High-Energy Gamma-ray and Neutrino Emission from Star-Forming Galaxies across cosmic time

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Main points of this work

- New model of high-energy gamma-ray and neutrino spectrum and luminosity of star-forming galaxies (SFGs), calibrated with data of nearby galaxies.
  - Fit observed gamma-ray luminosities better than empirical power-laws.
- Combine this model with cosmological galaxy formation model to predict cosmic background flux
  - SFGs produce ~ 20% of isotropic gamma-ray background and at most 22% of IceCube neutrinos.

SFGs as sources of high-energy particles

- Many previous studies predict SFGs can produce 1-50% of gamma-ray (GeV) & neutrino (TeV) background flux

  (Pavlidou & Fields 02, Thompson+07, Ando & Pavlidou 09, Fields+10, Makiya+11, Stecker & Venters 11, Ackermann+12, Chakraborty & Fields 13, Lacki+14, Linden+17, Lamastra+17, Komis+17; Loeb & Waxman 06, Thompson+06, Stecker 07, Lacki+11, Murase+13, He+13, Tamborra+14, Anchordoqui+14, Liu+14, Emig+15, Chang+15, Giacinti+15, Senno+15, Maharani & Razzaque 16, Chakrabortty & Izaguirre 16, Xiao+16, Bechtol+17)

- Usually rely on empirical relations (e.g. L_γ - SFR)
- Often assume only two types of galaxies (normal / burst)

- Need a physically-motivated model that takes diverse properties of galaxies into account

New model of galactic high-energy emissions

Objects	L_γ $[10^{39}$ erg $s^{-1}]$	SFR $[M_\odot$ $yr^{-1}]$	M_{gas} $[10^9$ $M_\odot]$	M_* $[10^9$ $M_\odot]$	R_{eff} [kpc]
MW	0.82±0.24	2.6	4.9	50	6.0
LMC	0.047±0.005	0.24	0.53	1.5	2.2
SMC	0.011±0.003	0.037	0.45	0.46	0.7
NGC253	6±2	7.9	4.3	21	3.7
M82	15±3	16.3	1.3	8.7†	1.2
NGC2146	40±21	17.5‡	4.1	20	1.8

Output

Input

- Refer to six nearby galaxies, with good measurements of SFR, gas mass, stellar mass, radius
- Make model of gamma-ray & neutrino spectrum, from these four physical quantities (next slide)
- Compare prediction with observed L_γs to calibrate model

New model of galactic high-energy emissions

- CR production rate: SFR
- CR spectrum at production : power-law with index Γ_{inj}
- Fraction of SN energy carried by CRs : parameter to fit data

- pp interaction rate: ISM density (M_{gas}, R, H) $H \propto R$

- Escape from the galaxy: advection or diffusion
  - Advection velocity : escape velocity from disk
  - Diffusion coefficient $D(E_p) = \frac{cl_0}{3}\left[(\frac{R_L}{l_0})^{1/3} + (\frac{R_L}{l_0})^2\right]$
  - Magnetic field : equipartition with energy density injected by supernovae within dynamical timescale

