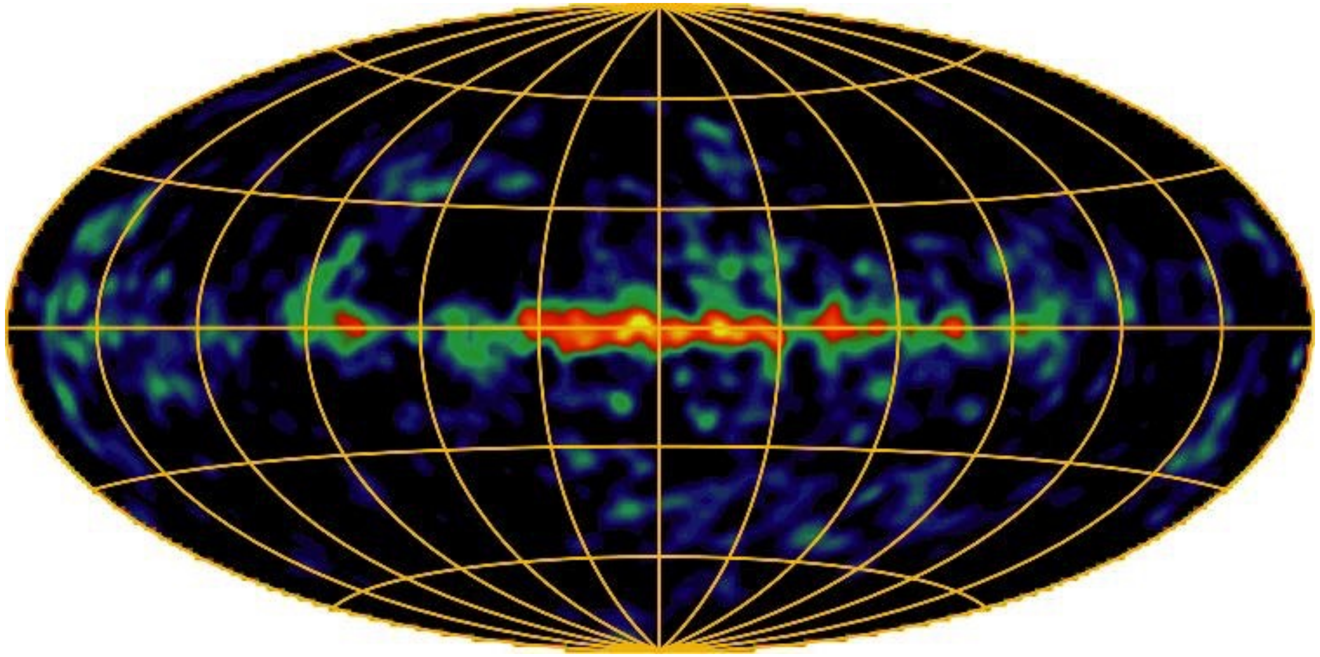
清華大學天文系
Department of Astronomy, Tsinghua University

The origin of 511 keV emission in the Galaxy



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Xiaoya Zhang, Jiahuan Zhu
Advisor: Hua Feng

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- Conclusions

The origin of 511 keV emission in the Galaxy

BACKGROUND

Annihilation of Positrons

- Annihilation of positronium (Ps, bound system of an e^+ and a e^-): composite spectrum with a low energy continuum and a 511 keV line
  - Para-Positronium (spin=0, 511 keV photons)
  - Ortho-Positronium (spin=1, continuum up to 511 keV)
- Direct annihilation of e^--e^+ : 511 keV γ ray

Prantzos et al., 2011, RvMP

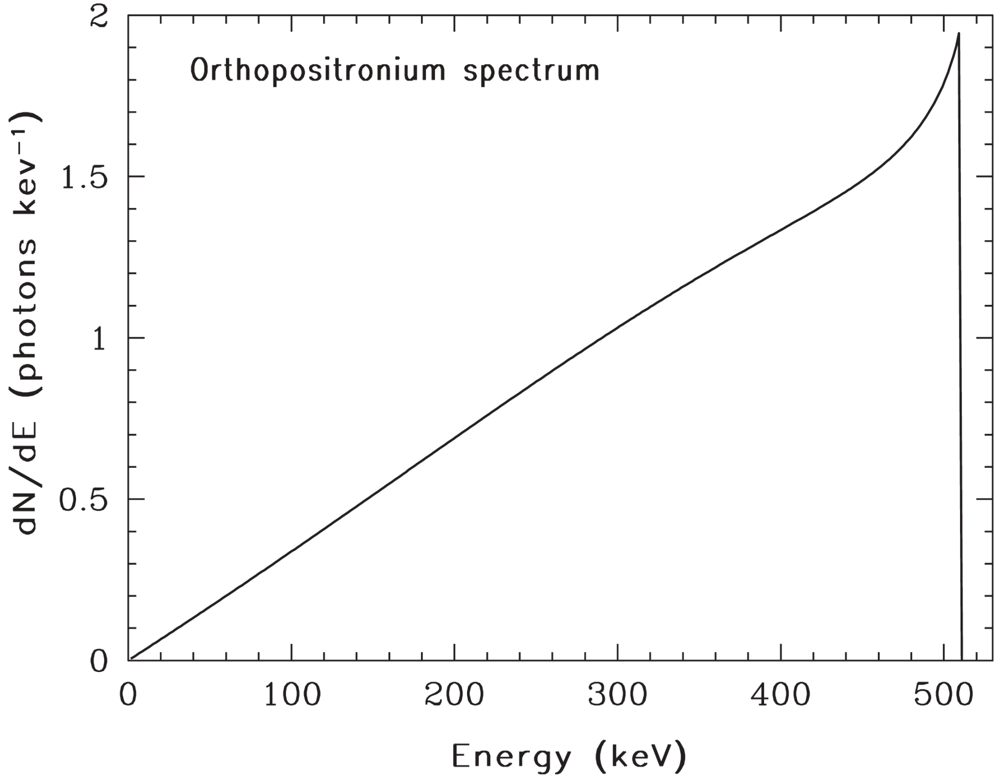
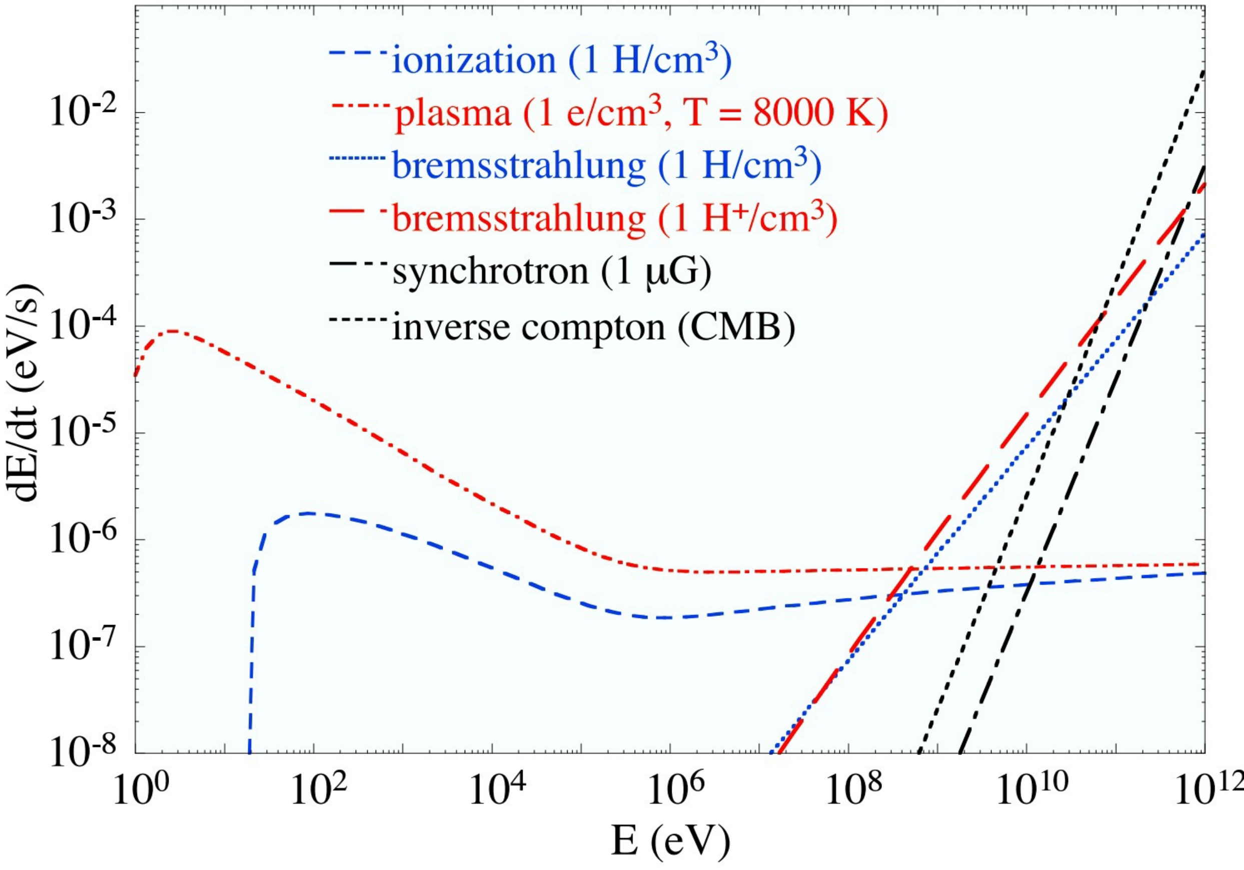


FIG. 1. Spectrum of ortho-positronium annihilation with the three-photon continuum. From Ore and Powell, 1949.

Annihilation of Positrons

- In-flight phase (~MeV to ~100 eV)
  - Coulomb energy losses (with free electrons)
  - Excitation and ionization of atoms (H, H_2, He)
  - Annihilation
    - Direct annihilation
    - Ps formation via charge exchange with H, H2 and He (<100 eV)

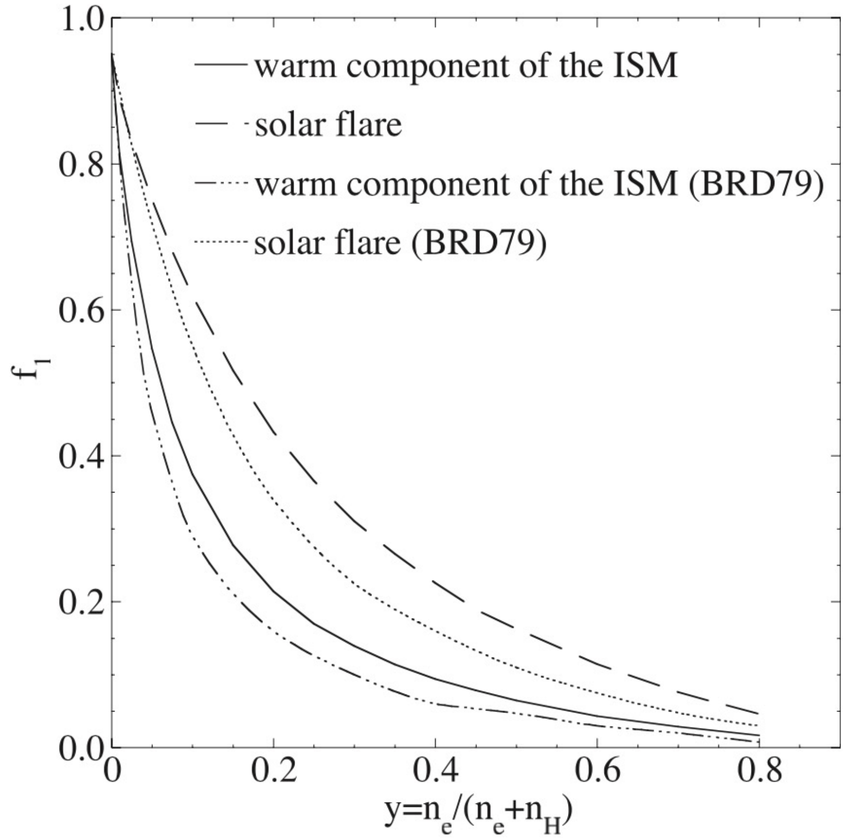
Prantzos et al., 2011, RvMP



Annihilation of Positrons

- Thermal phase
  - Charge exchange with H, H_2, He
  - Direct annihilation with free and bound electrons
  - Radiative combination (with free electrons)
  - Capture on grains
  - Positronium quenching

Guessoum et al. 2005, A&A 436, 171



f1: fraction of positrons forming positronium in flight by charge exchange with atomic hydrogen

Early Histories: Detection of Positrons on the Earth

- Terrestrial Origin:
  - Cosmic ray interaction
  - β^+ radioactivity of unstable nuclei (artificially created)

- Extraterrestrial Origin:
  - Positrons within cosmic rays

Production of Positrons

- β^+ decay of radioactive nuclei
  - nucleosynthesis in novae, supernovae, Wolf-Rayet and Asymptotic Giant Branch stars
- $\pi^+ \rightarrow \mu^+ \rightarrow e^+$
  - collisions of highly energetic (more than ≈200 MeV) cosmic rays with interstellar material (mostly protons)
- Pair production: $\gamma + \gamma \rightarrow e^- + e^+$
  - luminous compact objects: XRBs, micro-quasars, AGNs, etc.
- Pair production: $\gamma + B \rightarrow e^- + e^+$
  - pulsars, neutron stars ($B \gtrsim 10^{12}$ G)

Guessoum et al. 2005, A&A 436, 171

Galactic 511 keV: Candidate sources of positrons

- Astrophysical Origin:
  - Type Ia SNe; Type Ic associated with GRBs; LMXBs and micro-quasars; SMBHs; NS mergers

- Other Theories:
  - Annihilation or decay of MeV dark matter particles
  - De-excitation of GeV-TeV dark matter particles
  - Hawking radiation from primordial BHs
  - DM particles around primordial BHs

Galactic 511 keV: Before INTEGRAL / SPI

- Early Balloon & Satellite Observations (highlights)
  - Johnson et al. (1972): NaI-Detector
    - First detection of γ-ray line from outside the solar system
  - Leventhal et al. (1978): Ge-Detector
    - Separation of the narrow line (511 keV) and continuum component.

