γ-ray observations of Starburst galaxies

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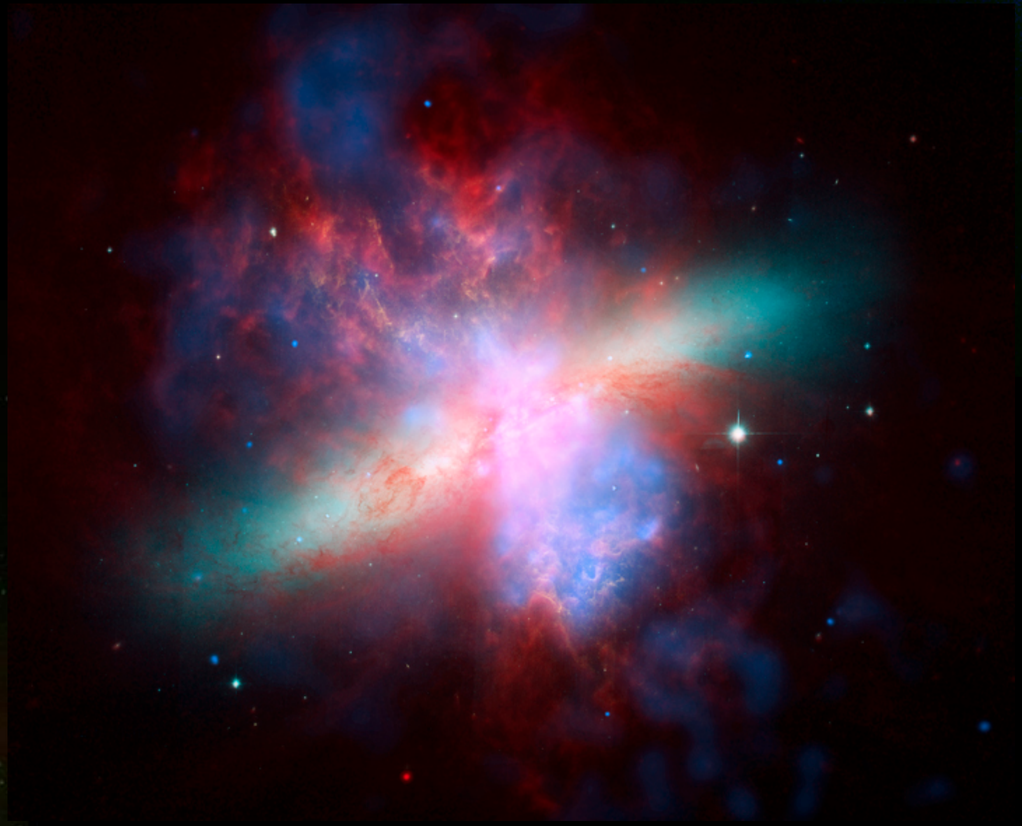

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collaborators: J. Hinton, W. Domainko, O. Reimer, H. Völk and others

