

Neutrinos and UHECRs from blazars

From a single-source model to a population study

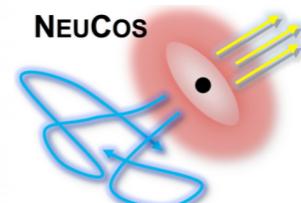
Xavier Rodrigues

ICRC 2019
July 25, 2019
Madison, WI



Talk on behalf of Xavier given by
Anatoli Fedynitch
University of Alberta

1



Introduction

- > We have investigated the possibility that UHECRs are accelerated in blazars and produce neutrinos through proton-photon interactions
- > How does the chemical CR composition affect the emitted neutrino spectrum?
- > What type of blazars (FSRQs, BL Lacs) produce neutrinos more efficiently?
- > What diffuse neutrino flux can we expect from the entire cosmological blazar distribution?

1. A model for blazars with heavy nuclei

Source model

Model ingredient list

Spherical radiation zone

$$R = c \times t_{\text{flare}} = c \times 1\text{day}$$

Magnetic field scaling as power law of L_γ

2nd order Fermi acceleration of protons

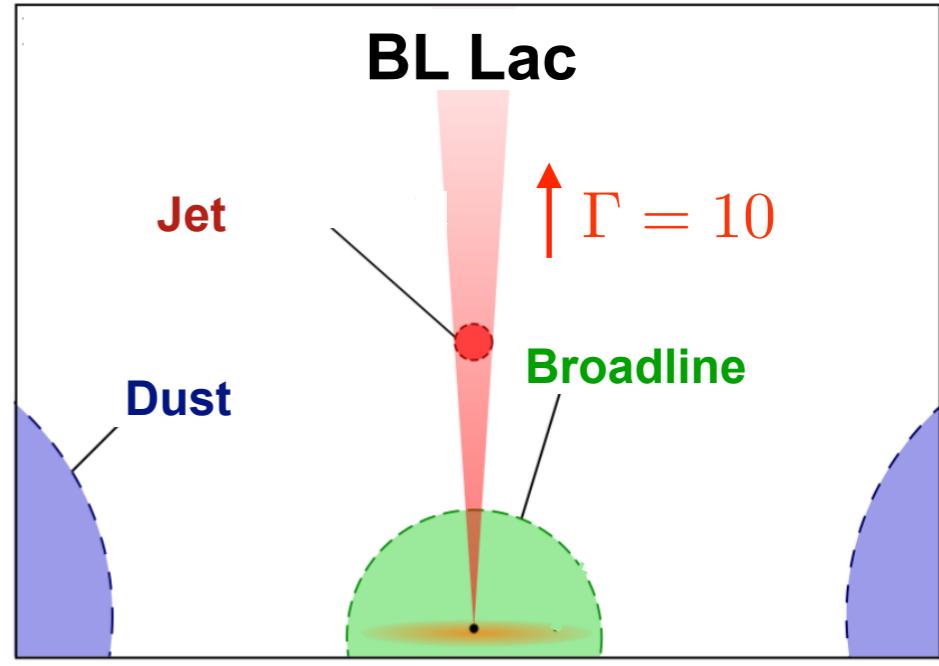
Different geometries for BL Lacs and FSRQs

low acceleration efficiency of $1\text{e-}3$

Low-luminosity blazars

No evidence of external fields

One-zone model



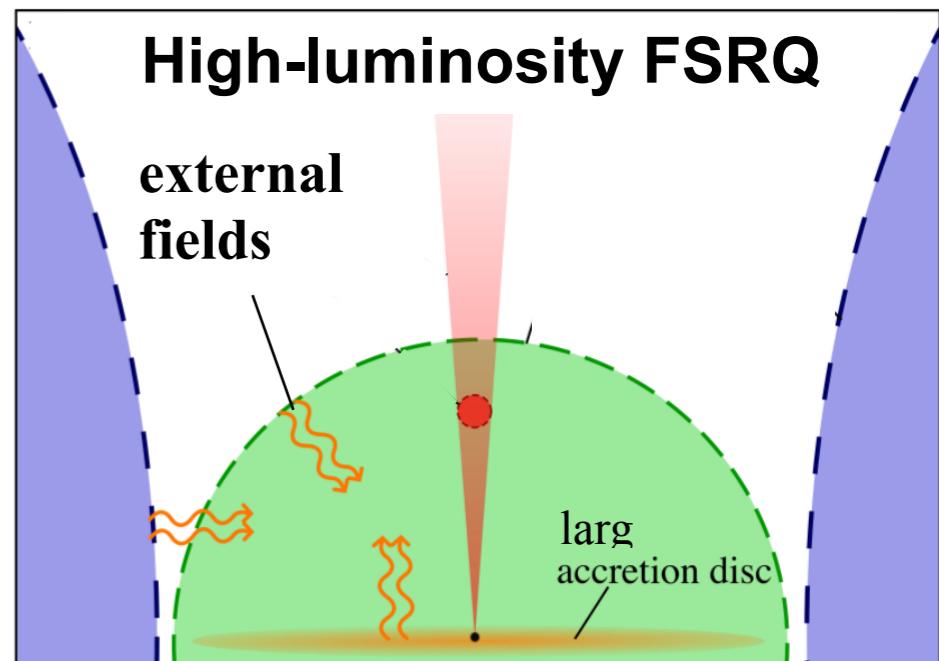
High-luminosity FSRQ

external fields

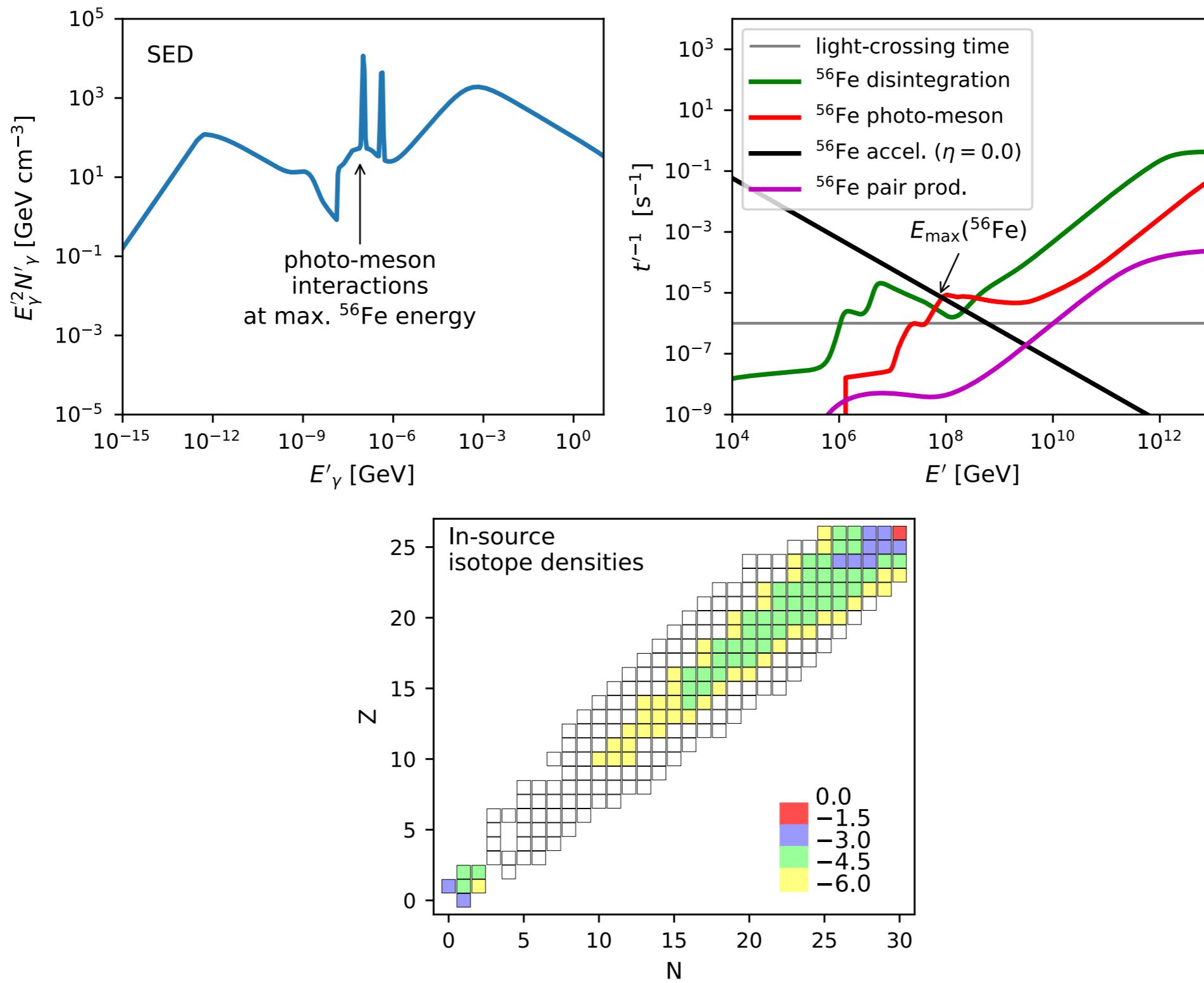
High-luminosity FSRQs

Large broadline region and dust torus

External contributions to the target photon field for CR interactions



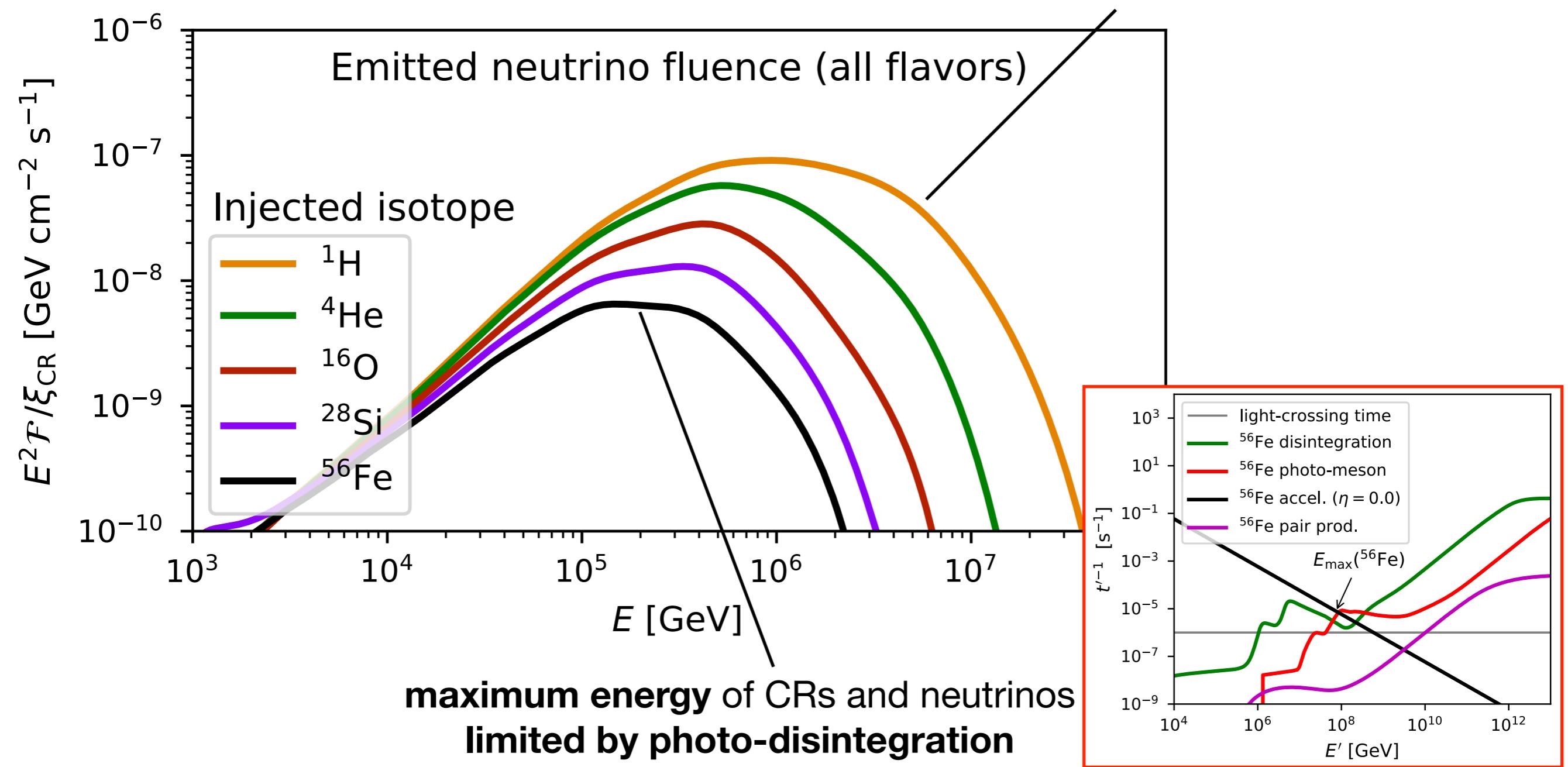
Nuclear disintegration in the jet



Based on the model in XR, Fedynitch, Gao, Boncioli, Winter, ApJ 854 (2018) no.1, 54

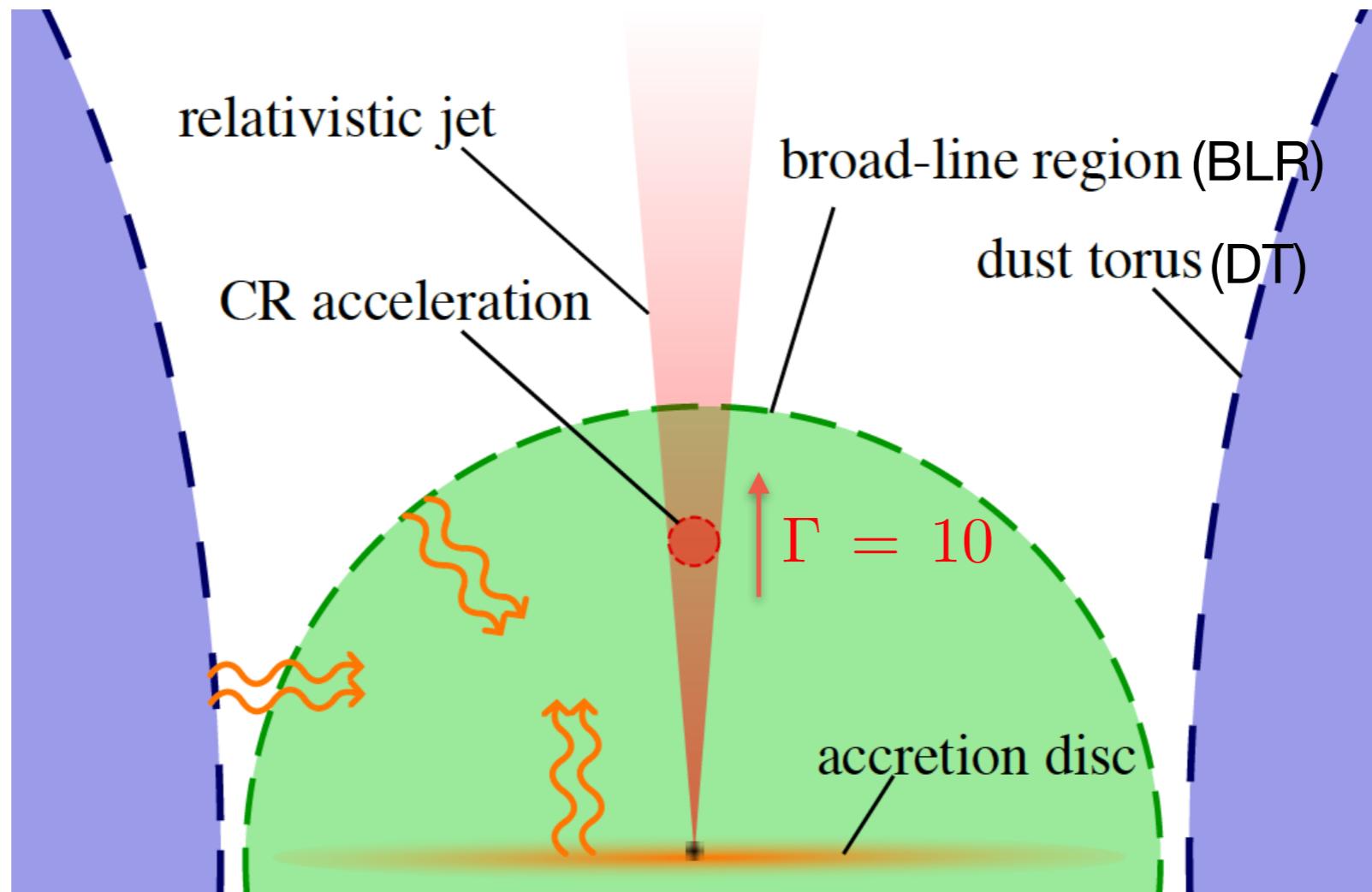
Neutrino emission from the jet

proton injection leads to
highest neutrino energy and yield



Based on the model in XR, Fedynitch, Gao, Boncioli, Winter, ApJ 854 (2018) no.1, 54

A model for High-Luminosity FSRQs



$$r_{\text{BLR}} \propto r_{\text{disk}} \propto \sqrt{L}$$

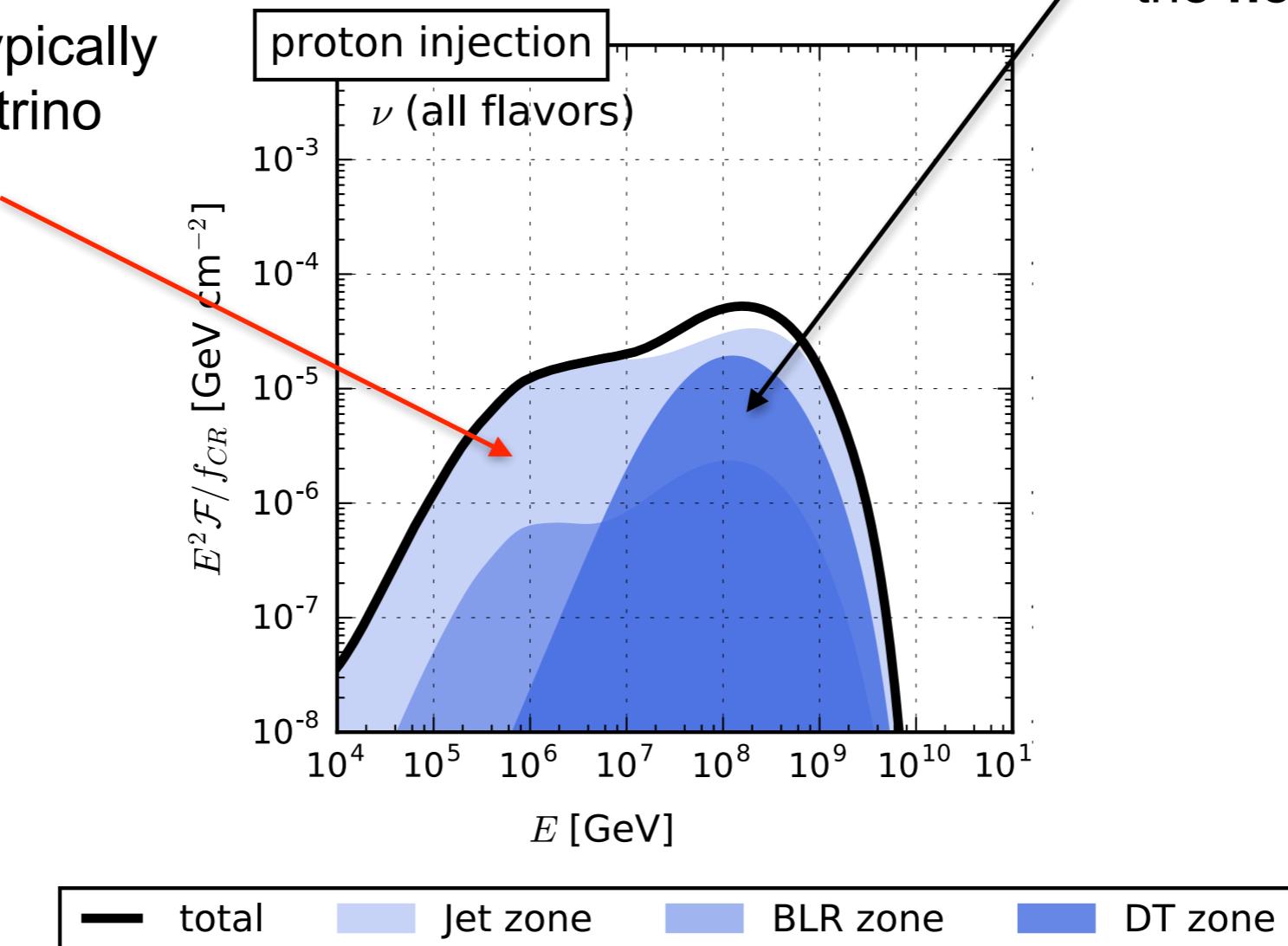
Murase et al, PRD 90 (2014)
Ghisellini et al MNRAS 387 (2008)

In bright FSRQs, the jet blob will lie inside BLR

What is the effect of the external zones?

