
High Angular Resolution (& Large Area) Satellite Array for Dark Matter Annihilation Gamma Ray Detection

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Large Area, Narrow Angle Gamma Telescope

To measure sources at resolution $\Theta_{\text{half-angle}} \ll 0.5 \text{ deg (8 mrad)}$, to determine dSph halo profile for the brightest/narrowest candidates.

Narrow angle reduces line-of-sight gamma background

Large area $> 10 \text{ m}^2$ improves the gamma signal event statistics from the chosen source

Rejection of other background particle events in detector elements will be significant challenge, new analysis methods of rejection (can't just use enclosing AC shield)

Design goal must also be for significantly lower cost per effective telescope area

dSph (Dwarf Spheroidal Galaxy) Dark Matter Annihilation Signal

RET II, FermiLAT Pass 7 - Excess... Pass 8 - No longer statistical excess, just a suggestion
... challenge fluxes ~few gamma per m² per year, effective area of FermiLAT 0.5-0.8 m²

Observation
 $\Theta_h = 0.57$ deg

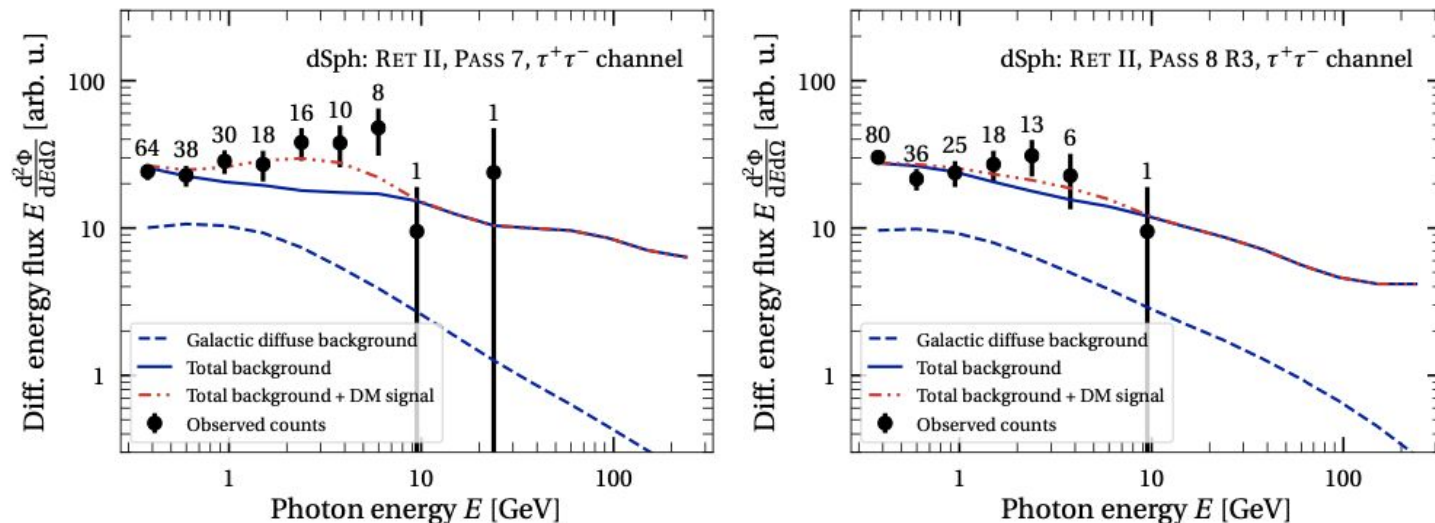
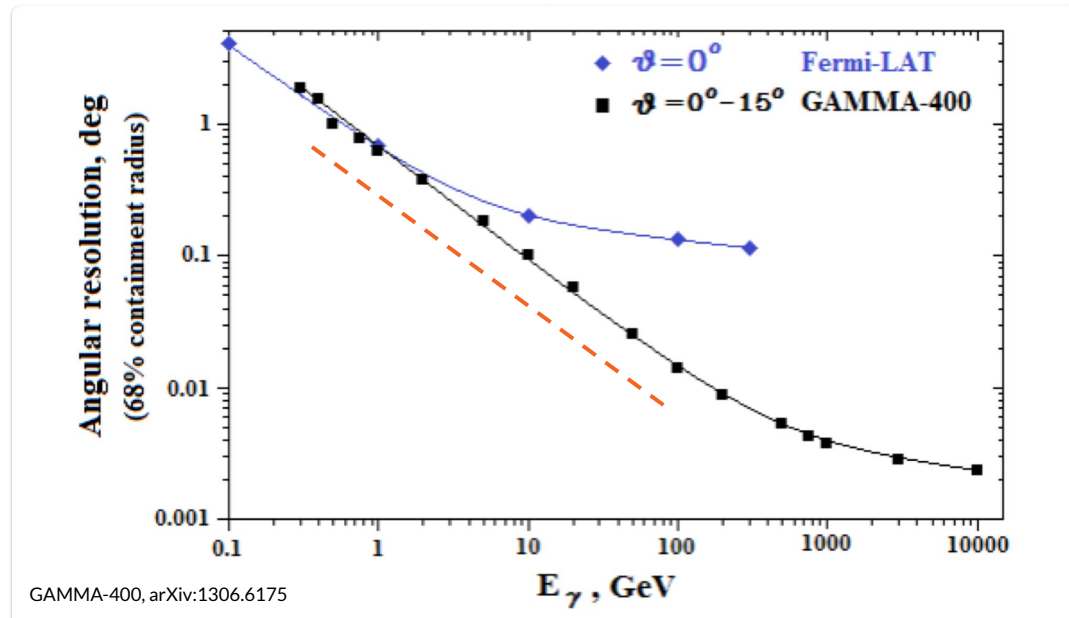


Figure 3: Spectra for 6.5 years of PASS 7 (*left*) and PASS 8 (*right*) data for RET II. We show the observed counts (black circles and numbers) with Poisson error bars, as well as the backgrounds (blue lines) and background plus DM signal (red lines), according to the best-fit parameters in the $\tau^+\tau^-$ channel. The best-fit DM mass is $m_\chi = 13.3$ GeV (left panel) and $m_\chi = 14.2$ GeV (right panel).

