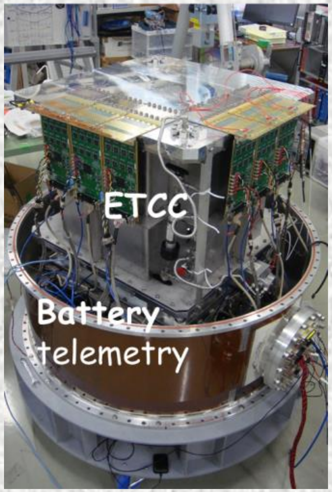
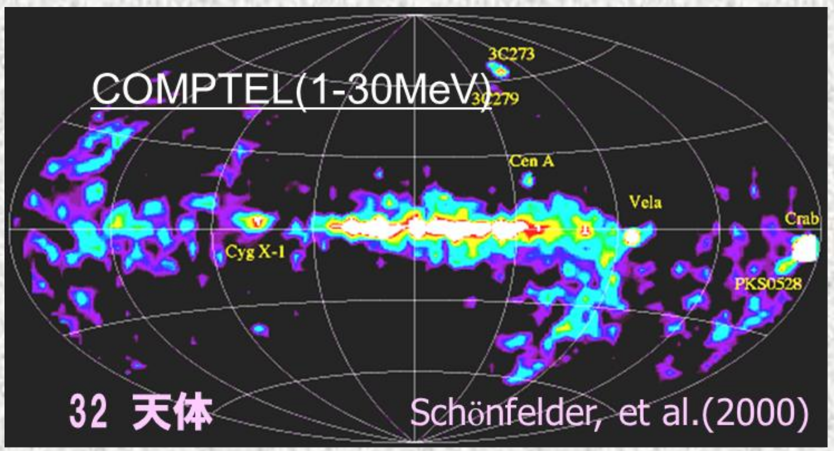
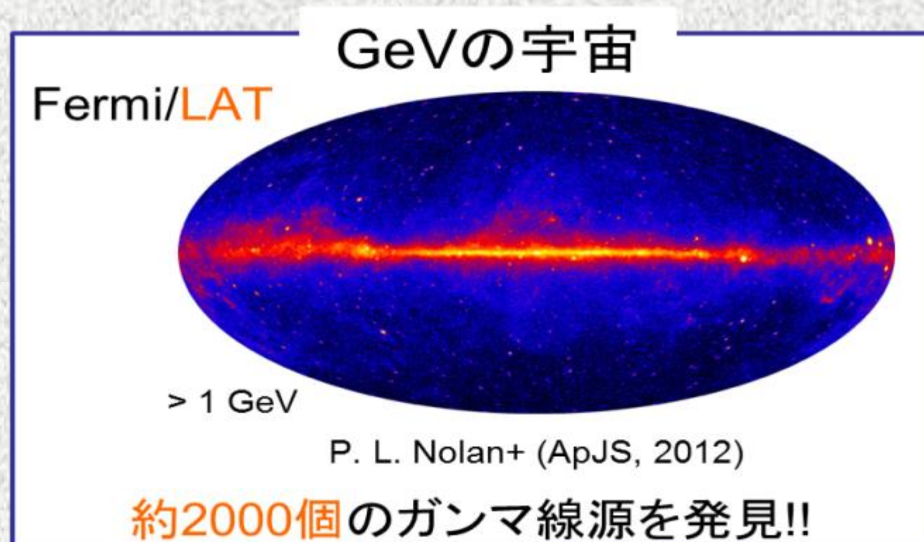
SMILE2+とSubGeV & MeV WIMPレビュー

SMILE-II+





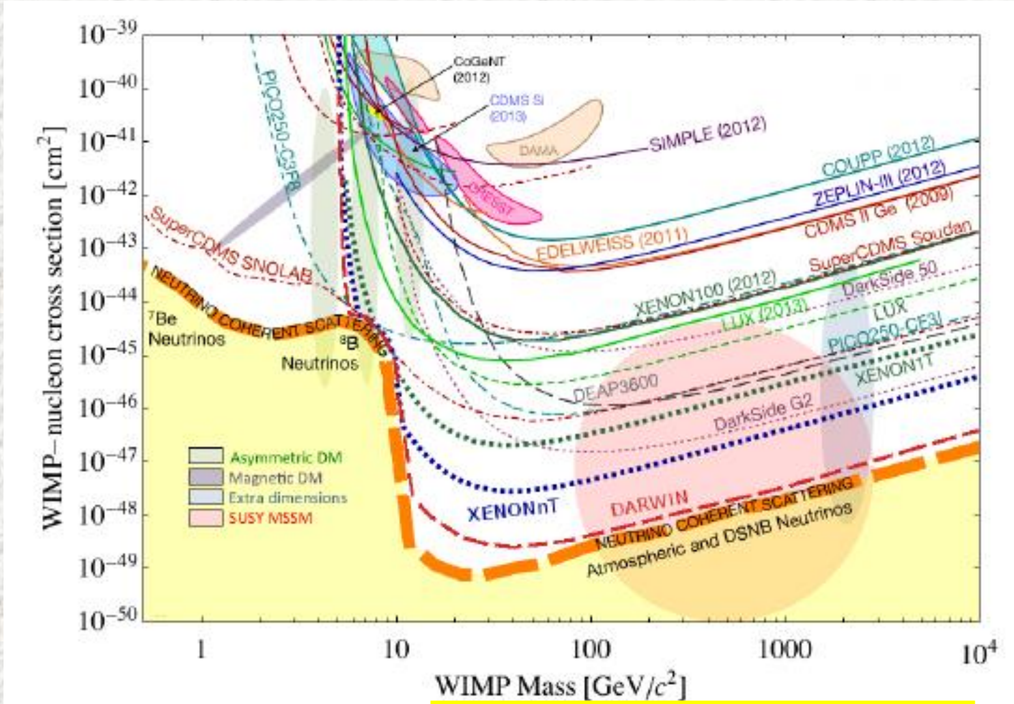


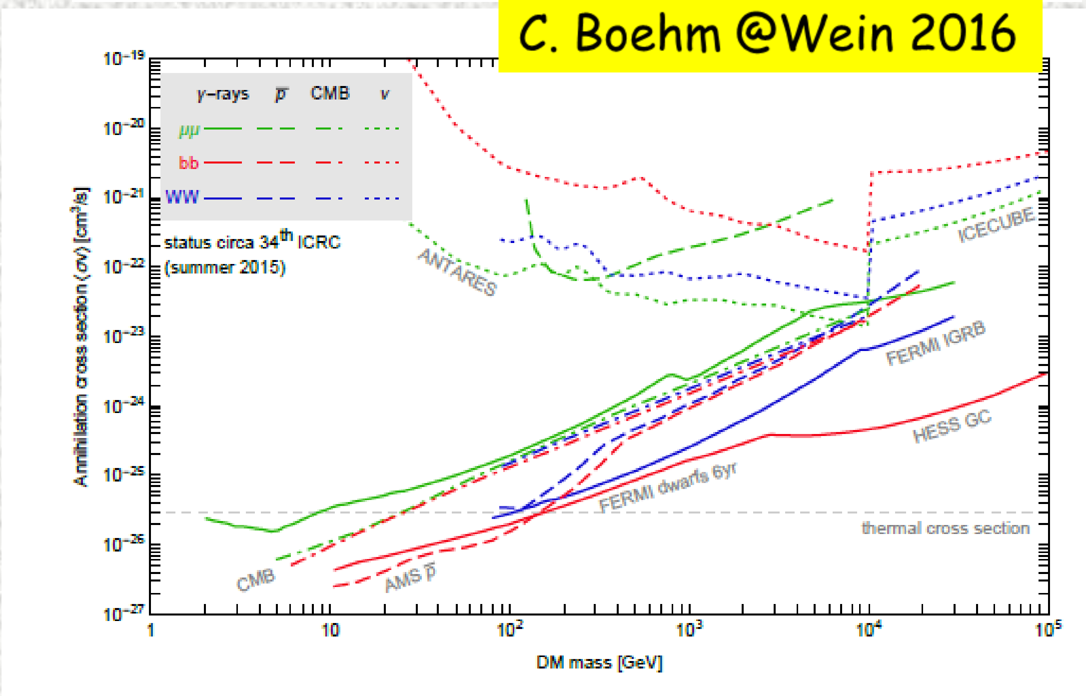
5th/July/2019@Waseda DM Meeting

T. Tanimori on behalf of SMILE-Project,
Cosmic-ray group, Physics Division, Kyoto University, Japan

Contents

- Indirect Search in GeV γ mainly Fermi results
- MeV Sub-MeV DMとは？
- MeV γ region の特徴
- SMILE 2+　紹介
- SMILE2+ 実験の解析
- まとめ





C. Boehm @Wein 2016

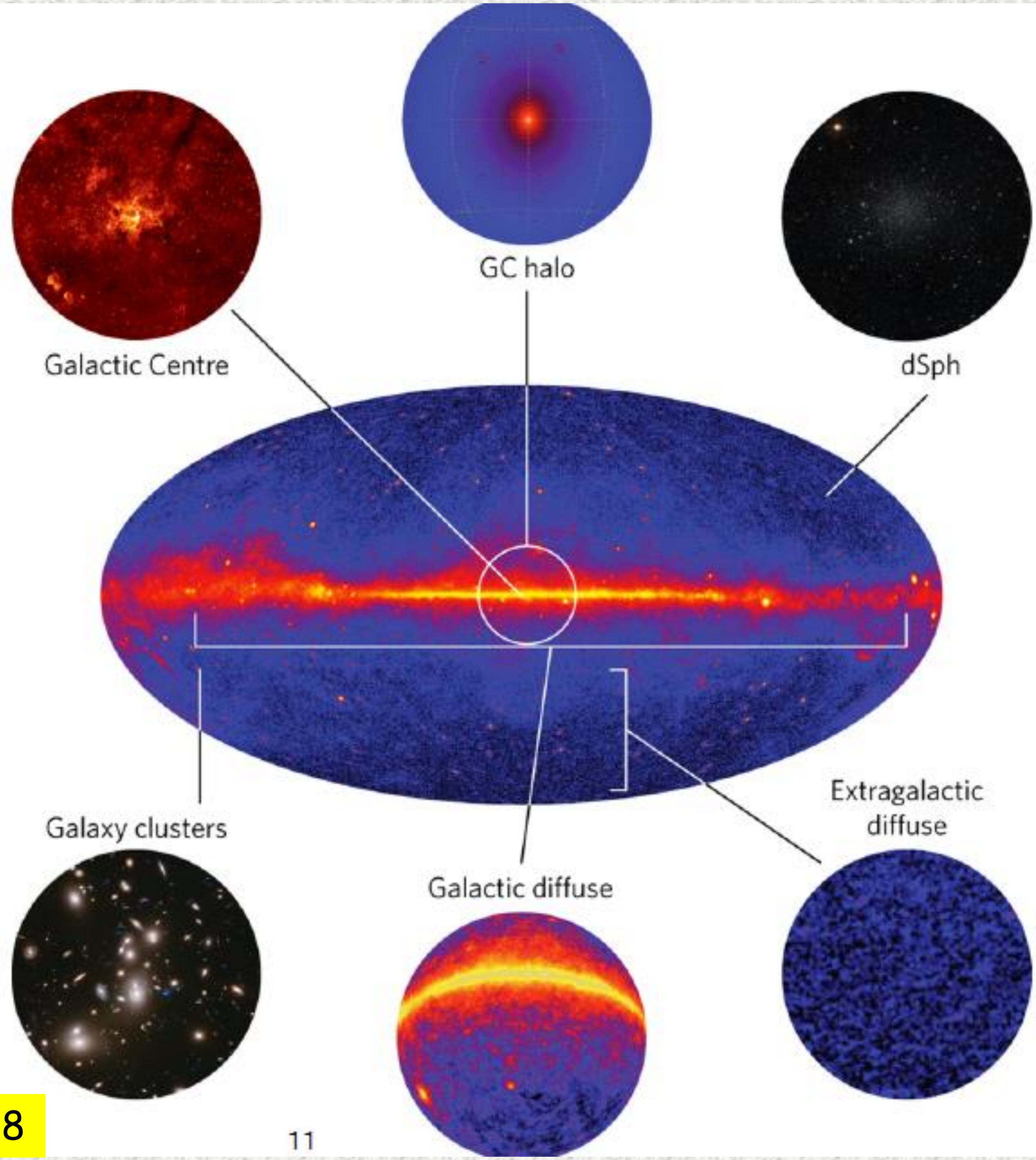
Targets for dark matter gamma-ray searches

$$\int d\ell\, \rho\left[r(\ell,\psi)\right]^2$$

- dedicated searches for gamma-ray lines
- similar targets for radio searches (synchrotron)

Conrad & Reimer
Nature Phys. 13 (2017)

