Indirect search for Dark Matter from Whipple to VERITAS and beyond

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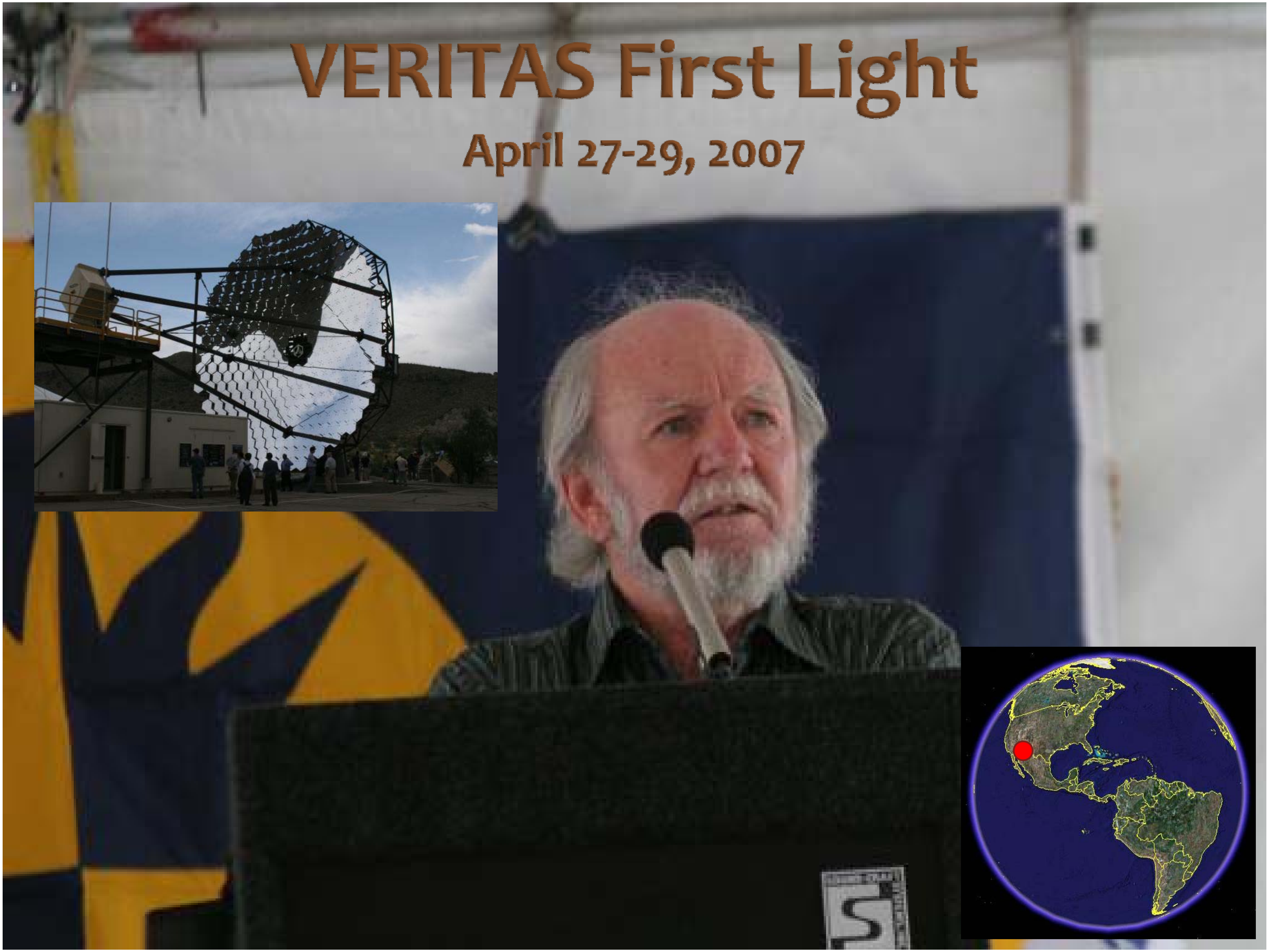
University of California, Los Angeles

Fermilab, May 10-12, 2007

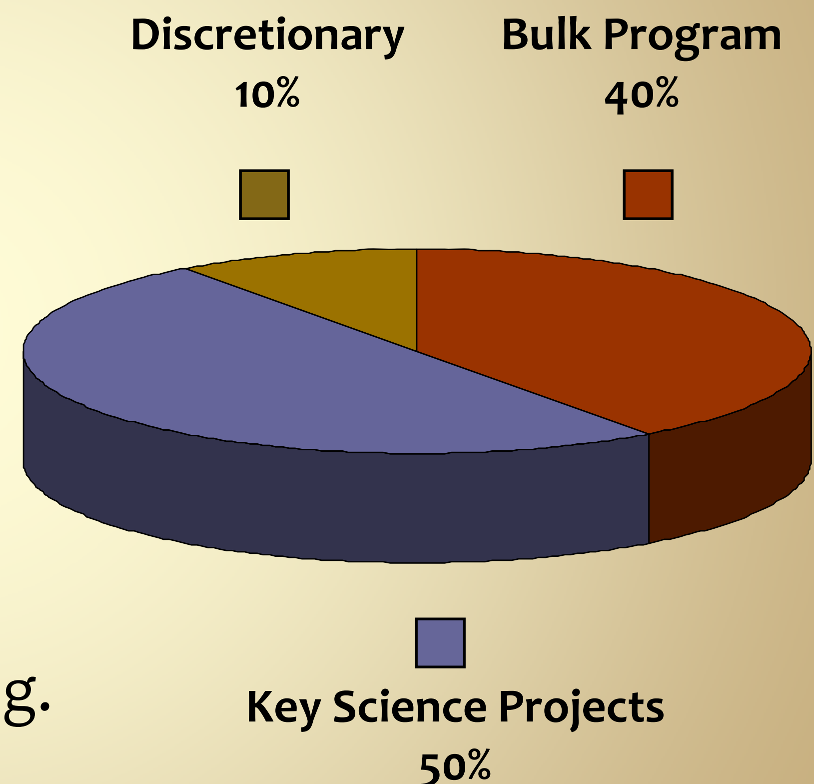
VERITAS First Light

April 27-29, 2007

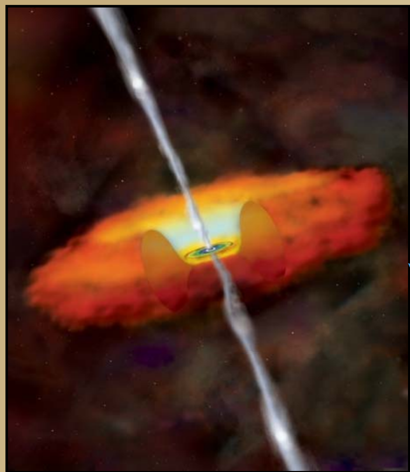


VERITAS Science Plan

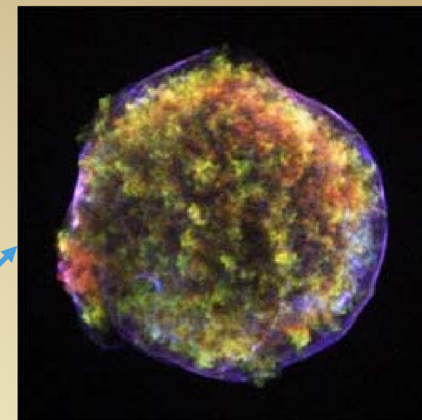
- **Key Science Projects:**
  - Four highlight science topics.
- **Bulk Science Program**
  - All possible topics.
  - Determined by TAC selection.
- **Discretionary Time**
  - ToO's, unique topics, engineering.
  - Determined by Spokesperson.



