



Gamma-rays from Dark Matter Mini-Spikes in Andromeda Galaxy M31

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based on astro-ph/0703757 by M. Fornasa, M. Taoso and G. Bertone



Adiabatic growth of a black hole: spike formation

From a power-law density profile, a “spike” can form with a new slope:

$$\rho(r) \propto \left(\frac{r}{r_s}\right)^{-\gamma} \longrightarrow \rho_{sp}(r) \propto \left(\frac{r}{r_{sp}}\right)^{-\gamma_{sp}} \quad \gamma_{sp} = \frac{9 - 2\gamma}{4 - \gamma}$$

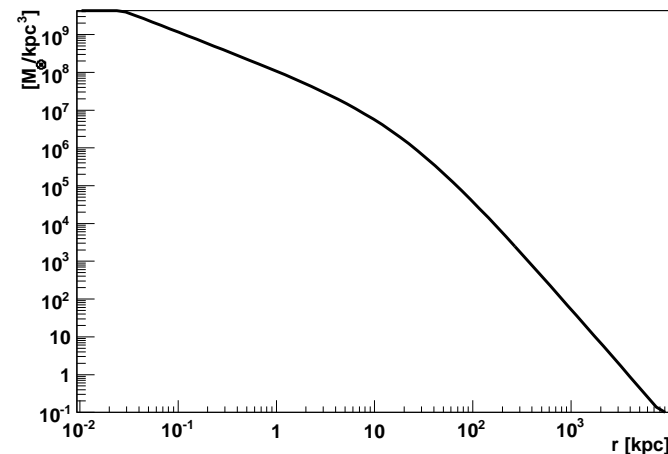
$$0 \leq \gamma \leq 1.5$$

$$2.25 \leq \gamma_{sp} \leq 2.4$$

Navarro-Frank-White DM profile:

$$\rho(r) = \rho_0 \left(\frac{r_s}{r}\right) \left(1 + \frac{r}{r_s}\right)^{-2}$$

$$\text{NFW } (\gamma_{\text{INNEP}} = 1) \longrightarrow \gamma_{sp} = 7/3$$

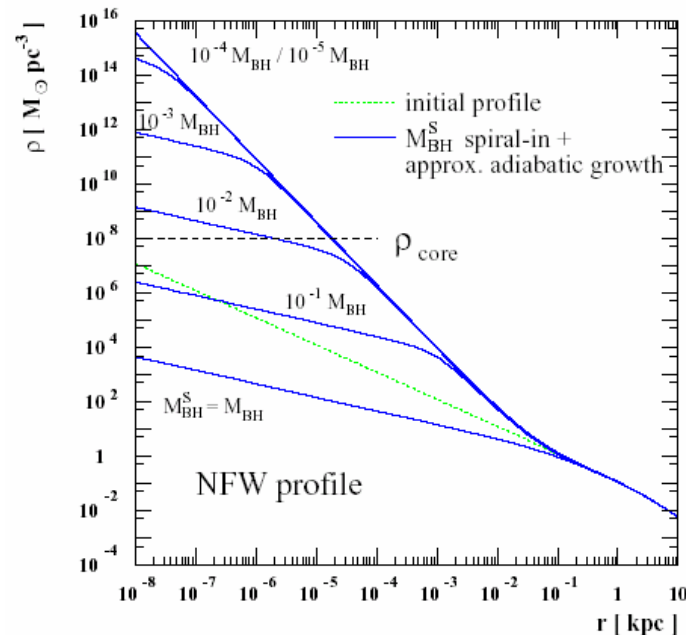




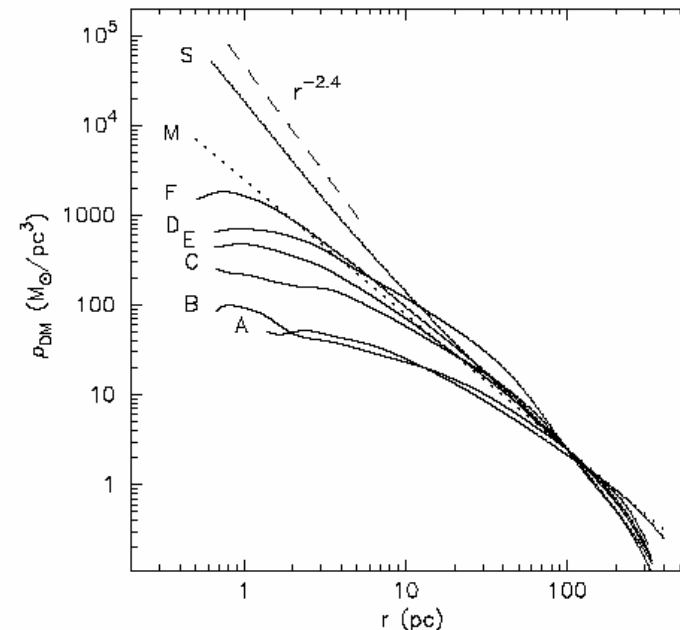
Spike formation at the Galactic center

Arguments against spikes formation:

- off-center black hole formation
- gravitational interaction with stars
- merger and BH binary effects