F. Calore@Fermi.sym.2018

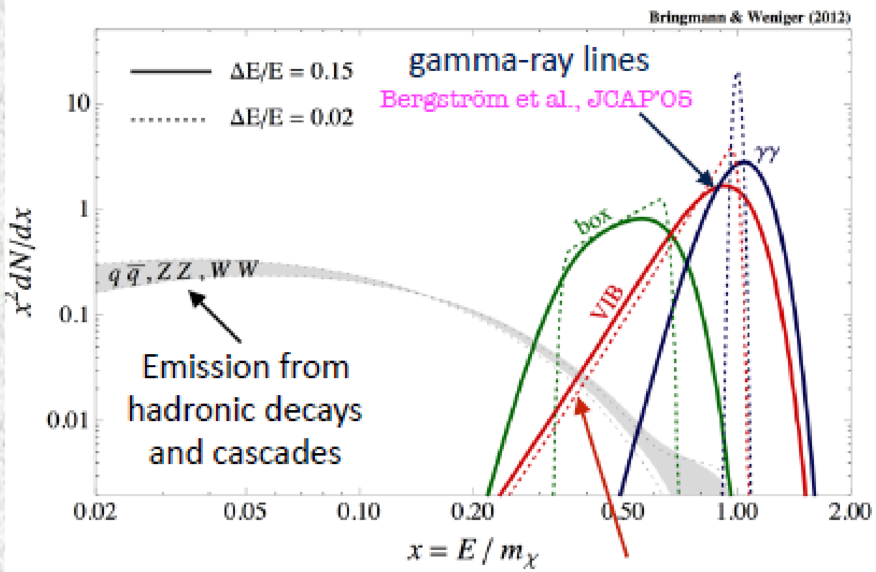


Dark matter signal predictions

F. Calore@Fermi.sym.2018

$$\Phi(E,\psi) = \frac{\sigma_A v}{8\pi m_\chi^2} \boxed{\frac{dN_\gamma}{dE}} \int d\ell \boxed{\rho\left[r(\ell,\psi)\right]^2}$$

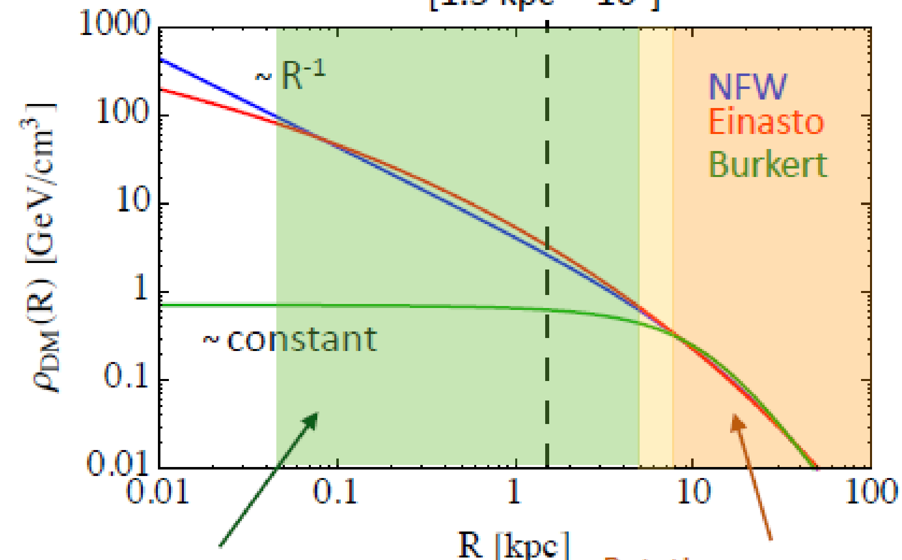
Spectral energy distribution (spectral features, Sommerfeld enhancement for TeV scale DM, radiative emission for leptonic final states)



EM and EW corrections

Bringmann, FC+ JHEP'08; Ciafaloni+ JCAP'11; Bringmann&FC PRL'14

Spatial distribution in astrophysical targets (asymmetric density profiles, substructures boost factor, local DM density)



Simulations w/ baryons

Schaller,FC+ MNRAS'16; FC+JCAP'15

Rotation curve

Iocco+ Nature Phys.'15

Dwarf spheroidal galaxies

Target:

- **dSphs galaxies**: "clean" target for DM searches, high light-to-mass ratio and no astrophysical emission Winter+ ApJ'16

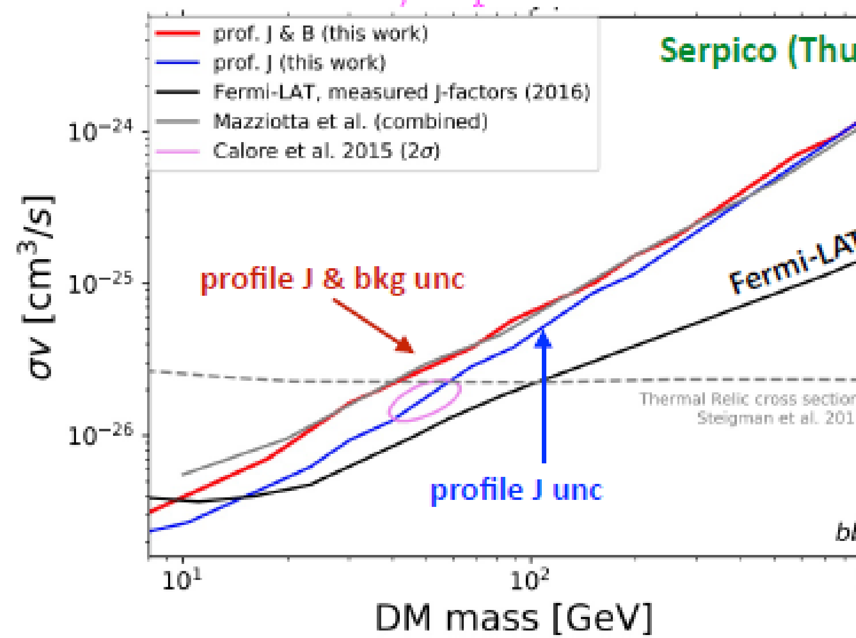
Status:

- Exclude thermal cross section below 100 GeV (16 dSphs stacking, 6 yr of data) Albert+ ApJ'17
- Syst unc **J-factor determination** for ultra-faint dSphs (tri-axiality, contamination, velocity anisotropy) Ullio&Valli JCAP'16, Hayashi+ MNRAS'16, Klop+ PRD'17
- Syst unc **background mis-modelling** are important (3x weaker limits) FC, Serpico & Zaldivar 1803.05508

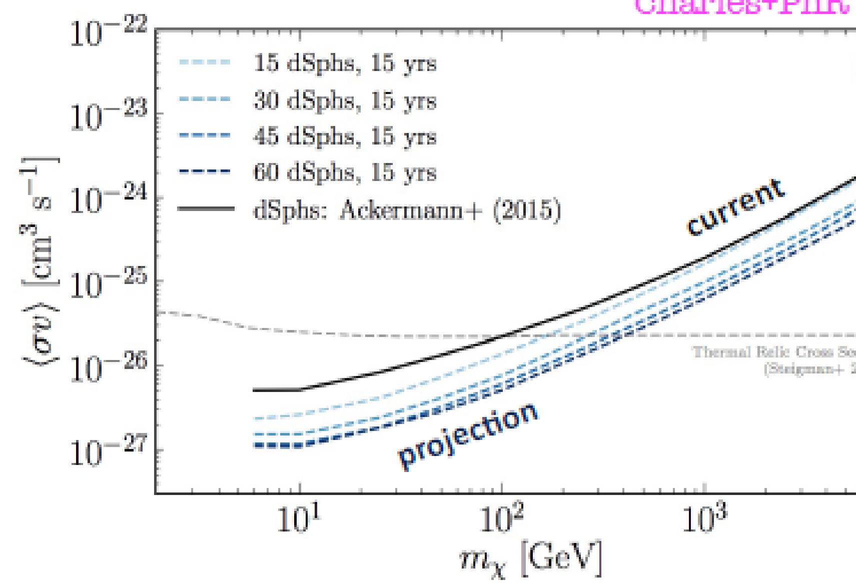
Future:

- New data from Fermi-LAT (improvement by a factor of 2-5) Charles+PhR'16
- Expected hundreds of new dSphs with SDSS, Pan-Starrs, DES and LSST (> 2019) Hargis+ApJL'14

FC, Serpico & Zaldivar JCAP'1



Charles+PhR'



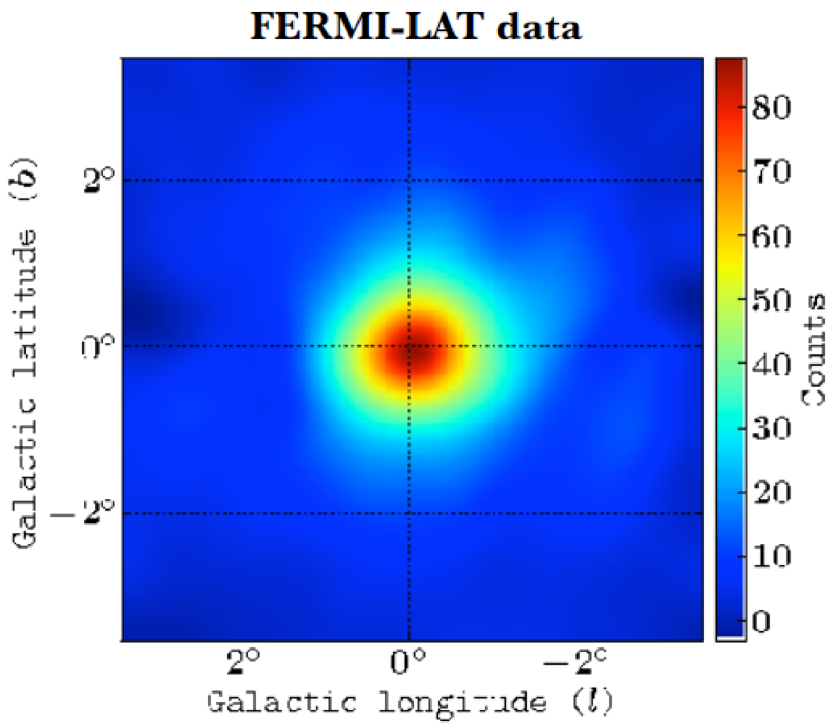
C. Boehm @Wein 2016

The GeV excess

Hooper&Goodenough 2009

FERMI-LAT 2009

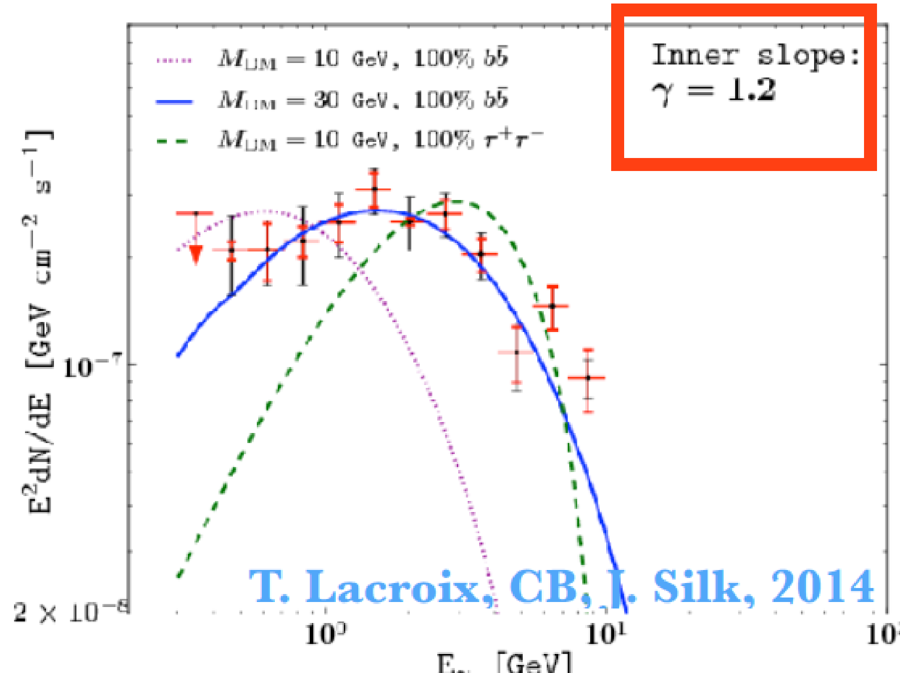
arXiv:1306.5725



10-30 GeV DM annihilating mostly into b-quarks or muons

30 GeV

$$\sigma v \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$



T. Lacroix, CB, J. Silk, 2014

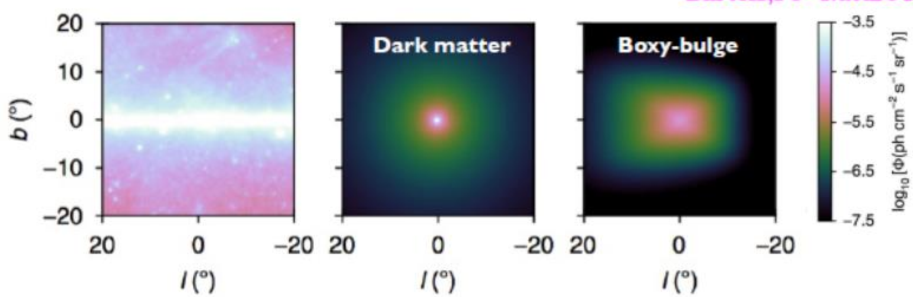
Astronomical sources

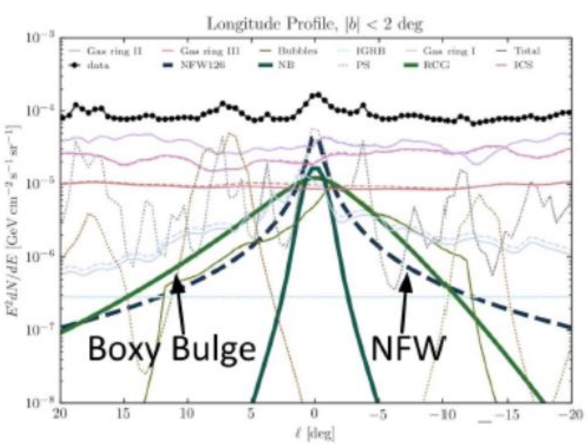
- 1. gammas from pion decays
  (ex. Stellar bulge, molecular clounds etc)
- millisecond pulsars in bulges

F. Calore@Fermi.sym.2018

Evidence for stellar bulge emission

Bartels,FC+ Nature Astronomy'18

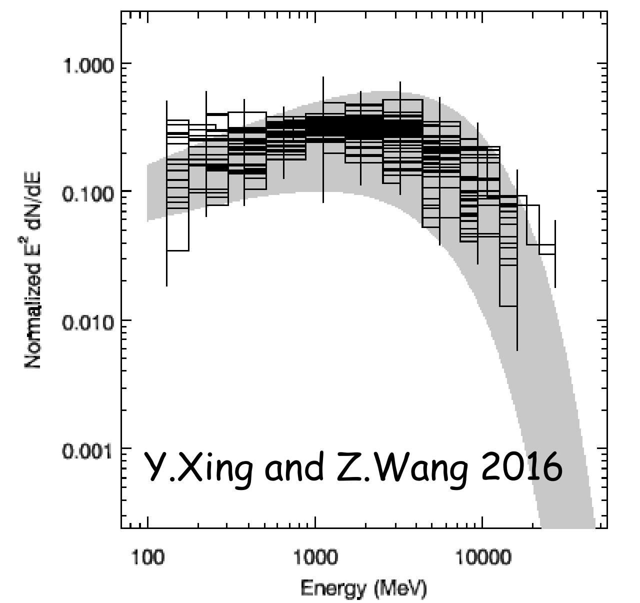




- ✓ **Stellar bulge model** (boxy + nuclear bulge) is **preferred** over (spherically symmetric) DM models with high statistical significance (16σ)
- ✓ **Morphology** of the GCE is **more oblate** than what found before
- ✓ Large enough ROI to discriminate foreground components (stable results)

[See also Macias+ Nature Astronomy'18]

Normalized spectra of 39 MSPs.

