TeV dark matter searches with gamma-ray telescopes from the ground: present and future

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Dark Ghosts

Brussels, 13-14 November 2018

2nd GNN Workshop on Indirect Dark Matter Searches with Neutrino Telescopes

Università degli Studi di Padova

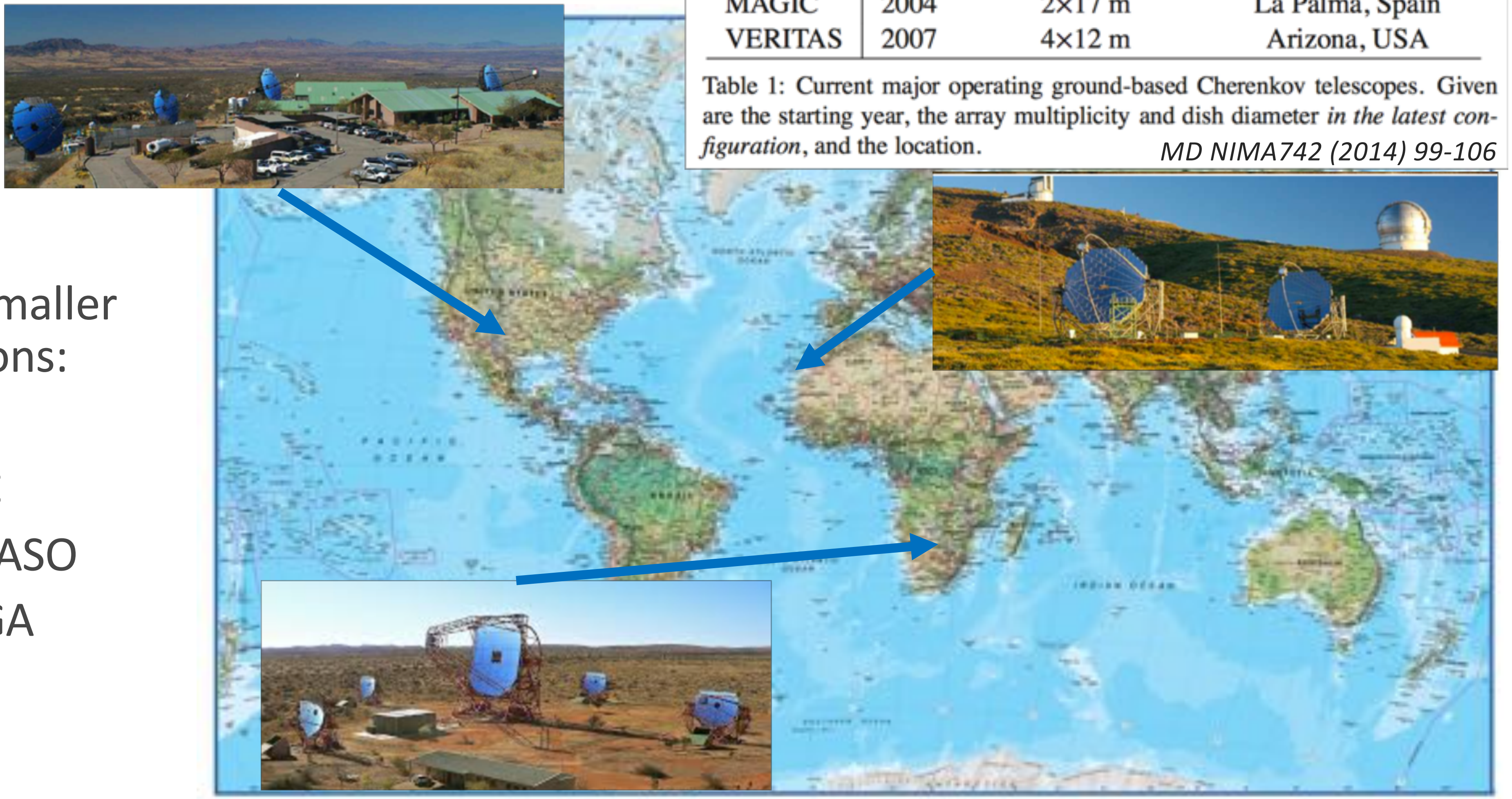
INFN Istituto Nazionale di Fisica Nucleare

Current major IACTs

IACT	Year	Nr. tels & diameter	Location
~~Whipple~~	~~1968~~	~~1×12 m~~	~~Arizona, USA~~
H.E.S.S.	2003	4×12 m+1×28 m	Gambserg, Namibia
MAGIC	2004	2×17 m	La Palma, Spain
VERITAS	2007	4×12 m	Arizona, USA

Table 1: Current major operating ground-based Cherenkov telescopes. Given are the starting year, the array multiplicity and dish diameter *in the latest configuration*, and the location.

MD NIMA742 (2014) 99-106

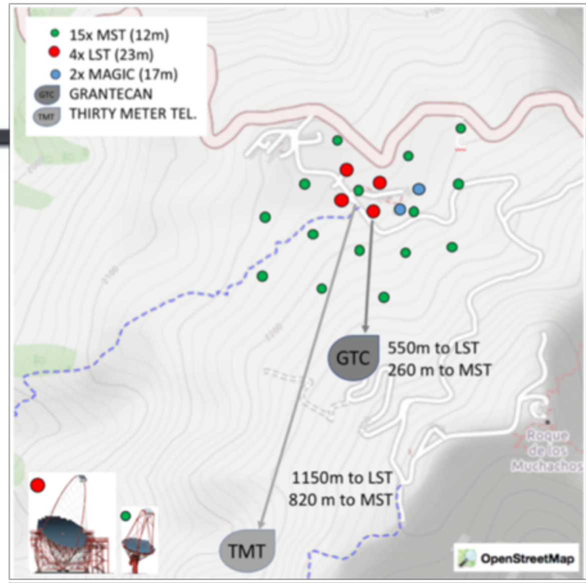


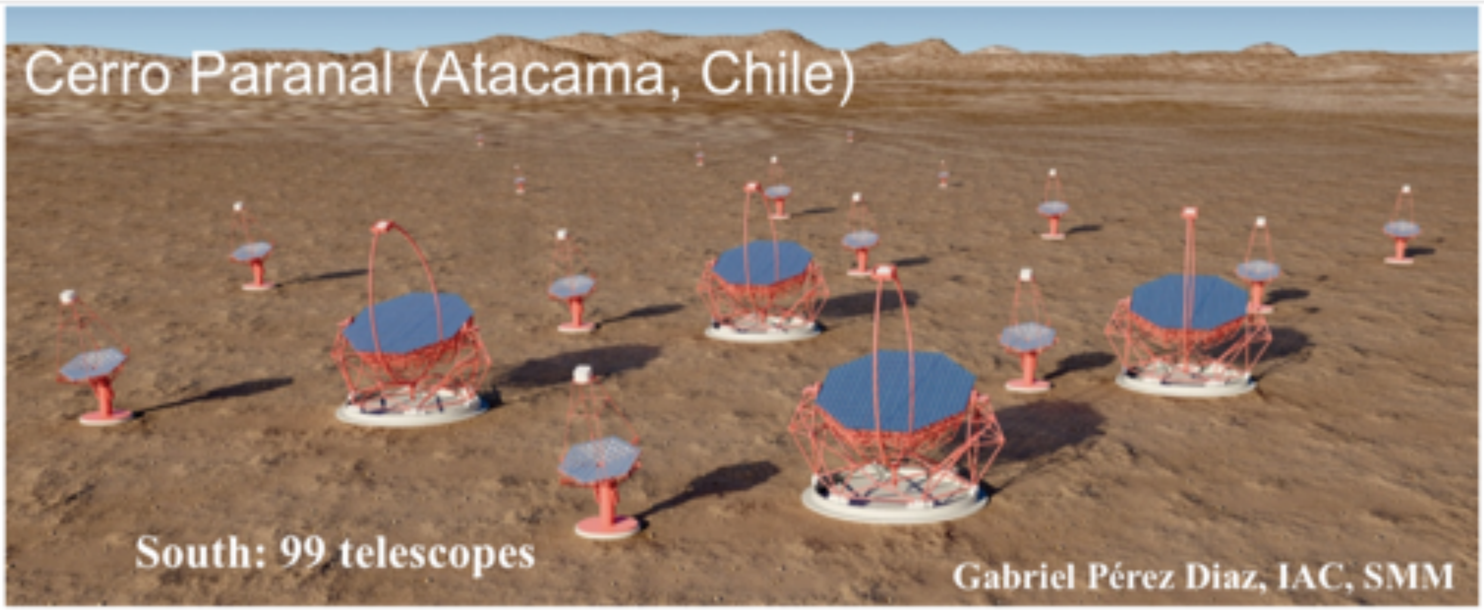
Several smaller installations:

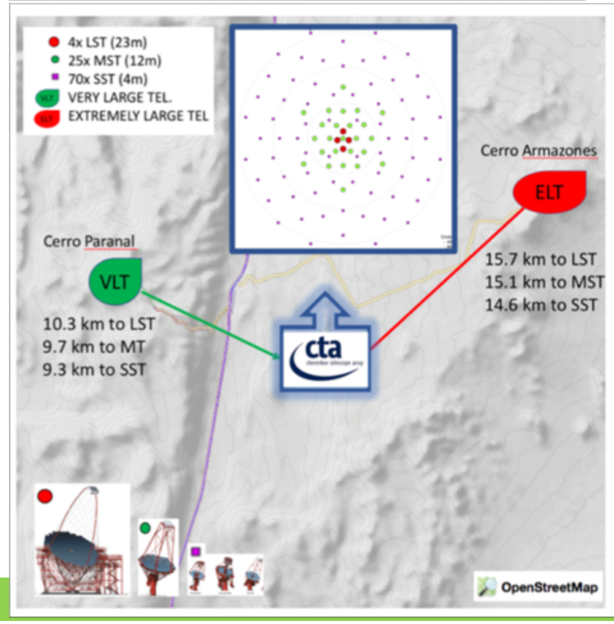
- FACT
- TACTIC
- In LHAASO
- In TAIGA
- …

