Difficulties of Star-forming Galaxies as the Source of IceCube Neutrinos

Takahiro Sudoh (Univ. of Tokyo)

Tomonori Totani (UTokyo), Norita Kawanaka (Kyoto Univ.)

accepted for publication in PASJ

マルチメッセンジャー天文学研究会@千葉大学　26 March 2018

This Work

- A new model of gamma-ray and neutrino from a star-forming galaxy from SFR, Mstar, Mgas, radius
- This model well reproduces gamma-ray luminosities of nearby galaxies detected by Fermi
- This model is combined with a cosmological galaxy formation model to predict background radiation
- Majority of the IceCube neutrinos cannot be explained by star-forming galaxies

Introduction

IceCube neutrinos from star-forming galaxies

- Star-forming galaxies emit neutrinos via pion decay
- Many previous studies (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)
    - lack of consensus (less than 10% ? more than 50% ?)
    - mainly rely on empirical relations
    - argument sensitive to assumed spectral index

GeV gamma-rays from star-forming galaxies

- Star-forming galaxies emit gamma-rays via pion decay
- Many previous studies (Strong+76, LichtiL78, Dar & Shaviv 95, Pavlidou & Fields 02, Thompson+07, Ando & Pavlidou 09, Fields+10, Makiya+11, Stecker & Venters 11, Ackermann+12, Chakraborty & Fields 13, Lacki+14, Lamastra+17)
  - 4-23% of Isotropic Gamma-ray Background (estimate by Fermi team)
  - mainly rely on empirical relations, which may introduce significant bias (Komis+17)

High-energy emissions from star-forming galaxies

- What we need for better prediction is…
  - Physically-motivated model of gamma-ray & neutrino emission from a star-forming galaxy
  - Gamma-ray constraints from nearby galaxies
  - Cosmological evolution of galactic properties such as SFR, mass, size from realistic galaxy formation theory.
- How much contribution galaxies can make to diffuse gamma-ray (Fermi unresolved) and neutrino (IceCube) background ?

Modelling Gamma-ray and Neutrino Emission from Galaxies

Modelling gamma-ray and neutrino from a galaxy

- Input : SFR, Mgas, Mstar, Reff, H ($\propto$ Reff)
- CR production rate : SFR
- CR spectrum at injection : $\frac{dN}{dtdE} = C \times \mathbf{SFR} \times E^{-\Gamma_{\rm inj}}$
- pp interaction rate : target ISM gas density ($\mathbf{M}_{\rm gas}, \mathbf{R}_{\rm eff}, \mathbf{H}$)
- escape time from galaxy : advection or diffusion
  - outflow velocity (σ) : escape velocity from galactic disk
  - diffusion coefficient : from Larmor radius ($\mathbf{R}_{\rm L}$) and fluctuation pattern of turbulent magnetic field
  - magnetic field : equipartition with energy injected by SNe

Cosmic ray diffusion in galaxy

- Diffusion coefficient : from Larmor radius and fluctuation pattern of turbulent magnetic field

$$D(E_p) = \begin{cases} \frac{c l_0}{3}\left[\left(\frac{R_L}{l_0}\right)^{\frac{1}{3}} + \left(\frac{R_L}{l_0}\right)^2\right] & \left(R_L \leq \sqrt{H_g l_0}\right) \\ \frac{c H_g}{3} & \left(R_L > \sqrt{H_g l_0}\right) \end{cases}$$

- Kolmogorov-type turbulence is assumed
- Coherent length l_0 : set to 30 pc from MW observation

Estimate of magnetic field in galaxy

- magnetic field : equipartition with energy density injected by supernovae

SN energy ~10^51 erg

SN rate

advection time

$$\frac{B^2}{8\pi} = \eta \frac{E_{\rm SN} r_{\rm SN} t_{\rm adv}}{V}$$

- Salpeter IMF assumed
- $\eta = 0.03$ to reproduce B = 6 μG in the Milky Way

Modelling gamma-ray and neutrino from a galaxy

- Input : SFR, Mgas, Mstar, Reff, H ($\propto$ Reff)
  - CR production rate : SFR
  - CR spectrum at injection : $\frac{dN}{dtdE} = C \times \mathbf{SFR} \times E^{-\Gamma_{\rm inj}}$
  - pp interaction rate : target ISM gas density ($\mathbf{M}_{\rm gas}, \mathbf{R}_{\rm eff}, \mathbf{H}$)
  - escape time from galaxy : advection or diffusion
    - outflow velocity (σ) : escape velocity from galactic disk
    - diffusion coefficient : from Larmor radius ($\mathbf{R}_{\rm L}$) and fluctuation pattern of turbulent magnetic field
    - magnetic field : equipartition with energy injected by SNe

