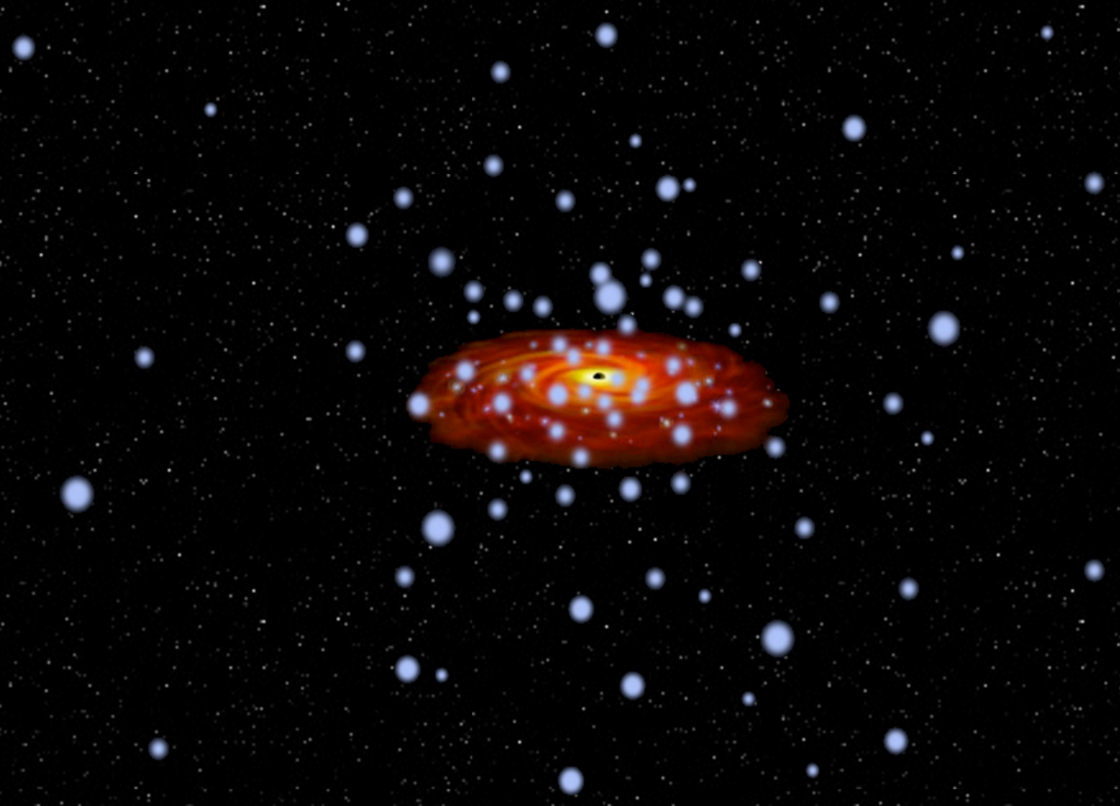
Black Holes as Dark Matter Annihilation *Boosters*

Gianfranco Bertone (INFN Padova, Italy)



Plan of the Talk

- *Introduction*
  - The connection with Physics beyond the SM
  - Evidence for DM
  - Direct, Indirect and Accelerator searches
- *Indirect Dark Matter searches*
  - DM annihilations: beyond the naïve picture
  - Conflicting claims, the case of the GC
  - How to convince a particle physicist?
- *The role of Black Holes*
  - Astrophysical Black Holes
  - BHs as DM annihilation 'boosters'
  - Mini-spikes
- *Conclusions*

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Open problems in Theoretical Physics & Cosmology...

	Theoretical Physics	Astrophysics and Cosmology
Problems	• Hierarchy problem • Quark/leptons, bosons/fermions • Unification • Quantization of gravity • ...	• Rotation curves of galaxies • Structure formation • CMB • UHE cosmic rays • SN Ia data • Galactic positrons • ...

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...possible solutions...

	Theoretical Physics	Astrophysics and Cosmology
Problems	• Hierarchy problem • Quark/leptons, bosons/fermions • Unification • Quantization of gravity • ...	• Rotation curves of galaxies • Structure formation • CMB • UHE cosmic rays • SN Ia data • Galactic positrons • ...
Speculations	• Supersymmetry • Extra dimensions • String theory?	• Dark Matter • Dark Energy
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...and experimental searches

	Theoretical Physics	Astrophysics and Cosmology
Problems	• Hierarchy problem • Quark/leptons, bosons/fermions • Unification • Quantization of gravity • ...	• Rotation curves of galaxies • Structure formation • CMB • UHE cosmic rays • SN Ia data • Galactic positrons • ...
Speculations	• Supersymmetry • Extra dimensions • String theory?	• Dark Matter • Dark Energy
Experiments	• LEP, Tevatron, * LHC *	• The Universe!!

Evidence for Dark Matter

Evidence for the existence of an unseen, "*dark*", component in the energy density of the Universe comes from several independent observations at different length scales. Most recent:

Clowe et al. ApJL 2006

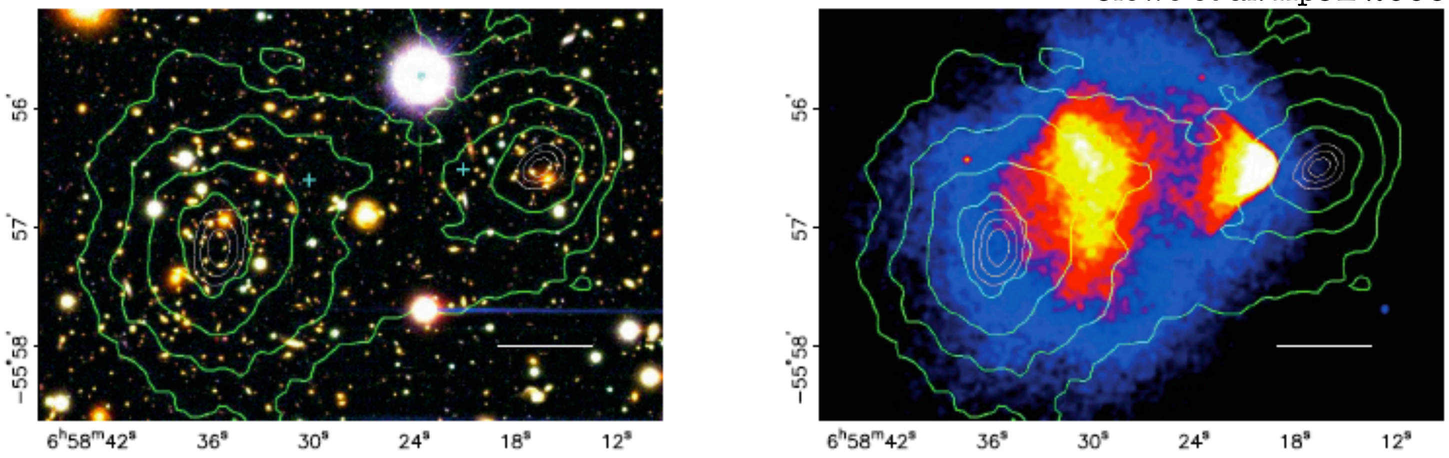
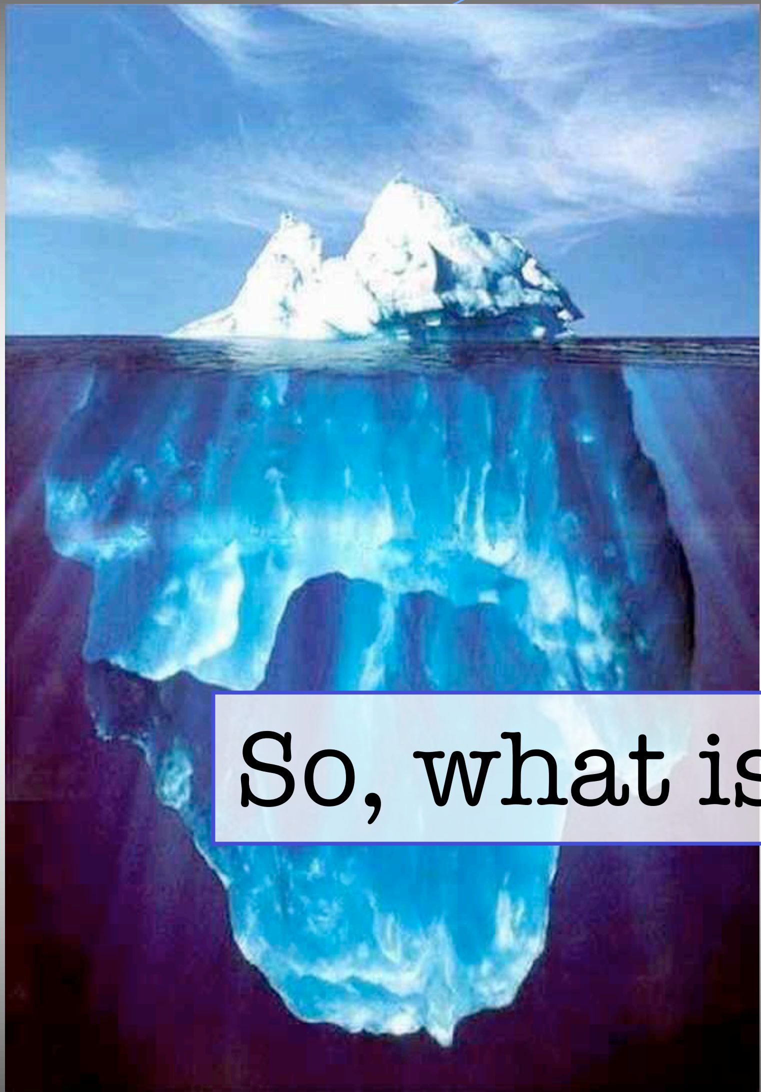
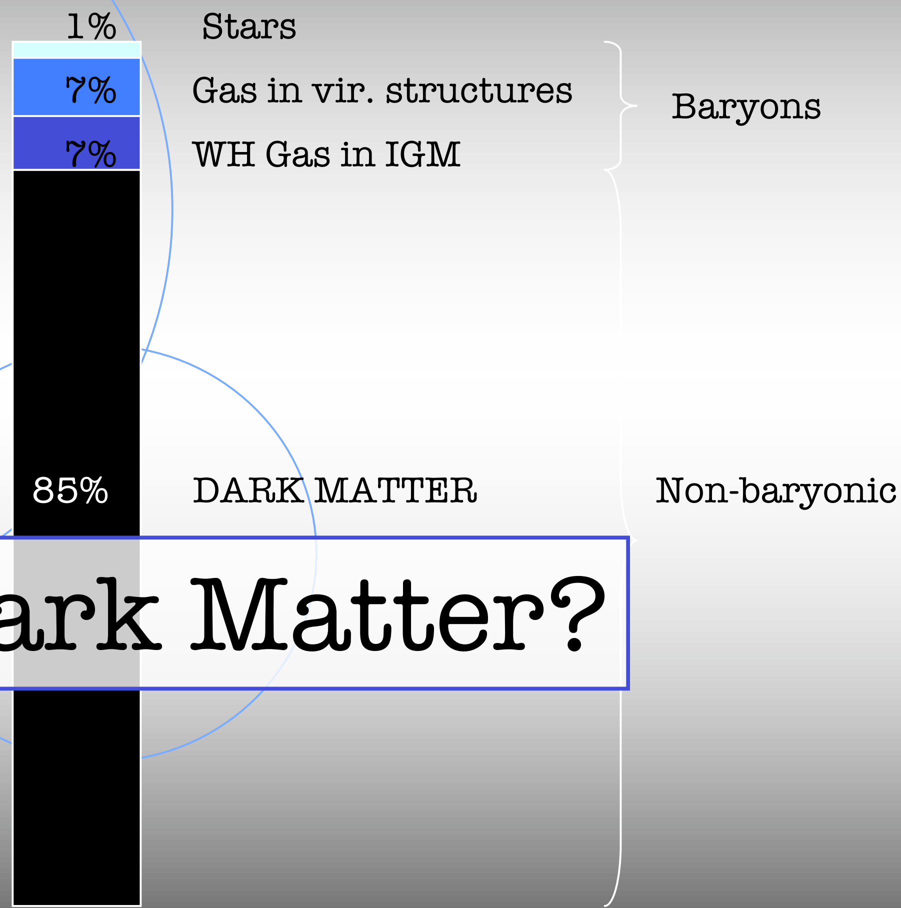


FIG. 1.—*Left panel*: Color image from the Magellan images of the merging cluster 1E 0657−558, with the white bar indicating 200 kpc at the distance of the cluster. *Right panel*: 500 ks *Chandra* image of the cluster. Shown in green contours in both panels are the weak-lensing κ reconstructions, with the outer contour levels at $\kappa = 0.16$ and increasing in steps of 0.07. The white contours show the errors on the positions of the κ peaks and correspond to 68.3%, 95.5%, and 99.7% confidence levels. The blue plus signs show the locations of the centers used to measure the masses of the plasma clouds in Table 2.

Recent reviews: GB, Hooper & Silk, hep-ph/0404175. Bergstrom, hep-ph/0002126.

An Inventory of Matter in the Universe





So, what is Dark Matter?