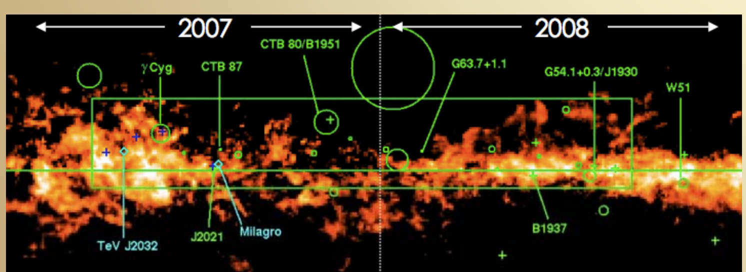
Key Science Projects



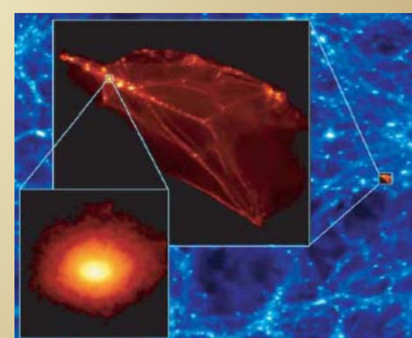
BLAZARS



SNRs/PWN



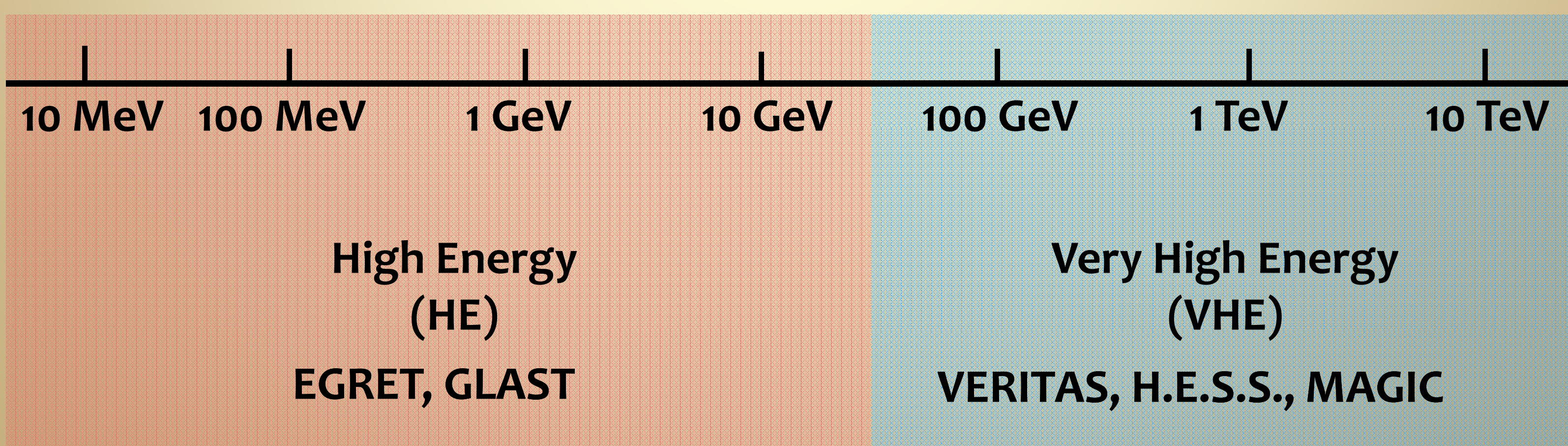
GALACTIC PLANE SURVEY



DARK MATTER
120 h / 2 years

Indirect DM Detection / VHE γ-rays
(required to establish particle identity with DM)

- **Pros**
  - Unambiguous spectral signature
  - Potential to constrain branching ratios from spectral endpoint region
  - Complementary to direct and accelerator searches
- **Cons**
  - Large theoretical uncertainties due to unknown DM distribution in the cores of DM halos
  - Potentially large conventional astrophysical backgrounds



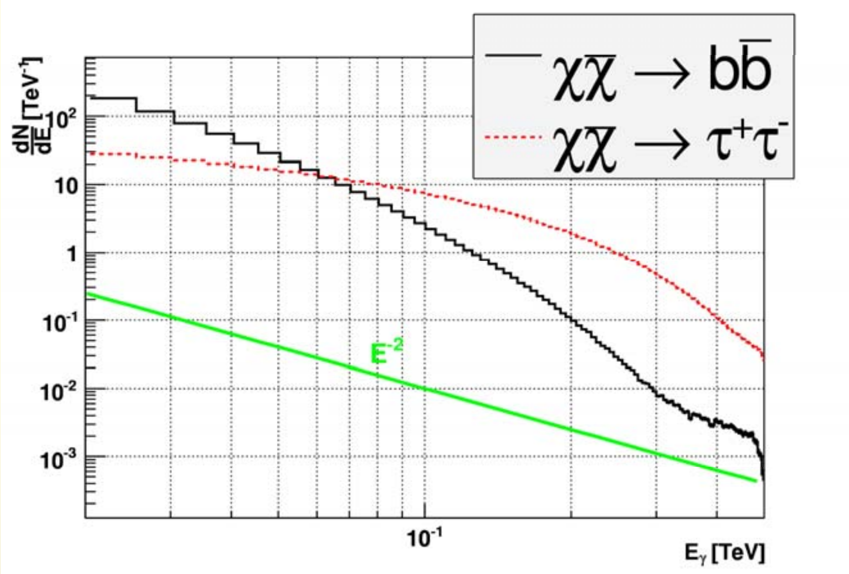
Neutralino DM annihilation

- Lightest super-symmetric particle, mixture of super-partners to γ, Z, H's
- Weakly interacting; $\langle\sigma\upsilon\rangle \sim 10^{-26}$ cm^3 s^{-1} (cont.)
- Non-relativistic (cold)
- Mass 60 GeV < m_χ < 10 TeV
- Annihilates to 2γ, γZ by 2nd order process giving rise to HE or VHE γ-ray line at m_χ
- 1st order decay into q,W,Z,H,… -> e,e$^+$,γ continuum

DM Annihilation Spectrum

- Distinguishable from astrophysical backgrounds
  - Not a power-law spectrum
  - Truncation and mono-energetic line at E = m_χ
  - Internal bremsstrahlung around E = m_χ (Birkedal et al. 2005)
- Extreme scenarios
  - Soft mode: $\chi\chi \rightarrow bb$
  - Hard mode: $\chi\chi \rightarrow \tau\tau$
- Typical DarkSUSY
  - $\chi\chi \rightarrow$ (10%) $\tau\tau$ + (90%) bb

Differential Photon Yield per Annihilation for m_χ = 500 GeV (PYTHIA MC Sjostrand et al. 2001)



(by M. Wood)

High resolution spectroscopy of truncation region may constrain neutralino annihilation branching ratios (!)