FermiLAT Angular Resolution close to Axis And previous GAMMA-400 goals

Tuning of internal converter-tracker layers thickness and pixel resolution



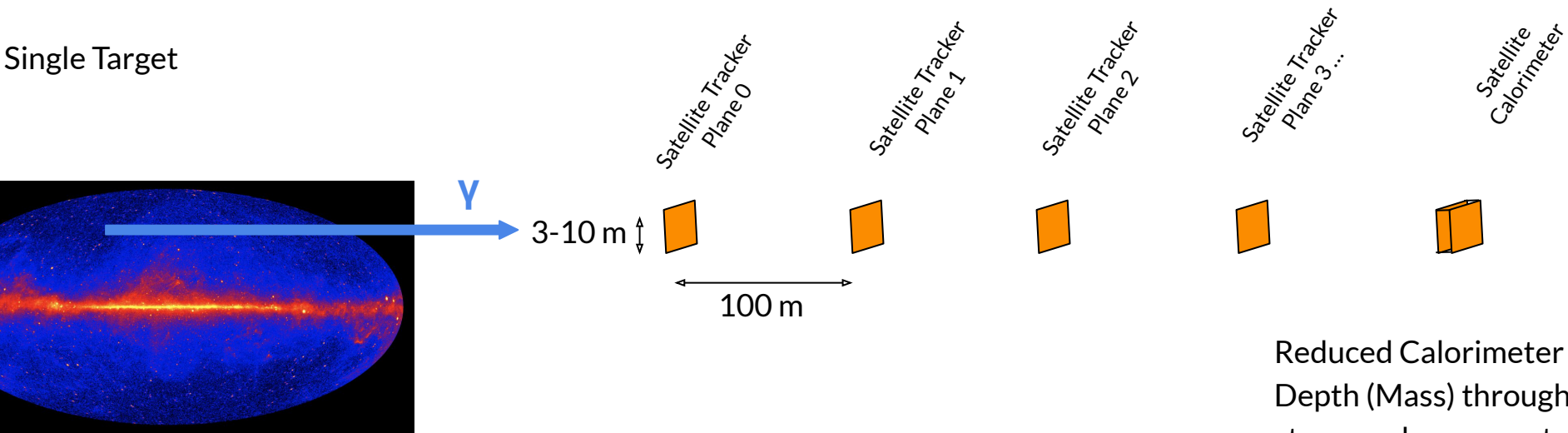
Previous designs use W converter and Si strip detector

Consider using entirely active detector material as both converter and tracker to deliver best angular resolution⁴

Large Area / High Angular Resolution / Narrow Field

Scale up the Tracker Area and Length, divide detectors into separate satellites

Single Target



dSph emission energy depends on Dark Matter Particle Mass and Annihilation Mechanism. Hints of Signals at ~ 5 GeV.
Conduct new search at that energy and also over a broader gamma energy range from target - what is the optimum dSph?

Reduced Calorimeter Depth (Mass) through strong enhancement of X_0 with Crystal Orientation (see Laura Bandiera previous talk)

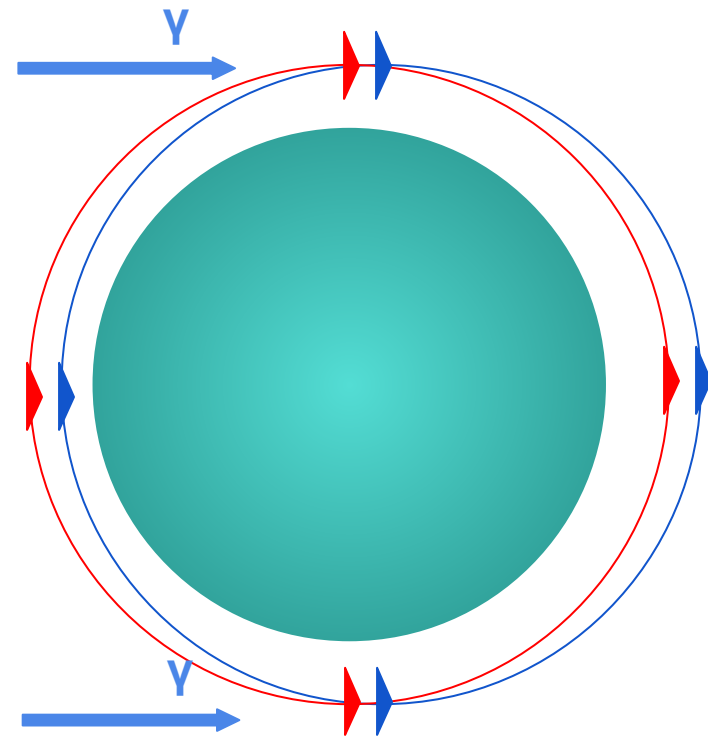
Relative Station-Keeping - Absolute Alignment in Space

The telescope satellite array needs to maintain absolute alignment of separate satellites along fixed axis (with ~ 10 mrad) pointing at target (e.g. dSph Segue 1). Orbits can allow variation in separation (factor $2^{\pm 1}$)

