Prospects of newly detecting nearby star-forming galaxies by the Cherenkov Telescope Array

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Star-forming galaxy as a gamma-ray emitter

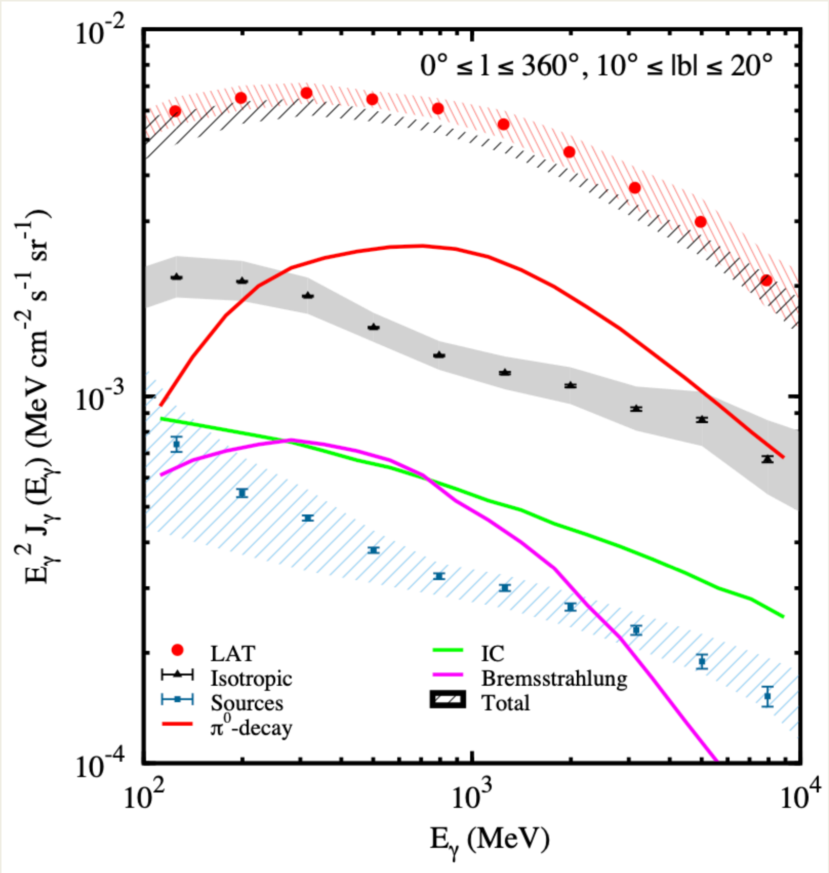
- Galaxies with star-forming activity (star-forming galaxies, SFGs) are gamma-ray emitters.

  Cosmic rays (CRs) accelerated by supernovae collide with ISM, and produce a pion. Then a pion produces photons.

  $$\mathrm{p} + \mathrm{p} \rightarrow \pi^0 \ , \qquad \pi^0 \rightarrow \gamma + \gamma$$

- This process is dominant component of galactic diffuse emission

Galactic emissivity



Abdo et al. 2009

Detection of gamma-ray from SFGs

- Fermi-LAT detected GeV gamma-ray from nearby galaxies:

  LMC, SMC, M31, NGC 253, M82, NGC 4945,

  NGC 1068, NGC 2146, Arp 220, Arp299, M33

  (Abdo et al. 2010, Ackermann et al. 2012, Tang et al. 2014,

  Peng et al. 2016, Ajello et al 2002, Xi et al 2020)

- H.E.S.S. and VERITAS detected TeV gamma-rays from NGC 253, and M82

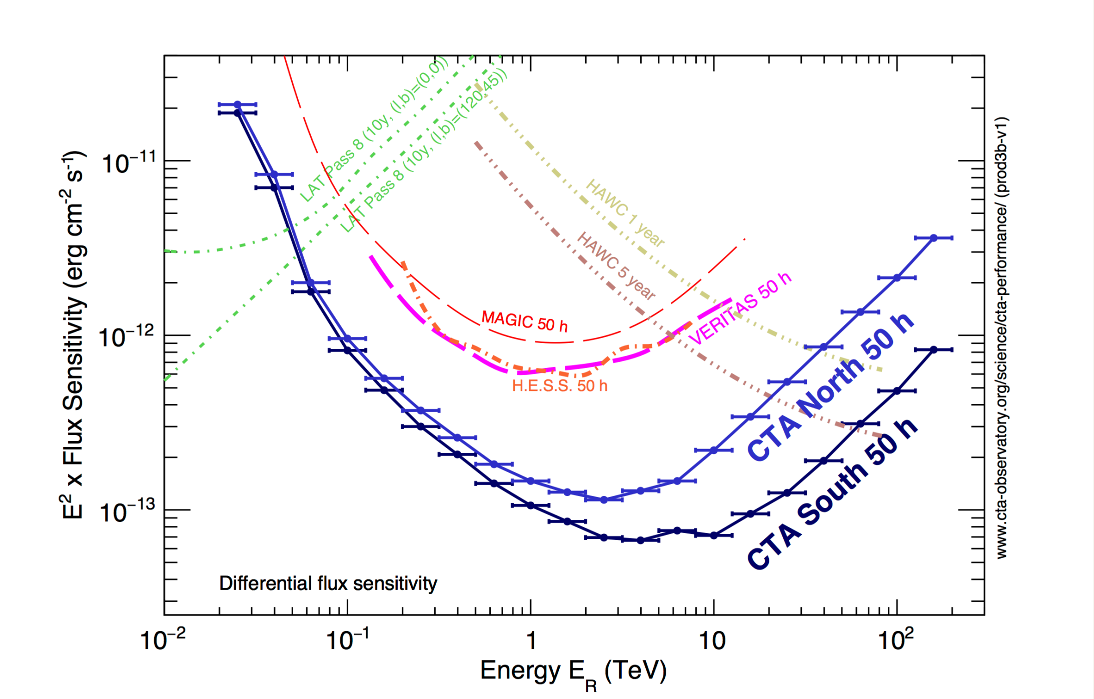
  (Acero et al. 2009, VERITAS Collaboration et al. 2009)

- These detection proves that gamma-ray from SFGs is ubiquitous.

Cherenkov Telescope Array Project

- More detections in TeV are expected by Cherenkov Telescope Array (CTA).
- Large Sample of SFGs in GeV-TeV will lead to the understanding of production and propagation of CRs in diverse galaxies.
- It is important to prepare theoretical prediction for gamma-ray luminosities and spectra of nearby SFGs.

Differential sensitivities of CTA and other telescopes



https://www.cta-observatory.org

Modeling in Past Studies

- Modeling of SFGs:
- Simply relate some of physical quantities (for many studies, one or two) of the galaxy with gamma-ray luminosity

  Torres 2004; Domingo-Santamaria & Torres 2005; Persic et al. 2008;

  Lacki et al 2010, 2011; Inoue 2010; Wang & Fields 2018
- Microphysical parameters are introduced as free parameter, and the these are fit to reproduce the observed gamma-ray luminosity of a galaxy.

  Yoast-Hull et al. 2013, 2014; Eichmann & Becker Tjus 2016; Peretti et al. 2019;

  Krumholz et al. 2020
- Simulations, though it is not convenient to predict for many galaxies

  Martin 2014, Pfrommer et al. 2017, Chan et al. 2019

- For the theoretical prediction of large sample of galaxies yet to be detected, the approach to simply relate some physical quantities of a galaxy with gamma-ray luminosity is appropriate.

The aim of this work

- Model constructed by Sudoh et al. 2018 (S18)

  Using four input parameters of a galaxy
  [Star-formation rate (SFR) (ψ), gas mass (M_{gas}), stellar mass (M_{star}), and effective radius (R_{eff})]

  This model can explain the observed luminosities of nearby galaxies better than the model using only SFR and/or gas mass.