γ 2012
Heidelberg: 12/07/2012

The γ-ray sky – in 2012

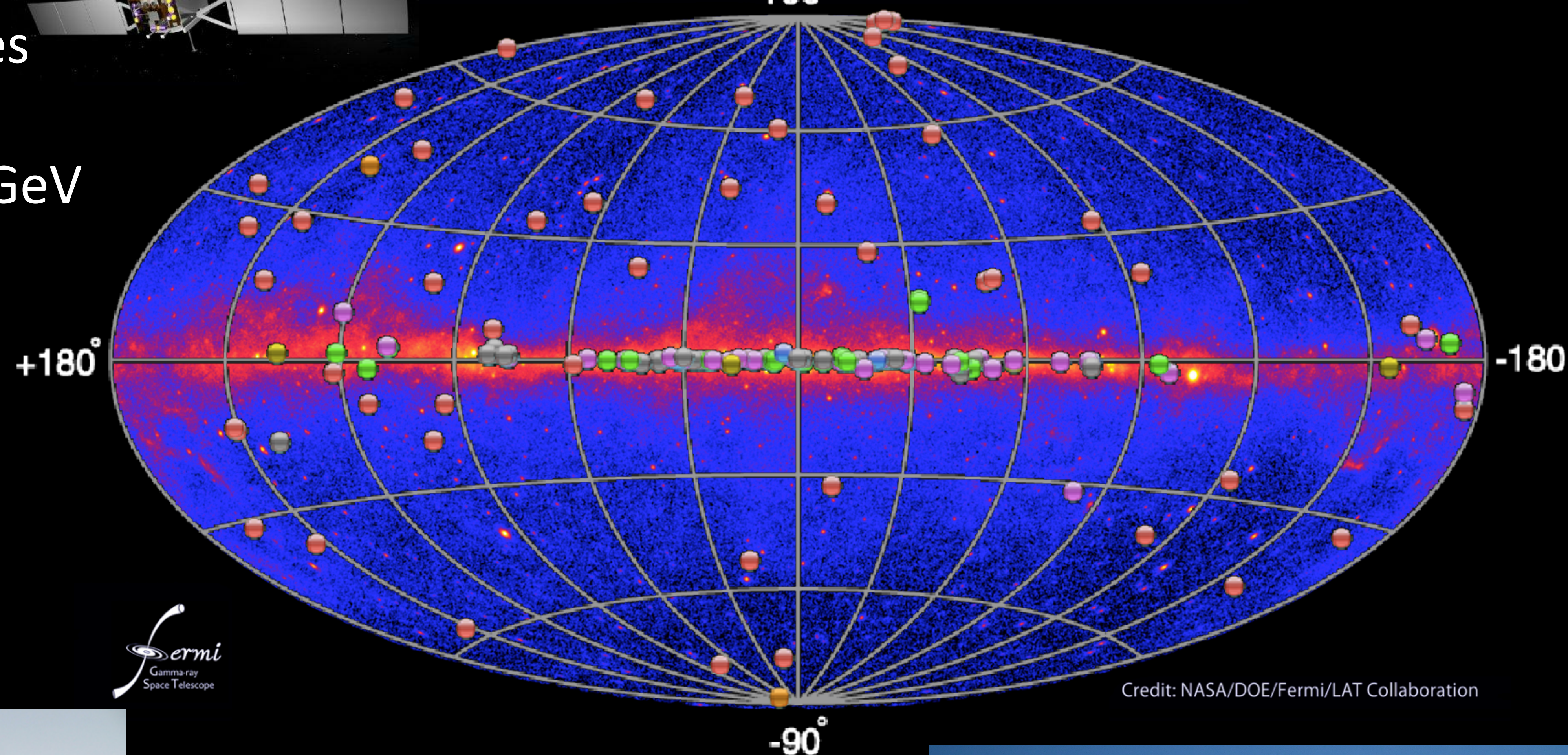
TeVCat

52 extragalactic sources

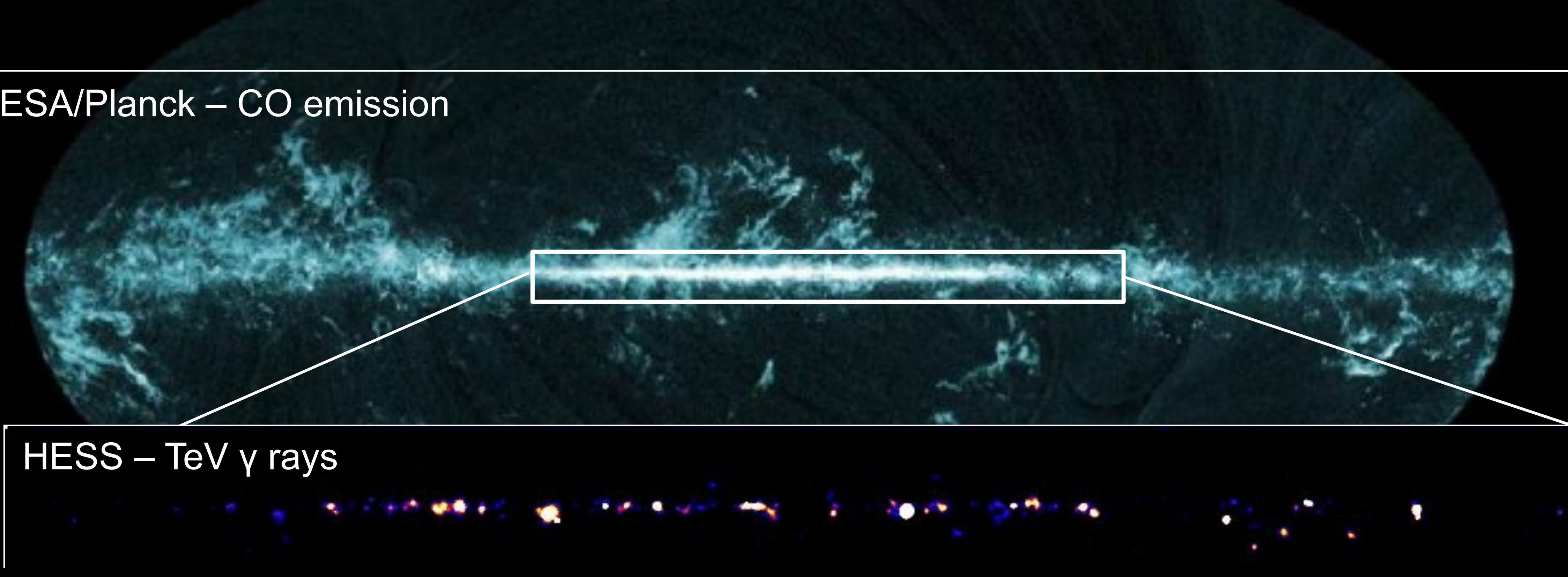
93 Galactic sources

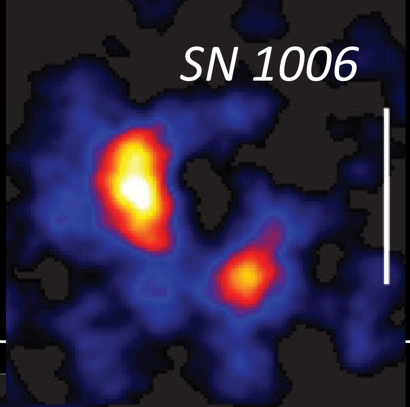
factor of ~10 more at GeV

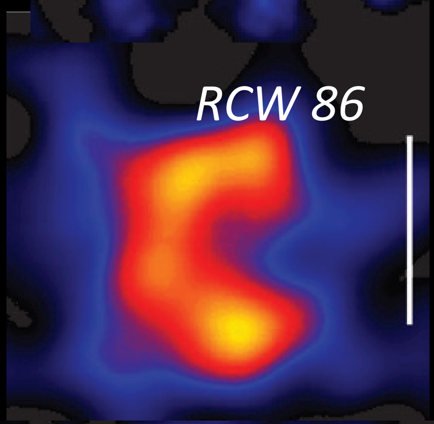
Fermi two-year all-sky map

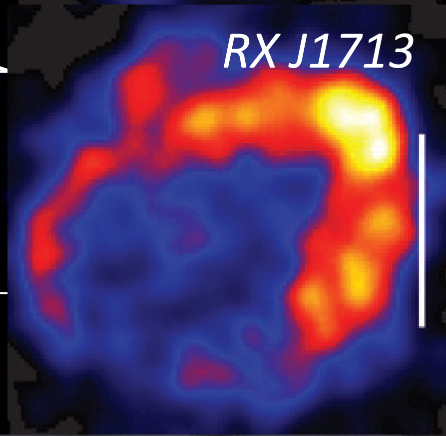


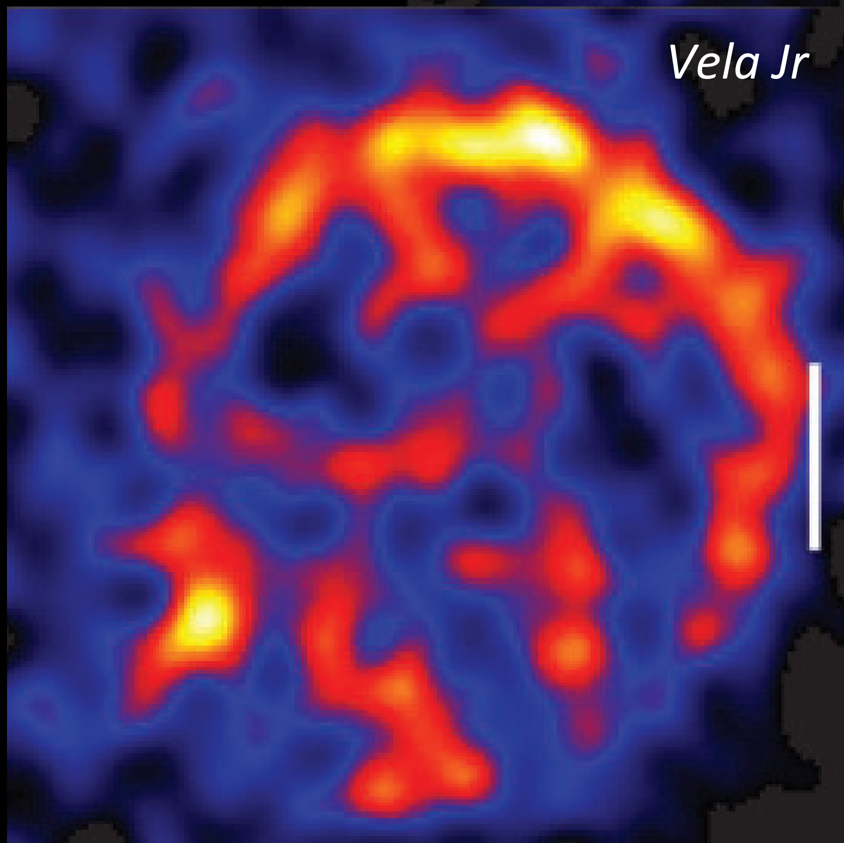
Galactic VHE γ-ray sources











- Galactic VHE γ-ray sources
  - Cluster tightly along the Galactic plane
  - Trace molecular gas and regions of massive star formation
  - Many sources coincident with objects at late stages of stellar evolution, such as

    → Pulsar Wind Nebulae (1/4)

    → Shell-type SNRs or SNR – MC interaction regions (1/5)

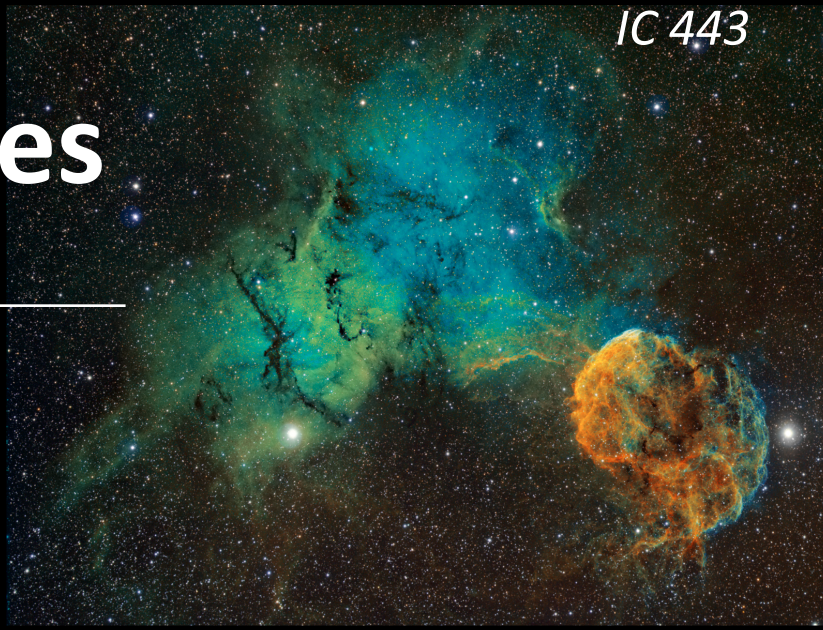
    → even stellar clusters start to emerge as new source class

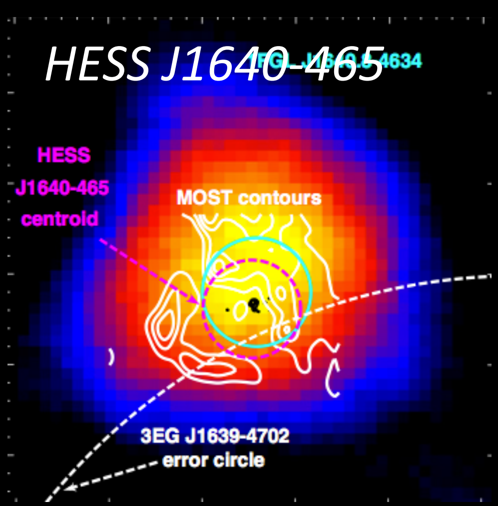
GeV – TeV spectra of Galactic sources

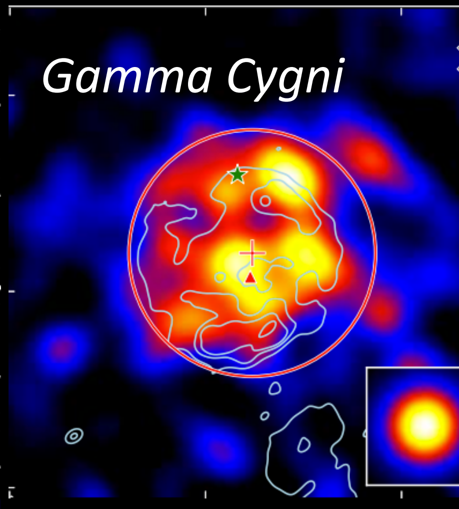
- More and more sources that are bright in TeV, have luminous GeV counterparts
  - e.g. W28, W44, W49B, W51C, IC 443, HESS J1640-465
- Sometimes even with smooth connection of GeV and TeV spectra (Γ~2.2 – 2.6)
- Often coincident with SNRs
  - in regions of ongoing star formation
  - at different evolutionary stages

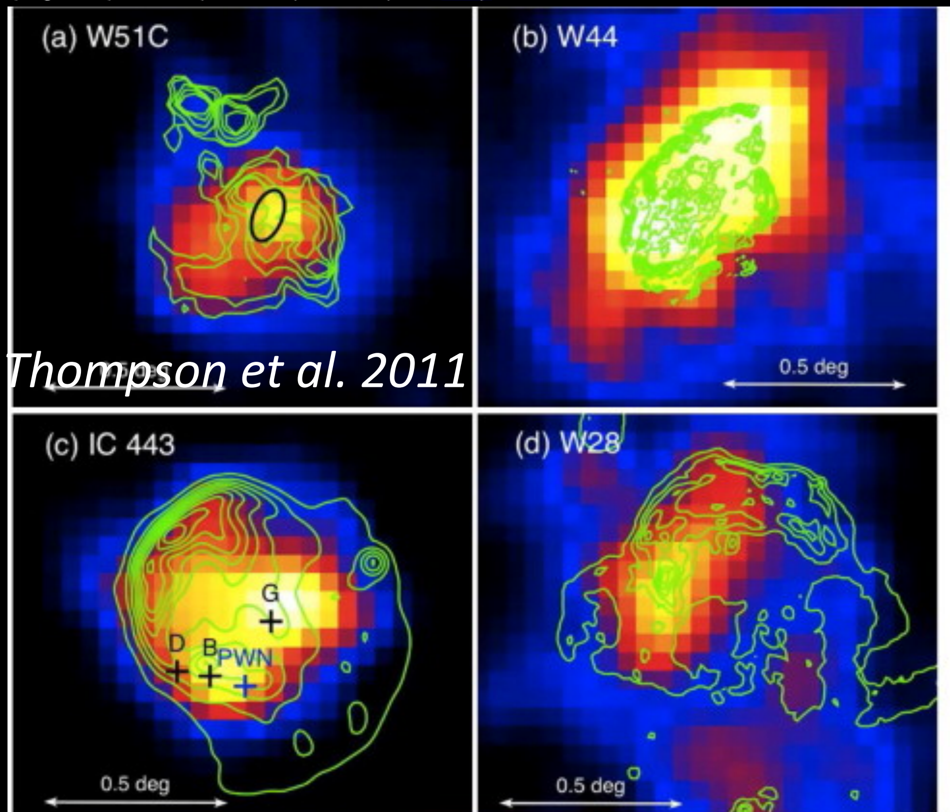
→ Increasing evidence for proton acceleration in these sources

- Star formation happens on different scales









Thompson et al. 2011

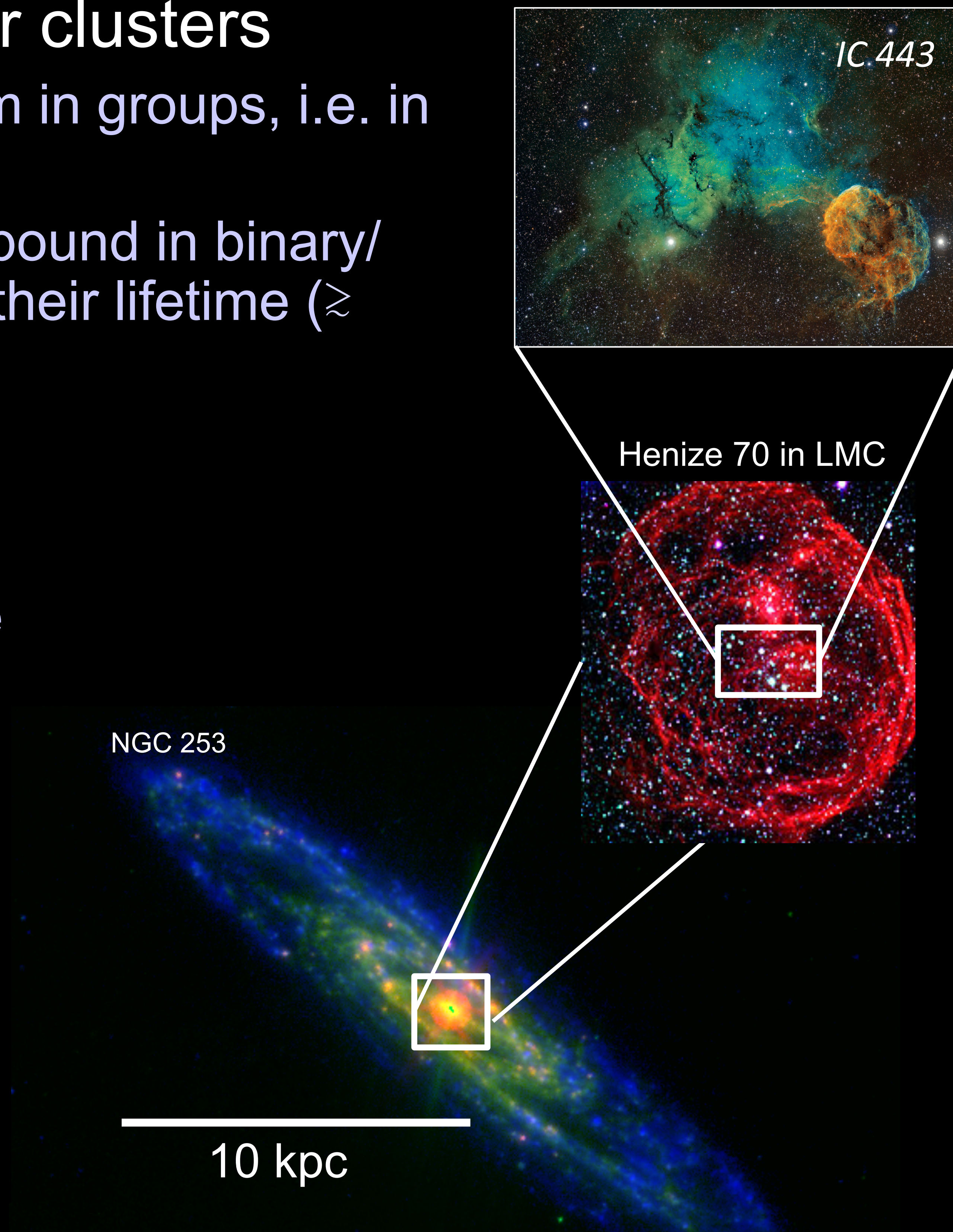
Star formation on different spatial scales