DM Annihilation Flux

Differential Flux:

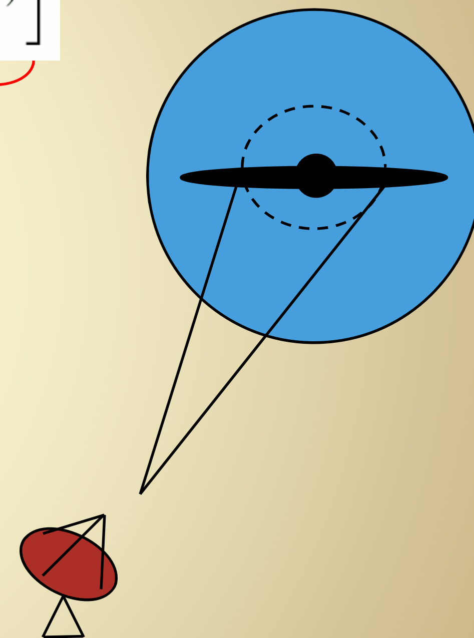
$$\frac{d\phi(\vec{\psi},\Delta\Omega)}{dE} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\left(\frac{dN_\gamma}{dE}\right)\left[\int_{\Delta\Omega} d\Omega \int \rho^2 ds(\vec{\psi})\right]$$

Cosmology/Particle Physics Component

Astrophysics Component

Astrophysical Enhancement Factor J:

$$J(\vec{\psi},\Delta\Omega) = \left(\frac{1}{\rho_c^2 R_H}\right)\int_{\Delta\Omega} d\Omega \int \rho^2 ds(\vec{\psi})$$



ρ_c =9.74 x 10^{-30} g cm^{-3} – critical density
R_H=4.16 Gpc – Hubble radius
$\Delta\Omega$= 6 x 10^{-5} sr (θ=0.25°)* ; r = 440 pc [D / 100kpc]

*) Sources discussed in this talk are point-like for VERITAS

VERITAS sensitivity limits

$$\frac{d\phi(\psi,\Delta\Omega)}{dE} = \phi_{1\%}\left(\frac{\langle\sigma v\rangle}{3\times10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}\right)\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^2\left(\frac{dN_\gamma/dE_\gamma}{10^{-2}}\right)\frac{J(\psi,\Delta\Omega)}{1.45\times10^4}$$

Detector   Cosmology/Particle Physics Component   Astrophysics Component

$\phi_{1\%}$ - is integral Crab nebula flux above 100 GeV

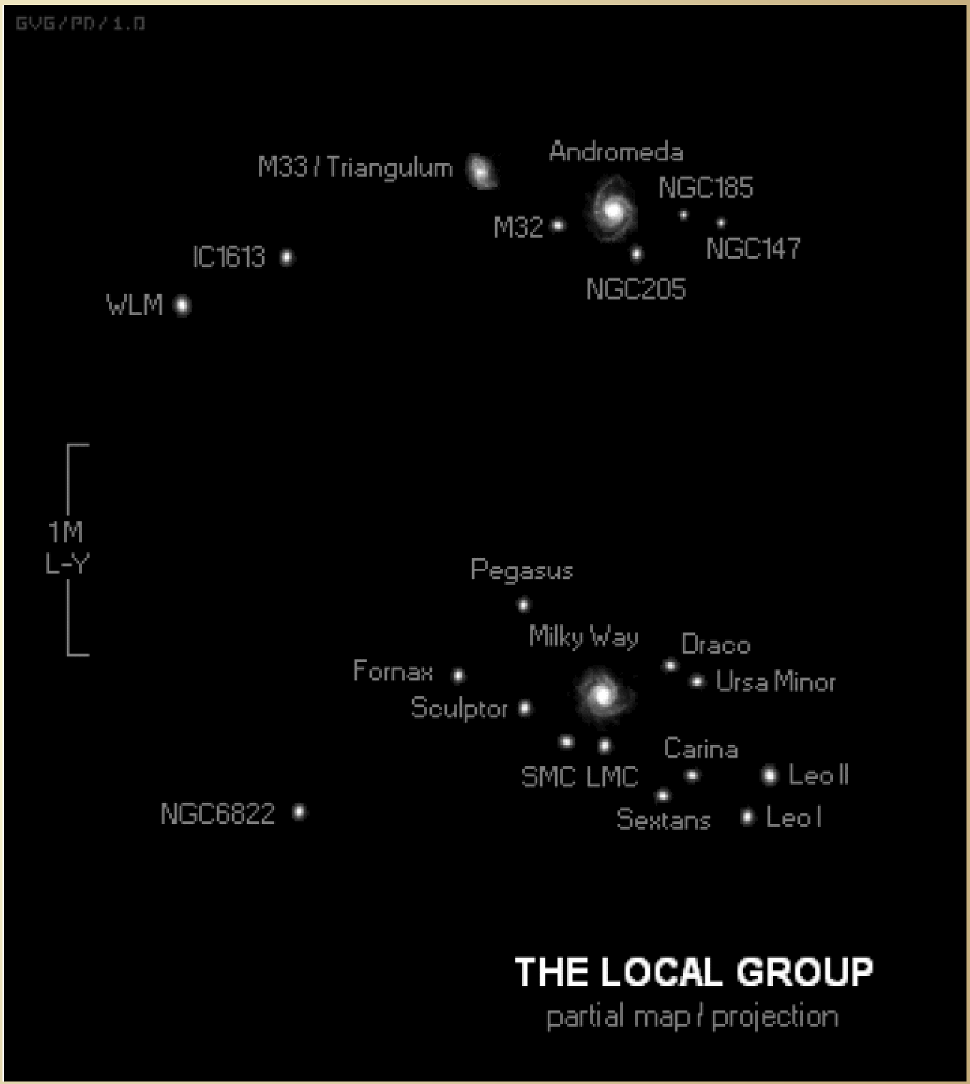
3% Crab	10 hours
1% Crab	80 hours
0.5% Crab	340 hours
0.1% Crab	Life time

J ~ 10^4 → Detectable Flux for $\langle\sigma v\rangle$ ~ 10^{-26} cm^3 s^{-1} and m_χ ~ 100 GeV

J ~ 10^3 → Detectable during lifetime of VERITAS observatory

Astrophysical Targets

- Flux scales as $V\rho_{DM}^2/D^2$
- Criteria
  - Nearby
  - Large Density of DM
- Targets
  - Galactic Center
  - Globular Clusters
  - Dwarf Galaxies
  - Local Group Galaxies
  - MW Satellites, DM sub-structures (random fields or guided by GLAST)



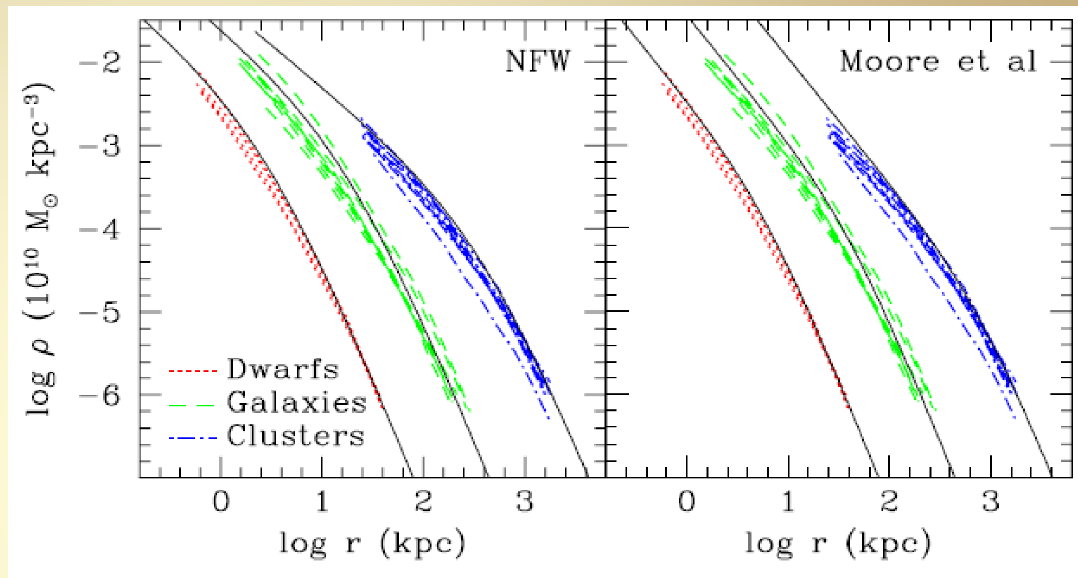
Diverse program with moderate exposure per target to sample different astrophysical environments (Js)