Galactic 511 keV: Before INTEGRAL / SPI

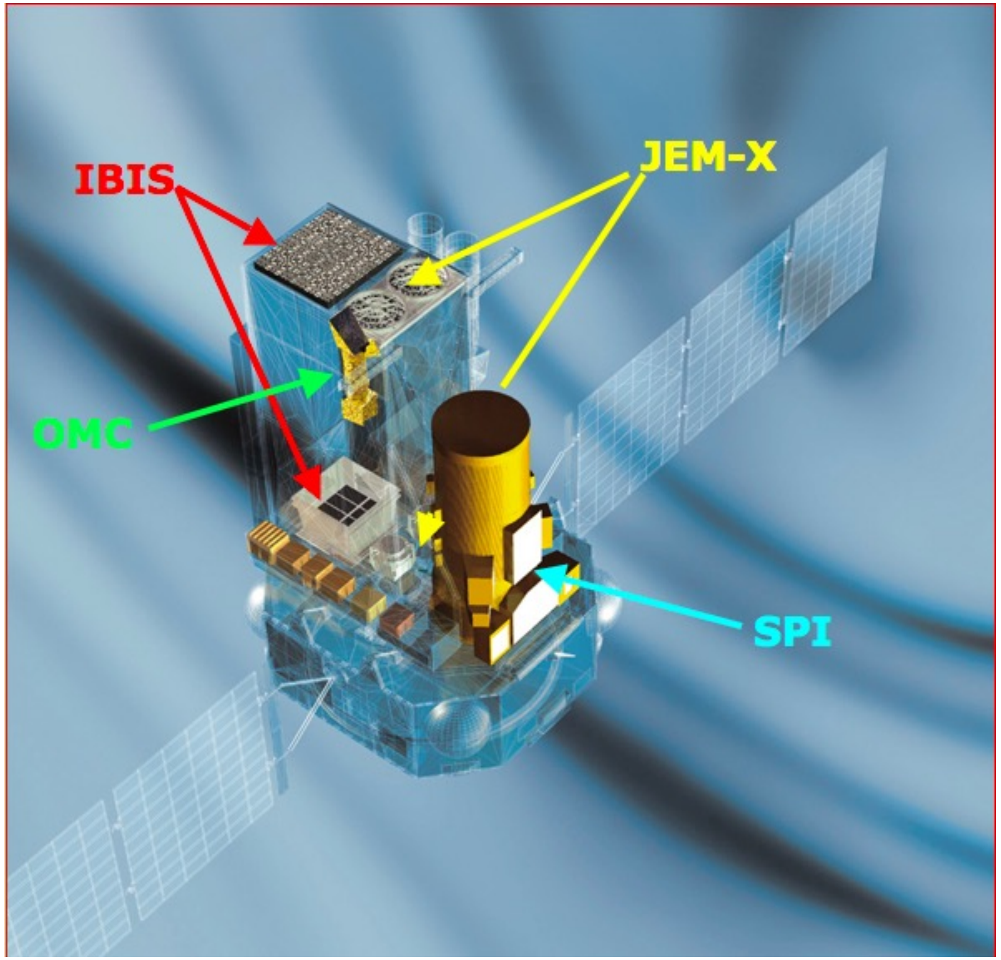
- Early Spatial Mapping CGRO/OSSE
  - Excluded a single point source
  - Symmetrical bulge + Galactic plane emission
    - Galactic Bulge: β^+ decay of Co^{56} by SNIa dominant
    - Galactic Disk: β^+ decay of Al^{26}, Co^{56}, and Ti^{44} from a variety of stellar sources

The origin of 511 keV emission in the Galaxy

OBSERVATIONS

INTEGRAL

(INTErnational Gamma-Ray Astrophysics Laboratory)



Launched in 2002

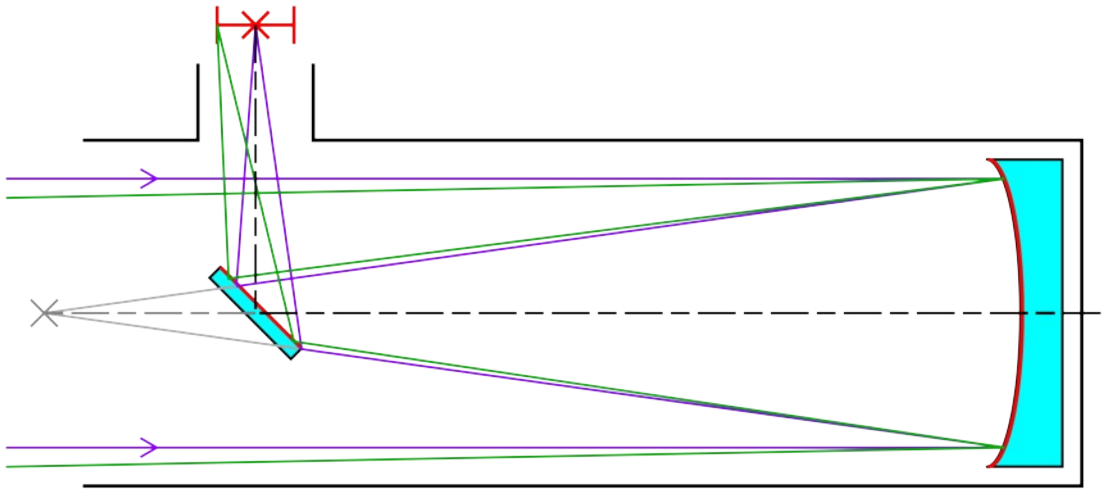
- **SPI**
  (SPectrometer on INTEGRAL)
  Energy range: 18 keV - 8 MeV
  Energy resolution: 2.2 keV (@1.3 MeV)
  FOV: 16°, angular resolution: 2.5°

- **IBIS**
  (Imager on Board the INTEGRAL Satellite)
  Energy range: 15 keV - 10 MeV
  Energy resolution: ~10%
  FOV: 8°, angular resolution: 12’

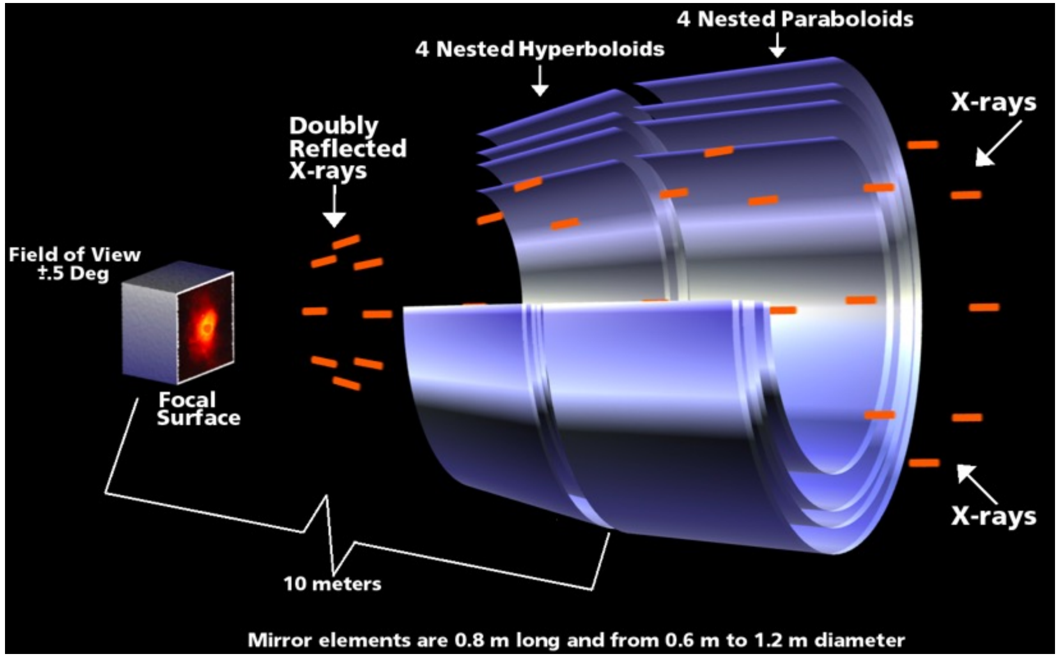
- **JEM-X**
  (Joint European X-Ray Monitor)

- **OMC**
  (Optical Monitoring Camera)

Imaging γ-ray



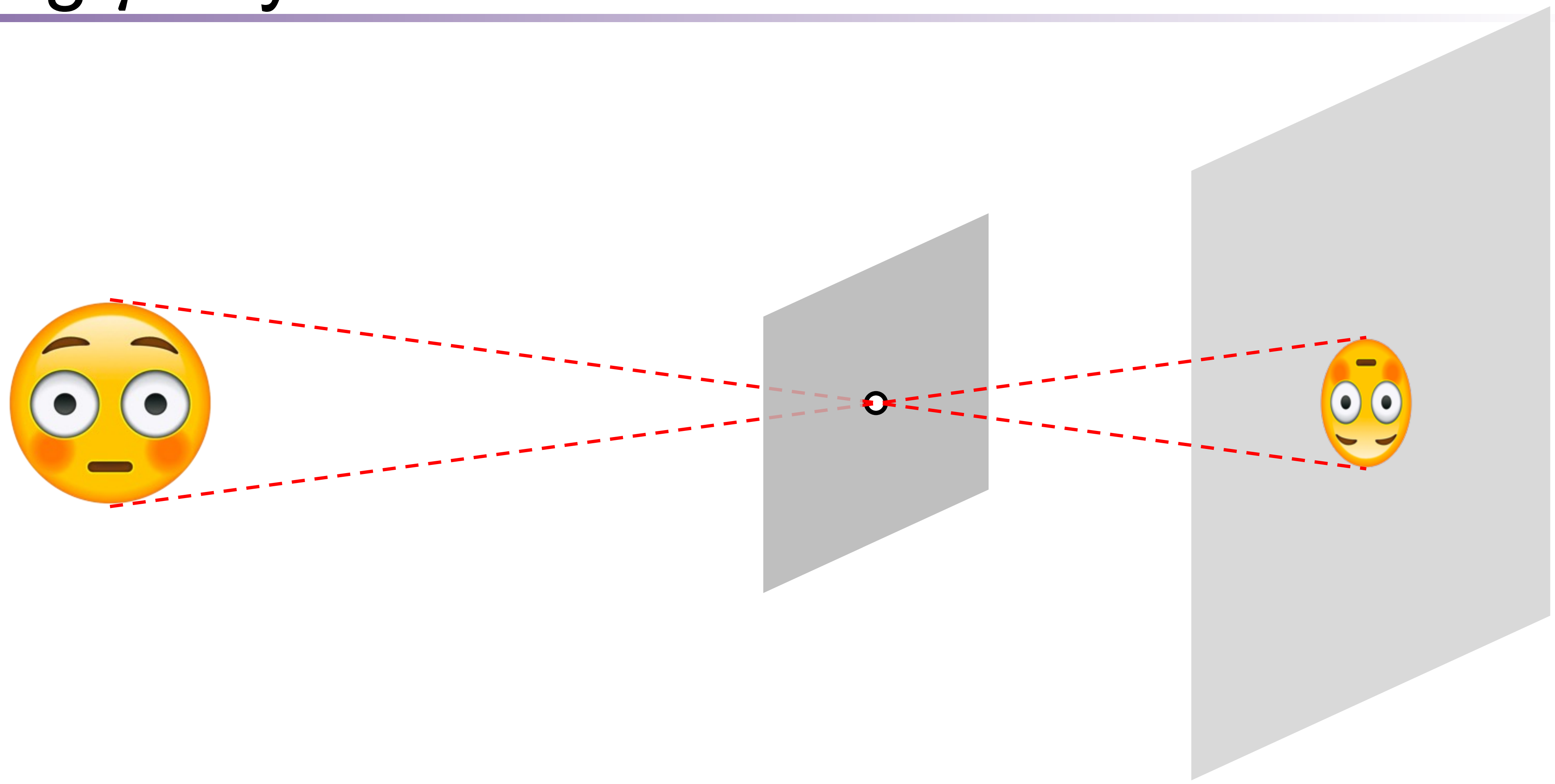
Optical (IR, NUV) band



Soft X-ray

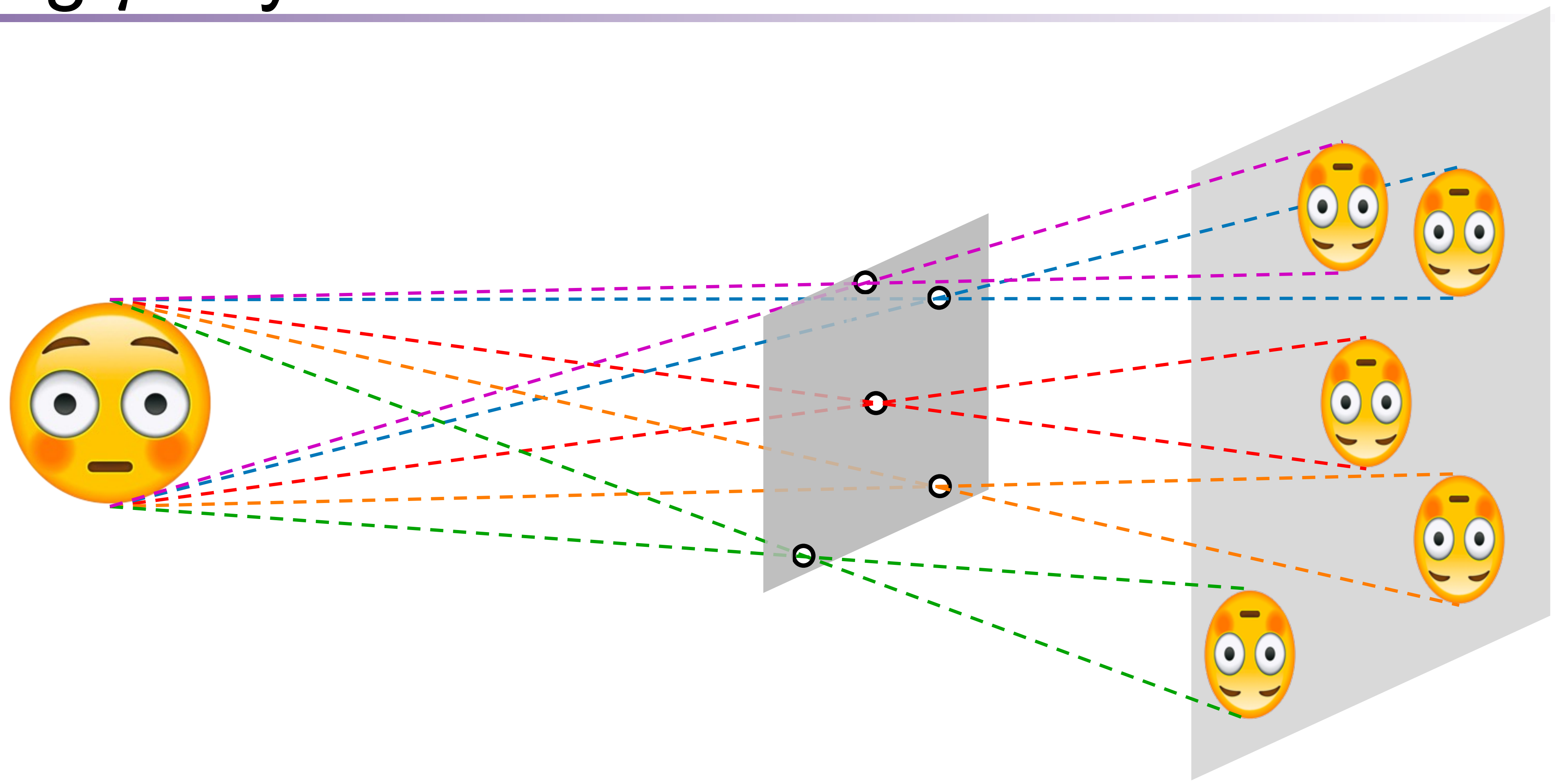
γ-ray can not be focused by a lens system

