

宇宙ガンマ線を用いた 宇宙線と星間ガスの研究

2015年7月29日

天文・天体物理夏の学校

@長野(信州・戸倉上山田温泉)

水野 恒史

(広島大学宇宙科学センター)

Fermi-LAT Collaboration

目次

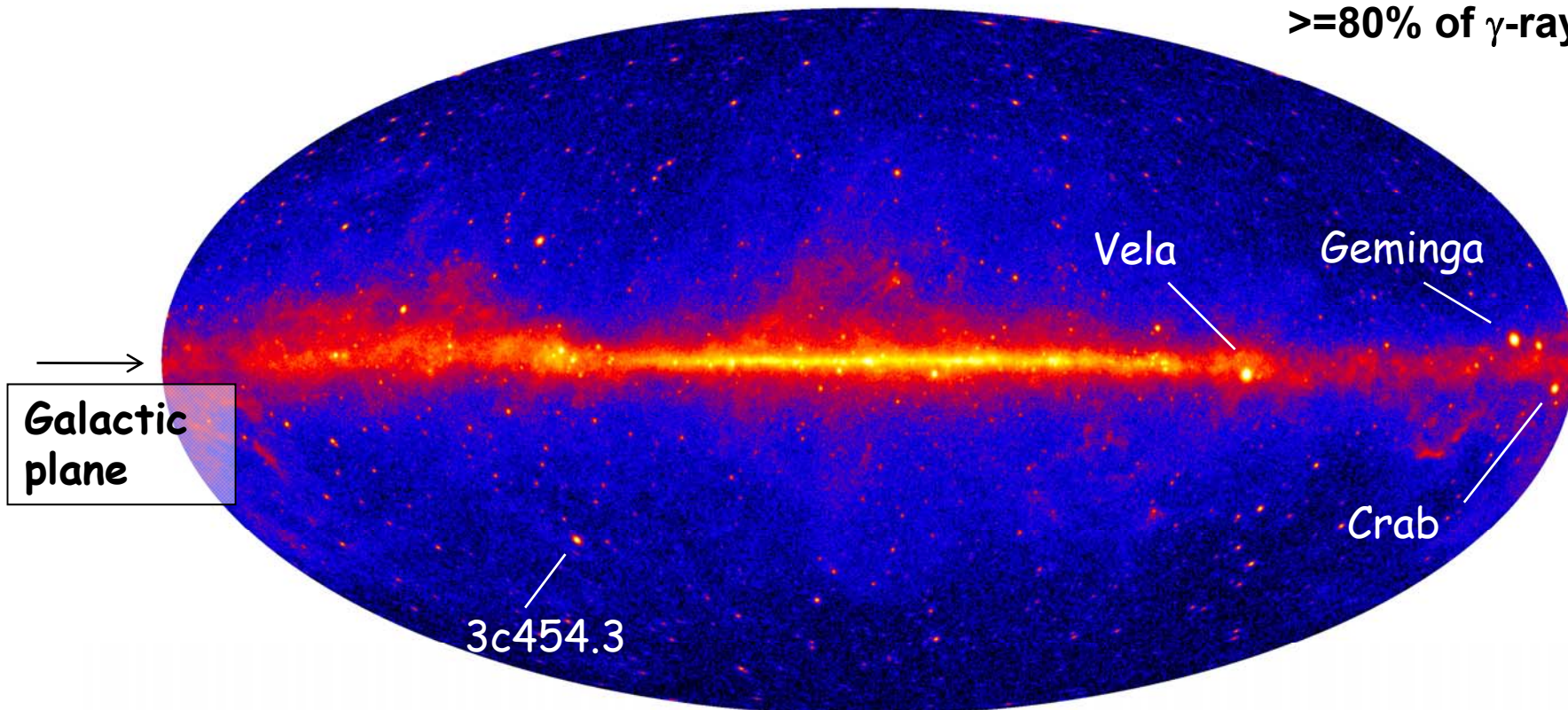
- 導入：星間空間の構成要素, およびガンマ線による宇宙線と星間ガスの探査
- Fermi-LATによる成果1: 比較的よく理解されている事から
- Fermi-LATによる成果2: まだ良くわかっていないこと, 今後の課題

- GeVガンマ線全天マップ

このガンマ線マップ(広がった放射)を理解できればOK

= ガンマ線点源 + 広がったガンマ線

$\geq 80\%$ of γ -rays



Fermi-LAT 4 year all-sky map (>1 GeV)

天の川銀河の構成要素

- 星+星間媒質

- 分子ガス
- 中性原子ガス
- 電離ガス
- ダスト
- 星間光子
- 星間磁場
- 宇宙線

- 星は星間ガスから生まれる
- 星間ガスを含む星間媒質は互いに影響を及ぼす



- 星形成や星間現象の理解には、多波長観測・理論研究・地上実験・宇宙線の直接観測などを用いた総合的研究が必要

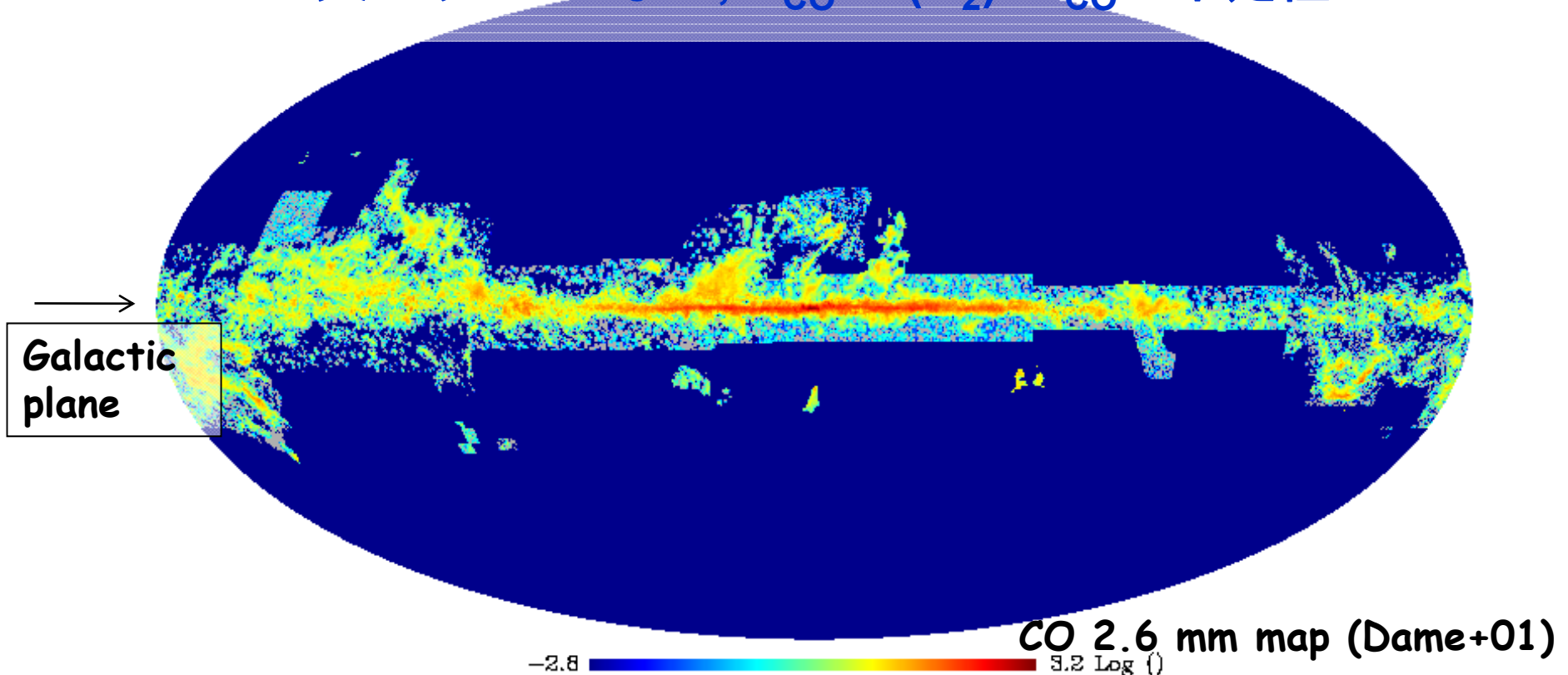
分子ガス

- 星の材料, scale height~70 pc
- CO輝線などでトレースする

典型的に

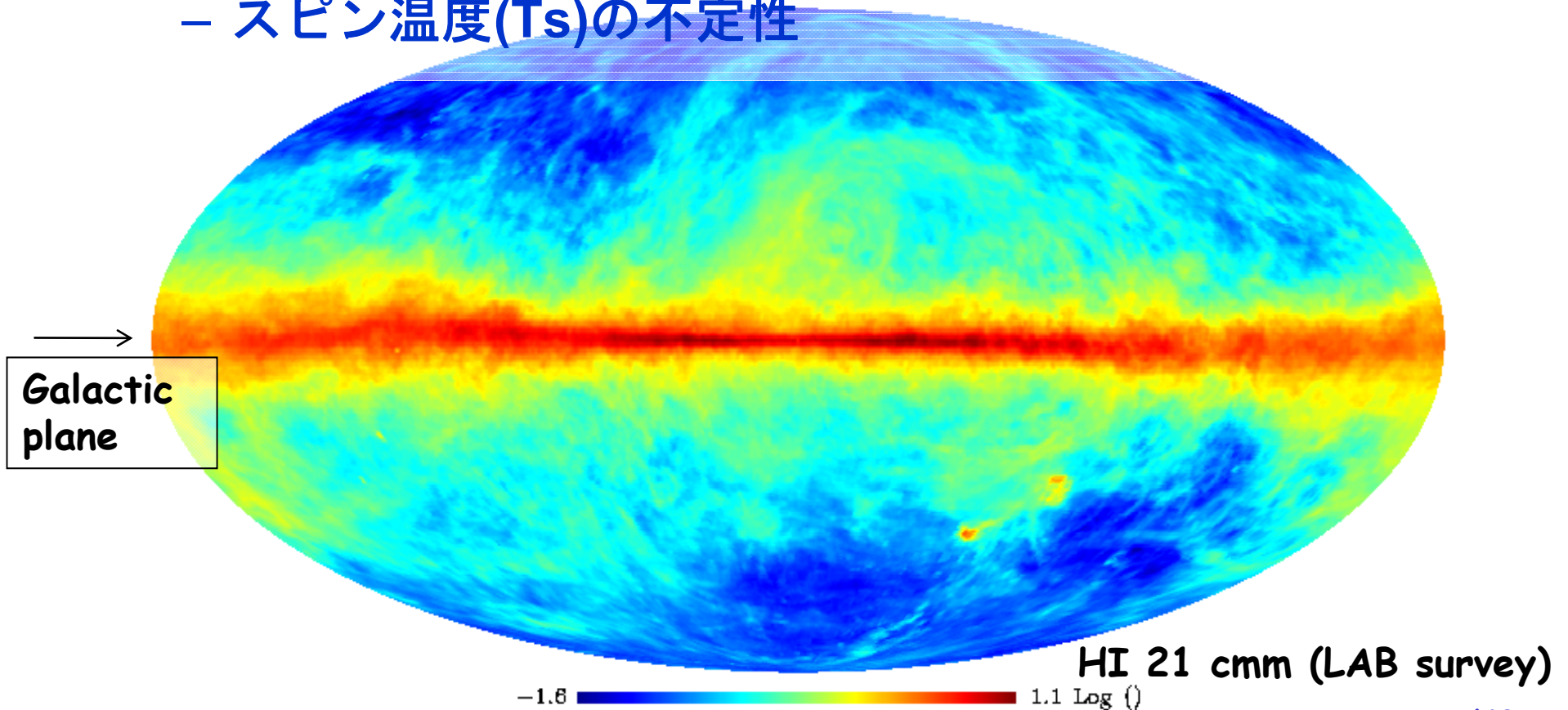
$$X_{\text{CO}} \sim 2 \times 10^{20} \text{ cm}^{-2} / (\text{K km/s})$$

– “全天マップ”がない, $X_{\text{CO}} = N(\text{H}_2) / W_{\text{CO}}$ の不定性



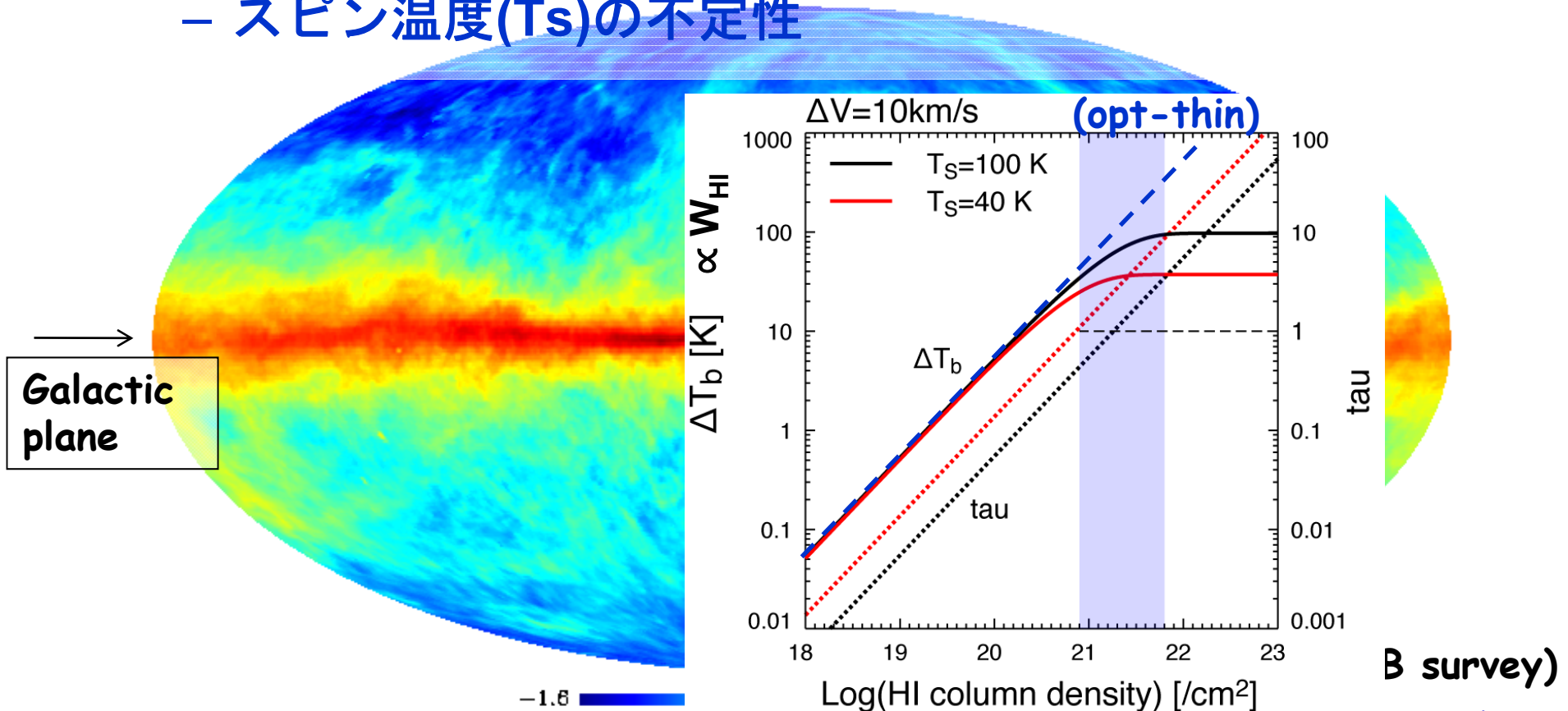
中性原子ガス

- 星間ガスの主成分, scale height~200 pc
- 21 cm線でトレースする
 - スピン温度(T_s)の不定性



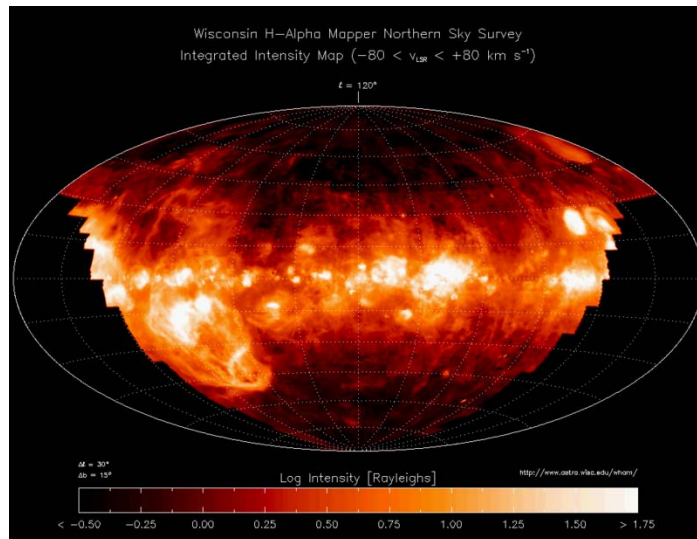
中性原子ガス

- 星間ガスの主成分, scale height~200 pc
- 21 cm線でトレースする
 - スピン温度(T_S)の不定性

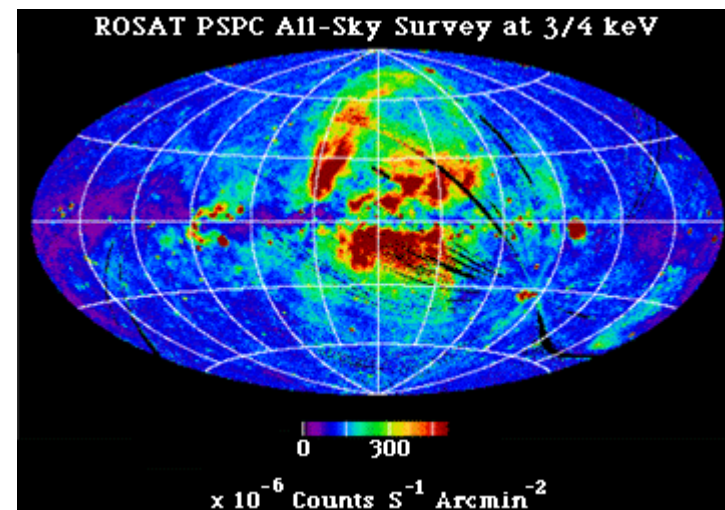


B survey)

- “Warm” ionized medium ($T \sim 10^4$ K)
 - 大質量星回りのHII領域+広がった電離ガス(scale height ~ 1 kpc).
H α 線やpulsar dispersion measureでトレース
- “Hot” ionized medium ($T = 10^5 - 10^6$ K)
 - scale height ~ 4 kpc. 軟X線や電離した重元素の吸収線でトレース



Wisconsin H α map

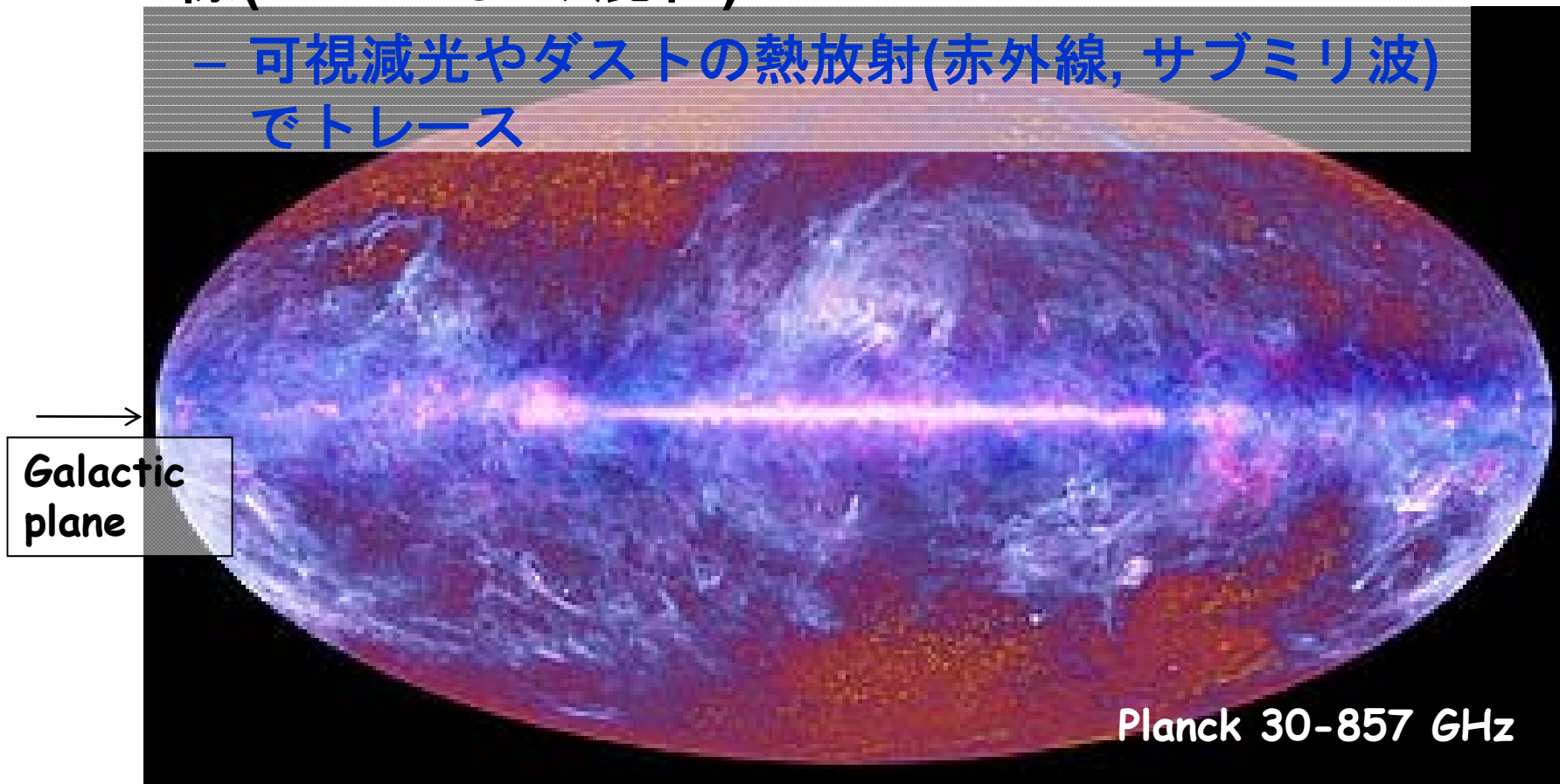


ROSAT 3/4 keV map

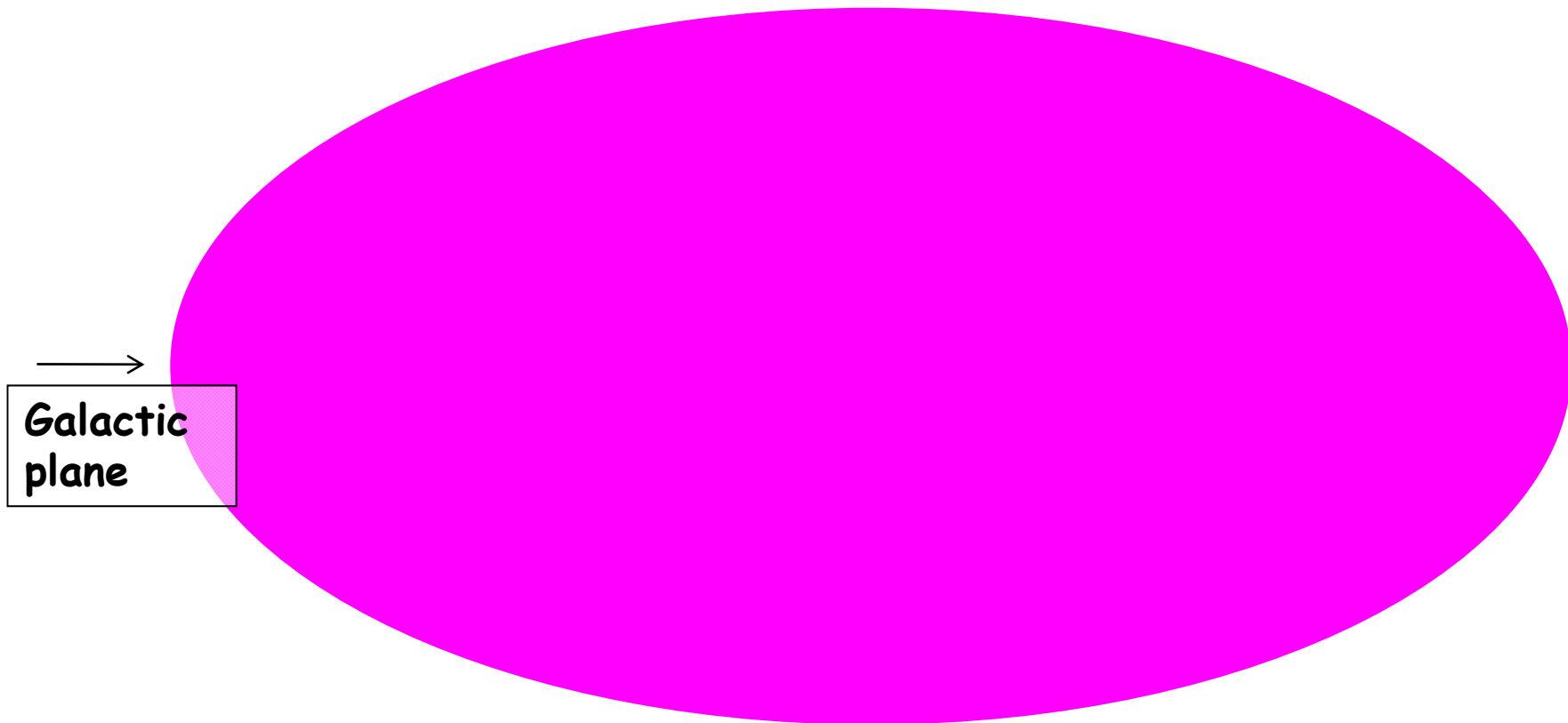
星間ダスト

- 星間分子形成の触媒, 星間ガス密度のよい指標(ガスとよく混在)