- The aim of this study:

  Applying S18 model to nearby galaxies that are not yet detected in TeV, we predict their gamma-ray emission properties and discuss the relation to galactic physical parameters.

The overview of our model

- Proton spectrum

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

C is determined by the fitting with Fermi-LAT observation

- Probability of collision with ISM, $f_\pi(E_p)$, is determined from collision timescale (t_{pp}) and escape timescale (t_{esc}) :i.e.

$$f_\pi = 1 - \exp\left(-\frac{t_{esc}}{t_{pp}}\right)$$

- Escape timescale is minimum of advection timescale and magnetic diffusion timescale
- Advection timescale is estimated by gravitational equilibrium along the perpendicular direction to the disc surface.
- Diffusion coefficient: D

$$D(E_p) = \begin{cases} \frac{cl_0}{3}\left[\left(\frac{R_L}{l_0}\right)^{\frac{1}{3}} + \left(\frac{R_L}{l_0}\right)^2\right] & \left(R_L \leq \sqrt{H_g l_0}\right) \\ \frac{cH_g}{3} & \left(R_L > \sqrt{H_g l_0}\right) \end{cases}$$

R_L: Larmor radius l_0: coherent length of turbulence H_g: scale height of a galaxy

Physical quantities for nearby GeV-detected SFGs

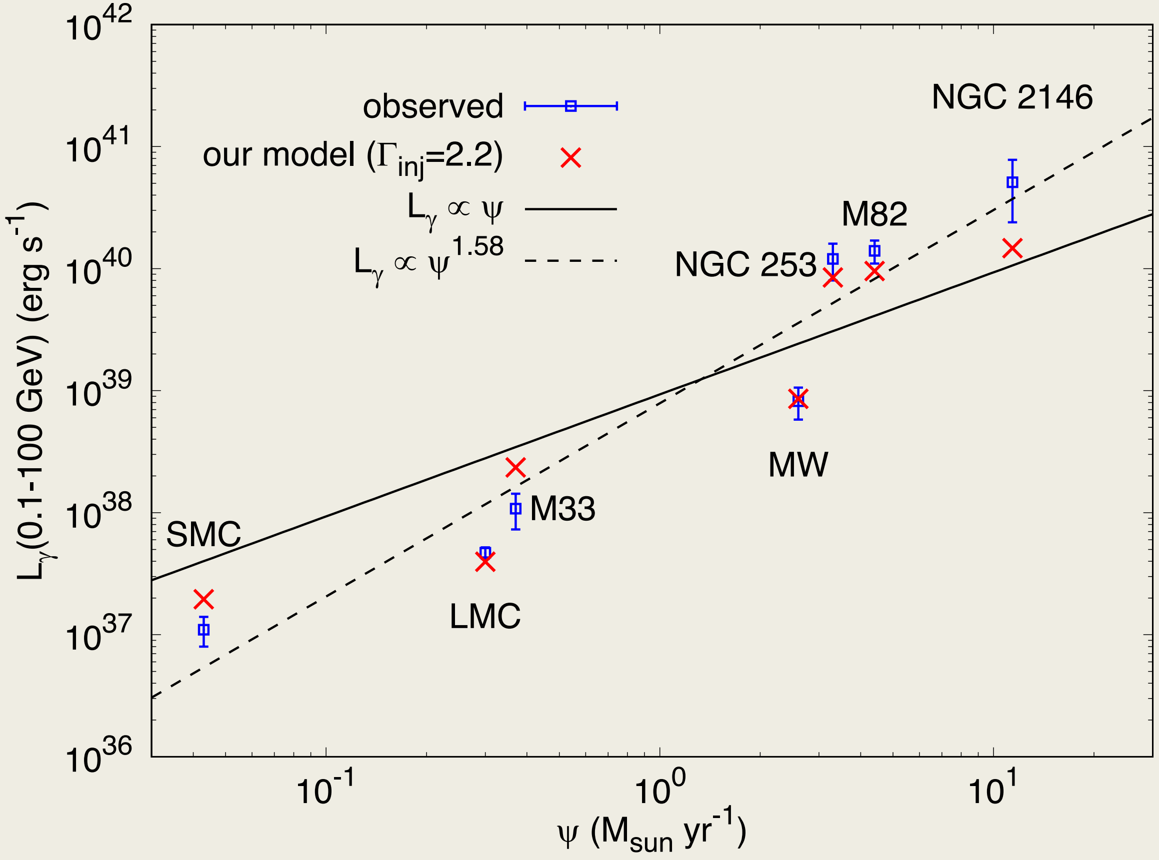
Objects	D (Mpc)	L_γ (0.1−100GeV) (erg s^{-1})	SFR ($M_\odot$ yr^{-1})	M_{gas} (10^9 $M_\odot$)	M_{star} (10^9 $M_\odot$)	R_{eff} (kpc)
MW		0.82 ± 0.27	2.6	4.9	50	6.0
LMC	0.05	0.047 ± 0.005	0.30	0.59	1.8	2.2
SMC	0.06	0.011 ± 0.003	0.043	0.46	0.30	0.7
NGC 253	3.5	12 ± 4	3.3	3.2	54.4	0.5
M82	3.3	14 ± 3	4.4	4.7	21.9	0.9
NGC 2146	17.2	51 ± 27	11.4	10.4	87.1	3.0

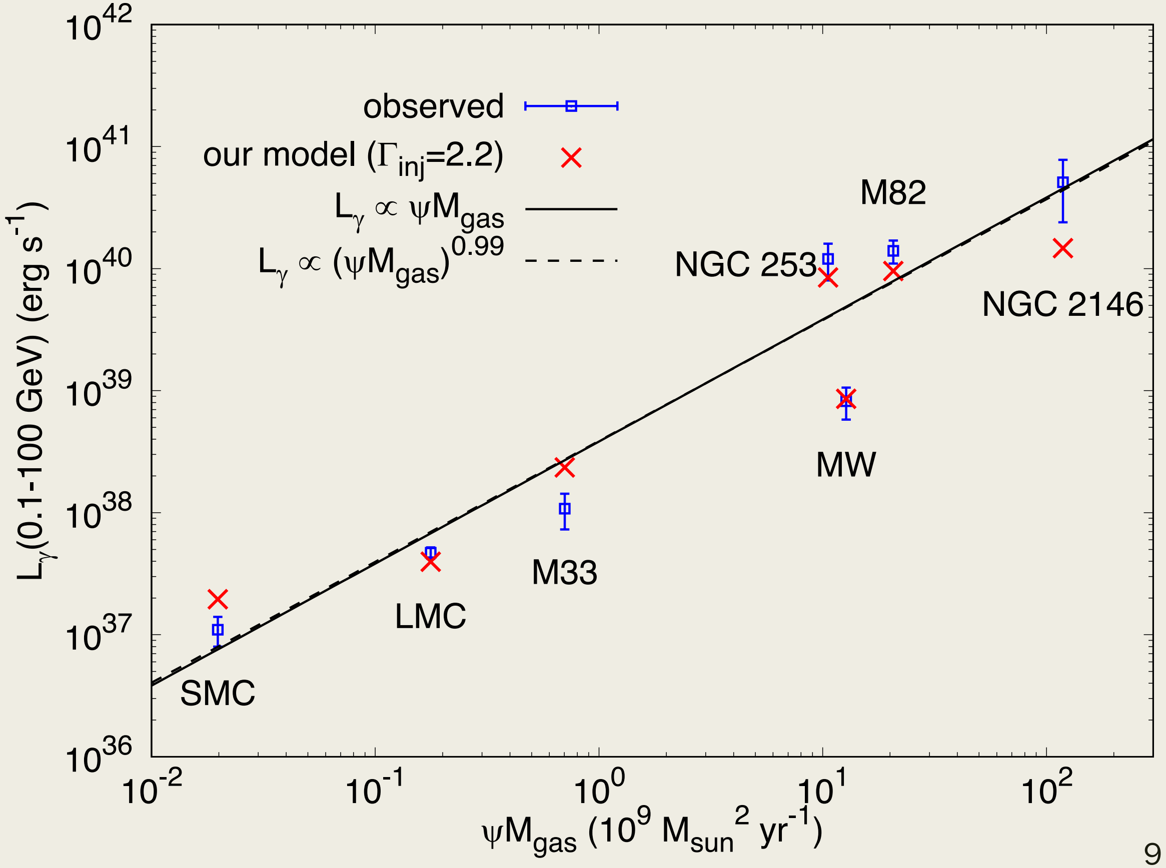
- Energy range of NGC 2146 is 0.2--100 GeV
- SFR is Derived from Infrared luminosity and Hα luminosity assuming Salpeter IMF.
- M_{gas} is sum of neutral hydrogen and molecular hydrogen, derived from 21-cm line flux and CO(1-0) line flux respectively .

