Starburst galaxies as sources of high energy particles

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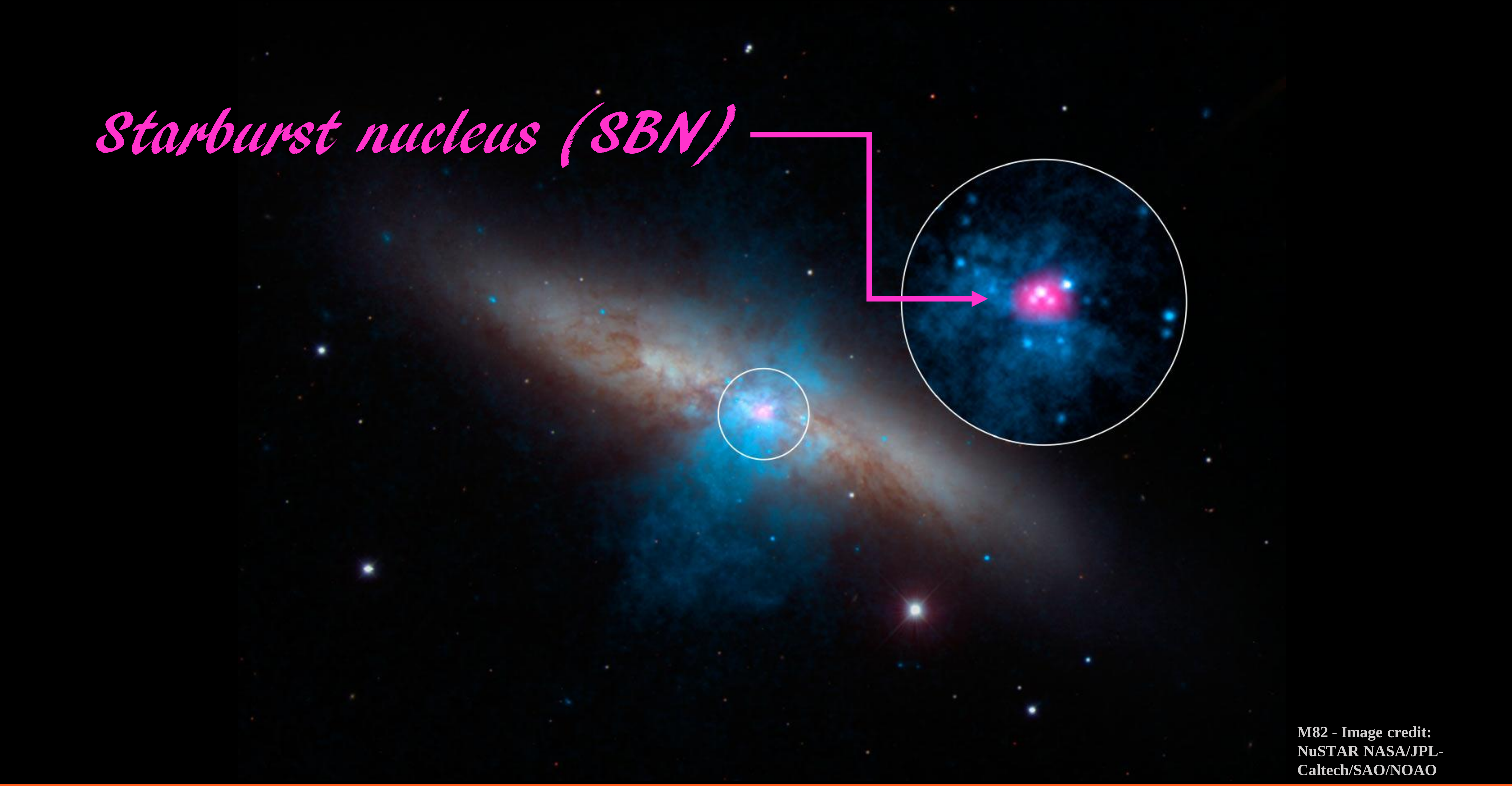
Outline

- Starburst galaxies
- Modeling non-thermal particles
- Diffuse gamma rays and neutrinos
- Wind termination shock

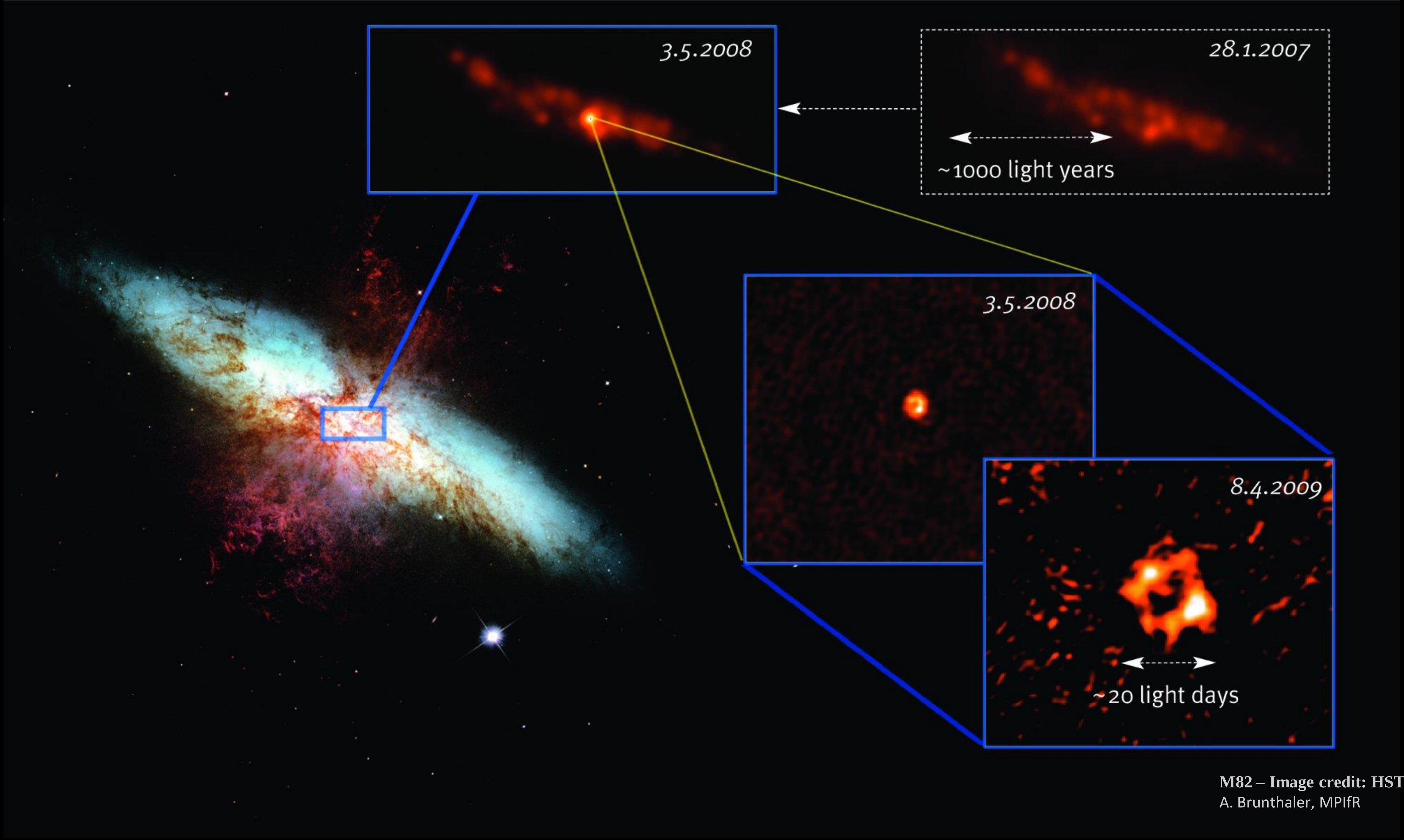
1 - WHY STARBURST GALAXIES??

Starburst galaxy M82 - APOD
Image credit: Daniel Nobre

Starburst nucleus (SBN)