Calibration of model

Objects	L_γ [10^{39} erg s^{-1}]	ψ [$M_\odot$ yr^{-1}]	$M_{\rm gas}$ [10^9 $M_\odot$]	M_* [10^9 $M_\odot$]	$R_{\rm eff}$ [kpc
MW	0.82±0.24	2.6	4.9	50	6.0
LMC	0.047±0.00	0.24	0.53	1.5	2.2
SMC	0.011±0.00	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

- Nearby galaxies detected in gamma-ray
- Note: NGC4935, NGC1068, Arp220 and M31 are not used in this work

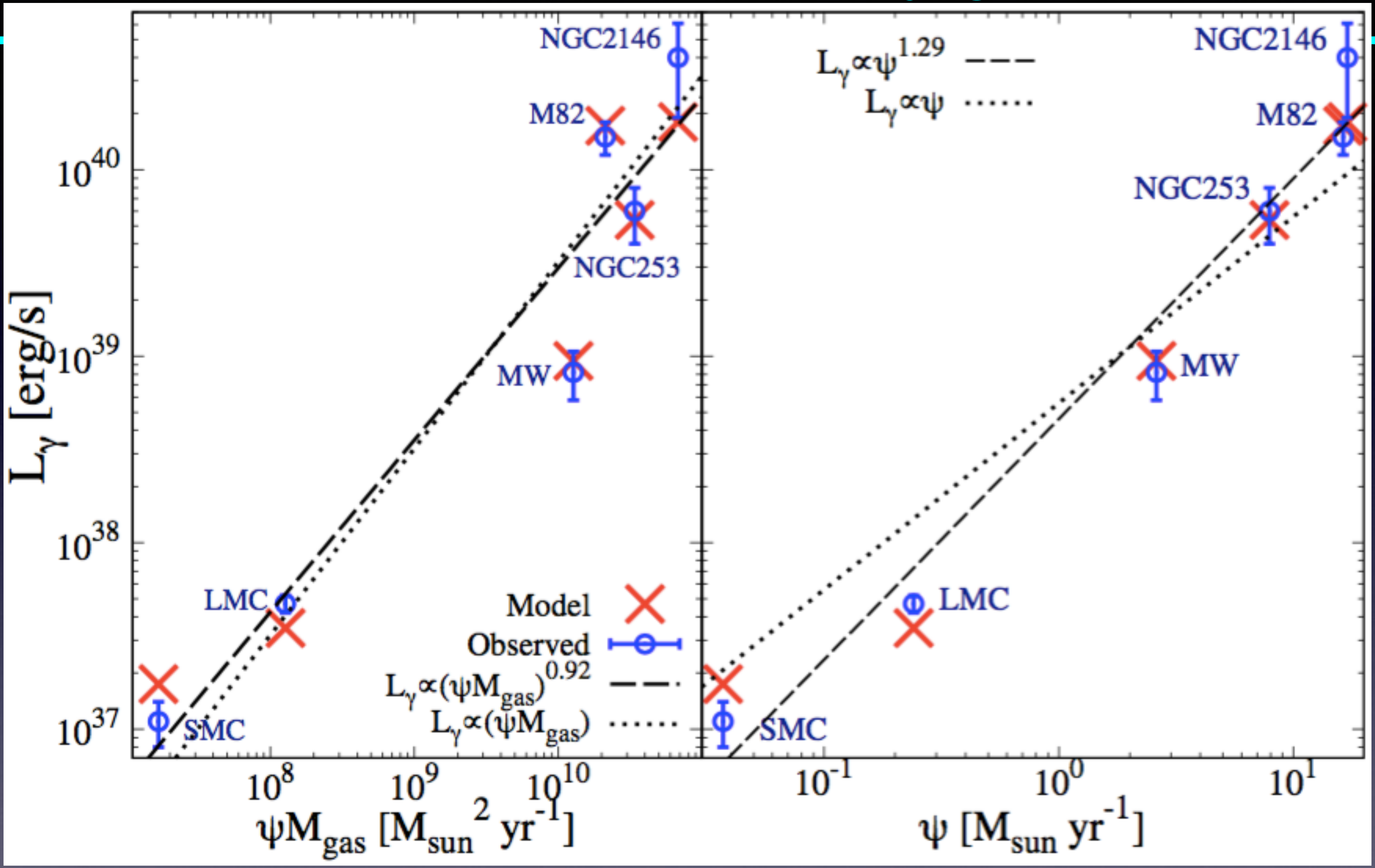
Model prediction $L_\gamma(C)$

$$\frac{dN}{dtdE} = C \times \mathbf{SFR} \times E^{-\Gamma_{\rm inj}}$$

Fix the free parameter C

- The value of C is converted to E_{CR} ~ 0.2 E_{SN}

Comparison with data of nearby galaxies



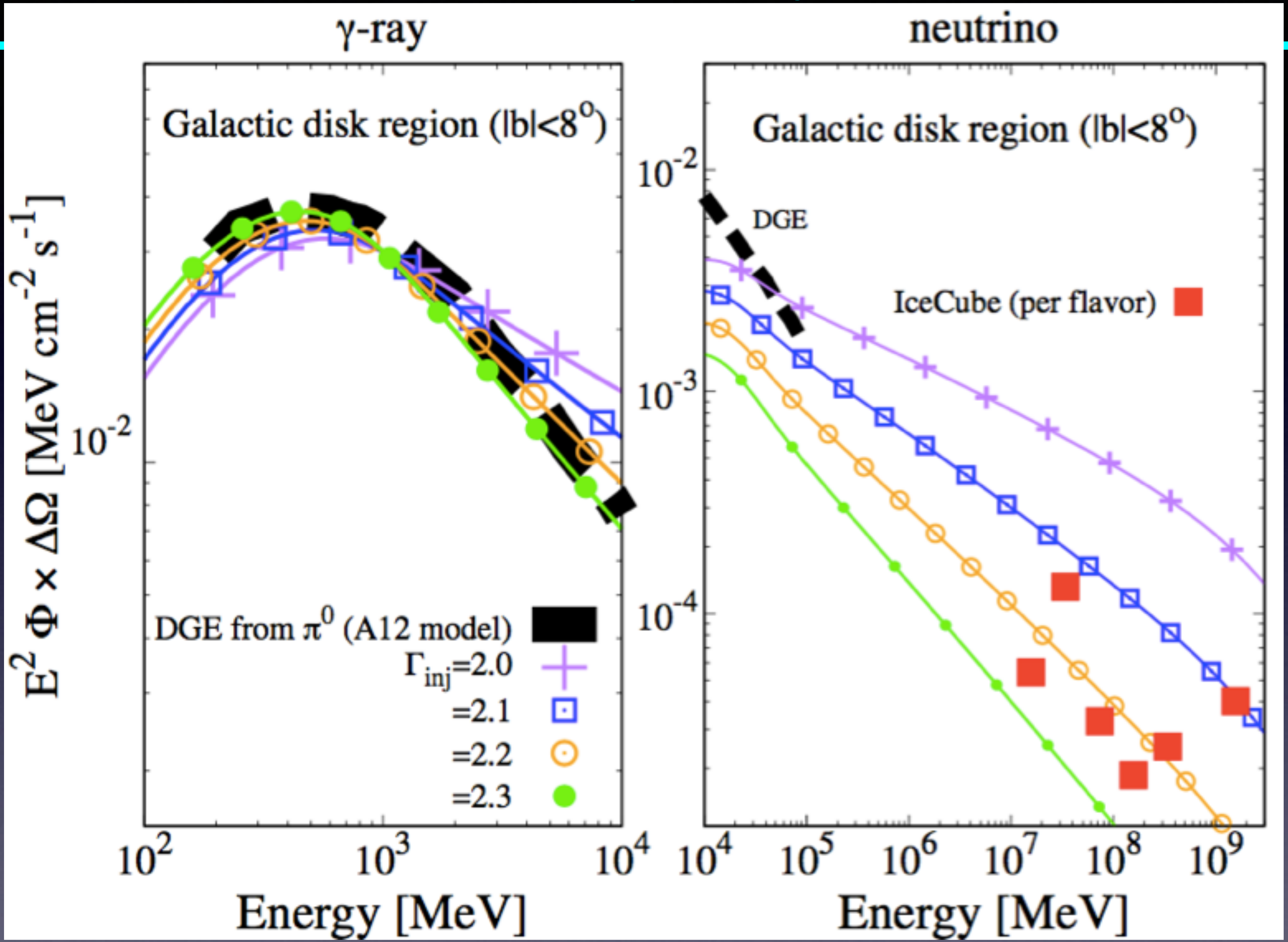
- Model agrees data well (better than simple powar-laws)
- Only one free parameter is included in the model