Dark Matter Candidates

Mirror Matter

Champs (charged DM)

D-matter

Cryptons

Self-interacting

Superweakly interacting

Braneworld DM

Heavy neutrino

NEUTRALINO

Messenger States in GMSB

Branons

Chaplygin Gas

Split SUSY

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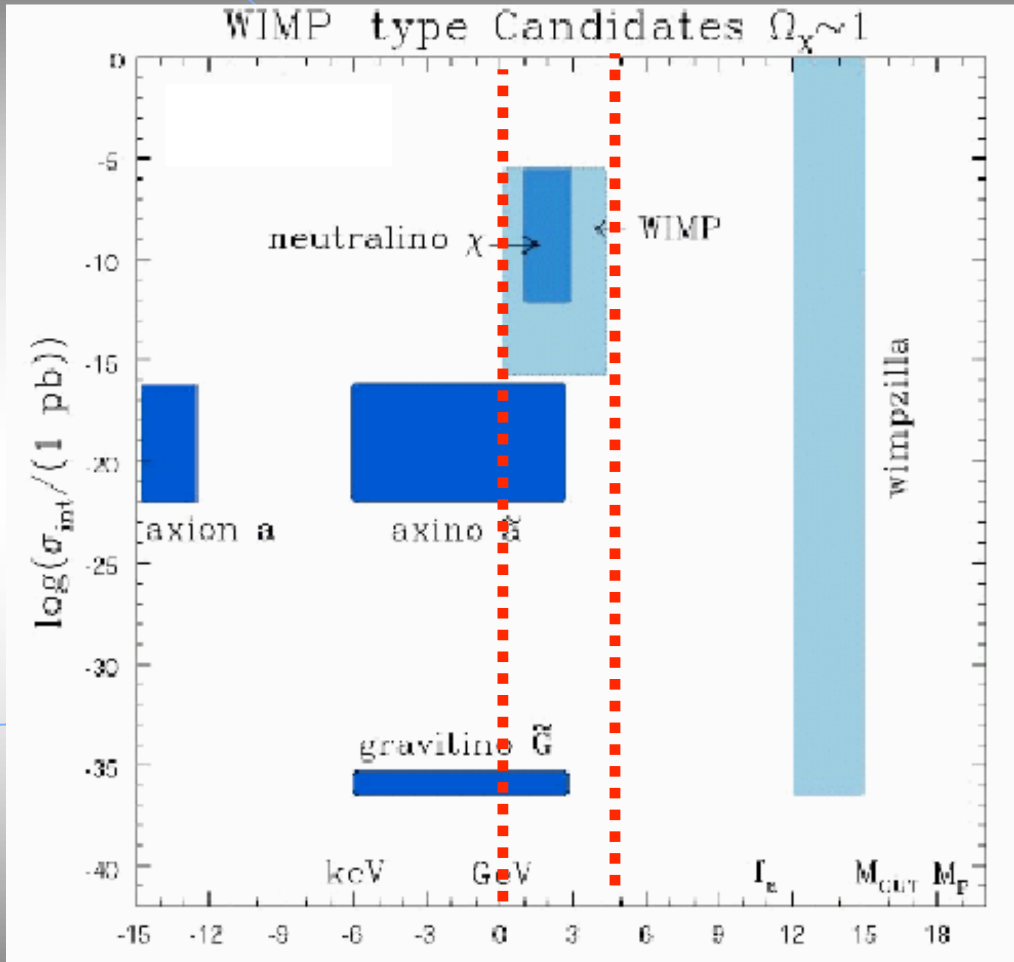
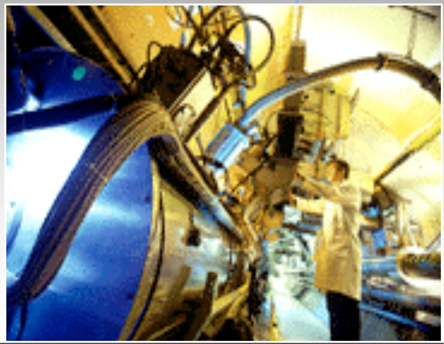
Primordial Black Holes

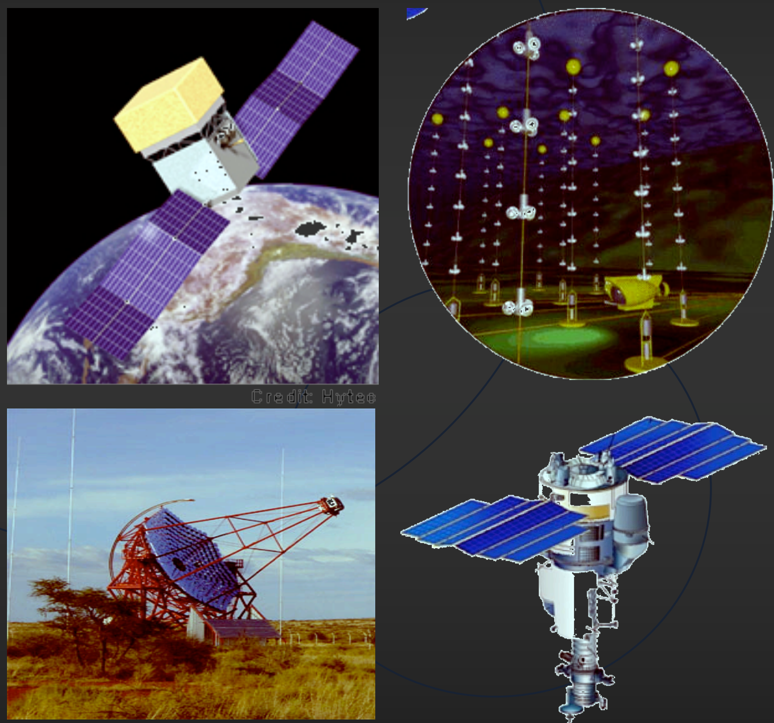


L. Roszkowski

The quest for Dark Matter



Colliders
Tevatron, LHC



Indirect Detection

Direct Detection

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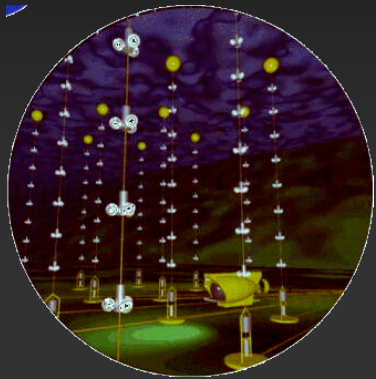
Indirect Dark Matter Searches



Indirect Detection

Gamma-ray telescopes

- Ground Based (CANGAROO, HESS, MAGIC, MILAGRO, VERITAS)
- Space satellite GLAST
- Plans for a future Cherenkov Telescope Array

Neutrino Telescopes

- Amanda, IceCube
- Antares, Nemo, Nestor
- Km3

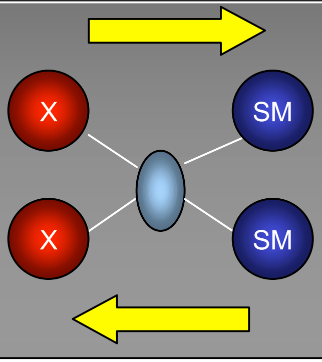
Anti-matter satellites

- PAMELA
- AMS-2

Why “annihilations”?

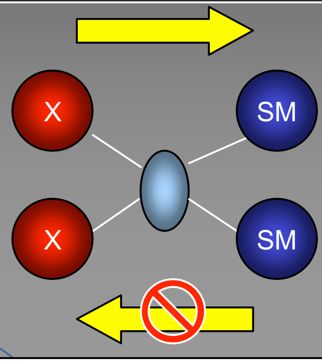
X = DARK MATTER SM = STANDARD MODEL PARTICLE

Early Universe



$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle\sigma v\rangle[n_\chi^2 - (n_\chi^{\rm eq})^2]$$

Today



$$\dot{n}_\chi(r,t) = -\sigma v\ n_\chi^2$$

Rough estimate of the relic density:

$$\Omega_\chi h^2 \approx \frac{3\times 10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle\sigma v\rangle}$$

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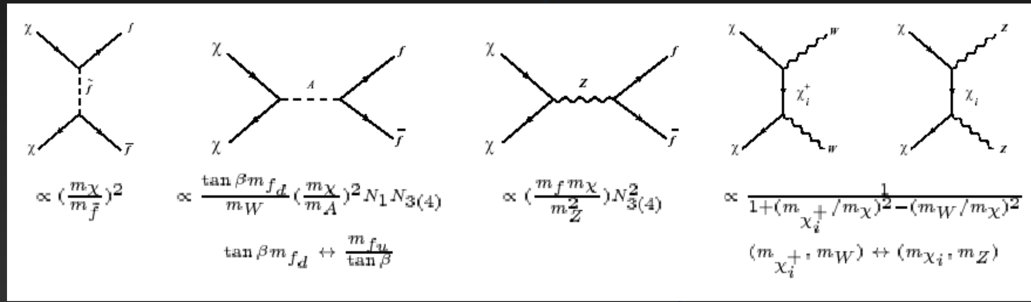
Electroweak-scale cross sections can reproduce correct relic density. LSP in SUSY scenarios KK DM in UED scenarios are OK!!

Annihilation Radiation

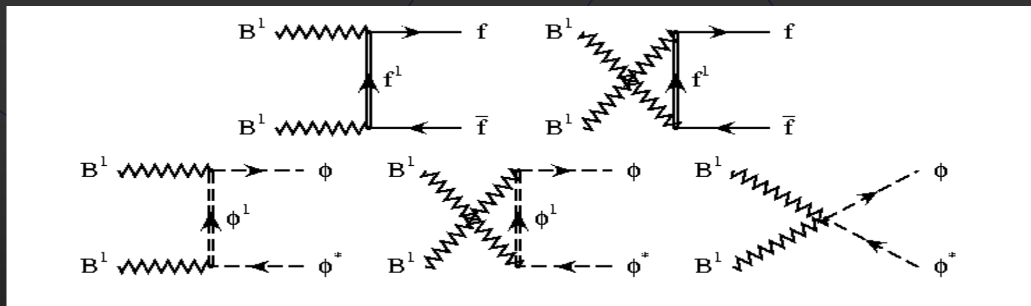
SUSY



E. Nezri et al, 2001

To compute fluxes, one has to go through the details of annihilation. Annihilation cross sections for neutralinos can be computed with the DarkSUSY code. Other codes are on the market, microMEGA among the most complete (and PUBLIC !)

UED



Servant & Tait, 2002

Servant & Tait recently worked out annihilation cross sections for $B^{(1)}$ particles, which, in the non-relativistic limit, only depend on the mass of the particle.

γ-ray flux from the GC

We can conveniently re-write the γ-ray flux from the GC as

$$\Phi_i(\Delta\Omega, E) \simeq 5.6 \times 10^{-12} \frac{dN_i}{dE} \left(\frac{\sigma v}{\mathrm{pb}}\right) \left(\frac{1\,\mathrm{TeV}}{m_{\mathrm{DM}}}\right)^2 \overline{J}(\Delta\Omega)\Delta\Omega\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

where J contains all information on Astrophysics

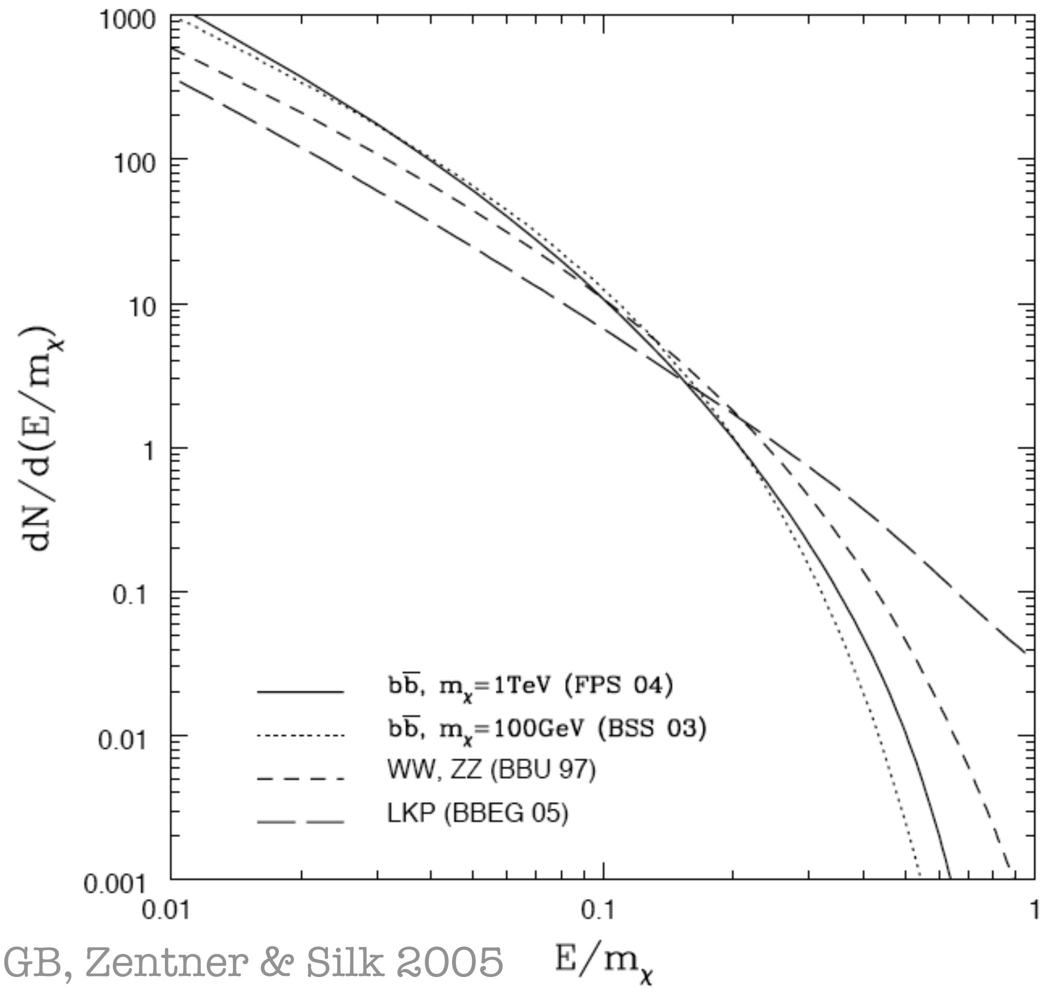
$$J(\psi) = \frac{1}{8.5\,\mathrm{kpc}} \left(\frac{1}{0.3\,\mathrm{GeV/cm^3}}\right)^2 \int_{\text{line of sight}} ds\, \rho^2(r(s,\psi))$$

and the DM profile is usually parametrized as

$$\rho(r) = \frac{\rho_0}{(r/R)^{\gamma}[1+(r/R)^{\alpha}]^{(\beta-\gamma)/\alpha}}$$

	α	β	γ	R (kpc)	$\overline{J}(10^{-3})$
Kra	2.0	3.0	0.4	10.0	2.166×10^1
NFW	1.0	3.0	1.0	20	1.352×10^3
Moore	1.5	3.0	1.5	28.0	1.544×10^5
Iso	2.0	2.0	0	3.5	2.868×10^1