Two CTA arrays

M.Gaug, MD, MNRAS 10.1093/mnras/sty2188→

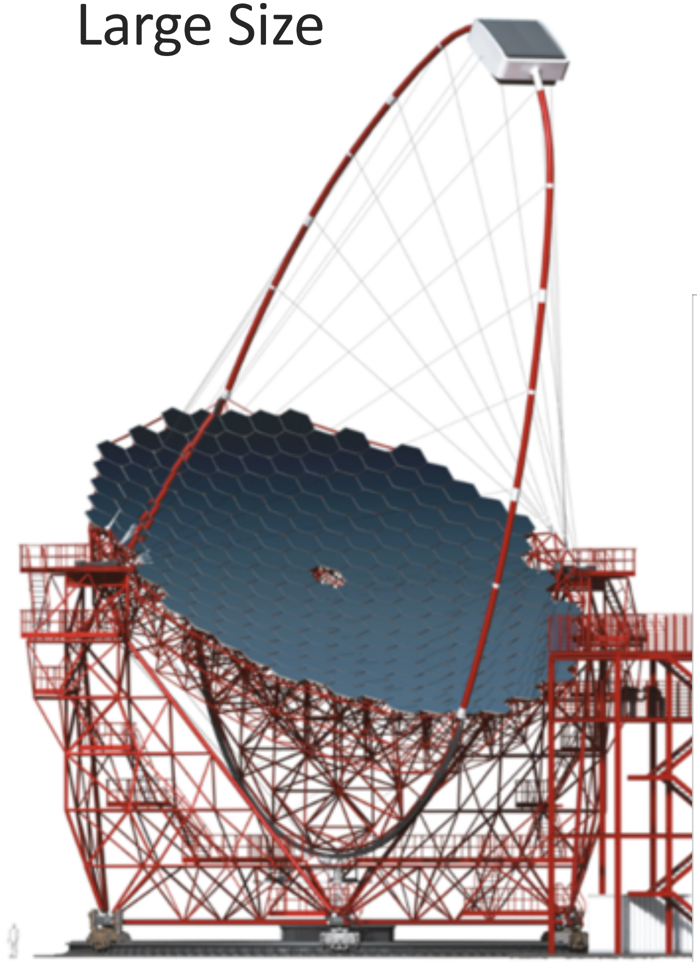




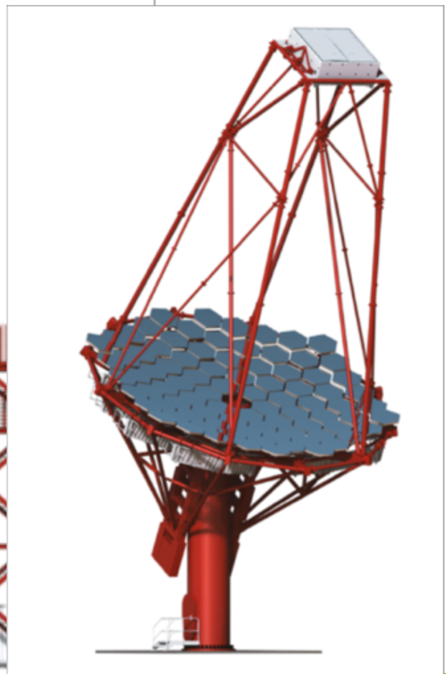


CTA: three telescope sizes

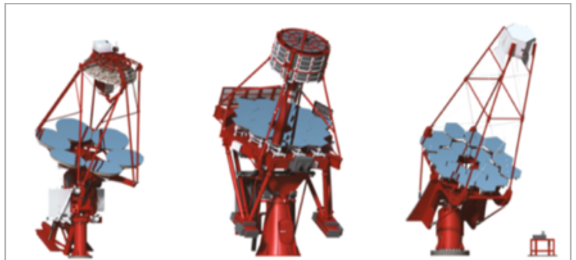
Large Size



Medium Size



Small Size



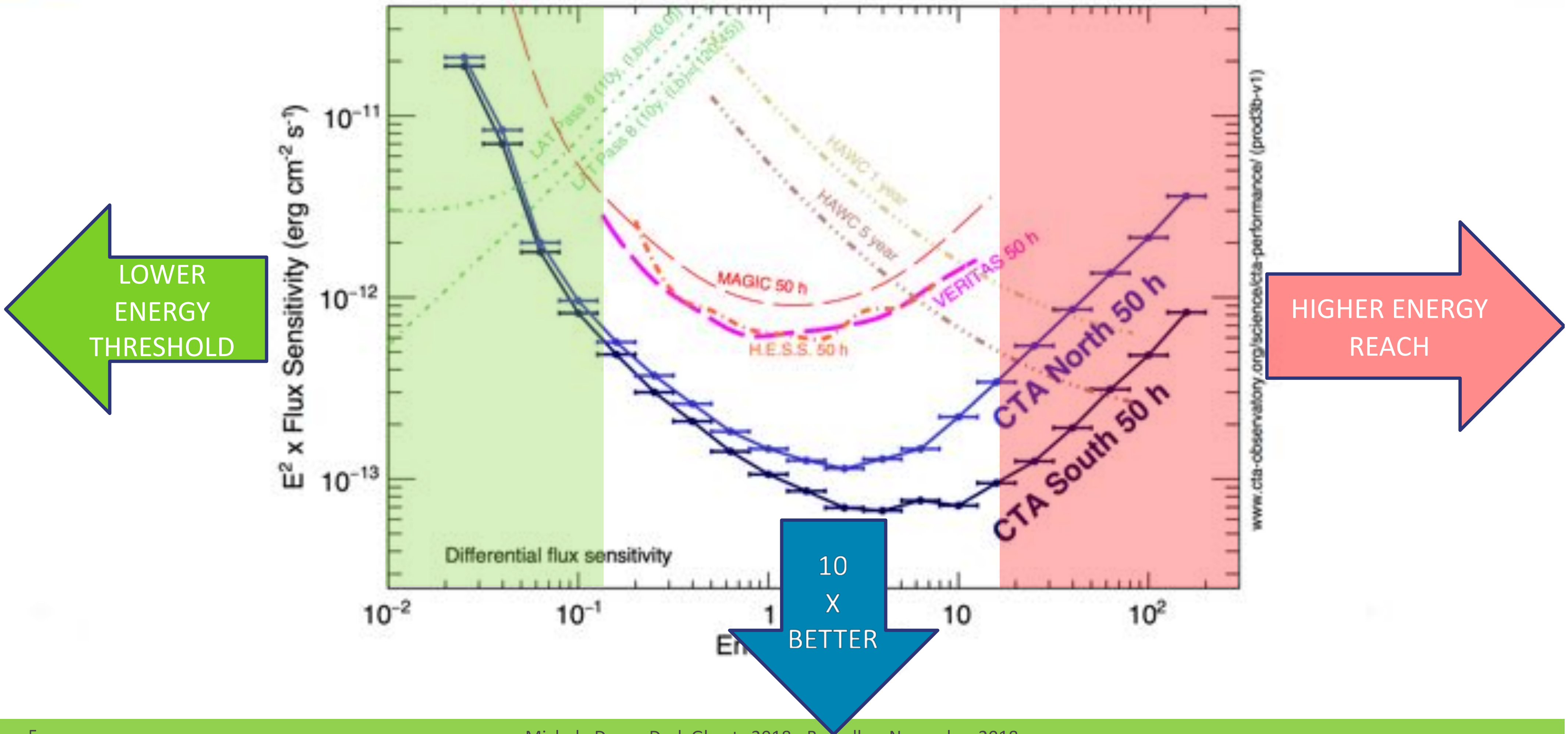
2017 Begin Pre-Construction

2022 Begin Operation

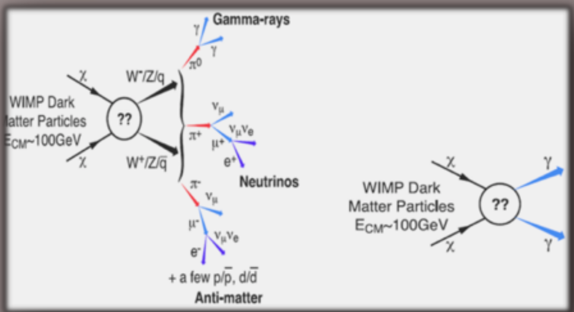
2022-25 Commissioning and Early Science

2025 Construction completion

A sensitivity leap

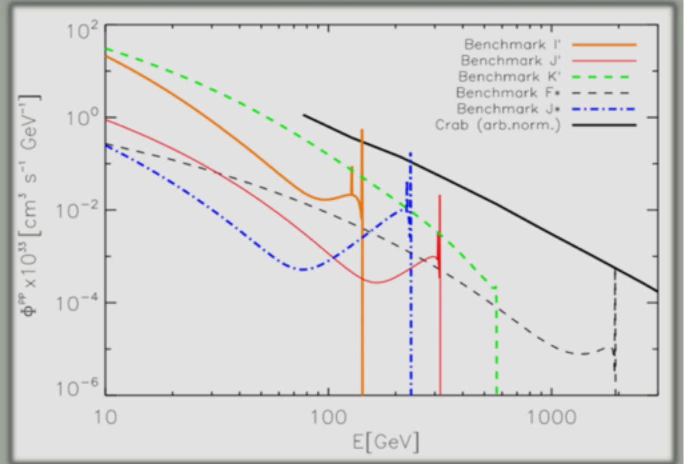


Four reasons for DM searches with gamma-rays

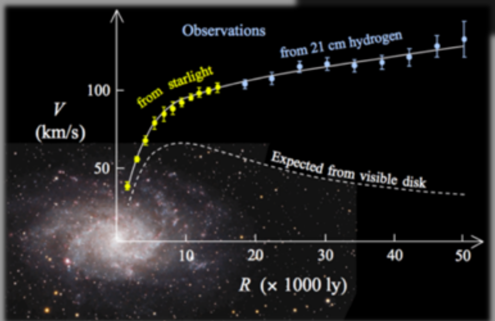


Interaction with SM

Features in spectra, and not distorted

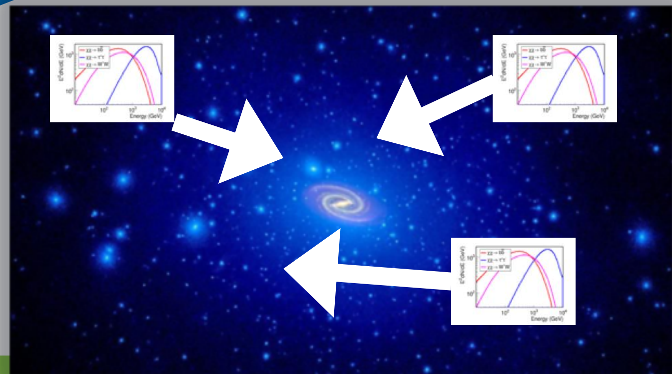


Point where DM is expected



γ

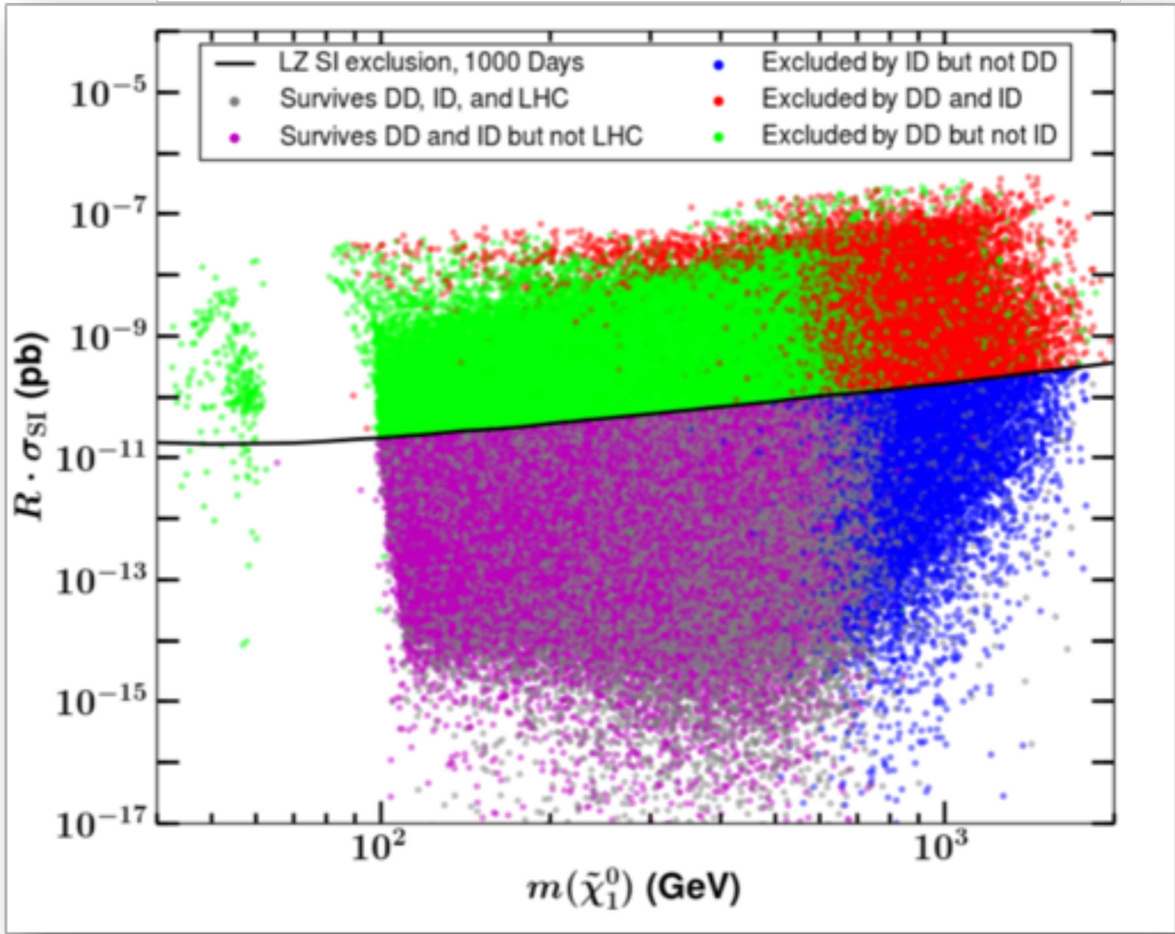
Universality of spectra



5th: Complementarity

- Where overlap: **cross-validation possible**
- Some regions **uniquely probed by CTA**

PHYSICAL REVIEW D **91,** 055011 (2015)



