Title: Gamma-ray Halos

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Abstract:

GAMMA RAY HALOS

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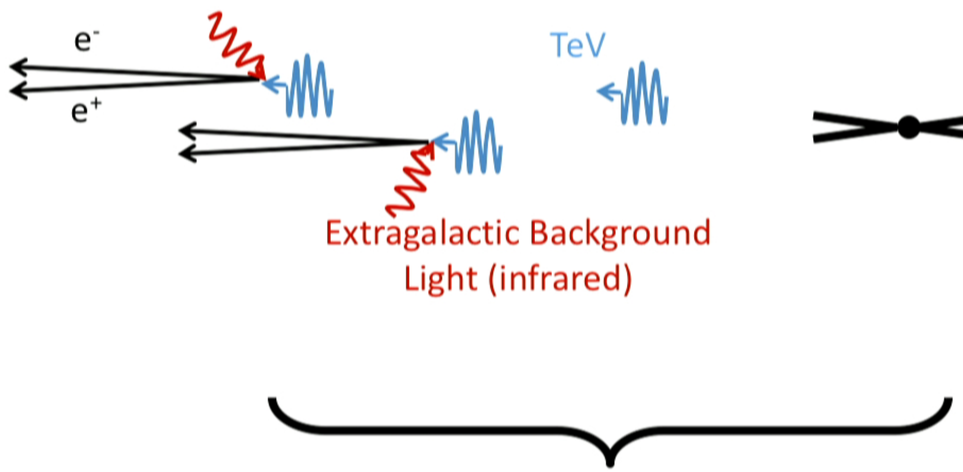
FROM GAMMA RAYS TO PAIRS

1. **Some AGN (jets?) emit beamed >TeV gamma rays**
2. **VHEGRs generate electron/positron pairs on EBL**



$$\approx 35 \left(\frac{E_\gamma}{\text{TeV}} \right)^{-1} f(z)\,\text{Mpc}$$

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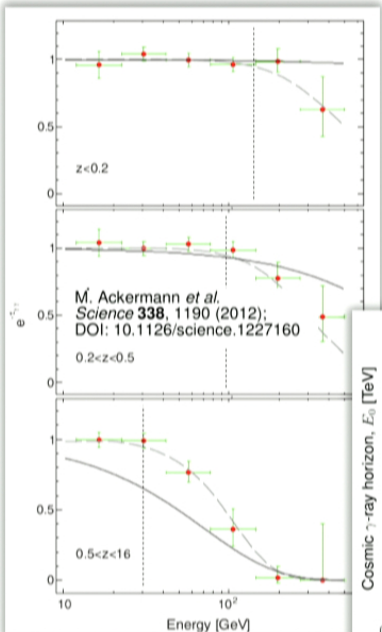

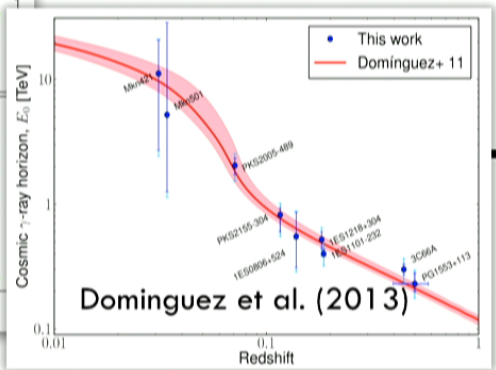

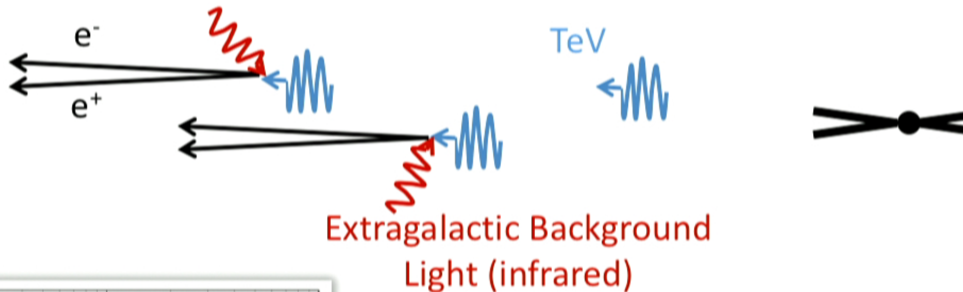

$$\approx 35\left(\frac{E_\gamma}{\mathrm{TeV}}\right)^{-1} f(z)\,\mathrm{Mpc}$$

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LOOKING FOR EVIDENCE OF ABSENCE/PRESENCE OF GAMMA-RAY HALOS

- **Indirect impact of plasma instabilities on gamma-ray sky**
  - Local statistics
  - Gamma-ray background

- **Direct detection/non-detection of gamma-ray halos**
  - Halos vs. bow ties in the sky
  - Searching for structure

WHAT IF GAMMA-RAY HALOS **DON'T** EXIST?

HINTS FROM THE GAMMA-RAY SKY

THE TEV BLAZAR LUMINOSITY FUNCTION

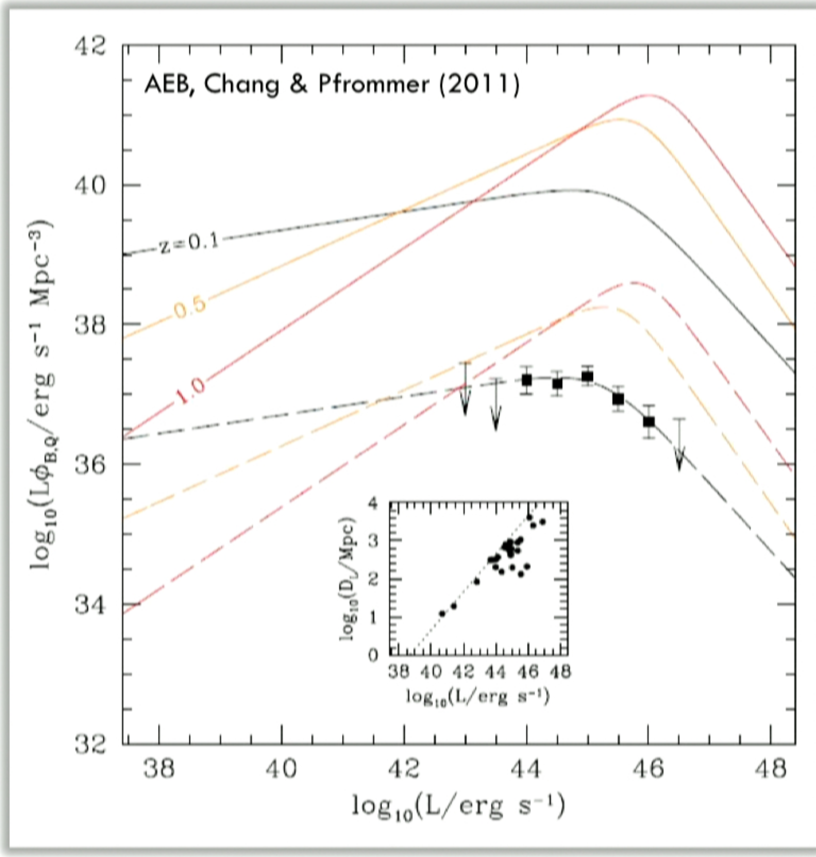
Assume:

TeV blazars = Fermi hard gamma-ray blazars
→ Correct for sky coverage, observation duty cycle, galactic occultation

TeV observations have nearly a single flux limit, 4.2×10^{-12} erg/cm^2/s

Ignore all of the biases in the TeV sample
(e.g., target selection, scheduling, etc.)

THE TEV BLAZAR LUMINOSITY FUNCTION



zars

duty cycle, galactic occultation

x limit, 4.2×10^{-12} erg/cm^2/s

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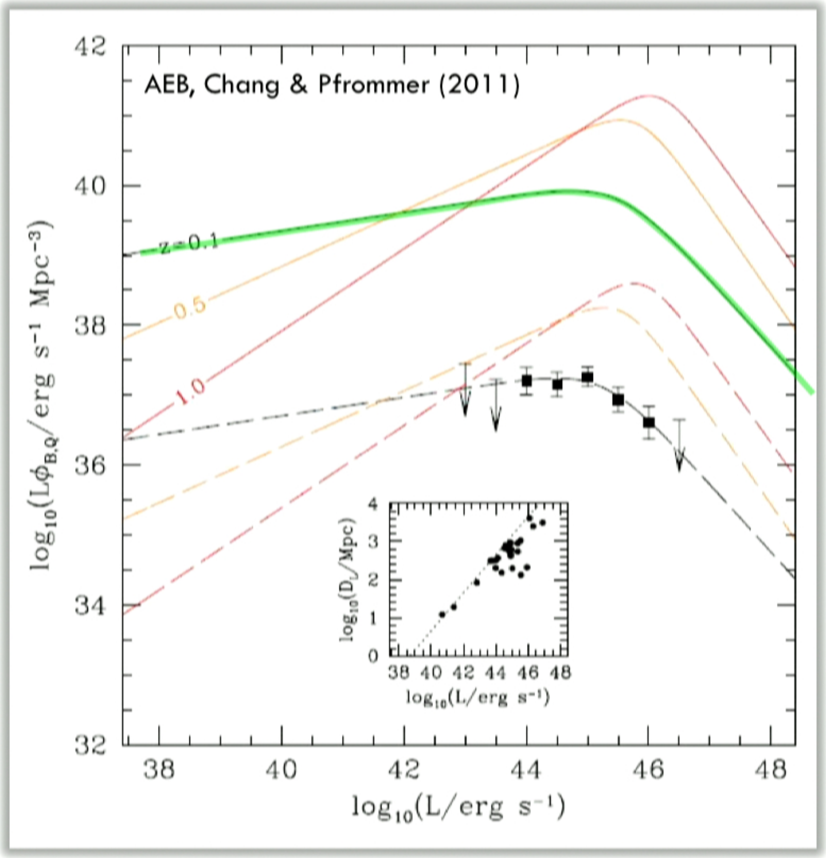
THE TEV BLAZAR LUMINOSITY FUNCTION



$$\phi_B(0.1, L) \simeq 3.8 \times 10^{-3} \phi_Q(0.1, 1.8L),$$

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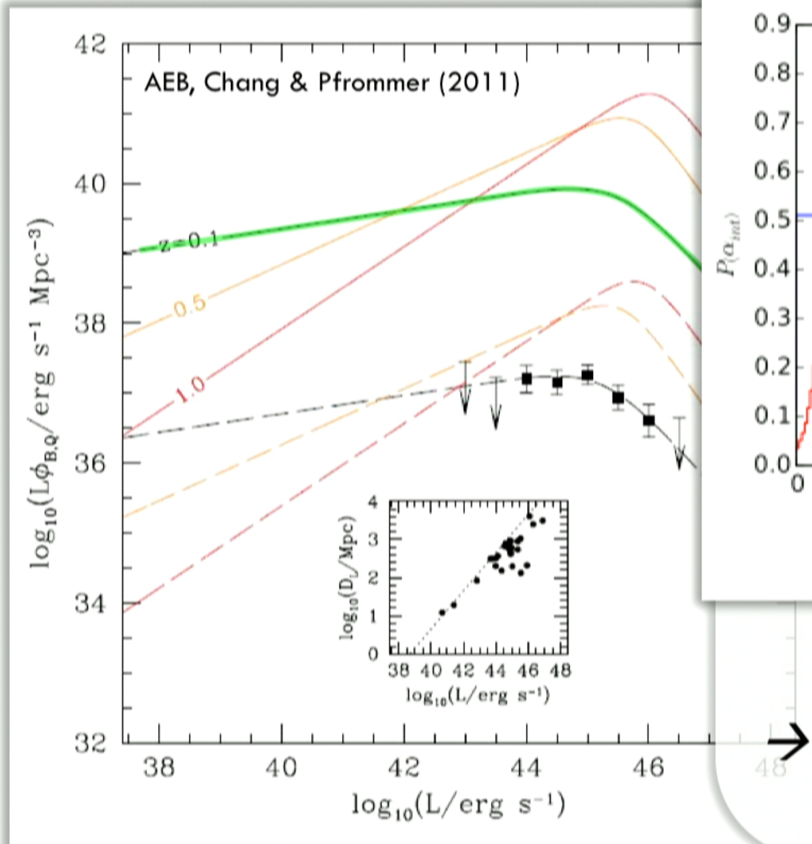
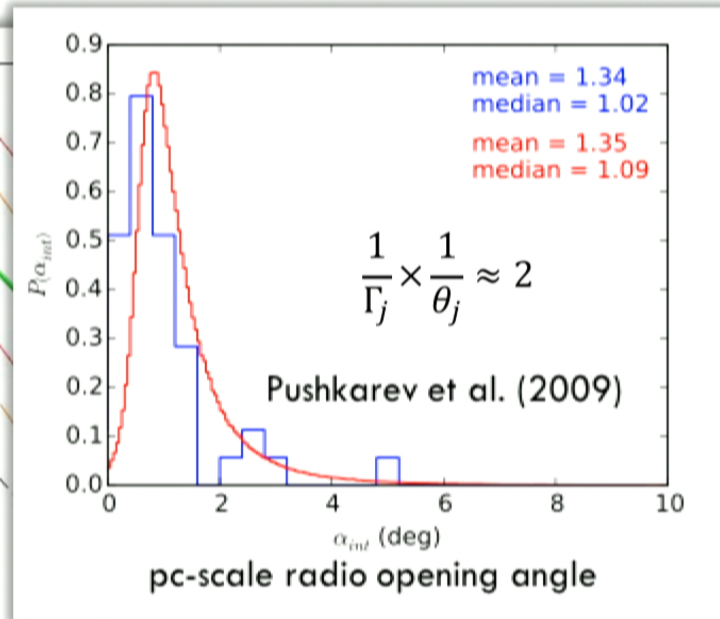
THE TEV BLAZAR LUMINOSITY FUNCTION





a single population

→ *Related in the past?*

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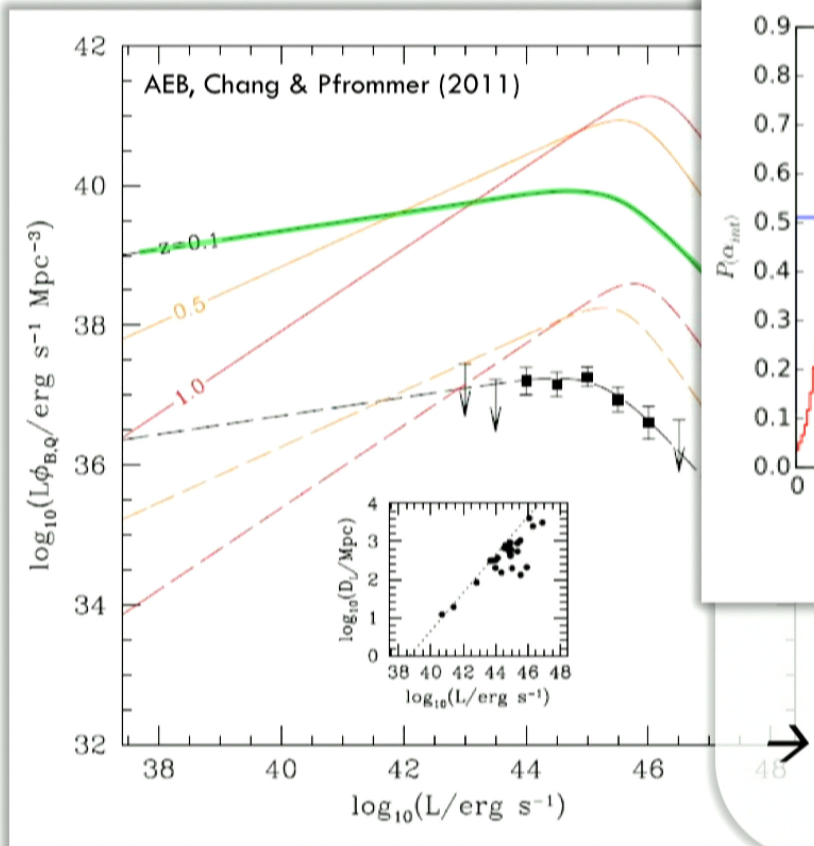
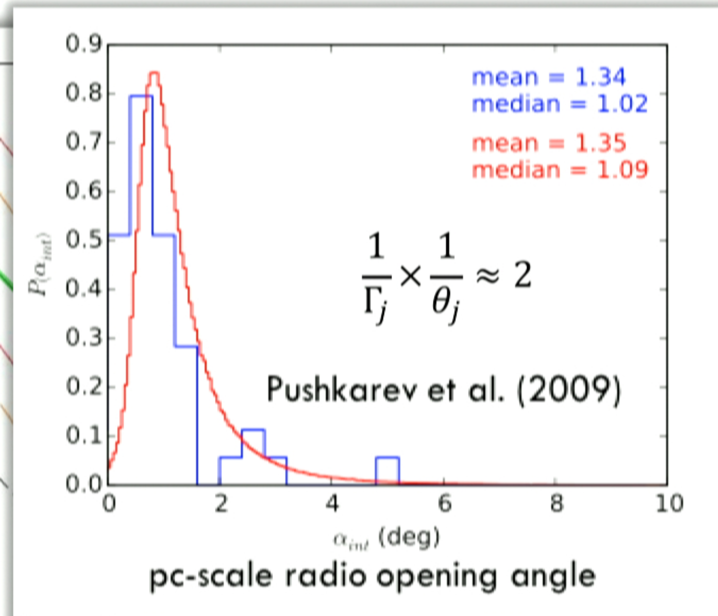
THE TEV BLAZAR LUMINOSITY FUNCTION





