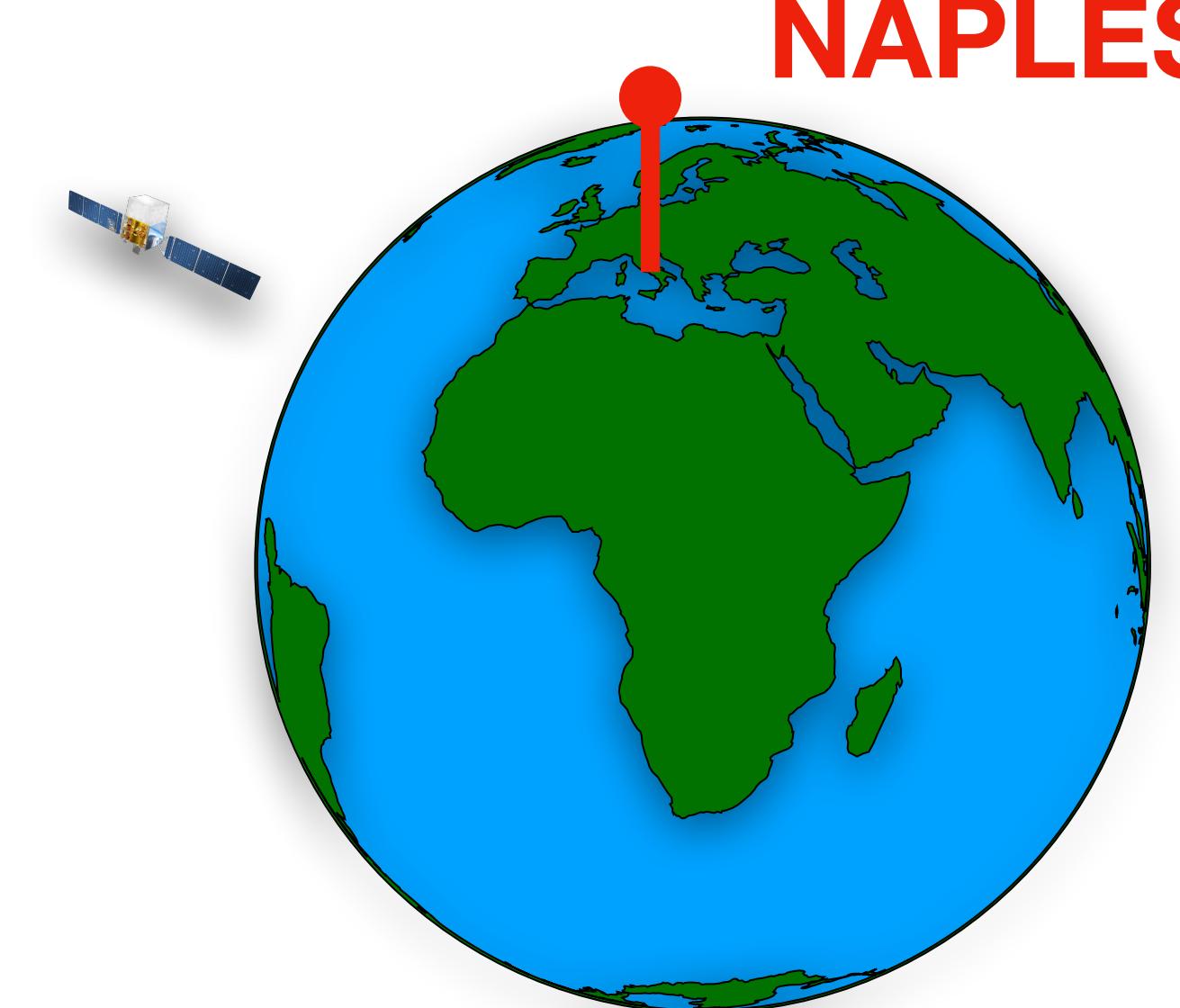
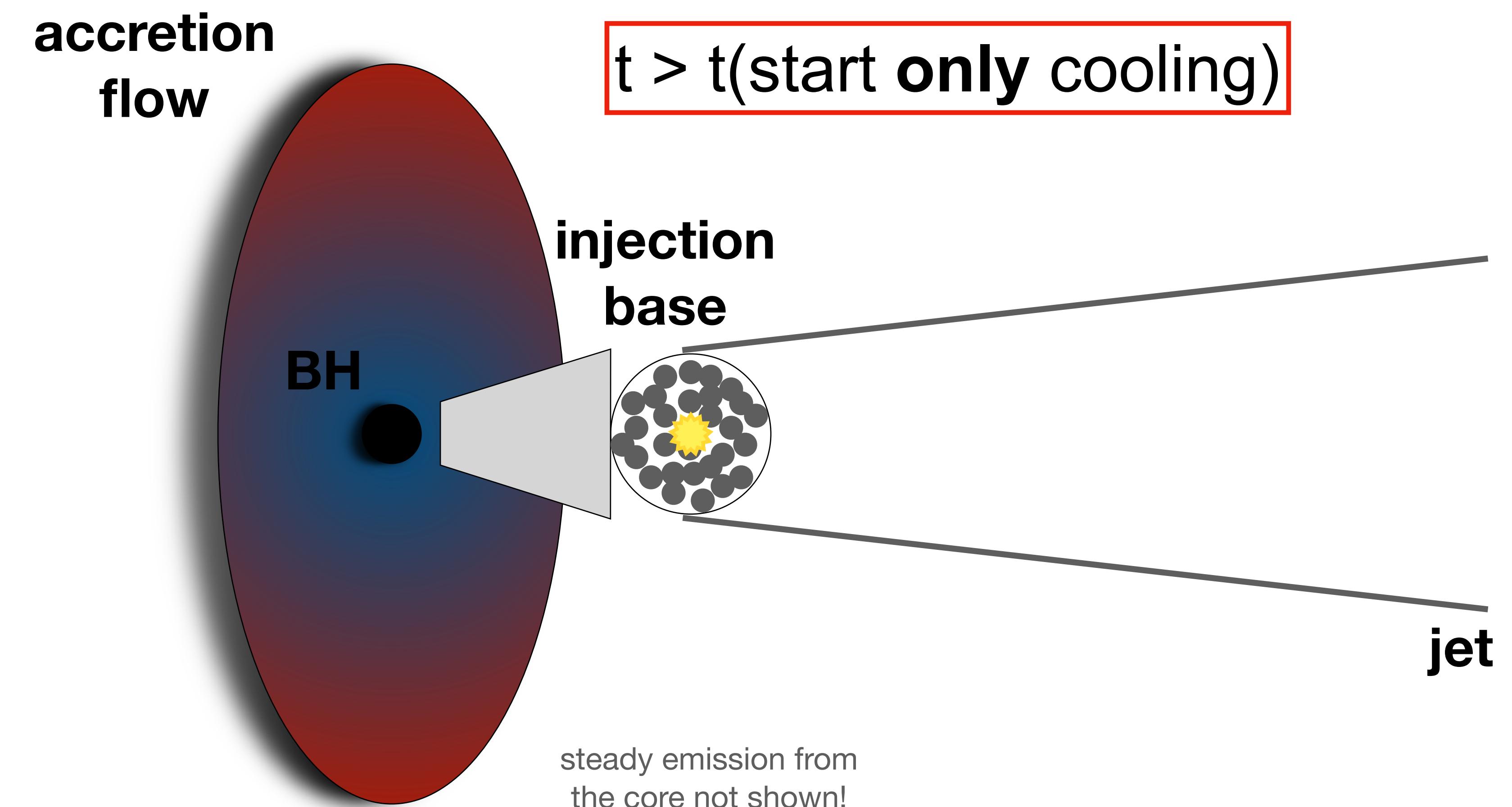
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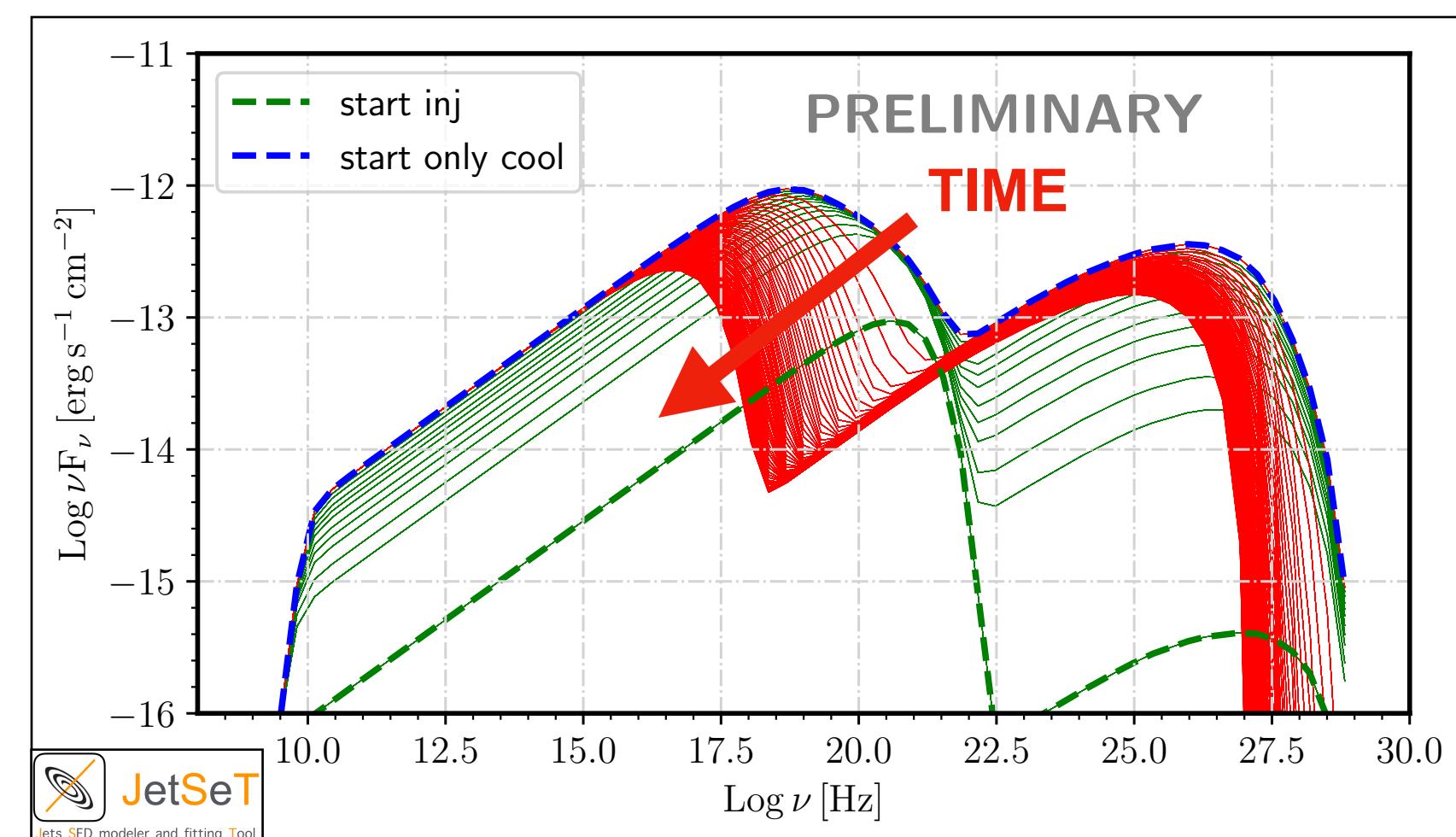
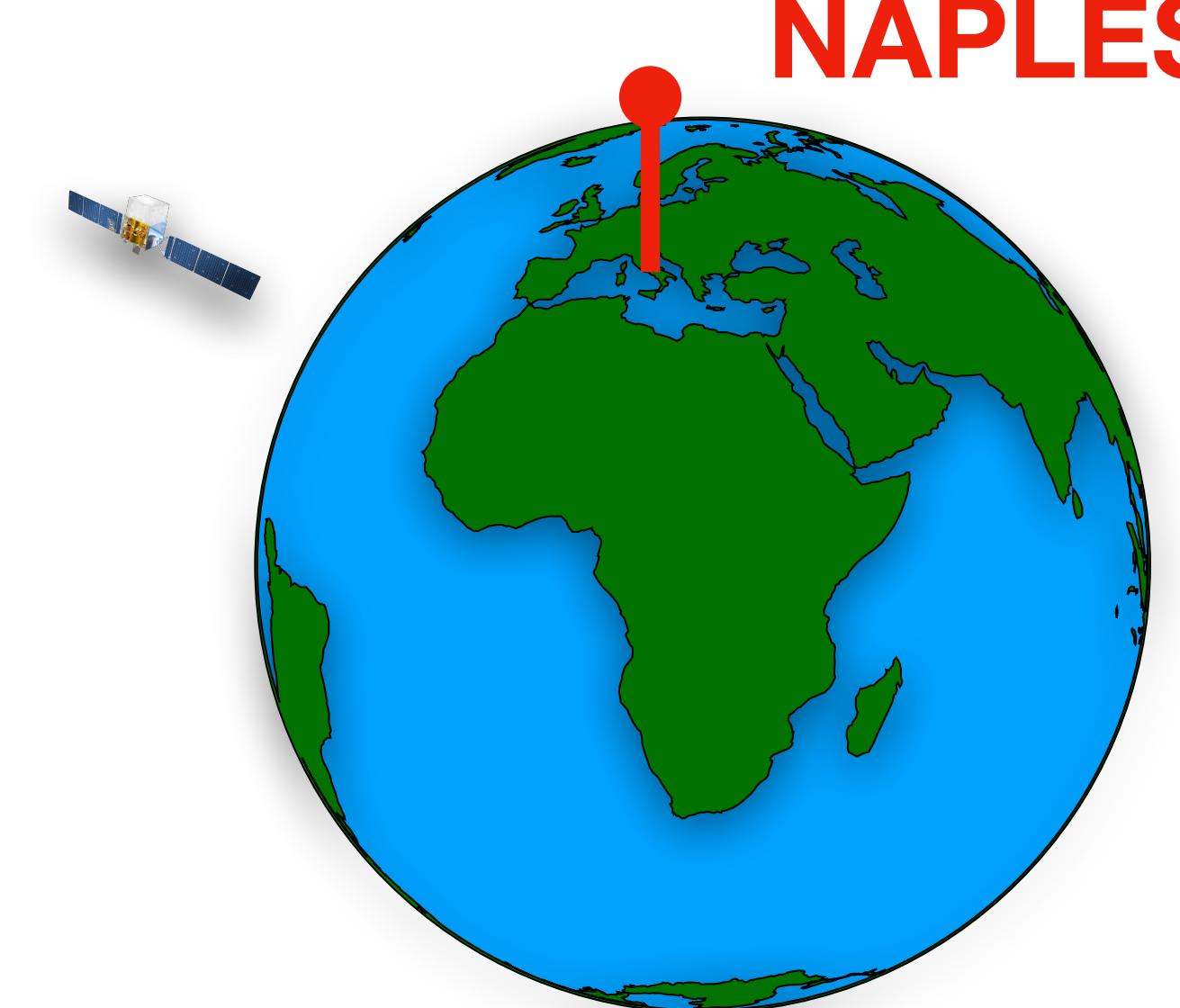
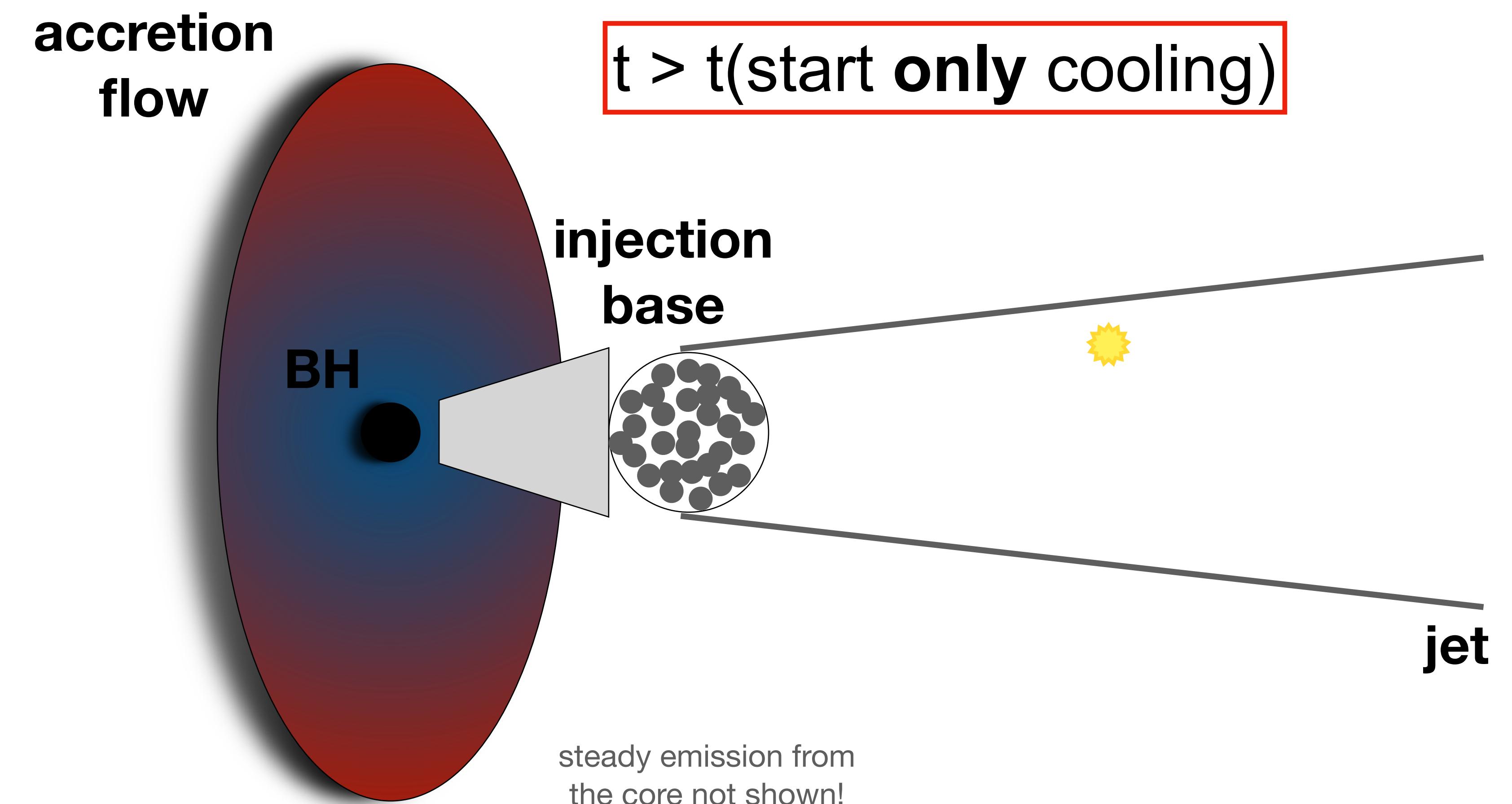
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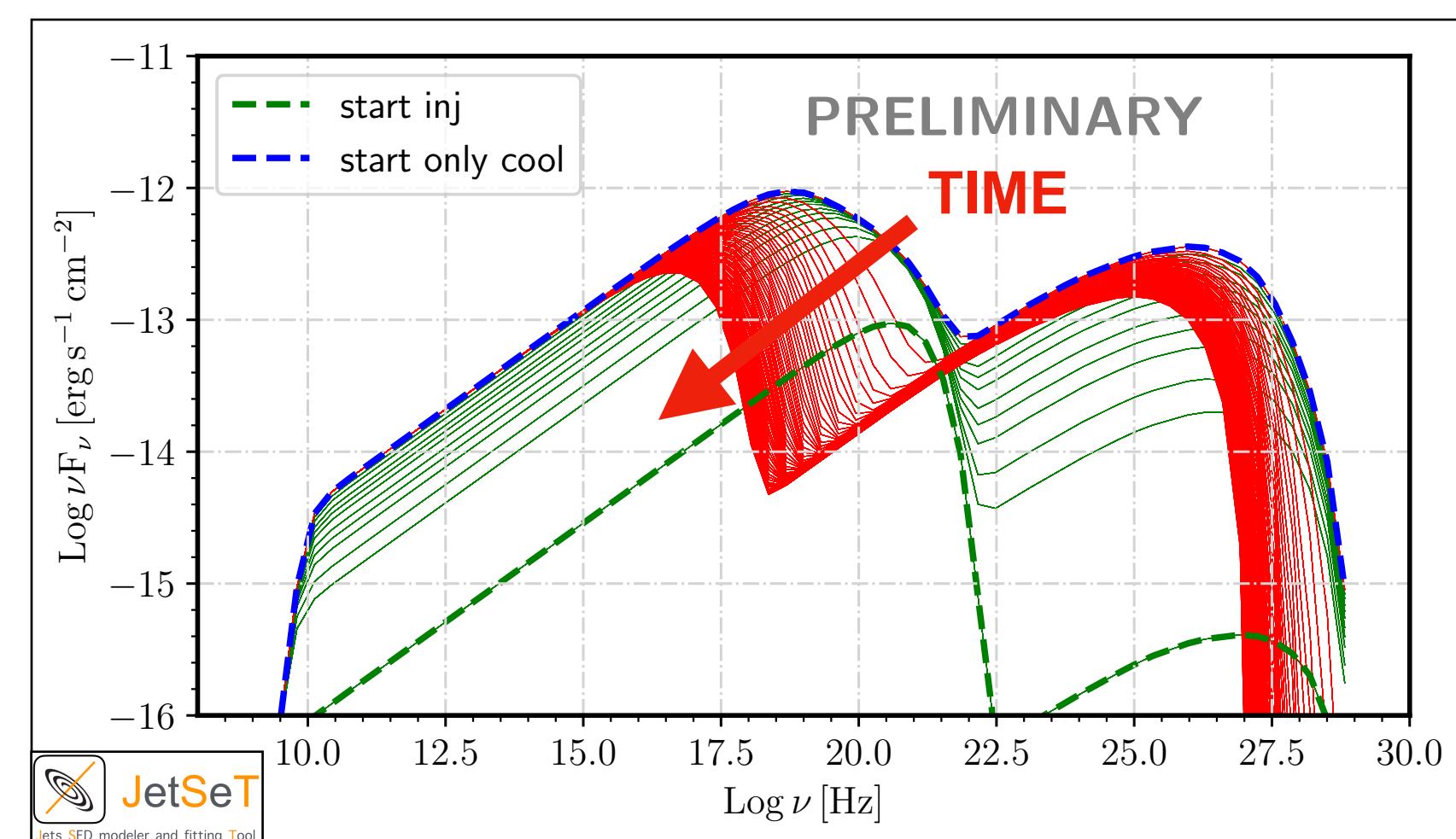