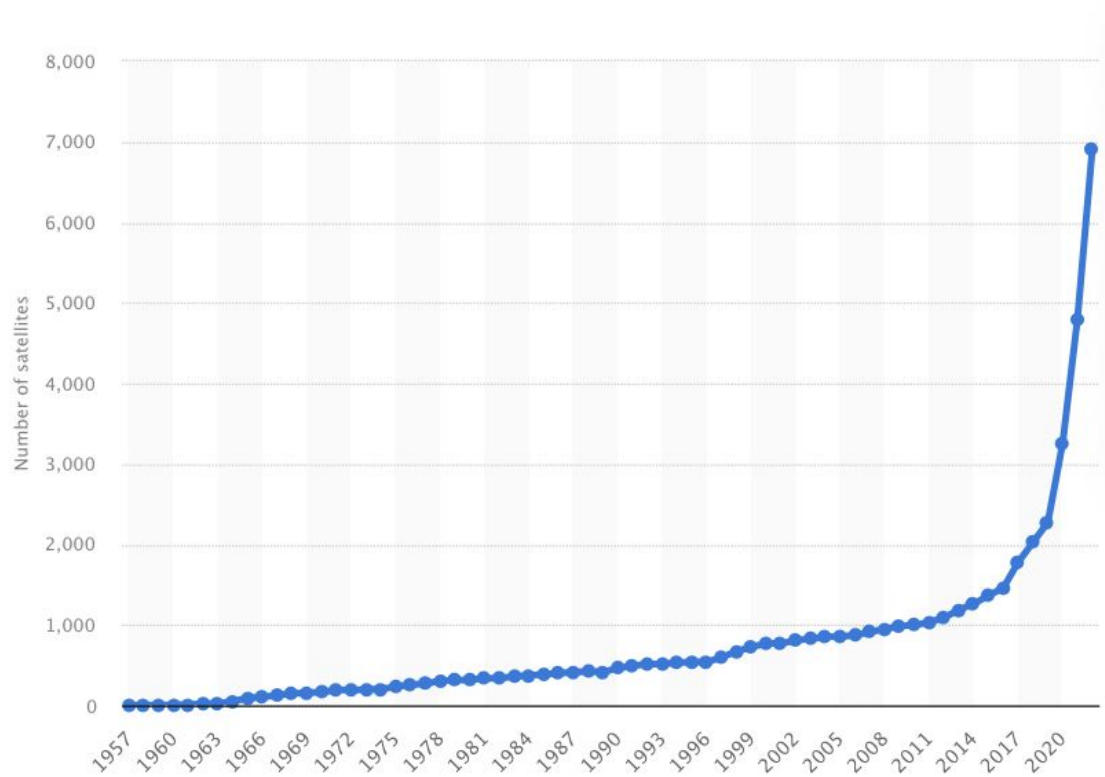
Requires $\Delta v \sim 1$ m/s per orbit to keep 1 satellite 100 m from a 2nd with a fixed absolute alignment (in two circular orbits, one around center displaced from gravitational center by 100 m)

The required thrust magnitudes are consistent with use of Hall-Effect Thrusters. Total propellant would limit mission duration during prototyping missions. Also investigate alternative LEO strategies using different orbital ellipticities and inclinations for satellites with lower overall Δv /orbit requirement. Later consider MEO, GEO orbits to further lower Δv /orbit.

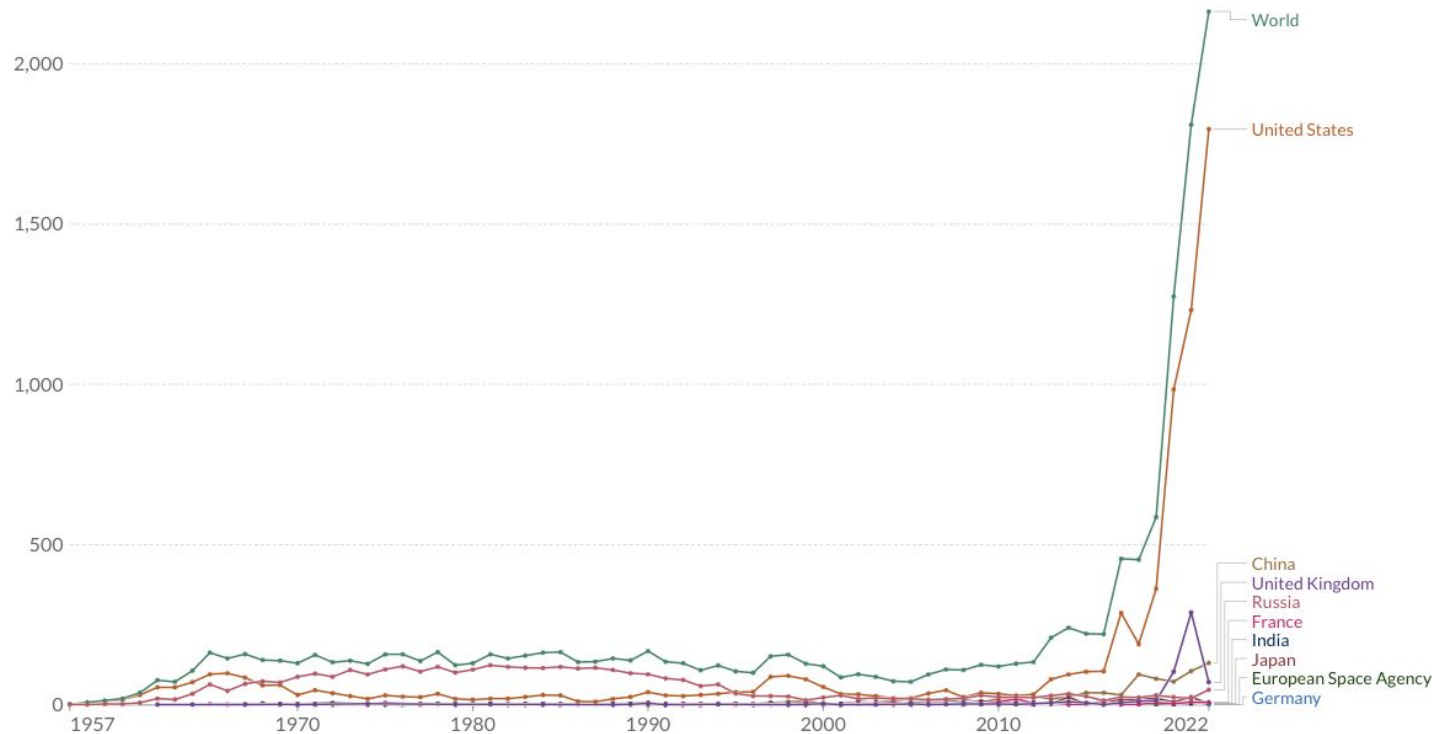
Are $\Delta V \sim MV$ relative electrostatic potentials possible between satellites to create useful additional attractive forces (create gravi-electro-L2)?



Total Number of Satellites in Orbit (1957-2022)



Annual Number of Objects Launched into Space (1957-2022)



Source: United Nations Office for Outer Space Affairs, Online Index of Objects Launched into Outer Space (2023)
Note: When an object is launched by a country on behalf of another one, it is attributed to the latter.