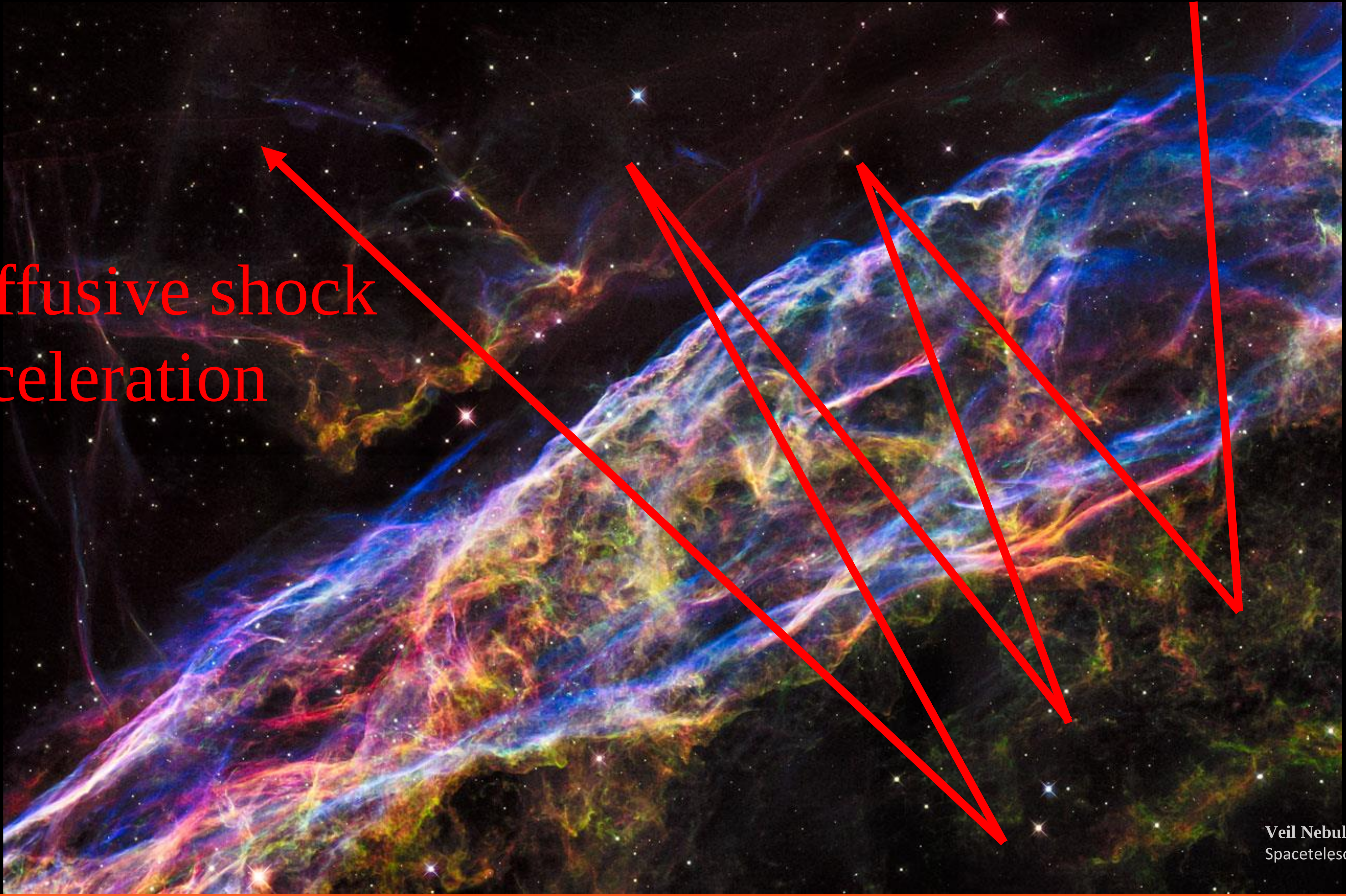


M82 - Image credit: NuSTAR NASA/JPL-Caltech/SAO/NOAO



M82 – Image credit: HST-VLA-VLBI
A. Brunthaler, MPIfR

Diffusive shock acceleration

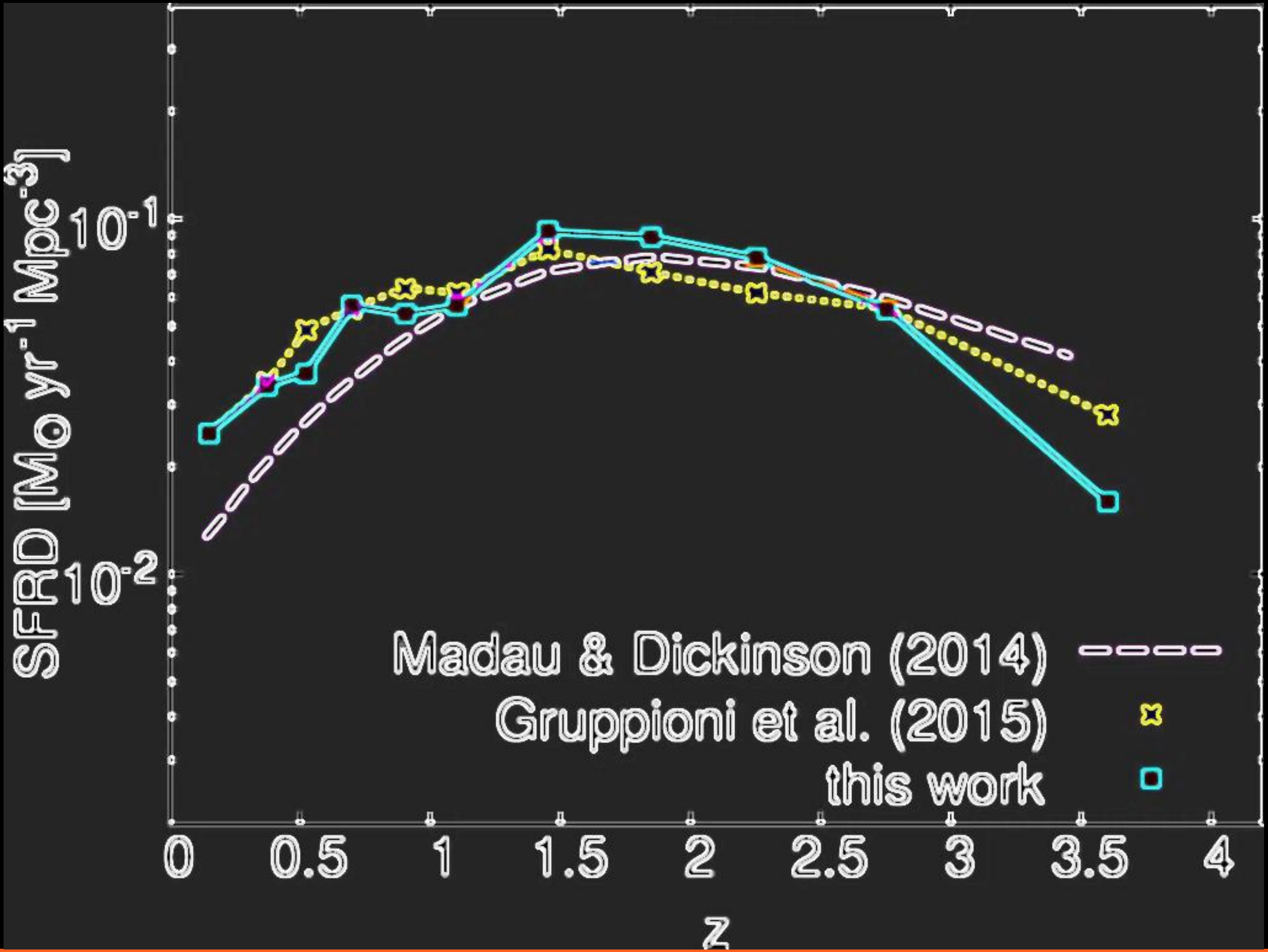


Veil Nebula– Image credit: HST
Spacetelescope.org/news/heic1520/

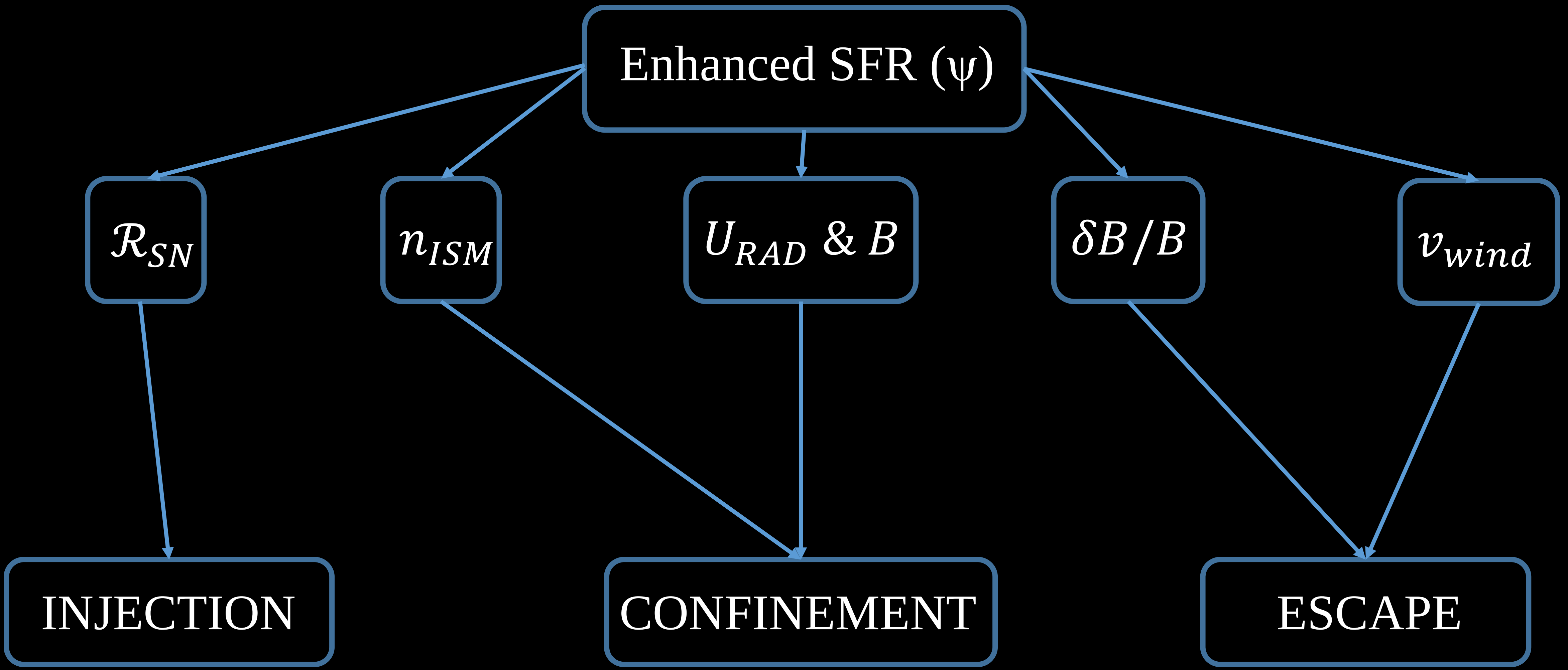
Starburst galaxy M82 - APOD
Image credit: Daniel Nobre

APOD – May 15 2020 – M81 and M82
Image credit: Dietmar Hager & Torsten Grossmann

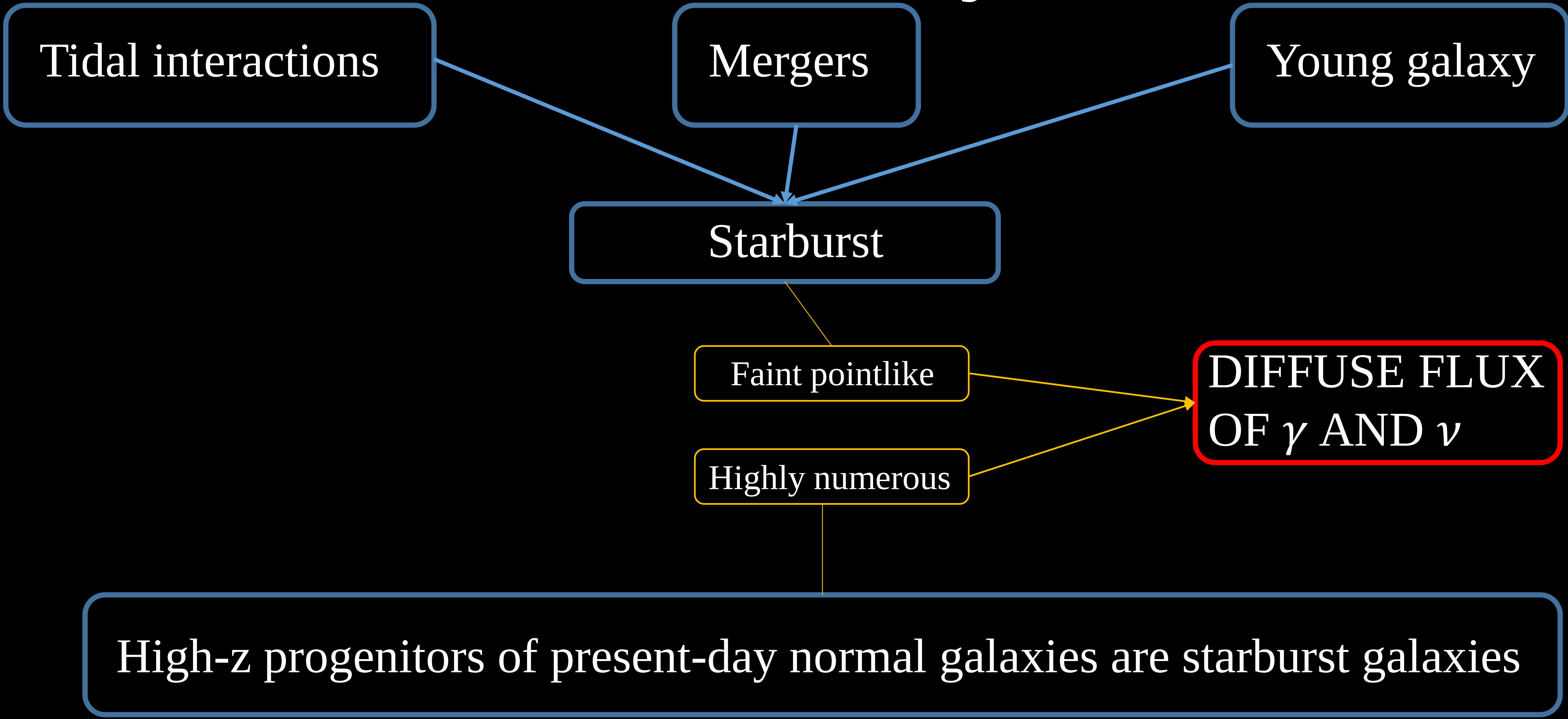
COSMOS field – Image credit: HST
Spacetelescope.org/images/heic1313b/


SFRD [M☉ yr⁻¹ Mpc⁻³]
10⁻¹
10⁻²
Madau & Dickinson (2014)
Gruppioni et al. (2015)
this work
0
0.5
1
1.5
2
2.5
3
3.5
4
z