Imaging γ-ray



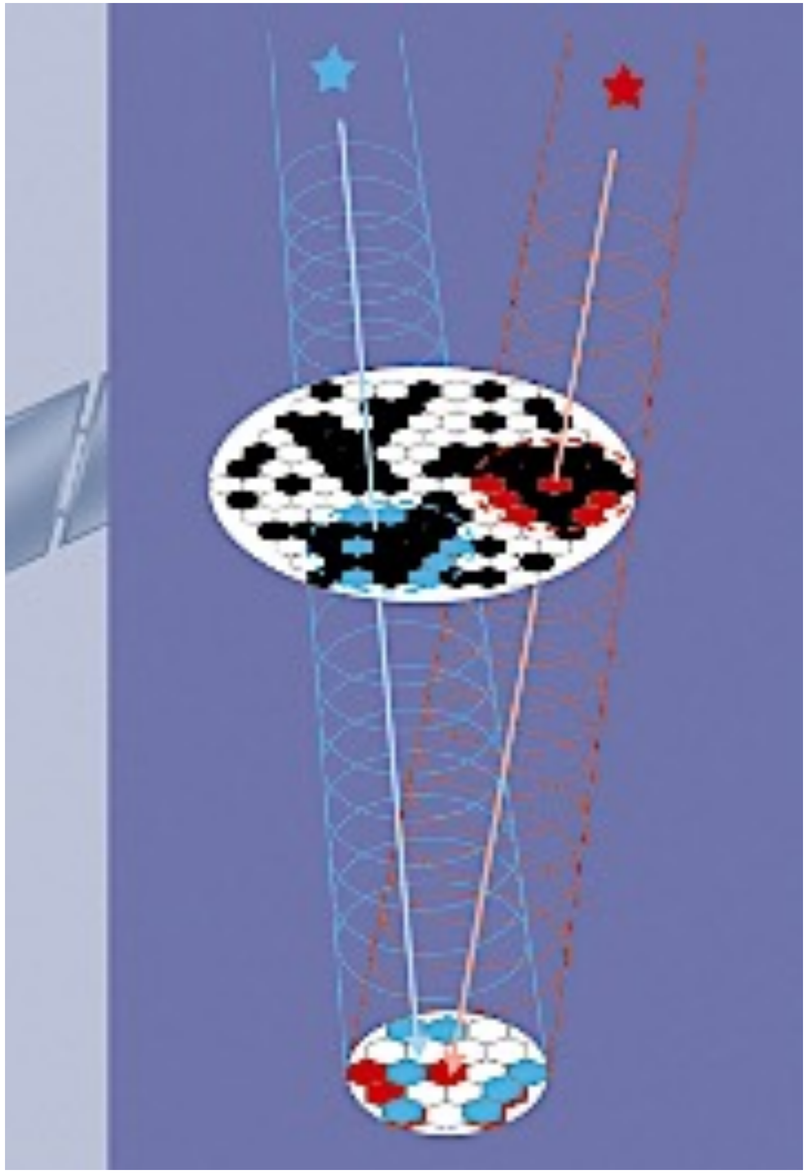
Pinhole: works for γ-ray, but not efficient

Imaging γ-ray



A lot of pinholes “=” coded mask

INTEGRAL/SPI



Coded Mask

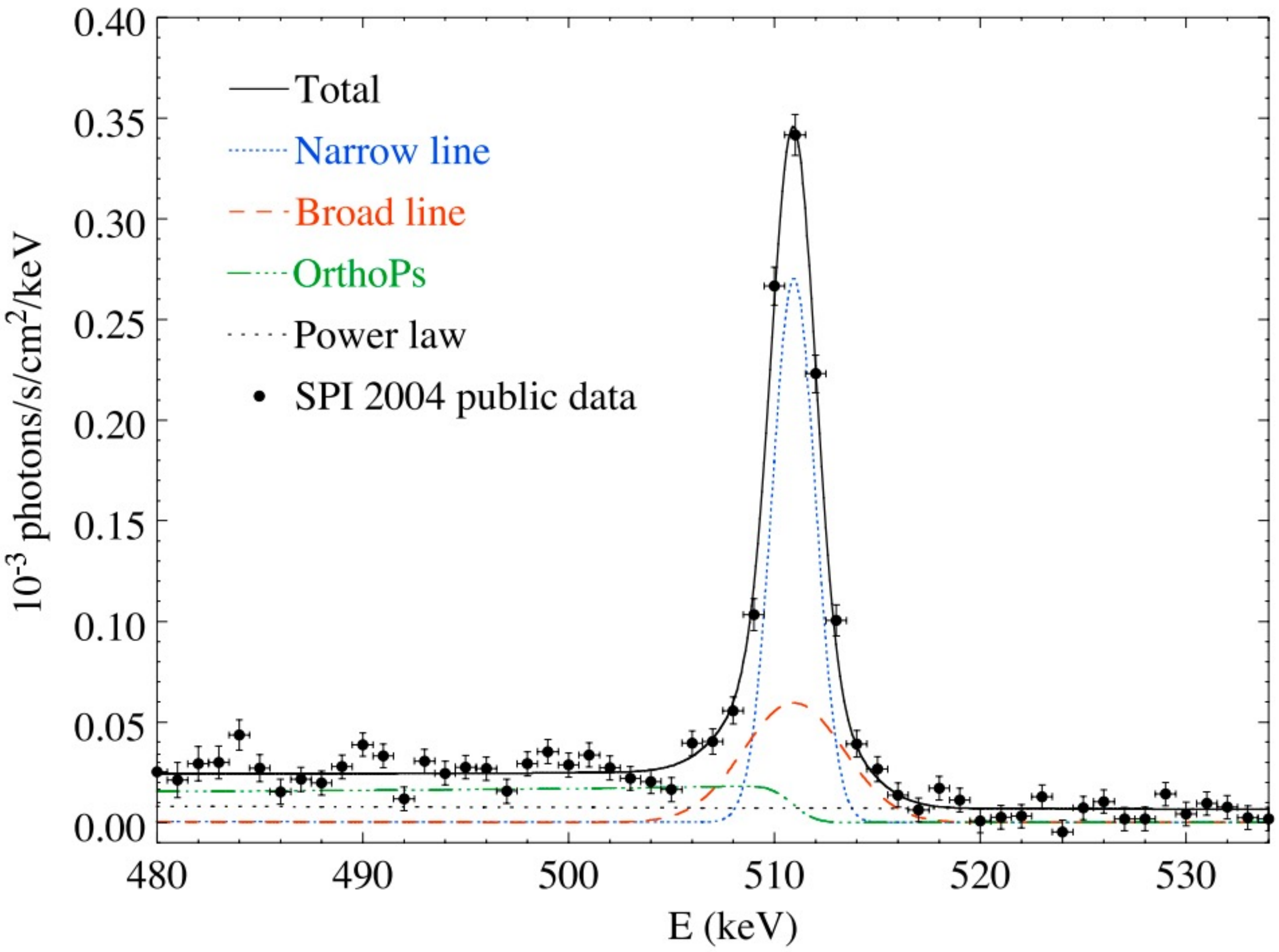
- Pixel-like “pinholes”
- Sources from different position create different patterns
- Reconstruct the image

Detector

- High purity Germanium (锗)
- Energy resolution ~ keV

Facts of 511 keV line

- **FACT 1** Total positron annihilation rate: $L_{e^+} \sim 2\times10^{43}\ s^{-1}$

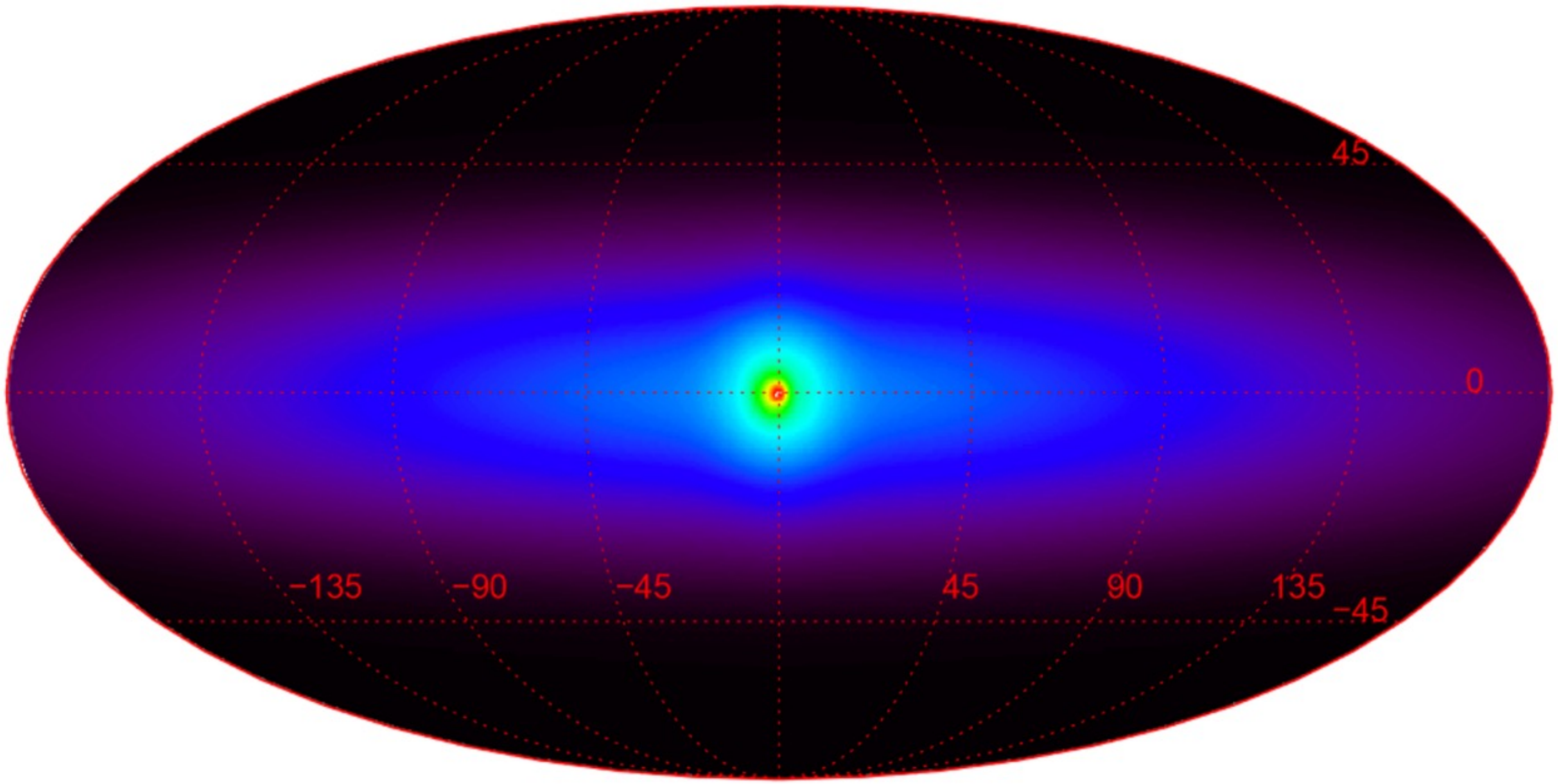


Total intensity of 511 keV line

$(2.74 \pm 0.25)\times10^{-3}$ ph cm^{-2} s^{-1}

Facts of 511 keV line

- **FACT 2** Bulge-Disk ratio of annihilation rate: $B/D \sim 0.6$



dense core + diffuse disk

Facts of 511 keV line

- **FACT 3** Positronium fraction: $97\% \pm 2\%$

$$f_{Ps} = \frac{8I_{3\gamma}/I_{2\gamma}}{9 + 6I_{3\gamma}/I_{2\gamma}},$$

2γ : 511 keV photons

direct e^{-}-e^{+} annihilation

p-Ps

(measured by 511 keV line)

3γ : three photons with total energy 1022 keV

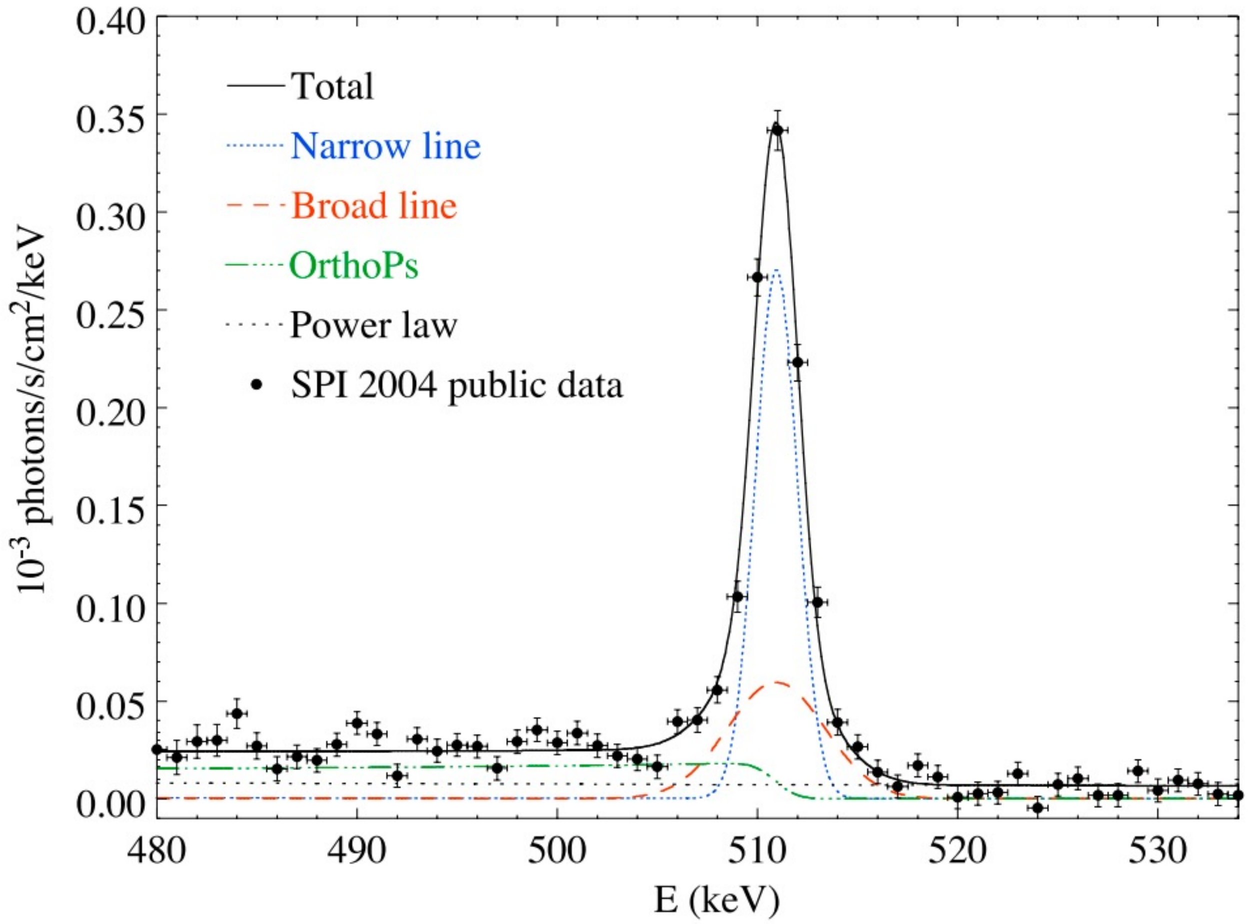
o-Ps

(measured by continuum)