– 可視減光やダストの熱放射(赤外線, サブミリ波)でトレース

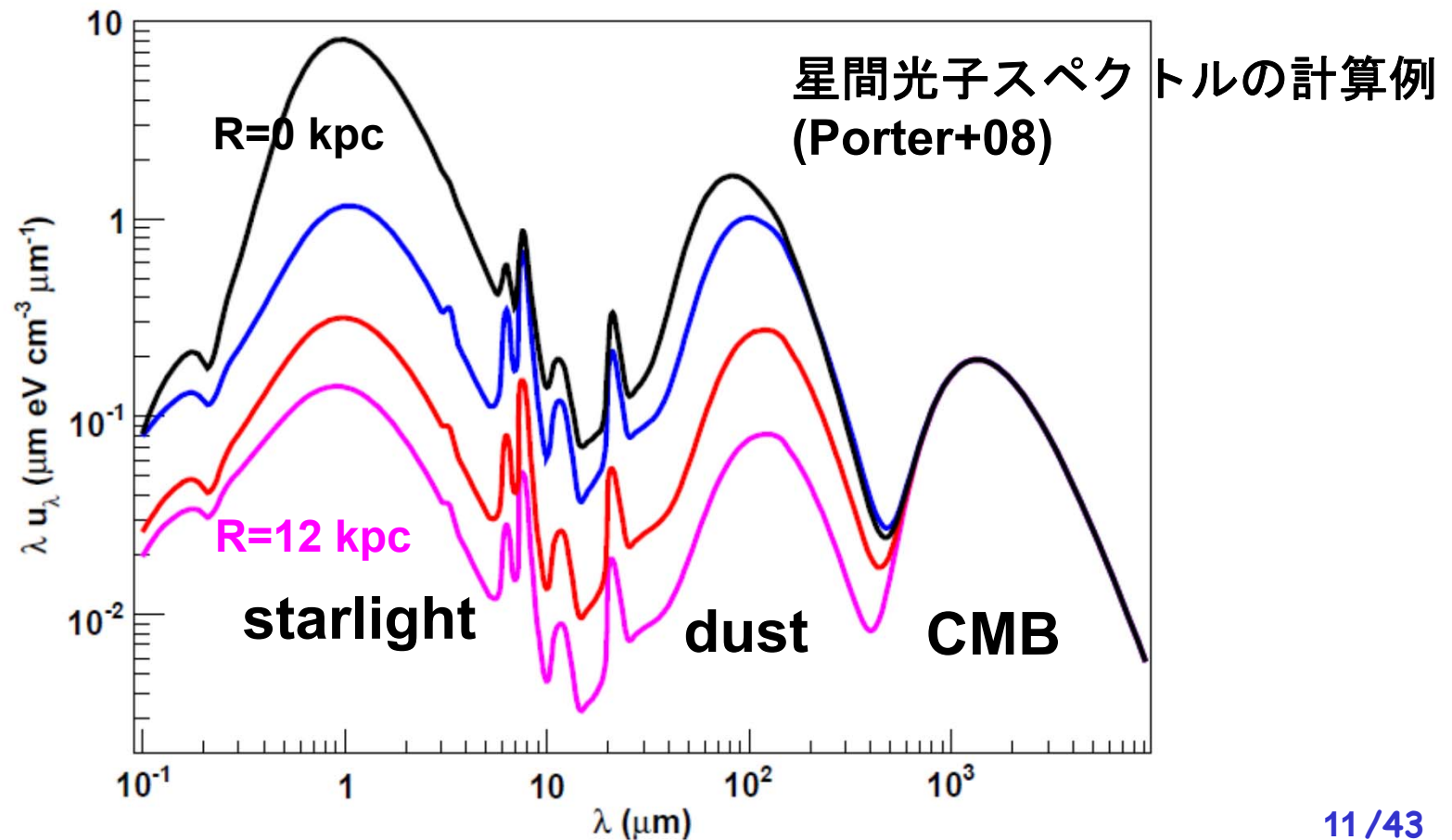


- Radio(CMB), Infrared(ダストの熱放射),
Optical(星の光)



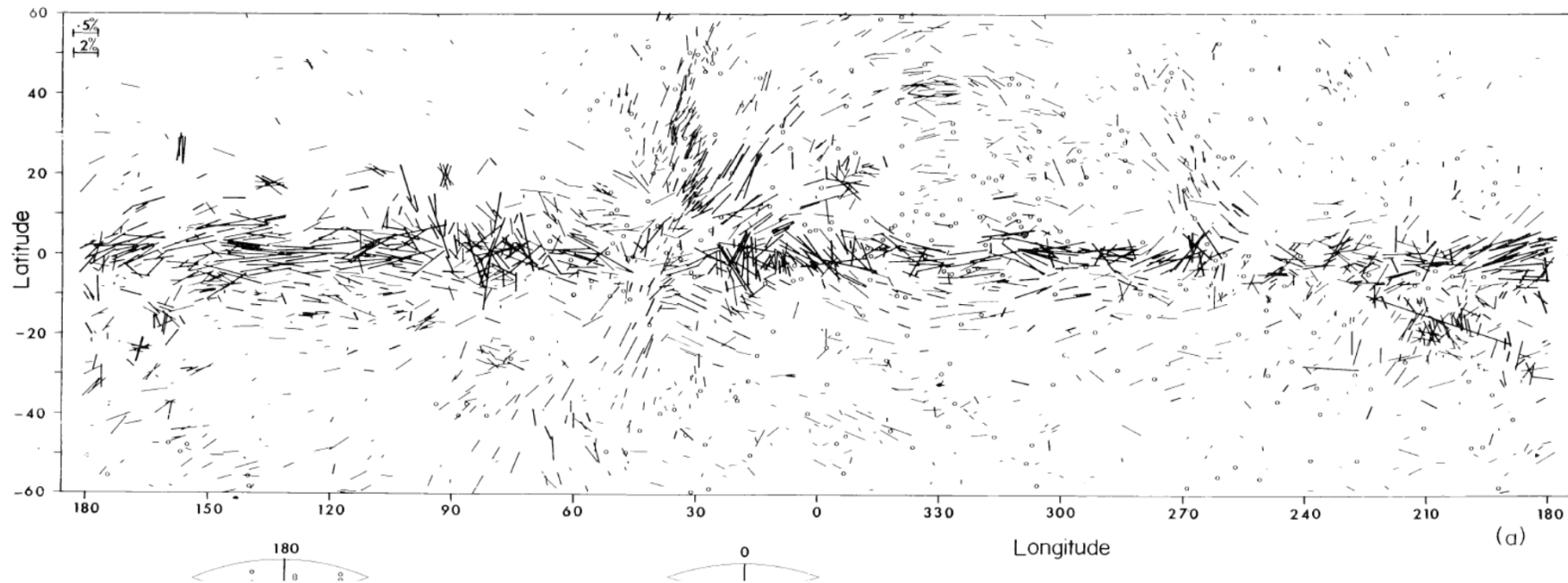
CMB ($T=2.73$ K) map???

- Radio(CMB), Infrared(ダストの熱放射), Optical(星の光)



星間磁場

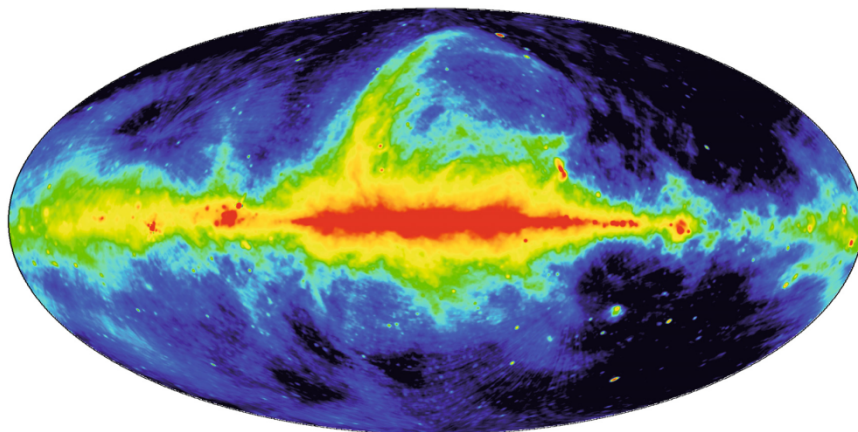
- 数 μG の磁場が存在. 宇宙線/星間磁場/星間ガスの間で力のやりとり, 宇宙線の伝播
 - 星間偏光(ダストの整列が起源)でトレース



Mathewson&Ford 70

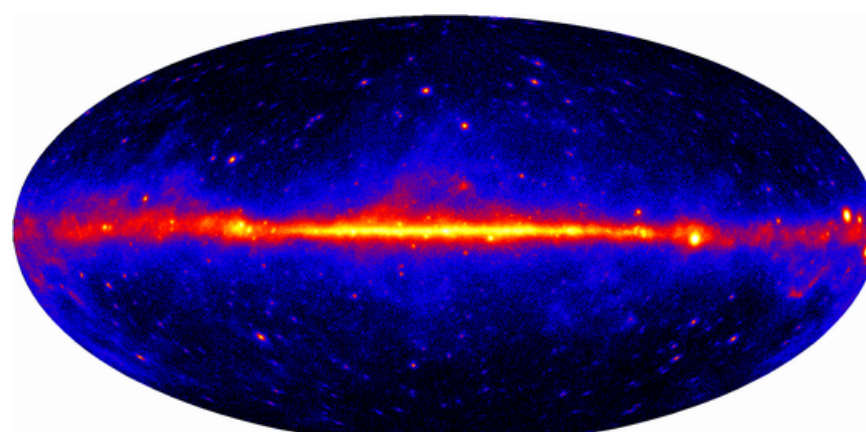
- 星間空間を飛び交う相対論的高エネルギー粒子
 - 超新星残骸で作られ, 星間空間を伝播
 - 星間磁場を介して星間ガスと力のやりとり, 星間ガスの電離(天の川銀河の主要な構成要素)
 - 星間磁場, 星間光子, 星間ガスと相互作用して電磁波を出す(シンクロトロン, 逆コンプトン, 制動放射, 核子-核子反応)

408 MHz



408 MHz radio map

(宇宙線電子×星間磁場のシンクロトロン放射)



Fermi GeV gamma-ray map

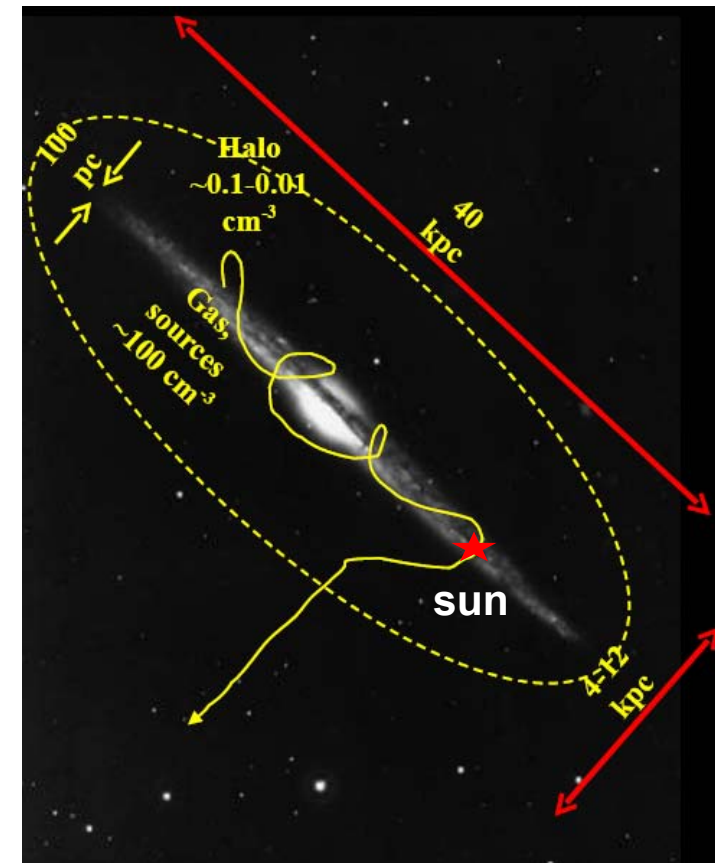
(宇宙線陽子×星間ガスの核子-核子反応)

宇宙線のエネルギー収支/起源

- 銀河円盤(宇宙線ハロー): 半径 ~ 10 kpc, 厚み ~ 4 kpc \Rightarrow
 $V_{\text{gal}} \sim 3 \times 10^{67} \text{ cm}^3$
- 宇宙線のエネルギー密度: $\mu_{\text{CR}} \sim 1 \text{ eV/cm}^3$
- 閉じ込め時間 τ は $\sim 10^7 \text{ yr} \sim 3 \times 10^{14} \text{ s}$ (宇宙線中の放射性同位体の観測から)
 - $P_{\text{CR}} = \mu_{\text{CR}} \times V_{\text{gal}} / \tau \sim (5 \times 10^{55} \text{ erg}) / (3 \times 10^{14} \text{ s}) \sim 10^{41} \text{ erg/s}$
を宇宙線に与える必要
- 超新星爆発が物質に与えるエネルギー: $\sim 10^{51} \text{ erg}$
- 超新星爆発の頻度: $1/30 \text{ yr} \sim 1/10^9 \text{ s}$
 - $P_{\text{inj}} \sim (10^{51} \text{ erg}) / (10^9 \text{ s}) \sim 10^{42} \text{ erg/s}$ の10%が宇宙線加速に使用すれば説明可能。超新星起源説の根拠

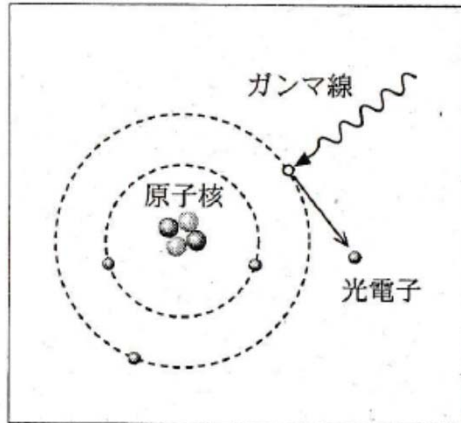
宇宙線の伝播

- 磁場による不規則な散乱
 - 拡散運動で星間空間を伝播
 - 閉じ込め領域の端から逃げ出す
- 電子は伝播中にエネルギー損失
 - 電離や放射
- 陽子は核子-核子反応
 - 組成の変化、ガンマ線の放射

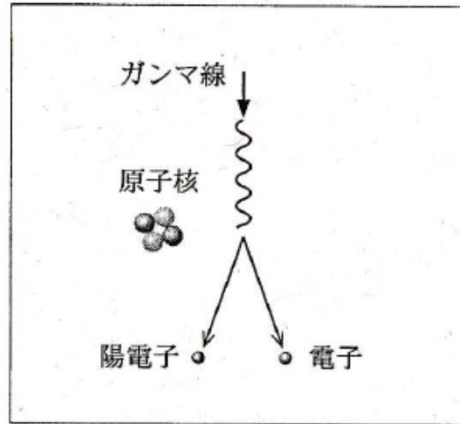


加速源でのスペクトル・組成に伝播中の変調を加味したものが、観測された宇宙線となる

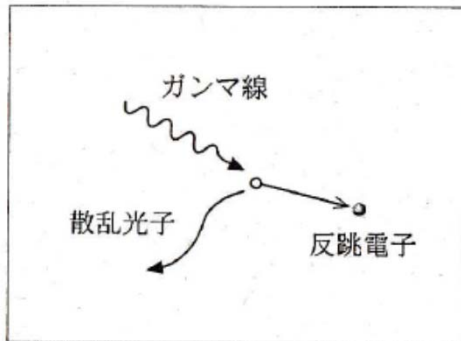
ガンマ線と物質の相互作用



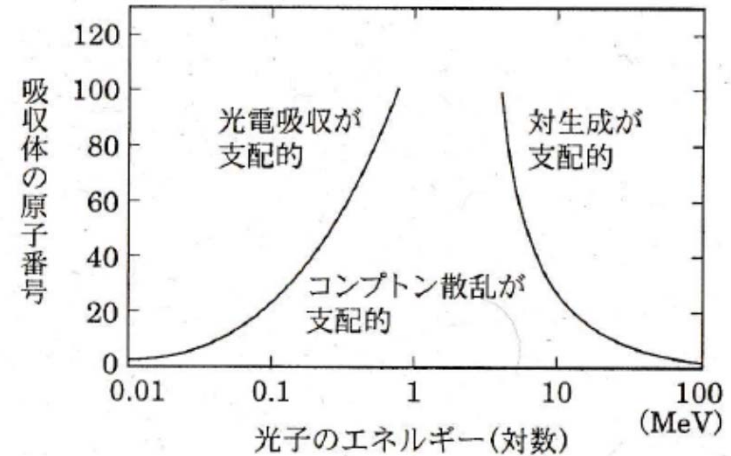
光電吸収



対生成



コンプトン散乱



現代の天文学17 「宇宙の観測III」

$$\lambda_{\text{pair}} \sim (9/7)L_{\text{rad}} \\ \sim 80 \text{ g/cm}^2 \\ \sim 500 \times 10^{23} / \text{cm}^2 \text{ (for pure H)}$$

(GeVガンマ線は対生成を用いて測定)

ガンマ線に対しては銀河面もほぼ完全に透明

**ガンマ線は天の川銀河の宇宙線および星間ガスを
探る強力なプローブ**

ガンマ線による宇宙線・星間ガスの探査

- $\mu_{CR} \sim 1 \text{ eV/cm}^3$ によるガンマ線放出率(主に陽子の反応)

$$Q_{\gamma}(>100\text{MeV}) \sim 1.6 \times 10^{-26} \text{ ph/s/sr/H-atom}$$

$$\sim 1.5 \times 10^{-28} \text{ erg/s/H-atom}$$

- 期待されるガンマ線光度

$$L_{\gamma}(>100\text{MeV}) \sim (M_{\text{gas}}/m_p) * Q_{\gamma}$$

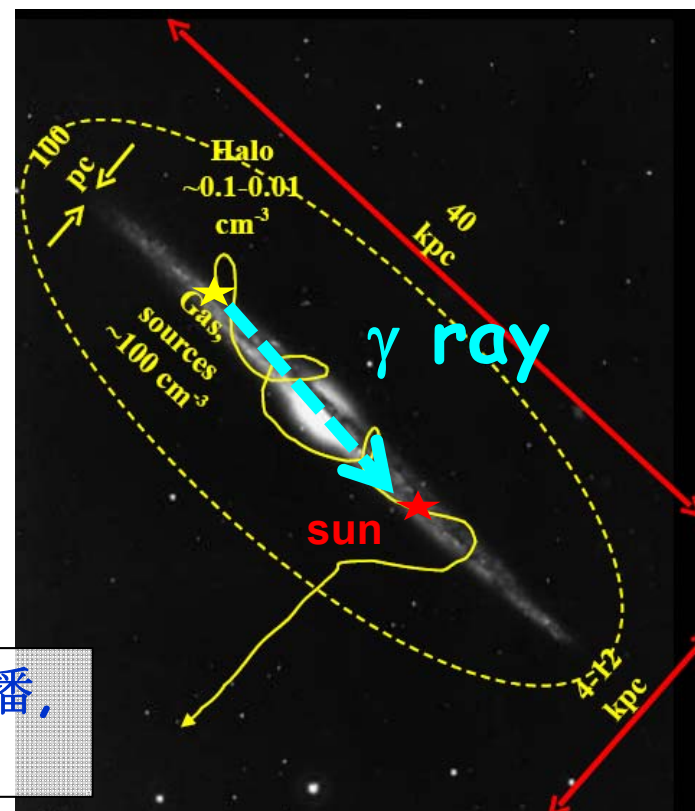
$$\sim 10^{39} \text{ erg/s}$$

$$(\sim 0.01 P_{CR})$$

(銀河面X線放射は 10^{38} erg/s程度)

