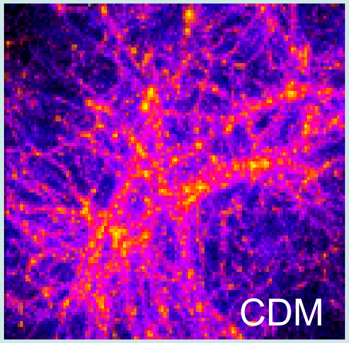
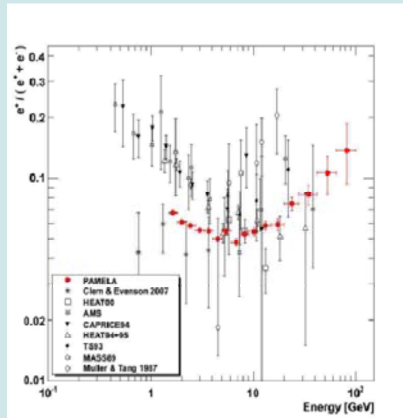
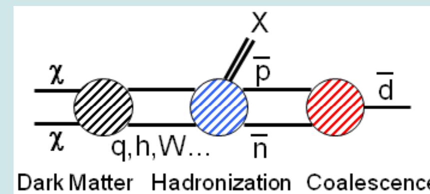
Astrophysical Signatures of Particle Dark Matter

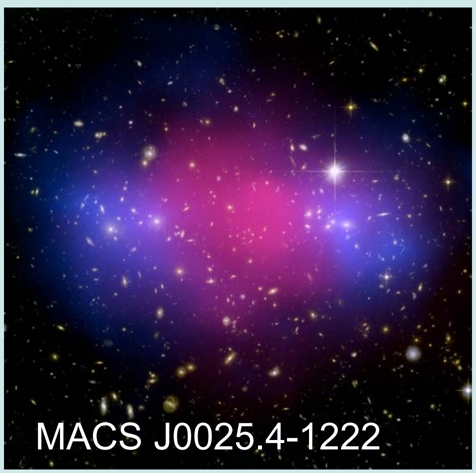


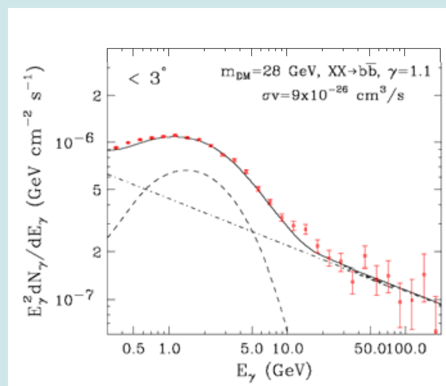


positrons ?

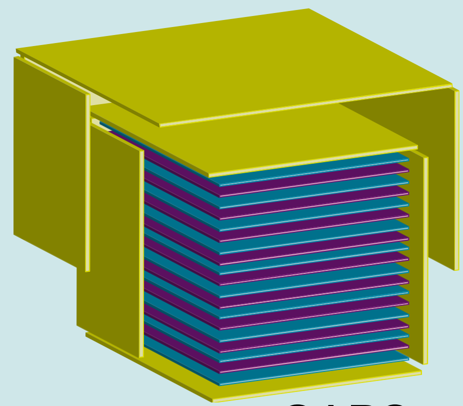
anti-deuterons ?







γ–rays?



GAPS

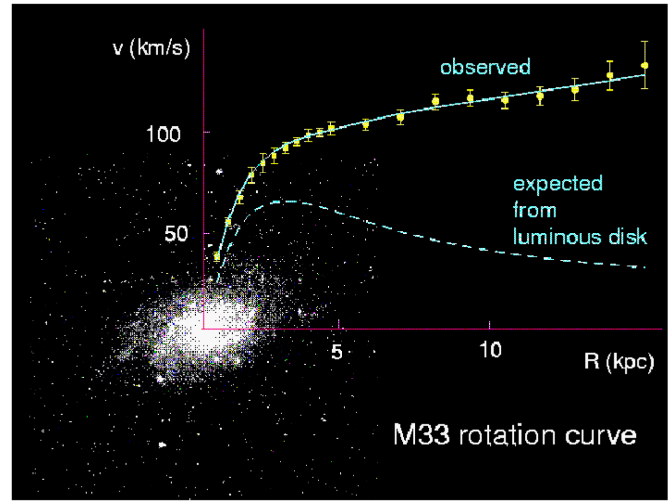
Rene A. Ong (UCLA) **McGill Astrophysics Seminar** **26 Oct 2010**

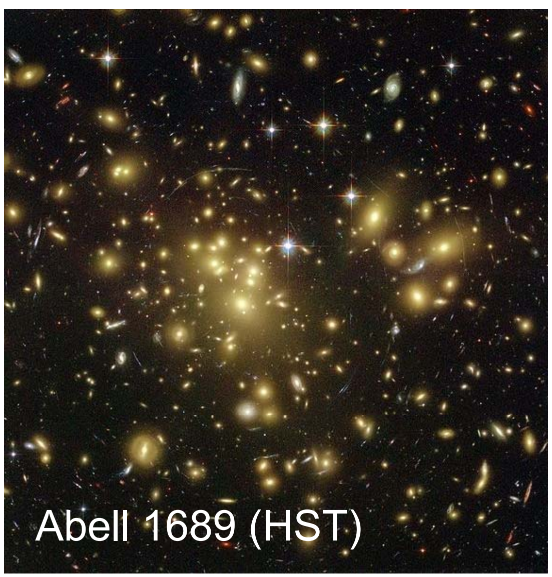
Outline

- Astrophysical evidence for dark matter.
- Motivation for a dark matter particle.
- Indirect Detection: γ, ν, and anti-matter.
- Searching for the **anti-deuteron** – the *why* and *how*.
- GAPS:
  an anti-deuteron search using a novel technique.
- Future prospects.

Astrophysical Evidence for DM

- Zwicky (1933) saw large velocity dispersion of galaxies in Coma cluster.
- Later, Virgo (1936) & Andromeda (1939).
- 1960's & 1970's: rotation curves of spirals (e.g. Rubin & Ford 1975) → clear evidence.
- Extended to ellipticals, LSB galaxies, MW.

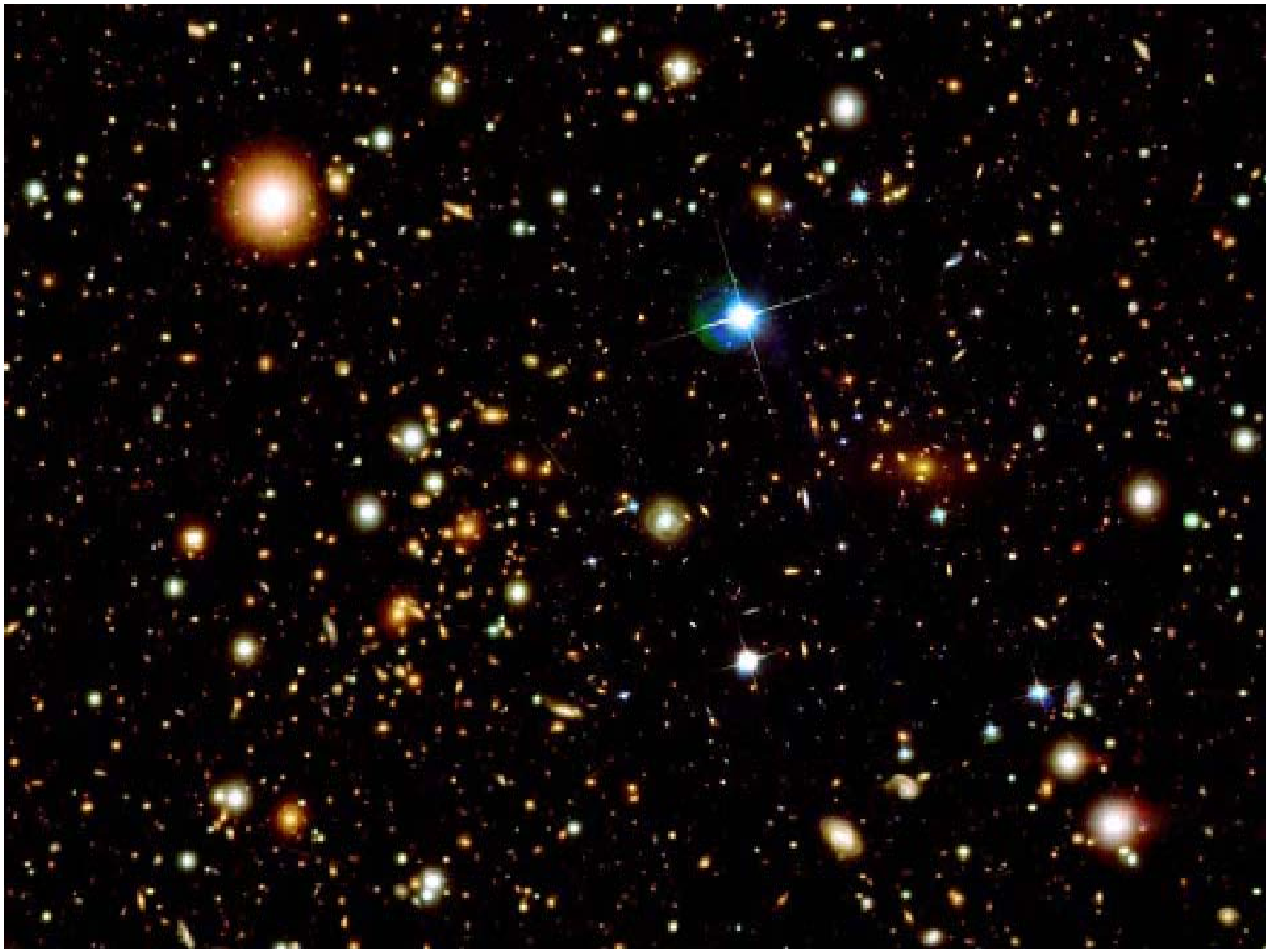




- Galaxy clusters – velocity dispersions & X-ray measurements of hot gas.
- Strong gravitational lensing.
- Weak lensing – galaxy surveys.
- etc. …

Colliding Galaxy Clusters

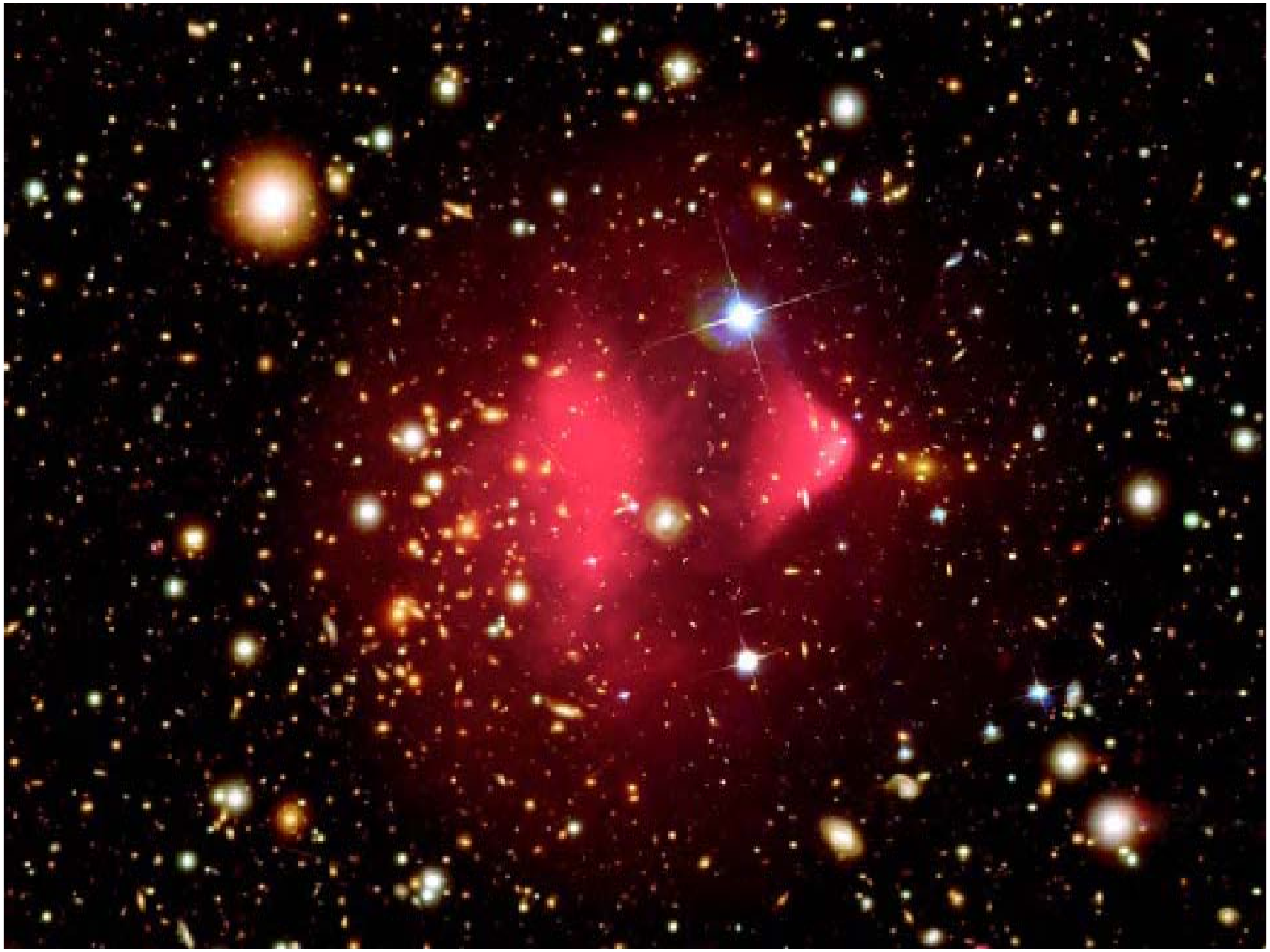
1E 0657-56 (Bullet Cluster)



Optical (HST, Magellan)

Colliding Galaxy Clusters

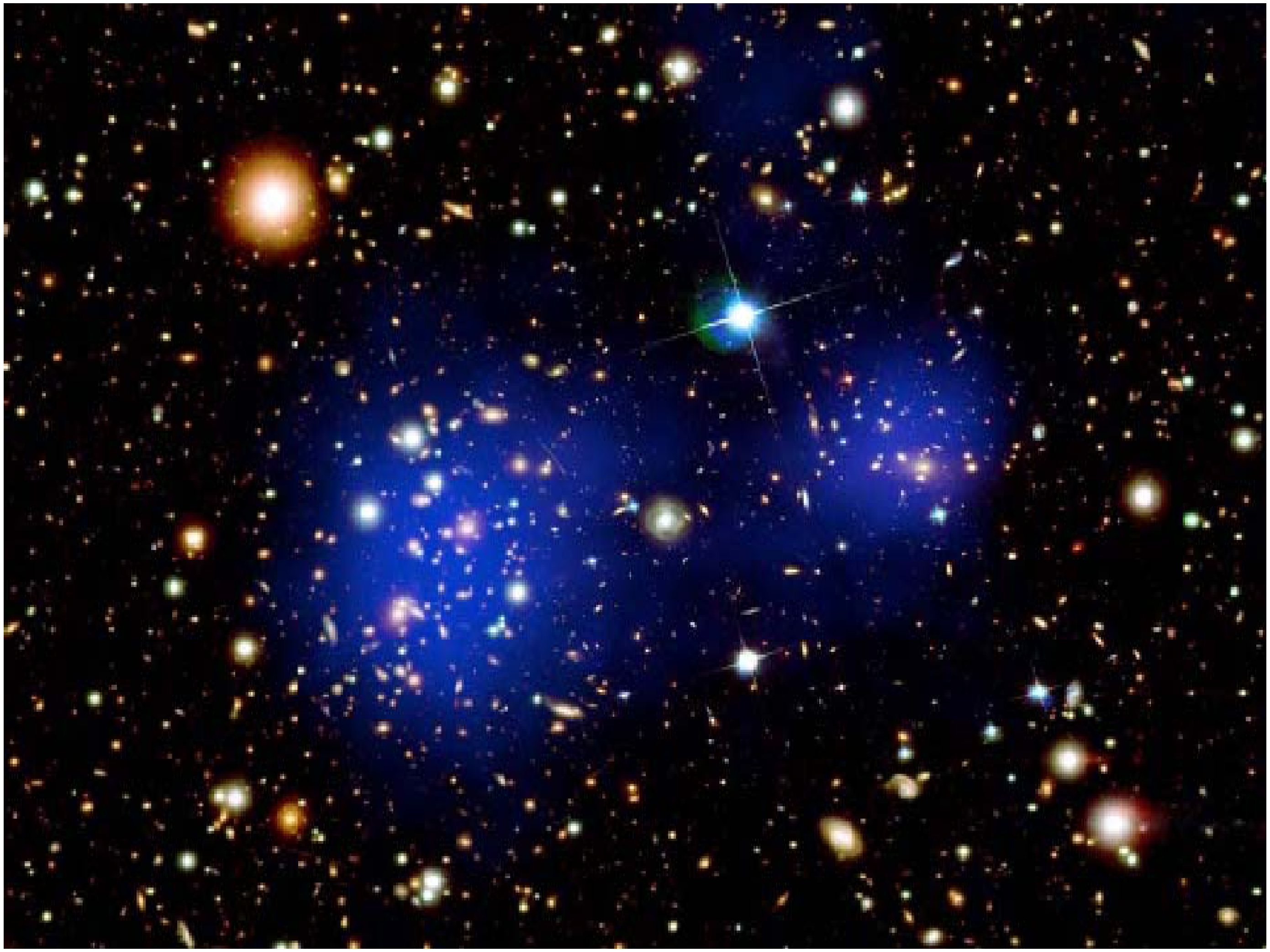
1E 0657-56 (Bullet Cluster)