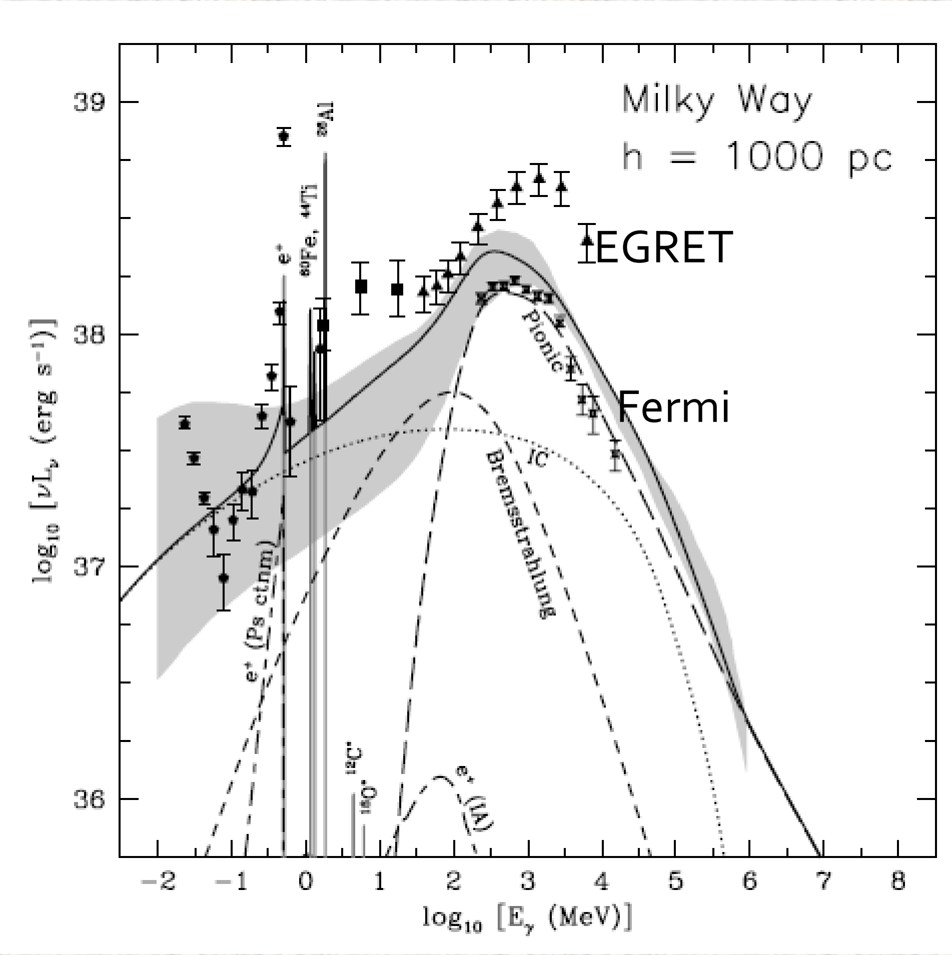


GeVからMeVへ

- GeV

Galactic Center Region
astnophysical sources 多数、Steller-bulge, Sgr A*, Molecular Clouds, Millisecond Pulsars,,,,

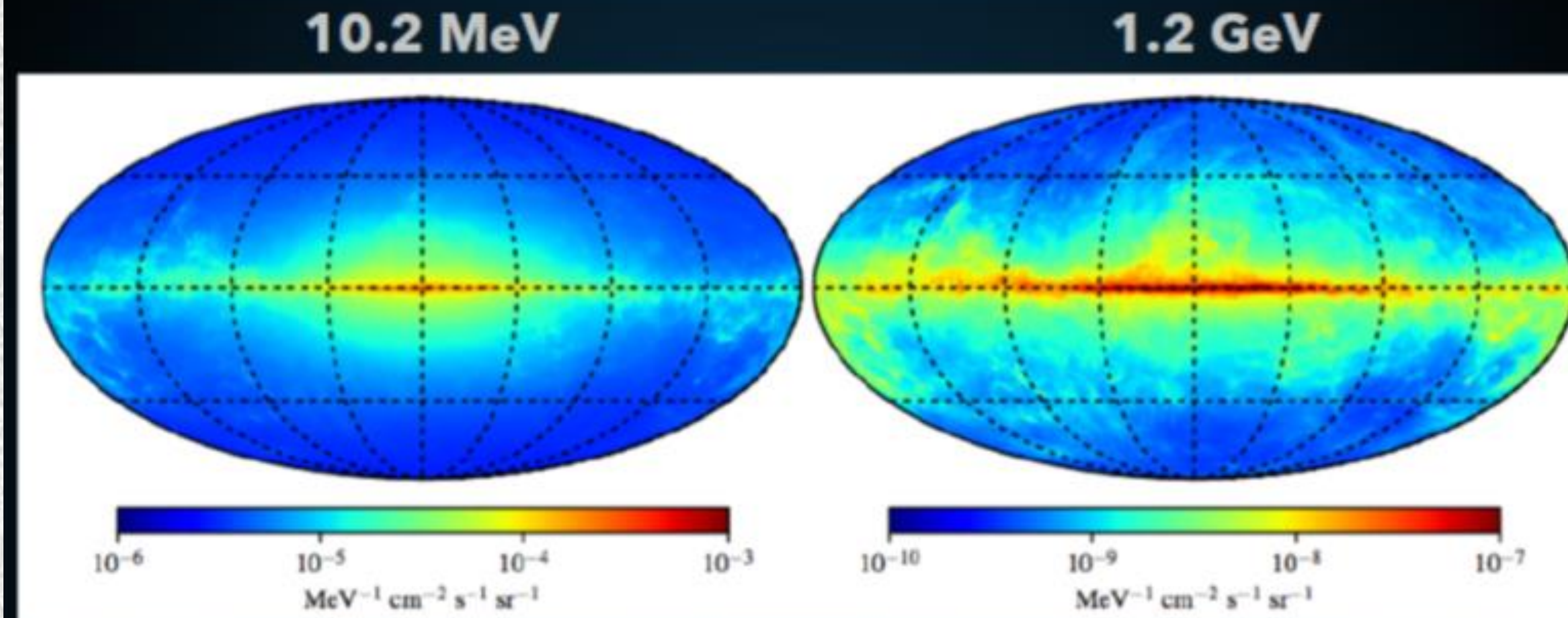
- MeV region <30MeV
gammas mainly from Inverse Compton and Bremss. from electron, positron



B. LACKI , S.HORIUCHI J F. BEACOM 2014 arXiv:1206.0772v3

T.LINDEN@AASM 2018

WHAT ABOUT THE BACKGROUNDS?



Porter et al. (1708.00816)

- The ISRF energy density is extremely smooth
  - Most of the substructure washes away, and you get very smooth background gamma-ray emission.

MeV ~Sub-GeV DM

Mass limit DM >~3MeV from CMB obs.

XX → γγ, $\pi^0\pi^0$->γγγ, γφ-> γγγ, φφ → γγγγ
XX →e+e-, $\pi^+\pi^-$, μ+μ-, φφ-> e+e-e+-e
Signal gammas from DM ,direct γ
& radiative γ from decayed e

＋ GEV DM からのe+ e-からのsecondary gammas
GeV より拡散が小さい！

それ以外 ●Axion Like Particles (ALPs)
10MeV gammas from SN （カットする）

●PBH thermail MeV gamma

THE ANNIHILATION SPECTRA WILL UNIVERSALLY BE HARD

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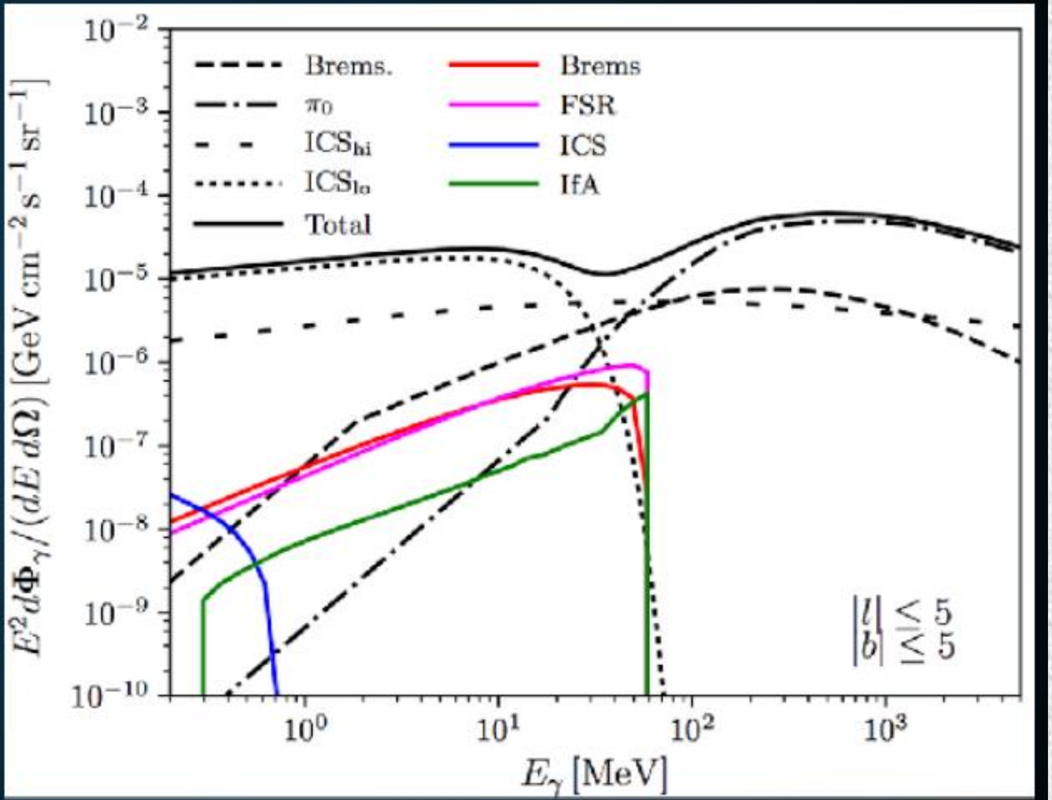
- Annihilation of 80 MeV DM -> e^+e^- produces gamma-rays primarily through final state radiation and bremsstrahlung.



- These spectra are brightest at the dark matter mass.