a single population

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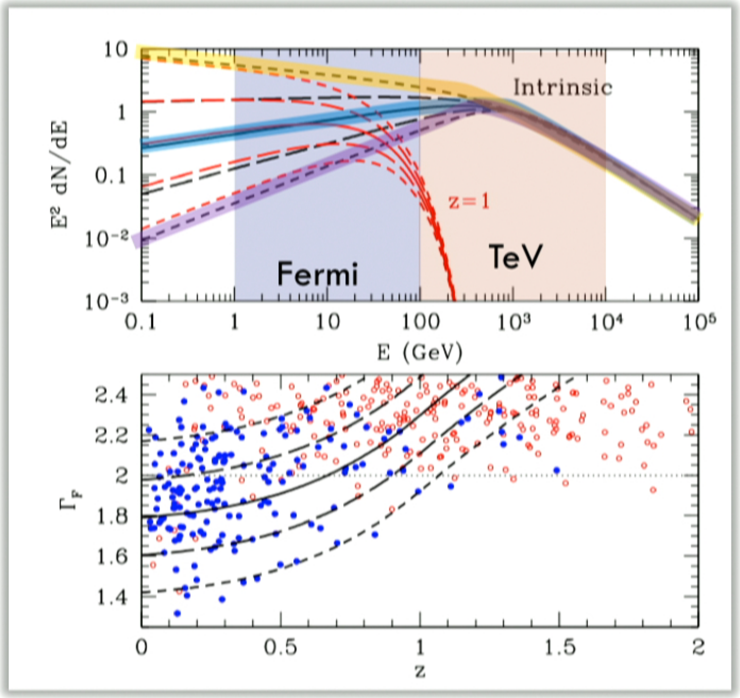
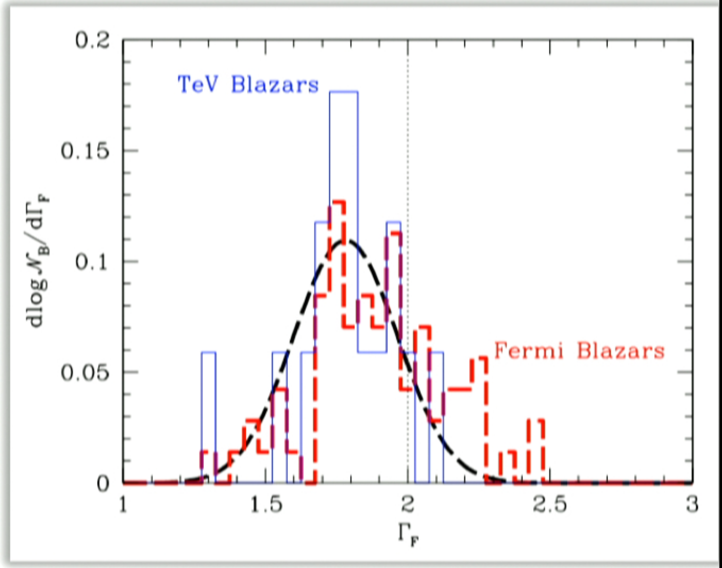
RELATING THE TEV AND FERMI BLAZAR LUMINOSITY FUNCTIONS

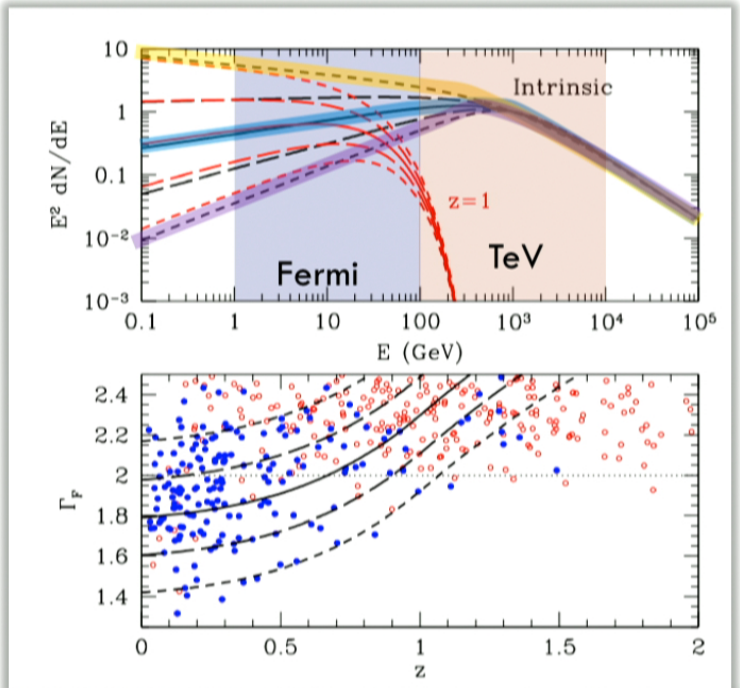


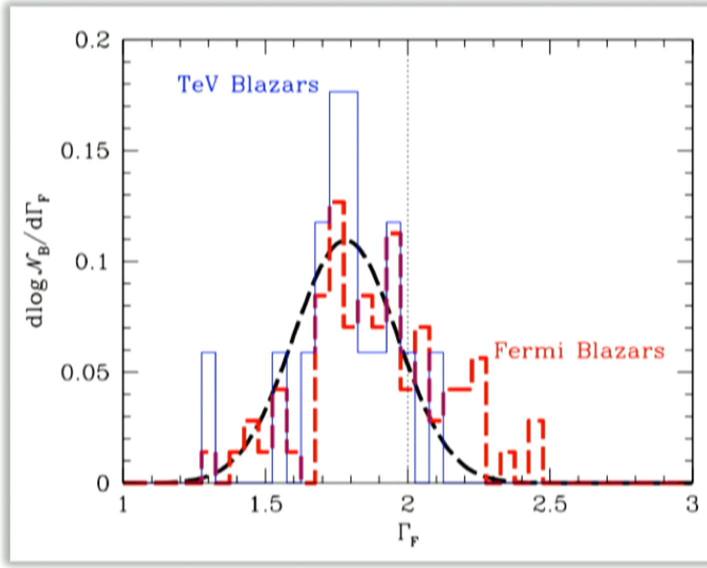


$$\tilde{\phi}_B(z, L_{\rm TeV}, \Gamma_l) \equiv \frac{d\mathcal{N}}{d\log_{10} L_{\rm TeV}\, d^3x\, d\Gamma_l}$$

$$= \tilde{\phi}_B(z, L_{\rm TeV}) \frac{e^{-(\Gamma_l - \bar{\Gamma}_l)^2/2\sigma_l^2}}{\sqrt{2\pi}\sigma_l} \,.$$

RELATING THE TEV AND FERMI BLAZAR LUMINOSITY FUNCTIONS





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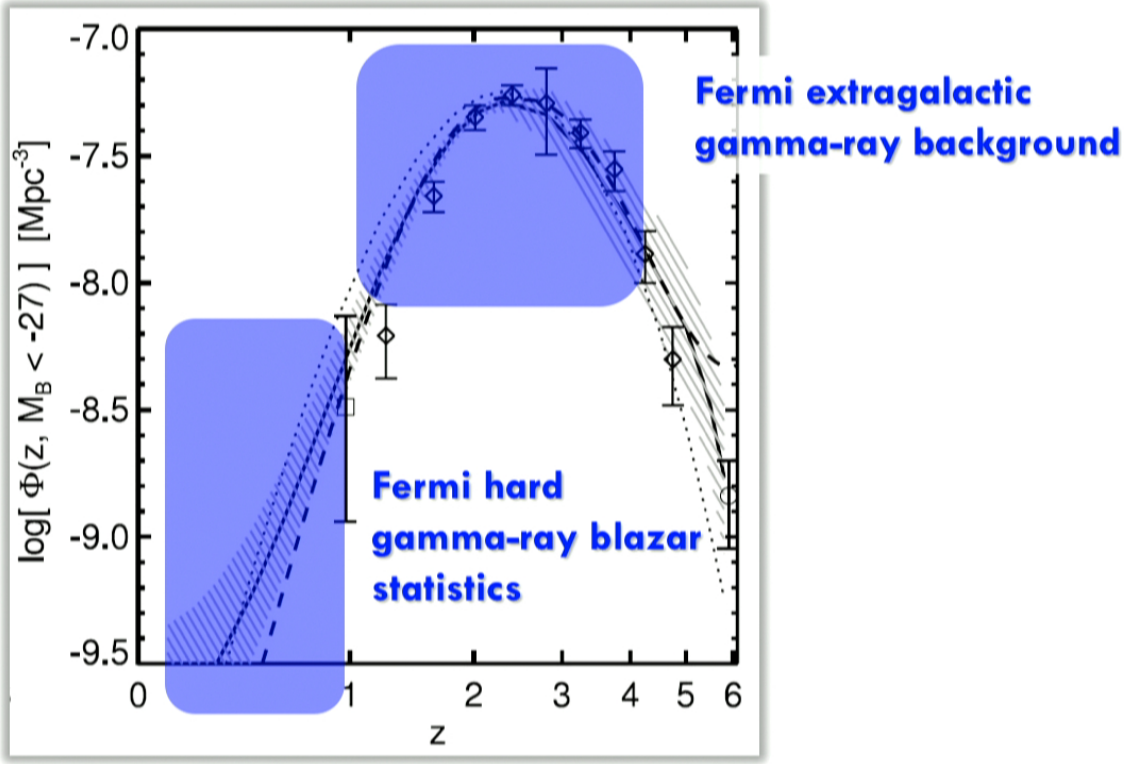
0-Parameter Model!

HOW MANY TEV BLAZARS ARE THERE?



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NEARBY FERMI STATISTICS

Redshift Distribution

$$\mathcal{N}_B(z) = \int_0^2 d\Gamma_l \int_0^z dz' \int_{\log_{10} L_{\mathrm{TeV}}(F_{25,\min}, z', \Gamma_l)}^{\infty} d\log_{10} L_{\mathrm{TeV}}$$

$$4\pi D_A^2 \frac{dD_P}{dz'} \Theta\left[2 - \Gamma_F(\Gamma_l, z')\right] \tilde{\phi}_B(z', L_{\mathrm{TeV}}, \Gamma_l),$$

Flux Distribution (10-500 GeV)

$$\mathcal{N} = \eta_F \int_0^2 d\Gamma_l \int_0^{\infty} dz \int_{\log_{10} L_{\mathrm{TeV}}(F_{45.7}, z, \Gamma_l)}^{\infty} d\log_{10} L_{\mathrm{TeV}}$$

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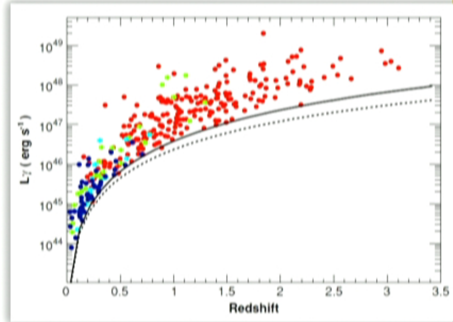

Redshift Distribution

$$\mathcal{N}_B(z) = \int_0^2 d\Gamma_l \int_0^z dz' \int_{\log_{10} L_{\rm TeV}(F_{25,\rm min},z',\Gamma_l)}^{\infty} d\log_{10} L_{\rm TeV}$$
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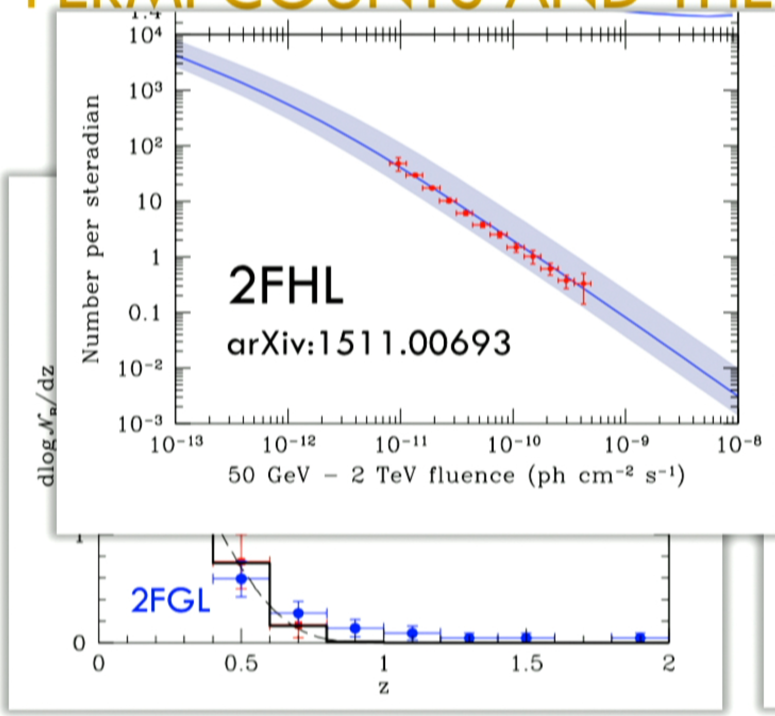
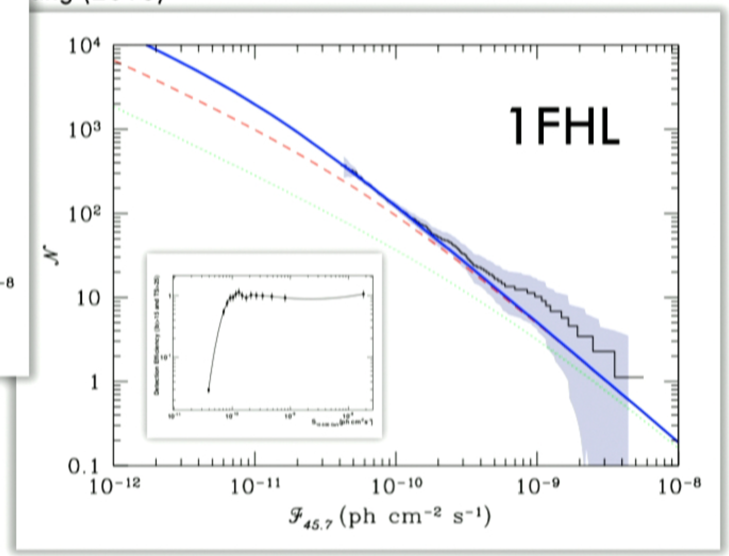
FERMI COUNTS AND THE LOW-Z BLF



ang (2013)



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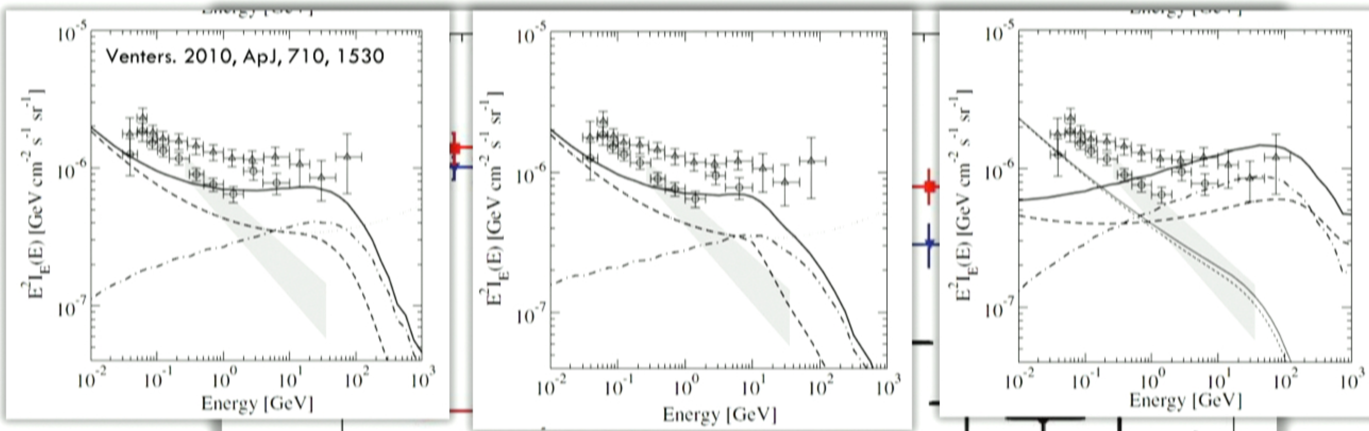
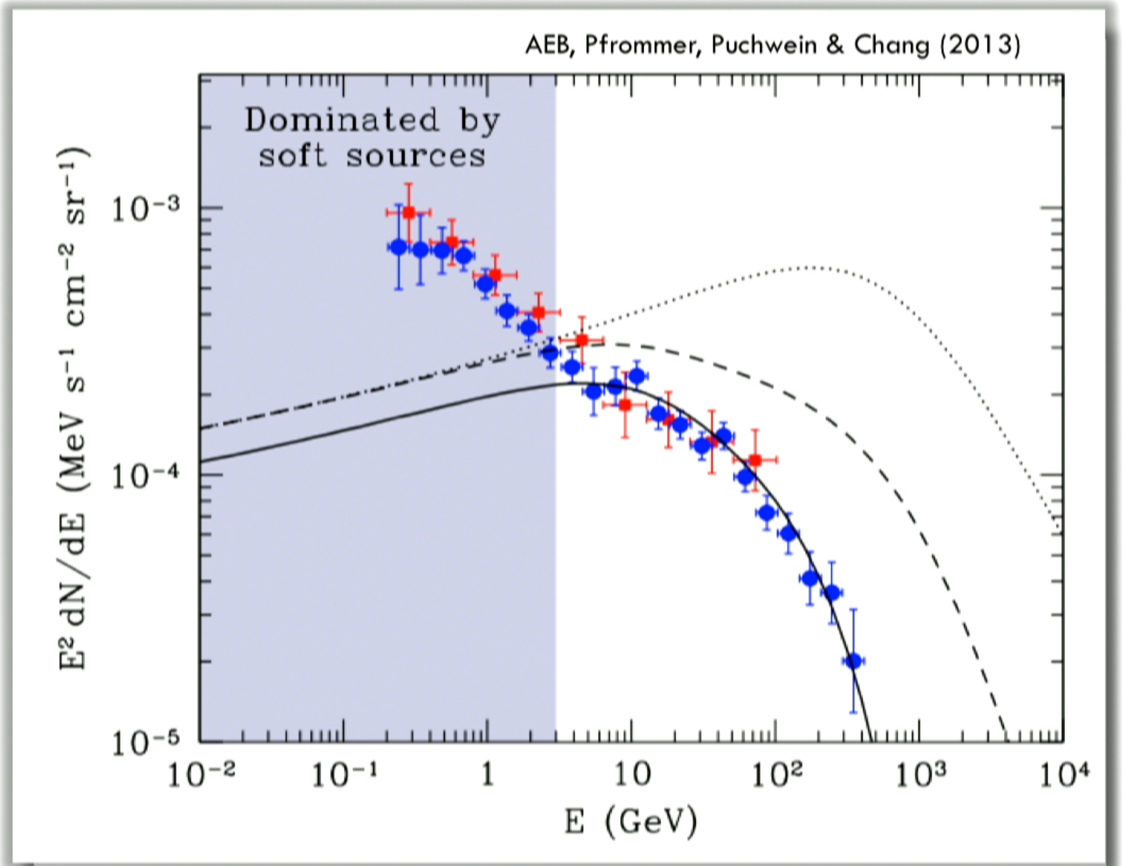
FERMI EGRB AND THE HIGH-Z LUMINOSITY FUNCTION



$$E^2 \frac{d\bar{N}}{dE\,d\Omega} = \frac{E}{4\pi} \int_0^2 d\Gamma_l \int_{z_{\rm 2LAC}}^{\infty} dz \int_0^{\infty} d\log_{10} L_{\rm TeV}$$
$$4\pi D_A^2 \frac{dD_P}{dz} \frac{L_{\rm TeV}}{4\pi D_L^2} \hat{I}_{E(1+z)} e^{-\tau(E,z)} \tilde{\phi}_B(z, L_{\rm TeV}, \Gamma_l)\,,$$