Spectrum per annihilation



GB, Zentner & Silk 2005

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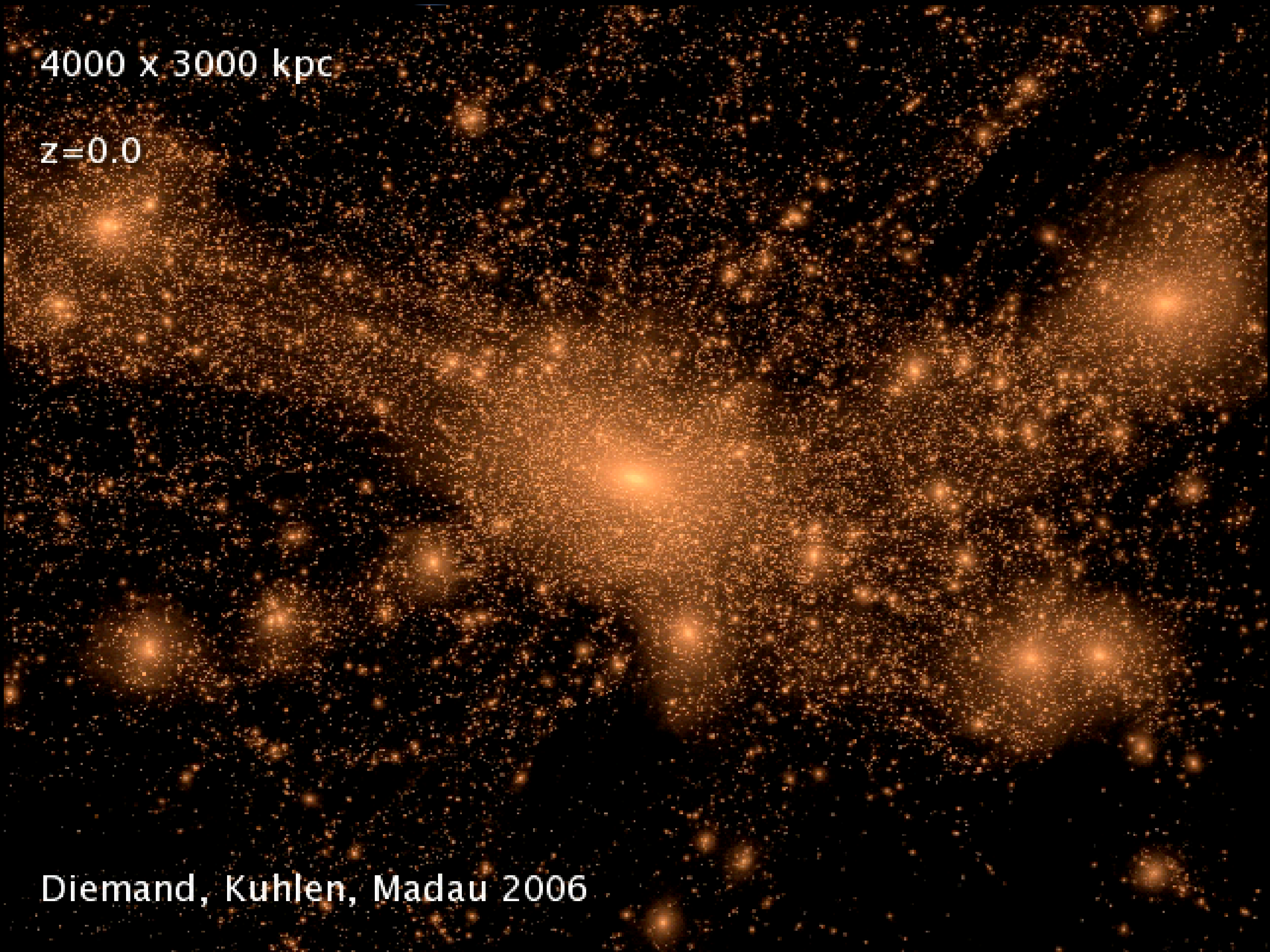
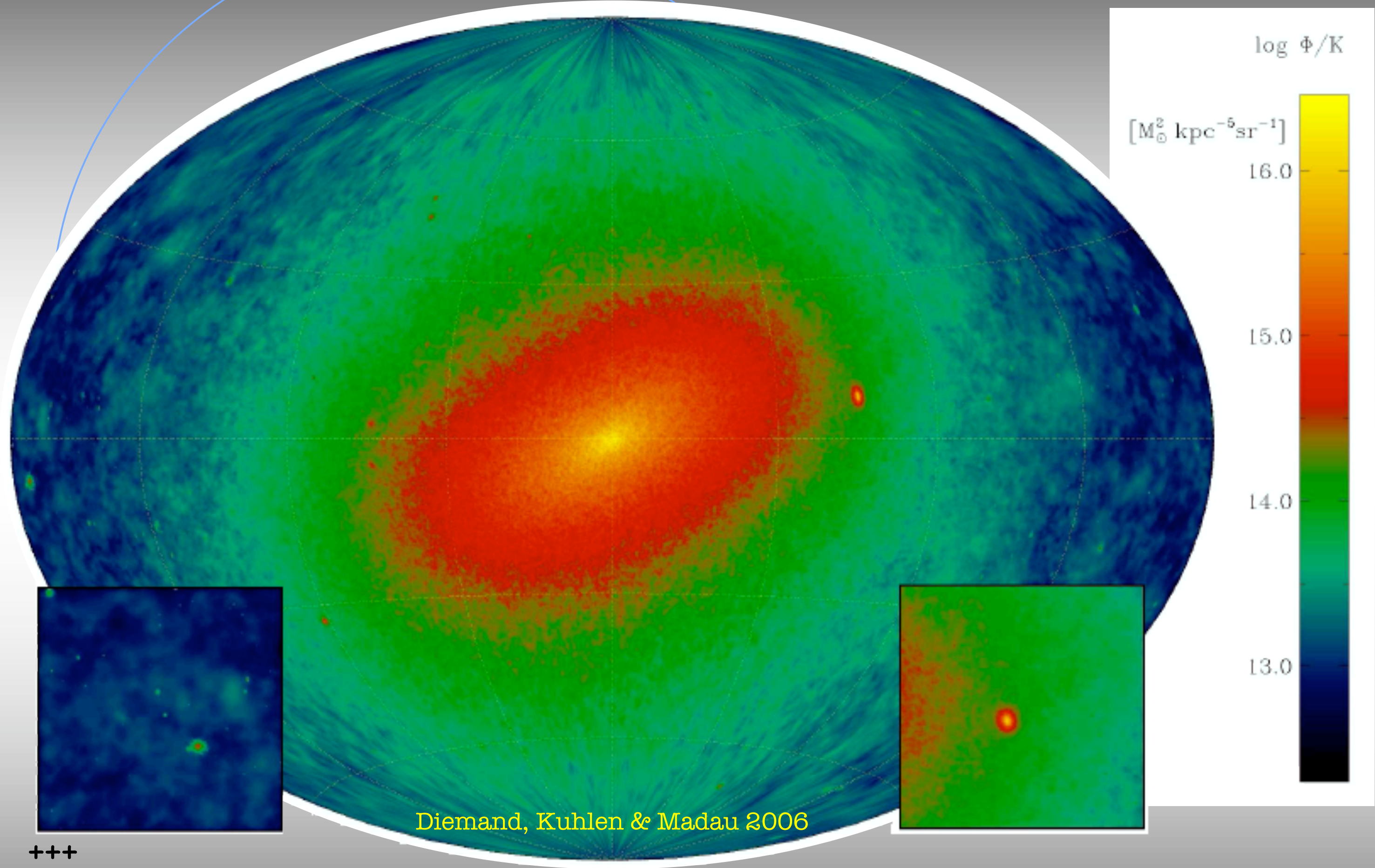

4000 x 3000 kpc
z=0.0
Diemand, Kuhlen, Madau 2006

High resolution simulation of the Milky Way

Miliky Way: Annihilation signal



γ-ray flux from the GC

Predictions for KK dark matter and neutralinos in the case of a NFW profile *without central spike.* Fluxes are always below the EGRET normalisation, but within the reach of several future experiments. Possibility of constraining B(1) mass. Importance of the dark matter density profile.

GB, Servant & Sigl 2003

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GB, Servant & Sigl, 2003

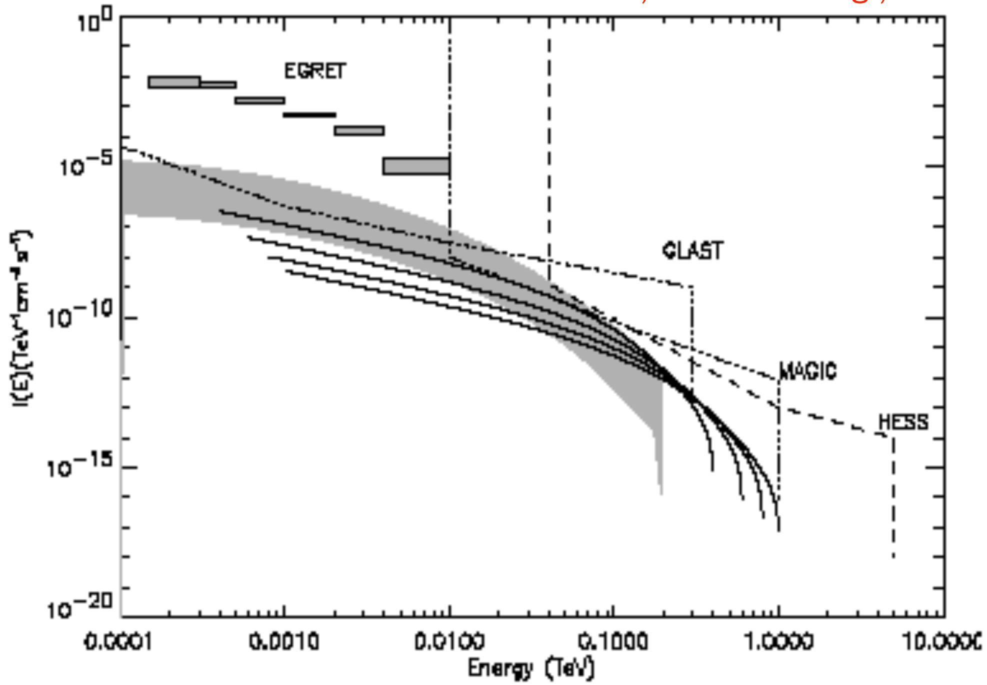
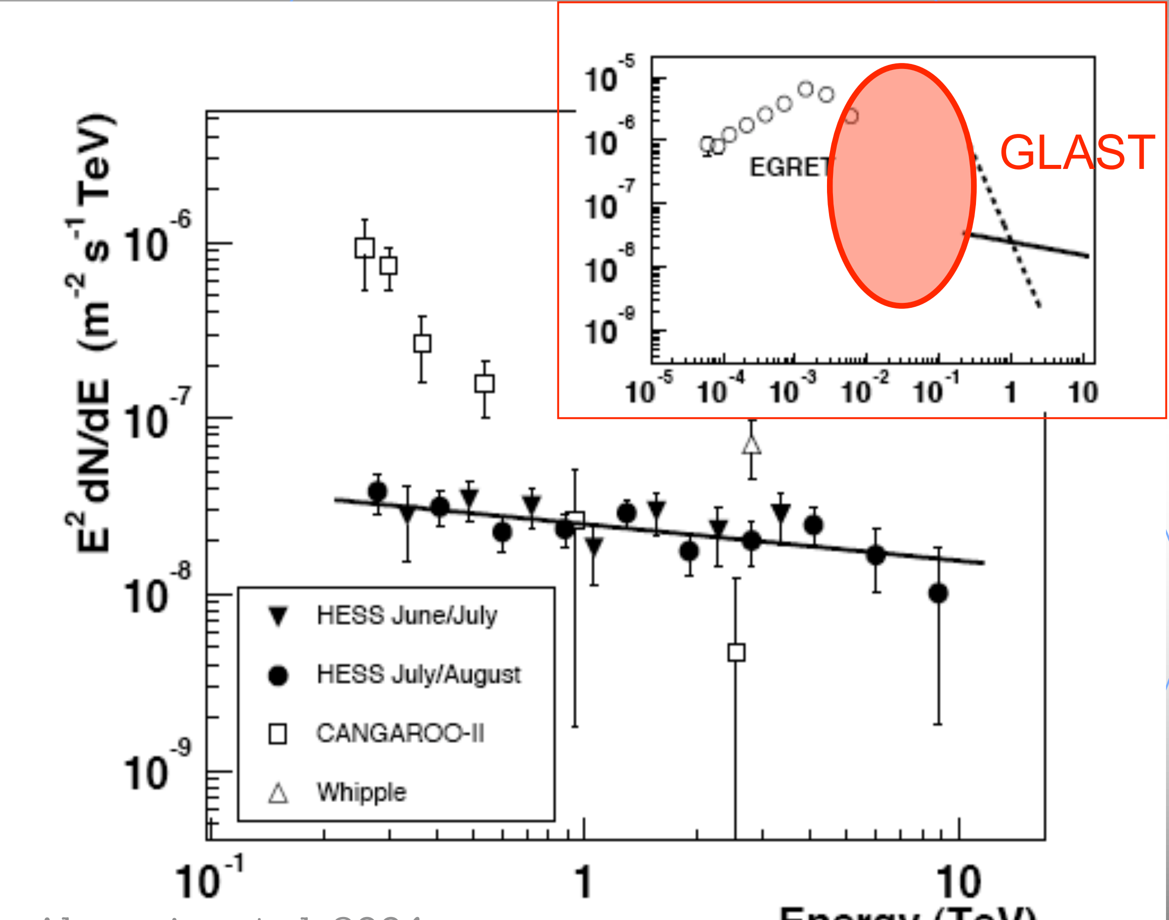


FIG. 4: Expected $\gamma-$ray fluxes for (top to bottom) $M = 0.4$, 0.6, 0.8, and 1 TeV and $\overline{J}\left(10^{-3}\right) = 500$. For comparison shown are typical $\gamma-$ray fluxes predicted for neutralinos of mass $\simeq 200$ GeV, as well as EGRET data and expected sensitivities of the future GLAST, MAGIC and HESS experiments.