- Excluded by ID but not DD
- Excluded by DD and ID
- Excluded by DD but not ID

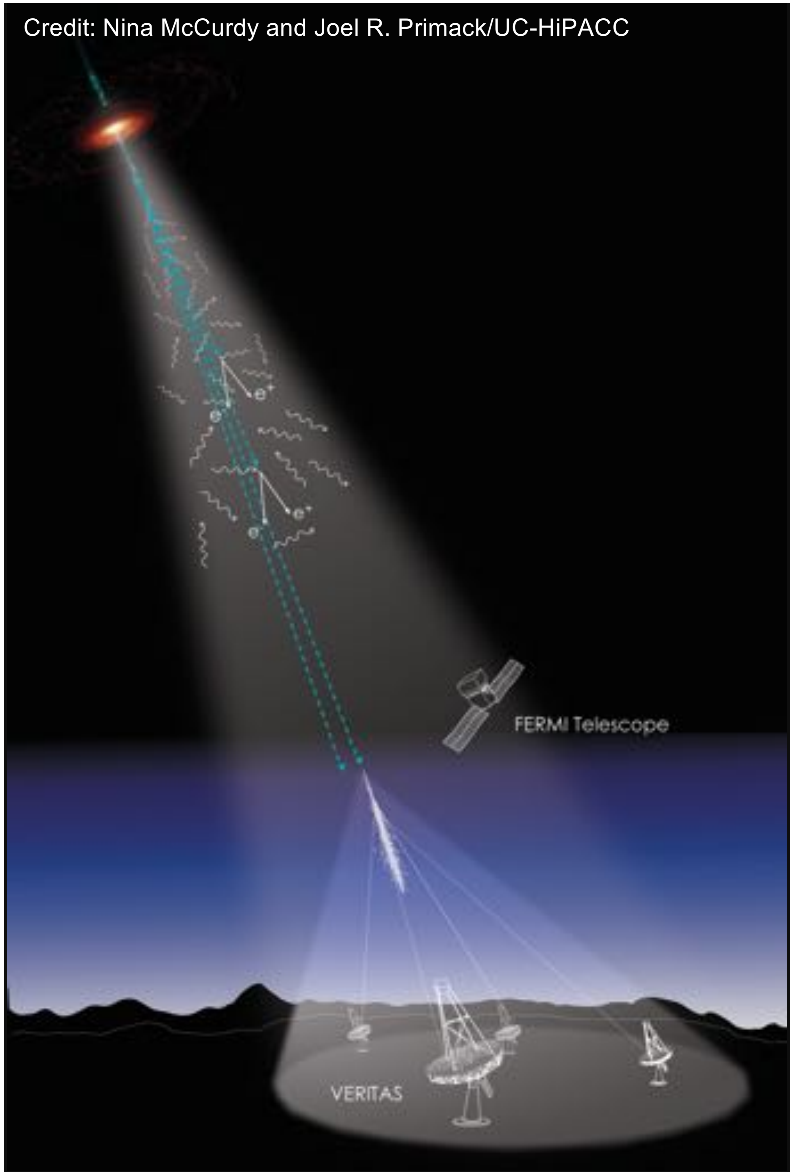
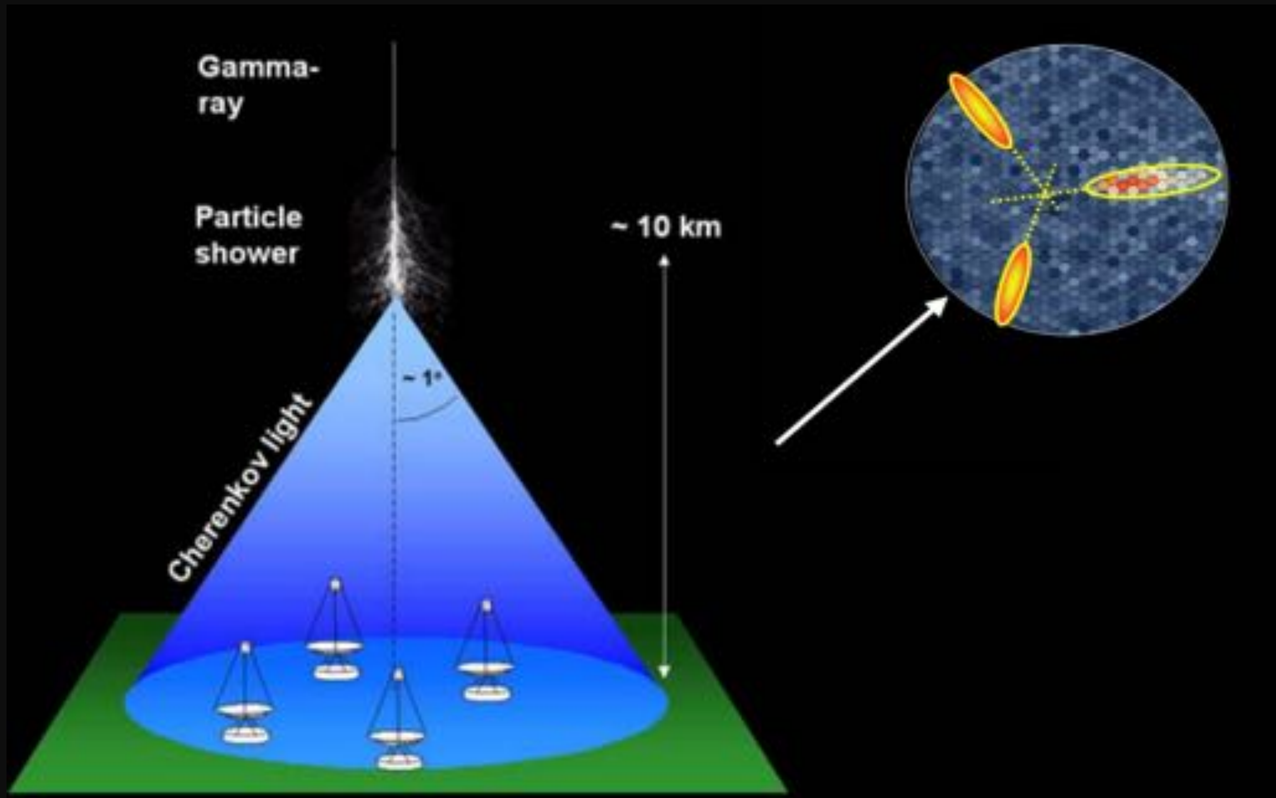


Figure of merits of current generation:

- FOV 5x5 deg
- 50 GeV- 100 TeV
- Eff.Area ~ 10^5-10^6 m^2
- Dark time: ~1000 h/year
- ~10-50 h source for detection
- ~0.1 angular resolution
- ~10-20% energy resolution