- **Comparison of multiple targets becomes significantly easier at MeV energies - look for identical energy cuts!**

ADDITIONAL COMPLEXITIES IN BACKGROUND MODELING

$$D_{xx} = \beta D_0 \left(\frac{\rho}{4\,\mathrm{GV}} \right)^{\delta}$$

$$t^{p}_{\rm pp} \simeq 3.1 \times 10^5\ \mathrm{yr} \left(\frac{n_H}{120\ \mathrm{cm}^{-3}} \right)^{-1},$$

$$t^{e}_{\rm inztn} \simeq 6.7 \times 10^5\ \mathrm{yr} \left(\frac{E}{\mathrm{GeV}} \right) \left(\frac{n_H}{120\ \mathrm{cm}^{-3}} \right)^{-1},$$

$$t^{e}_{\rm brems} \simeq 2.4 \times 10^5\ \mathrm{yr} \left(\frac{n_H}{120\ \mathrm{cm}^{-3}} \right)^{-1},$$

- Assuming Kolmogorov Diffusion in the MeV regime:
  - A ~10 GeV proton which produces a 1 GeV gamma-ray travels approximately: 2.8 kpc.
  - A 100 MeV electron which produces a ~1-10 MeV gamma-ray travels approximately: 0.5 kpc.
- **MeV diffuse emission will be more sensitive to local injection around 100 MeV.**

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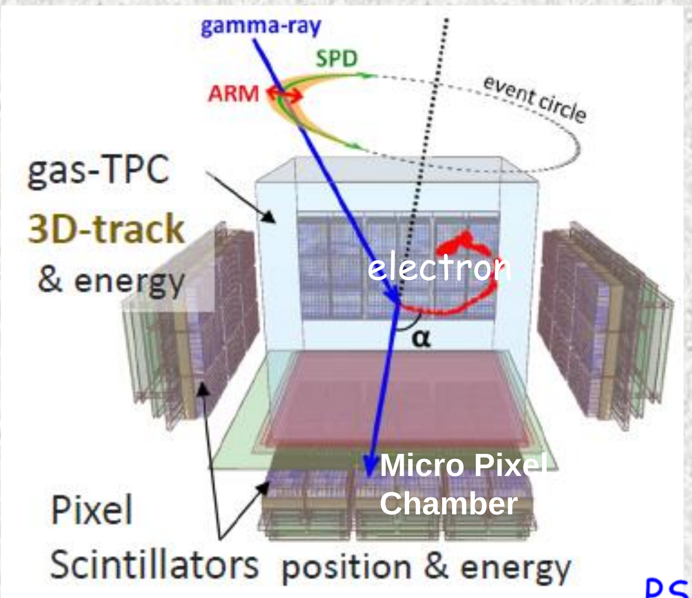
Electron Tracking Compton Camera (SMILE-II)

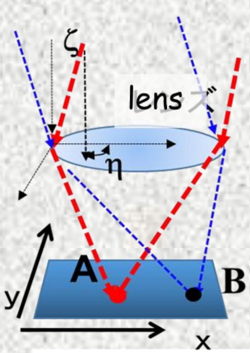


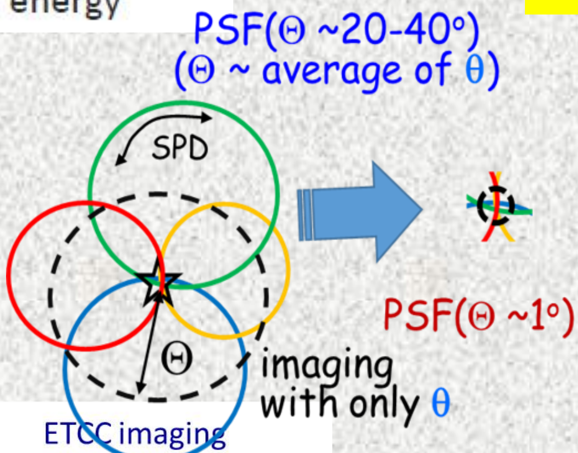
30cm-cubic Gas Time Projection Chamber
\+ Scintillator Array for scattered γ
--- tracking of recoil electron ---

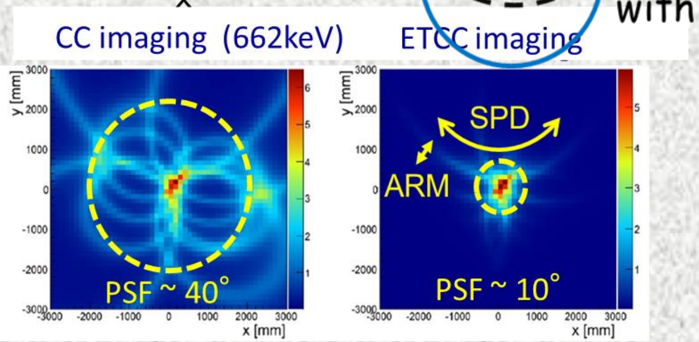
Measuring all parameters of Compton process

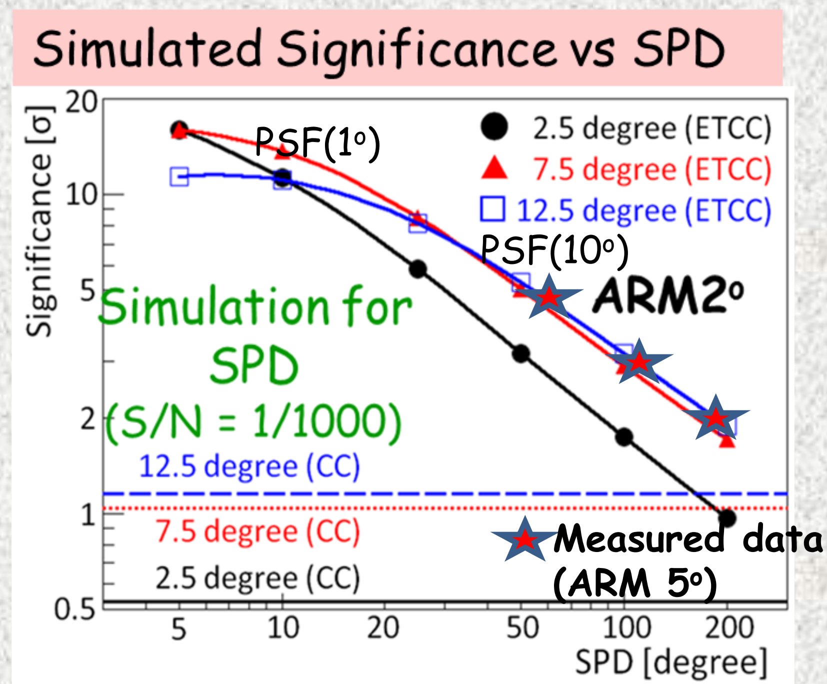
1. well-defined 2D-PSF similar to Xray & GeV
2. dE/dx + kinematical test using α
3. large Field of View (>4str)

Θ is a Half Power Radius (HPR)



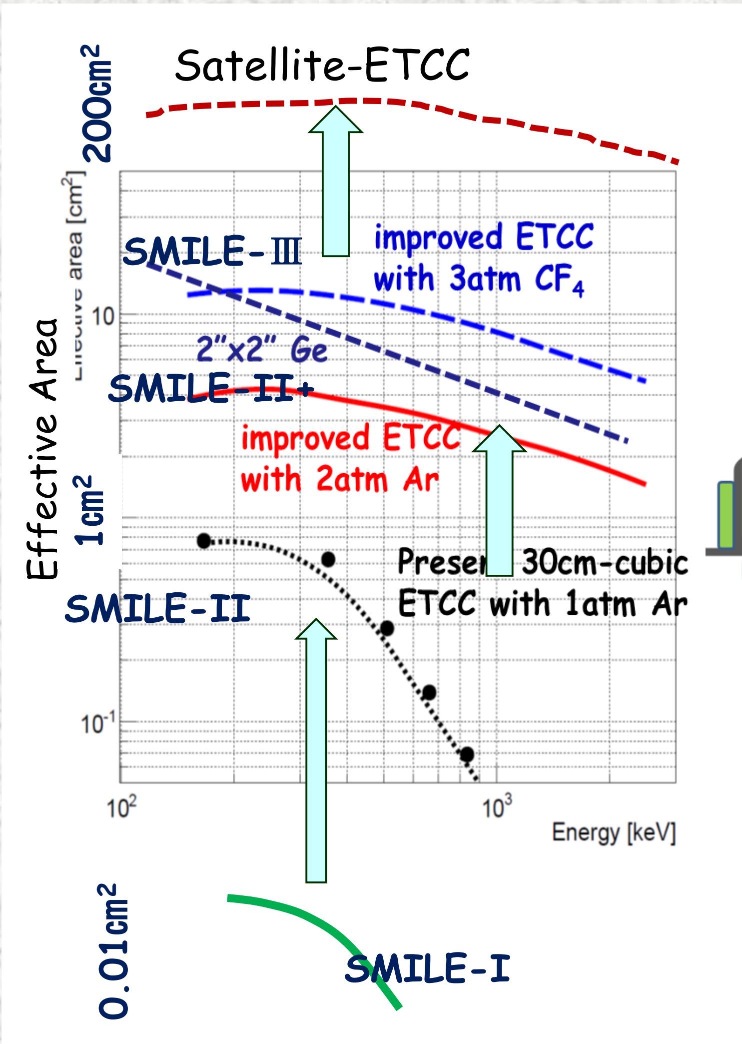




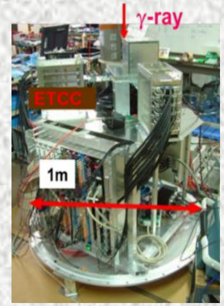


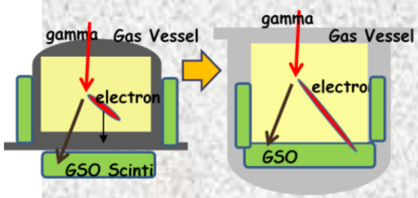
Sub-MeV gamma-ray Imaging Loaded-on-balloon Experiment (SMILE-Project)

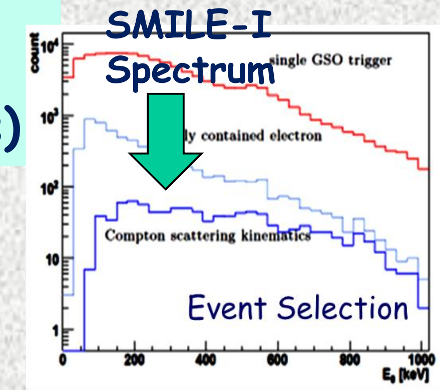
From basic research of nuclear γ imaging spectroscopy to Satellite observation with sub-m Crab sensitivity (4orders improvements)



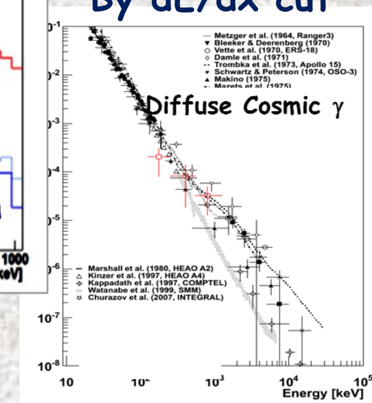
2006 SMILE-I
10cm cubic ETCC



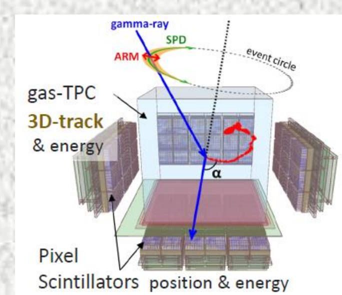




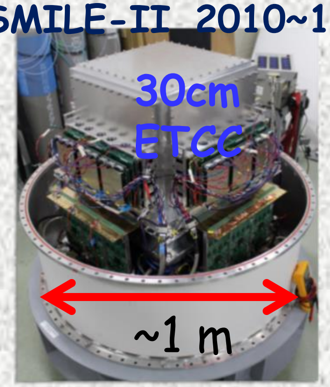
Two order
BG rejection
By dE/dx cut

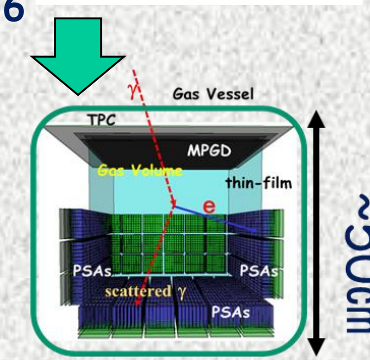


Takda et al. ApJ (2011)

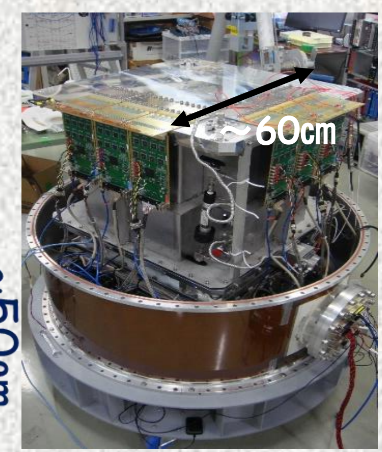


SMILE-II 2010~16





SMILE-II+ 30cmETCC
2016~2020?