- From individual SNRs to stellar clusters
  - Massive stars (predominantly) form in groups, i.e. in *associations* or *stellar clusters*
  - Most (if not all) massive stars are bound in binary/ multiple systems at some point in their lifetime ($\gtrsim$ 25-50% are interacting)

- From stellar clusters to Starburst galaxies
  - On larger scales, multiple massive stars

  → Massive stellar clusters or even superbubbles

  - On even larger scales
  - Star formation on 500 pc scales in central regions of Starburst galaxies



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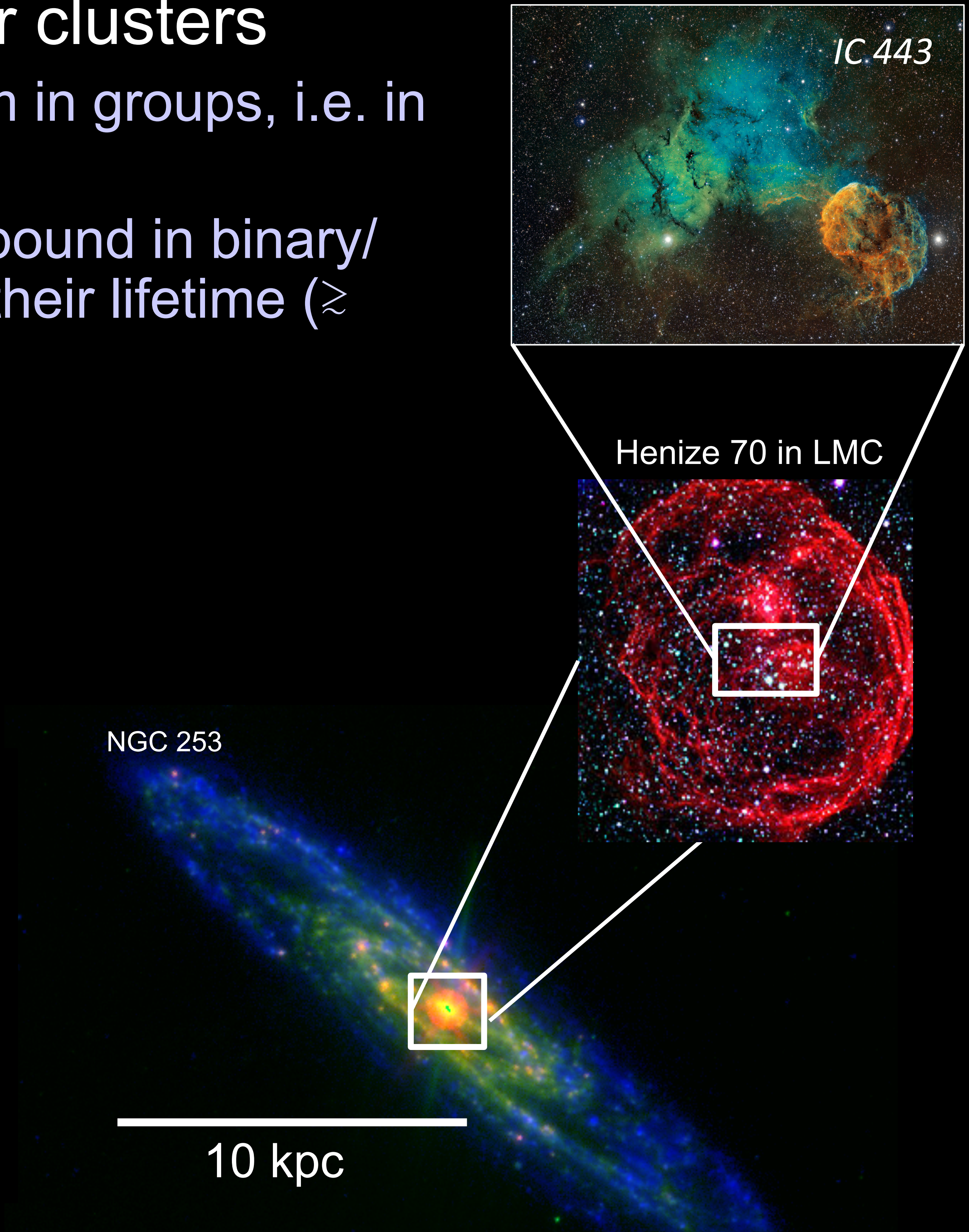
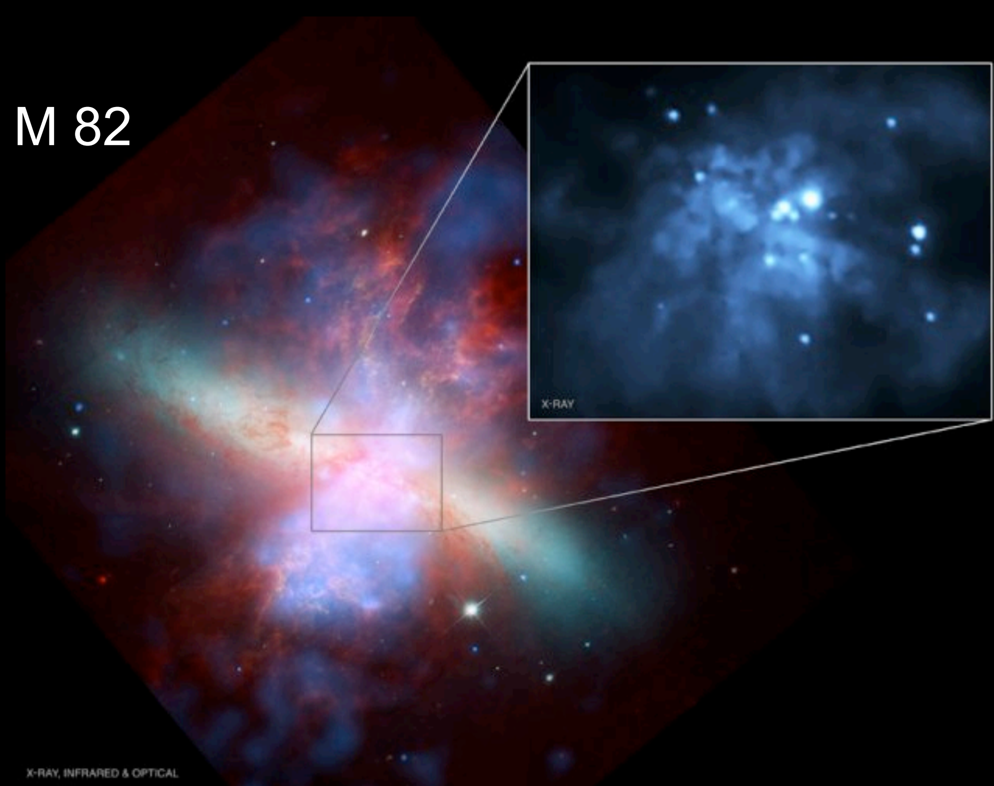


- → Test the paradigm of CR acceleration in SNR shells by looking at γ-ray emission of Starburst galaxies

HE/VHE γ rays from Starburst galaxies

- Starbursts
  - undergo evolutionary phase of enhanced star formation
  - triggered by galaxy merger, close fly-by of galaxies or Galactic bar instabilities
  - activity mainly in the central region, the SB nucleus
  - often drive super-Galactic winds

M 82



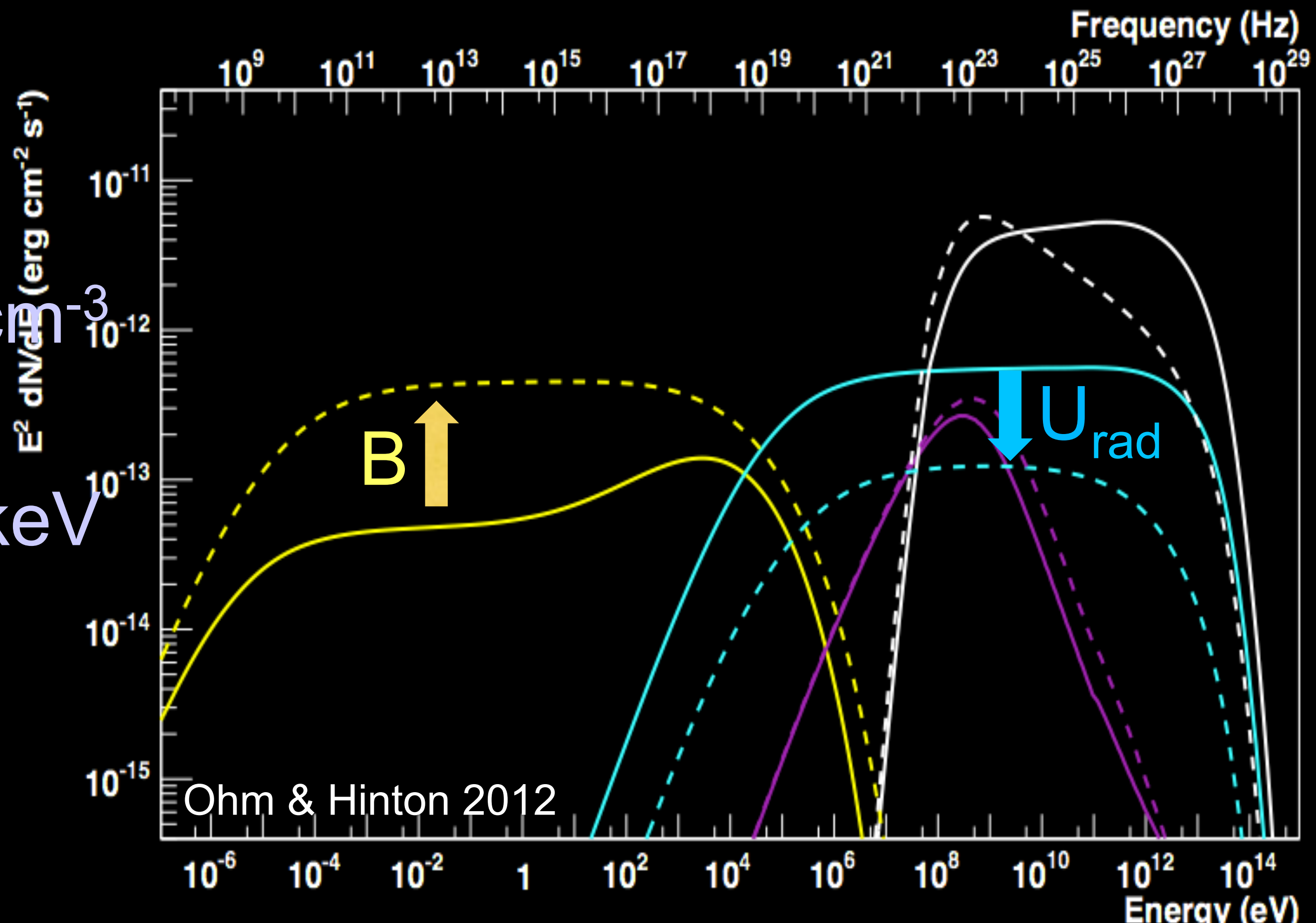
- HE/VHE γ-ray production
  - Regions of very dense gas
  - → subsequent star formation
  - → enhanced SN rate
  - expected to have a high cosmic-ray density
  - This + high gas density = expected HE/VHE γ-ray emitter