Fitting to nearby SFGs

- C is the only parameter determined by the fitting.
- Our model can explain observed luminosities of nearby galaxies better.

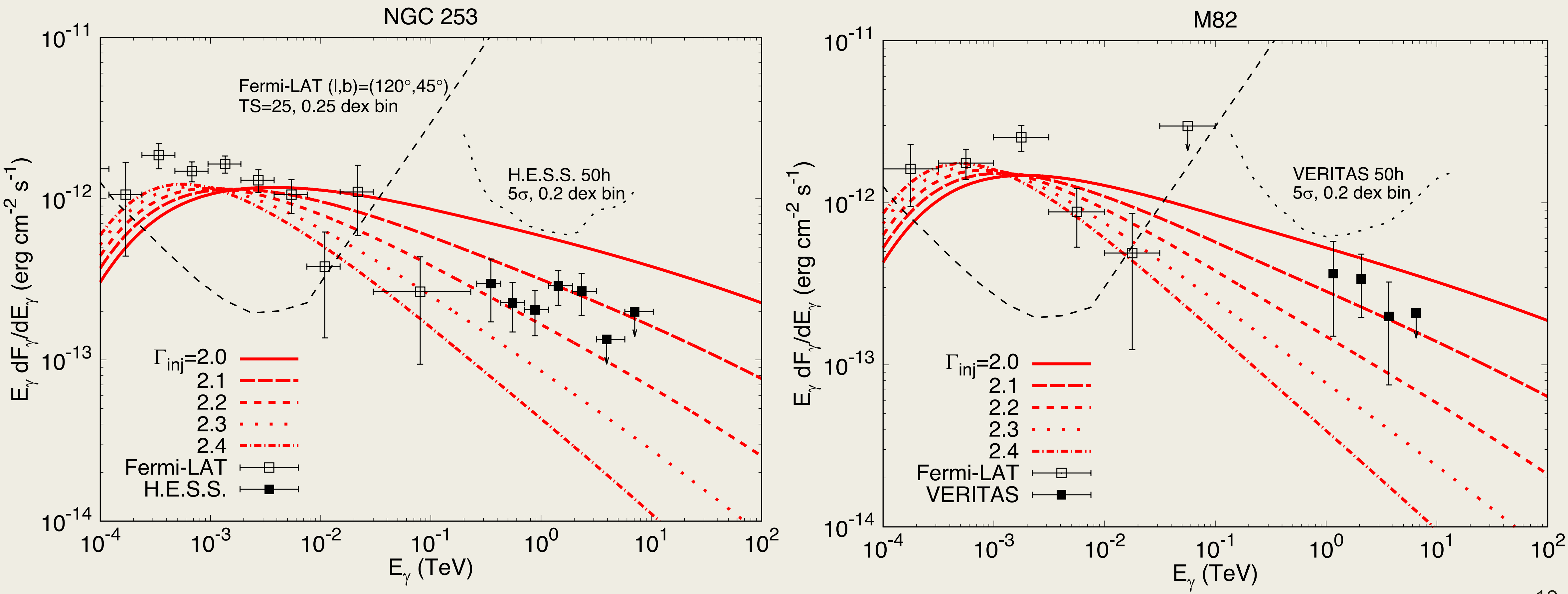
Our model vs. simple assumption ($L_\gamma \propto \psi$ and $L_\gamma \propto \psi \mathrm{M_{gas}}$)





Test of our model in TeV energy range

- GeV-TeV gamma-ray spectra of NGC 253 and M82 fit well when $\Gamma_{\mathrm{inj}} \sim 2.2$
- Our model works well both in GeV and TeV



Galaxy Sample

- 59 galaxies in KINGFISH (Key Insights on Nearby Galaxies: a Far-infrared Survey with Herschel)

  Galaxy catalog aimed to understand physical process of star-forming activity and ISM

  SFR, $M_{\rm gas}$, and $M_{\rm star}$ of these galaxies are compiled (Remy-Ruyer et al. 2014, 2015)

  We apply our model to 59/61 galaxies in KINGFISH catalog.
  (2 galaxies, NGC 1377 and NGC 1404 are omitted due to lack of information.)

- Other 8 galaxies

  Because KINGFISH is not a complete catalog of nearby galaxies, and we might miss galaxies

  whose emissions can be detected by the CTA,

  we add 8 galaxies based on their SFRs and distances.

  Among these galaxies,

  M33 and NGC 2043 have been already detected by Fermi-LAT observations

  The emission of NGC 2403 perhaps originate from not diffuse emission, but SN

Our model predictions

- Our model fluxes are typically lower than simple $L_\gamma \propto \psi$ estimates by a factor of 10 for 1 TeV and 6 for 3 GeV

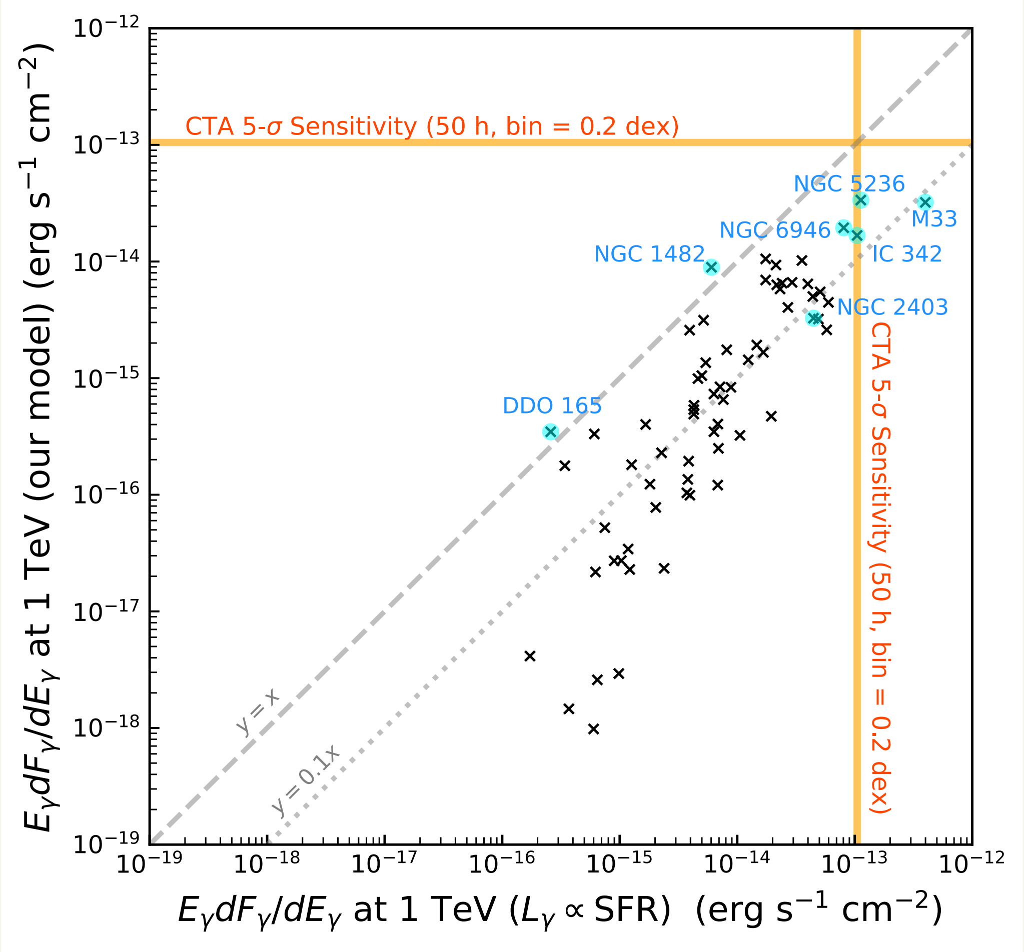
- Estimate of 1 TeV luminosity from SFR:

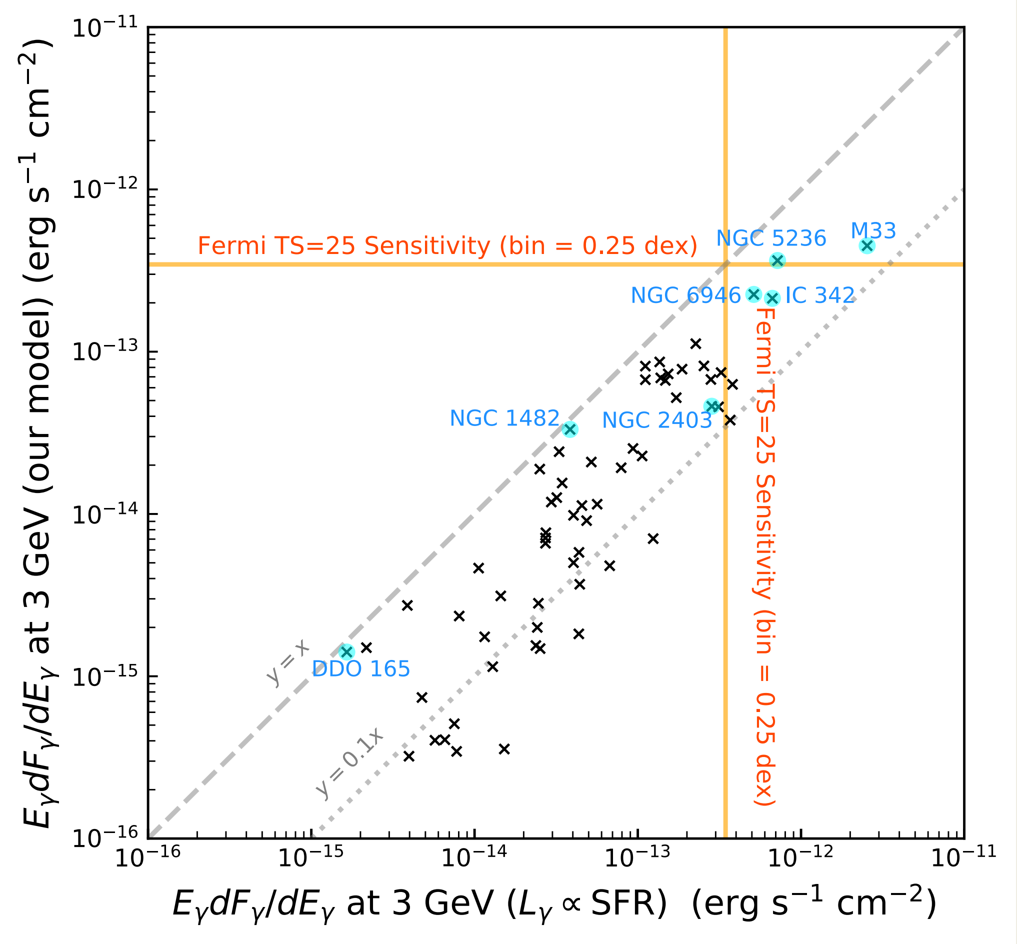
$$\frac{L(1\ \mathrm{TeV})}{\mathrm{erg\ s^{-1}}} \sim 9.1\times10^{37} \frac{\psi}{\mathrm{M_\odot\ yr^{-1}}}$$

- Estimate of 3 GeV luminosity from SFR:

$$\frac{L(3\ \mathrm{GeV})}{\mathrm{erg\ s^{-1}}} \sim 5.8\times10^{38} \frac{\psi}{\mathrm{M_\odot\ yr^{-1}}}$$

These coefficients are determined based on NGC 253





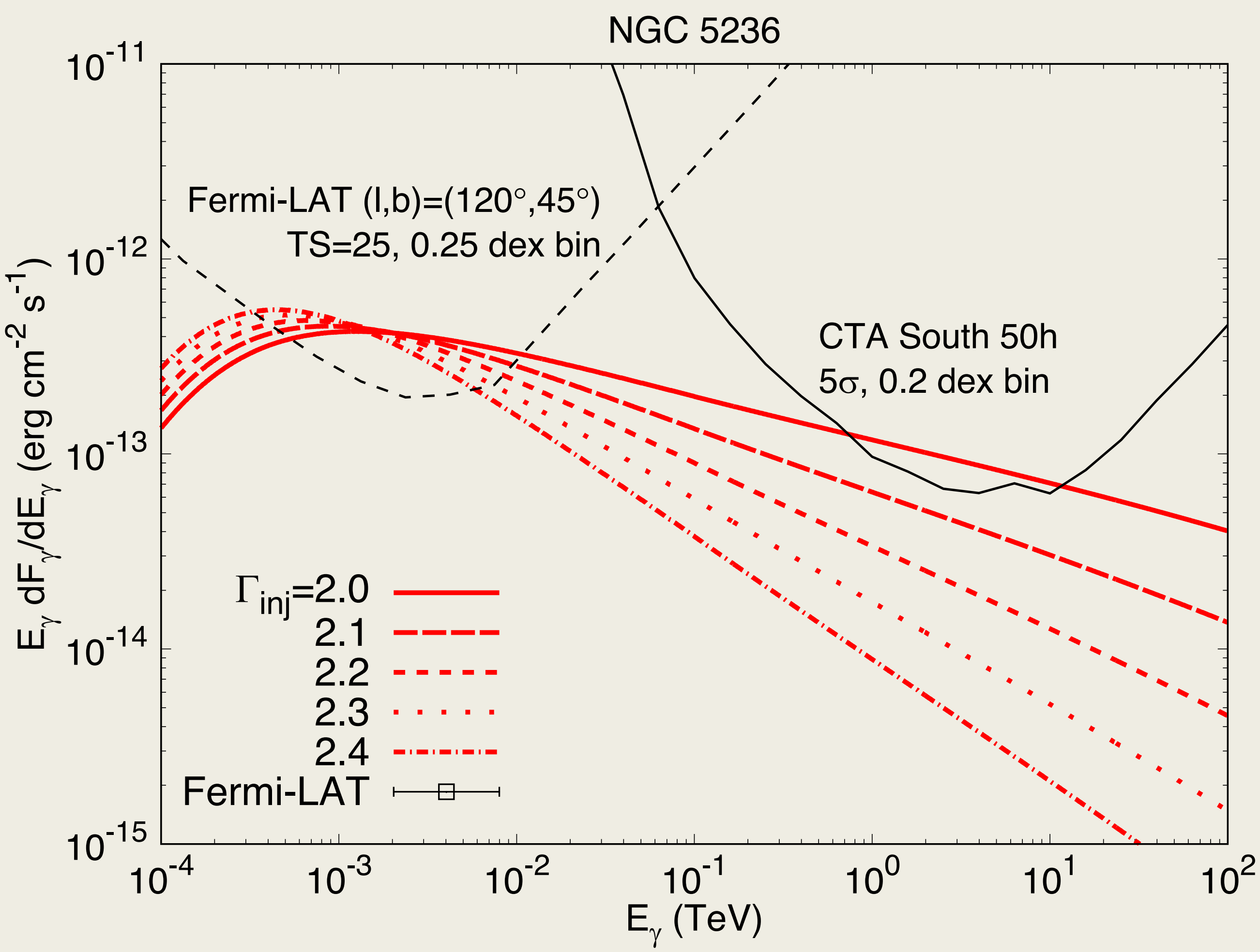
Predicted spectrum

- ~2-3 times lower flux than CTA sensitivity (per energy bin) will be detectable considering the condition of detection of NGC 253 and M82