Sources (1st year)

- **Dwarf Galaxies (Ursa Minor, Draco, Sextans)** – Gravitational potential is dominated by DM on all scales. Can be well constraint by stellar kinematics. Provides minimal uncertainty in J value.
- **Baryon Condensation and BH growth (M15, M32)** – the formation of a steep central cusp in the baryonic density profile and/or slow growth of a BH may create a DM spike.
- **Rapid Core Relaxation Time (M33)** – To the extent that the annihilation rate is determined dynamically, objects with small two-body relaxation times may produce large annihilation fluxes.
- **Interacting systems (M31)** – Interaction of gravitationally massive objects may create asymmetrical enhanced DM density regions with substantially increased neutralino annihilation rates.
- **Extremely Massive BH (M87)** – DM cusp can be build through the mergers between BHs of very different masses without disruption during coalescence. There is known astrophysical background.
- **Galactic Center (GC)** – closest BH, concentrated DM component, search for spectrum truncation.

DM Density profiles

N-body CDM simulations:
Universal DM density profile
for dwarf galaxies → clusters



Navarro et al. 2004

NFW and Burkert profiles represent possible range of DM inner halo

$$\rho(r) = \rho_s \left(\frac{r}{r_s}\right)^{-\gamma} \left(1+\left(\frac{r}{r_s}\right)^{\alpha}\right)^{-\frac{\beta-\gamma}{\alpha}}$$

$$\rho(r) = \rho_s \left(1+\frac{r}{r_s}\right)^{-\gamma} \left(1+\left(\frac{r}{r_s}\right)^{\alpha}\right)^{-\frac{\beta-\gamma}{\alpha}}$$

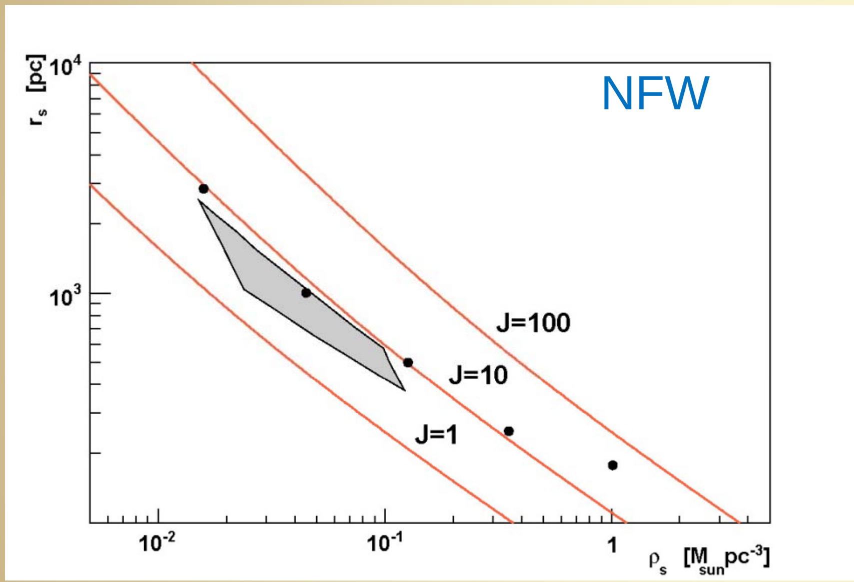
NFW Profile
$(\alpha,\beta,\gamma) = (1,3,1)$

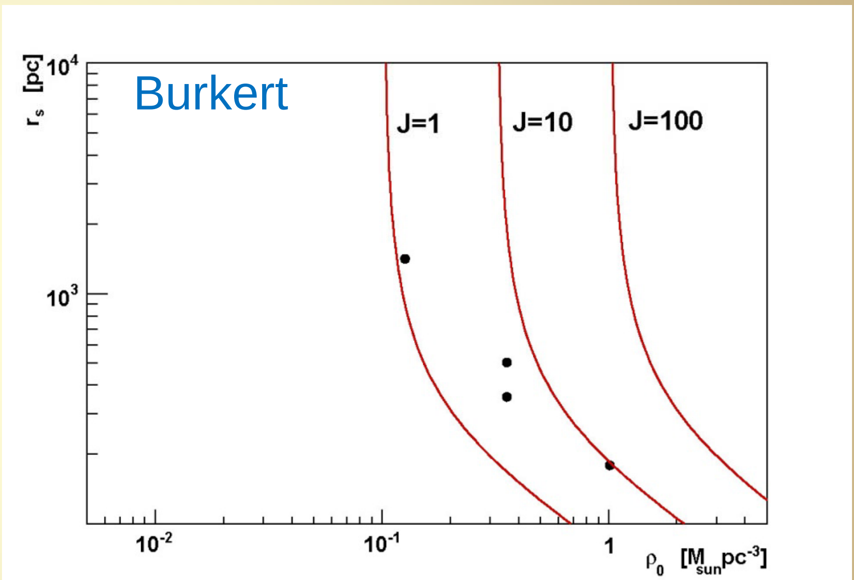
Moore Profile
$(\alpha,\beta,\gamma) = (1.5,3,1.5)$

Burkert Profile (1995)
$(\alpha,\beta,\gamma) = (2,3,1)$

Draco & Ursa Minor

Gravitational potential is DM dominated on all spatial scales
Can be robustly constrained using stellar kinematics (radial velocities)





(Strigari et al. 2006)
(Mashchenko et al. 2006)

(Mashchenko et al. 2006)

(Data by Wilkinson et al. 2004 and Munoz et al. 2005)