Facts of 511 keV line

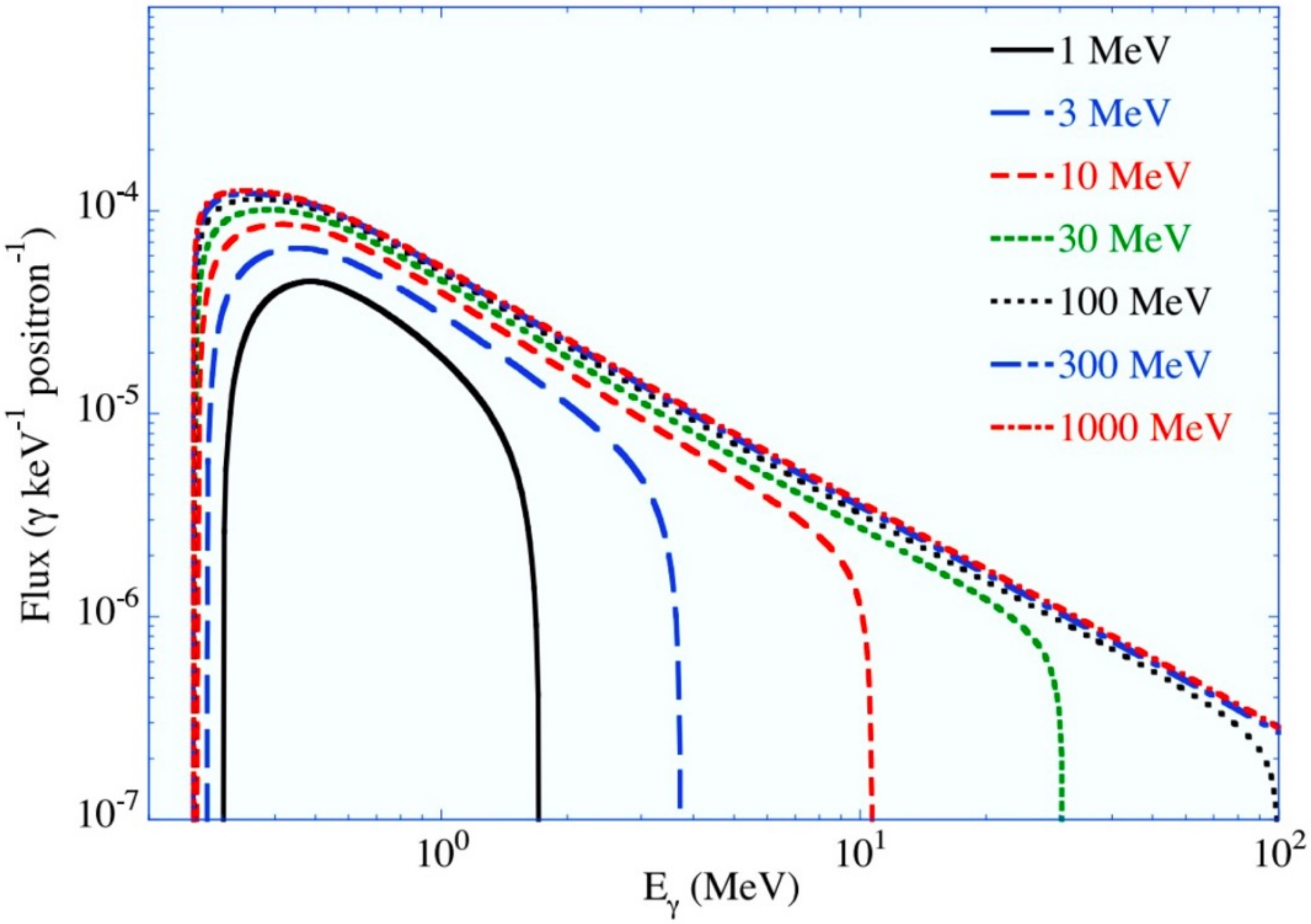
- **FACT 3** Positronium fraction: $97\% \pm 2\%$

$$f_{Ps} = \frac{8 I_{3\gamma}/I_{2\gamma}}{9 + 6 I_{3\gamma}/I_{2\gamma}},$$



Facts of 511 keV line

- **FACT 4** Kinetic energy of Positron: $< 3 - 7\ \mathrm{MeV}$



Facts of 511 keV line

FACT 1 Total positron annihilation rate: $L_{e^+} = 2{\times}10^{43}\ \mathrm{s}^{-1}$

FACT 2 Bulge-Disk ratio of annihilation rate: $B/D \sim 0.6$ (?)

FACT 3 Positronium fraction: $97\% \pm 2\%$

FACT 4 Kinetic energy of Positron: $< 3 - 7\ \mathrm{MeV}$

Challenges of the Coded Mask

观测过程： $d = Cs + b$

d – 观测图像

C – 码板

s – 源空间分布

b – 背景

反解过程： $s' = Md = MCs + Mb$

Prof. Feng @ High Energy Astrophysics

Challenges of the Coded Mask

观测过程： $d = Cs + b$

d – 观测图像
C – 码板
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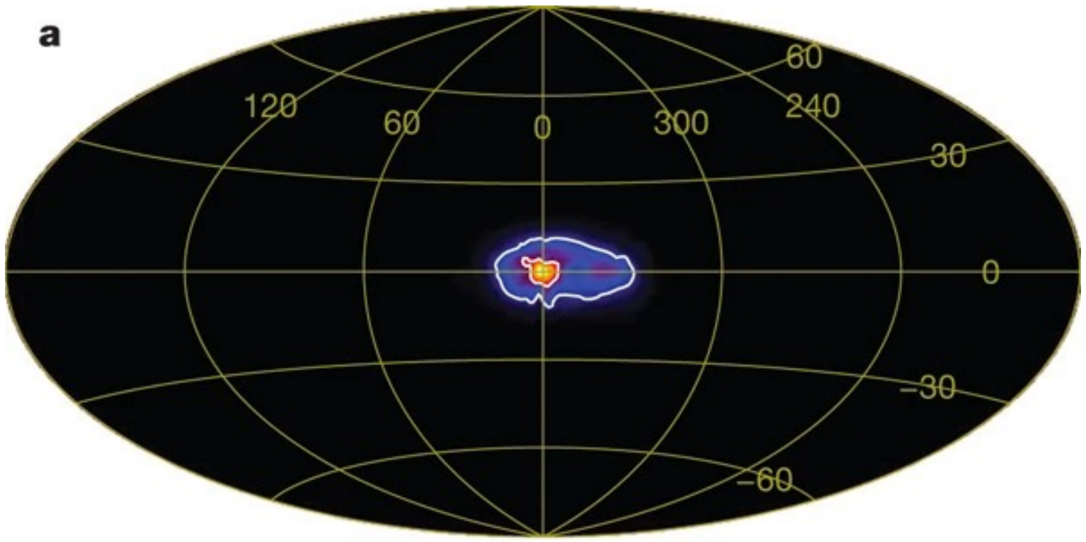
反解过程： $s' = Md = MCs + Mb$

Prof. Feng @ High Energy Astrophysics

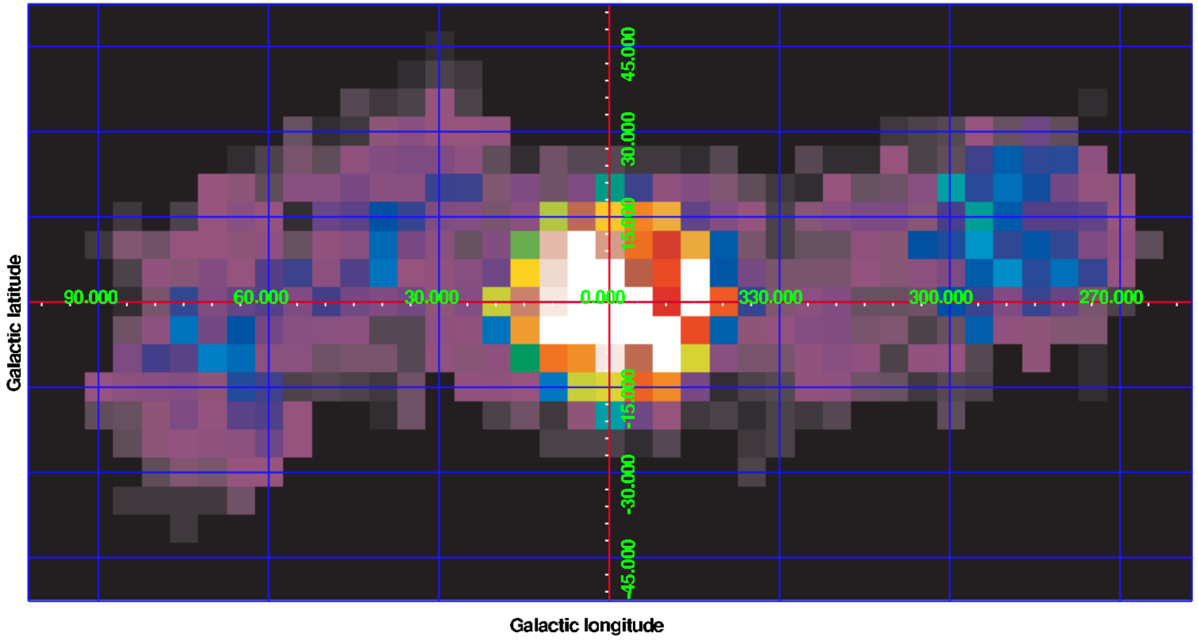
Challenges of the Coded Mask

(Use different reconstruction algorithms)

Asymmetric disk component
(Weidenspointner et al. 2008)



No evidence for a disk asymmetry
(Bouchet et al. 2008, 2010)

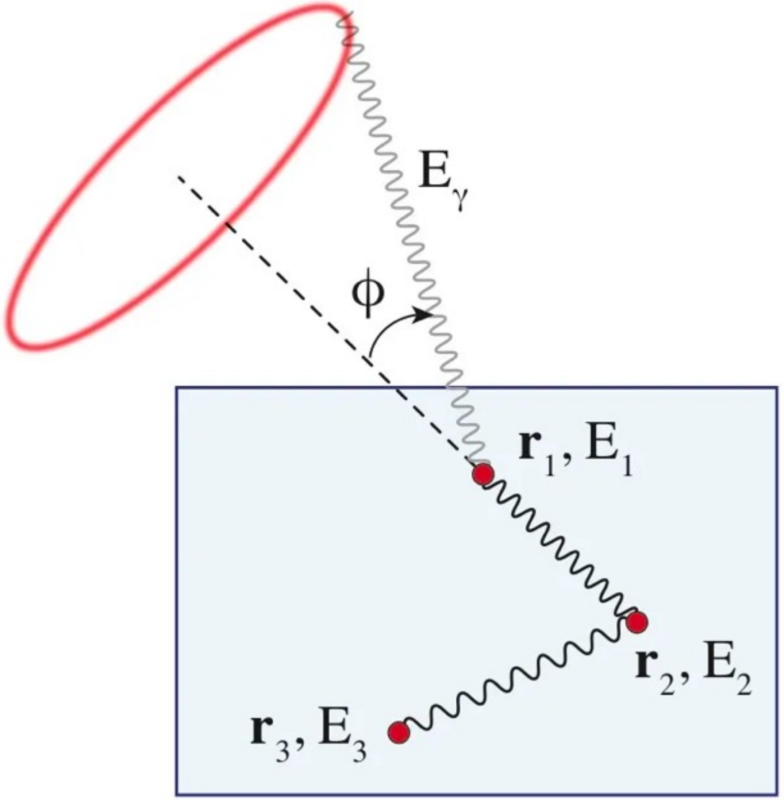


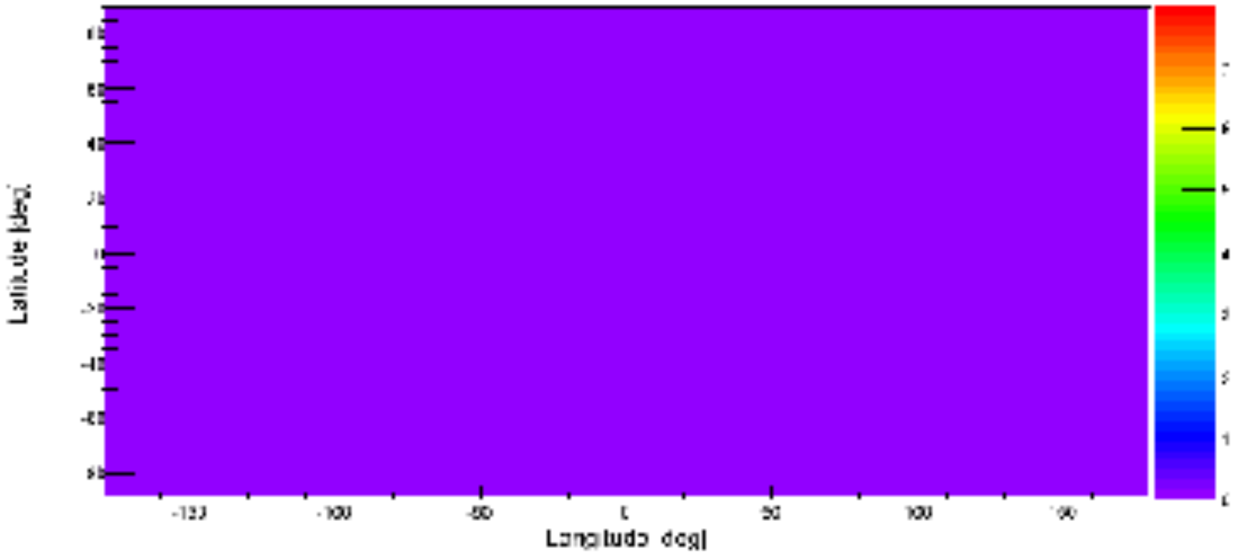
Reconstructing extended sources is a challenge for coded mask instruments

Future Observation

COSI

THE COMPTON SPECTROMETER AND IMAGER





https://i0.wp.com/cosi.ssl.berkeley.edu/wp-content/uploads/2020/11/bp_anim.gif

Summary

FACT 1 Total positron annihilation rate: $L_{e^+} \sim 2 \times 10^{43}\ \mathrm{s}^{-1}$

FACT 2 Bulge-Disk ratio of annihilation rate: $B/D \sim 0.6$ (?)