HE/VHE γ rays from Starburst galaxies

- Theoretical predictions
  - CRs lose energy via:
    - Diffusion (energy-dependent)
    - Advection (energy-independent)
    - p-p interaction (energy-independent)
    - e^+e^- additionally suffer radiative losses
- Typical starburst environment
  - Average density of n~100 – 1000 cm^{-3}
  - Magnetic fields of B~50 – 250 μG
  - Radiation field densities of U_{rad}~1 keV
  - v_{wind} of ~500 km s^{-1}
  - u_{SN} ~0.03 – 0.3 yr^{-1}
  - Starburst lifetime ~10 Myrs
  - Typical cooling times
    - t_{pp} ~ 10^5 (n/250 cm^{-3}) years
    - t_{IC} ~ 300 $(E/TeV)^{-1}$ years
    - t_{sync} ~ 200 $(E/TeV)^{-1}$ years

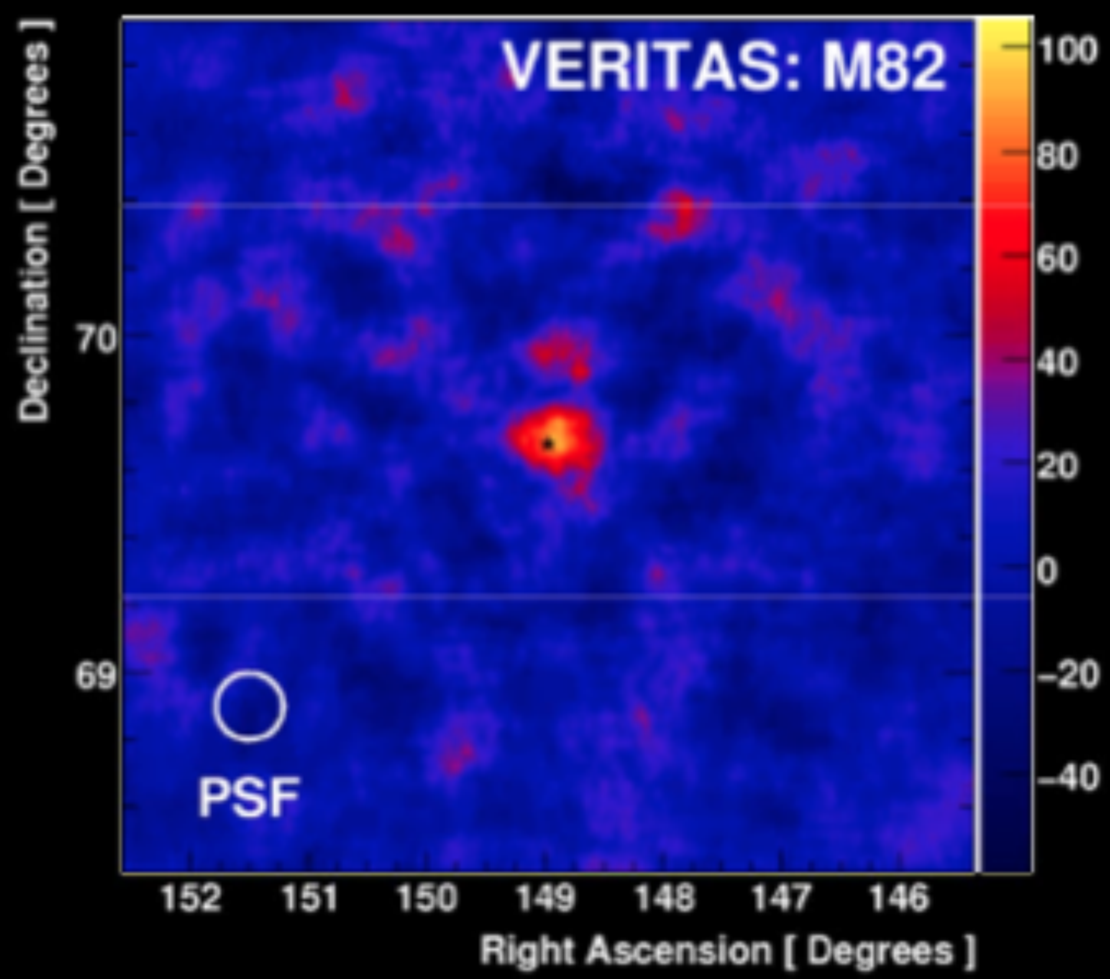
- Model SED

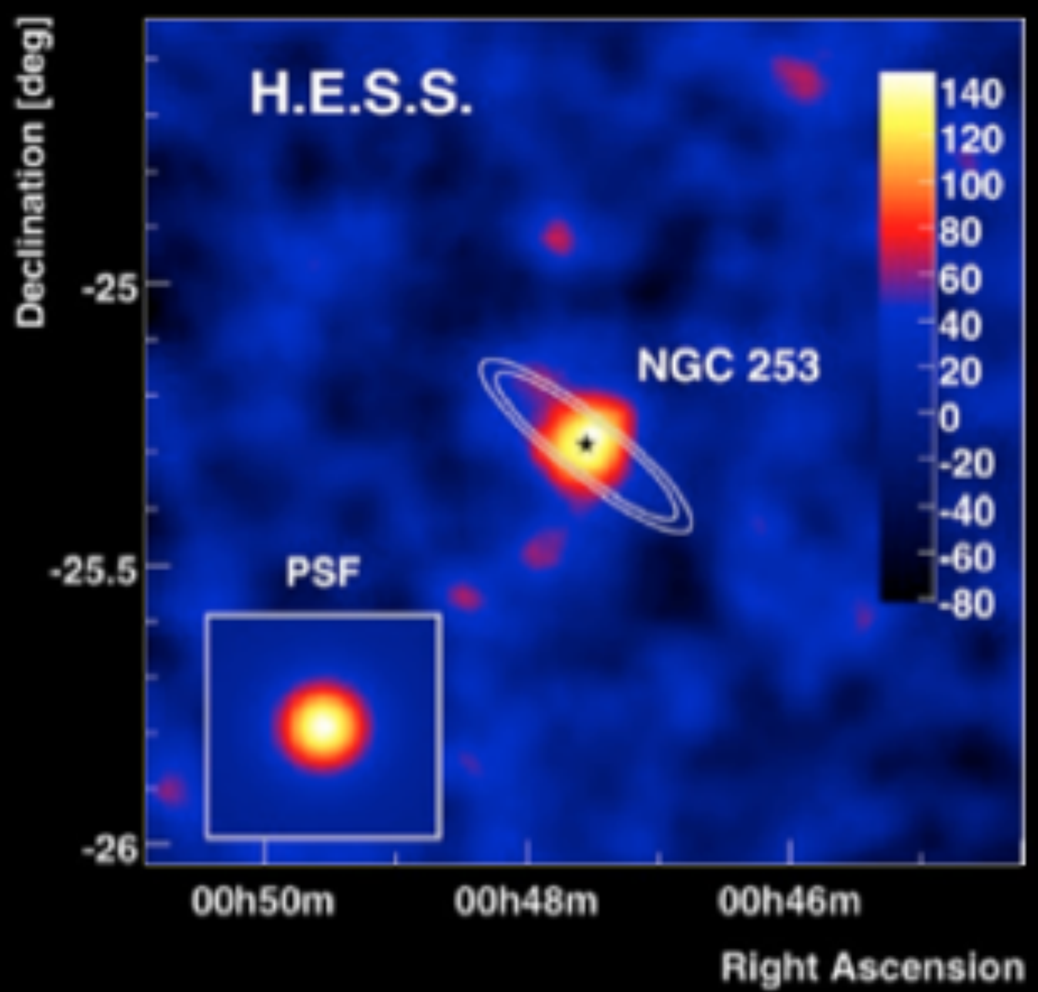
Inject 10% of typical SN energy every 10 years over 10^5 years, see what happens to the SED



→ Nearby SB galaxies (M82 and NGC 253) should be visible with Fermi-LAT and HESS/VERITAS

The “prototypical” TeV Starbursts





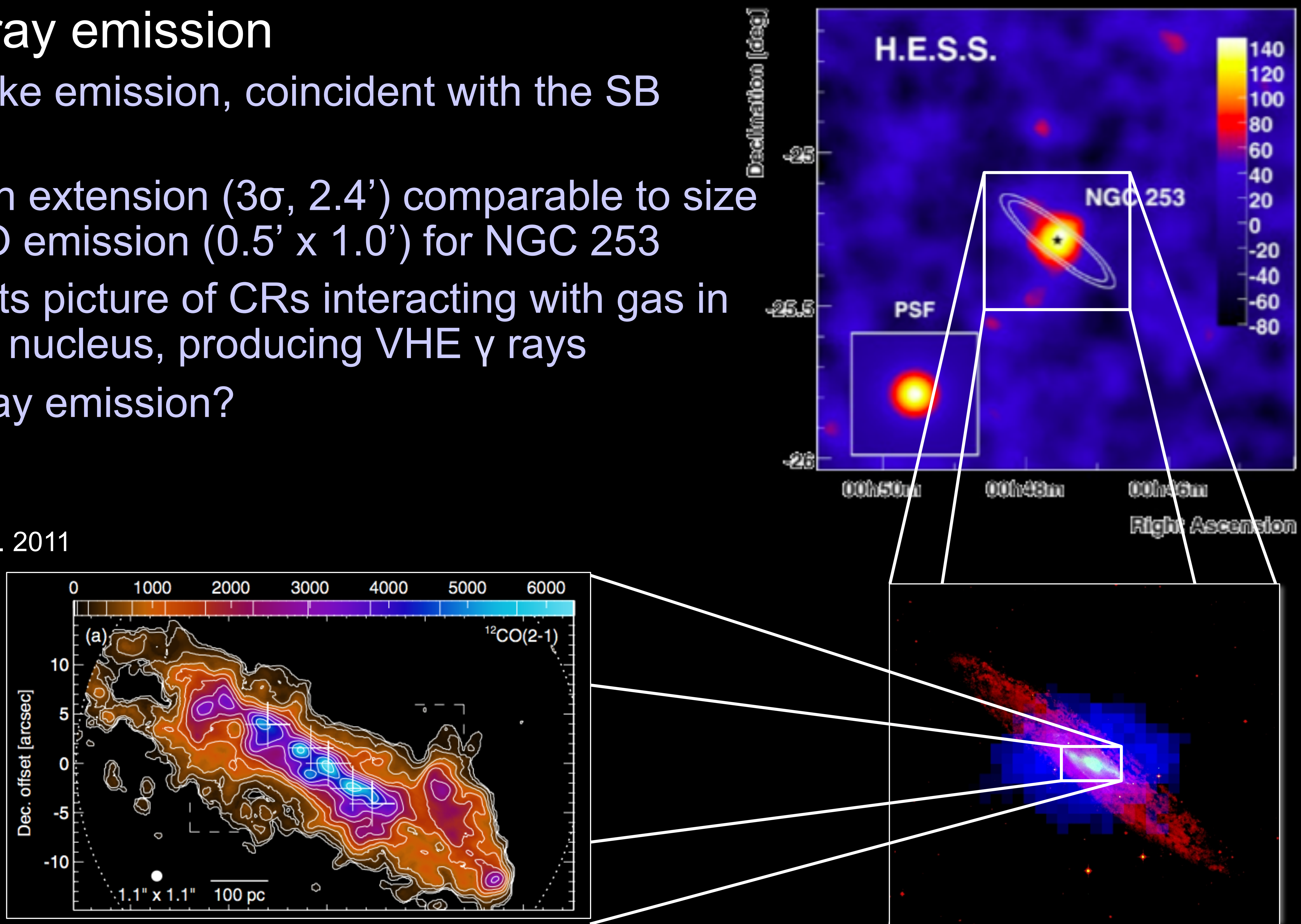
- VHE γ-ray emission
  - Detection of VHE γ-ray emission from the SB galaxies NGC 253 and M82 reported in 2009
  - Flux at a level of 10^{-13} erg cm^{-2} s^{-1}
  - Very long exposures were required to detect the first non-active galaxies in TeV γ rays
  - Weakest VHE γ-ray sources known to date

The “prototypical” TeV Starbursts

Acero et al., 2009

- VHE γ-ray emission
  - Point-like emission, coincident with the SB nuclei
  - Limit on extension (3σ, 2.4’) comparable to size of ^{12}CO emission (0.5’ x 1.0’) for NGC 253
  - supports picture of CRs interacting with gas in the SB nucleus, producing VHE γ rays
  - HE γ-ray emission?

