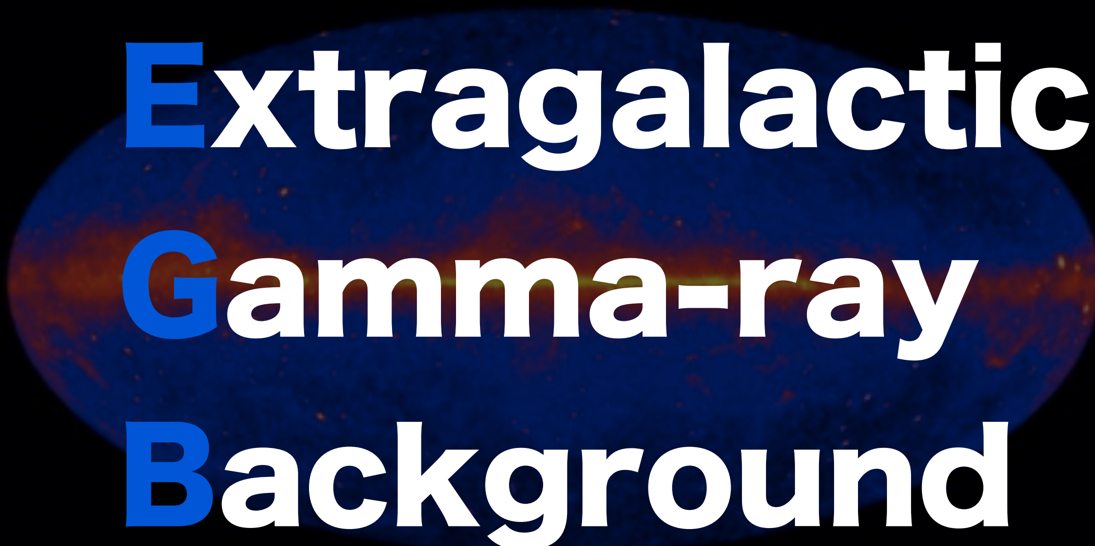
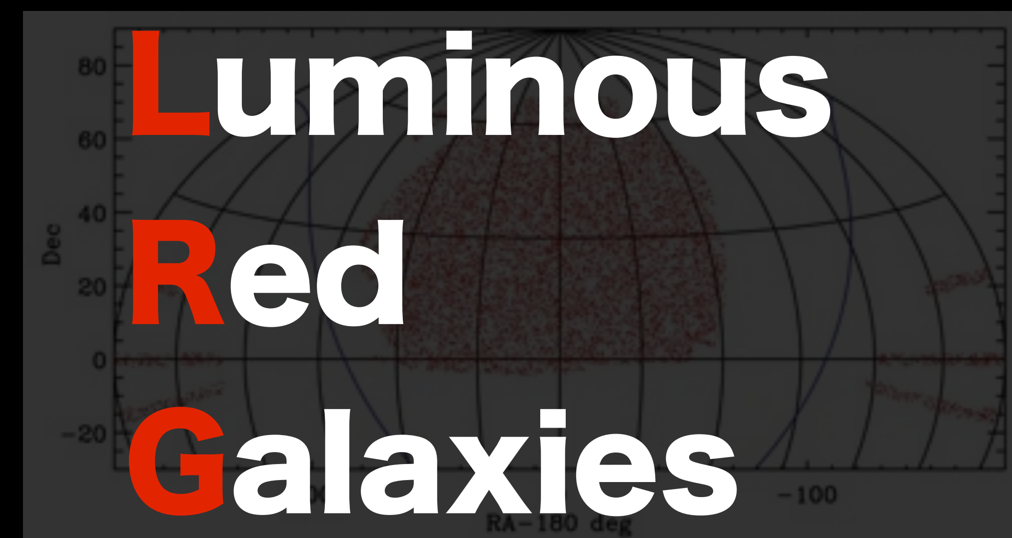
Cross-Correlation of

Extragalactic **G**amma-ray **B**ackground with **L**uminous **R**ed **G**alaxies





白崎正人 (NAOJ)

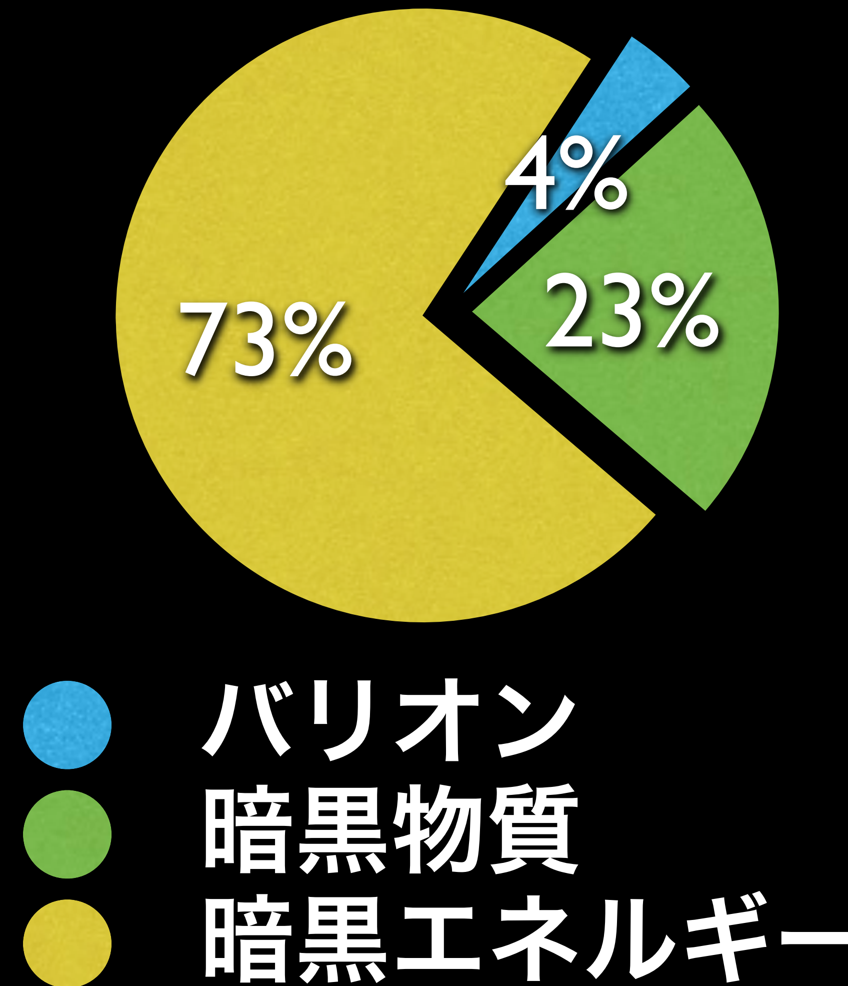
吉田直紀 (KIPMU), 堀内俊作 (Virginia Tech)

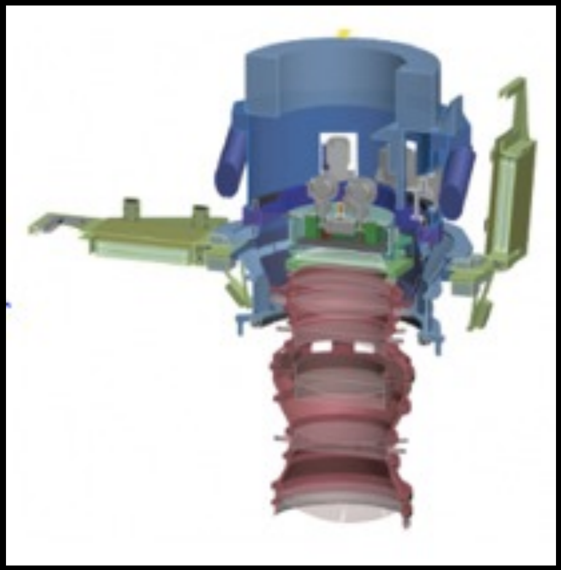
2015.11.19

第４回観測的宇宙論ワークショップ@京大基研

観測的宇宙論の現状

- 複数の大規模天文観測は、ある特定の宇宙モデル(標準宇宙模型)を示唆する
- 標準宇宙模型に残された謎
  - **暗黒物質の素粒子的な性質は？**
- 銀河撮像分光観測を利用すれば、暗黒物質分布を精密に調査できるだろう
- 暗黒物質の対消滅や崩壊などの性質は探れるか？





http://subarutelescope.org/Projects/HSC/j_hsccamera.html

Relic density of annihilating dark matter

$$\frac{\mathrm{d}n_{\mathrm{dm}}}{\mathrm{d}t} + 3Hn_{\mathrm{dm}} = -\langle\sigma v\rangle(n_{\mathrm{dm}}^2 - n_{\mathrm{dm,eq}}^2),$$

$$n_{\mathrm{dm,eq}} = g\left(\frac{m_{\mathrm{dm}}T}{2\pi}\right)^{3/2}\exp\left(-\frac{m_{\mathrm{dm}}}{T}\right),$$

仮定：対消滅断面積は一定

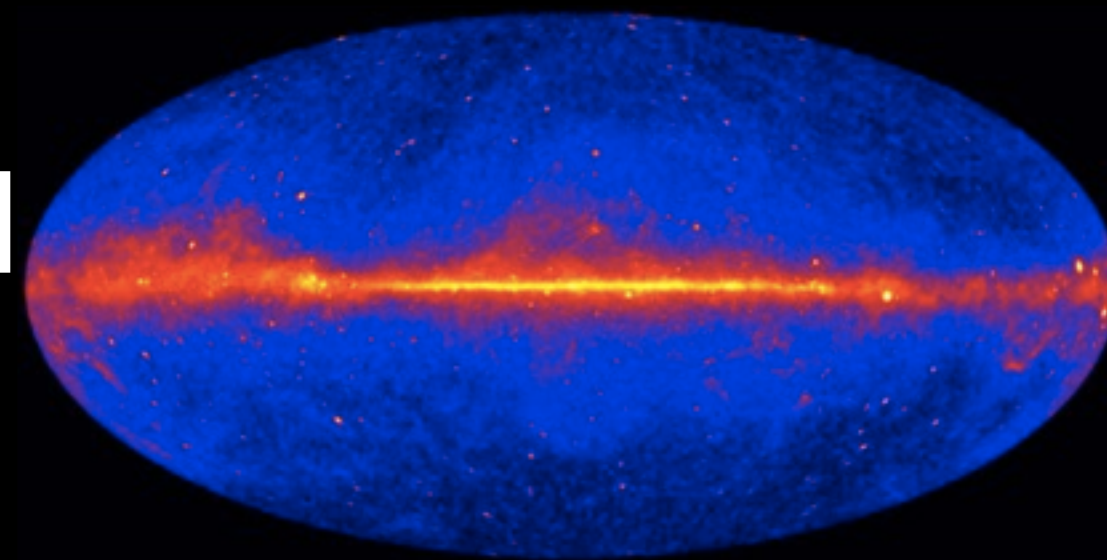
$$\Omega_{\mathrm{m0}}h^2 \simeq \frac{3\times10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle\sigma v\rangle}.$$