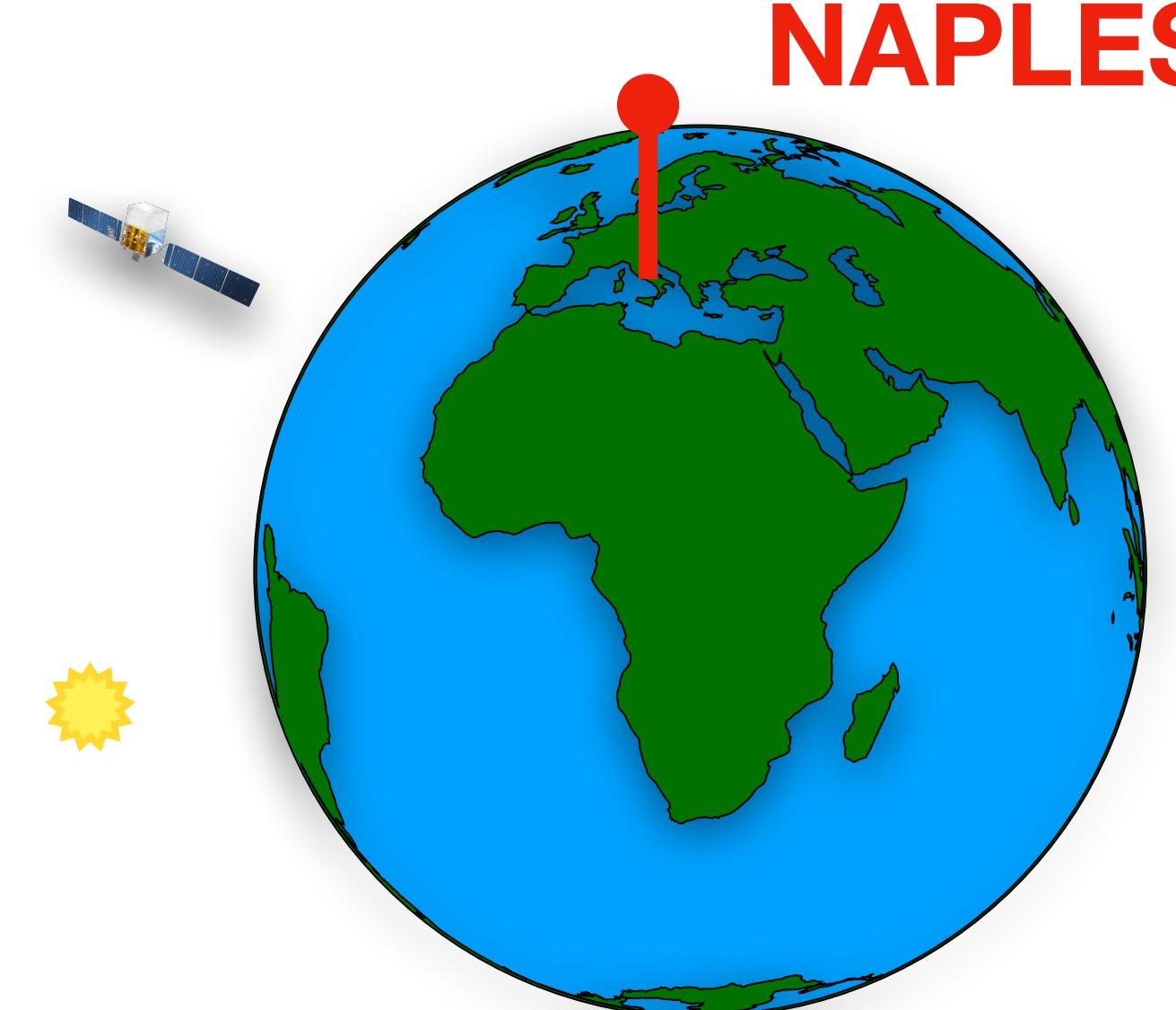
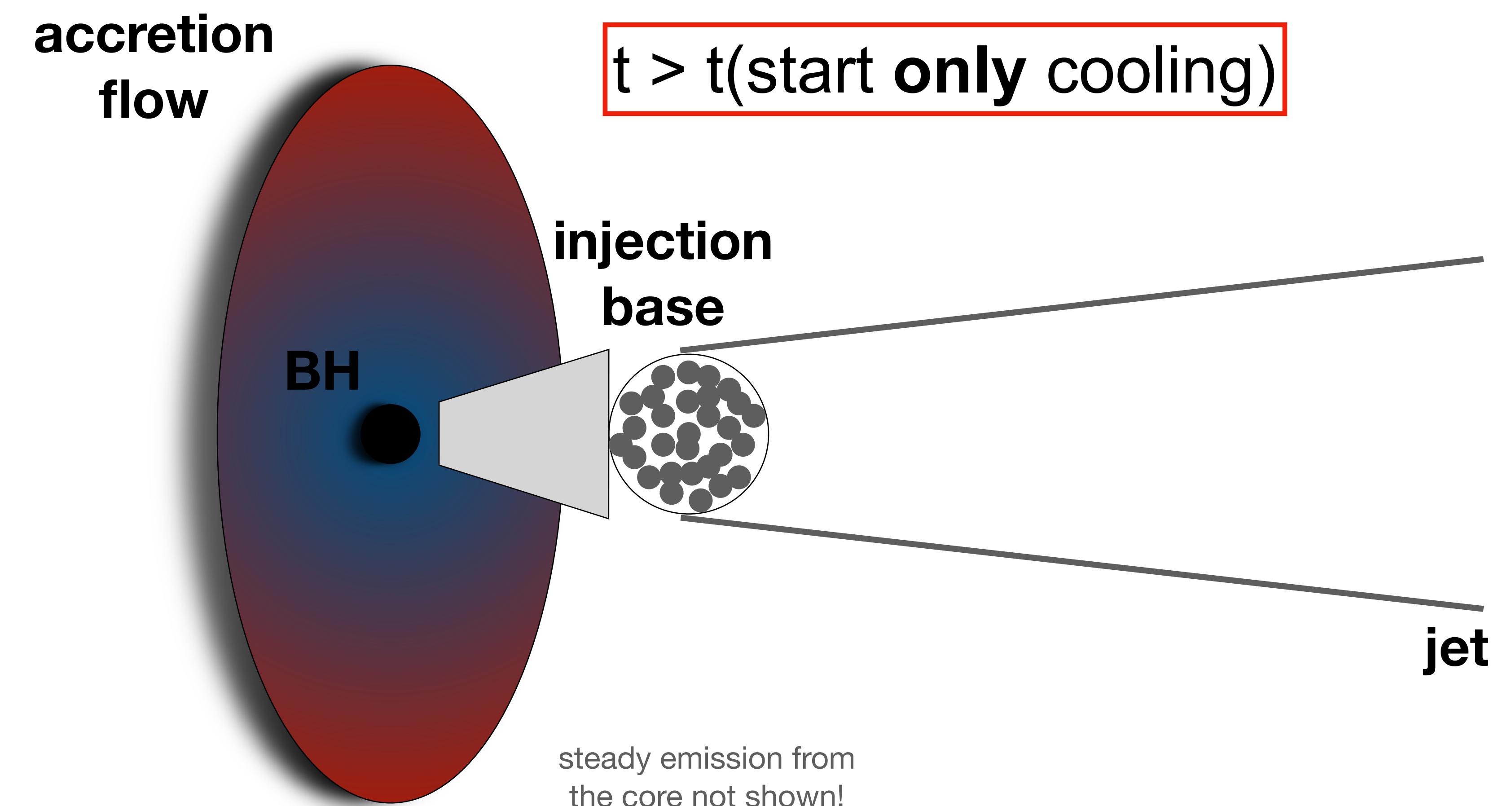
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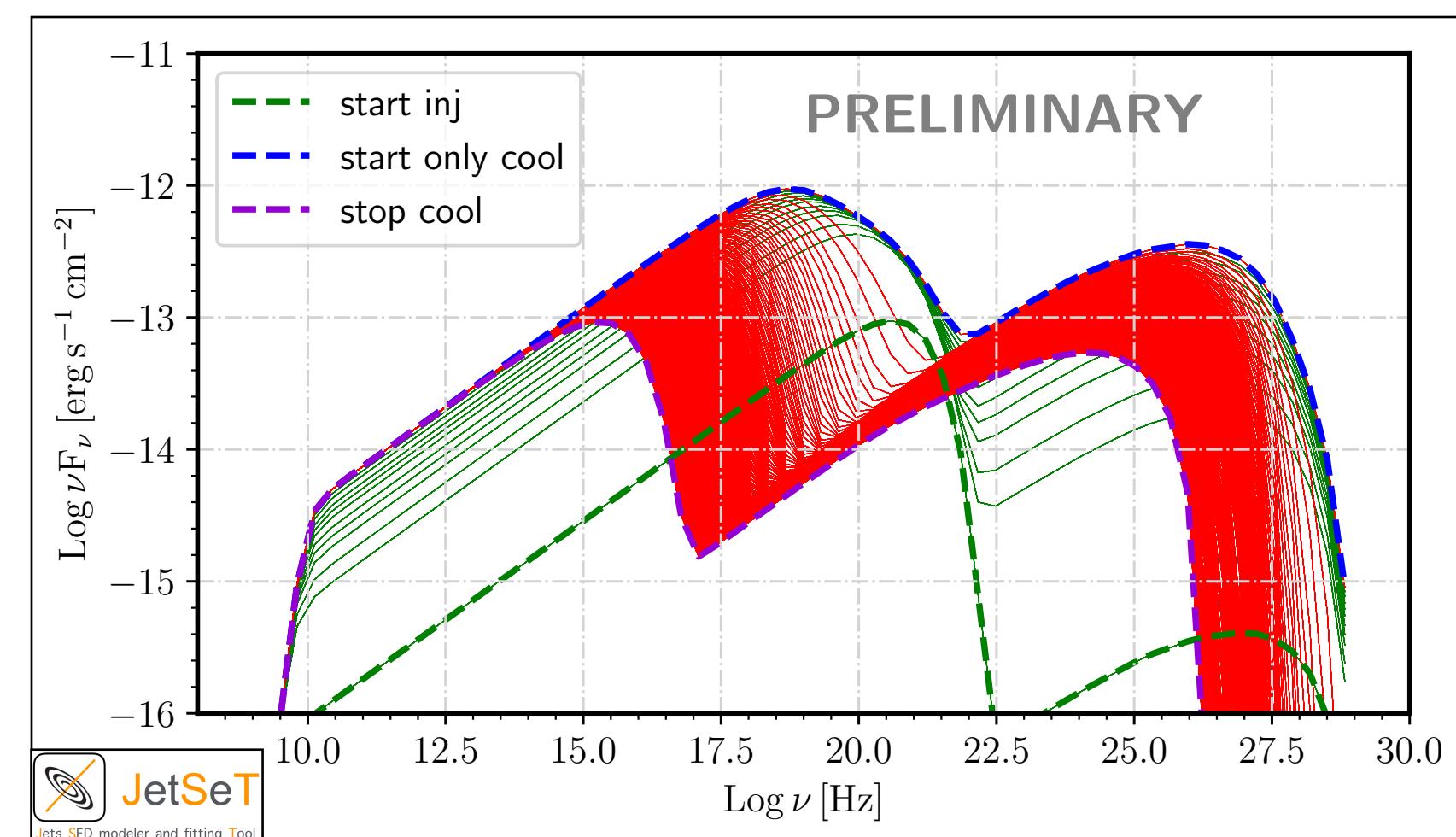
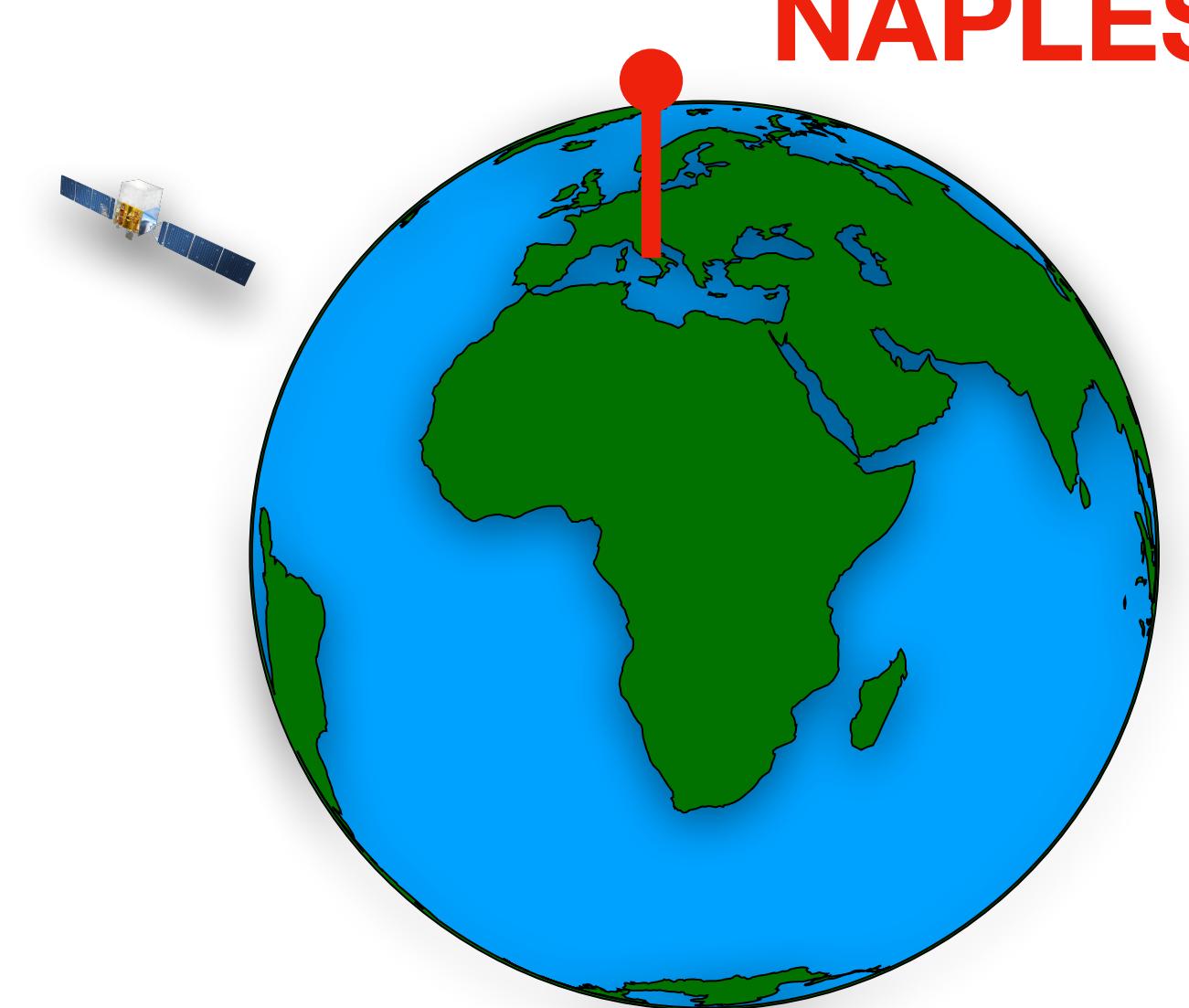
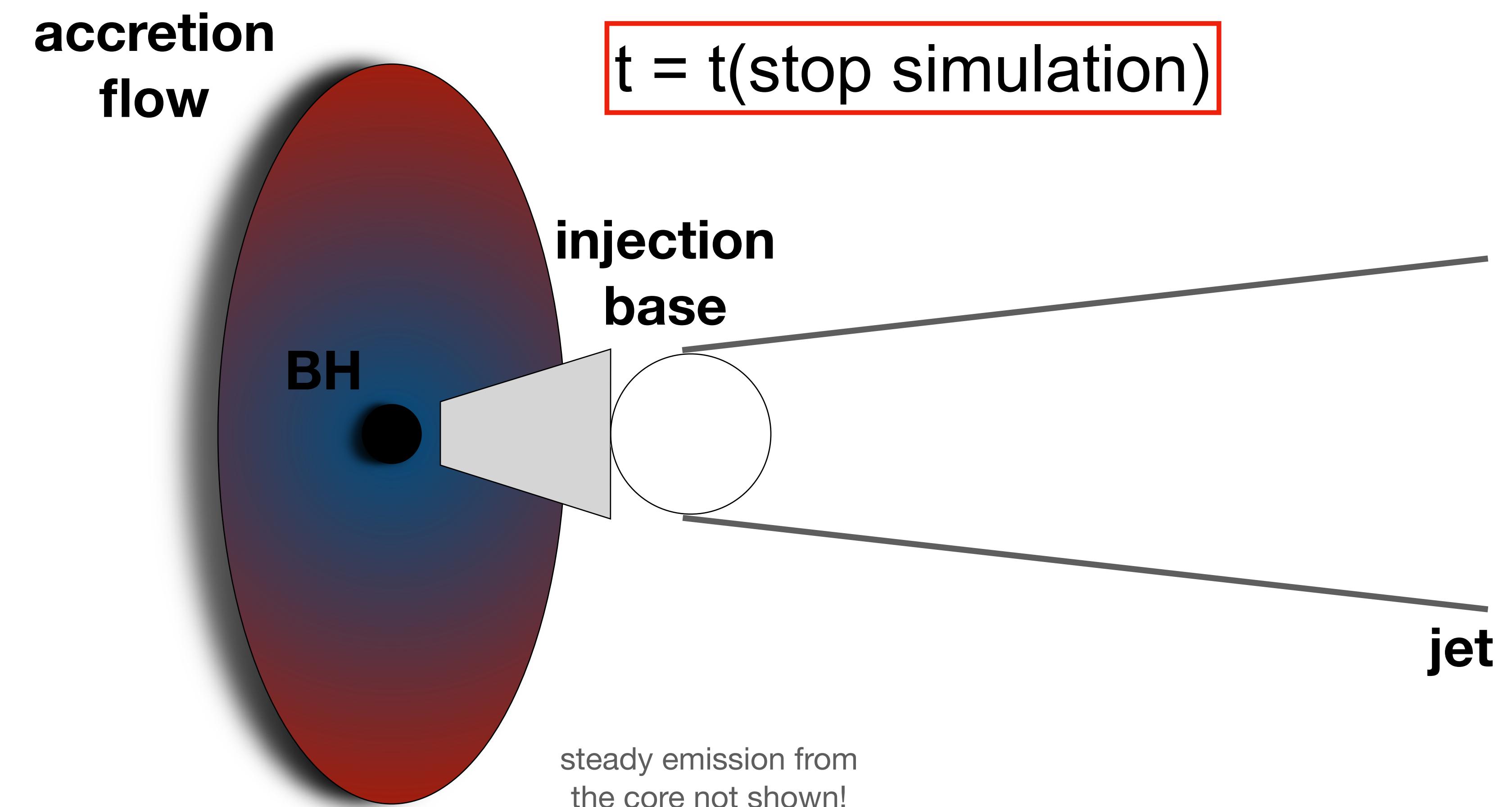
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Tramacere+09, Tramacere+11, Tramacere+20