OurWorldInData.org/space-exploration-satellites • CC BY

Starlink Satellites v1.5, v2 mini, and v2

Starlink v1.5 (270 kg, launched in SpaceX Falcon 9, 51 per launch)

→ Starlink v2 Mini (800 kg, 21 launched at a time in SpaceX Falcon 9),

Body 11 m², Panels 105 m²

(May 2023) 4,400 sat. already launched >90% fully operational

Starlink v2 (~50 per launch in future SpaceX Starship)

Body 25 m², 1200 kg

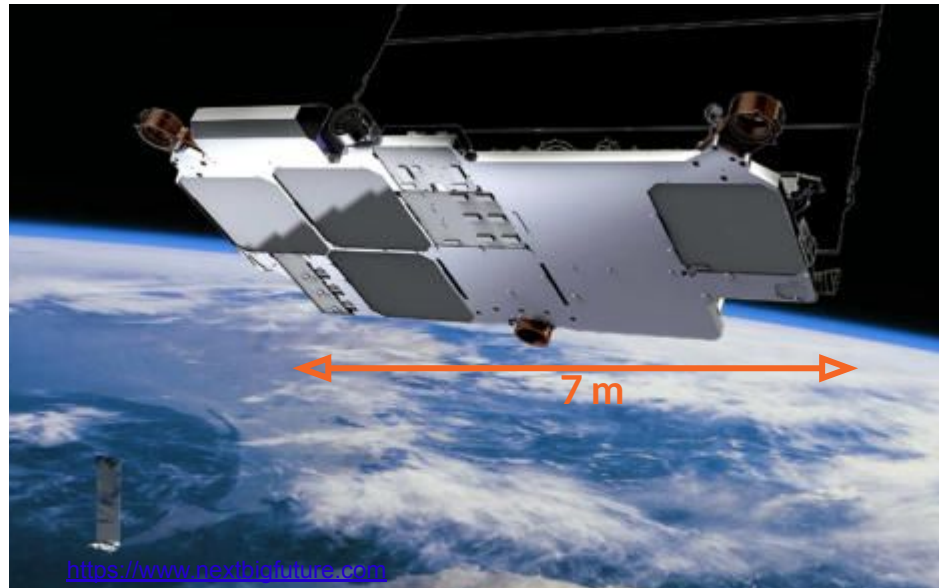
Starlink: Mass Produced Satellites
42k in Constellation is the goal

Starlink V2 Mini



4 m

Starlink / NASASpaceFlight



2023 ASAPP, Rick Gaitskell (Brown)

Physicists want in ...

Research Physicists should be in on the new game, ubiquitous satellites / experimentation

- this also trains new generations of satellite experienced physicists → commercial sector

Satellites - becoming common short period from design, build and launch - evolving designs

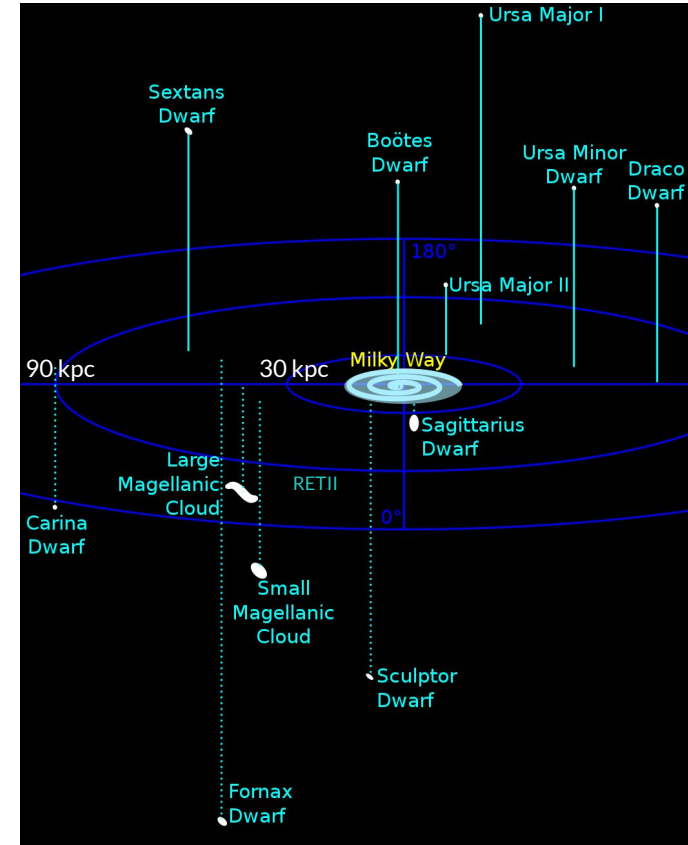
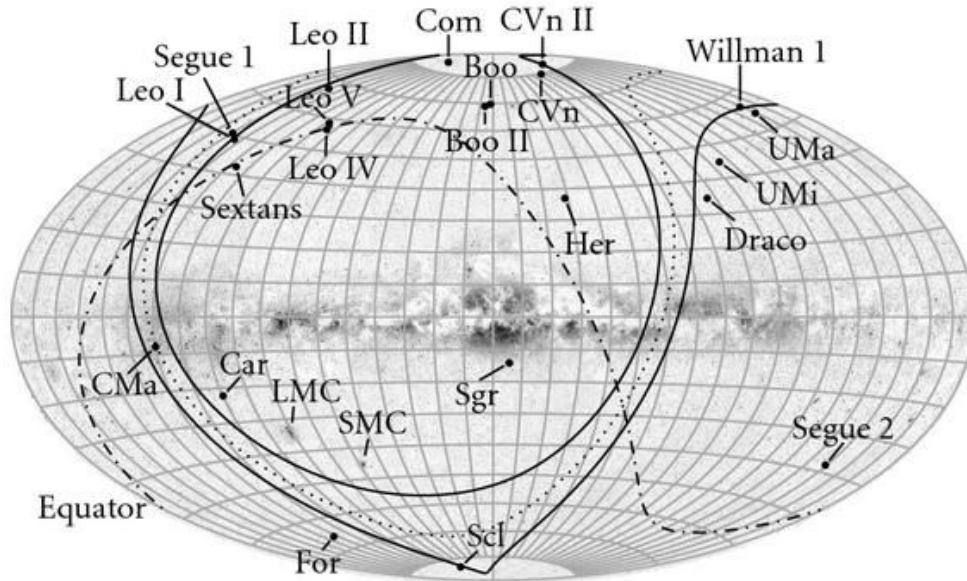
- focused missions / focused functionality
- doesn't need to be a broad survey mission

Significantly lower launch costs / high cadence

Operate arrays of satellites / achieve larger instrumented areas

Dwarf Satellite Galaxies in Milky Way

Sources of Dark Matter Annihilation Gamma Rays, very low in baryons so no alternative gamma sources