FACT 3 Positronium fraction: $97\% \pm 2\%$

FACT 4 Kinetic energy of Positron: $< 3 - 7\ \mathrm{MeV}$

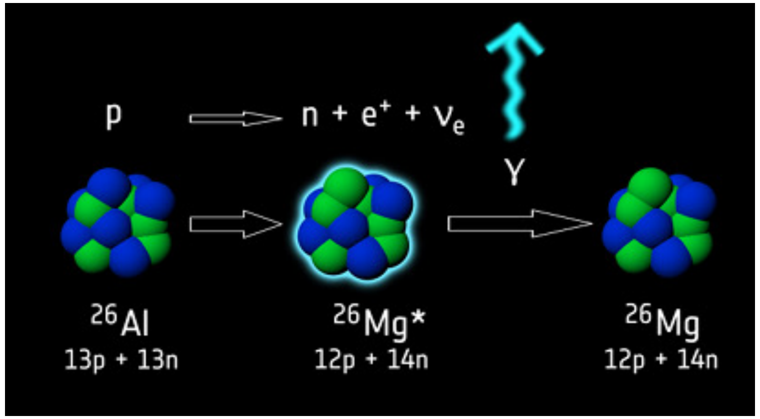
Theoretical interpretations should explain all the observational facts

The origin of 511 keV emission in the Galaxy

EXPLANATIONS: ASTROPHYSICS

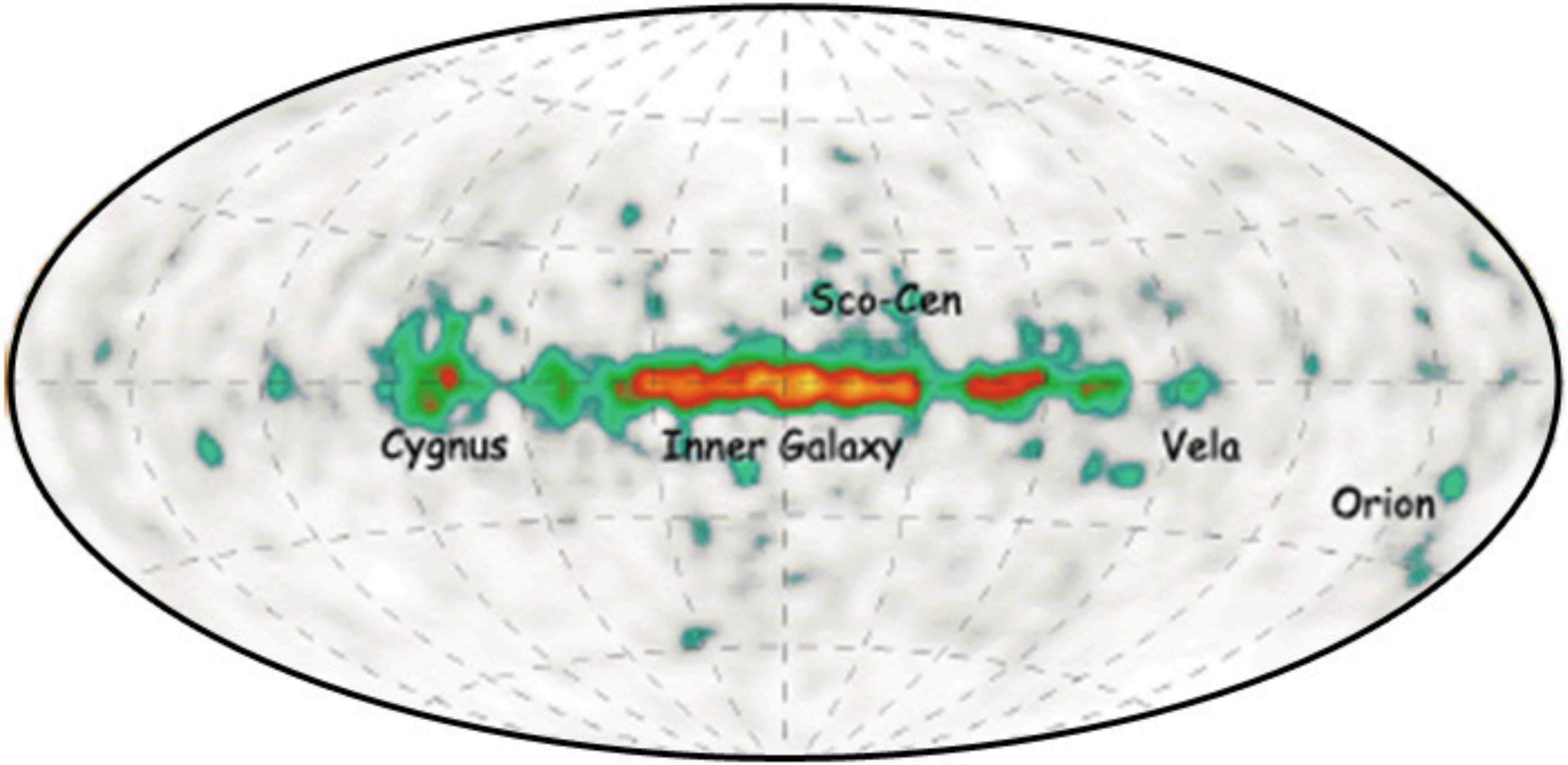
Astrophysics——^{26}Al

Decay chain	Half life	γ-ray [keV] (BR)	Production site
$^{26}_{13}\mathrm{Al} \to ^{26}_{12}\mathrm{Mg}$	7.4×10^5 yr	1809(1)	WR stars, CCSN
$^{44}_{22}\mathrm{Ti} \to ^{44}_{21}\mathrm{Sc} \to ^{44}_{20}\mathrm{Ca}$	59 yr	68(0.94), 78(0.96), 1157(1)	CCSN
$^{22}_{11}\mathrm{Na} \to ^{22}_{10}\mathrm{Ne}$	2.6 yr	1275(1)	Novae
$^{56}_{28}\mathrm{Ni} \to ^{56}_{27}\mathrm{Co} \to ^{56}_{26}\mathrm{Fe}$	77.2 d	847(1), 1238(0.68), 1771(0.15), 2598(0.17)	SNIa



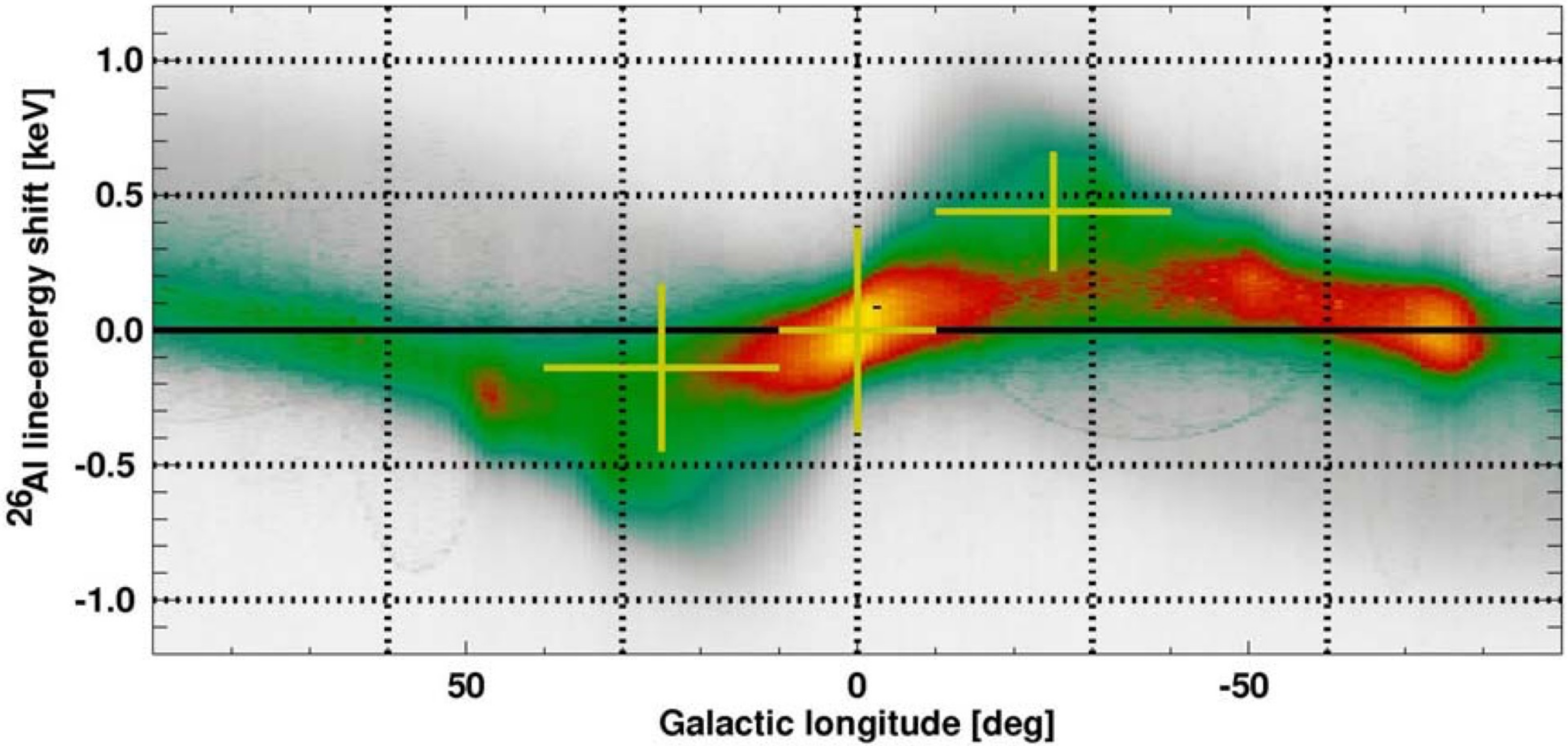
82%: β+; 18%: EC

COMPTEL ^{26}Al all sky map



Massive stars are the dominant source (Diehl et al. 1995)
Wolf-Rayet stellar winds or supernova explosion (dominant)
(Limongi and Chieffi 2006)

Doppler shift of ^{26}Al (INTEGRAL)

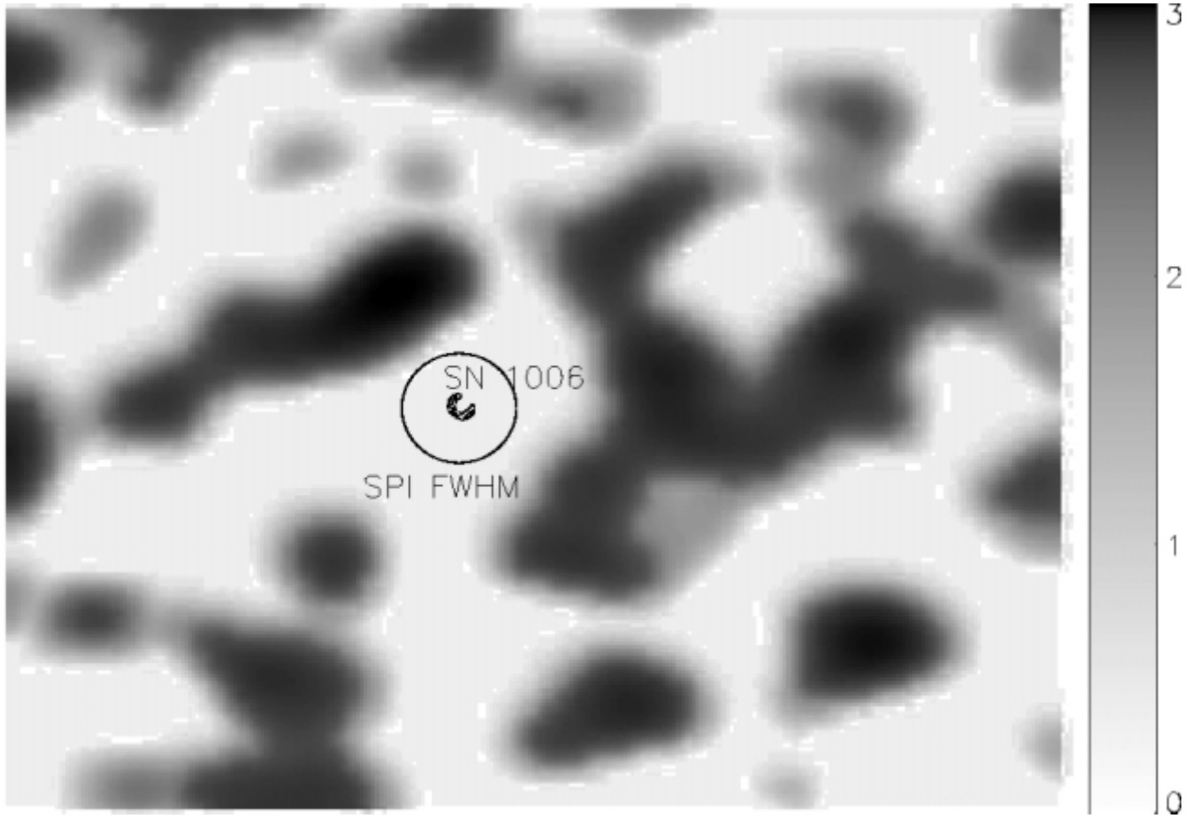


$$\dot{N}_{e^+,26} = 3.5 \times 10^{42}\ \mathrm{s}^{-1}$$

About one-half of the disk emission(~10^{43})can be explained by radioactivity of ^{26}Al; The other half may be explained with ^{44}Ti

Supernova: $^{56}Ni \rightarrow {}^{56}Co \xrightarrow{\beta^+ \text{decay}} {}^{56}Fe$

- Type Ia SNe
  - the escape of positrons produced in ^{56}Co decays.

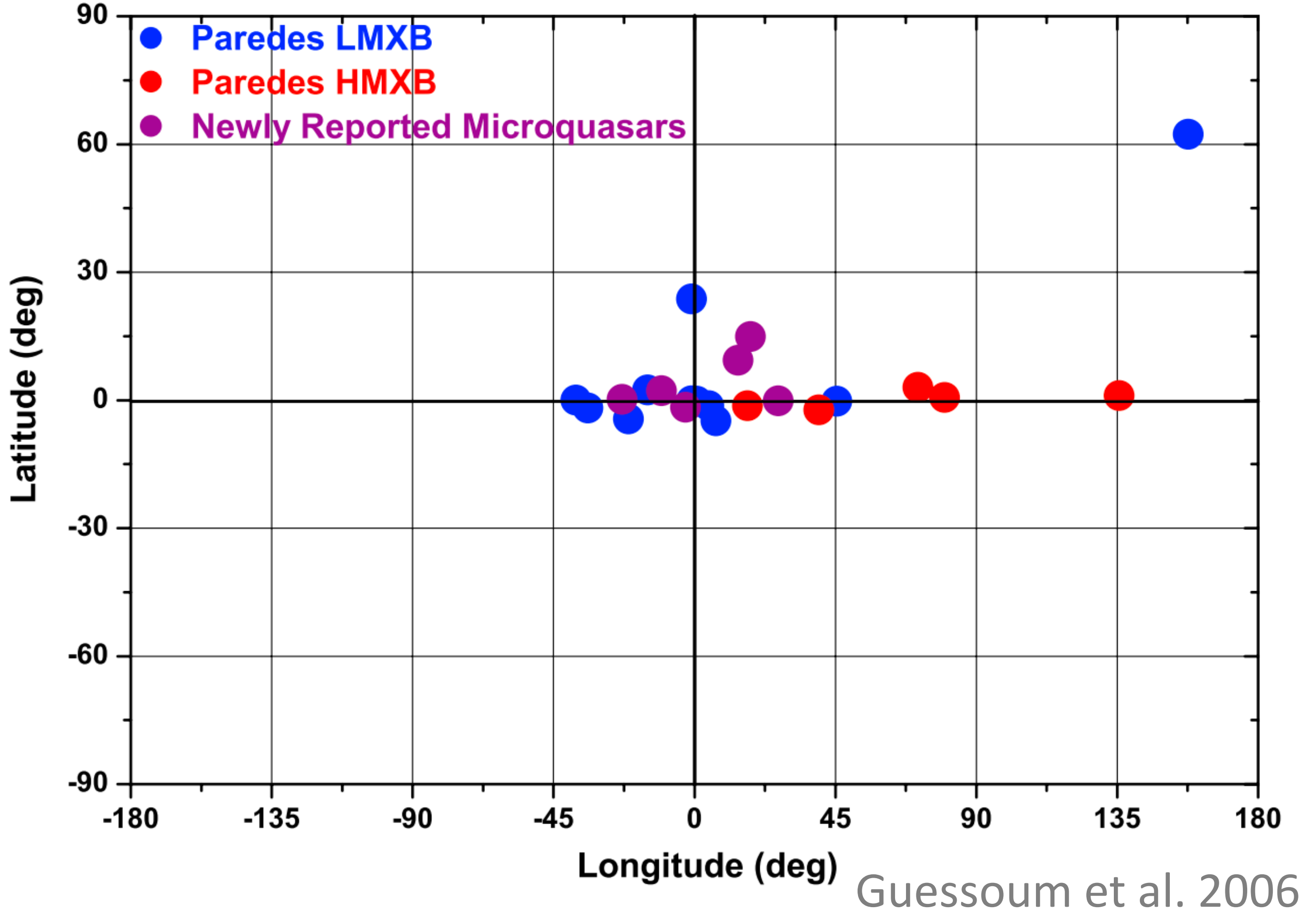


SPI significance image in the 508.5–513.5 keV band (Kalemci et al. 2006)

- Type Ic associated with GRBs
  - a large amount of ^{56}Ni and ejects
  - e.g. SN 2003dh, that is associated with a gamma-ray burst (GRB).