天の川銀河はガンマ線で明るい

GeVガンマ線により宇宙線加速器, 伝播, 星間ガス分布を精度よく探査できる

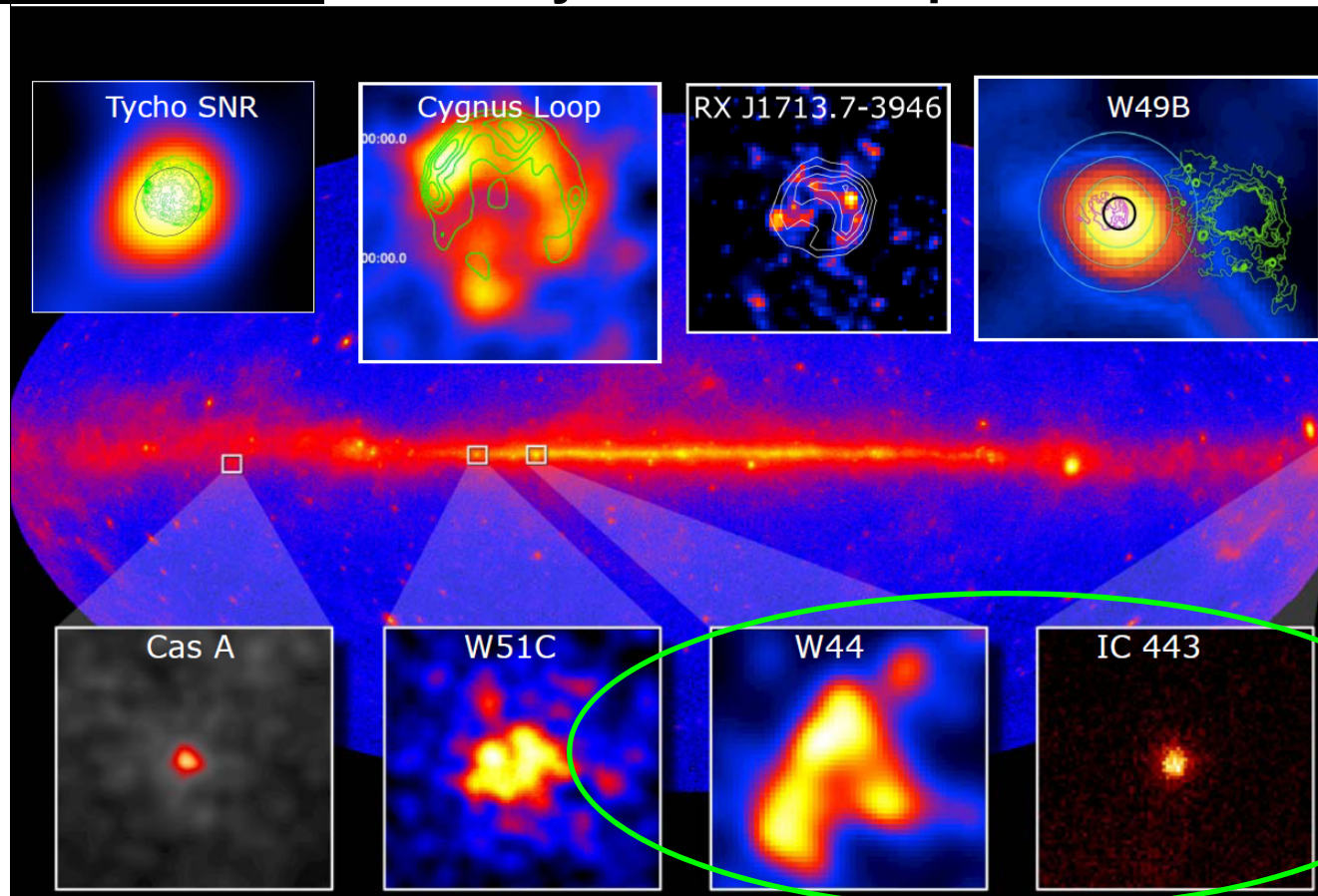


目次

- 導入：星間空間の構成要素, およびガンマ線による宇宙線と星間ガスの探査
- **Fermi-LATによる成果1: 比較的よく理解されている事から**
- Fermi-LATによる成果2: まだ良くわかっていないこと, 今後の課題

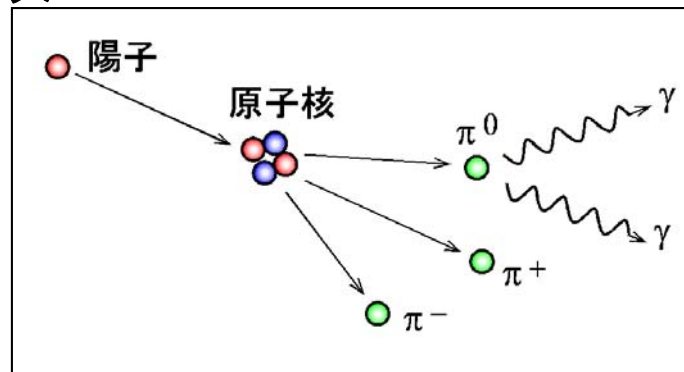
SNRs seen by Fermi-LAT

- In 2FGL, 10 sources are now identified as, or associated with, SNR (# of possible association ~60)
- Hadronic scenario is usually favored to explain SED



宇宙線陽子/原子核の反応

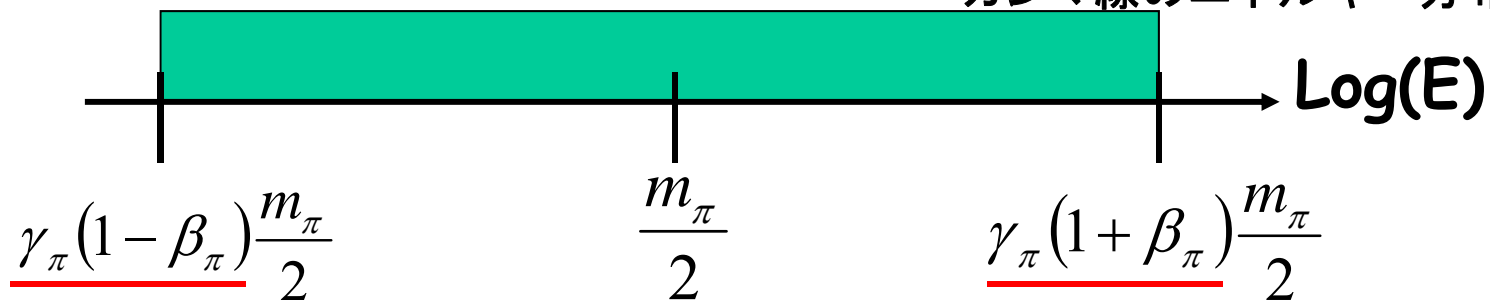
- 宇宙線陽子(原子核)は星間ガスと衝突し、原子核反応を起こす
 - 原子核反応なのでガスの状態によらない
- 中性パイ中間子は直ちに光子に崩壊。質量が~140 MeVなので、静止系で70 MeVのガンマ線を放出。観測者系では陽子のエネルギーを反映



$$\pi^{+-}: 2.6 \times 10^{-8} \text{ s } (\mu^+ \text{ を介して } e^{+-})$$

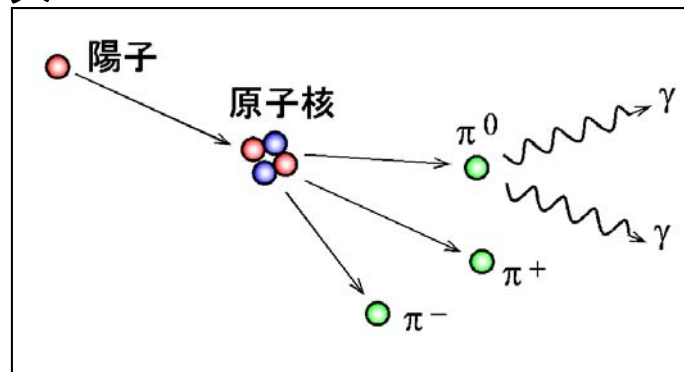
$$\pi^0: 8.4 \times 10^{-17} \text{ s}$$

ガンマ線のエネルギー分布



宇宙線陽子/原子核の反応

- 宇宙線陽子(原子核)は星間ガスと衝突し、原子核反応を起こす
 - 原子核反応なのでガスの状態によらない
- 中性パイ中間子は直ちに光子に崩壊。質量が~140 MeVなので、静止系で70 MeVのガンマ線を放出。観測者系では陽子のエネルギーを反映



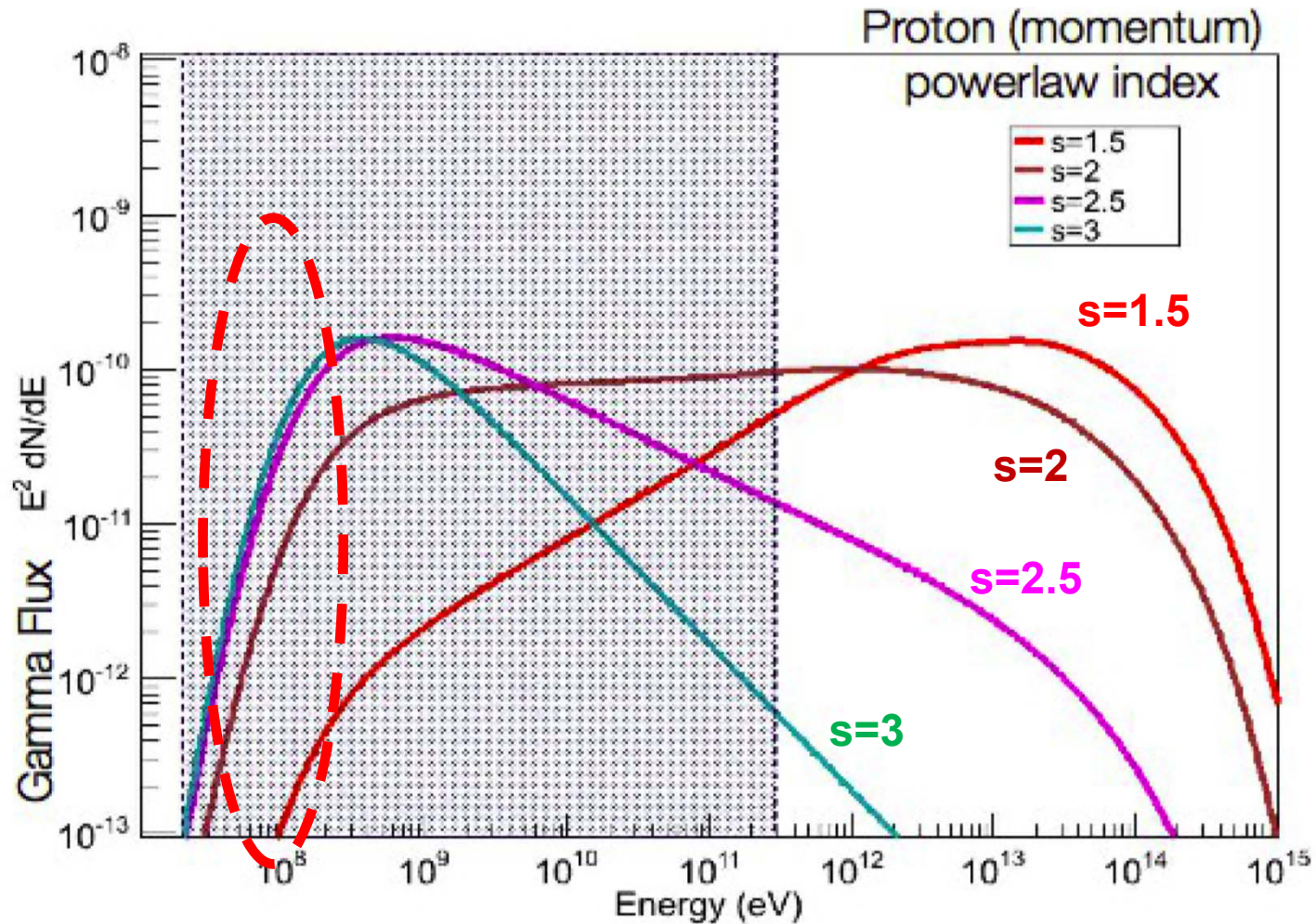
$$\pi^{+-}: 2.6 \times 10^{-8} \text{ s } (\mu^+ \text{ を介して } e^{+-})$$

$$\pi^0: 8.4 \times 10^{-17} \text{ s}$$

- 高E: $N(E_{\text{proton}}) dE_{\text{proton}} \propto E_{\text{proton}}^{-p} dE_{\text{proton}} \rightarrow E_{\gamma}^{-p} dE_{\gamma}$
- 低E: E ≤ 200 MeVで(高Eからの延長に対し)cutoff

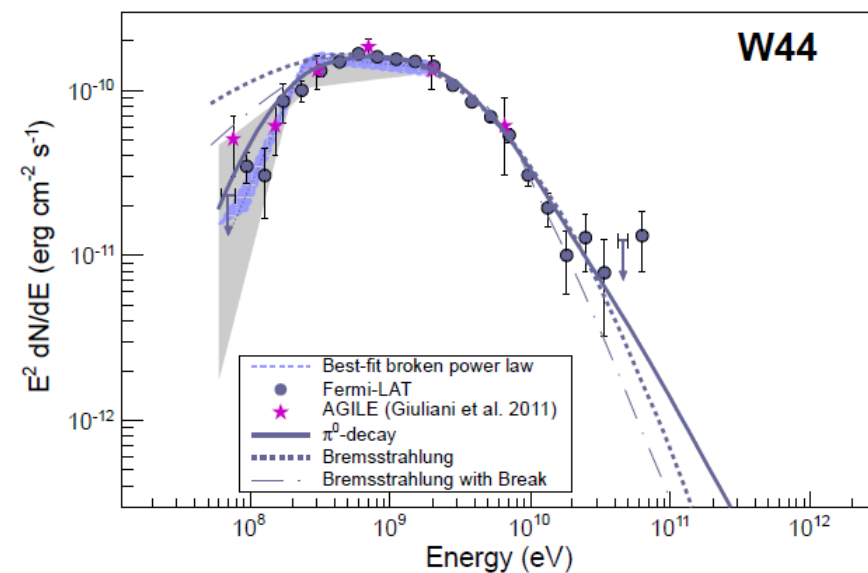
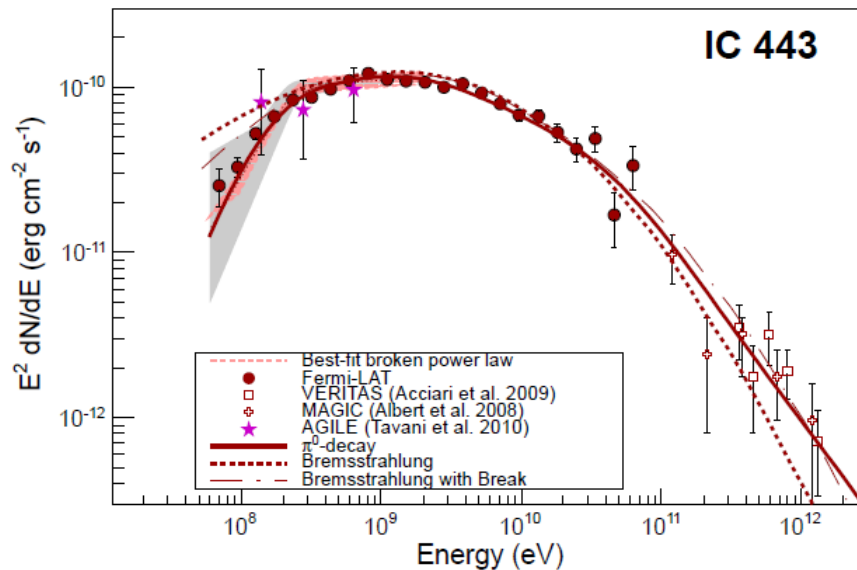
Pion-Decay Signature in LowE Spectrum

- Hadronic scenario predicts a clear cutoff below 200 MeV



Pion-Decay Signature in LowE Spectrum

- Spectrum below 200 MeV clearly deviates from bremsstrahlung and agrees well with a hadronic scenario



	IC443	W44
W_{SN}	1×10^{51} erg	5×10^{51} erg
W_{CR}	$4 \times 10^{49} (n/20 \text{cm}^{-3})^{-1}$ erg	$4 \times 10^{49} (n/100 \text{cm}^{-3})^{-1}$ erg

Convincing evidence of proton acceleration at SNR,

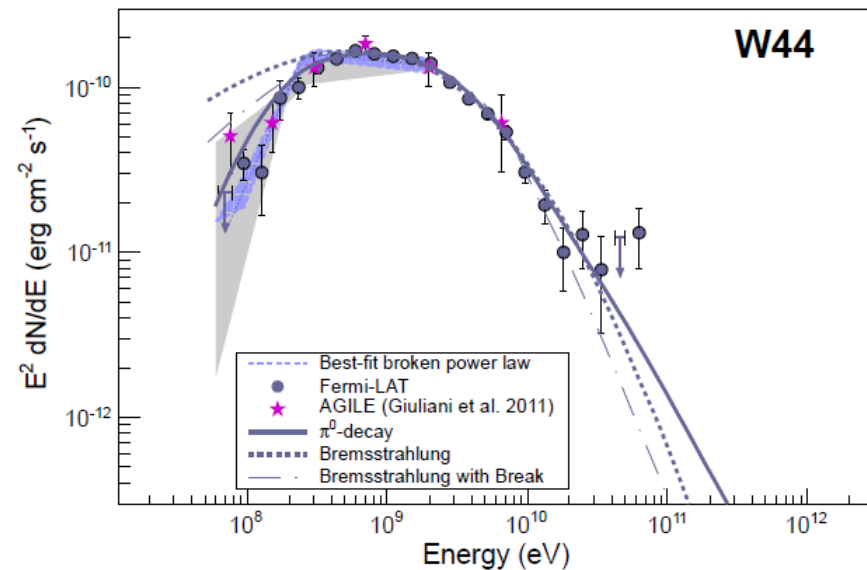
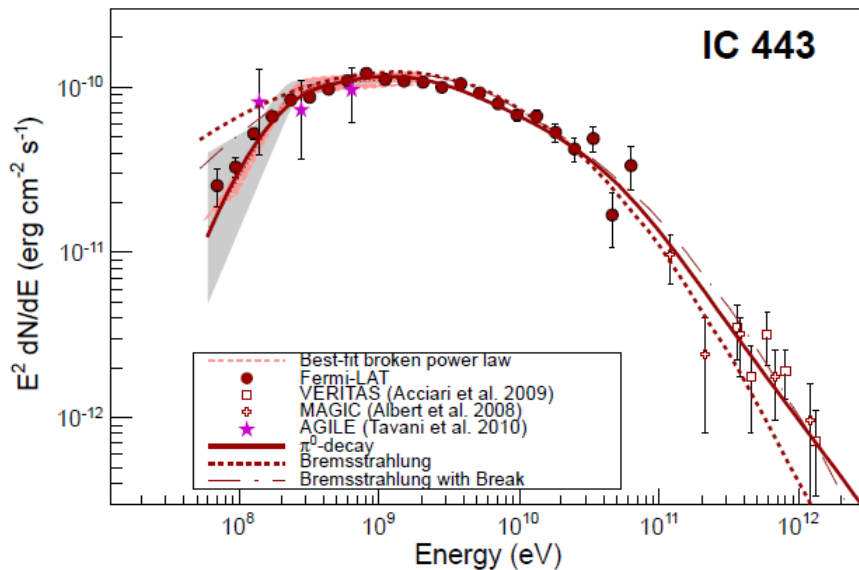
$$E_{SN} \eta = W_{CR} \sim 10^{50} \text{ erg}$$

T. Mizuno et al.

Ackermann+13, Science 339, 807
(CA: Funk, Tanaka, Uchiyama)

Pion-Decay Signature in LowE Spectrum

- Spectrum below 200 MeV clearly deviates from bremsstrahlung and agrees well with a hadronic scenario

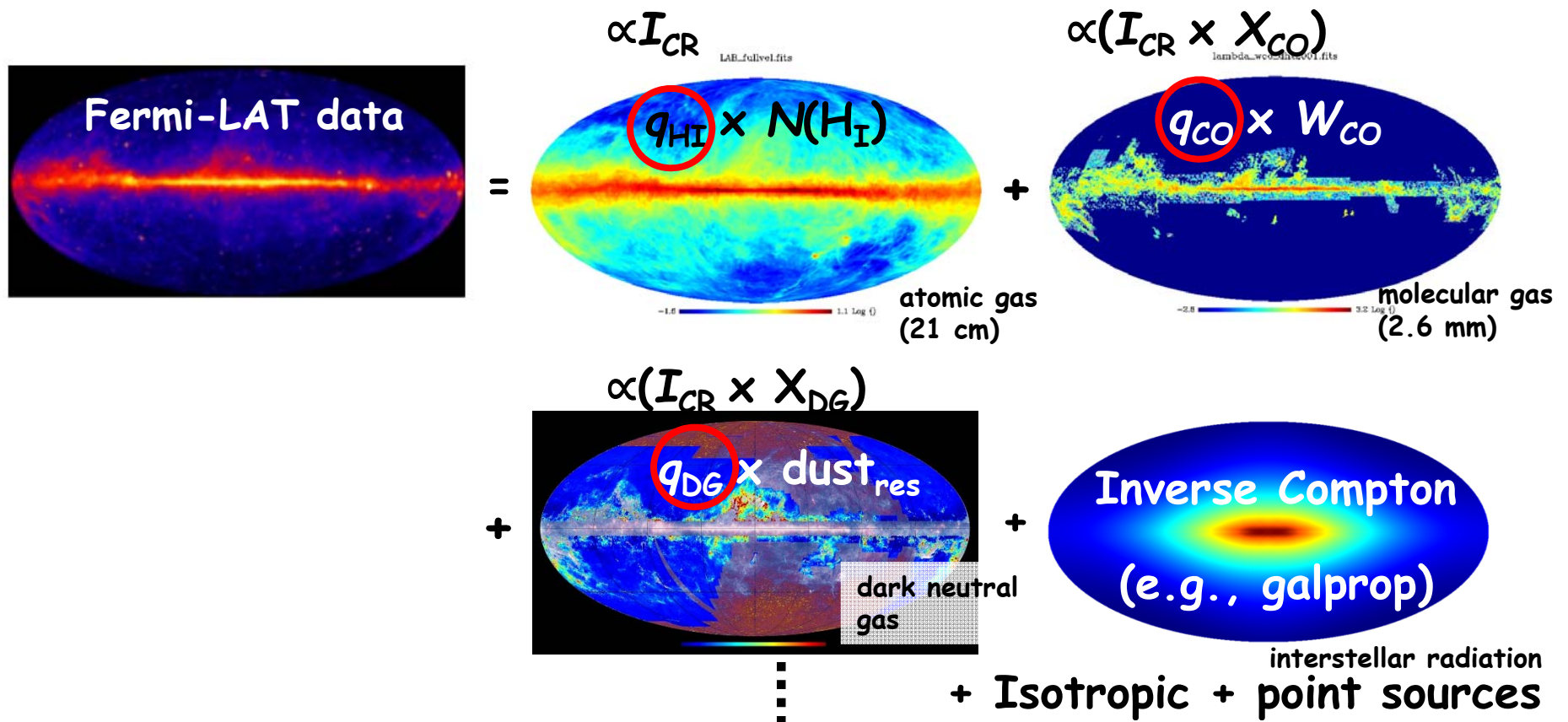


	IC443	W44
W_{SN}	1×10^{51} erg	5×10^{51} erg
W_{CR}	$4 \times 10^{49} (n/20 \text{cm}^{-3})^{-1}$ erg	$4 \times 10^{49} (n/100 \text{cm}^{-3})^{-1}$ erg

Then, what about CR distribution (and propagation)?