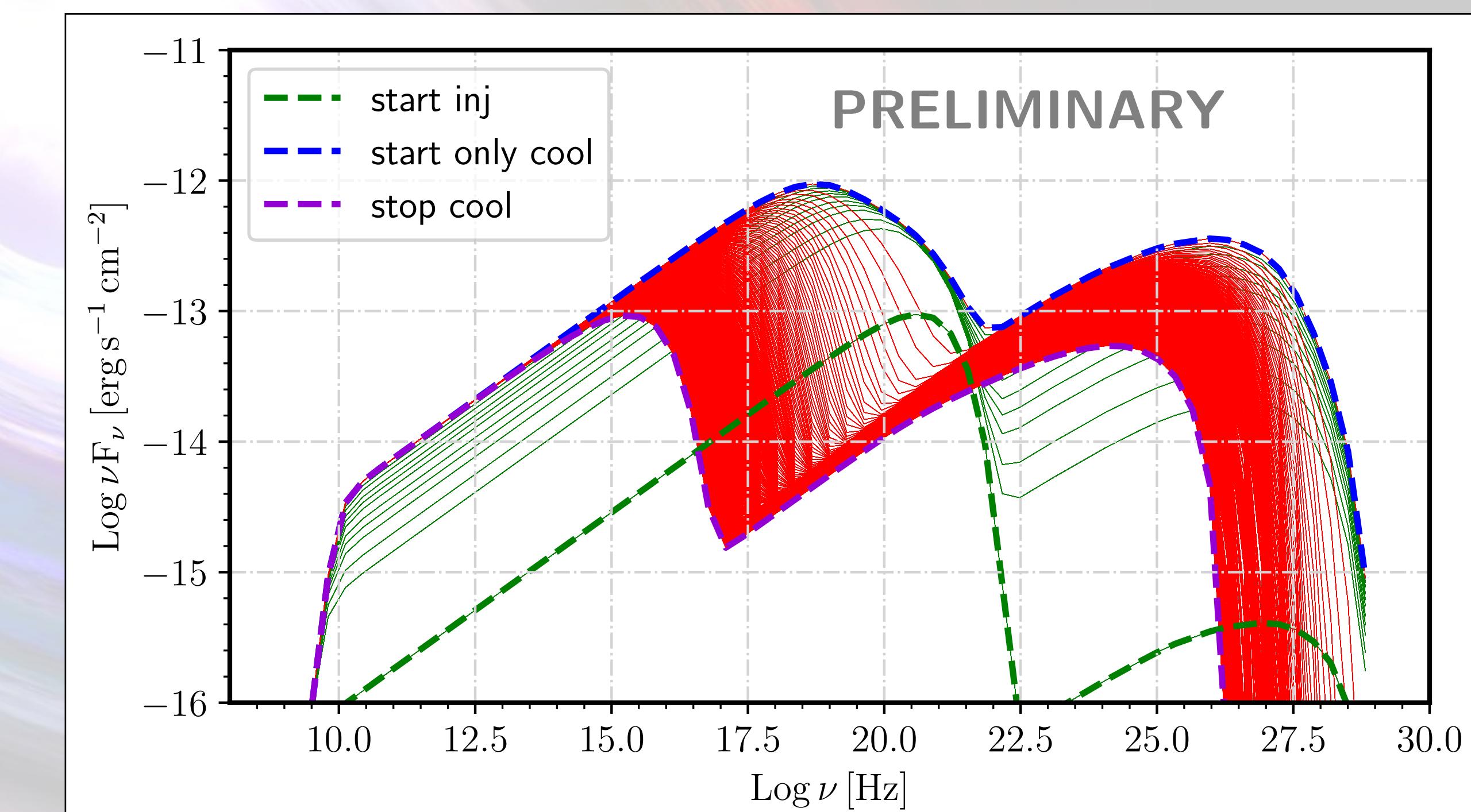
<https://jetset.readthedocs.io/en/latest/>