Calibration by nearby galaxies

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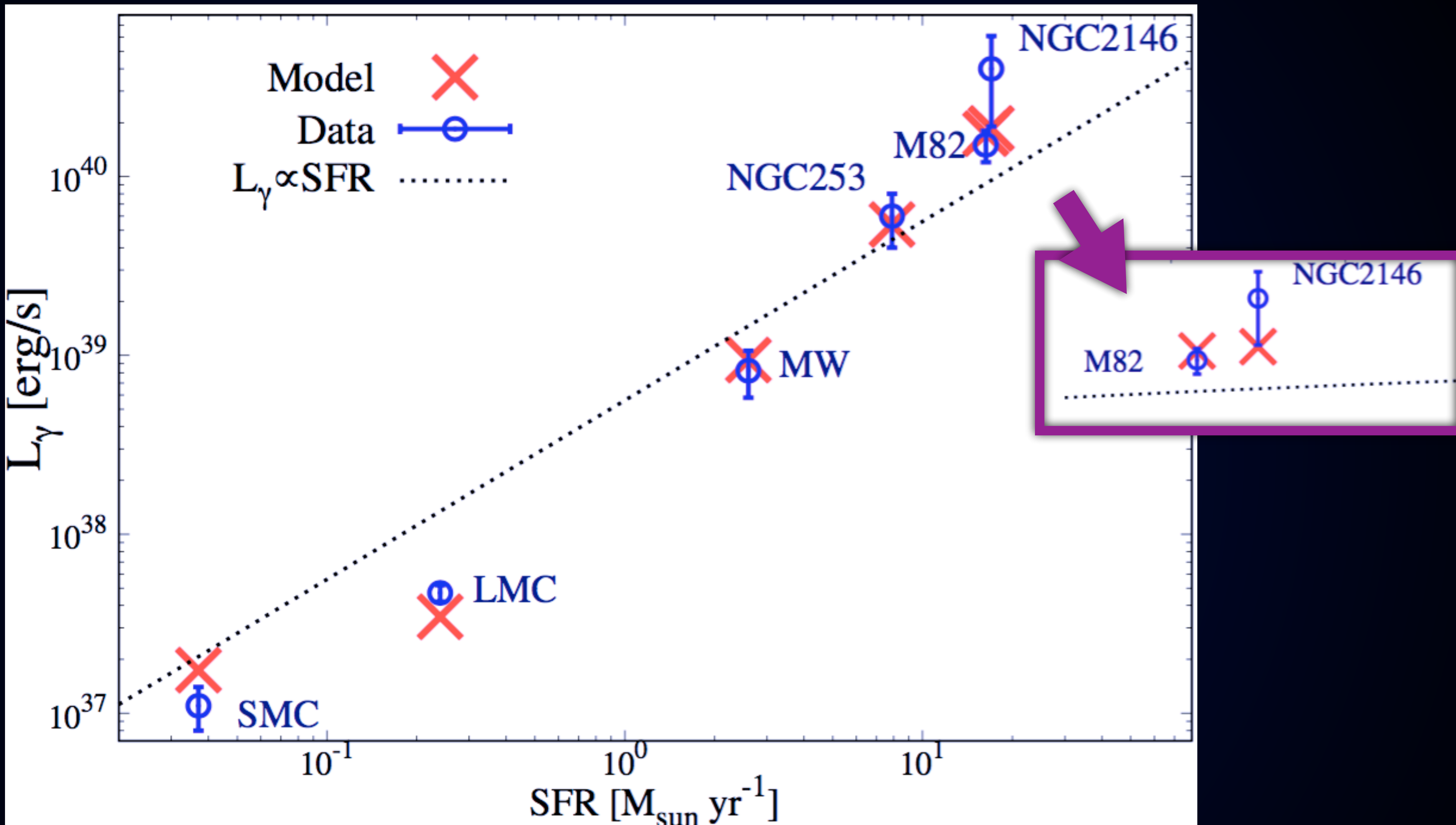
Output

Input

- Use data of six galaxies to fix one model parameter (= fraction of SN energy carried by CRs)
- One free parameter to fit six galaxies
- Obtained best-fit value ~20%