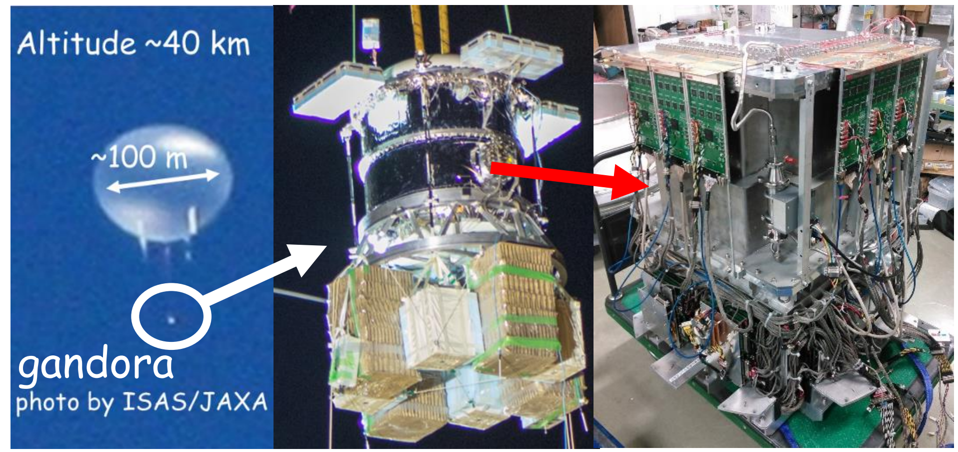
SMILE-2+

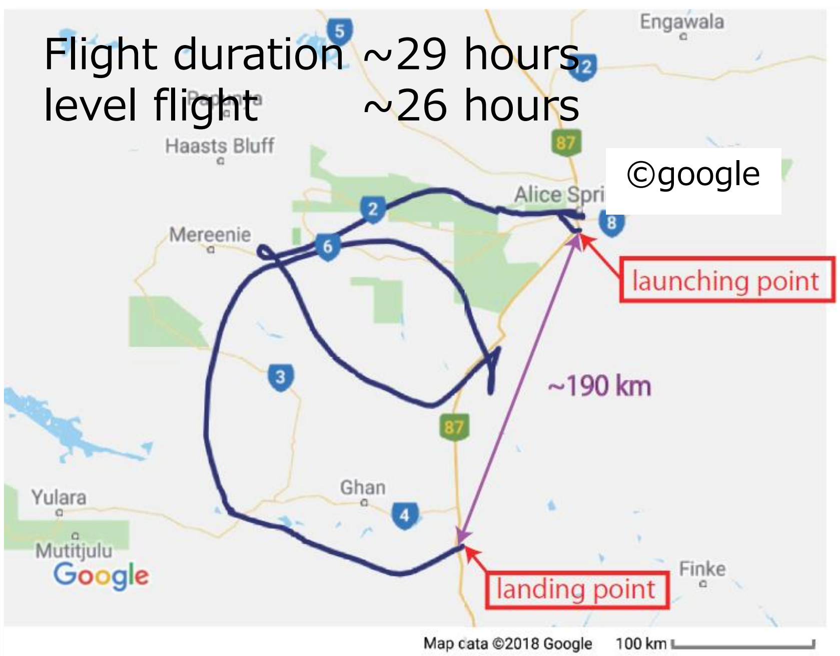
Aim : certificate imaging spectroscopy of ETCC using celestial objects

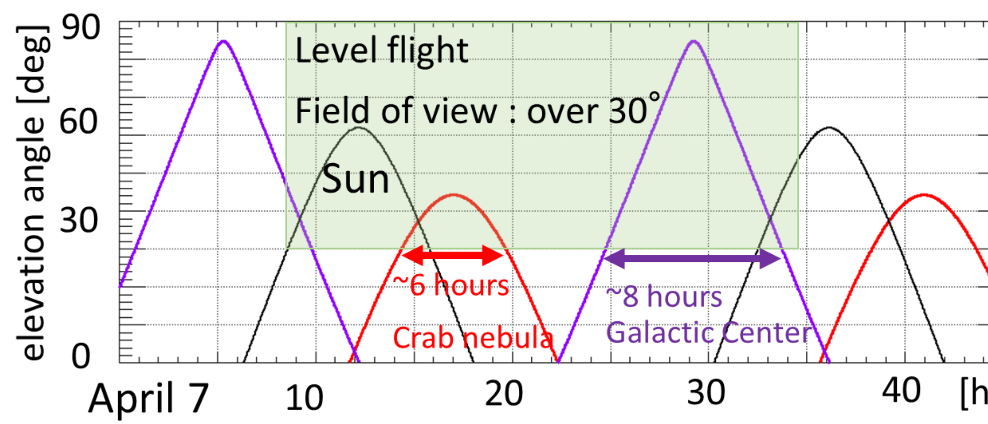
Targets : $e^{\pm}$ annihilation line from the galactic center region / Crab nebula

オーストラリア

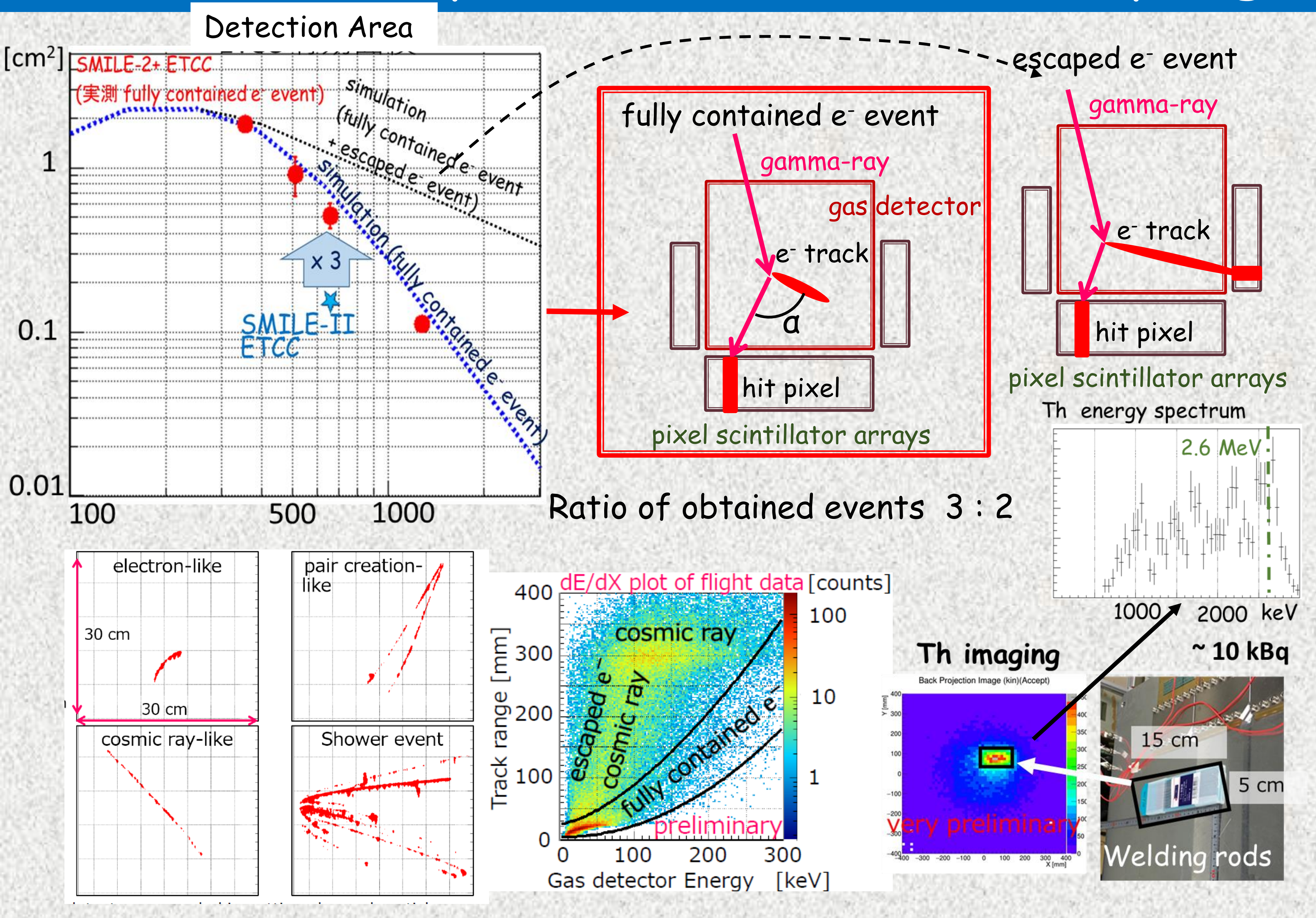
SMILE-2+ balloon, Flight Model, ETCC



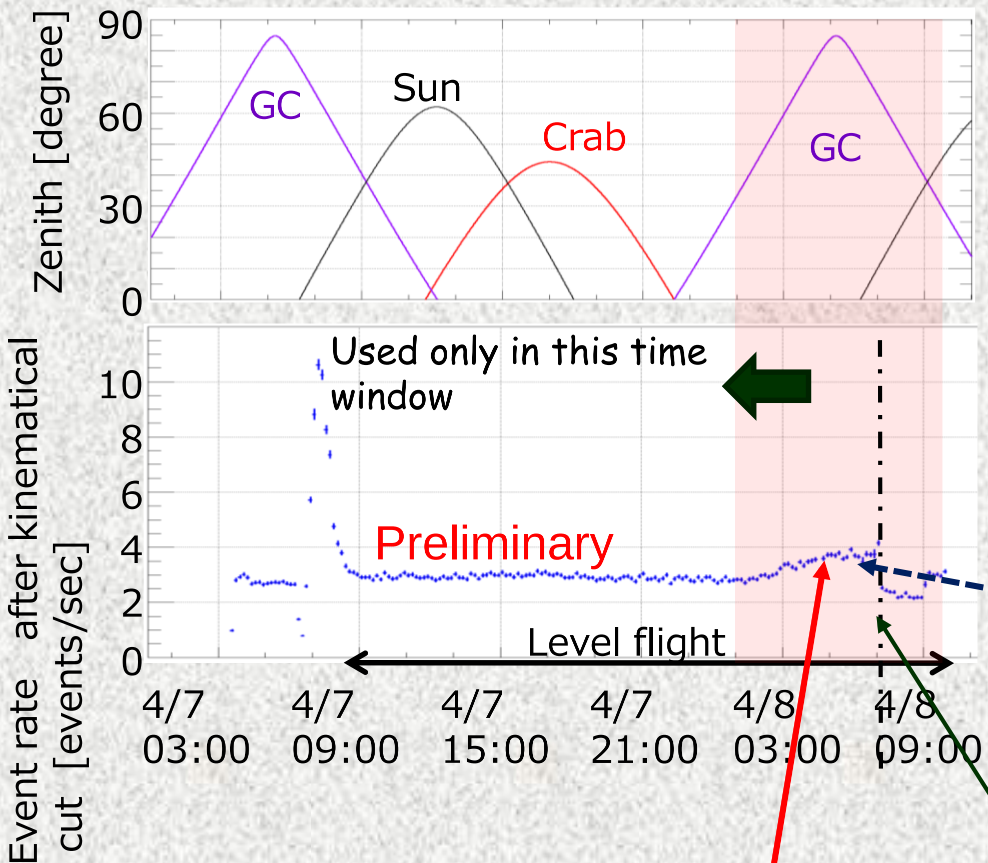




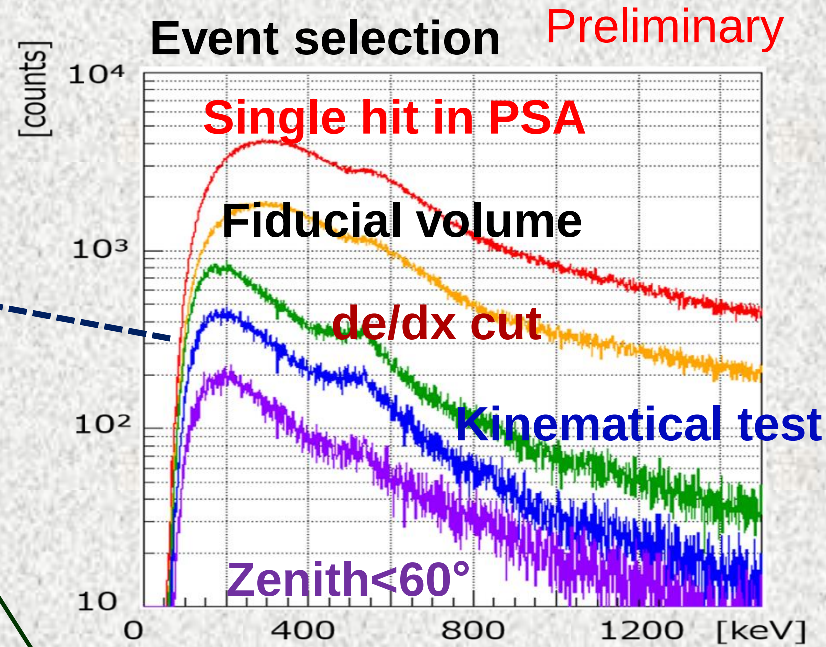
SMILE-II+ Exp. 2018 4/7~8 in Alice Spring



Time Variation of detection rate of gamma-ray events



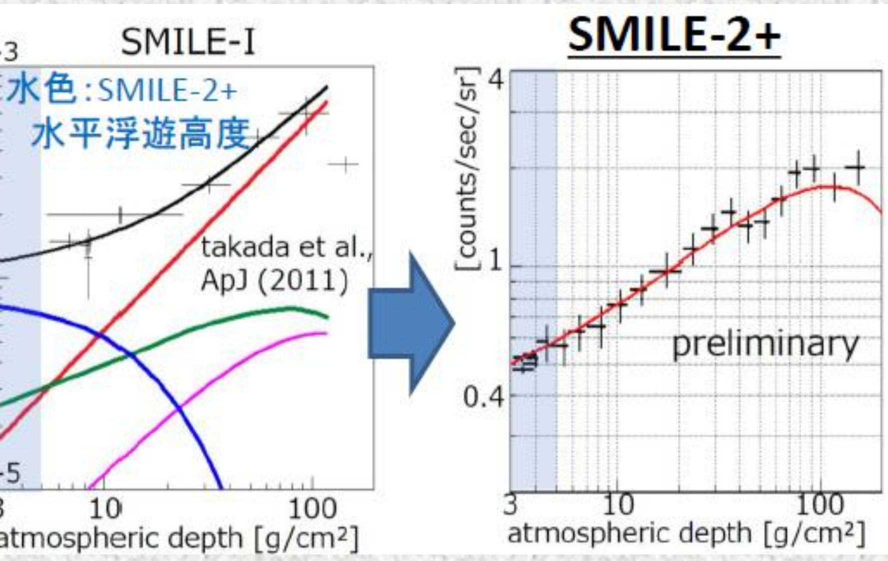
- Fly horizontally 26 times
- Height ~39 km
- Galaxy center field ~8 time