→ *Very few TeV blazars at high z*

FERMI EGRB AND THE HIGH-Z BLF



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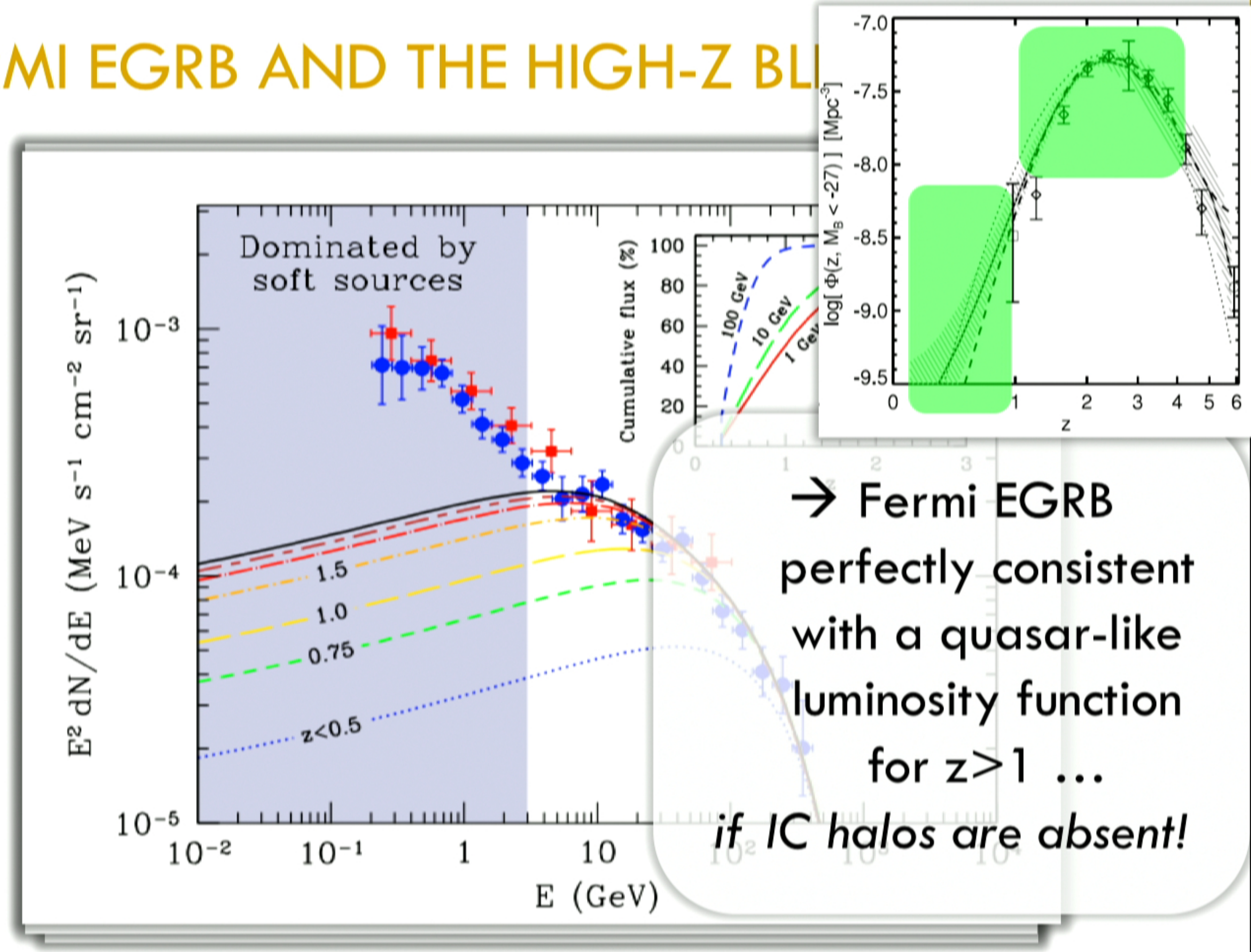
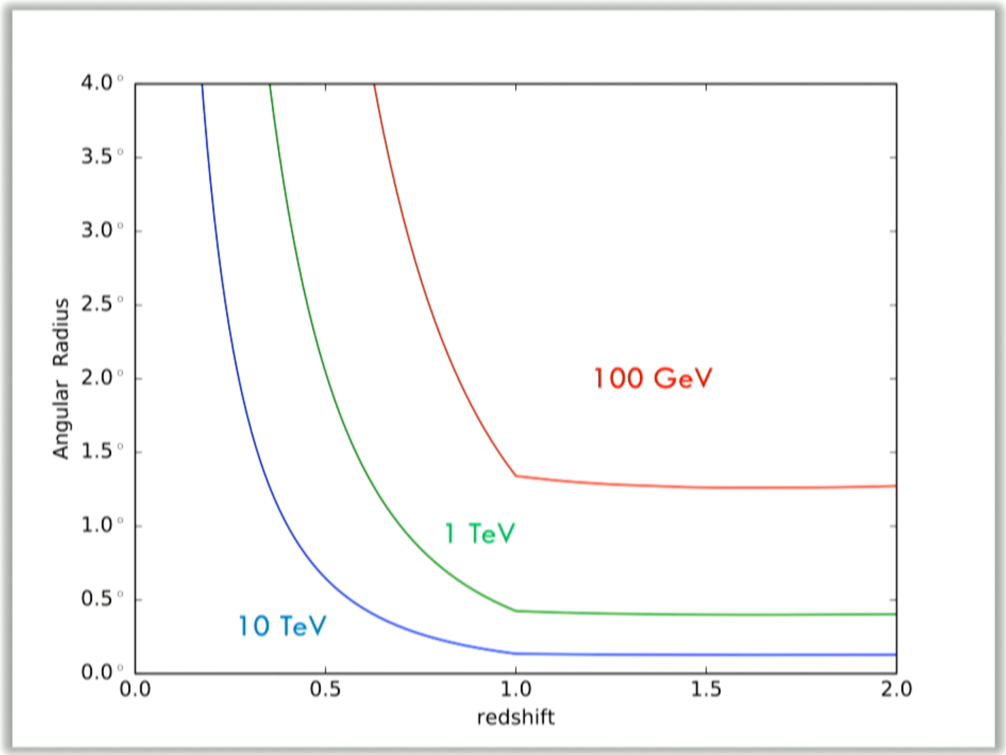
FERMI EGRB AND THE HIGH-Z BL



→ Fermi EGRB perfectly consistent with a quasar-like luminosity function for z>1 …

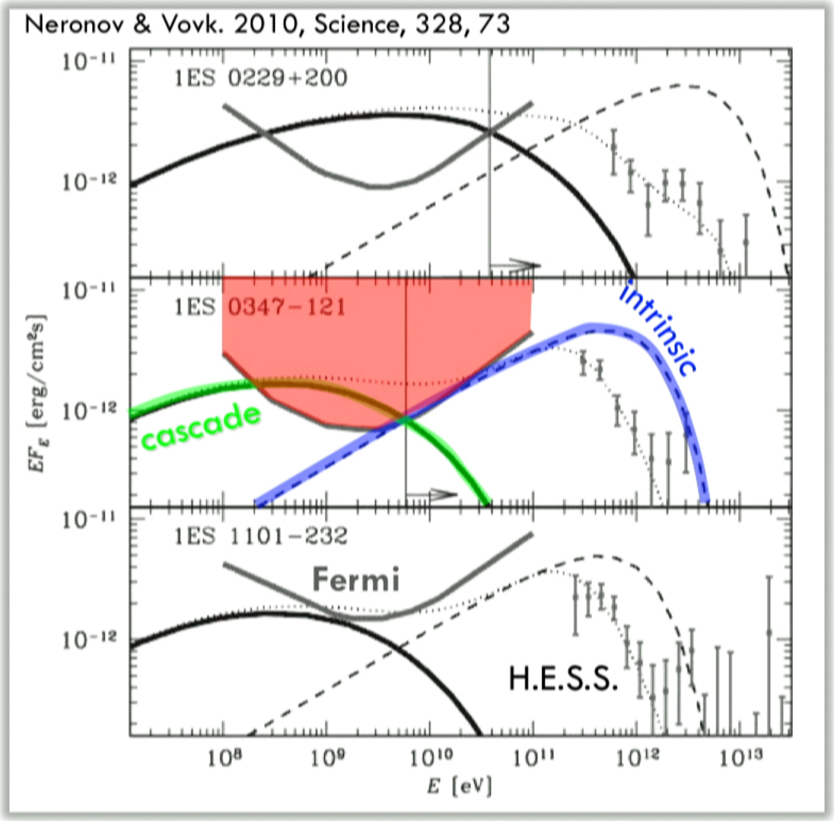
if IC halos are absent!

BIG AND DIM!



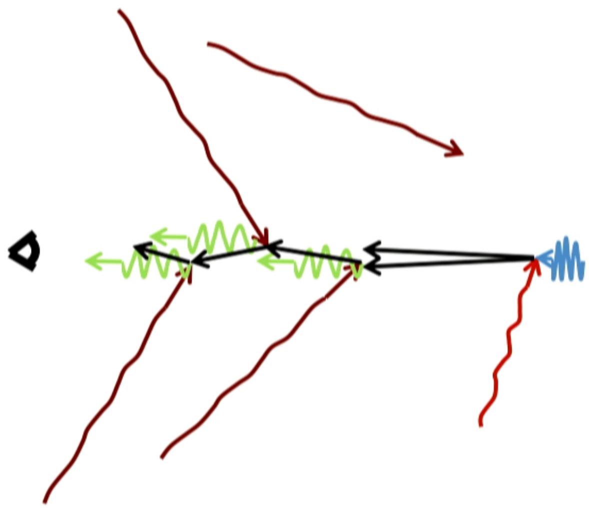
4.0°
3.5°
3.0°
2.5°
2.0°
1.5°
1.0°
0.5°
0.0°
Angular Radius
0.0
0.5
1.0
1.5
2.0
redshift
100 GeV
1 TeV
10 TeV

BIG AND DIM AND MAGNETIZED!!



There *must* be a strong IGMF!

$$B \geq 10^{-15} - 10^{-20}\ \mathrm{G}$$



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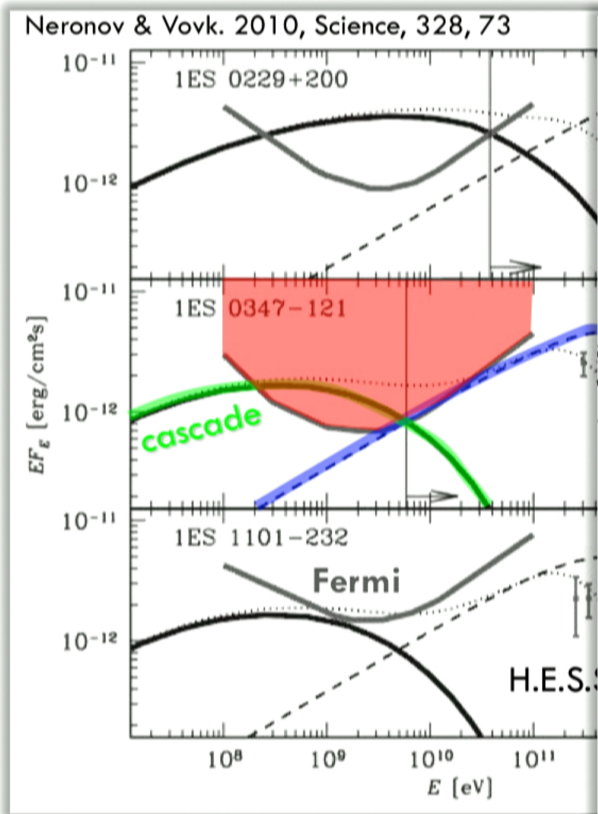