宇宙論的に期待される断面積 = **3×10^{-26} cc/s**

How to search for DM annihilation

- 背景成分のレベルでは、暗黒物質は対消滅していない
- 重力非線形性に基づく構造形成は、暗黒物質の高密度領域を生み出す
- **対消滅反応率は数密度の２乗に比例する**から、暗黒物質リッチな領域では対消滅しているかもしれない
- 暗黒物質対消滅による生成物にはガンマ線がある
- 暗黒物質がたくさん存在している(であろう)領域から、ガンマ線が出ているかを調べることは、暗黒物質対消滅を探る良い手法
    - Dwarf galaxies, Galactic center
- **宇宙論的なスケールにわたって広がる暗黒物質も、銀河系外から来るガンマ線に寄与するはずである**

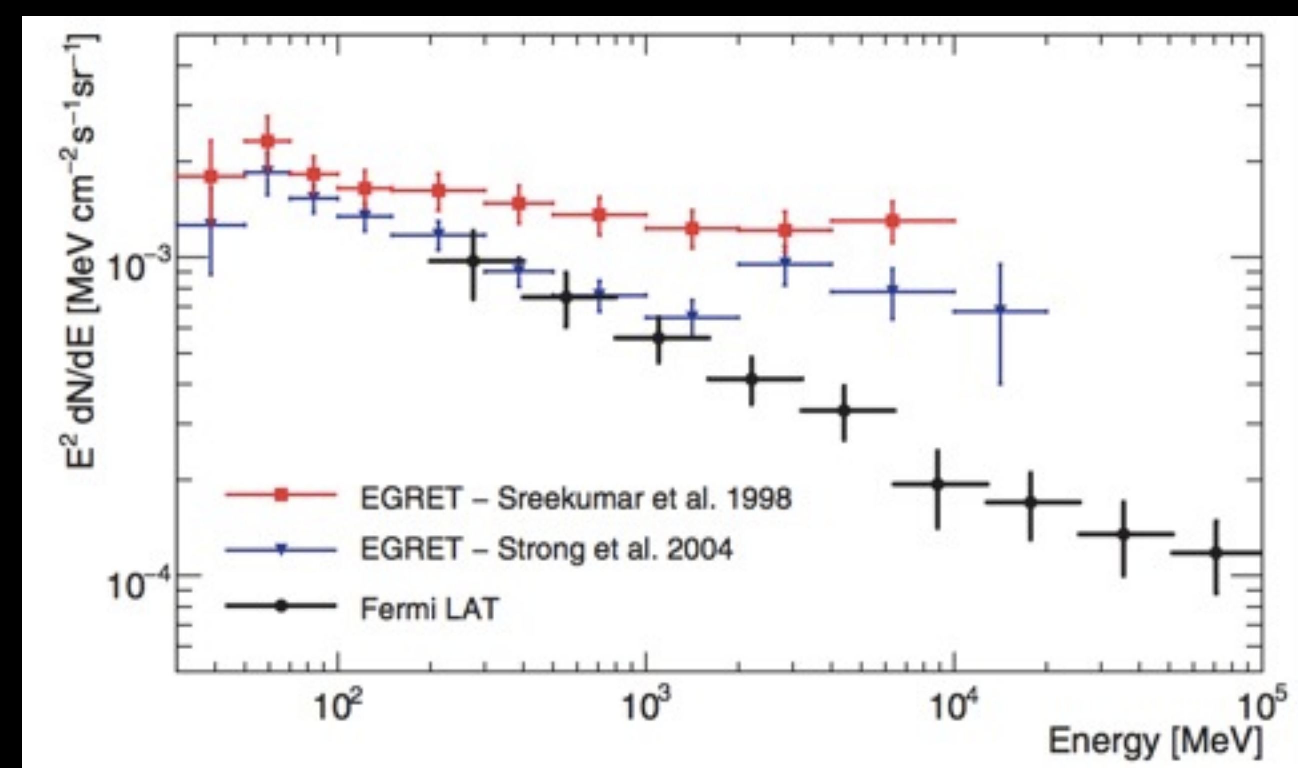
Extragalactic Gamma-Ray Background



Entire sky at energies greater than 1 GeV
based on five years of data
from Fermi Gamma-Ray Telescope

http://fermi.sonoma.edu/multimedia/gallery/

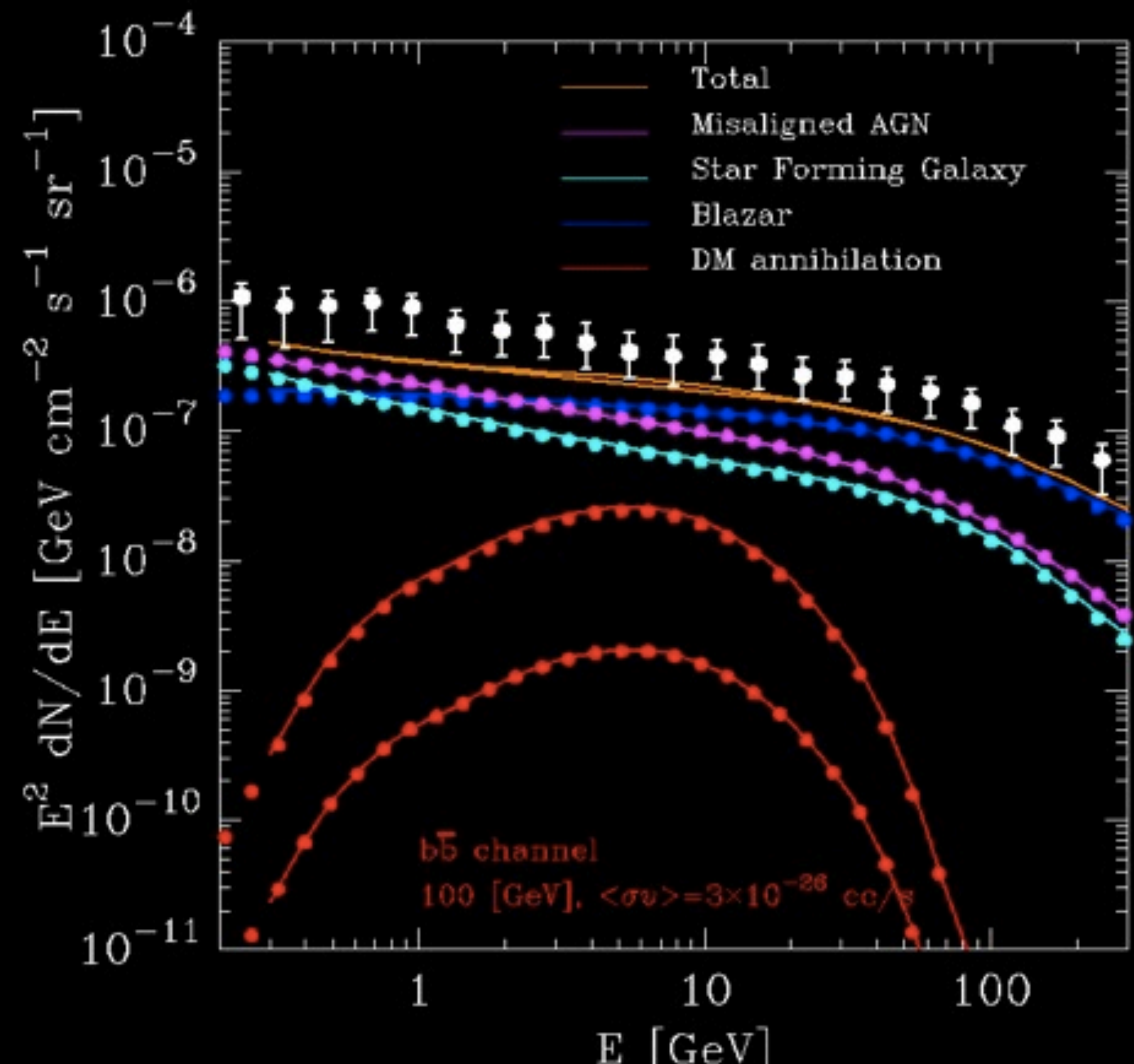
- 観測されたガンマ線から系内成分をさしひいたもの
- 系内成分1: 宇宙線陽子と原子核の衝突による中性パイ中間子が崩壊することによるガンマ線 (The detailed modeling based on the spectral survey of HI and CO)
- 系内成分2: 宇宙線電子と系内輻射場の逆コンプトン散乱によるガンマ線 (Theoretical modeling with simulation)
- スペクトルは100MeV - 100 GeVにわたり、冪型でよく近似できる



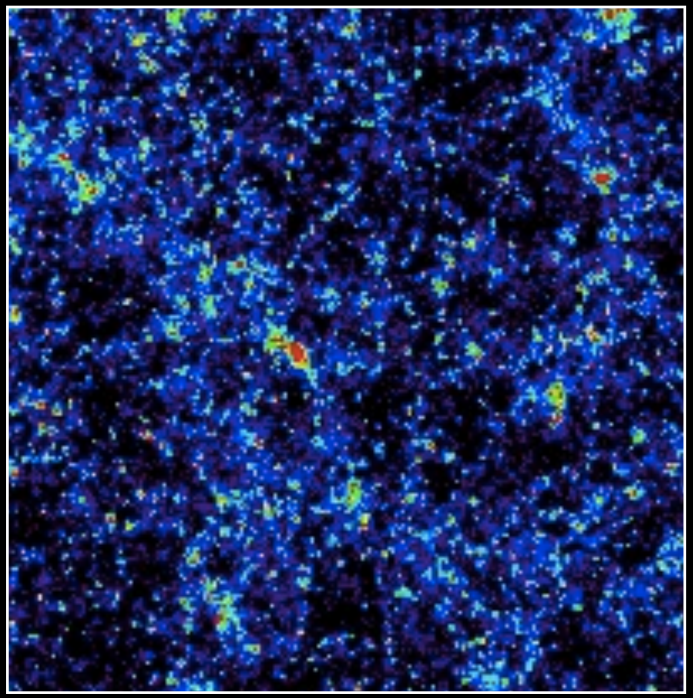
Abdo et al (2010)