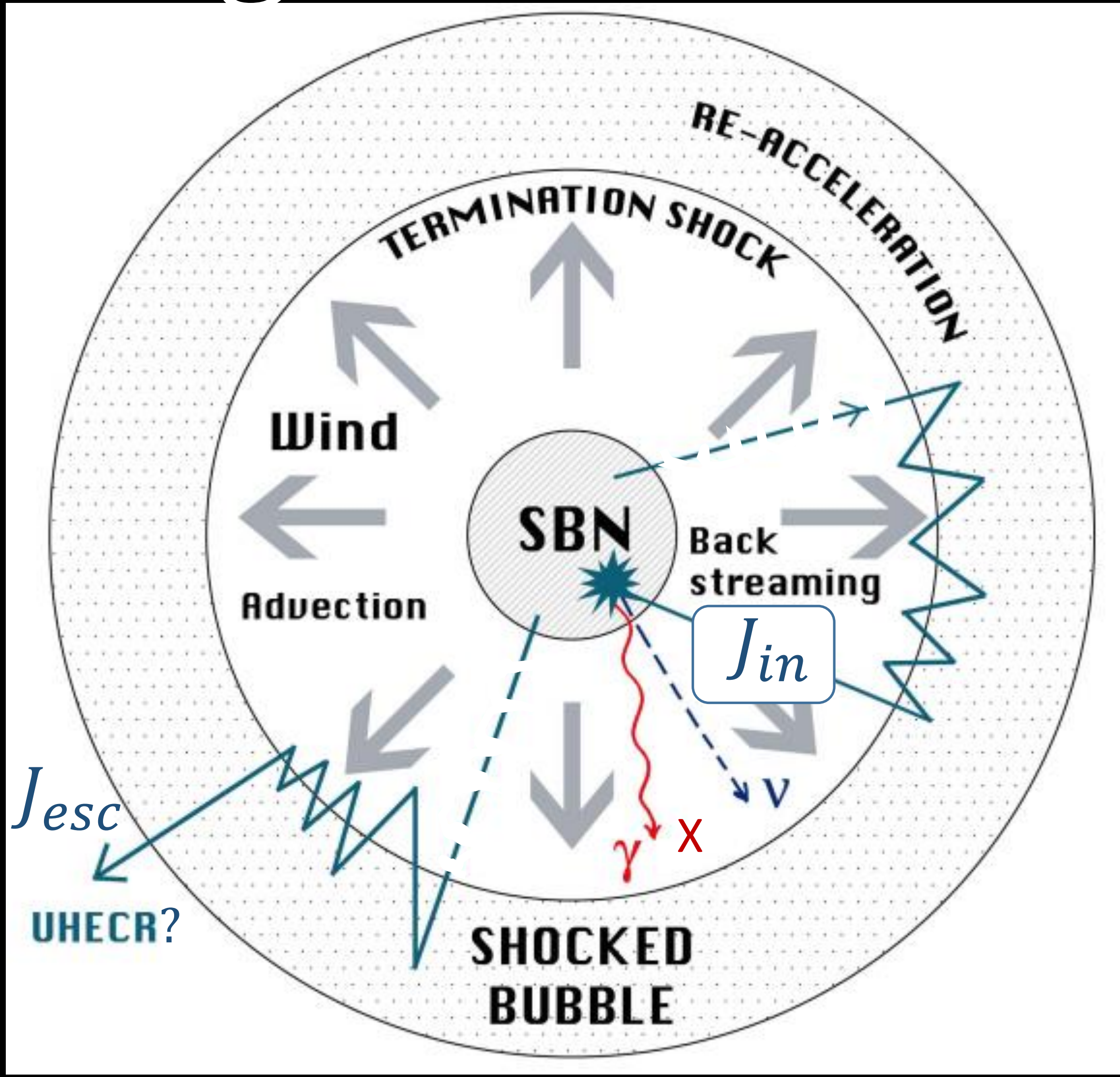
SBGs are unique sources



SBGs are everywhere

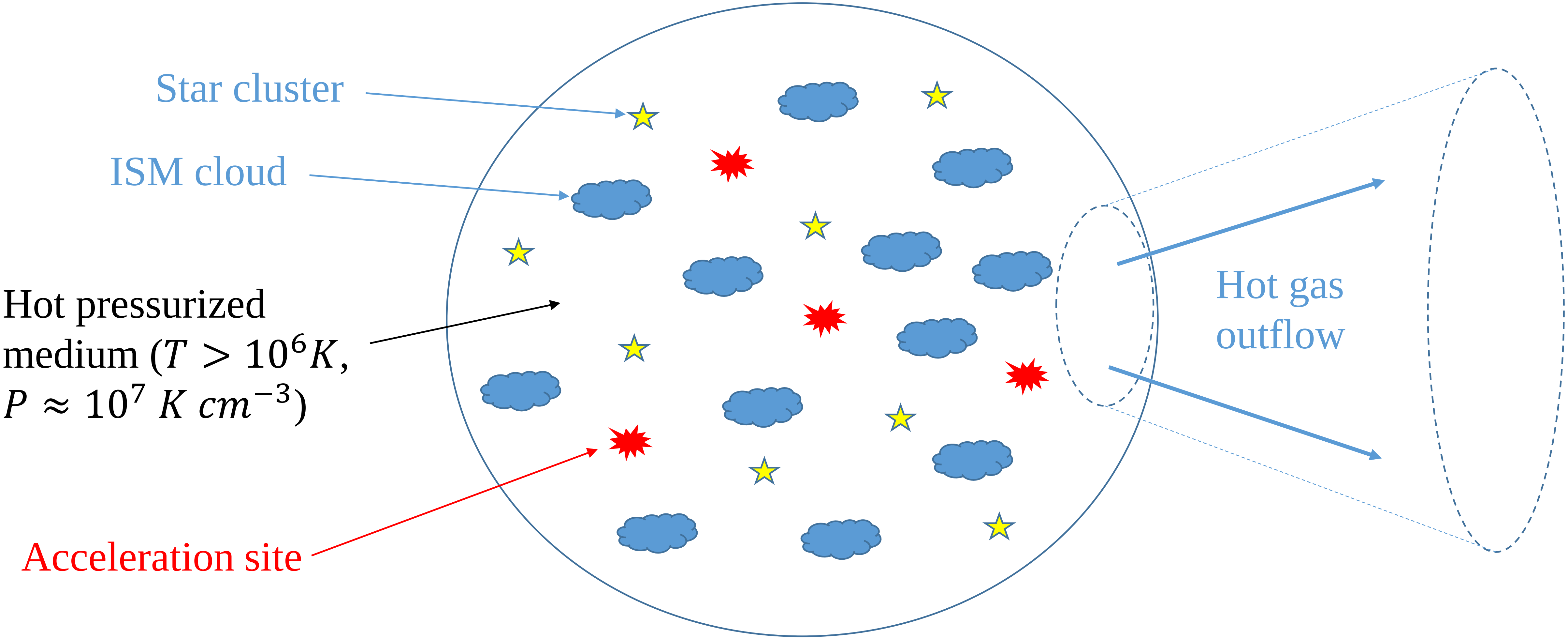


Promising wind bubble system

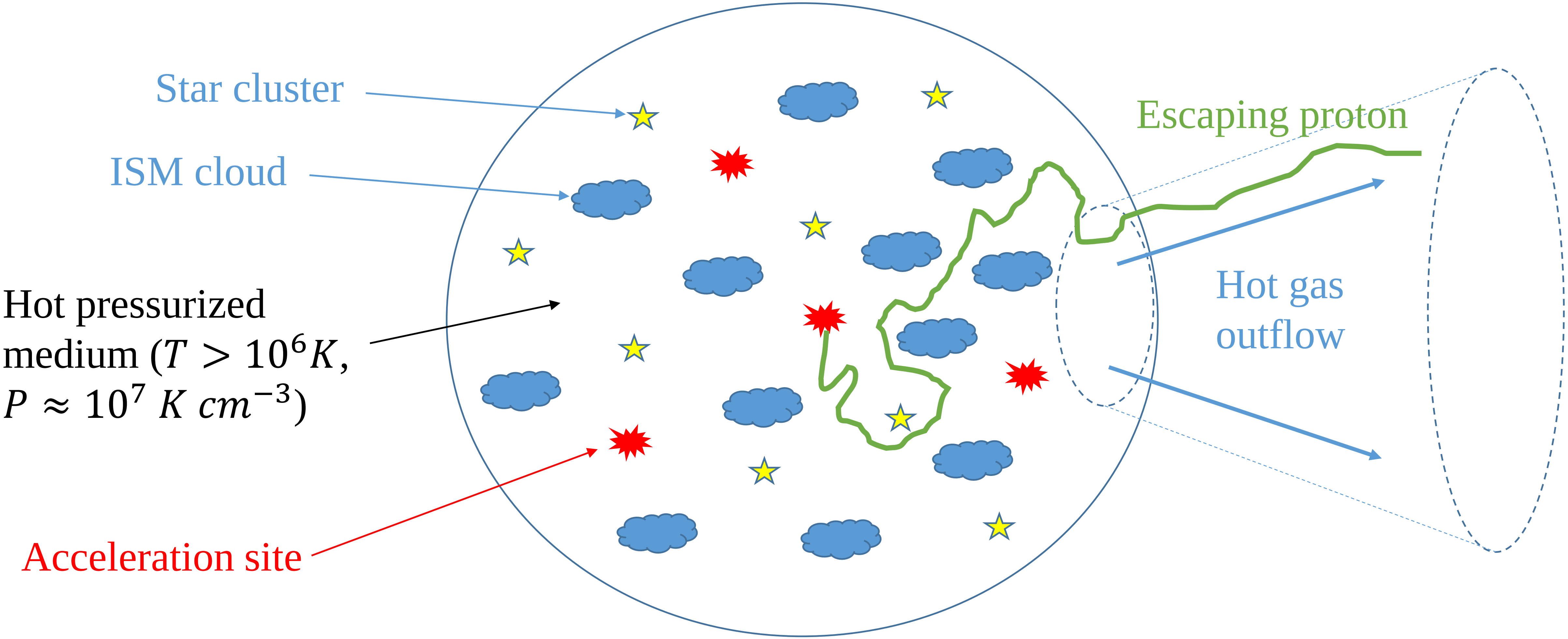


2 - STARBURST NUCLEI

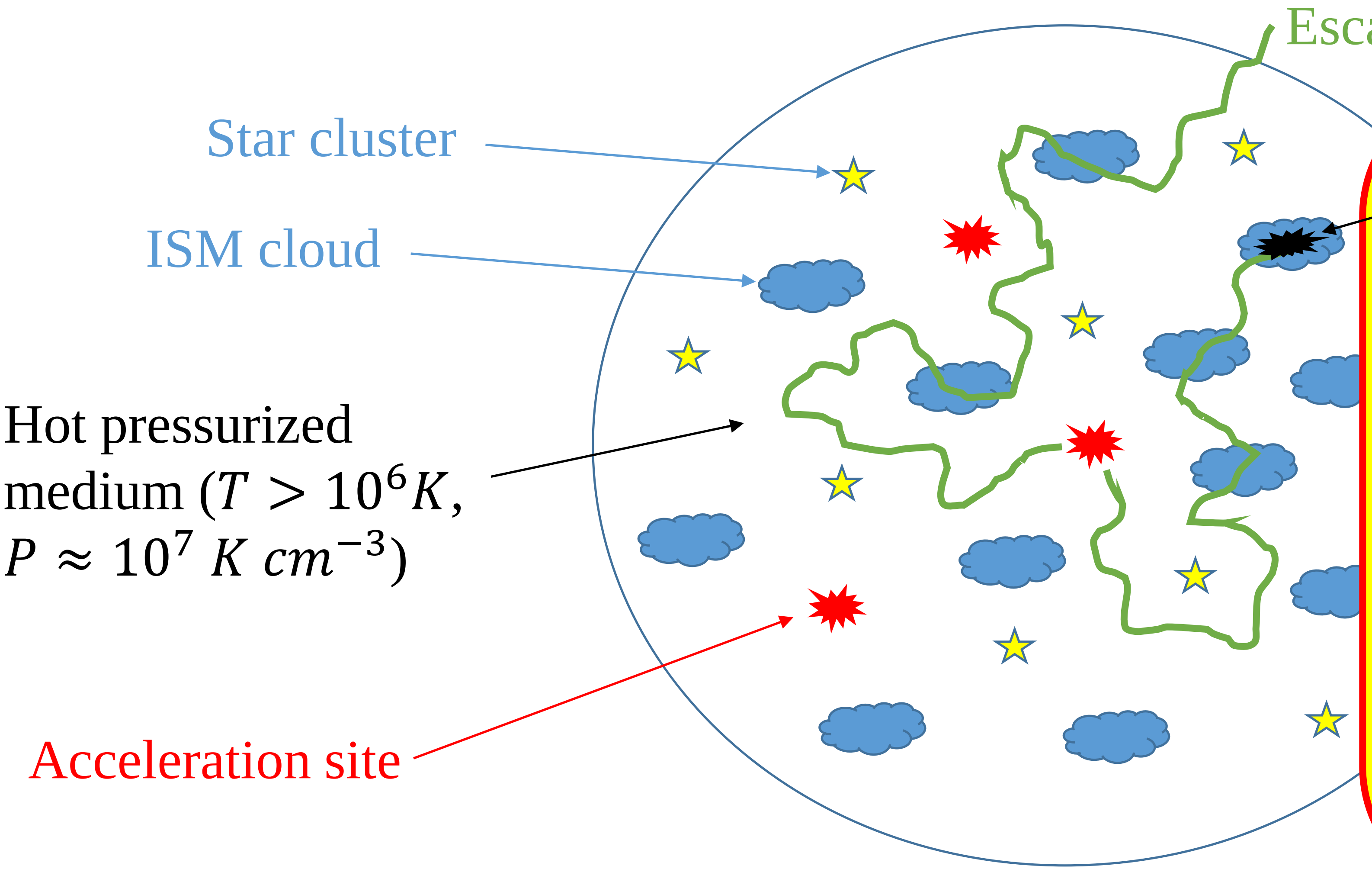
Particles in SBNi



Particles in SBNi



Particles in SBNi



$$p + p \rightarrow p + p + \pi^0 + \pi^+ + \pi^-$$

$$\pi^\pm \rightarrow e^\pm + \bar{\nu}_\mu + \nu_\mu + \nu_e(\bar{\nu}_e)$$

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\gamma_{VHE} + \gamma_{BKG} \rightarrow e^+ + e^-$$

Particle transport in SBNi

- Shocks are present in the entire starburst nucleus
- The medium is complex and highly fragmented

Leaky-box approximation

$$\frac{f(p)}{\tau_{loss}(p)} + \frac{f(p)}{\tau_{adv}(p)} + \frac{f(p)}{\tau_{diff}(p)} = Q(p)$$

Particle transport in SBNi

$$\tau_{loss}(p) = \left\{\sum_j \left[\frac{1}{E}\left(\frac{dE}{dt}\right)_j\right]\right\}^{-1} \qquad \tau_{adv} = R/v_{wind} \qquad \tau_{diff}(p) = R^2/D(p)$$

The particle injection is balanced by losses and escape

$$\frac{f(p)}{\tau_{loss}(p)} + \frac{f(p)}{\tau_{adv}(p)} + \frac{f(p)}{\tau_{diff}(p)} = Q(p)$$

Injection of particles

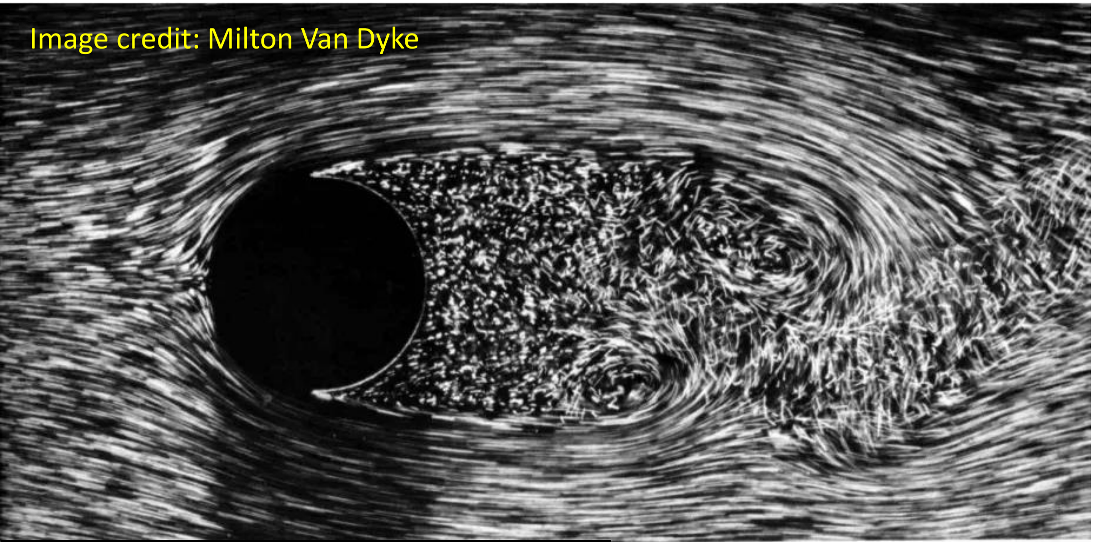
Particles are injected by SNRs as $\mathcal{N}_{SN}(p) \propto\ p^{-\alpha} e^{-p/p_{max}}$

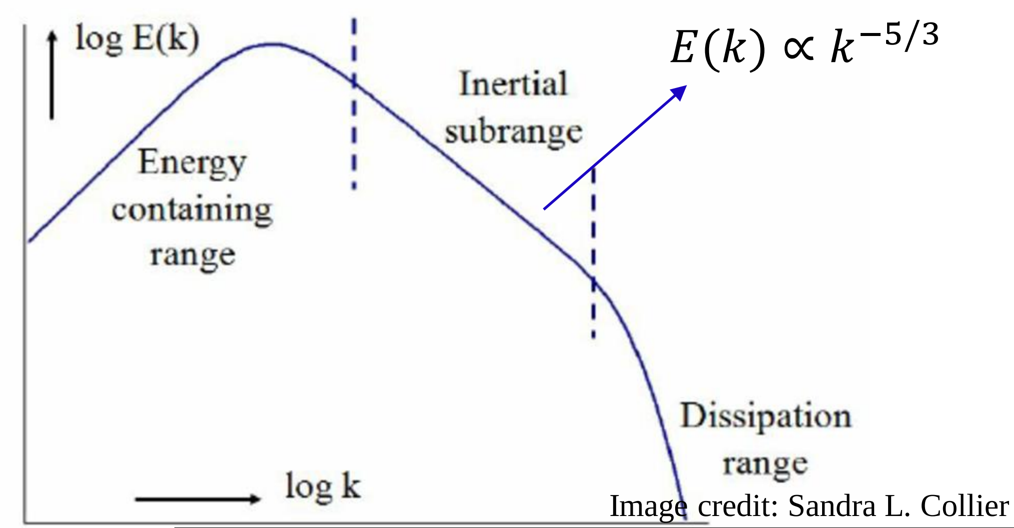
$$\xi\ E_{SN} = \int dp\ 4\,\pi\, p^2 T(p) \mathcal{N}_{SN}(p)$$

The injection term of the transport equation

$$Q_p(p) = \frac{\mathcal{R}_{SN} \mathcal{N}_{SN}(p)}{V} \propto \frac{\mathcal{R}_{SN}}{V} \left(\frac{p}{mc}\right)^{-\alpha} e^{-p/p_{max}}$$

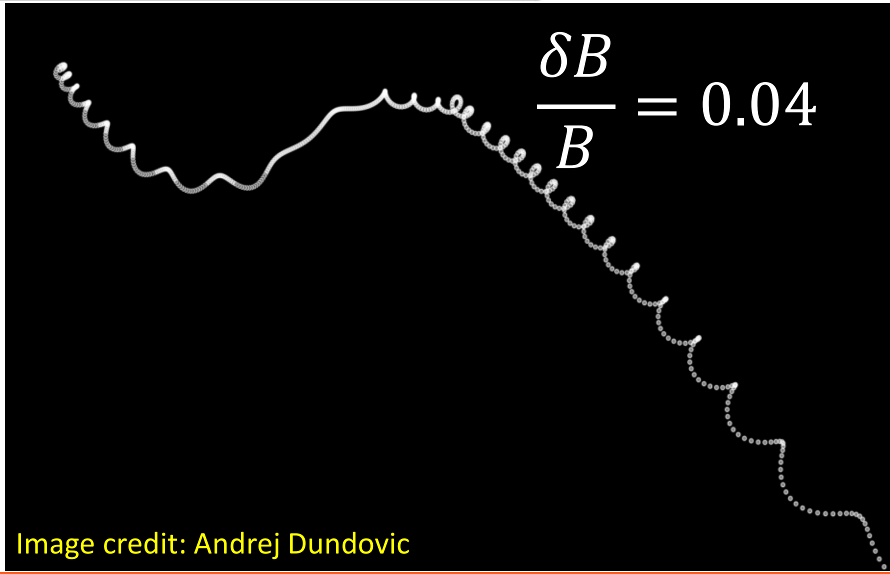
Turbulence and diffusion





For δB/B«1 particles follow helical trajectories around magnetic field lines

For δB/B≈1 particles are confined for longer time



Diffusion models

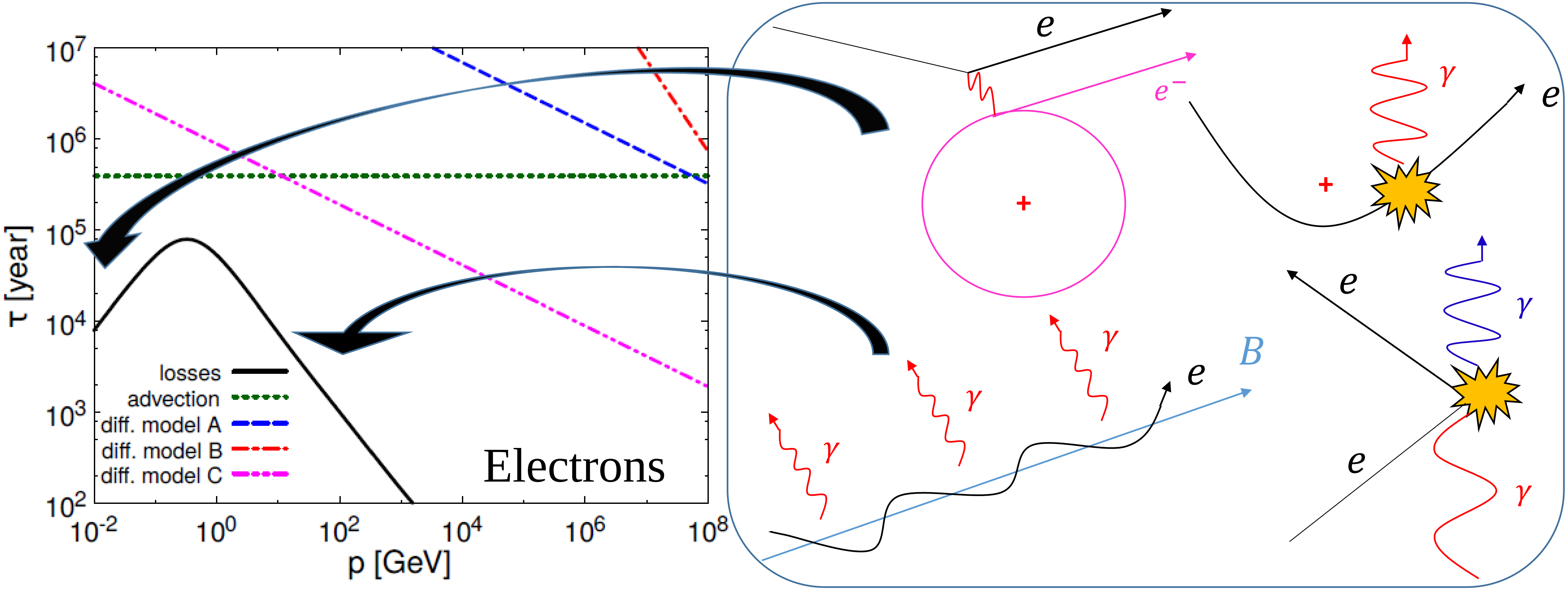
$D(p) = r_L(p)v(p)/3\mathcal{F}(k) \leftrightarrow Diffusion\ coefficient$

$\int_{k_0}^{\infty} dk\ \mathcal{F}(k)/k = (\frac{\delta B}{B})^2 = \eta_B \leftrightarrow How\ much\ turbulent?$