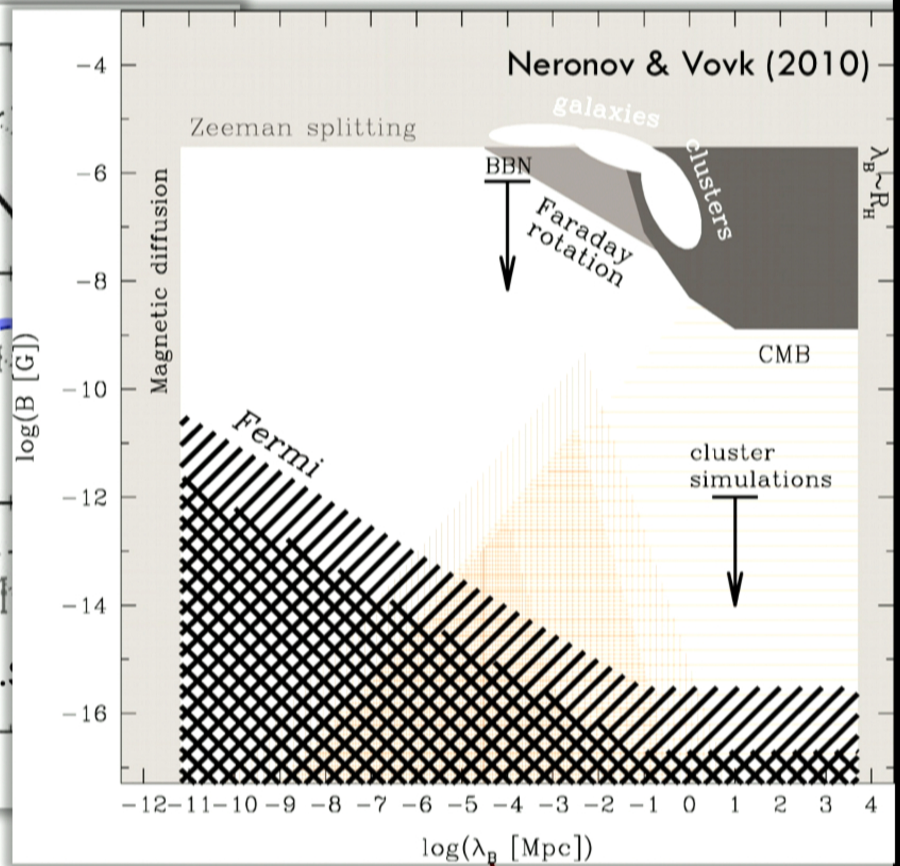

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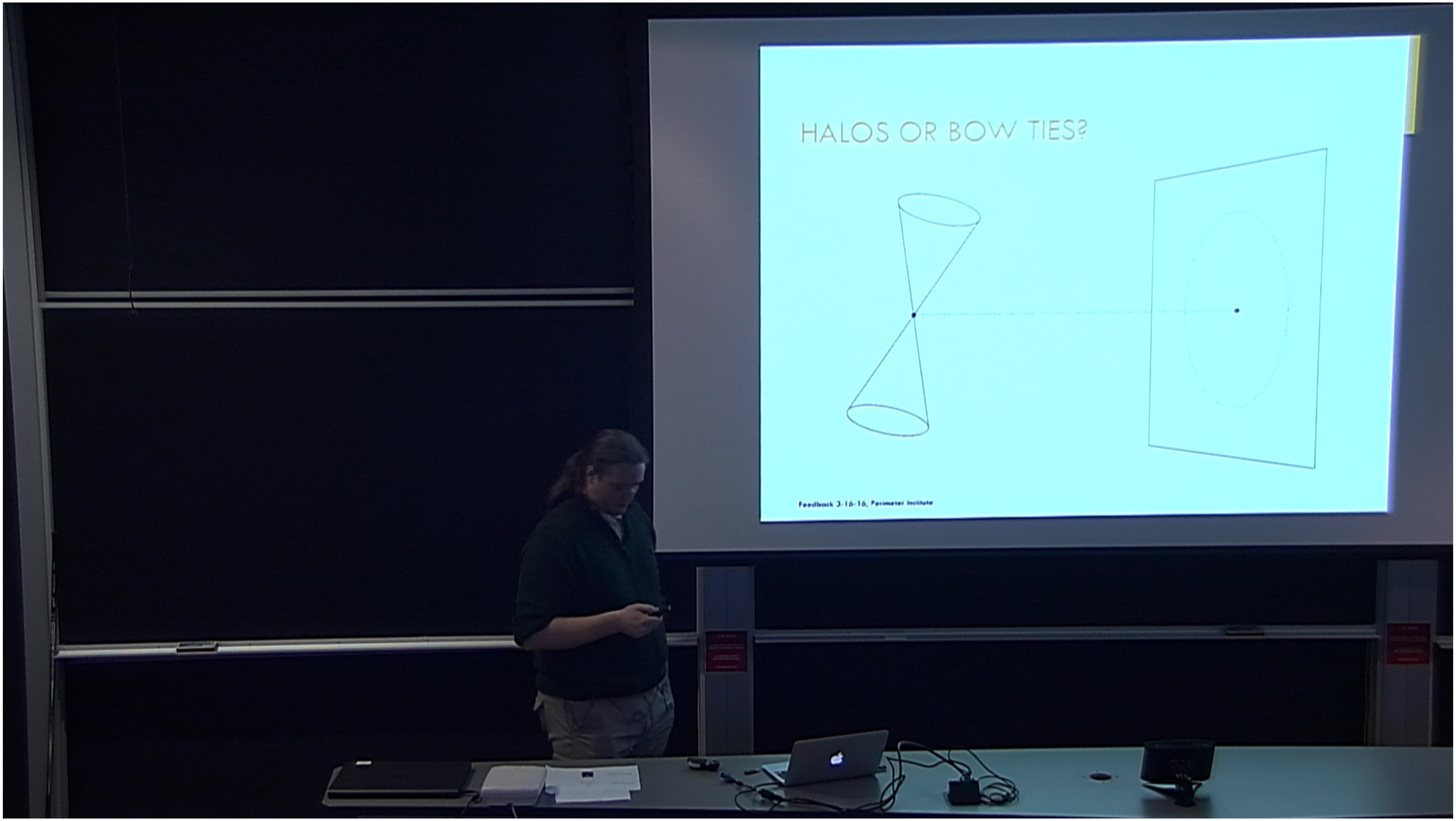
HALOS OR BOW TIES?
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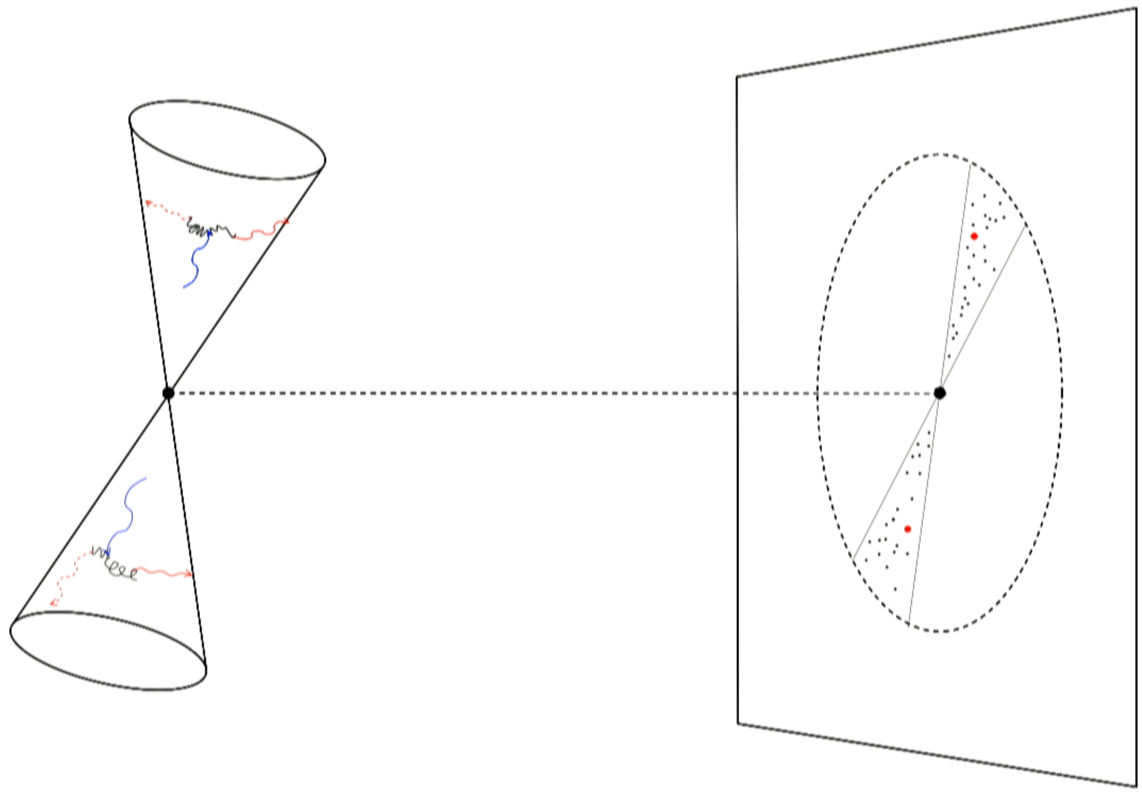

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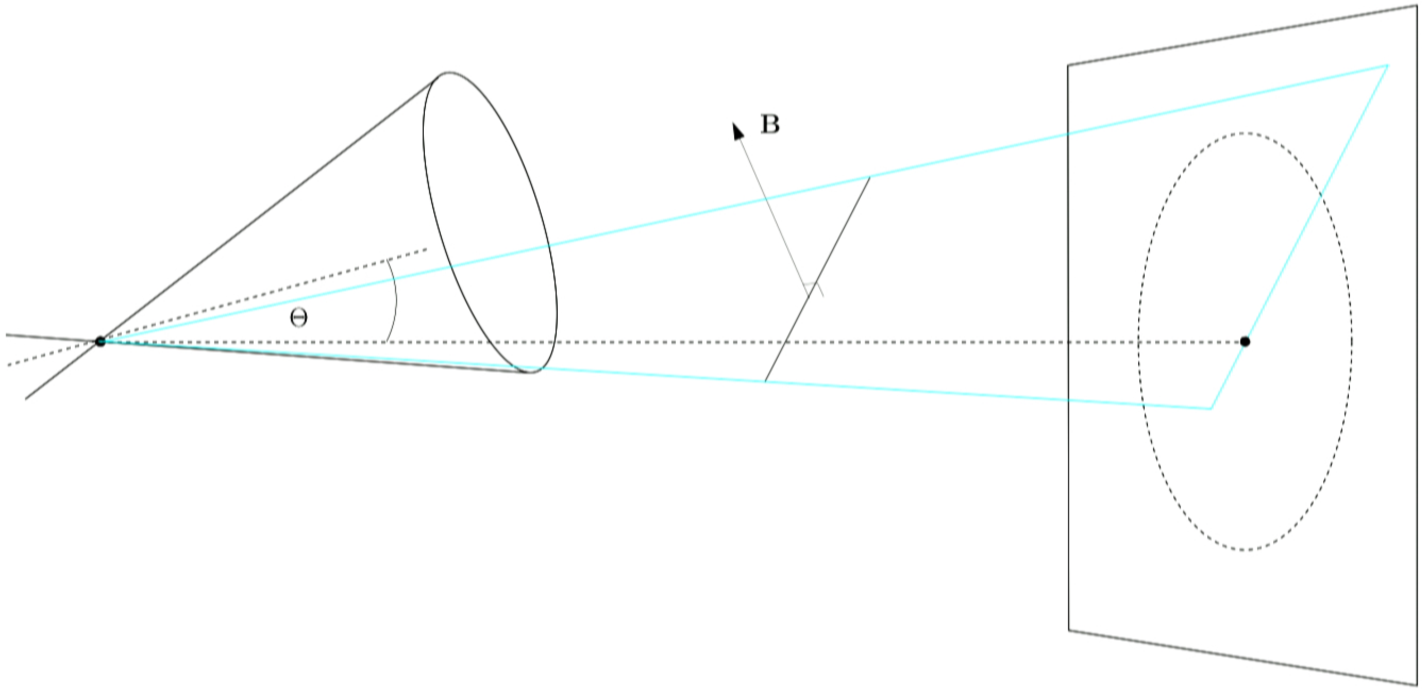

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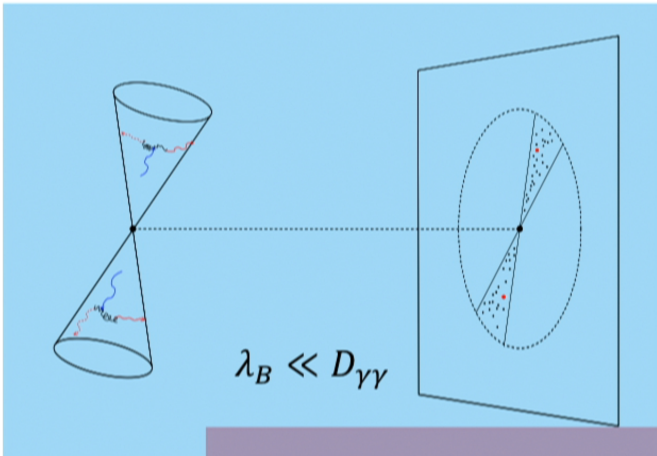
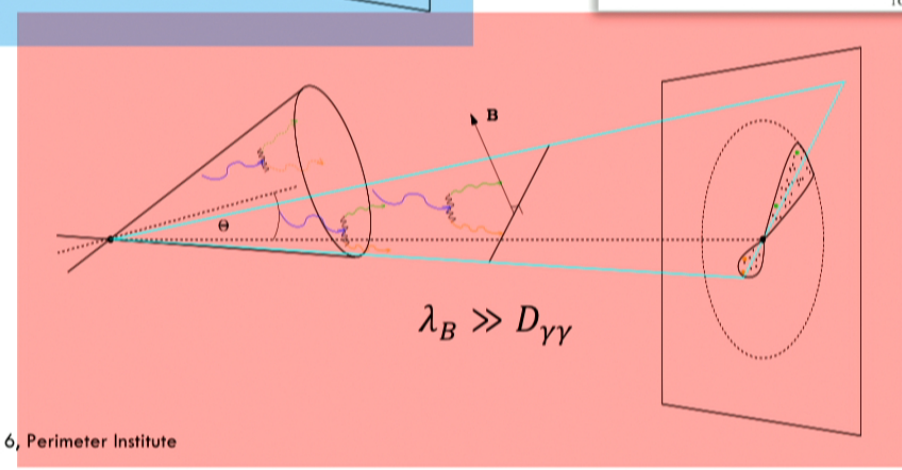
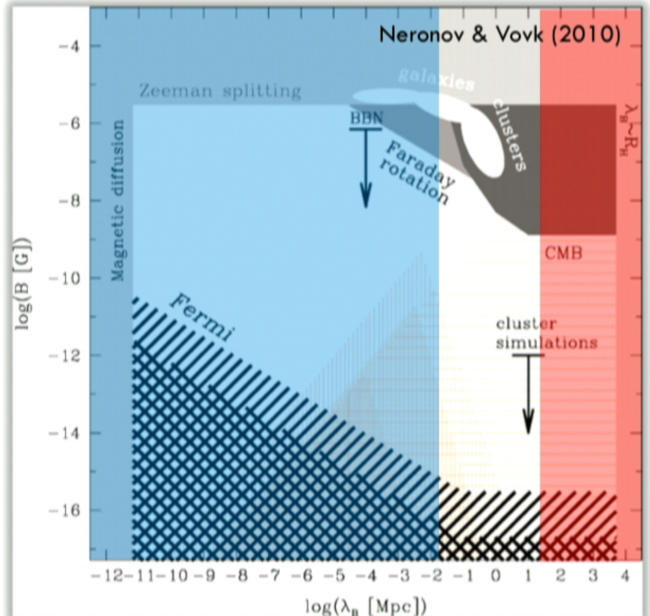
HALOS OR BOW TIES?







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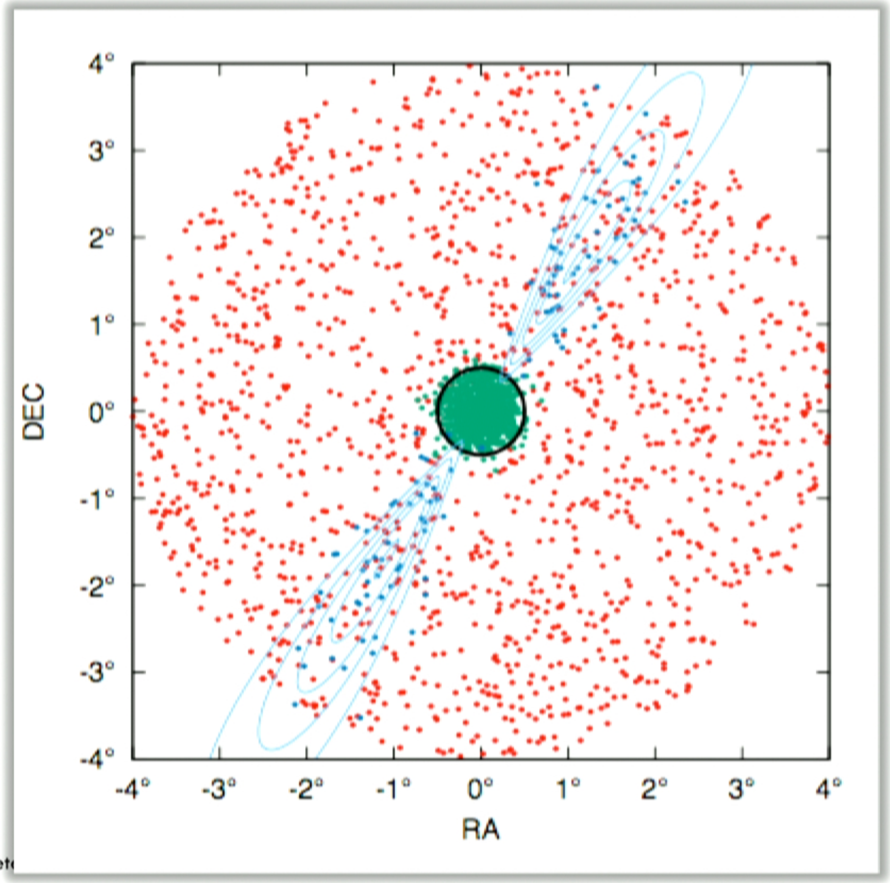
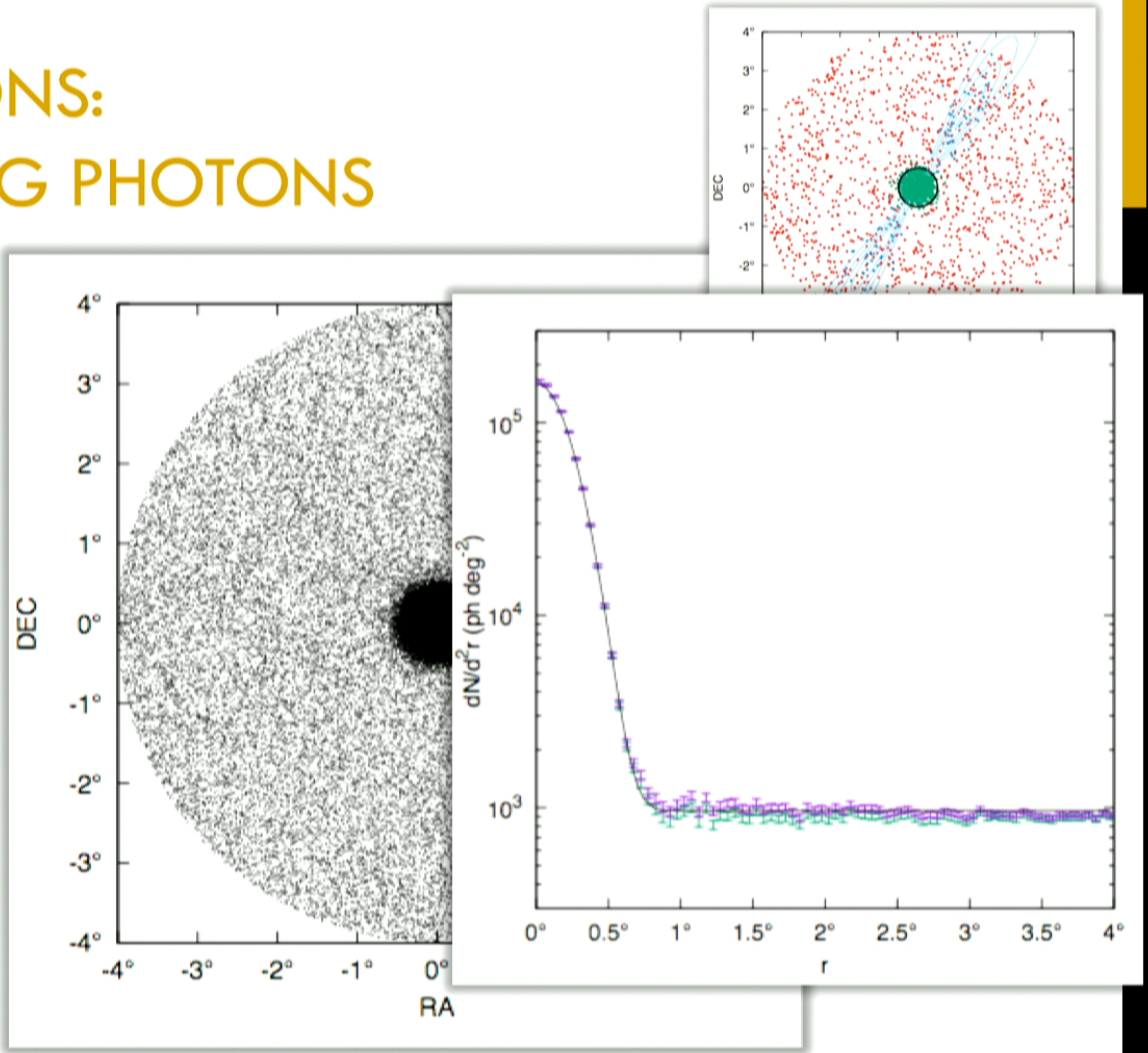
CARTOONS