- Galaxies with high possibilities of TeV detection by CTA :

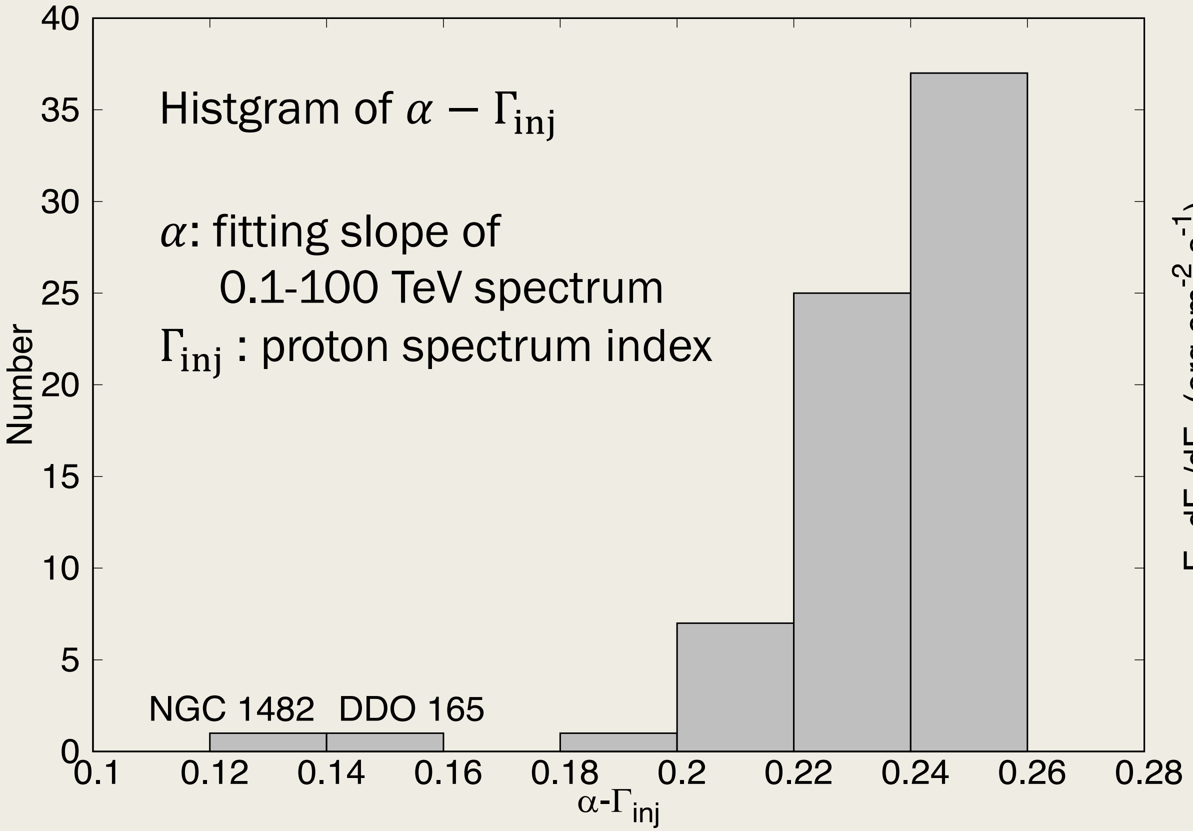
NGC 5236, M33 NGC 6946, IC 342, ...