- Jet emission typically dominates neutrino fluence

➤ External zones can contribute significantly to the neutrino peak

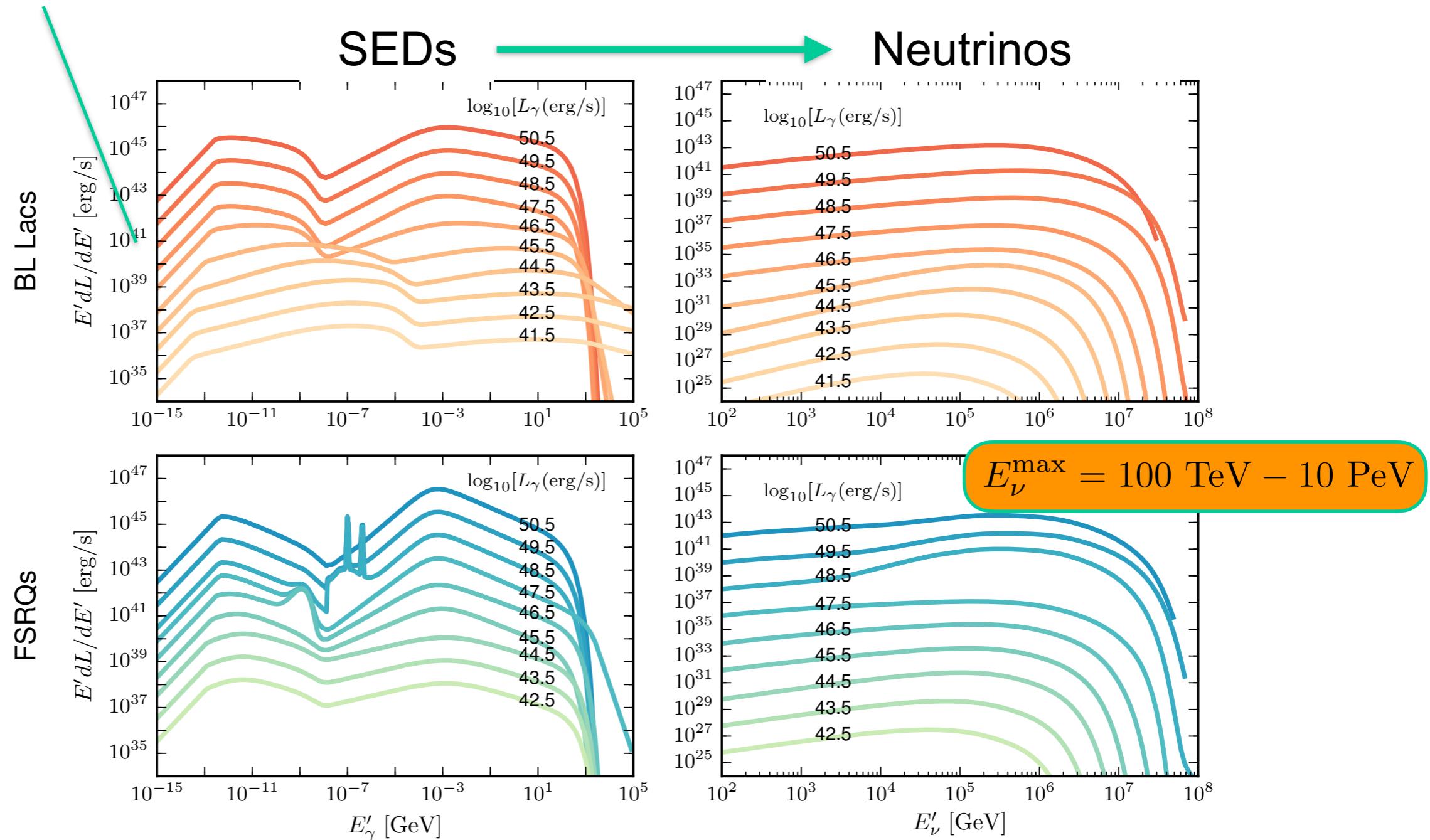


XR, Fedynitch, Gao, Boncioli, Winter, ApJ 854 (2018) no.1, 54

(see also Murase et al, PRD 90 (2014))

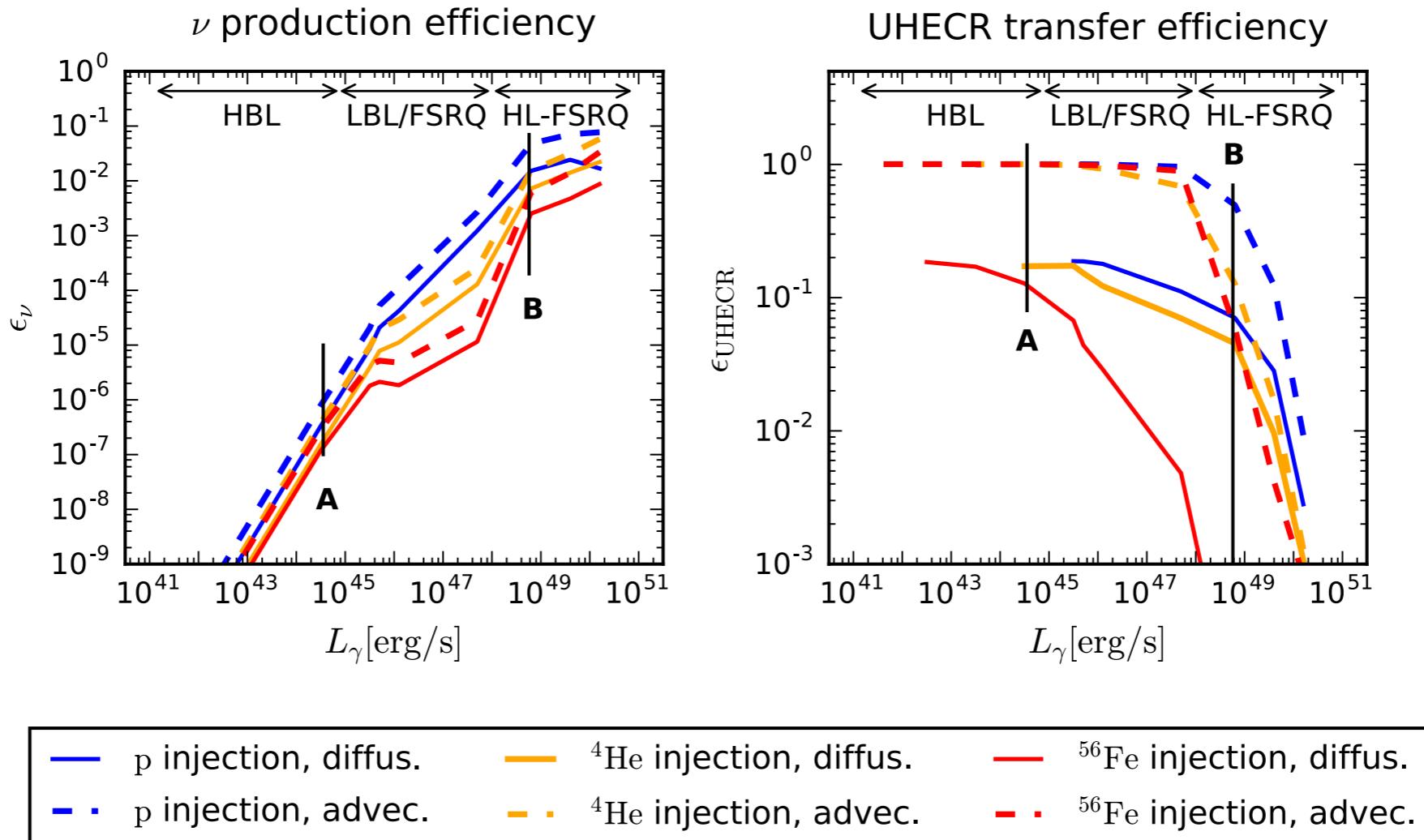
Applying the model to the “Fermi” blazar sequence

Take SEDs as input from the blazar sequence by [Ghisellini+ 2017](#)



Neutrino and CR efficiency of blazars

Neutrinos vs CRs: opposite trends



XR, Fedynitch, Gao, Boncioli, Winter, ApJ 854 (2018) no.1, 54

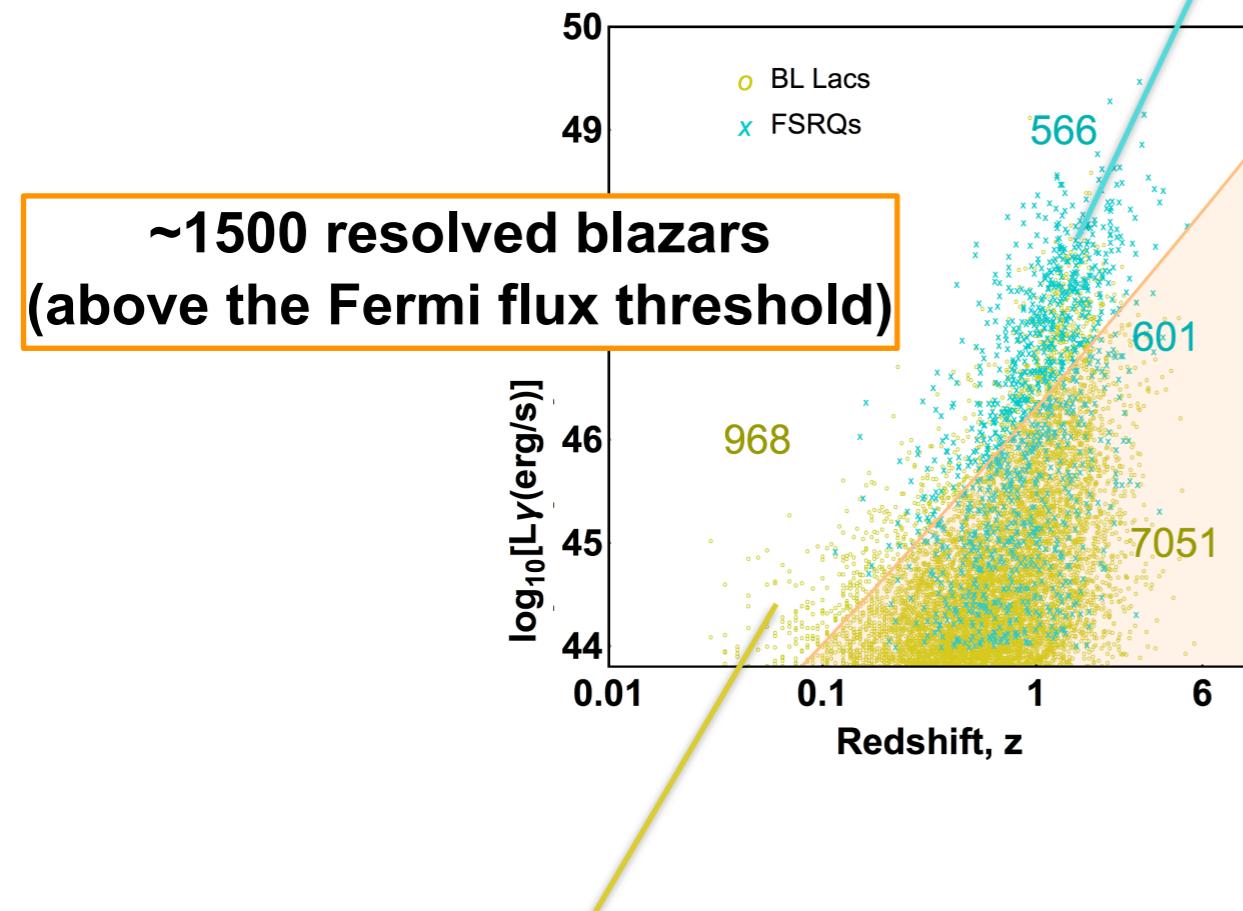
Low-lum blazars: good CR emitters
High-lum blazars: good neutrino emitters

2. Implications for the entire blazar population

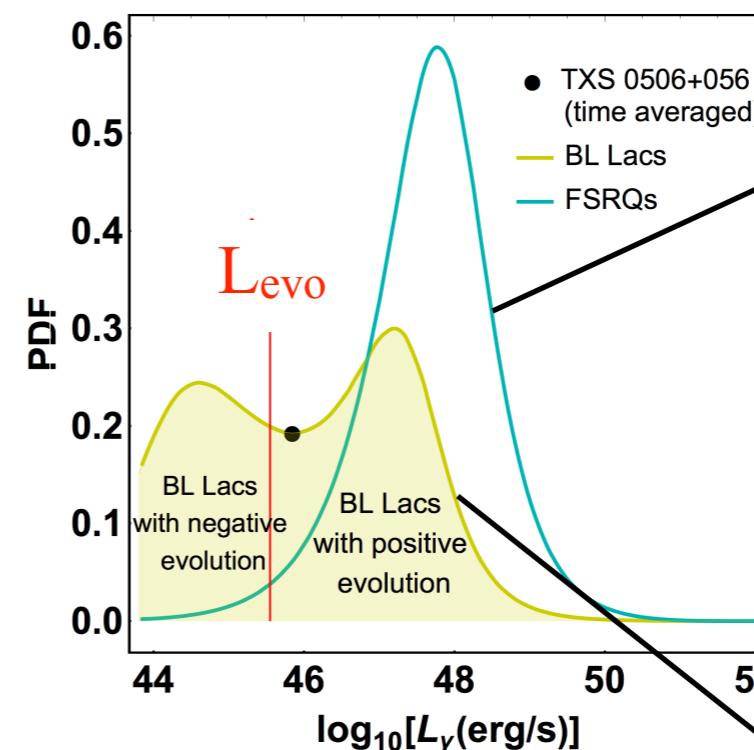
Source distribution

Based on Ajello et al. 2012 (1110.3787) and 2014 (1310.0006)

50% of FSRQs resolved by *Fermi*



~1500 resolved blazars
(above the Fermi flux threshold)



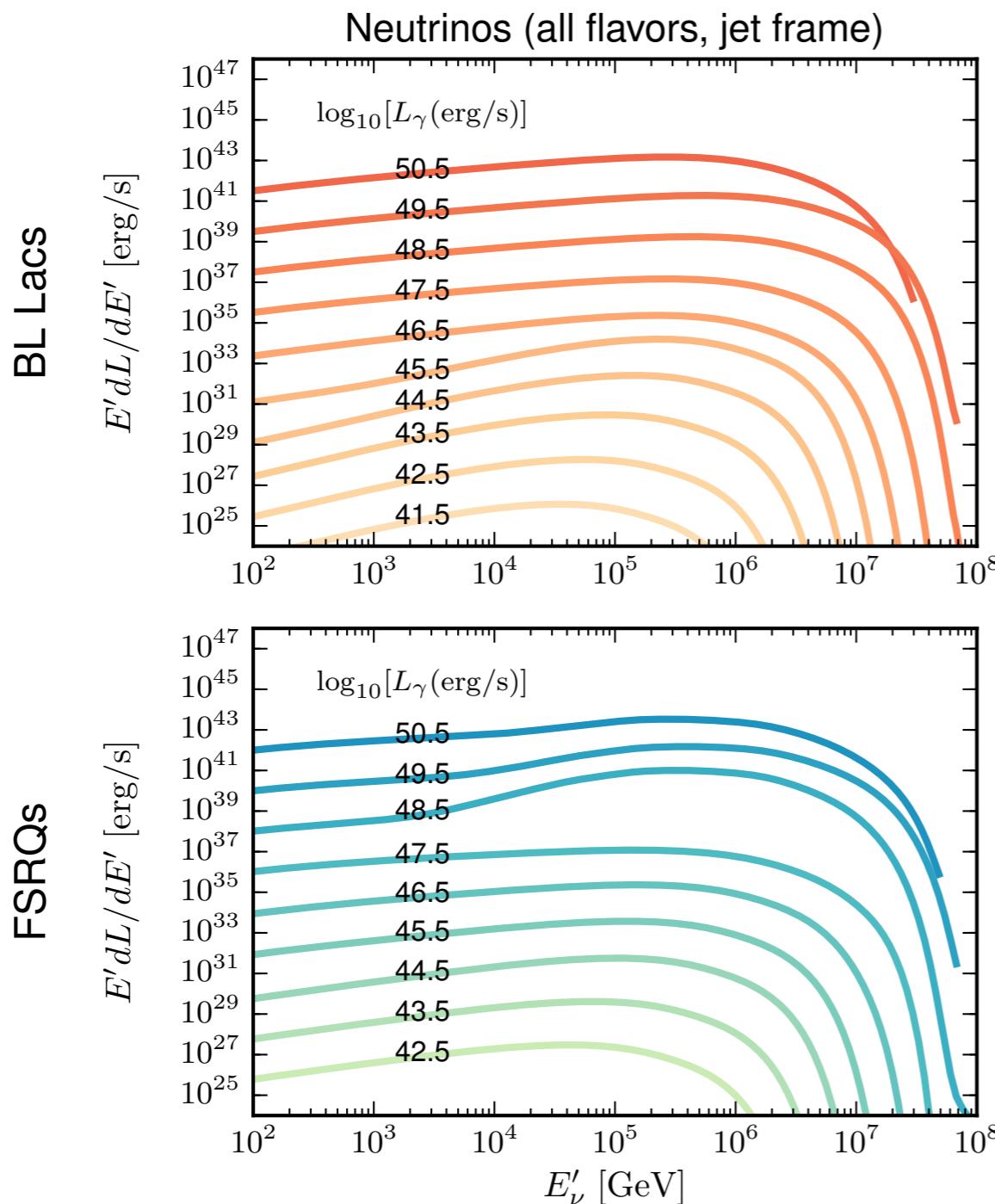
FSRQs peak around 10^{48} erg/s

2 populations of BL Lacs

only 15% of BL Lacs resolved by *Fermi*

Palladino, XR, Gao & Winter, ApJ 871 (2019) no.1, 41

Baryonic loading



The model provides the **neutrino production efficiency** as a function of luminosity

$$L_\nu = \eta_\nu \times \xi_p \times L_\gamma$$

The **Baryonic loading** remains a free parameter:

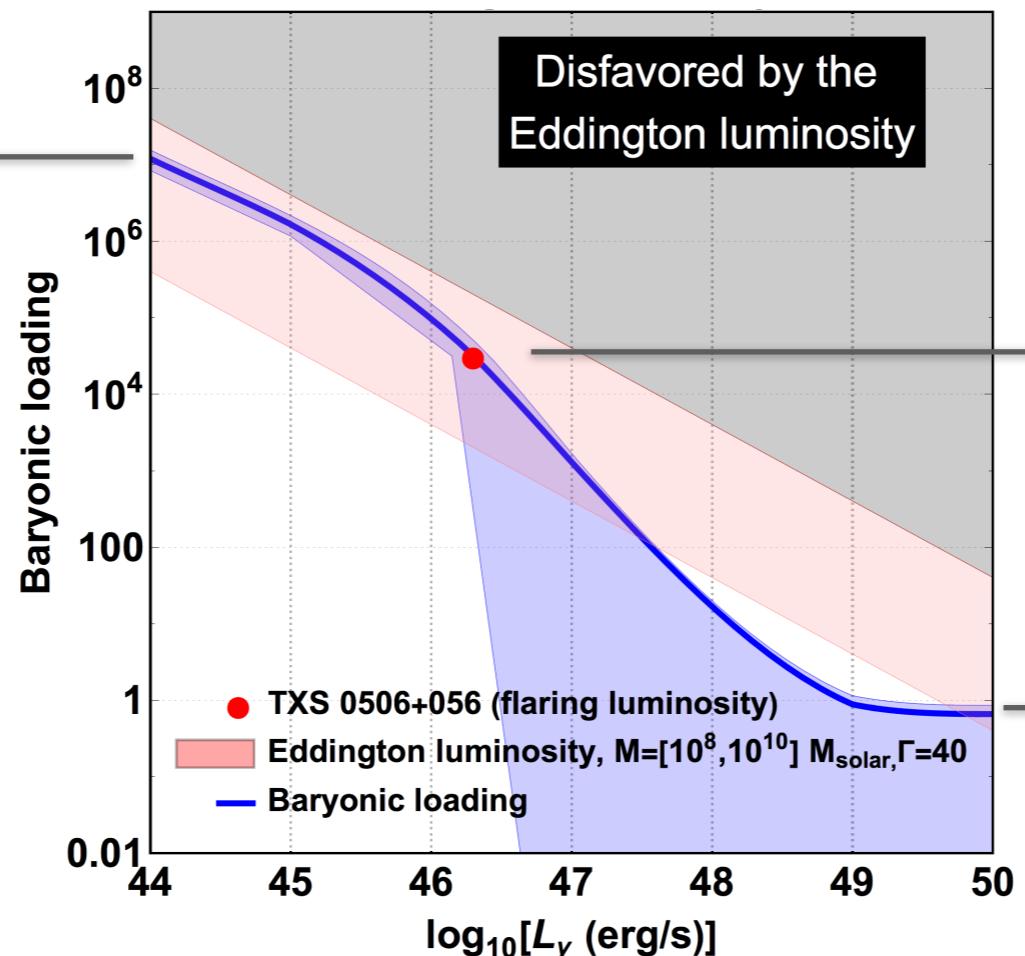
$$\xi_p = \frac{L_{\text{CR}}}{L_\gamma}$$