Optical (HST, Magellan) + X-ray (Chandra)

Colliding Galaxy Clusters

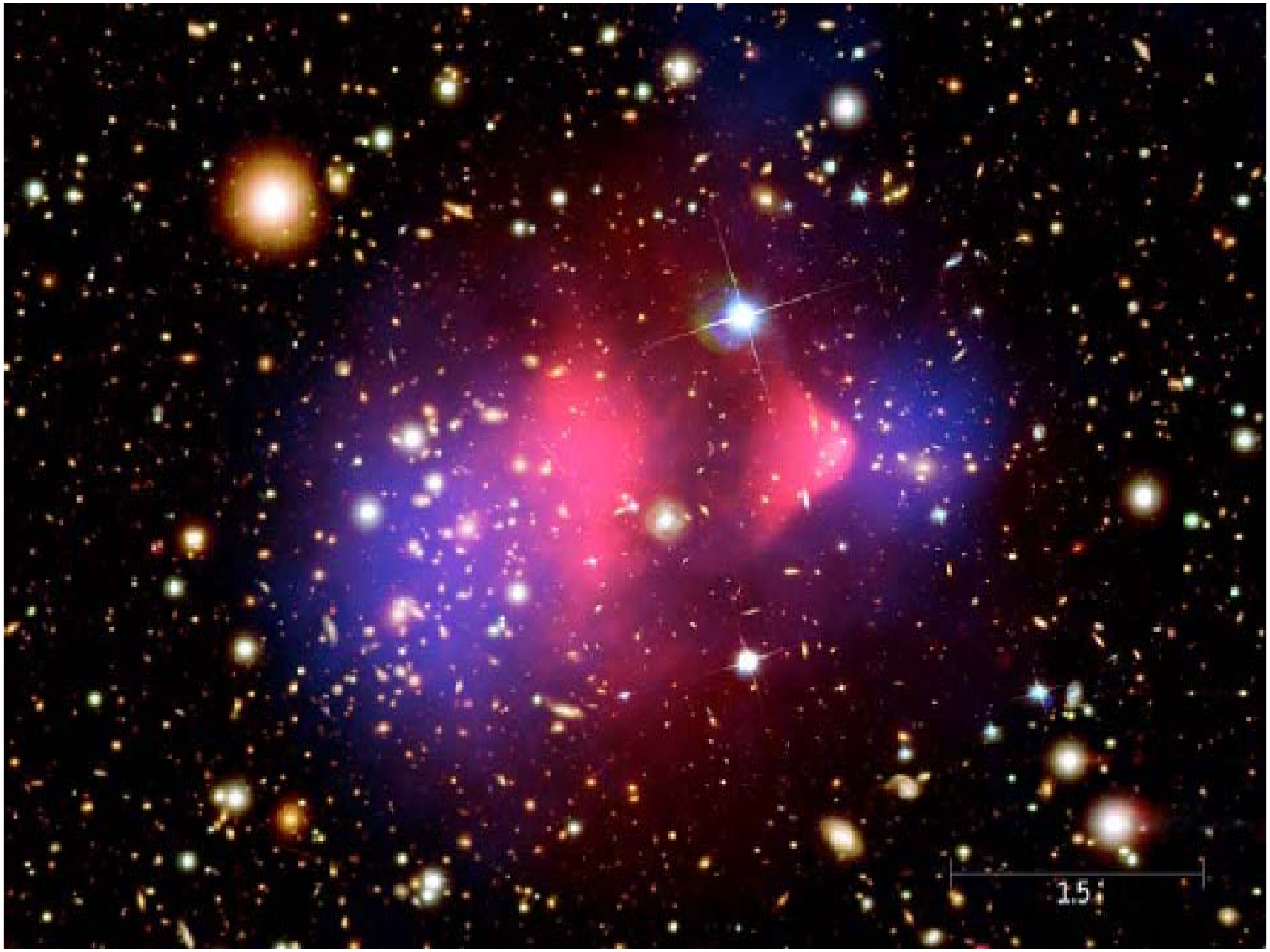
1E 0657-56 (Bullet Cluster)



Optical + Lensing (HST, Magellan, ESO WFI)

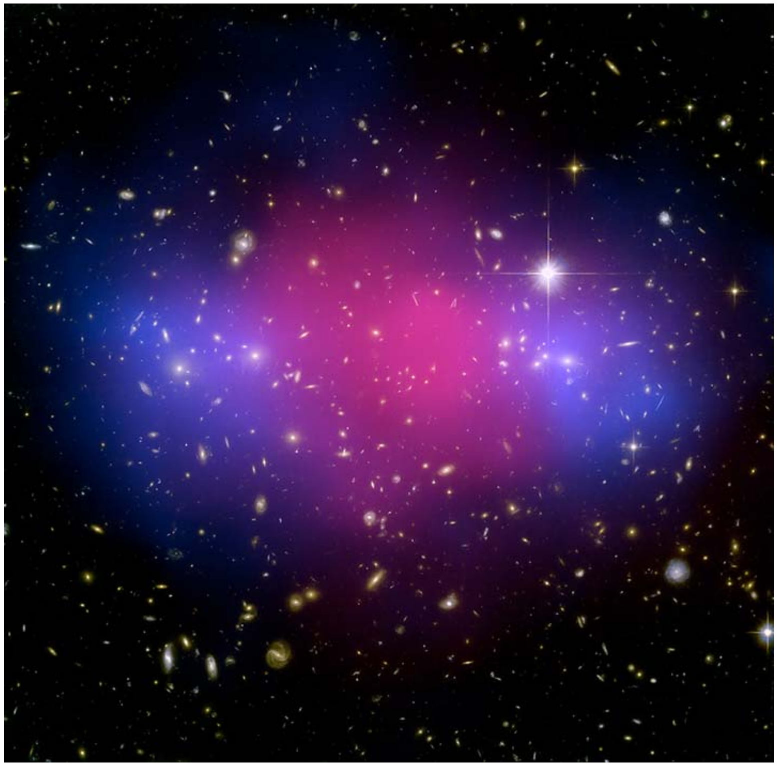
Colliding Galaxy Clusters

1E 0657-56 (Bullet Cluster)



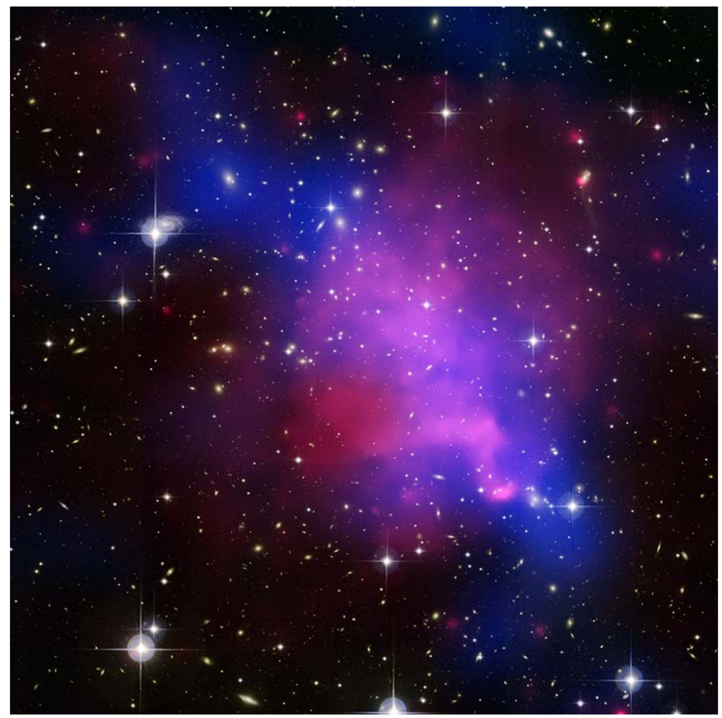
Optical + Lensing (HST, Magellan, ESO WFI)

More Evidence

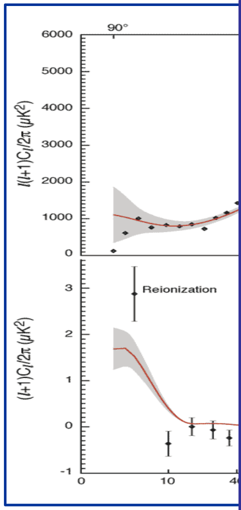


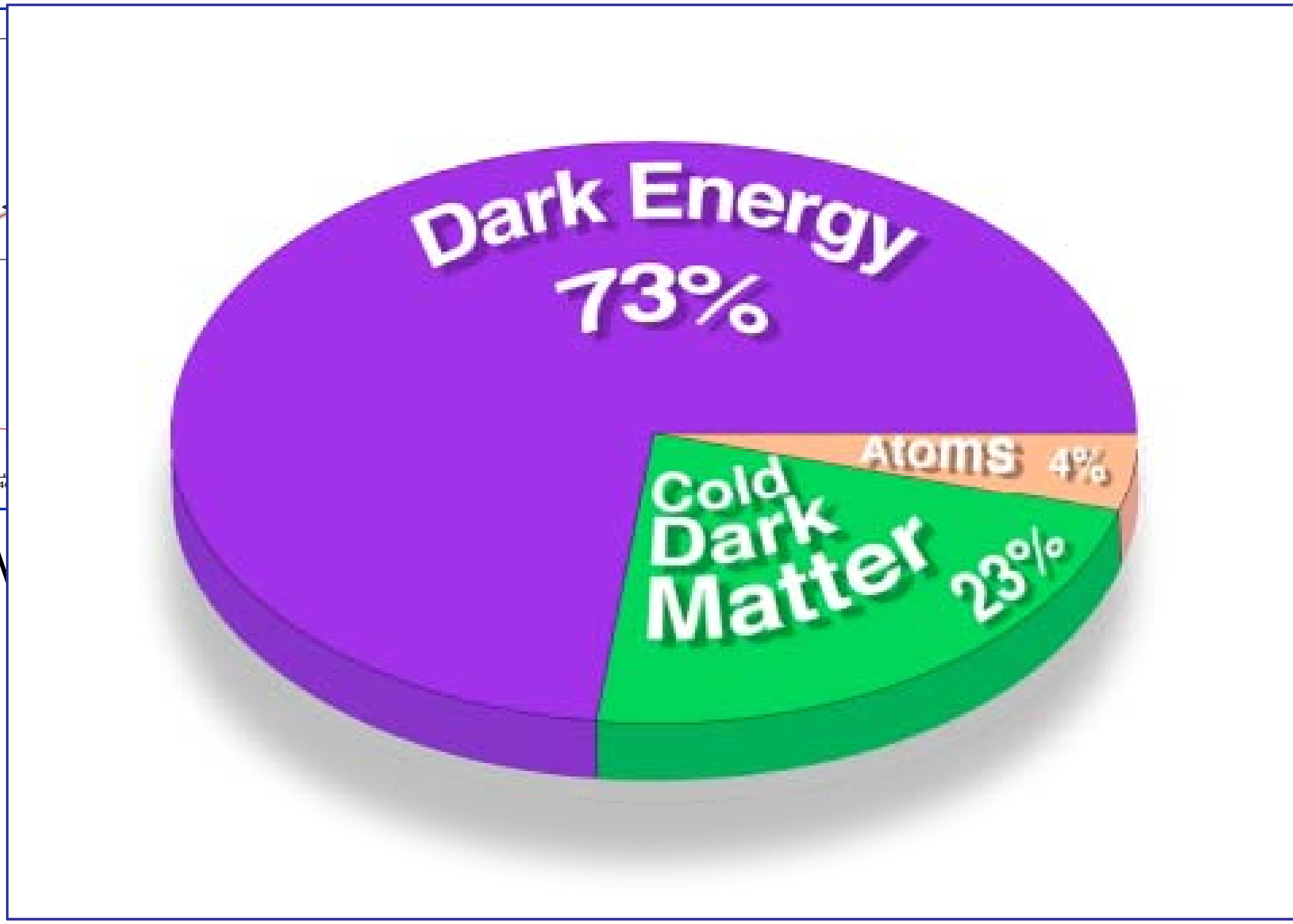
MACS J0025.4 -1222
(Chandra, HST)

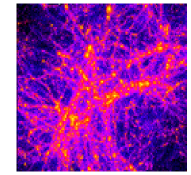
Abell 520
(Chandra, CFH, Subaru)

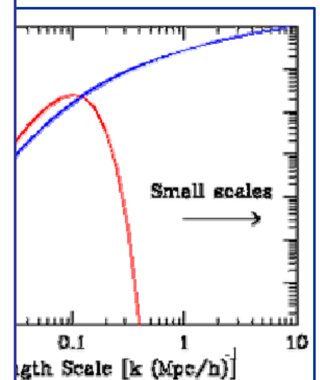


Key Pieces from Cosmology









CM
(+

e Formation

ic, forms large
s that fragment
ical, bottom-up

DM is non-baryonic.

DM is not hot.

Comments

- There are “other” dark matter problems – e.g. in Galactic disk, the solar neighborhood, etc.
- There are problems with CDM, including:
  small scale features not observed – e.g. “cuspy” halos
  “missing satellites” problem …
- Alternatives to CDM include:
  - WDM
  - self-interacting DM
  - decaying DM
  - “fuzzy” DM
  - strong-interacting DM
  - etc. etc.

→ **CDM hypothesis needs testing/verification. This motivates need to detect particle DM.**

Cold DM Candidates

Many candidates:

- Primordial BH's – possible, but production mechanism unknown.
- Axions – motivated by particle physics ; searches underway.
- Weakly interacting massive particles (WIMPs):

Motivated by "fact" that present relic density is consistent with that expected for a particle that has weak-scale (~TeV) interactions.