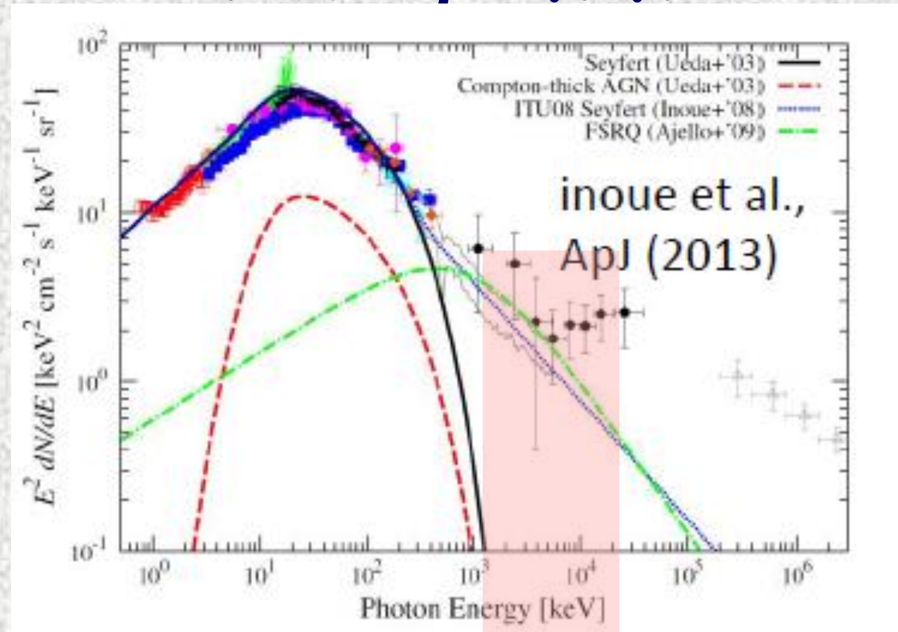


Enhancement looks consistent with the observation ratio of the cosmic diffusion and galactic diffusion of about 3:1

- After 7 o'clock 4/8 heavy nose in TPC Now we used data before 7

Cosmic background MeV gammas

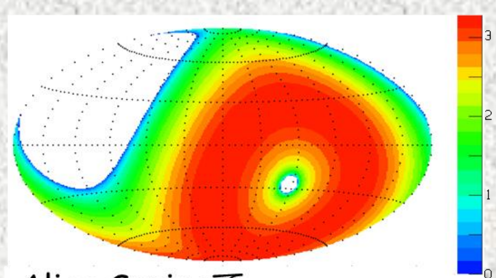




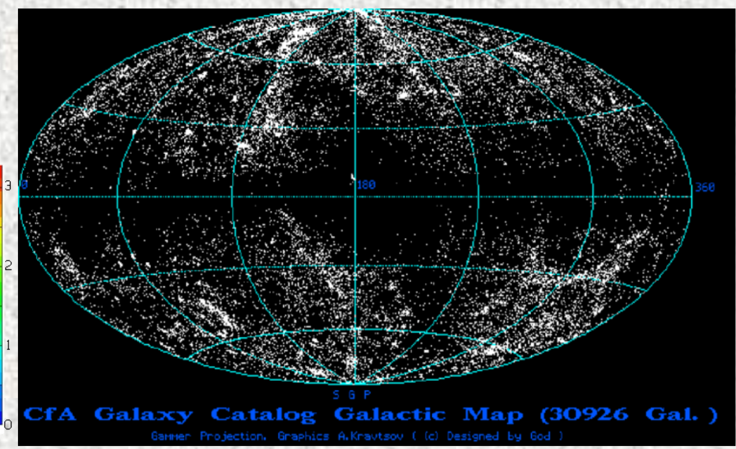
Zenith angle more z>60 degrees => more 10^5 gamma rays
Backgrounds of air diffuse & equipment gamma ray are expected less than a few 10% in total.

DM探査

- 0.5-5MeVのスペクトル変化
- 全天の2/3をカバー、今後、超銀河団、銀河団、矮小銀河等との相関を調べる。



Alice Springで
1日観測した場合のexposure

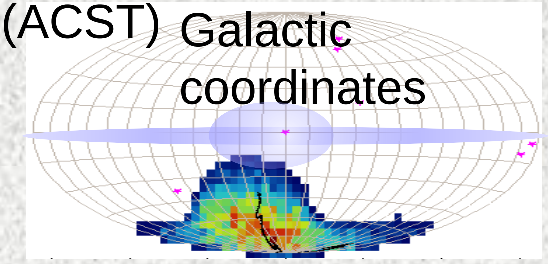


Excess gamma rays from Galactic Center

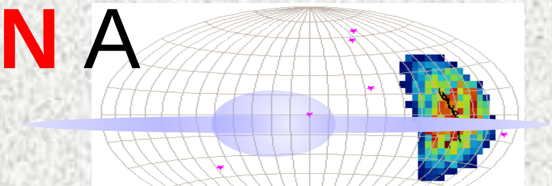
Analysis of the event rate in the ON and OFF
Select the high Declination center of the field of view to OFF
zenith angle (only available for 30 °)
(Currently, because there is indeterminable in the azimuth direction, only the field information is used)

4/7 9:00-13:00 (ACST)

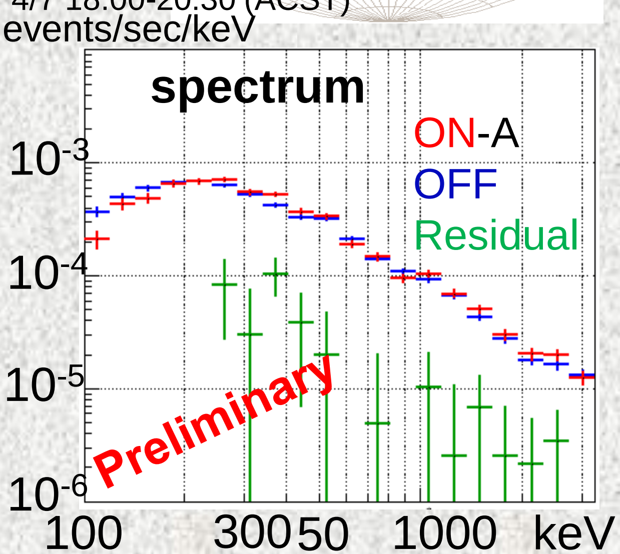
OFF time



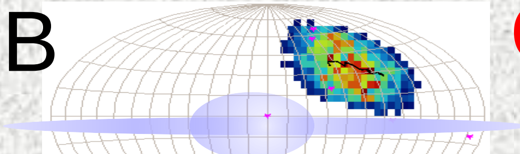
ON A



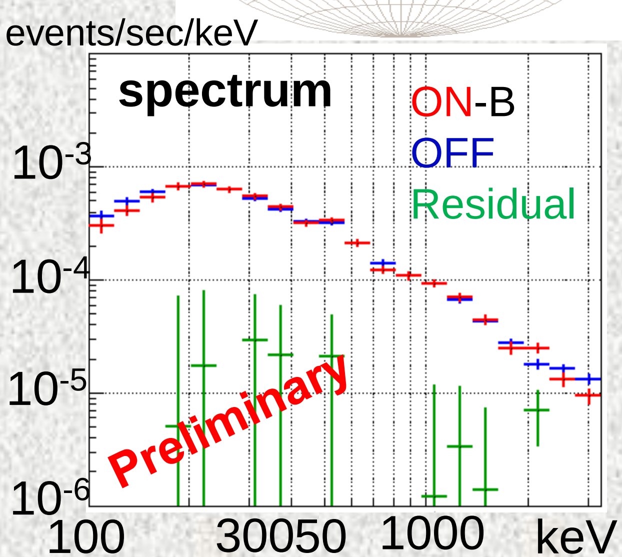
4/7 18:00-20:30 (ACST)



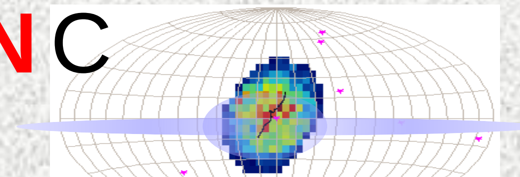
ON B



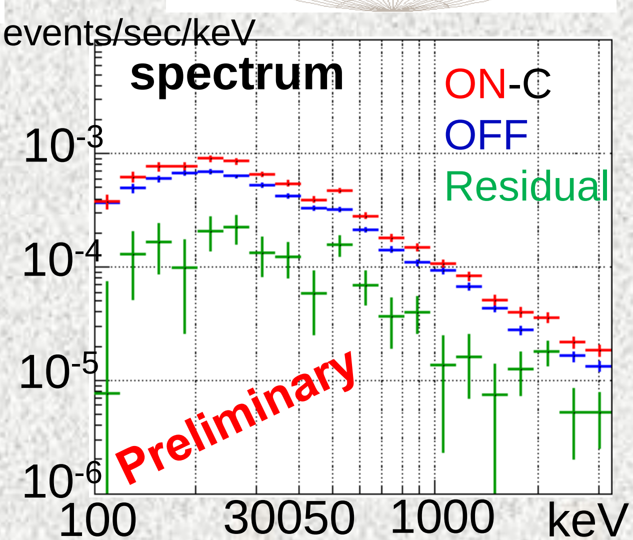
4/7 22:00-24:30 (ACST)



ON C



4/8 4:00-6:30 (ACST)

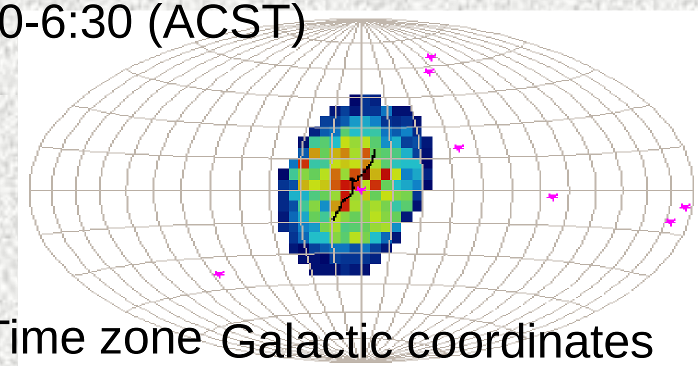


An excess of ~ 511 keV & diffuse components in G.C. is observed.

Excess gammas from Galactic Center

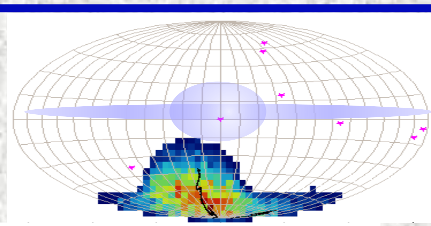
Analysis of the event rate in the ON and OFF time zones
OFF of the View Center is far from the galactic plane
Select two time zones
Ground coordinate zenith angle (only available for 30 °)

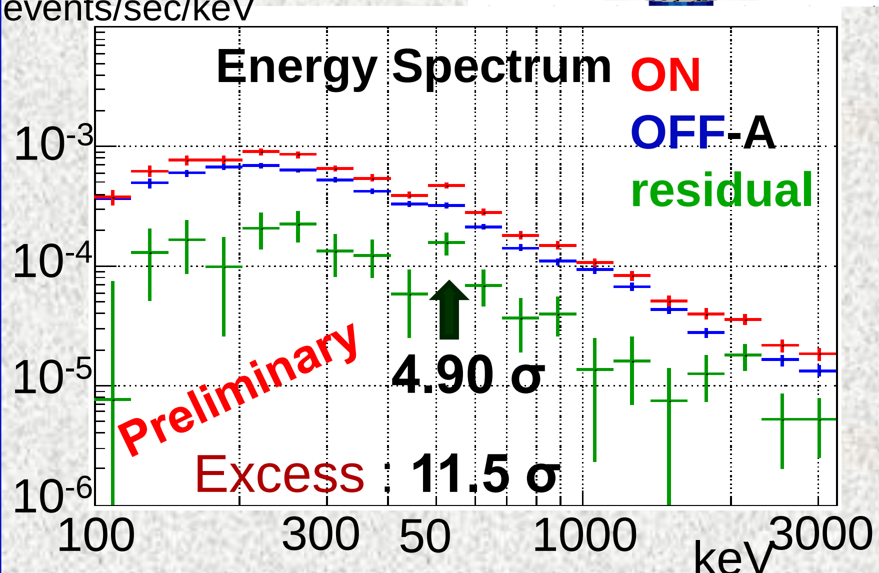
4/8 4:00-6:30 (ACST)



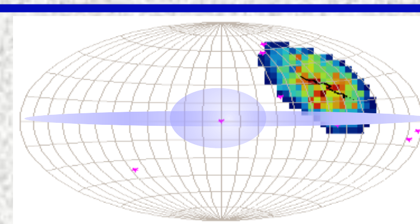
ON Time zone Galactic coordinates

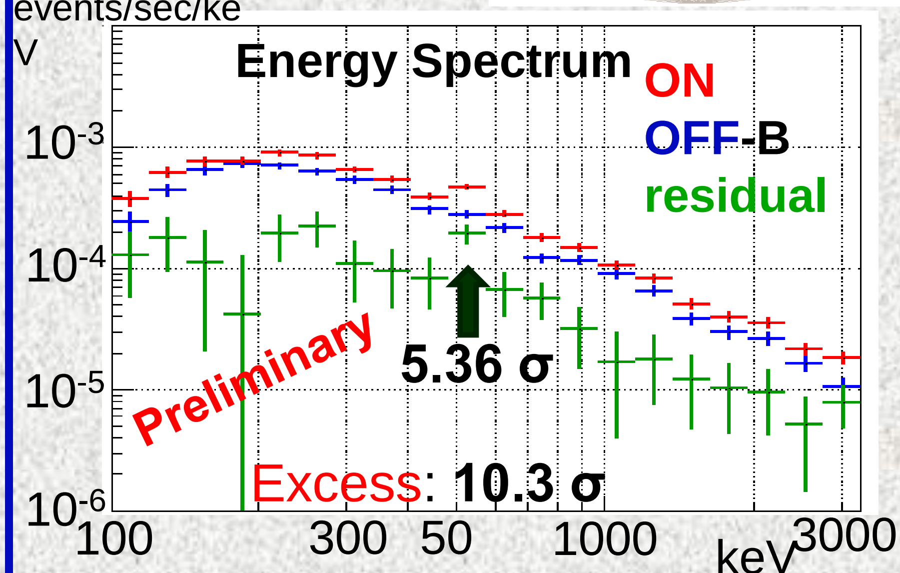
OFF Time zone A
4/7 9:00-13:00 (ACST)