Palladino, XR, Gao & Winter, ApJ 871 (2019) no.1, 41

Baryonic loading with luminosity

High baryonic loading
of low-luminosity
sources
(mostly **BL Lacs!**)

$L_\nu / L_\gamma = 10.5\%$
(model-independent)



TXS 0506+056 flare:
intermediate baryonic
loading $\xi_p = 3 \times 10^4$

High-luminosity sources
(mostly **FSRQs!**)
must be predominantly
leptonic

$L_\nu / L_\gamma < 0.5\%$
(model-independent)

Palladino, XR, Gao & Winter, ApJ 871 (2019) no.1, 41

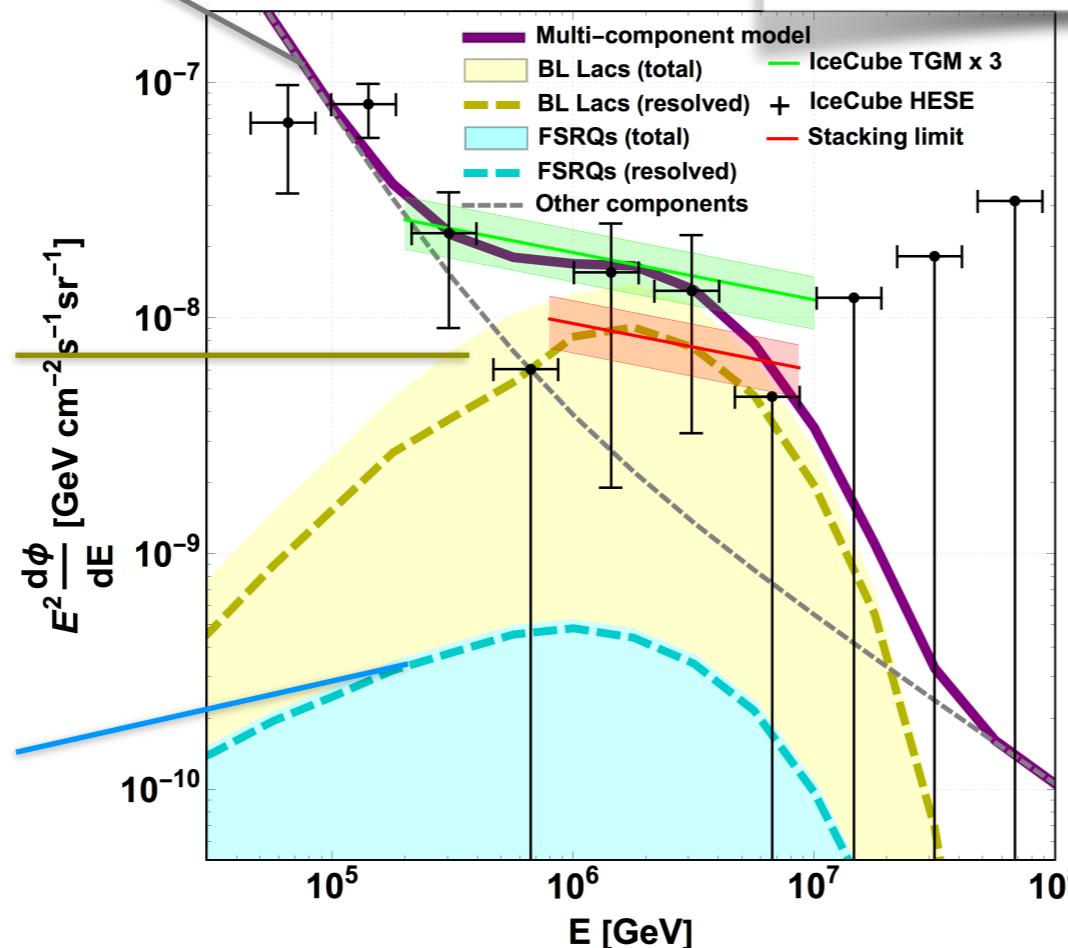
Diffuse neutrino spectrum

$E \sim 100$ TeV:
galactic component +
residual atmospheric background
[\[Palladino & Winter 1801.07277\]](#)

In order for power to the IceCube flux:

- **BL Lacs** must have high baryonic content (with baryonic loadings up to 10^6)
- **FSRQs** must be almost purely leptonic

BL Lacs
can power the PeV
neutrino flux

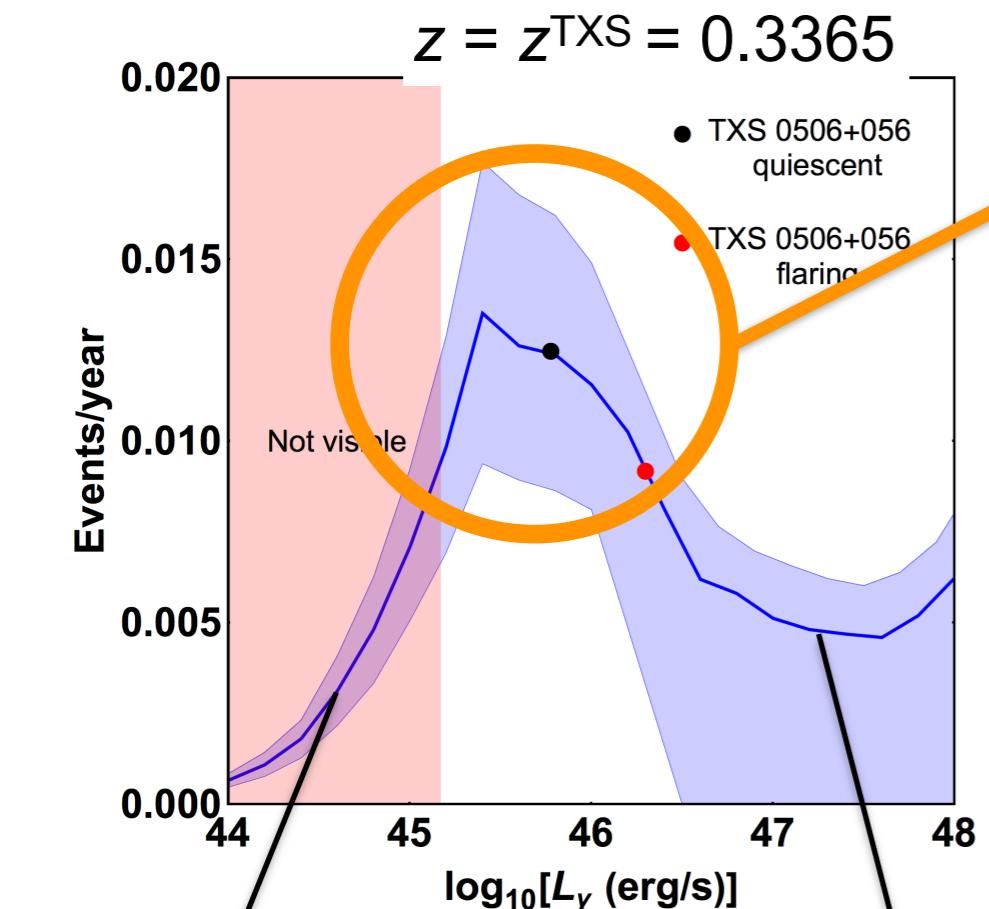


FSRQ contribution
must be **highly suppressed**
not to violate
stacking bounds

[Palladino, XR, Gao & Winter, ApJ 871 \(2019\) no.1, 41](#)

The case of TXS 0506+056

(the first potential neutrino blazar)



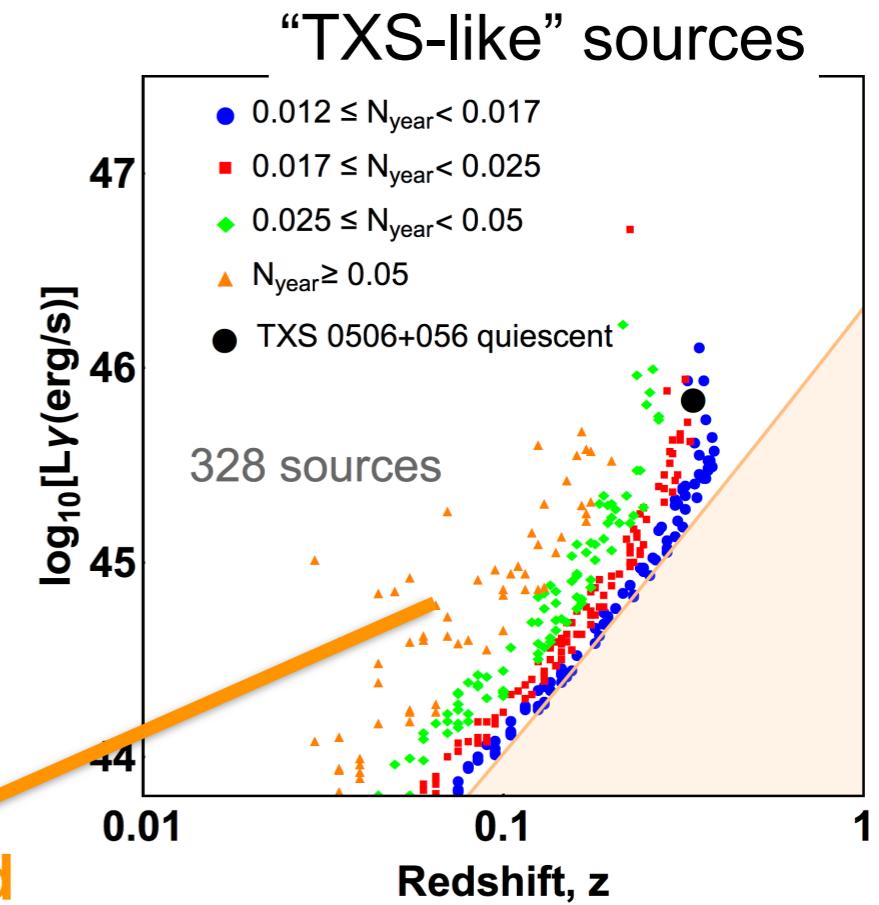
Low luminosities:
low neutrino efficiency

High luminosities:
neutrino flux suppressed by low baryonic loading

We expect future detections to come from sources with luminosities similar to TXS

328 catalogued blazars
capable of emitting more neutrinos than TXS

Palladino, XR, Gao & Winter, ApJ 871 (2019) no.1, 41



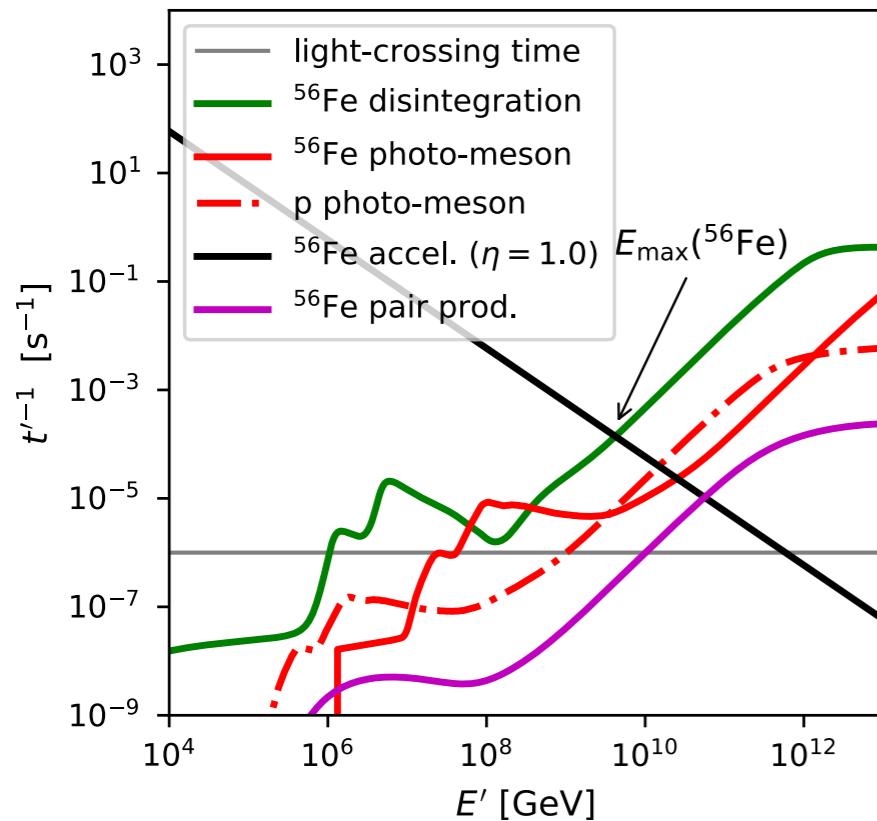
Expected **0.96 correlations / year**

Conclusion

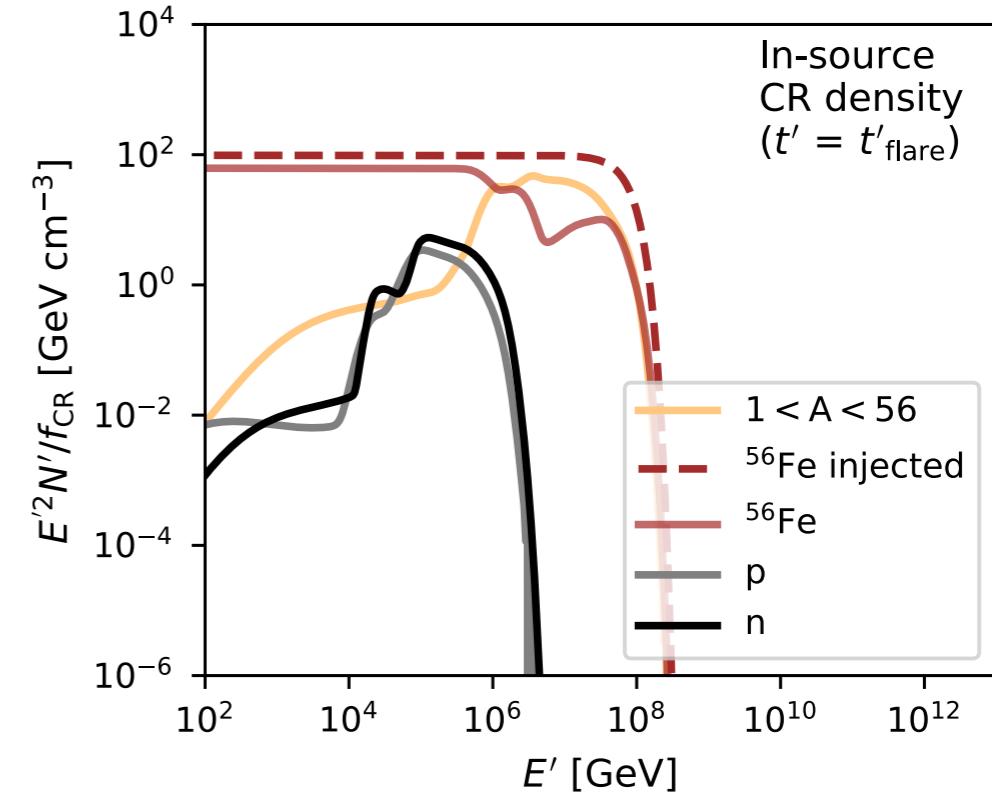
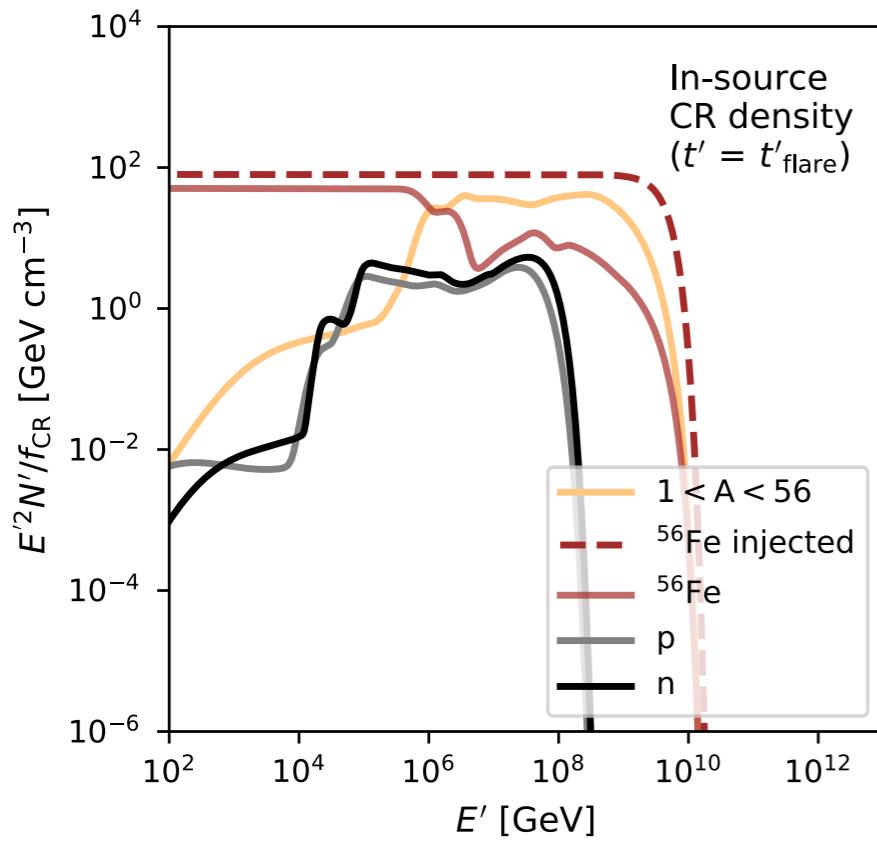
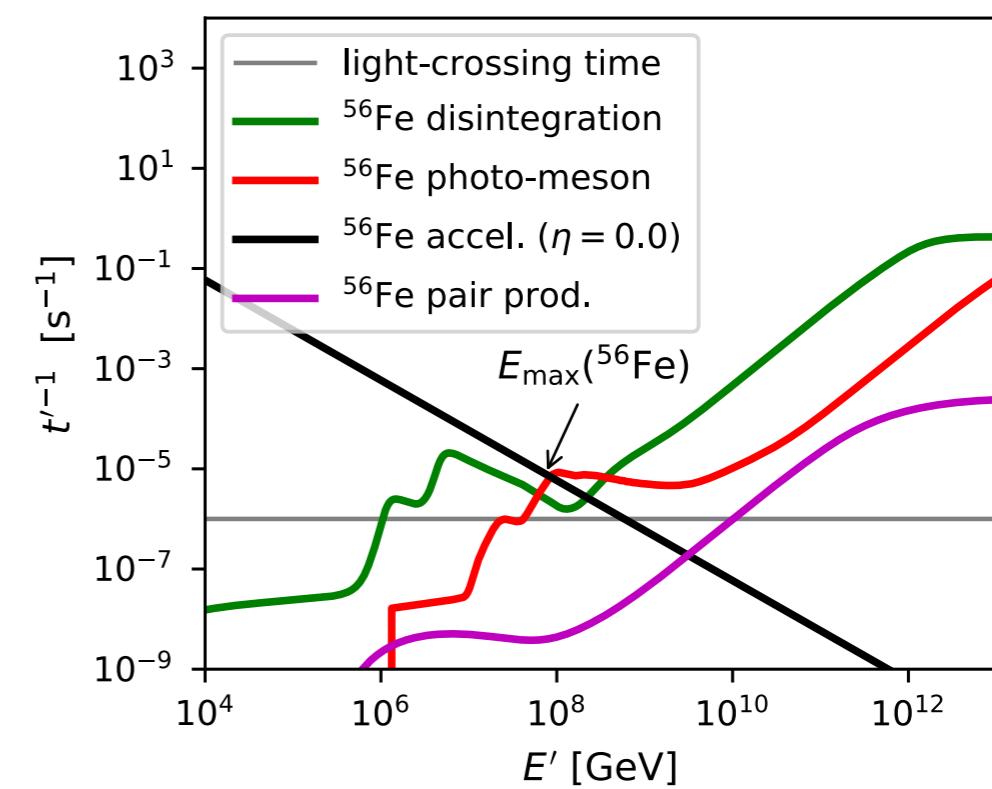
- We have quantified the UHECR and neutrino efficiency of blazars:
 - Powerful blazars like **FSRQs** are **good neutrino emitters** with low UHECR efficiency
 - **HBL Lacs** are good sources of UHECR, with **low neutrino production efficiency**
 - Heavier chemical compositions lead to lower neutrino cutoff energies due to disintegration
-
- Unresolved blazars can **power the diffuse IceCube PeV flux** without violating the limits imposed by lack of correlations with known sources, **provided that:**
 - High-luminosity blazars, especially **FSRQs**, must be **mostly leptonic**
 - BL Lacs have high baryonic loadings (without exceeding typical Eddington luminosity)
 - We expect future coincidences to be associated to nearby sources with $L_\gamma \sim 10^{45}$ erg/s