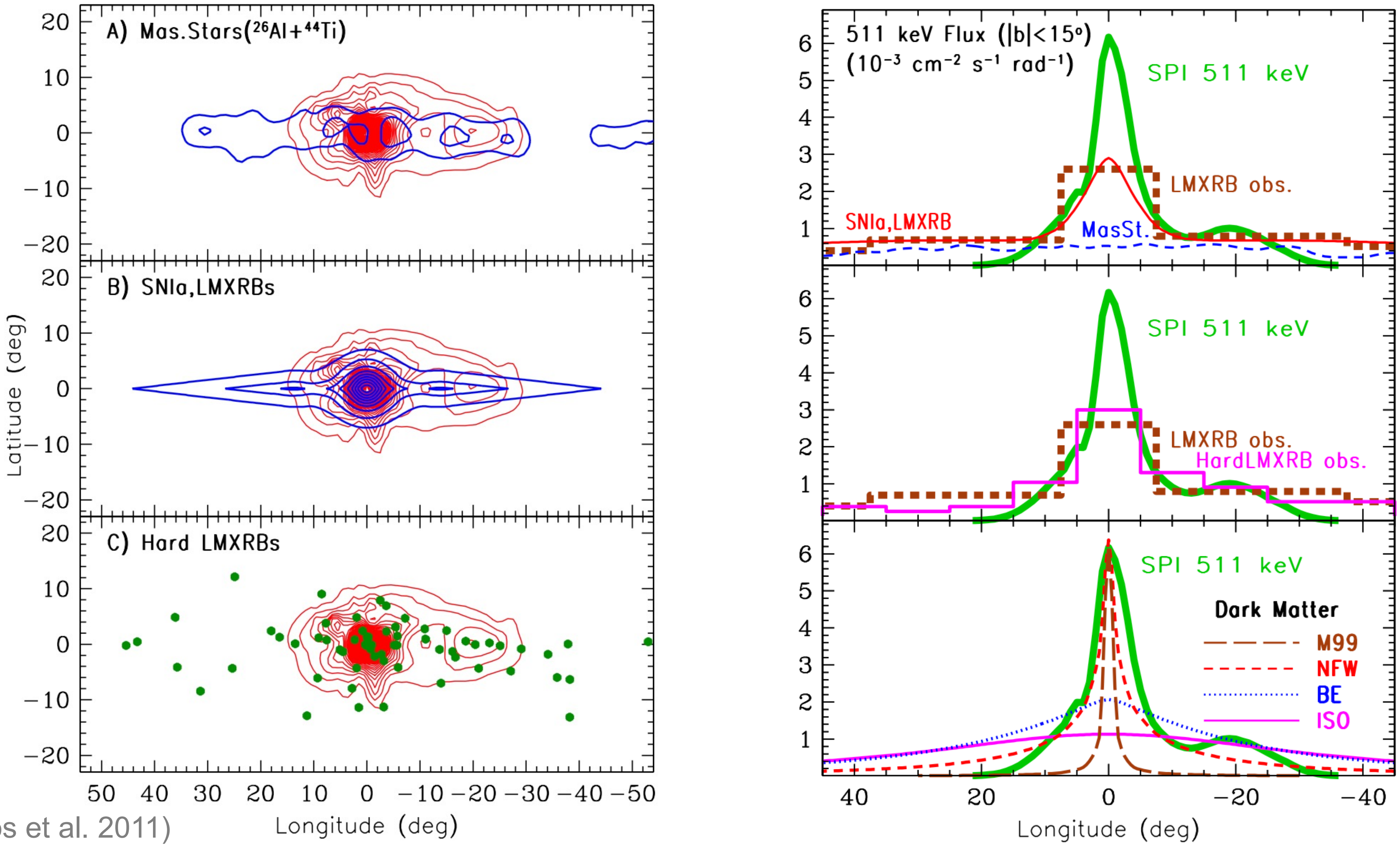
LMXBs and microquasars

- In the case of LMXBs, positrons should be produced as $e^+ - e^-$ pairs in the hot inner regions of their accretion discs.
- a non-negligible fraction of positrons would be channeled out by jets



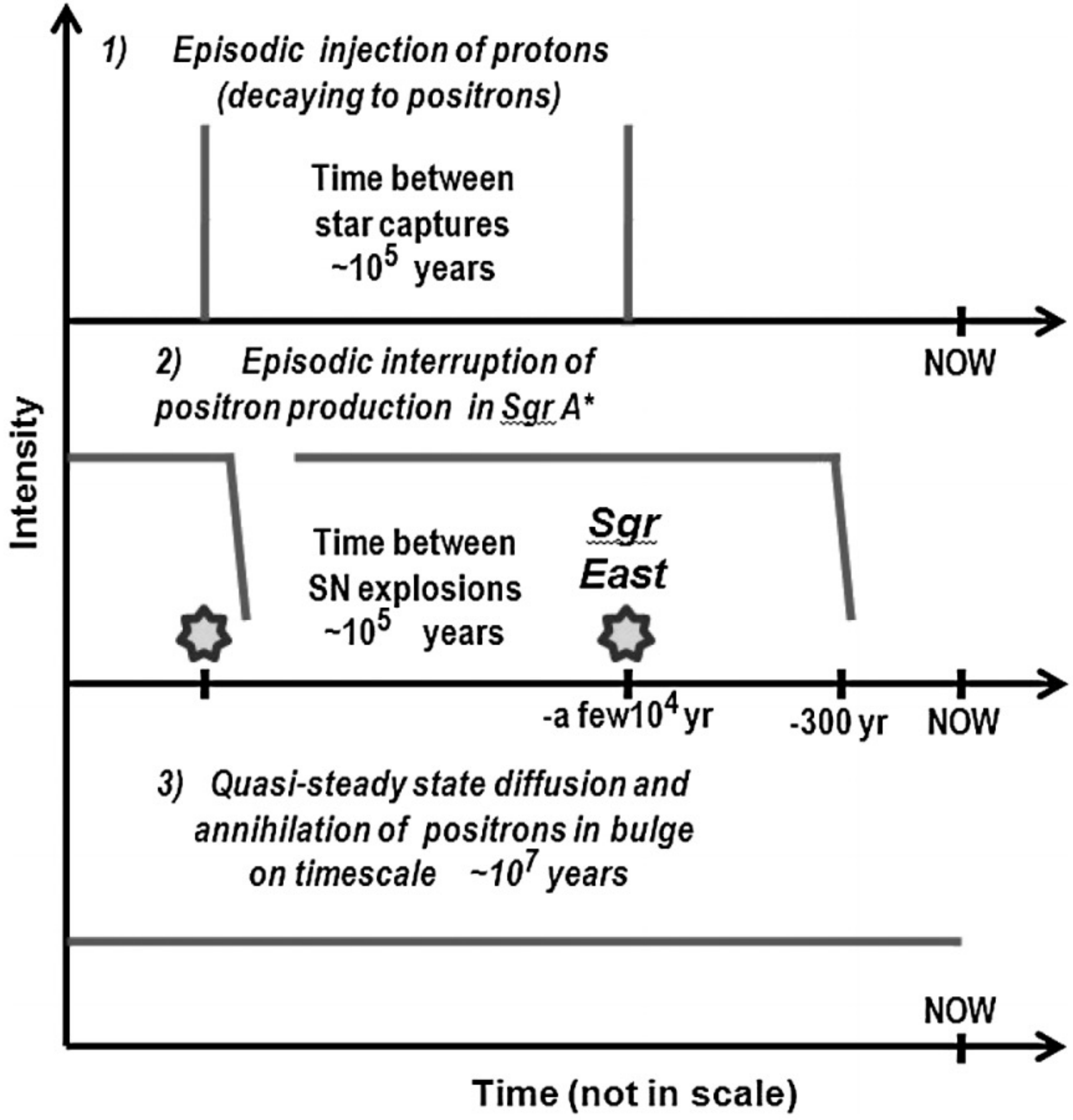
Guessoum et al. 2006

511 keV morphology



(Prantzos et al. 2011)

Supermassive BHs



Prantzos 2011

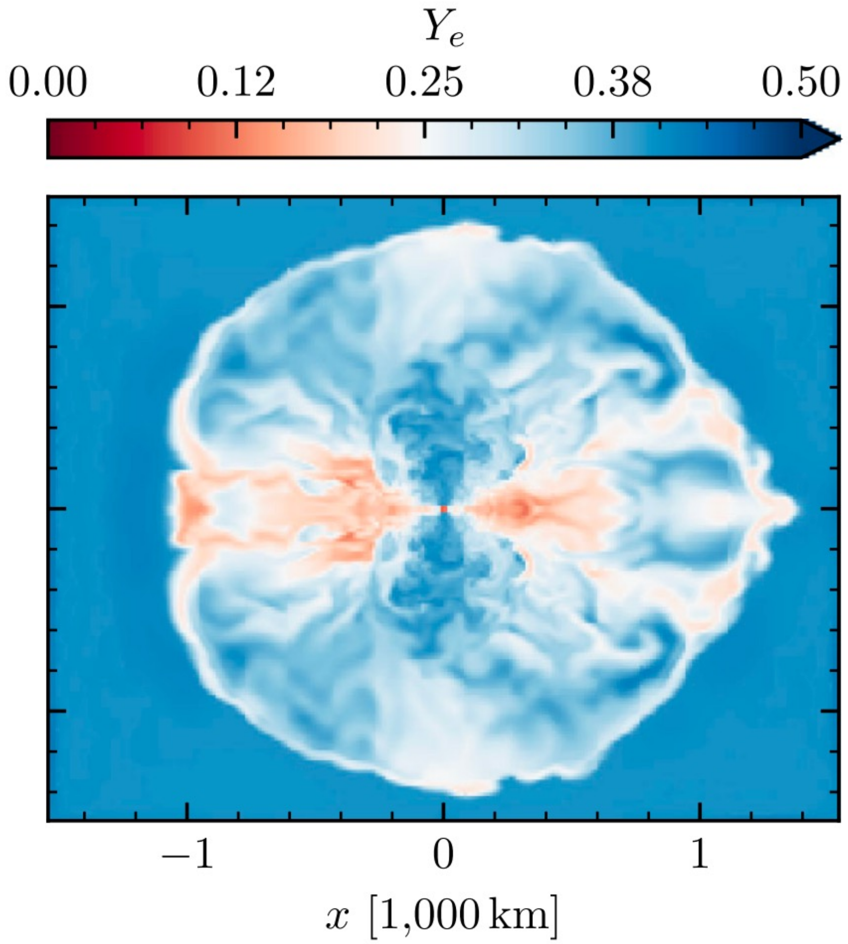
- a significant amount of positrons should have been created during the higher activity phase

  1) Tidal disruption of nearby stars and subsequent accretion

  2) accretion flow is interrupted by the passage of the shock front of a nearby SN explosion

NS merger

- heated by nuclear processes to temperatures of a few hundred keV, resulting in a population of electron-positron pairs.
- positrons escape from the outer layers of the ejecta.



electron fraction profiles of the ejected material at 10 ms after merger. (Fuller et al. 2019)

Summary

1. Astrophysical sources (massive stars, SNe Ia, LMXB…) can explain the total flux on the disk

2. Other explanation (supermassive black hole, NS merger…) may help explain the bulge flux but require observational evidence

The origin of 511 keV emission in the Galaxy

EXPLANATIONS: PBH & DM PARTICLES

Primordial Black Holes

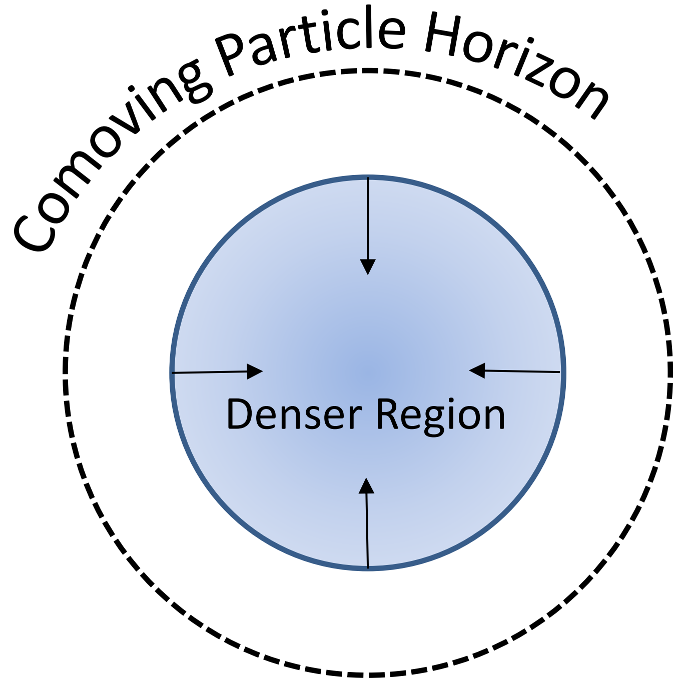
Form in early universe due to inhomogeneity

Mass:

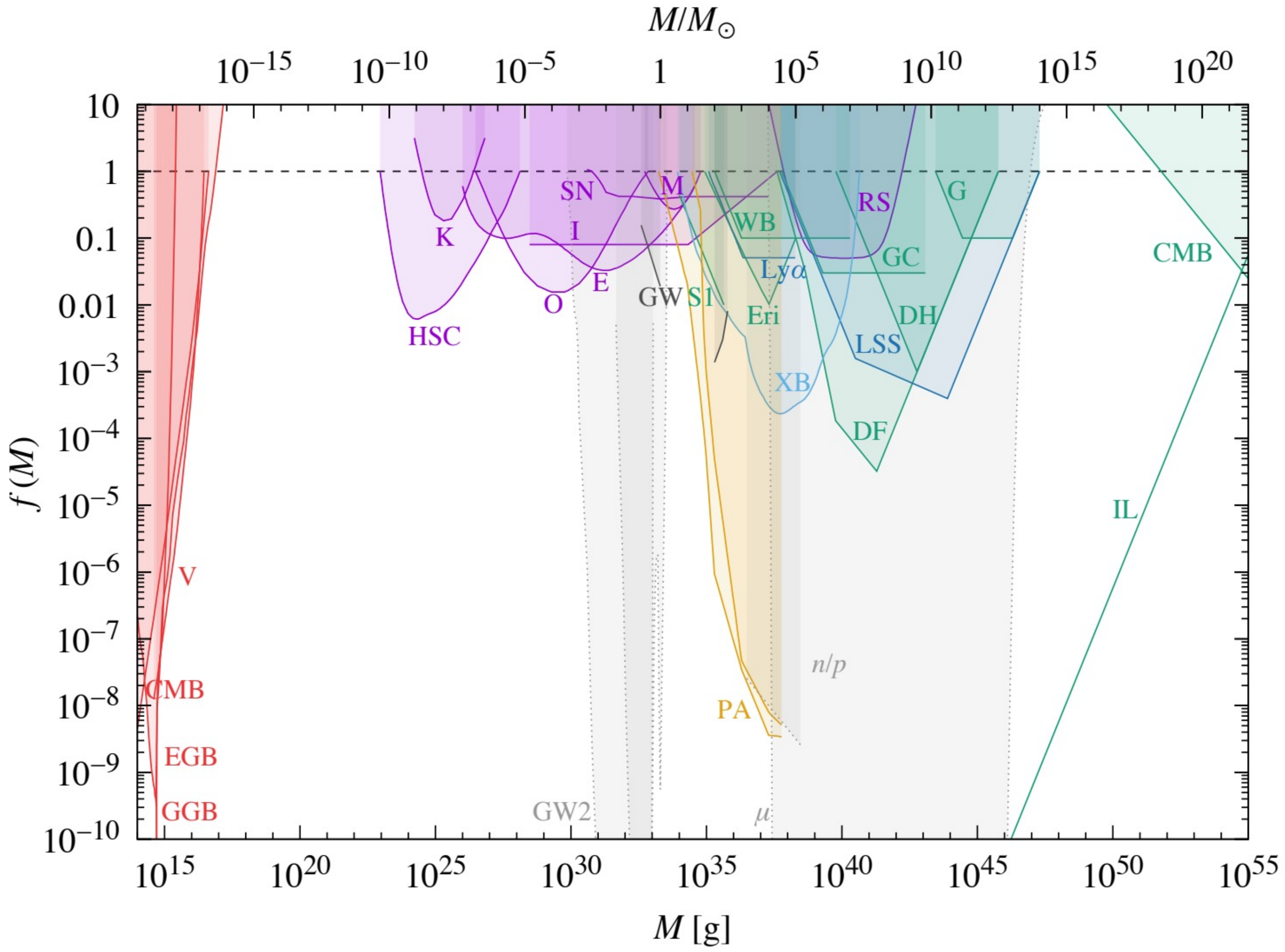
$$M_H(t) \approx \frac{c^3 t}{G} \approx 10^{15} \left(\frac{t}{10^{-23}\ s}\right) g$$