J_{min}~4 **J_{max} ~40**

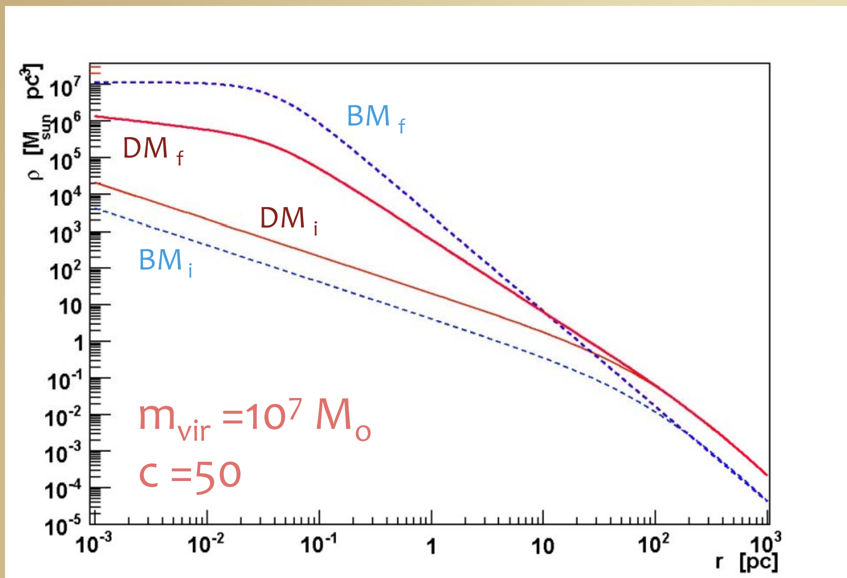
DM-BM Physics

Small Scales

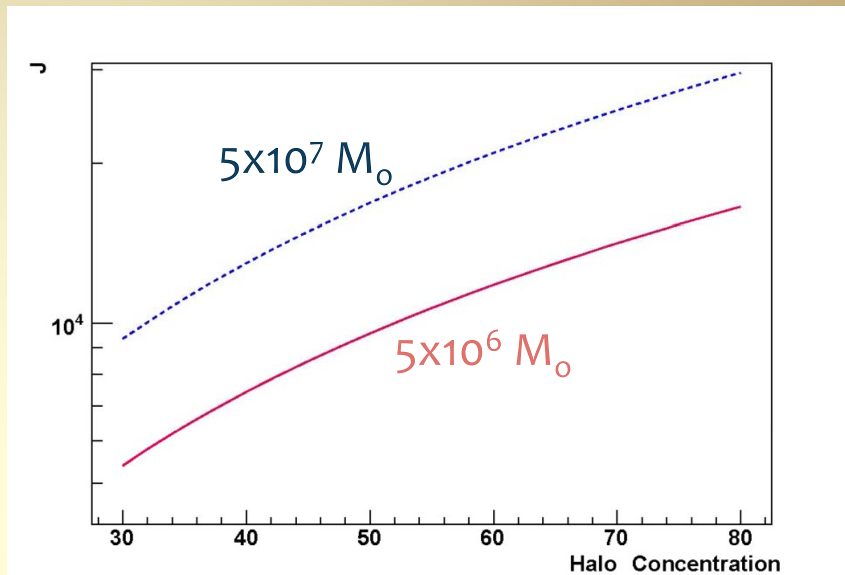
- Limitations of CDM simulations
  - Resolution of ~ 0.1 – 1 kpc
  - Effects of baryonic matter on small scale DM distribution is rarely simulated

- Additional considerations on small scales (< 10-100 pc)
  - Enhancement Factors
    - Condensation of stars/gas (e.g. core-collapse)
    - Growth of a central SMBH
  - Depletion Factors
    - Galactic merger events
    - Heat transfer to dark matter particles by stars and inspiraling SMBHs
  - Initial spectrum of perturbations on small scales is unknown

Case for M15



M15 Adiabatic Contraction



(by M. Wood)

Observational data provide weak upper limit on DM

5×10^{5} M_o(baryonic mass) < m_{vir} of DM halo < 5×10^{7} M_o(dynamical friction limit)

$r_{vir}/r_s = c(m_{vir})$ (Bullock et al. 2001) + Adiabatic Contraction

$$c = 9\left(\frac{m_{vir}}{1.5\times10^{13}h^{-1}M_\odot}\right)^{-0.13}$$

$$\Delta \log c \simeq 0.14.$$

J_{min}~7 (NFW no AC) **J_{max} ~2 x 10^4 (NFW + AC)**

Relatively conservative assumptions

J estimates

Source	Model	J_{min}	J_{max}
Draco	Burkert	1	10
	NFW	4	40
Ursa Minor	NFW	4	20
M15	NFW	7	150
	NFW+AC	8×10^3	2×10^4
M32	Burkert	0.6	?
	NFW +AC	1	
M33	Burkert	0.03	?
	NFW+CR/AC	0.2	

Small scales sub-structures in DM halo can further enhance J

Whipple 10m Observations

Data

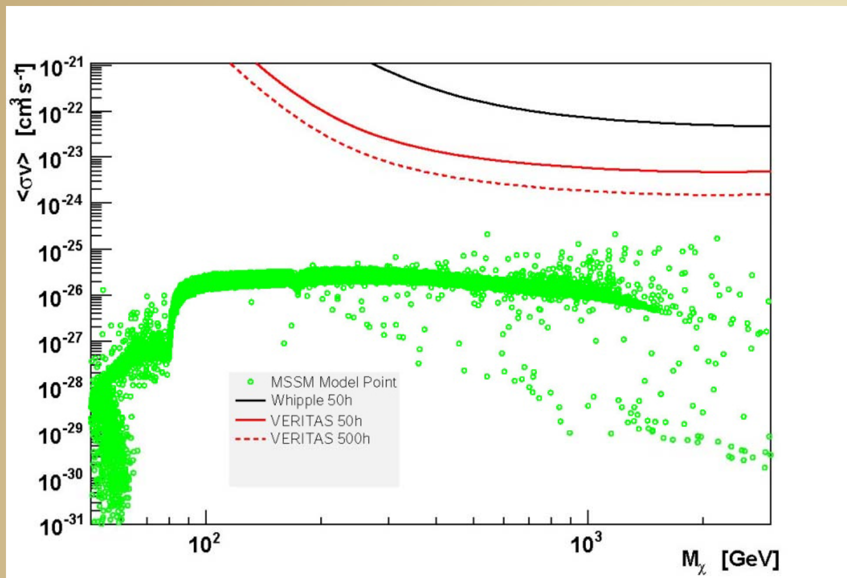
Source	Period	t_{ON} (hours)	t_{TRK} (hours)	t_{ON+TRK} (hours)
Draco	Mar 2003 - Jul 2003	7.4	6.9	14.3
Ursa Minor	Jan 2003 - Jul 2003	7.9	9.3	17.2
M32	Sep 2004 - Dec 2004	6.9	0	6.9
M33	Oct 2002 - Dec 2004	7.9	9.2	17.0
M15	Oct 2001 - Jul 2002	0.9	2.1	3.1

Limits

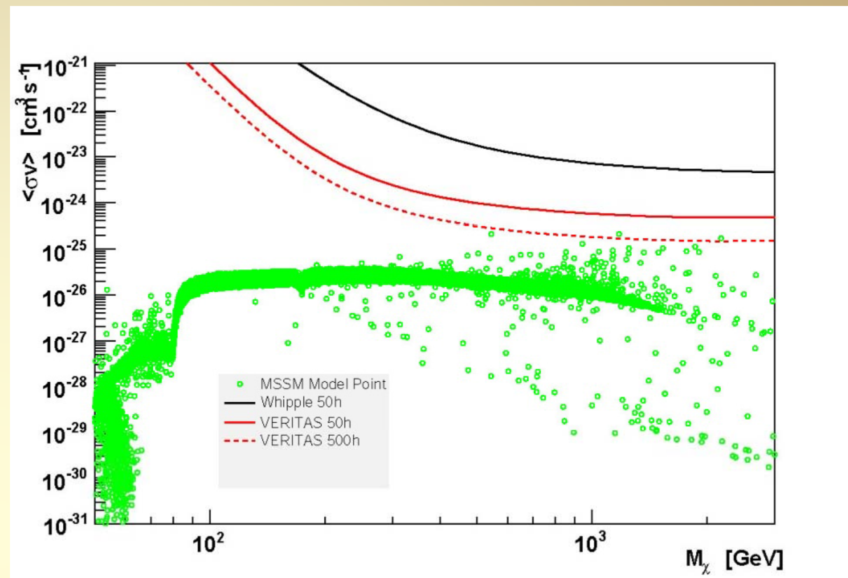
Source	Excess (γ min^{-1})	95% U.L. (γ min^{-1})	σ	400 GeV Integral Flux Upper Limit (erg cm^{-2} s^{-1})	400 GeV Integral Flux Upper Limit (% Crab)
Draco	0.001 ± 0.066	0.14	0.02	1.02×10^{-11}	6.23
Ursa Minor	0.075 ± 0.070	0.20	1.07	1.46×10^{-11}	8.94
M32	-0.240 ± 0.170	0.21	-1.44	1.20×10^{-11}	7.34
M33	-0.012 ± 0.085	0.16	-0.14	1.15×10^{-11}	7.04
M15	0.084 ± 0.270	0.59	0.31	3.38×10^{-11}	20.6