by A. Tramacere

← Try it, it's powerful!

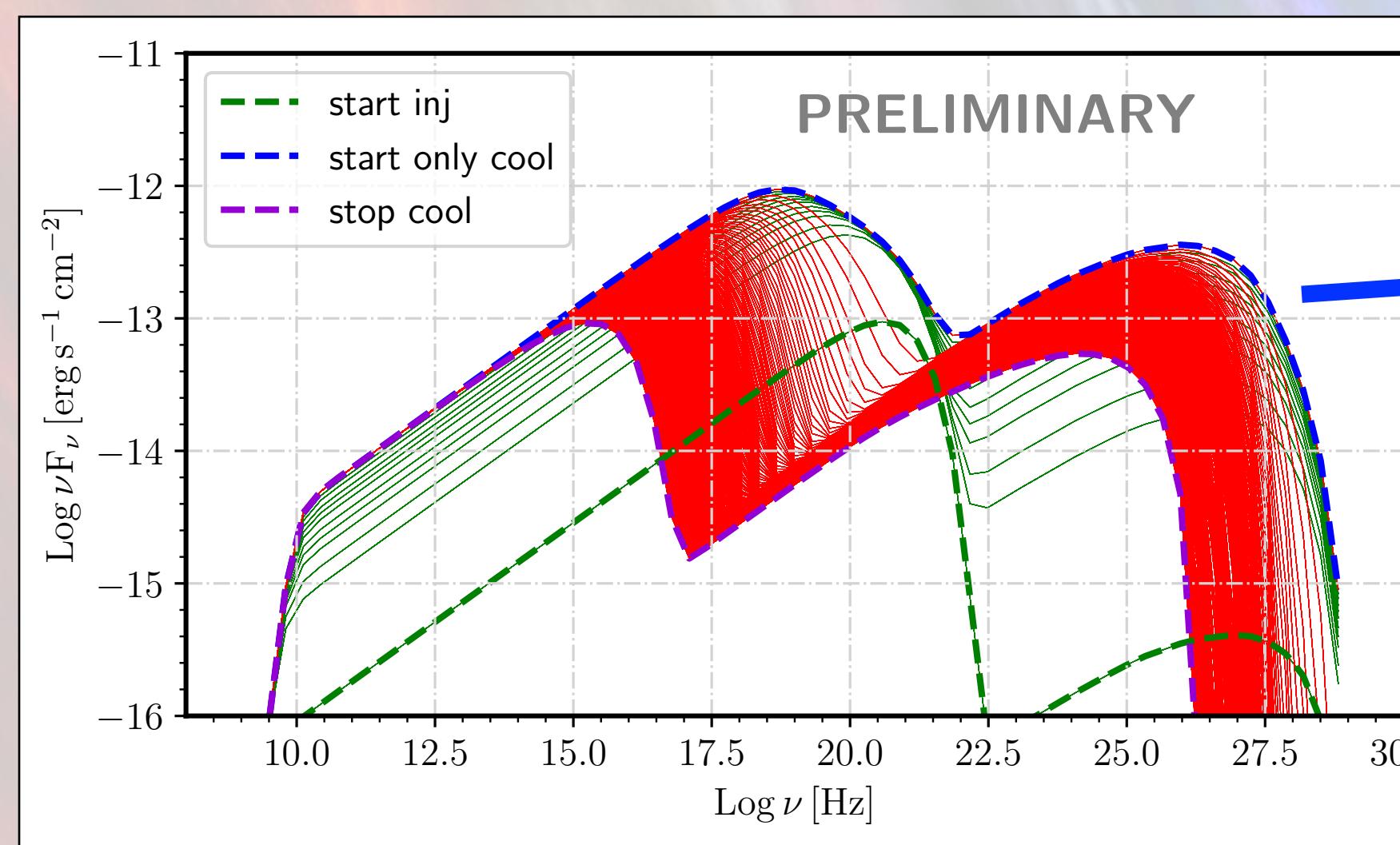
Main assumptions:

- only sync radiative cooling in action
- no acceleration or adiabatic losses of the blob considered
- no particles escape

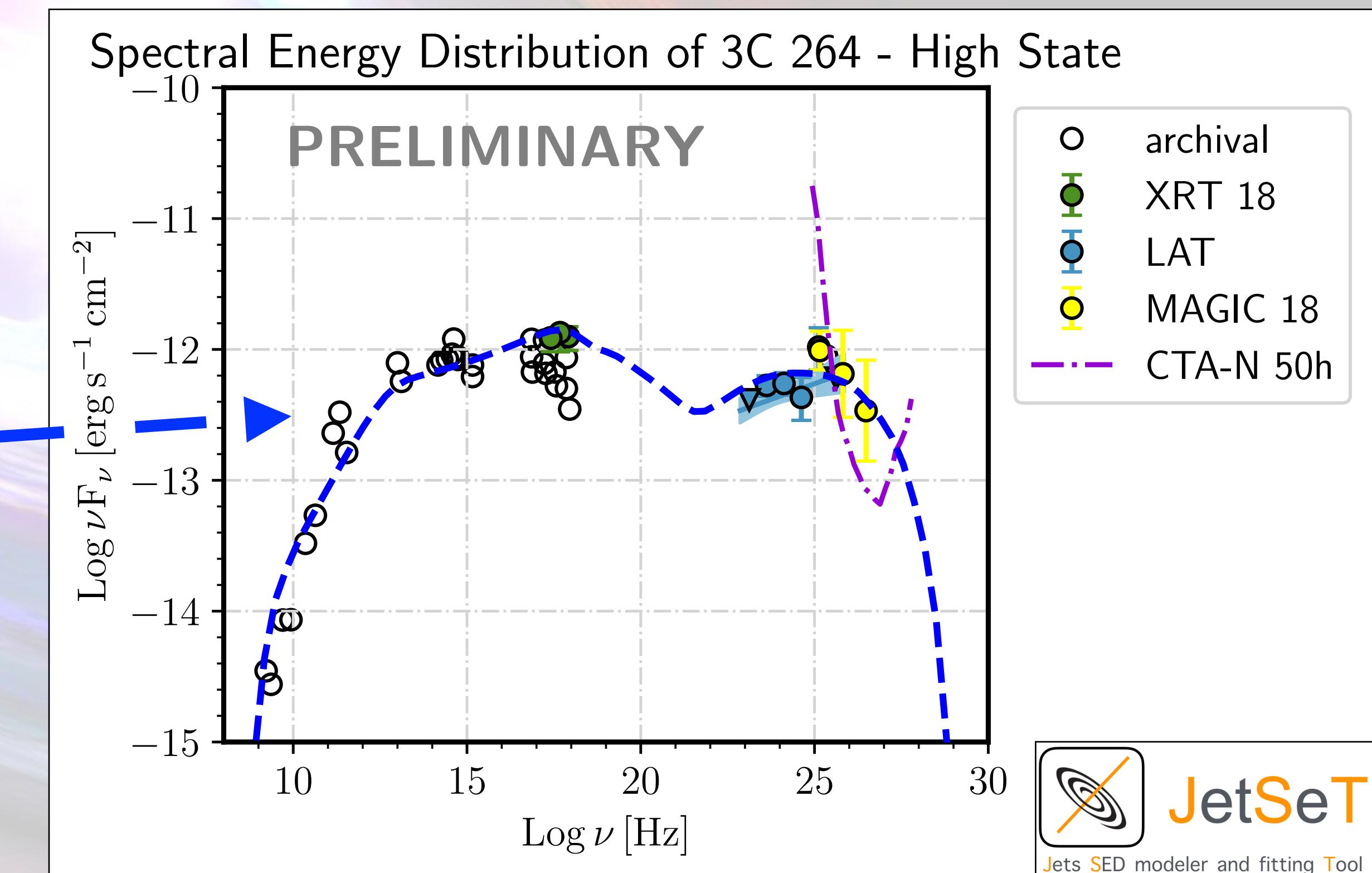


# 3C 264: SED modeling of the highest state

- $R = 10^{16} \text{ cm}$
- $B \sim 10^{-2} \text{ G}$
- $p = 2.4$
- $\gamma_{\min} = 1$
- $\gamma_{\max} = 10^6$
- $\Delta t_{\text{inj}} = 2.5 \times 10^6 \text{ s}$  (blob rest frame)
- $L_{\text{inj}} = 3 \times 10^{41} \text{ erg/s}$

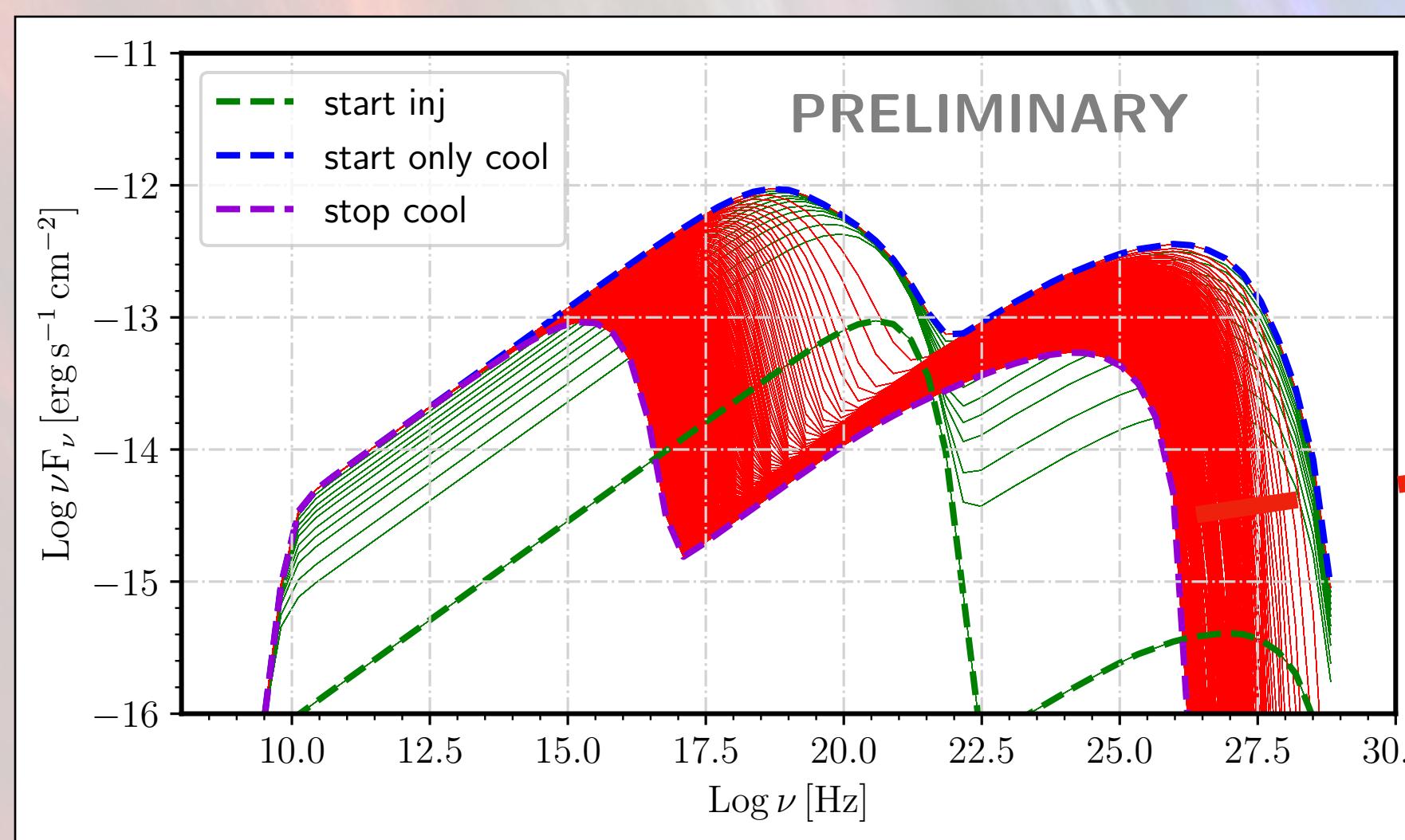


$t = t(\text{start only cooling})$

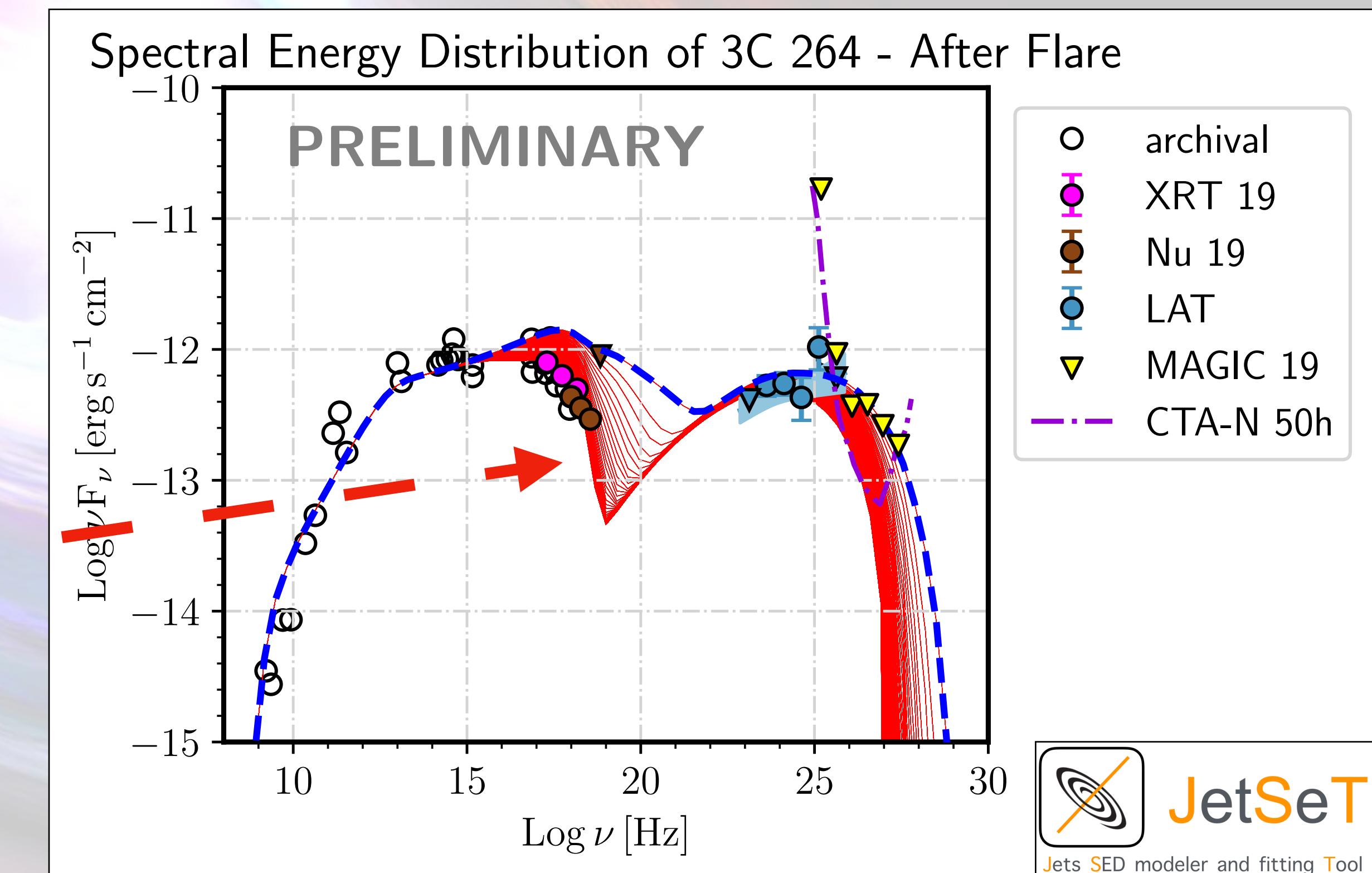


# 3C 264: SED modeling after flare

- $R = 10^{16} \text{ cm}$
- $B \sim 10^{-2} \text{ G}$
- $p = 2.4$
- $\gamma_{\min} = 1$
- $\gamma_{\max} = 10^6$
- $\Delta t_{\text{inj}} = 2.5 \times 10^6 \text{ s}$  (blob rest frame)
- $L_{\text{inj}} = 3 \times 10^{41} \text{ erg/s}$



$t > t(\text{start only cooling})$



 **JetSeT**  
Jets SED modeler and fitting Tool

# Summary

To sum up:

- 3C 264: second most distant TeV detected radio galaxy observed by VERITAS and MAGIC
- X-TeV common behaviours (low/high in 2018/2019)
- no statistically significant GeV variability
- “softening when fading” trend after 2018
- **new scenario** to explain these observational results of 3C 264:
  - **steady core** emission from radio to GeV
  - the **injection of new energetic particles in the ejection flow** might be able to explain
    - X-TeV high states
    - “softening when fading” after 2018

Note: this project is part of my PhD thesis, that I have just began!