CARTOONS: STACKING PHOTONS



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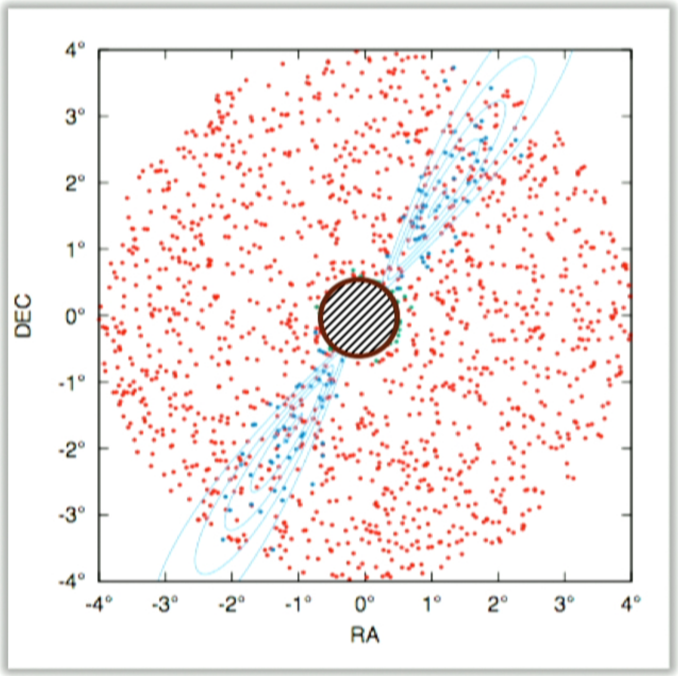
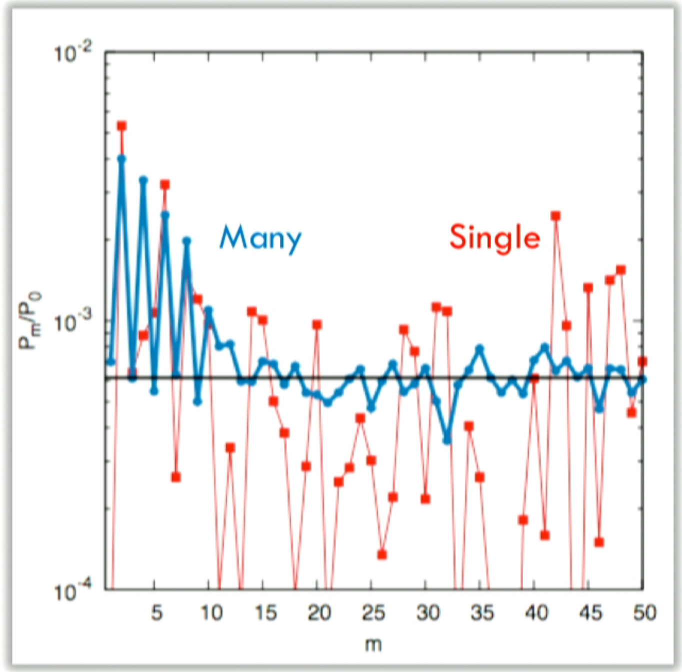
CARTOONS: STACKING STRUCTURE





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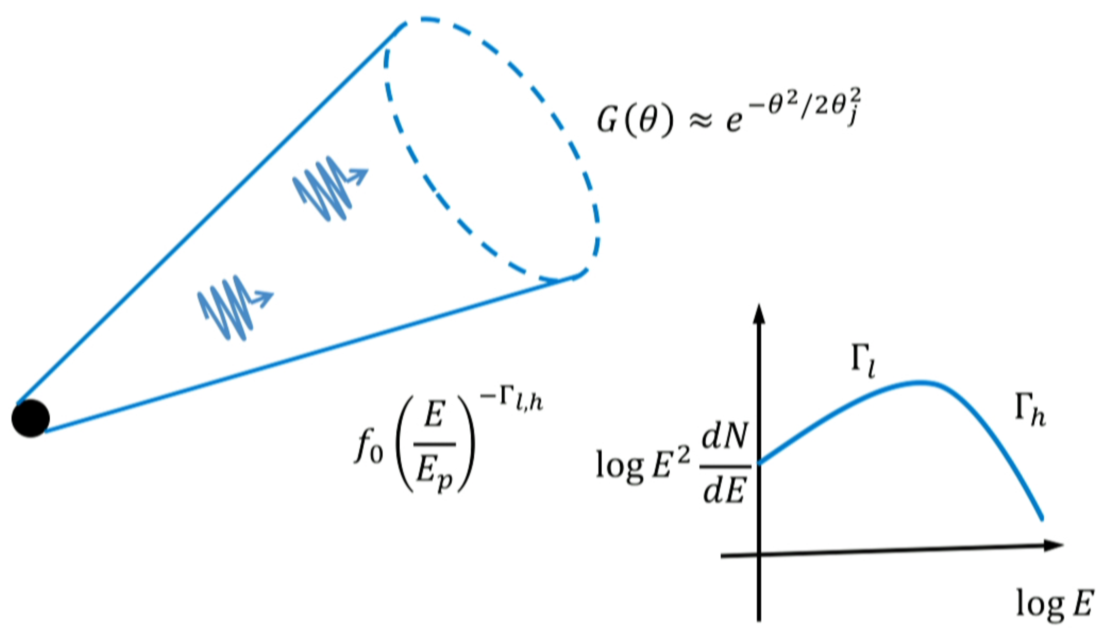
PRIOR VS. POSTERIOR EXPERIMENTS

Typical AGN has ~3000 photons from 1 GeV – 100 GeV

→ *Must make quantitative predictions!*

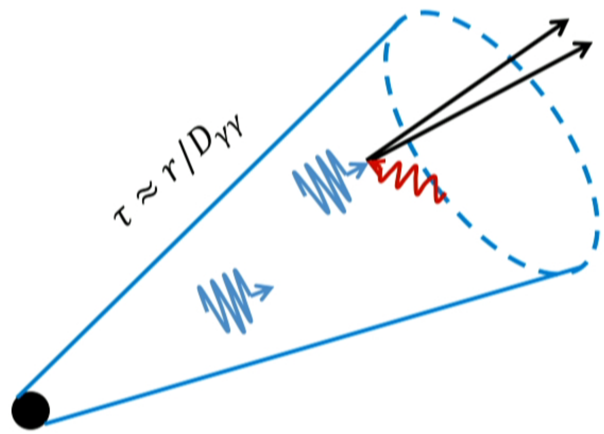
PHYSICAL INGREDIENTS OF A REALISTIC GAMMA-RAY HALO

- **VHEGR distribution** $$\frac{dN_{AGN}}{dt\,dE\,d\Omega} = f_0\left(\frac{E}{E_p}\right)^{-\Gamma} G(\theta)$$



PHYSICAL INGREDIENTS OF A REALISTIC GAMMA-RAY HALO

- **VHEGR distribution** $$\frac{dN_{AGN}}{dt\,dE\,d\Omega} = f_0\left(\frac{E}{E_p}\right)^{-\Gamma} G(\theta)$$
- **Pair production distribution** $$\frac{dN_{e^\pm}}{dt\,dE\,d^3x} = \frac{2}{r^2}\frac{d\tau}{dr}e^{-\tau}\left.\frac{dN_{AGN}}{dt\,dE\,d\Omega}\right|_{2E}$$



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- **Pair evolution** $$v \cdot \nabla f + \nabla_p \cdot [(\dot{p} + W) f] = \dot{f}_{inj}$$
- **Inverse Compton scattering of the CMB**

$$\frac{dN_{IC}}{dt\, dE\, d^2\alpha} = \sum_{e^\pm} \frac{A_{eff}}{(1+z)^4} \frac{3 m_e^4 c^5}{16\, t_{IC}\, \varepsilon^2} \sqrt{\frac{E}{2\varepsilon}} \int d\ell\, f_{e^\pm}\left(x, 2\sqrt{\frac{E}{2\varepsilon}}\hat{\ell}\right)$$

(Forward scattering, $\varepsilon \ll E$, etc.)

WHERE AND WHERE NOT TO LOOK FOR GAMMA RAY HALOS

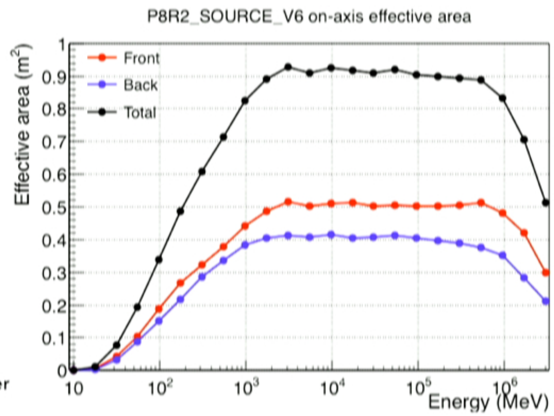
- **Halo's are marginally harder than background:**

$$\Gamma_{halo} \approx \frac{\Gamma_h}{2} + 1 \approx 2 - 2.5, \qquad \Gamma_{bkgnd} \approx 2.4$$

- **Energetics:**

$$E \approx 2\gamma^2 \varepsilon \approx 1.4 \left(\frac{E_\gamma}{1\ \mathrm{TeV}}\right)^2 \mathrm{GeV} \approx 1.4 \left(\frac{D_{\gamma\gamma}}{800\ \mathrm{Mpc}}\right)^{-2} \mathrm{GeV}$$

- **Efficiency:**



$$1\ \mathrm{GeV} < E < 100\ \mathrm{GeV}$$

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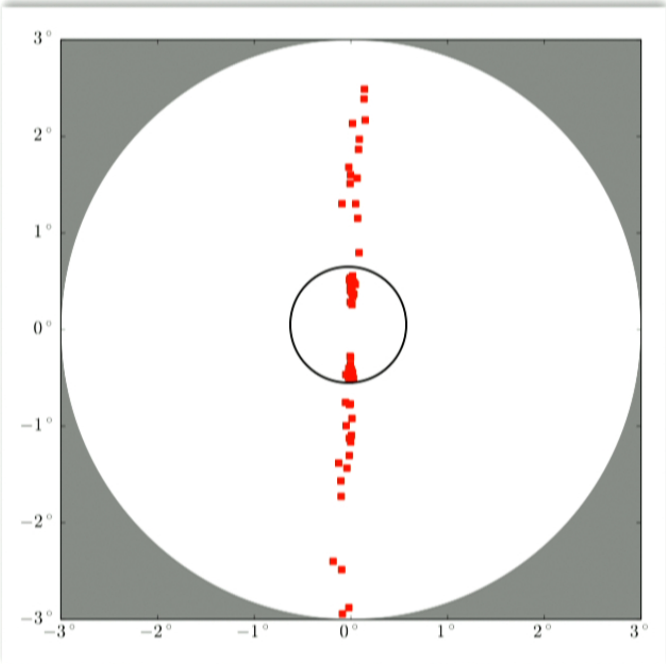
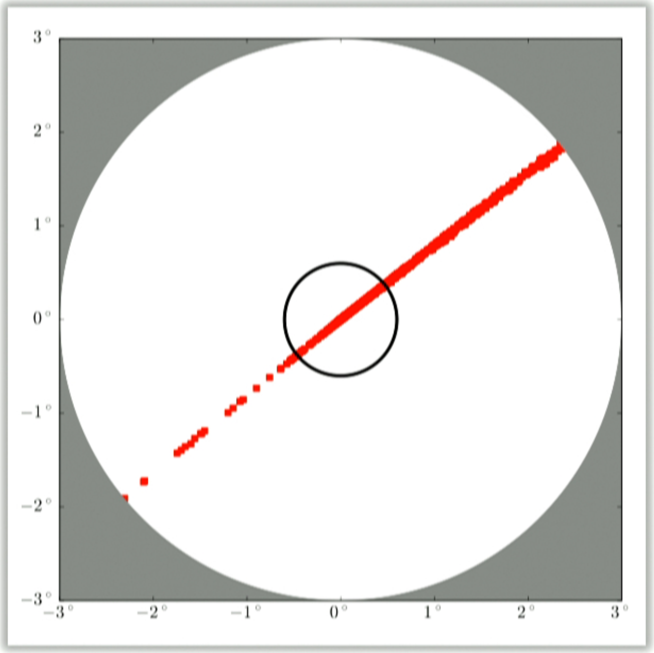
EXAMPLE PHYSICAL HALOS

$\lambda_B \ll D_{\gamma\gamma}$



$\lambda_B \gg D_{\gamma\gamma}$



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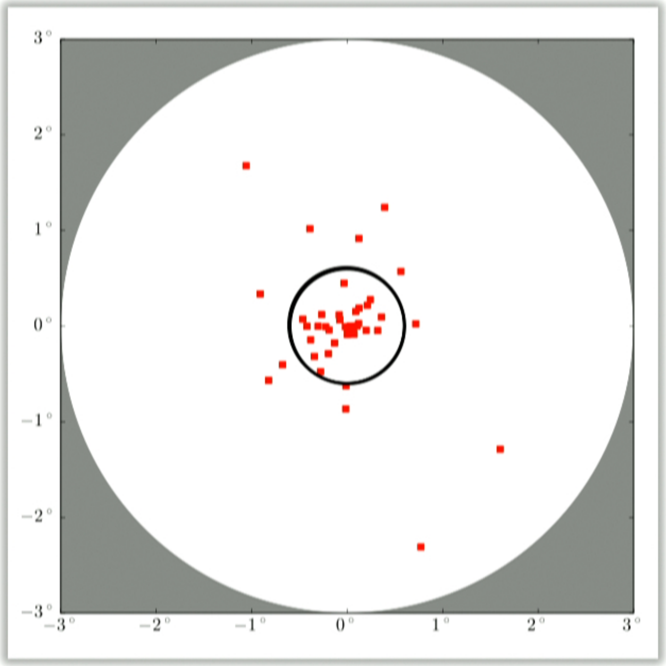

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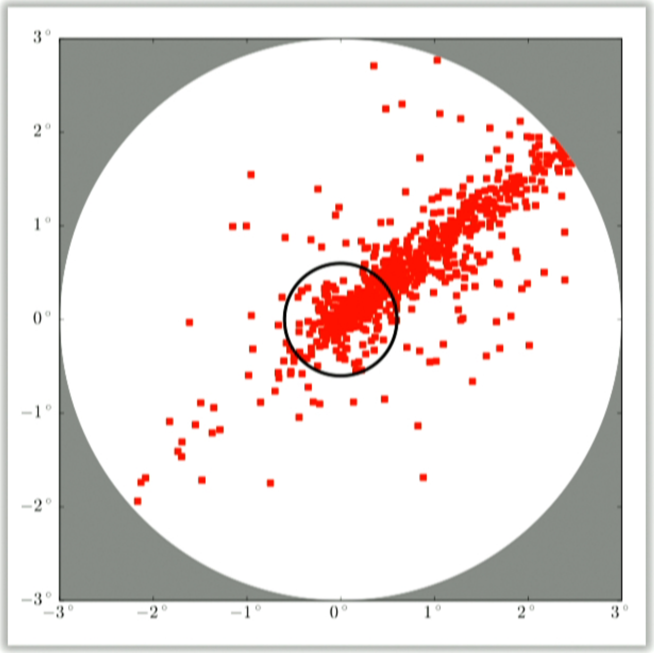
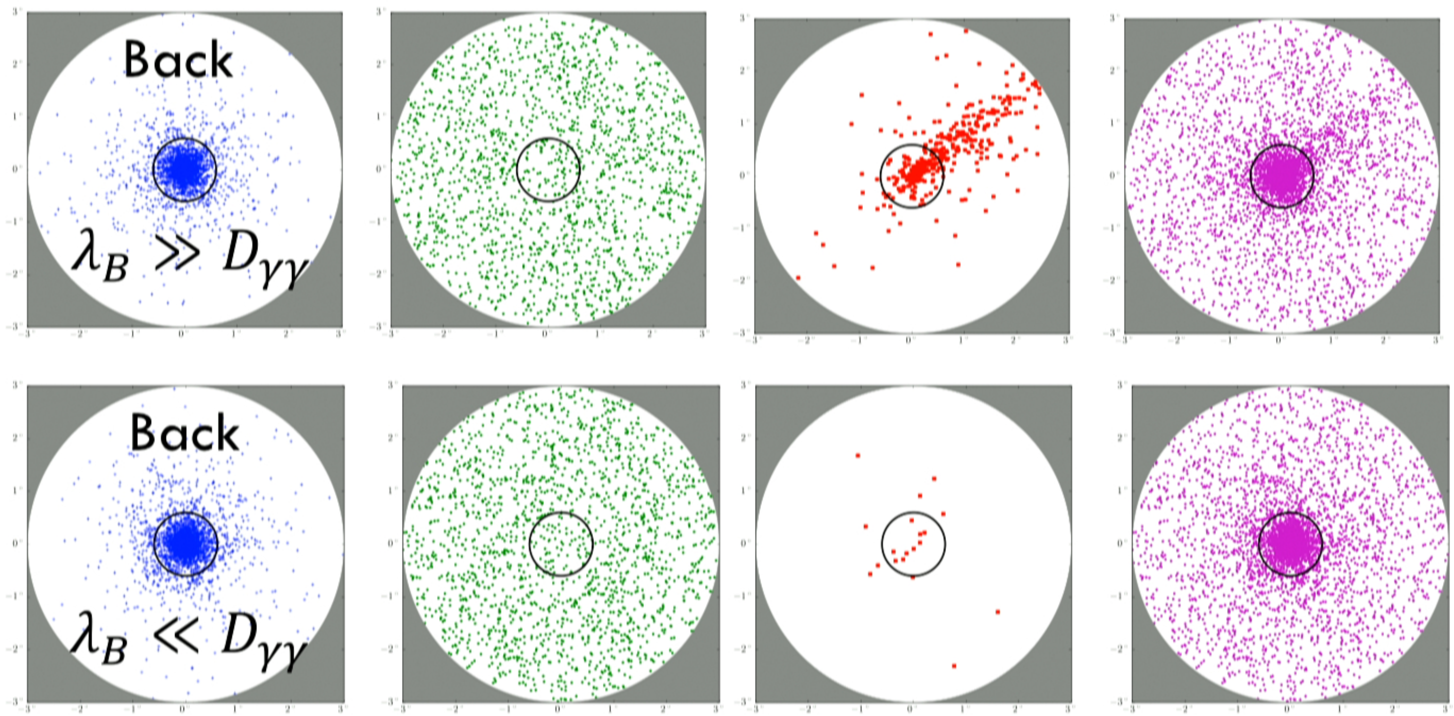
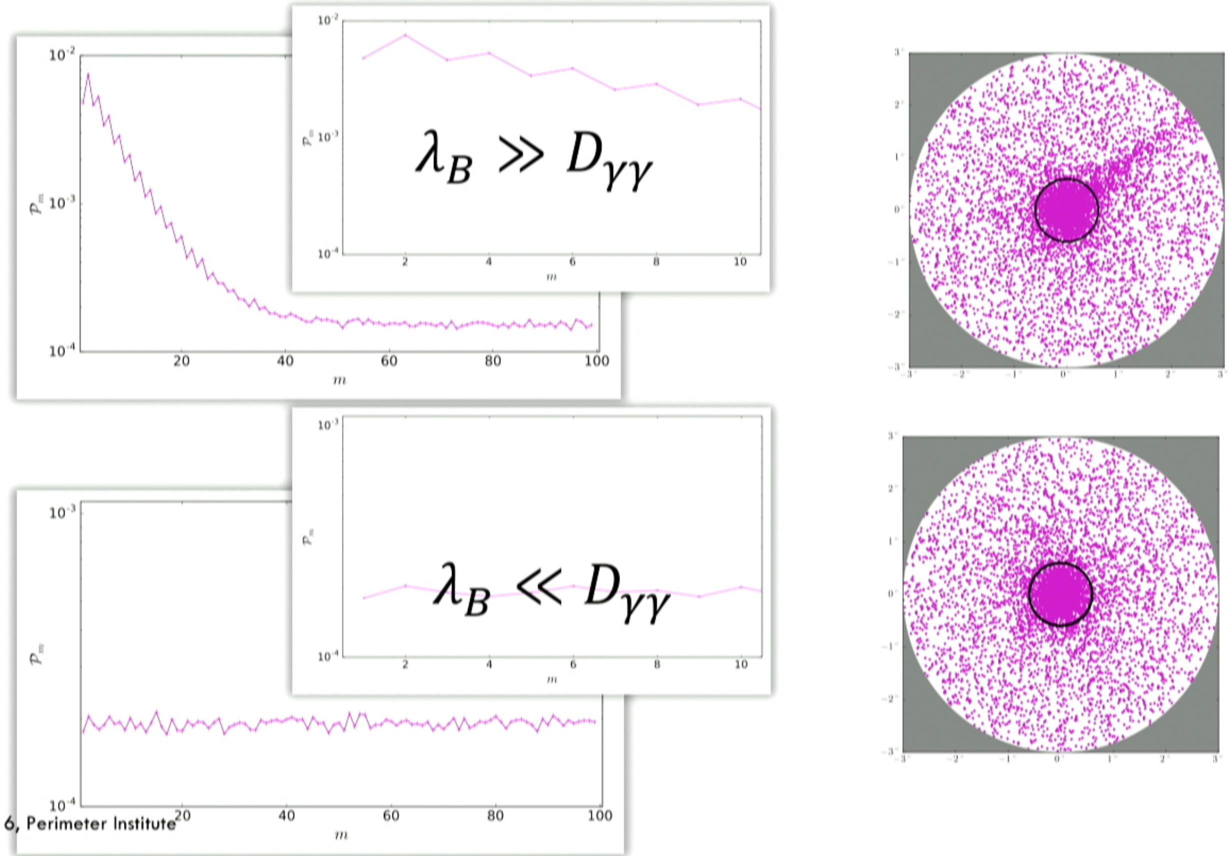