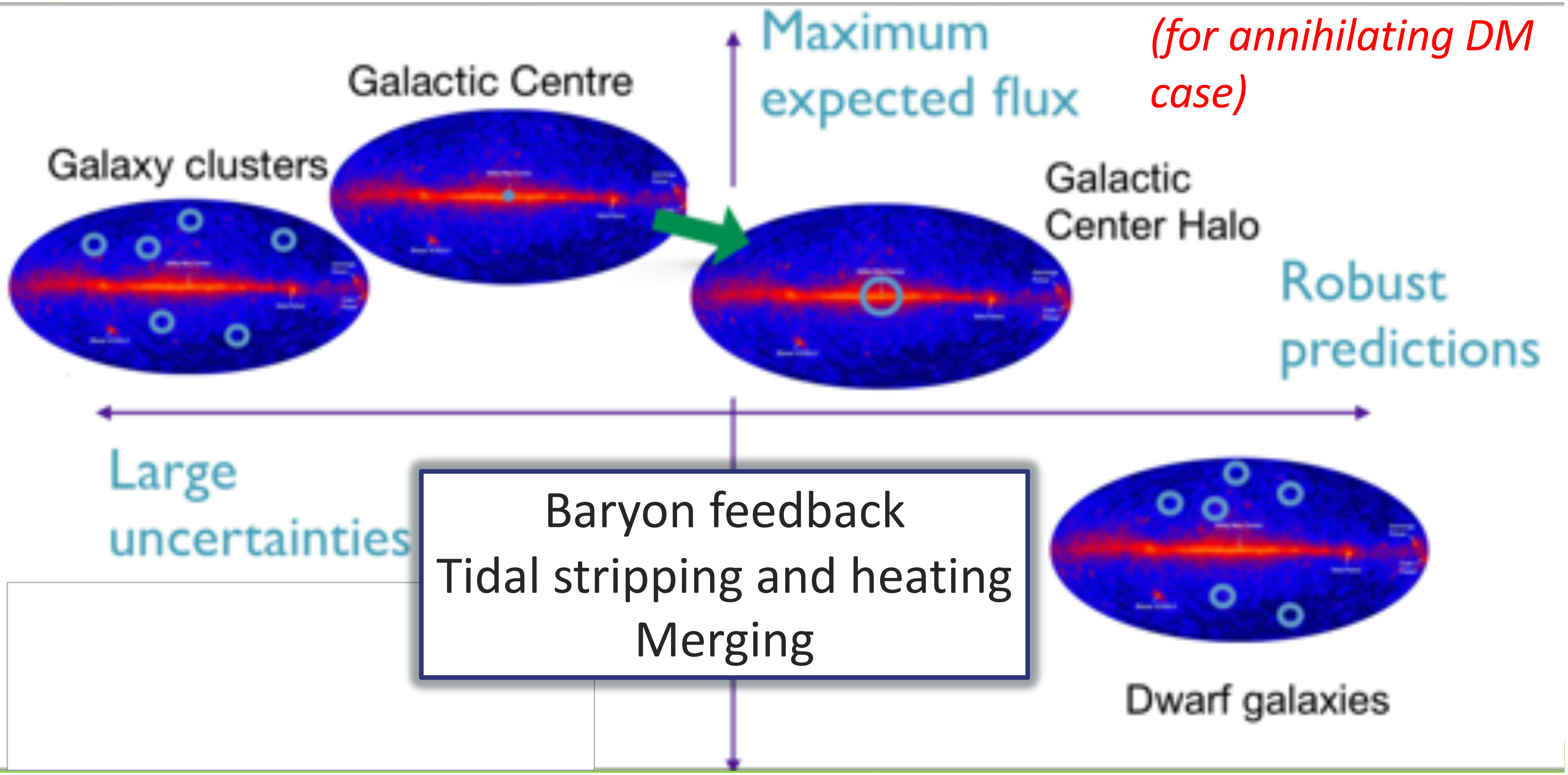
What influences the flux on Earth

$$\frac{d\Phi(\Delta\Omega)}{dE'} = \frac{d\Phi^{PP}}{dE'} \times J(\Delta\Omega)$$

	Particle Physics factor:	Astrophysical factor:
Annihilation:	$\frac{d\Phi^{PP}}{dE'} = \frac{1}{4\pi}\frac{\langle\sigma_{ann}v\rangle}{2m_\chi^2}\frac{dN}{dE'}$	$J_{ann}(\Delta\Omega) = \int_{\Delta\Omega}\int_{los}\rho^2(l,\Omega)dl d\Omega.$
Decay:	$\frac{d\Phi^{PP}}{dE'} = \frac{1}{4\pi\ \tau_\chi m_\chi}\frac{dN}{dE'}$	$J_{dec}(\Delta\Omega) = \int_{\Delta\Omega}\int_{los}\rho\ (l,\Omega)dl d\Omega.$
	Large uncertainties from Fund. Phys. No target dependences (straightforward stacking analysis)	Large uncertainties from DM profiles (robust limits from less uncertain targets)

- Hunting the **highest J-factor**
- Left with huge **uncertainties in the particle physics**

Different target classes



What ground gamma-ray telescopes have accomplished

CACTUS claim

TABLE II. The approximate energy distribution of events reported by CACTUS compared to the prediction from various annihilating dark matter scenarios. The CACTUS observations appear to be consistent with a ~500 GeV dark matter particle annihilating to $b\bar{b}$, a ~300 GeV dark matter particle annihilating to W^+W^-, or a ~200 GeV dark matter particle annihilating to $\tau^+\tau^-$. In the last column, the number of events which EGRET should have seen is given for each case.

	Total	>100 GeV	>125 GeV	EGRET
CACTUS observation	30 000	7000	4000	–
600 GeV, $b\bar{b}$	30 000	9000	5000	290
500 GeV, $b\bar{b}$	30 000	7700	3900	400
400 GeV, $b\bar{b}$	30 000	6000	2700	630
400 GeV, W^+W^-	30 000	9200	5100	280
300 GeV, W^+W^-	30 000	7100	3500	470
200 GeV, W^+W^-	30 000	4000	1300	1100
300 GeV, $\tau^+\tau^-$	30 000	15 000	9500	2.8
200 GeV, $\tau^+\tau^-$	30 000	9200	4200	7.2
150 GeV, $\tau^+\tau^-$	30 000	5000	1300	16

- CACTUS (Converted Atmospheric Cherenkov Telescope Using Solar-2) was a ACT located in California.
- It was originally a solar power plant called Solar Two, converted to an observatory in 2001, installing a 6 meter secondary that imaged the field onto an array of 80 PMTs.

Bergstrom Hooper 2005

1,2,..,20dSphs

- All instruments launched in the search!...but investing few hours

Dwarf Satellite Galaxies				
Draco	2003	7.4	Whipple	10
	2007	7.8	MAGIC	12
	2007	18.4	VERITAS	13
Ursa Minor	2003	7.9	Whipple	10
	2007	18.9	VERITAS	13
Sagittarius	2006	11	H.E.S.S.	14,15
	–	–	H.E.S.S.	In prep.
Canis Major	2006	9.6	H.E.S.S.	16
Willman 1	2007 – 2008	13.7	VERITAS	13
	2008	15.5	MAGIC	17
Sculptor	2008	11.8	H.E.S.S.	15,18
Carina	2008 – 2009	14.8	H.E.S.S.	18
	2008 – 2012	23	H.E.S.S.	15
Segue 1	2008 – 2009	29.4	MAGIC	19
	2010 – 2011	48	VERITAS	20
	2010 – 2013	158	MAGIC	21,22
Boötes	2009	14.3	VERITAS	13
Coma Berenices	2010 – 2013	8.6	H.E.S.S.	15
Fornax	2006? – 2012?	6	H.E.S.S.	15
Ursa Major 2	2014 – 16	95	MAGIC	23
UNDISCL.	2016 – 17	50	MAGIC	In prep.
UNDISCL.	– –	170	VERITAS	In prep.
UNDISCL.	– –	170	VERITAS	In prep.
UNDISCL.	– –	130	VERITAS	In prep.
UNDISCL.	2017 – 18	–	MAGIC	Ongoing

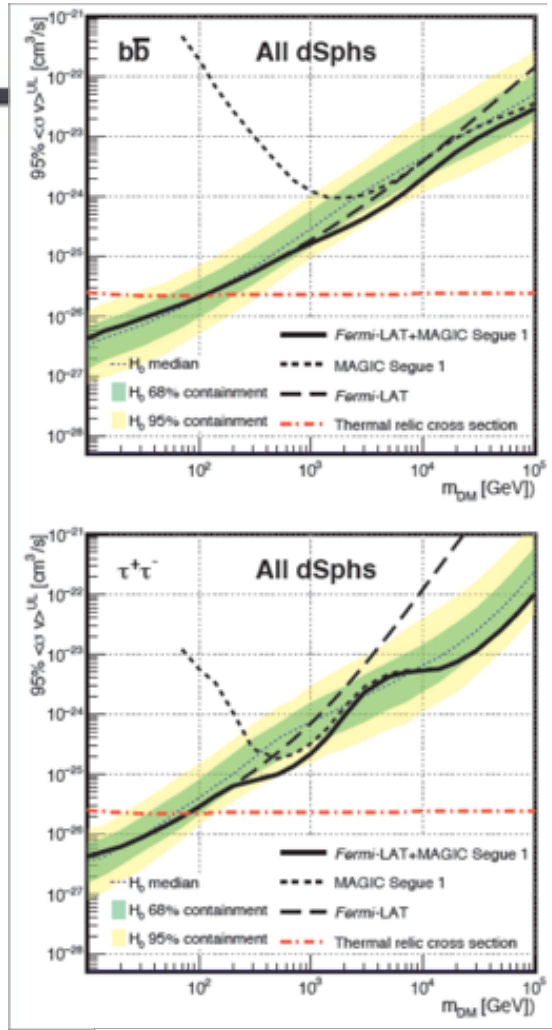
MD, NIM A 742 (2014)

MAGIC + Fermi combined

- MAGIC: Segue 1 (158 h) and Fermi-LAT: 15 dwarfs (6 years, Pass8)

- **Effective combination (2x stronger constraints) in the range 300-500 GeV**

JCAP 02 (2016) 039



JCAP02(2016)039

Segue + Fermi statistical treatment

- In all DM searches, **we try to measure the same universal parameter, e.g. <σv>** through gamma-ray flux:

$$\frac{d\Phi(\Delta\Omega)}{dE'} = \frac{d\Phi^{\rm PP}}{dE'} \times J(\Delta\Omega)$$

  - Different observations of different targets differ in the astrophysical or J-factor

$$J_{\rm ann}(\Delta\Omega) = \int_{\Delta\Omega}\int_{los} \rho^2(l,\Omega)dl\,d\Omega.$$

- **Aim: combine measurements** of <σv> from different targets and instruments

See Aleksic+ JCAP 1210 (2012) 032

Different experiments can be combined through ad-hoc likelihood:

Generic Instrument *j* and particular target *i*

$$\mathcal{L}_i(\langle\sigma v\rangle; J_i, \mu_i | \mathcal{D}_i) = \prod_{j=1}^{N\ instrument} \mathcal{L}_{ij}(\langle\sigma v\rangle; J_i, \mu_{ij} | \mathcal{D}_{ij})$$

nuisance parameters

input data set

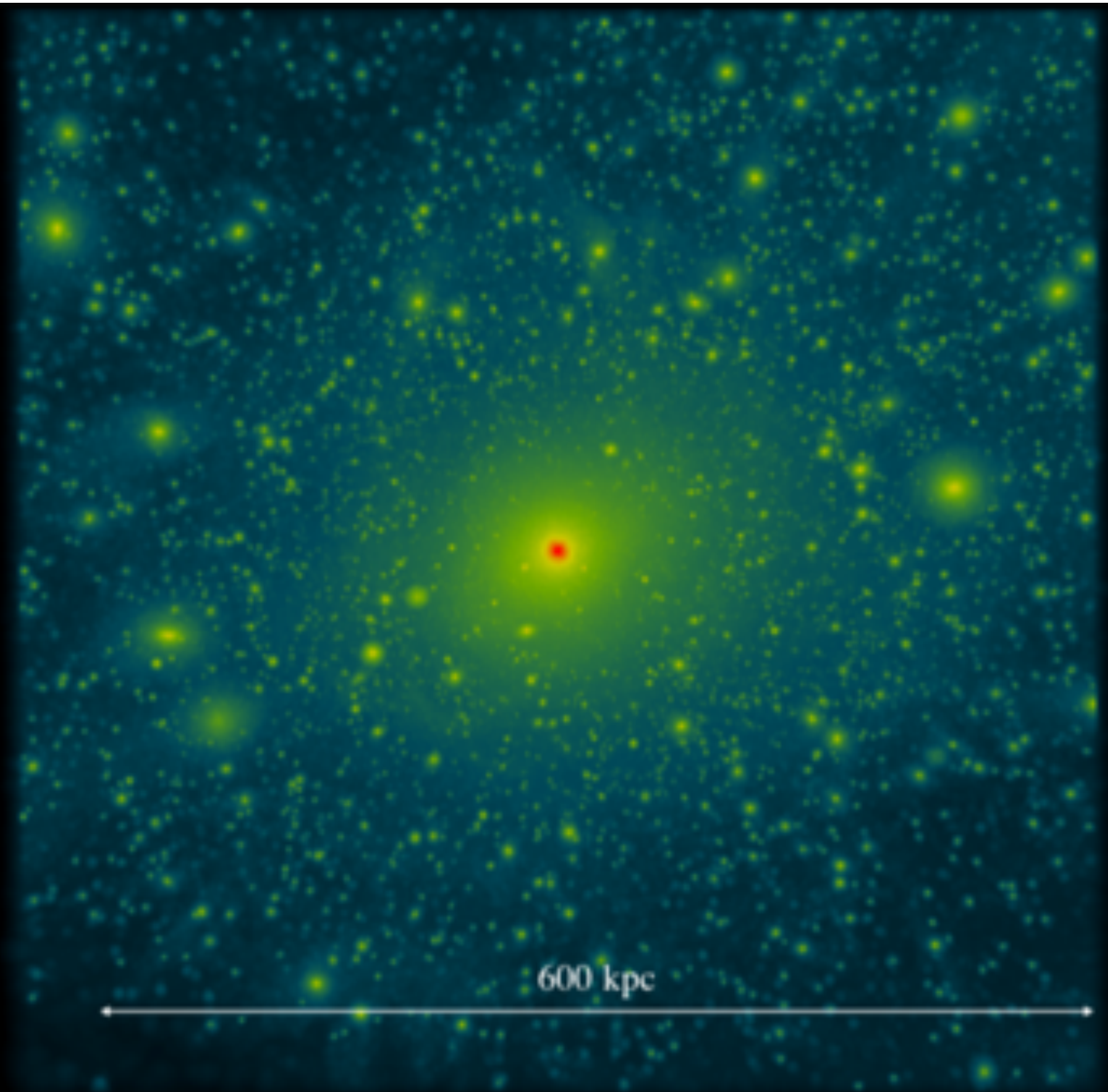
The instrument response functions do not need to be combined, but can be used on individual factor of the likelihood→GREAT ADVANTAGE

RESULTS FROM DIFFERENT INSTRUMENTS AND DIFFERENT TARGETS CAN BE NOW COMBINED TO IMPROVE SENSITIVITY

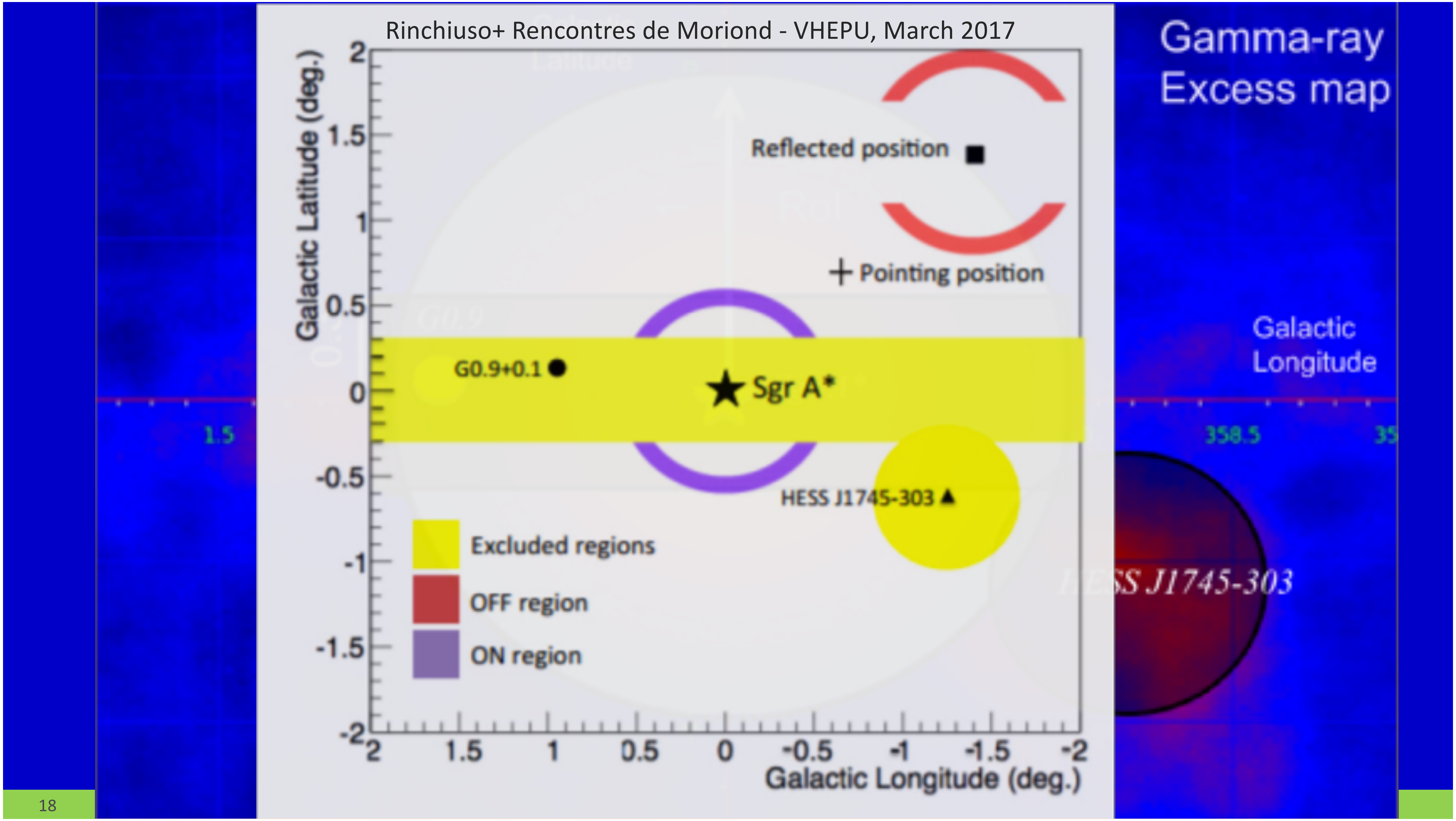
«Gather them all»

- **A project between MAGIC, VERITAS, HESS and Fermi started *to gather them all***
  - 300+ h MAGIC
  - 300+ h VERITAS
  - 100+ h HESS
  - Fermi-dSph
- Great expectations!