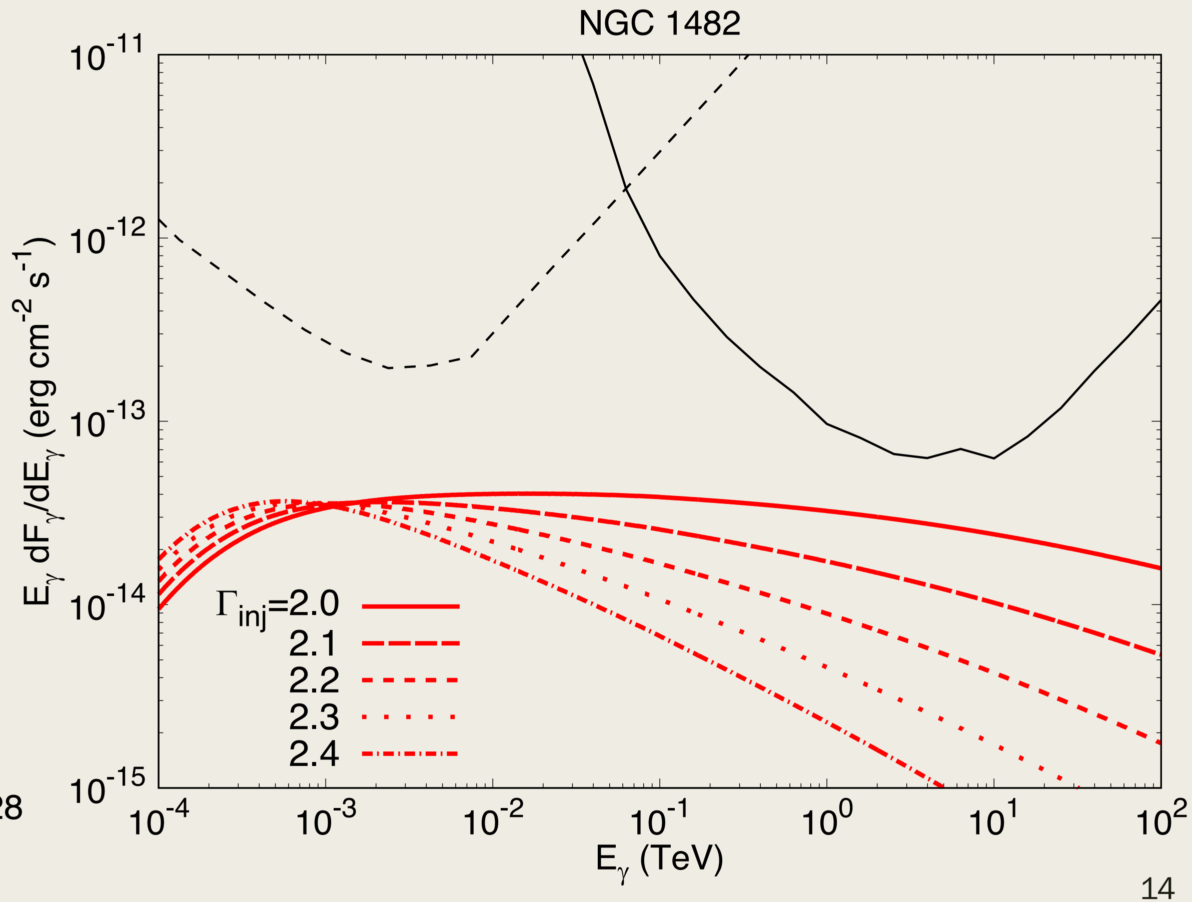
Example of derived spectrum



Hardness of galaxies

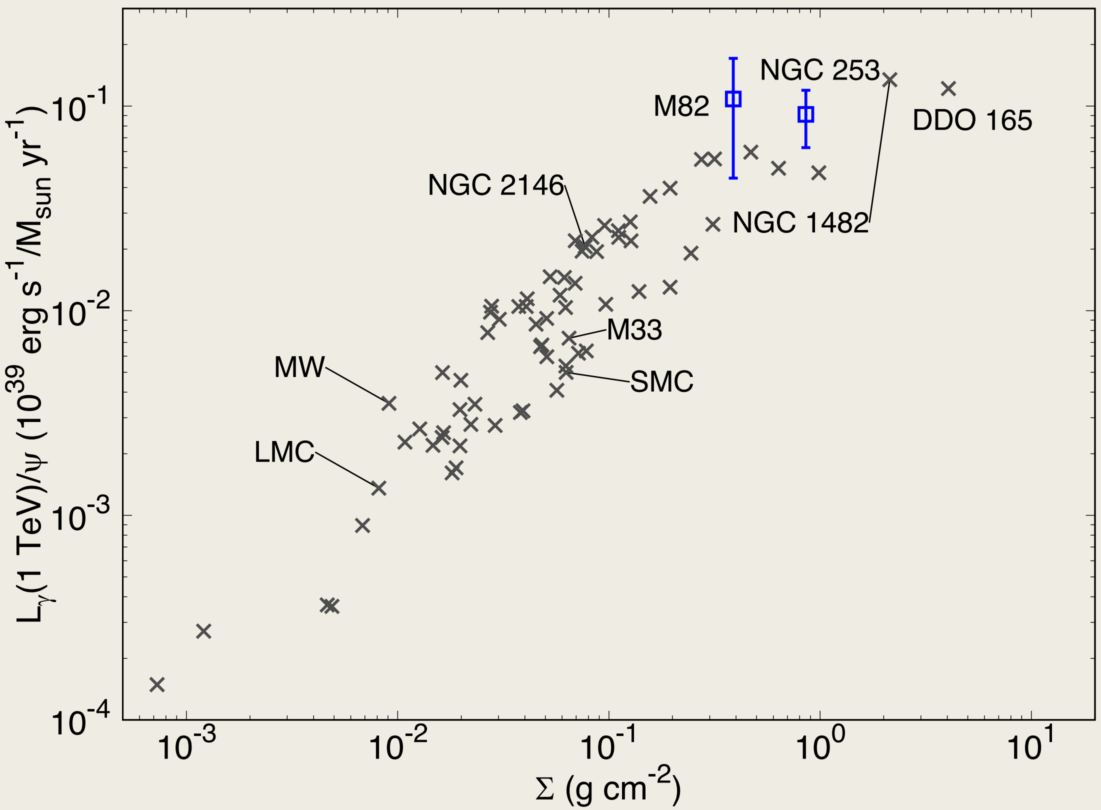
- NGC 1482 and DDO 165 have smaller $\alpha - \Gamma_{\mathrm{inj}}$ value compared with other galaxies
- If NGC 1482 has hard spectrum, and there is a chance of detection.
- DDO 165 has no chance of detection (too faint)

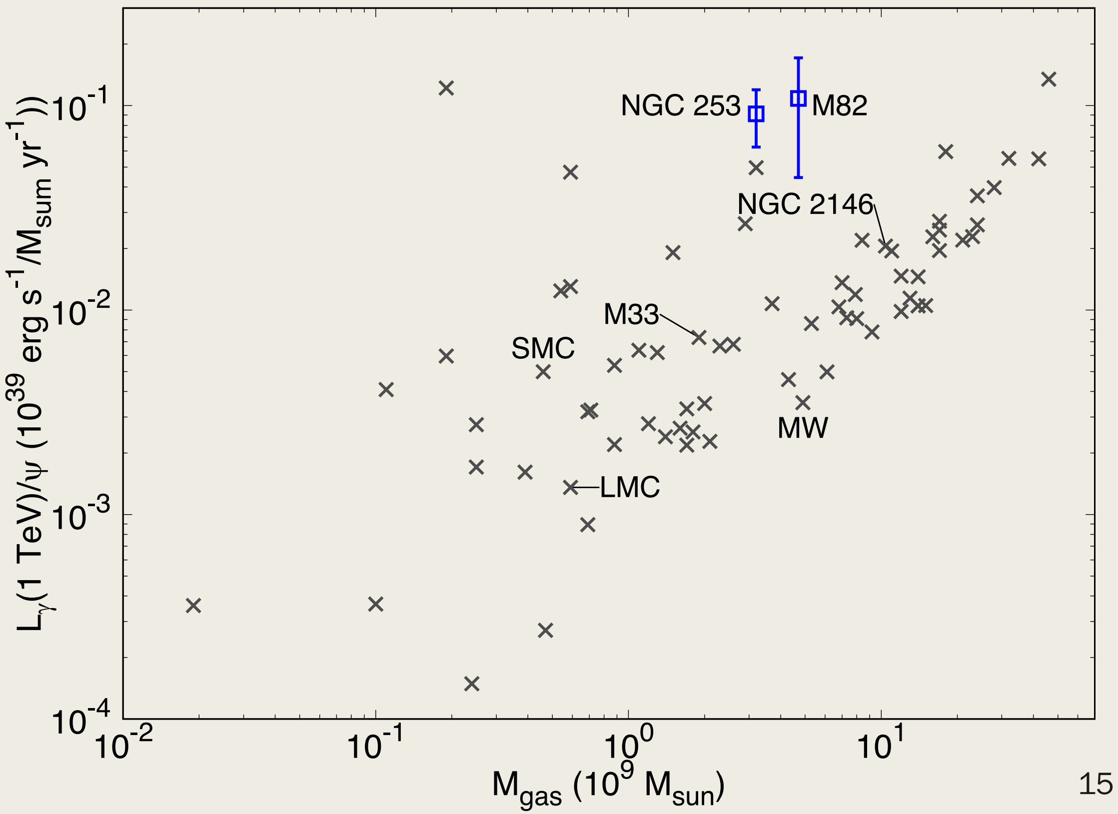




Relationships between gamma-ray luminosities and other physical quantities (1)

- The relationships between $L_\gamma(1\ \mathrm{TeV})/\psi$ and surface gas density (Σ) or M_{gas} are investigated.
- If cosmic-ray protons are completely confined in a galaxy, $L_\gamma(1\ \mathrm{TeV})/\psi$ is expected to be a constant. This trend is seen for Σ region (NGC 1482 and DDO 165)
- The relationship between $L_\gamma(1\ \mathrm{TeV})/\psi$ and M_{gas} has a large dispersion, which indicates a limitation of using ψM_{gas} an an indicator of gamma-ray luminosity.