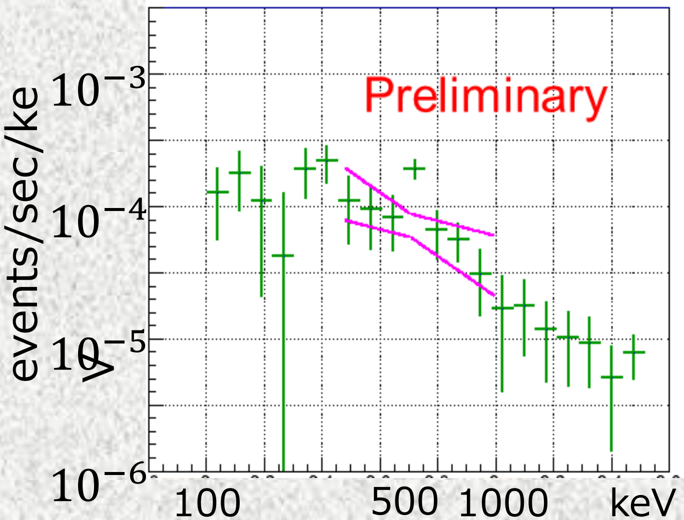
OFF Time zone B
4/7 21:00-23:00 (ACST)



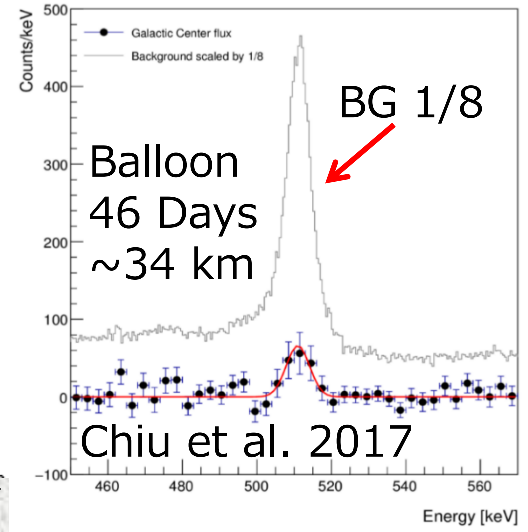


Comparison of significance with other observations

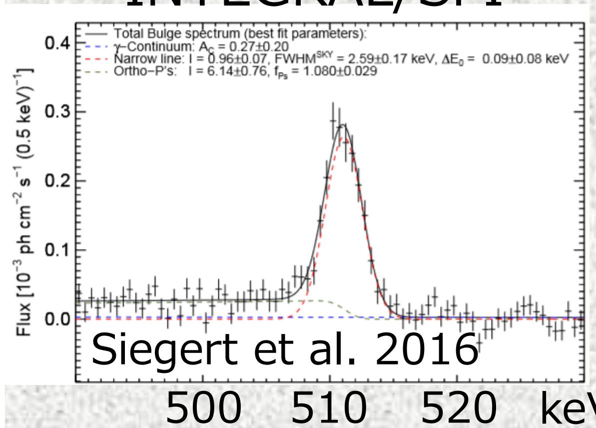
SMILE-2+



COSI 2016



INTEGRAL/SPI



- 511 keV line 58 σ
- 3-gammas 29 σ
- combined 65 σ

SMILE-2+ 511 keV bin ~5 σ

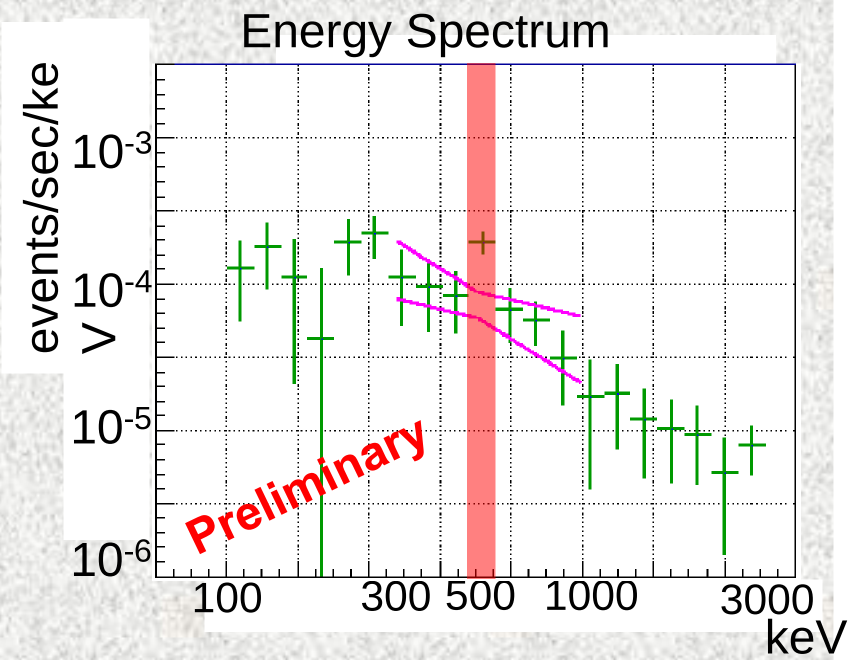
511 keV bin over duffuse ~2 σ

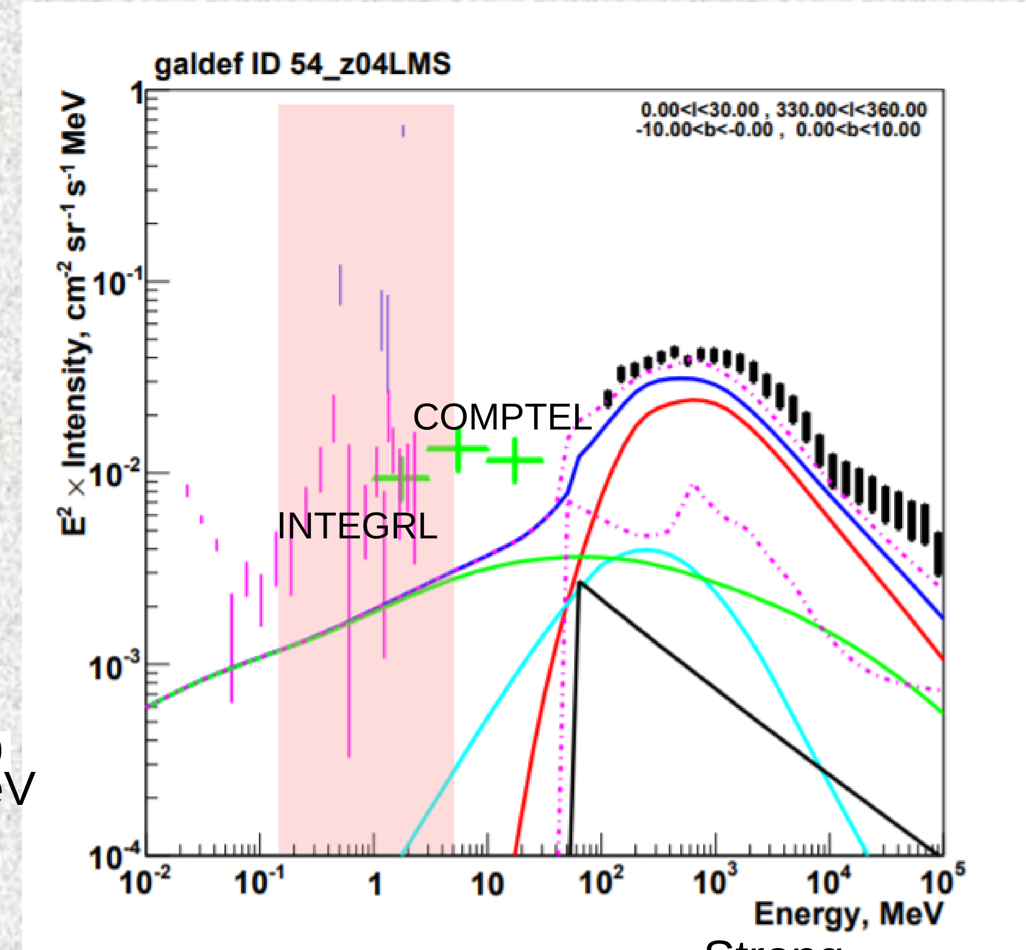
Same time with COSI : $\sim 5\ \sigma \times \sqrt{\frac{6.1 \times 10^5 \mathrm{sec}}{6.4 \times 10^3 \mathrm{sec}}} = 20 \sim 48\ \sigma$

INTEGRAL/SPI same time: $\sim 5\sigma \times \sqrt{\frac{1.6 \times 10^9\ \mathrm{cm}^2\ \mathrm{sec} / 75 \mathrm{cm}^2}{6.4 \times 10^3 \mathrm{sec}}} = 140 \sim 295\ \ \sigma$

Instum.	Eff. Area	ΔE/E	Normalized Sensitivity to SPI
SPI	$75 cm^2$	<1%	1 Coded Mask with Veto
COSI	$\sim 10 cm^2$	<1%	5 x Conventional CC with Veto
SM2+	$1 cm^2$	13%	100—200 x ETCC with no-veto

galactic diffuse gamma rays





Strong +(2011)

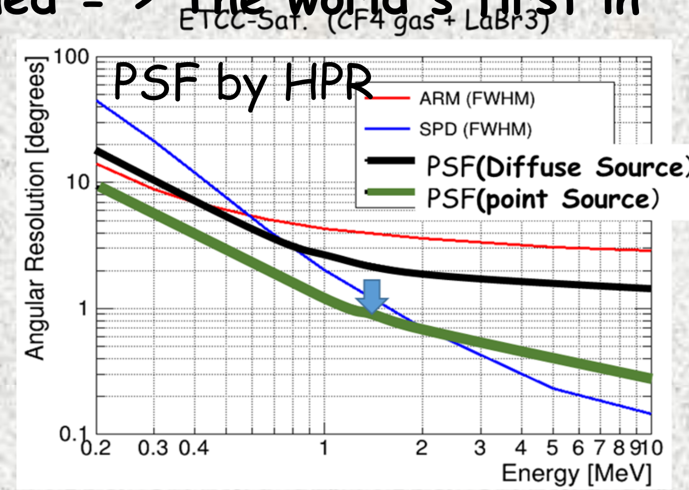
All excess : **10～11σ**

clarify the radiation mechanism of the diffuse Mev gamma rays

Expected Sensitivity based on well-defined PSF

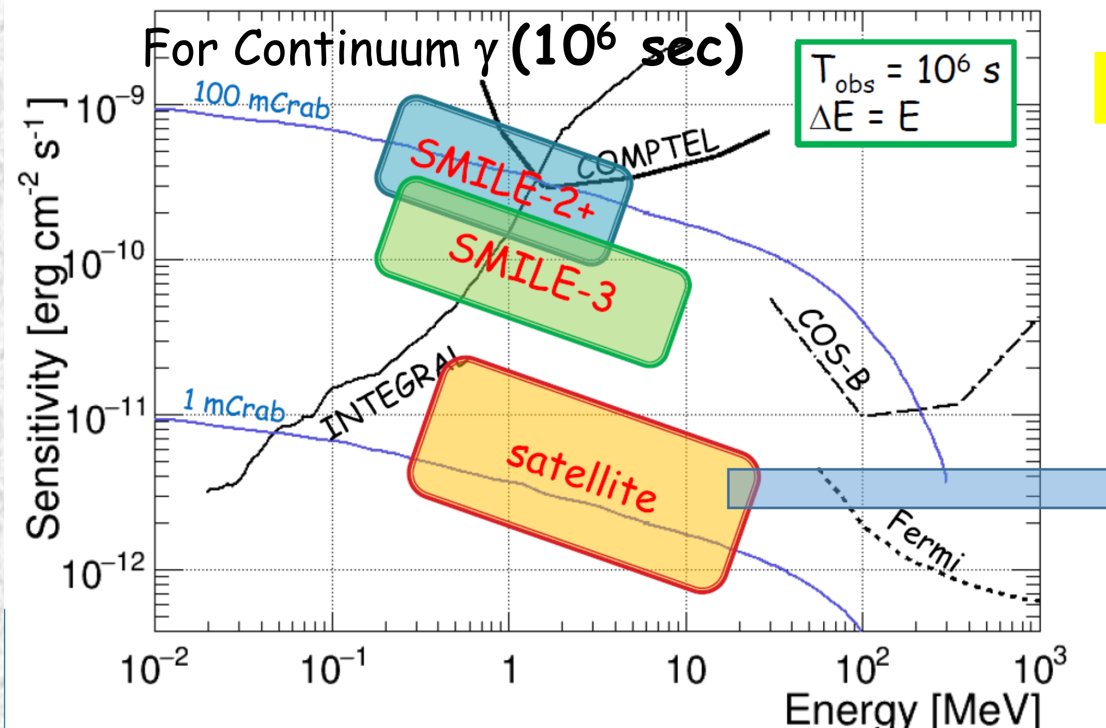
SMILE2 + = > Crab, Galaxy 511keV Galaxy diffuse & cosmic background MeV gamma Detected by the sensitivity as planned = > The world's first in MEV!!