Modeling of γ -ray Data

- Under the assumption of a uniform CR density, γ rays can be represented by a linear combination of template maps



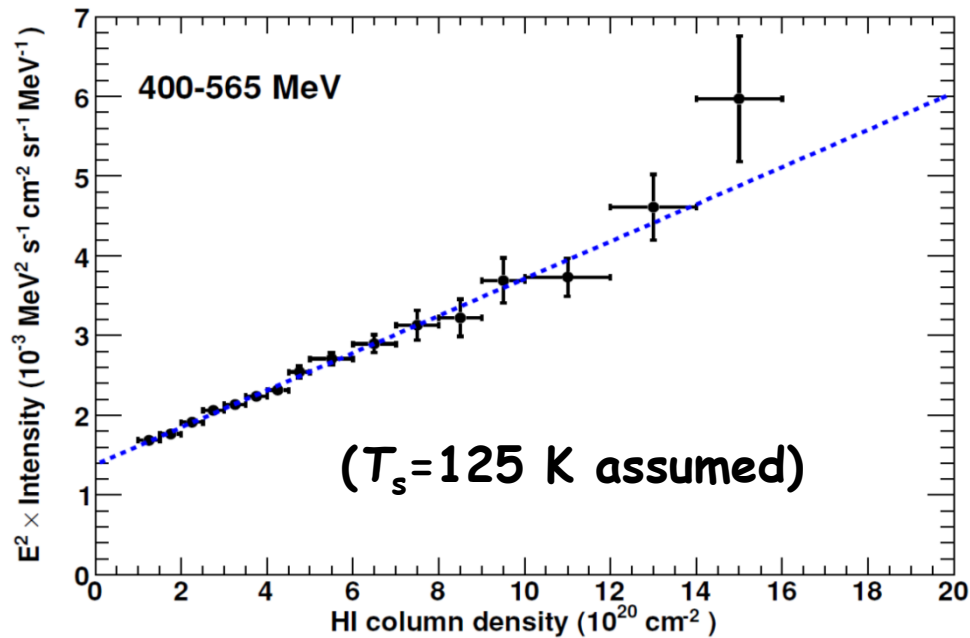
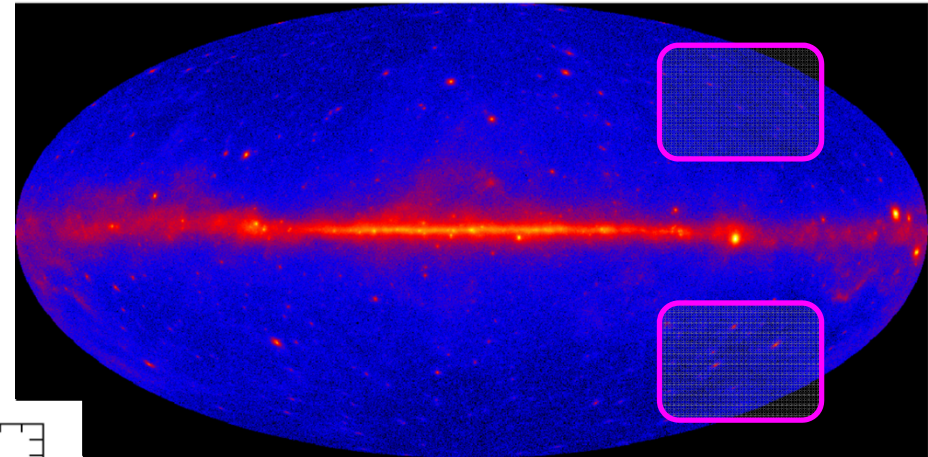
(H_I is usually obtained assuming a uniform T_s)

(W_{CO} is not a all-sky map, may miss some fraction of H_2)

Measurement of local I_{CR} (1)

High lat. H_I cloud in 3rd quadrant

- small contamination of IC, molecular and dark gas
- correlate γ -ray intensity with $N(\text{H}_I)$



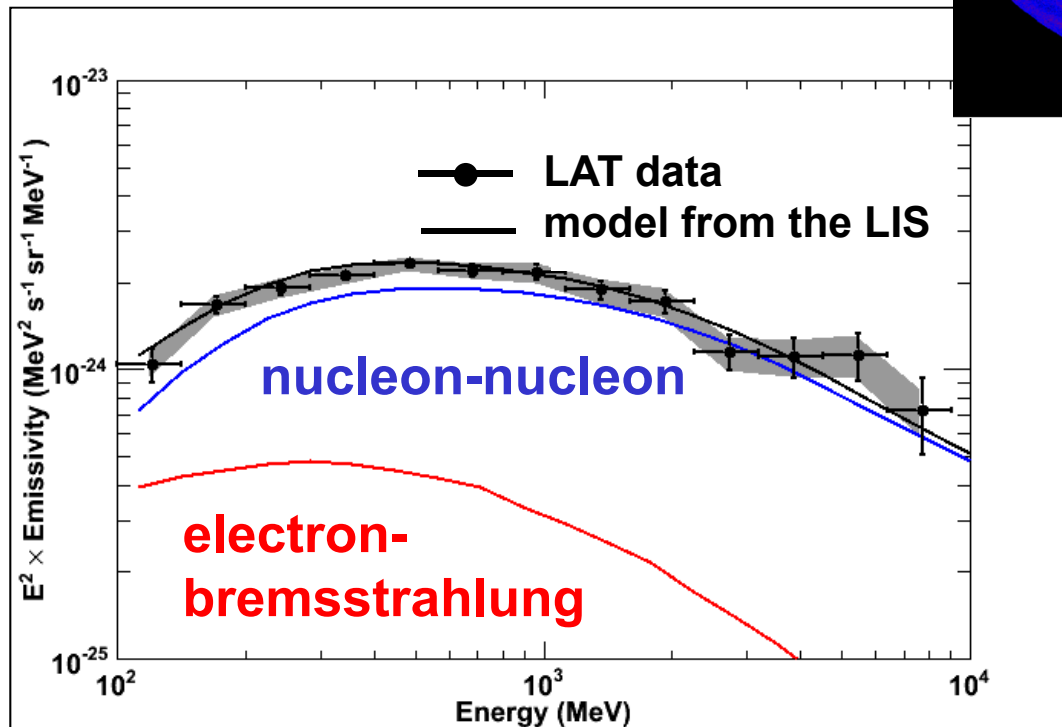
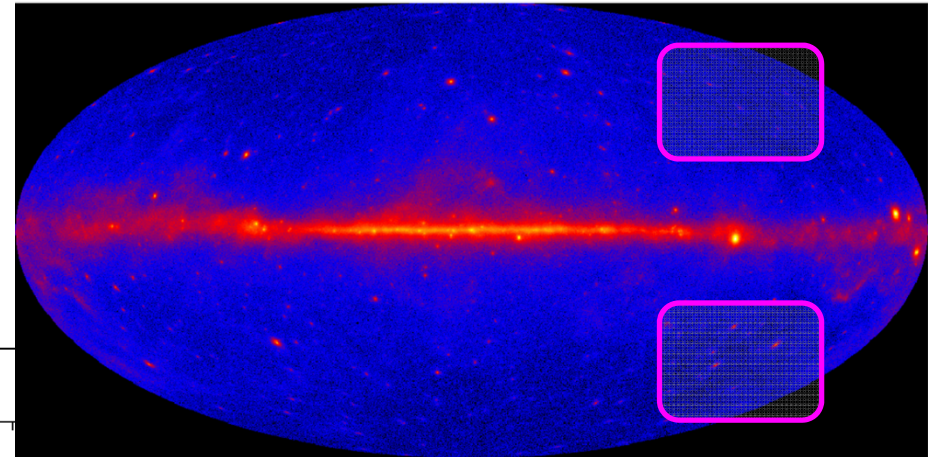
- Linear relation between $N(\text{H}_I)$ and I_γ indicates uniform CR density in ROI

Abdo+09, ApJ 703, 1249
(CA: TM)

Measurement of local I_{CR} (2)

High lat. H_I cloud in 3rd quadrant

- small contamination of IC, molecular and dark gas
- correlate γ -ray intensity with $N(H_I)$

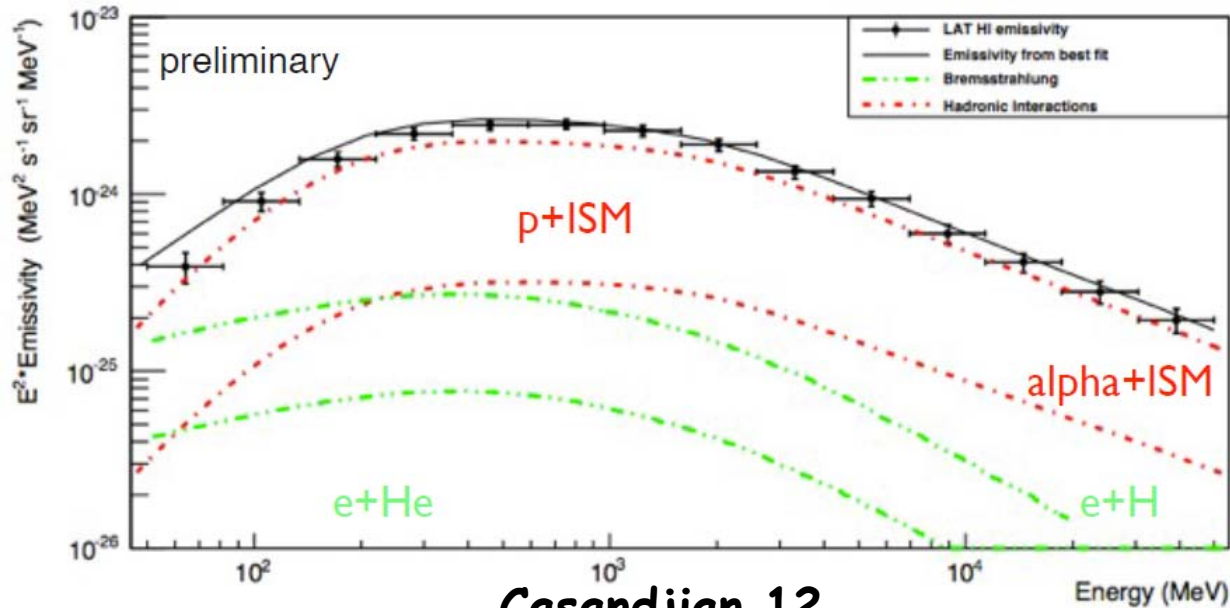
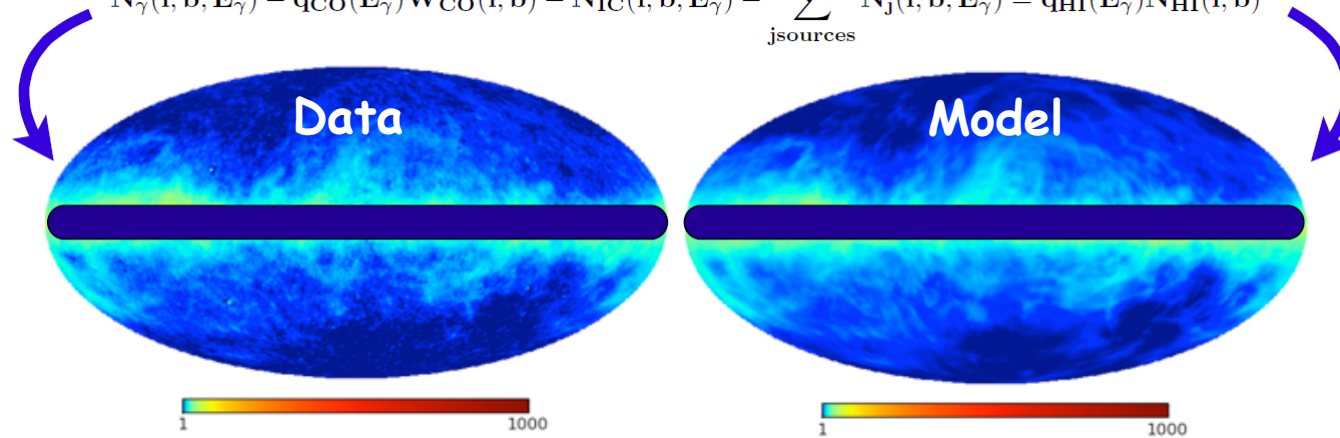


- Local CR spectra ~ those directly measured at the Earth ($u_{CR} \sim 1 \text{ eV/cm}^3$)

Abdo+09, ApJ 703, 1249
(CA: TM)

All-Sky Average local I_{CR}

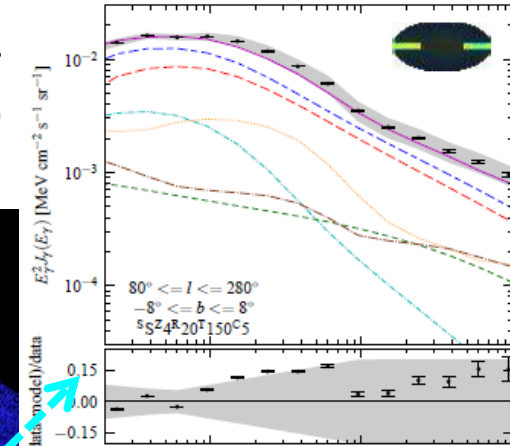
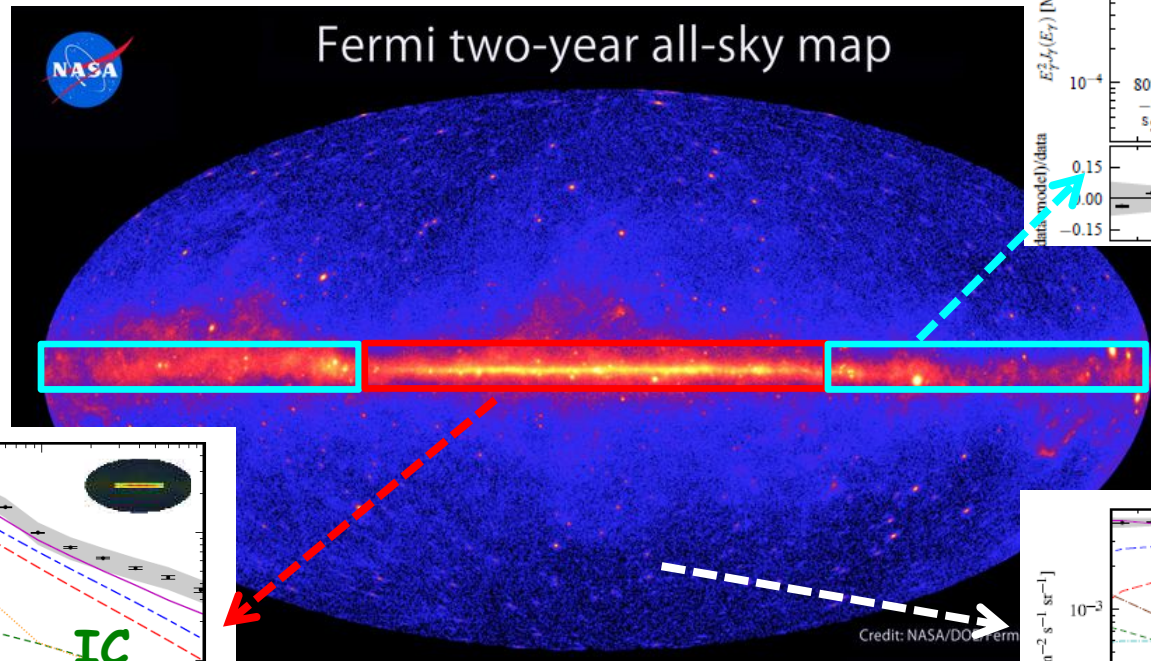
$$N_{\gamma}(l, b, E_{\gamma}) - q_{CO}(E_{\gamma})W_{CO}(l, b) - N_{IC}(l, b, E_{\gamma}) - \sum_{j \text{ sources}} N_j(l, b, E_{\gamma}) = q_{HI}(E_{\gamma})N_{HI}(l, b)$$



- on average, local CR spectra ~ those measured at the Earth ($u_{CR} \sim 1 \text{ eV/cm}^3$)

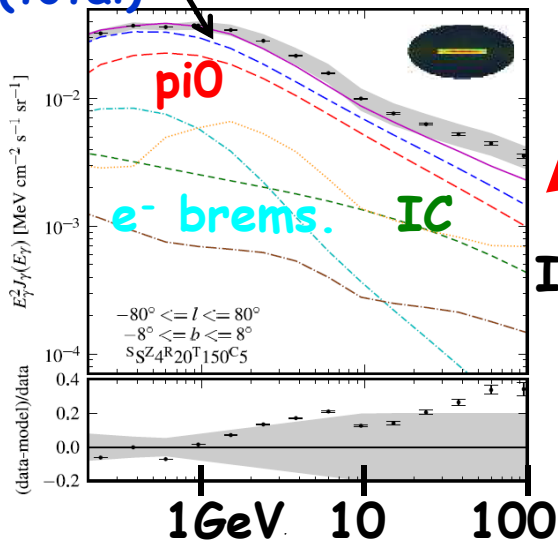
CRs on Galactic Scale

No single model to reproduce the all-sky data best, but overall agreement is good

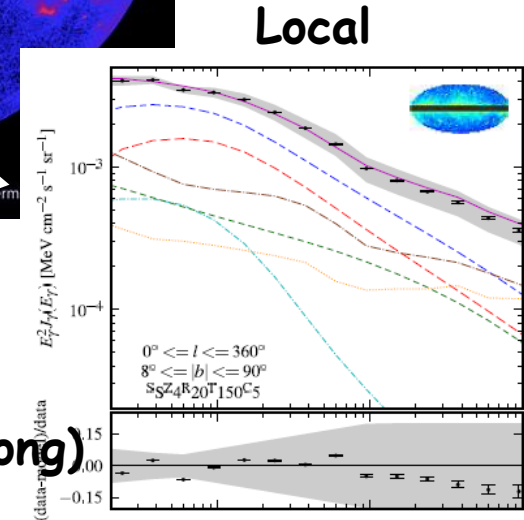


Outer Galaxy

Diffuse model (total)



Inner Galaxy



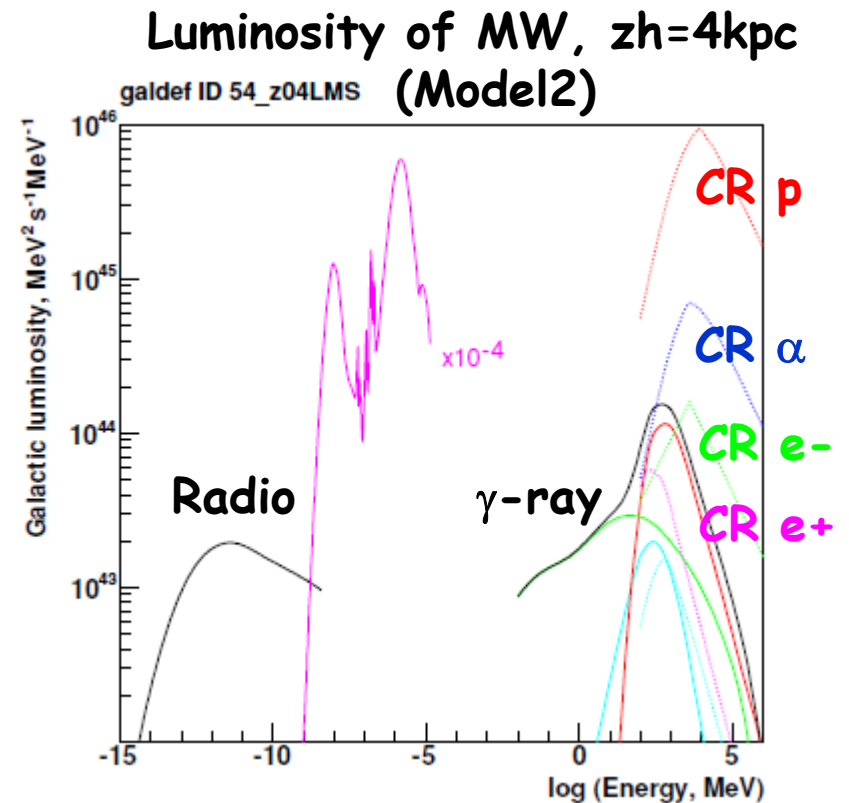
Local

Ackermann+12, ApJ 750, 3
(CA: Johannesson, Porter, Strong)

CR Luminosity Inferred from a Model

- $P_{CR}=(6-8)\times 10^{40}$ erg/s and $L_{\gamma}=(7-10)\times 10^{38}$ erg/s are inferred by (particular) set of models

Component	Diffusive Reacceleration		
	Model 1	Model 2	Model 3
Cosmic rays (0.1–100 GeV):	805	790	698
Protons	737	724	633
Helium	56	55	48
Leptons	12.2	14.5	16.9
Primary e^-	8.8	11.1	13.4
Secondary e^-	0.78	0.77	0.83
Secondary e^+	2.6	2.6	2.7
γ -rays (0.01–100 MeV):	2.32	3.34	6.22
π^0 -decay	0.24	0.23	0.23
Inverse Compton	1.80	2.81	5.63
Primary e^-	1.31	2.20	4.41
Secondary e^{\pm}	0.49	0.61	1.22
Bremsstrahlung	0.27	0.30	0.36
Primary e^-	0.11	0.15	0.19
Secondary e^{\pm}	0.16	0.15	0.17
γ-rays (0.1–100 GeV):	8.86	9.12	10.3
π^0 -decay	6.75	6.46	6.59
Inverse Compton	1.25	1.76	2.59
Primary e^-	1.15	1.66	2.43
Secondary e^{\pm}	0.10	0.10	0.16
Bremsstrahlung	0.87	0.88	1.08
Primary e^-	0.51	0.58	0.74
Secondary e^{\pm}	0.36	0.30	0.34



Models by numerical calculation,
Strong+10 (ApJ 722, L58) 30/43

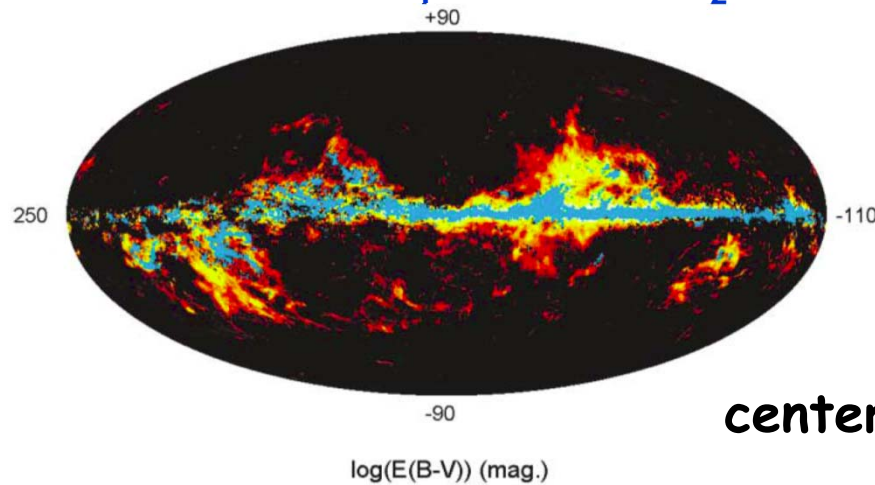
目次

- 導入：星間空間の構成要素, およびガンマ線による宇宙線と星間ガスの探査
- Fermi-LATによる成果1: 比較的よく理解されていることから
- Fermi-LATによる成果2: まだ良くわかっていないこと, 今後の課題

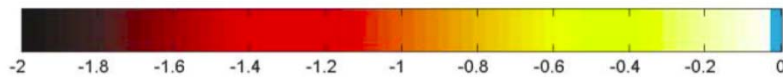
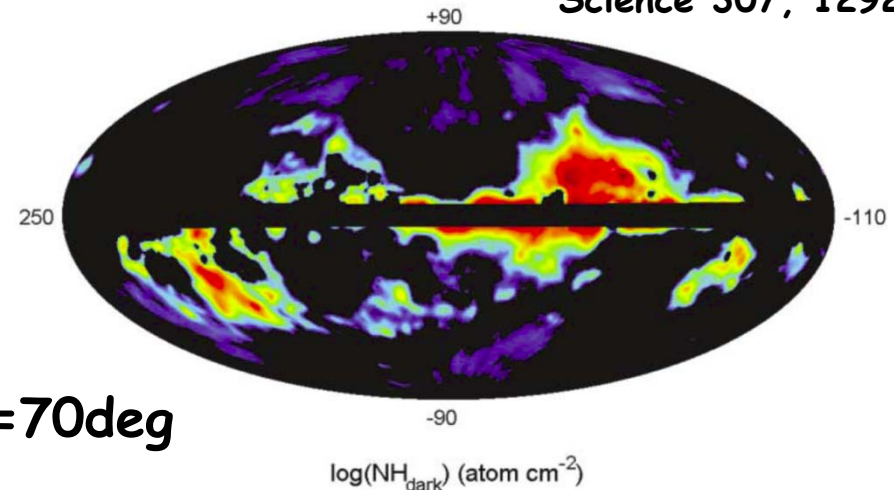
Dark Neutral Gas

- Grenier+05 claimed there exist considerable amount of gas not properly traced by radio surveys (H_1 by 21 cm, H_2 by 2.6 mm CO) surrounding nearby CO clouds
 - cold H_1 ? CO-dark H_2 ?