The TeV source at the GC: spectrum



Aharonian et al. 2004

HESS data

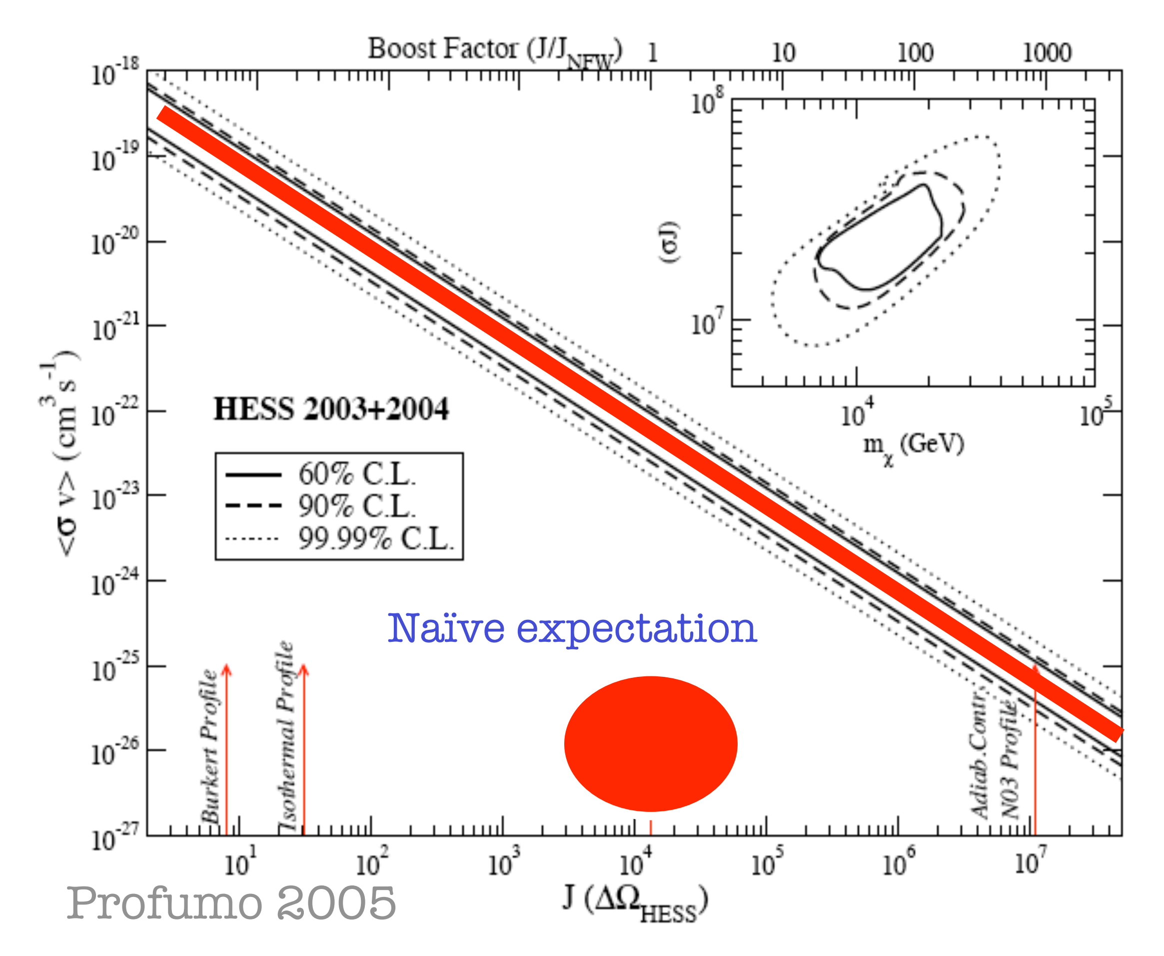
- Power-law is a good fit
- Extend above 20 TeV
- Don't match EGRET data

Looks like an astrophysical source...

Possible origin?

- Sgr A*, Supermassive BH at the GC (*Aharonian and Neronov 2005, Liu et al. 2006*)
- Sgr A East, Supernova Remnant (*e.g. Grasso and Maccione 2006*)
- Annihilations? Uhm...

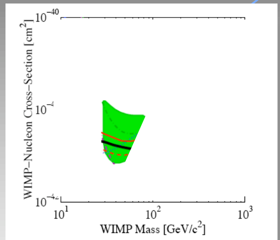
Constraints on the DM interpretation



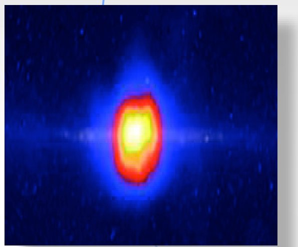
DM Intepretation

- Mass scale too high for standard candidates (SUSY, UED etc.)
- Profile very steep to compensate for large mass suppression,
- Power-law really seems to suggest an astrophysical origin
- BUT, this doesn't mean we won't see anything with GLAST (search for excess below HESS threshold

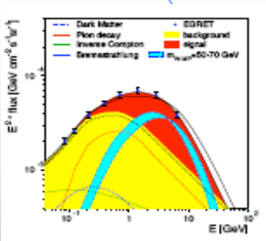
Controversial Claims



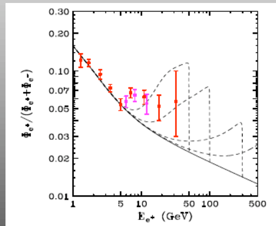
DAMA Direct Detection
<u>Evidence for</u>: 50 GeV WIMP
Bernabei et al (1996,2000,2005)



INTEGRAL 511 keV
<u>Evidence for</u>: MeV Dark Matter
Boehm et al (2003,2004)

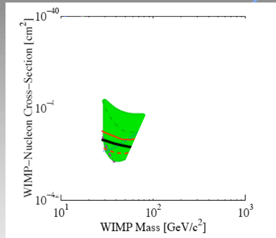


GC: EGRET, HESS
<u>Evidence for</u>: GeV / multi-TEV DM
E.g.: *De Boer (2005)*



HEAT Positron flux
<u>Evidence for</u>: GeV DM
See e.g. reviews cited above

Controversial Claims



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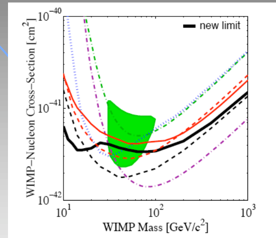
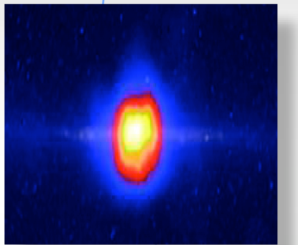


DAMA Direct Detection

Not consistent with more recent searches, in particular Edelweiss and CDMS II. See experimental papers, plus Gelmini & Gondolo 2005 for possible explanation



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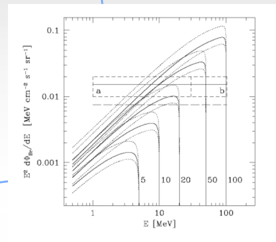
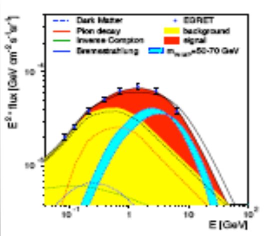


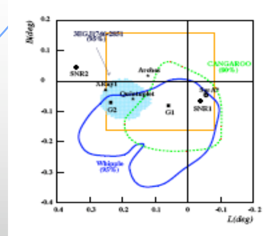
INTEGRAL 511 keV

Scenario is severely constraine: Beacom, Bell & Bertone 2003, Beacom and Yuksel 2004, Hooper, Sigl and Fayet 2006
.



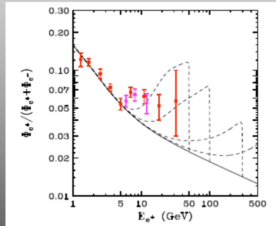
GC: EGRET, HESS

Evidence for: GeV / multi-TEV DM
E.g.: *De Boer (2005)*



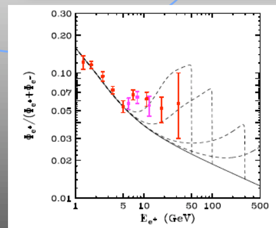
GC: EGRET, HESS

Anti-proton flux in conflict with De Boer et al. HESS: Mass scale “not natural”, astrophys. source? See papers by: *Bergstrom, Bertone, Hooper, Profumo, Ullio…*



HEAT Positron flux

Evidence for: GeV DM
See e.g. reviews cited above



HEAT Positron flux

Possible, but typically need large boost factors. Discussion in Bertone et al 2005, Bergstrom 2003

Astrophysical Black Holes

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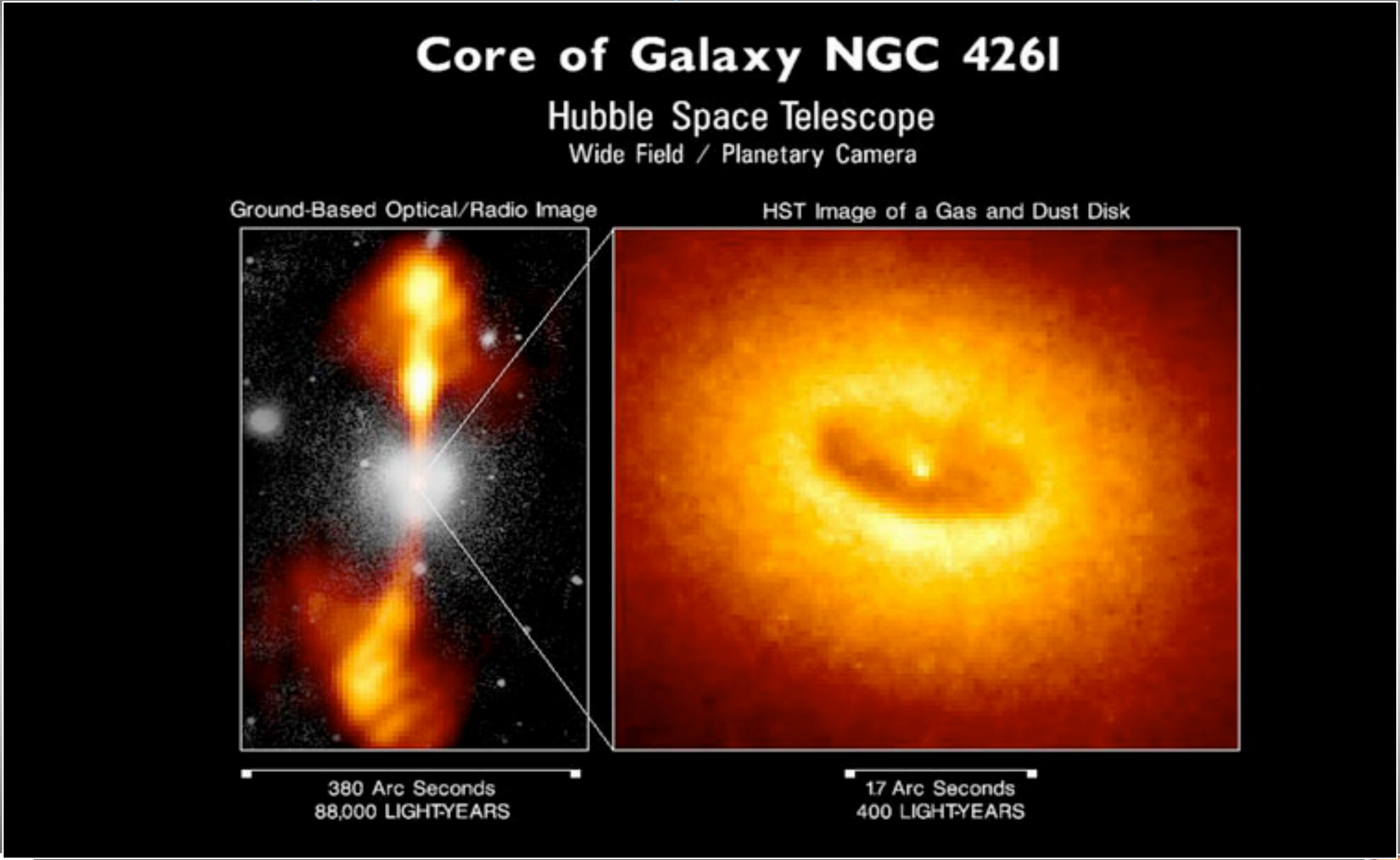
(Somewhat arbitrary)

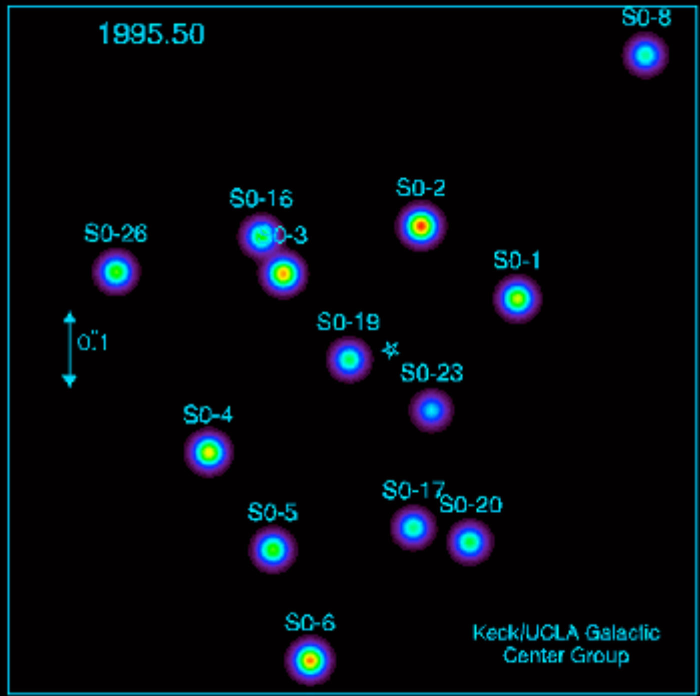
Black Holes: Definitions

$M \leq 10^2 M_\odot$	$10^2 M_\odot \leq M \leq 10^6 M_\odot$	$10^6 M_\odot \leq M \leq 10^9 M_\odot$
		
Stellar Mass BHs	Intermediate Mass BHs	Supermassive BHs
• Endpoint of stellar evolution • Indirectly observed • Robust evidence • Lower limits on mass from obs.	• Maybe form in Glob. clusters • Maybe observed as ULXs • Seed for SMBHs? • Speculative but probable!	• Unknown origin • Ubiquitous! • Robust evidence • Mass correlated with host halo