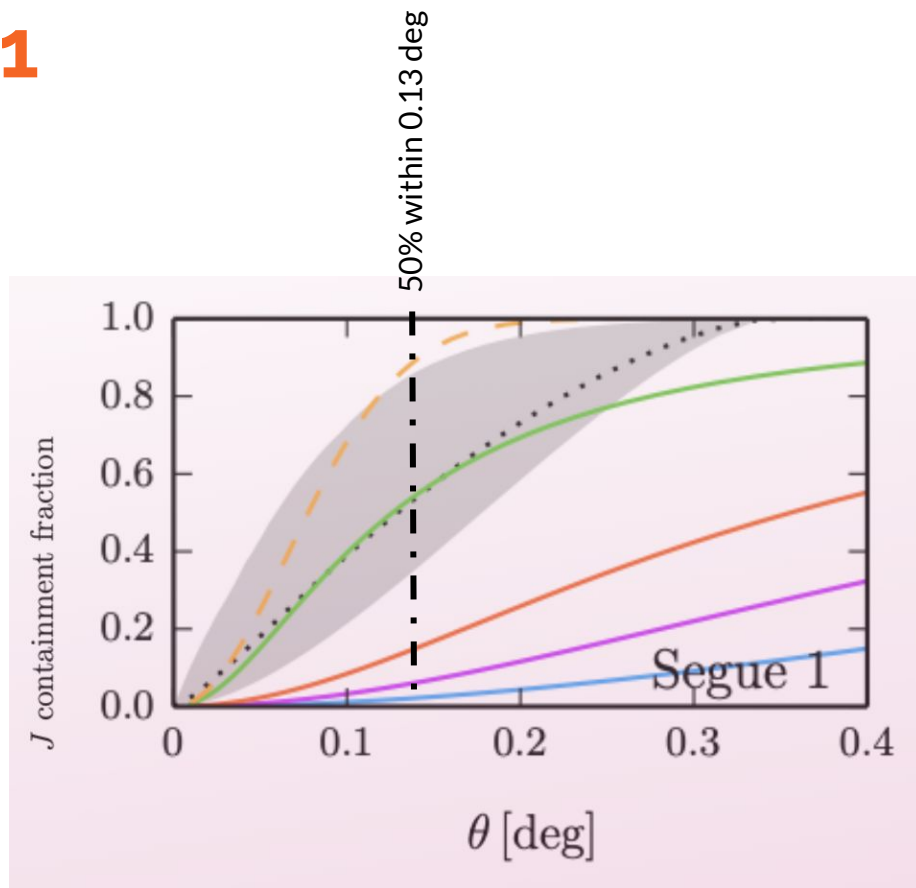


Angular Scale of Segue 1

(See poster, Alexei Sytov at ASAPP, Wednesday)

Containment fraction for DM annihilation as a function of angular distance from the center of Segue 1.

The dotted line shows the median value of the containment fraction while the shaded band corresponds to the 16th and 84th percentiles at each angle.



<https://indico.cern.ch/event/1208314/contributions/5342905/attachments/2667684/4625624/Ferrara%202023%20Koushiappas.pdf>

dSph (Dwarf Spheroidal Galaxy) Targets

Narrowest of dSph Sources present significant enhancement concentration relative to surrounding gamma backgrounds

(See Poster, Alexei Sytov at ASAPP, Wednesday)
On angular scale of Segue 1

	[kpc]	Theta for 50% Flux [1]			Concentration of Signal (Relative)
		Median Value for angle estimate [deg]		J scale in linear units (Arb)	
Dwarf Galaxies (Favored in Bold)	Distance	Theta_0p5	+Error	J_0p5 / 1e18	J_0p5 / (Theta_0p5)^2
UrsaMinor	66	0.06	0.07	8.51	2364
Segue1	23	0.13	0.05	22.91	1356
Leoll	205	0.04	0.05	0.93	583
UrsaMajorII	30	0.24	0.06	26.30	457
Coma	44	0.16	0.02	10.47	409
Sculptor	92	0.15	0.05	3.47	154
RET II	30	0.57	0.05	39.81	123