$k_0^{-1} = L_0 = 1\,pc \leftrightarrow Injection\ scale$

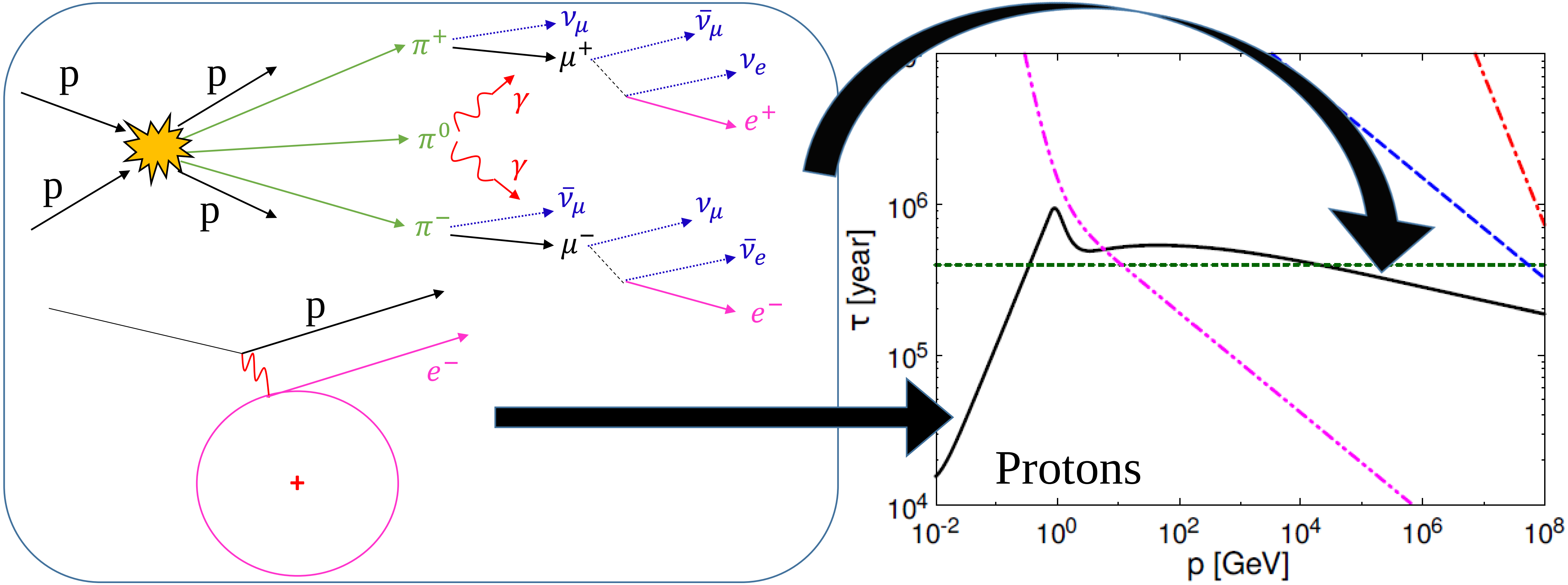
A) $\mathcal{F}(k) \propto k^{-2/3}$ - $\eta_B \approx 1 \leftrightarrow Strong\ turbulence$
B) $\mathcal{F}(k) = 1 \leftrightarrow Extreme\ turbulence$
C) $\mathcal{F}(k) \propto k^{-2/3}$ - $\eta_B \ll 1 \leftrightarrow MW - like\ turbulence$

Particle lifetime in SBNi



D_L(Mpc)	$\mathscr{R}_{SN}(yr^{-1})$	$R(pc)$	α	$B(\mu G)$	$v_{wind}(\frac{km}{s})$	$n_{ISM}(cm^{-3})$	$U_{RAD}(\frac{eV}{cm^3})$
3.8	0.05	200	4.25	200	500	125	3400

Particle lifetime in SBNi



D_L(Mpc)	$\mathscr{R}_{SN}(\mathrm{yr}^{-1})$	$R(pc)$	α	$B(\mu\mathrm{G})$	$v_{\mathrm{wind}}(\frac{\mathrm{km}}{\mathrm{s}})$	$n_{\mathrm{ISM}}(\mathrm{cm}^{-3})$	$U_{\mathrm{RAD}}(\frac{\mathrm{eV}}{\mathrm{cm}^3})$
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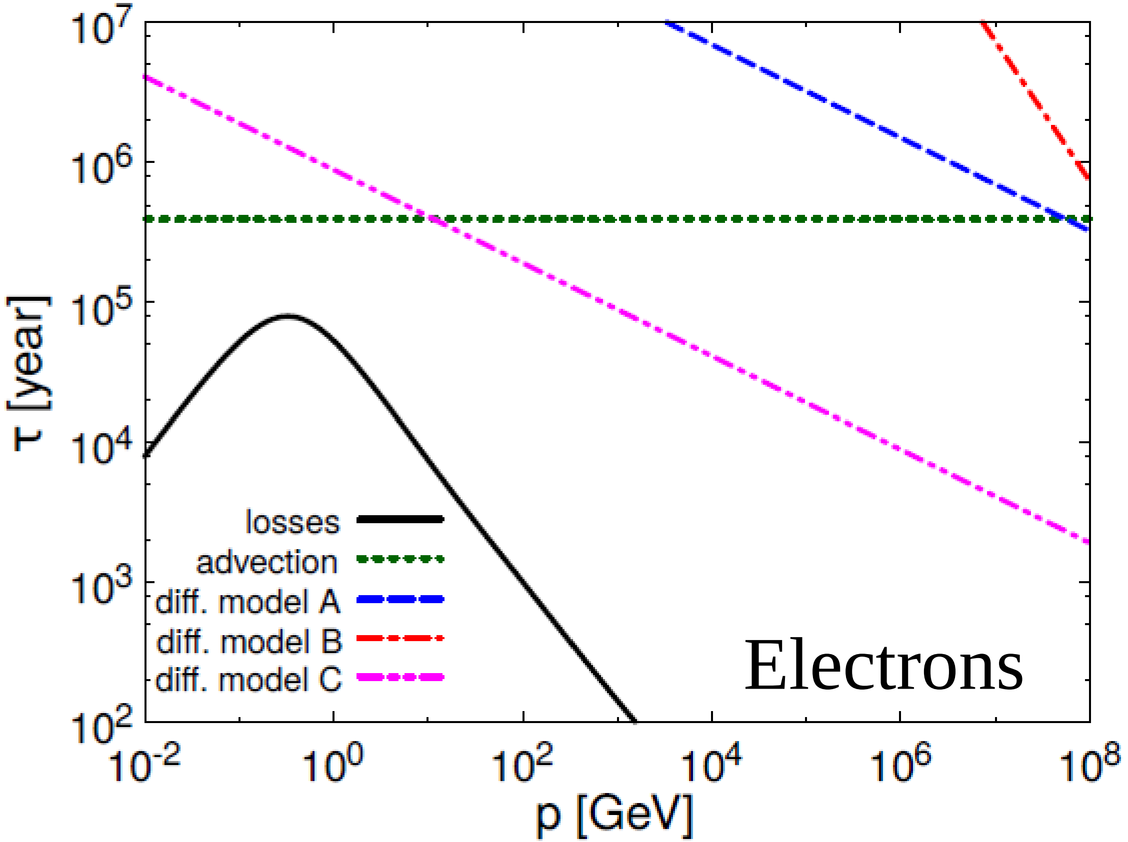

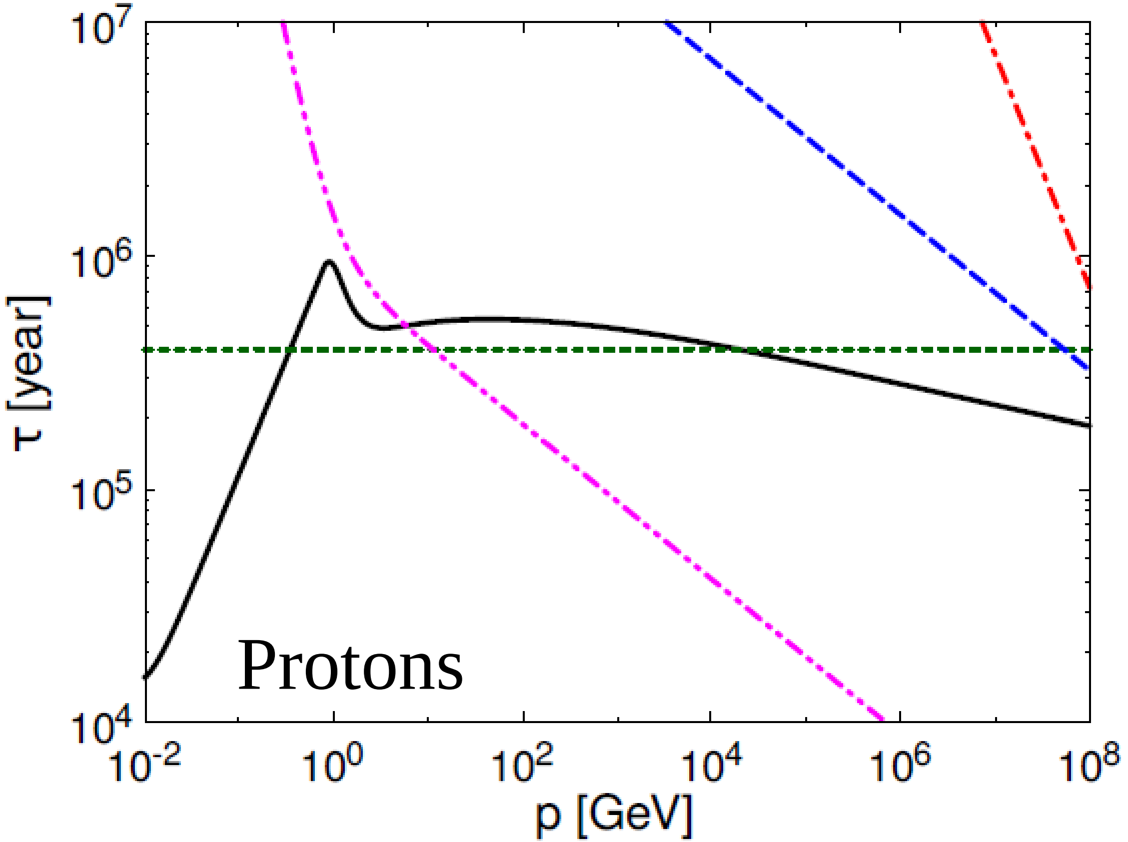

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Confinement and calorimetry

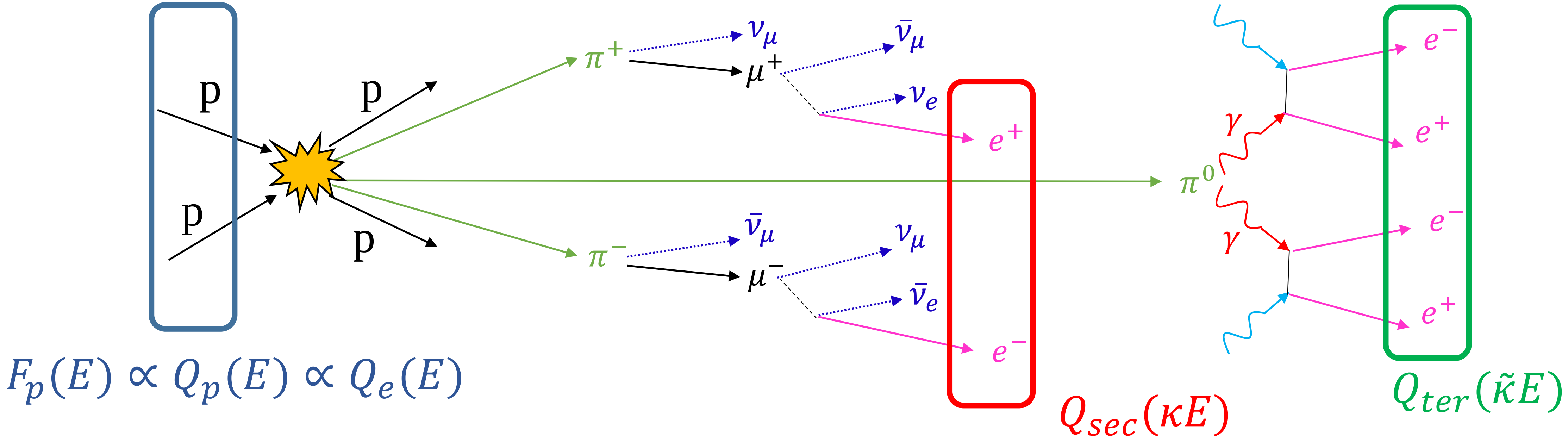
1. Electrons are likely well confined in starburst environment due to local n_{ISM}, B & U_{RAD}

2. Proton calorimetry is not guaranteed but

- High level of turbulence
- High ISM density

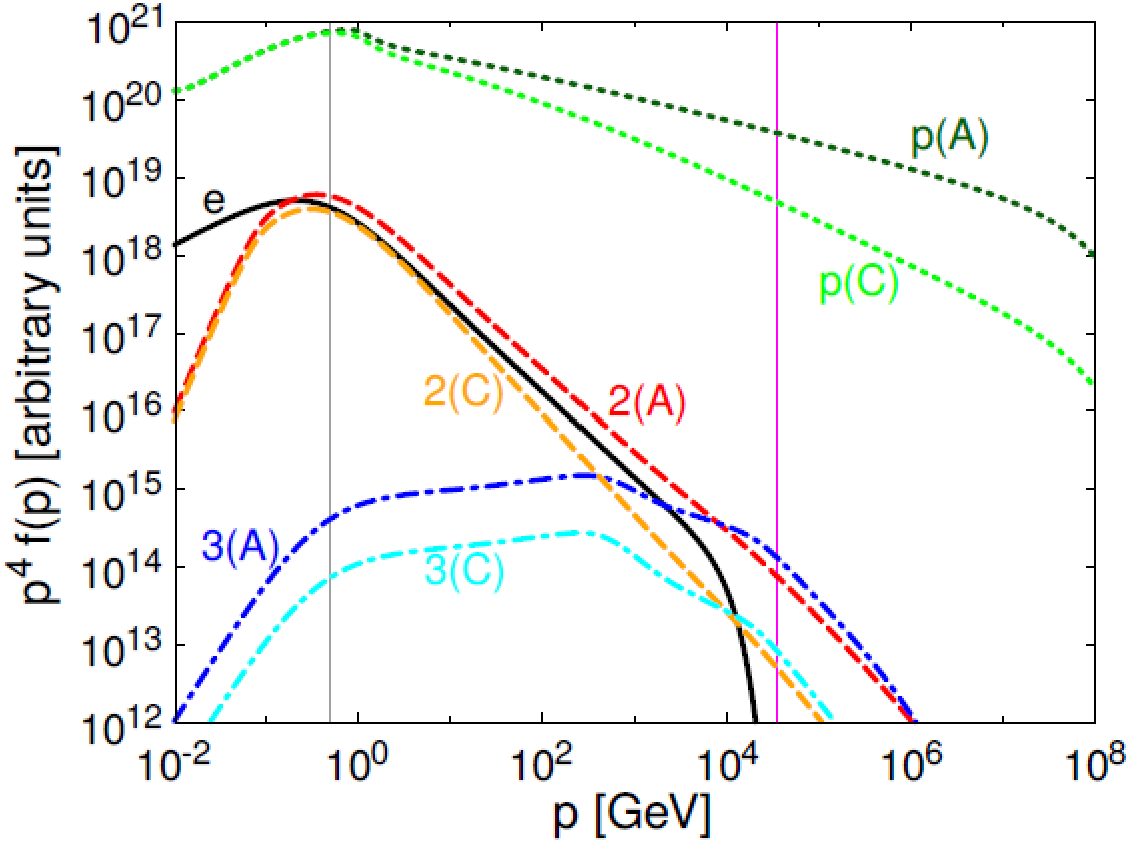
suggest that diffusion escape might be negligible and energy losses can compete with the advection in shaping the transport