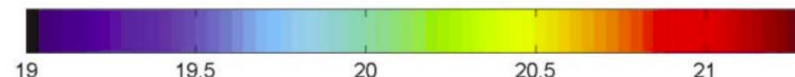
Grenier+05,
Science 307, 1292



center@l=70deg



$E(B-V)_{\text{excess}}$ (residual gas inferred by dust)
and W_{CO}



"Dark-gas" inferred by γ -rays
(CGRO EGRET)

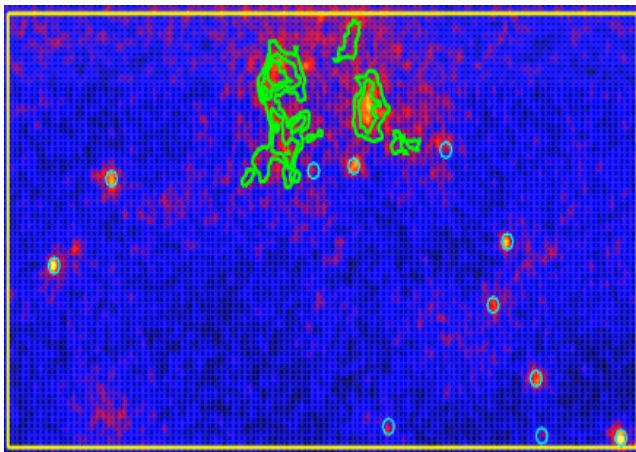
Confirmation and detailed study by current telescopes are important

Dark Gas Seen in GeV γ -rays (1)

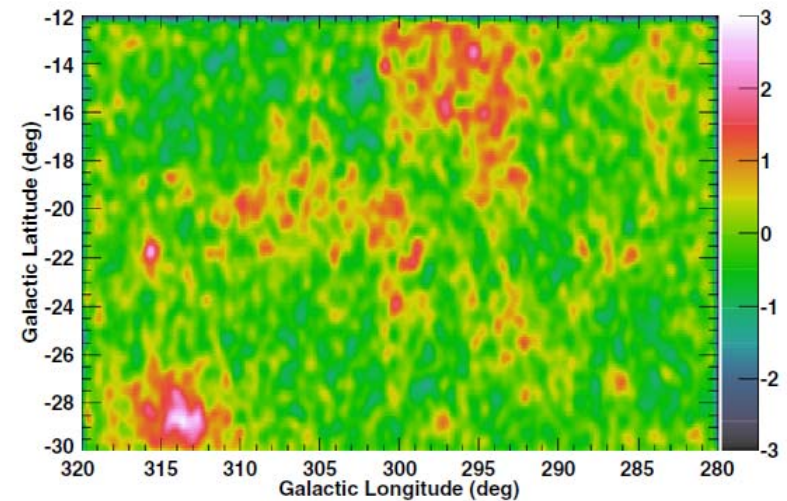
- ISM has been mapped by radio surveys (H_I by 21 cm, H_2 by 2.6 mm CO)
- Fermi revealed a component of ISM not measurable by those standard tracers

Chamaeleon Molecular Cloud

γ -rays w/ CO contour



Residual γ -rays when fitted by $N(H_I) + W_{CO}$

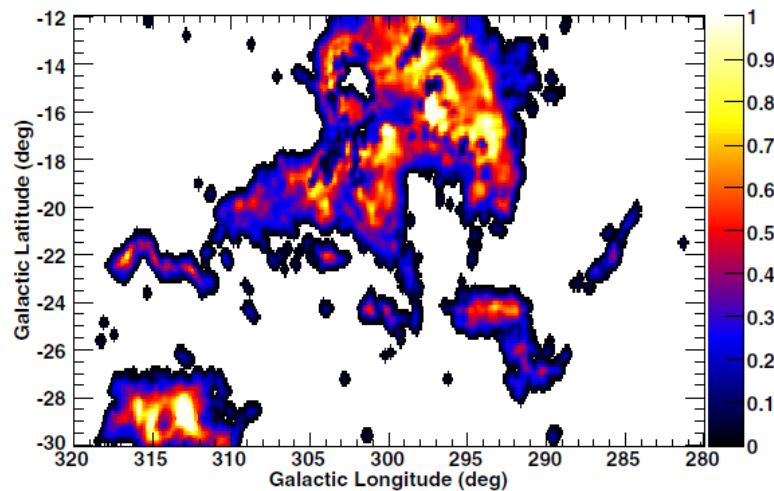


Ackermann+12, ApJ 755, 22
(CA: Hayashi, TM)

Dark Gas Seen in GeV γ -rays (2)

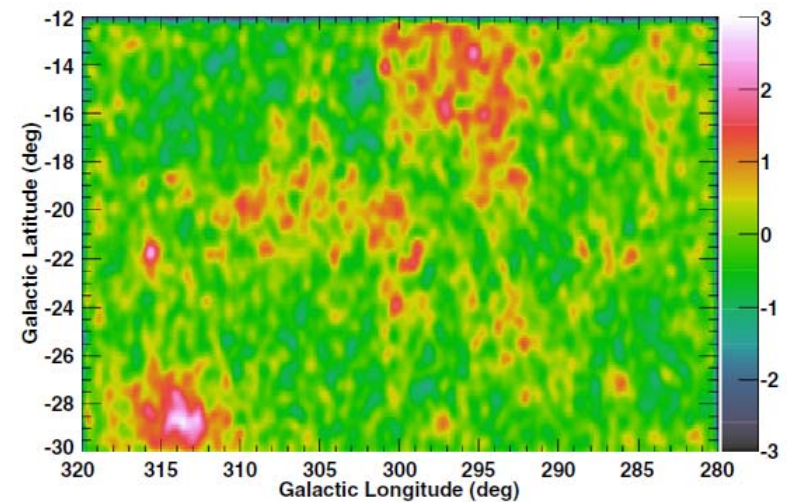
- ISM has been mapped by radio surveys (H_I by 21 cm, H_2 by 2.6 mm CO)
- Fermi revealed a component of ISM not measurable by those standard tracers, **confirming an earlier claim based on EGRET study (Grenier+05)**

Residual gas inferred by dust



Ackermann+12, ApJ 755, 22
(CA: Hayashi, TM)

Residual γ -rays when fitted by $N(H_I) + W_{CO}$

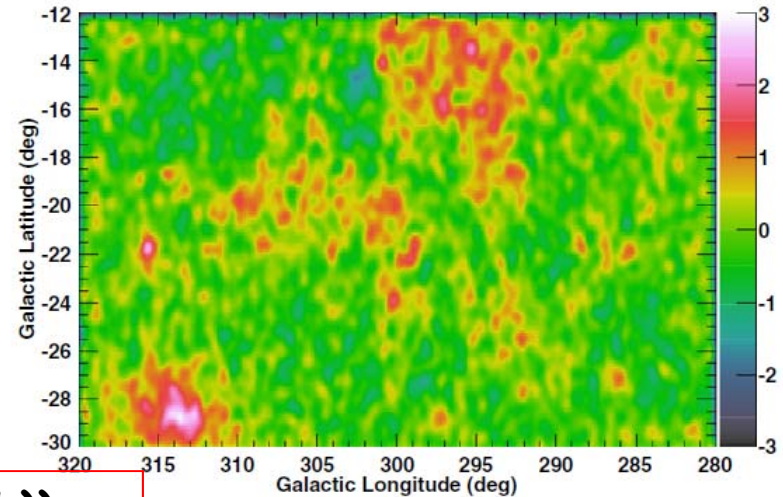


("dark-gas" no longer dark in γ -rays)

Amount of Dark Gas

- Fermi revealed a component of ISM not measurable by those standard tracers
- Amount of “dark gas” is comparable to or greater than gas mass traced by W_{CO}

Residual γ -rays when fitted by $N(H_I) + W_{CO}$



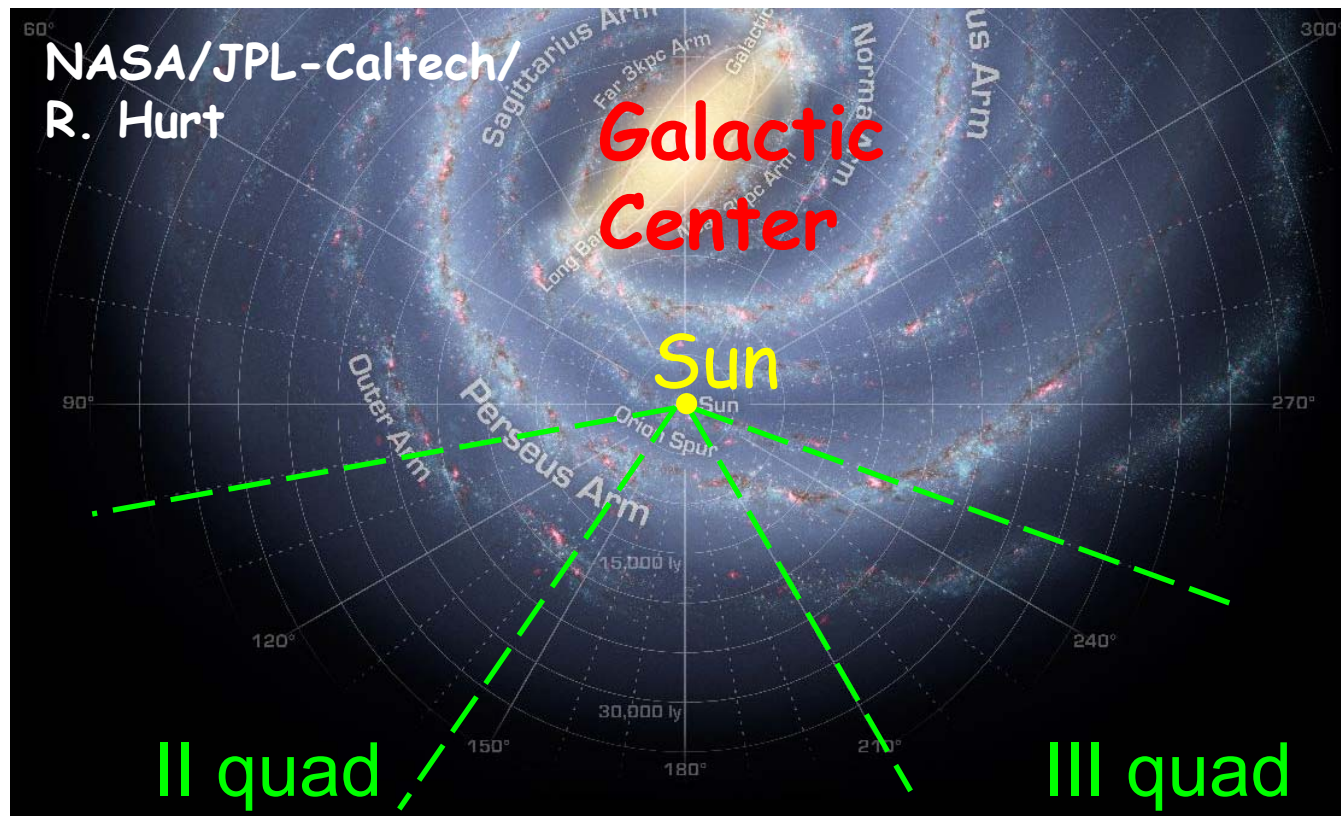
(Both M_{CO} and $M_{DG} \propto I_{CR} \propto N(H_I)$)

Molecular cloud	Gas mass traced by CO (M_{solar})	“dark gas” (M_{solar})
Chamaeleon	$\sim 5 \times 10^3$	$\sim 2.0 \times 10^4$
R CrA	$\sim 10^3$	$\sim 10^3$
Cepheus & Polaris	$\sim 3.3 \times 10^4$	$\sim 1.3 \times 10^4$

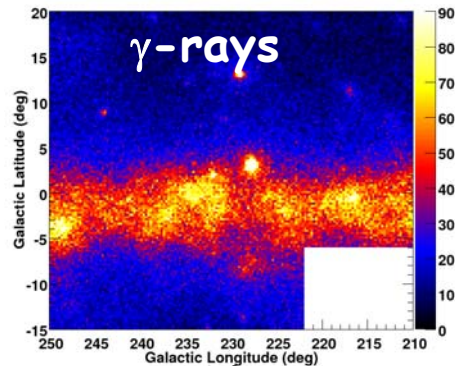
See also Abdo+10 (ApJ 710, 133), Ackermann+11 (ApJ 726, 81)
and Ackermann+12 (ApJ 756, 4)

CR Propagation: The Outer Galaxy

- No distance ambiguity in velocity separation of gas in outer Galaxy

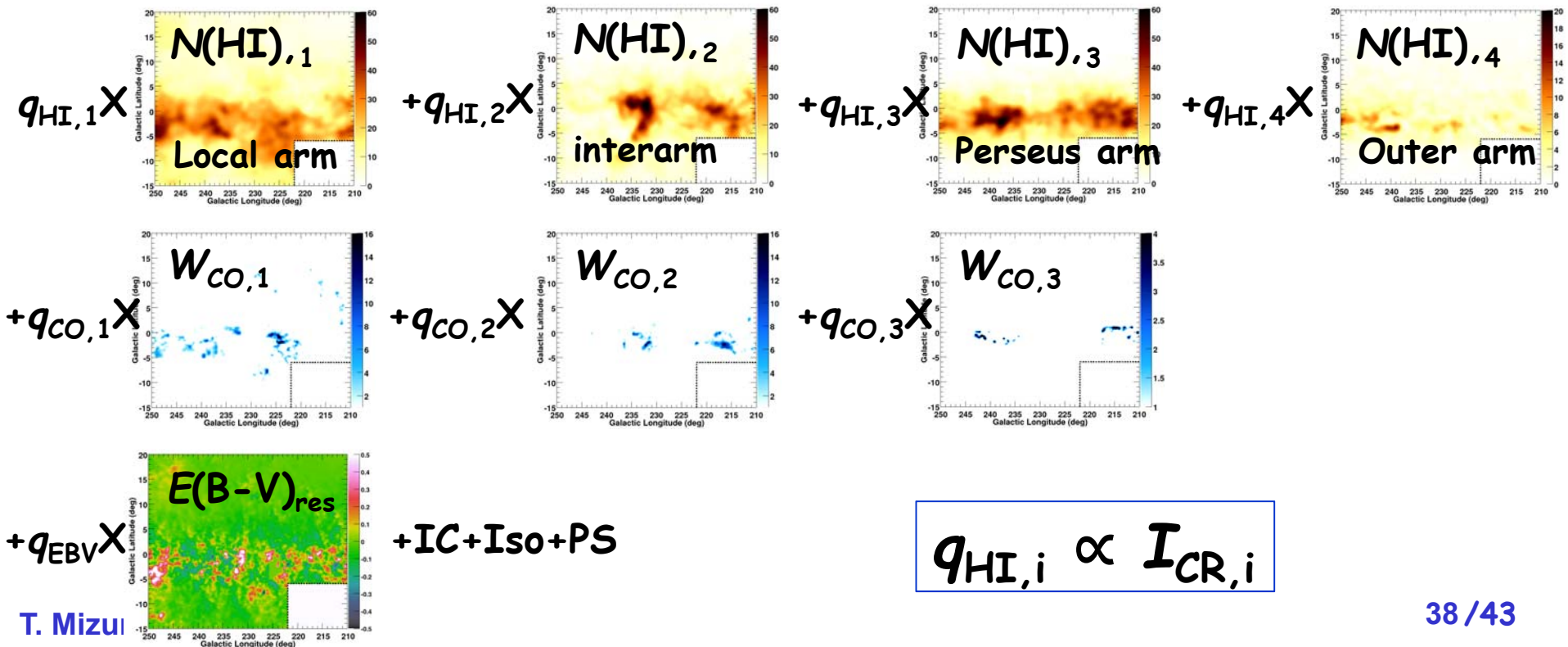


Data Analysis



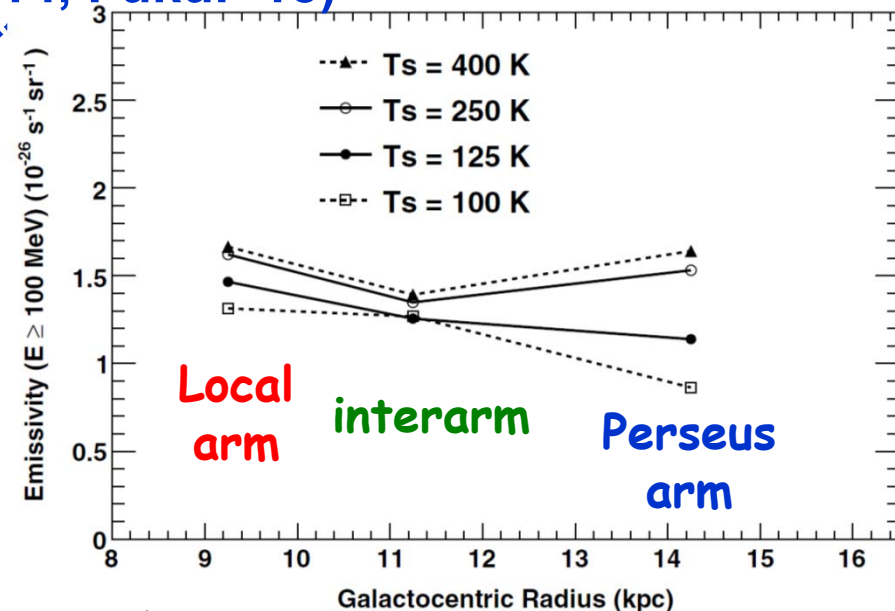
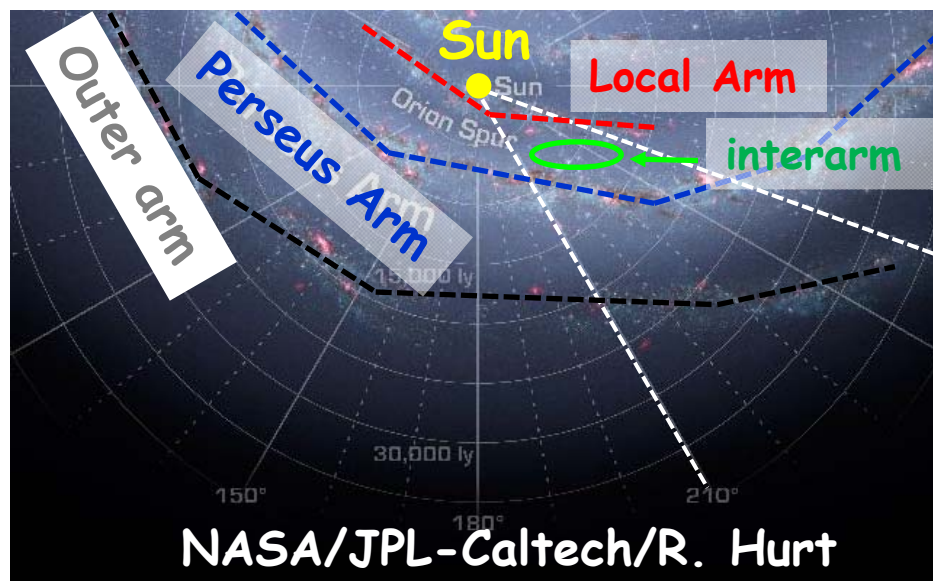
“Standard” approach:

- linear combination of ISM maps
- no a-priori assumption of CR spectra



Uncertainty of I_{CR} due to H_I Optical Depth

- γ -ray emissivity (or I_{CR}) was measured with high precision. But it depends on H_I optical depth assumption
 - uncertainty by a factor of ~ 1.5 . also affects M_{H_2} , M_{DG}
 - cross correlation among γ -rays, radio, IR and optical is crucial (e.g., Planck collaboration 14, Fukui+15)

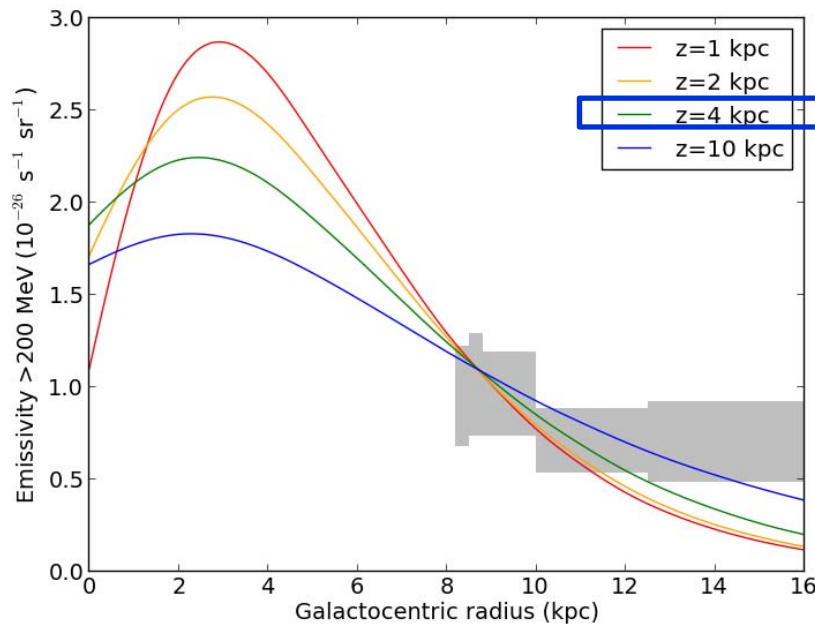
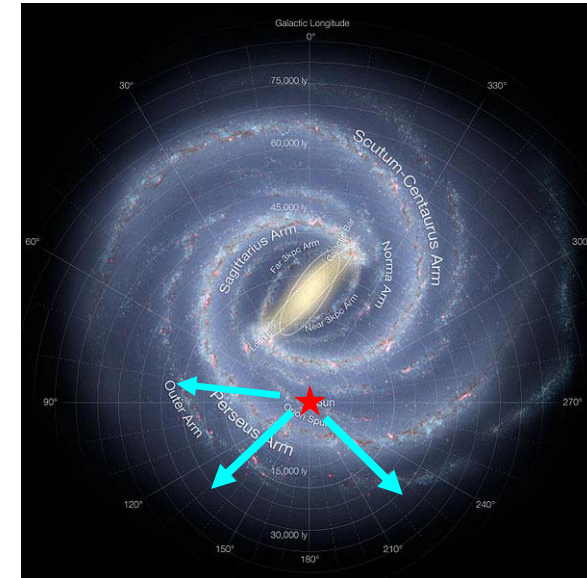


Ackermann+11, ApJ 726, 81

(CA: Grenier, Mizuno, Tibaldo) 39/43

CR Density Gradient

- **CR densities greater than expected in outer Galaxy**
 - larger propagation halo, more CR sources, non-uniform diffusion, etc.