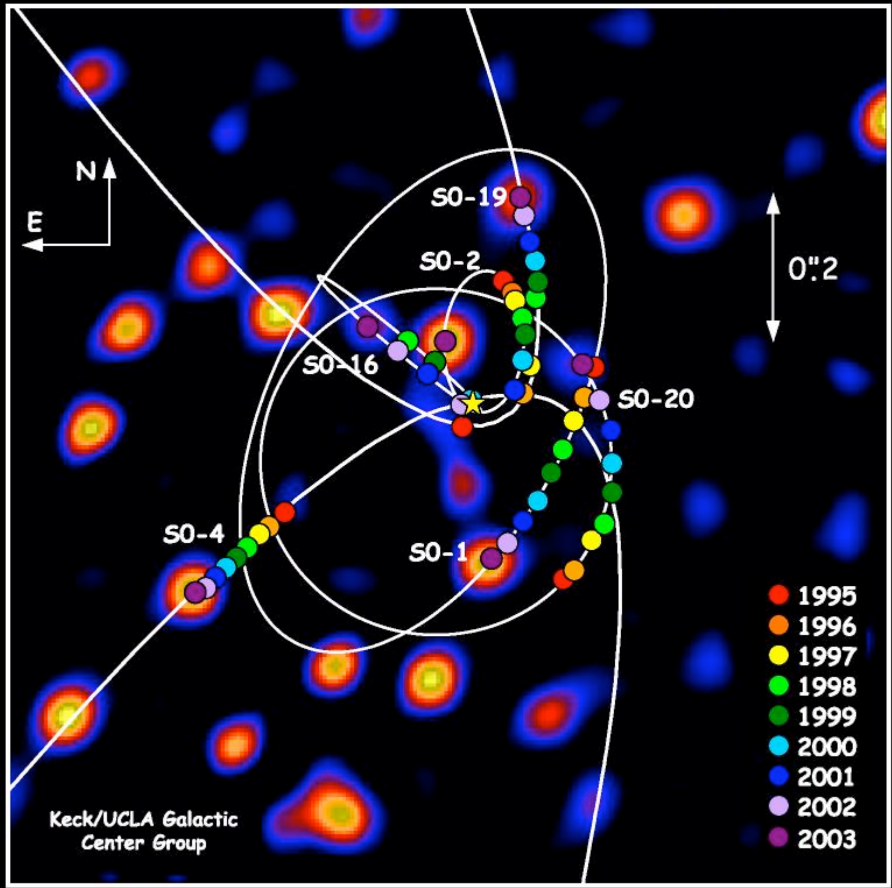
Evidence for Black Holes



Evidence for *Supermassive* Black Holes in our (cosmic) backyard…



Evidence for a *Supermassive* Black Hole at the GC



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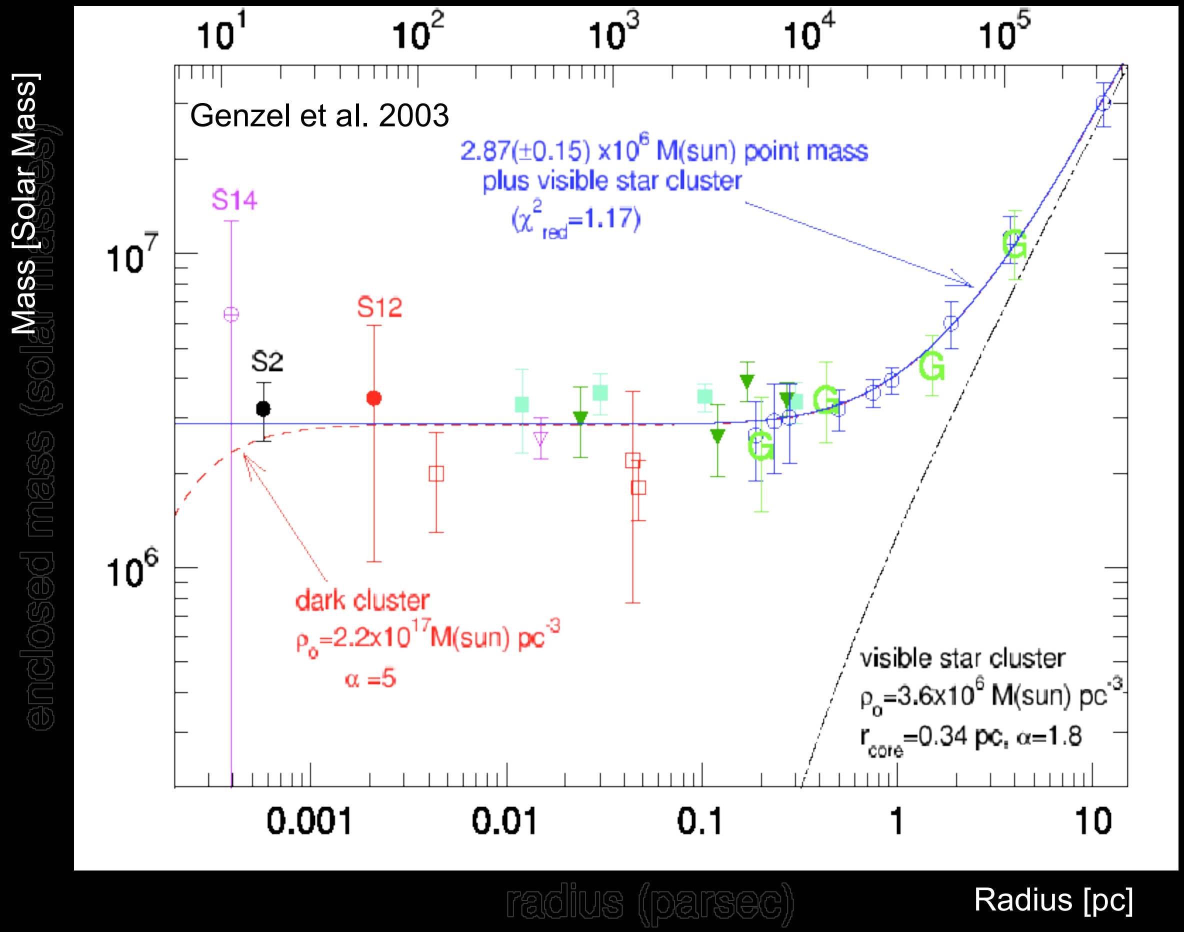
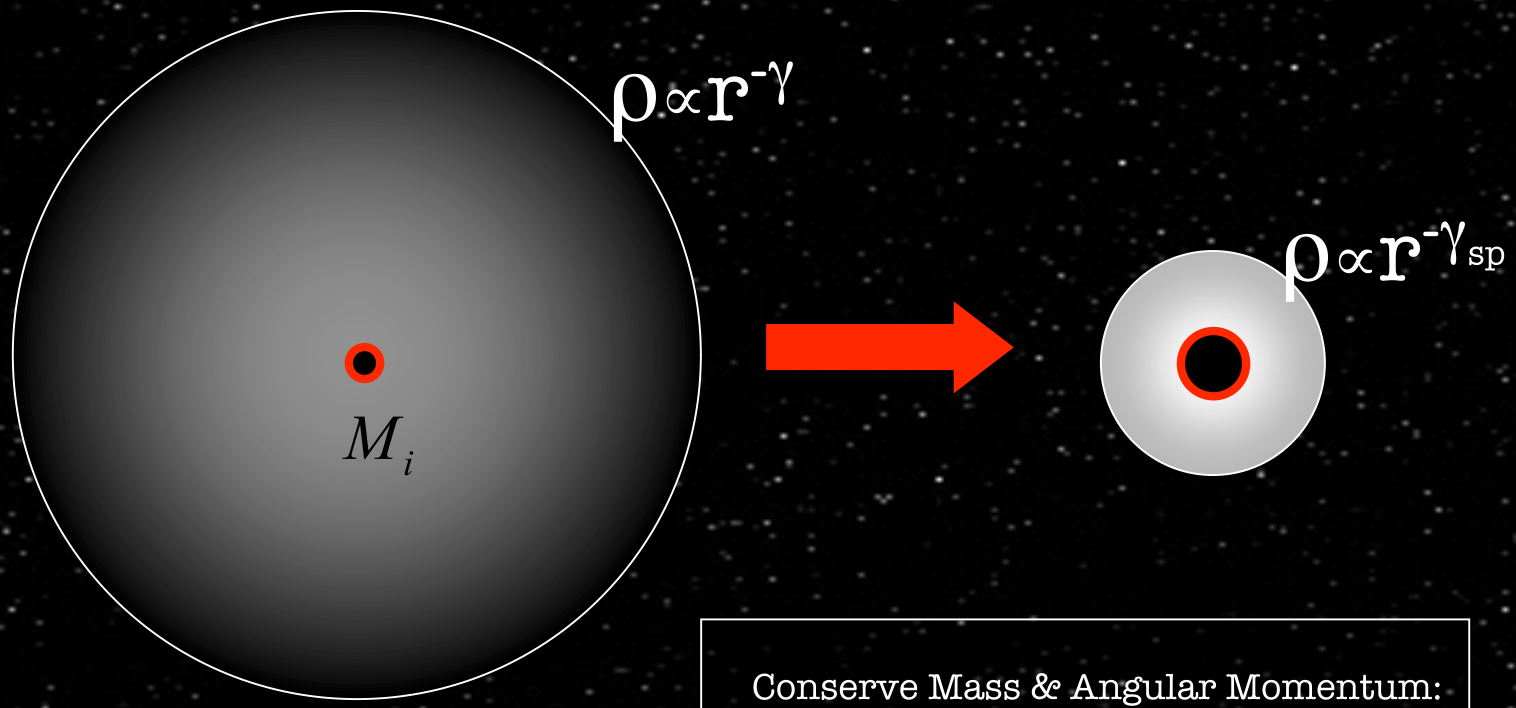


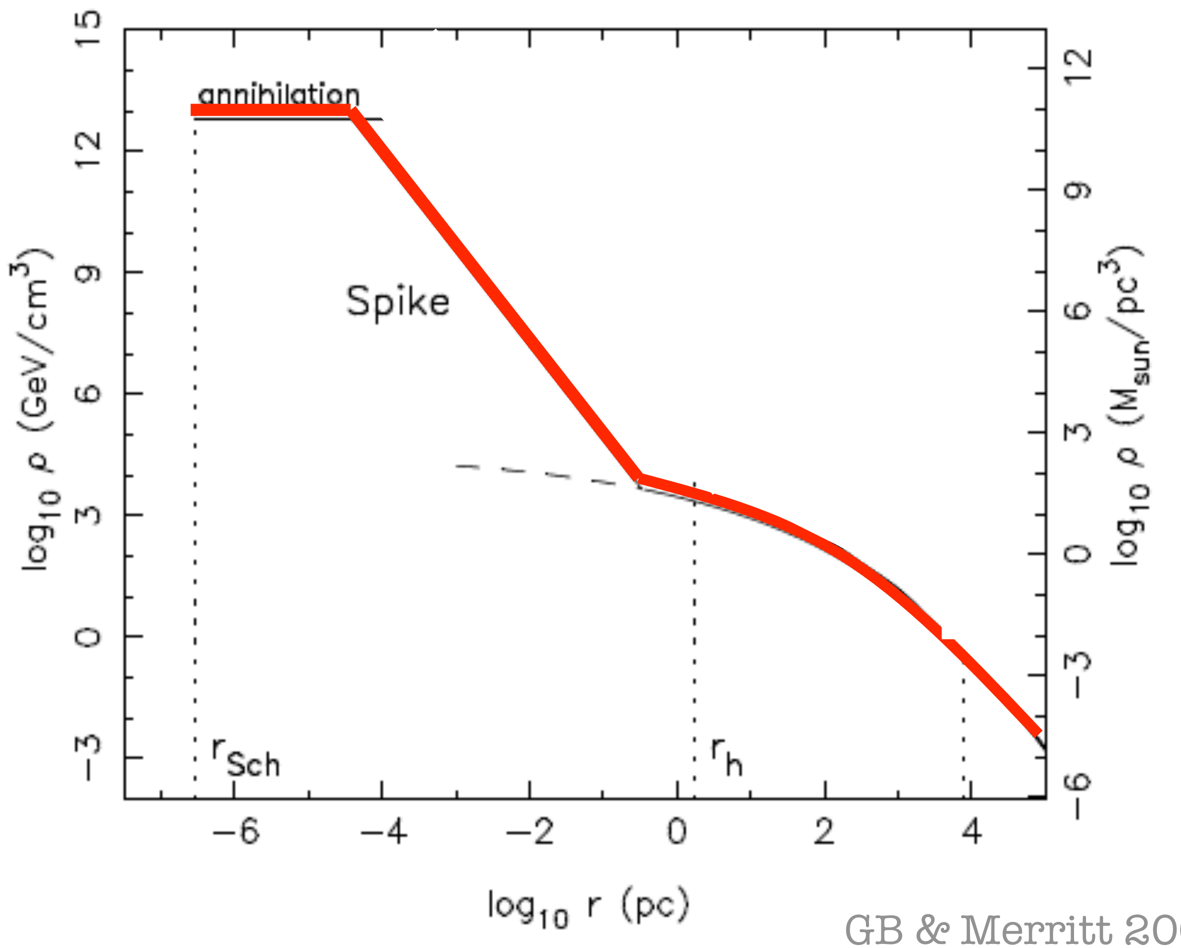
Adiabatic growth of a Black Hole: BHs as "*Annihilation Boosters*"!



Conserve Mass & Angular Momentum:

$$\gamma_{sp} = \frac{9-2\gamma}{4-\gamma}$$

An intuitive description of Dark Matter "Spikes"



GB & Merritt 2005

The inner parsec

What happens in the inner parsec?

Profiles are modified due to

- The presence of the SMBH (spike) *Gondolo and Silk 2000*
- Scattering off the stellar cusp (heating of DM, scatter into the SMH) *Merritt 2004*
- Annihilations

Combined evolution of Dark and baryonic matter

Bertone & Merritt 2005

Fokker-Planck equation

$$\frac{\partial f}{\partial t} = -\frac{1}{4\pi^2 p}\frac{\partial F_E}{\partial E} - f(E)\nu_{coll}(E) - f(E)\nu_{loss}(E)$$

$$F_E(E) = D_{EE}(E)\frac{\partial f}{\partial E},$$

$D_{EE}(E)$ = energy diffusion coefficient

$$\nu_{coll}(E) = \left\langle m_\chi^{-1}\rho\sigma v\right\rangle_{\text{orbit-averaged}}$$

$\nu_{loss}(E)$ = scattering rate into black hole

The inner parsec

What happens in the inner parsec?