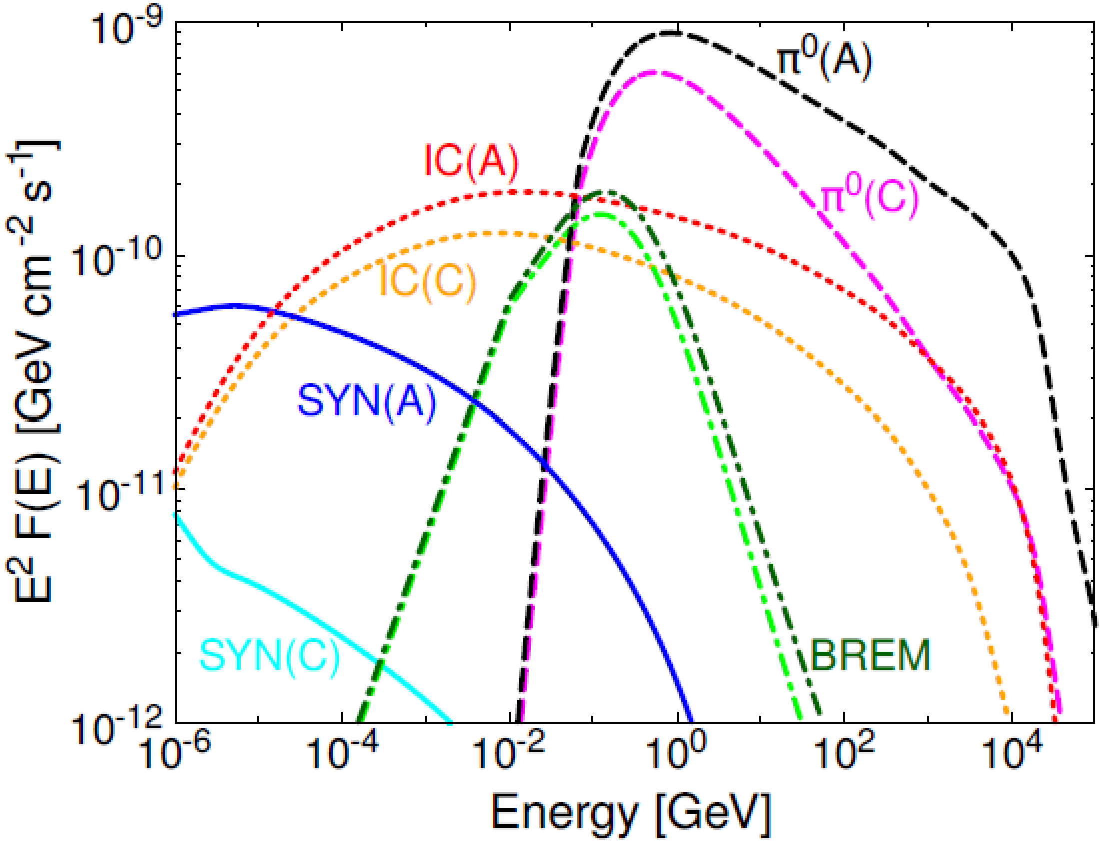
Secondaries and pairs in a calorimeter



$$\begin{cases} Q_{sec}(\kappa E) \propto Q_p(E) \\ Q_{ter}(\tilde{\kappa} E) \propto \tau^*_{\gamma\gamma}(E) Q_p(E) \end{cases} \Longrightarrow \frac{Q_{ter}(E)}{Q_{sec}(E)} \approx (2)\tau^*_{\gamma\gamma}(E)(\tilde{\kappa}/\kappa)^{\alpha-3}$$

Particle spectra and HE SED

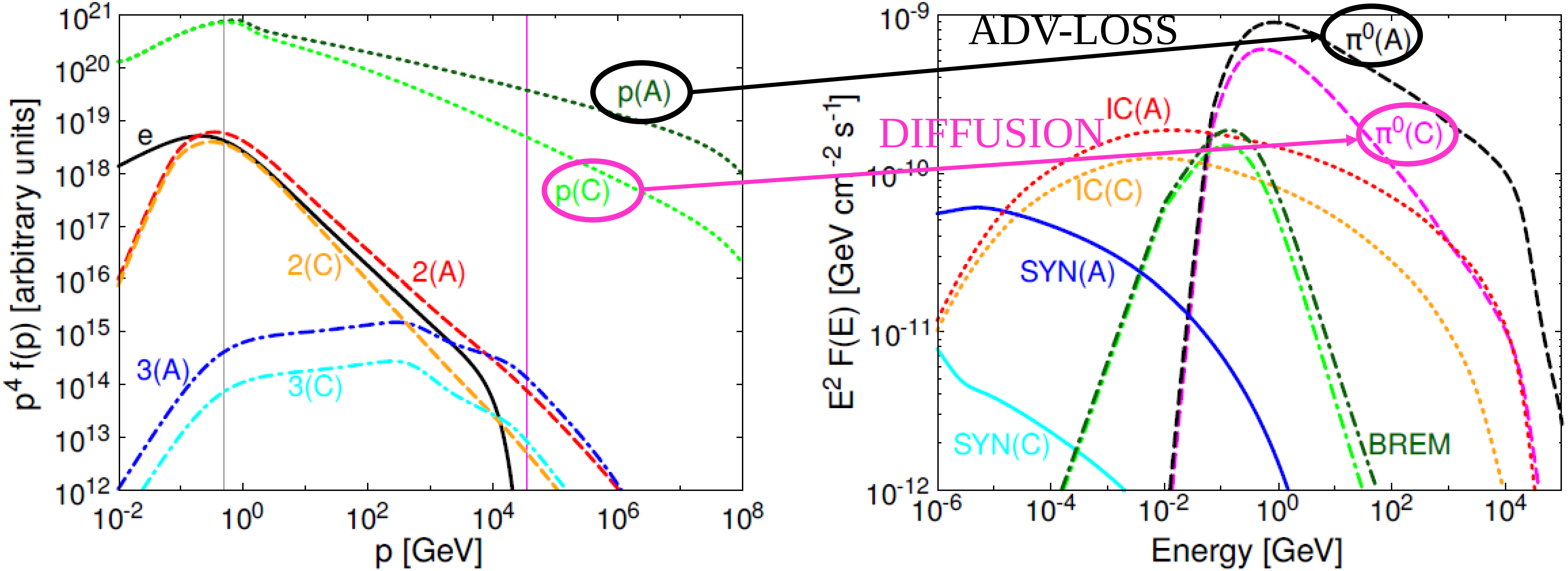




A = B → STRONG TURBULENCE

C → MILD TURBULENCE

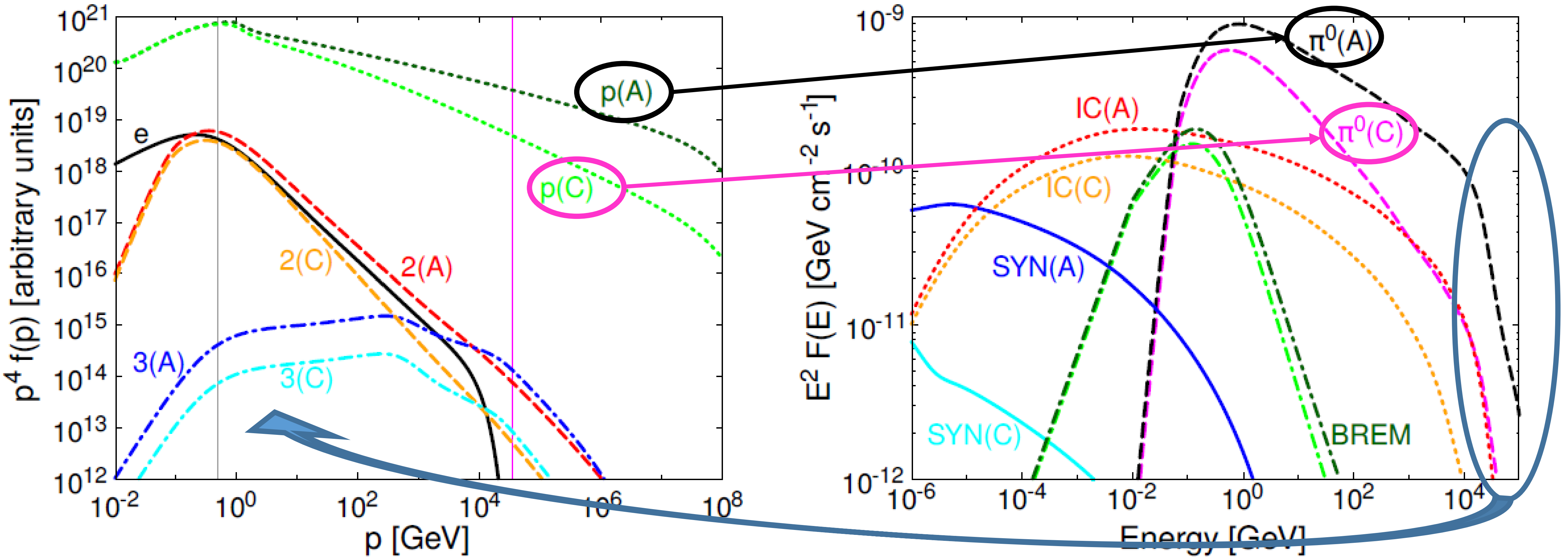
Impact of D on the HE gammas



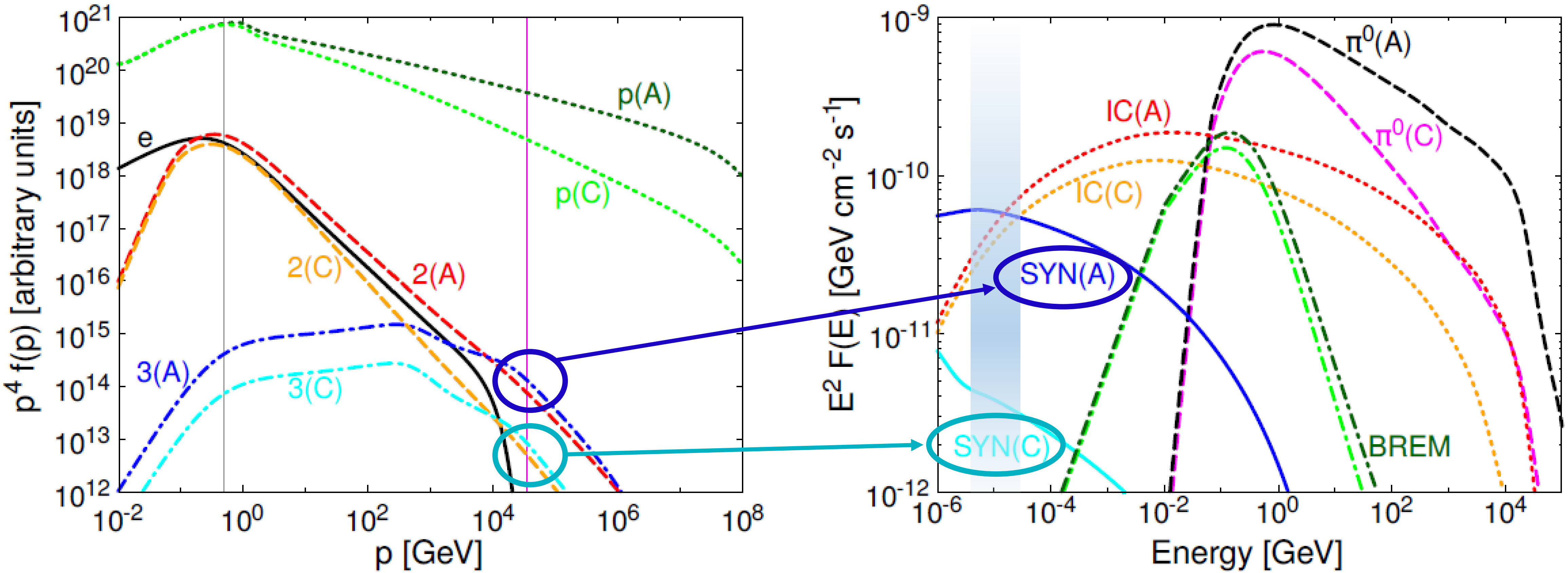
A = B → ADV-LOSS TRANSPORT

C → DIFF TRANSPORT

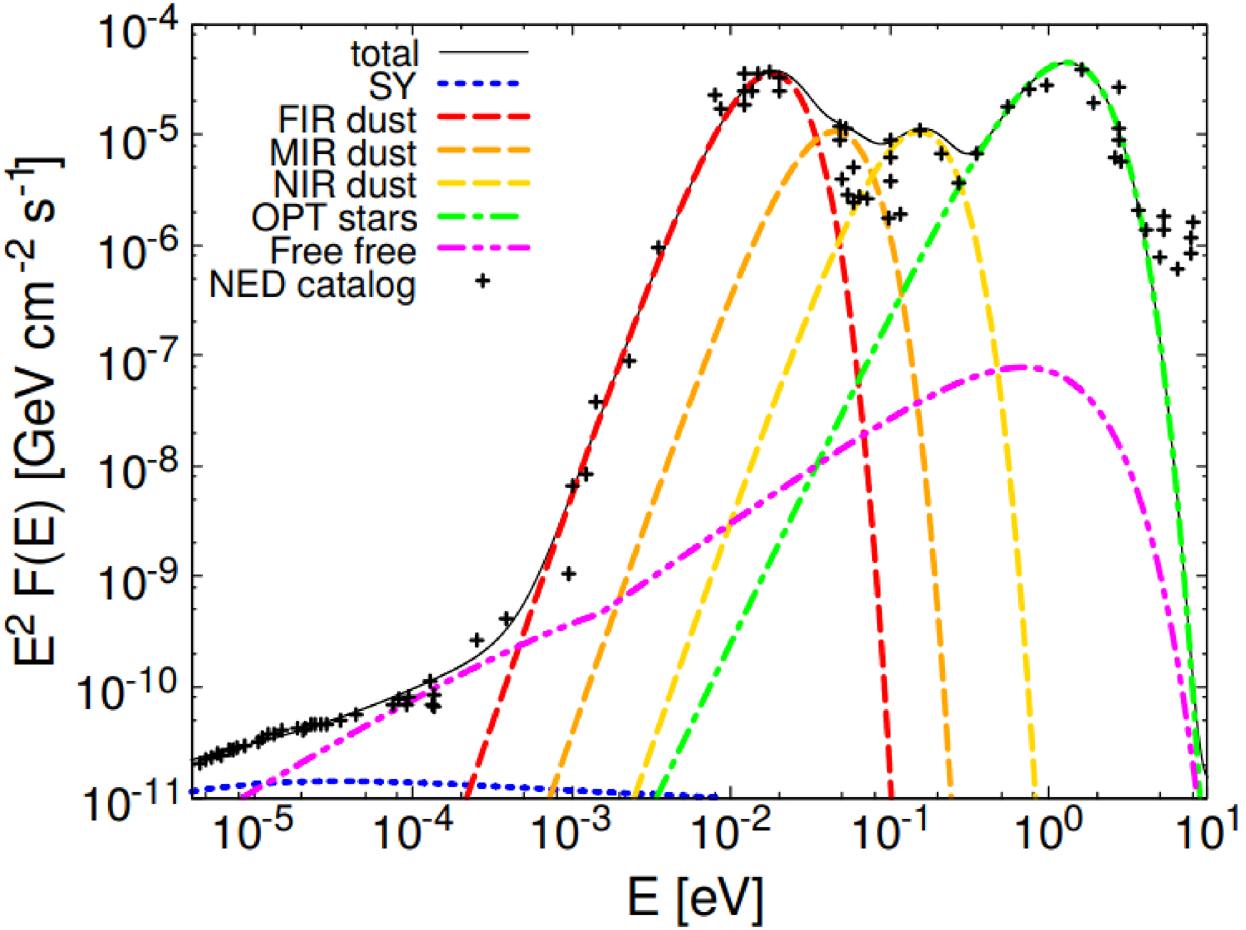
Gamma absorption and pairs

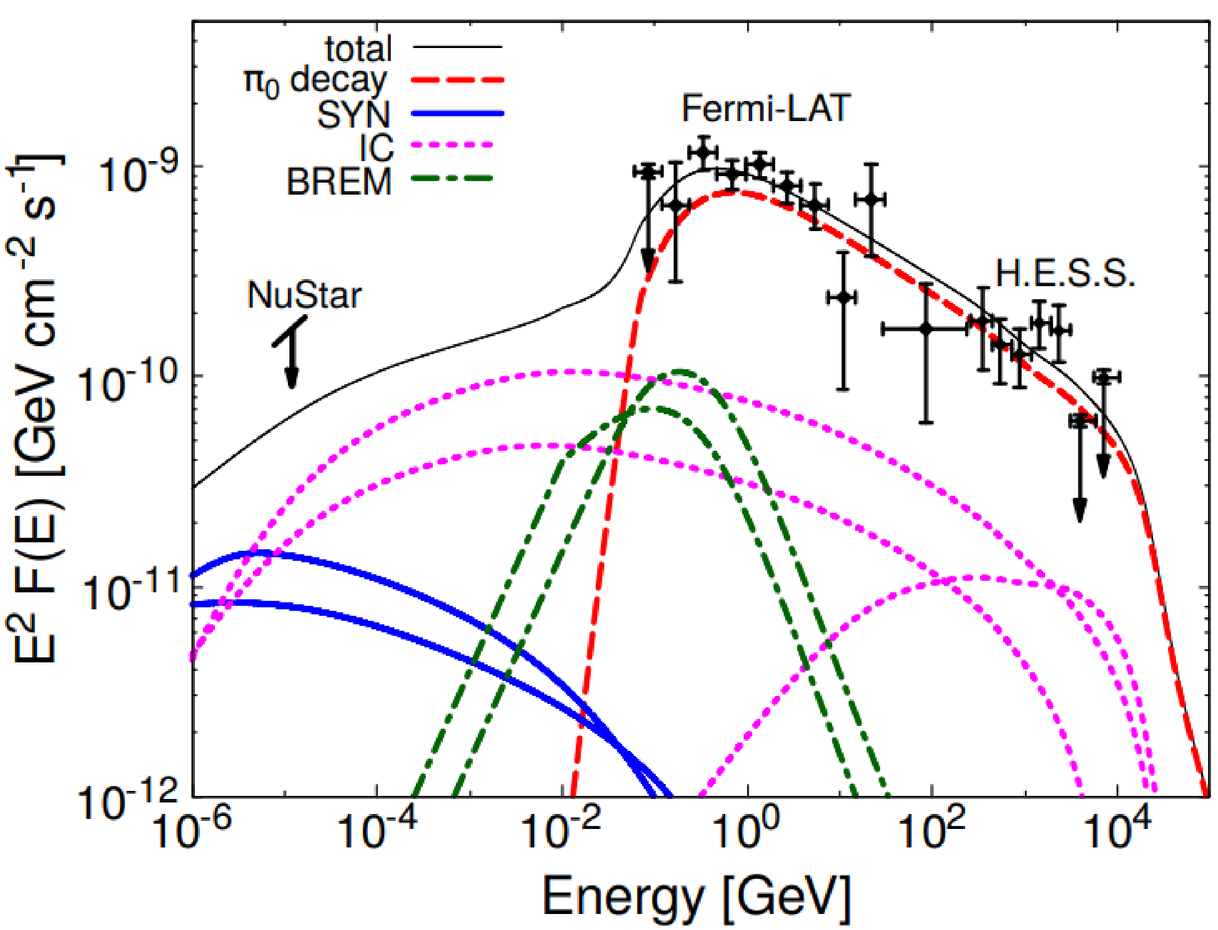


Hard X-rays as hadronic marker



The case of NGC 253





Conclusions – Part 1

- SBNi are unique environments for particle acceleration and confinement where the transport is regulated mostly by advection and energy losses

