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

Takahiro Sudoh (UTokyo)
Tomonori Totani (UTokyo)
Norita Kawanaka (Kyoto University)

IceCube Neutrino

- Astrophysical TeV - PeV neutrinos
  - Isotropic arrival direction … extragalactic origin?
  - No identified individual source
- Various source models
  - Cosmic-ray sources (GRB, AGN)
  - Cosmic-ray reservoirs (star-forming galaxy, cluster)
- Star-forming galaxies among possible sources
  - high density & strong magnetic field

  --> efficient production of high-energy neutrinos?

Neutrino from Galaxies

- Previous studies
  - Simple estimate by using IR luminosity (e.g. Tamborra+14, Chang+15) or EGB observation (e.g. Bechtol+17)
  - Bechtol+17 : SBGs should not produce more than 30 % of IceCube data at 100 TeV (for $\Gamma = 2.2$)
    - Sensitive to gamma-ray spectral index Γ (parameter)

- It may still be possible that SBGs make larger contribution (e.g. Xiao+16, Chakraborty & Izaguirre 16)
  - Xiao+16 : SBGs may contribute ~50 % of the > 100 TeV flux

This Work

- New calculation of contribution of galaxies to diffuse gamma-ray/neutrino backgrounds with a cosmological galaxy formation model
- Realistic estimation based on physical quantities of individual galaxies at various redshifts
- Robust calibration using gamma-ray luminosities of nearby galaxies

Semi-Analytical Model of Galaxy Formation

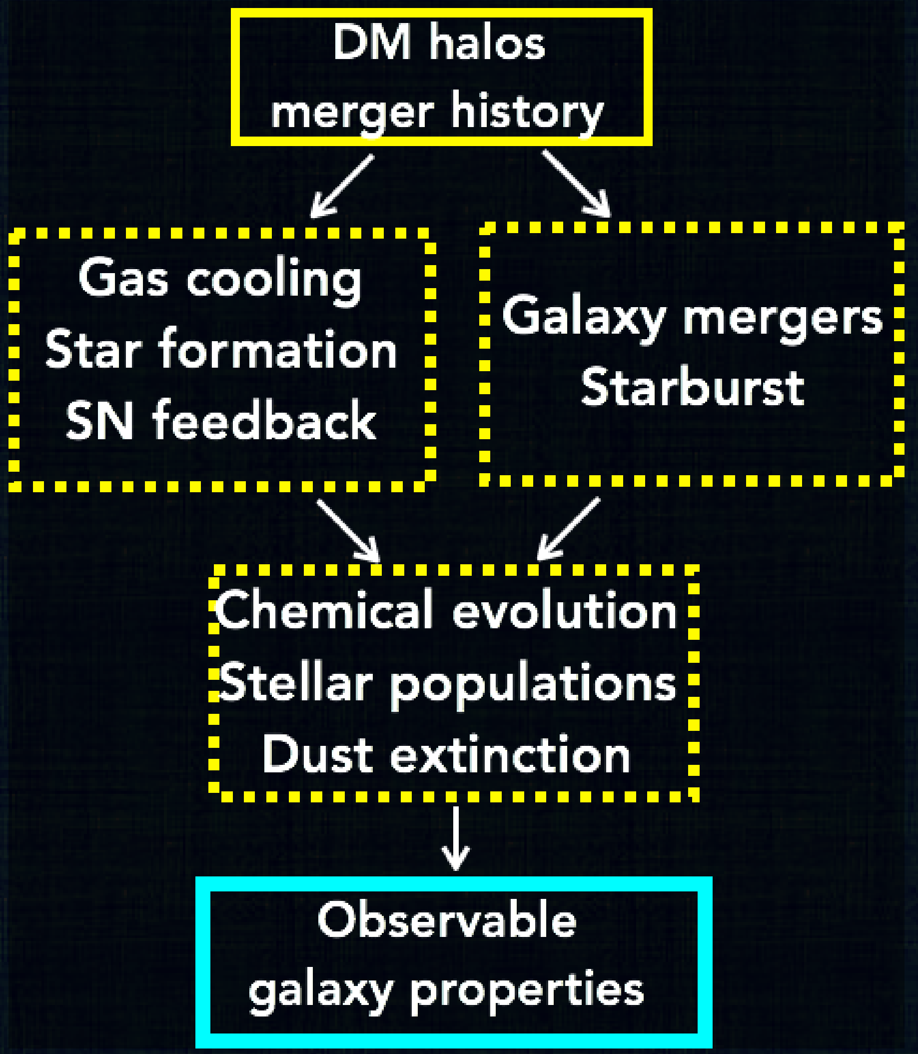
- Analytical calculation of dark halo merger trees (based on Press-Schechter)