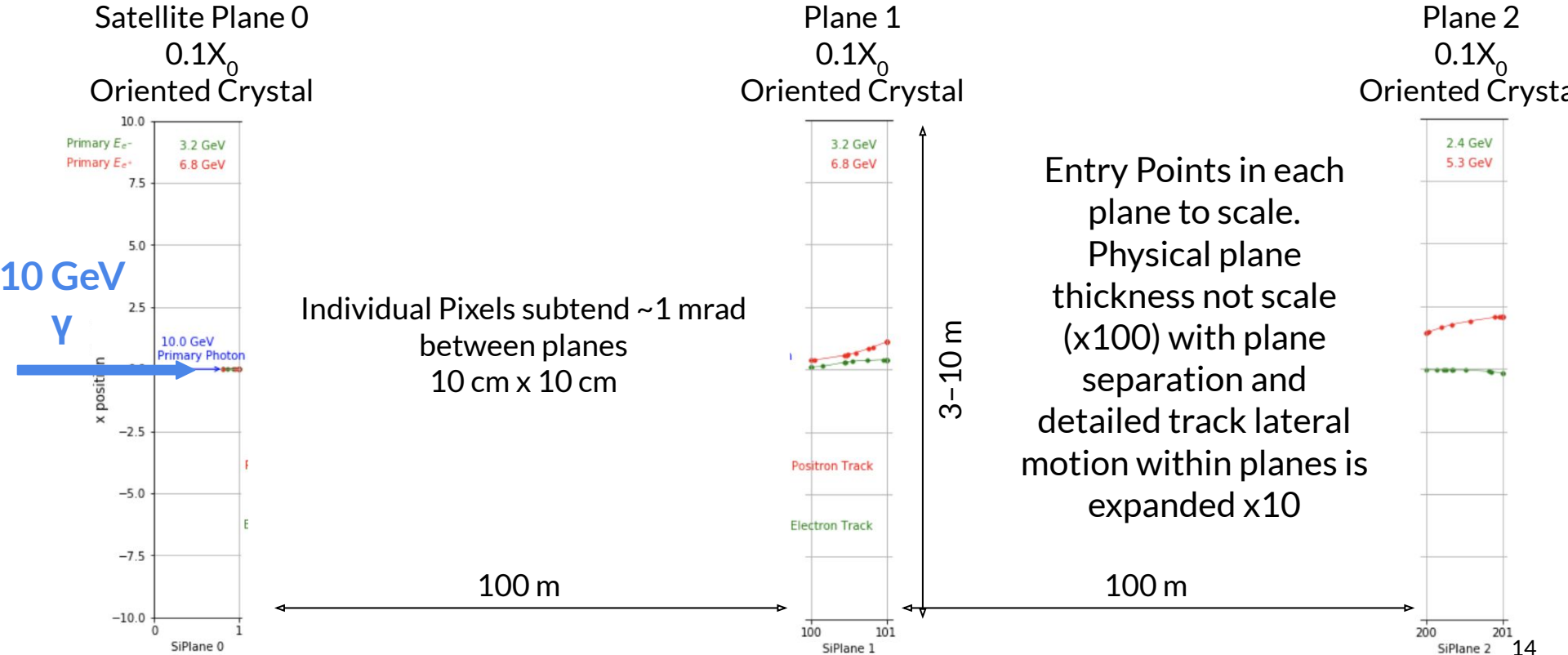
0.1 deg = 1.7 mrad

As a next step this analysis still needs to compare predicted concentrated signal to the detailed backgrounds in each region seen by FermiLAT

[1] Table data based on results from A Geringer-Sameth, SK, MW, 2015 ApJ 801 74, <https://doi.org/10.1088/0004-637X/801/2/74>

Tracker - Individual Satellite Plane Arrangement

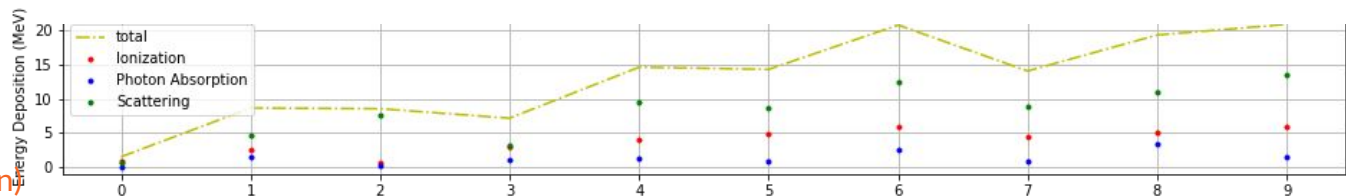
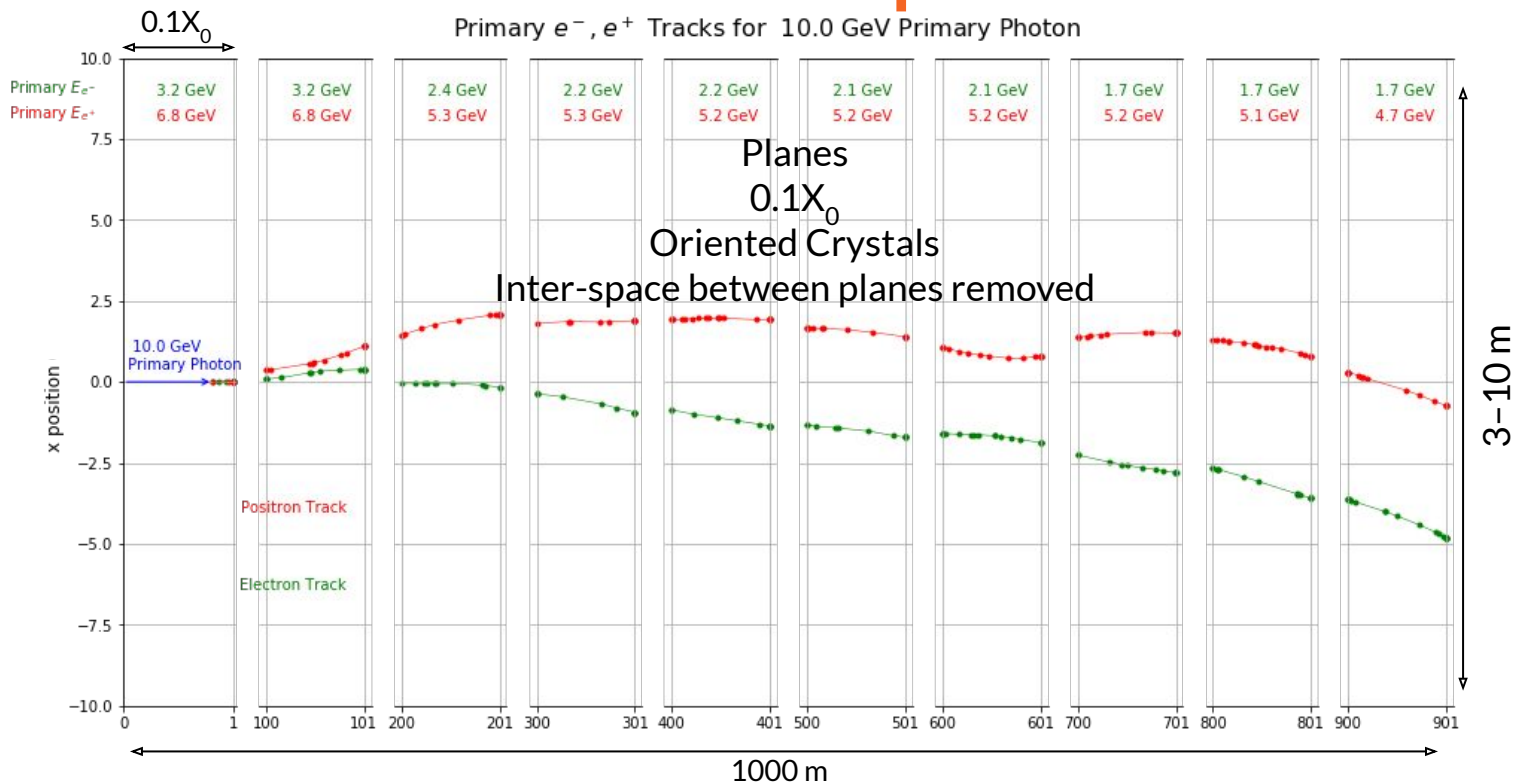
Conversion Probability Enhanced Along Primary Axis (Crystal Axes aligned)



Tracker Satellites (shown with inter-space removed)