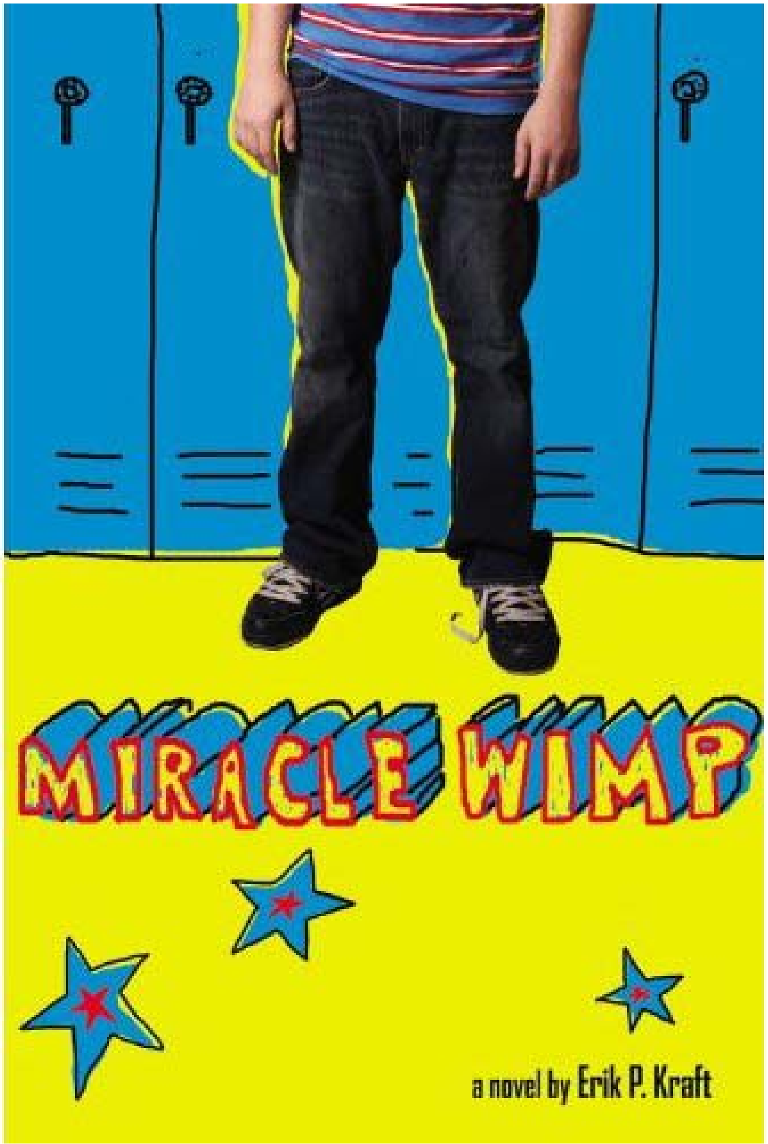
i.e. WIMPs (χ) were in thermal equilibrium and then "froze out":

$$\Omega_\chi h^2 \approx 10^{-27} cm^3 s^{-1} / < \sigma_A \mathrm{v} >$$

implies a suitable relic density for σ_A, m_χ at electroweak scale.

"WIMP Miracle"

Not to be confused with …



Another miracle ?

There is the additional motivation from particle physics trying to explain electroweak symmetry breaking (EWSB):

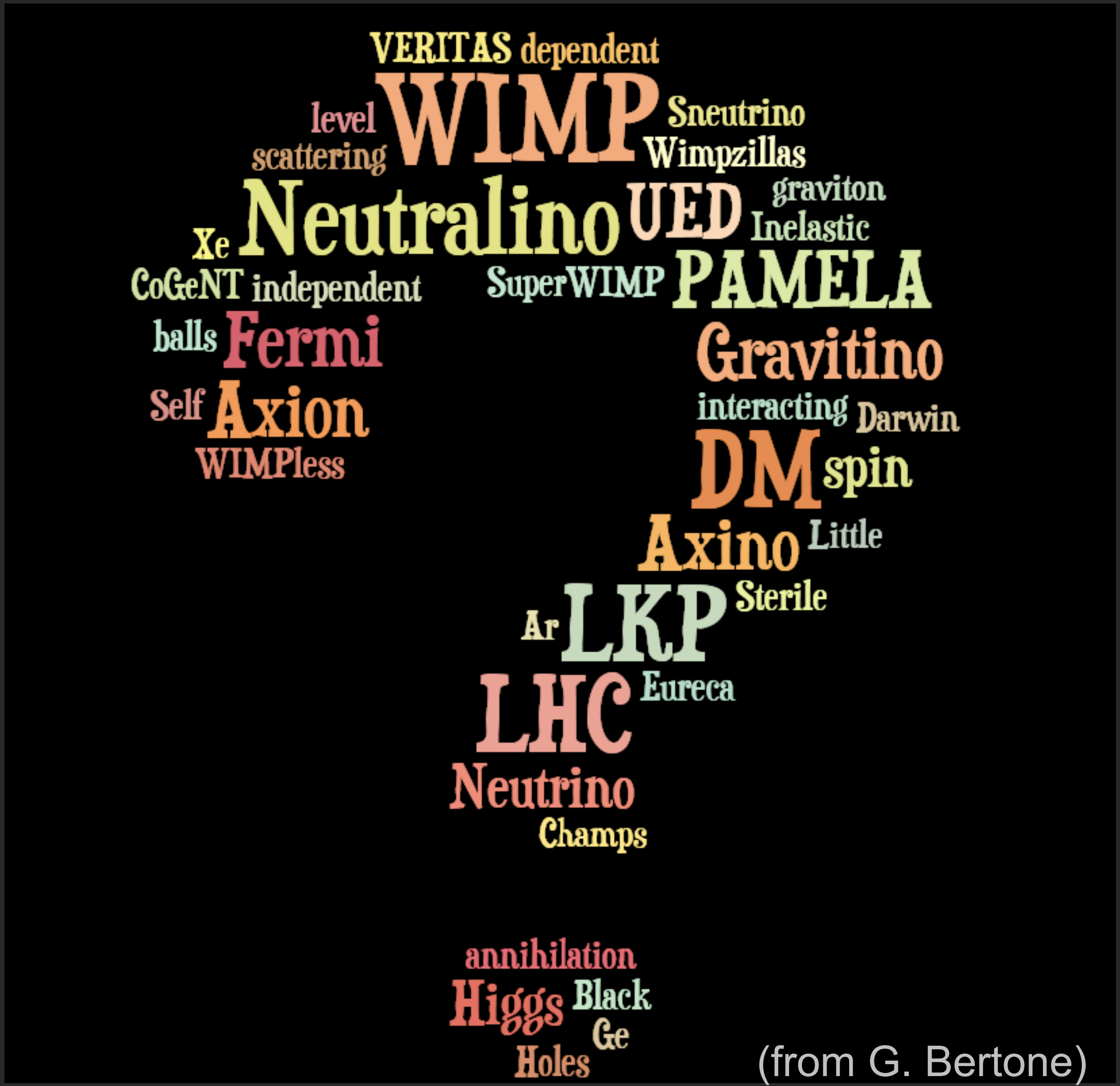
→ New physics at ~ TeV scale

– This has spawned an enormous amount of theoretical activity and many viable candidates for CDM as a new particle, e.g.:
    Supersymmetry (SUSY): WIMP = LSP
    Kaluza-Klein theory (UED): WIMP = LKP (U(1) gauge boson)

Important point:
New particle physics models have many parameters, none of which are known. Thus, we have a:
→ large uncertainty in properties of DM particle (e.g. cross-sections).
→ difficulty in placing meaningful constraints on theory.

("*You're only allowed one miracle*.", L. Rosenberg, 1990.)

Actually, we have no idea !



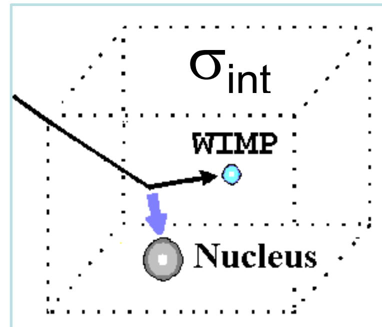
… and we really need to detect a DM particle.

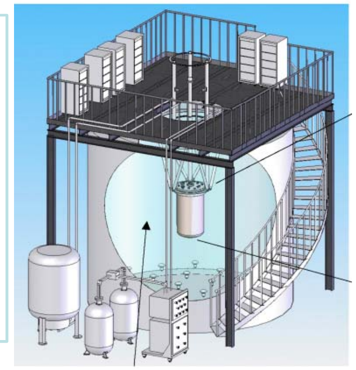
Complementary Approaches

Produce DM particle in accelerators

LHC at CERN

Direct DM Detection





Xe Detector

Astrophysical Indirect Detection

Sextens dwarf galaxy

Annihilation (σ_A)
$\chi\chi \rightarrow$
γ's, ν's,
anti-matter

Why Different Approaches?

LHC could well see evidence for a new particle and measure its mass, but LHC will not:

- tell us whether this particle is stable,
- measure the couplings/interactions of this particle in detail, or
- tell us whether this particle makes up all/any of the DM.

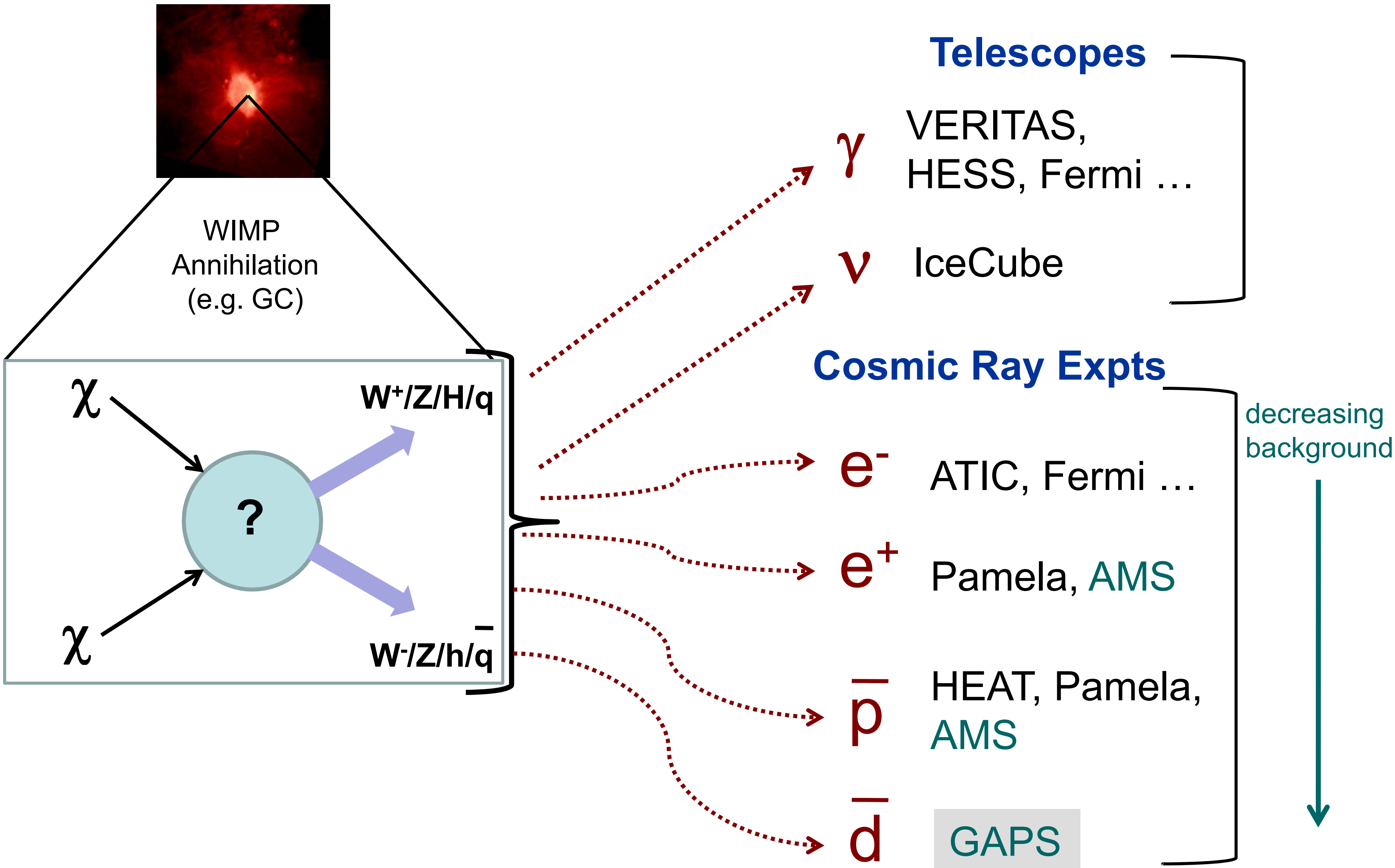
Similarly, direct detectors could well find a dark matter candidate and measure its interaction cross-section, but they will not:

- determine the particle decay modes and couplings or
- study the DM distribution outside the vicinity of Earth.

Indirect detection experiments can provide important information relating to the astrophysics and particle physics of DM.
It’s a promising approach …

… but significant difficulties (e.g. backgrounds) exist.

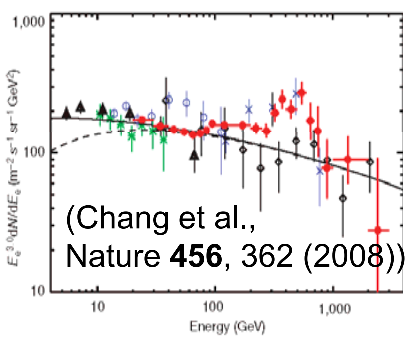
Indirect Detection



Recent Interesting Results

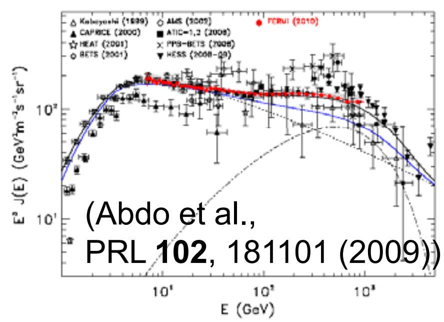
e^-/e^+

ATIC e^- “bump”



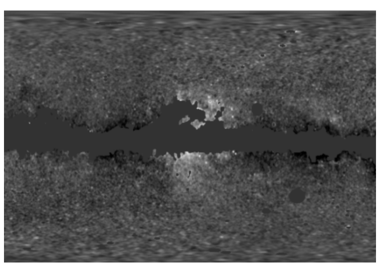
(Chang et al.,
Nature **456**, 362 (2008))

Fermi e^- “non-bump”



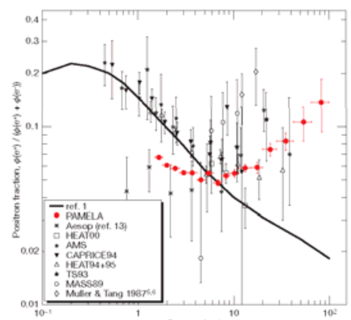
(Abdo et al.,
PRL **102**, 181101 (2009))

WMAP “haze”



(Hooper, Finkbeiner & Dobler,
PRD **76**, 083012 (2007))

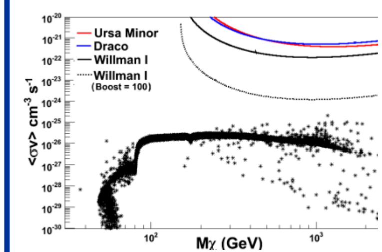
Pamela e^+ excess



(Adriani et al.,
Nature **458**, 607 (2009))

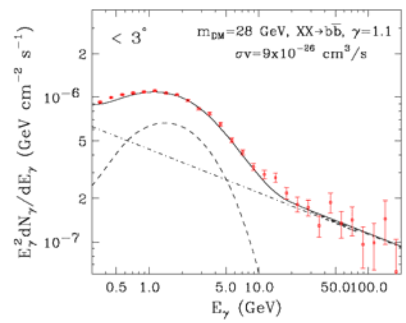
γ

VERITAS Limits
(also Fermi, HESS,
& MAGIC)



(Acciari et al.,
ApJ **720**, 1174 (2010))

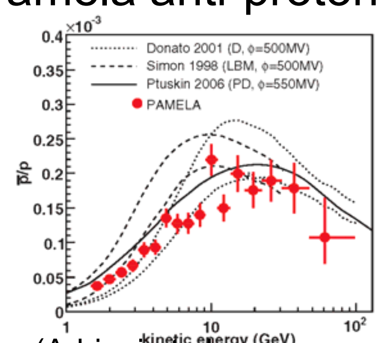
Fermi GC excess



(Goodenough & Hooper,
arXiv:0910.2998v2)