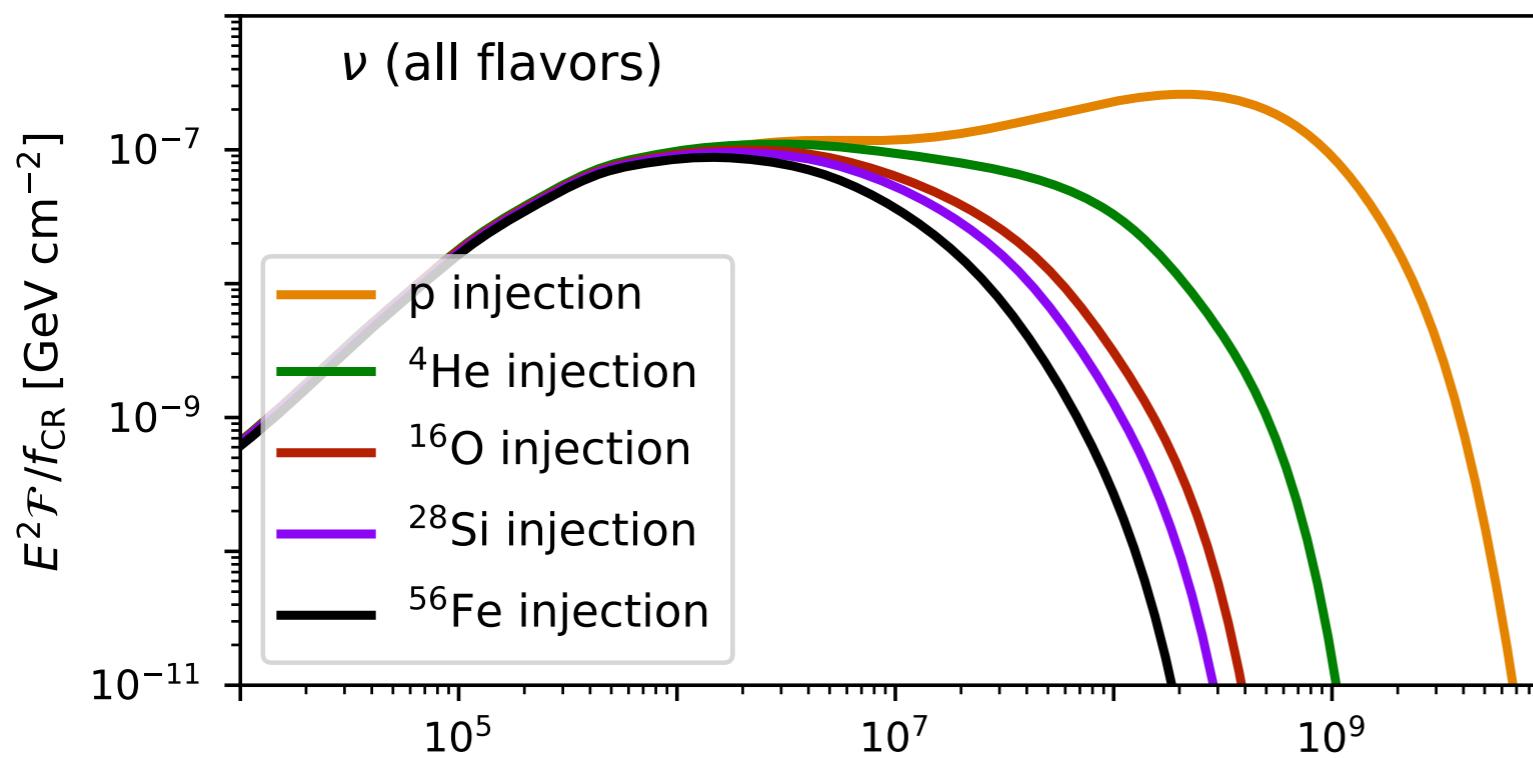
Backup

acceleration efficiency 1

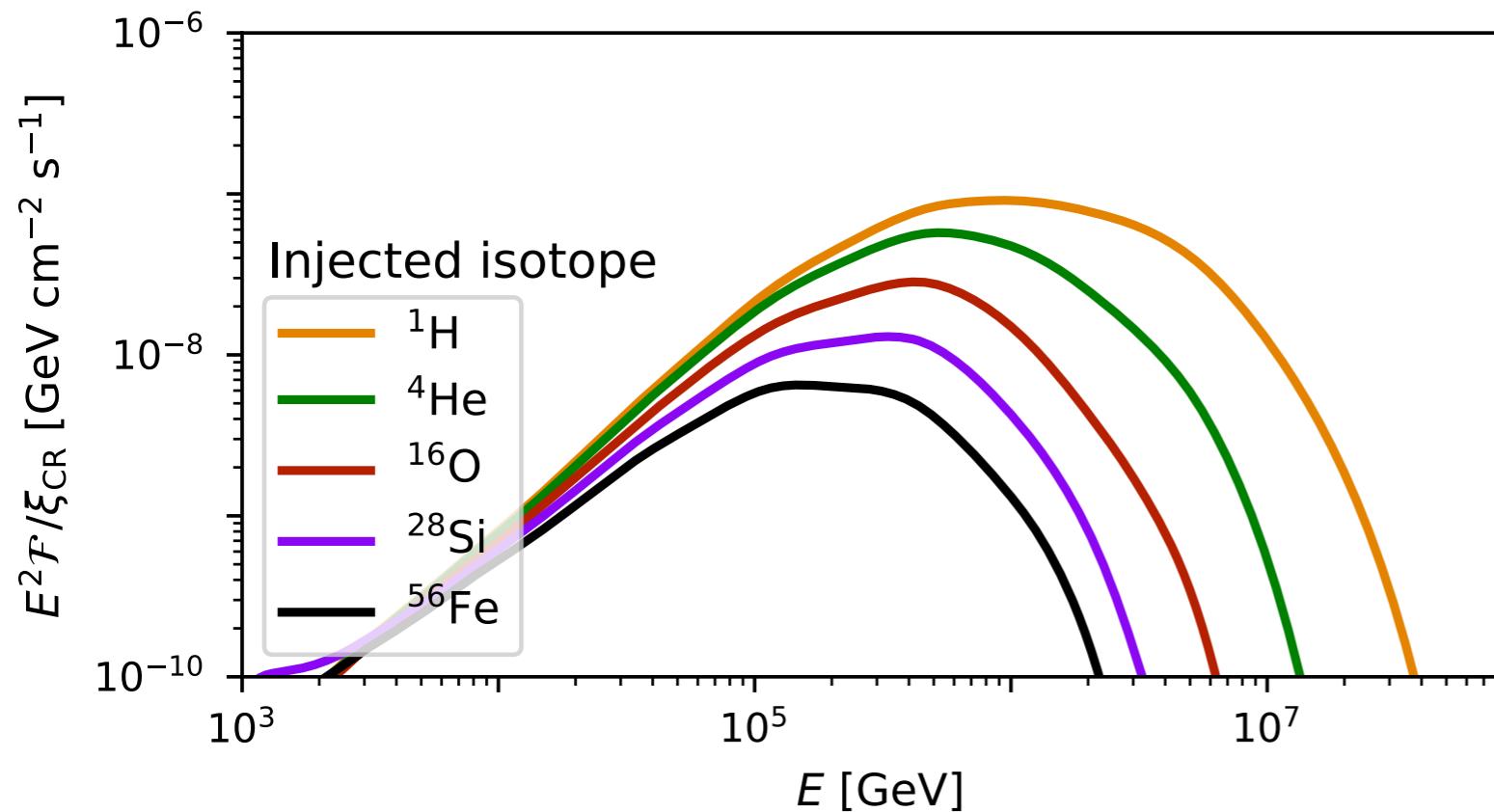


acceleration efficiency 1e-3





acceleration efficiency 1



acceleration efficiency 1e-3

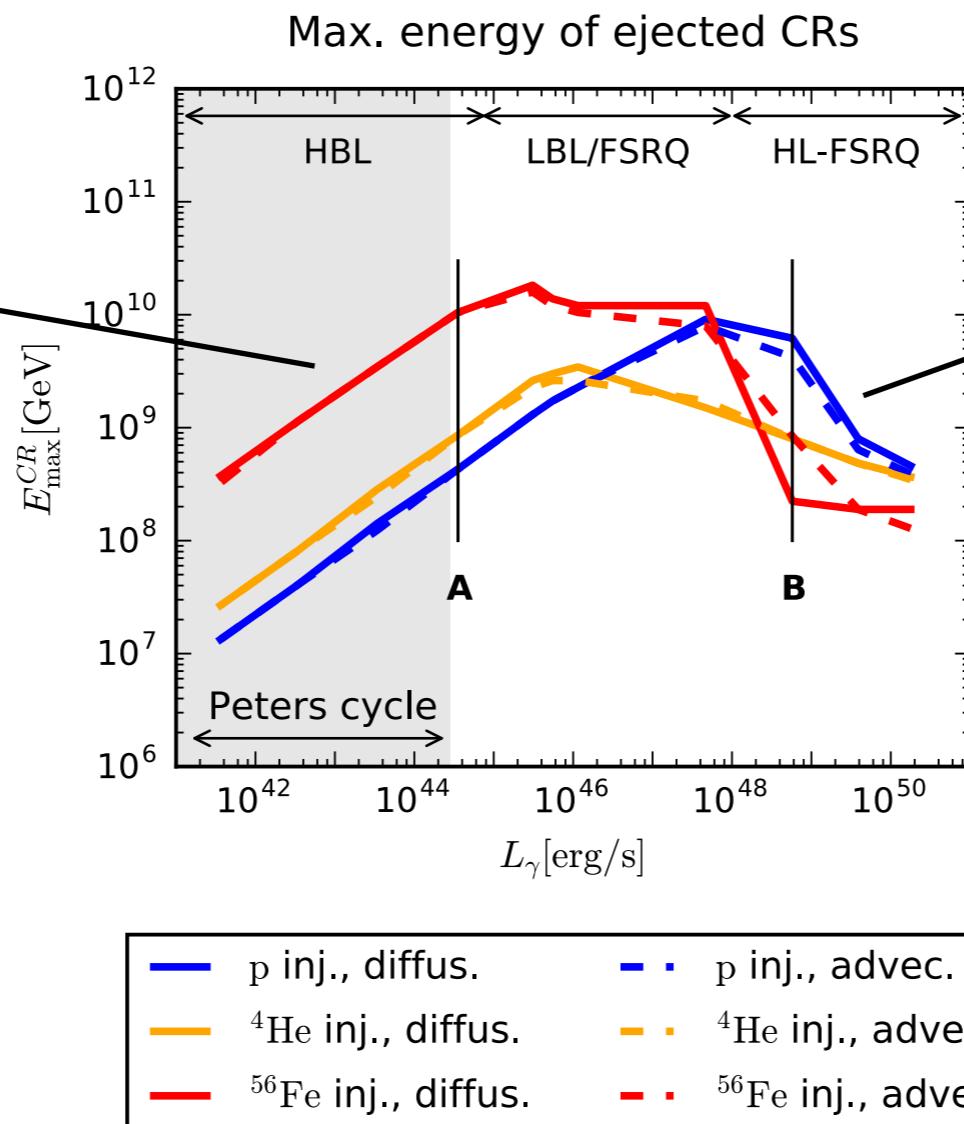
Maximum ejected CR energy

Low luminosity

- > E_{max} only limited by blob size

↓

$$E_{max} \sim B \sim L_{\gamma}^{1/2}$$



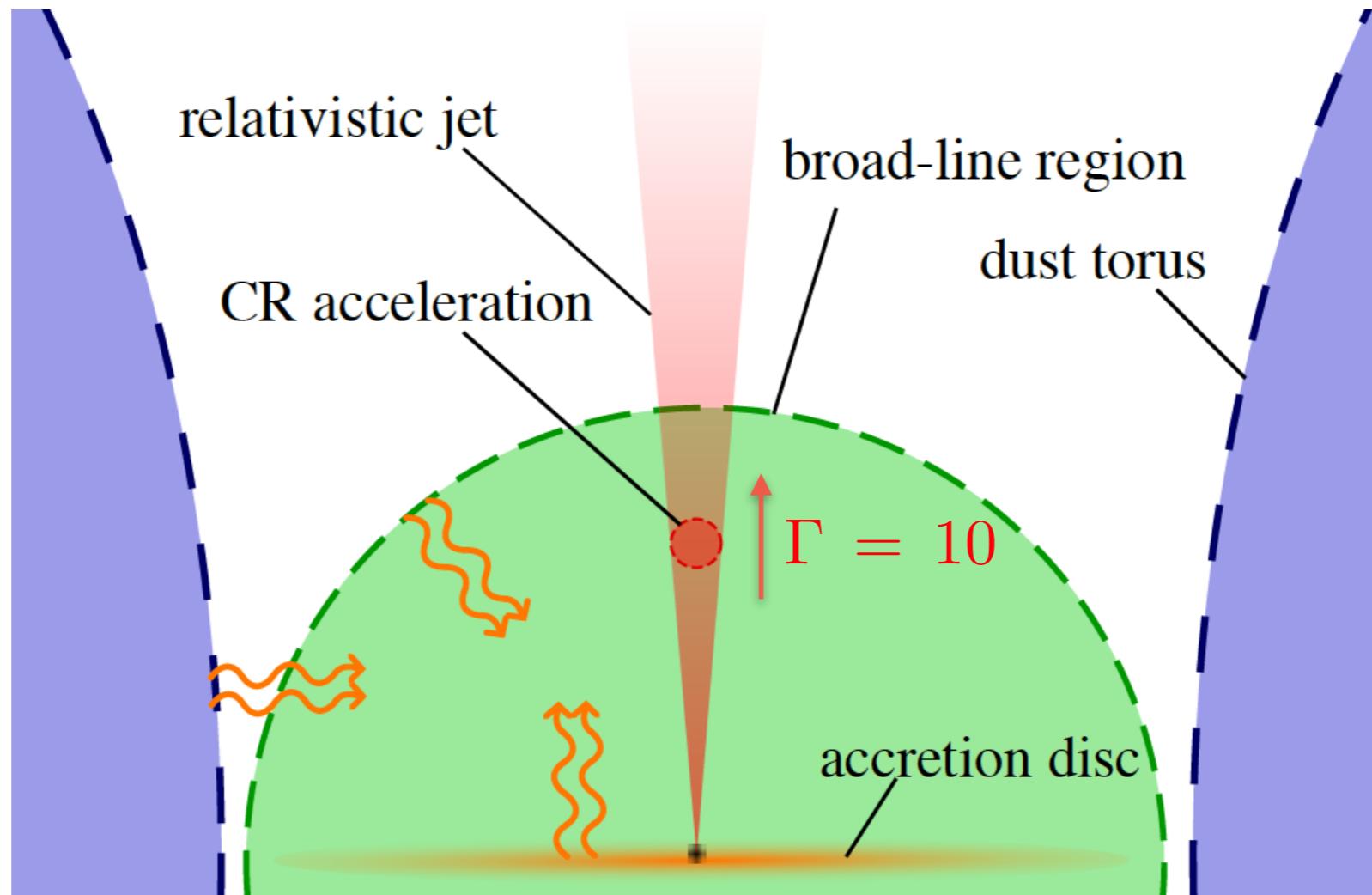
High luminosity

- > E_{max} limited by photo-hadronic losses

↓

- > Starts decreasing with luminosity

A model for High-Luminosity FSRQs



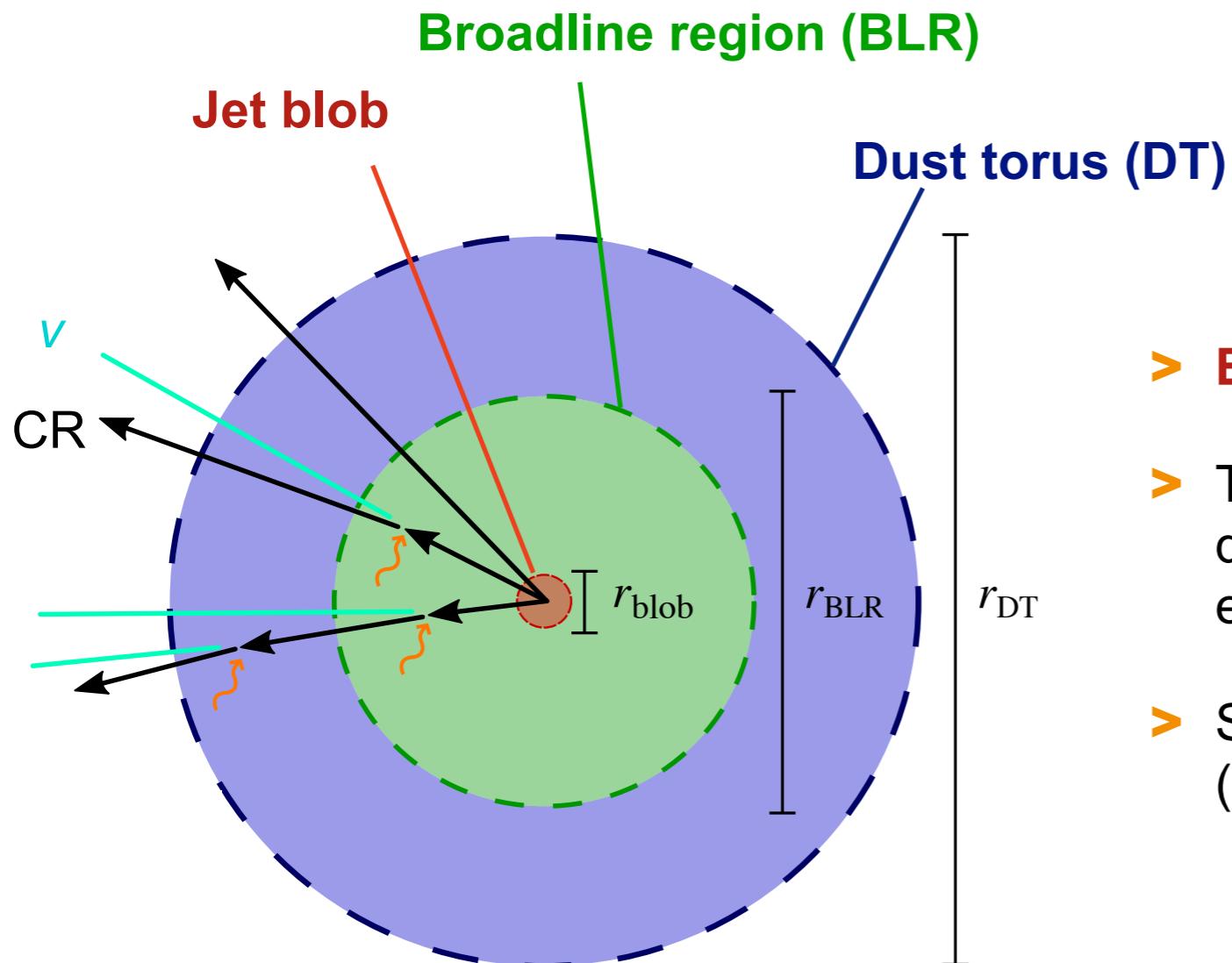
$$r_{\text{BLR}} \propto r_{\text{disk}} \propto \sqrt{L}$$

Murase et al, PRD 90 (2014)
Ghisellini et al MNRAS 387 (2008)

↓
Jet blob inside BLR for bright FSRQs

A model for High-Luminosity FSRQs

Simulation setup

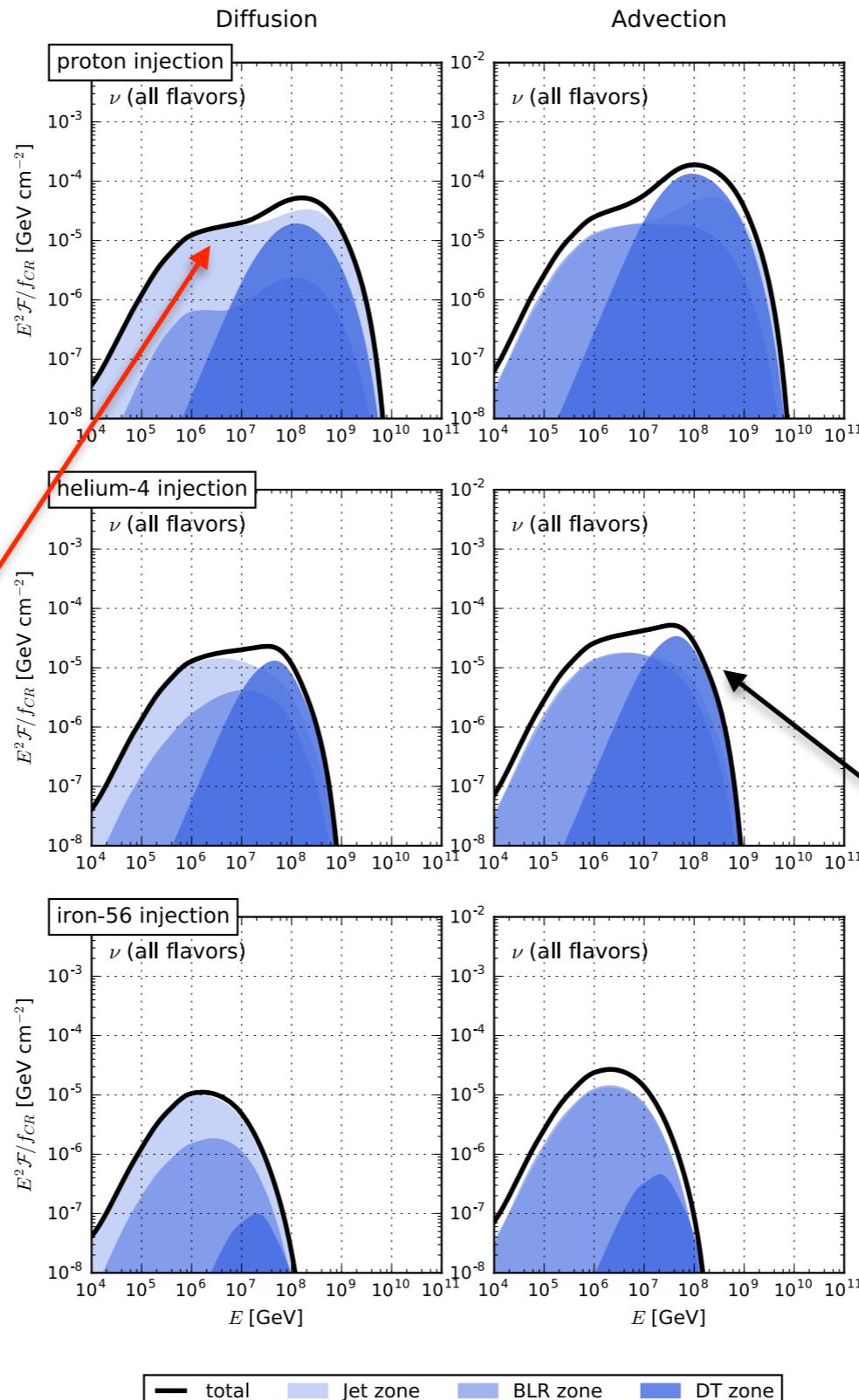


- > **Blob** simulation halts at $t' = t'_{flare} \sim 10^6$ s
- > The escaping CR are Lorentz boosted and dumped into the **BLR** where they interact or escape into the **DT**
- > Simulation runs until $t = r_{DT}/c$
(all CR will have decayed or escaped)

What is the effect of the external zones?