Modelling gamma-ray and neutrino from a galaxy

- Now we can calculate gamma-ray & neutrino spectrum from a galaxy using SFR, Mstar, Mgas, Reff
- Combine this model with cosmological galaxy formation model to predict background radiation
- Before that, we constrain Γ_{inj} from emission from the Galactic disk

Emission from Galactic Disk

Emissions from the Milky Way disk

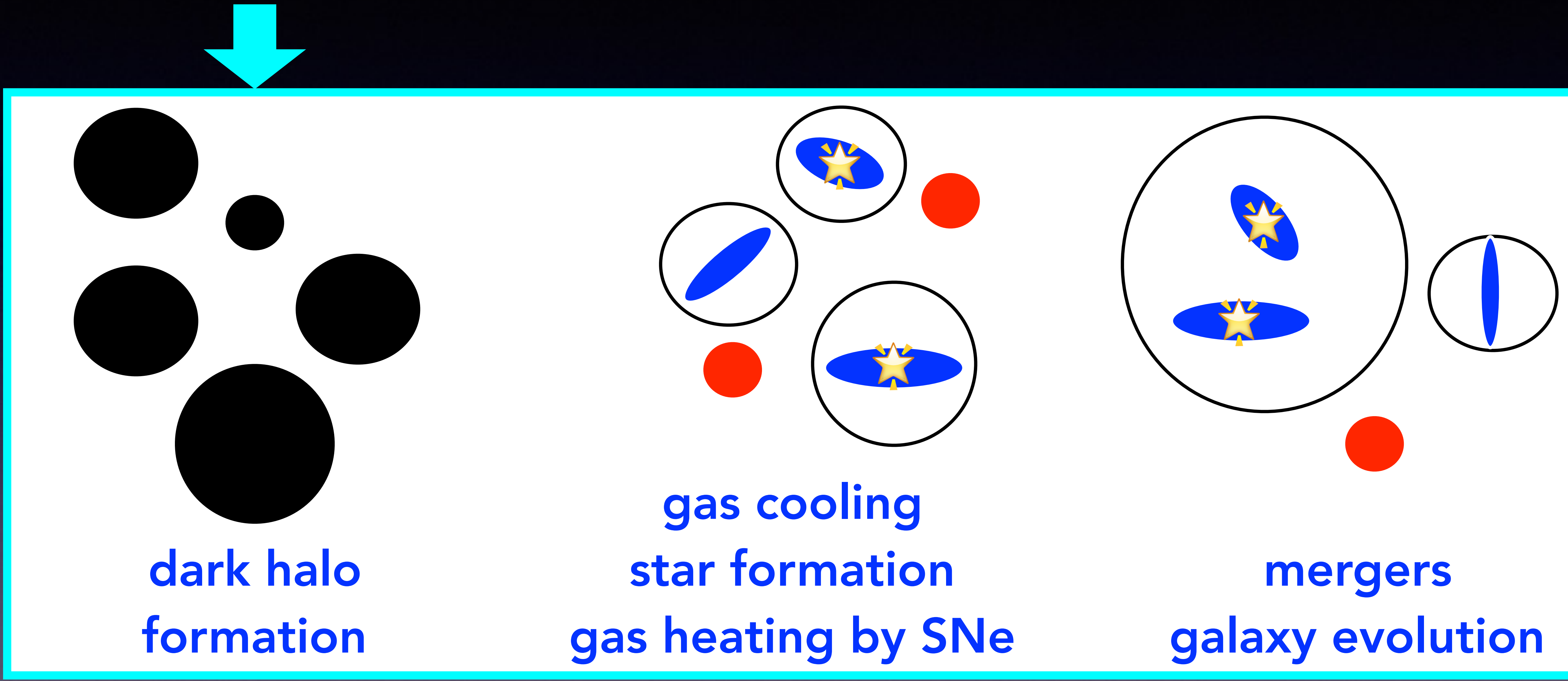


- Observation: MW disk is not dominant (no anisotropy)
- Γinj <~ 2.2 or cutoff below E~10^14 eV is necessary

Cosmological Background Radiation

Semi-analytic galaxy formation model

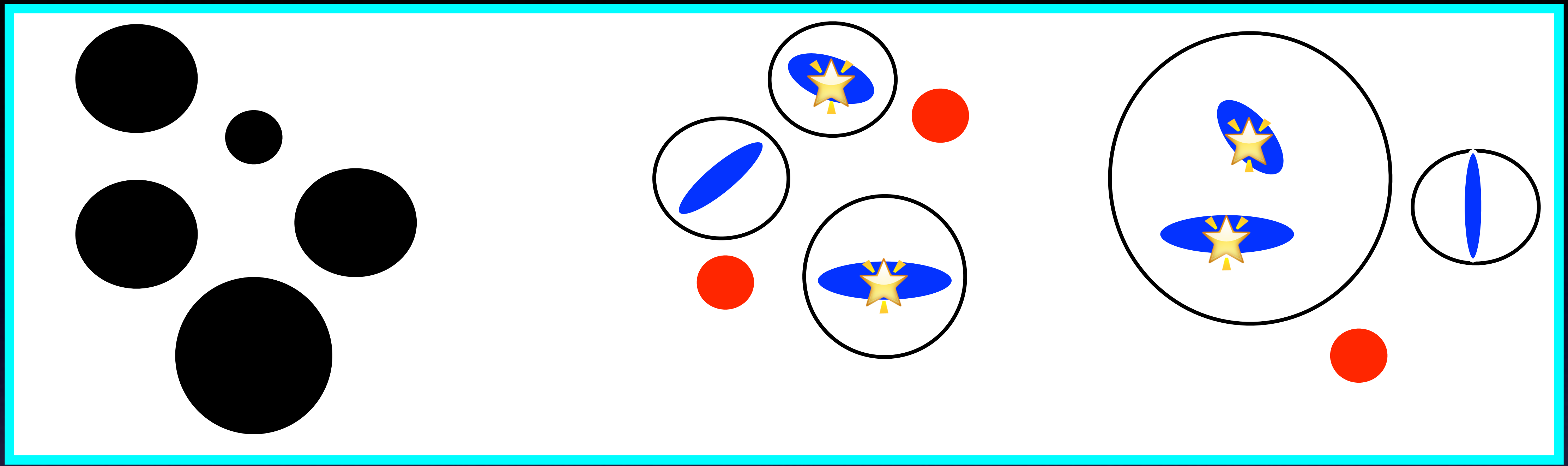
Cosmological parameter



Properties of galaxies

(SFR, Mstar, Mgas, size etc.)