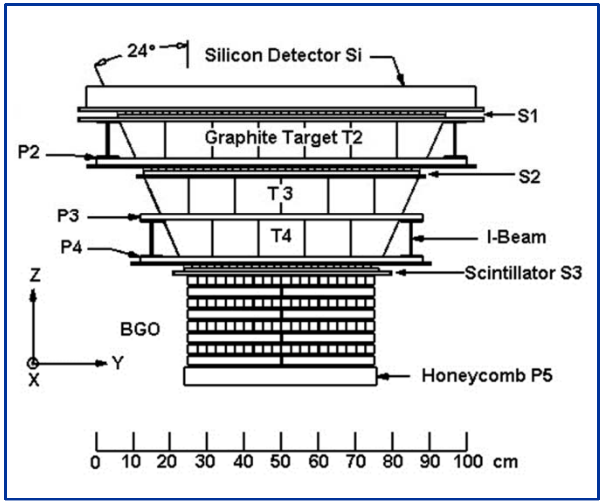
$\bar{p}$

Pamela anti-protons

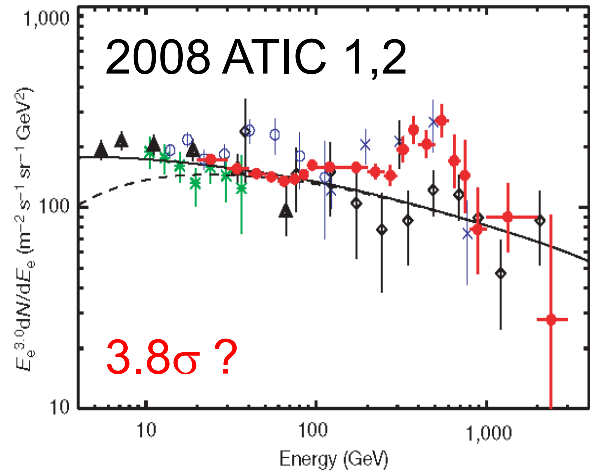


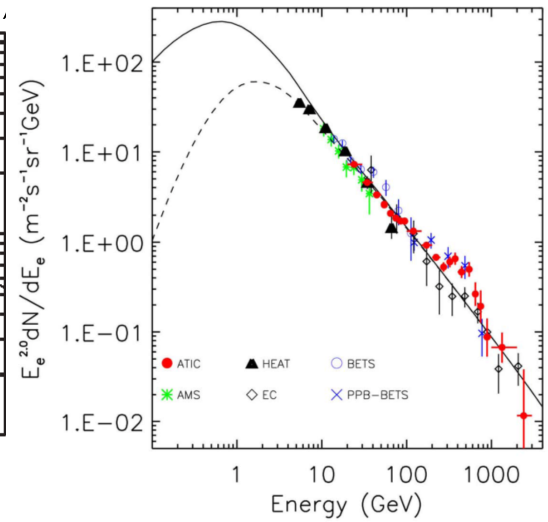
(Adriani et al.,
PRL **102**, 051101 (2009))

ATIC (2008, 2010)



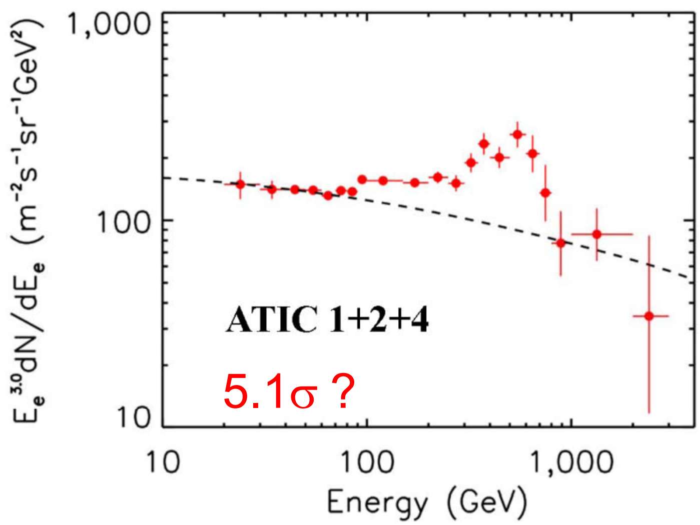
(Chang et al., Nature **456**, 362 (2008))





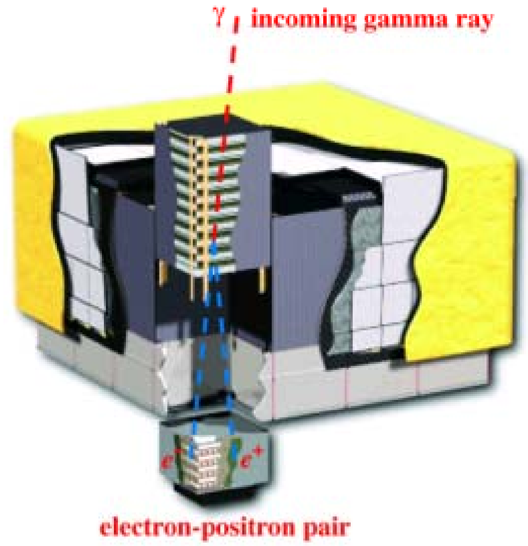
Balloon expt. (Antarctica)
Tracker, BGO Calorimeter (18 X_o)
- No magnet

Latest data, plus ATIC 4 (2010)



Clearly see a "feature".
Experimental difficulties:
- No particle ID redundancy.
- No direct measurement of background rejection.

Fermi (2009)



Large Area Telescope (LAT)

- Si-strip tracker
- CsI Calorimeter (10 X_o)
- Very detailed shower simulation

Fermi/HESS see possible enhancement in e spectrum, but no “bump”.

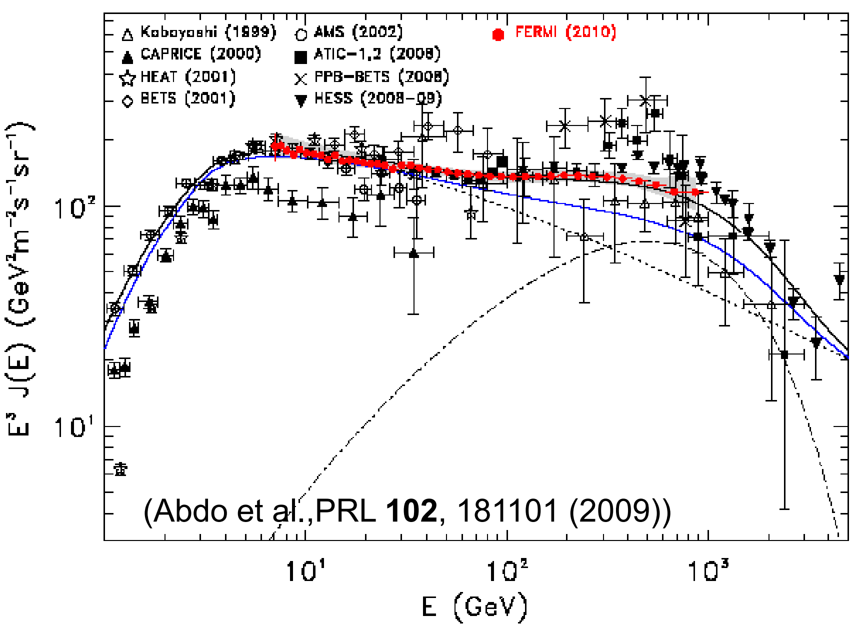
Many possible explanations – relatively easy to produce e^- astrophysically:

- Local sources (SNRs, pulsars).
- Shrouded sources.
- “Special” location.
- Secondary e^- model incorrect (GALPROP).

Dark matter models require

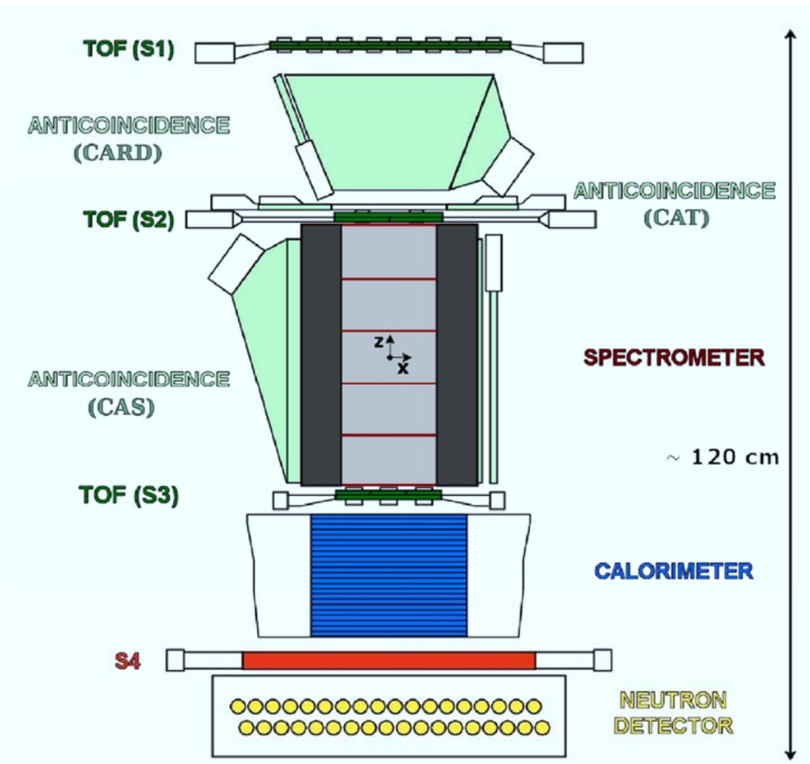
- “Leptophilic” models
- Boost factors of 10^2 – 10^3.

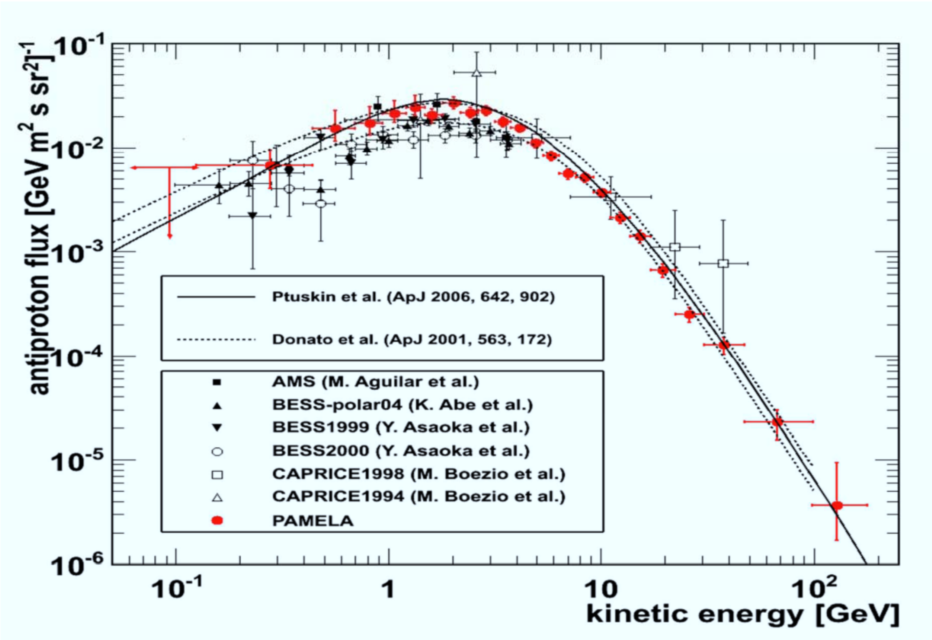
Dark matter hypothesis is shaky.



(Abdo et al.,PRL **102**, 181101 (2009))

PAMELA $\bar{p}$





Satellite instrument (launch 2006).

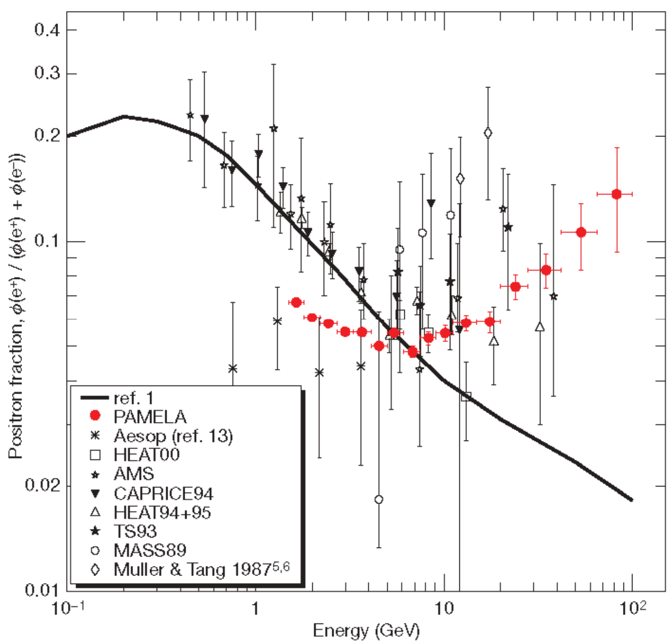
- Particle ID: TOF, Tracker, Calorimeter
- Magnet (0.45T) for +/- separation.

Excellent anti-proton identification.

Anti-proton flux agrees with predictions for secondary particle production.

PAMELA e^+

(Adriani et al.,Nature **458**, 607 (2009))

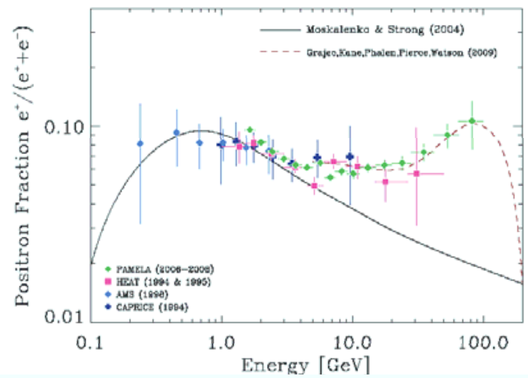


Significant enhancement in Positron fraction above 10 GeV.

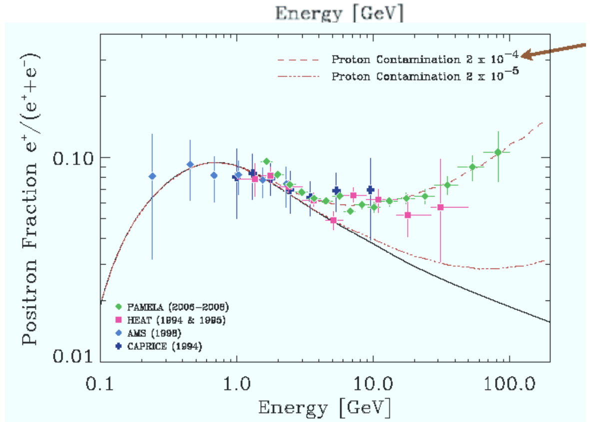
Real effect ? But no independent verification of bkgnd rejection.

Very possibly background or a local source.

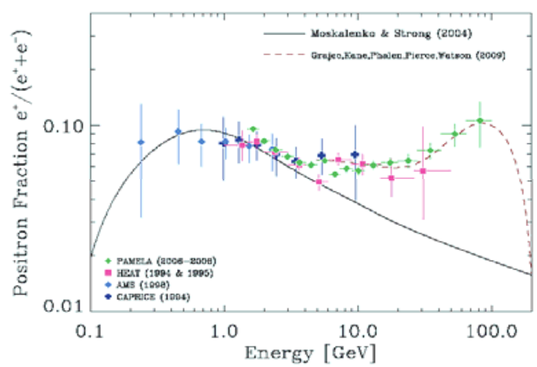
From G.Tarle (UCLA DM Meeting 2010):



Local pulsar
(Yuskel,Kistler, & Stanev, PRL **103**, 051101 (2009)).