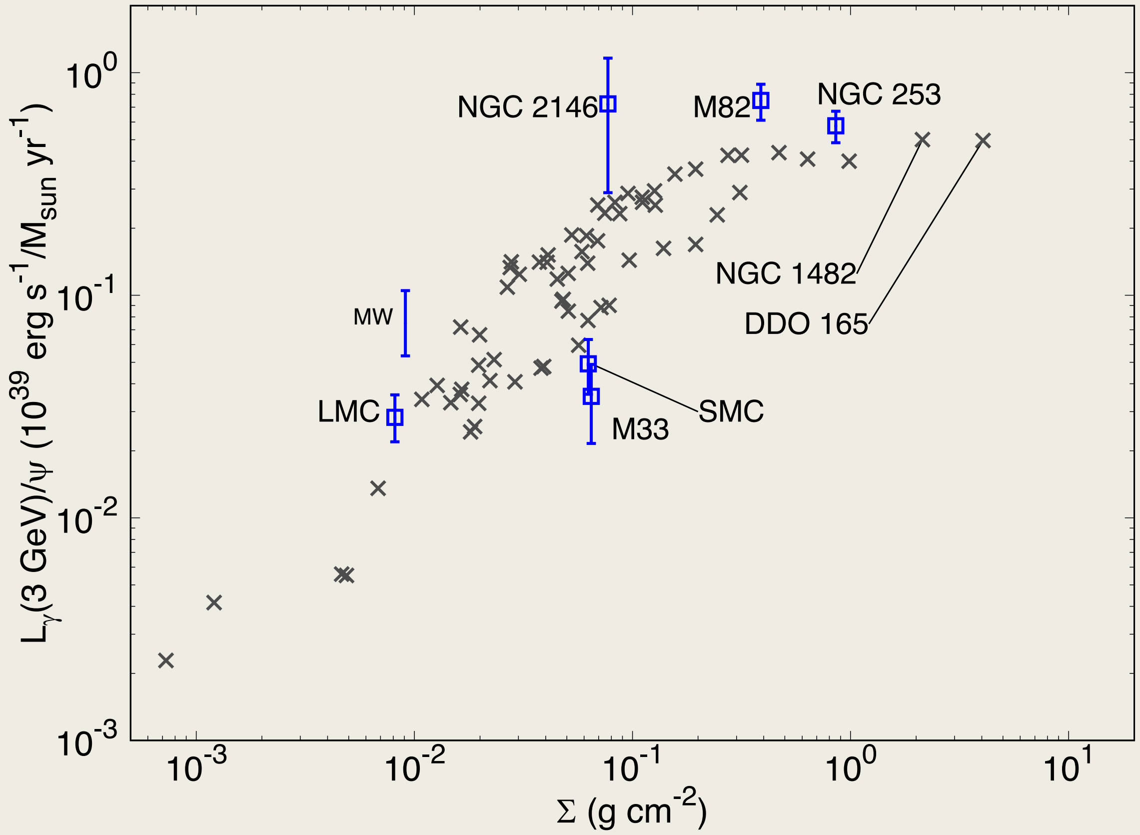


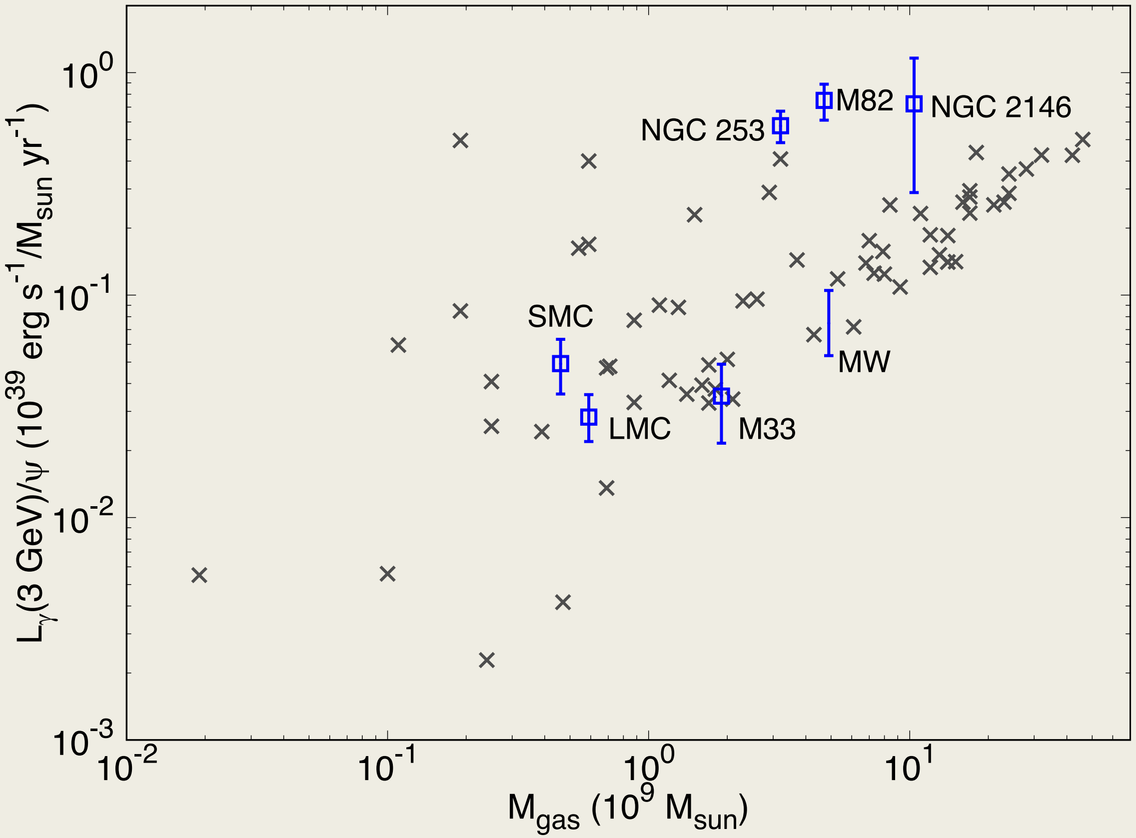


Relationships between gamma-ray luminosities and other physical quantities (2)

- Same figures as the previous slide, but this time gamma-ray luminosities are at 3 GeV.
- $L_\gamma(3\ \mathrm{GeV})/\psi$ becomes flat at lower Σ than TeV case,

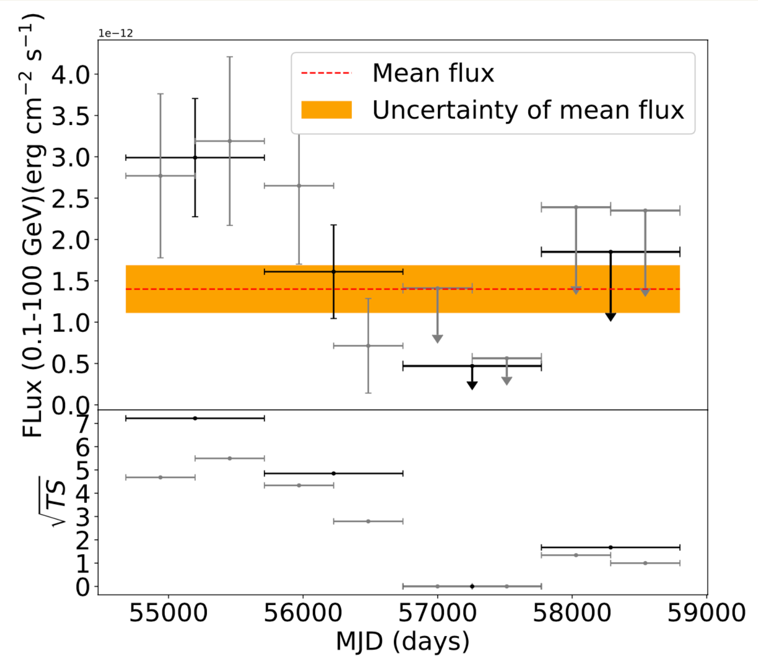
  which is expected because protons responsible for GeV gamma rays are more confined.
- Roughly consistent with the study by Lacki et al. (2011)