Ullio, Zhao, Kamionkowski,
astro-ph/0101481

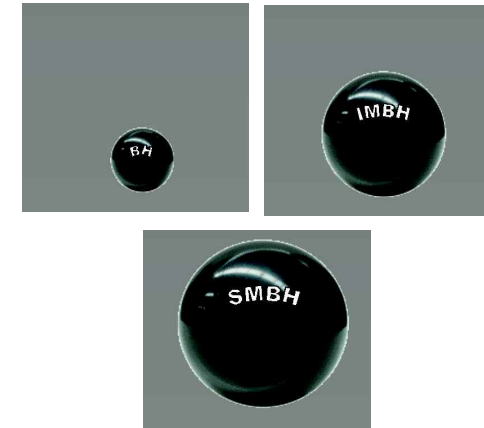


Merritt, Milosavljevic, Verde, Jimenez
astro-ph/0201376



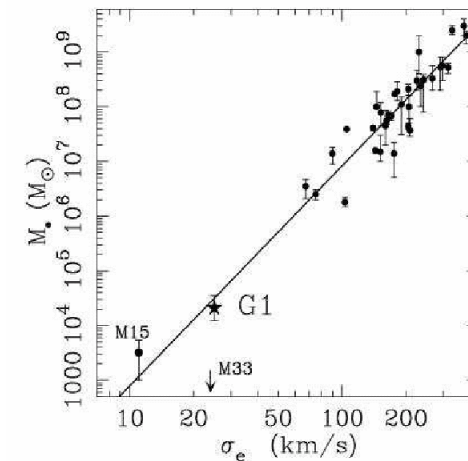
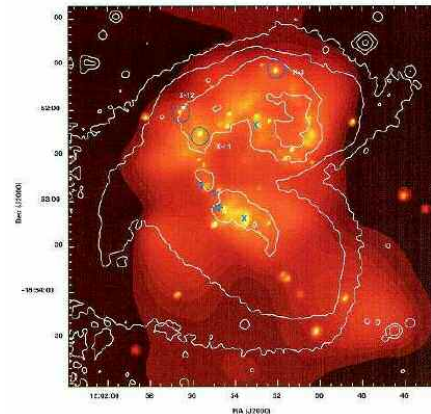
Intermediate Mass Black Holes (IMBHs)

- mass from $20 M_{\odot}$ to $10^6 M_{\odot}$
- no one actually ever “detected” an Intermediate Mass Black Hole



Evidences for IMBHs:

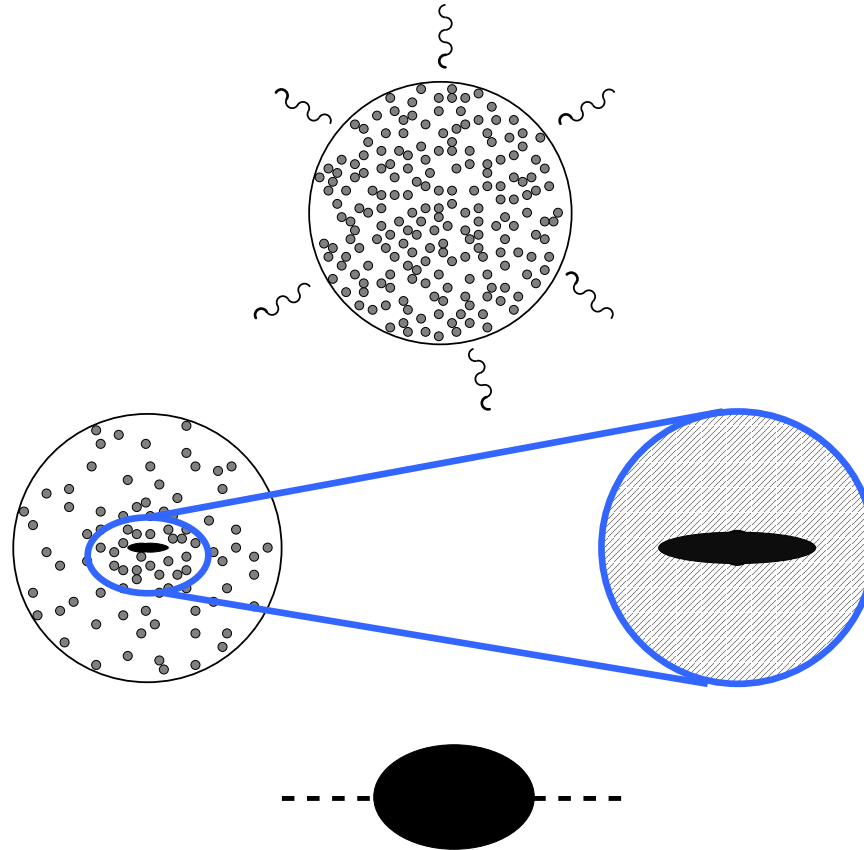
- Ultra Luminous X-ray sources (ULXs)
- extrapolation of M - σ relation of SMBHs to globular clusters
- IMBHs would provide massive seeds for the growth of SMBHs



Miller, Colbert, astro-ph/0308402



Intermediate Mass Black Holes (IMBHs)



$$M_{\bullet} = 3.8 \cdot 10^4 M_{\odot} \left(\frac{\kappa}{0.5} \right) \left(\frac{f}{0.03} \right)^{3/2} \left(\frac{M_{vir}}{10^7 M_{\odot}} \right) \cdot \left(\frac{1+z}{18} \right)^{3/2} \left(\frac{t}{10 \text{ Myr}} \right)$$