Exploring DM signal

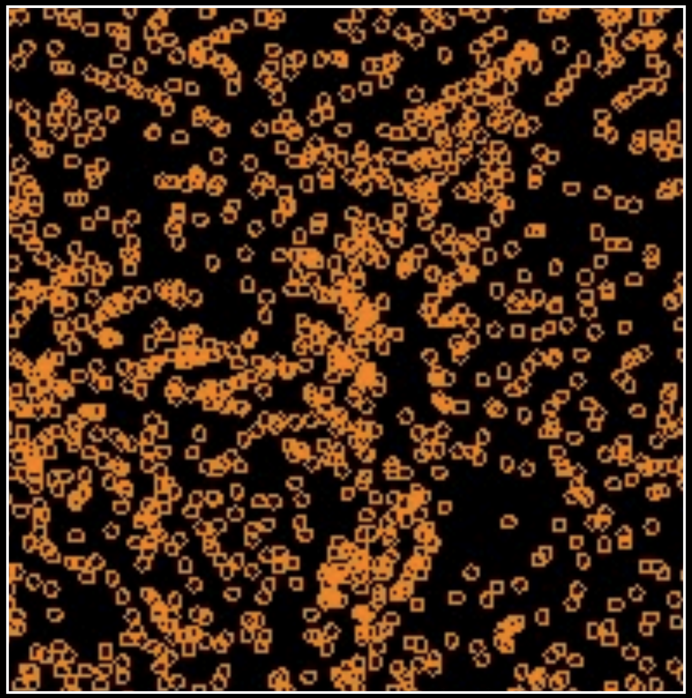
- 暗黒物質対消滅は有力なガンマ線源
- 観測されたエネルギースペクトルは冪型
- This suggests DM can not play a leading role in the range of 0.1 - 100 GeV because DM signal would have spectral feature
- 平均値の先に進む：**非等方性**



Simple Picture



Dark Matter
(gamma-ray)



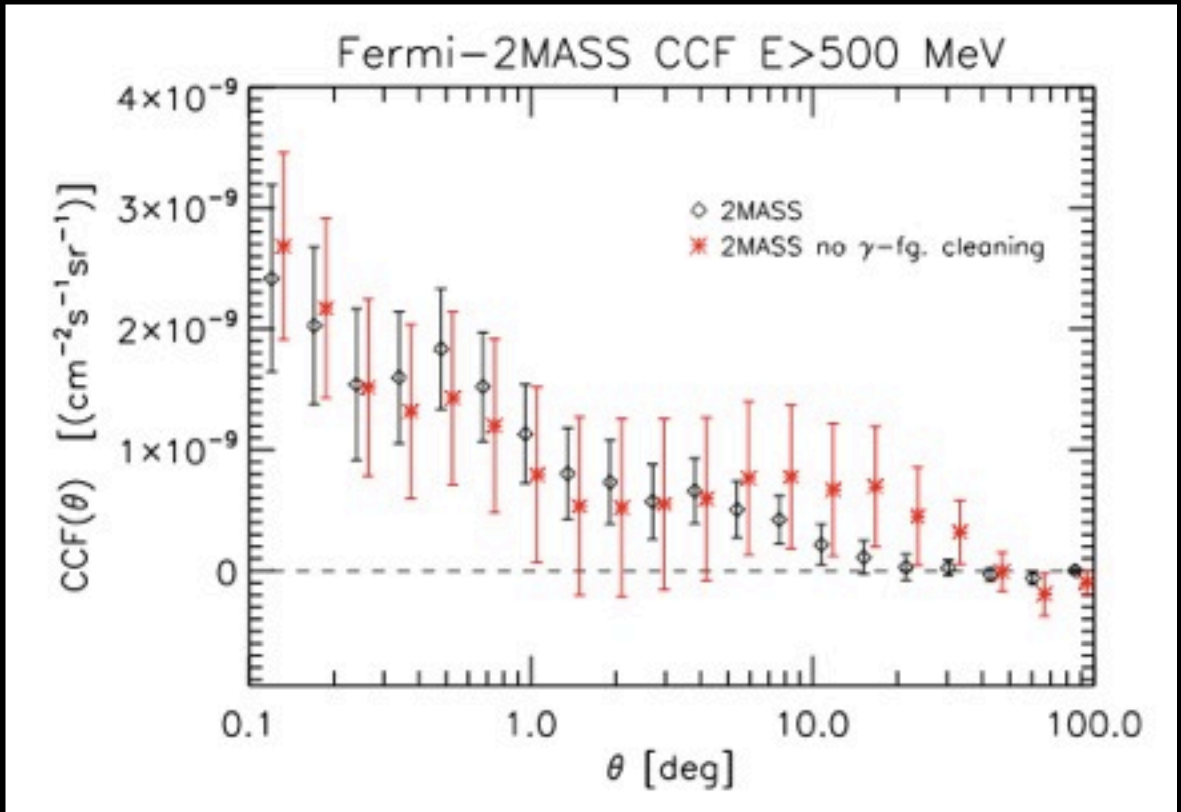
Massive Galaxy

If DM would annihilate, high density region in the Universe would emit gamma rays
Massive galaxies would live in the high density region

Recent progress on Gamma-ray studies

The detection of angular correlation of the position of galaxies and gamma-ray maps!

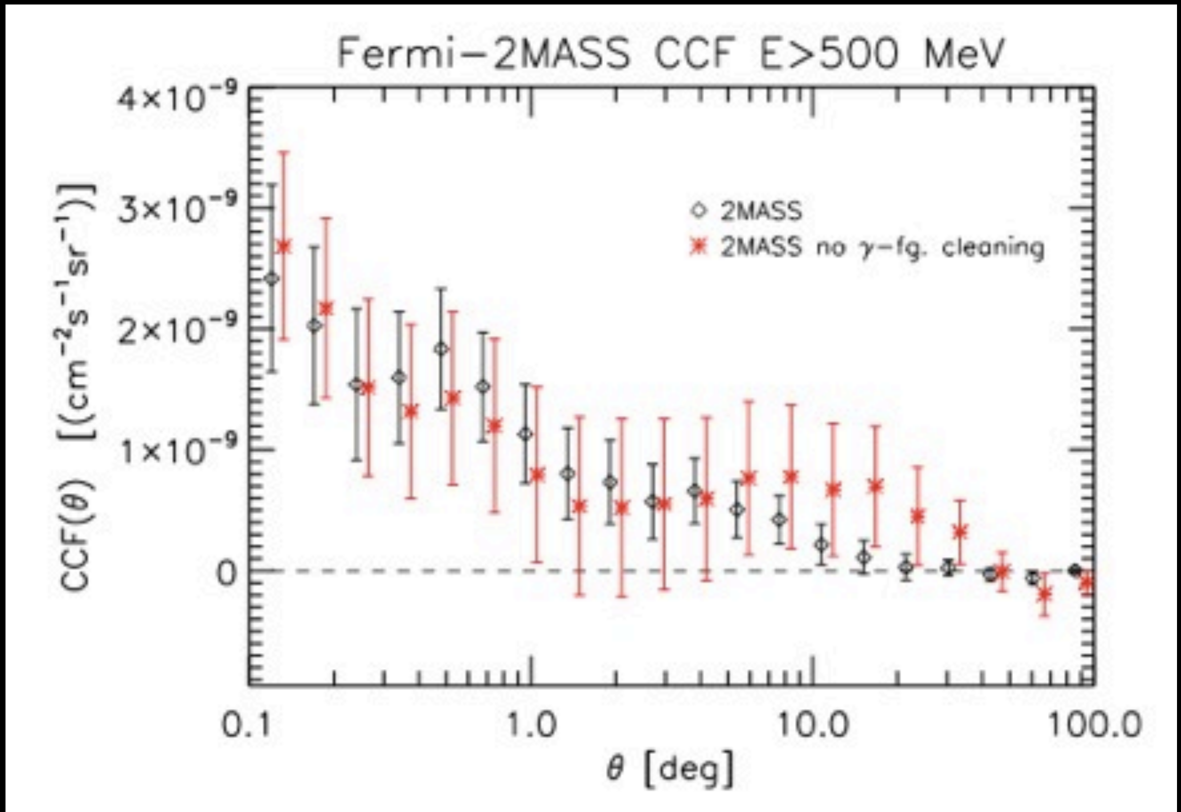
- 大規模構造とガンマ線マップとのCross correlationは暗黒物質対消滅のプローブになりうる
  - 暗黒物質対消滅：高密度領域はガンマ線源
  - 相関の強さは、系外DMハローでのガンマ線生成率に比例する
- 暗黒物質対消滅以外にも、系外でガンマ線を作る機構はいろいろ存在する
  - 活動銀河核：**ブレイザー**
  - 超新星残骸による宇宙線と銀河内ガスの衝突によるパイ中間子が生むガンマ線：**星生成銀河**



Xia et al. (2015)

Recent progress on Gamma-ray studies

The detection of angular correlation of the position of galaxies and gamma-ray maps!



Xia et al. (2015)

Toward the detection of DM annihilation

- We should consider some optimized targets for indirect search for DM annihilation.
- The conditions to be considered
  - they should live in high density regions in the Universe
  - they should be less affected by astro sources
  - their statistical properties should be well constrained
  - it is desirable to know the relation to their host dark matter halos

LRGs seem to be nice, let us examine the case of LRGs!