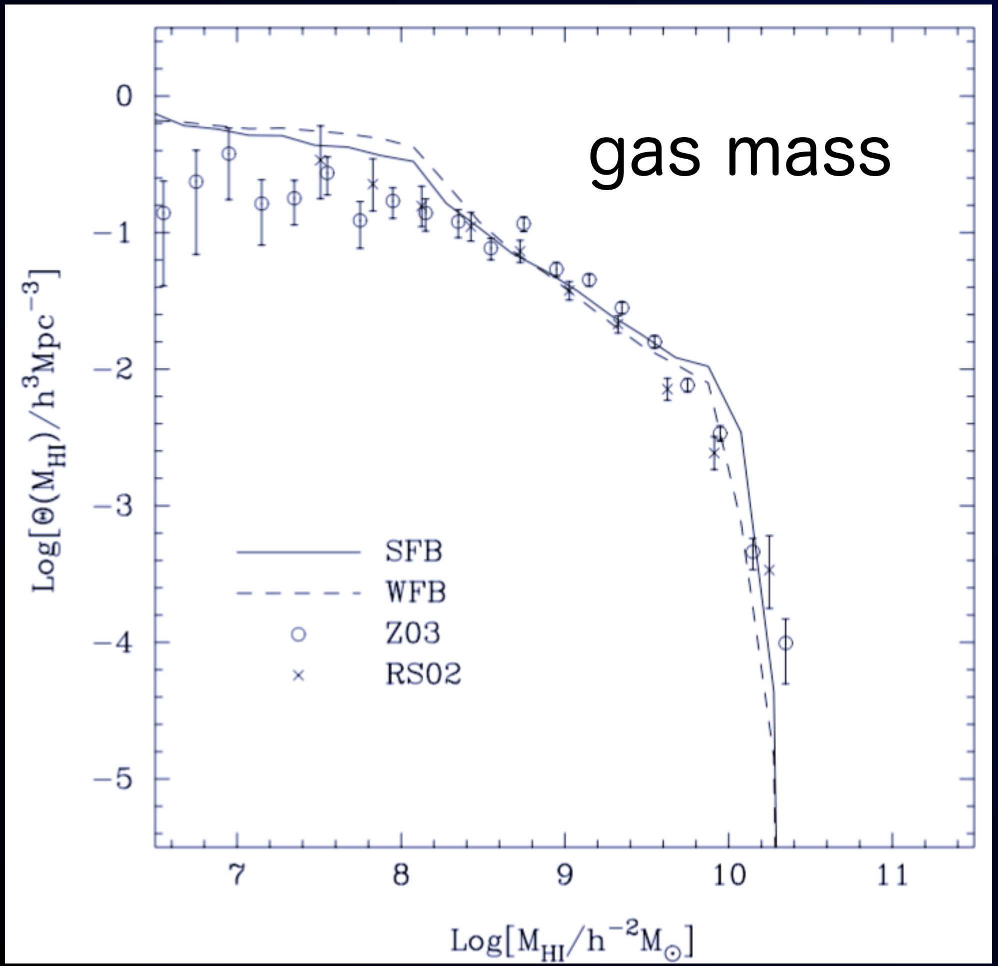
Comparison with nearby galaxies

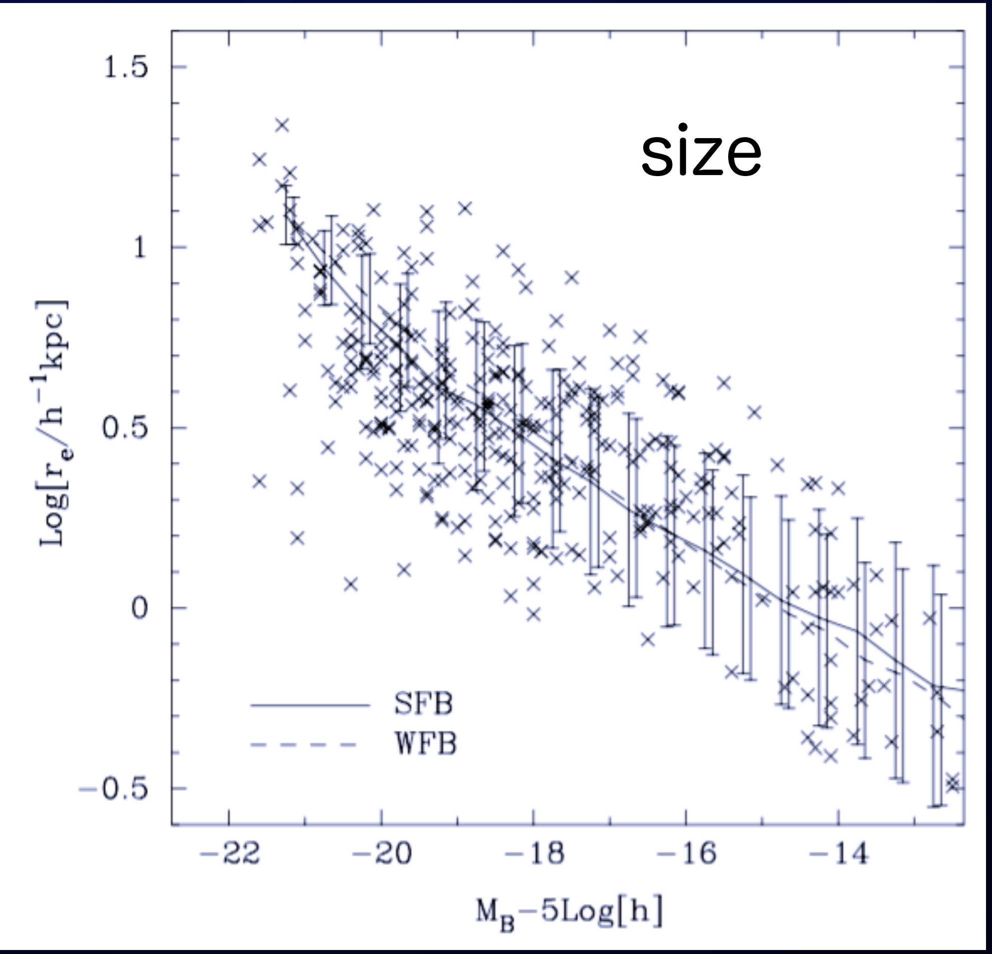


- Model well fit gamma-ray luminosities of six galaxies

Cosmological galaxy formation model

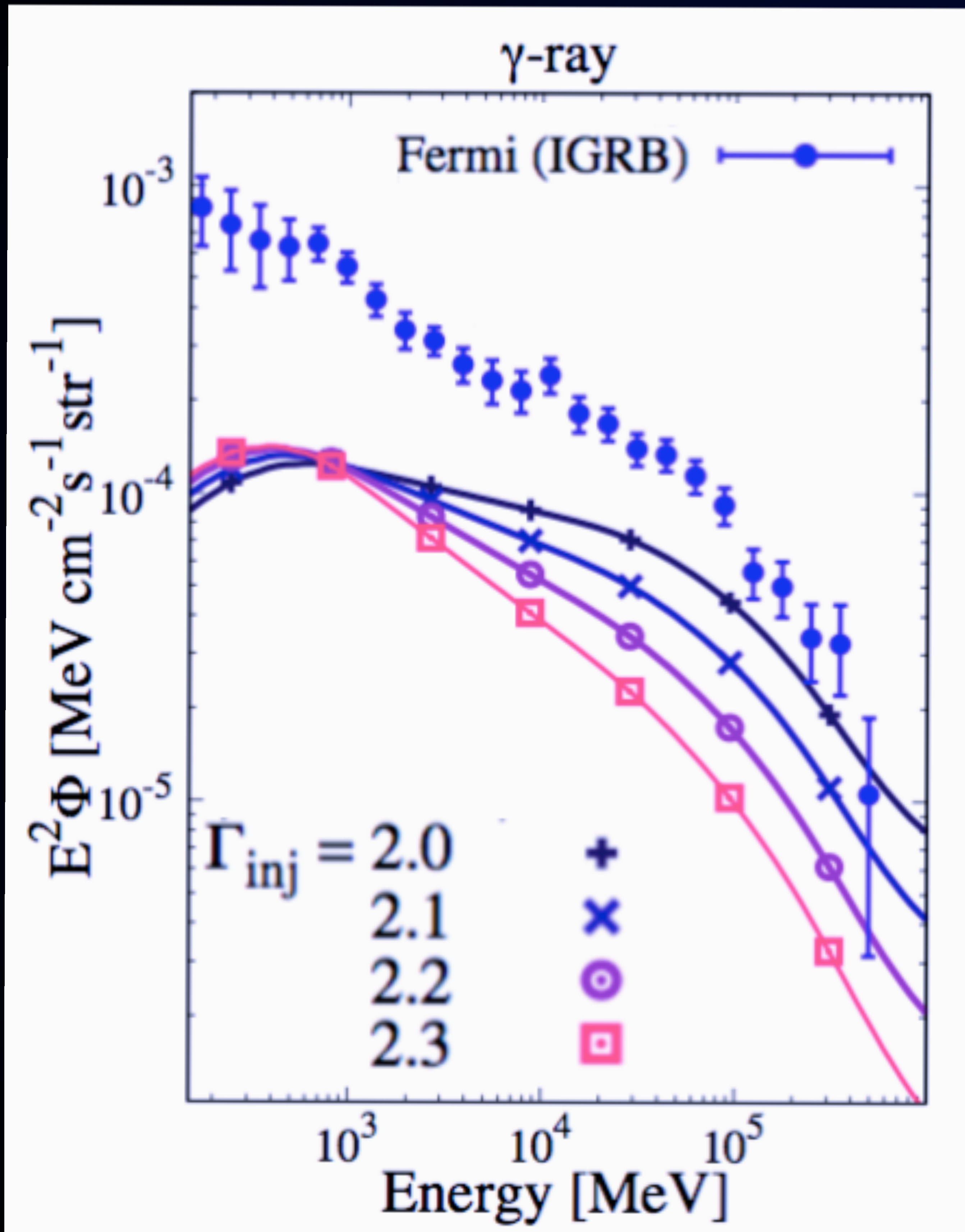
- Semi-analytical models of galaxy formation
  - Standard tools in studies of galaxy evolution
  - Reproduce many observed properties of galaxies
  - Produce mock galaxy catalogues with physical quantities (SFR, mass, size …)