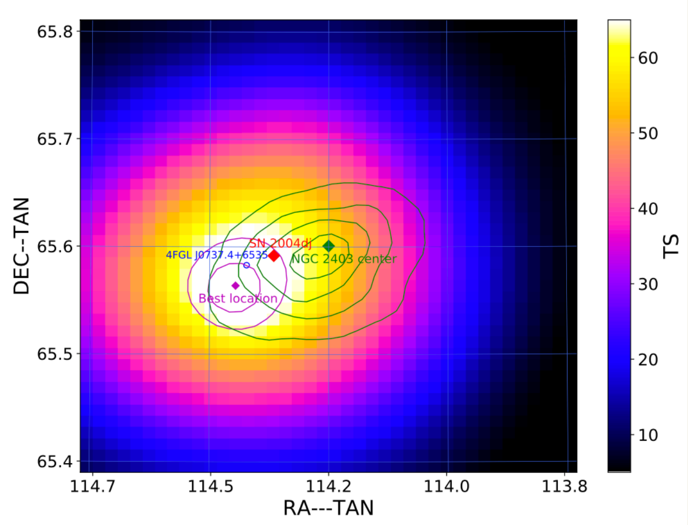




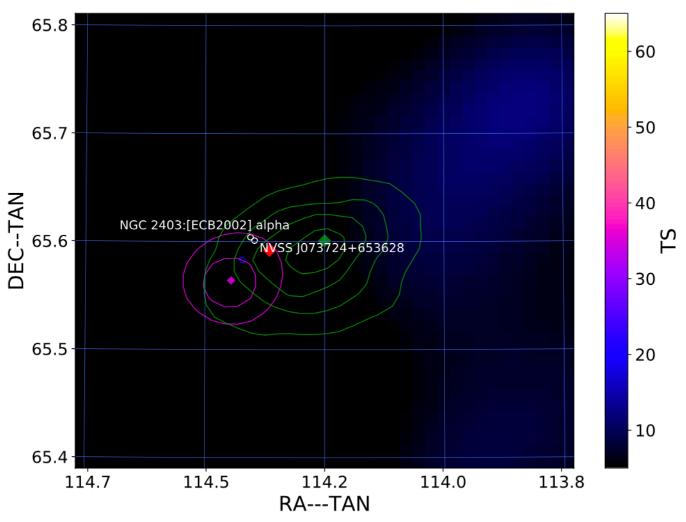
The origin of GeV emission form NGC 2403 (1)

- GeV gamma-ray detected from the direction of NGC 2403 is proposed to originate from SN 2004dj.
- Flux decreases with time
- TS peak coincidence with SN 2004dj





TS map for the first 5.7 years



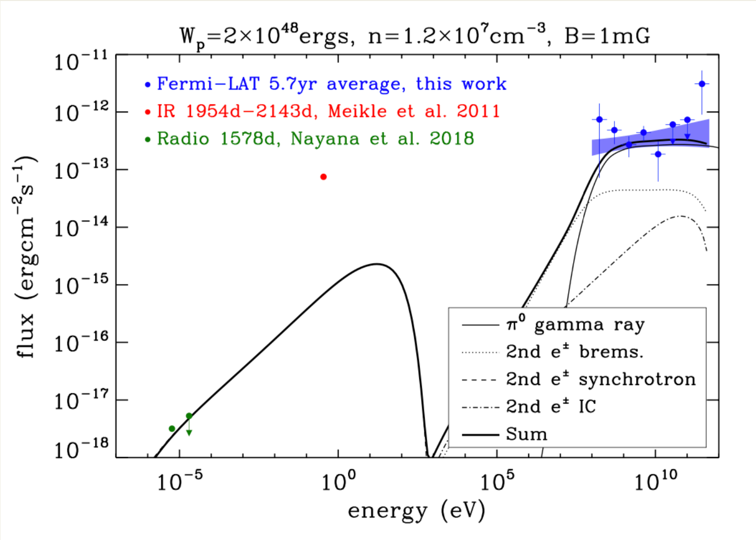
TS map for the second 5.7 years

All figures are taken from Xi et al. 2020

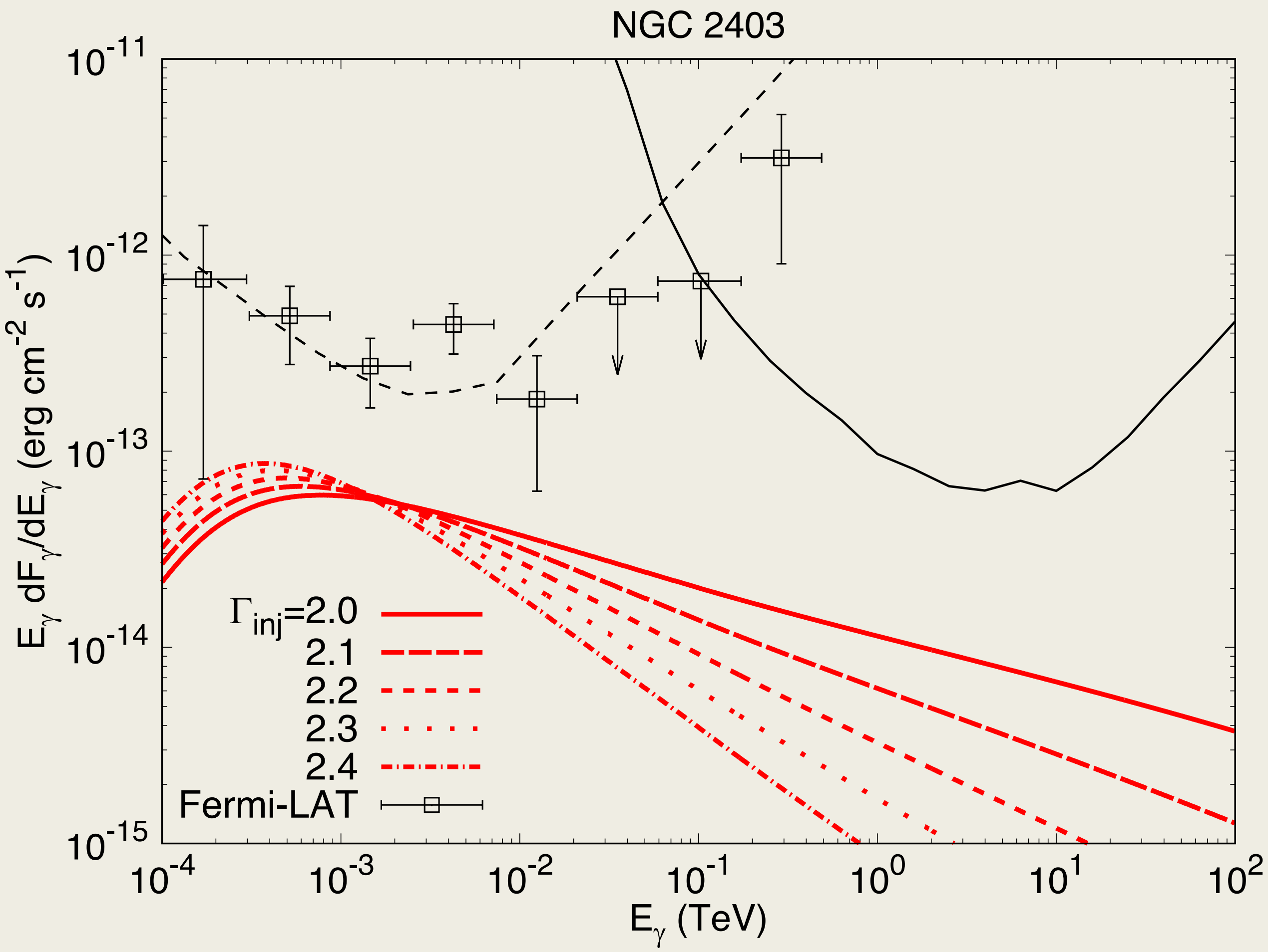
The origin of GeV emission from NGC 2403 (2)

- Our model spectrum cannot explain observed GeV emission of NGC 2403
- This result support the conclusion that GeV detection from NGC 2403 originates from SN 2004dj

SN model spectrum



Xi et al. 2020



Observation data is taken from Xi et al. 2020

Summary

- SFGs are gamma-ray emitters, and CTA is expected to detect TeV gamma rays from nearby SFGs.
- Understanding GeV–TeV emission mechanism of SFGs leads to understanding of production and propagation of CRs in diverse galaxies.
- We apply S18 model to nearby galaxies mainly from KINGFISH catalog.
- NGC 5236, M33, NGC 6946, and IC 342 are expected to be detected in TeV with high possibilities, and NGC 1482 might be detected if it has hard spectrum.
- Gamma-ray emission has significant dependence on surface gas density of a galaxy.