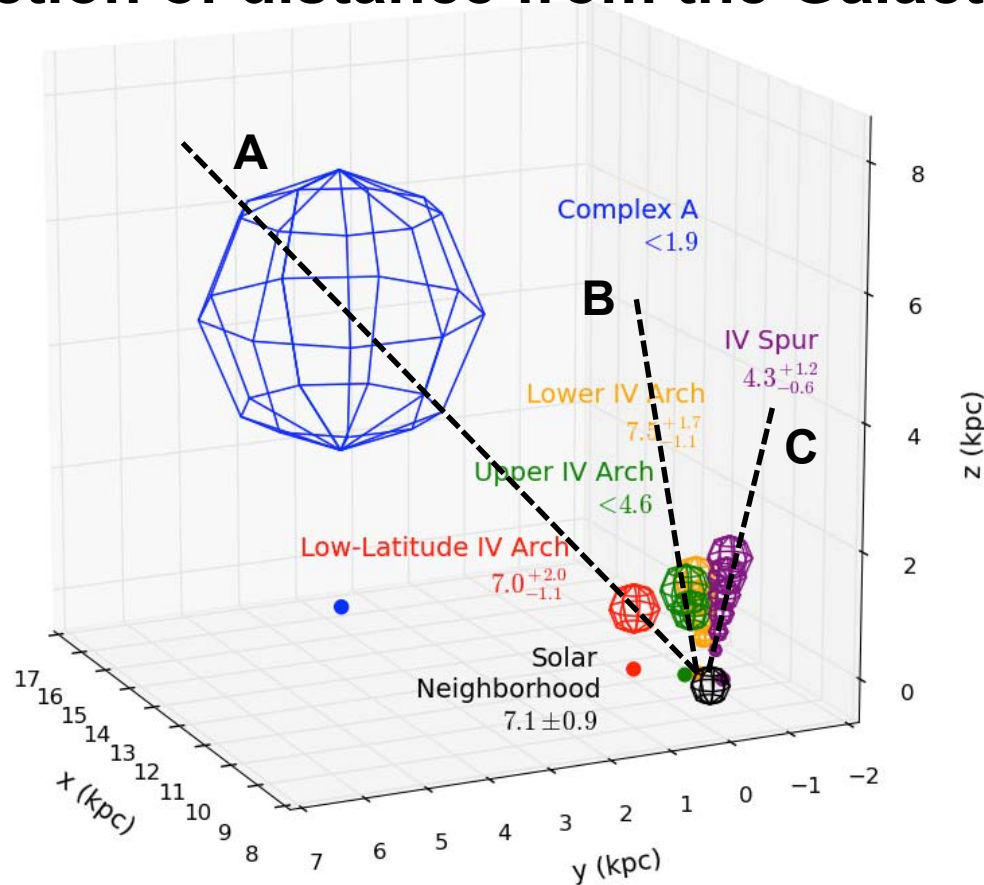


usually assumed

Abdo+10, ApJ 710, 133
 Ackermann+11, ApJ 726, 81
 Ackermann+12, A&A 538, A71

Constraining CR Halo

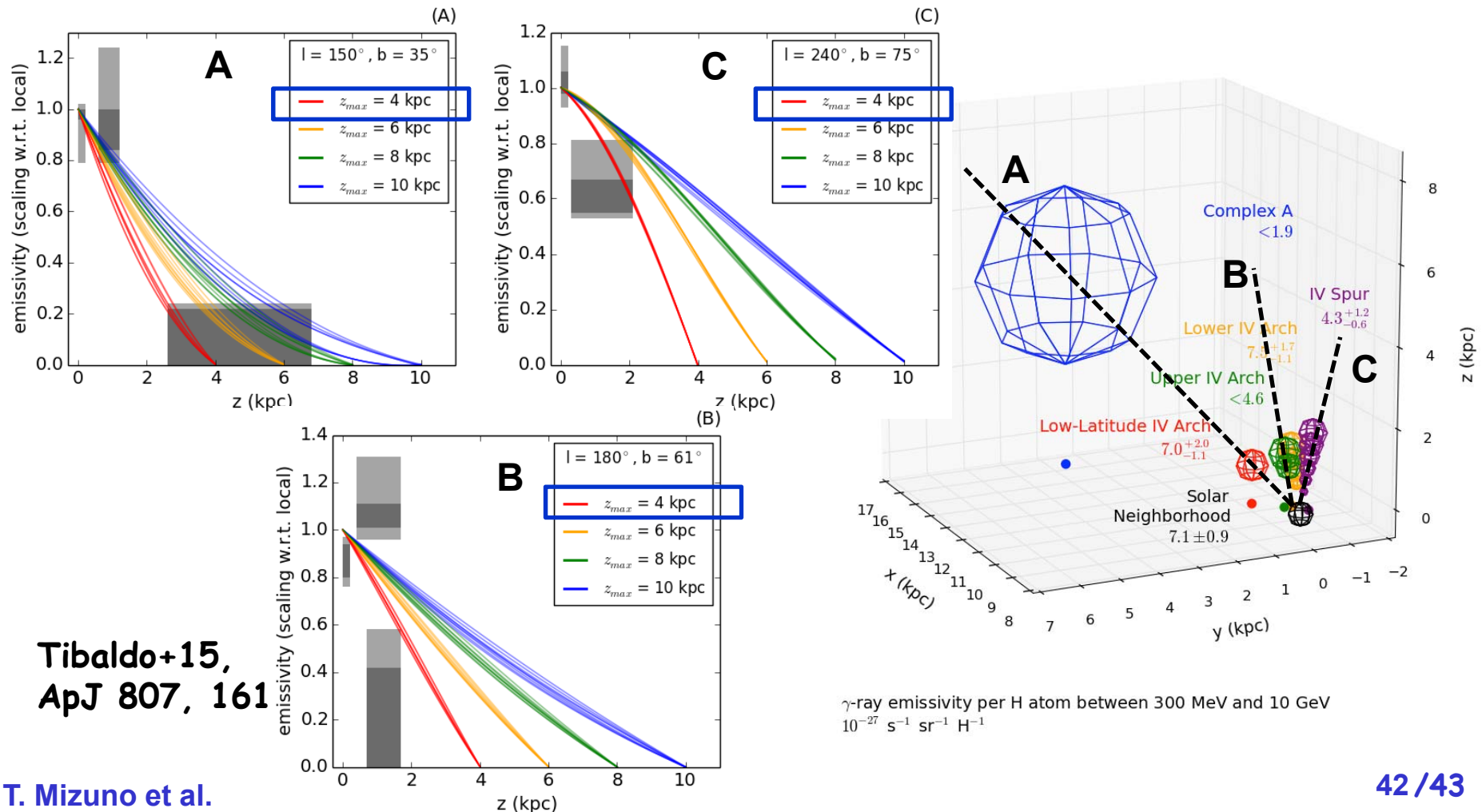
- Intermediate-velocity cloud (IVC) and high-velocity cloud (HVC) allow us to directly measure CR density as a function of distance from the Galactic plane



Tibaldo+15, ApJ 807, 161

Comparison to Propagation Models

- Comparison to galprop diffusion models favors smaller z_{max} , though limitation exists (e.g., boundary condition)



Tibaldo+15,
ApJ 807, 161

Summary

- 天の川銀河の構成要素：星間ガス・光子・磁場・宇宙線
 - ガンマ線は星間ガスと宇宙線を探る強力なプローブ
- Fermi-LATによる研究の進展
 - 超新星残骸における陽子加速の証拠
 - 近傍の宇宙線スペクトル
 - 天の川銀河スケールでの宇宙線の理解
- ホットな話題/今後取り組むべき課題
 - ダークガスの正体、存在量
 - 宇宙線強度の不定性(主にHI opacity)
 - 宇宙線ハローおよび伝播モデル

Thank you for your Attention

- 現代の天文学4 「銀河」, 現代の天文学6 「星間物質と星形成」
- 現代の天文学17 「宇宙の観測III」
- Ferrier 2001, Rev. of Mod. Phys. 73, 1031

- Mathewson and Ford 1970, MNRAS 74, 139
- Grenier et al. 2005, Science 307, 1292
- Porter et al. 2008, ApJ 682, 400

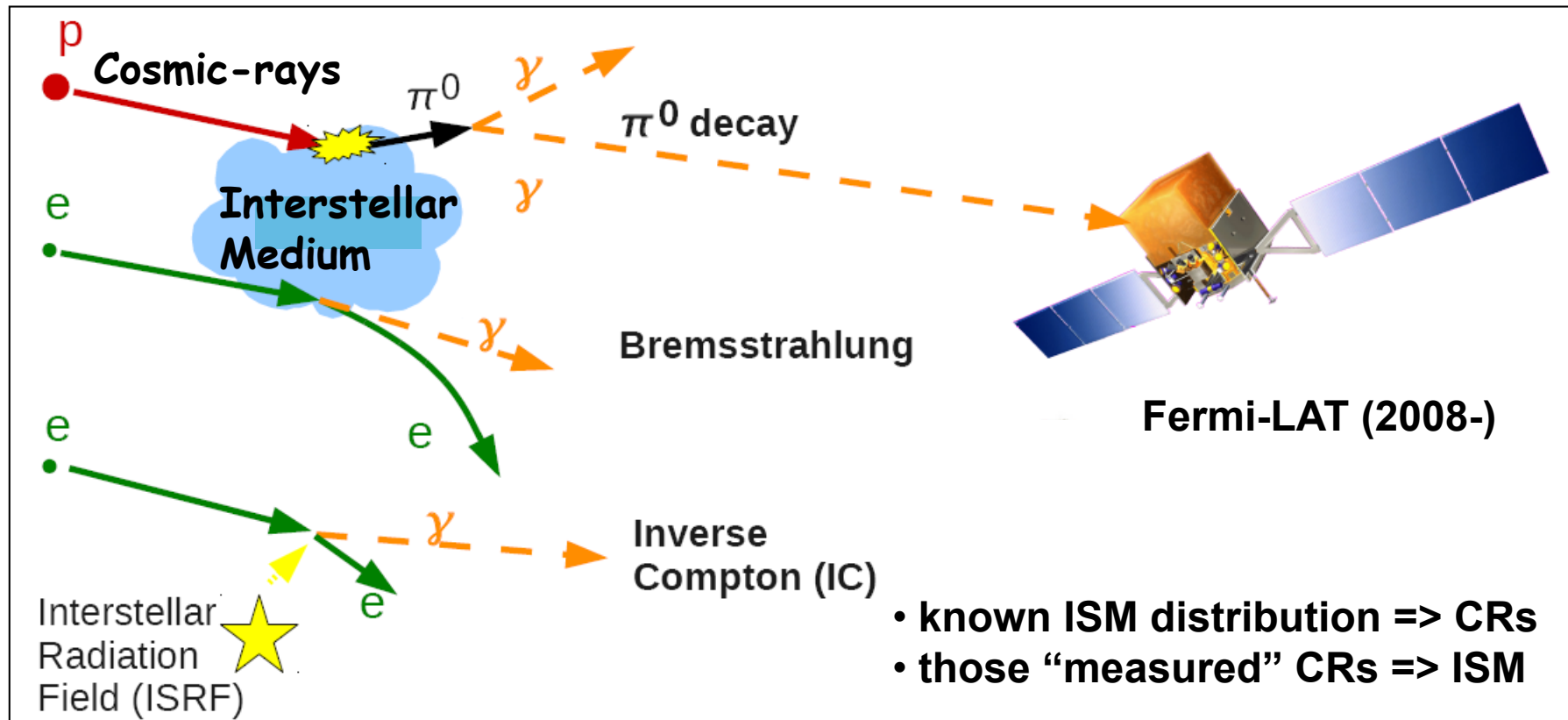
- Abdo et al. 2009, ApJ 703, 1249
- Abdo et al. 2010, ApJ 710, 133
- Atwood et al. 2009, ApJ 687, 1071
- Ackermann et al. 2011, ApJ 726, 81
- Ackermann et al. 2012, ApJ 750, 3
- Ackermann et al. 2012, ApJ 755, 22
- Ackermann et al. 2012, ApJ 756, 4
- Ackermann et al. 2012, ApJS 203,
- Ackermann et al. 2012, A&A 538, A71
- Ackermann et al. 2013, Science 339, 807
- Strong et al. 2010, ApJL 722, 58
- Casandjian 2012, AIP Conf Proc. 1505, 37
- Tibaldo et al. 2015, ApJ 807, 161

- Planck collaboration 14, A&A 571, A11
- Fukui et al. 2014, ApJ 796, 59; Fukui et al. 2015, ApJ 798, 6

Backup Slides

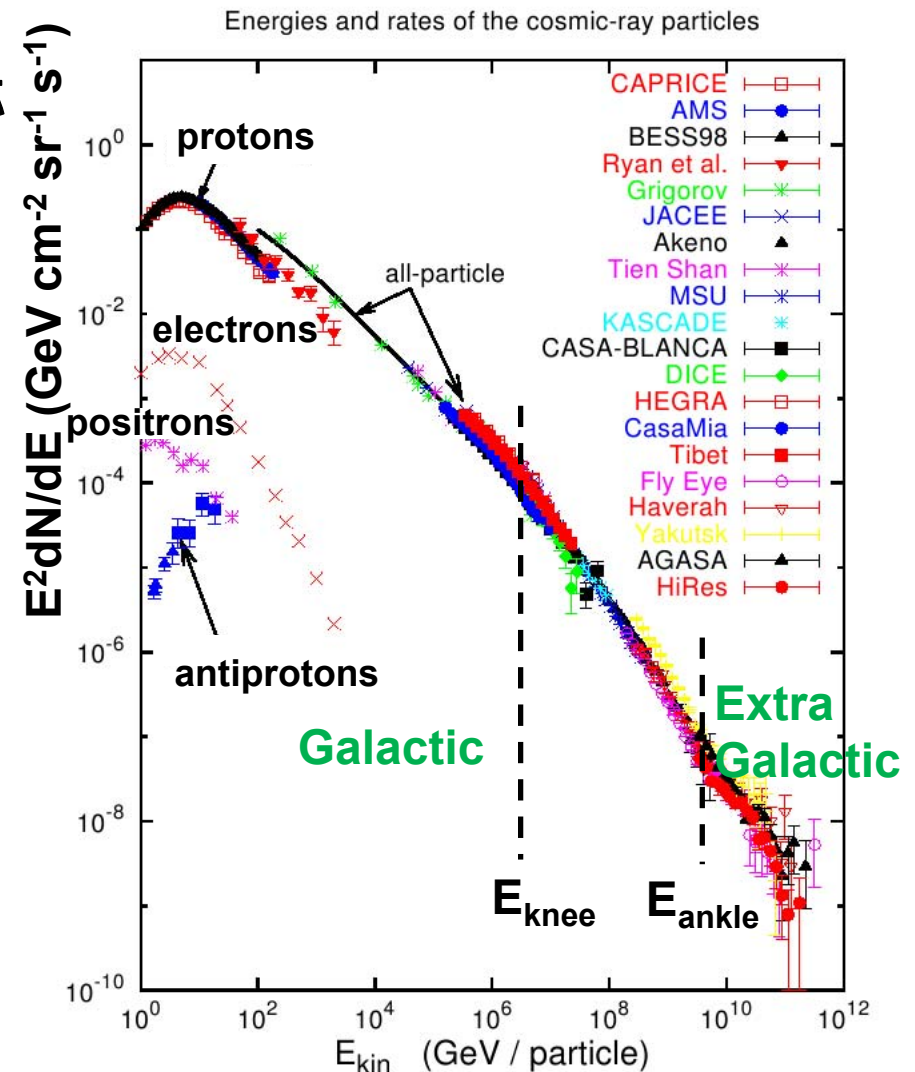
ガンマ線による宇宙線・星間ガスの探査

γ -rays \propto CRs \times ISM (or ISRF)



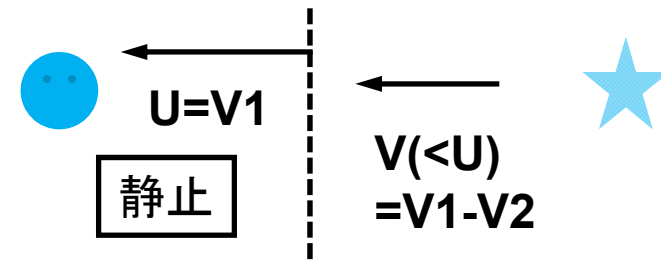
A powerful probe to study CRs (and ISM) in distant locations

- 相対論的エネルギーに加速された高エネルギー粒子の総称
- 10^{20} eVまで伸びるベキ関数
- 陽子(核子)が主成分
 - 0.1-1 %の電子と陽電子
 - 陽子のベキは~2.7、電子は~3
- kneeおよびankleと呼ばれる折れ曲がりが存在
 - 加速源や、閉じ込めの情報を反映
- 異方性が小さく、星間磁場により繰り返し散乱を受けていると考えられる(拡散運動)

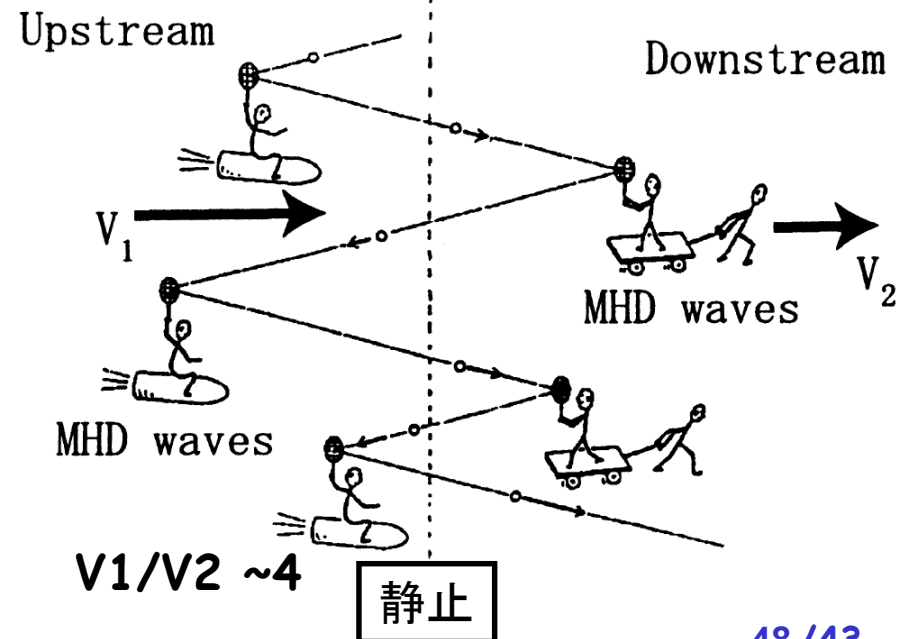


- 超新星の爆風が星間物質中に衝撃波を作る
- 荷電粒子の一部は周りの電磁流体乱流で繰り返し散乱され、エネルギーを得る (Fermiの統計加速)
- E^{-2} を予言し、宇宙線加速として都合がよい

(観測者系=星間空間の静止系)

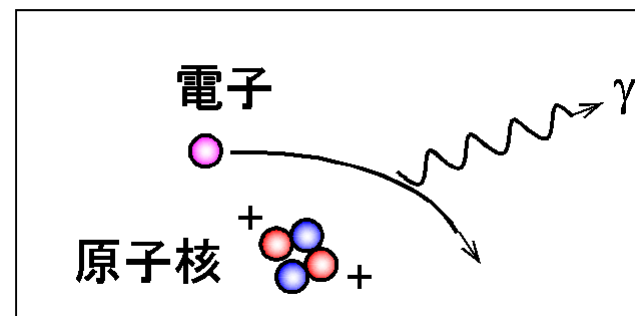


(衝撃波面の静止系) ront



- N は的となるガスの密度, Z は原子番号
- $\bar{g} \sim 1$ (電子のエネルギーや電離状態に弱く依存)
- r_e は古典電子半径、 $\alpha = 1/137$ は微細構造定数
- 制動放射によるエネルギー損失は、エネルギーに比例
 - 中程度のエネルギーを持った電子のエネルギー損失および放射

$$-\frac{1}{E} \left(\frac{dE}{dt} \right)_{\text{bremss}} = 4NZ^2 r_e^2 \alpha c \bar{g}$$

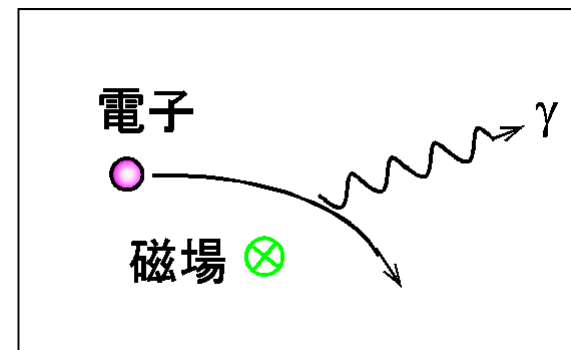


$$N(E_e) dE_e \propto E_e^{-p} dE_e \rightarrow E_\gamma^{-p} dE_\gamma$$

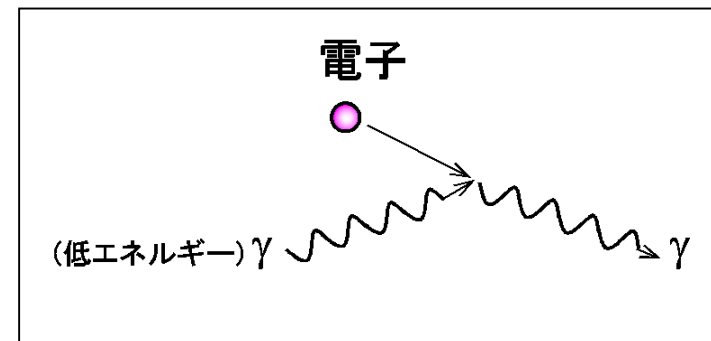
シンクロトロン放射・逆コンプトン散乱

- 反応相手は星間磁場・光子
- σ_T はトムソン散乱の断面積
- エネルギー損失はエネルギーの二乗に比例
 - 高エネルギー電子のエネルギー損失および放射

$$-\left(\frac{dE}{dt}\right)_{\text{sync}} = \frac{4}{3}\sigma_T c \gamma^2 U_{\text{mag}}$$



$$-\left(\frac{dE}{dt}\right)_{\text{IC}} = \frac{4}{3}\sigma_T c \gamma^2 U_{\text{rad}}$$