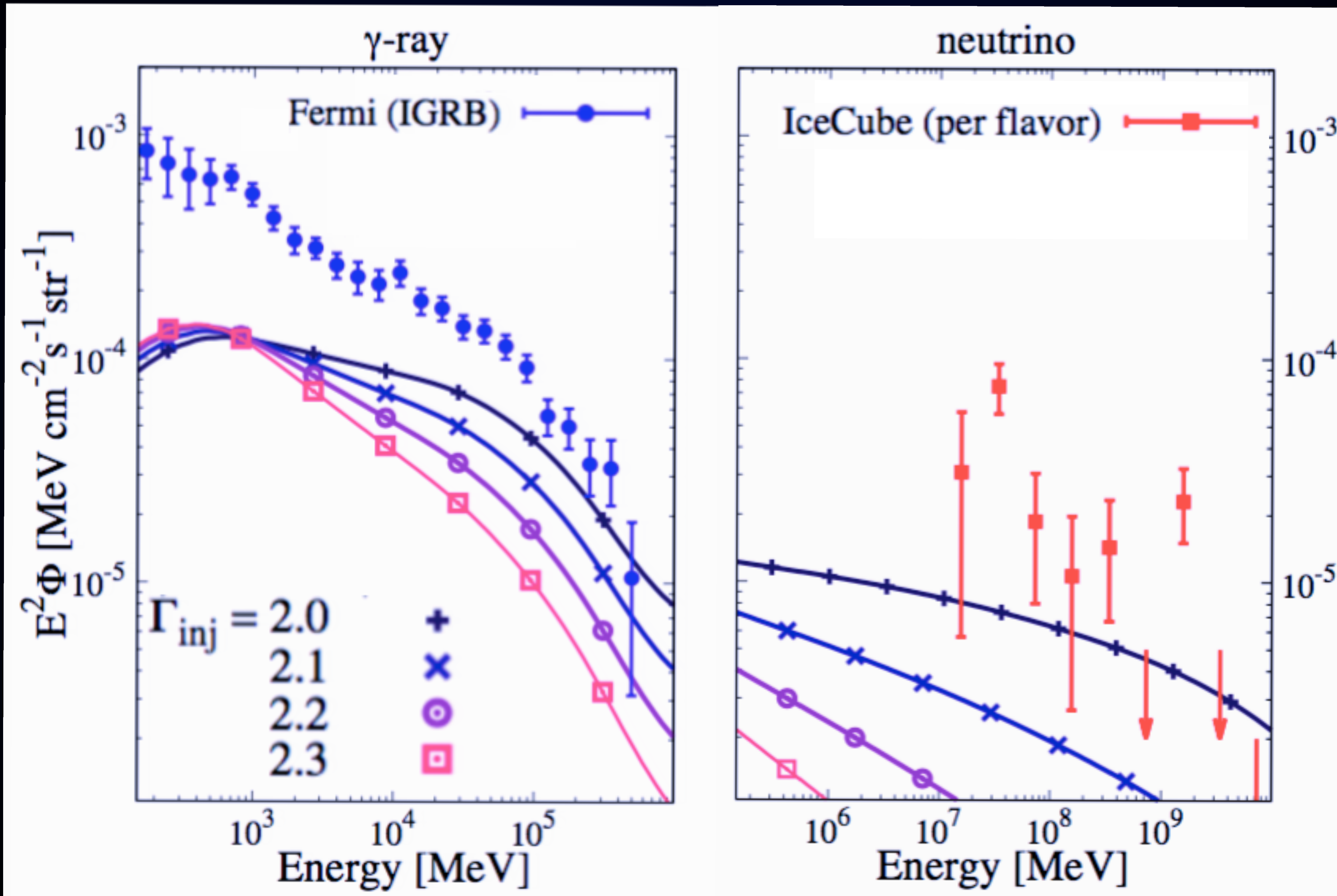
Nagashima & Yoshii 2004
Nagashima et al. 2005