SDSS DR7 LRG

- Kazin et al 2010, ApJ, 710, 1444
- Passive galaxies used for cosmological analyses (i.e. galaxy clustering & BAO measurement)
- 30272 spectroscopic galaxies
- exist 160 mock catalogs (LasDamas simulations)
- typical halo mass ~ $10^{13\text{-}14}$ M_{sun}/h (derived from g-g lensing and clustering analysis)

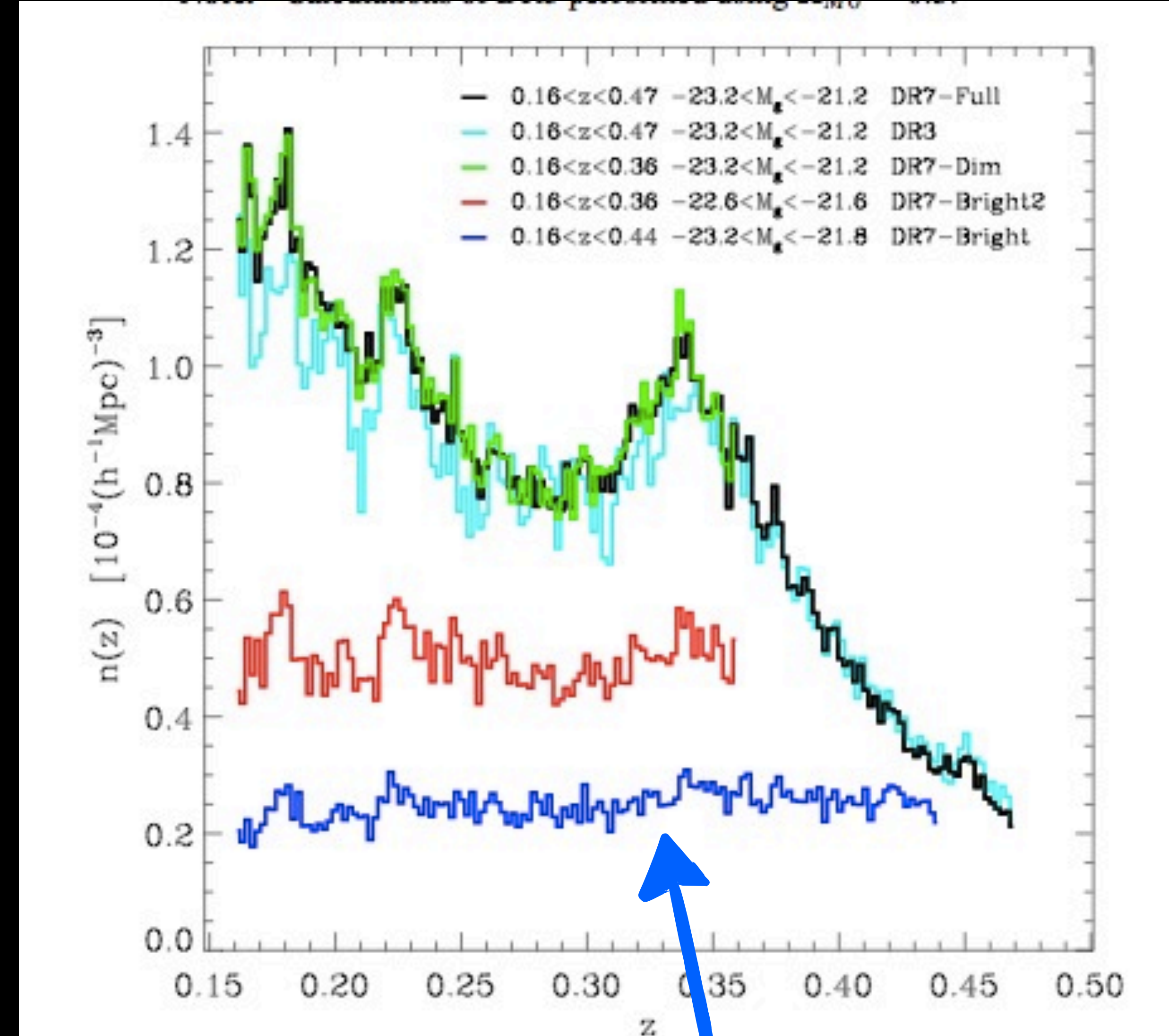
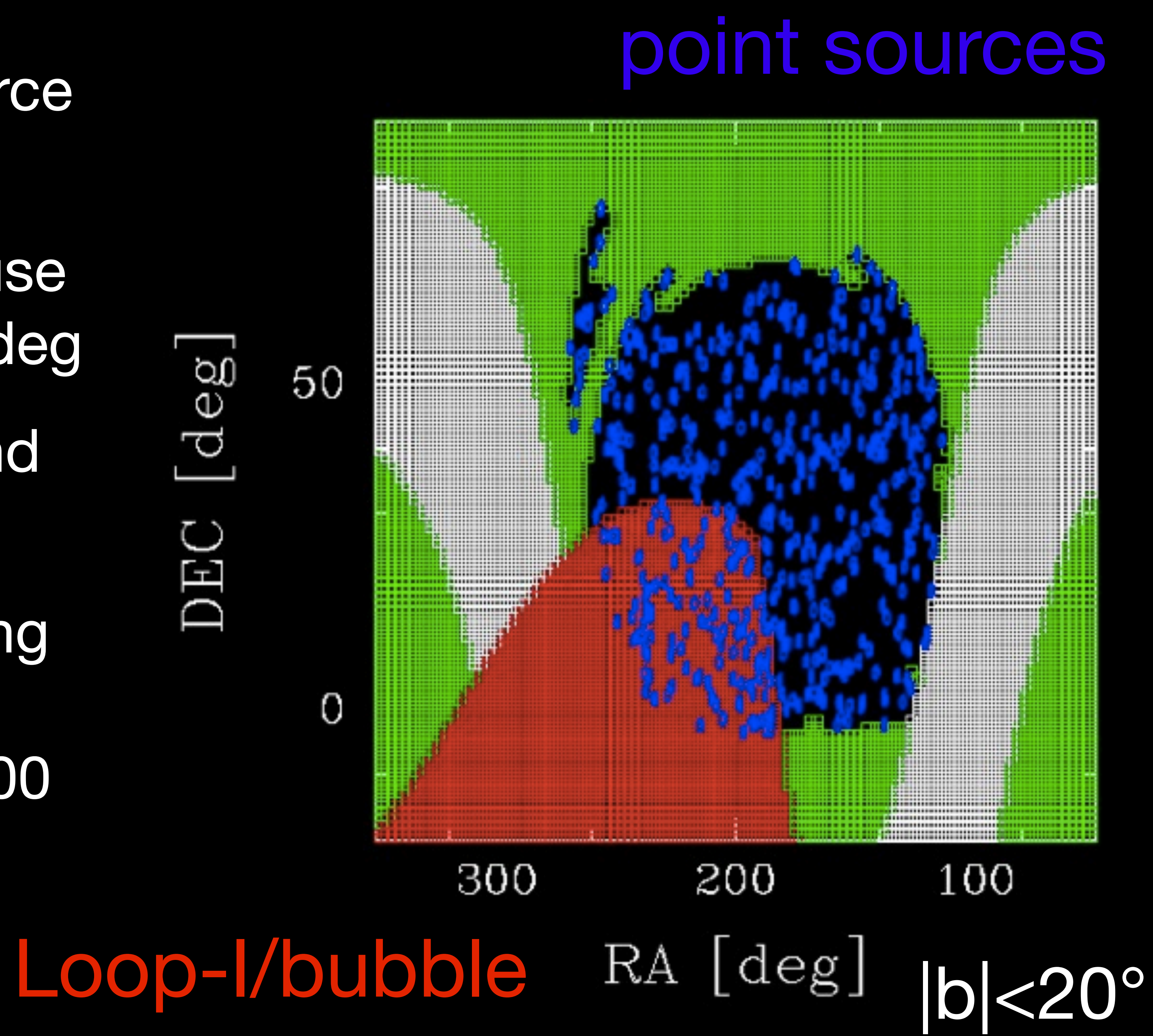


Figure 2. Radial selection function: comoving number density $n(z)$ of the full DR7 (DR7-Full; black) and its subsamples DR7-Dim (green), DR7-Bright (blue), DR7-Bright2 (red), and DR3 (cyan).

use blue one!

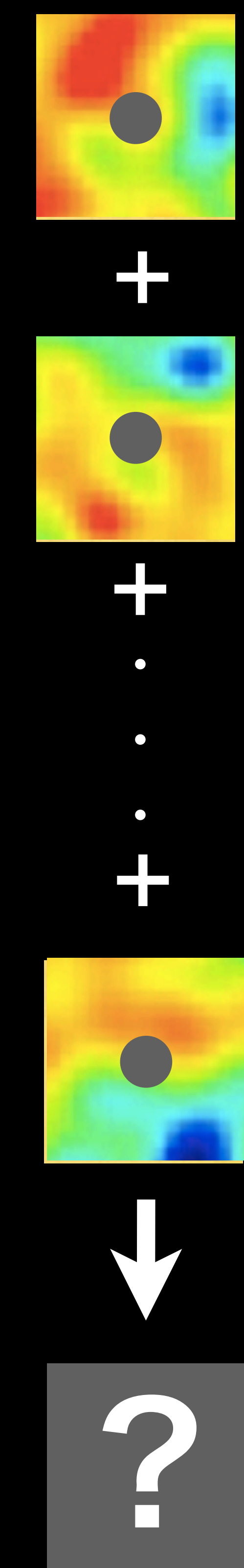
Survey region

- use 3rd year point source catalog
- find 507 sources and use mask with radius of 1 deg
- also remove |b|<20° and Loop-I/bubble regions
- sky fraction of remaining regions ~ 0.10 (corresponding to ~4000 deg^2)