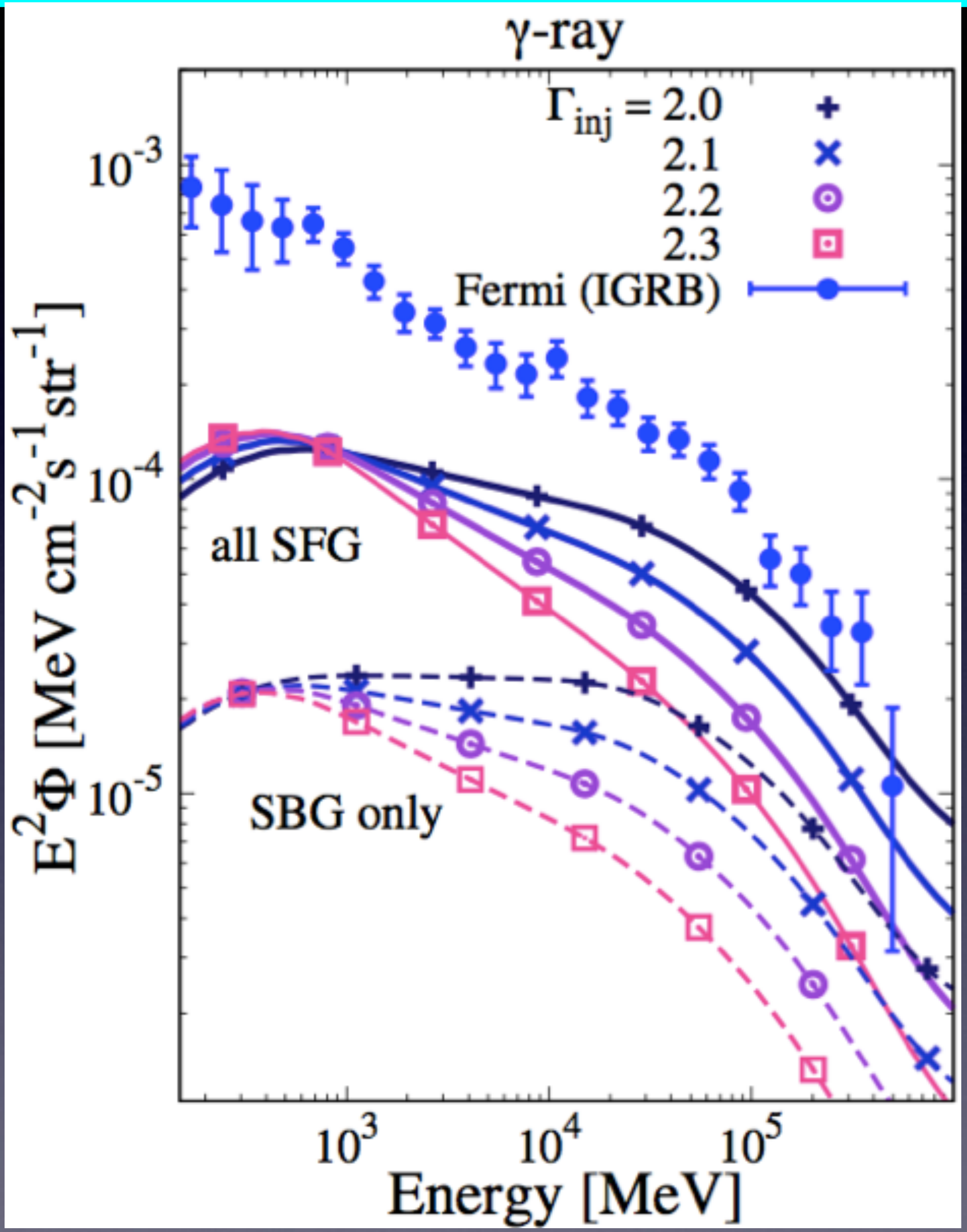
Semi-analytic galaxy formation model



- Mitaka model (Nagashima & Yoshii 2004)
- reproduce observations of local and high-z galaxies (luminosity functions, luminosity-density, etc.)
- starburst occurs at galaxy merger (5% contribution to CSFRD at z=0)