10 GeV Photon
Primary

Only showing
primary e-/e+
Pair Tracks



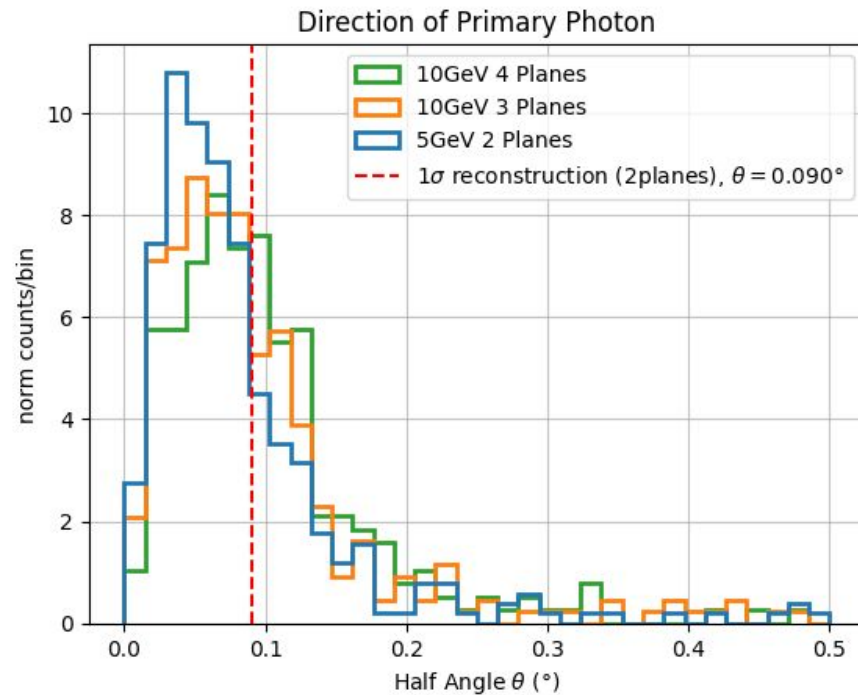
Direction Reconstruction

0.1 deg = 1.7 mrad

Using simple deposited-energy-weighted centroid through successive planes the correlation to original gamma trajectory can be established < 0.1 deg

GEANT4 simulation using successive $0.1X_0$ XY detector planes

(Thanks to Napali Raymundo & Nat Swanson, Brown Univ.)

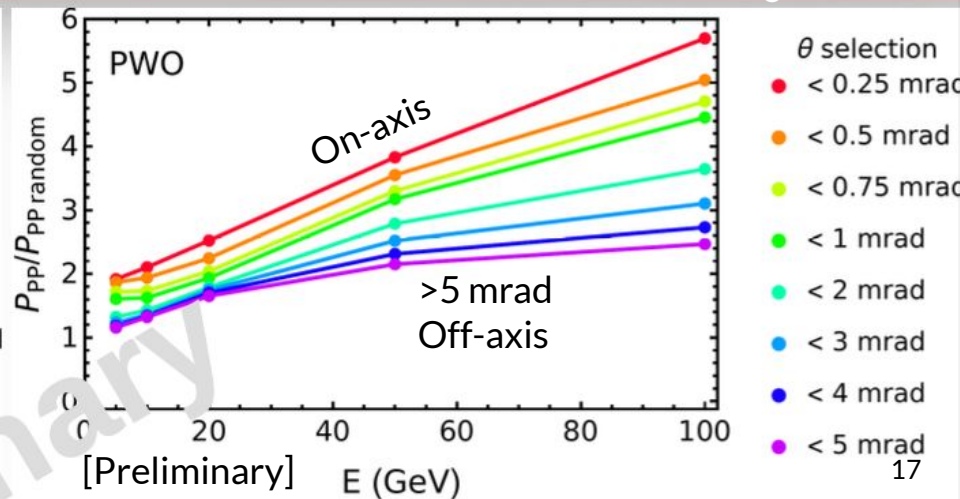
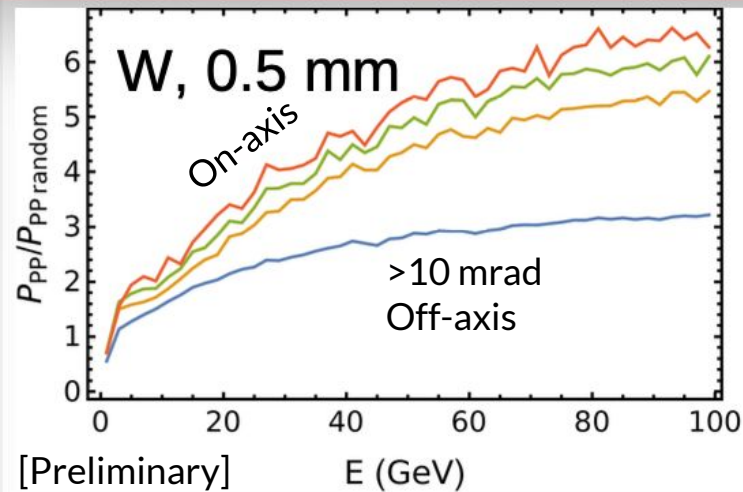


Enhancement of Pair Production in Oriented Crystals

Calculations in Tungsten (W) and PbWO₄ (PWO)

Alexei Sytov (KISTI, INFN) calculations of strongly enhanced bremsstrahlung/pair production - moving to GEANT4 framework

Pair production probability enhancement for PWO 0.1 cm
 $\sim 0.1 X_0$



Compact Calorimeter (see Laura Bandiera talk)

Laura Bandiera (Ferrara) - (previous talk) - Very clear experimental demonstrations of enhanced interactions/shorter radiation length when the trajectories of electrons/photons are aligned with the crystalline axes or planes in an oriented crystal

A significantly reduced radiation length for oriented crystals allow reduction in physical thickness of required absorber while still having optimum depth in radiation lengths.