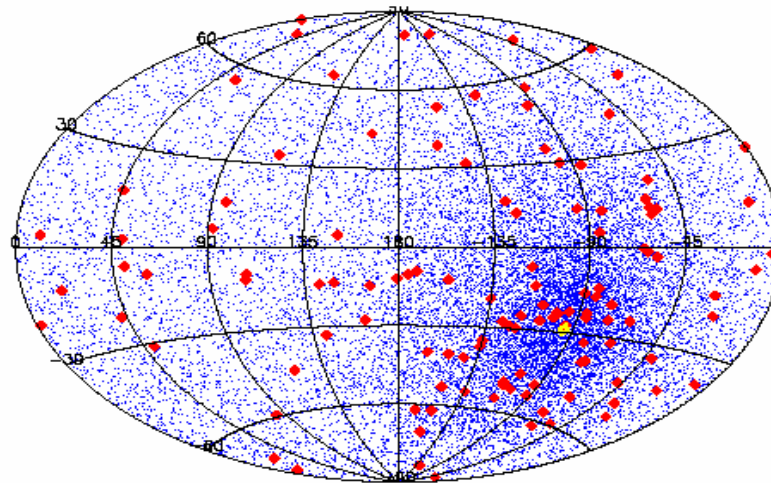
Koushiappas, Bullock, Dekel, astro-ph/0311487



IMBHs in the Milky Way

- initial catalogue of IMBHs in mini-halos
- merging tree
- selection of unmerged mini-halos
- no baryonic content and the BH lays in the center

Bertone, Zentner, Silk, astro-ph/0509565





IMBHs catalogue for Andromeda

How IMBHs are characterized:

- realization ID
- Black Hole Mass [M_{\odot}]
- IMBH distance from the center of the Galaxy [kpc]
- r_{sp} [kpc]
- $\rho(r_{sp})$ [M_{\odot}/kpc^3]

	Milky Way	Andromeda
Distance to the center	8.5 kpc	784.0 kpc
Virial Mass	$1.0 \cdot 10^{12} M_{\odot}$	$6.8 \cdot 10^{11} M_{\odot}$
Virial Radius	205 kpc	180 kpc

M31 IMBHs average values: Number = 65.2 ± 14.5

Mass = $1.5 \cdot 10^5 M_{\odot}$

Distance to the center R = 32.3 kpc.



Annihilation Fluxes

$$\Phi(E) = \frac{\sigma v}{2m_\chi^2} \frac{1}{d^2} \int_{r_{cut}}^{r_{sp}} \rho^2(r) r^2 dr \frac{dN_\gamma(E)}{dE}$$

- DM candidate: lightest neutralino in MSSM
- focused on hadronization of b quarks
- fit from simulated data, using standard package as PYTHIA ($x=E/m_\chi$)

$$\frac{dN_\gamma^b(x)}{dx} = x^a e^{b+cx+dx^2+ex^3}$$

$$a=-1.5$$

$$b=0.37$$

$$c=-16.05$$

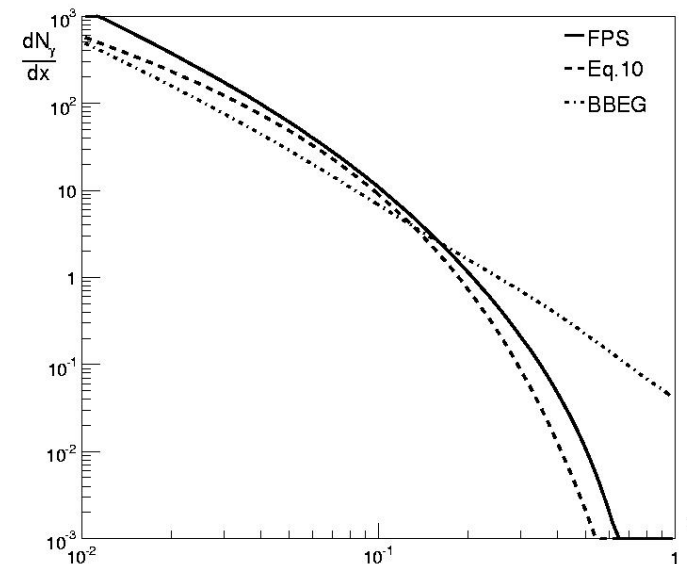
$$d=18.01$$

$$e=-19.50$$

for $m_\chi=1$ TeV

Fornengo, Pieri, Scopel,

hep-ph/0407342





Detection of IMBHs with ACTs

$$n = \frac{n_\gamma}{\sqrt{n_{bkg}}} = \sqrt{T} \frac{\int A_{eff}(E, \theta) \frac{d\Phi}{dE} dE d\theta}{\sqrt{\int A_{eff}(E, \theta) \frac{d\Phi_{bkg}}{dE} dE d\theta}}$$

Origin of background:

- EGRET:

$$\frac{d\Phi_{extra/gal}}{d\Omega} = 2.29 \cdot 10^{-6} E^{-2.1} \frac{\gamma}{\text{cm}^2 \text{s GeV sr}}$$

- Hadronic and electronic:

$$\frac{d\Phi_h}{d\Omega} = \epsilon_h \cdot 1.49 \cdot E^{-2.74} \frac{p}{\text{cm}^2 \text{s GeV sr}}$$