**ONGOING PROJECT**

# Summary

To sum up:

- 3C 264: second most distant TeV detected radio galaxy observed by VERITAS and MAGIC
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Note: this project is part of my PhD thesis, that I have just began!

**ONGOING PROJECT**

**Interested in proposing observations with MAGIC?**

Next MAGIC observing call (Cycle-19) will come very soon. It will be posted here:

<https://magic.mpp.mpg.de/public/magicop/>  
(Deadline for submitting proposals in the end of October or beginning of November)

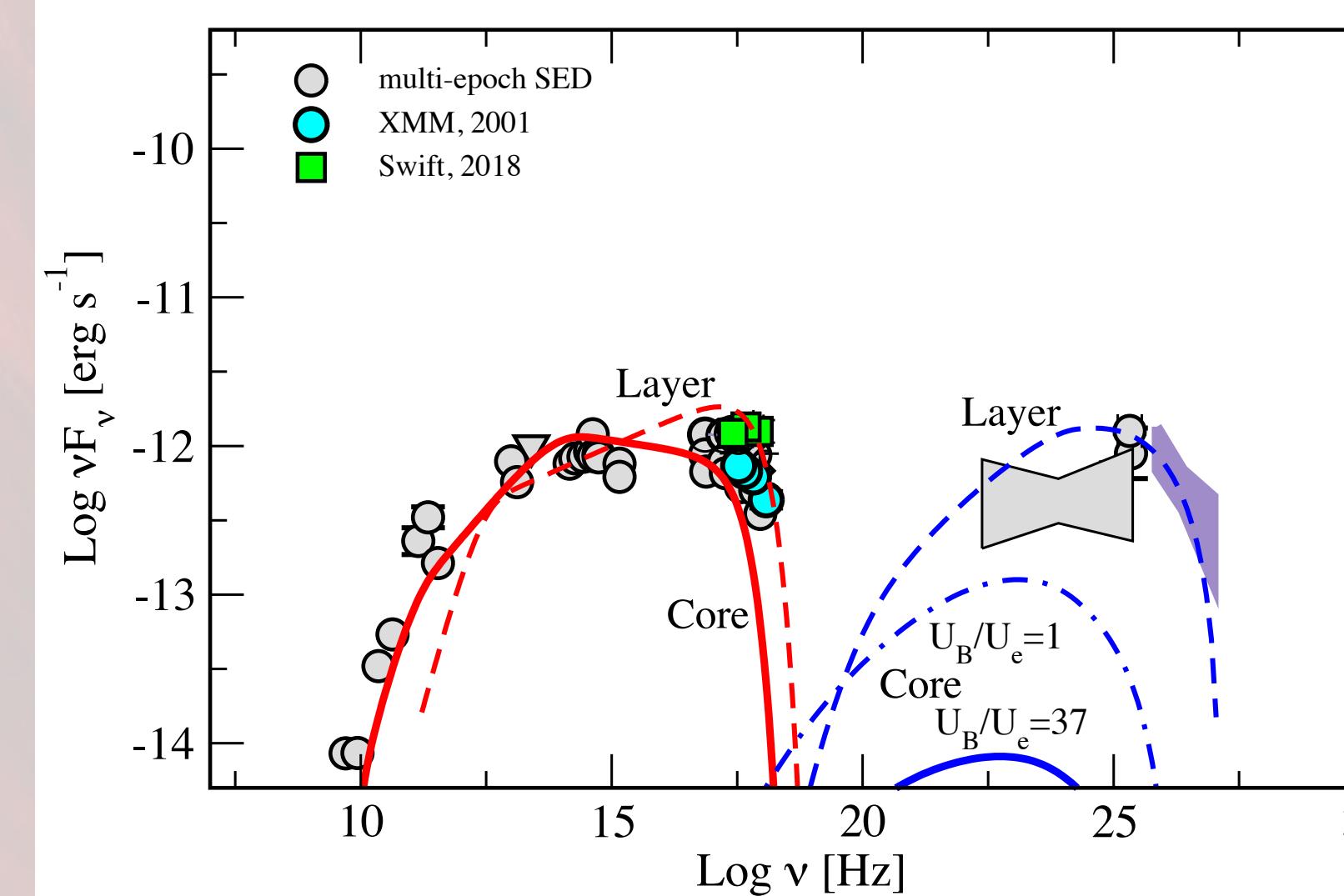
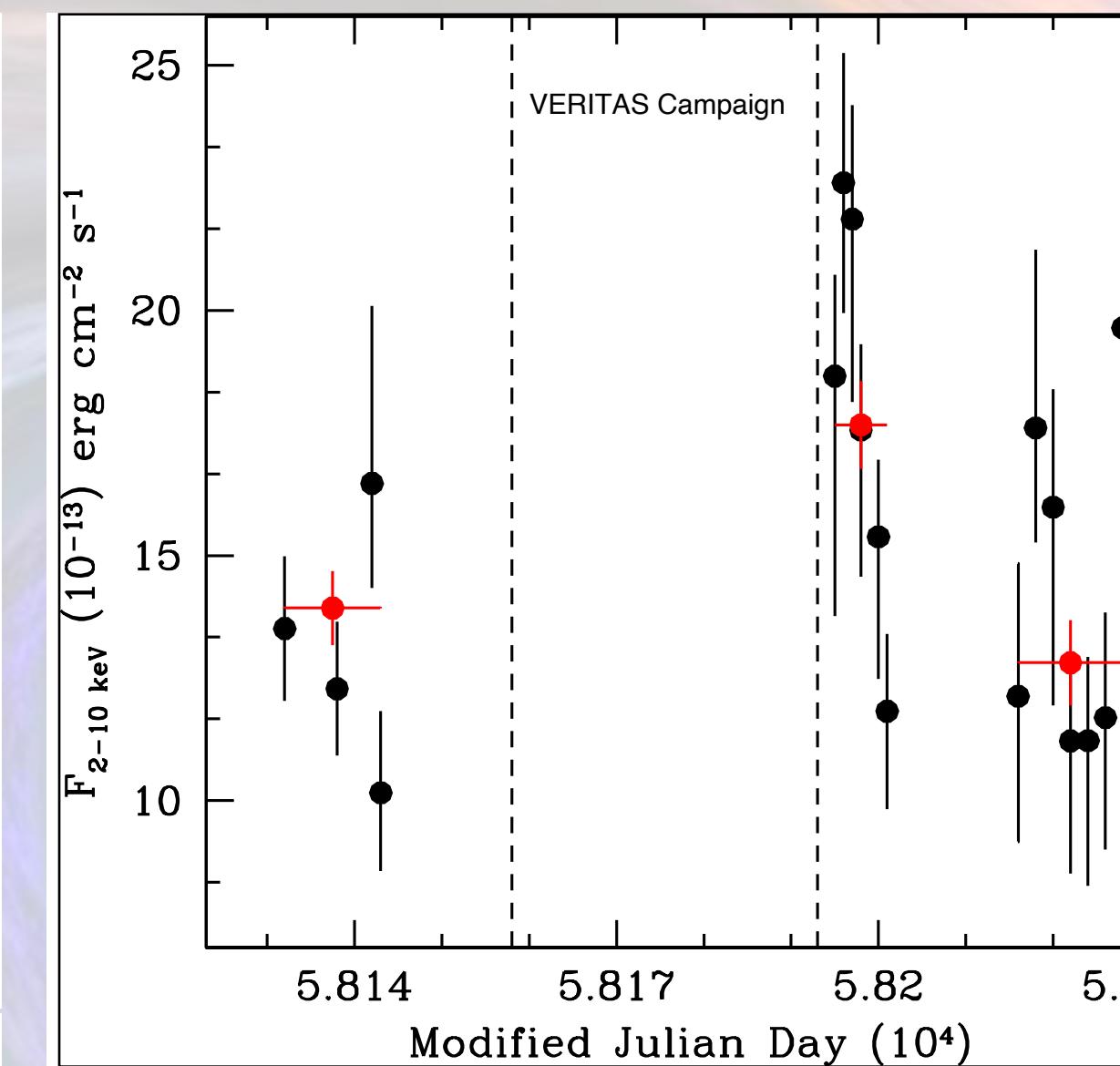
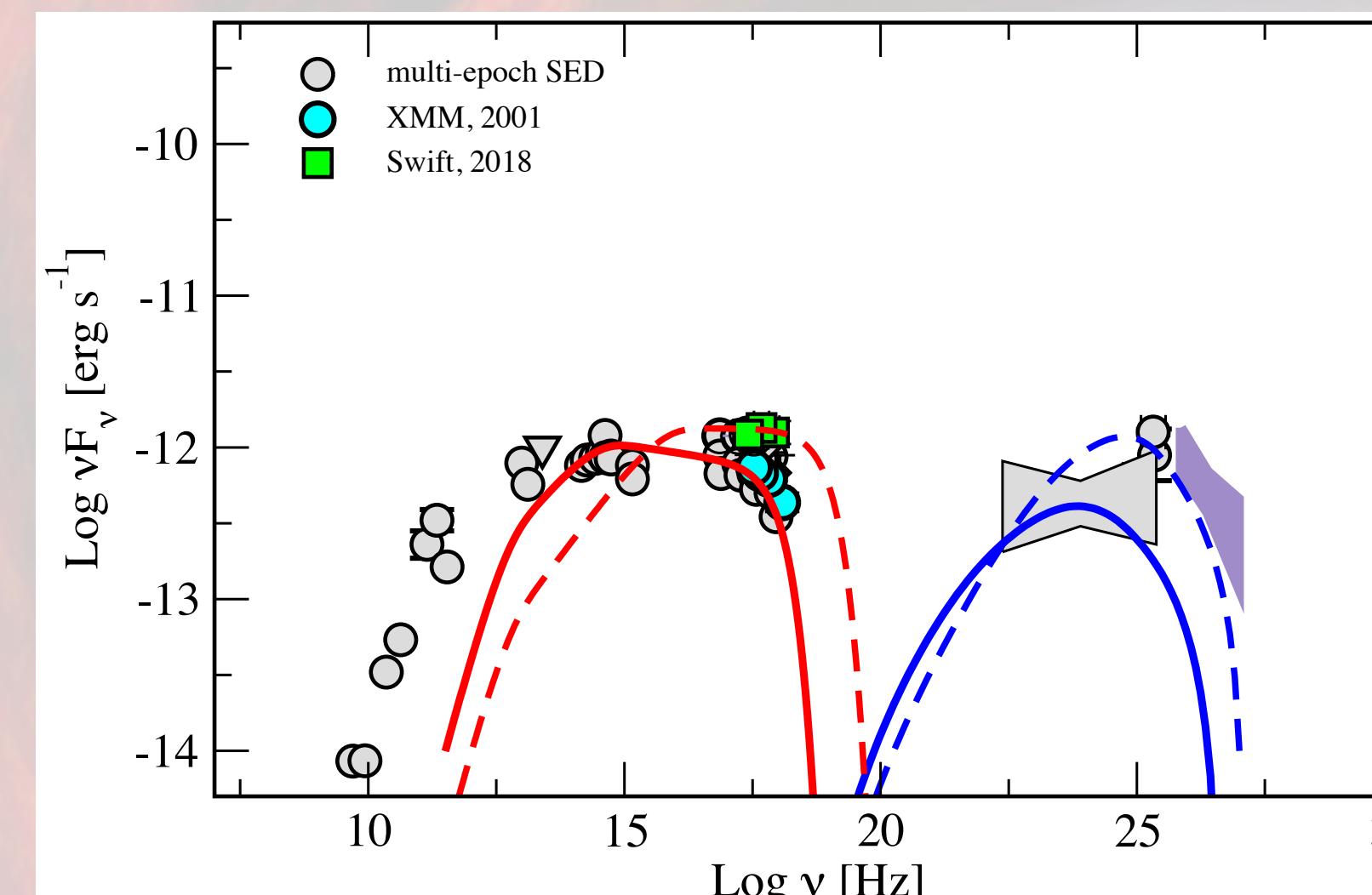
MAGIC observations of 3C 264 obtained in this way by R. Angioni (external P.I.)