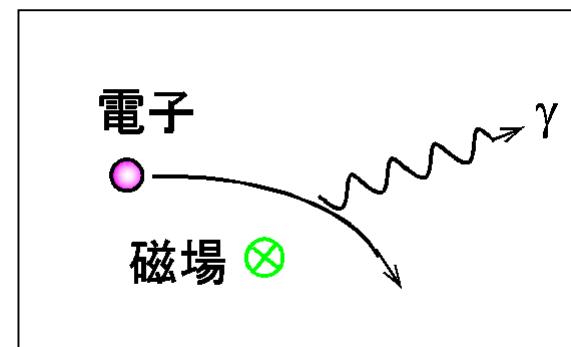
$$N(E_e)dE_e \propto E_e^{-p}dE_e \rightarrow E_\gamma^{-(p+1)/2}dE_\gamma$$

シンクロトロン放射

- 反応相手は星間磁場
- σ_T はトムソン散乱の断面積
- エネルギー損失はエネルギーの二乗に比例
- 強度が最大となる周波数は γ^2 に比例する。数字を入れると

$$\nu_{\max} = 0.12(\gamma / 10^4)^2 (B / 1 \mu\text{G})(\sin \alpha)[\text{GHz}]$$

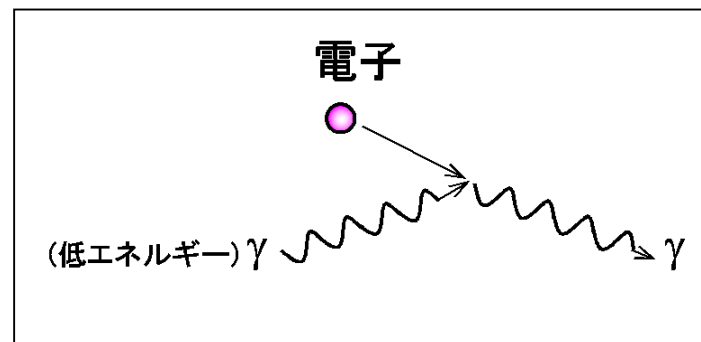
したがって星間空間のGeV電子は、~1 GHzの電波を出す。



- 反応相手は星間光子
- σ_T はトムソン散乱の断面積
- エネルギーの二乗に比例
- 平均すると、元の光子のエネルギーの $\sim\gamma^2$ 倍になるので、1 GeVの電子に対し
 - CMB (~ 1 meV) \rightarrow 4 keVつまりX線
 - 可視光(~ 1 eV) \rightarrow 4 MeVつまりガンマ線

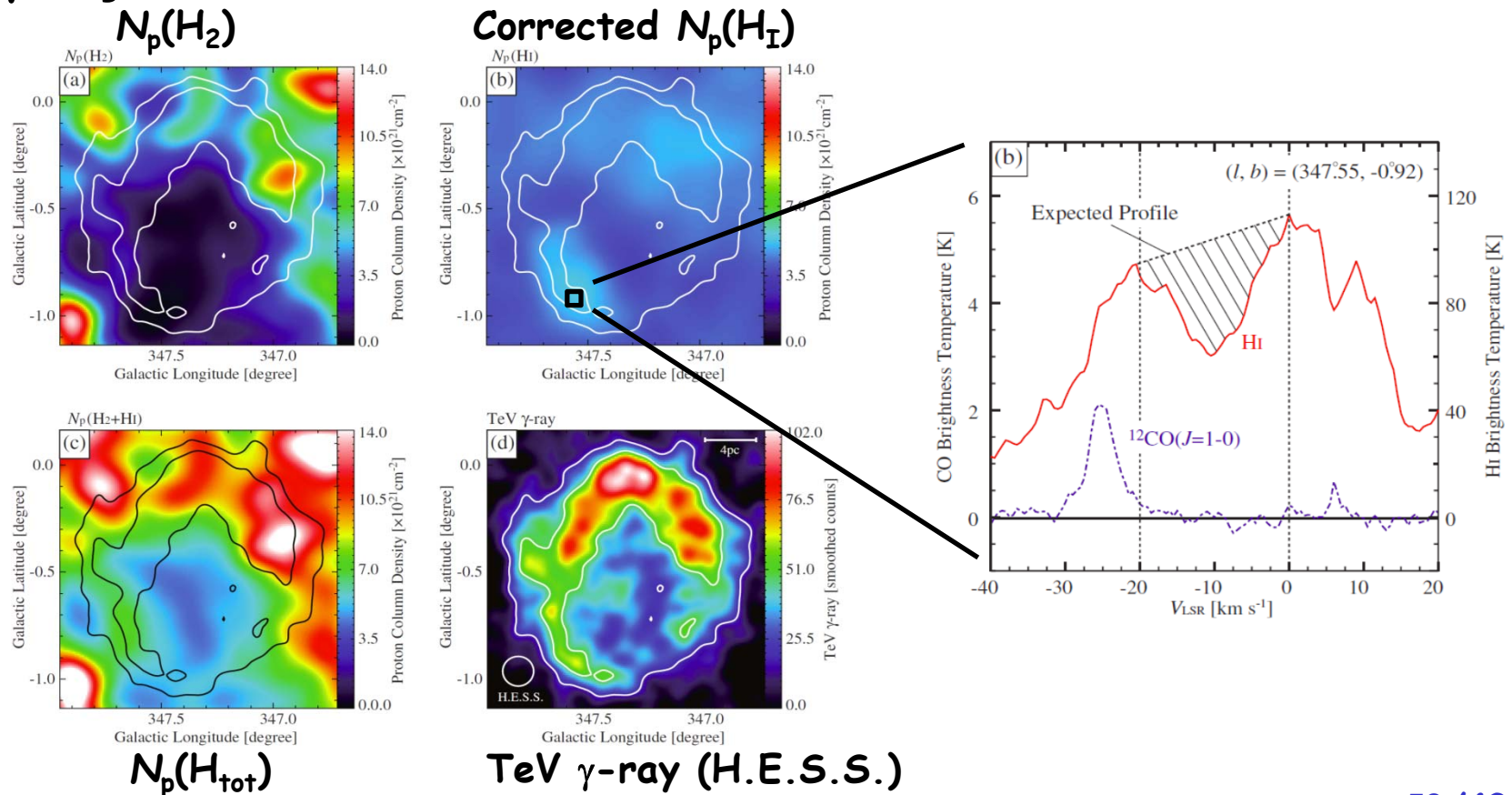
$$-\left(\frac{dE}{dt}\right)_{\text{IC}} = \frac{4}{3} \sigma_T c \gamma^2 U_{\text{rad}}$$

$$\overline{E_{\text{IC}}} = \frac{4}{3} \gamma^2 E_0$$



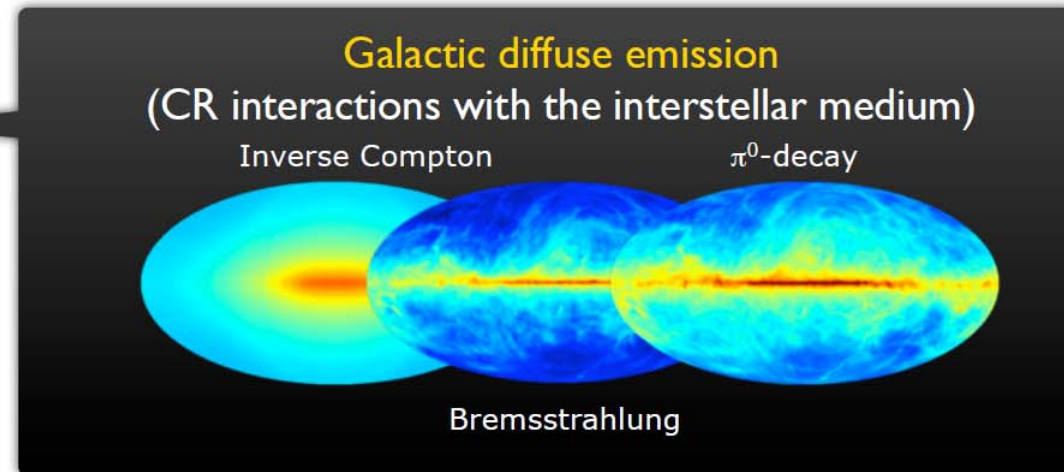
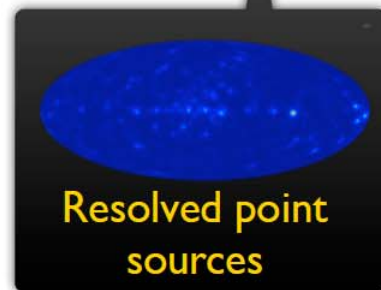
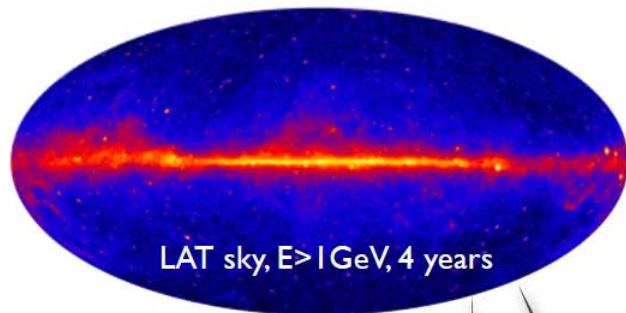
Dark Gas Seen in TeV γ -rays

- Fukui+12 claimed there exist considerable amount of “dark H_I ” in RX J1713.7-3946 by comparing H_I , CO and γ -rays



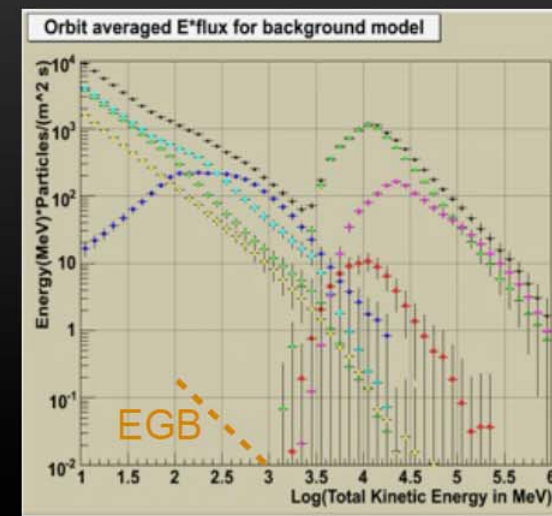
Extragalactic Gamma-ray Background (EGB)

(taken from M. Ackermann's talk)



Residual charged cosmic rays
Protons, nuclei, electrons +
positrons, misclassified as
gamma-rays by event
selection filters

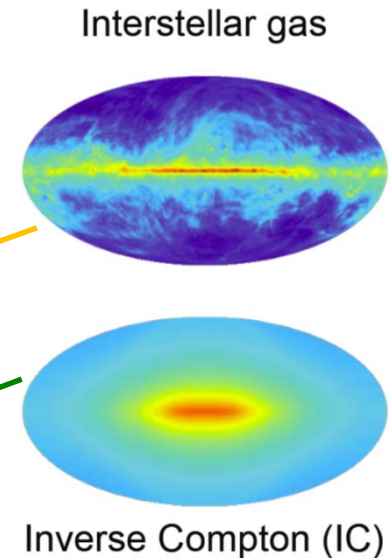
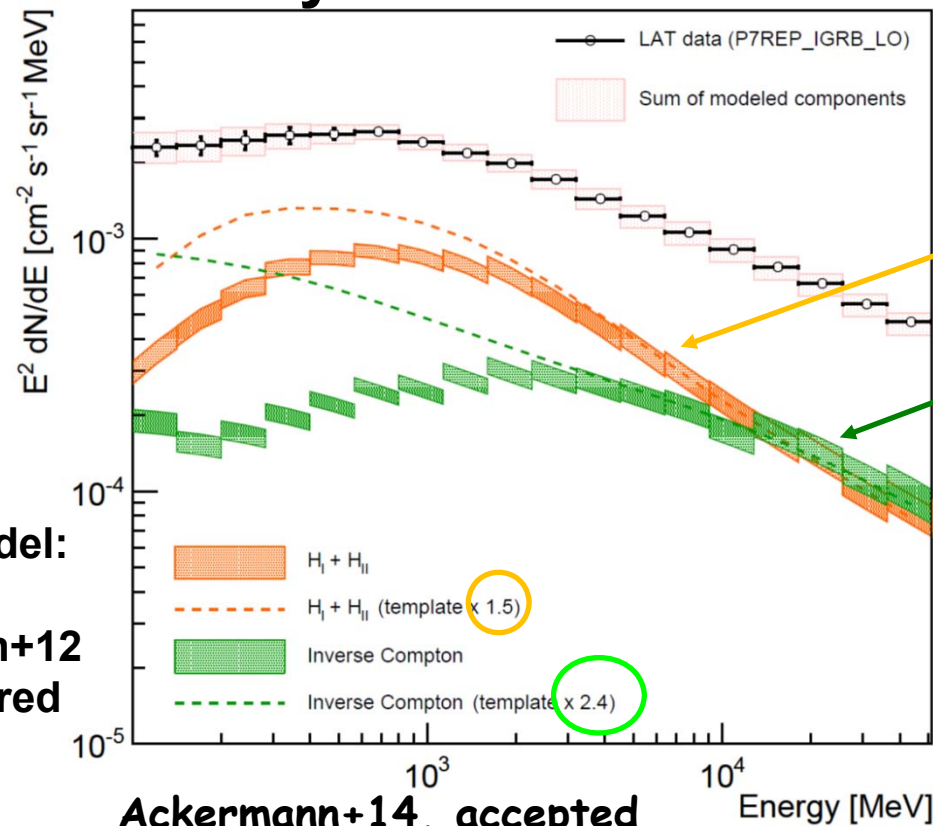
γ -rays from the Earth limb
 γ -rays $\ll 1 \text{ GeV}$ with poor
directional reconstruction



Uncertainty of IC inferred from EGB study

(taken from M. Ackermann's talk)

- Study of extragalactic γ -ray background (EGB) shows not only gas component (CR-p) but also IC (CR-e) is not fully understood yet

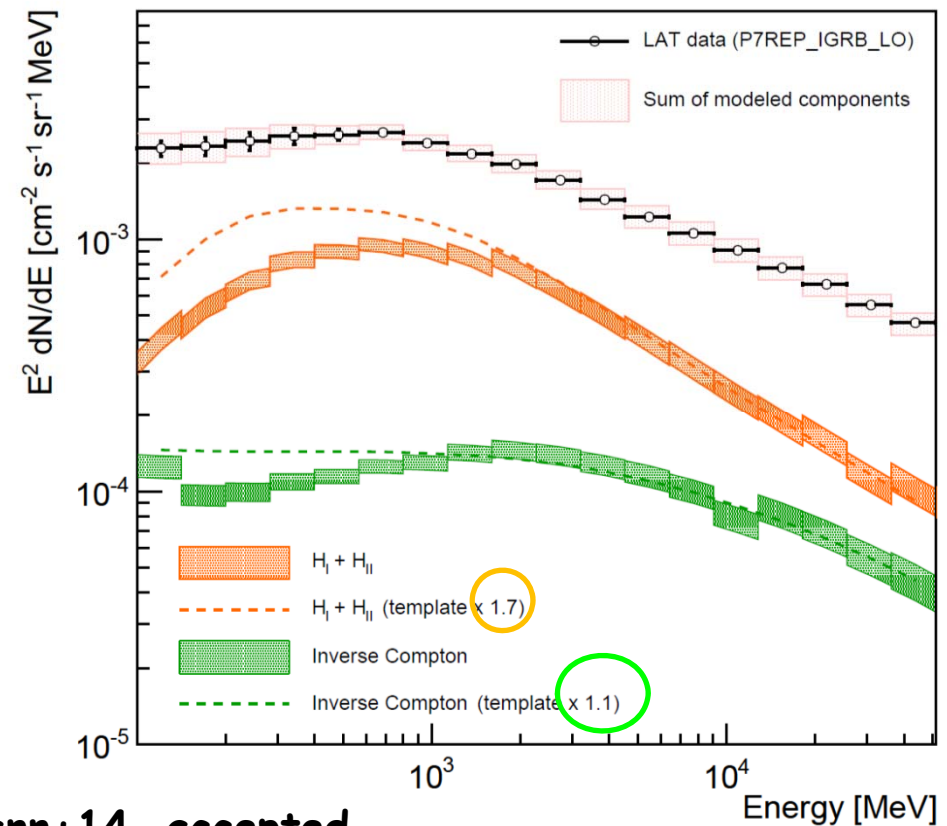
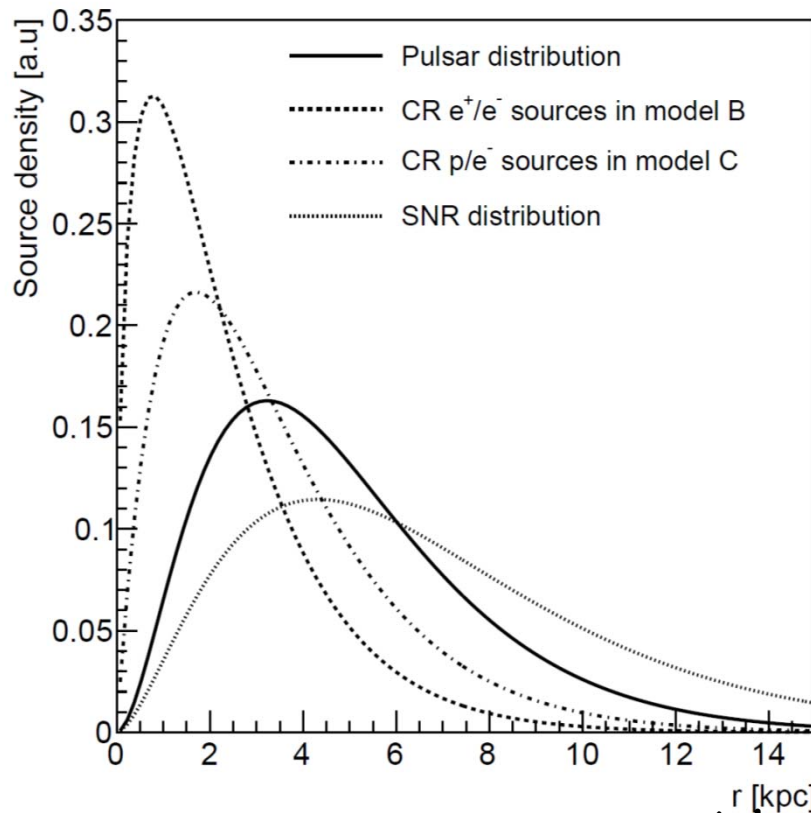


Results by a baseline model:
CR injection/propagation
scenario as in Ackermann+12
(not a canonical or preferred
model)

Ackermann+14, accepted
(CA: Ackermann, Bechtol)

An alternative foreground model

- Model B: an additional population of electron-only sources located near the Galactic center (just as an example to better represent measured IC)**



Ackermann+14, accepted
(CA: Ackermann, Bechtol)

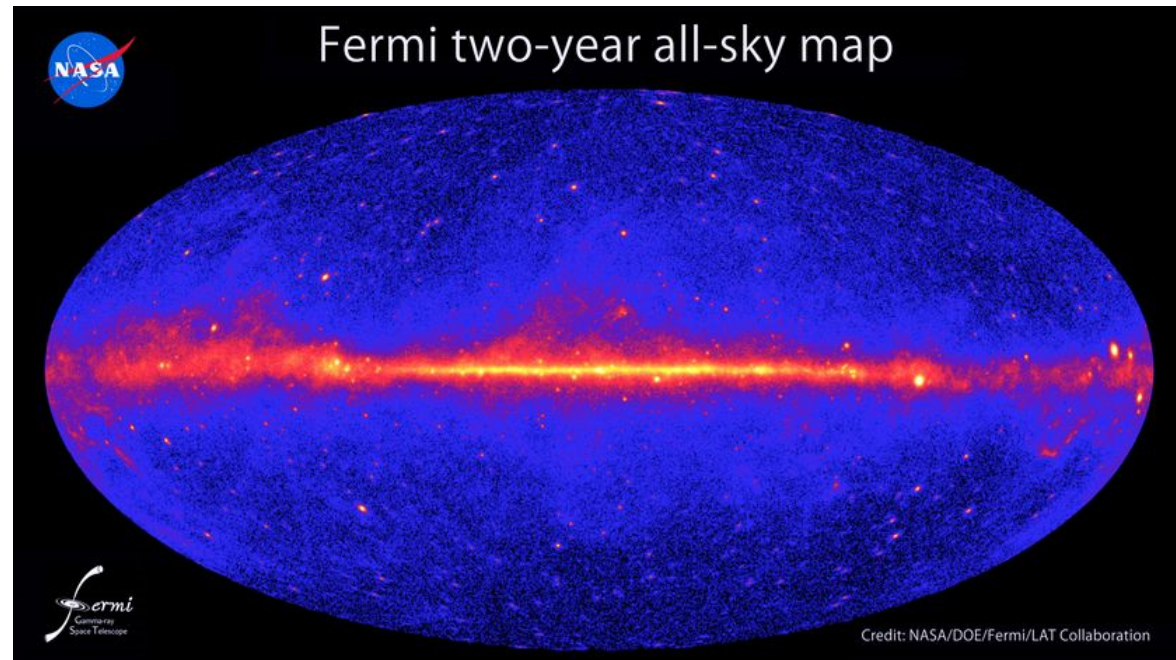
Fermi Gamma-ray Space Telescope

- Fermi = LAT + GBM
- LAT = GeV Gamma-ray Space Telescope (20 MeV ~ >300 GeV; All-Sky Survey)
(GC-emphasized observation started in 2013 Dec.)