Dark Matter Candidate

$$f_{\mathrm{PBH}}(M) = \frac{\Omega_{\mathrm{PBH}}(M)}{\Omega_{\mathrm{CDM}}}$$



Primordial Black Holes



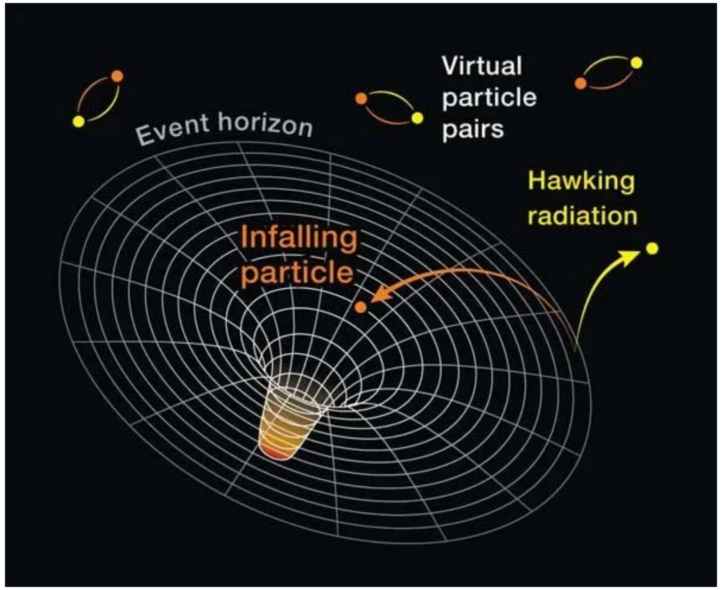
Arxiv: 2002.12778

Primordial Black Holes

Hawking radiation:

$$T_H = \frac{M_P^2}{8\pi M} \sim 4\times10^{-10}\left(\frac{M_P}{M}\right)\text{kg} \sim 10^{31}\text{K}\left(\frac{M_P}{M}\right)$$

$$\tau(M) \sim \frac{G^2M^3}{\hbar c^4} \sim 100\tau_P\left(\frac{M}{M_P}\right)^3$$



Evaporation: $\frac{dM}{dt} \propto -M^{-2}$

$$M_{max} \sim 10^{36}\text{kg}, M_{rad} \sim 10^{24}\text{kg}, M_{min} \sim 10^{12}\text{kg}$$

Primordial Black Holes

A simple estimation:

DM in the Galactic Center $\sim 10^{34}$kg
$f_{PBH} = 1$ (at center)
Estimate positron produce rate $\sim 10^{43}/s$ for all PBH at M_{min}

Mod. Phys. Lett. A 2005.20:1573-1576

Dark matter (Particle)

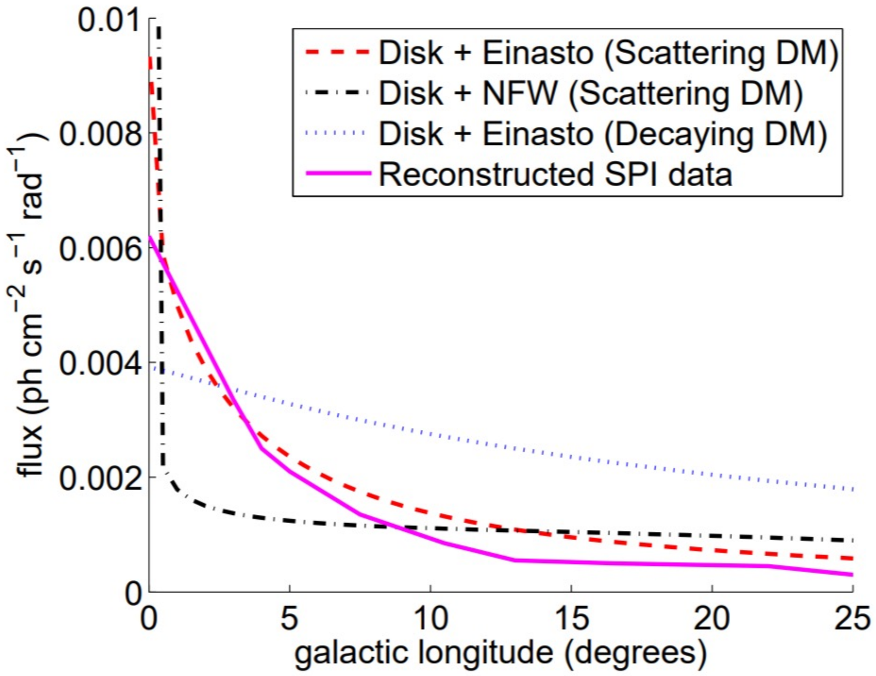
	Light DM (MeV)	Heavy DM (GeV-TeV)
Decay	Decay $\chi \to e^- + e^+ + \cdots$	Deexciting $\chi^* \to e^- + e^+ + \chi + \cdots$
Scattering	Annihilation $\chi + \chi \to e^- + e^+$	Upscattering/ Downscatteriing

Dark matter (Particle)

Decay scenario:

$$\Phi_{511,\gamma} \propto \text{integral of } \rho_{DM} \text{ along LOS}$$
$$\dot{n}_{e^+} = n_\chi \Gamma$$

Sterile neutrino DM $N_1 \to e^- + e^+ + \nu$



Wrong with morphology!

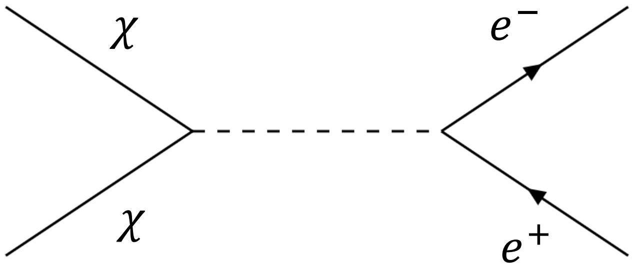
Khalil et al,0804.0336

Aaron C. Vincent et al JCAP04(2012)022

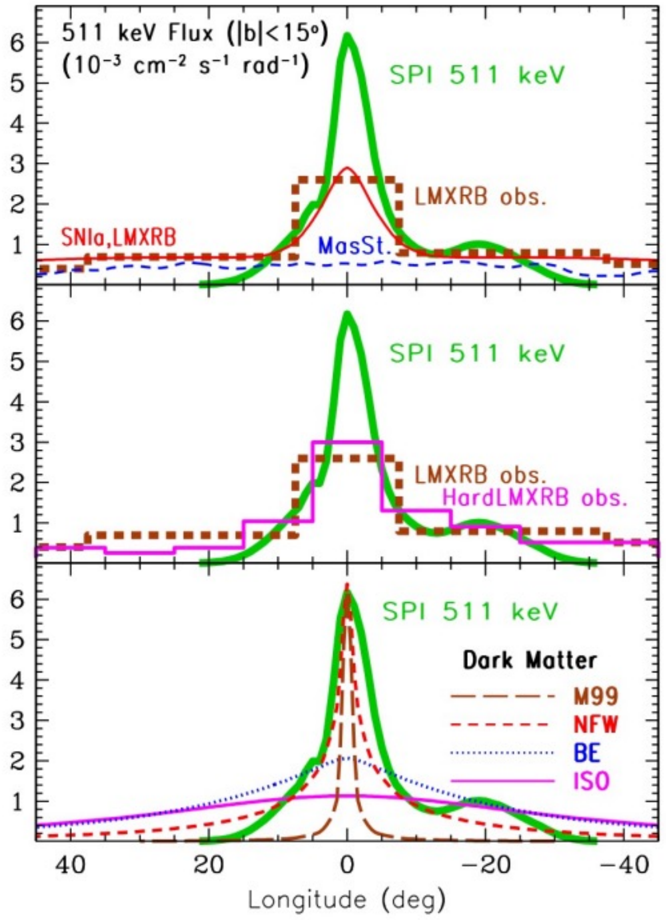
Dark matter (Particle)

Scattering scenario:

$$\Phi_{511,\gamma} \propto \text{integral of } \rho_{DM}^2 \text{ along LOS}$$



$$\dot{n}_{e^+} = n_\chi^2 < \sigma v >/2$$

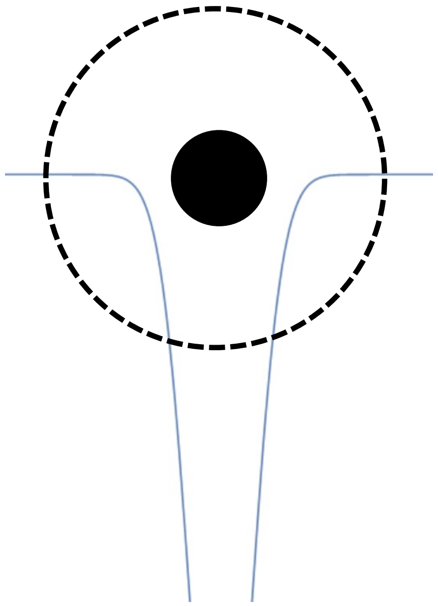


Hooper et al. PRD 77,087302 (2008)

A mixed model

DM halo around the PBH：

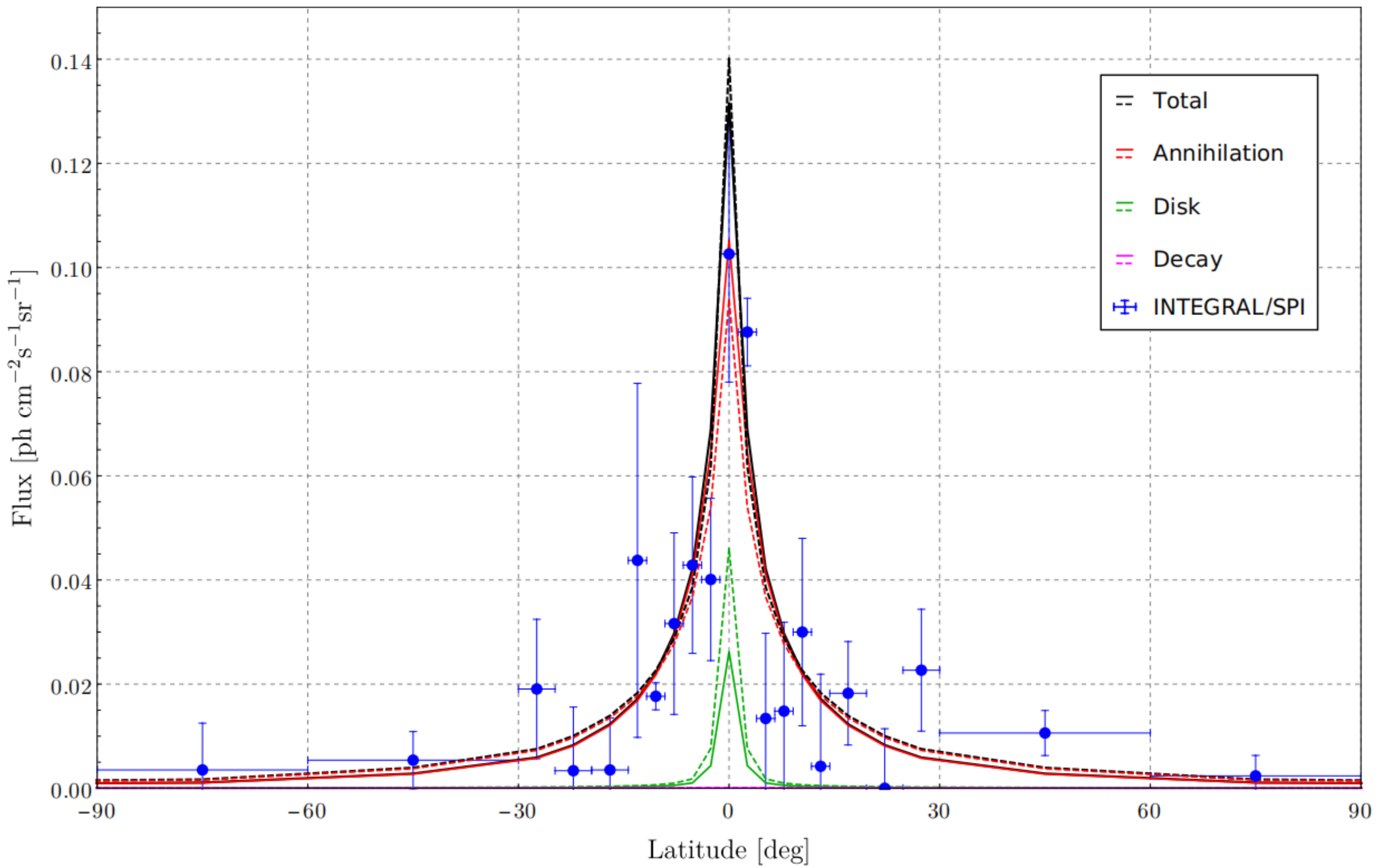
$$\dot{n}_{e^+} = n_{PBH}\Gamma_{PBH}$$



Consider multiple components：
(self-)annihilating DM + PBH + β^+ emission(disk)