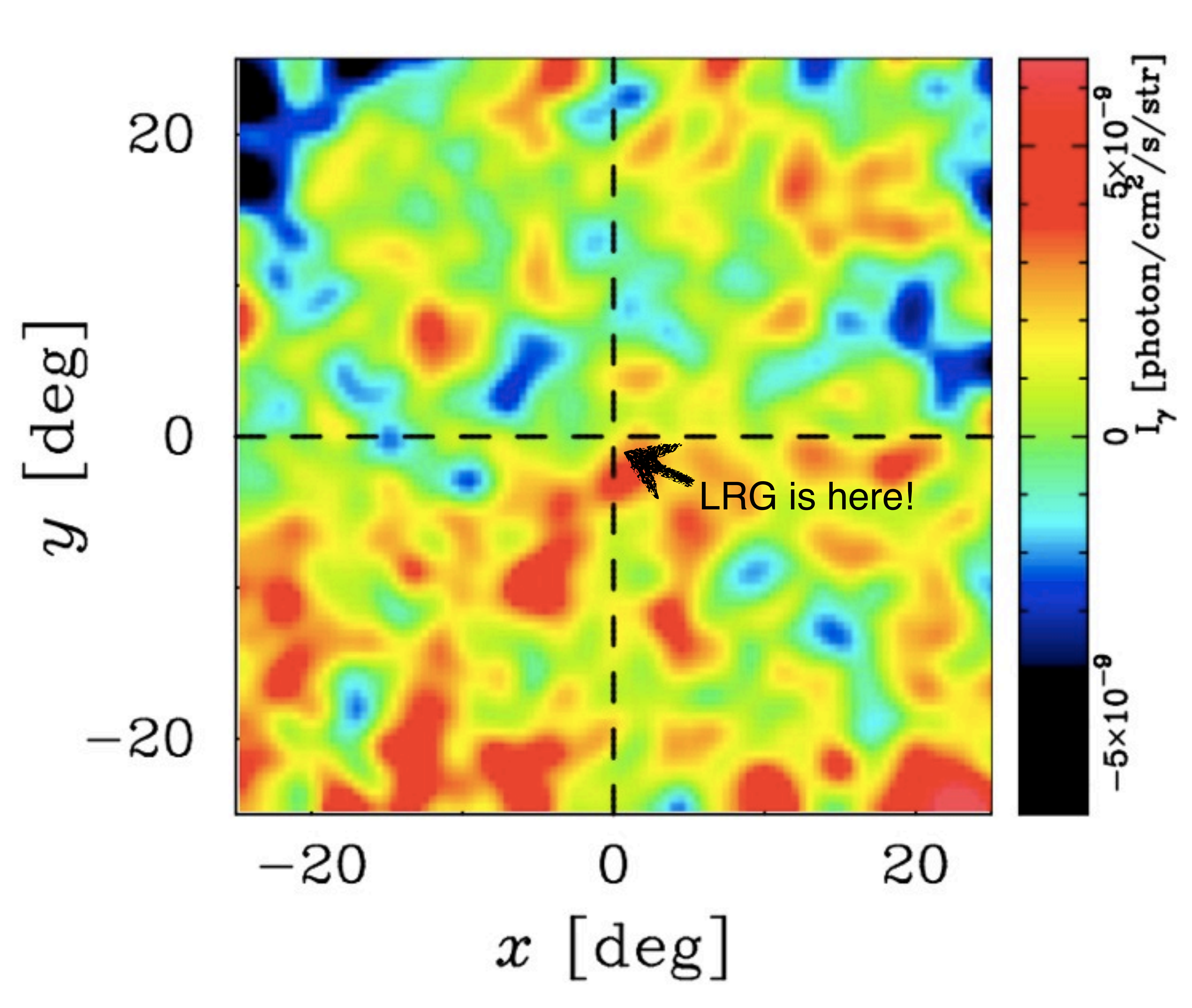


Cross correlation

- use 1-500 GeV gamma-ray intensity
- P7rep ultraclean class taken from Aug. 2008 to Dec. 2014
- we have subtracted the galactic component
- use 17465 LRGs
- analysis performed in real space
- estimate covariances by using LasDamas Mocks and poisson photon catalog



Stacked image

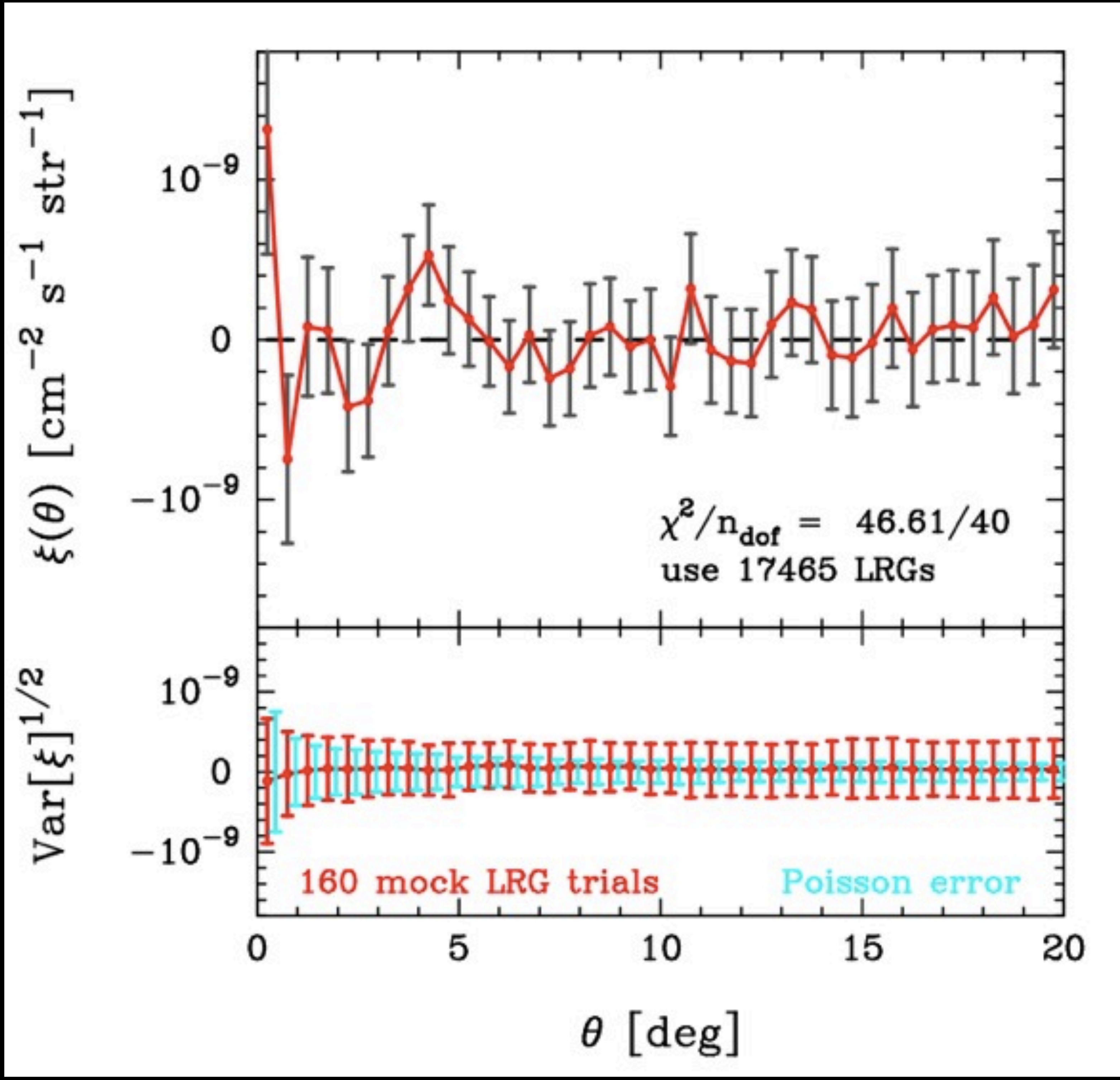


Cross correlation signal

Measured signal is
consistent with a null signal

our analysis passed
the null test (i.e. correlation of
mock LRGs with EGB)→

sampling variance of LRG
~ photon poisson error



Modeling of correlation

Fourier counterpart of cross correlation

DM property

3D cross power spectrum of galaxies and density-squared

$$C_{\rm gal,dm}(\ell) = \int \frac{d\chi}{\chi^2} W_{\rm gal}(\chi) W_{\rm dm}(\chi) P_{{\rm gal},\delta^2}\left(k = \frac{\ell+1/2}{\chi}, z(\chi)\right),$$

$$W_{\rm dm}(\chi) = \frac{\langle\sigma v\rangle}{8\pi}\left(\frac{\bar{\rho}_{\rm dm}}{m_{\rm dm}}\right)^2 (1+z)^3 \int_{E_{\gamma,\rm min}}^{E_{\gamma,\rm max}} dE_\gamma \frac{dN_\gamma}{dE'_\gamma} e^{-\tau(E'_\gamma, z)},$$

Here we adopt two characteristic spectra corresponding to annihilation with 100% branching ratios to bb and $\tau^+\tau^-$ final states

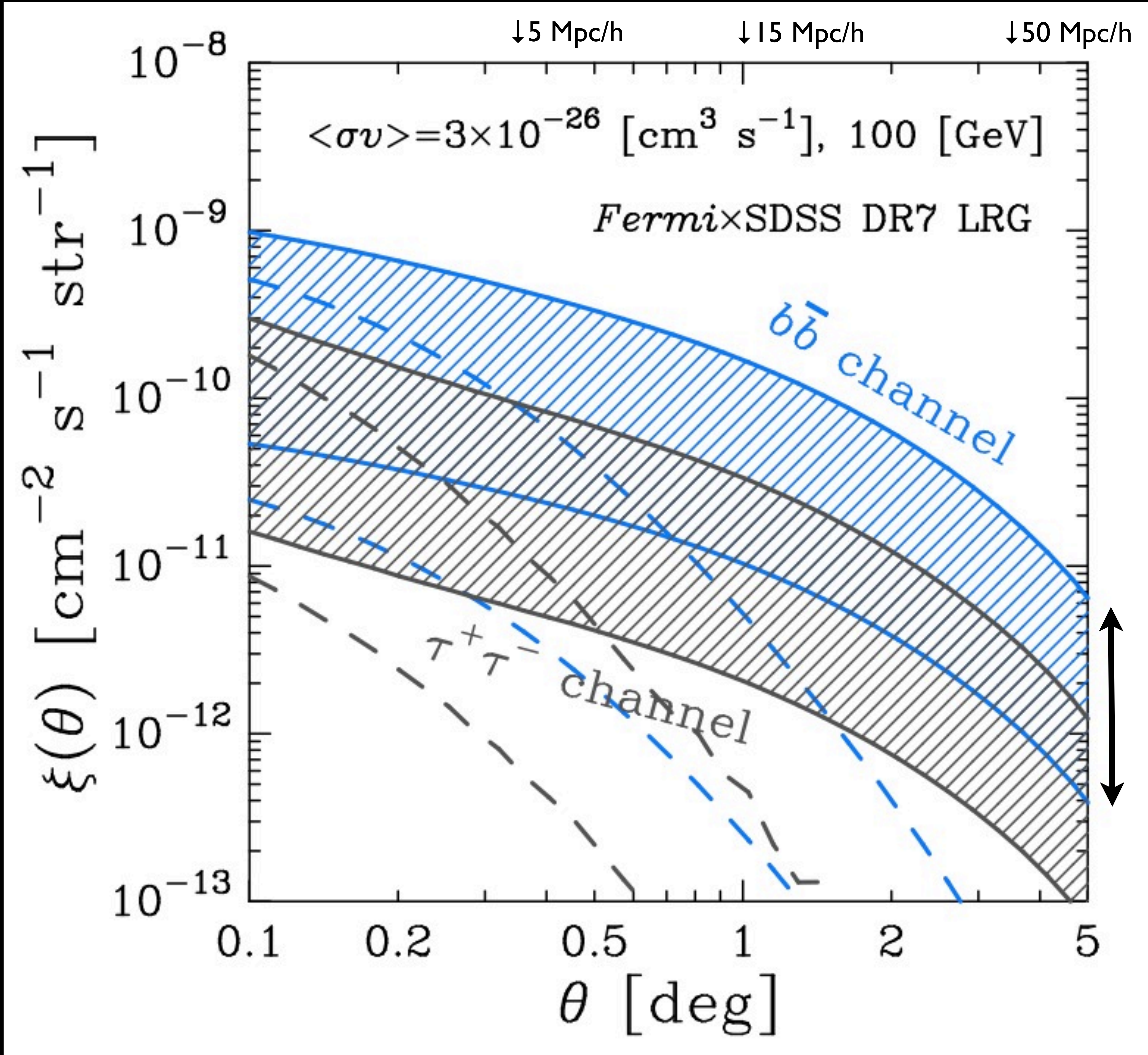
$$P_{{\rm gal},\delta^2}(k,z) = P^{1h}_{{\rm gal},\delta^2}(k,z) + P^{2h}_{{\rm gal},\delta^2}(k,z),$$