Sakamoto et al. 2011



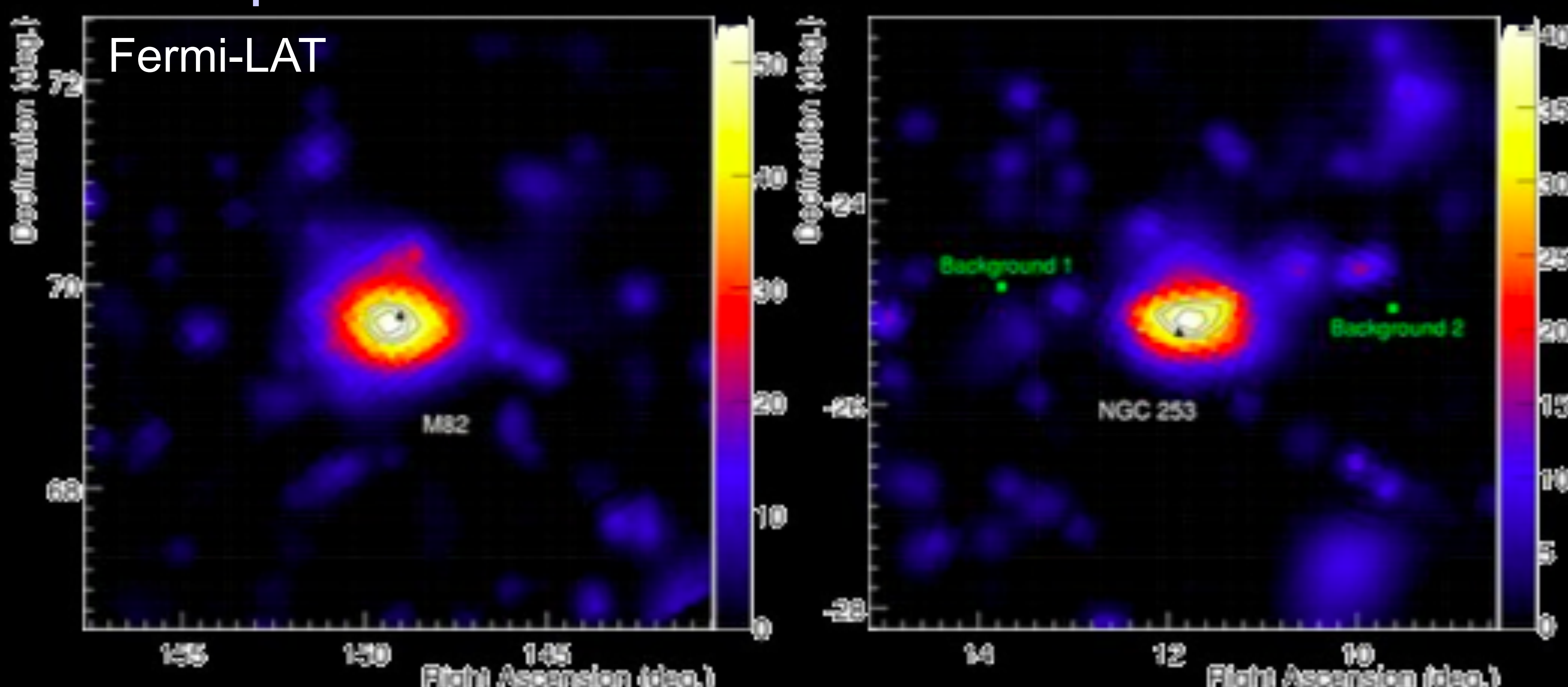
HE γ rays from NGC 253 & M82

- HE γ-ray emission
  - Shortly after H.E.S.S. and VERITAS, Fermi announced detection of both galaxies at GeV energies
  - Also point-like, non-variable emission detected
  - As in the TeV regime, M82 slightly more luminous
  - Both objects very faint – only a few significant points in the spectrum

→ How does the energy spectrum look like?

→ What is the dominant emission mechanism?

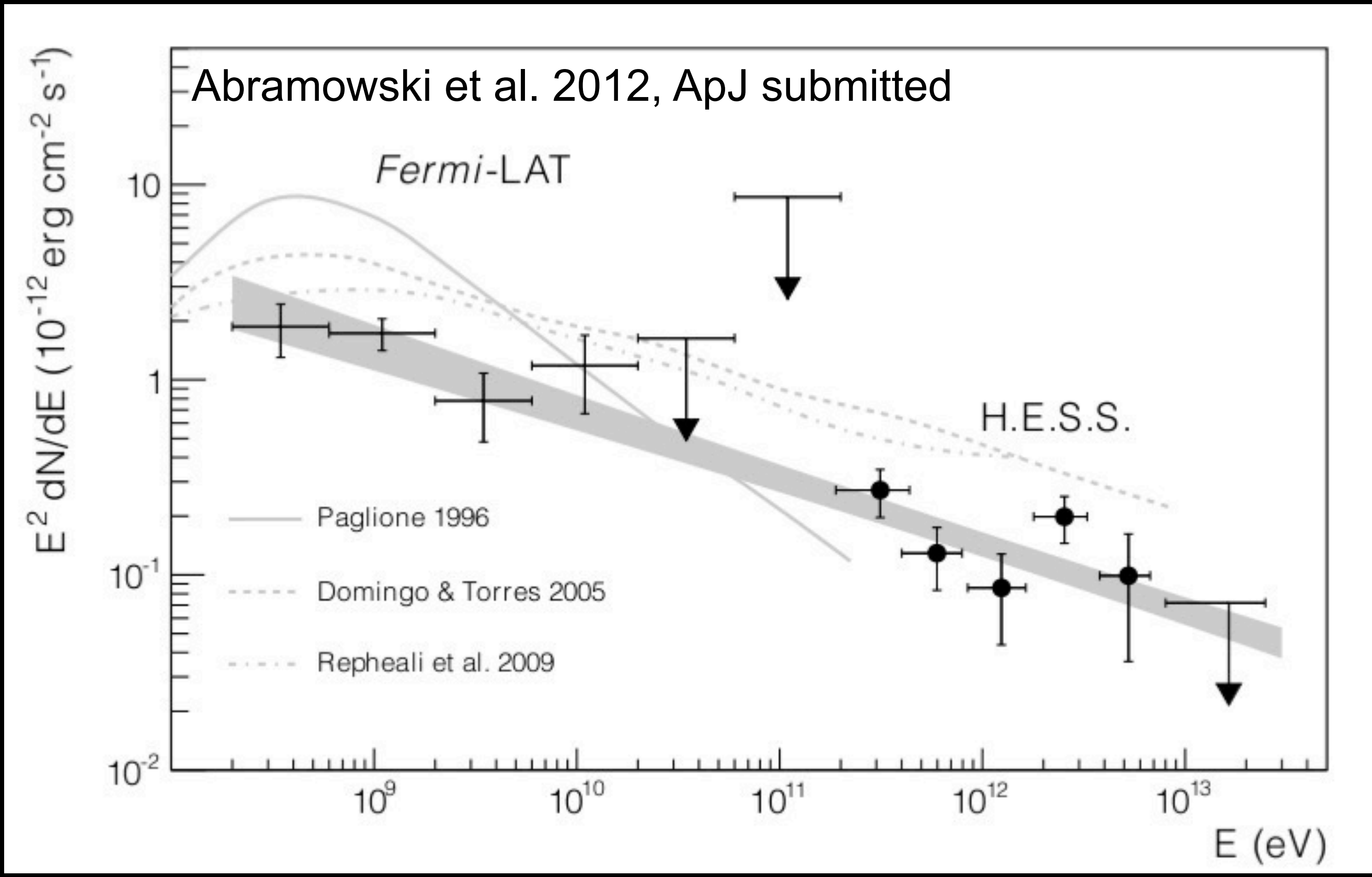
→ Features in the spectrum?



HE and VHE γ rays from NGC 253

- Example of NGC 253
  - ~180 hours of H.E.S.S. data, 30 month Fermi-LAT data set
  - Power law in Fermi and H.E.S.S. range with indices of Γ ~ 2.2 ± 0.2
  - Extrapolation of H.E.S.S. flux to GeV energies and vice versa agrees with data
  - Combined fit gives Γ_c ~ 2.3 ± 0.03 with a 30% fit probability
  - Fit of broken power law results in $\Delta\Gamma$ = 0.1 ± 0.3, compatible with no break