\+ phenomological treatment of baryonic processes in DM haloes

- Calculate properties of galaxies a various out put redshifts
  - SFR, size, mass, morphology, SF mode (quiescent/burst), etc.
  - Reproduce many observations

- We use the "Mitaka model"

(Nagashima & Yoshii 2004)



Cole+00

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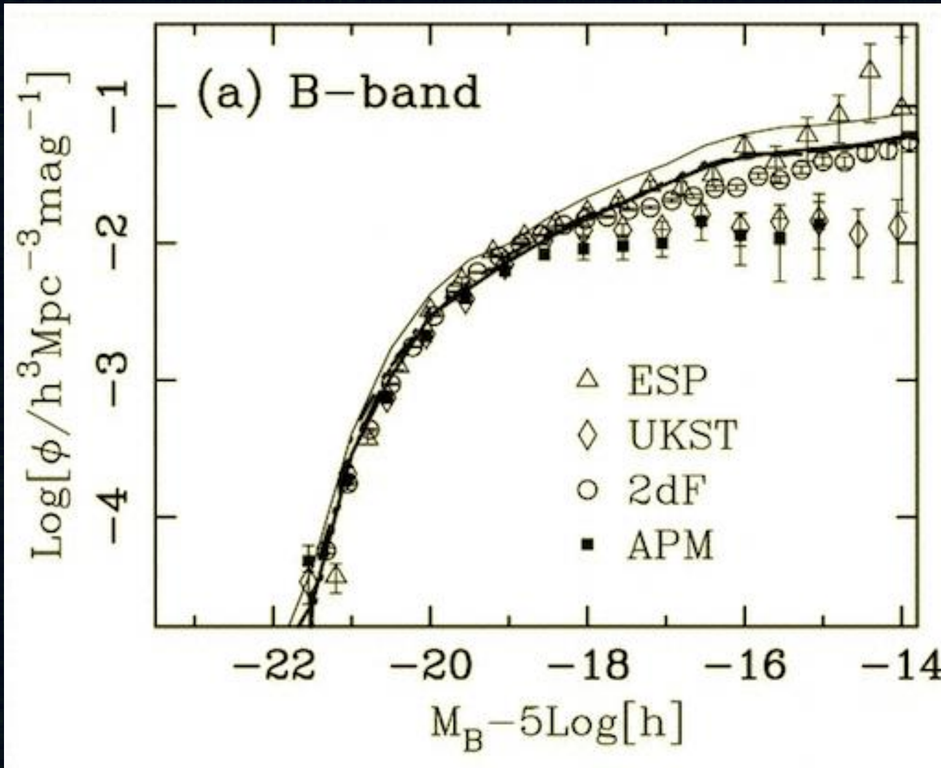

(Nagashima and Yoshii 2004)

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Modelling Neutrinos from Galaxies

- Neutrinos from a galaxy

$$\frac{dN_{\nu_i}}{dtdE_\nu}(E_\nu) = \int_{E_\nu}^{\infty} f_\pi(E_p) \frac{dN_p}{dtdE_p}(E_p) F_{\nu_i}(\frac{E_\nu}{E_p}, E_p) \frac{dE_p}{E_p}$$

Pion production efficiency

CR spectrum at injection

Neutrino spectrum from a *pp* interaction (Kelner+06)

- $$\frac{dN_p}{dtdE_p}(E_p) = C(\frac{\mathrm{SFR}}{\mathrm{M_\odot yr^{-1}}})(\frac{E_p}{\mathrm{GeV}})^{-\Gamma_{\mathrm{inj}}}$$