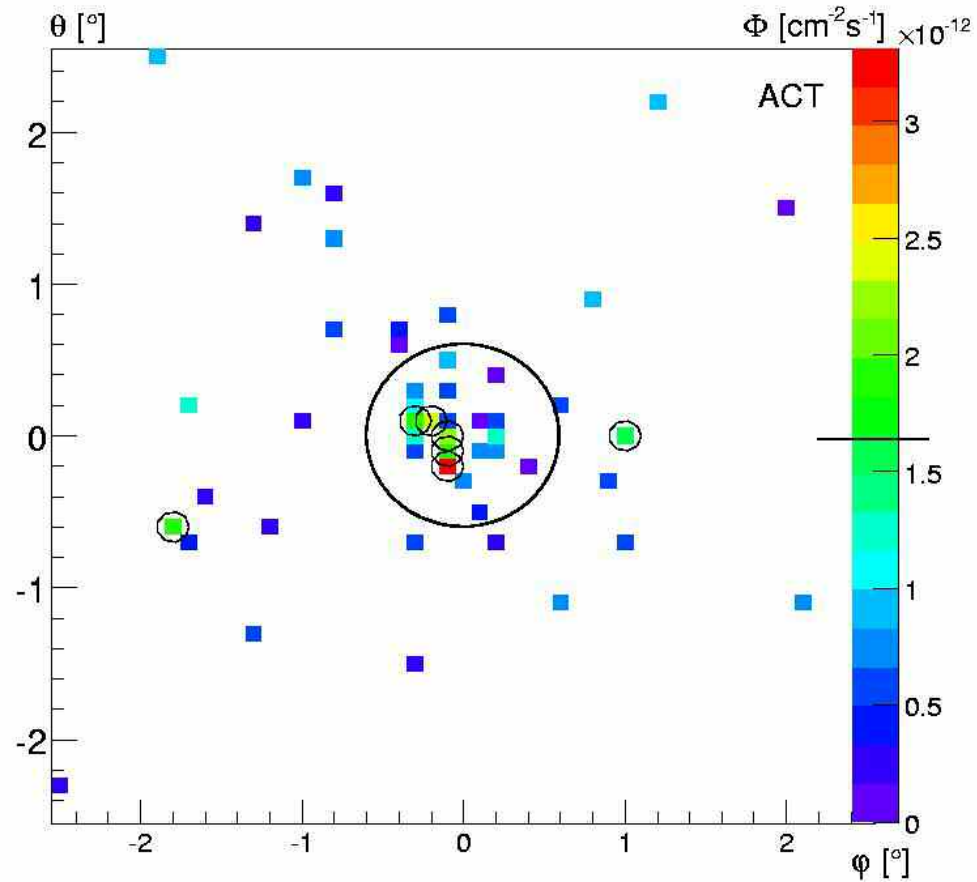
$$\frac{d\Phi_e}{d\Omega} = 6.9 \cdot 10^{-2} E^{-3.3} \frac{e}{\text{cm}^2 \text{s GeV sr}}$$

- $m_\chi = 1 \text{ TeV}$ and $\sigma v = 3 \cdot 10^{-26} \text{ cm}^3 \text{s}^{-1}$
- $E_{th} = 100 \text{ GeV}$
- ACT angular resolution: 0.1°
- ACT effective area is $3 \cdot 10^4 \text{ m}^2$
- exposure time: 100 hours

ACT sensitivity for a 5σ detection: $1.6 \cdot 10^{-12} \text{ cm}^{-2} \text{s}^{-1}$



Detection of IMBHs with ACTs



Number of IMBHs over ACT sensitivity is
 5.2 ± 3.1 for $m_\chi = 1$ TeV



Detection of IMBHs with GLAST

- $m_\chi = 150 \text{ GeV}$ and $\sigma v = 3 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1}$
- $E_{\text{th}} = 10 \text{ MeV}$
- Effective area X the exposure time (2 months) = $8 \cdot 10^9 \text{ cm}^2 \text{ s}$
- ACT angular resolution:
 3° (10 MeV - 500 MeV), 0.5° (500 MeV - 4 GeV), 0.15° ($E > 4 \text{ GeV}$)



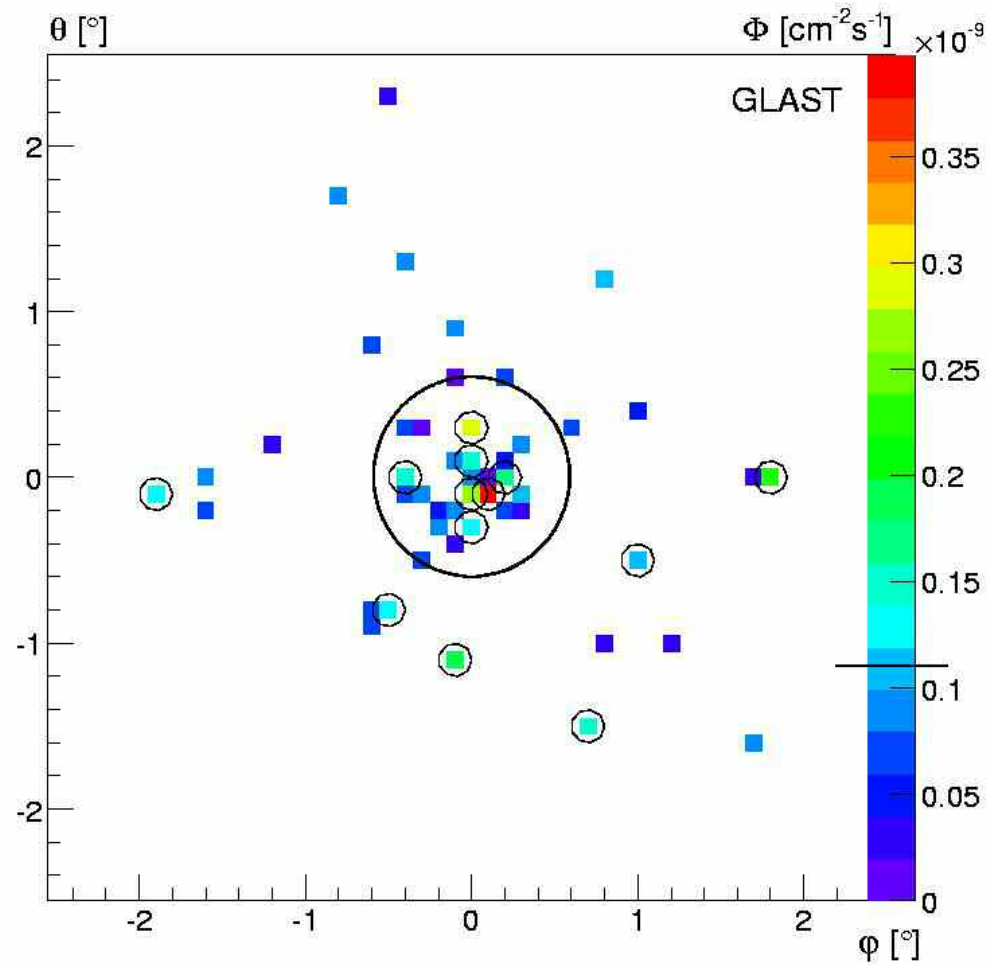
A selection is made: only high-energy photons (above 4 GeV) are considered