one-halo: two-point correlation in a single halo

two-halo: two-point correlation due to the clustering of halos

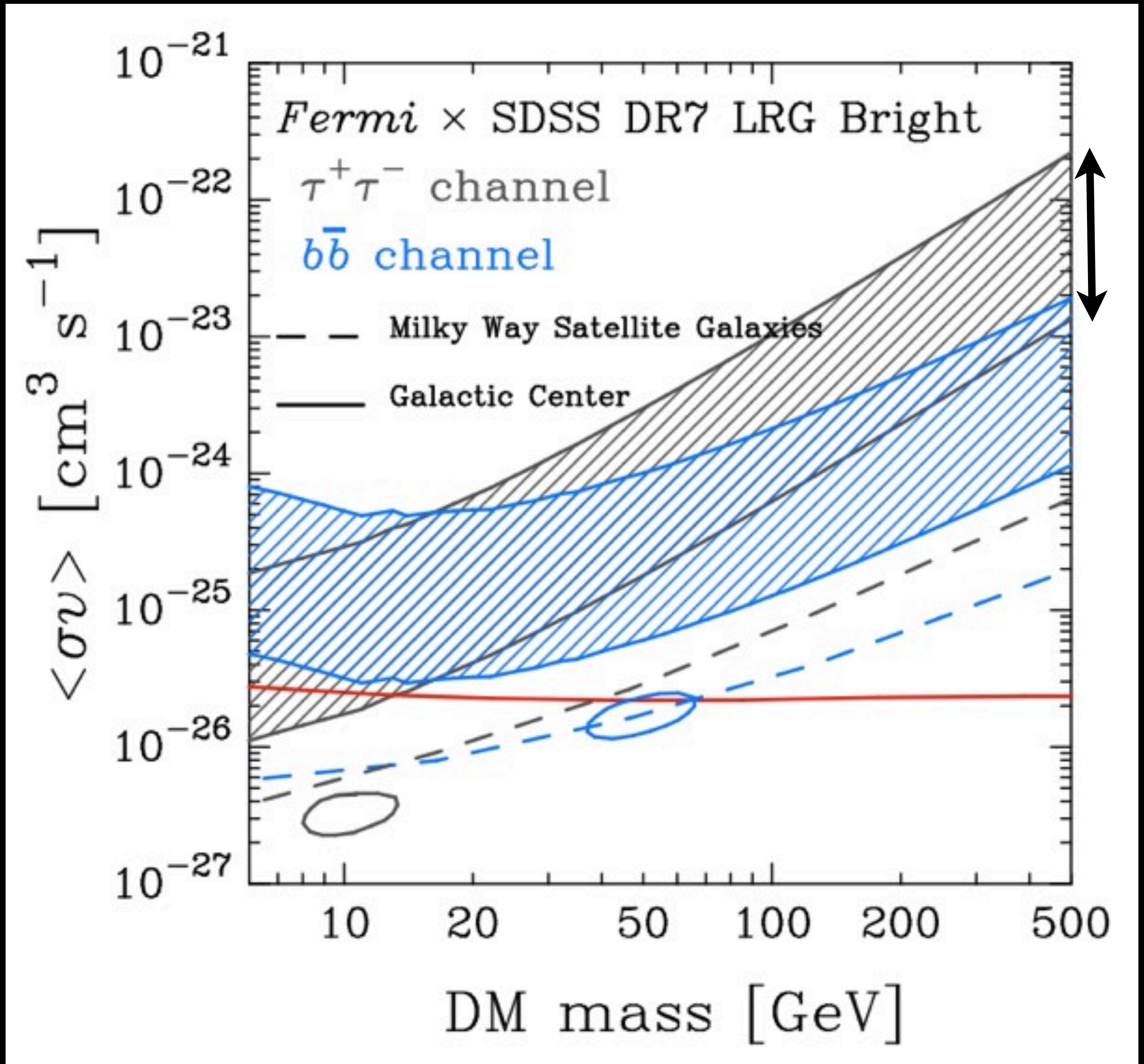
Modeling of correlation

- Halo Occupation Distribution (HOD): the mean number of galaxies in a host halo of mass of M
- HOD constrained by number count, clustering and lensing
- we apply so-called Halo model approach
- Redshift distribution of LRGs determined by spec-z
- （Almost the only）remaining uncertainty = **boost factor**
  - model A : Gao et al (boost factor~300 for DM halo with mass of $10^{13\text{-}14}$ M_{sun}/h)
  - model B : Sanchez et al (boost factor~30 for DM halo with mass of $10^{13\text{-}14}$ M_{sun}/h)
- PSF effect is also taken into account



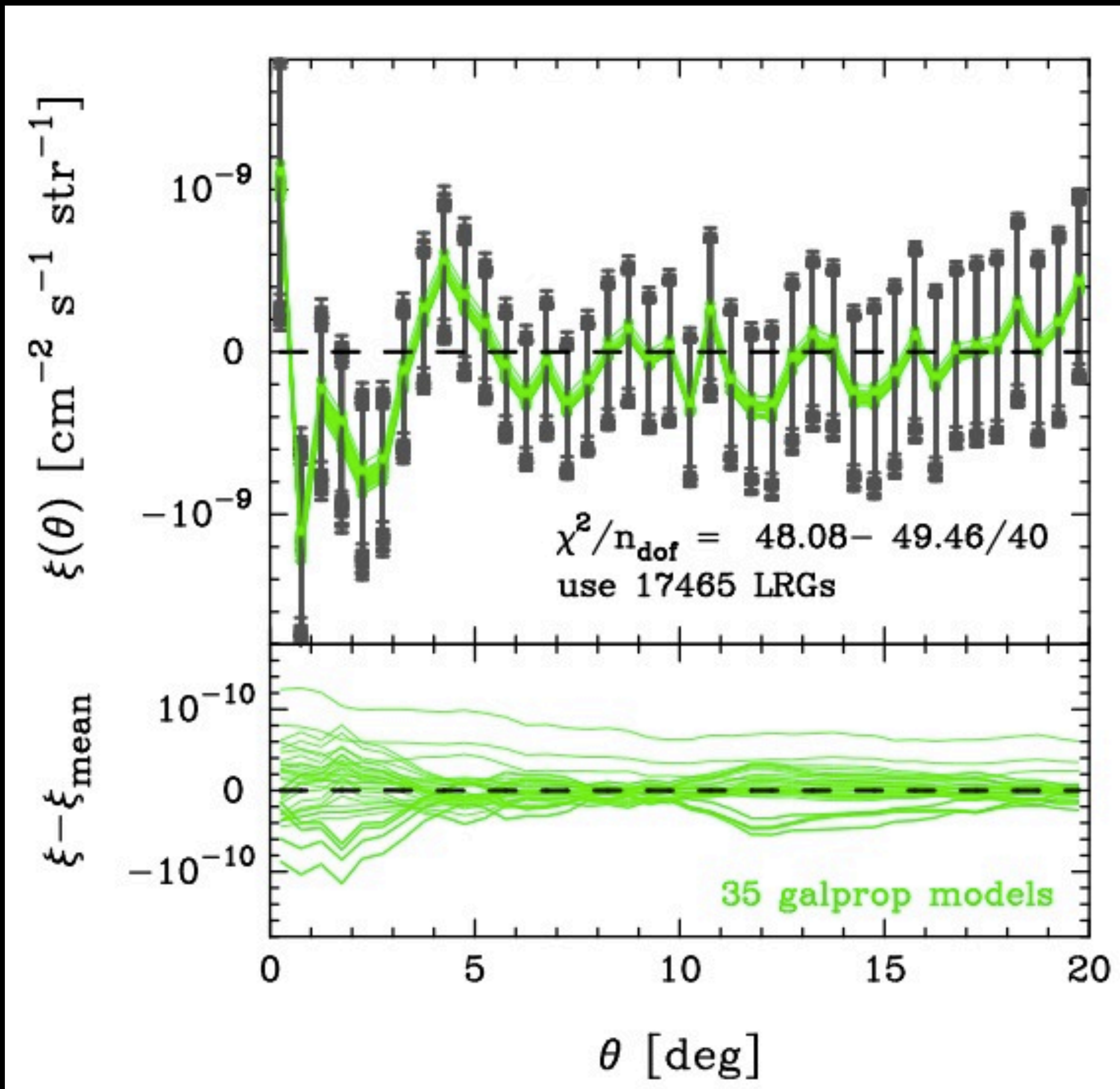
model uncertainty due to substructure in a single halo