Diffusion

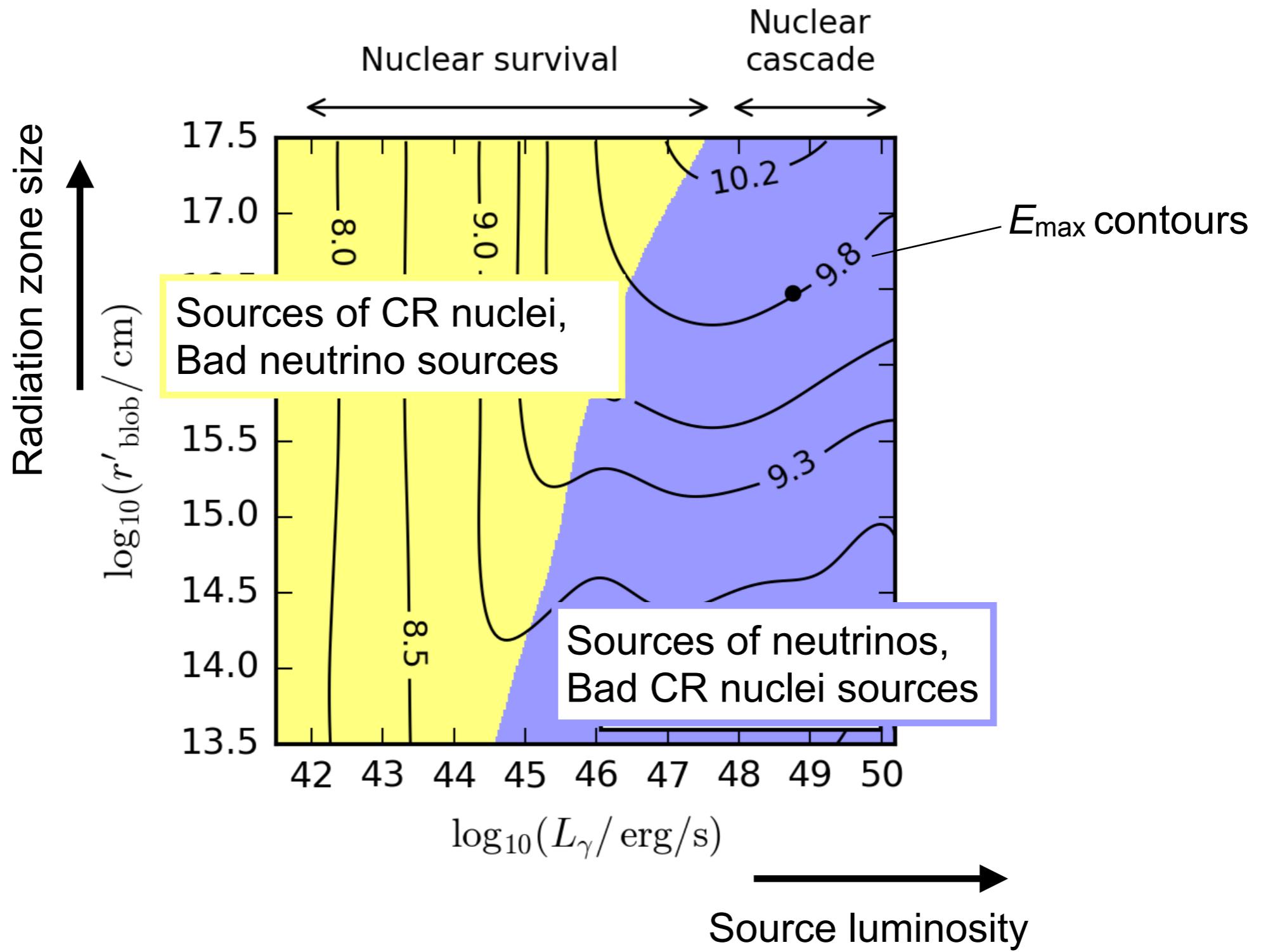
- CRs do not get to interact with the external environment (mag. confinement)
- Jet emission typically dominates neutrino fluence



Advection

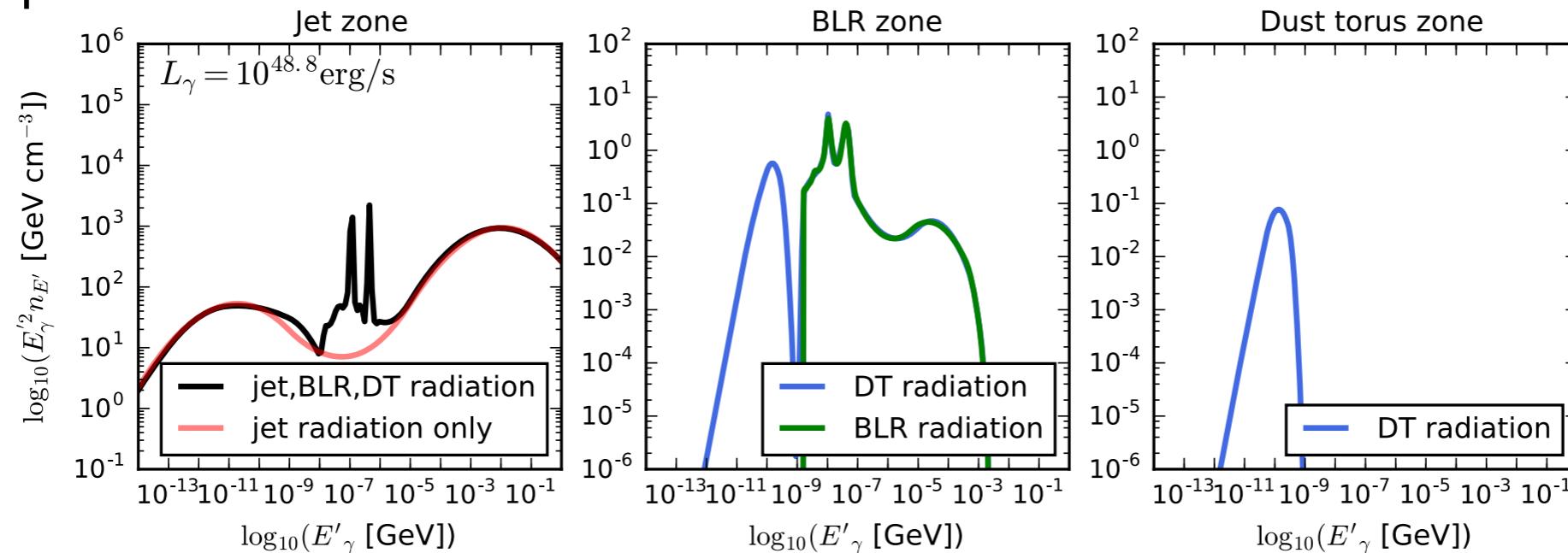
- Free stream of CRs out of the jet
- CRs produce abundant neutrinos in the external fields
- BLR or DT dominate neutrino peak