Gyroradius

The pointing of the e-,e+ trajectories between planes can be influenced by magnetic field environment. However, [Syrov] we can also possibly measure the charge and momentum of the particles through their trajectory curvature during inter-plane space

$$r_g/(10^5 \text{ m}) = \frac{p_{\perp}}{qB} = \frac{(E/\text{GeV}) (v_{\perp}/c)}{(q/e) (B/(33 \mu\text{T}))}$$

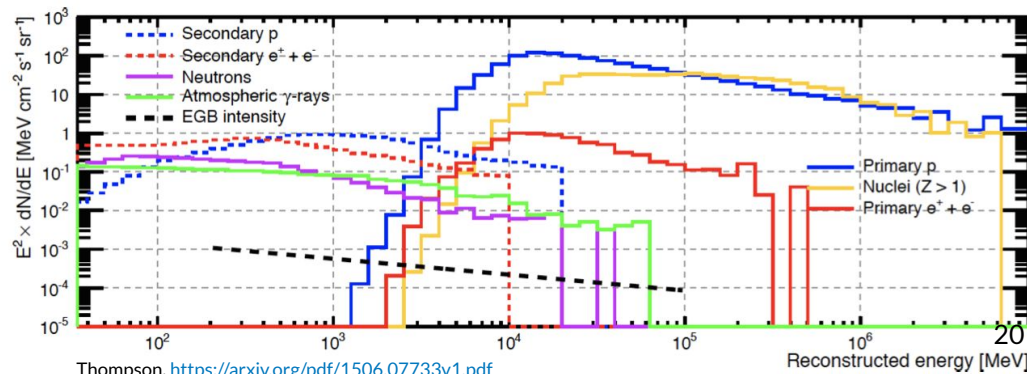
So for 1 GeV e+,e- with trajectory perpendicular to B-field ($\sim 30 \mu\text{T}$) at orbital altitude of 400 km would create gyroradius $r_g \sim 100 \text{ km}$. This would move hit location (from zero field trajectory) between two detection layers 1 km apart by 5 mrad ($\sim 0.29 \text{ deg}$)

For higher energy particles, or more closely spaced planes the angular deviations would fall below 0.1 deg pointing required for dSph, but if higher XY resolution detection planes were implemented may still be used.

Rejecting Particle Backgrounds

Looking for time coincidences and consistent geometries across multiple tracker-layers and final calorimeter with consistent trajectory

- Require very narrow timing windows to correlate the hits in successive layers. 100 m propagation introduces 333 ns offset per layer
- Conventional use of AC shield only possible with the converter-tracker layer in which first gamma conversion occurs. AC no longer encloses all tracker+cal together. This is a significant challenge.
- Subsequent tracker layers will primarily be detecting e^+, e^- from pair production. Requires use of timing information relative to previous tracker event and possibly some local topology of particle entry
- Detailed studies of backgrounds fluxes will be necessary to assess if rejection strategies possible and at what energies



Individual Tracker Plane Thickness and Total Plane Count

As fun as it is to show so many tracker layers the actual pointing is achieved using first few planes directly after the plane in which the primary e^+e^- pair is created by gamma.

The need for many tracker layers is to increase the effective thickness (radiation length) of the tracker stage. This gives higher collection efficiency.

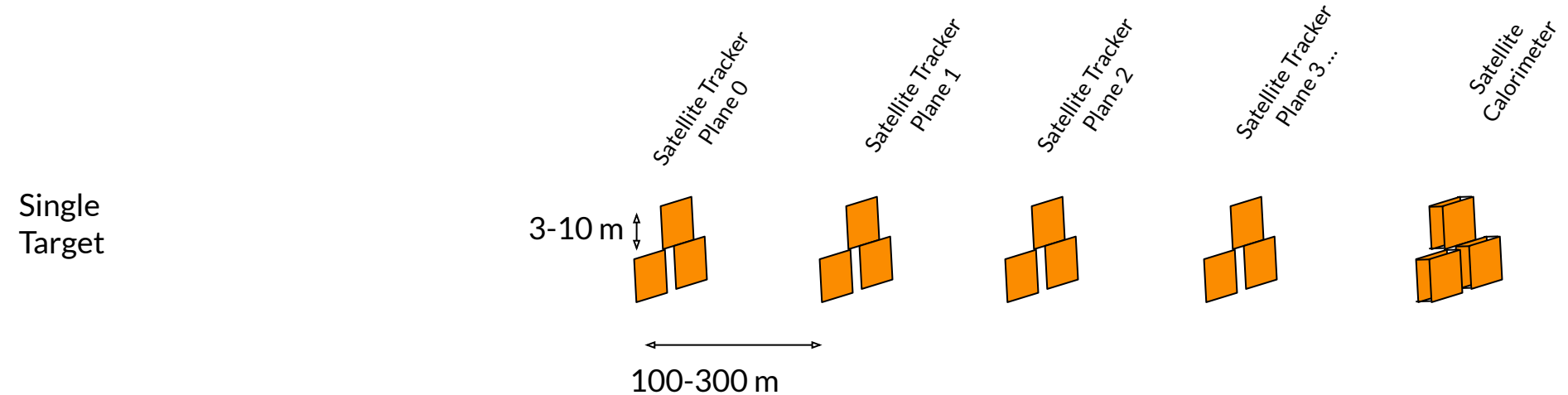
As has been the case with previous gamma ray missions the optimization of thickness of individual tracker satellites will be based on trade off between e^+e^- scattering affecting angular resolution and conversion efficiency.

Use of entirely active oriented crystals doing role of both converter and segmented tracker should help optimization.

Design of array is modular and so additional satellites could be sent up to enlarge/increase the effective area/sensitivity of array

Large Area / High Angular Resolution / Narrow Field

Modular approach to building increased area



Conclusion

New approach - scalable, modular, coordinated satellite arrays. Rapid design, build and launch. Low cost.

Create gamma ray telescope in range 1 GeV–100+ GeV for observing single target at a time in < 1 deg of sky

- Gamma-pair production detection lends itself well to a modular plane-based detector array
- Scale of Calorimeter sets the upper energy of observation

Investigate gamma instrument cost/design savings that are possible with oriented crystal / large pixel / narrow angular acceptance

- Large pixel \rightarrow lower channel count. Suitable cost effective route to achieve large effective area

Alignment of crystal orientation provides significant reduction in X_0 for γ pair-production and $e+e-$ detection, peaked directional response, achieving higher sensitivity to specific source direction

- Choice of active detector also as converter material would seem optimal
- Specific materials choice based on crystal E-field/energy range / thickness / timing / light yield requirements

Use satellite cluster in spatially synchronized orbit to point in one absolute direction. Development of new satellite bus techniques for position maneuvering. (Additional applications of coordinated array likely.)

~ 10 's m along line, ~ 1 m lateral for alignment, so not too demanding for first implementations

Modularity allows reconfiguration of optimal energy/extension of effective area of measurement

Continue study of likely best gamma emission targets for narrow field instrument

- Narrow angular scale dSph gamma excess directly testable