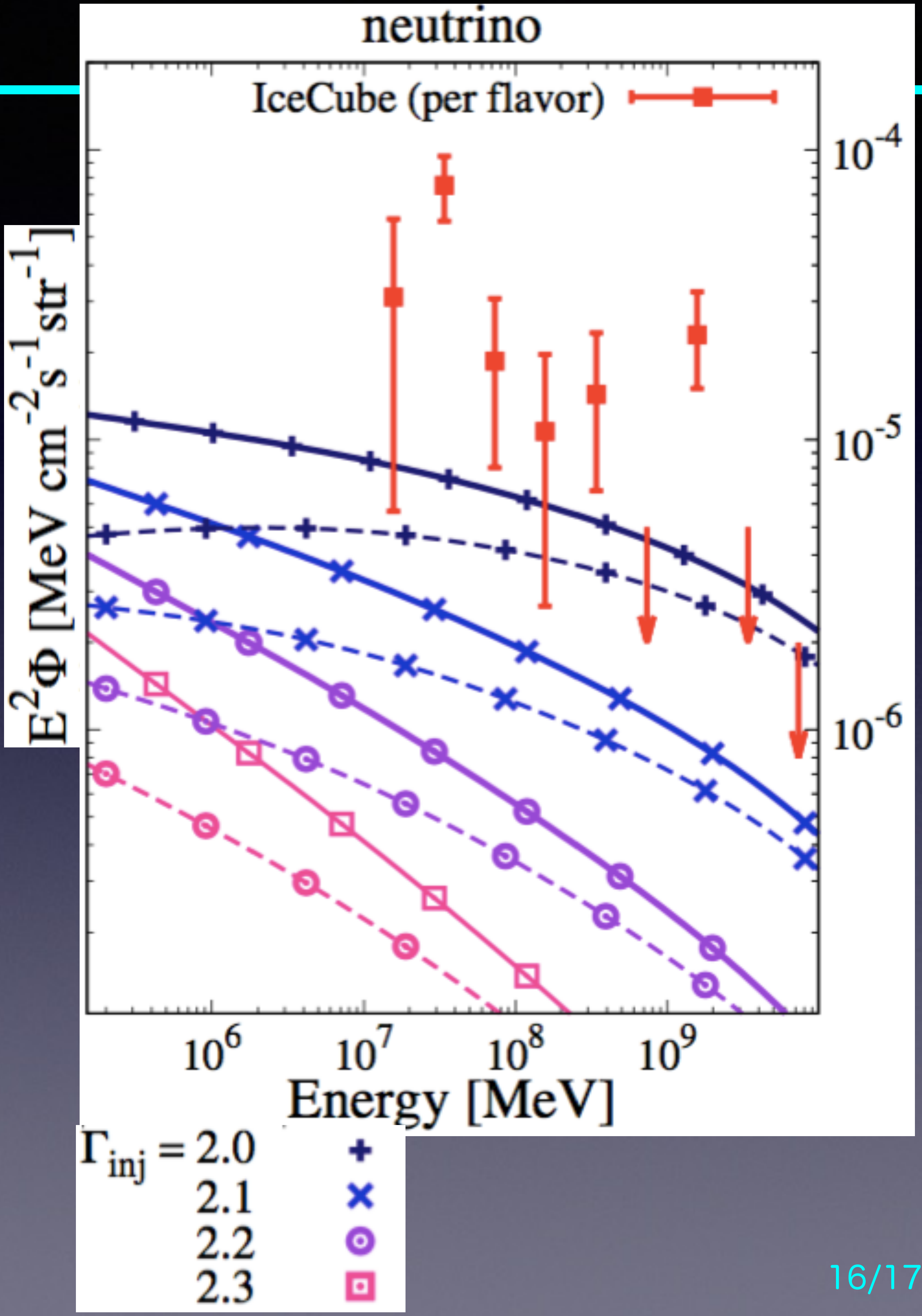
Gamma-ray background

- including cascade emission
- 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)



Neutrino background

- Starburst galaxies dominate at TeV-PeV
- only 0.5% for Γinj = 2.3
- 22% even if Γinj = 2.0 (extremely optimistic)
- majority of IceCube data cannot be explained by star-forming galaxies



Summary

- A new model of gamma-ray and neutrino from SFG from four physical quantities: SFR, Mstar, Mgas, Reff
- This model well reproduces L_γ of nearby galaxies & can be tested by future TeV observation (CTA!)
- This model is combined with a cosmological galaxy formation model to predict background radiation
- SFGs make ~20% of isotropic γ-ray background and 22% of the IceCube flux for most optimistic case (Γ_{inj} = 2.0) based on gamma-ray constraints of nearby galaxies