- C : determined from Lγ of nearby galaxies
- $f_\pi = 1 - \exp(-t_{\mathrm{esc}}/t_{\mathrm{pp}})$: calculated from properties of each galaxy (see next slide)

Calculation of Pion Production Efficiency

- $t_{\rm pp} = (n_{\rm gas}\sigma_{\rm pp}^{\rm inel.}c)^{-1}$
- $t_{\rm esc}$: Advection timescale = H/V_c (V_c: dark halo circular velocity)

  Diffusion timescale = H^2/D (D: diffusion coefficient)

  $t_{\rm esc} = \min[t_{\rm adv}, t_{\rm diff}]$ and lower limit is set to H/c

- H (gas scale height) : $H = R_{\rm eff}$ for elliptical and $H \propto R_{\rm eff}$ for disk

- Diffusion coefficient D(E) depends on B, l_0, δ
  - B (magnetic field) : assuming $\epsilon_{\rm CR} = \epsilon_{\rm B}$ in each galaxy
  - l_0 (outer scale of turbulence) : equal to scale height ($l_0 = H$)
  - δ (turbulence spectrum) : Kolmogorov-type ($\delta = 1/3$)

$\rightarrow t_{\rm esc}/t_{\rm pp}$ from $M_{\rm gas}$, V_c, $R_{\rm eff}$ and morphology of each galaxy

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Directly derived from galaxy formation model

Model Calibration

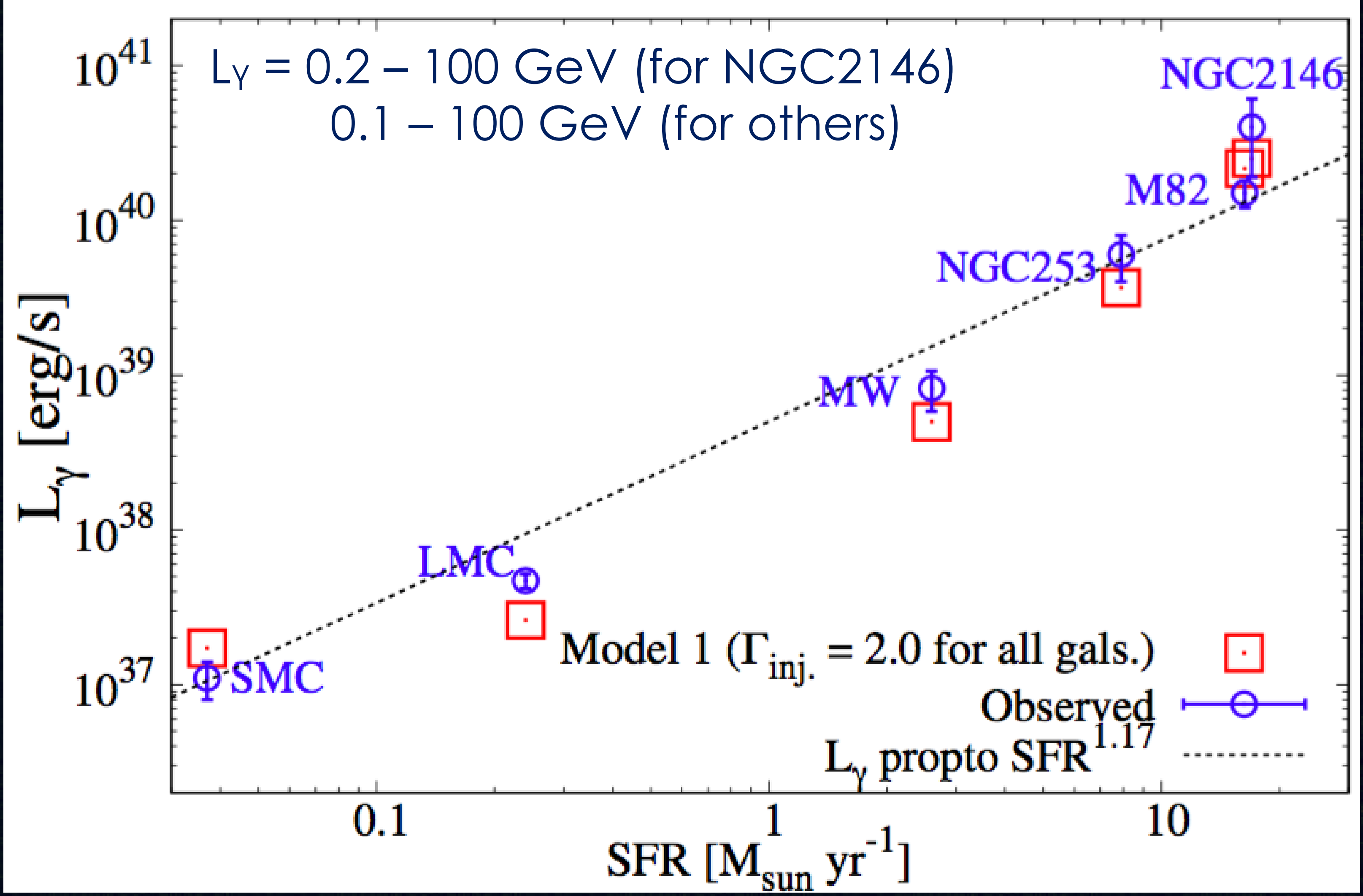
$$\frac{dN_p}{dtdE_p}(E_p) = C\left(\frac{\mathrm{SFR}}{M_\odot \mathrm{yr}^{-1}}\right)\left(\frac{E_p}{\mathrm{GeV}}\right)^{-\Gamma_{\mathrm{inj}}}$$