Profiles are modified due to

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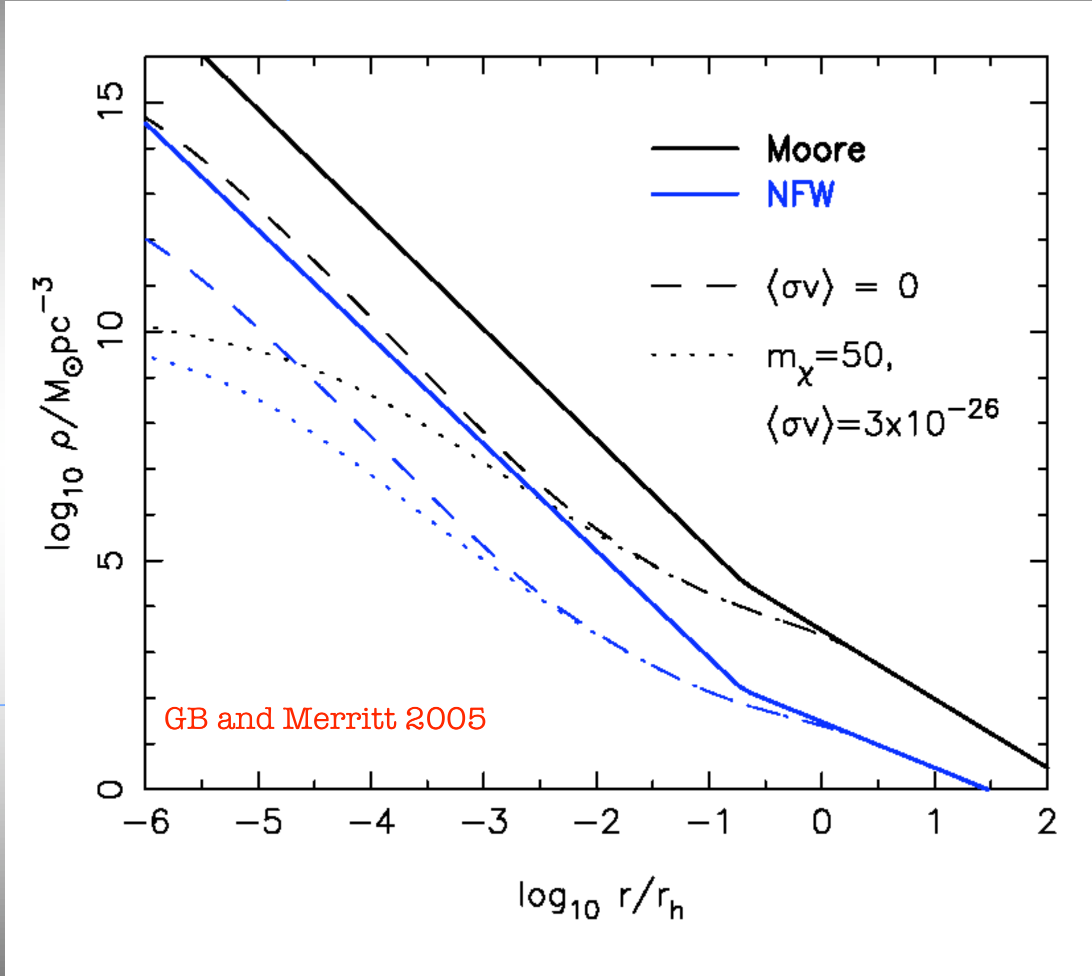
Combined evolution of Dark+++ *and baryonic matter*



Formation of Crests (Collisionally REgrown STructures)

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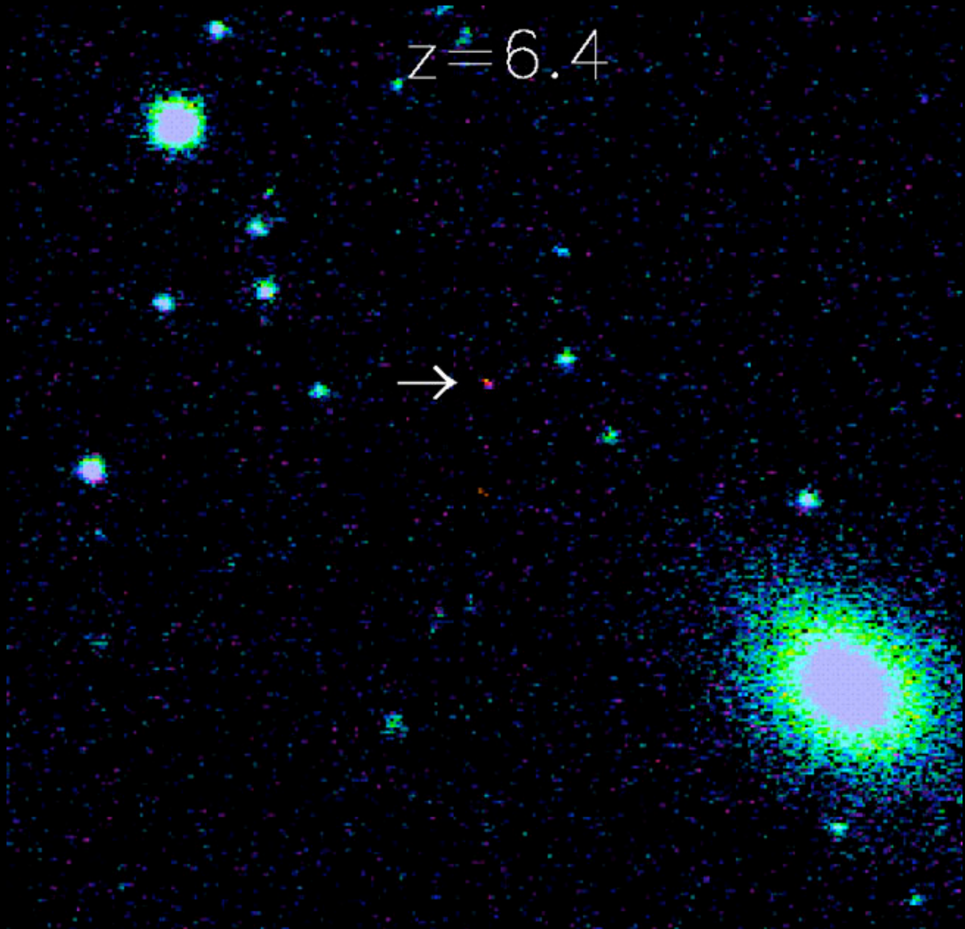
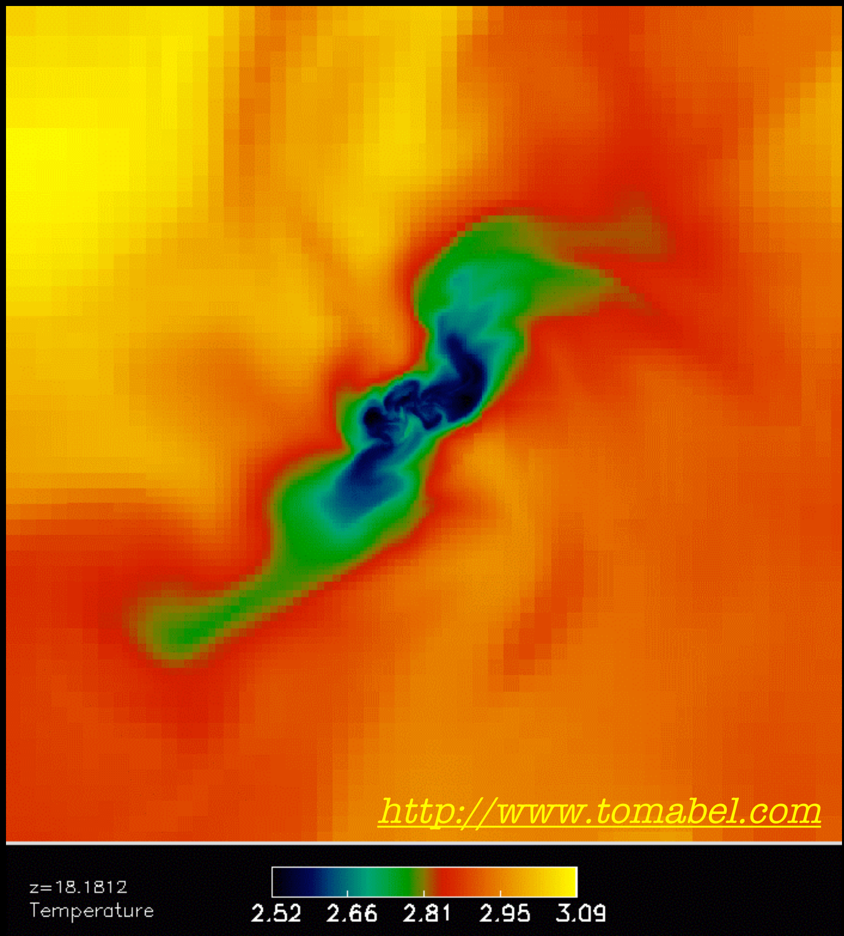
Where do the observed SMBHs come from?



CREDIT: Sloan Digital Sky Survey, Apache Point Observatory

- We don't know. But they are ubiquitous!
- High-redshift quasars suggest that 10^9 Msun BHs were already in place when the Universe was only 1Gyr old
- Circumstance that can be understood in terms of rapid growth starting from ***massive seeds***

Scenario I: Seeds of 10^2 Msun



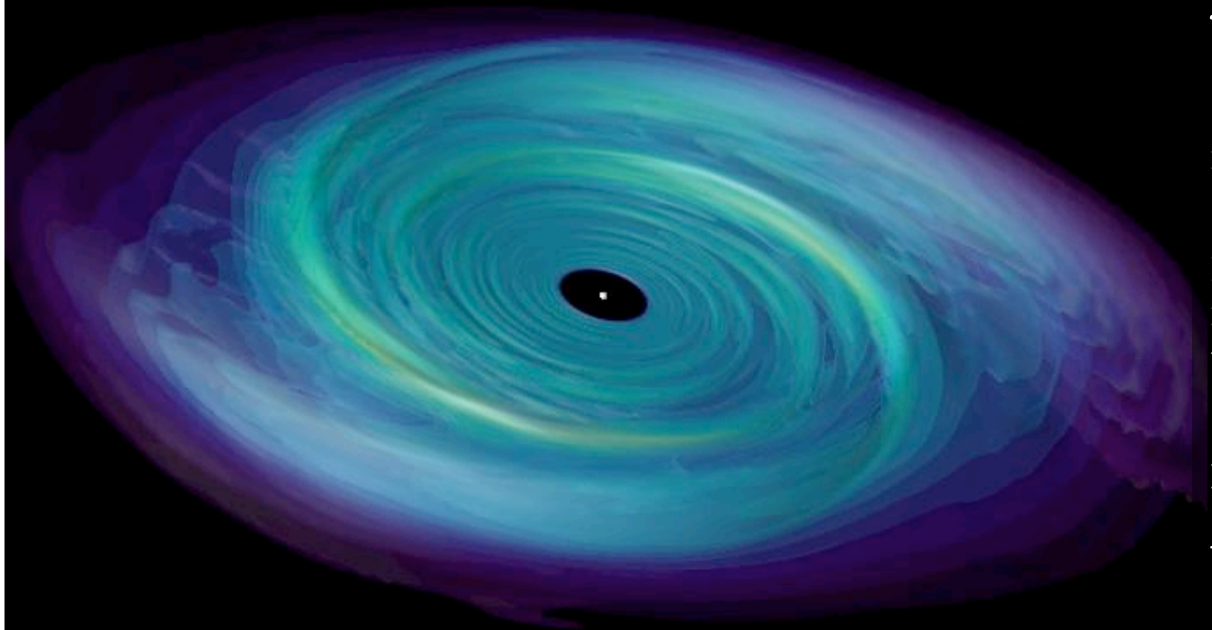
- At z ≈ 18, first stars form (image: formation of a protostar, from http://www.tomabel.com)

- Zero metallicity Pop III stars with masses in the range M ≈ 60 - 140 Msun and M > 260 Msun collapse directly to black holes

- Stars with 140 < M/ Msun < 260 disrupted by pulsation pair production instability, leaving behind no remnant

Gebhardt, Rich, & Ho 2002, Heger, Fryer, Woosley, Langer and Hartmann 2003; Madau & Rees 2001; Islam Taylor & Silk 2003

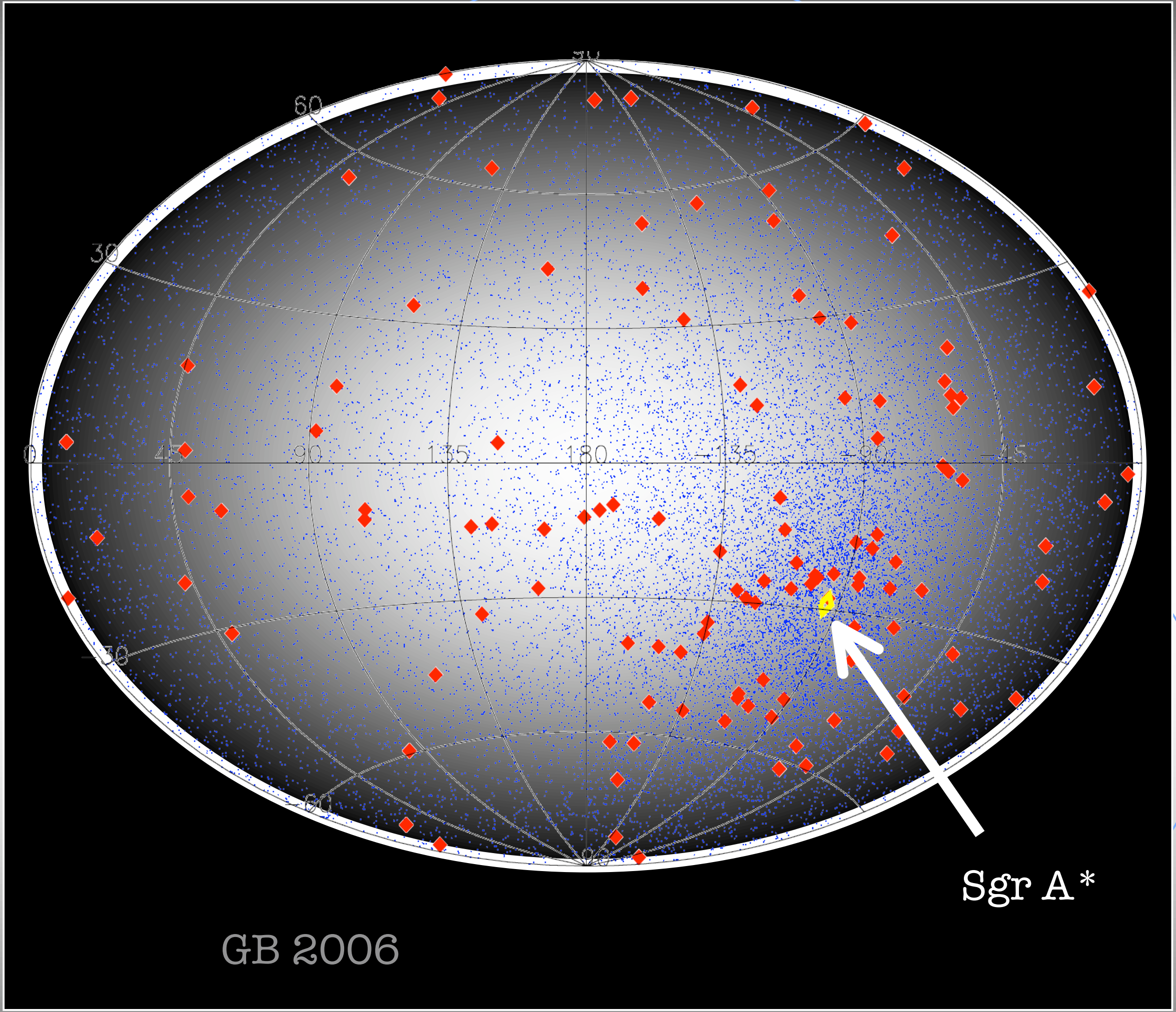
Scenario II: Seeds of 10^5 Msun



- In halos with efficient molecular hydrogen cooling and which do not experience any major mergers, a ***protogalactic disk*** forms and can evolve uninterrupted.
- Effective viscosity transfers mass inward
- A baryonic mass of order 10^5 Msun loses its angular momentum and is transferred to the center of the halo.
- Central object may be briefly pressure-supported, but it eventually collapses to form a black hole