Galactic Center

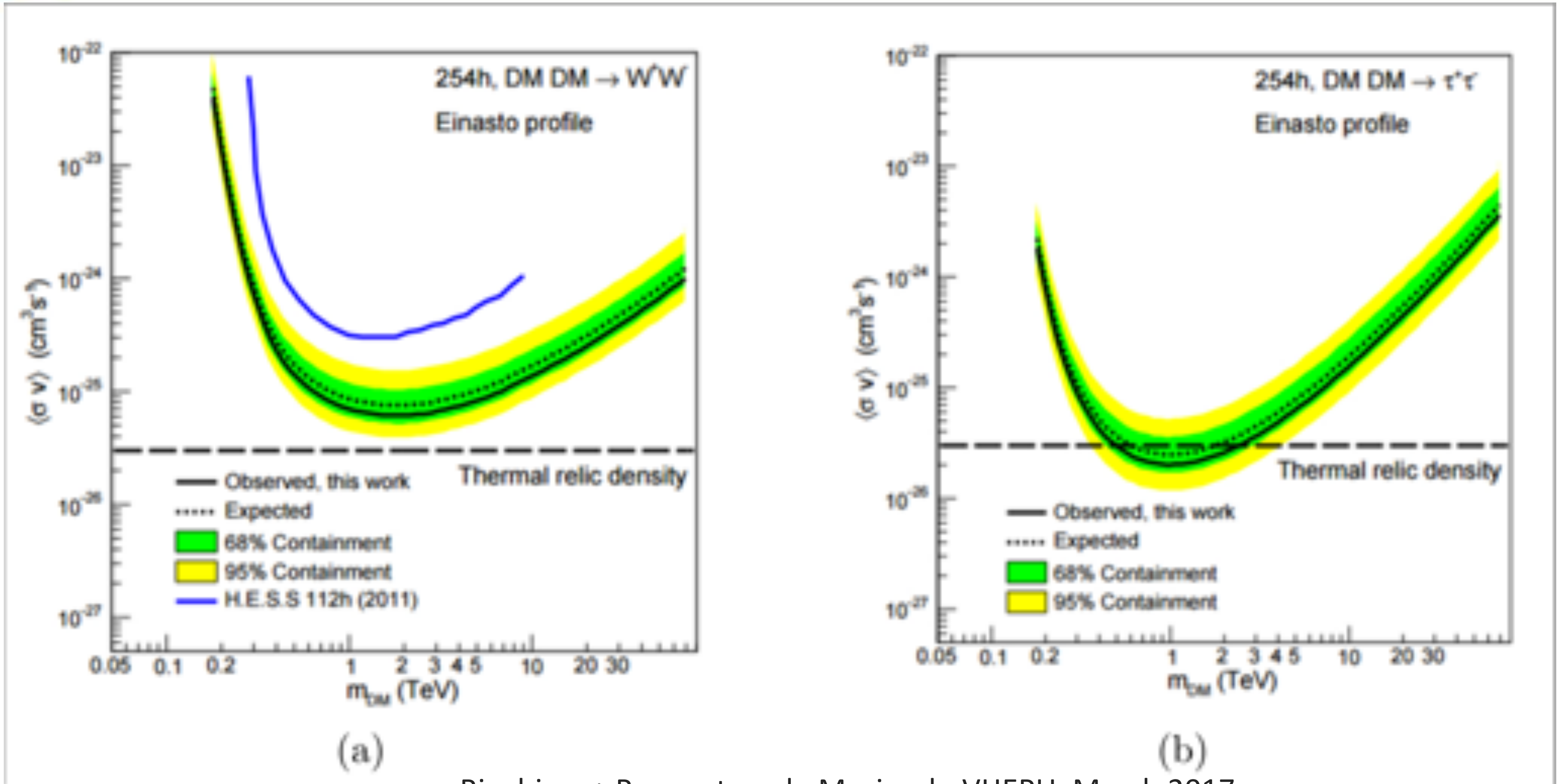


Garrison-Kimmel et al. 2018



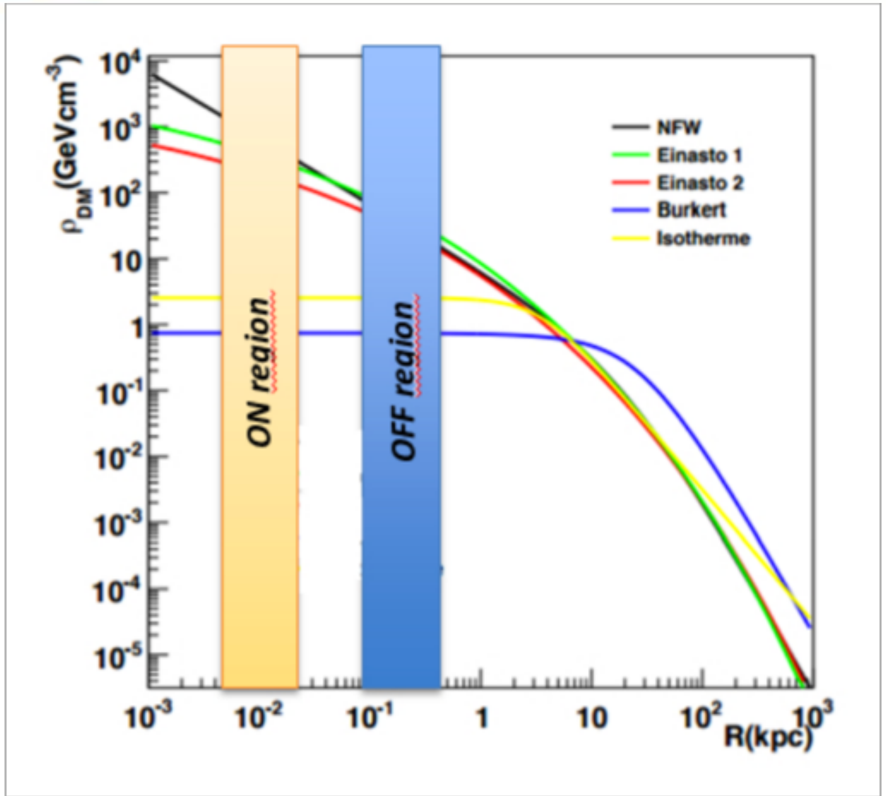
Rinchiuso+ Rencontres de Moriond - VHEPU, March 2017
Gamma-ray Excess map
Galactic Longitude
Galactic Latitude (deg.)
Galactic Longitude (deg.)
Reflected position
Pointing position
G0.9+0.1
Sgr A*
HESS J1745-303
Excluded regions
OFF region
ON region
1.5
358.5

Strong limits: 254h observation



Rinchiuso+ Rencontres de Moriond - VHEPU, March 2017

Uncertainties



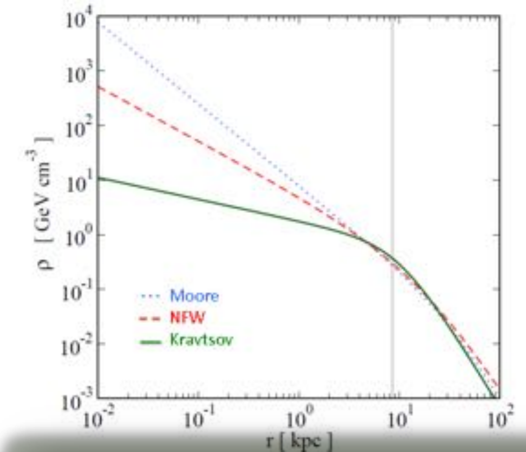
- Ordinary matter strongly influence GC dynamics
- Baryon infall can cause contraction → increase DM density
- Baryon feedback can central depletion → decrease DM density
- Interaction with central BH hole