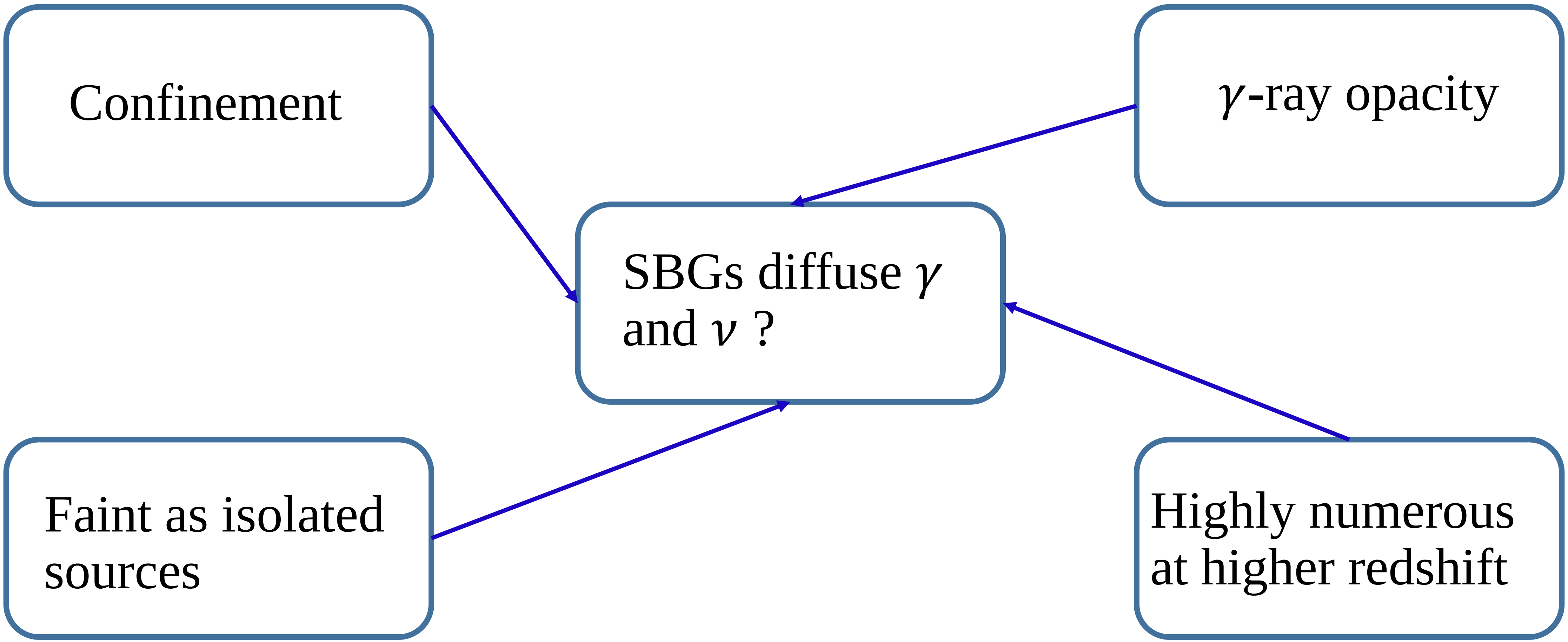
- HE gamma rays are likely dominated by hadronic emission with strong absorption at VHE

- The hard X-ray emission from hadronic secondaries and pairs can support calorimetry

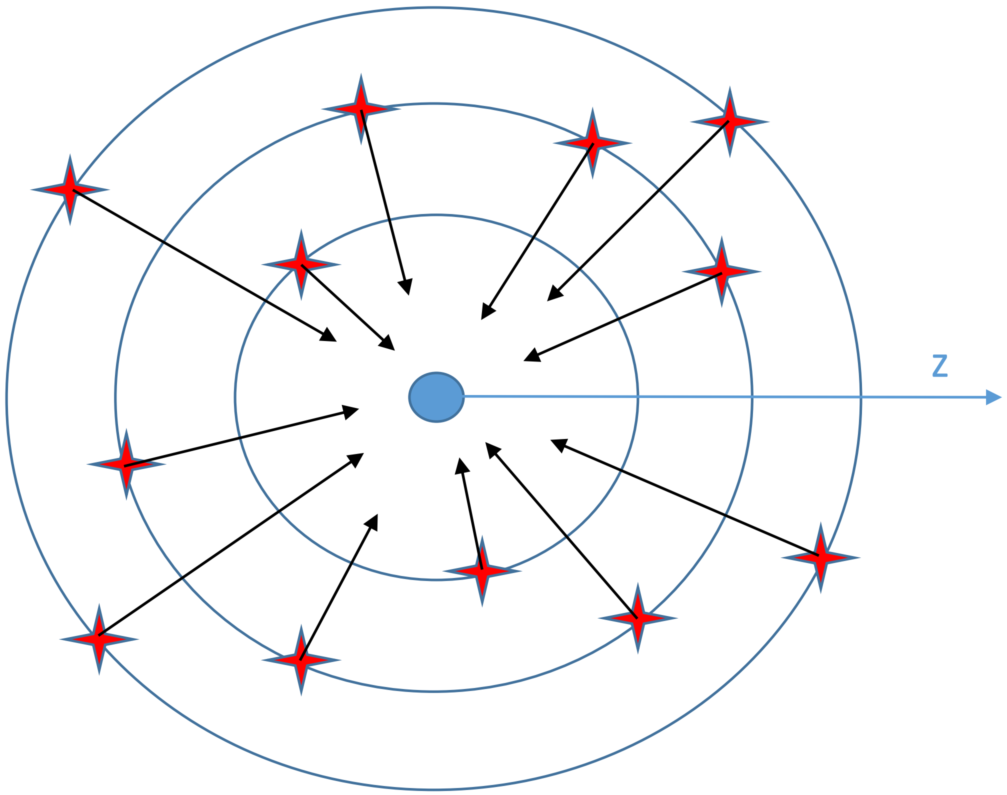
- Neutrinos from individual starbursts are approximately 2 orders of magnitude below current IceCube sensitivity for pointlike sources

3 – DIFFUSE FLUX OF STARBURST ORIGIN

Starburst contribution to the diffuse flux



Diffuse flux - ingredients



- Flux scaling with the SFR - prototype
- Redshift dependence of sources
- Number of objects as a function of z
- Volume element and EBL absorption

$$\Phi_{\gamma,\nu}(E) = \frac{1}{4\pi}\int d\Omega \int_0^{4.2} dz \frac{dV_C(z)}{dz\, d\Omega}\int_{\psi_{min}}^{\infty} d\ln\psi\ \Phi_{SFR}(\psi,z)[1+z]^2 f_{\gamma,\nu}(E[1+z],\psi)e^{-\tau_{\gamma\gamma}(E,z)}$$

Prototype starburst-calorimeter and SFR-scaling

We define as starburst an object that succesfully confines particles

$$\tau_{loss}(E,\psi) \leq \tau_{esc}(E,\psi) \rightarrow \psi_{min}$$

The injection of gamma rays and neutrinos scales linearly with the SFR when the source is calorimetric

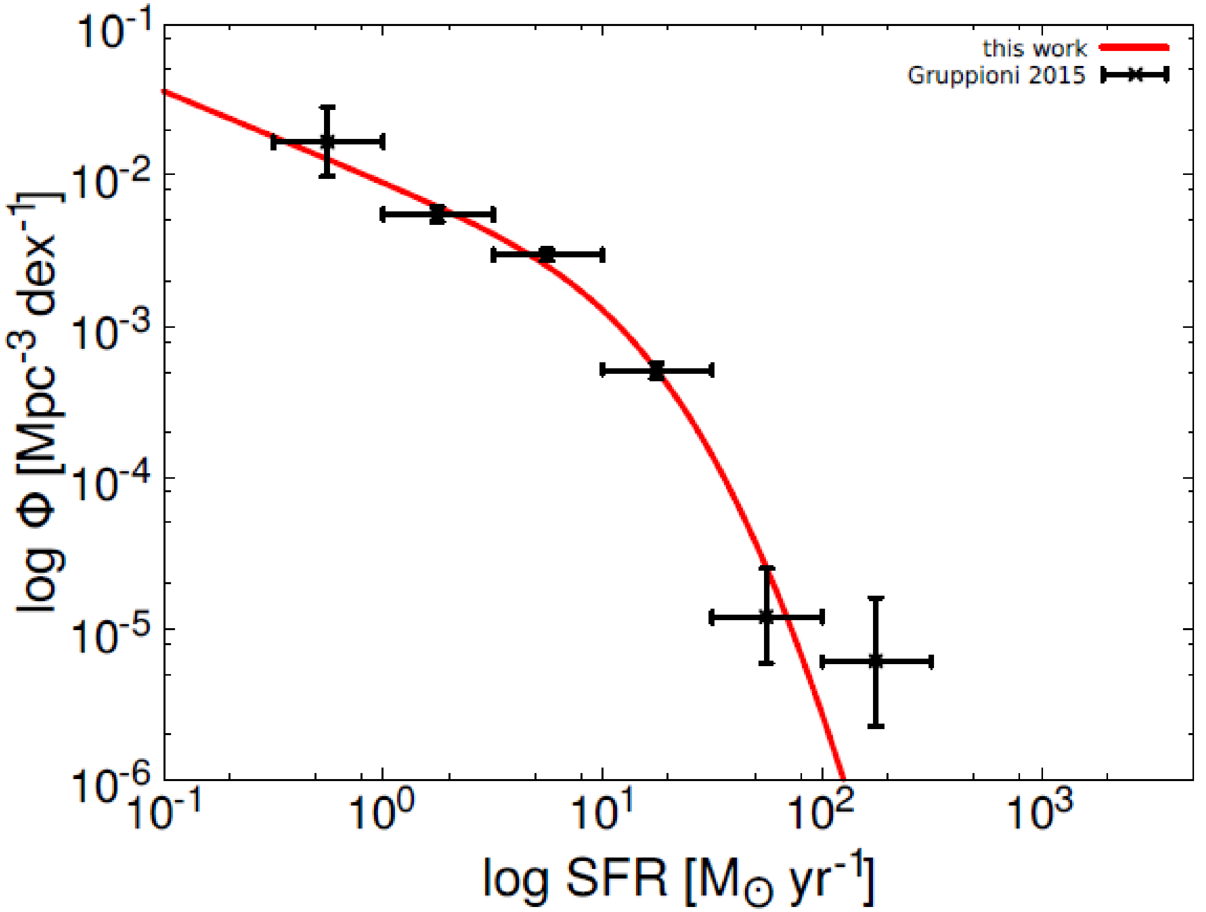
$$Q_{\gamma,\nu}(E,\psi) = \left(\frac{\psi}{\psi_{M82}}\right) \times Q_{\gamma,\nu}^{(M82)}(E)$$

Counting sources: SFRD & SFRF

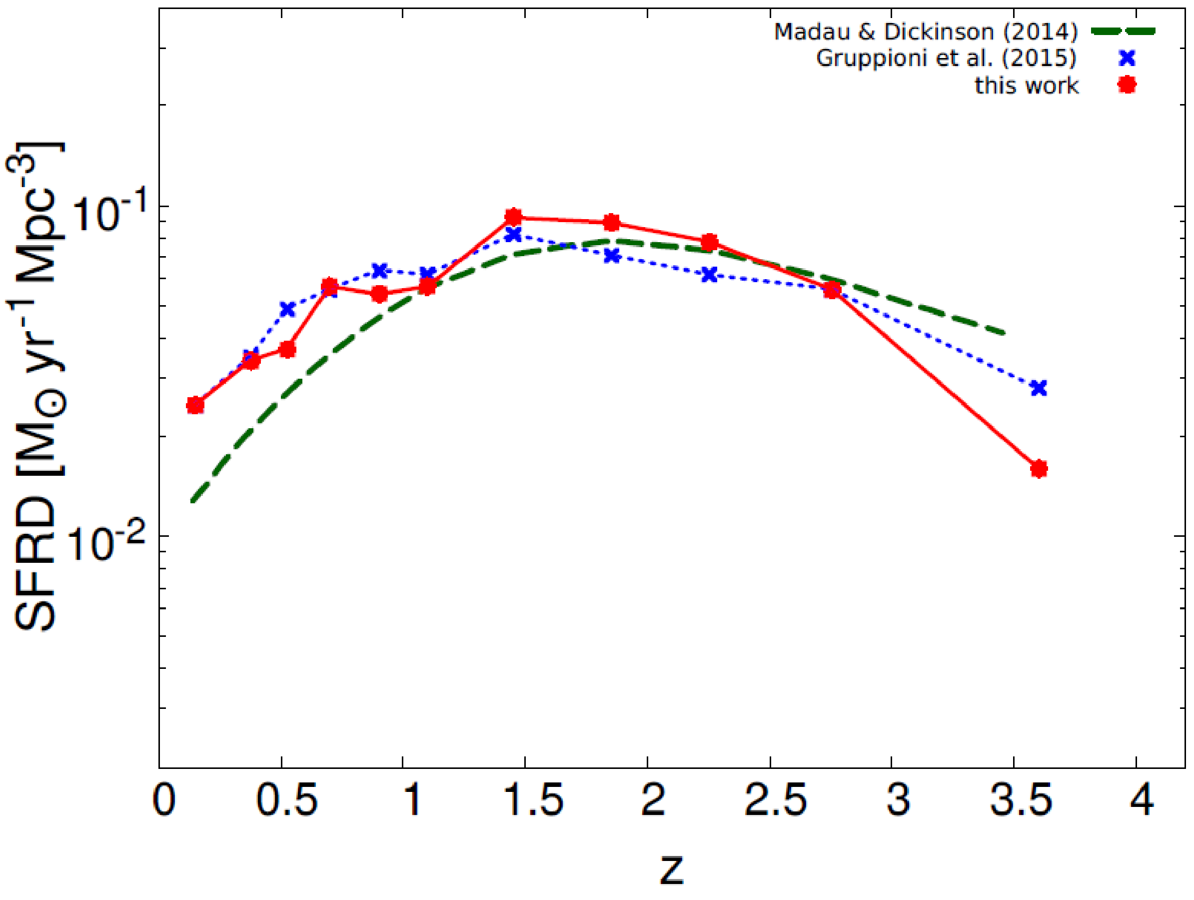
The star formation rate function (SFRF) allows to count the number density of galaxies as a function of the SFR