Parameter space of the jet

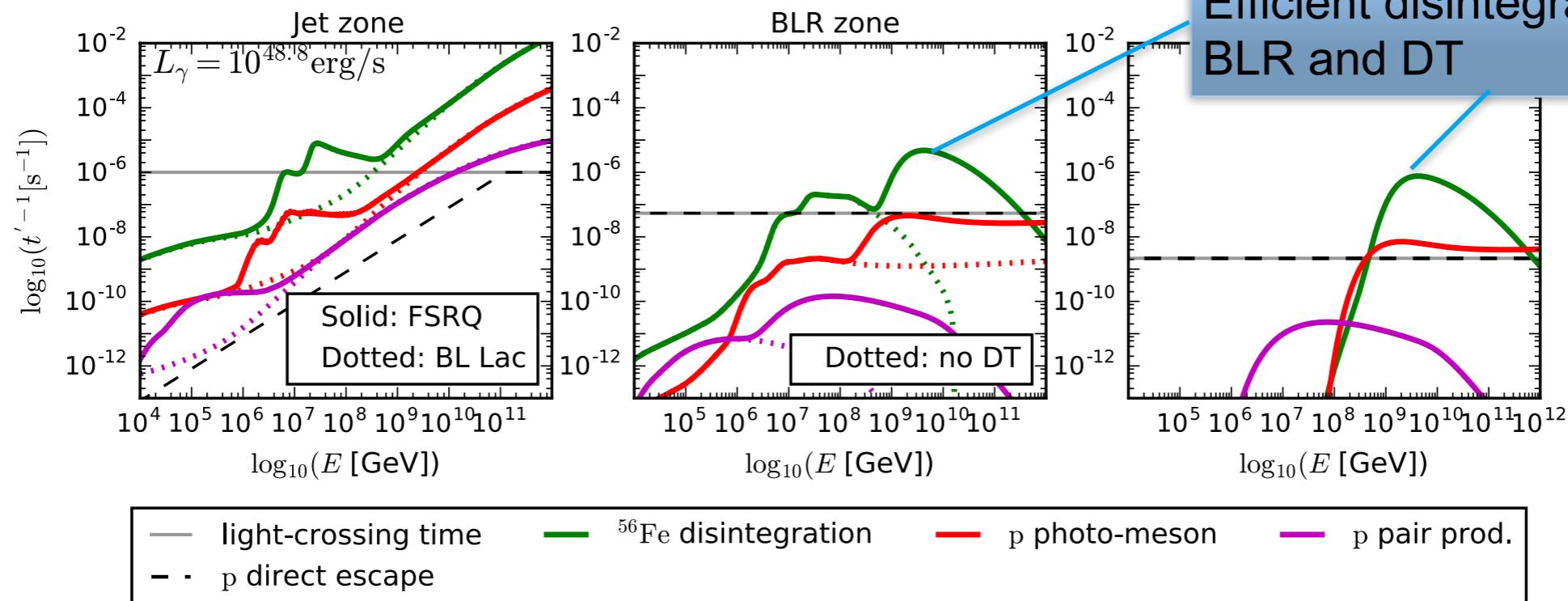


A model for High-Luminosity FSRQs

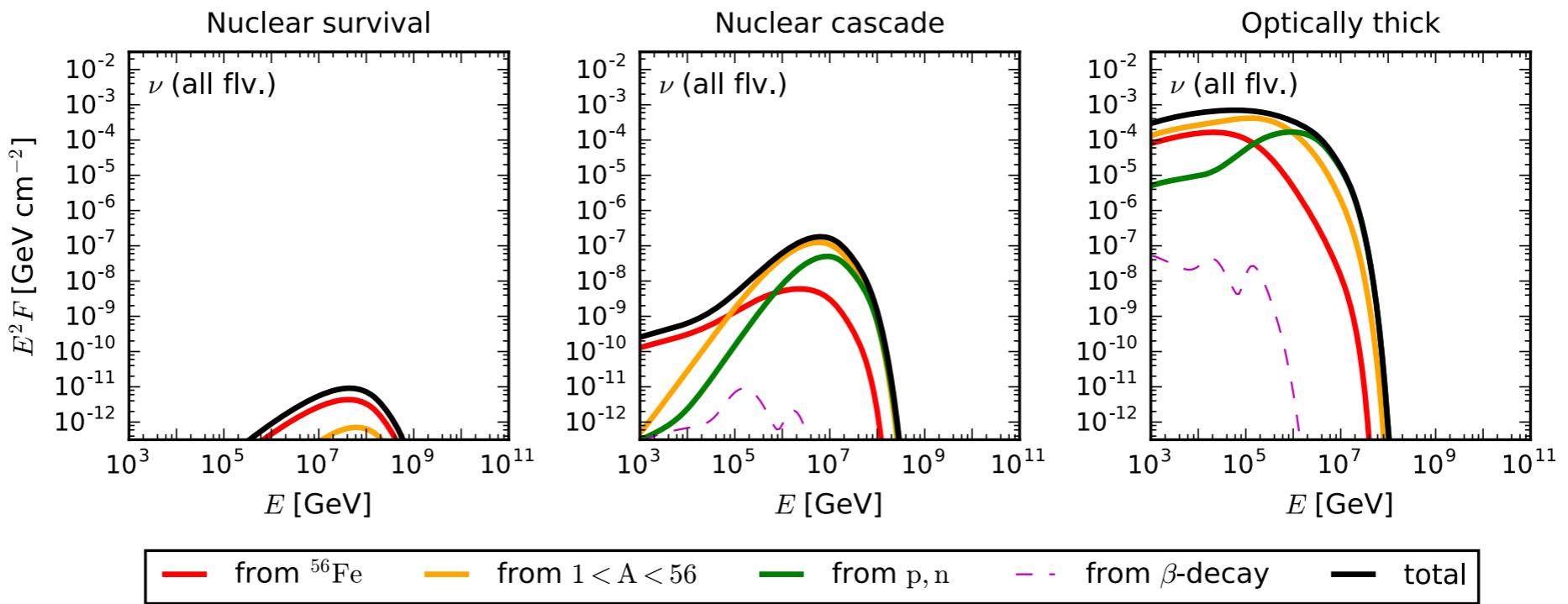
► Static photon field



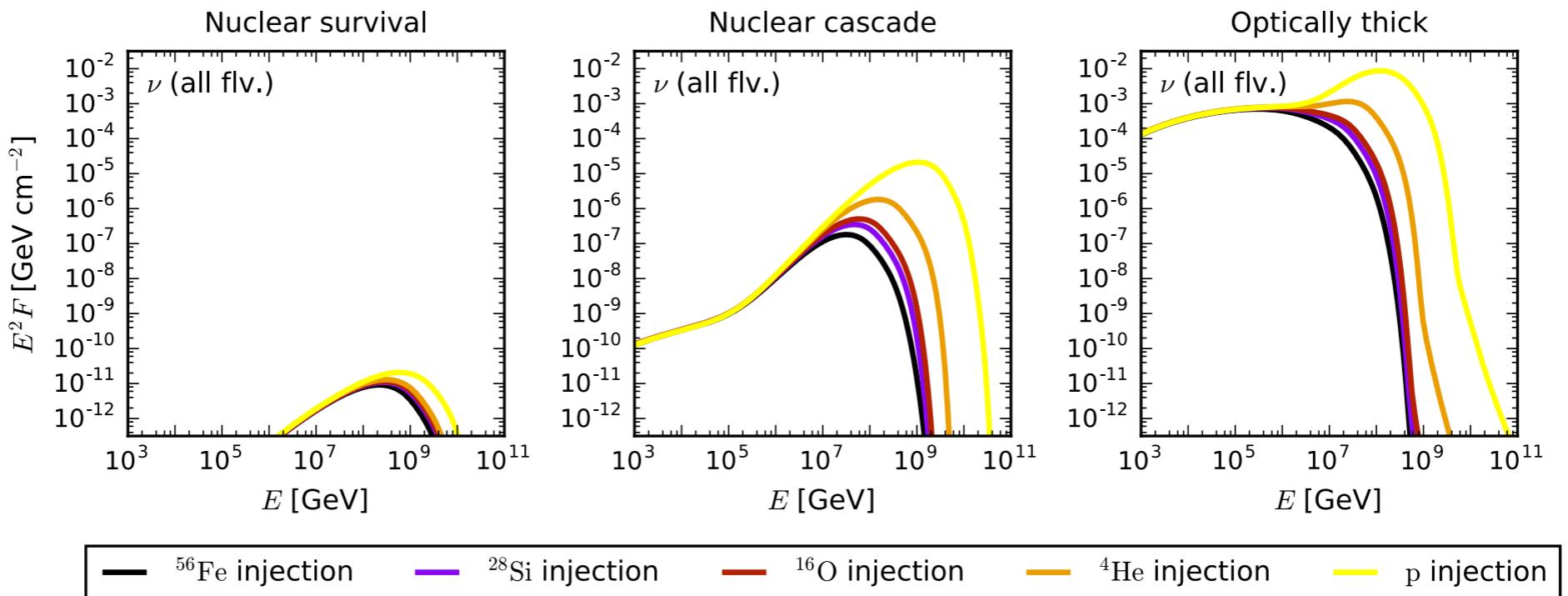
► Process rates



Neutrino emission from the jet



➤ Other isotopes

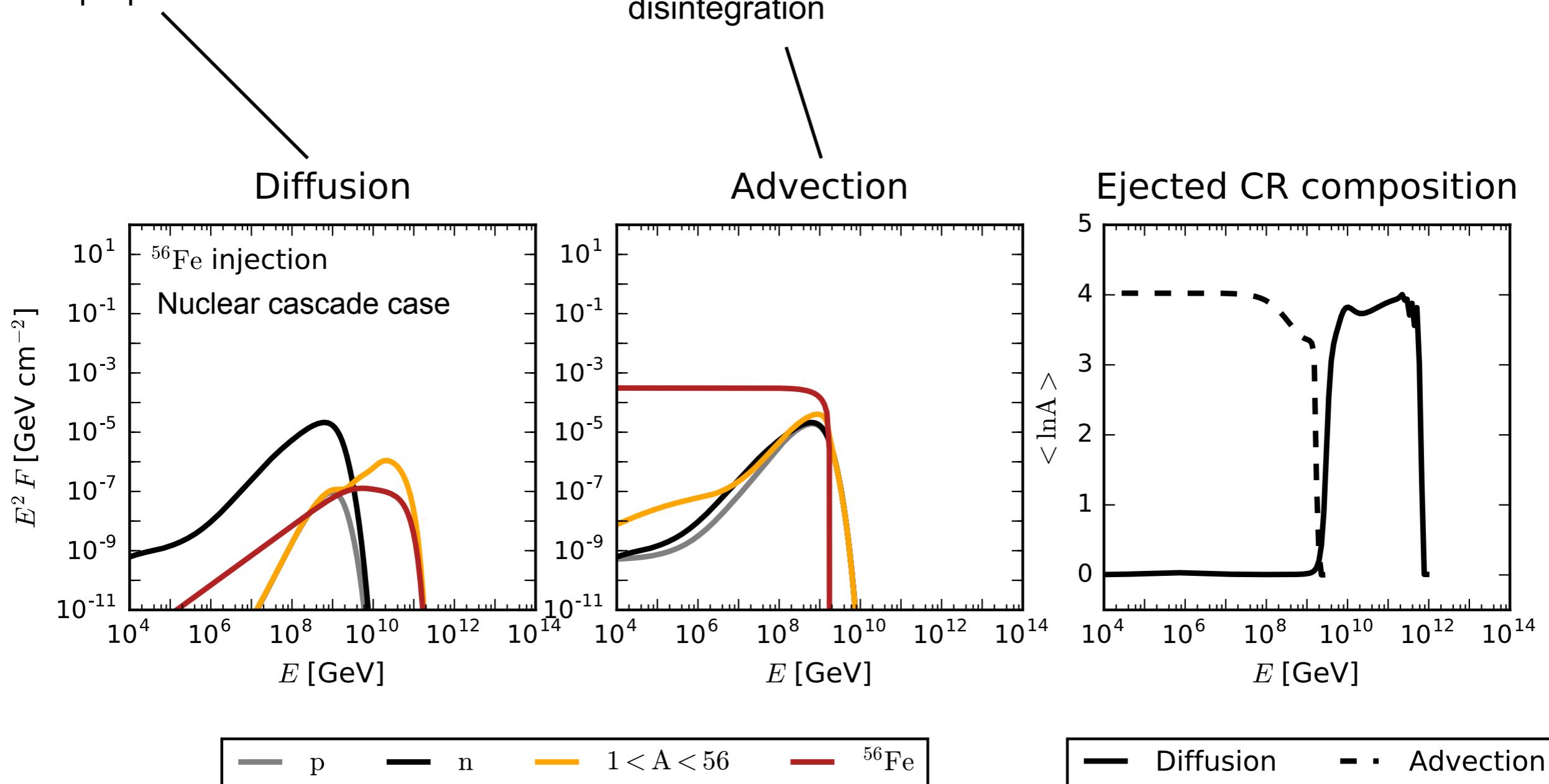


Jet model — CR escape

- Magnetic confinement
- Rate proportional to Larmor radius

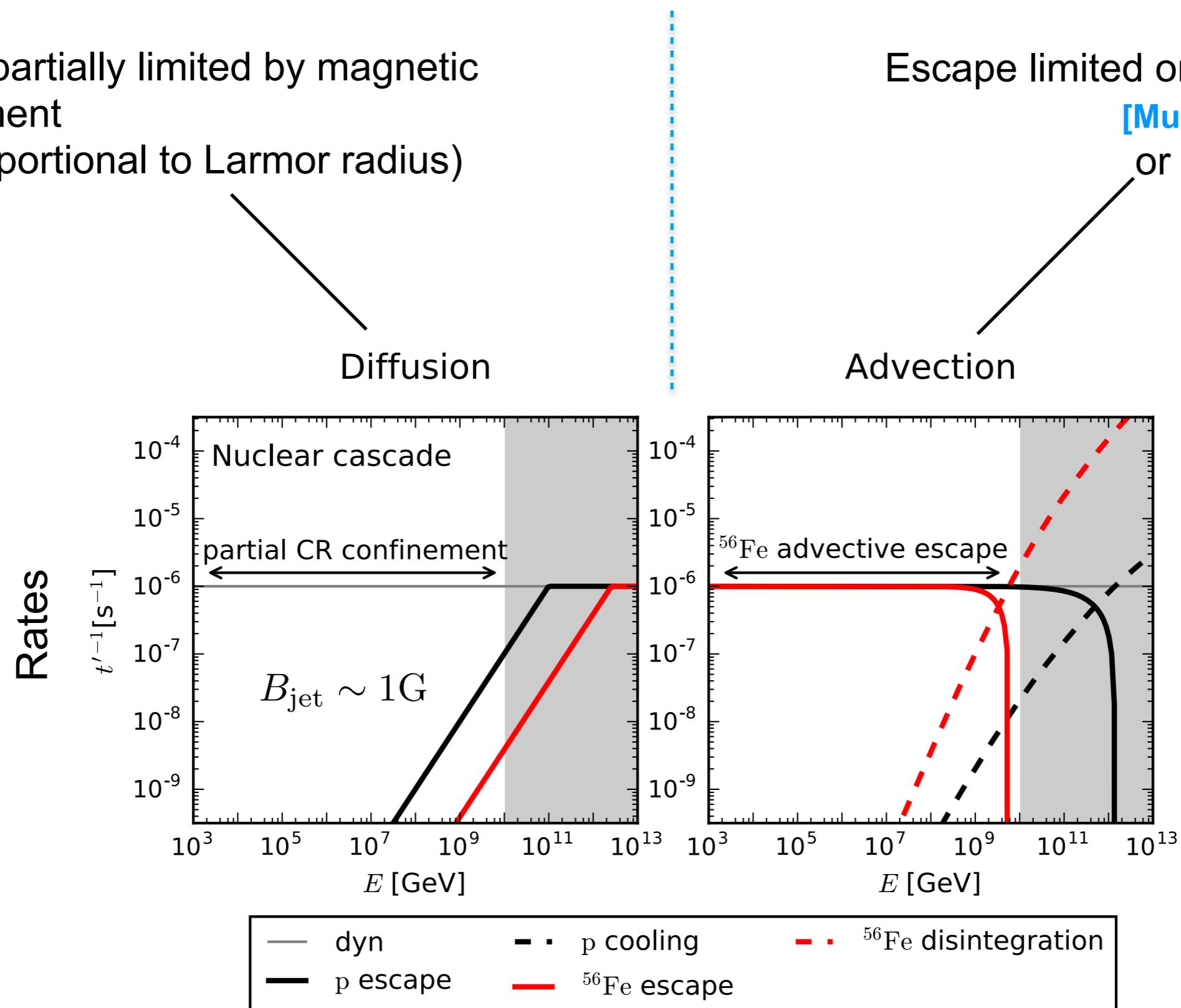
- Escape limited only by cooling
[\[Murase et al 2014\]](#)

or



Jet model — CR escape

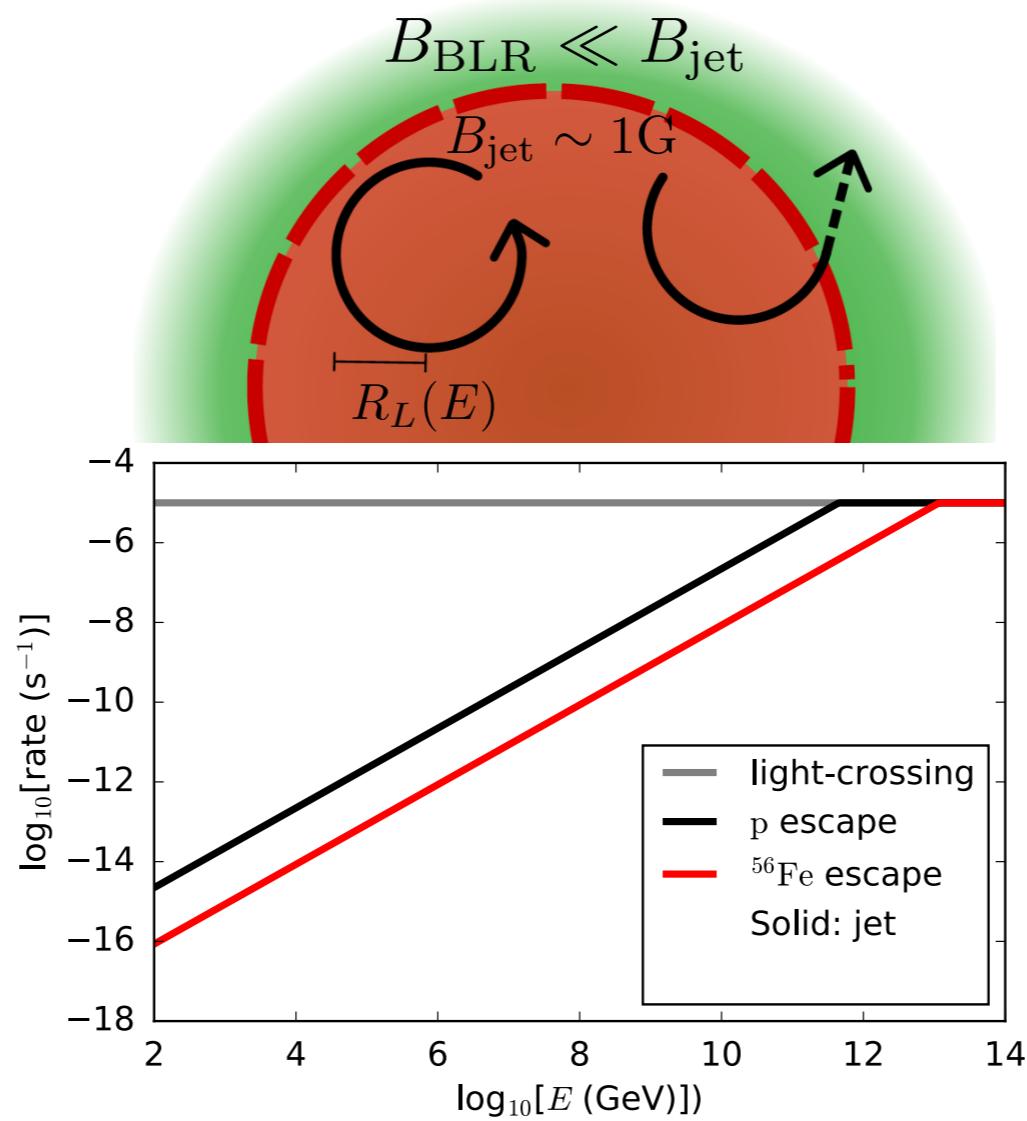
Escape partially limited by magnetic confinement
(rate proportional to Larmor radius)



Jet model — CR escape

- Diffusion-dominated escape (Bohm-like)

$$t_{\text{esc}}^{-1}(E) = t_{\text{light-cross}} \frac{R_L(E)}{R_{\text{zone}}} \propto \frac{E}{qB}$$

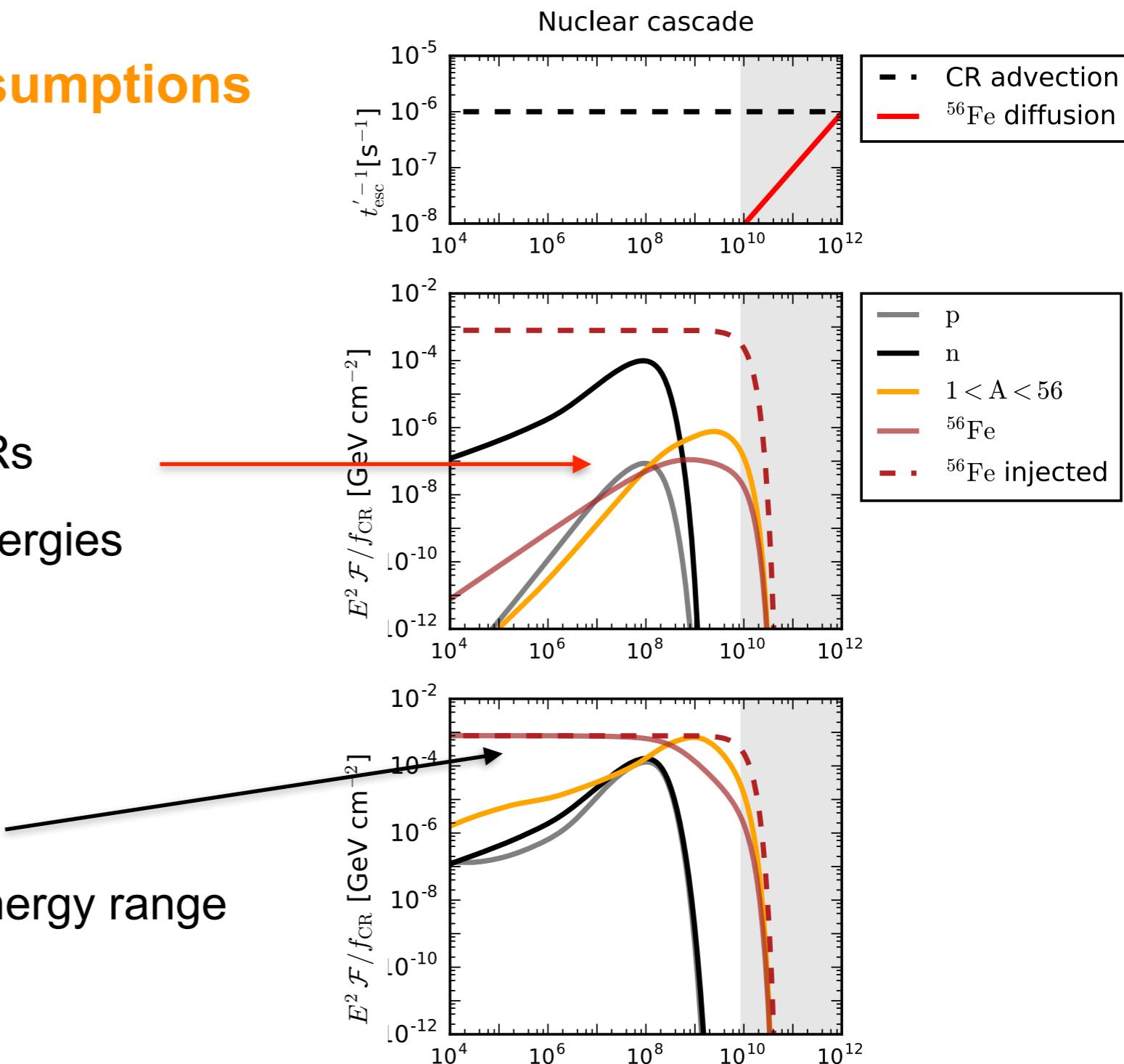


CR escape mechanism

We test two extreme escape assumptions

> Bohm-like diffusion

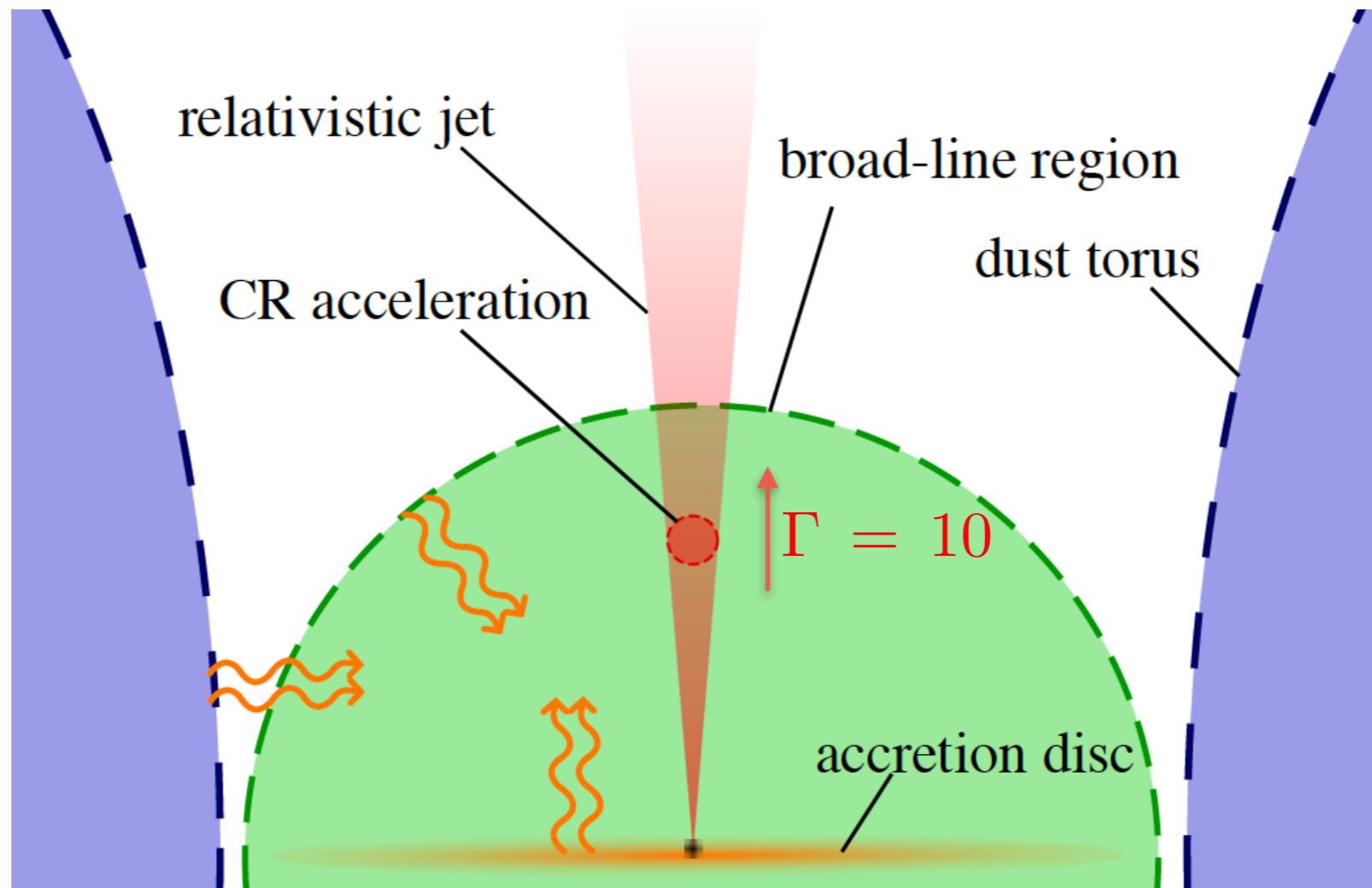
- esc. rate $\sim R_{\text{Larmor}} \propto E$
- High spectral index of charged CRs
- Average CR mass high at high energies



> Advective escape

- Same power law as injection
- High ejected CR mass for wide energy range

A model for High-Luminosity FSRQs



$$r'_{\text{blob}} = c t'_{\text{flare}} = 3 \cdot 10^{16} \text{ cm}$$

$$r_{\text{BLR}} \approx 10^{17} \text{ cm} \left(\frac{L_{AD}}{10^{45}} \right)$$

$$r_{\text{DT}} \approx 25 r_{\text{BLR}}$$

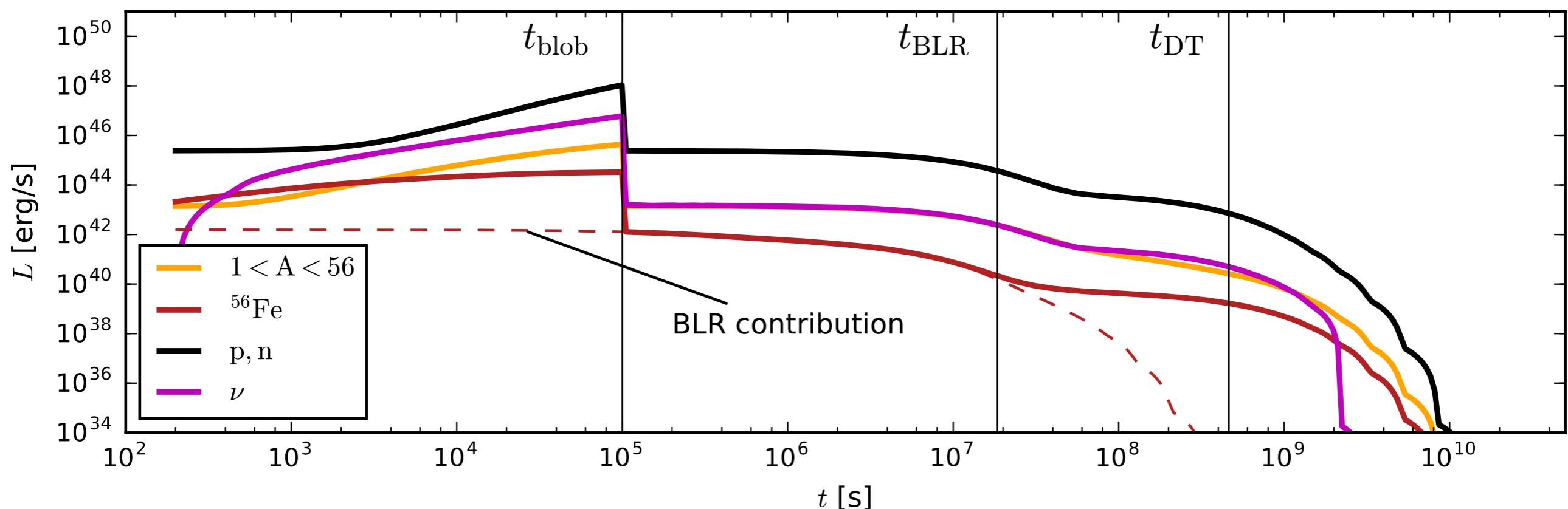
Murase et al, PRD 90 (2014)
Ghisellini et al MNRAS 387 (2008)