GENERATING MOCK IMAGES

Source + Background + Halos = Total



FROM IMAGES TO POWER SPECTRA



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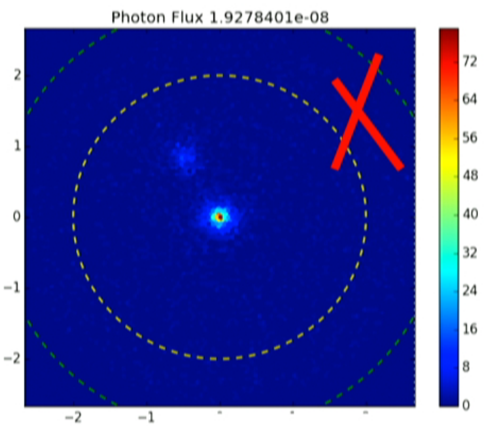
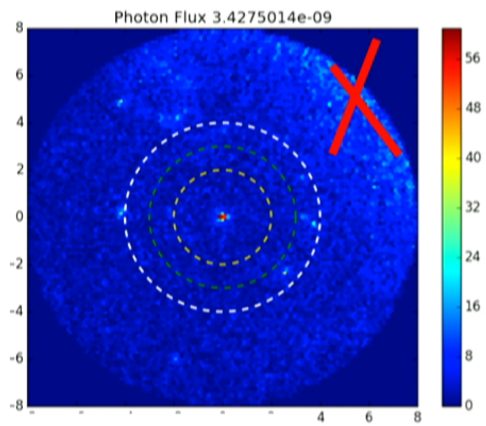
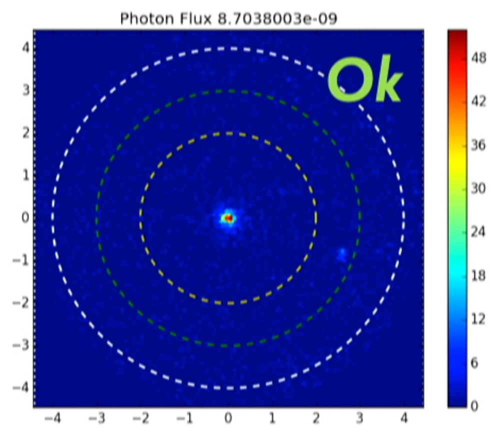
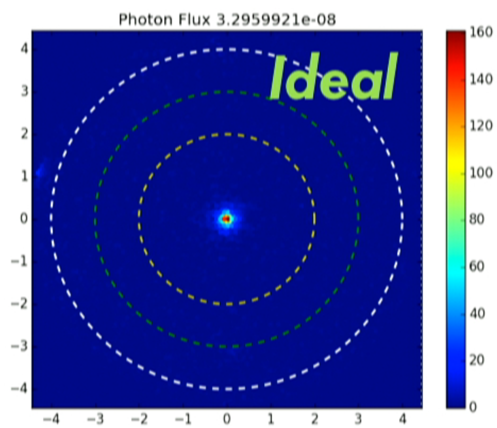
THE FERMI SAMPLE: CONTAMINANTS AND REQUIREMENTS







Feedback 3

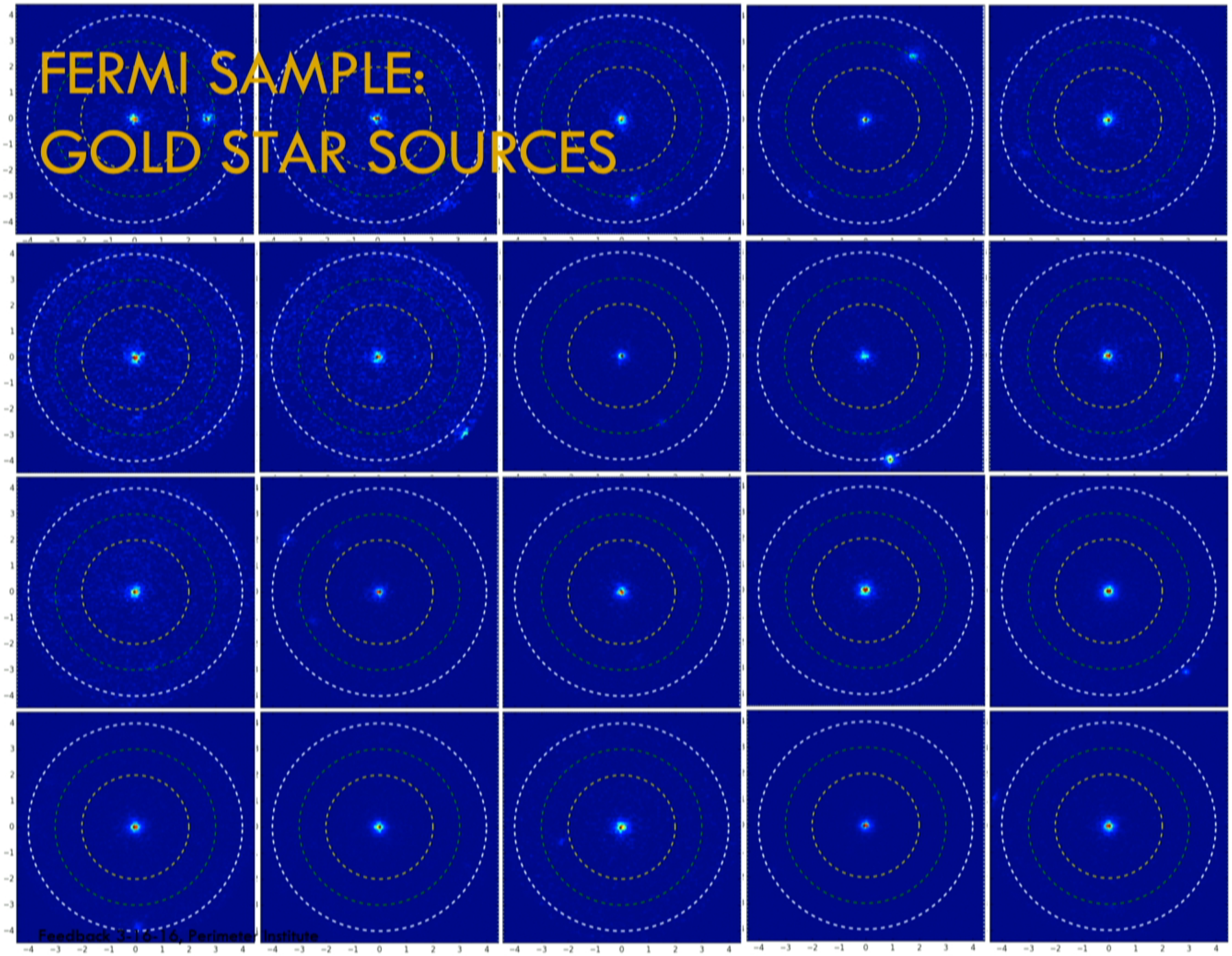


Need:

- Redshifts
- >2 halo photons!

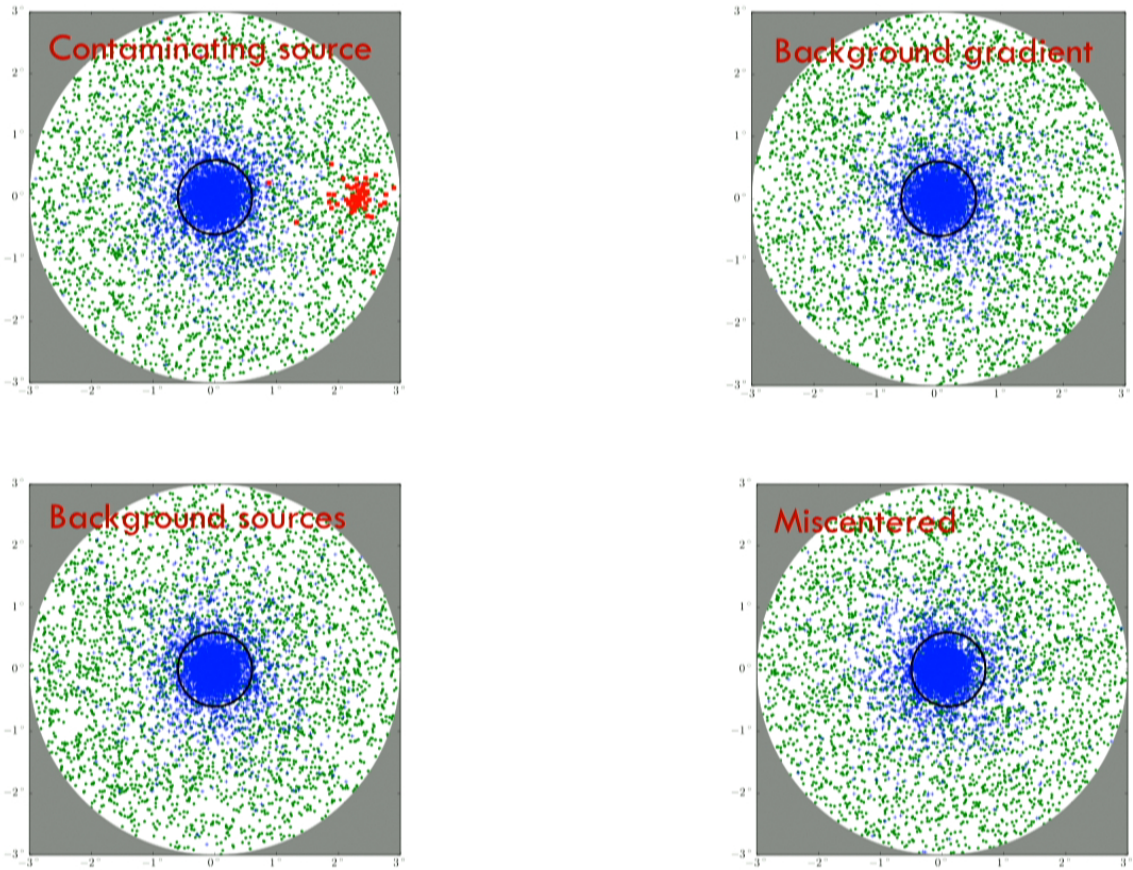
  → $F > 4{\times}10^{-9}\ \mathrm{ph/cm^2 s}$