Objects	L_γ 10^{39} erg/s	SFR $M_\odot$/yr	M_{gas} 10^9 $M_\odot$	R_{eff} kpc	V_c km/s
MW	0.82±0.24	2.6	4.9	6.0	200
LMC	0.047±0.005	0.24	0.53	2.2	120
SMC	0.011±0.003	0.037	0.45	0.7	60
NGC253	6±2	7.9	4.3	3.7	190
M82	15±3	16.3	1.3	1.2	136
NGC2146	40±21	13.8	4.0	1.8	220

M31, Arp220, NGC4945, NGC1068 not used in this work

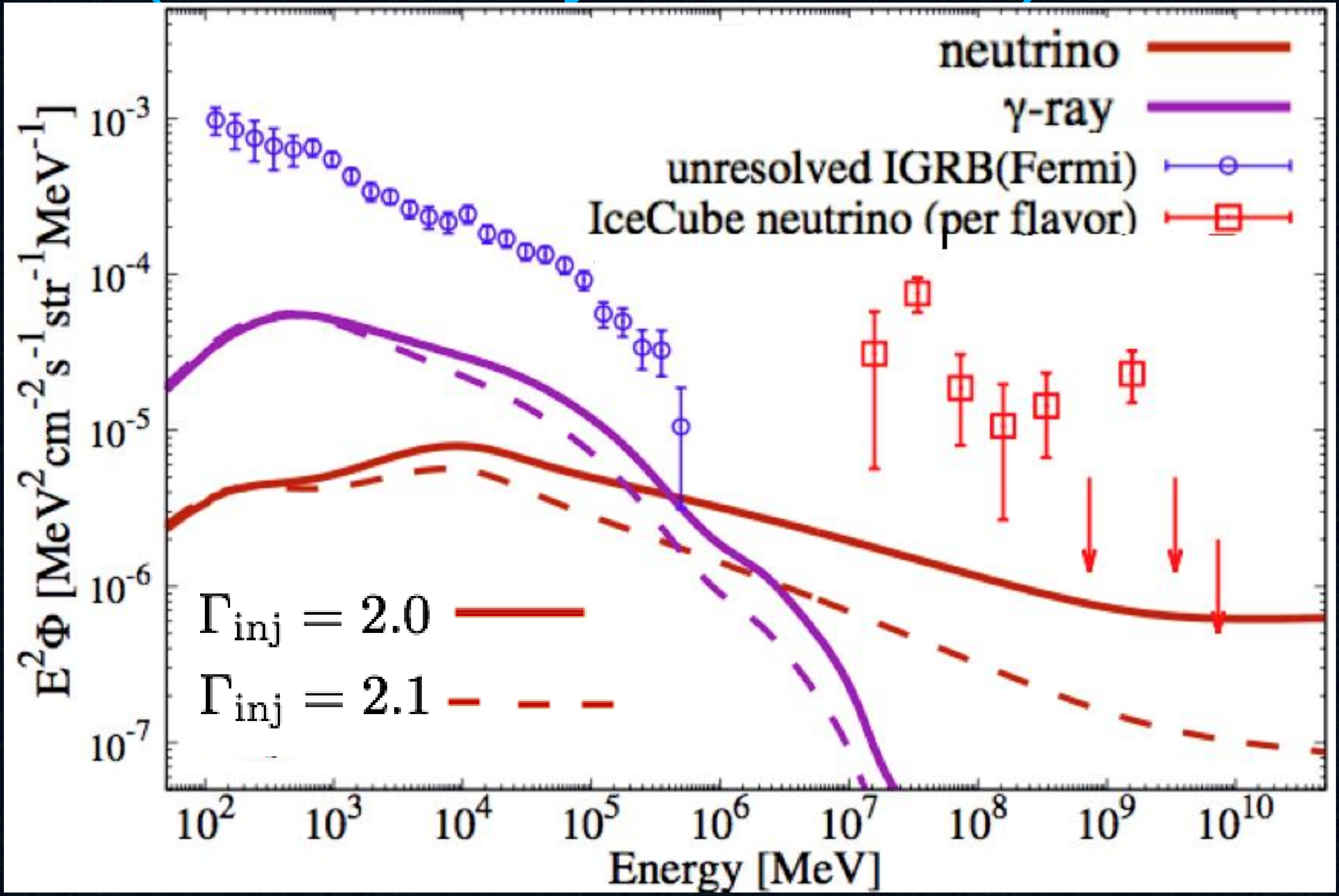
- Calculate $L_\gamma^{\mathrm{model}}$ for nearby galaxies from SFR, M_{gas}, V_c, R_{eff}
- Minimize $\chi^2(C) = \sum_{i=1}^{N_{\mathrm{gal}}} \frac{(L_{\gamma,i}^{\mathrm{obs}} - L_{\gamma,i}^{\mathrm{model}}(C))^2}{\sigma_{L_\gamma,i}^2}$ to fix C