Bkgd Rejection=10^{-4}
(important because of flux and index of protons)



DM Model
(Grajek et al.,
PRD **79**, 043506 (2009))

Summary of cosmic-ray probes

Particle	Kinematic Range	Experimental Challenges	Backgrounds
e^-	> 100 GeV	particle ID	e^-'s are ubiquitous in CR's !
e^+	> 20 GeV	p background	local sources secondary production
$\bar{p}$	> 20 GeV	large aperture	secondary production
$\bar{d}$	**< 2 GeV**	**low flux**	**no known backgrounds**

The unique possibilities of anti-deuterons as a background-free probe of new physics → a big interest from theoretical community, e.g.:

F. Donato et al, PRD **62**, 043003 (2000)
J. Edsjo et al, JCAP Phys. **09**, 004 (2004)
H. Baer & S. Profumo, Astroparticle Phys. 12, 008 (2005)
M. Kadastik et al, arXiv:0908.157 (2009)
C. Brauninger & M. Cirelli, arXiv:0904.1165 (2009)
Y. Cui, J. Mason, & L. Randall, arXiv:1006.0983 (2010)
… and many more.

Why Anti-deuterons ?

Unlike anti-protons, which are easy to produce as secondary particles, anti-deuteron secondaries are severely suppressed at low energies.

Primary Component (DM):

$\chi\,\chi \rightarrow \gamma, \bar{p}, \bar{d}$

Secondary Component:

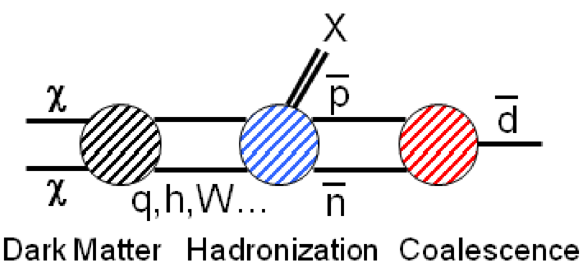
$p\,A \rightarrow \bar{d}\,X$ [via $p(\bar{p}\bar{n})n$]

where A = p, He

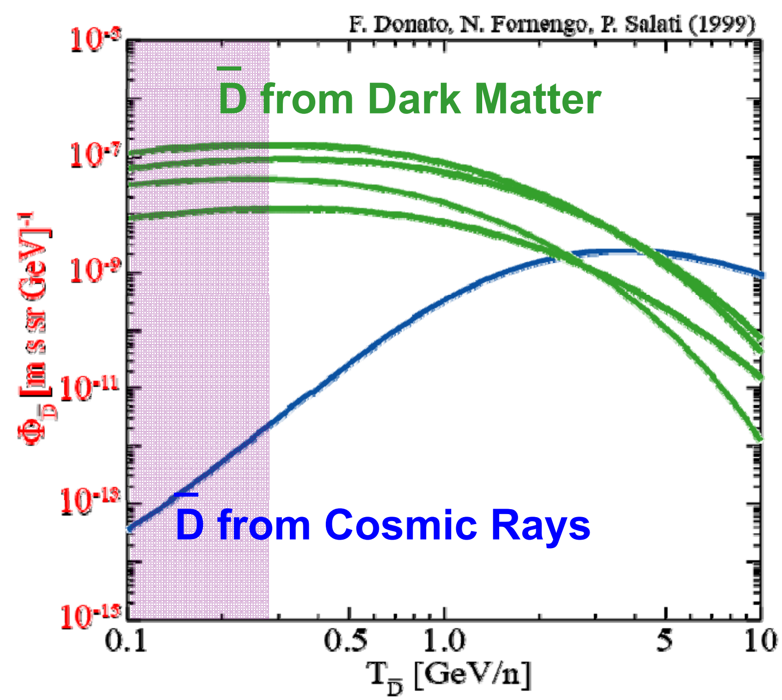
Anti-deuterons provide extremely clean signature, but low fluxes result in a daunting experimental challenge !

→ New experiment"
→ General AntiParticle Spectrometer (GAPS)

DM production of $\bar{d}$

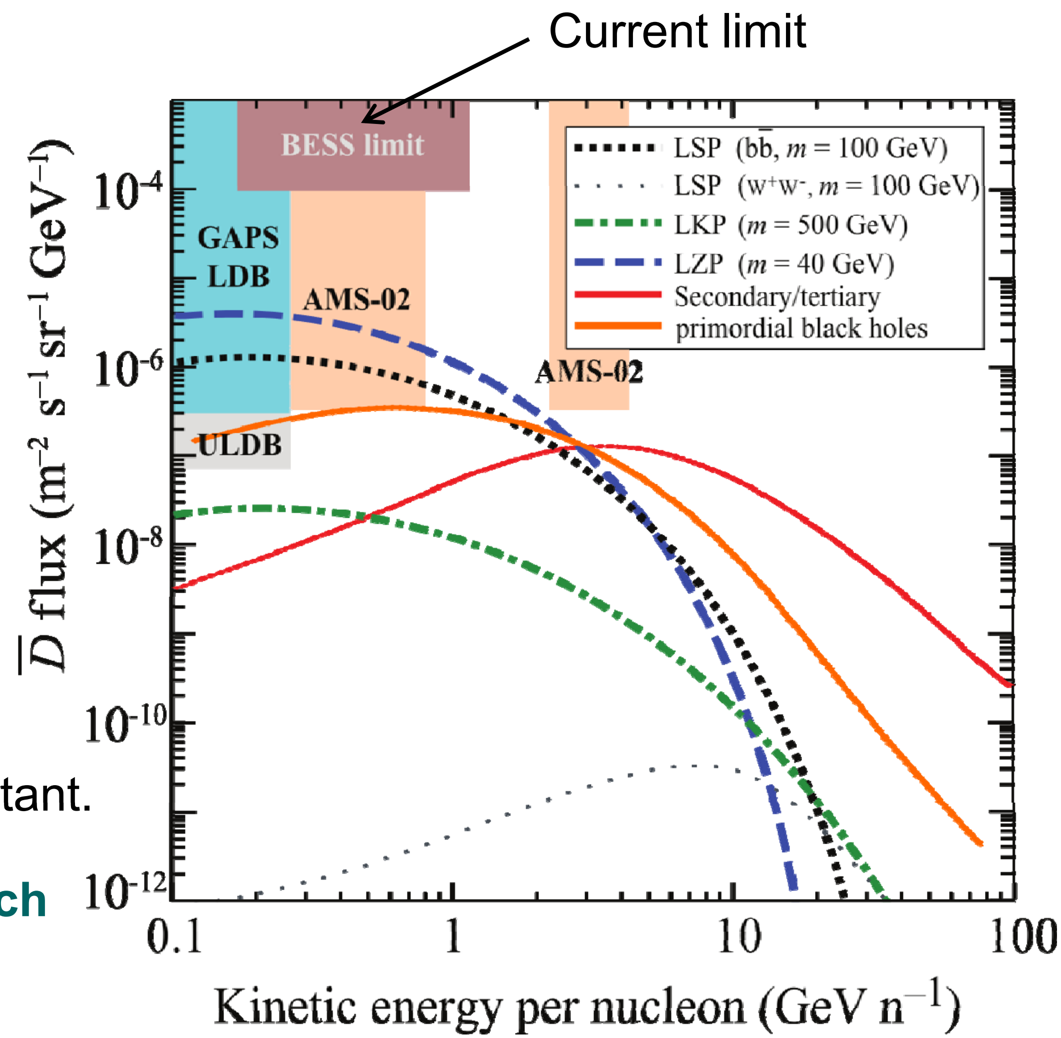


Anti-deuteron flux at the earth (w/propagation and solar modulation)



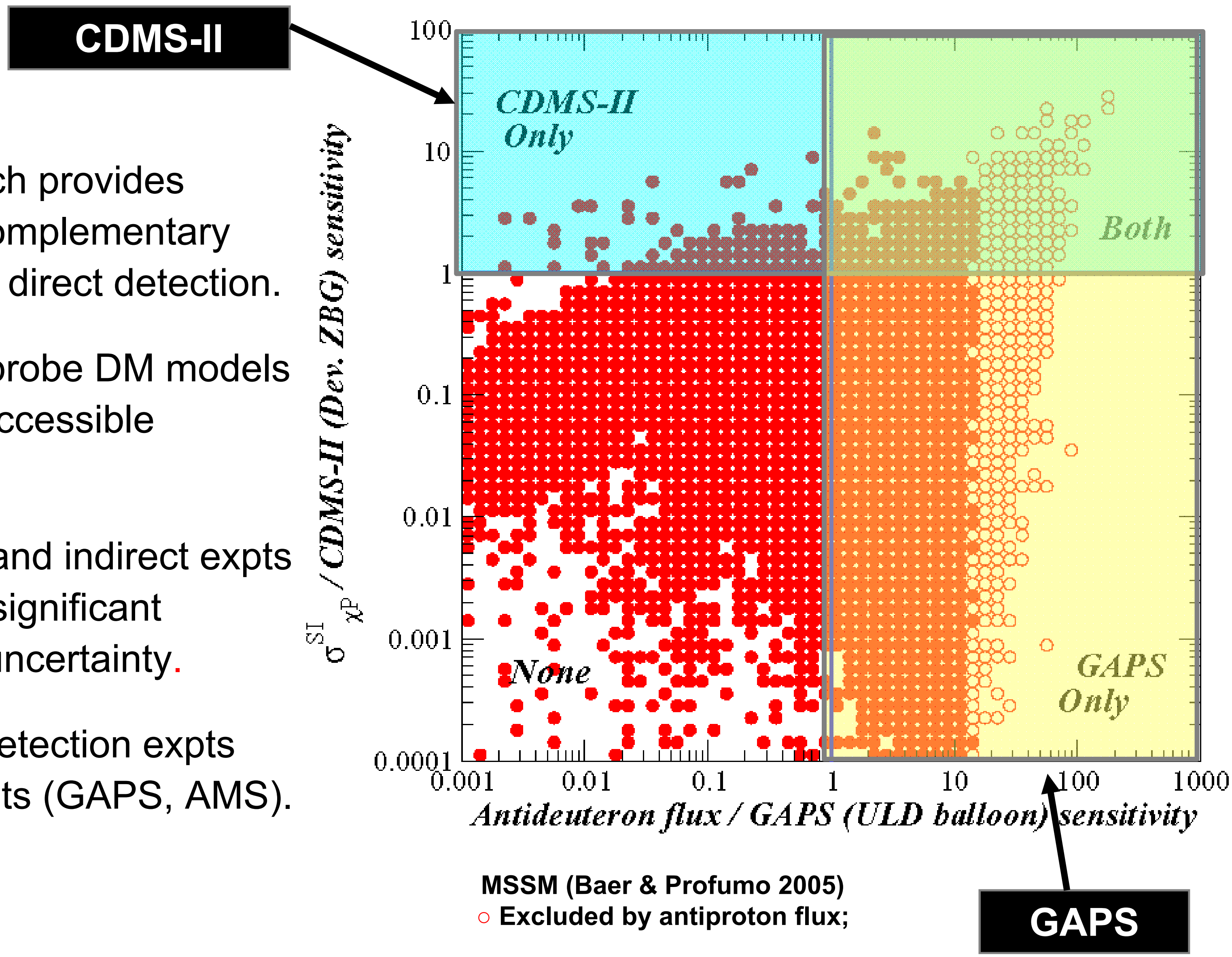
GAPS anti-D Sensitivity Reach

- Cosmic anti-D have never been detected. Could be produced by new physics.
- Primary anti-D production:
  - Supersymmetry (LSP)
  - Kaluza-Klein UED (LKP)
  - Warped ED (LZP)
  - Primordial BH's !
- Sub-GeV region essentially background free; the detection of even a single, clean event is important.
- **GAPS will extend sensitivity reach by 2-3 orders of magnitude**.



Synergy with Direct Detection

- Anti-D search provides important complementary capability to direct detection.
- GAPS can probe DM models not easily accessible otherwise.
- Both direct and indirect expts suffer from significant theoretical uncertainty.
- >25 direct detection expts
  2 anti-D expts (GAPS, AMS).



MSSM (Baer & Profumo 2005)
○ Excluded by antiproton flux;

GAPS Collaboration

Columbia University in the City of New York

Berkeley University of California

UCLA

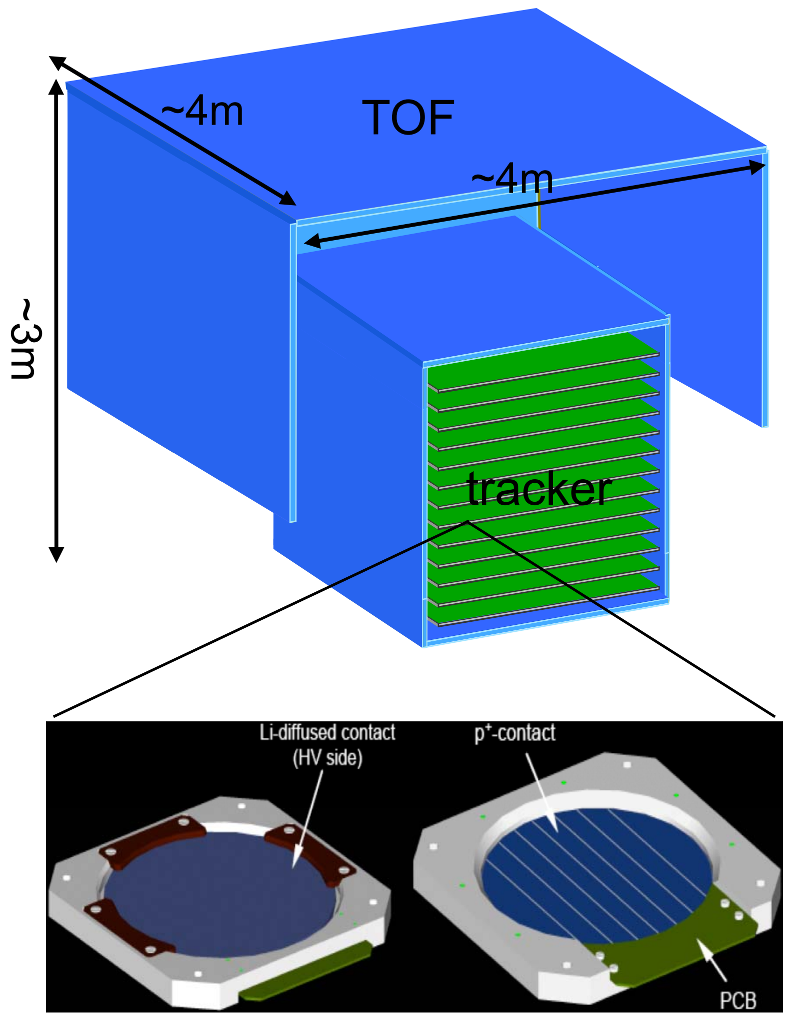
JAXA Japan Aerospace Exploration Agency

(+ LLNL, Univ. of Latvia)

Collaboration meeting, UCB May 2010

T. Aramaki, N. Bando, S. Boggs, W. Craig, P. von Doetinchem, H. Fuke, F.H. Gahbauer, **C. Hailey(PI)**, J. Koglin, N. Madden, I. Mognet, K. Mori, R.A. Ong, A. Takada, T. Yoshida, T. Zhang, J.A. Zweerink

GAPS Concept



LDBalloon flight planned in 2014

GAPS consists of two detectors (acceptance ~2.7 m^2sr):

Si(Li) Detector (target and tracker):

- Si(Li) tracker:13 layers of Si(Li) wafers
- relatively low Z material
- good X-ray resolution
- circular modules segmented into 8 strips
  → 3D particle tracking
- 270 per layer (total: ~3500)
- timing: ~50 ns
- dual channel electronics
  5-200 keV: X-rays (resolution:~2 keV)
  0.1-200 MeV: charged particle

Time of flight and anticoincidence shield:

- plastic scintillator with PMTs surrounds tracker
- track charged particles, dE/dX
- velocity measurement
- anticoincidence for charged particles

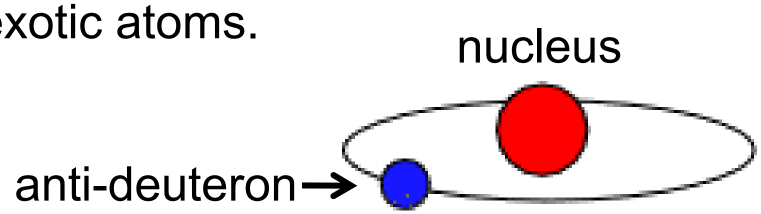
Designed for low-energy anti-deuterons:

- no need for a magnet
  (heavy, complicated/expensive … e.g. AMS)

GAPS Detection Technique

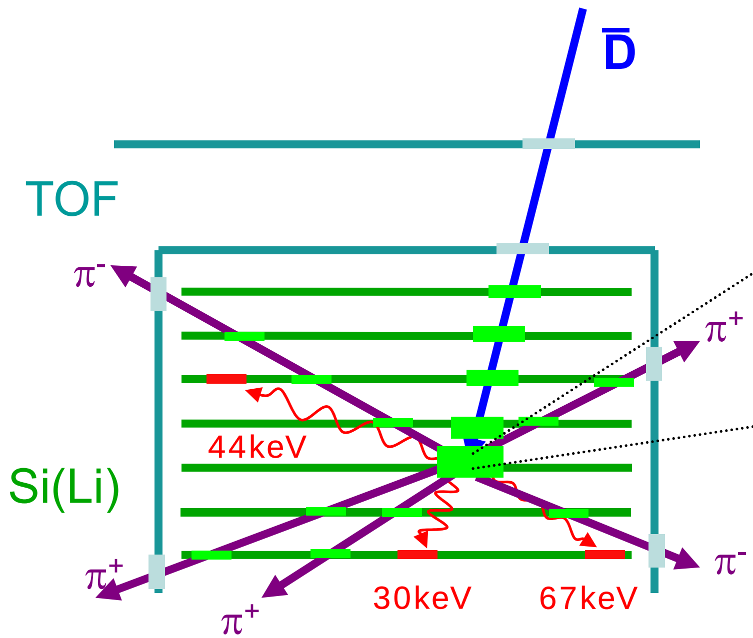
- Conventional method of magnetic mass spectrometer is not optimal for GAPS. (Very large magnets with thin detector materials are needed for a deep survey).