FERMI SAMPLE: GOLD STAR SOURCES

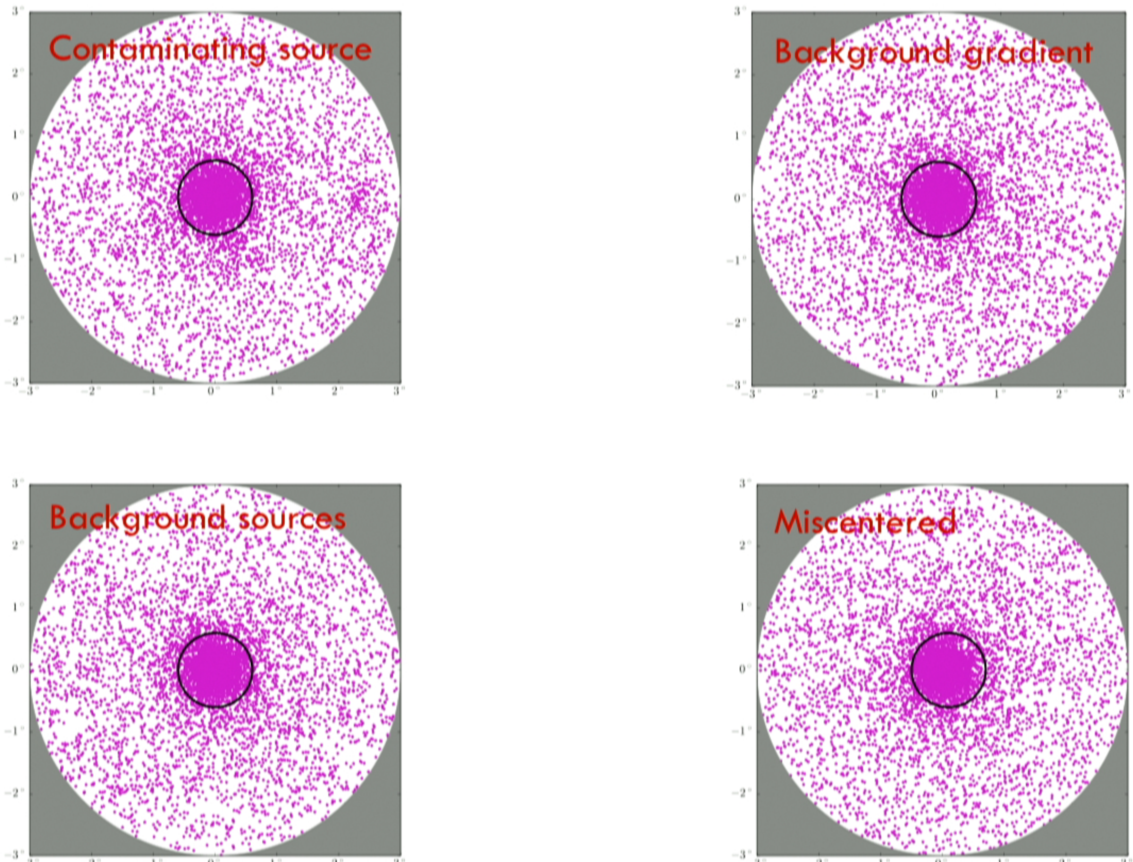


Feedback 3-16-16, Perimeter Institute

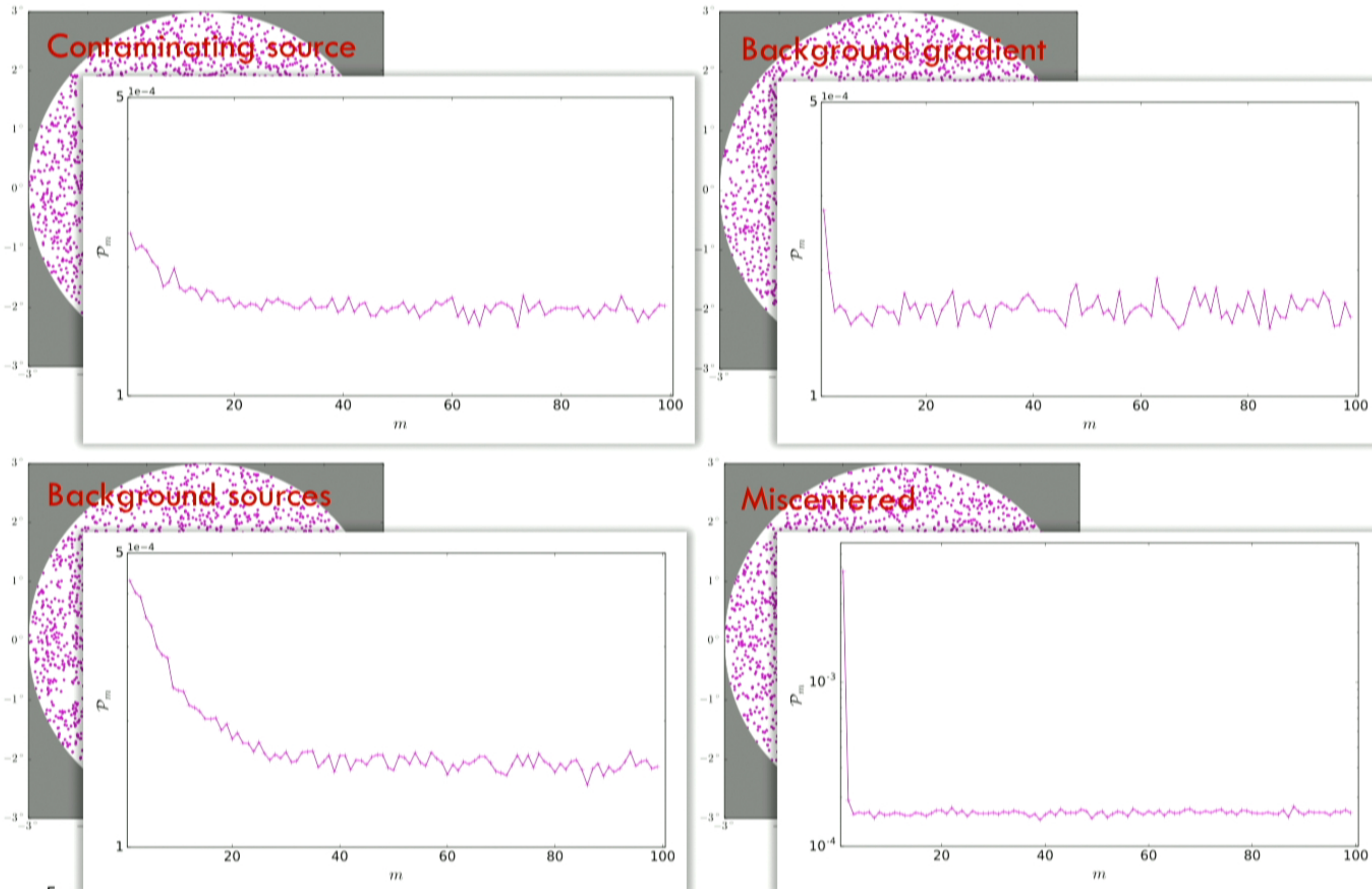
BAD APPLES?


Contaminating source
Background gradient
Background sources
Miscentered

BAD APPLES?


Contaminating source
Background gradient
Background sources
Miscentered

BAD APPLES?



Feedback 3-10-16, Perimeter Institute

PRE-DICTIONS NOT ***POST***-DICTIONS
MODELING THE FERMI SAMPLE

- **Source location:** $\vec{x}_c$
- **Redshift:** z
- **1-100 GeV Flux:** F_{35}
- **Spectral shape:** Γ_l, Γ_h
- **Orientation:** Θ, Φ
- **Jet structure:** θ_j
- **Magnetic field:** $\vec{B}$
- **Stochastic Realizations**

PRE-DICTIONS NOT *POST*-DICTIONS
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- **Spectral shape:** Γ_l, Γ_h
- **Orientation:** Θ, Φ
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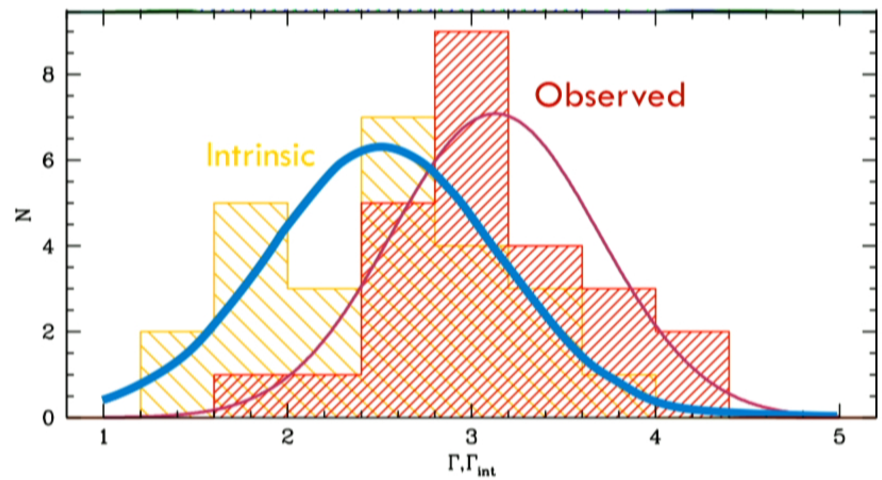
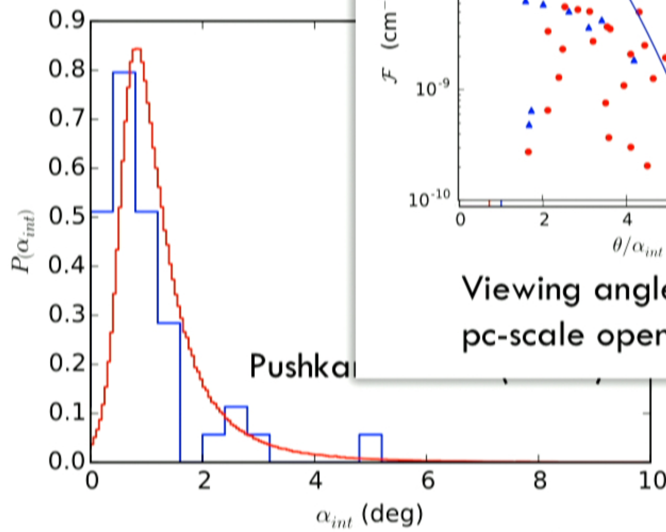
- **Stochastic Realizations**

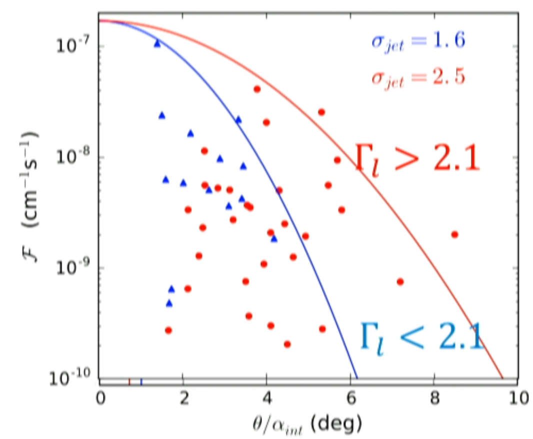


PRE-DICTIONS NOT POST-DIC
MODELING THE FERMI SAMPL

- **Source location: $\vec{x}_c$**
- **Redshift: z**
- **1-100 GeV Flux: F_{35}**
- **Spectral shape: Γ_l, Γ_h**
- **Orientation: Θ, Φ**
- **Jet structure: θ_j**
- **Magnetic field: $\vec{B}$**
- **Stochastic Realizations**



pc-scale radio opening angle



Viewing angle in units of pc-scale opening angle

$$\theta_j \approx 1.6\alpha_{int}$$

Radio blazars! → $\Theta \leq \dfrac{1}{\Gamma_{jet}} \approx 3\alpha_{int}$

Feedback 3-16-16, Perimeter Institute

PRE-DICTIONS NOT ***POST***-DICTIONS
MODELING THE FERMI SAMPLE

- **Source location:** $\vec{x}_c$
- **Redshift:** z
- **1-100 GeV Flux:** F_{35}
- **Spectral shape:** Γ_l, Γ_h
- **Orientation:** Θ, Φ
- **Jet structure:** θ_j
- **Magnetic field:** $\vec{B}$
- **Stochastic Realizations**

Where needed:

- Fix magnitude
- Choose random direction

PRE-DICTIONS NOT ***POST***-DICTIONS
MODELING THE FERMI SAMPLE

- **Source location: $\vec{x}_c$**
- **Redshift: z**
- **1-100 GeV Flux: F_{35}**
- **Spectral shape: Γ_l, Γ_h**
- **Orientation: Θ, Φ**
- **Jet structure: θ_j**
- **Magnetic field: $\vec{B}$**
- **Stochastic Realizations**

Procedure:

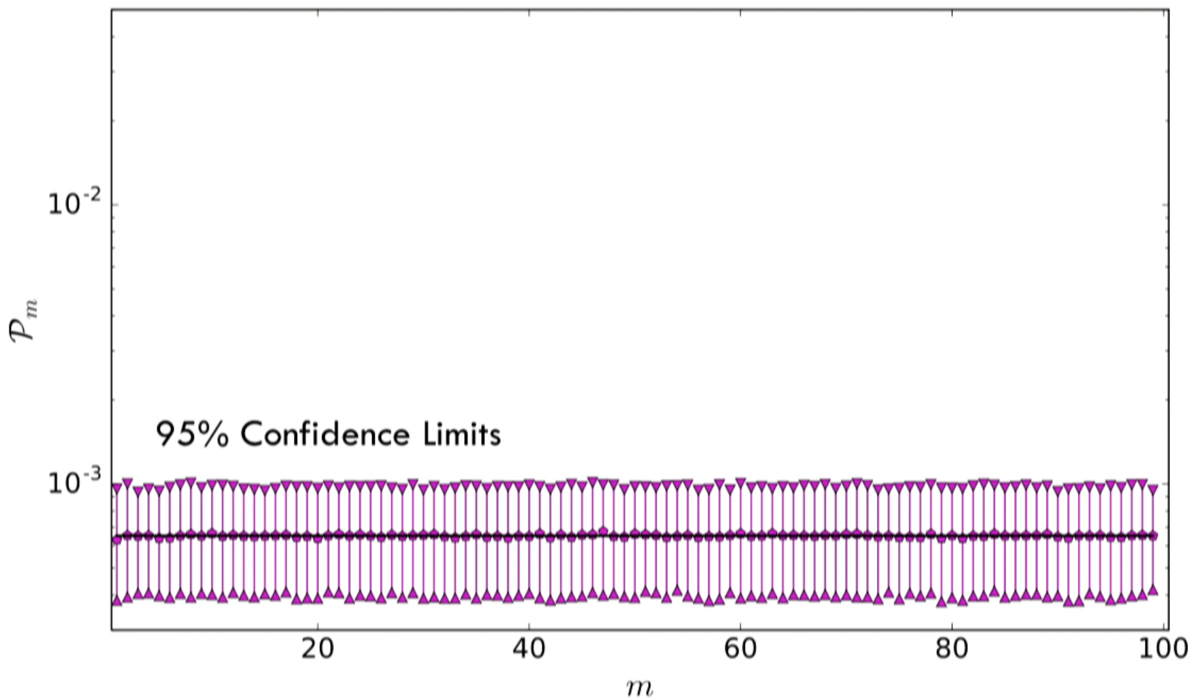
1. **Draw a set of unknown source parameters for the Gold Star Sample**
2. **Draw a set of gamma-rays from halo + src + bkgnd models**
3. **Construct & stack power spectra:**

$$P_m = \frac{1}{N}\sum_{src}\frac{1}{N_{ph}}\left|\sum_{k=1} e^{im\theta_k}\right|^2$$

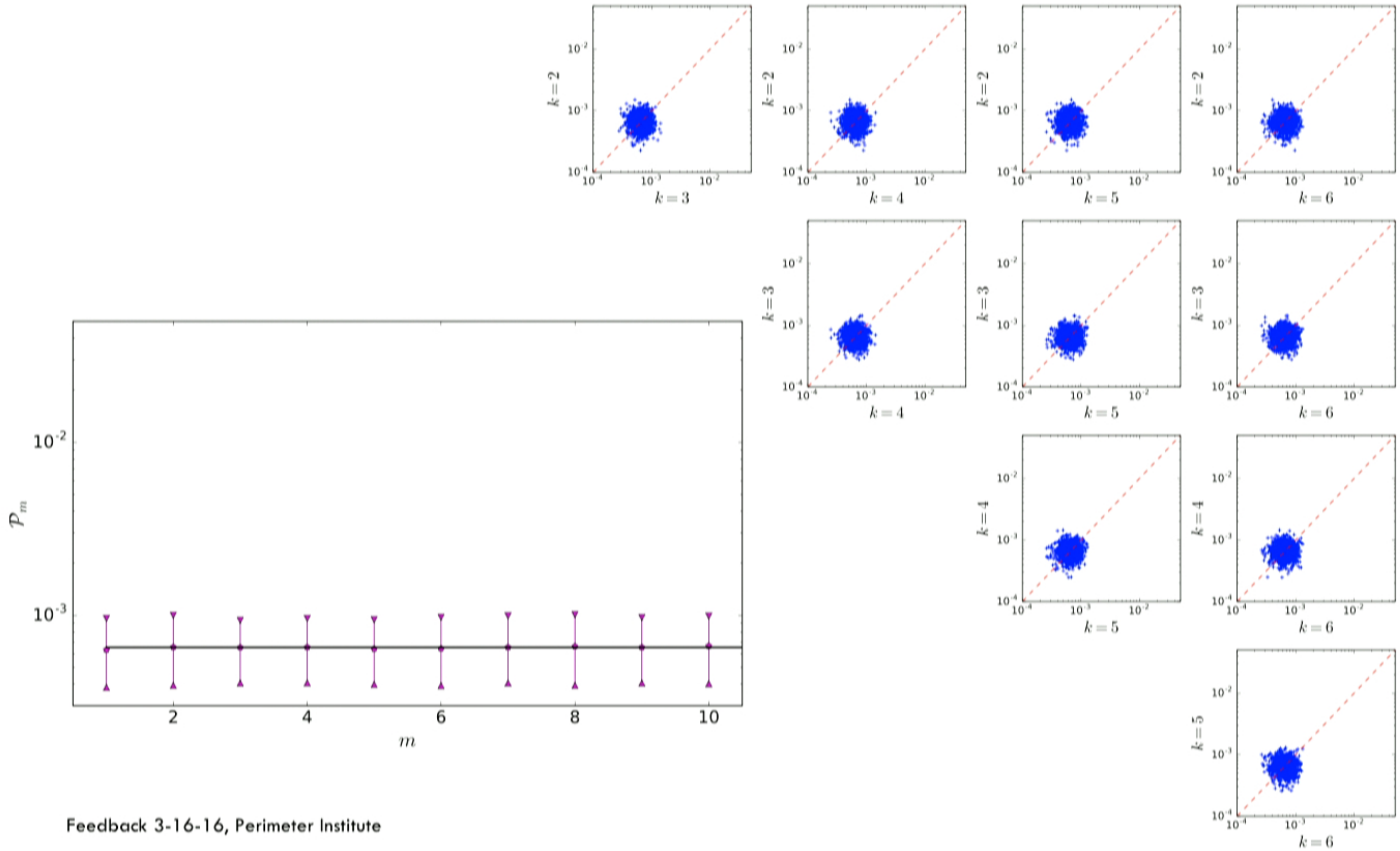
4. **REPEAT!**

   → Get Confidence Levels

HALO POWER SPECTRA BY TYPE: NULL – NO HALOS AT ALL!

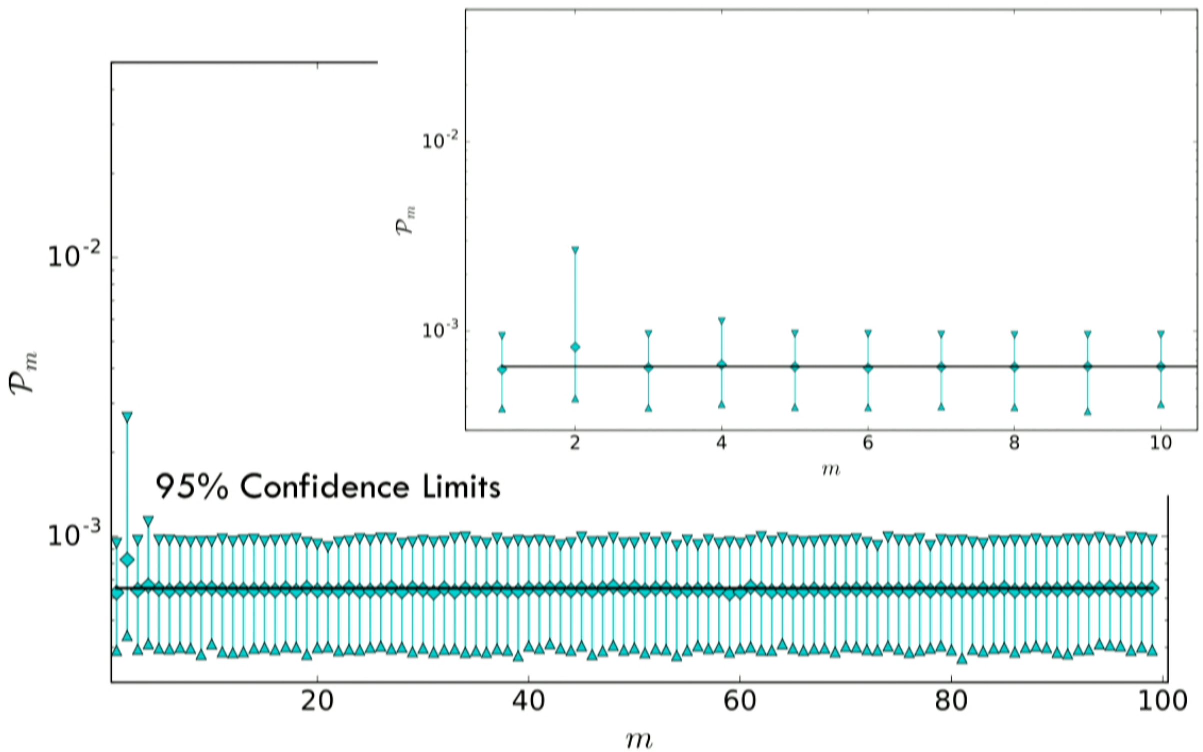


HALO POWER SPECTRA BY TYPE: NULL – NO HALOS AT ALL!