(M. Wood, J. Hall)

SUSY Limits



J=100



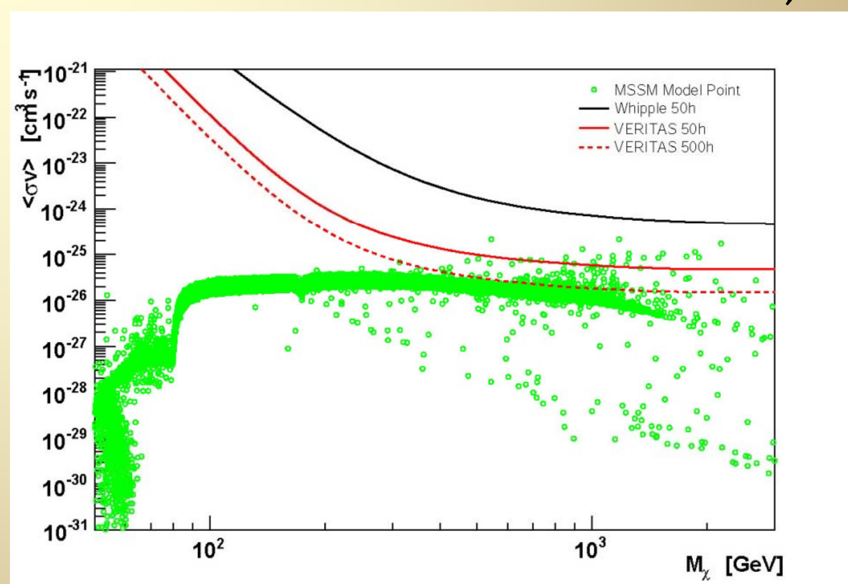
J=1,000

Whipple 10m (50h) → J~10^5

VERITAS (50h, 500h) → J~10^4

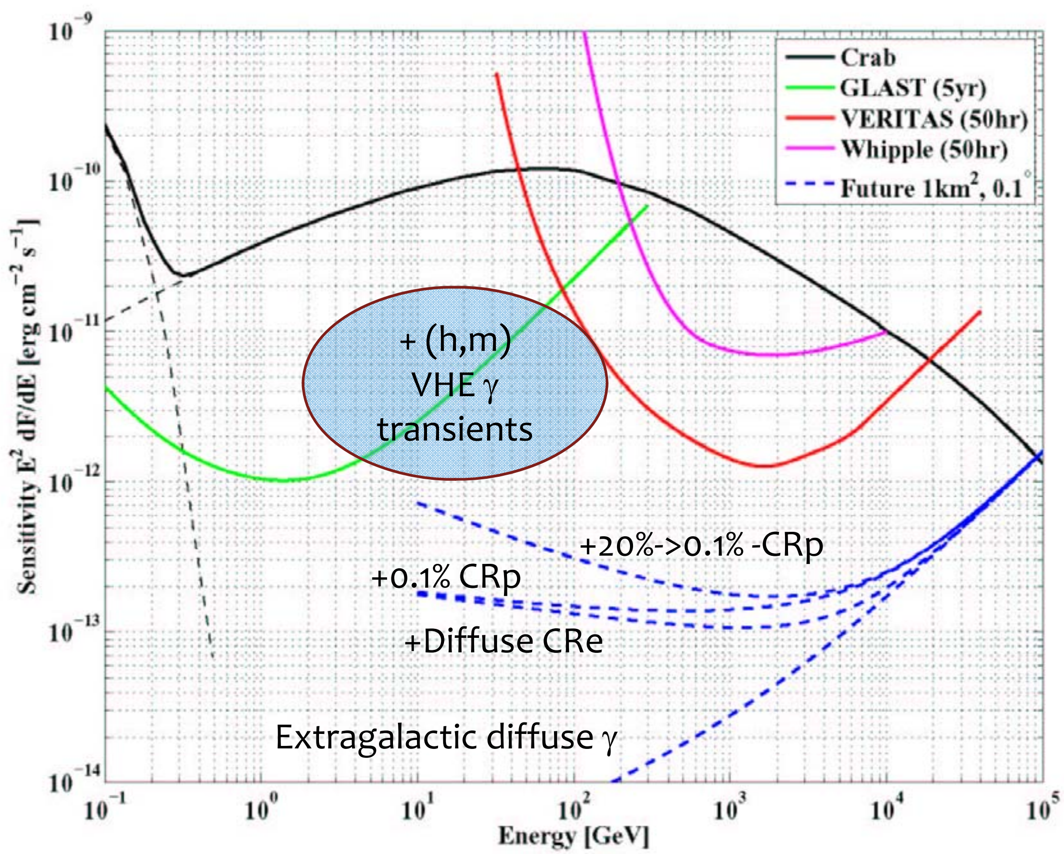
Scan of 10^6 MSSM Models with DarkSUSY (Gondolo et al. 2004)

All models within 3σ of current WMAP Constraints on Ωh^2



J=10,000

Science Opportunity



(S. Fegan & V. Vassiliev)

Differential sensitivity of ideal 1km² IACT array

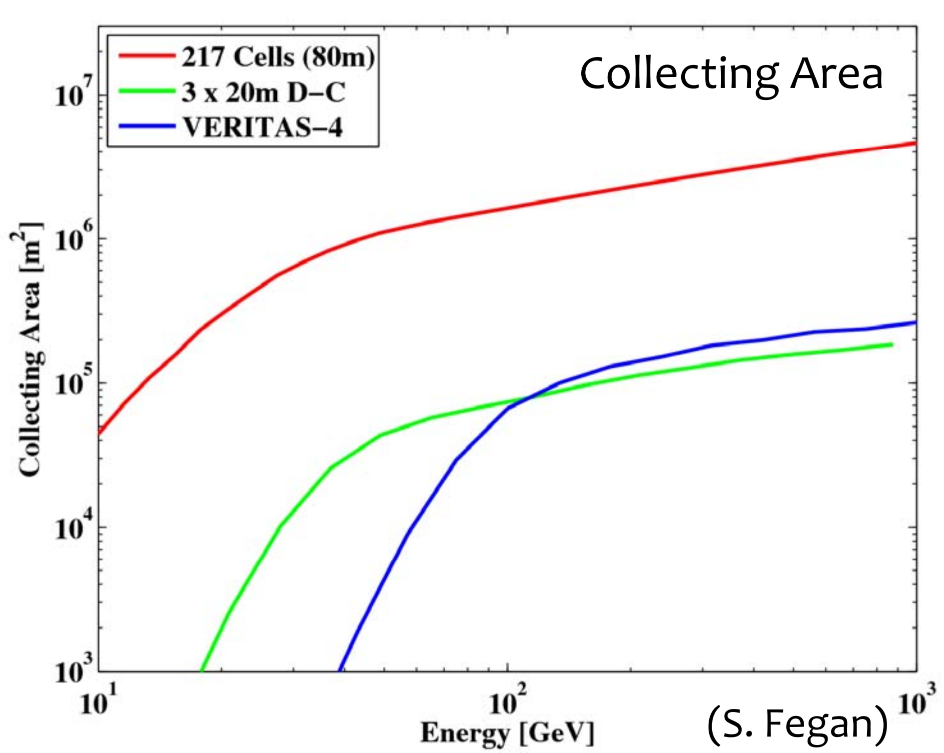
Future Project

Area: 1 km^2
Angular resolution: 0.1°
$\Delta E/E=0.58$ (4 bins per decade)