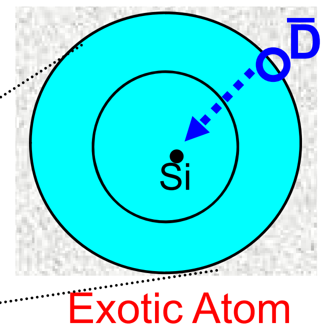
- GAPS introduces an original method. GAPS utilizes the de-excitation sequence of exotic atoms.

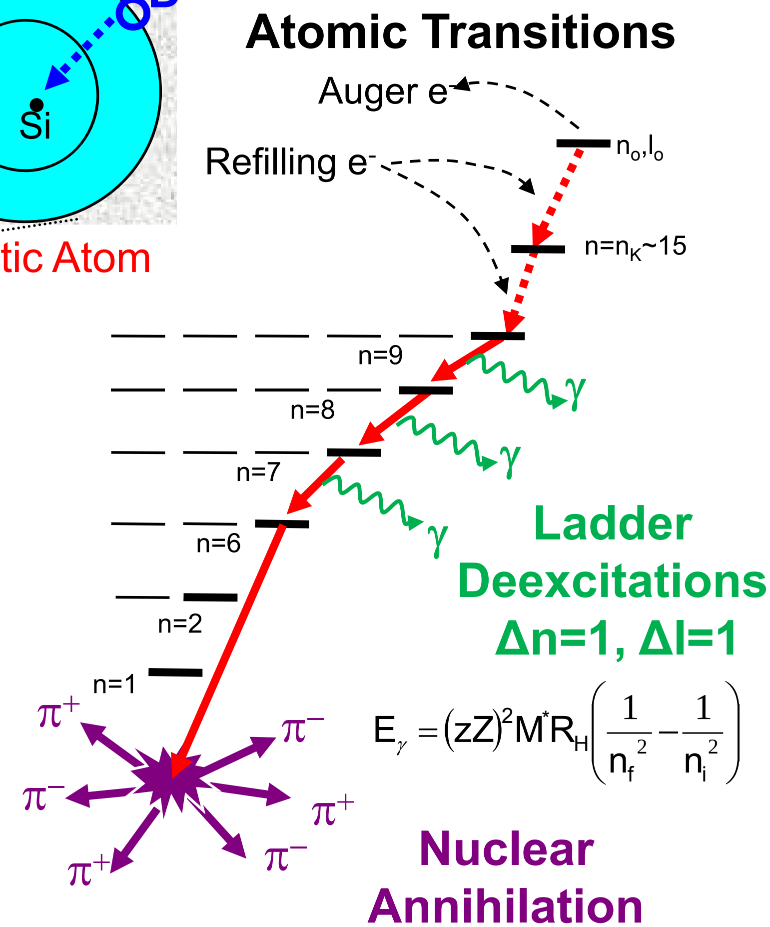


GAPS Detection Technique

- Conventional method of magnetic mass spectrometer is not optimal for GAPS. (Very large magnets with thin detector materials are needed for a deep survey).







1. Once D̄ is slowed down and stopped in the target,
2. an excited exotic atom is formed,
3. which deexcites with emitting X-rays,
4. and annihilates with producing a pion shower.

- Detection principle was verified and high X-ray yield was shown in accelerator tests (KEK antiproton beam, ’04 - ’05).

Main Challenges for GAPS

- Basic detection technique has been established, but the difficulty is to translate to a full-scale instrument.
  - Large scale Si(Li) production at reasonable cost.
  - Building a hermetic detector (i.e. no cracks, etc.).

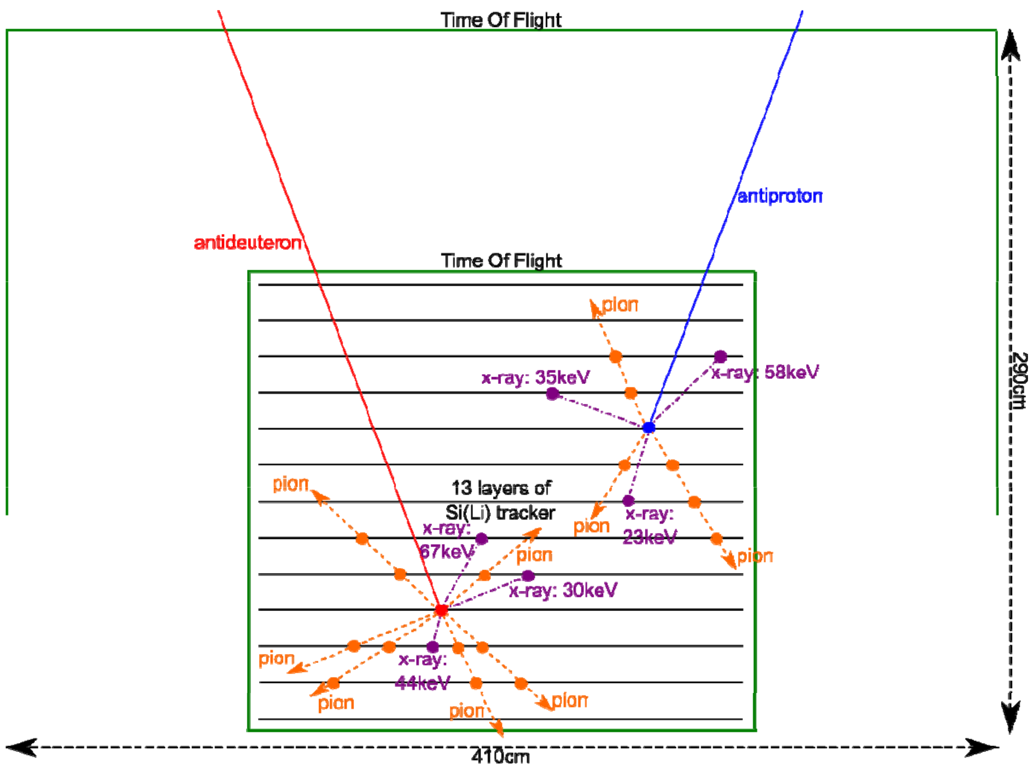
- Rare-event detector → backgrounds need to be fully modeled and understood.

- A prototype / test experiment is essential: pGAPS (2011).

- Additional note: there is significant uncertainty in anti-D flux estimation arising from:
  - Dark matter halo profile.
  - Modeling the nuclear reactions (coalescence model).
  - Propagation of anti-D through Galaxy to Earth.

  (last item is believed to give largest uncertainty).

Backgrounds



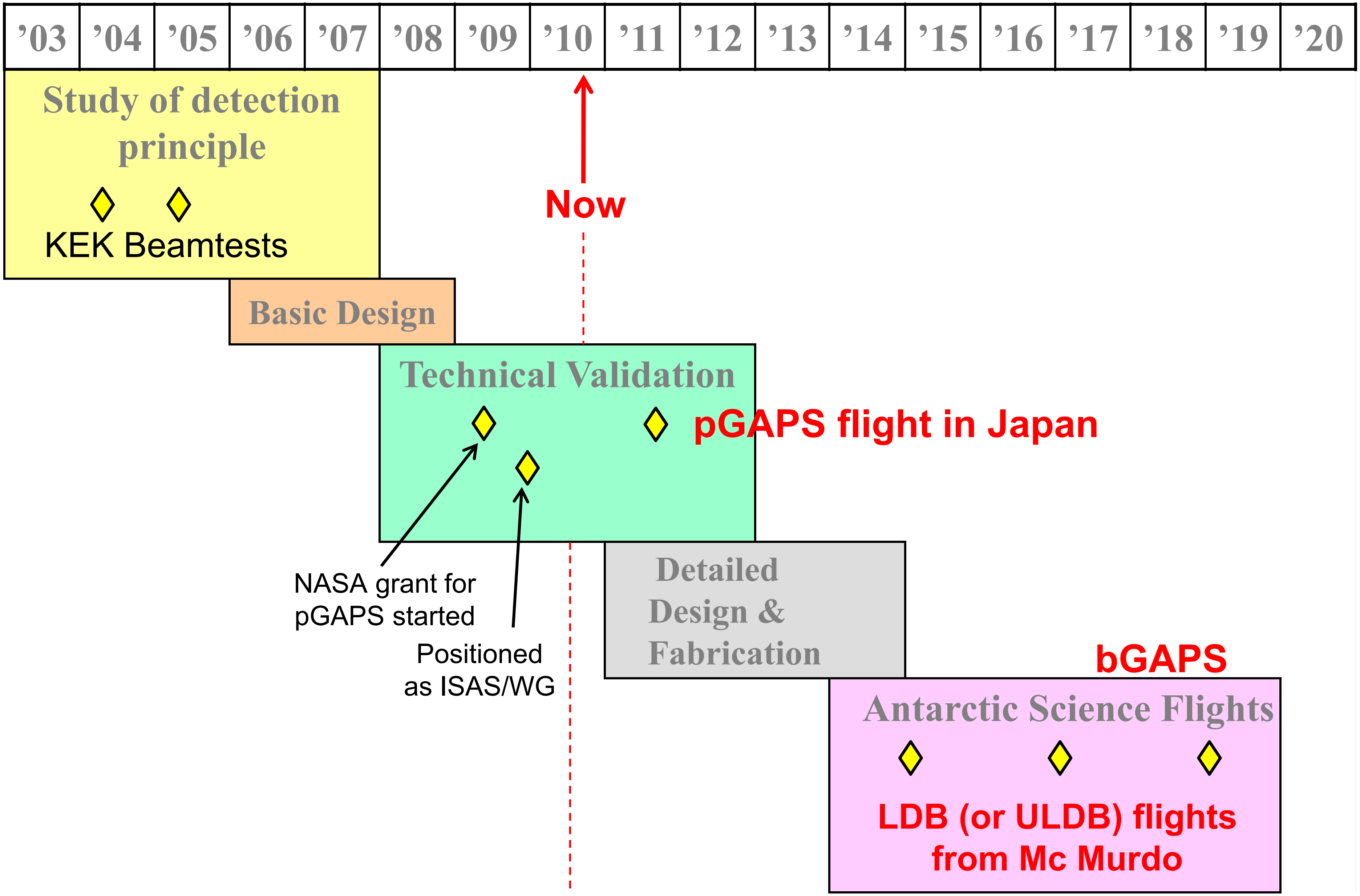
anti-P and anti-D interactions in GAPS

GAPS needs very reliable particle identification:

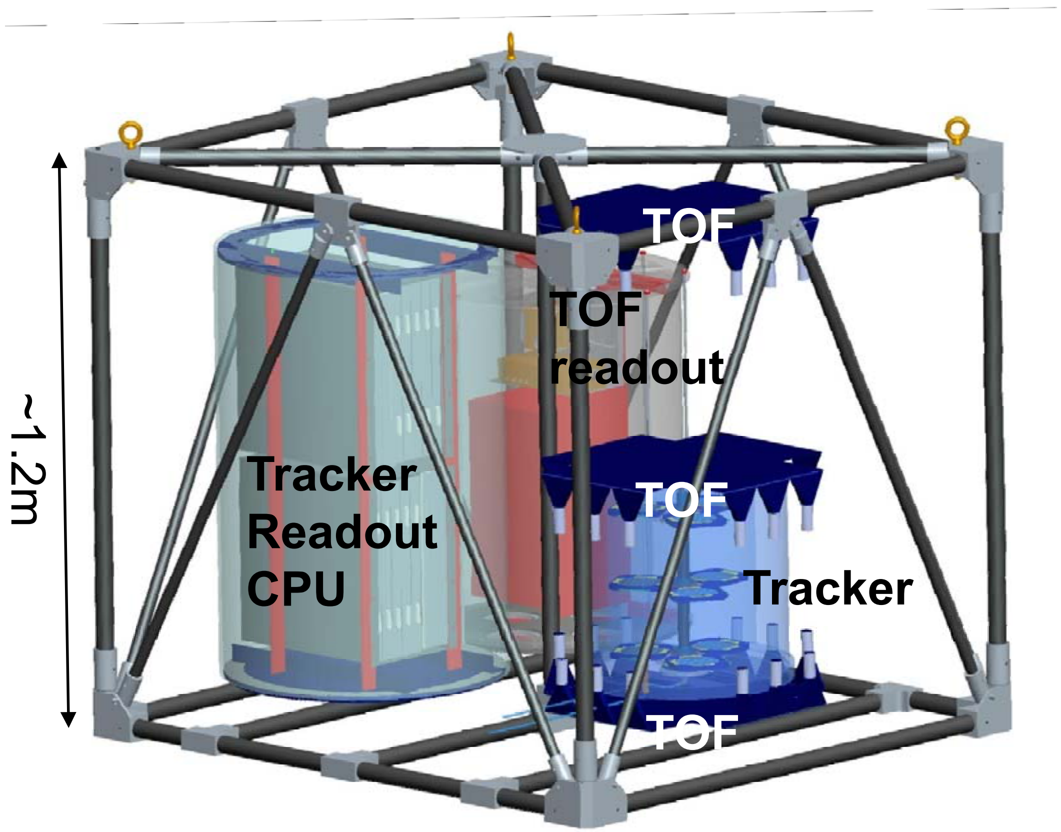
- Identification uses:
  - TOF velocity and tracks
  - depth in tracker
  - X-rays
  - pions from annihilation
- Important background sources for anti-deuteron events:
  - anti-protons
  - protons, electrons, neutrons in coincidence with cosmic X-rays
  - atmospheric production of antideuterons
  - etc...

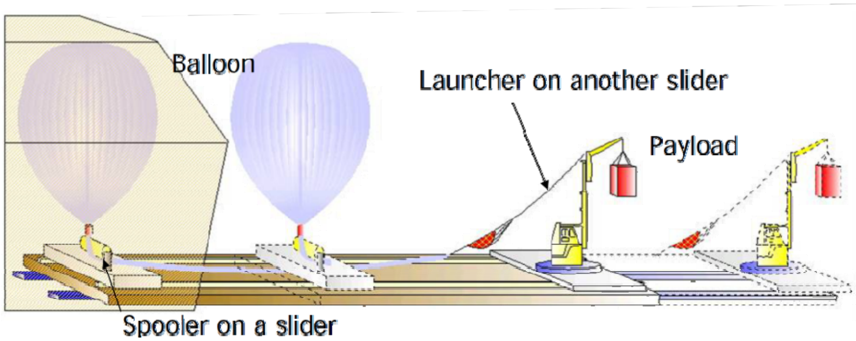
Very detailed Monte-Carlo simulation is required.