Koushiappas, Bullock & Dekel 2004

Populating the MW halo with mini-spikes



- **Populate halos at high z** with prescription from given IMBHs model
- Evolve mini-halos with **semi-analytic codes** (*Zentner, Bullock 2003, Zentner et al. 2004*)
- Obtain **statistical realization** of MW halo at z=0 (RED dots)
- **Iterate** (BLUE dots)
- **Average** results over realizations (*GB, Zentner & Silk 2005*)

Gamma-Rays from Mini-spikes around IMBHs

Inserting typical values for the DM candidate and the spike, we find in scenario II

$$\Phi(E,D) = \Phi_0 \frac{dN}{dE}\left(\frac{\sigma v}{10^{-26}\mathrm{cm}^3/\mathrm{s}}\right)\left(\frac{m_\chi}{100\mathrm{GeV}}\right)^{-2}\left(\frac{D}{\mathrm{kpc}}\right)^{-2}\left(\frac{\rho(r_{\mathrm{sp}})}{10^2\mathrm{GeV cm}^{-3}}\right)^{2}\left(\frac{r_{\mathrm{sp}}}{\mathrm{pc}}\right)^{\frac{14}{3}}\left(\frac{r_{\mathrm{cut}}}{10^{-3}\mathrm{pc}}\right)^{-\frac{5}{3}}$$

$$\Phi_0 = 9\times 10^{-10}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

- One would naïvely expect that the flux scales with $\sigma v/m^2$
- BUT The maximum density is higher for the pessimistic case, and $r_{cut}=r_{cut}$(m,\sigma v). This partially compensates for the decrease in flux due to the prefactor $\sigma v/m^2$
- The final luminosity of mini-spikes is thus proportional to ~ $(\sigma v)^{2/7} m^{-9/7}$

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KEY POINT!

Gamma-Rays from Mini-spikes around IMBHs

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$$\Phi(E,D) = \Phi_0 \frac{dN}{dE}\left(\frac{\sigma v}{10^{-26}\mathrm{cm}^3/\mathrm{s}}\right)\left(\frac{m_\chi}{100\mathrm{GeV}}\right)^{-2}\left(\frac{D}{\mathrm{kpc}}\right)^{-2}\left(\frac{\rho(r_{\mathrm{sp}})}{10^2\mathrm{GeV\,cm}^{-3}}\right)^{2}\left(\frac{r_{\mathrm{sp}}}{\mathrm{pc}}\right)^{\frac{14}{3}}\left(\frac{r_{\mathrm{cut}}}{10^{-3}\mathrm{pc}}\right)^{-\frac{5}{3}}$$

$$\Phi_0 = 9\times 10^{-10}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Note the normalization of the flux:

Each Black Hole would be as luminous

(in terms of annihilation radiation) as the whole Galaxy!!

KEY POINT!

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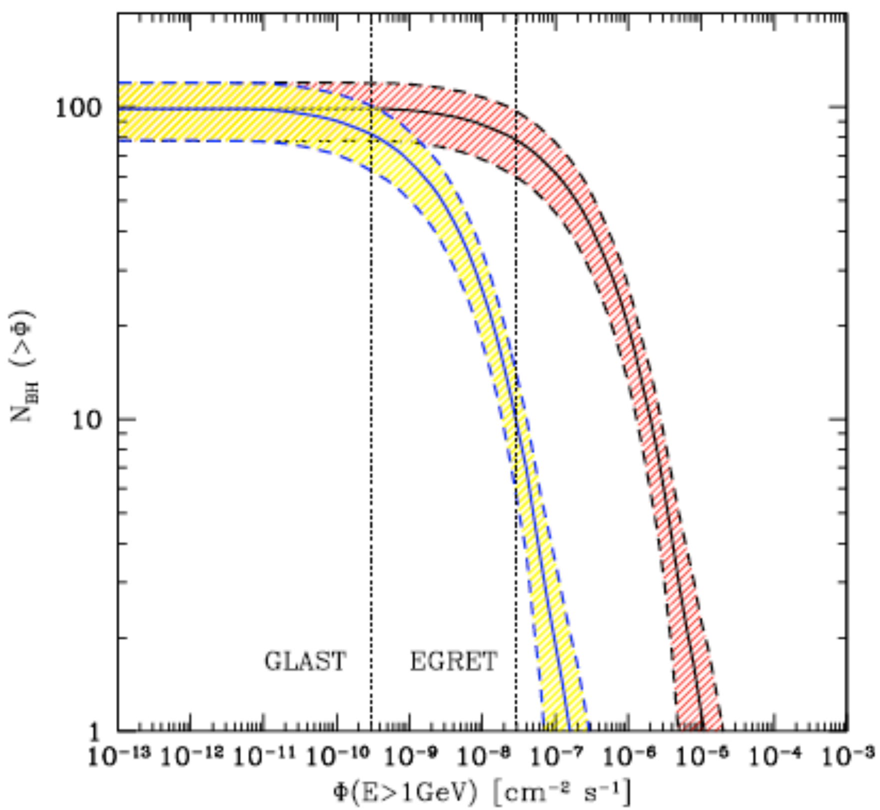
IMBH Scenario 2 (10^5 M_{sun})



GB, Zentner & Silk 2005

Results:

•Very high fluxes!

•Sources off the disk (need large field of view to search for them)

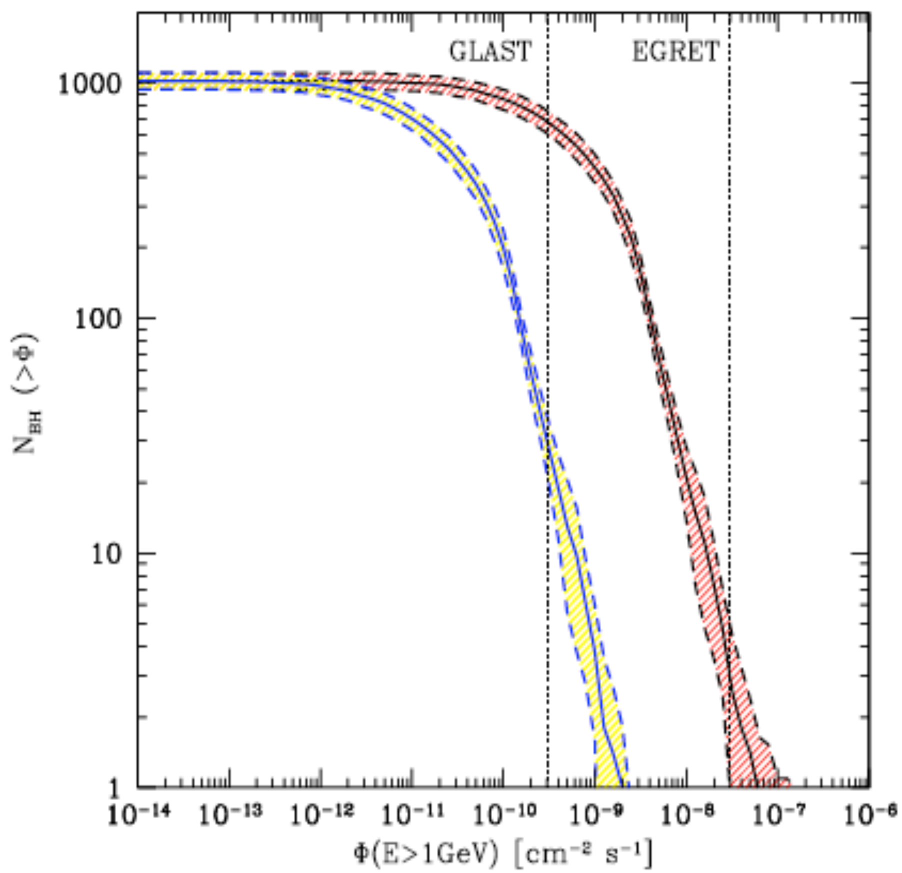
•Tens of sources with IDENTICAL spectrum: smoking-gun for DM

Smoking gun!

•Scatter among different realizations relatively small

•Can use ACTs to study sources ≥ 300 GeV

IMBH Scenario 1 (10^3 Msun)



GB, Zentner & Silk 2005

Different predictions for different scenarios, but in most cases GLAST should see a signal

--

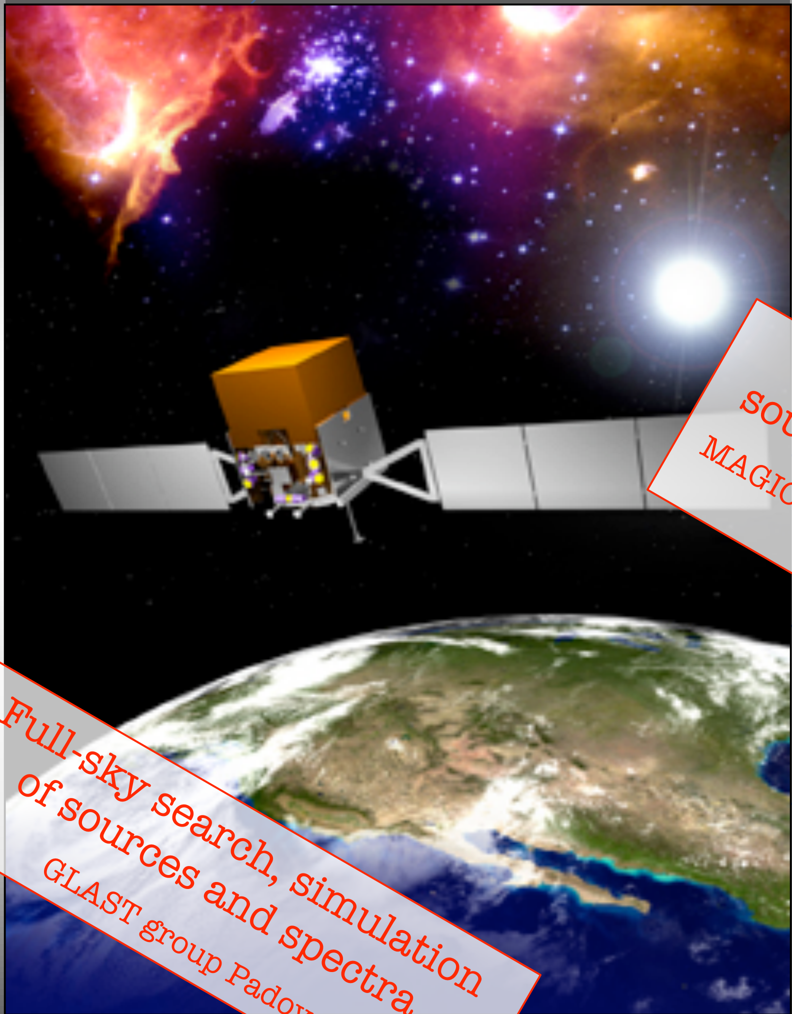
Use HESS, MAGIC or other ACTs to re-observe *selected* unidentified EGRET sources.