- extragalactic background
- hadronic and electronic backgrounds are absent

Sensitivity for a 5σ detection in 2 months: $1.1 \cdot 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$



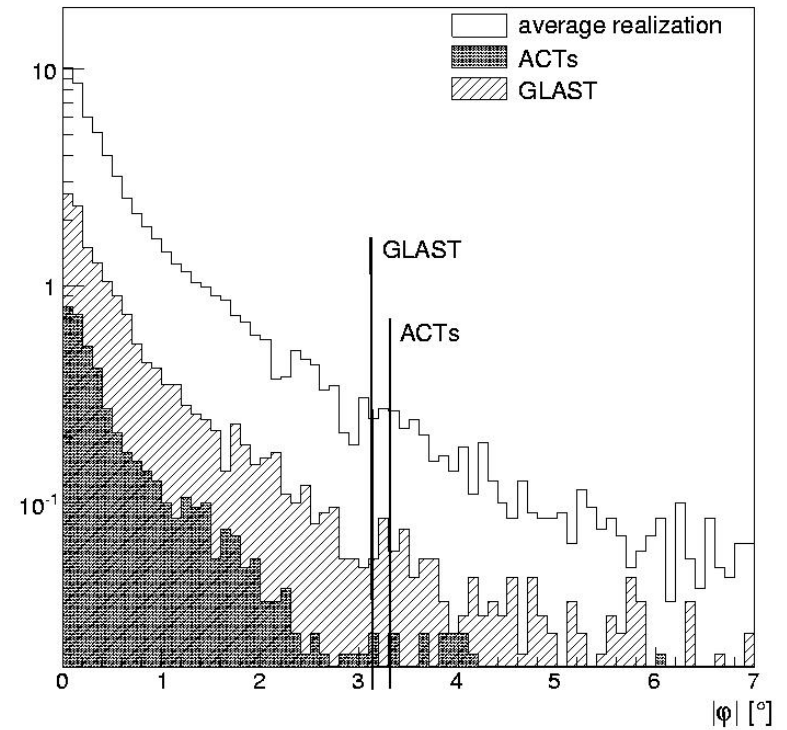
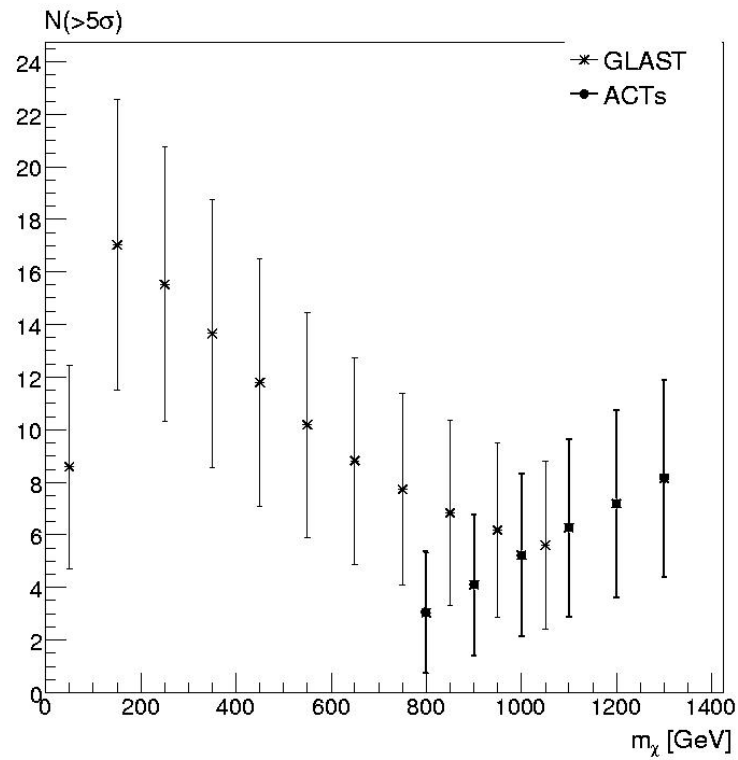
Detection of IMBHs with GLAST