GAPS Timeline



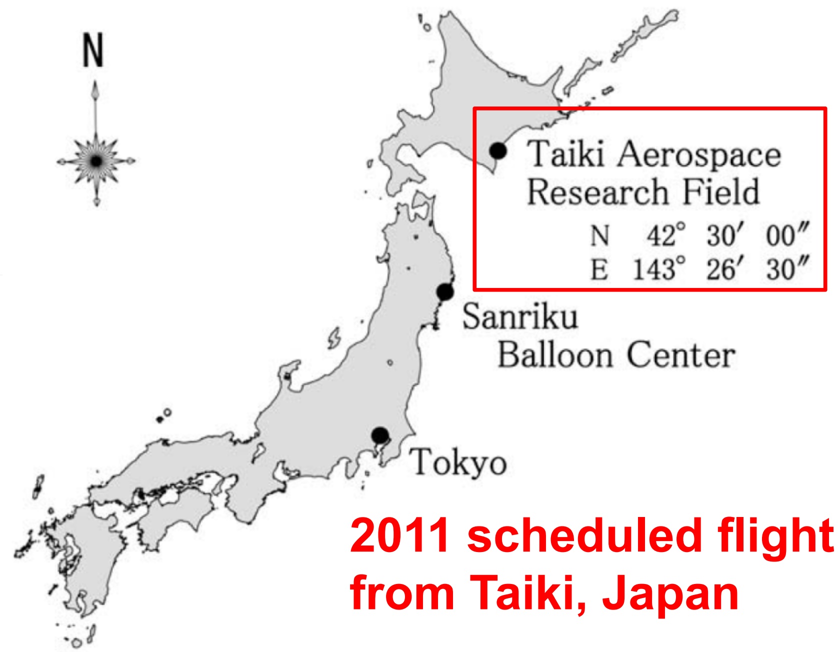
Prototype Experiment





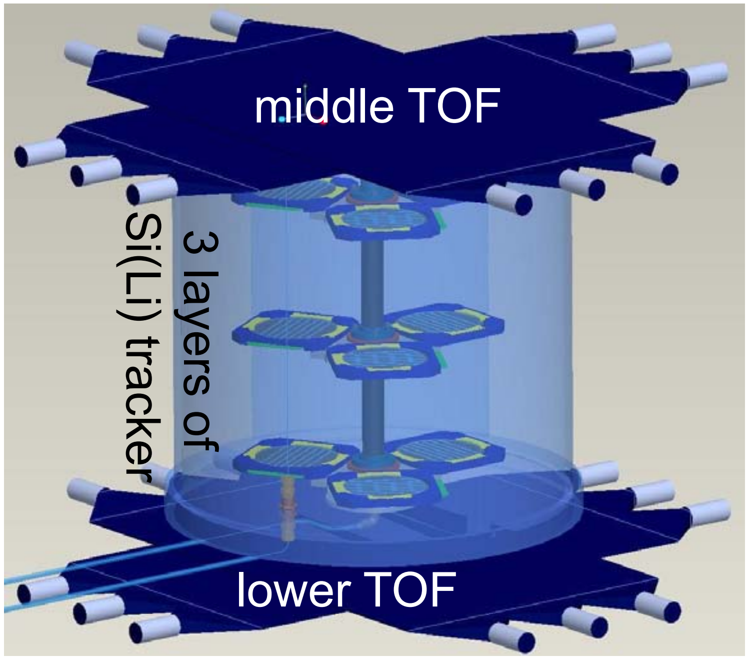
Prototype GAPS (pGAPS) goals:

- demonstrate stable, low noise operation of components at float altitude and ambient pressure.
- demonstrate the Si(Li) cooling approach and verify thermal model.
- measure incoherent background level in a flight-like configuration.

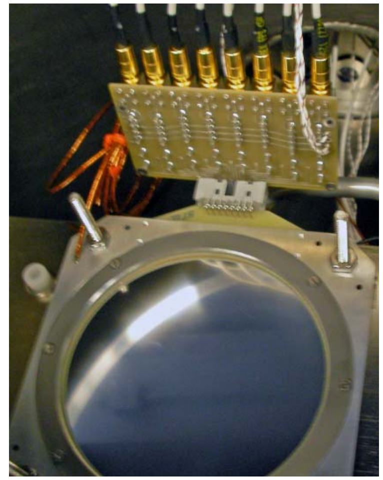


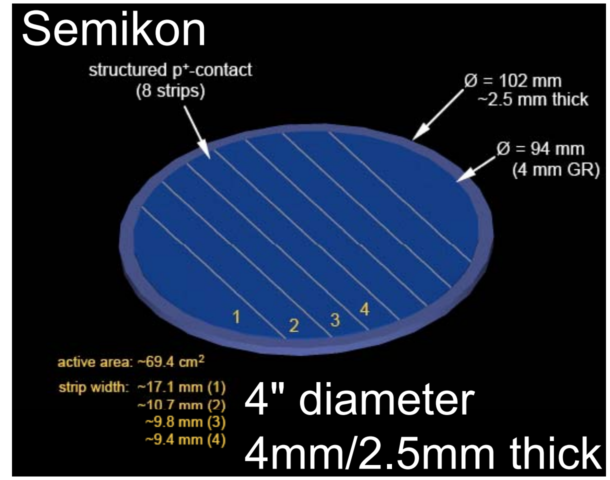
2011 scheduled flight from Taiki, Japan

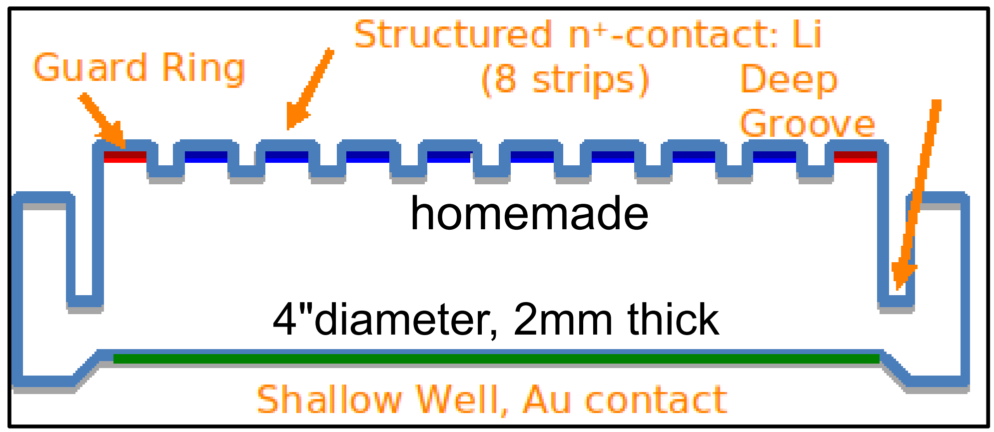
Si(Li) Tracker



- 7 commercial Semikon detectors.
- 2 homemade detectors
  (test for the bGAPS fabrication).
- Energy resolution < 3 keV @ 60keV.
- operation at ambient pressure.
  (8mbar).
- cooling system delivers: -35°C.





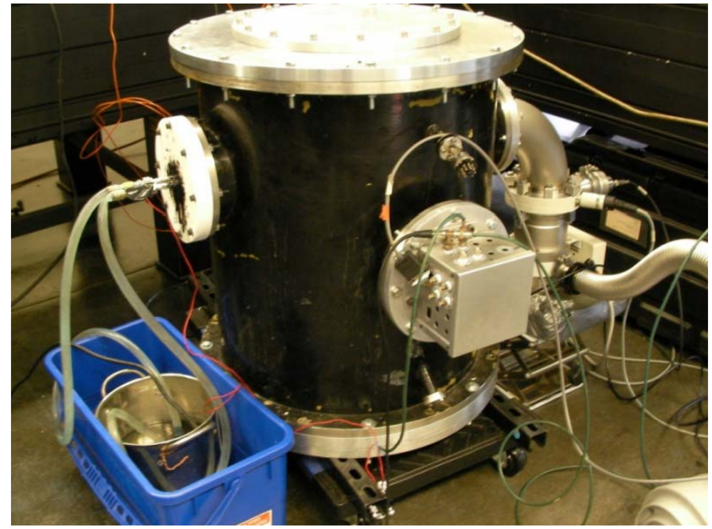


Semikon: N+: Lithium contact
P+: Boron implanted (strips)

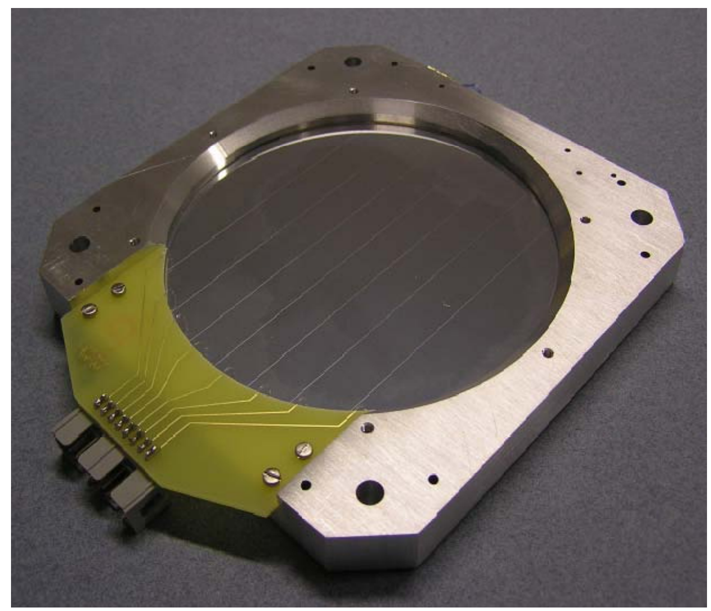
Homemade: N+: Lithium contact (strips)
Au contact with shallow well

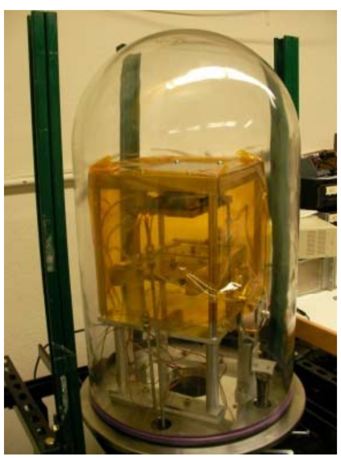
Si(Li) Detectors

- Performance check in a vacuum chamber.
  - Energy resolution ΔE: < 3keV.
  - Pre-amplifier
    individual read out for each strip
    with dual E range (for X-ray and π).
  - Surface coating -operation in vacuum.
  - SEMIKON-made vs. home-made.

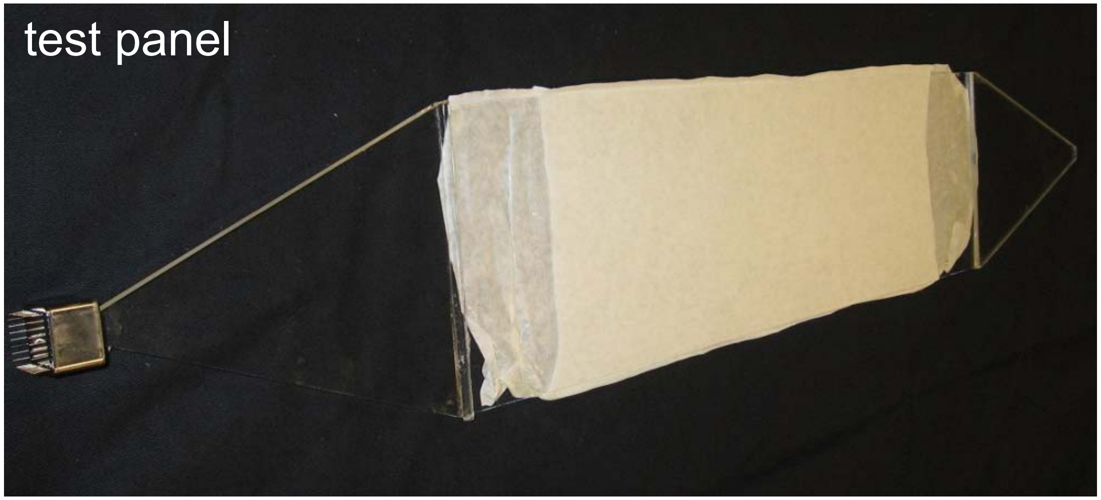


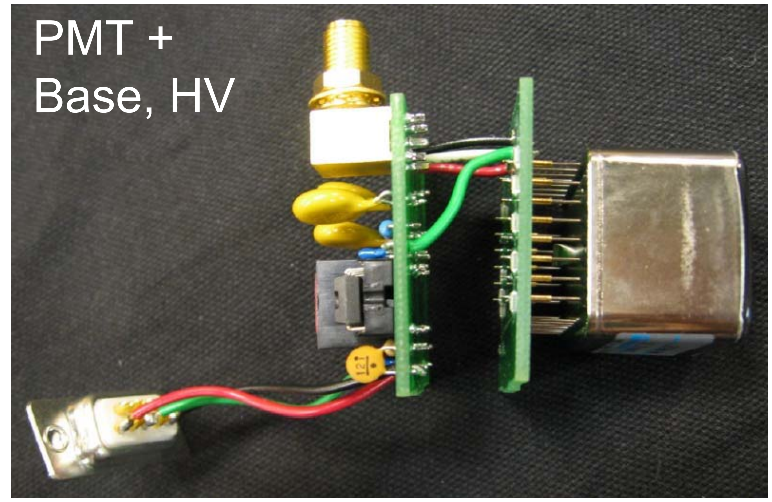
- Si(Li) fabrication.
  - In-house, mass fabrication.