we have certificated a high realiability of ETCC

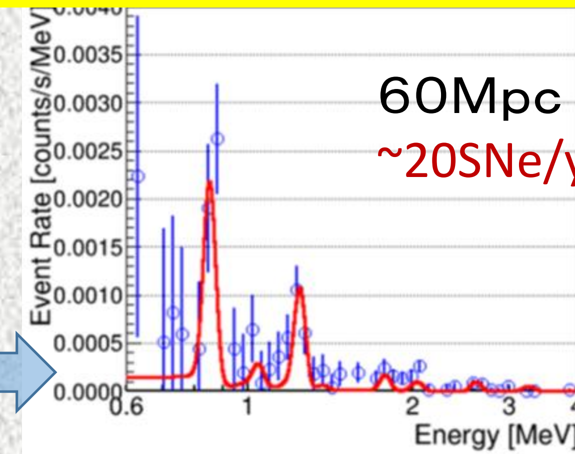


ETCC-Satellite 50cm-cubic ETCC (CF_4 3atm)
with >5RL Scinti. x 4 modules
Effective Area ~200cm^2@1MeV and PSF:HPR-2^o

将来計画の予想検出感度



ラインガンマ線はさらに1桁近い感度向上。



New MeV gamma Astronomy beynond 1mCrab

Summary

- SM2＋ in the ETCC technology demonstrated in the Compton area (50kev-30MeV) imaging spectroscopic technique for the first time, as well as x-ray, GEV,
- GeV 領域　Astrophysical sourcesが多く、DMとの判断が困難。
- GeV、sub-GeV. MeV のDM信号は30MeV以下の電子の寄与のみの領域が最も判別が確かであり、今後重要となる。
- GeV-MeV　全天探査が可能、銀河と他の銀河、銀河団などが同時に測定できる。
- SM2+のデータ　DM関係で、Galactic Diffuse　gamma（スペクトル、分布），　Cosmic Diffuse gamma（スペクトル、分布），PBH in Solar system の論文は出す
- Balloon SMILE-3 project with NASA long duration balloon ＝＞ 5times better sensitivity than COMPTEL
- 2020年代　sau-MeV, MEV はSMILEの独断場の可能性大！

Primordial Black Holes in Solar System

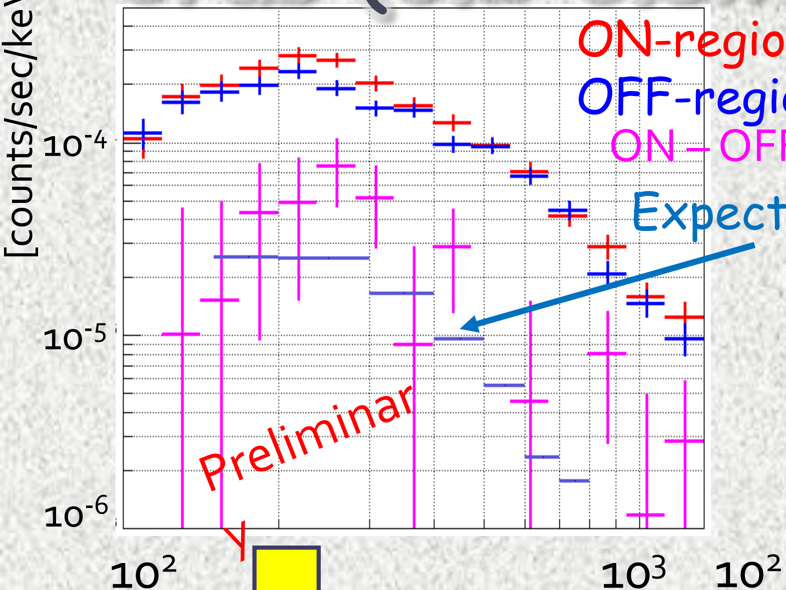
$$\tau \sim \frac{M^3}{\hbar} \sim 10^{10}\,\mathrm{yr}\left(\frac{M}{10^{15}\,\mathrm{g}}\right)^3 \quad \frac{dE}{dt} \sim 10^{20}\,\mathrm{erg\,s^{-1}}\left(\frac{10^{15}\,\mathrm{g}}{M}\right)^2 \quad \hbar\omega \sim 100\,\mathrm{MeV}\left(\frac{10^{15}\,\mathrm{g}}{M}\right)$$

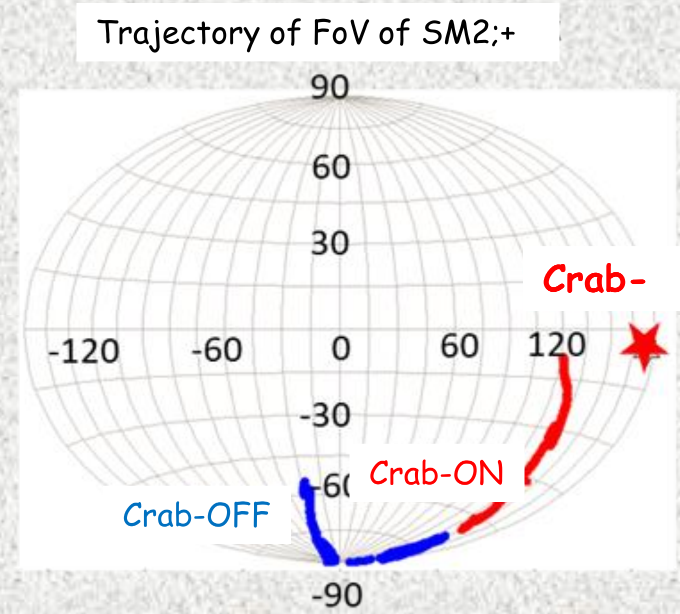
Primordial B.H. still surviving
would emit ~20MeV thermal M~ 10^{15} g , ~ 10^{20} erg/s

Density ~10^4 pc^{-3} (flat 分布で)
10^4 pc^{-3} -> ~10 BH <Oort cloud (10^4AU)
Condensation Factor in Galactic halos x ~10^6
＝＞ 100AU 球に~10BHs

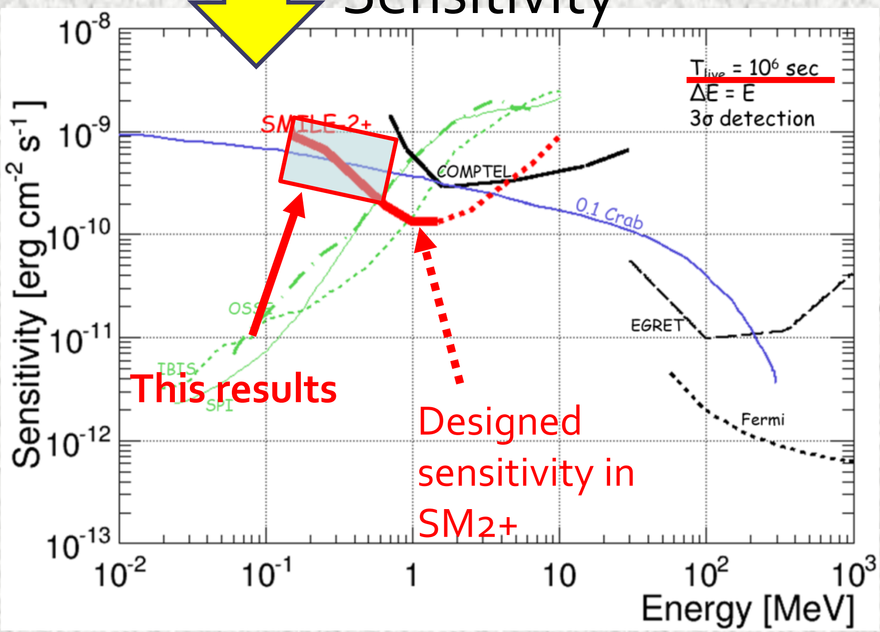
Satellite-ETCC γ線10個 (1MeV)s^{-1} @1AU for 10^{20}erg/s
BHが10^6sの間同じ天球位置として、検出限界100γ@10^6s
この場合、300AUのBHまで観測可能 数10個のBHが見える。
さらに太陽系の増幅効果、ディスク（黄道面）分布、太陽近傍集中
1桁以上の増加、さらにコメット軌道（数日、明るい）、

Crab (0.2-0.8MeV)





Sensitivity



<u>Here pointing is done only for Zenith</u>

Enhancement of gamma-rays

Obs, time ~10^4sec, 3σ

=>Obs. time~10^6sec, ~0.1 Crab(3σ detection)

Achieved for the first time that observed sensitivity is consistent with original design in MeV gamma-ray telescopes

Comment

In COSI, 511keV signal from G.C. is obtained by the subtraction of ~70times large 511kev background peak.

In SMILE2+., as shown in light curve of gammas, gamma rate of G.C. region was stronger than the background region (side region of Galactic plane),

The Galactic centre GeV excess

F. Calore@Fermi.sym.2018

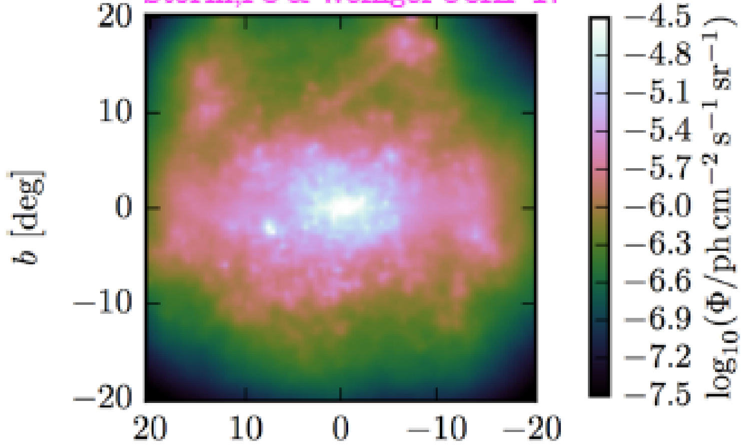
Signal:

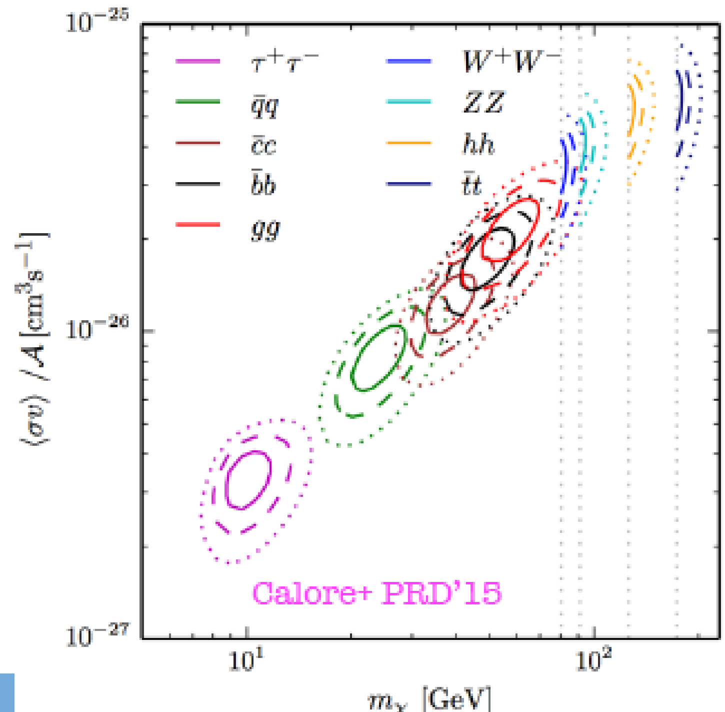
- Well-established excess of Fermi-LAT GeV photons from the inner Galaxy**
- Peculiar spectrum peaked at a few GeV
- Extended emission up to ~10 degrees (~1.5 kpc), almost spherically symmetric (but not quite so)

Interpretations:

- Diffuse emission from electrons/positrons at the Galactic centre (ehnanced SF or activity GC)
  Gaggero+ JCAP'15; Carlson+PRD'15; Petrovic+ JCAP'14; Cholis,FC+JCAP'15
- Sub-threshold millisecond pulsar-like point sources
  Bartels+PRL'16; Lee+PRL'16; Ackermann+'17
- Dark matter annihilation: large freedom in channel/masses thanks to syst uncertainties
  Calore+ PRD'15; Agrawal+JCAP'15

Storm,FC & Weniger JCAP'17





**Some Refs. since 2009: Hooper&Goodenough '09; Vitale&Morselli '09; Abazajian&Kaplinghat PRD'12; de Boer+'16; Macias+'16; Hooper&Slatyer PDU'13; Huang+ JCAP'13; Zhou+ PRD'15; Daylan+ '14; Calore+ JCAP'15; Gaggero+ 2015; Ajello+ 2015; Huang+JCAP '15; Linden+PRD'16; Horiuchi+'16; Ackermann+ApJ'17; Ackermann+2017

- **What can light dark matter annihilate into?**

(i) $\gamma\gamma$: Accessible at all energies. The final state is C-even.

(ii) $\gamma\pi^0$: Accessible for $\sqrt{s} > m_{\pi^0}$. The final state is C-odd.

(iii) $\pi^0\pi^0$: Accessible for $\sqrt{s} \geq 2m_{\pi^0}$. The final state is C-even.

(iv) $\pi^+\pi^-$: Accessible for $\sqrt{s} \geq 2m_{\pi^\pm}$. The final state is C-even or C-odd.

(v) $\bar{\ell}\ell$ ($\ell = e, \mu, \nu$): Accessible for $\sqrt{s} \geq 2m_\ell$. The final state is either C-odd or is weak suppressed.

- **In general - annihilation into uncharged states is better for gamma-ray observation.**