A 3-parameter mixed model：$C_A, C_D, \dot{n}_{YD}$

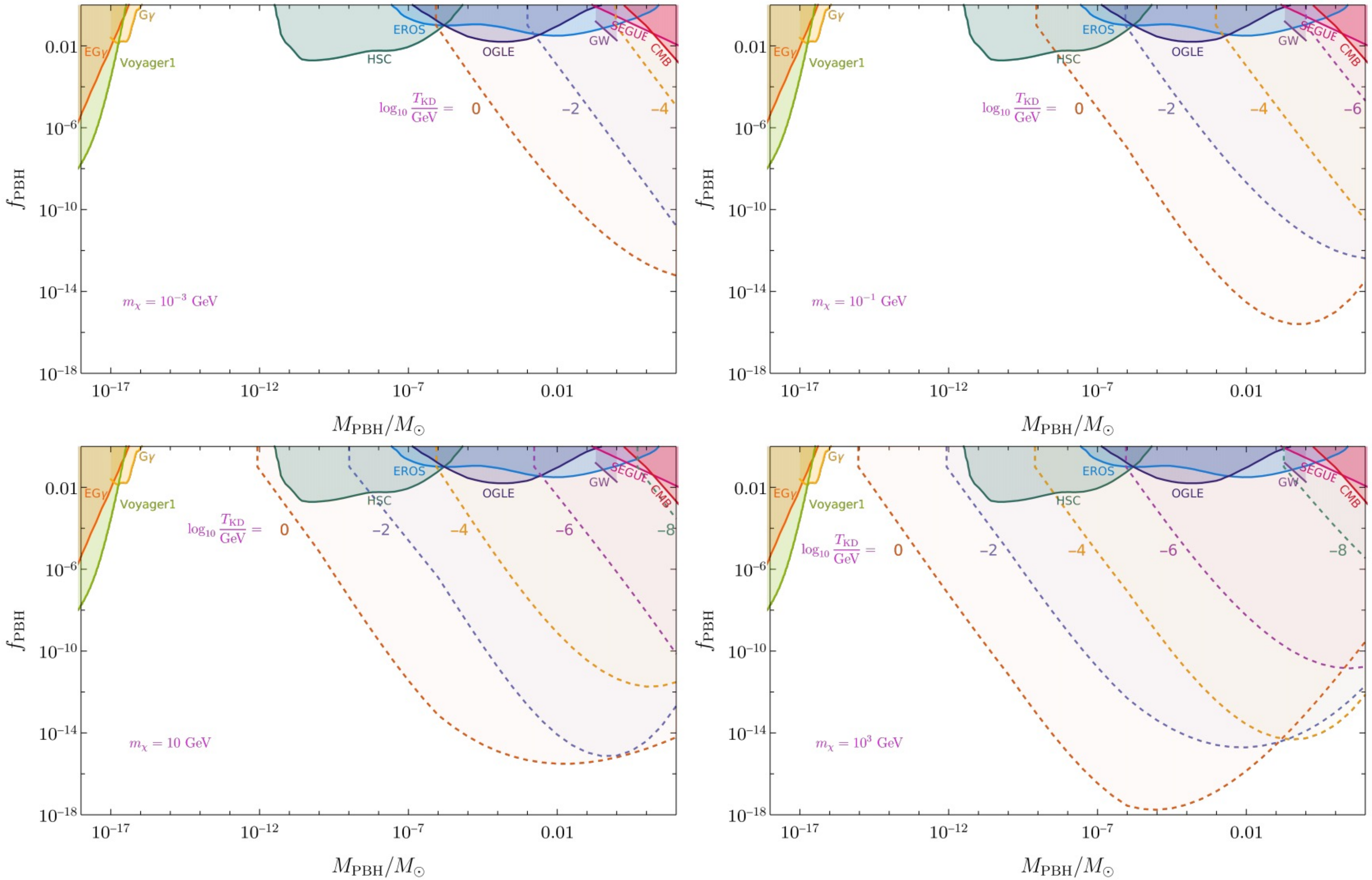
A mixed model



$\frac{C_D}{C_A} < 0.37$ (Einasto Profile)

2007.11804 Cai et al.

A mixed model

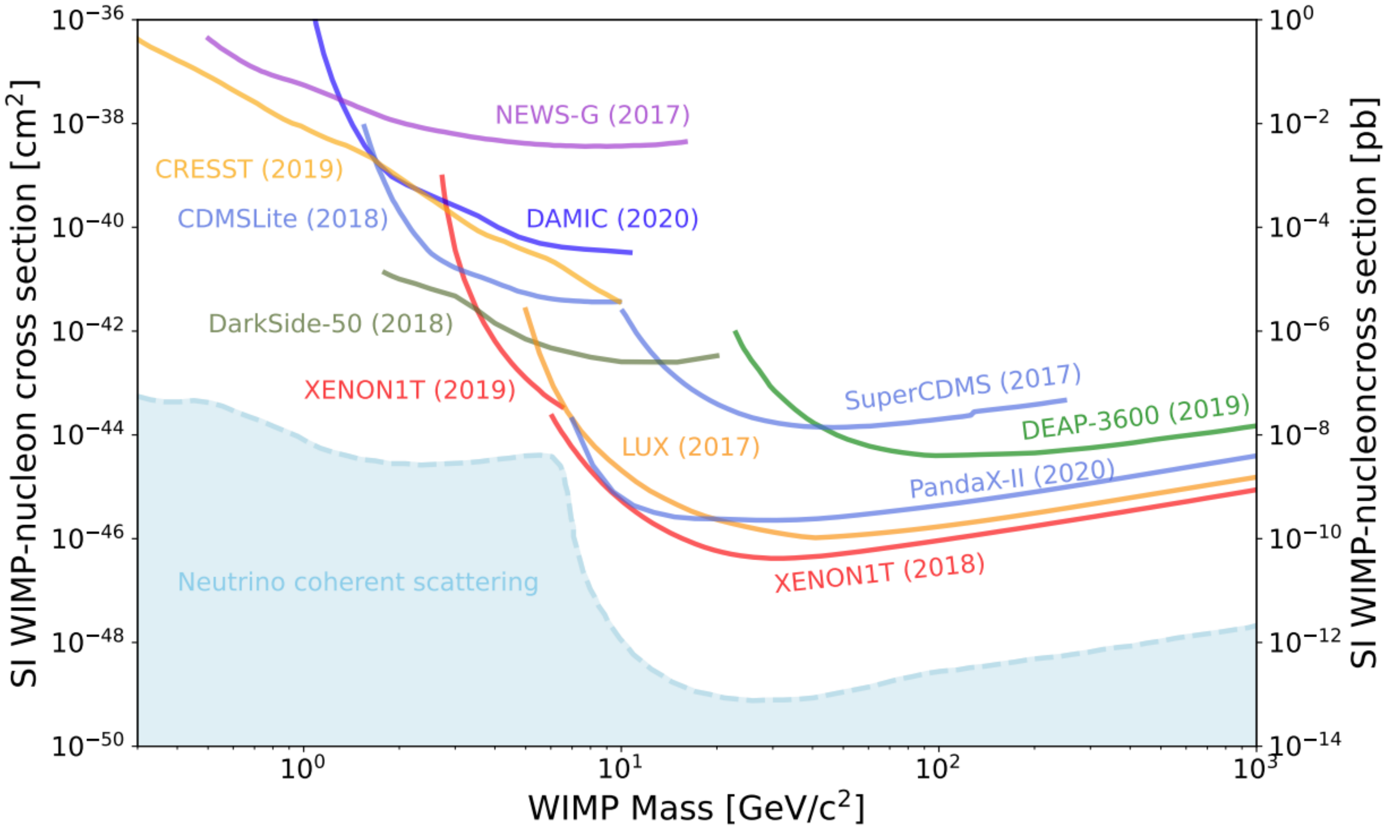


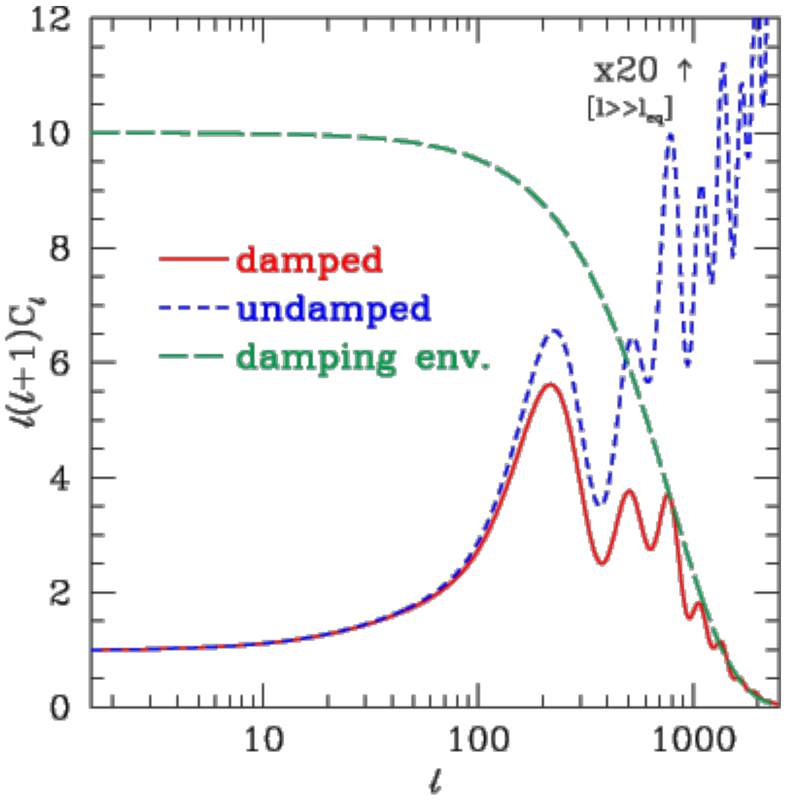
2007.11804 Cai et al.

Comments

1. The DM particle and PBH have not been found
2. Large parameter space for many DM models,

More observation constraint on DM is needed.

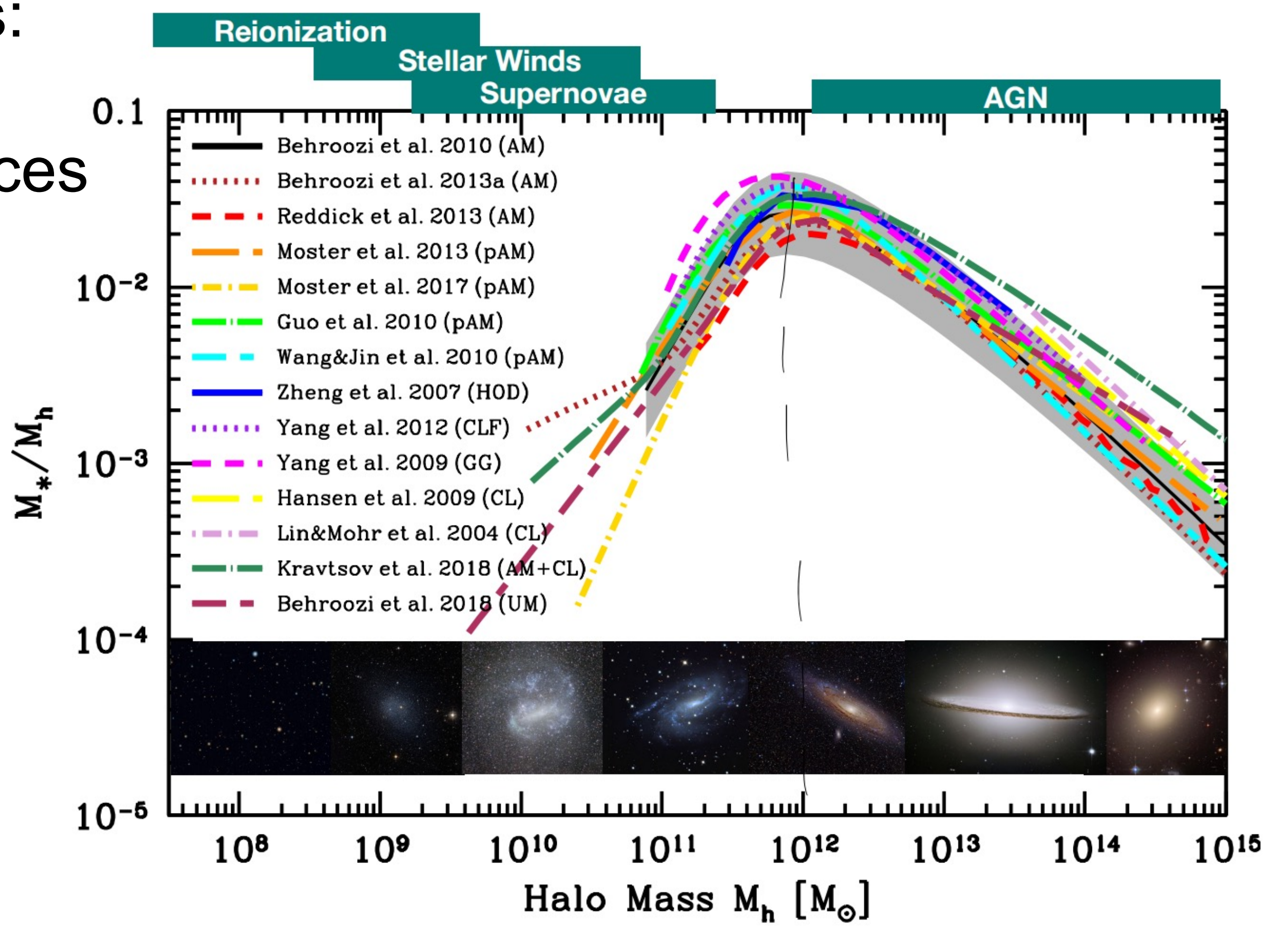




Comments

3. Observations on dwarf galaxies:

More DM, less astrophysical sources



Take home message

1. 511 keV emissions are ~100% from low-energy Ps annihilation from both Galactic bulge and disk, and the two components are comparable.

2. Astrophysics can explain the total flux on the disk but hardly match the bulge flux

3. DM and PBH can be the explanation for 511 keV emission GCE but need more constraint by observation

Candidate e^+ sources

TABLE IX. Properties of candidate positron sources in the Milky Way.

Source	Process	$E(e^+)$[a] (MeV)	e^+ rate[b] $\dot{N}_{e^+}$ (10^{43} s^{-1})	Bulge/disk[c] B/D	Comments
Massive stars: ^{26}Al	β^+ decay	$\sim$1	0.4	<0.2	$\dot{N}$, B/D: Observationally inferred
Supernovae: ^{24}Ti	β^+ decay	$\sim$1	0.3	<0.2	$\dot{N}$: Robust estimate
SNIa: ^{56}Ni	β^+ decay	$\sim$1	*2*	<0.5	Assuming $f_{e^+,\mathrm{esc}} = 0.04$
Novae	β^+ decay	$\sim$1	*0.02*	<0.5	Insufficient e^+ production
Hypernovae/GRB: ^{56}Ni	β^+ decay	$\sim$1	?	<0.2	Improbable in inner MW
Cosmic rays	p-p	$\sim$30	0.1	<0.2	Too high e^+ energy
LMXRBs	γ-γ	$\sim$1	*2*	<0.5	Assuming $L_{e^+} \sim 0.01\ L_{\mathrm{obs},X}$
Microquasars (μQs)	γ-γ	$\sim$1	*1*	<0.5	e^+ load of jets uncertain
Pulsars	γ-γ/γ-γ_B	>30	*0.5*	<0.2	Too high e^+ energy
ms pulsars	γ-γ/γ-γ_B	>30	*0.15*	<0.5	Too high e^+ energy
Magnetars	γ-γ/γ-γ_B	>30	*0.16*	<0.2	Too high e^+ energy
Central black hole	p-p	High	?		Too high e^+ energy, unless $B > 0.4$ mG
	γ-γ	1	?		Requires e^+ diffusion to $\sim$1 kpc
Dark matter	Annihilation	1 (?)	?		Requires light scalar particle, cuspy DM profile
	Deexcitation	1	?		Only cuspy DM profiles allowed
	Decay	1	?		Ruled out for all DM profiles
Observational constraints		<7	2	>1.4	

[a]Typical values are given.
[b]e^+ rates: in roman: observationally deduced or reasonable estimates; in italic: speculative (and rather close to upper limits).
[c]Sources are simply classified as belonging to either young ($B/D < 0.2$) or old (< 0.5) stellar populations.

(Prantzos et al. 2011)