Gamma-ray background unresolved by Fermi



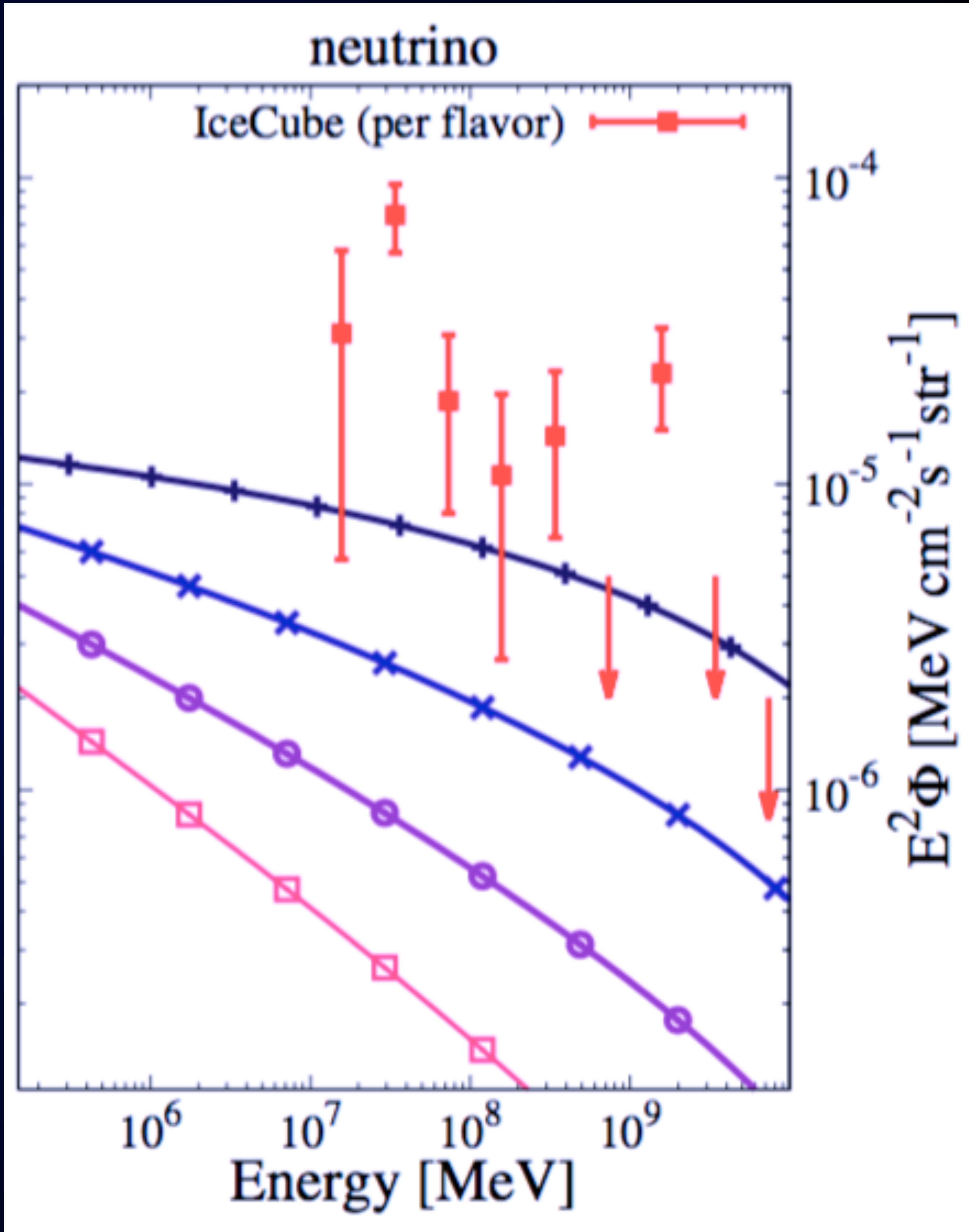
- Spectrum at SNR is a parameter ($\Gamma_{inj} \sim 2.3$ from MW observation)
- Star-forming galaxies make about 20% contribution to isotropic gamma-ray background (0.1-100 GeV)
- Consistent with estimate by Fermi-LAT (4-23%, Ackermann+12)

Gamma-ray (GeV) & Neutrino (TeV) from SFGs



Neutrino background by IceCube

- Only 0.5% of data can be explained with $\Gamma_{inj} = 2.3$
- 22% even if $\Gamma_{inj} = 2.0$ (theory of acceleration, but extremely optimistic)
- Majority of IceCube data cannot be explained by star-forming galaxies (including starburst)
- Note: our calculation only include contributions from supernovae



Summary

- A new model of gamma-ray and neutrino from SFGs
  - Use four physical quantities: SFR, Mstar, Mgas, radius
  - Well fit gamma-ray luminosities from dwarfs to starbursts

- Cosmic background of gamma-ray and neutrinos from SFGs
  - Use cosmological model of galaxy formation
  - ~20% of Fermi unresolved gamma-ray background
  - 0.5 - 2% of the IceCube flux for Γ_{inj} = 2.2 - 2.3, and 22% for the most optimistic case of Γ_{inj} = 2.0