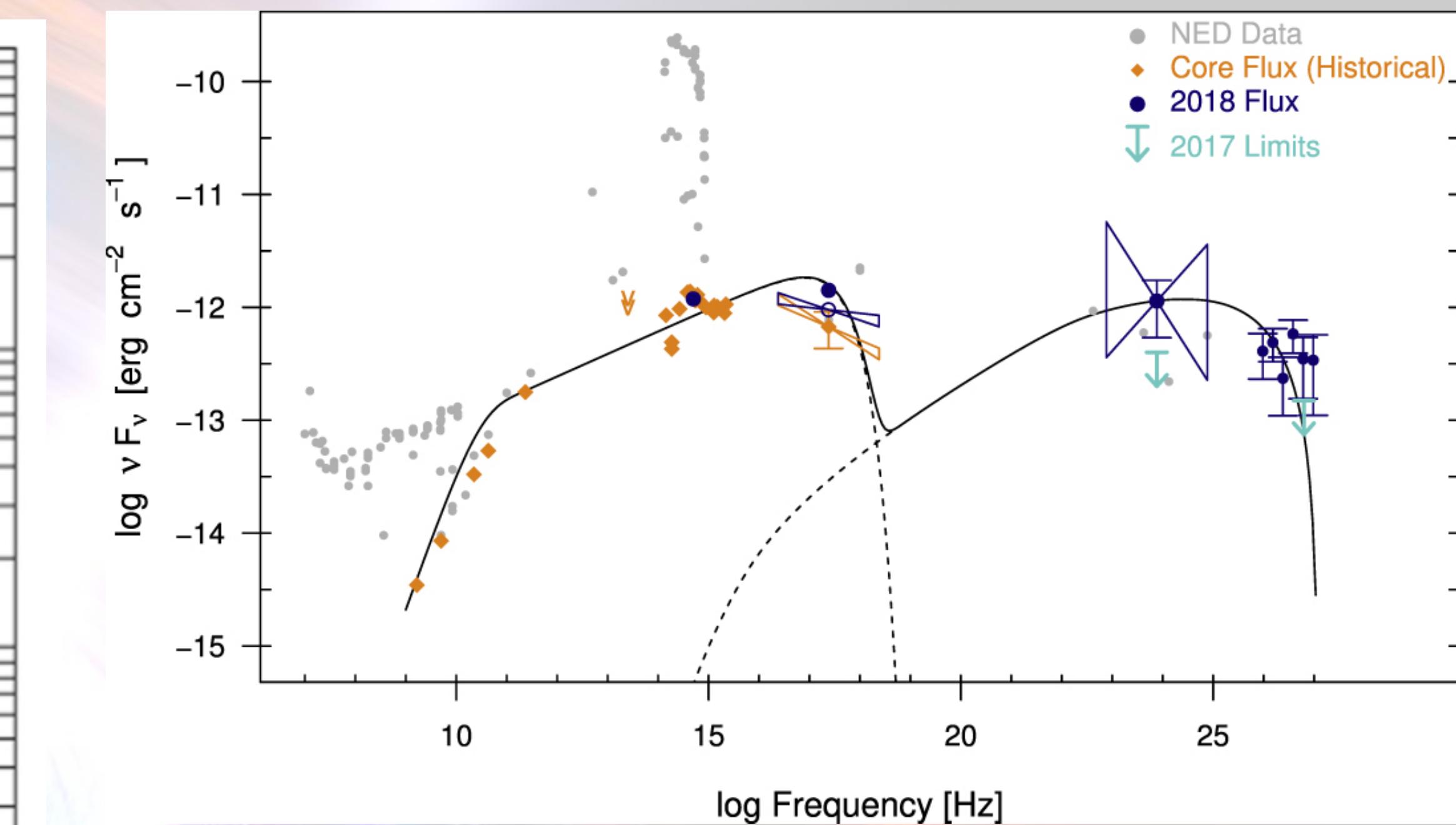
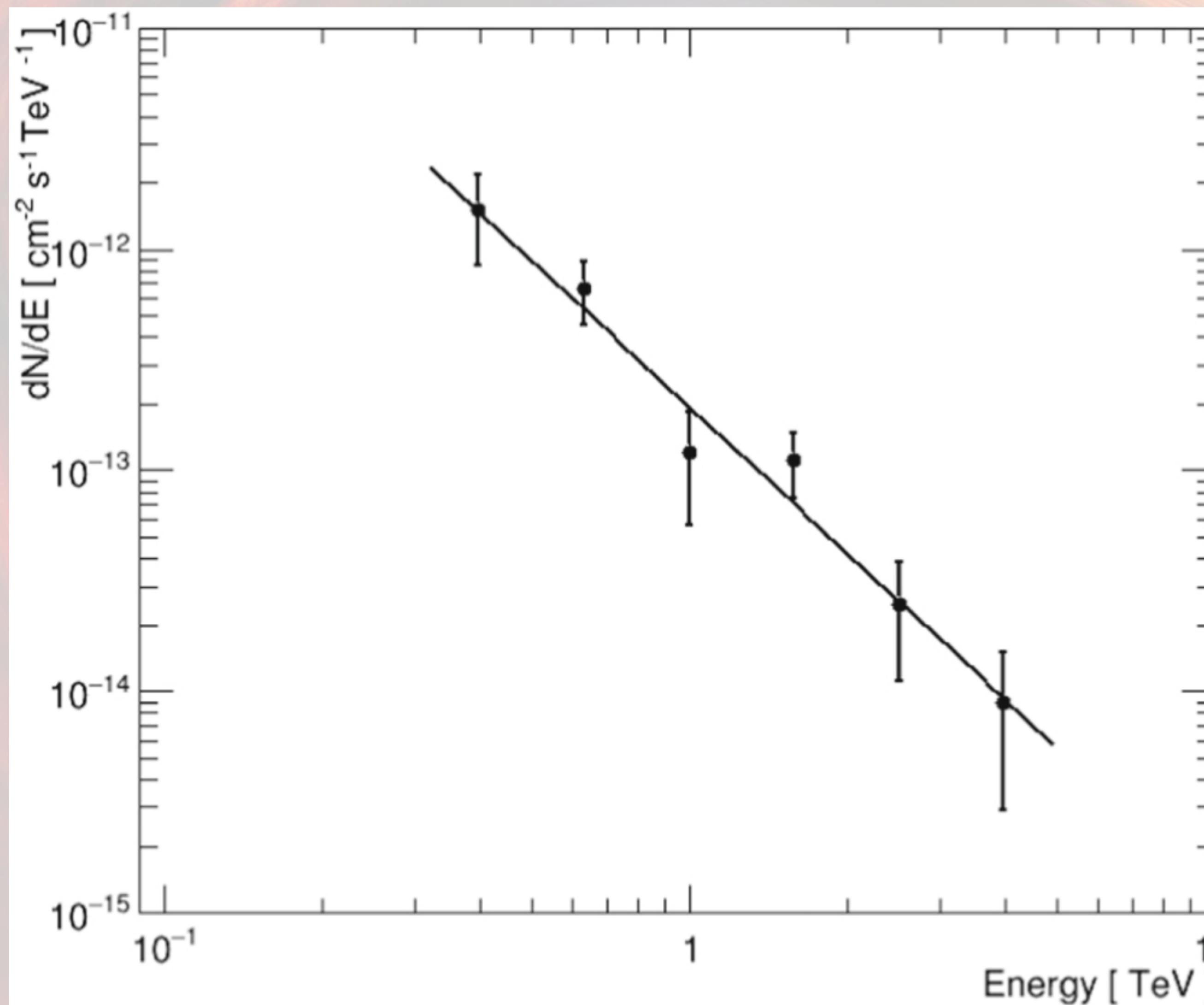
*That's all folks!*



# BACKUP SLIDES



Model Parameters	SLS		HHS		
	Core Model 1	Core Model 2&3	Core Model 1	Layer Model 2	Spine Model 3
$\Gamma_{bulk}$	2.0	2.0	2.0	5.0	8.0
$\theta$	10.0	10.0	10.0	10.0	5.0
$B$ (G)	0.055	0.12	0.062	0.0075	0.0035
$B_{eq}$ (G)	0.09	0.04	0.15	0.03	0.023
$R$ (cm)	$6.5 \times 10^{16}$	$3 \times 10^{17}$	$2.3 \times 10^{16}$	$1.15 \times 10^{17}$	$7 \times 10^{16}$
$\gamma_{min}$	$2 \times 10^3$	$2 \times 10^2$	$2 \times 10^3$	$3 \times 10^3$	$3 \times 10^3$
$\gamma_{max}$	$1 \times 10^6$	$4 \times 10^5$	$3 \times 10^6$	$2 \times 10^6$	$2 \times 10^6$
$\gamma_{break}$	$2 \times 10^4$	$4 \times 10^3$	$8.5 \times 10^4$	$3.5 \times 10^3$	$5 \times 10^3$
$p_1$	2.2	2.2	2.1	2.2	2.1
$p_2$	3.1	3.1	3.0	2.7	2.66
$U_B/U_e$	0.13	37.0	0.021	0.002	0.0003
<b>Powers</b>					
$L_{rad}$ (erg/s)	$2.4 \times 10^{41}$	$3.1 \times 10^{41}$	$5.1 \times 10^{41}$	$6.0 \times 10^{41}$	$1.3 \times 10^{41}$
$L_B$ (erg/s)	$1.7 \times 10^{41}$	$1.7 \times 10^{43}$	$2.6 \times 10^{40}$	$6.8 \times 10^{40}$	$1.4 \times 10^{40}$
$L_e$ (erg/s)	$5.3 \times 10^{41}$	$2.3 \times 10^{41}$	$6.3 \times 10^{41}$	$1.5 \times 10^{43}$	$2.1 \times 10^{43}$
$L_p$ (erg/s)	$1.6 \times 10^{41}$	$6.3 \times 10^{41}$	$1.4 \times 10^{41}$	$3.9 \times 10^{42}$	$5.0 \times 10^{42}$
$L_{kin}$ (erg/s)	$7.0 \times 10^{41}$	$8.6 \times 10^{41}$	$7.7 \times 10^{41}$	$1.9 \times 10^{43}$	$2.6 \times 10^{43}$