Model Calibration



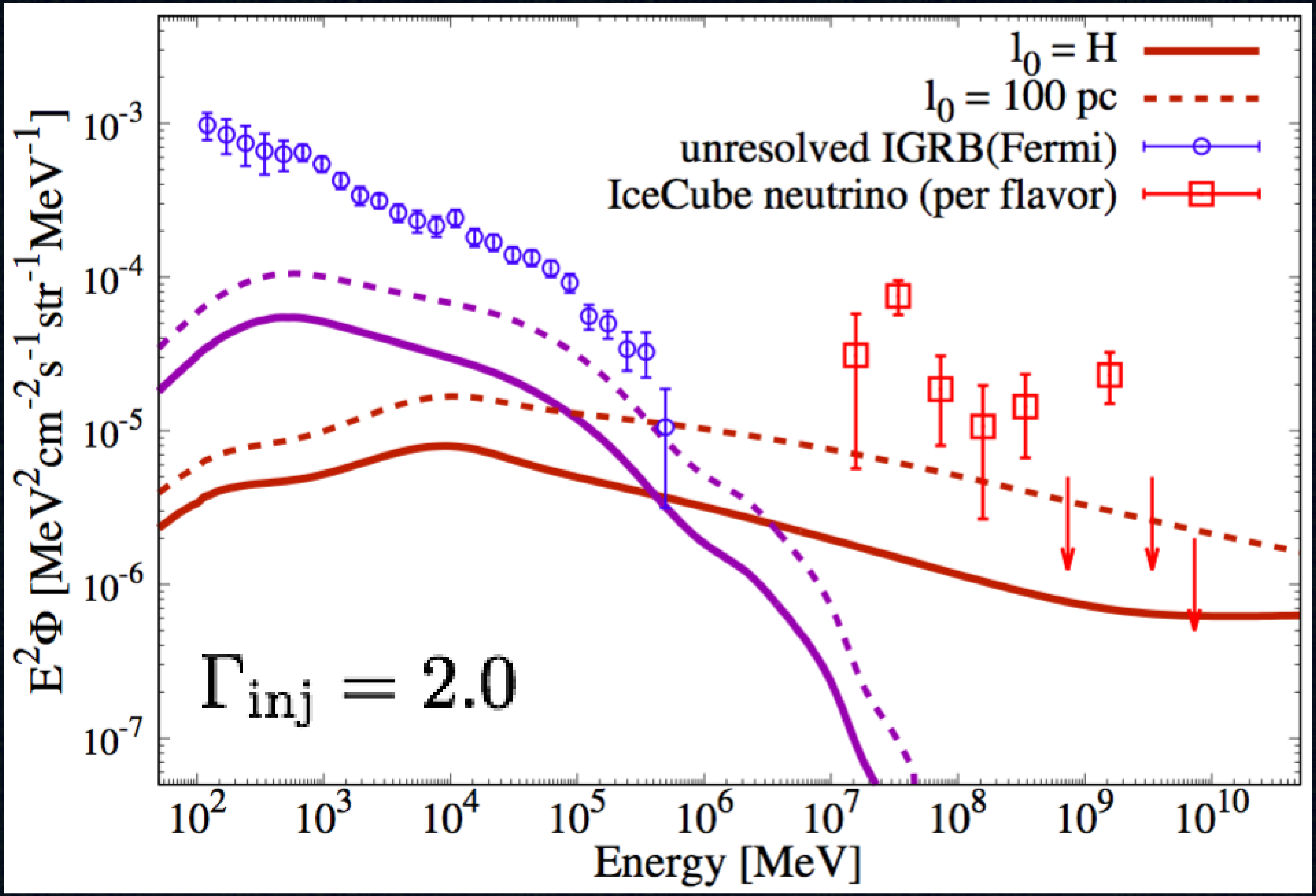
- $\Gamma_{\rm inj}$ is set to 2 in all galaxies
- Model agrees very well with observation !

Result (Gamma-ray & Neutrino)



- Star-forming galaxies make ~10 % contribution to IGRB
- and less than 10 % contribution to IceCube data
- even when $\Gamma_{inj} = 2$ in all galaxies (optimistic)

Result (Dependence on Modelling)



- We check dependence on modelling of H and l_0
- E.g.) If we set $l_0 = 100\ \mathrm{pc}$ in all galaxies, the result changes by a factor of ~2 but still cannot explain data.

Summary

- Calculated γ-ray and neutrino fluxes
  with a cosmological galaxy formation model

- Calibrated models from L_γ of nearby six galaxies

- SFG can explain less than **10** % of IceCube data
  → other source(s) should be dominant