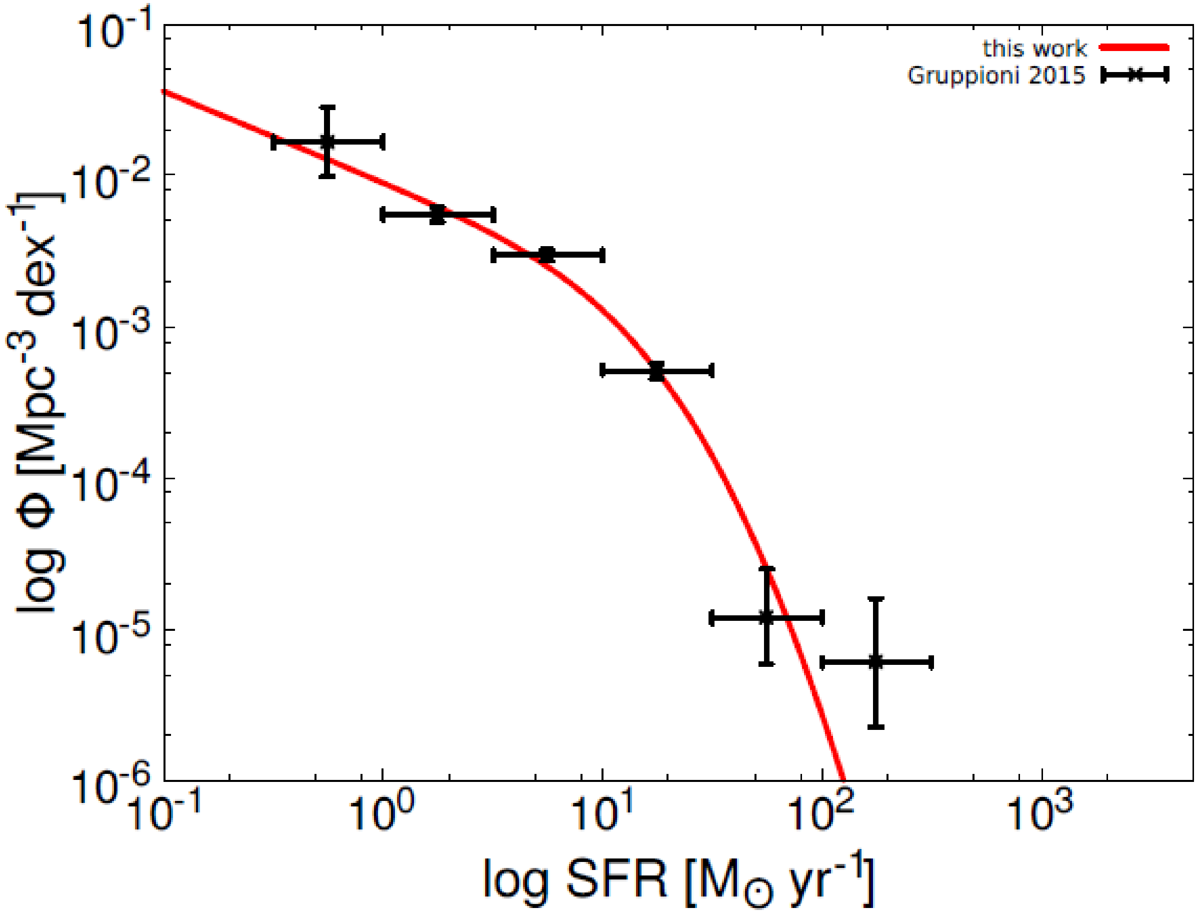
$$\phi(\psi, z) = \frac{dN(\psi,z)}{d\ln\psi \; dV_c}$$

$$n_{SBG}(z) = \int_{\psi_{min}}^{\infty} d\ln\psi \;\; \phi(\psi, z)$$

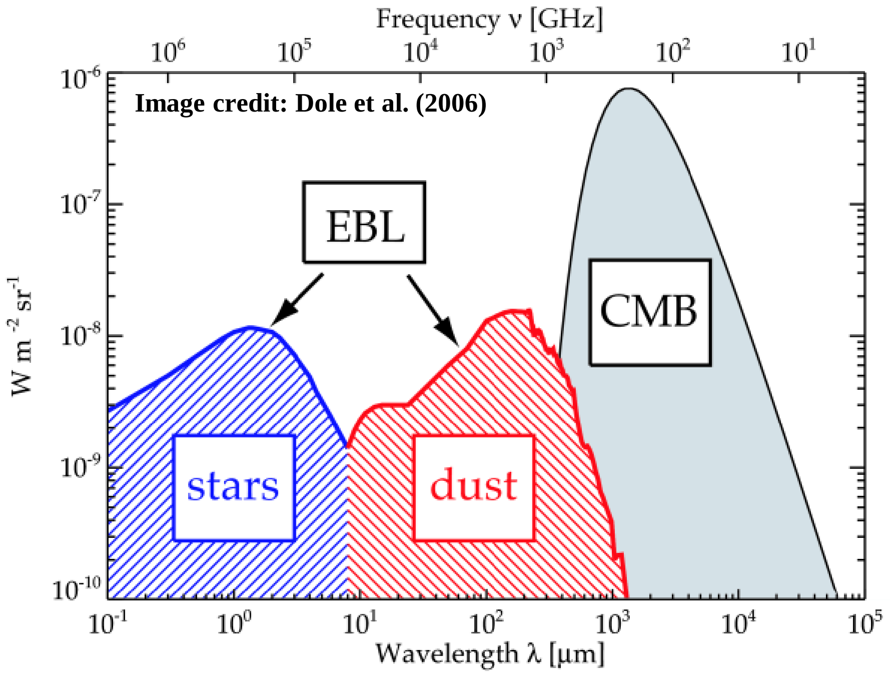


Counting sources: SFRD & SFRF



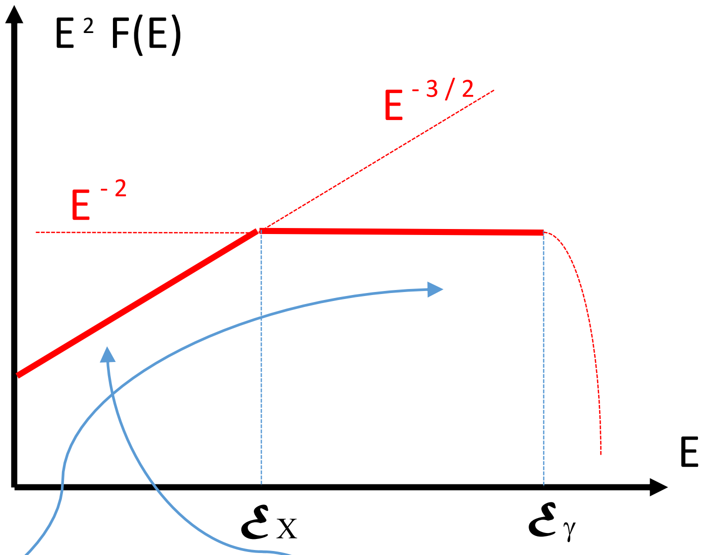


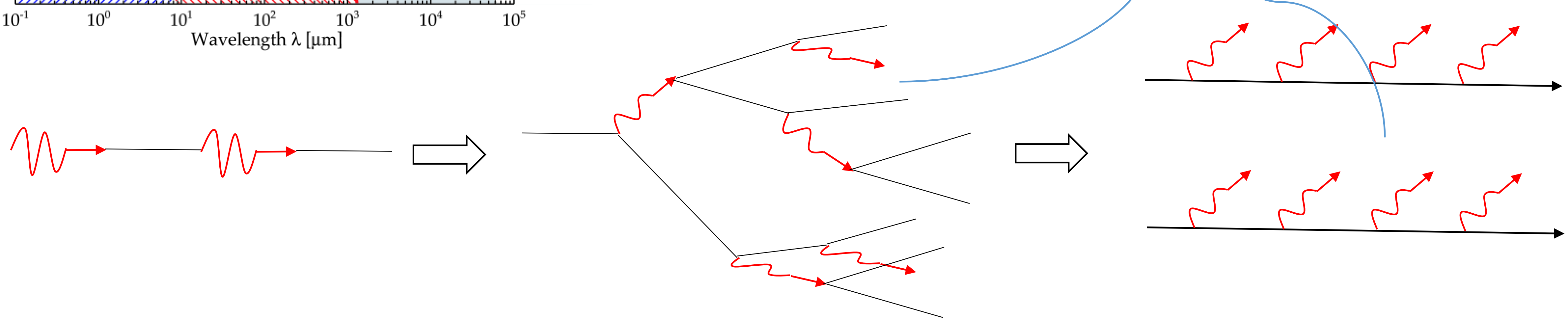
EBL-CMB and electromagnetic cascade



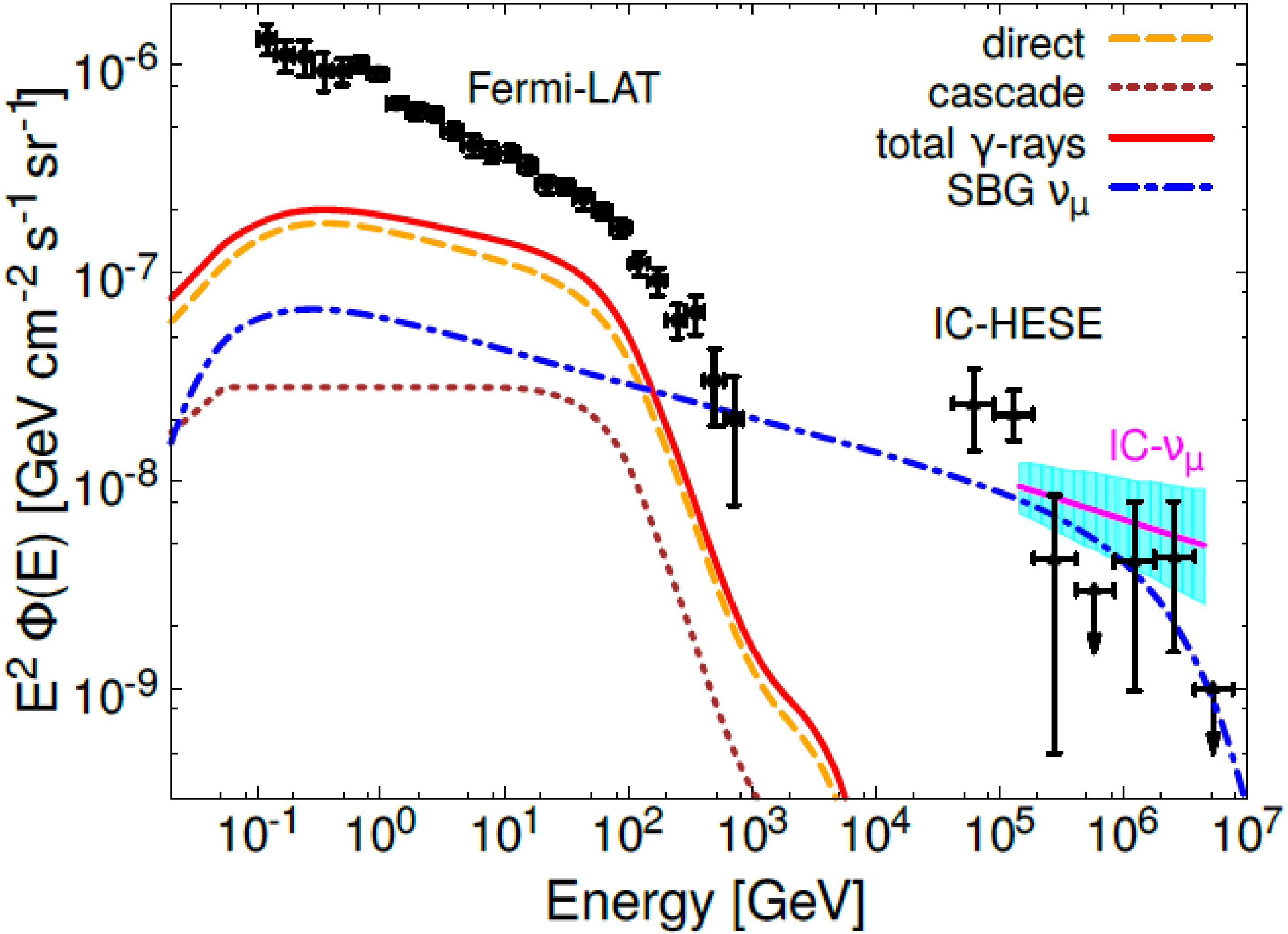
$\mathcal{E}_\gamma \rightarrow$ Minimum energy for PP on the EBL

$\mathcal{E}_X \rightarrow$ IC from the least energetic pair





Diffuse γ and ν flux from SBGs



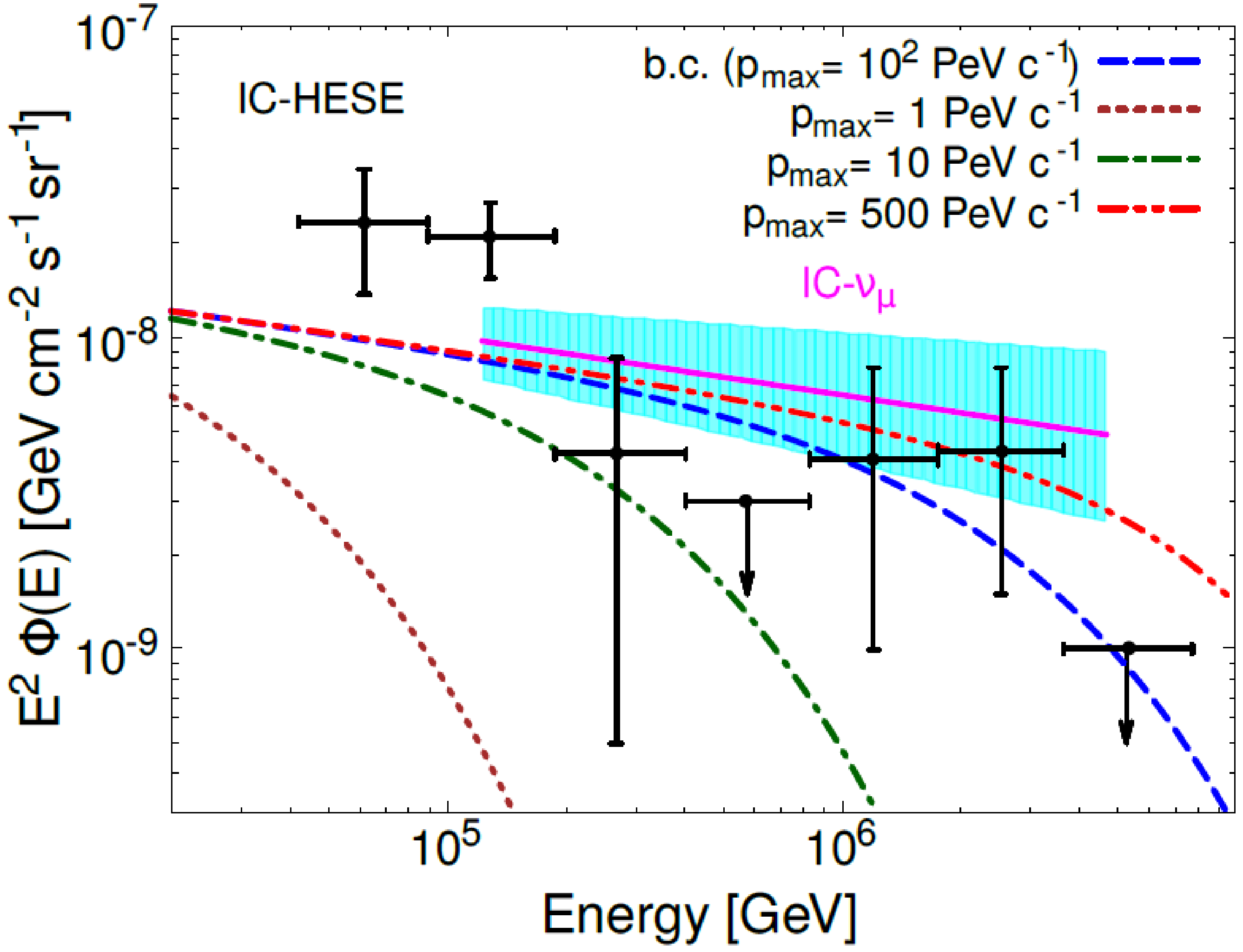
On the maximum energy

Starburst contribution to IceCube neutrinos strongly depends on the maximum energy achievable in SBNi