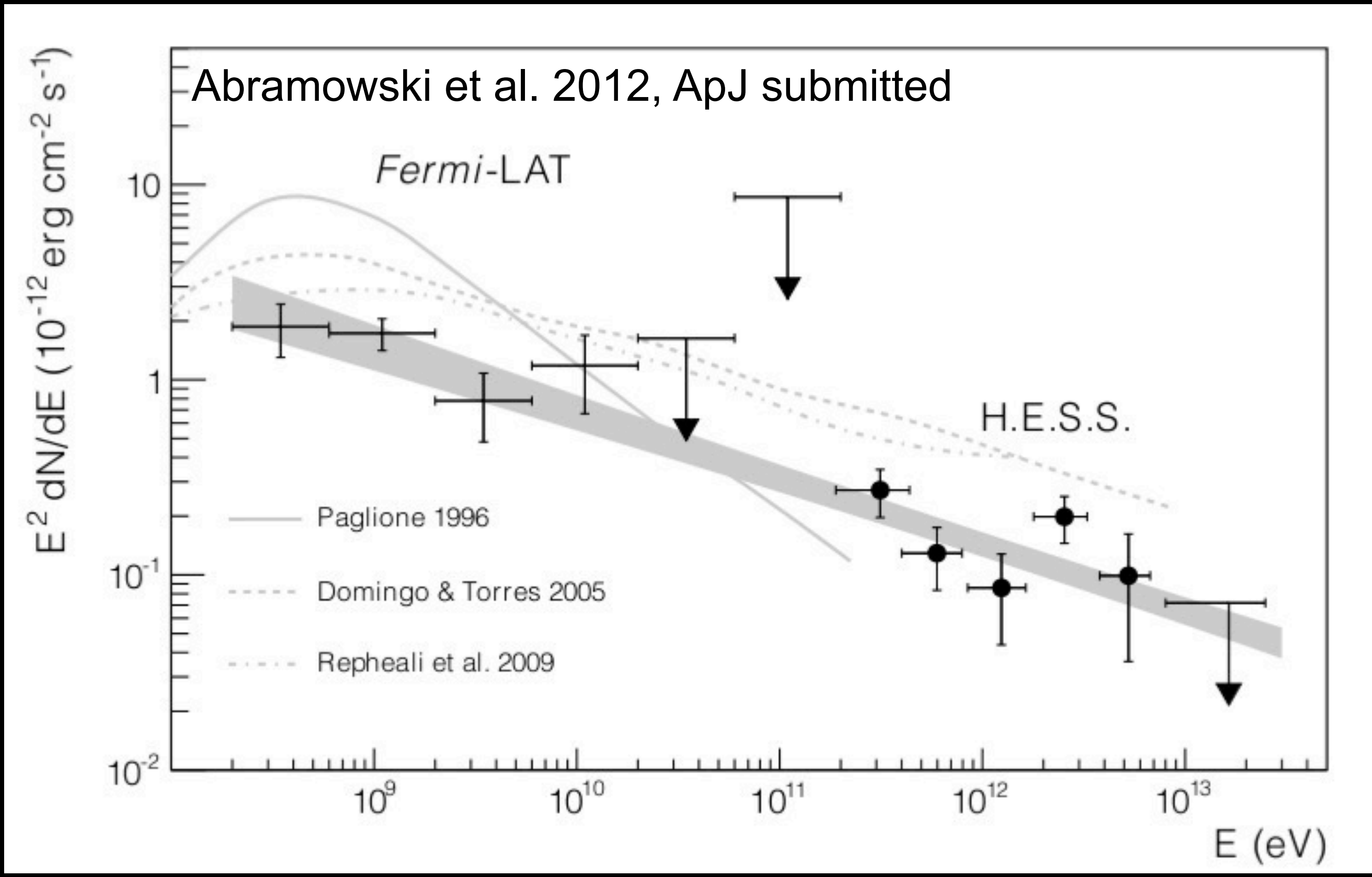
- luminosity of L_γ~8 x 10^{39} erg s^{-1} at 3.5 Mpc distance
- factor 10 more luminous then the Milky Way



HE and VHE γ rays from NGC 253

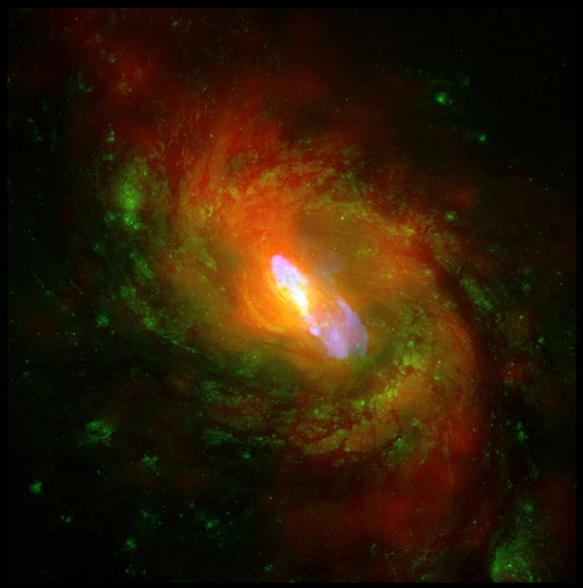
- Implications
  - Roughly compatible with theoretical models (also see Brian's talk)
  - Suggests hadronic origin of emission (electrons cool too fast)
  - ~500 SNe are required to explain emission level
  - Comparison between HE/VHE γ-ray flux and total p-p production rate suggests system is ~20 – 30% calorimetric (assuming canonical values for E_{SN} of 10^{51} erg and $\theta_{SN \rightarrow CR}$ of 10%)

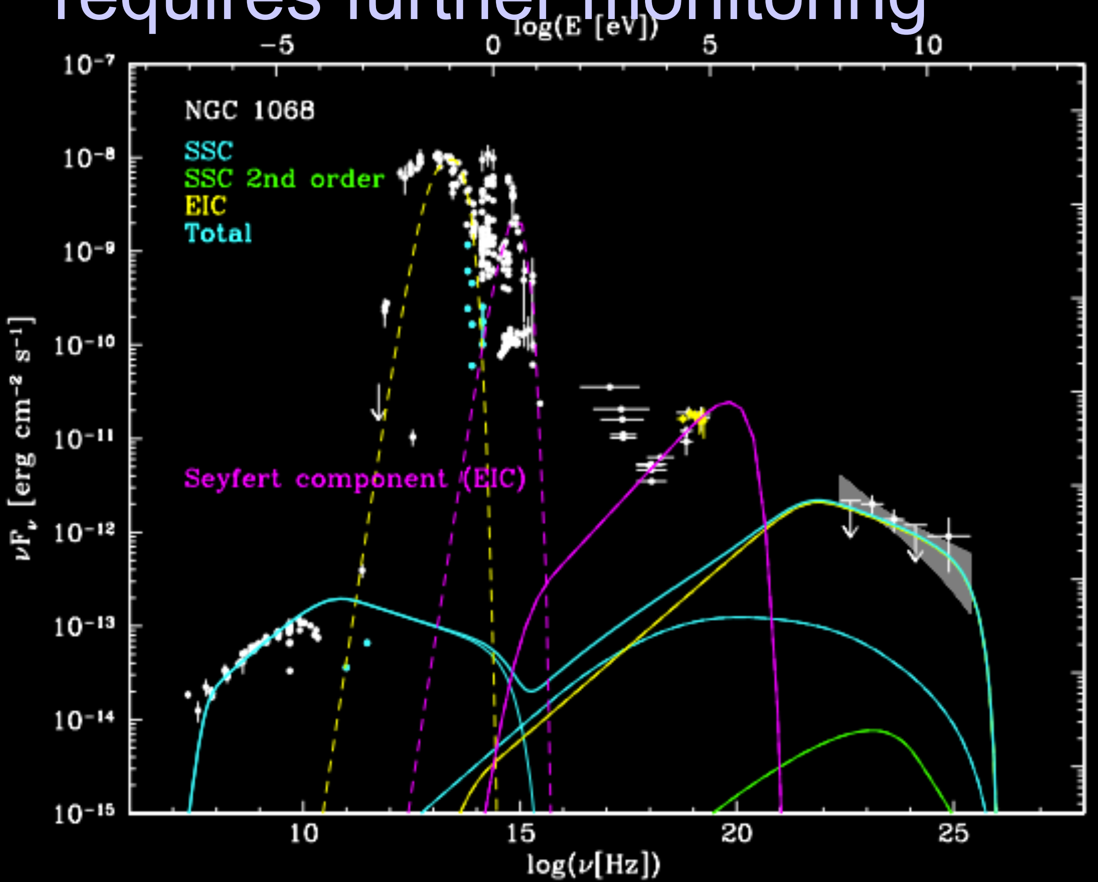
  - Smooth alignment of HE and VHE γ-ray spectrum implies
    - likely dominated by energy-independent transport/loss processes, i.e. advection, adiabatic expansion of the SB region and p-p interaction
    - in this case, γ-ray spectrum would correspond to mean CR source spectrum

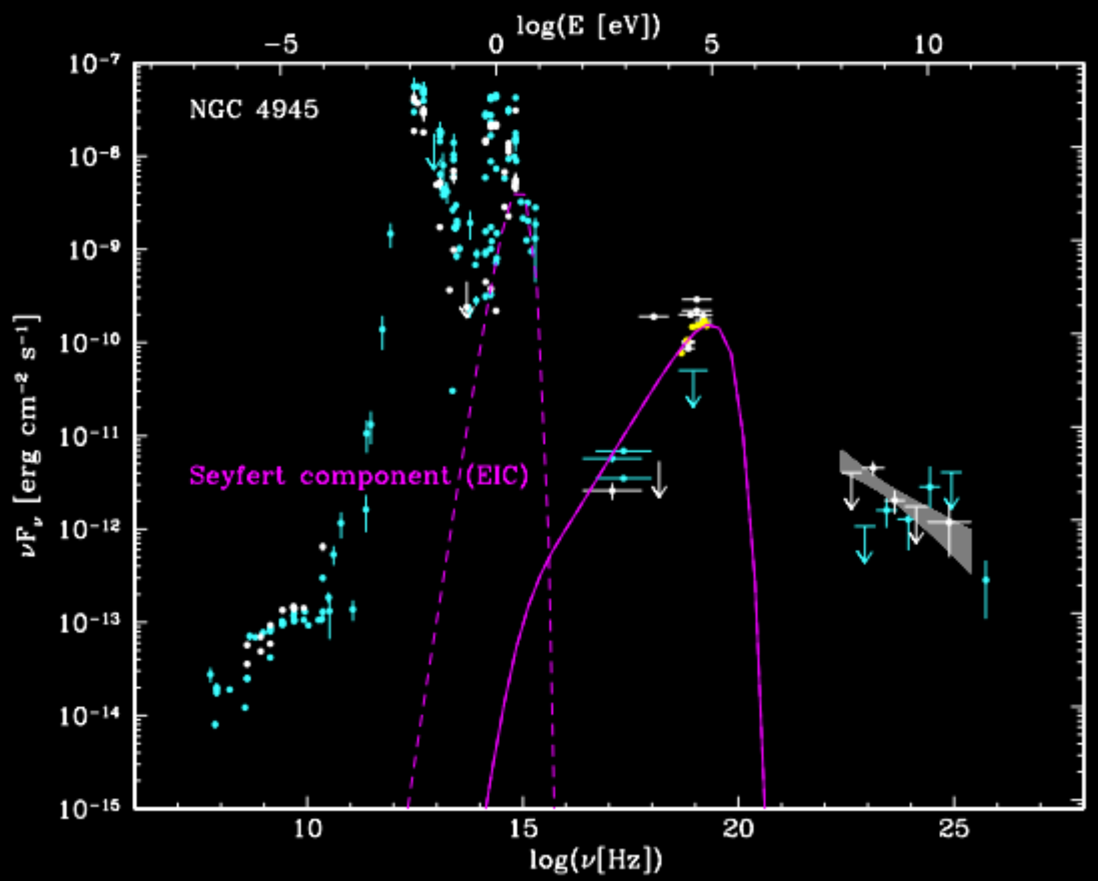


HE and VHE γ rays from other Starbursts?