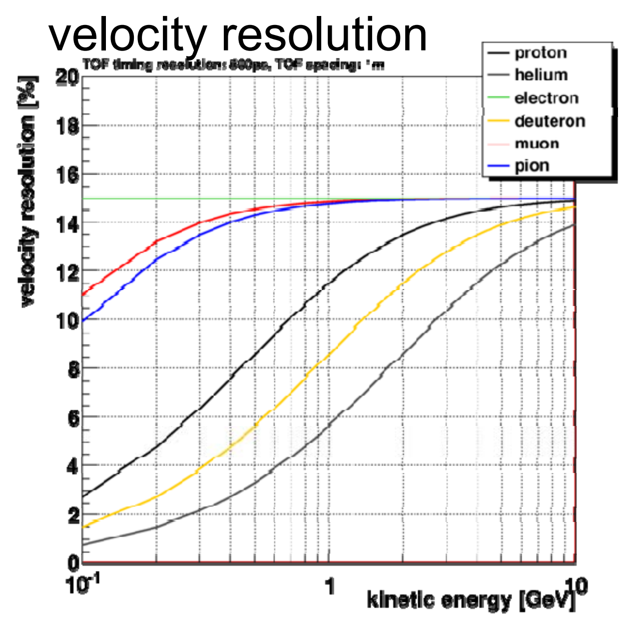


Time-of-Flight System



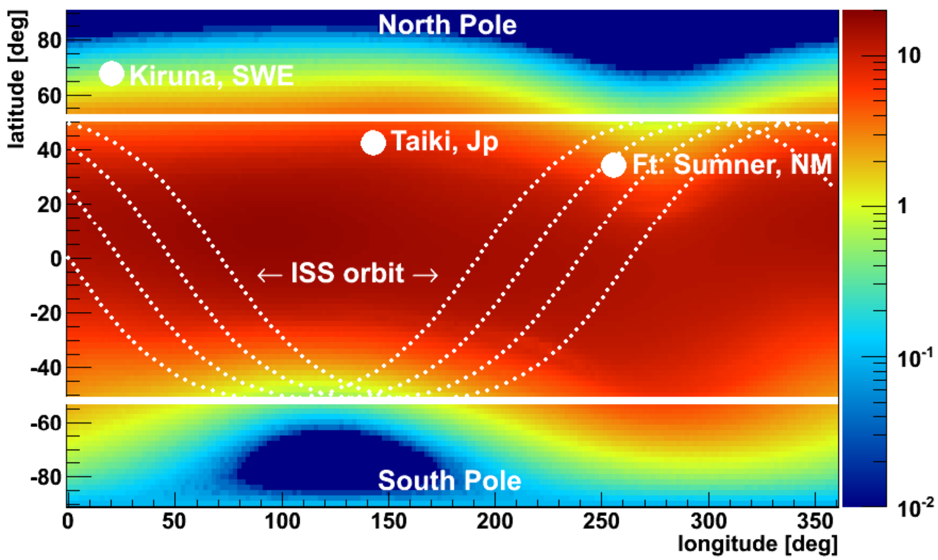


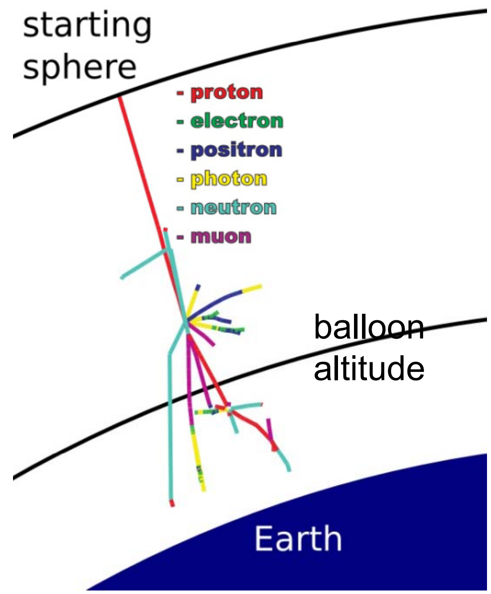
- 3 planes of TOF.
  1 plane consists of 3×3 crossed panels.
  1 panel has 2 PMTs.
  = **18 panels and 36 PMTs**
- 3mm scintillator from Eljen (EJ-200) or Bicron (BC-408).
- Hamamatsu R-7600 PMT (UBA).
- timing resolution: **< 400ps**
- charge resolution: **< 0.30e**
- MOP value: **~15 photo electrons**
- angular resolution: **8°**

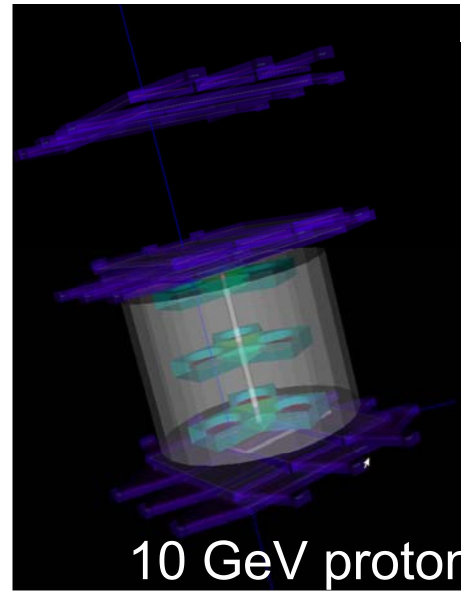


Simulations

cosmic antideuterons	atmospheric simulation	detector simulation	exotic atomic physics







Atmospheric and geomagnetic simulations with PLANETOCOSMICS based on GEANT 4.9.2

- geomagnetic simulations as a function of position and direction.
- atmospheric fluxes are in good agreement with measurements.

Instrument simulation with GEANT, ROOT output format:

- electromagnetic, hadronic, optical physics are completed.
- basic components are implemented, frames/structures must be added.
- ion and exotic physics are under development.

More details at Geant4 Space Users Workshop 2010, Seattle

Taiki Aerospace Research Field (TARF)

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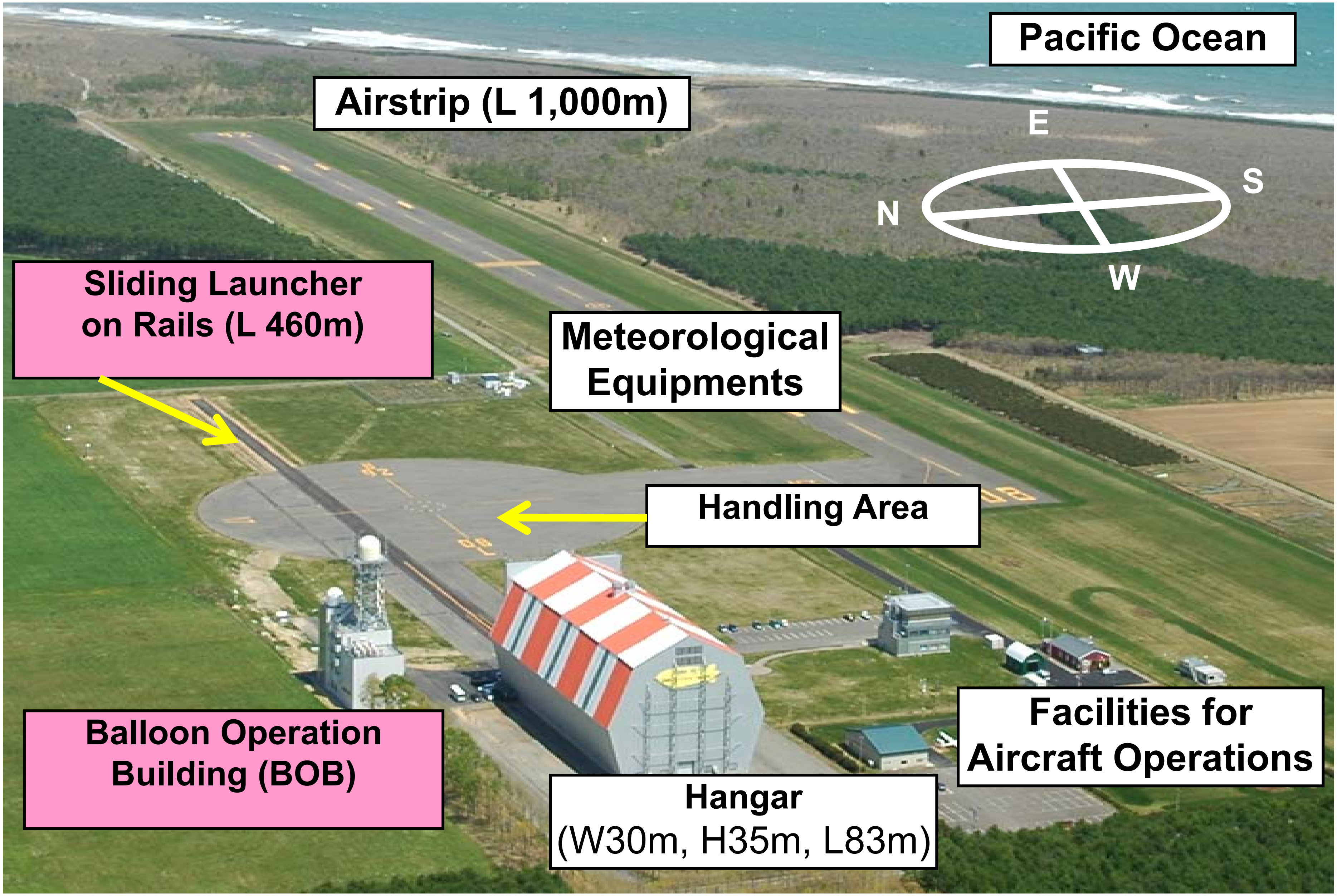


Future Prospects

GAPS Program:

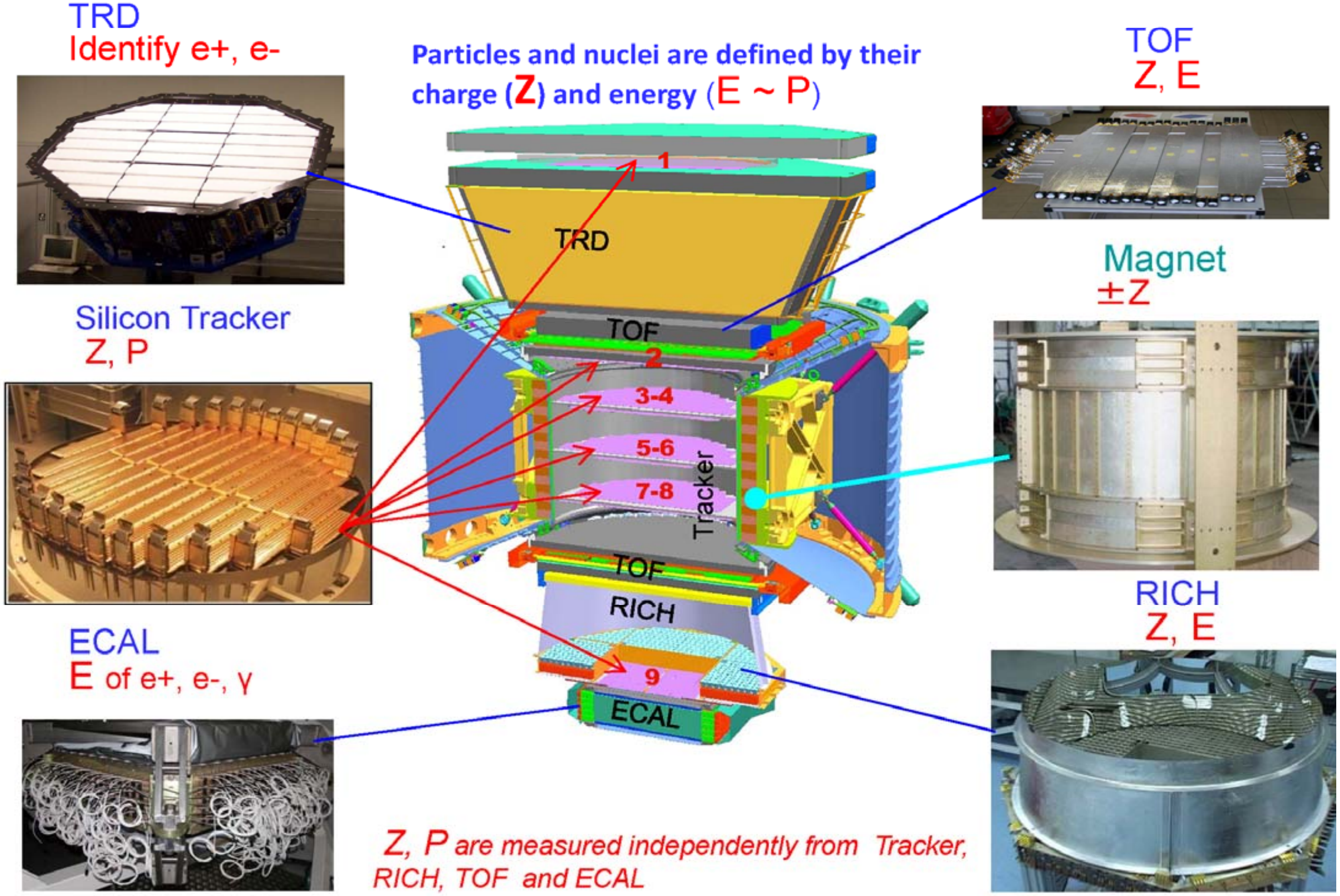
- Prototype instrument to be flown in 2011 from Taiki.
- Plan for LDB instrument in 2014/15. Cost ~$6-8M.
- ULDB (300 day) flights, when available, would improve sensitivity reach.
- (Possible future satellite instrument).

Alpha Magnetic Spectrometer (AMS-2)

- AMS-I had space shuttle flight in 1999. AMS-II, a much more sophisticated detector, was scheduled for deployment on ISS in 2005, but postponed numerous times.
- 2010: failure of cooling system forced delay, replacement of SC magnet by conventional magnet. Impact ??
- AMS-II scheduled for (last) shuttle flight in February 2011.
- Overall cost ~ $1.5B ??

Other future missions	Space:	CALET (e)
	Balloon:	CREST(e), PEBS (e^+,e^-,$\bar{p}$)

AMS-2

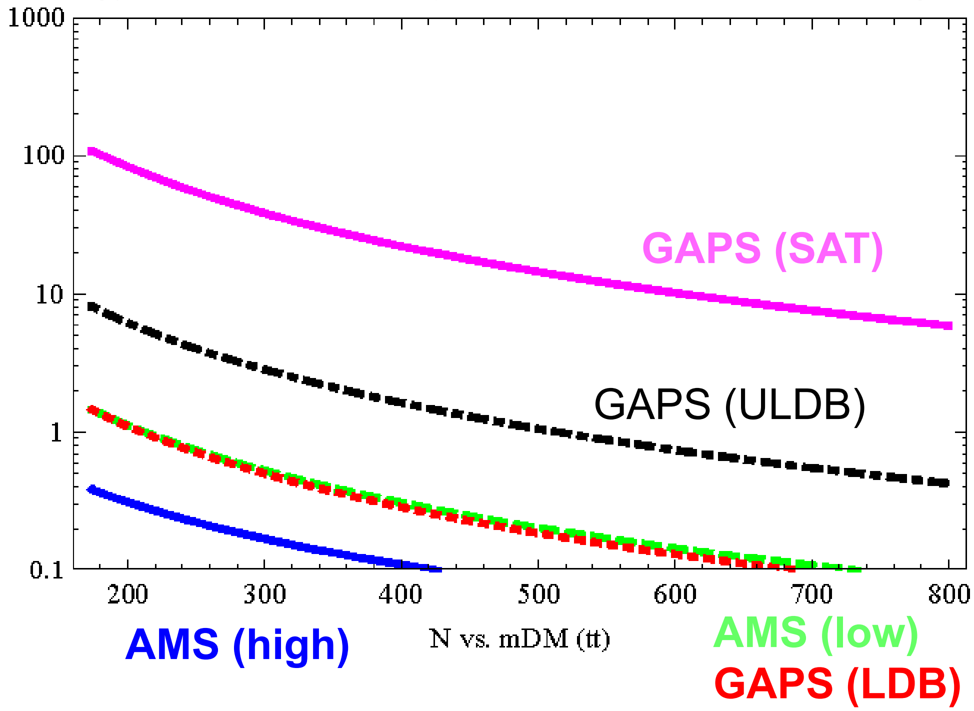


- Main science goal: anti-HE search.
- Extend range of positron, anti-proton measurements.
- anti-deuteron search.

Latest Predictions

Y. Cui, J. Mason, & L. Randall, arXiv:1006.0983 (2010)

anti-D vs Mass:
(generic new physics model, tt channel)



Mass reach of experiments:

Experiment	$\bar{q}q$	$\bar{t}t$	h^0h^0	gg	W^+W^-	N_{crit}
AMS-02 high (3σ)	50	$< m_t$	$< m_h$	100	$< m_W$	3
AMS-02 low (3σ)	100	$< m_t$	$< m_h$	200	100	2
GAPS (LDB) (3σ)	140	200	140	300	120	1
GAPS (ULDB) (3σ)	250	400	250	500	160	2
GAPS (SAT) (3σ)	500	700	500	900	240	10

Note: assumes "med" propagation parameters & background-free.

Summary

- Gravitational evidence for DM is very strong.
  The majority of DM is non-baryonic and is not hot.
- Particle DM has motivation from astrophysics & particle physics.
  WIMP CDM is cool idea… it might even be right.
- Indirect detection is promising; it is able to directly test the particle hypothesis and is complementary to other methods.
- Anti-deuterons are a unique probe of DM, but as interesting is the question of whether they even exist in the cosmic rays.
- GAPS is a new balloon instrument using the exotic atom technique to search for anti-deuterons.
  - Prototype flight scheduled for 2011.
  - Science flight proposed for 2014.

"*Great scientific discoveries have been made by men seeking to verify quite erroneous theories about the nature of things,* " Aldous Huxley, 1929.