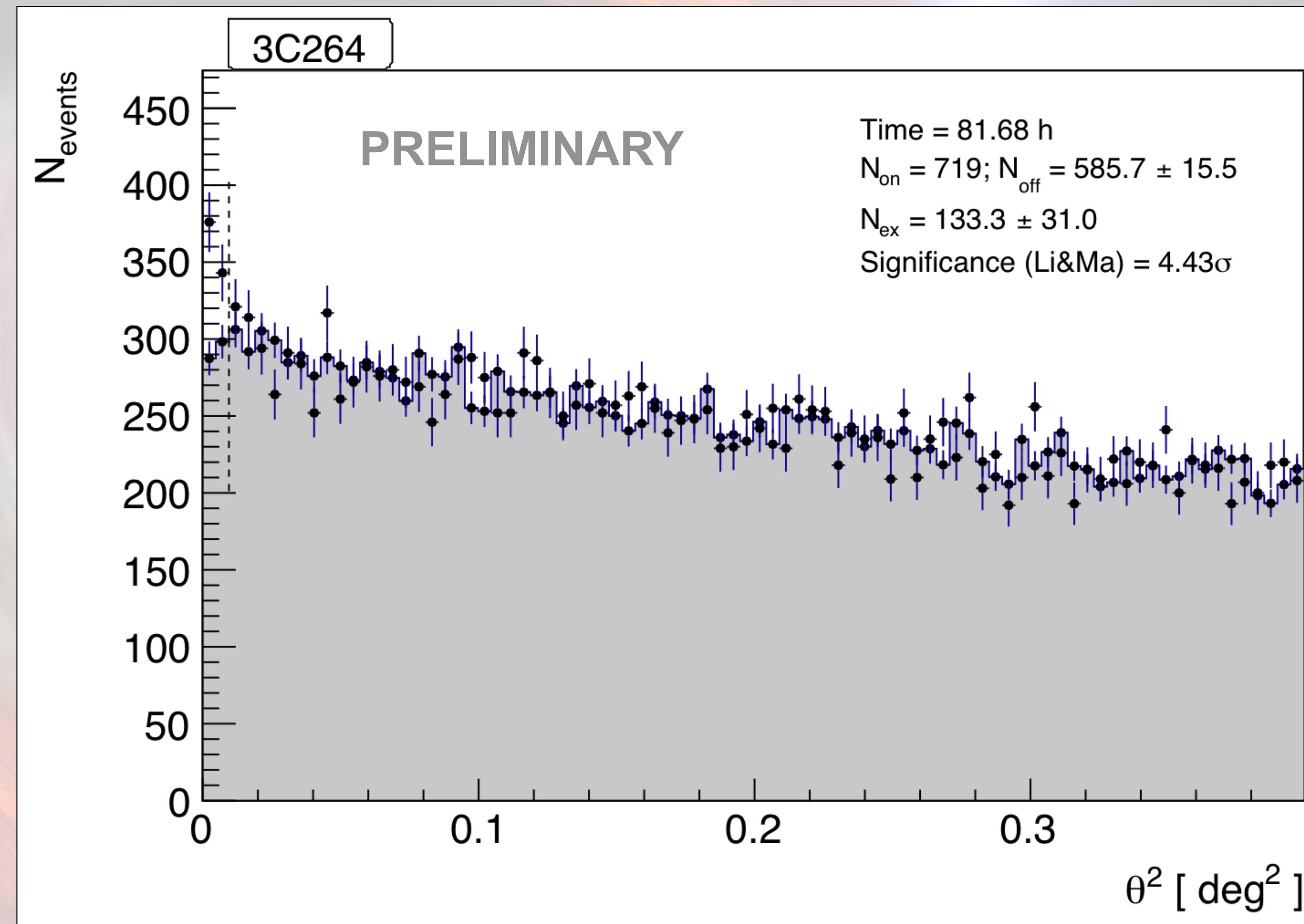


Significance = 7.8 sigmas

Int. time ~57 hrs

$\Gamma = 2.20 \pm 0.27$

$$F_{>315 \text{ GeV}} = (7.6 \pm 1.2_{\text{stat}} \pm 2.3_{\text{syst}}) \times 10^{-13} \text{ ph cm}^{-2} \text{ s}^{-2}$$



# Core emission

model name	name	par type	units	val	phys. bound. min	phys. bound. max	log	frozen
jet_leptonic	R	region_size	cm	3.000000e+17	1.000000e+03	1.000000e+30	False	False
jet_leptonic	R_H	region_position	cm	1.000000e+14	0.000000e+00	--	False	True
jet_leptonic	B	magnetic_field	gauss	8.000000e-03	0.000000e+00	--	False	False
jet_leptonic	NH_cold_to_rel_e	cold_p_to_rel_e_ratio		1.000000e+00	0.000000e+00	--	False	True
jet_leptonic	theta	jet-viewing-angle	deg	1.000000e+01	0.000000e+00	--	False	False
jet_leptonic	BulkFactor	jet-bulk-factor	lorentz-factor*	1.500000e+01	1.000000e+00	1.000000e+05	False	False
jet_leptonic	z_cosm	redshift		2.170000e-02	0.000000e+00	--	False	False
jet_leptonic	gmin	low-energy-cut-off	lorentz-factor*	1.000000e+02	1.000000e+00	1.000000e+09	False	False
jet_leptonic	gmax	high-energy-cut-off	lorentz-factor*	3.500000e+06	1.000000e+00	1.000000e+15	False	False
jet_leptonic	N	emitters_density	1 / cm3	9.000000e-01	0.000000e+00	--	False	False
jet_leptonic	gamma_break	turn-over-energy	lorentz-factor*	8.000000e+03	1.000000e+00	1.000000e+09	False	False
jet_leptonic	p	LE_spectral_slope		2.000000e+00	-1.000000e+01	1.000000e+01	False	False
jet_leptonic	p_1	HE_spectral_slope		2.900000e+00	-1.000000e+01	1.000000e+01	False	False

delta=3.84

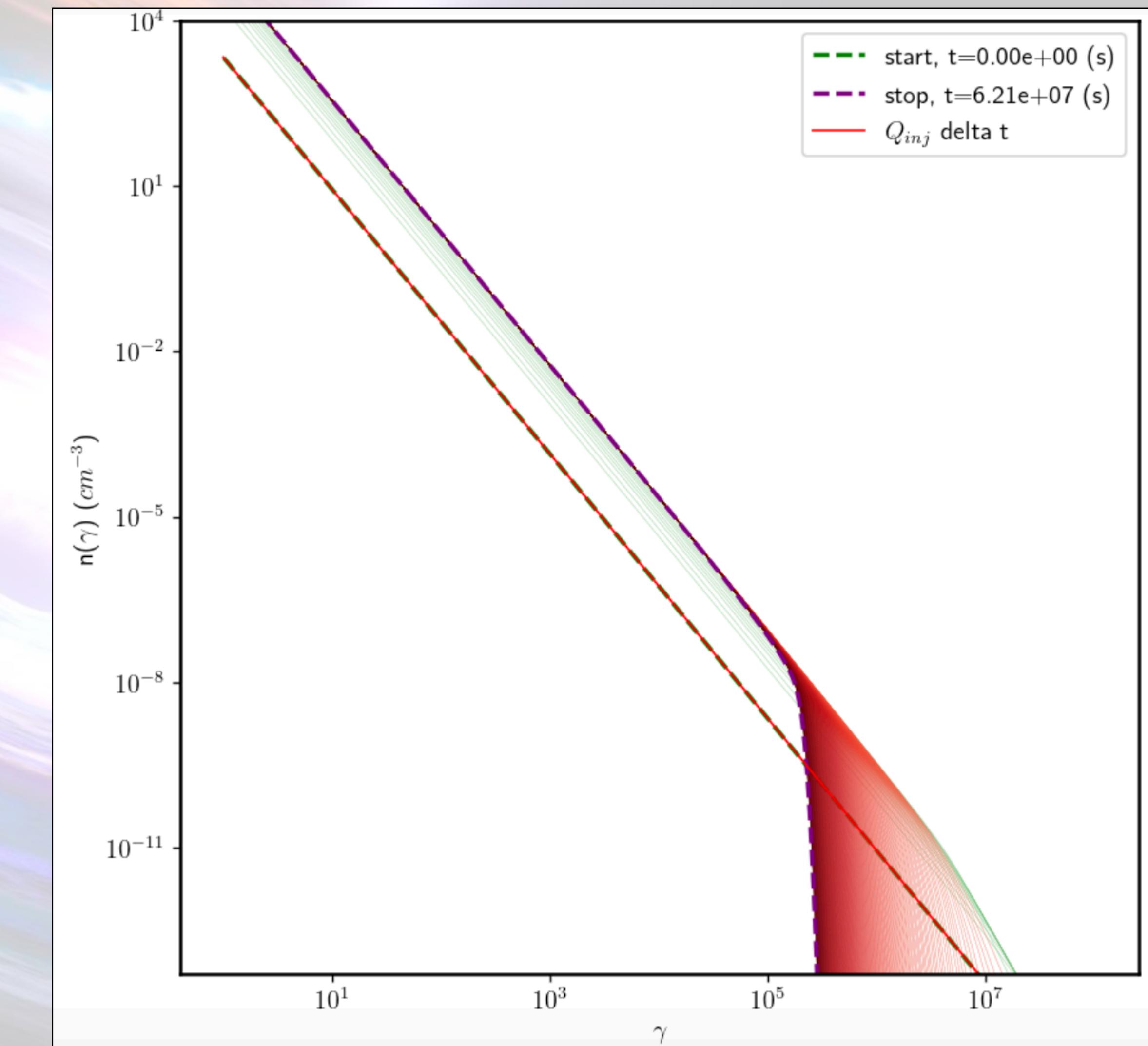
Core  $\rightarrow U_B/U_e = 0.006$

jet_L_Sync	jet Lum.	erg / s	2.960000e+42
jet_L_SSC	jet Lum.	erg / s	1.402269e+42
jet_L_EC_Disk	jet Lum.	erg / s	0.000000e+00
jet_L_EC_BLR	jet Lum.	erg / s	0.000000e+00
jet_L_EC_DT	jet Lum.	erg / s	0.000000e+00
jet_L_EC_CMB	jet Lum.	erg / s	0.000000e+00
jet_L_pp_gamma	jet Lum.	erg / s	0.000000e+00
jet_L_rad	jet Lum.	erg / s	4.362269e+42
jet_L_kin	jet Lum.	erg / s	3.347592e+45
jet_L_tot	jet Lum.	erg / s	3.356801e+45
jet_L_e	jet Lum.	erg / s	7.729928e+44
jet_L_B	jet Lum.	erg / s	4.845833e+42
jet_L_p_cold	jet Lum.	erg / s	2.574600e+45

# Injection of particles

model name	name	par type	units	val	phys. bound. min	phys. bound. max	log	frozen
jet_time_ev	duration	time_grid	s	6.220800e+07	0.000000e+00	--	False	True
jet_time_ev	gmin_grid	gamma_grid		1.000000e+00	0.000000e+00	--	False	True
jet_time_ev	gmax_grid	gamma_grid		1.000000e+08	0.000000e+00	--	False	True
jet_time_ev	gamma_grid_size	gamma_grid		1.500000e+03	0.000000e+00	--	False	True
jet_time_ev	TStart_Inj	time_grid	s	0.000000e+00	0.000000e+00	--	False	True
jet_time_ev	TStop_Inj	time_grid	s	2.500000e+06	0.000000e+00	--	False	True
jet_time_ev	T_esc_rad	escape_time	(R/c)*	1.000000e+10	--	--	False	True
jet_time_ev	Esc_Index_rad	fp_coeff_index		0.000000e+00	--	--	False	True
jet_time_ev	R_rad_start	region_size	cm	1.000000e+16	0.000000e+00	--	False	True
jet_time_ev	R_H_rad_start	region_position	cm	1.000000e+17	0.000000e+00	--	False	True
jet_time_ev	m_B	magnetic_field_index		1.000000e+00	1.000000e+00	2.000000e+00	False	True
jet_time_ev	t_jet_exp	exp_start_time	s	1.000000e+09	0.000000e+00	--	False	True
jet_time_ev	beta_exp_R	beta_expansion	v/c*	1.000000e+00	0.000000e+00	1.000000e+00	False	True
jet_time_ev	B_rad	magnetic_field	G	8.000000e-03	0.000000e+00	--	False	True
jet_time_ev	t_size	time_grid		1.000000e+03	0.000000e+00	--	False	True
jet_time_ev	num_samples	time_ev_output		3.000000e+02	0.000000e+00	--	False	True
jet_time_ev	L_inj	inj_luminosity	erg / s	3.000000e+41	0.000000e+00	--	False	True

model name	name	par type	units	val	phys. bound. min	phys. bound. max	log	frozen
jet_leptonic	R	region_size	cm	1.000000e+16	1.000000e+03	1.000000e+30	False	False
jet_leptonic	R_H	region_position	cm	1.000000e+14	0.000000e+00	--	False	True
jet_leptonic	B	magnetic_field	gauss	8.000000e-03	0.000000e+00	--	False	False
jet_leptonic	NH_cold_to_rel_e	cold_p_to_rel_e_ratio		1.000000e+00	0.000000e+00	--	False	True
jet_leptonic	theta	jet-viewing-angle	deg	5.000000e+00	0.000000e+00	--	False	False
jet_leptonic	BulkFactor	jet-bulk-factor	lorentz-factor*	8.000000e+00	1.000000e+00	1.000000e+05	False	False
jet_leptonic	z_cosm	redshift		2.170000e-02	0.000000e+00	--	False	False
jet_leptonic	gmin	low-energy-cut-off	lorentz-factor*	1.000000e+00	1.000000e+00	1.000000e+09	False	False
jet_leptonic	gmax	high-energy-cut-off	lorentz-factor*	1.000000e+06	1.000000e+00	1.000000e+15	False	False
jet_leptonic	N	emitters_density	1 / cm <sup>3</sup>	1.000000e+02	0.000000e+00	--	False	False
jet_leptonic	gamma_break	turn-over-energy	lorentz-factor*	1.000000e+04	1.000000e+00	1.000000e+09	False	False
jet_leptonic	p	LE_spectral_slope		2.500000e+00	-1.000000e+01	1.000000e+01	False	False
jet_leptonic	p_1	HE_spectral_slope		3.500000e+00	-1.000000e+01	1.000000e+01	False	False



# Injection of particles