Appendix

- derived values for nearby galaxies in our model

	H [pc]	B [μG]	D (E=10 GeV) [cm^2 s^{-1}]	$n_{\rm gas}$ [cm^{-3}]	$t_{\rm esc}$ (E=10 GeV) [yr]	t_{pp} [yr]	f_π (E=10 GeV)
MW	150	4.1	8.9×10^{28}	11.5	8.0×10^4	3.1×10^6	2.6×10^{-2}
SMC	17	1.7	2.8×10^{28}	670	3.4×10^{3}	5.4×10^4	6.2×10^{-2}
LMC	50	2.4	5.1×10^{28}	34	1.6×10^4	1.1×10^6	1.4×10^{-2}
NGC253	93	8.2	5.2×10^{28}	43	5.2×10^4	8.2×10^5	6.2×10^{-2}
M82	28	19	1.7×10^{28}	500	1.4×10^4	7.2×10^4	0.18
NGC2146	45	16	2.6×10^{28}	350	2.4×10^4	1.0×10^5	0.21

- Input: SFR, $M_{\rm gas}$, V_c, $R_{\rm eff}$

Appendix

- Cosmic ray energy density

$$\epsilon_{\mathrm{CR}} = \frac{\dot{E}_{\mathrm{CR}}\tau_{\mathrm{esc}}}{V}$$

- τ_{esc} : Estimated for E = GeV
  - The result is not changed when we use E = 100 MeV or 10 GeV instead.