FSRQs: CR must go through zones 2 and 3

BL Lacs: CR go into space after escaping zone 1

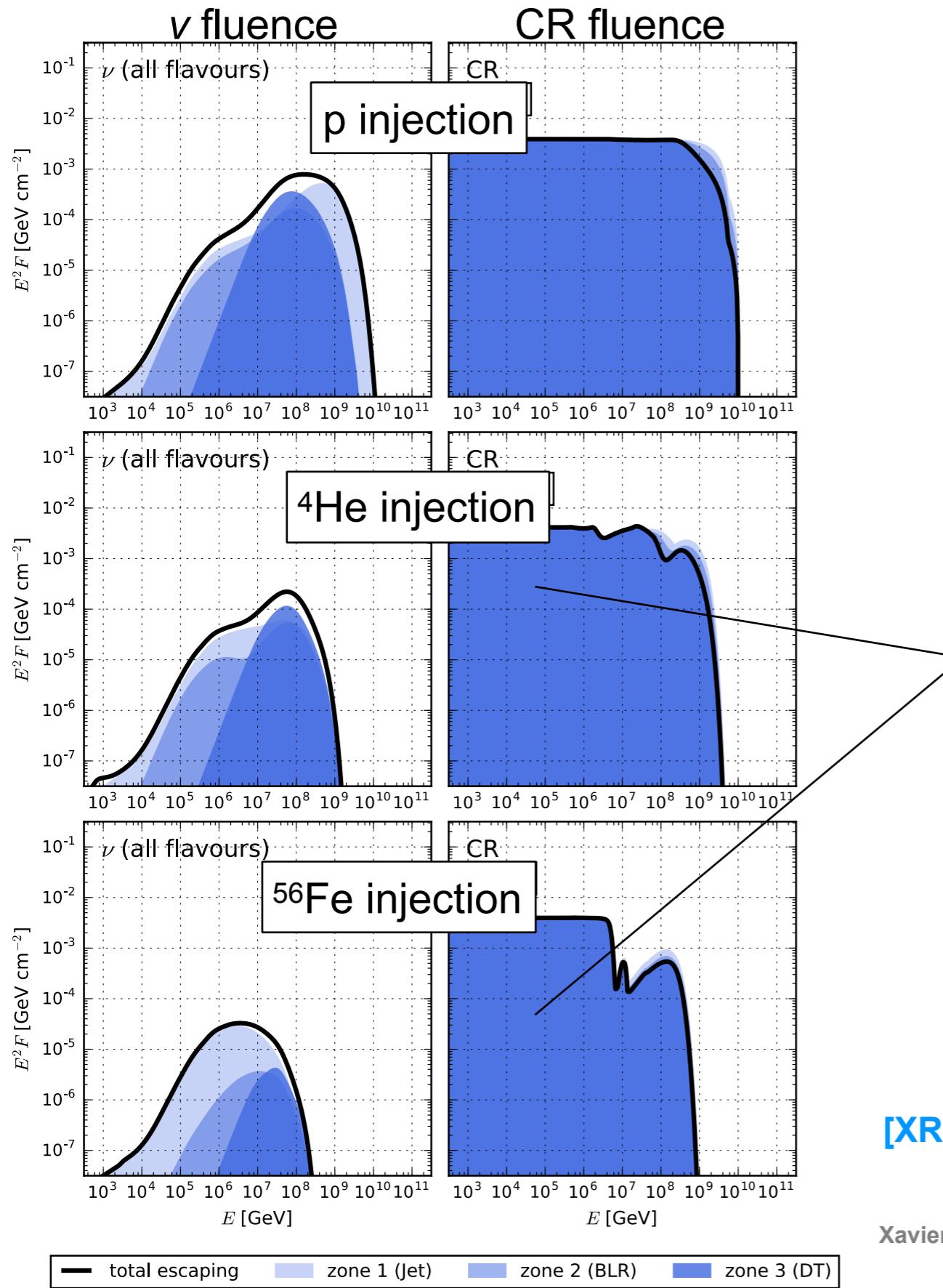
A model for High-Luminosity FSRQs

> Lightcurves from the 3-zone model (example for $L_\gamma = 10^{49.1} \text{ erg/s}$)



[XR, Fedynitch, Boncioli, Gao, Winter — in preparation]

High-Luminosity FSRQs — Ejected spectra



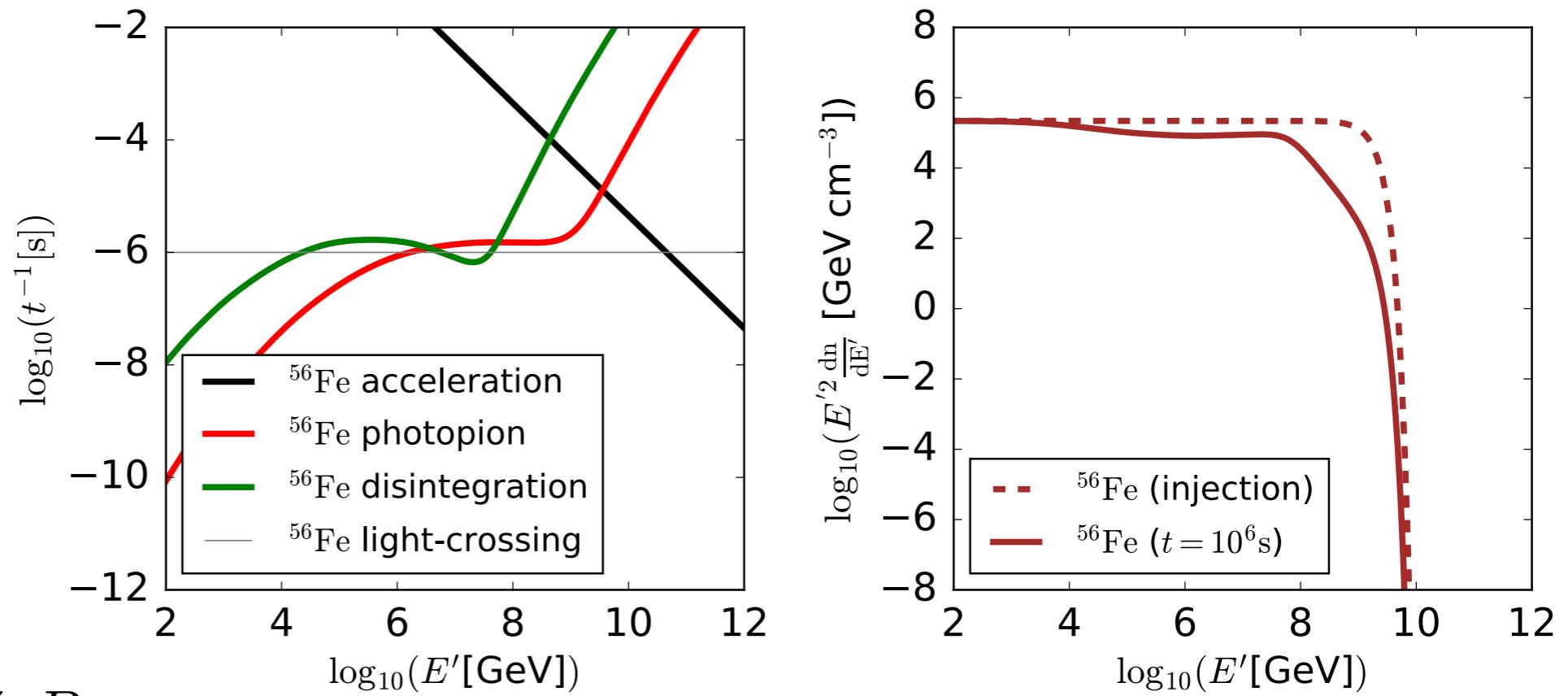
Advective escape assumption

- Neutrino spectra unaffected
- At low energies the injected isotope escapes unscathed

Assumption leads to heavy composition at low energies

[XR, Fedynitch, Boncioli, Gao, Winter — in preparation]

Process rates



$$t_{\text{accel}}^{-1}(E) = \eta \frac{c^2 Z e B}{E}$$

$$t_{\text{synch}}^{-1}(E) = \left(\frac{Z e}{m} \right)^4 B^2 c^3$$

$$E_{\text{injection}}^{\max} = E : t_{\text{acc}}^{-1}(E) = \sum t_{\text{rad losses}}^{-1}(E) + t_{A\gamma}^{-1}(E) + t_{\text{disintegration}}^{-1}(E)$$

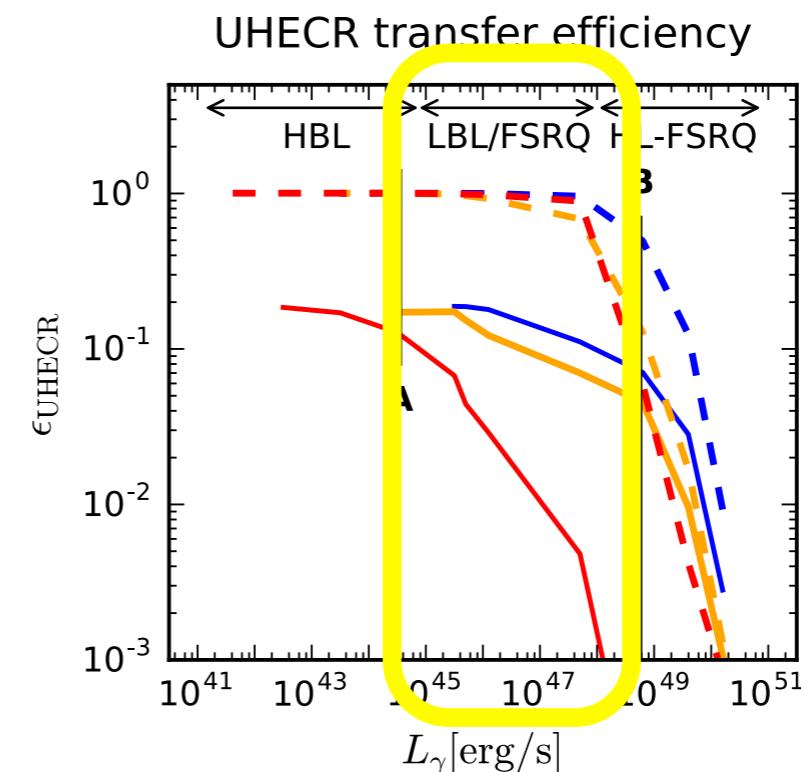
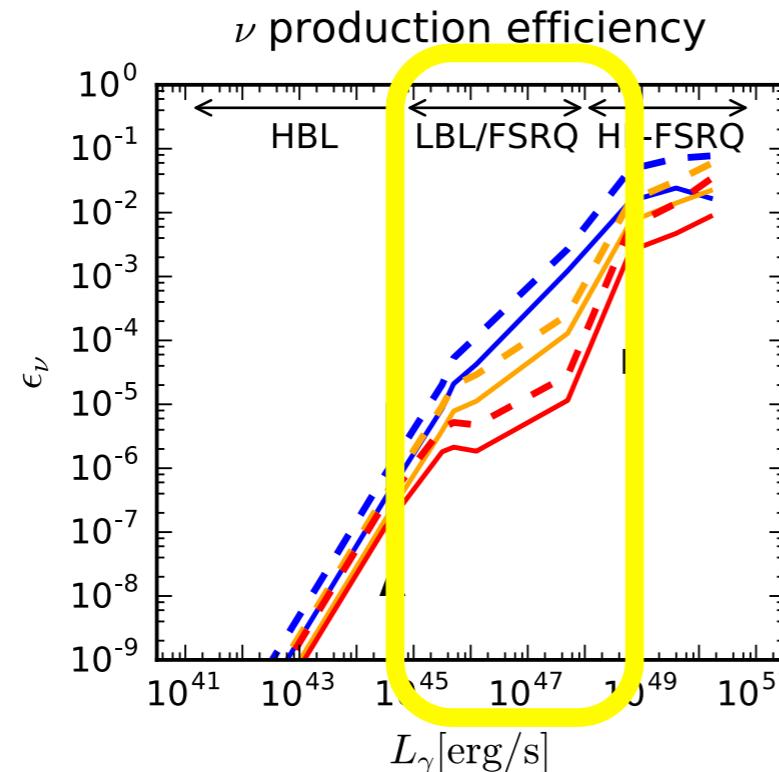
Neutrino and CR efficiency of blazars

Neutrinos vs CRs: opposite trends

HL-FSRQs are good neutrino emitters

HBLs are good CR emitters

“Sweet spot” could lie in the LBL/FSRQ range



- | | | |
|-------------------------|---------------------------------------|--|
| — p injection, diffus. | — ${}^4\text{He}$ injection, diffus. | — ${}^{56}\text{Fe}$ injection, diffus. |
| - - p injection, advec. | - - ${}^4\text{He}$ injection, advec. | - - ${}^{56}\text{Fe}$ injection, advec. |

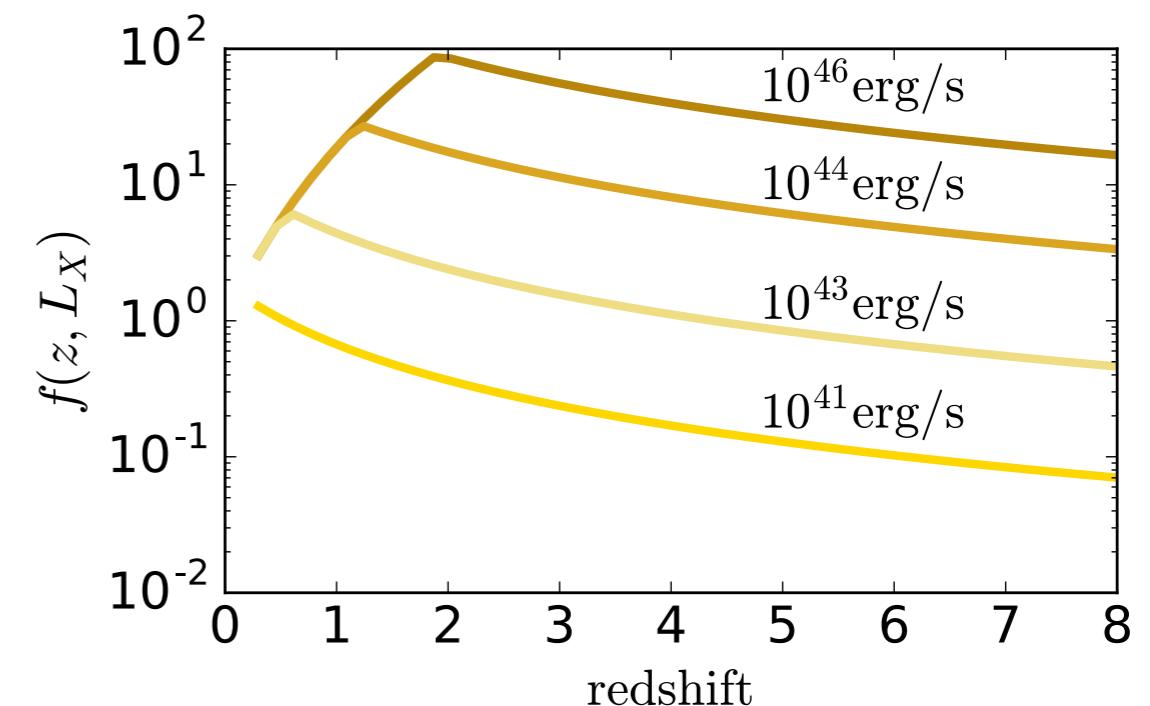
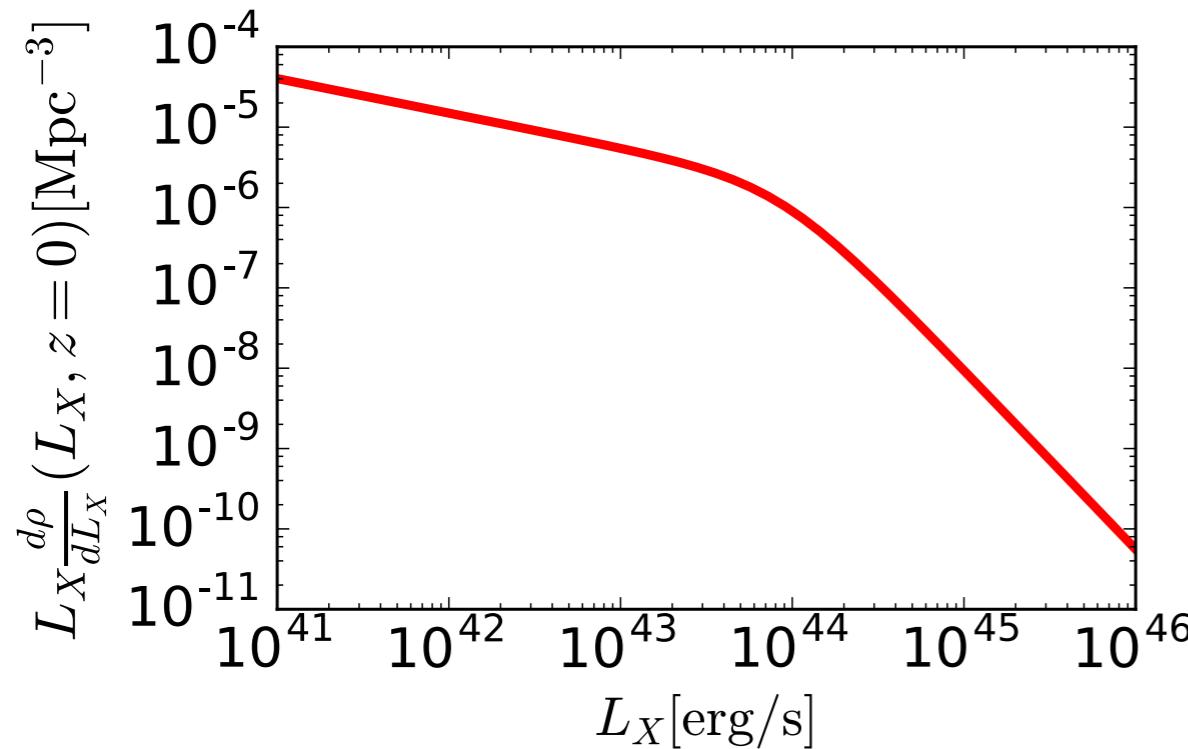
XR, Fedynitch, Gao, Boncioli, Winter, ApJ 854 (2018) no.1, 54

Source distribution

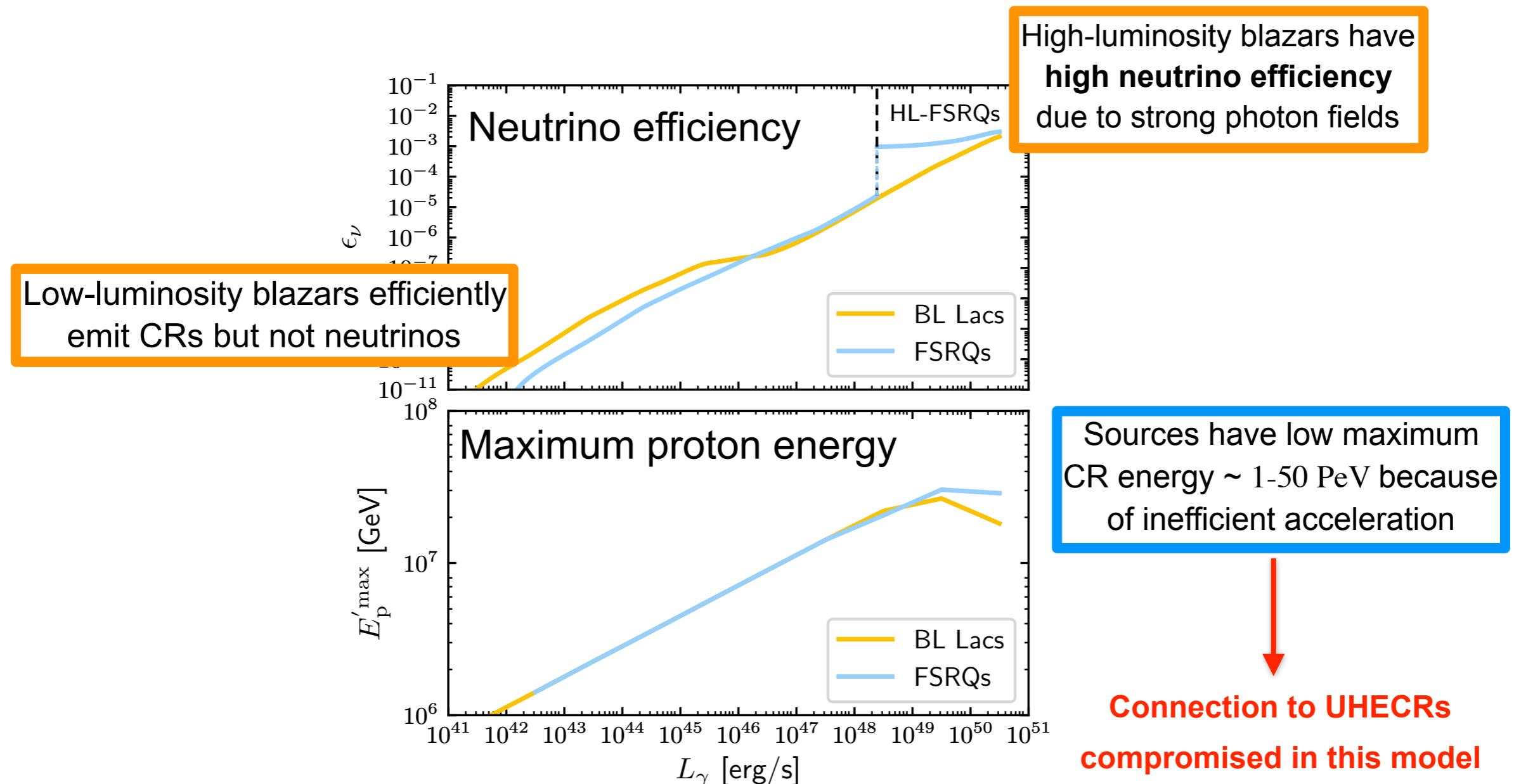
Based on Ajello et al. 2012 (1110.3787) and 2014 (1310.0006)

$$\Phi_\nu = \frac{c}{4\pi} \int^{z_{\max}} \frac{dz}{H(z)} \int dL_\gamma \frac{d\rho}{dL_\gamma}(L_\gamma, z) \left(\frac{1}{E_\nu} \frac{dL_\nu}{dE_\nu} \right)$$