Cape Canaveral,
Florida

T. Mizuno et al.



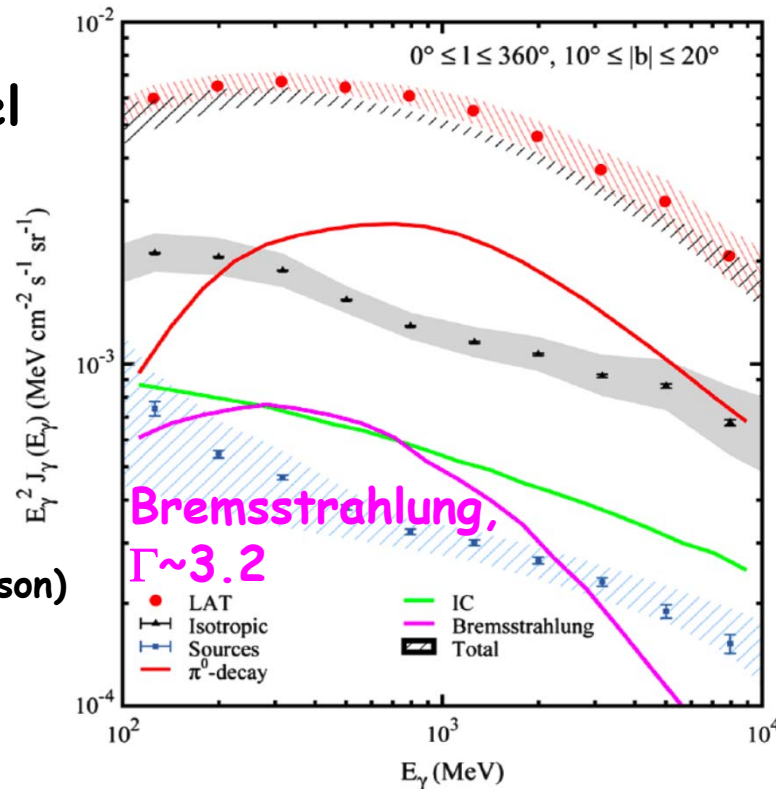
1873 sources
Nolan+ 2012, ApJS 199, 31

Processes to Produce γ -rays (2)

$$\gamma\text{-rays} = \text{CRs} \times \text{ISM (or ISRF)}$$

γ -ray data and model
(mid-lat. region)

Abdo+09, PRL 103, 251101
(CA: Porter, Strong, Johanneson)



π^0 decay, $\Gamma \sim 2.7$

(isotropic)

Inverse Compton, $\Gamma \sim 2.1$

Bremsstrahlung, $\Gamma \sim 3.2$

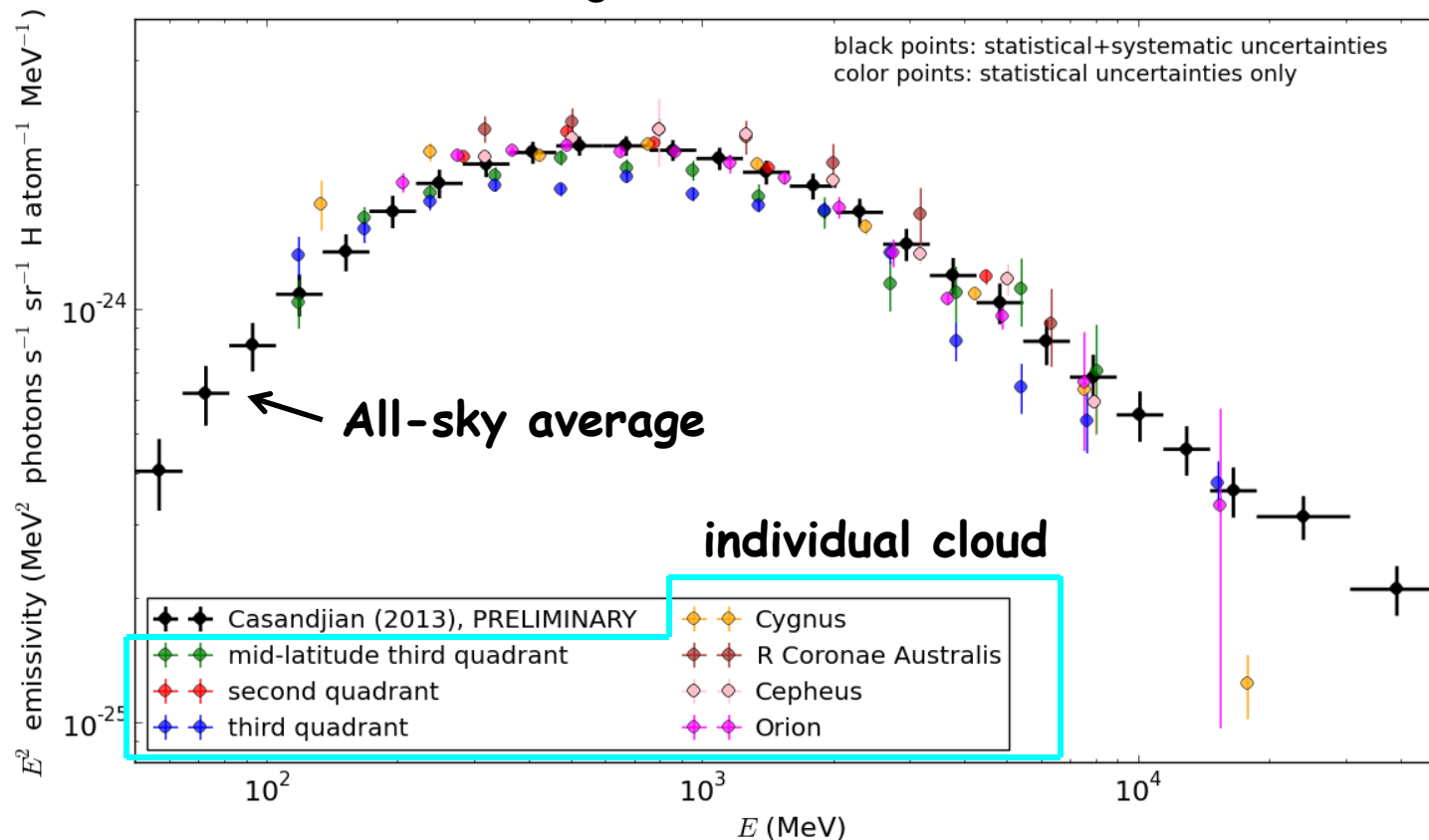
A powerful probe to study CRs and ISM

Pro: optically-thin, "direct" tracer of all gas phases

Con: low-statistics, contamination (isotropic, IC), depend on CR density

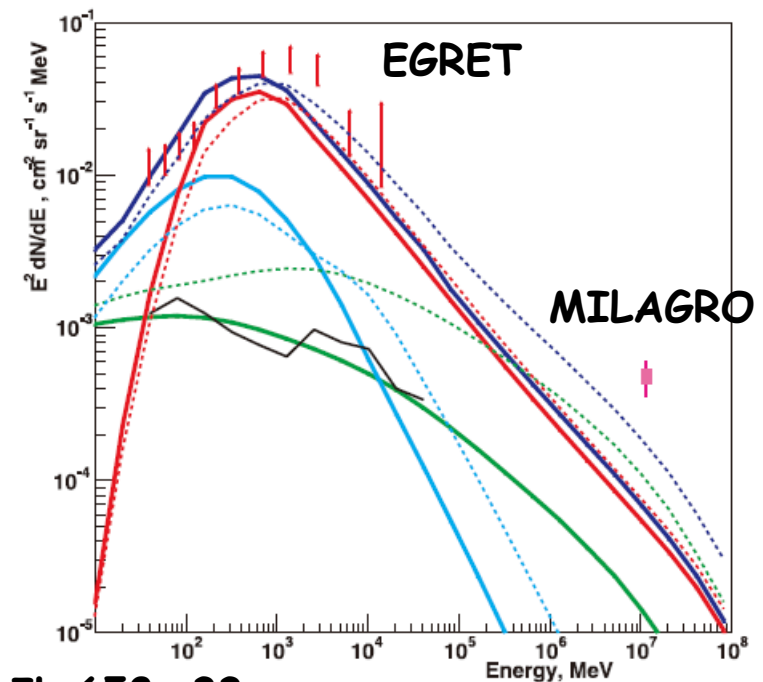
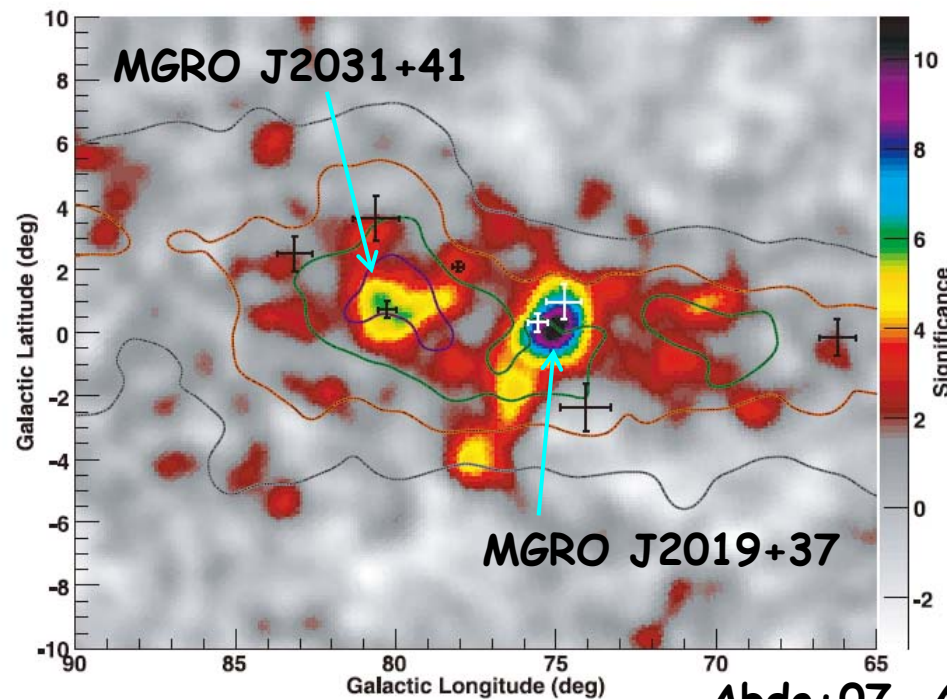
Compilation of local I_{CR}

- “local” CR densities among regions agree by a factor of 1.5, within systematic uncertainty (mostly due to the assumption of T_s)



The Cygnus Region (MILAGRO)

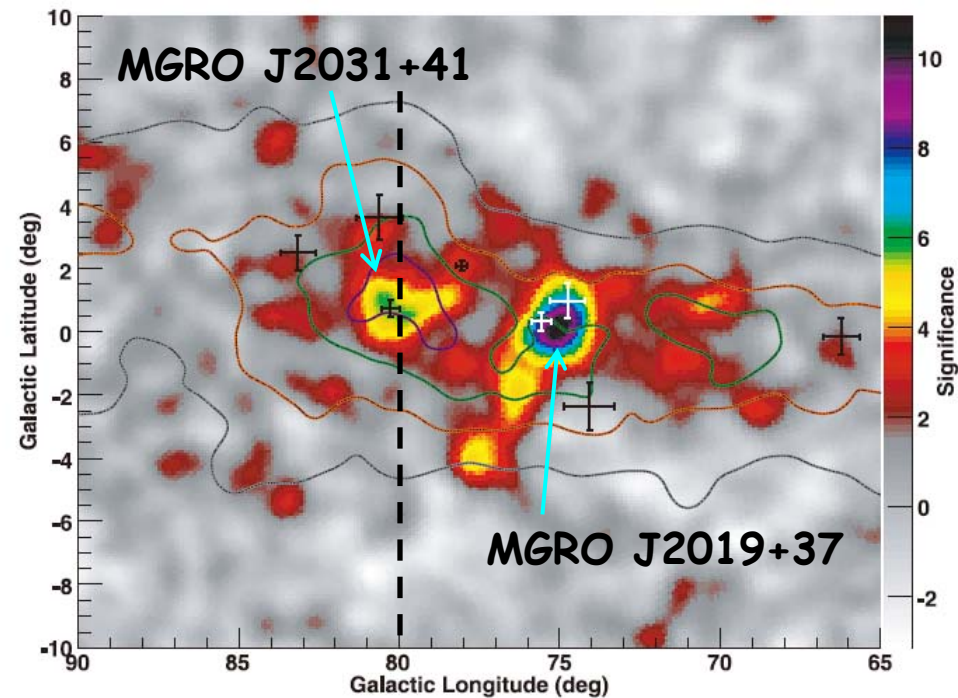
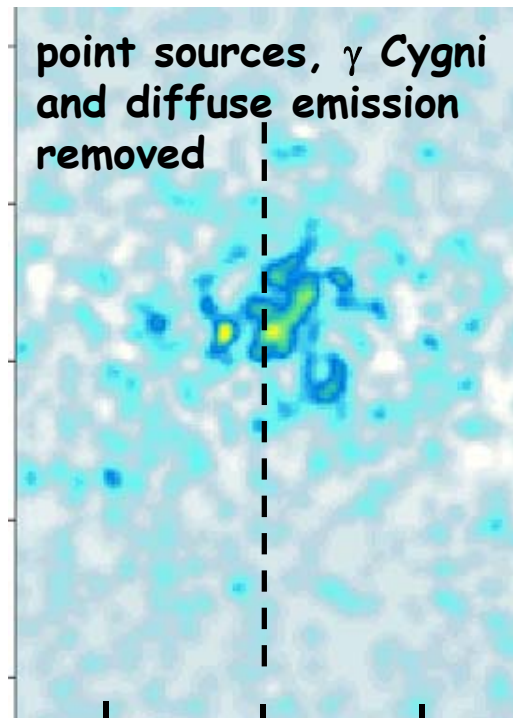
- Very rich region of massive-star formation at 1.4 kpc
- Two sources + diffuse emission at TeV (MILAGRO)
 - correlation with matter density
 - diffuse flux exceeds the prediction by local CR (solid line)



Abdo+07, ApJL 658, 33
Abdo+08, ApJ 688, 1078

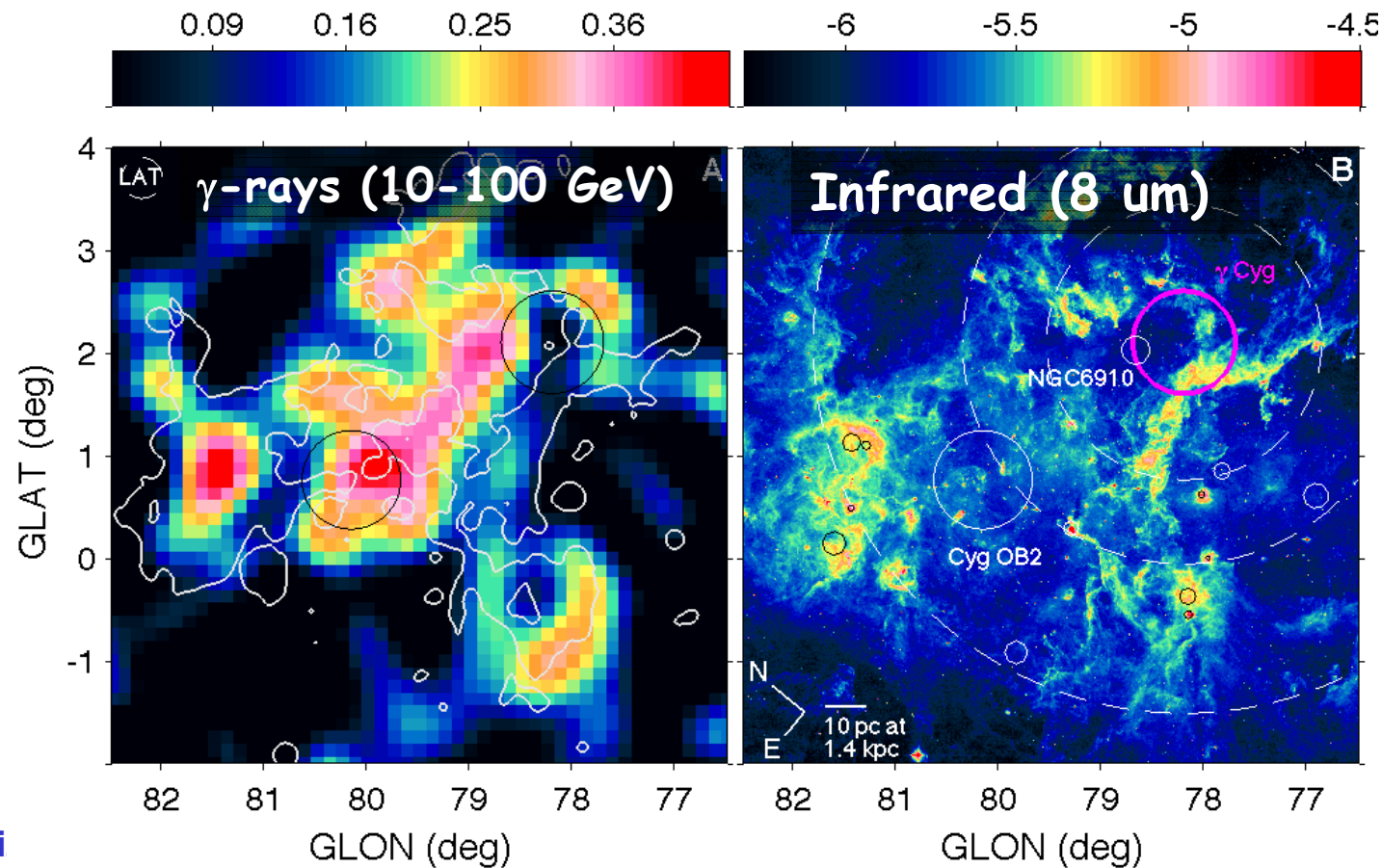
The Cygnus Region (Fermi)

- Very rich region of massive-star formation at 1.4 kpc
- Detailed study by Fermi-LAT
 - with known sources and diffuse gammas subtracted, extended hard (>10 GeV) excess revealed in OB2 association



γ -ray Excess in the Cygnus Region

- γ -ray excess fills the cavities carved by stellar winds and ionization fronts
 - likely interstellar origin rather than multiple sources



Spectra of CRs in Cygnus Cocoon

- CRs with local spectrum are too weak or too soft
- Hard, freshly accelerated CRs are required

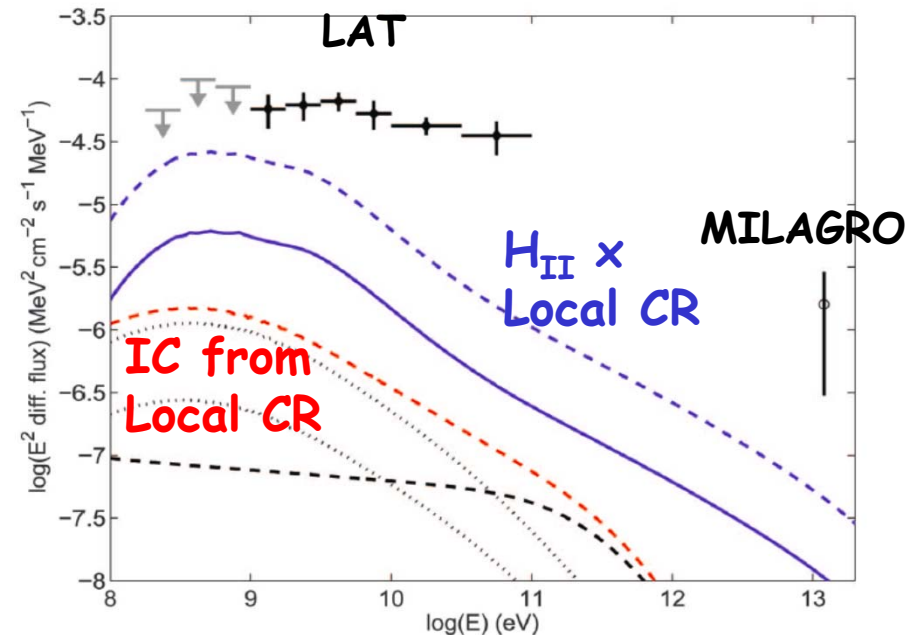
– Hadronic

$$\left(\frac{dN}{dE}\right)_{\text{loc}} \times (1.5 - 2) \left(\frac{E}{10 \text{ GeV}}\right)^{0.3}$$

– Leptonic

$$\left(\frac{dN}{dE}\right)_{\text{loc}} \times 60 \left(\frac{E}{10 \text{ GeV}}\right)^{0.5}$$

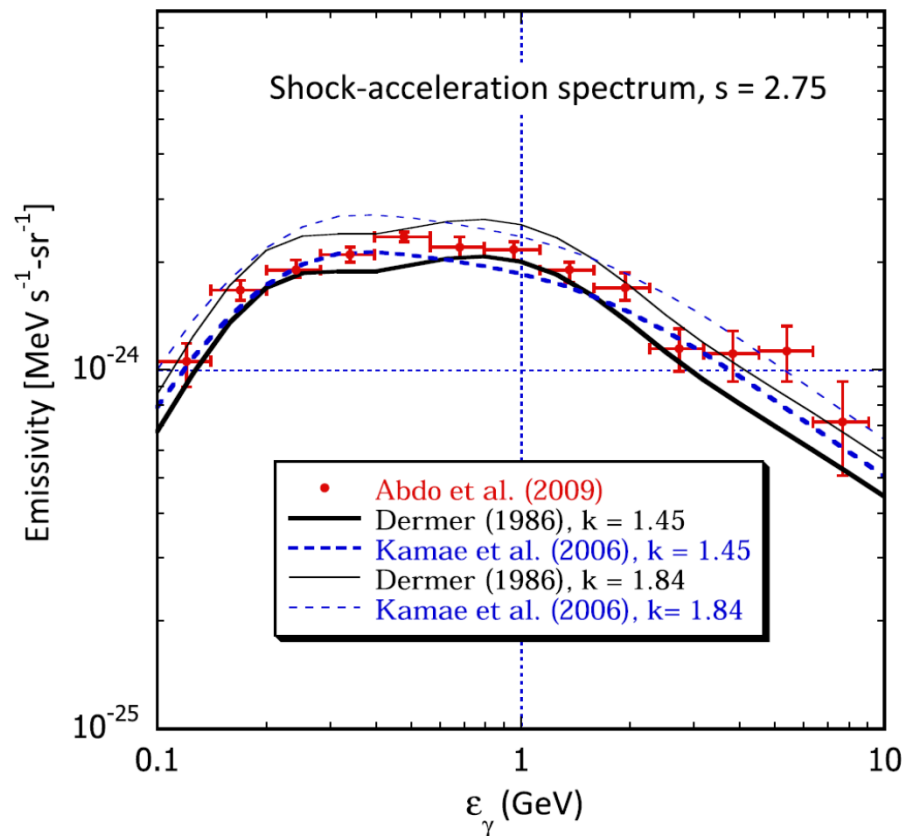
Evidence for
freshly-accelerated CRs
from star-forming regions



Ackermann+11, *Science* 334, 1103
(CA: Tibaldo, Grenier)

Uncertainty of Physics Process Model

- **Uncertainty of the Physics Model affects the γ -ray emissivity, or I_{CR} , at 10-20% level**



Dermer12, PRL 109, 091101

Dust- W_{HI} Relation

- Large scatter of dust- W_{HI} relation has been recognized recently. Whether this is due to (1) optically-thick H_I , or (2) non-uniform dust property, is under debate. (e.g., Fukui+14, Planck Collaboration 2013)
- Correlation with γ -ray is important to settle the issue