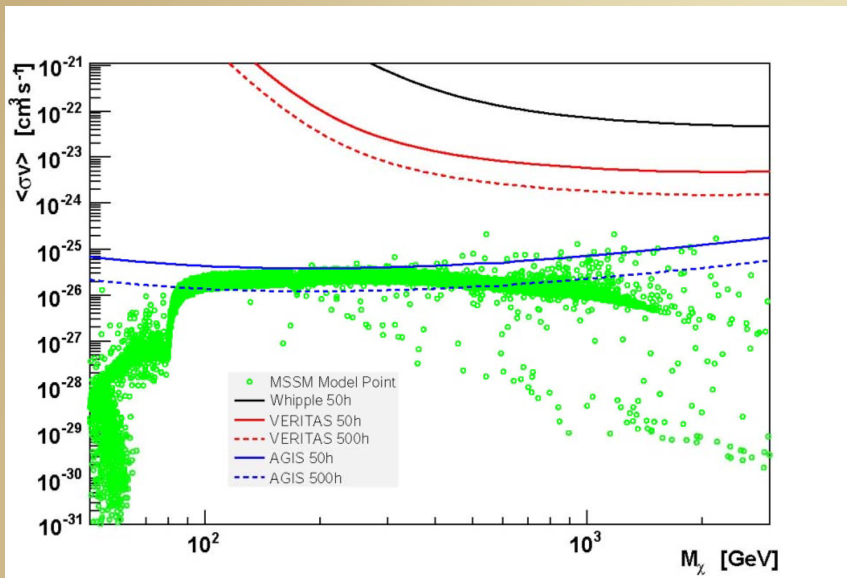
Advanced Gamma-ray Imaging System

(artist view by J. Buckley, Wash.U.)

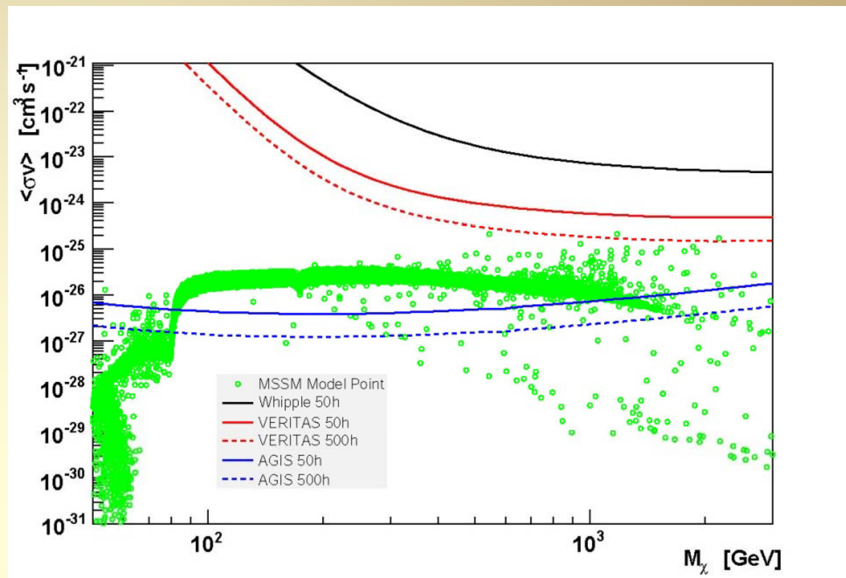
Science goal: to be finalized by WP
Budget: ~130M$, “Moderate Initiative”
Observatory: ~1km² array of mid-IACTs
IACTs: 150-50 identical telescopes (+…)
CT Aperture: 5-15 m (#CTs & aperture TBD)
Technology: demonstrated AC technique
R&D: Novel Camera, OS , Trigger, DAQ
Field of View: 5-12° (TBD)
OS & Camera: (TBD)
DAQ Elec.: (TBD)
Telescope & Array Trigger: (TBD)
Site Elevation: ~1500-4200