Likelihood Analysis 95% confidence level



model uncertainty due to substructure in a single halo

Systematic error due to modeling of galactic components



repeat the same analysis for different 35 galactic model templates

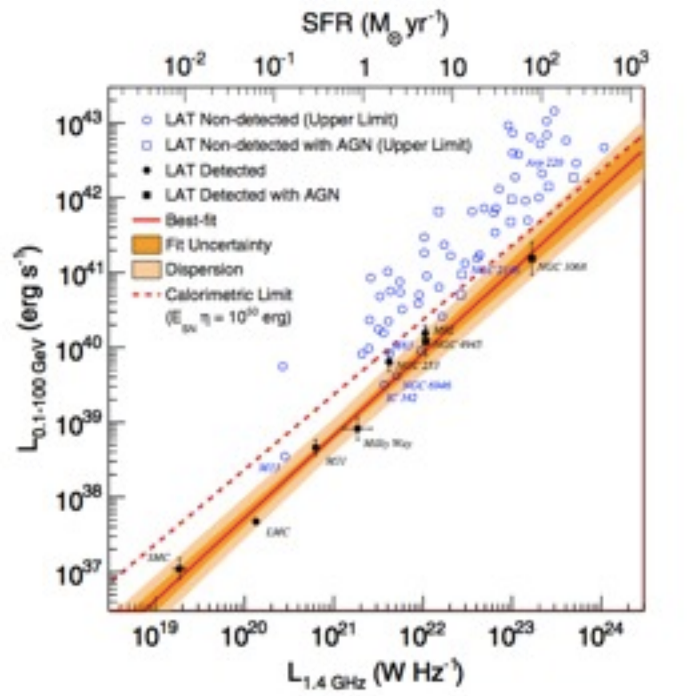
typical uncertainty
$\Delta\chi^2 \sim 1$

stat. error
$\sim$ 10 times syst. error

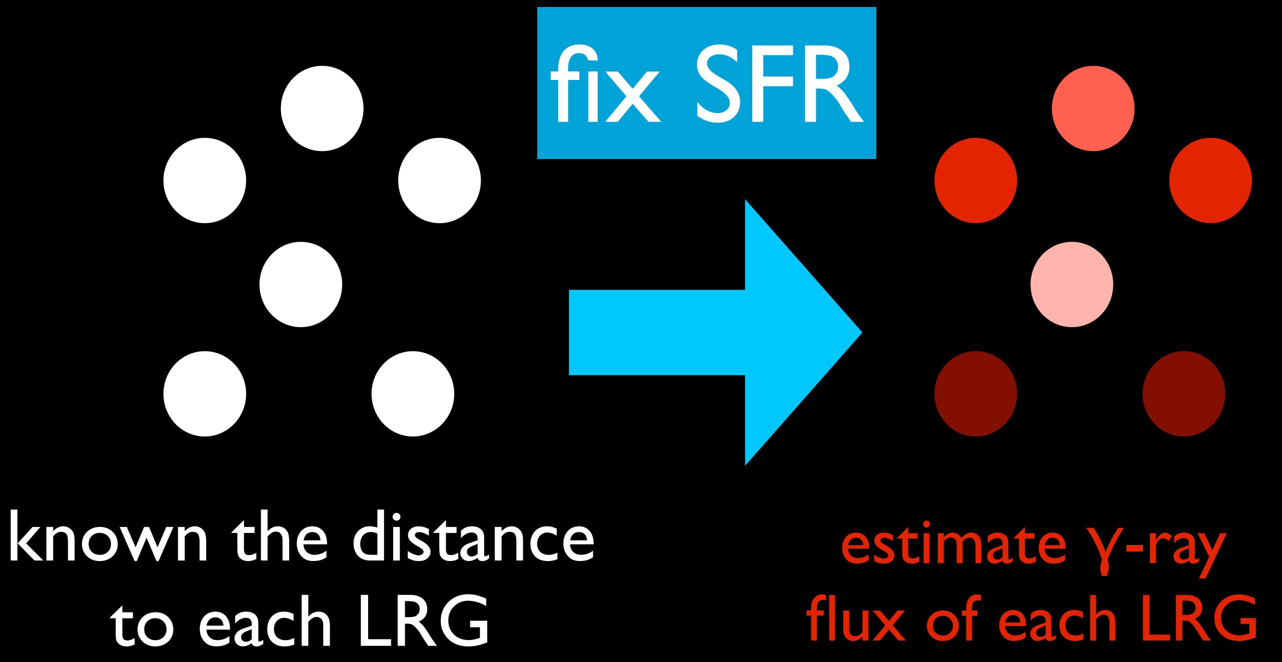
Less important even for future surveys

Possible correlation by star forming in LRG

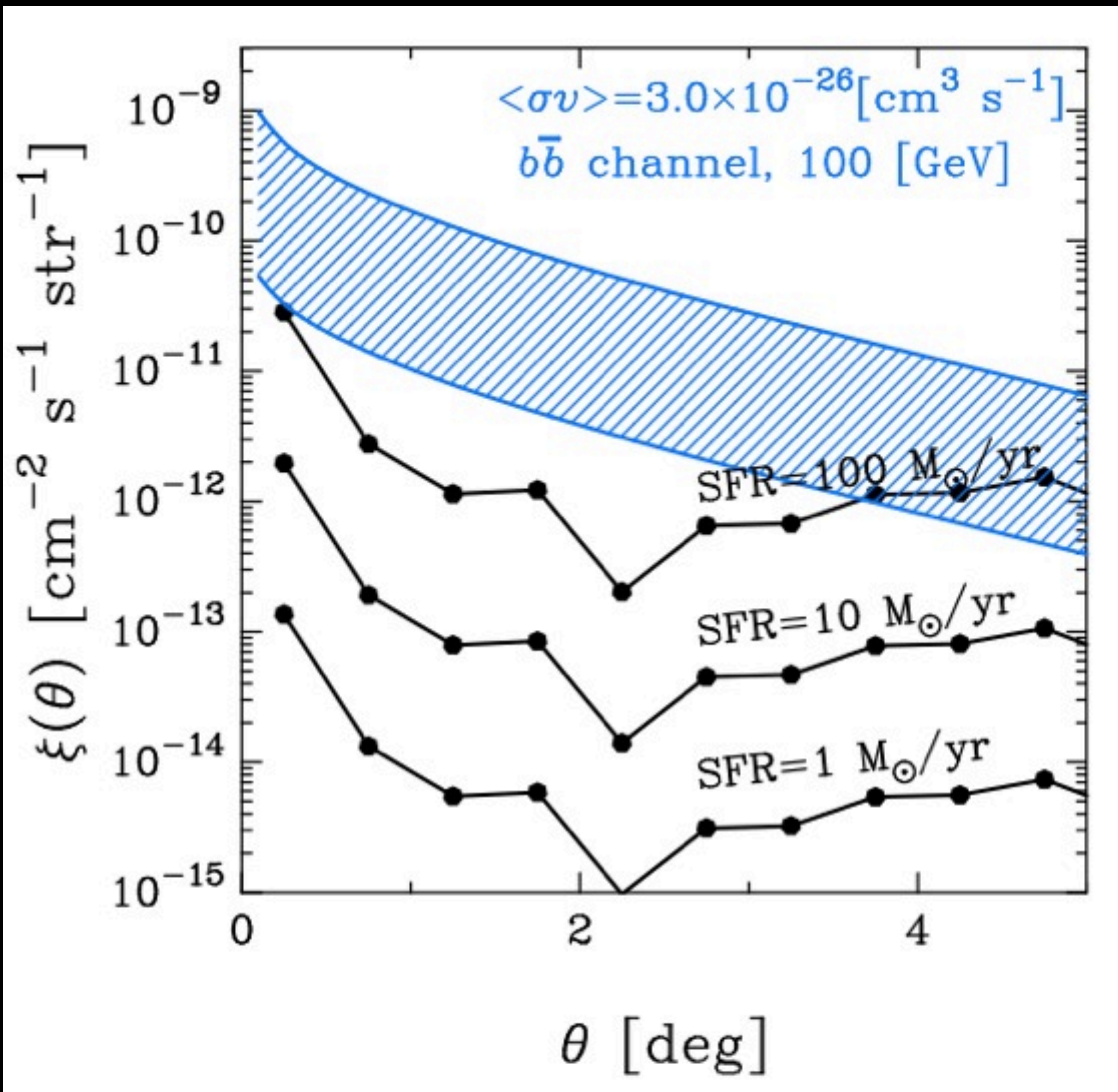
- already detected the gamma-rays from nearby star forming galaxies
- we examine how large correlations would be found if LRGs form stars with some rate
- Let us consider the simplest case: all the LRGs have the same star forming rate (SFR)
- Using the correlation of L_γ and SFR, we can evaluate the gamma-ray flux of each LRG in our catalog



Ackermann et al (2012)