Criteria for EGRET:

- Off the disk
- Appropriate spectrum
- Extrapolate spectra at high energies for a reasonable guess on the detectability

Observational Strategies

Full-sky search with GLAST



Full-sky search, simulation of sources and spectra

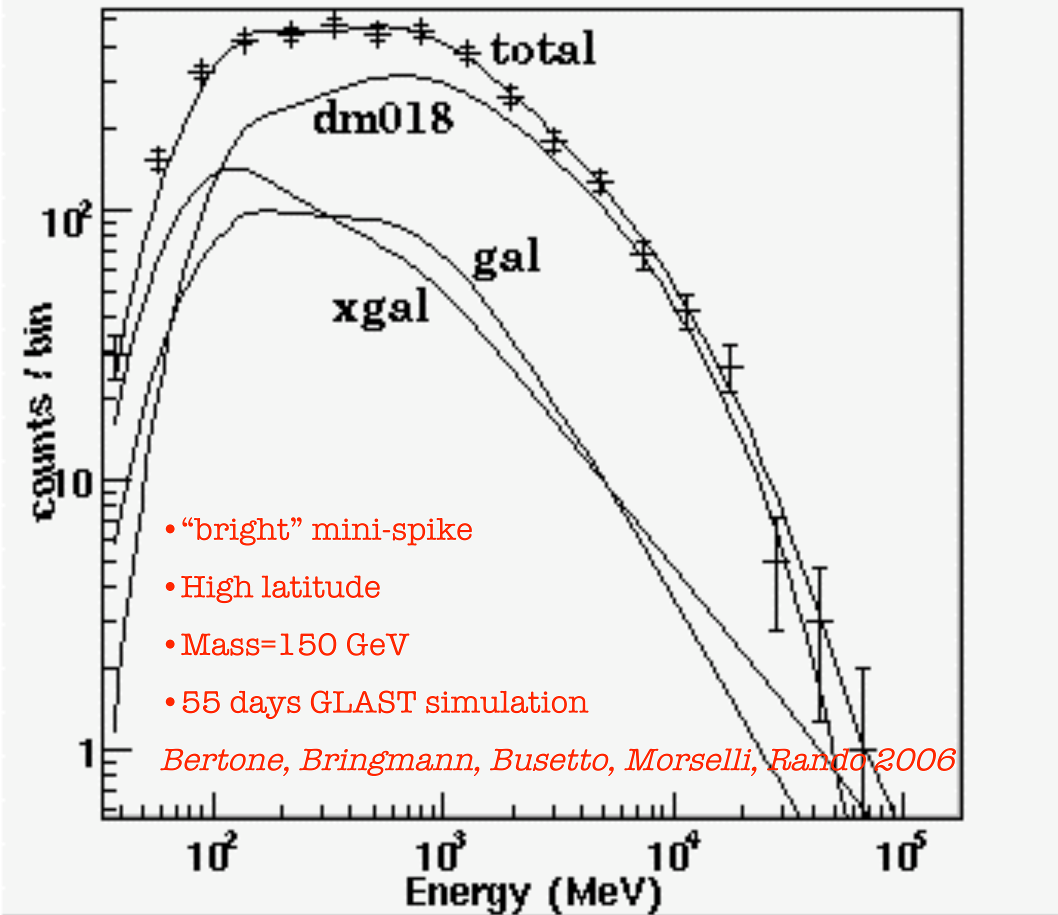
GLAST group Padova

Probe high m_χ with ACTs

Re-observation of EGRET sources, selection of candidates

MAGIC group Padova: M. Doro, M. Gaug, M. Mariotti, V. Scalzotto

Work in progress: Simulation of mini-spikes with GLAST



Detectability with GLAST

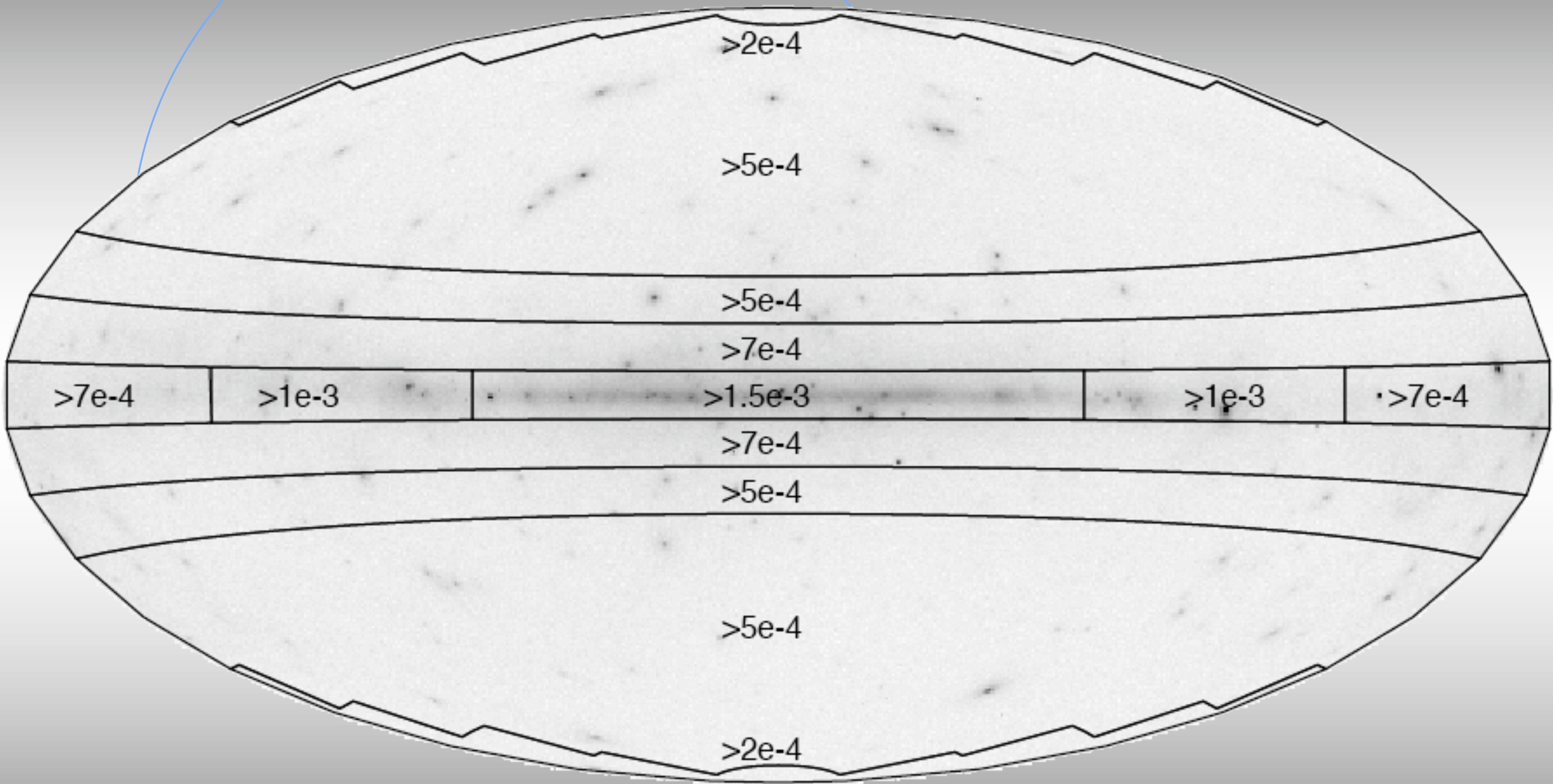
Random realization with 122 sources, m=150 GeV, 55 days of GLAST data

Results

- 57 Detected sources
- 12 Marginal detection
- 53 Lost
- Spectrum consistent with a broken power-law
- Mass reconstructed

m_{obs} = (145±12) GeV

GLAST sensitivity map
to point sources of annihilation radiation



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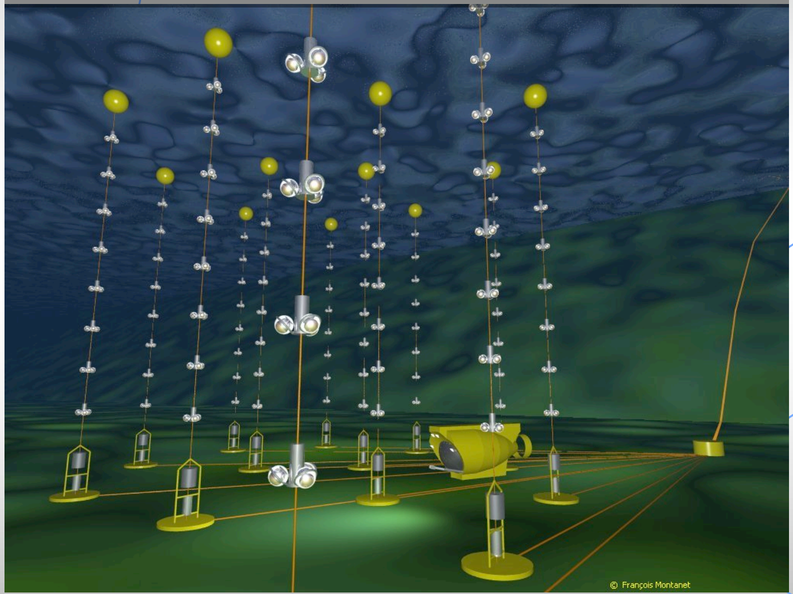
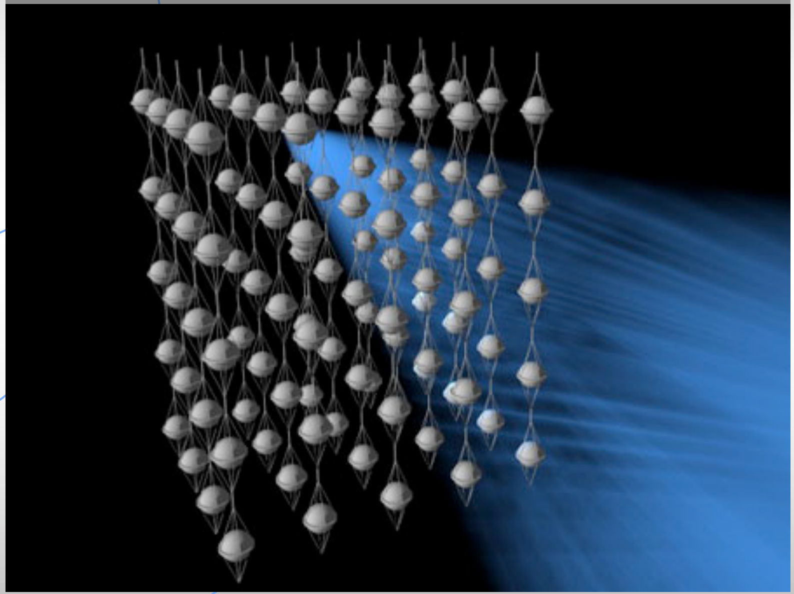
Bertone, Bringmann, Busetto, Morselli, Rando 2006

Interesting alternative: Neutrino Telescopes

Antares



IceCube



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Estimate of the Rate in a Neutrino Telescope

Flux of neutrinos of flavor l from one mini-spike

$$\Phi^0_{\nu_\ell}(E) = \phi_0 m^{-2}_{\chi,100} (\sigma v)_{26} D^{-2}_{\rm kpc} L_{\rm sp} N_{\nu_\ell}(E)$$

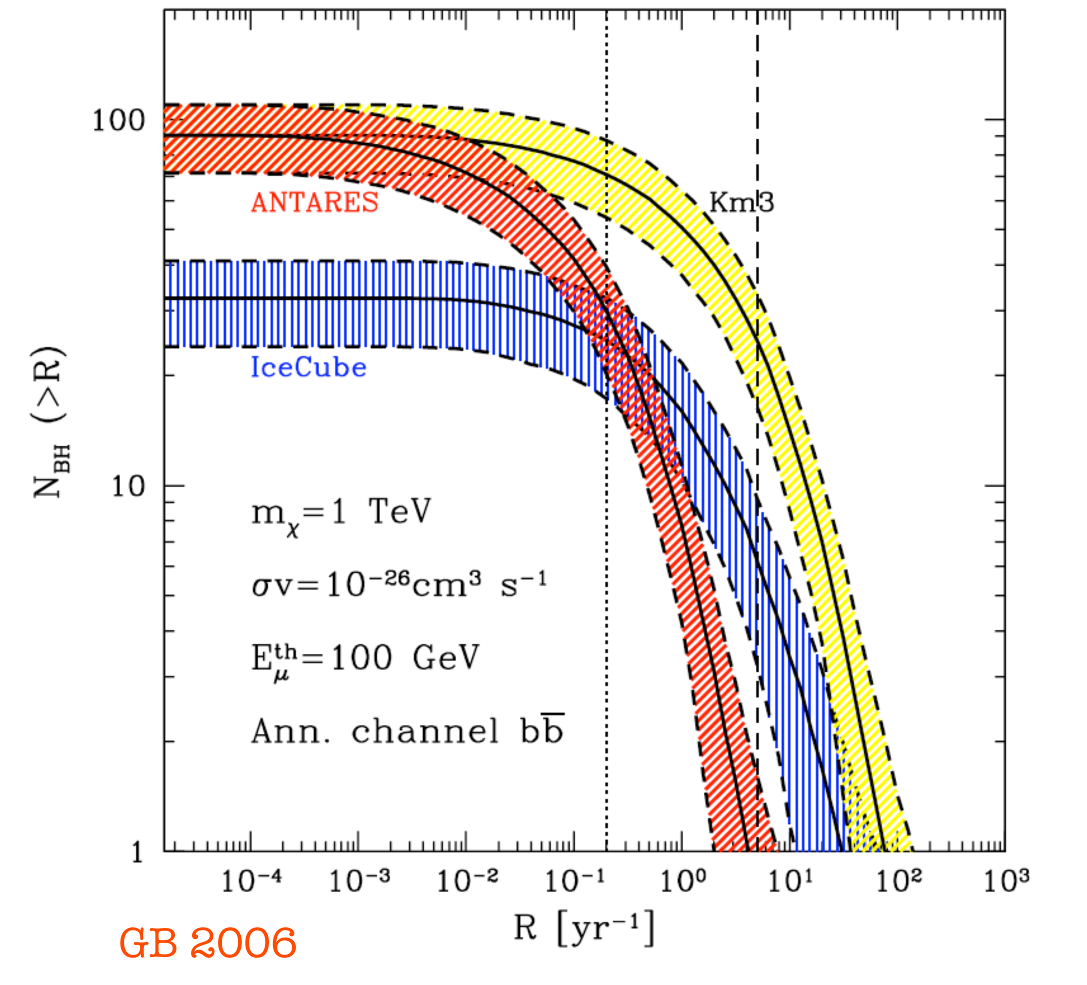
Flux of neutrinos after oscillations

$$\Phi_{\nu_\mu}(E) = \sum_{\ell=e,\mu,\tau} P(\nu_\ell \to \nu_\mu)\Phi^0_{\nu_\ell}(E)$$

Rate induced in a neutrino telescope

$$\mathrm{R} = V_\phi(\delta) \int_{E_\mu^{\rm thr}}^{m_\chi} dE_\nu \int_0^{y_\nu} dy\, A(E_\mu) P_\mu(E_\nu, y) \Phi_{\nu_\mu}(E_\nu)$$

Prospects for detection with Neutrino Telescopes



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CONCLUSIONS

- Particle Astrophysics experiments can open a window on an otherwise *dark* universe!
- We can go beyond the "naïve picture" of indirect detection, but (given the many conflicting claims) we need appropriate strategies to claim detection
- Black Holes are ubiquitous in Astrophysical environments and can effectively act as "DM annihilation boosters"
- *Intermediate Mass Black Holes* may represent a unique opportunity to actually *discover* Dark Matter particles, and the scenario has the undisputed virtue of being falsifiable!

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- Exciting opportunity to detect / constrain new physics with astrophysical observations