- NGC 4945 & NGC 1068
  - Seyfert 2 galaxies, but with a Starburst core
  - Both galaxies detected in GeV γ rays (Lenain et al. 2011)
  - No variable signal which would favour AGN activity
  - Emission from NGC 1068 likely dominated by central AGN
  - NGC 4945 not so clear – could be starburst activity
  - No detection at TeV energies reported so far
  - requires further monitoring

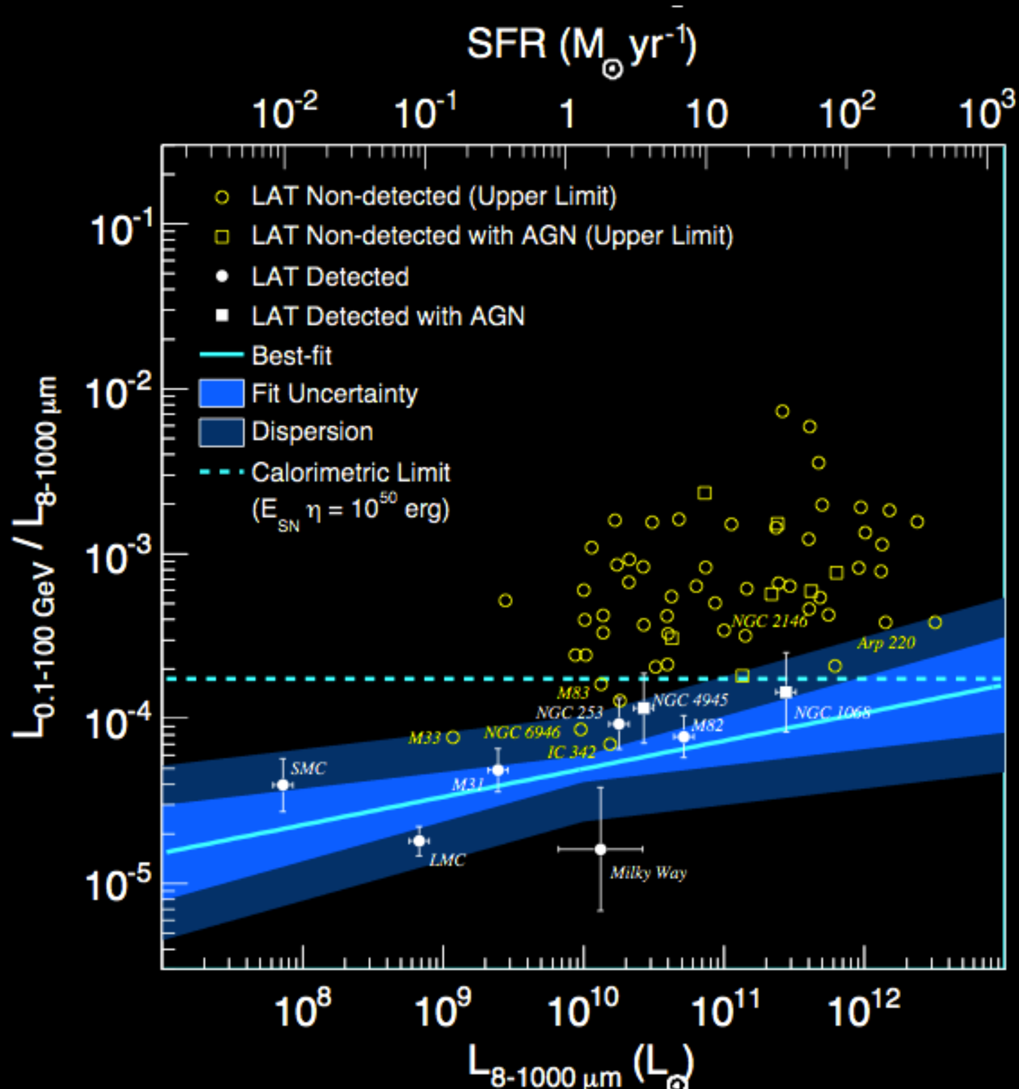


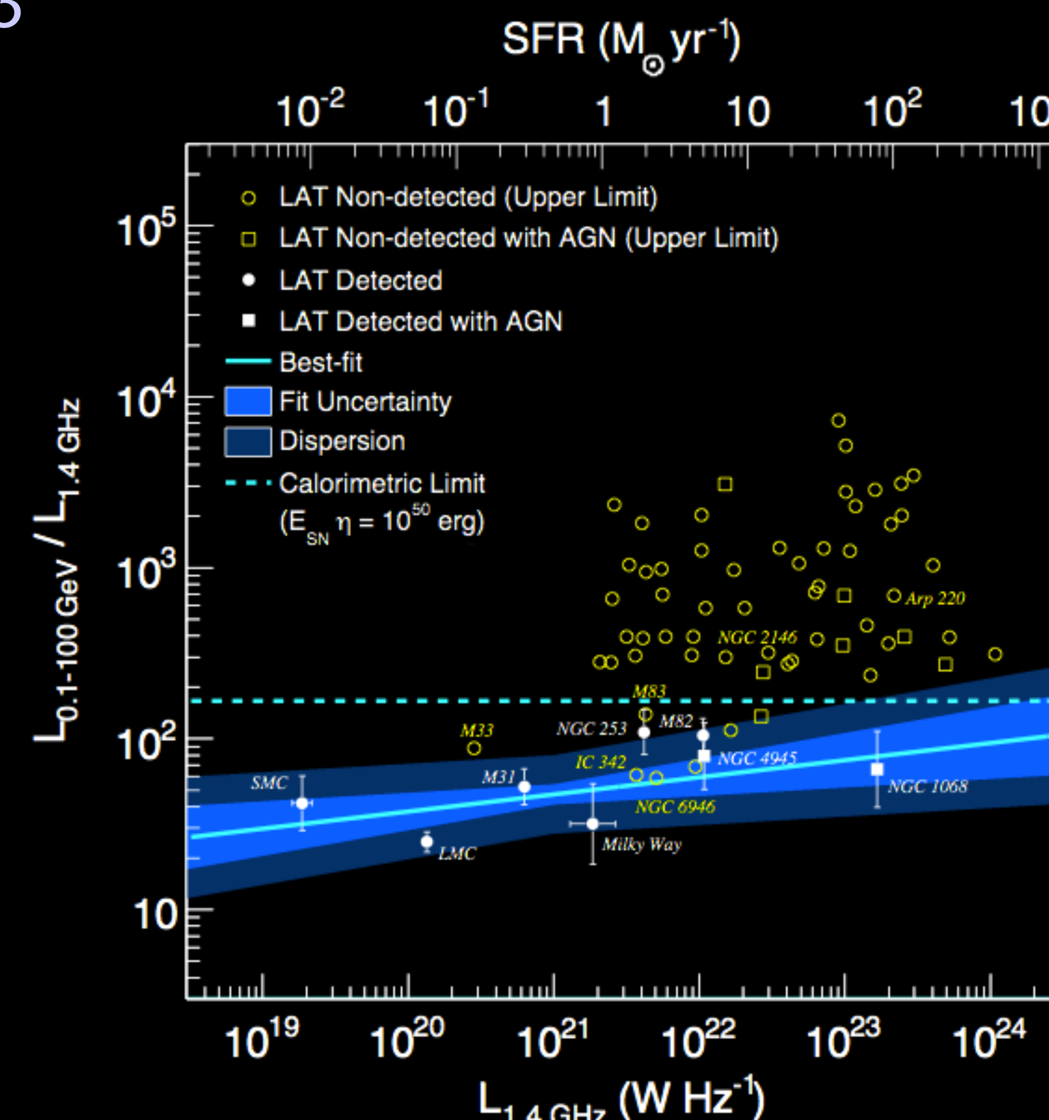




Increasing the sample in HE γ rays…

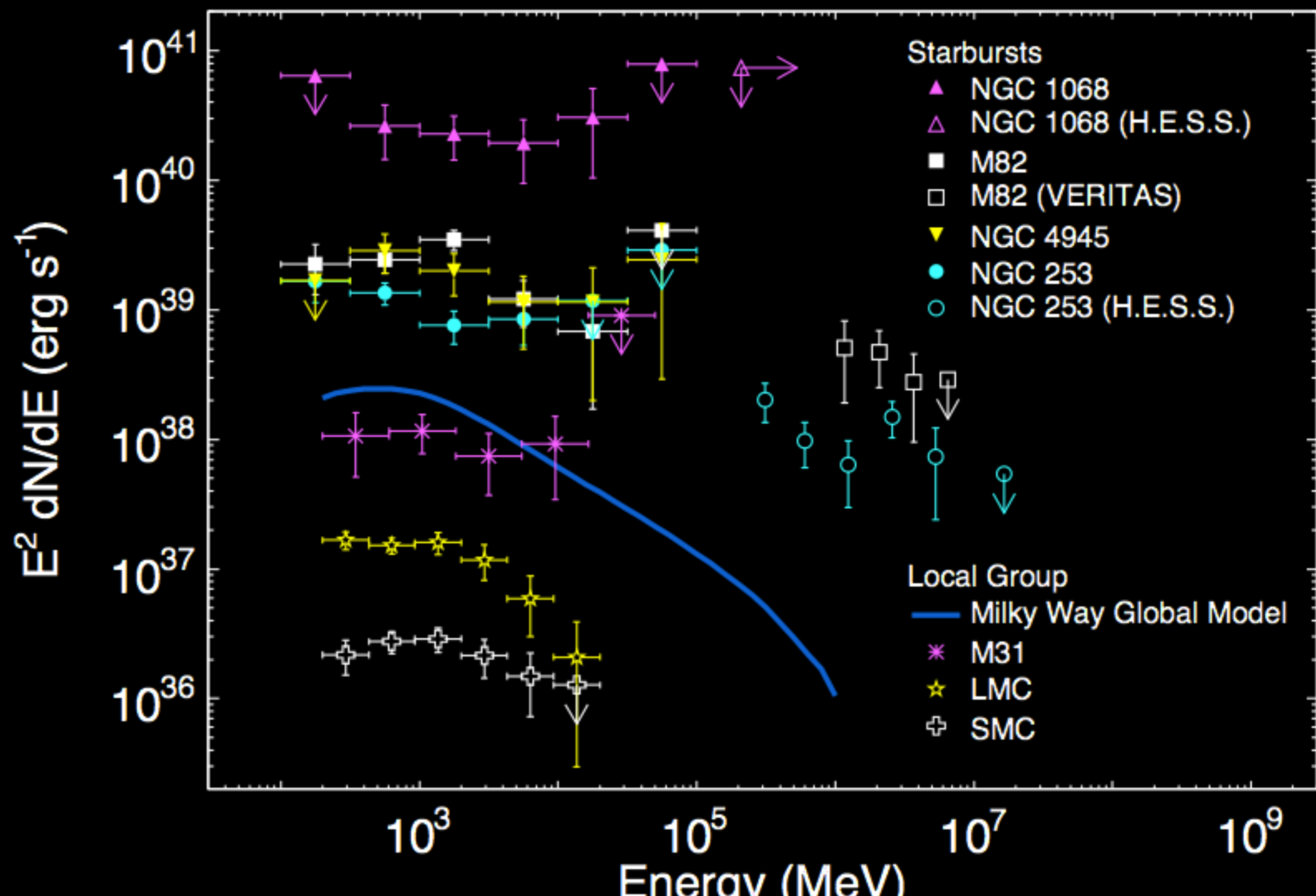
- Recent Fermi publication (arXiv:1206.1346)
  - Search for GeV γ-ray emission in sample of 69 dwarf, spiral, luminous and ultra-luminous galaxies
  - Study the connection between star-formation rate and γ-ray luminosity
  - Find quasi-linear scaling relation between γ-ray luminosity and star-formation indicators, i.e. IR & radio continuum luminosity
  - $\log(L_\gamma/L_{radio})$ = ~ 1.7, $\log(L_\gamma/L_{dust})$ = ~ -4.3,
  - Indication of emission from NGC 2146 & M83