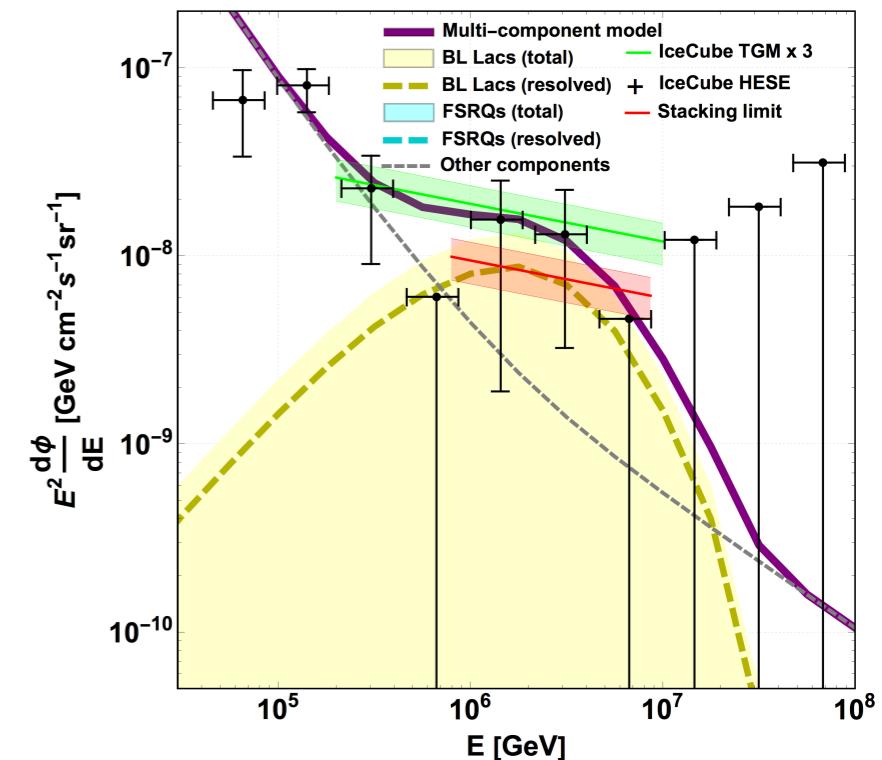
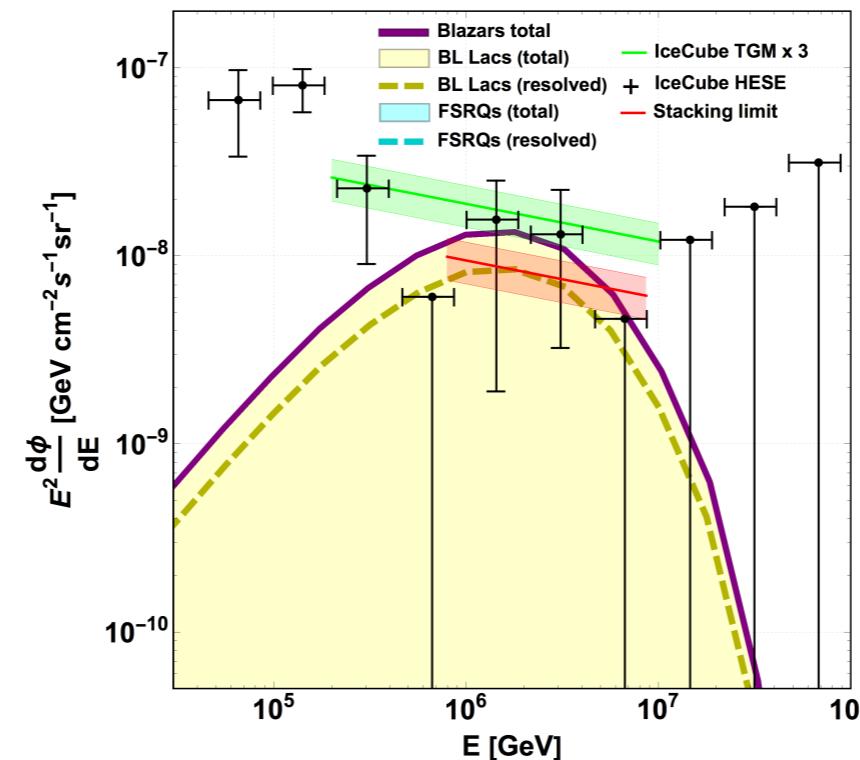
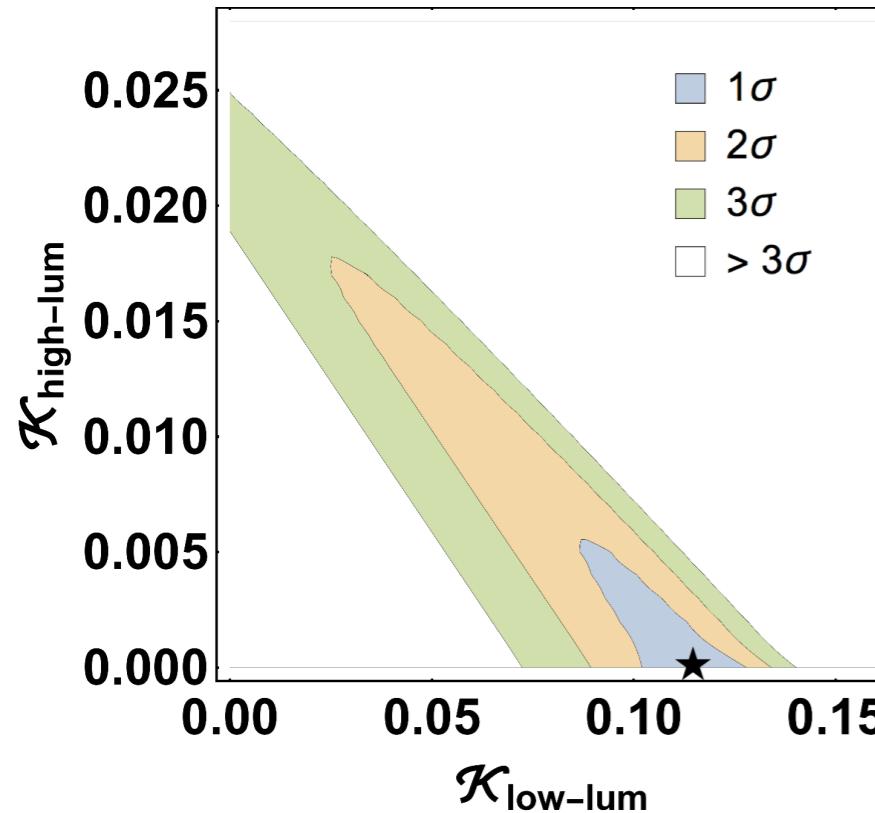
$$\frac{d\rho}{dL_\gamma}(L_\gamma, z) = k \frac{dL_X}{dL_\gamma} \frac{d\rho}{dL_X}(L_X, z=0) f(L_X, z)$$



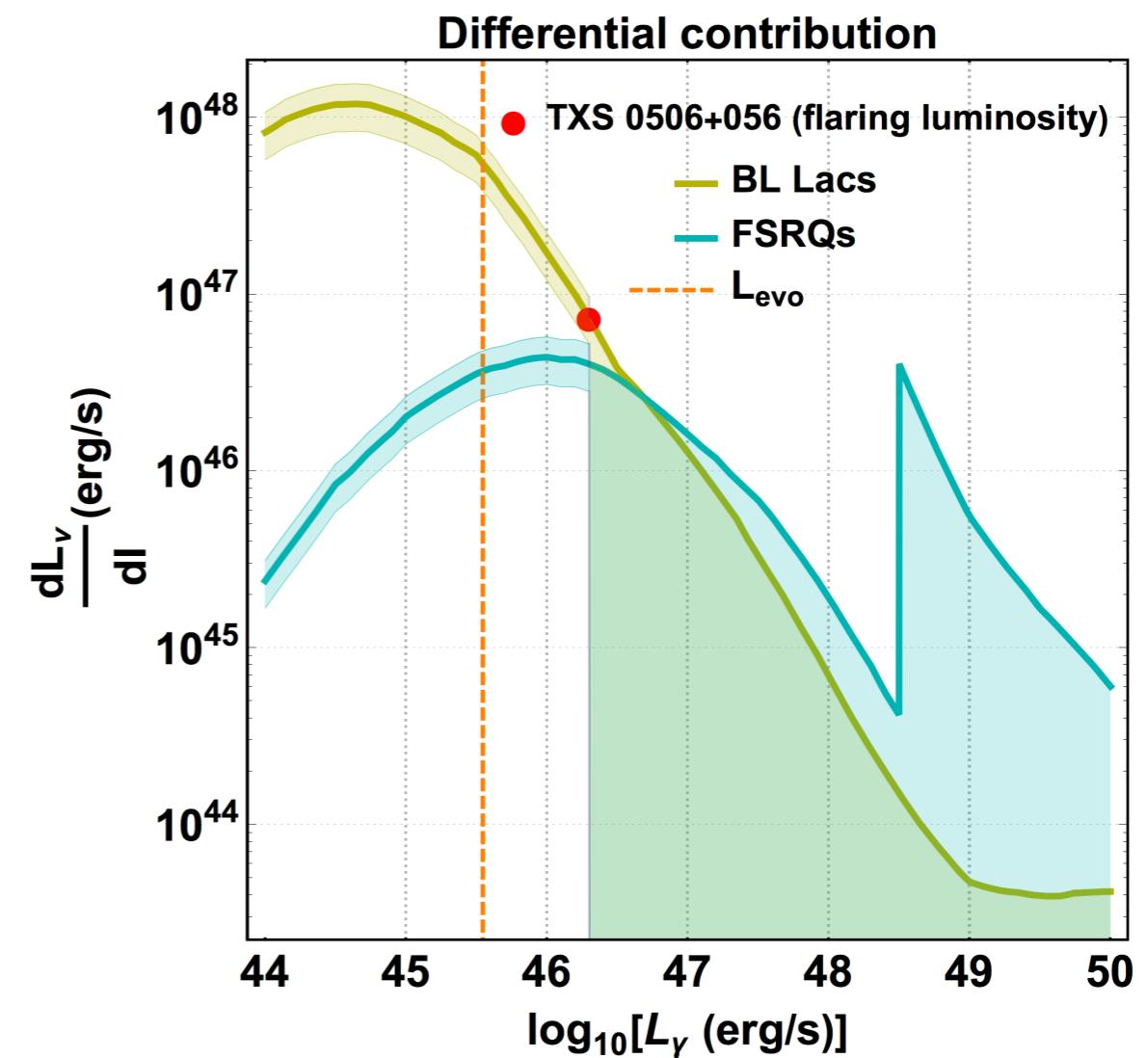
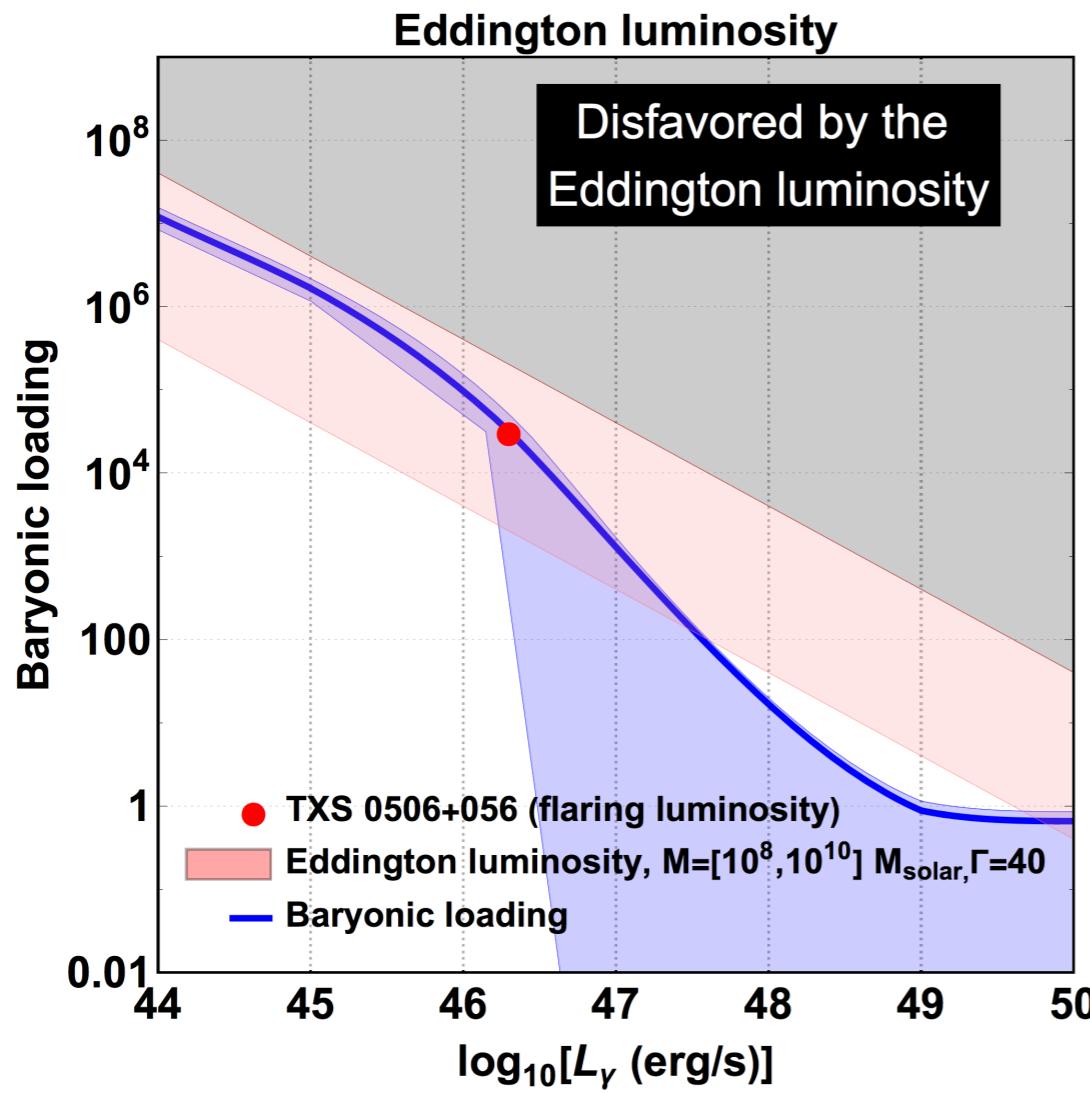
Applying the model to the “Fermi” blazar sequence



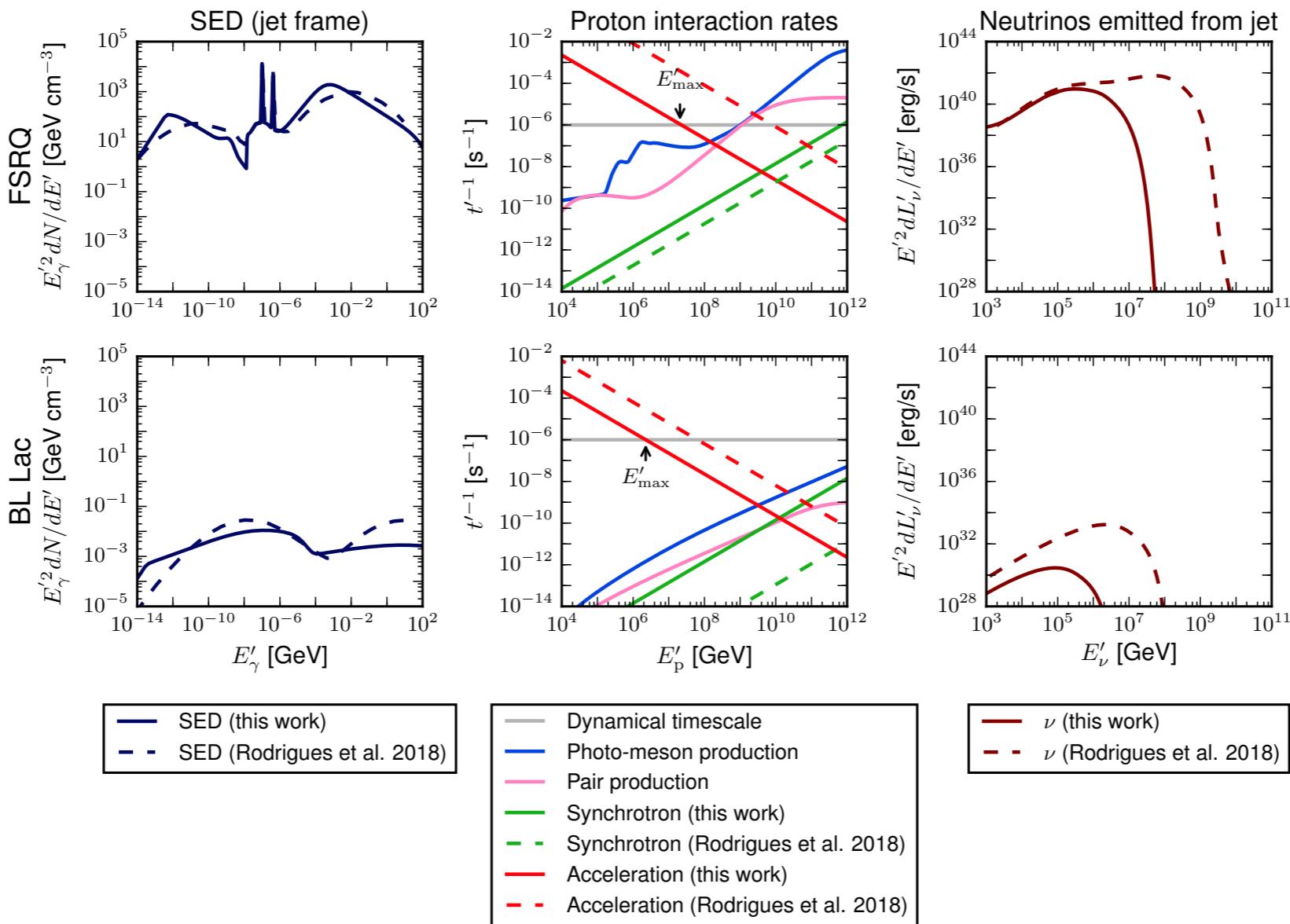
Backup



Backup

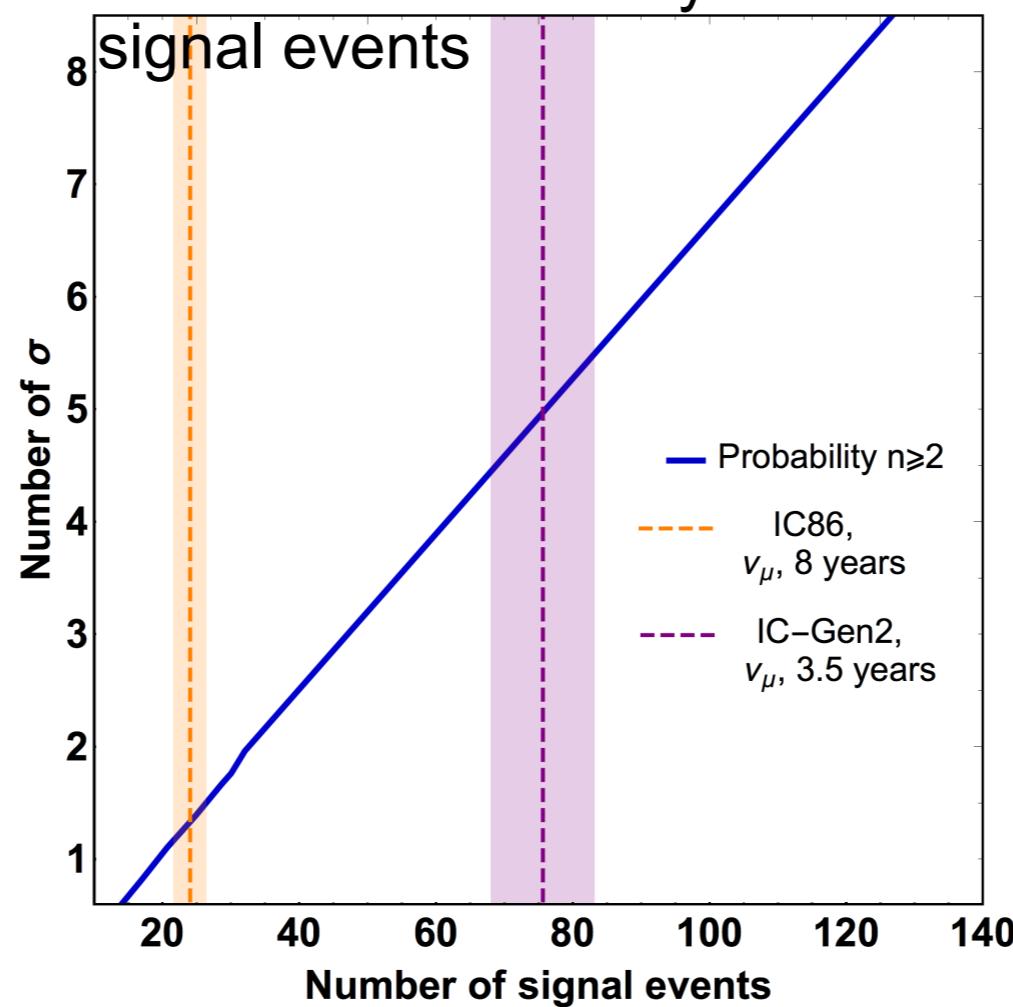


Backup



Backup

36 thgoughgoing muons,
2/3 of which are likely to be



Backup