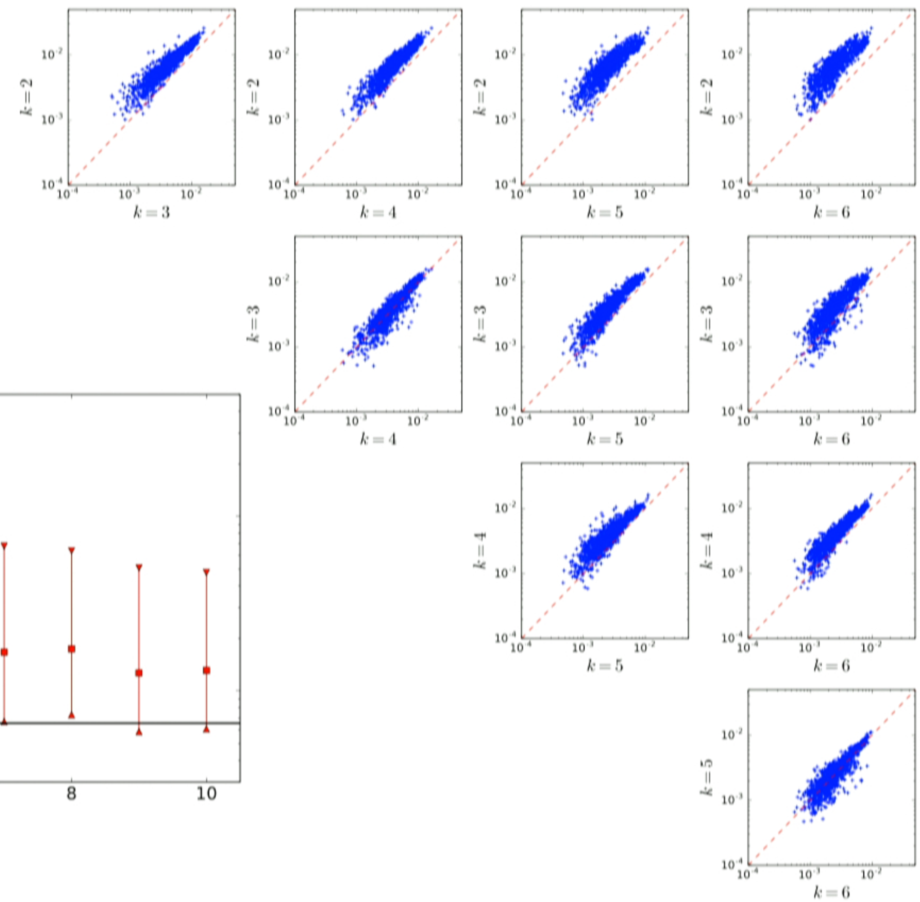
Feedback 3-16-16, Perimeter Institute

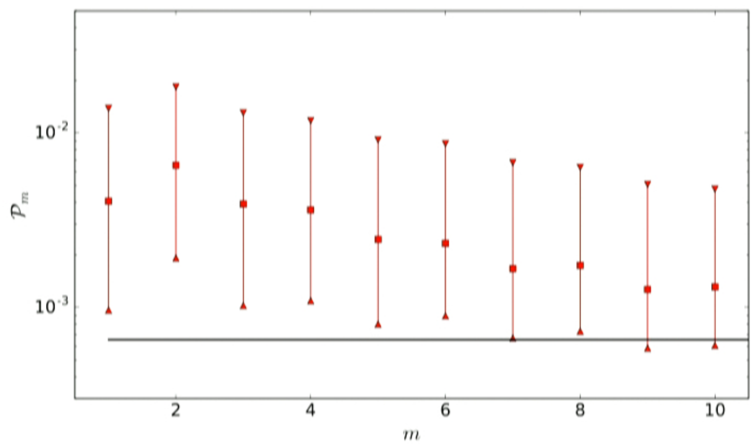
HALO POWER SPECTRA BY TYPE: $\lambda_B \ll D_{\gamma\gamma} \rightarrow$ ISOTROPIZED



Feedback 3-16-16, Perimeter Institute

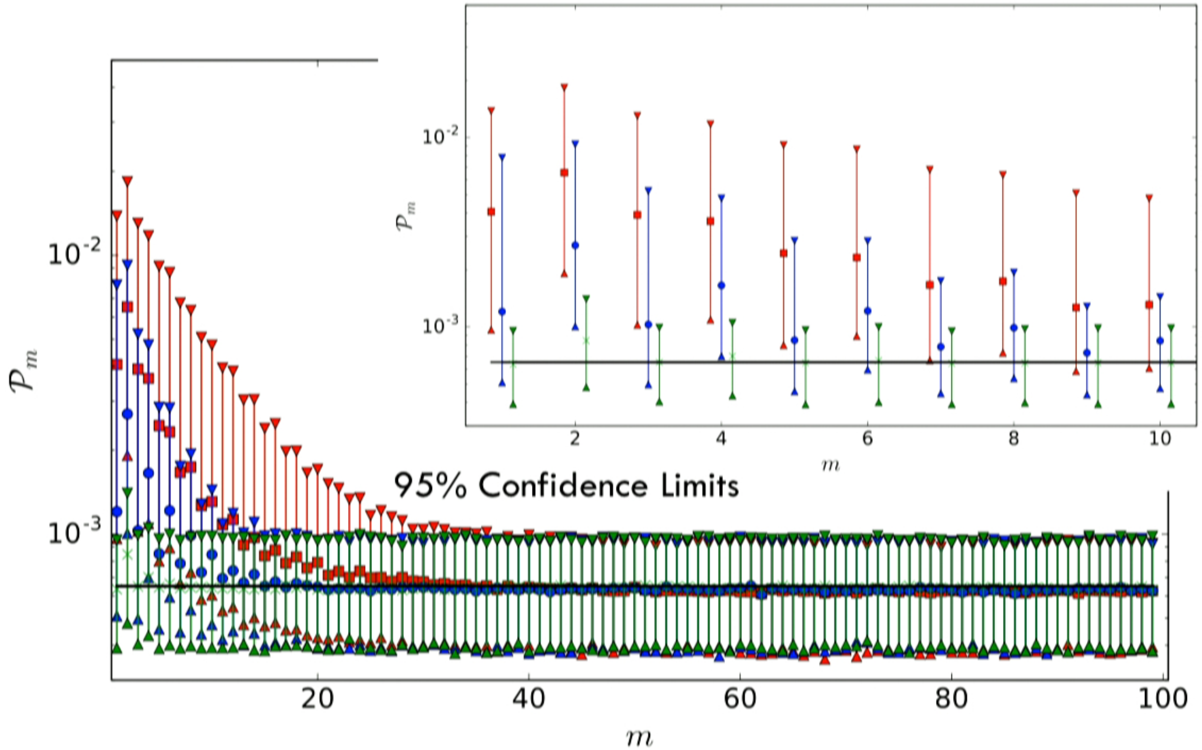
HALO POWER SPECTRA BY TYPE: $\lambda_B \gg D_{\gamma\gamma},\ B = 10^{-15}$ G





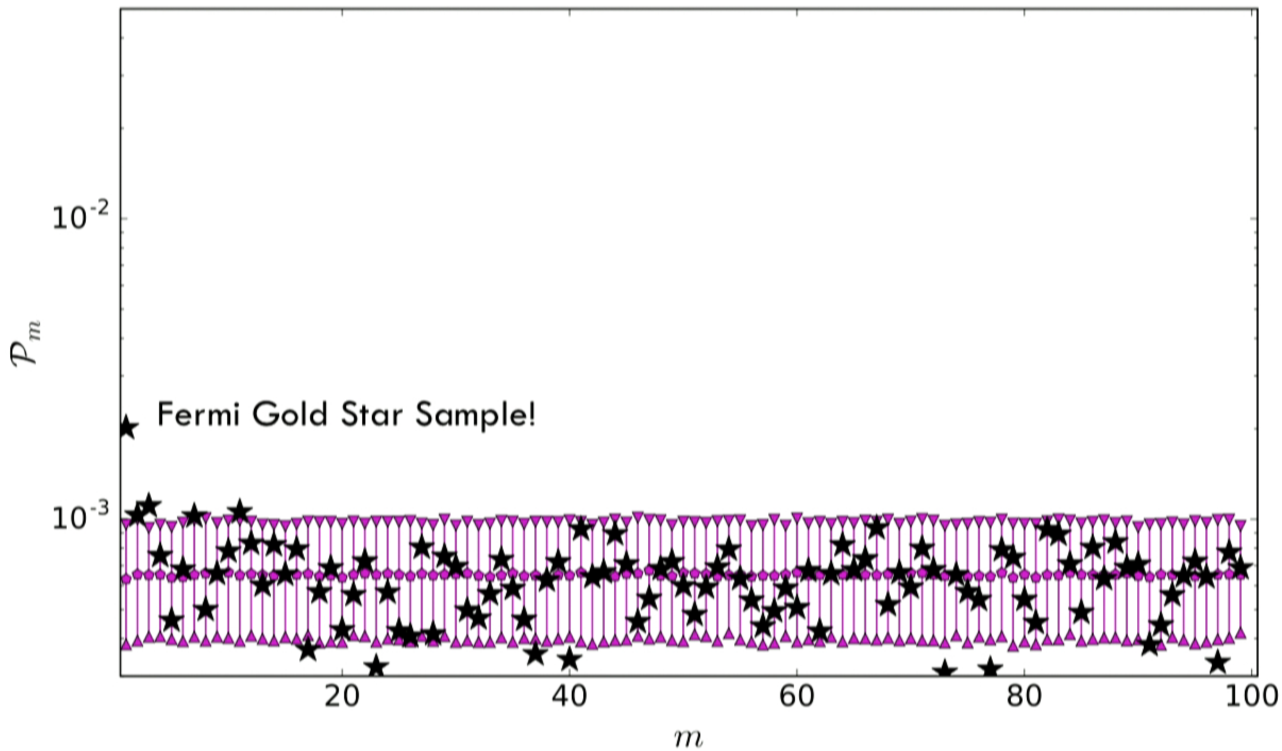
HALO POWER SPECTRA BY TYPE:

$\lambda_B \gg D_{\gamma\gamma},\ B = 10^{-15}, 10^{-16}, 10^{-17}$ G



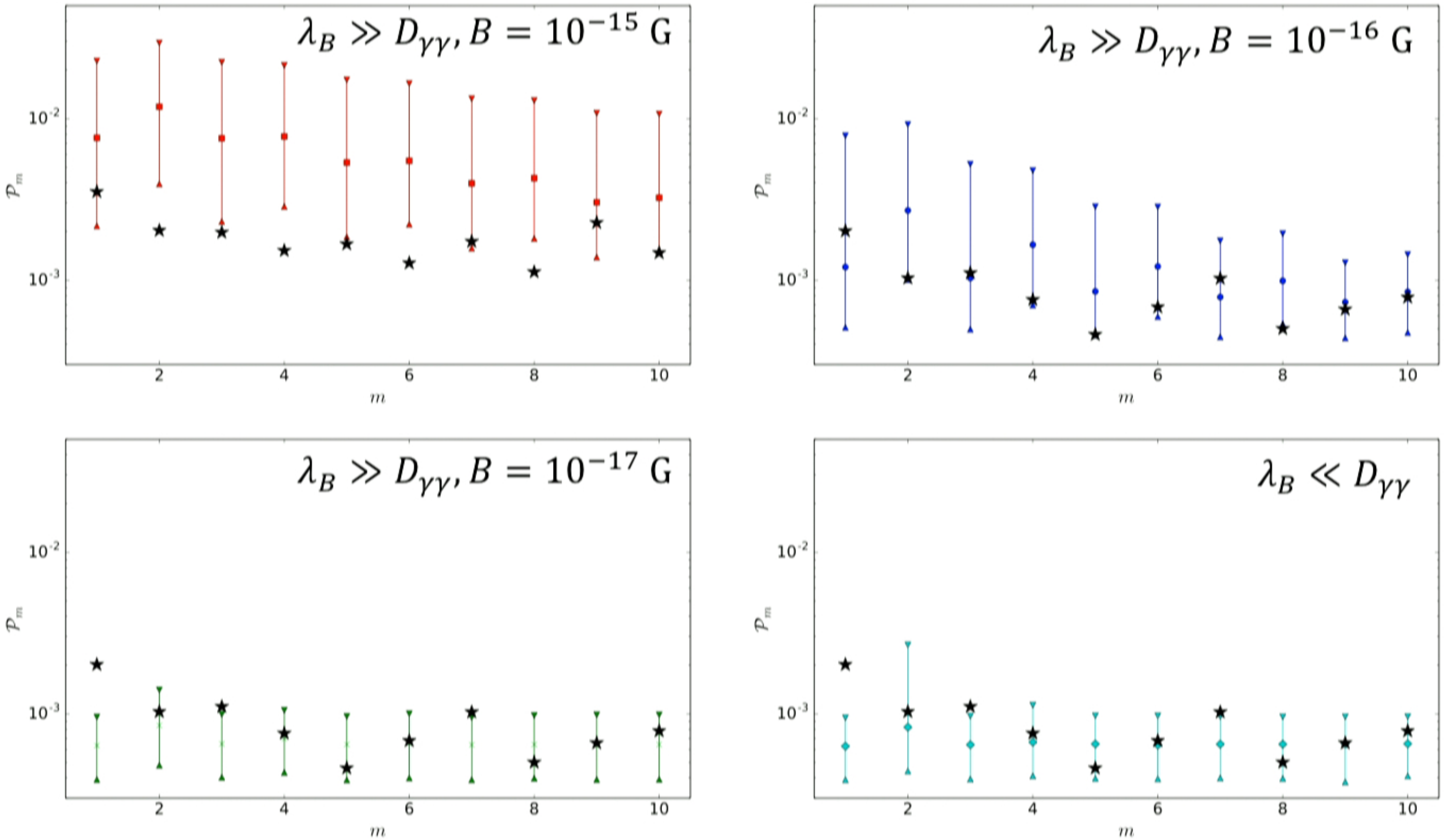
Feedback 3-16-16, Perimeter Institute

ENTER DATA!
CONSISTENT WITH NULL!



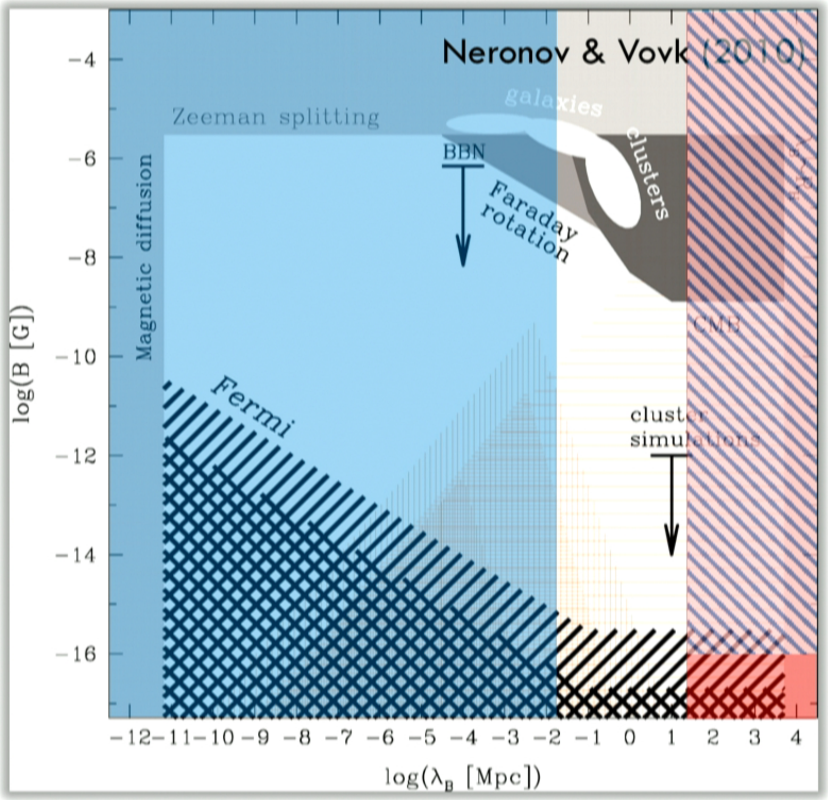
Feedback 3-16-16, Perimeter Institute

ENTER DATA!
INCONSISTENT WITH $\lambda_B \gg D_{\gamma\gamma},\ B \geq 10^{-16}$ G



Feedback 3-16-16, Perimeter Institute

MISSING HALOS IN CONTEXT



Feedback 3-16-16, Perimeter Institute

If no plasma instabilties
$\lambda_B \gg 30$ Mpc ruled out!

If plasma instabilities:
$\lambda_B \approx c/\omega_P$ generated!

SUMMARY OF GAMMA-RAY LIMITS FOR PLASMA INSTABILITIES

- **IC halos a natural probe of plasma instabilities also!**
- **In *absence* of halos, TeV blazars unified with AGN, 0-parameter fits to:**
  - Hard-blazar ($\Gamma < 2$) flux distribution (1FHL, 2FHL)
  - Hard-blazar ($\Gamma < 2$) redshift distribution (2LAC)
  - Extragalactic Gamma-ray Background
- **In presence of halos, searches based on structure**
  - Beaming or Gyration = bipolar structure!
  - Insensitive to known contaminants (e.g., PSF!)
  - Fermi Gold Star Sample is ***consistent with no halos***!
  - No halos with IGMF with $B > 10^{-16}$ G, $\lambda_B \gg 30$ Mpc
  - Developing sample for $\lambda_B < 10$ Mpc