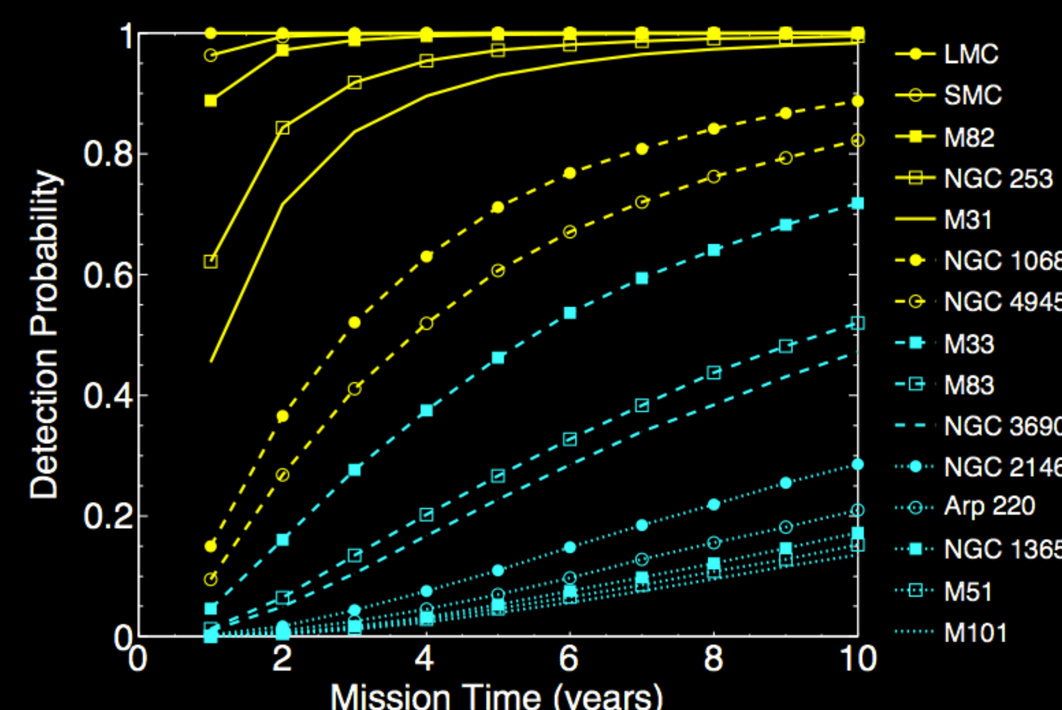




Increasing the sample in HE γ rays…

- Recent Fermi publication (arXiv:1206.1346)
  - Collective intensity of star-forming galaxies with $0 < z < 2.5$ could be 4 – 23% of the isotropic diffuse emission seen by the LAT
  - GeV spectra look remarkably similar
  - Suggestive of a smooth connection between GeV and TeV energies for M82 and NGC 253
  - Extrapolating the simple scaling relation would allow to detect up to 10 external galaxies in total in 10 years





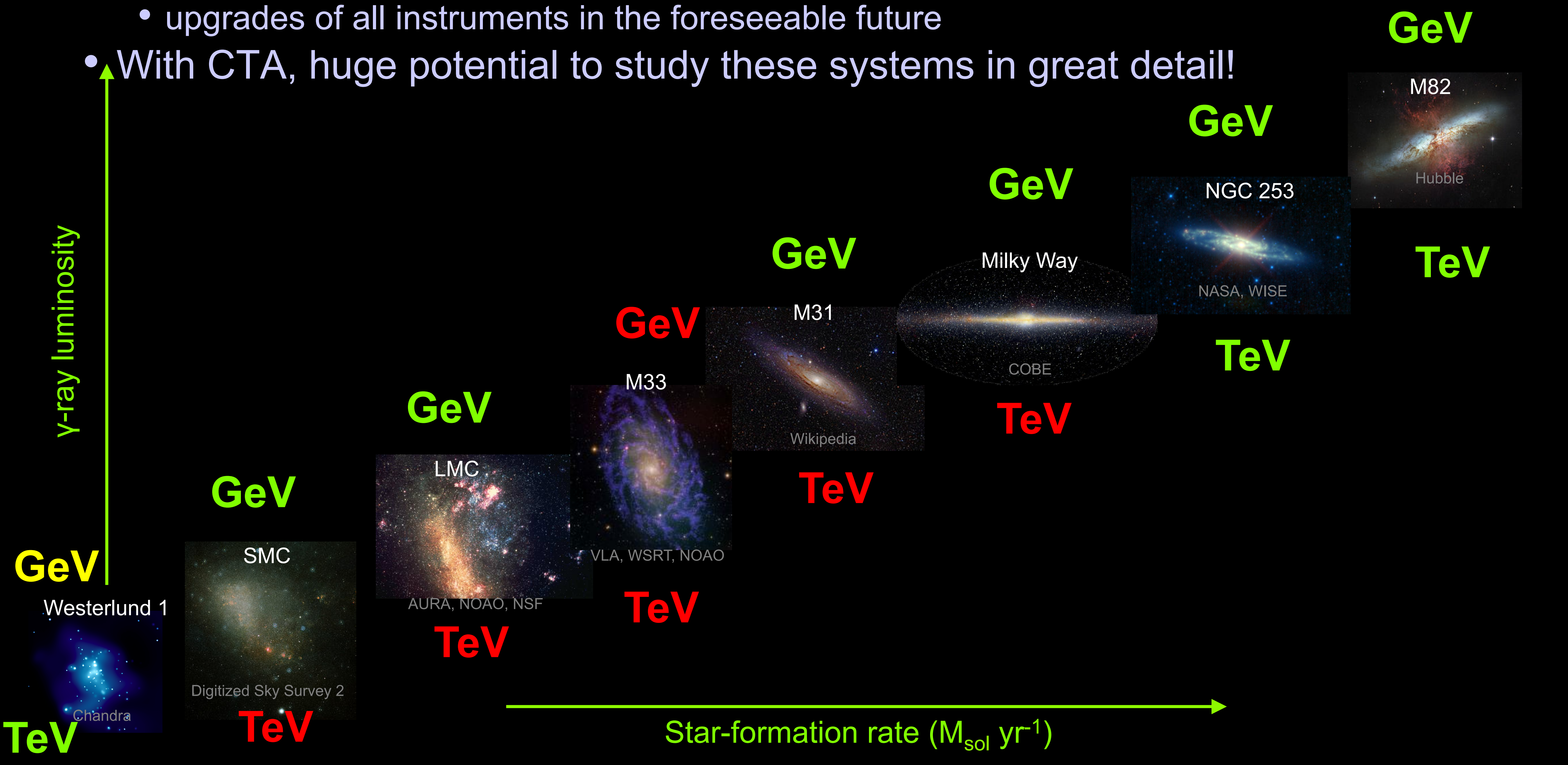
HE VHE γ rays from Starburst galaxies *Implications*

- Interesting implications from the detection/spectra of Starburst galaxies, i.e.
  - Proton calorimetry
  - Leptonic or hadronic dominance
  - CR ionisation
  - AGN contribution
  - Magnetic fields
  - …

→ ***see next talk by Brian Lacki***

HE/VHE γ rays from star-forming environments
The present and future

- Star-formation rate vs γ-ray luminosity
  - Very nice correlation in GeV energies
    - extent to Galactic systems, i.e. superbubbles?
  - Only the tip of the iceberg seen with current generation of IACTs
    - upgrades of all instruments in the foreseeable future
  - With CTA, huge potential to study these systems in great detail!



Backup

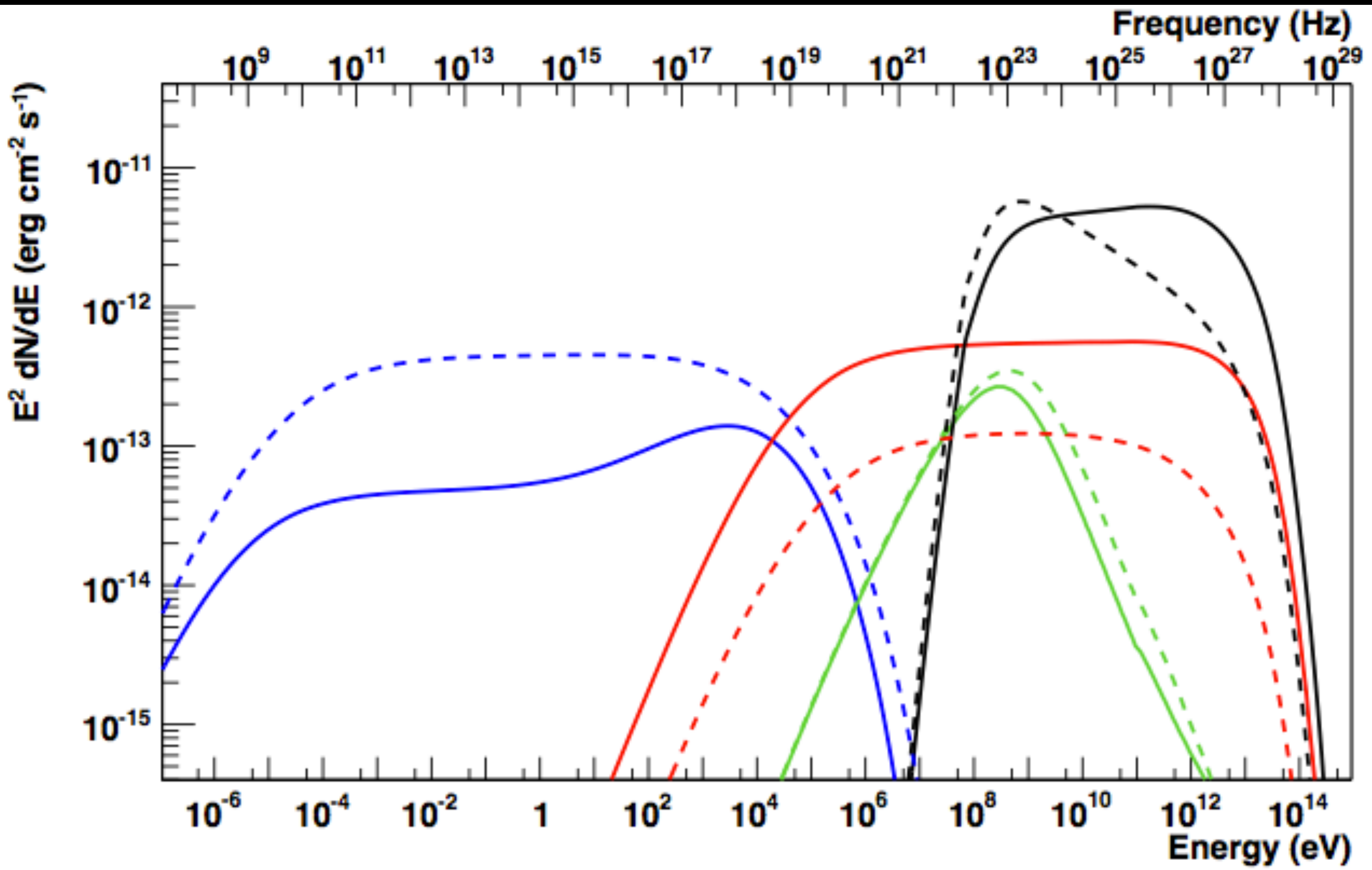


Figure 1. Simple model SED for a representative starburst region at a distance of 3.5 Mpc. Colours indicate the contributions of IC (red), synchrotron (blue), Bremsstrahlung (green) and π^0-decay (black) in a single-zone, time-dependent model for the continuous injection of electrons and protons over 2×10^5 yr. For the solid lines (model 1), a magnetic field strength of $B = 100\,\mu$G, a radiation field energy density of $U_{\rm rad} = 2500$ eV of a black-body with temperature 50 K, and an average density $n_{\rm H}$ of 250 particles per cm^3 are assumed. The energy input is 3×10^{40} erg s^{-1} for electrons and an order of magnitude higher for protons. An injection spectrum index of $\alpha = 2.0$ and maximum accelerated particle energy of $E_{\rm max} = 100$ TeV are used for this model. Dashed lines (model 2) illustrate the effect of reducing $U_{\rm rad}$ by a factor of 10 and doubling the magnetic field strength. A proton spectral index of 2.3 is used in this second case. A colour version of this figure is available online (Ohm & Hinton (2012)).

HE/VHE γ rays from star-forming environments
The future

- The Cherenkov Telescope Array aims for
  - order of magnitude better sensitivity at all energies
  - extending the covered energy range at low and high energies (opening up a completely unexplored window at >50 TeV
  - a factor 5 better resolution than current instruments
  - larger field-of-view (5 degrees for LSTs, 8 – 9 deg for MSTs & SSTs
  - first light with a pathfinder mini array in 2015/16(?)