SUSY Limits



J=100



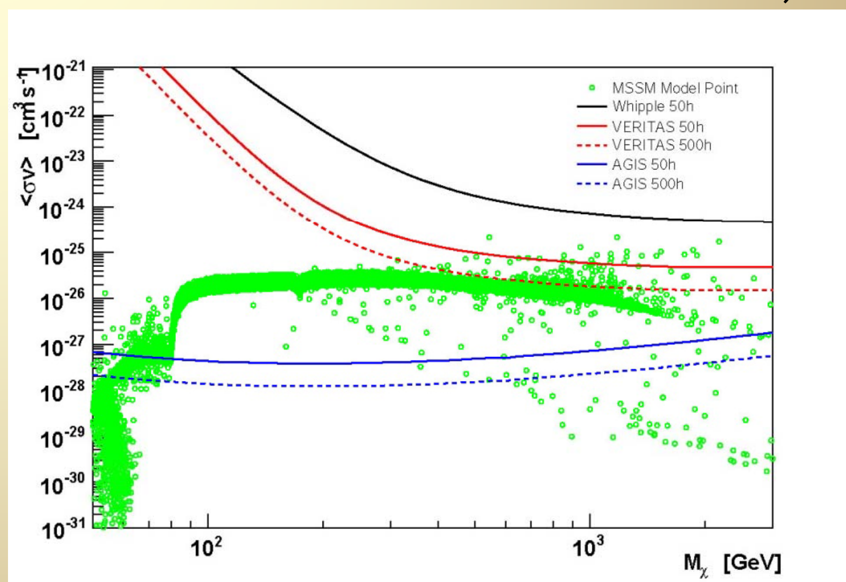
J=1,000

Whipple 10m (50h) → J~10^5

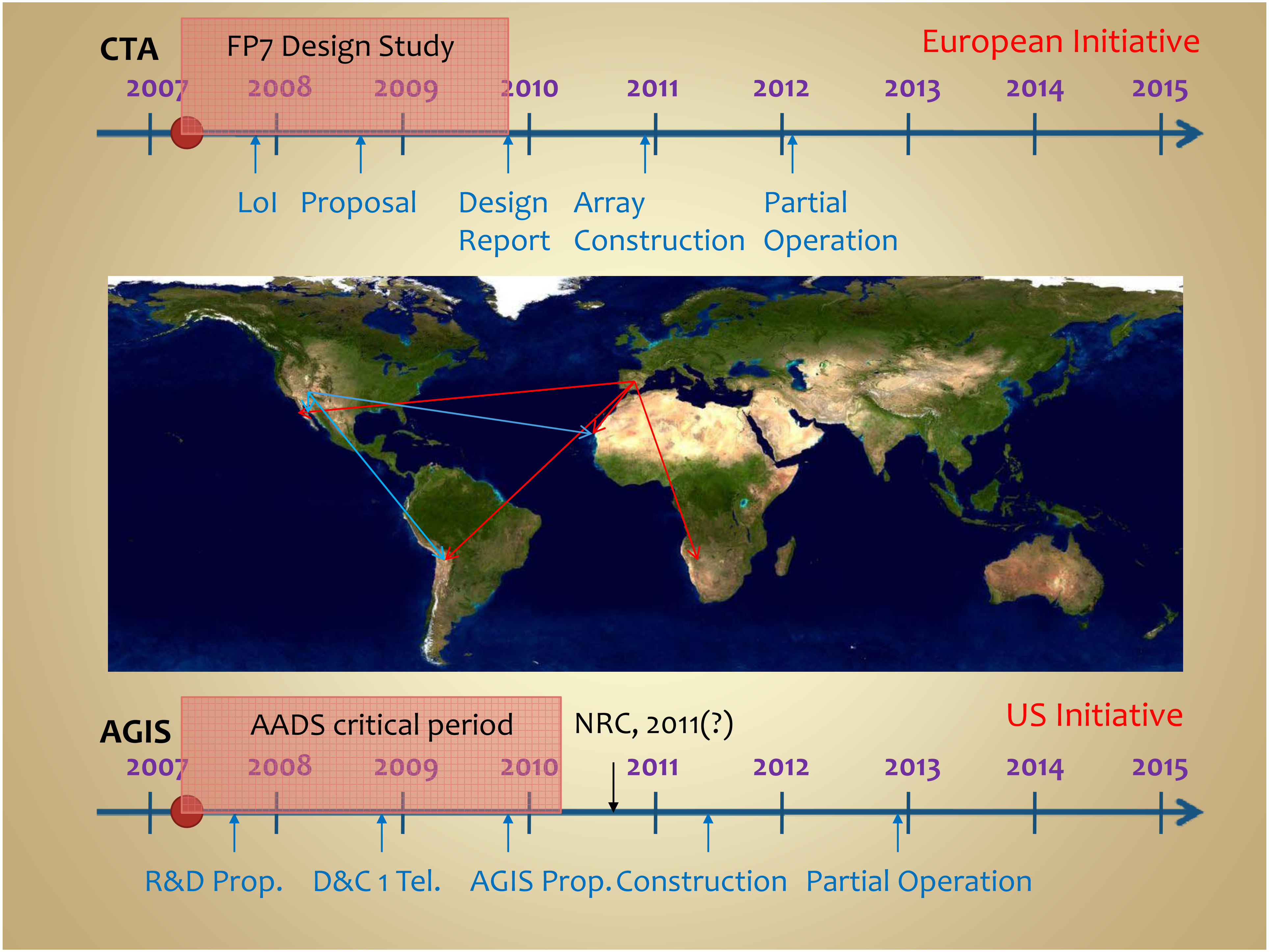
VERITAS (50h, 500h) → J~10^4

AGIS (50h, 500h) → J~10^2

VERITAS	AGIS
E_{peak} ~300 GeV	E_{peak} ~30 GeV
$A(E_{peak})$ 8×10^4 m²	$A(E_{peak})$ 6×10^5 m²



J=10,000


CTA
FP7 Design Study
European Initiative
2007
2008
2009
2010
2011
2012
2013
2014
2015
LoI
Proposal
Design Report
Array Construction
Partial Operation
AGIS
AADS critical period
NRC, 2011(?)
US Initiative
2007
2008
2009
2010
2011
2012
2013
2014
2015
R&D Prop.
D&C 1 Tel.
AGIS Prop.
Construction
Partial Operation

US Activities

"Towards the Future…"

- "Ground-based Gamma-ray Astronomy: Towards the Future", October 20-21, 2005, UCLA, Mays' landing, Malibu, CA http://gamma1.astro.ucla.edu/future_cherenkov/

- "Ground Based Gamma Ray Astronomy: Towards the Future", May 11-12, 2006, LANL, Santa Fe, NM, http://www.lanl.gov/orgs/p/g_a_d/p-23/gammaworkshop

- "Ground Based Gamma Ray Astronomy: Towards the Future", May 13-14, 2007, ANL & UC, Chicago, IL, http://www.hep.anl.gov/byrum/next-iact/index.html

White Paper

Extensive discussions of the status of VHE γ-ray Astronomy with James Ryan, Chair of the APS DAP, took place during Santa Fe meeting. As a result the APS solicited a White Paper with the following official charge:

"The Division of Astrophysics of the American Physical Society invites you **to prepare a review or white paper on the status and future of ground based TeV gamma-ray astronomy**. With the upcoming commissioning of VERITAS and the success of HESS and other is this emerging field, **a review of the science accomplishments and potential** would be welcome. Furthermore, given the long lead time for designing, developing and deploying new instruments, we need **a clear path for proceeding beyond the near term.**"

Dear Colleagues,

The Division of Astrophysics of the American Physical Society invites you to prepare a review or white paper on the status and future of ground based TeV gamma-ray astronomy. With the upcoming commissioning of VERITAS and the success of HESS and others in this emerging field, a review of the science accomplishments and potential would be welcome. Furthermore, given the long lead time for designing, developing and deploying new instruments, we need a clear path for proceeding beyond the near term.

Understanding that this is a significant task, we would ask you to do the following:

- Consider yourselves the editorial board for this white paper. This entails being ultimately responsible for the drafting, formatting and distribution of the report.
- Recruit, as necessary, a very small number of other people to augment you as an editorial board. These people might be important players in TeV gamma-ray astronomy or astrophysics who might lend their expertise and stature to the preparation of the report. Please ensure that a spectrum of researchers is represented on the board to promote objectivity and avoid the appearance of advocacy.
- Delegate, as necessary, to willing and knowledgeable people in the field the collection and synthesis of information necessary for drafting this report. These people would likely draft sections of the report that you would, in turn, edit and merge with other sections.

There is little time to prepare this report for release at the April 2007 APS meeting, however, it would fitting if this report could be released at the April 2008 meeting. If is available a sufficient time before the April 08 meeting, we should consider releasing it by other means for the benefit of the community.

We suggest that as soon as possible you begin soliciting financial support from interested agencies, institutions and parties. The costs for travel and production of the report will not be trivial.

Although, I am in no position to offer financial support from the DAP you are free to ask for such support, but as members you know the limitations of our resources and the difficulty of maintaining them.

The Executive Committee appreciates your investment of time and energy into the future directions of this important field. If we, the Executive Committee, can be of help, please feel free to ask.

On Behalf of the DAP Executive Committee,
Sincerely Yours,
Jim
James Ryan
Chair

B. Dingus (LANL / MILAGRO)
H. Krawczynski (WU / VERITAS, EXIST)
M. Pohl (ISU / Theory, GLAST)
V. Vassiliev (UCLA / VERITAS)

W. Hofmann (MPI / HESS)
S. Ritz (GSFC, NASA / GLAST)
F. Halzen (U. W-M / Ice Cube)
T. Weekes (CfA / VERITAS)

Formed in Sep – Nov, 2006

Conclusions

- Whipple 10m ACT had probed neutralino SUSY parameter space under assumption of extreme astrophysical conditions ($J>10^5$) in the cores of a sample of local group galaxies and globular clusters. No DM annihilation candidate was found.

- VERITAS, HESS, and MAGIC observatories will be able to test hypothesis of neutralino being a DM particle in a more realistic astrophysical environments ($J>10^3$), in which, however, baryon-DM interaction must play a prominent role to increase neutralino density. Regrettably regions of high baryon density are subjected to natural VHE astrophysical backgrounds also. Detection of sub-structures (mini-halos) in MW DM halo represents an opportunity for GLAST observations which will be followed ground based ACTs.

- Next generation instruments AGIS/CTA can make a decisive contribution to indirect DM searches above ~100 GeV by probing dark matter dominated (“baryon independent“) astrophysical systems ($J>10^1$) with reduced astrophysical uncertainties allowing exclusion of significant part of SUSY parameter space. Detection would be better!

"Ground Based Gamma Ray Astronomy: Towards the Future", May 13-14, 2007, ANL & UC, Chicago, IL, http://www.hep.anl.gov/byrum/next-iact/index.html

We solicit your contribution(s) to WP effort and invite joining AGIS (US) / CTA initiative