Number of IMBHs over GLAST sensitivity is
 17.1 ± 5.8 for $m_\chi = 150$ GeV



Prospects for detection





Conclusions

- fluxes from DM annihilations in mini-halos around IMBHs that populate the Andromeda Galaxy have been computed
- detection with an ACT is very challenging, due to the hadron background
- the scenario with GLAST is more promising, even if the best angular resolution is achieved only after a strict selection (very high-energy photons)
- the picture is that of isolated, point-like, bright sources in a region 3° wide around the Andromeda center



Differential energy spectrum

FPS (Fornengo-Pieri-Scopel)

- MSSM is assumed and the DM candidate is a neutralino
- focused only on the main channel (hadronization of b quarks)
- fit from simulated data, using standard package as PYTHIA ($x=E/m_\chi$)
- differential spectrum for τ leptons hadronization is presented too (see later)

$$\frac{dN_\gamma^b(x)}{dx} = x^a e^{b+cx+dx^2+ex^3} \quad \frac{dN_\gamma^\tau(x)}{dx} = x^a (bx + cx^2 + dx^3) e^{ex} \quad (17)$$

$(a, b, c, d, e) = (-1.5, 0.37, -16.05, 18.01, -19.50)$ $(a, b, c, d, e) = (-1.31, 6.94, -4.93, -0.51, -4.53)$

Kretzer Fragmentation Functions

- DM candidate is again a neutralino
- FF is the probability to have an hadron h with xQ^2 from a parton p with Q^2



Differential energy spectrum

- focused on the photon production from a π^0 resulting from quarks b (i.e. $p=b$, $h=\pi^0$)

$$f(x) = \frac{7.53}{x^{0.87} e^{14.62x}} \quad (18)$$

- a flat spectrum for photons from pions is assumed

$$\frac{dN_\gamma(x)}{dx} = \int_x^1 f(x') \frac{2}{x'} dx' \quad (19)$$

BBEG (Bergstrom-Bringmann-Eriksson-Gustafsson)

- differential spectrum is calculated for a DM candidate from Universal Extra-Dimension, what is called $B^{(1)}$
- contribution of primary photons from charged leptons is no longer neglected ($B^{(1)}B^{(1)} \rightarrow \gamma l^+ l^-$)

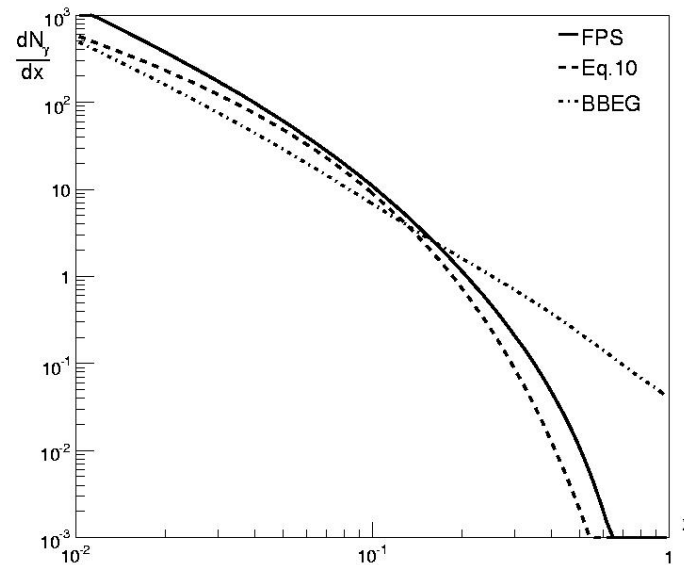
$$\frac{dN_\gamma^l(x)}{dx} = \sum_{l=e,\mu} \frac{\alpha}{\pi} \frac{x^2 - 2x + 2}{x} \ln \left[\frac{m_{B^{(1)}}^2}{m_l^2} (1 - x) \right] \quad (20)$$



Differential energy spectrum

	Flux from Andromeda
FPS	$1.33 \cdot 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$
Kretzer FFs	$9.79 \cdot 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$
BBEG	$1.60 \cdot 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$

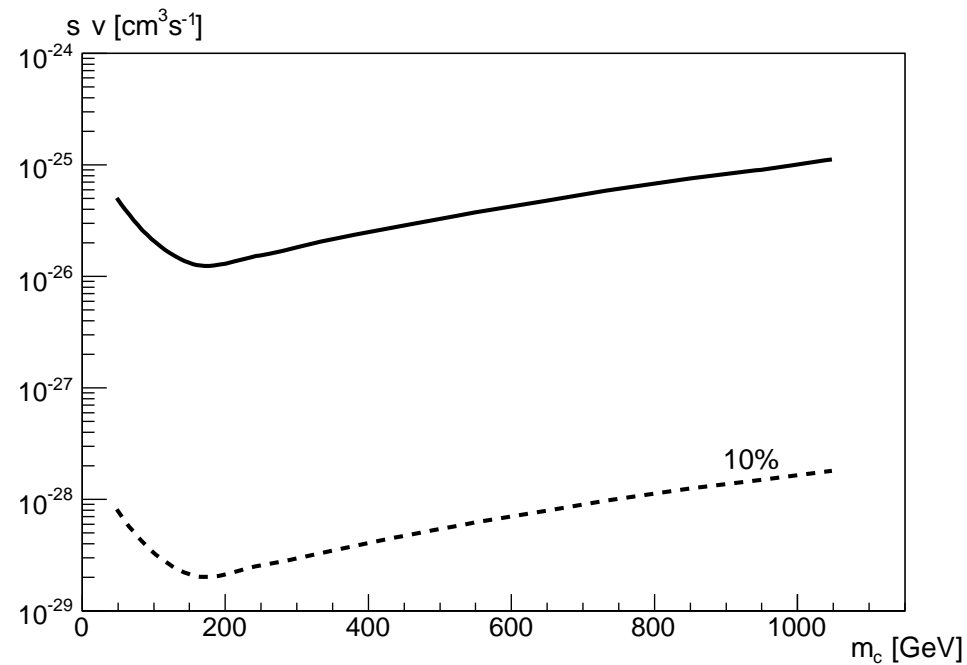
From now on, only the FPS parametrization will be used