Possible correlation by star forming in LRG

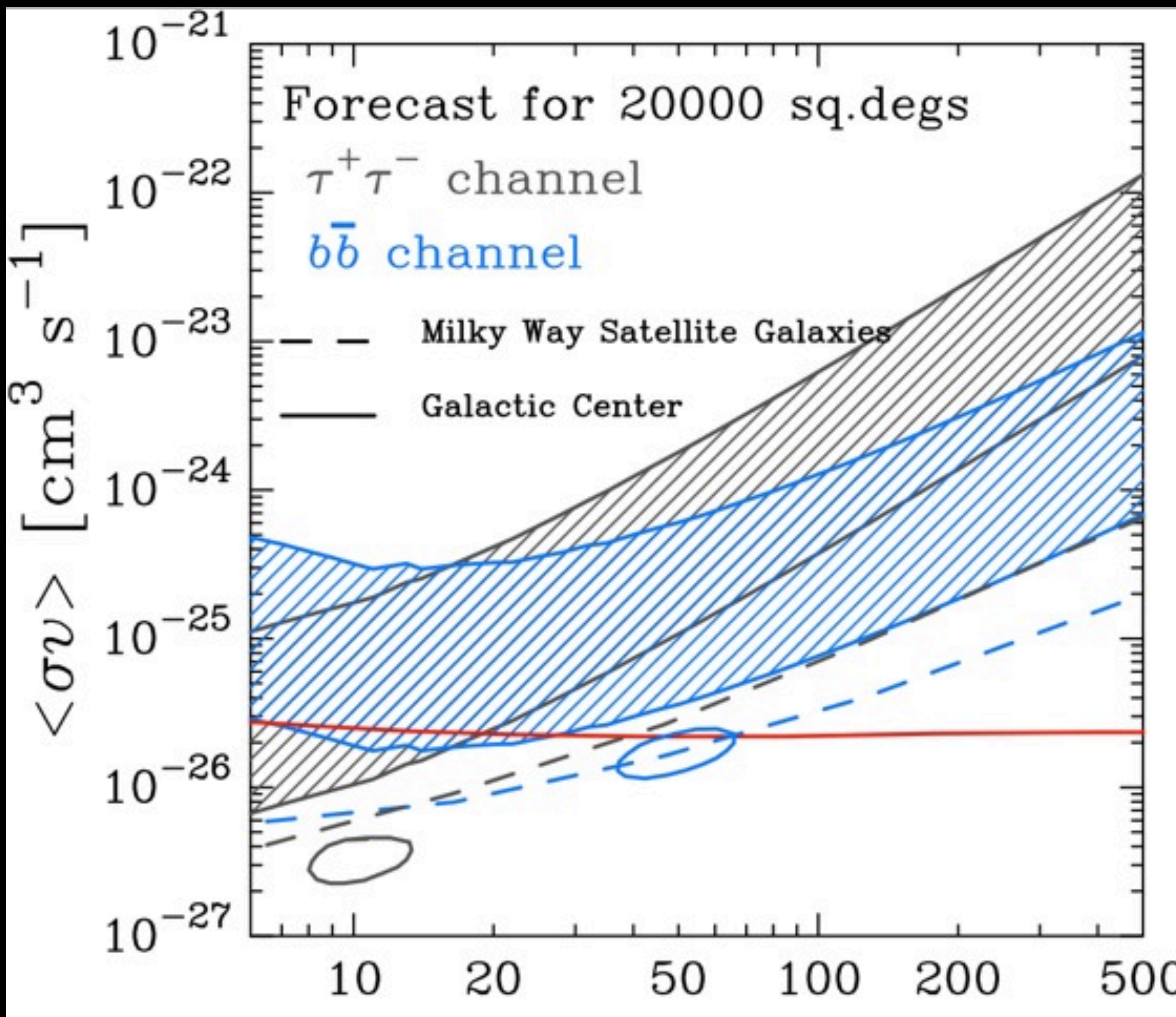


Gamma-rays due to star forming would have **less** affect on our analysis even in the case of SFR = 10 M_{sun}/yr

Summary

- Cross correlation of SDSS DR7 LRGs and Fermi EGB
- **LRG is one of the best targets to search for DM annihilation**
  - well-studied HOD/typical halo mass
  - passive star forming (less contaminated by astrophysical sources)
  - spec-z is available and they are relatively closer (z=0.1-0.4)
- The main model uncertainty = boost factor only (except for dN/dE)
- **Our measurement is consistent with null detection**
  - put constraints on DM annihilation for DM halos with mass of 10^{13-14} M_{sun} and redshift of z=0.1-0.4
- impact of model uncertainty of galactic gamma-ray
- One of possible contaminants = Star forming in LRGs
  - gamma-rays by star forming phenomena would have a small influence on our correlation analysis

Future Prospect

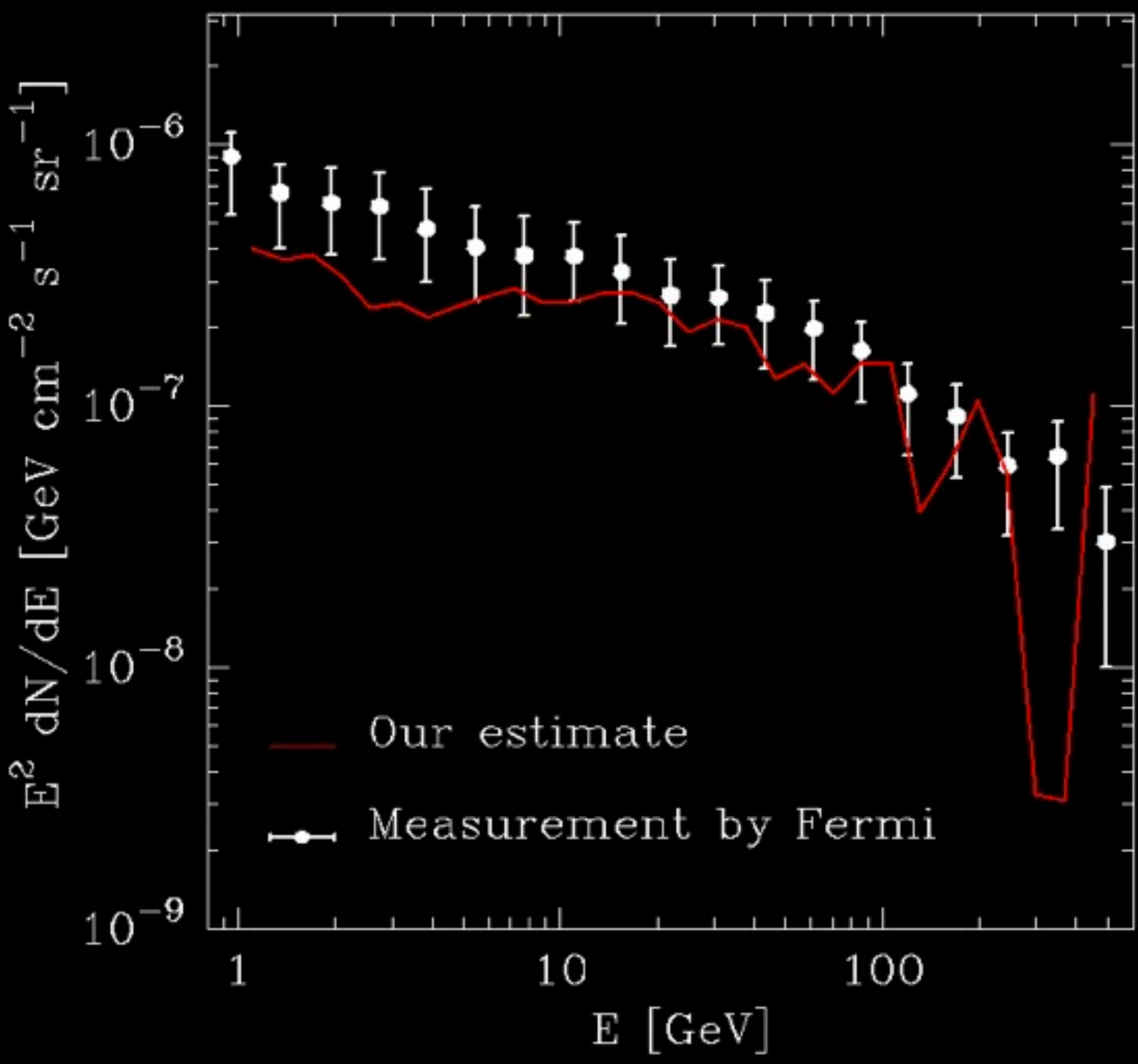


DM mass [GeV]

Cross-correlation with LRGs would be promising for probe of annihilating DM with mass of tens of GeV

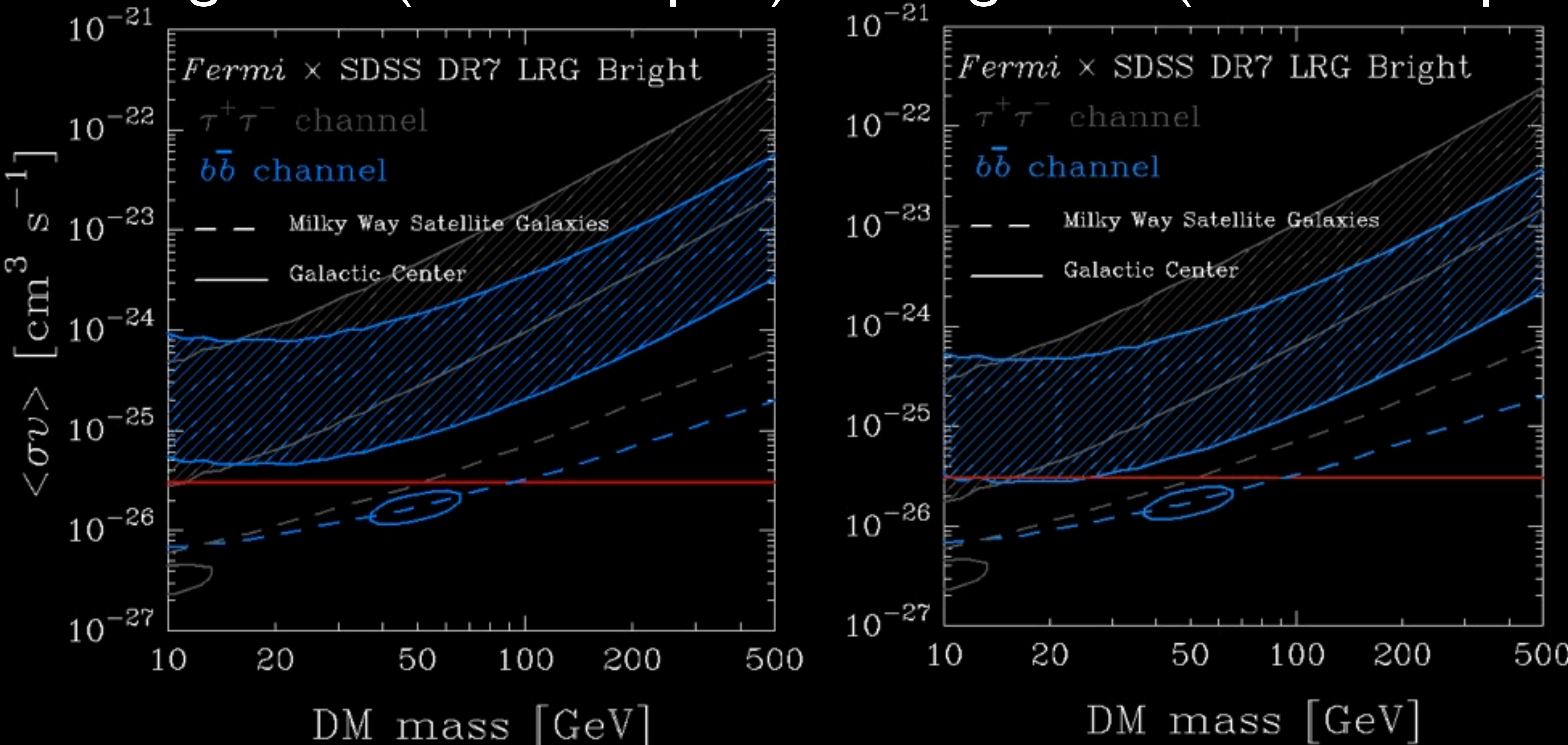
Question.
How can we reduce the model uncertainty of boost factor in an *observational* way?

EGB intensity



Case of Larger mask

2deg mask (8944 samples) 1deg mask (17465 samples)



The improvement is simply caused
by the increase of number of LRGs