SNR in case of Bohm diffusion:

$$E_{max} = 30\ PeV\ \times R_3 u_4 B_{mG}$$

- Magnetic field amplification can allow reaching 10-100 PeV



Conclusions – Part 2

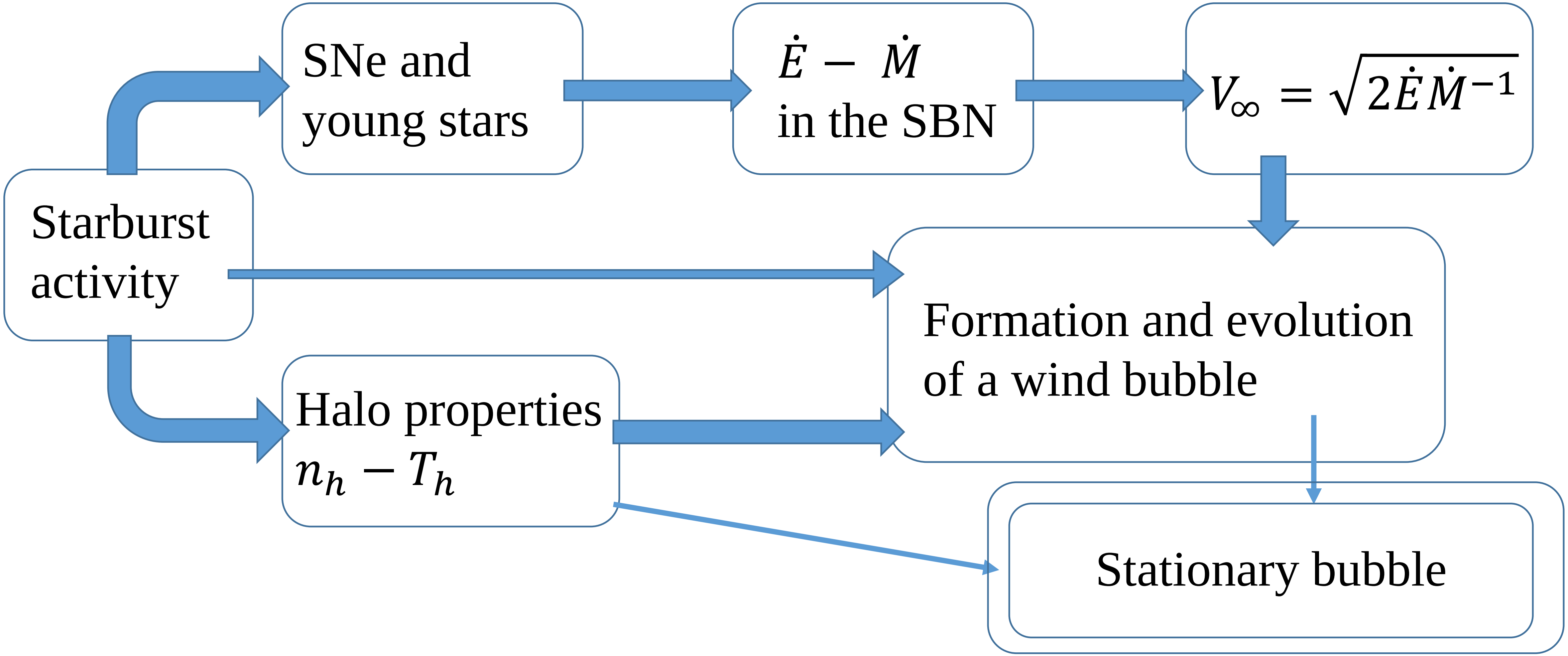
- The high number density of starbursts expected from the SF-history could provide a diffuse neutrino flux that can be the leading contribution to current IceCube observations > 200 TeV

- Gamma rays from starbursts can explain a consistent part of the diffuse flux observed by Fermi-LAT

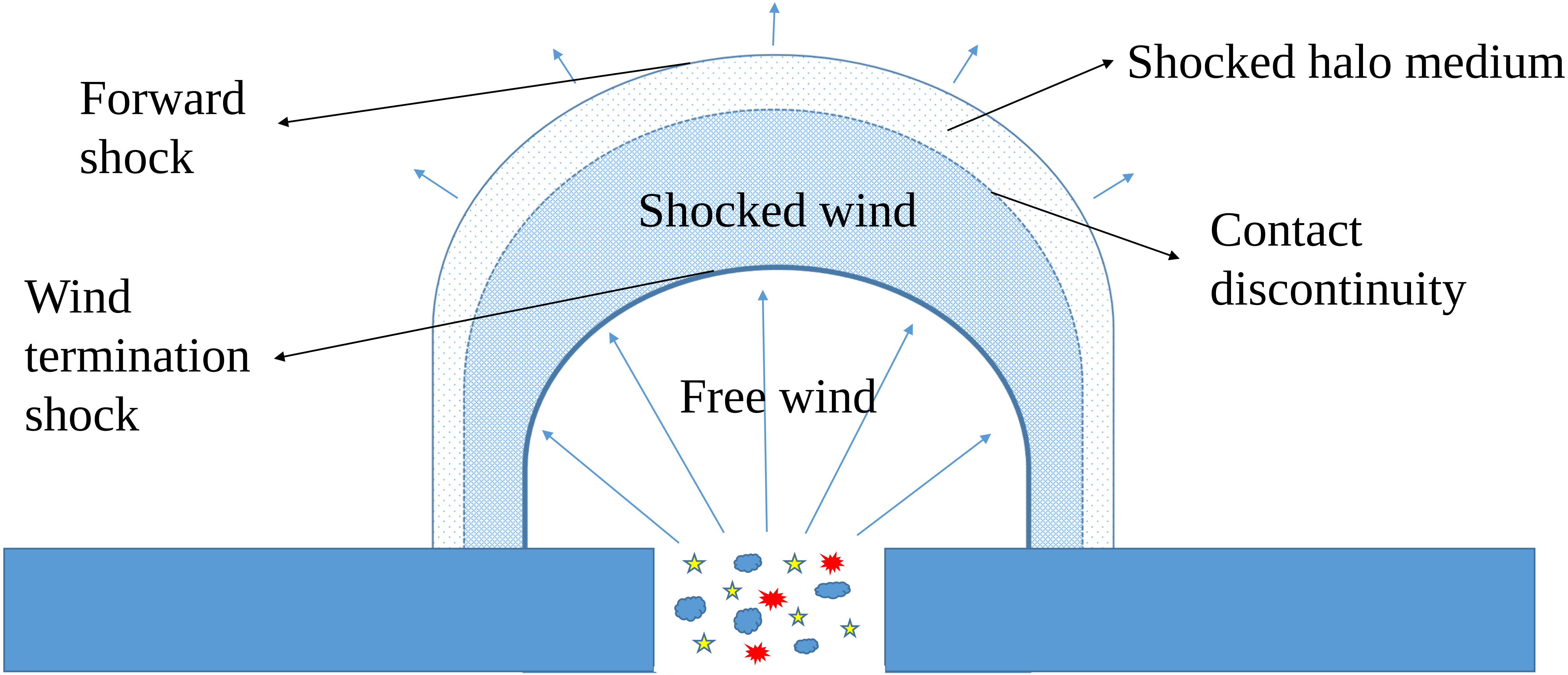
- The maximum energy at SNRs in SBNi strongly affects neutrinos, but not gamma rays

4 – STARBURST WIND TERMINATION SHOCK

Launching of a galactic wind



Structure of a wind bubble

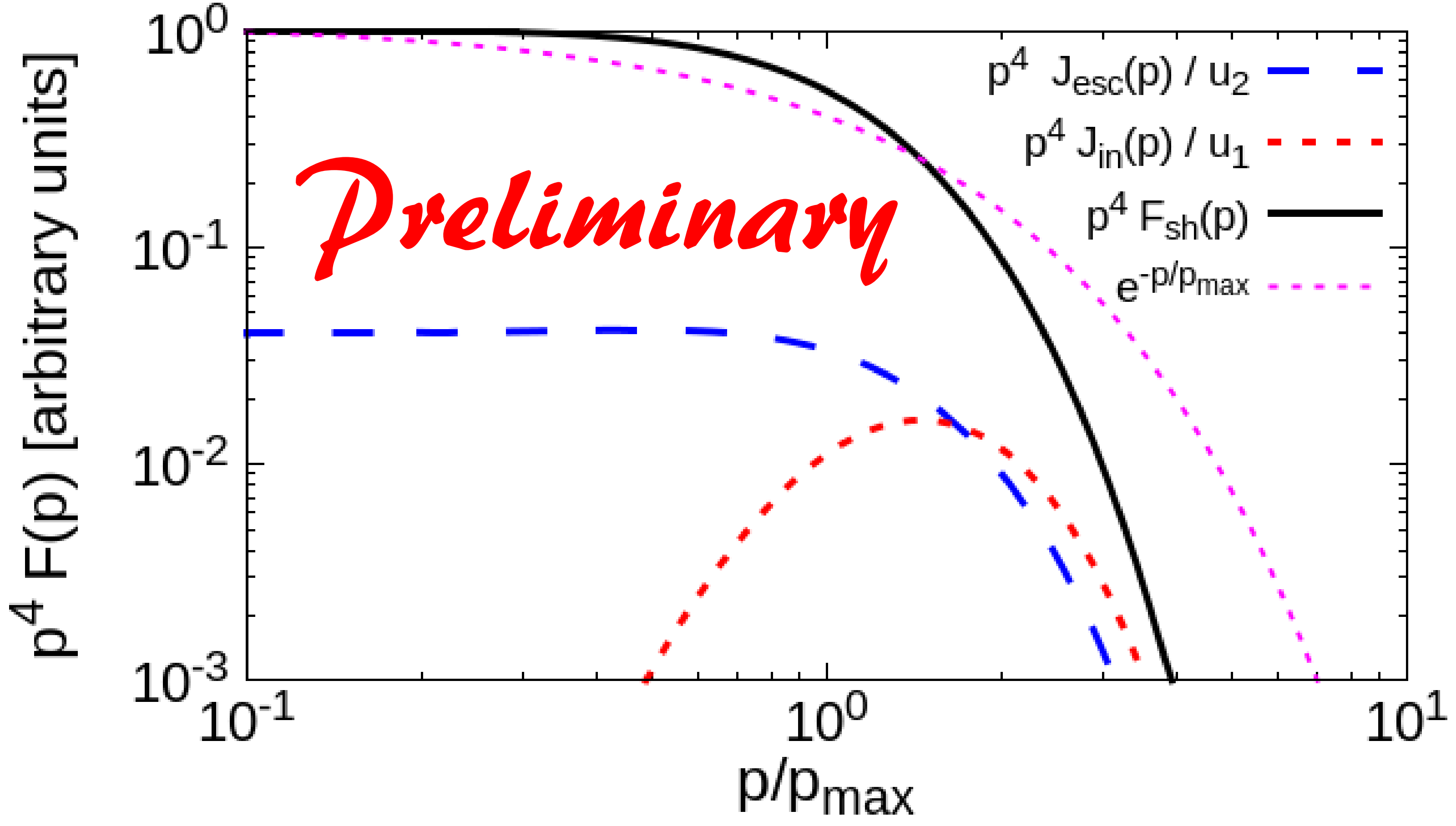


Transport properties and maximum energy

- The geometry of the system is non standard with escape of particles allowed only from the downstream region of the shock
- Particles diffusing upstream feel an effective wind speed
- The maximum energy of the system is limited from above by the dimension of the shocked bubble

$$\langle \lambda_D \rangle_d = \left\langle {}^{D}/_{V} \right\rangle_d \approx R_{esc} - R_{sh} \rightarrow \ E_{max} \sim 10^2\ PeV$$

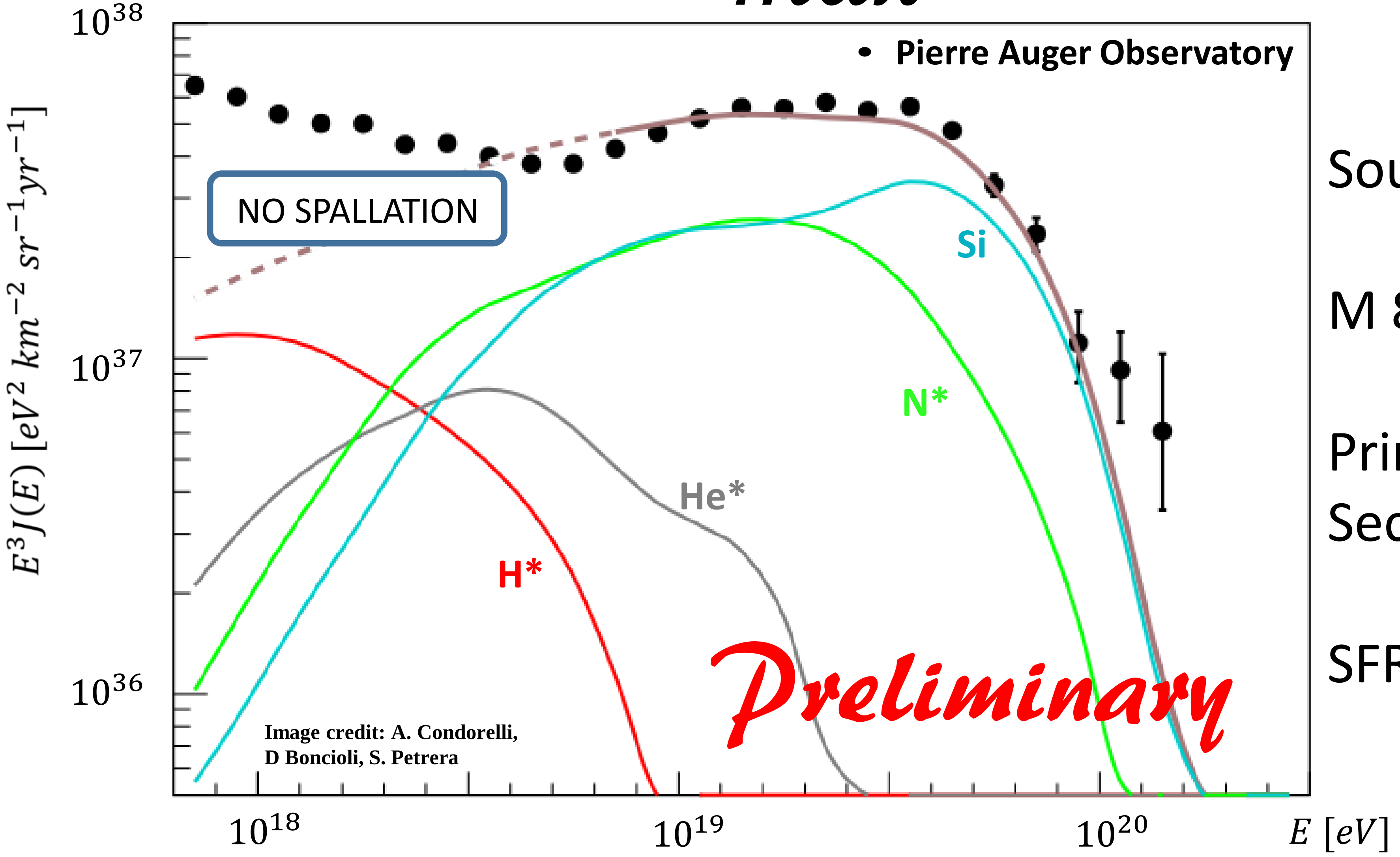
A gamma-ray opaque neutrino source



Preliminary results

- The (stationary) wind termination shock can inject HE particles in the starburst system with multi-PeV energy
- Particles diffusing upwind can produce neutrinos with absorbed gamma-ray counterpart
- Possible contribution of escaping particles to UHECR

What if $E_{max} = 10^{18.5}\, Z\, eV$



Source propagation model

M 82 FIR photon field

Primary Si ($\alpha = 1$)
Secondary N, He and H

SFR evolution of sources

Summary

Starburst nuclei are capable of confining most of particles injected with unique consequences in terms of multiwavelength and neutrino emission

Starburst galaxies contribute substantially to the diffuse fluxes of γ and ν

The **wind termination shock** has breakthrough potential in multimessenger astrophysics

New open questions: maximum energy in SBN and at wind shocks? Role of SBGs as multimessenger sources? Are SBGs sources of UHECRs? Interplay SB - AGN?