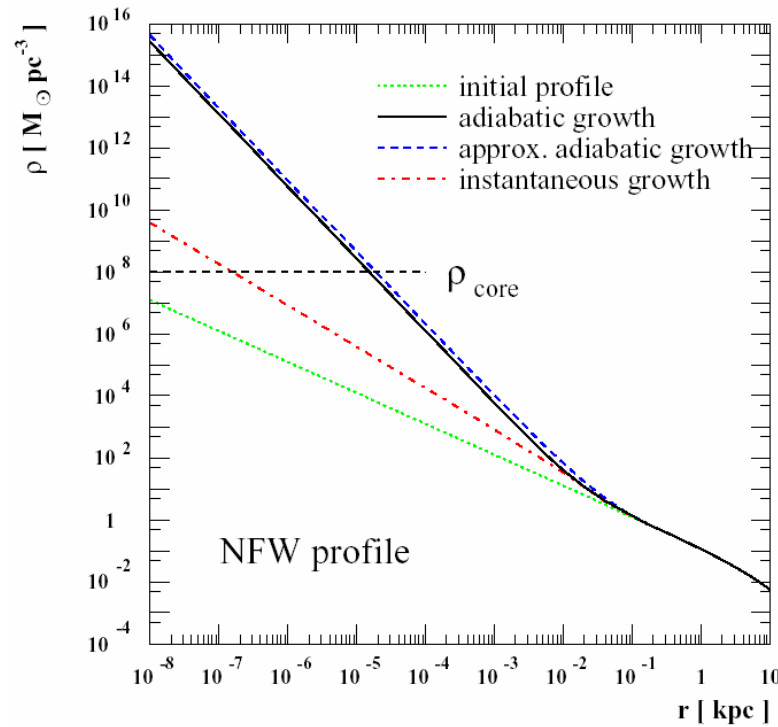
Exclusion Plot

- Solid line: all realizations with at least one detectable IMBH
- Dashed line: 20 realizations over 200 with at least one detectable IMBH





Spike formation at the Galactic center



Ullio, Zhao, Kamionkowski,
astro-ph/0101481

$$\rho_{lim} = \rho_{sp}(r_{lim}) = \frac{m_{\chi}}{\sigma v(t - t_f)}$$

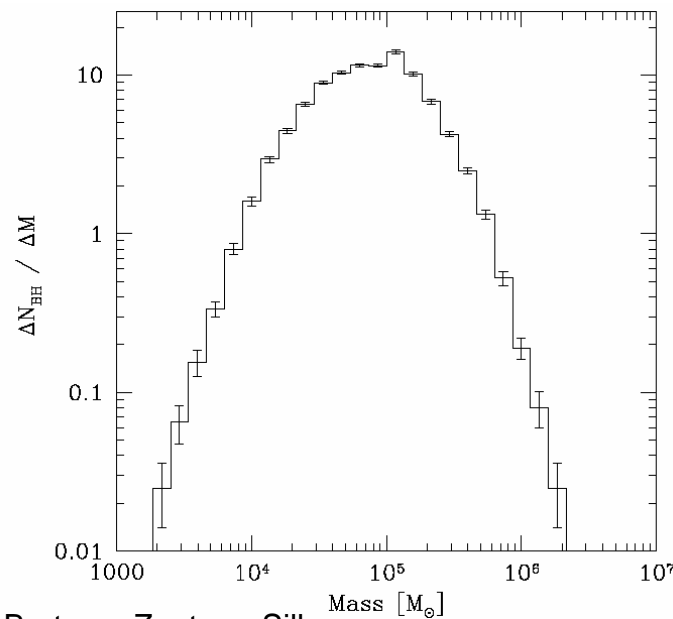
$$r_{cut} = \text{Max}[4R_{Schw}, r_{lim}]$$



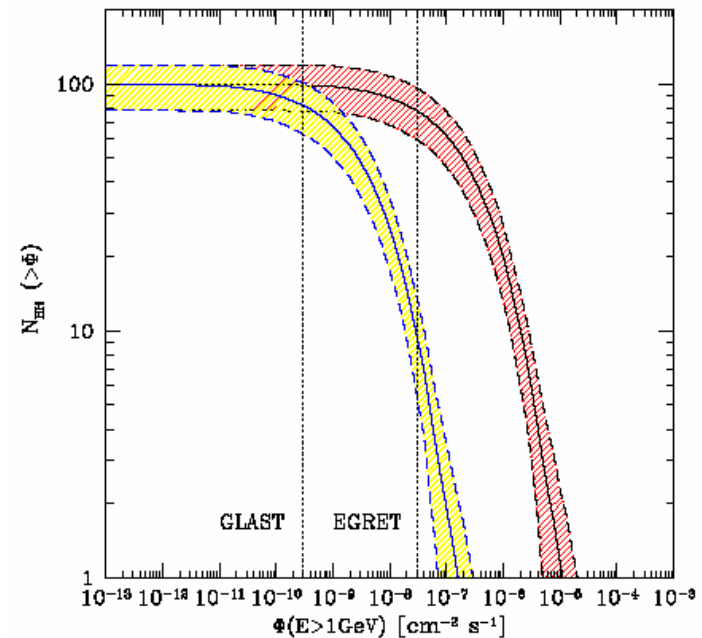
IMBHs in the Wilky Way

astro-ph/0509565, Bertone, Zentner and Silk:

- initial catalogue of IMBHs
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- no baryonic content and the BH lays in the center



Bertone, Zentner, Silk,
Astro-ph/0509565

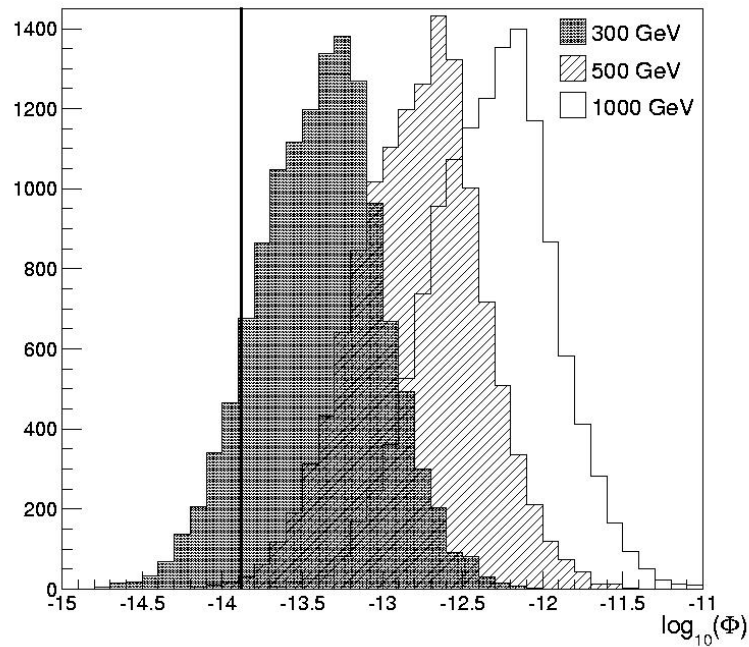




Threshold effect

$$\Phi(E) \sim (\sigma v)^{2/7} m_\chi^{-9/7} \quad (11)$$

$$\Phi = \int_{E_{thr}}^{m_\chi} \Phi(E) dE \quad (12)$$



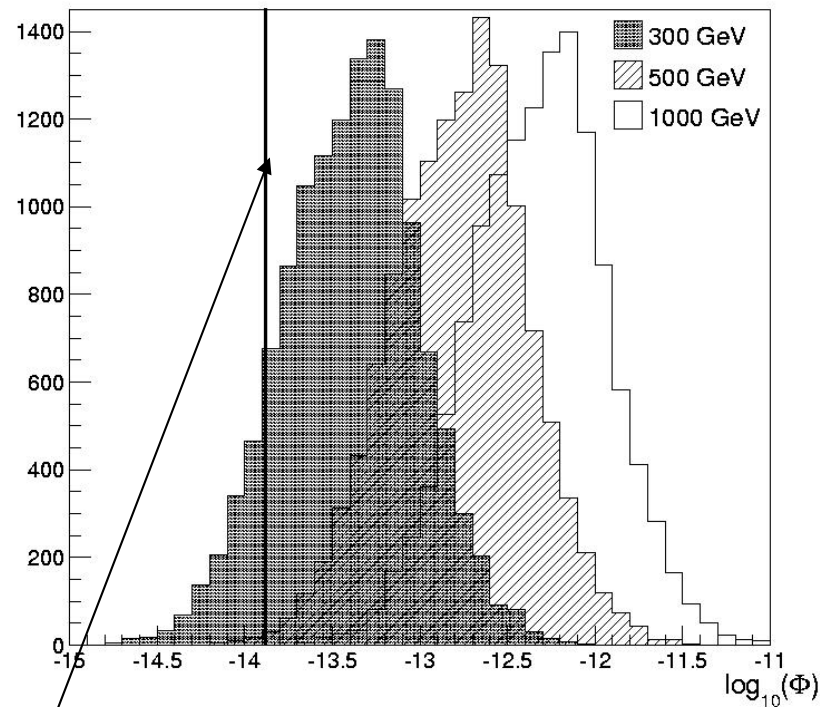
	$\Phi (E_{thr}=4 \text{ GeV})$
$m_\chi = 50 \text{ GeV}$	$5.26 \cdot 10^{-11} \text{ cm}^{-2}\text{s}^{-1}$
$m_\chi = 150 \text{ GeV}$	$7.65 \cdot 10^{-11} \text{ cm}^{-2}\text{s}^{-1}$
$m_\chi = 300 \text{ GeV}$	$6.92 \cdot 10^{-11} \text{ cm}^{-2}\text{s}^{-1}$
$m_\chi = 500 \text{ GeV}$	$5.81 \cdot 10^{-11} \text{ cm}^{-2}\text{s}^{-1}$

	E_{thr}	m_χ
ACTs	100 GeV	1 TeV
GLAST	4 GeV (see later)	150 GeV



Annihilation Fluxes

Luminosity function of IMBHs
(Integral fluxes over 100 GeV, $\sigma v = 3 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1}$)



Flux from the Andromeda NFW profile
($m_\chi = 1 \text{ TeV}$)