See e.g. discussion in JCAP10(2013)029

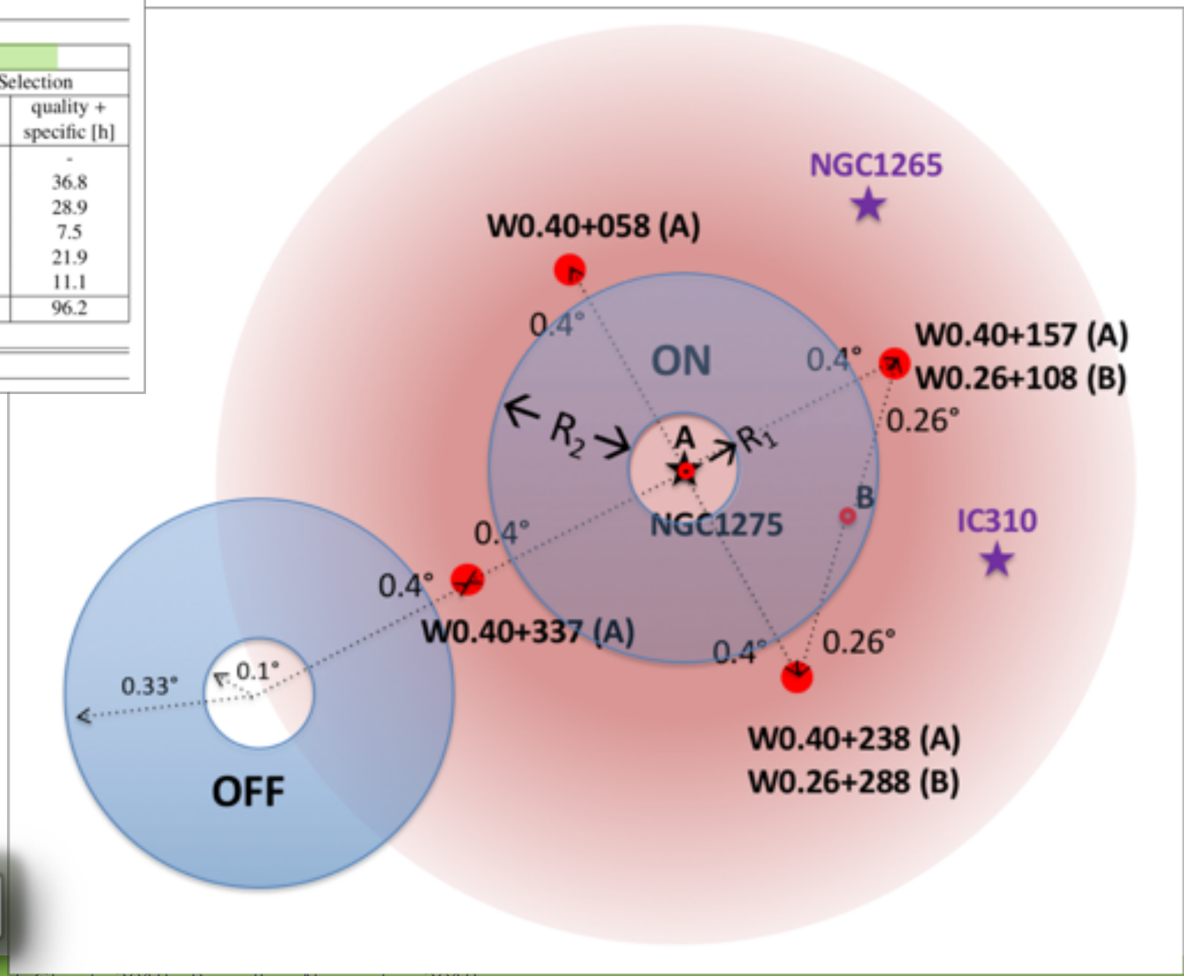
Decaying (dark) matter in the Perseus (Galaxy cluster)

Complex observing region: decay DM case

Period	Dates	Telescope Pointing $\mathcal{A}$: All data [h]	$\mathcal{A}$ Data Selection: quality [h]	$\mathcal{A}$ Data Selection: quality + specific [h]	Telescope Pointing $\mathcal{B}$: All data [h]	$\mathcal{B}$ Data Selection: quality [h]	$\mathcal{B}$ Data Selection: quality + specific [h]
$\mathcal{P}1$	2009.11.01-2011.06.01	94.7	56.4	45.4	-	-	-
$\mathcal{P}2$	2012.09.01-2013.01.17	9.2	9.1	9.1	59.4	40.2	36.8
$\mathcal{P}3$	2013.07.27-2014.08.05	17.5	16.7	14.8	55	30.2	28.9
$\mathcal{P}4$	2014.08.31-2014.11.22	16.6	10.4	10.1	21.7	21.7	7.5
$\mathcal{P}5$	2014.11.24-2016.04.28	6.8	3.9	3.9	29.3	22.32	21.9
$\mathcal{P}6$	2016.04.29-2017.08.02	44.1	41.9	12.2	20.5	16.02	11.1
TOTAL		185.9	138.4	106.1	188.9	119.2	96.2
Global sample selected					202.2 h		

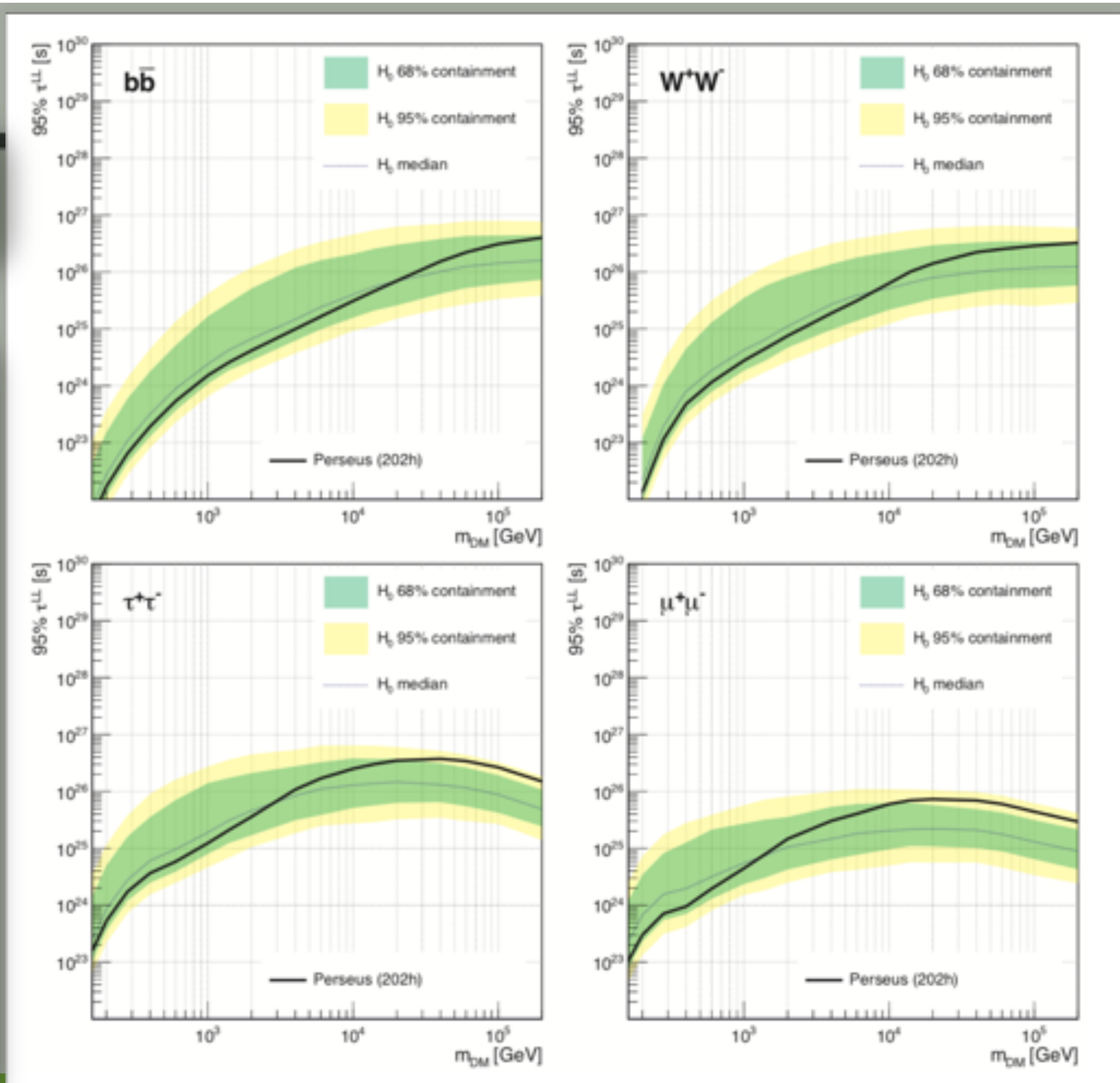


decay J-factor of 1.5×10^{19} GeV cm^{-2}.

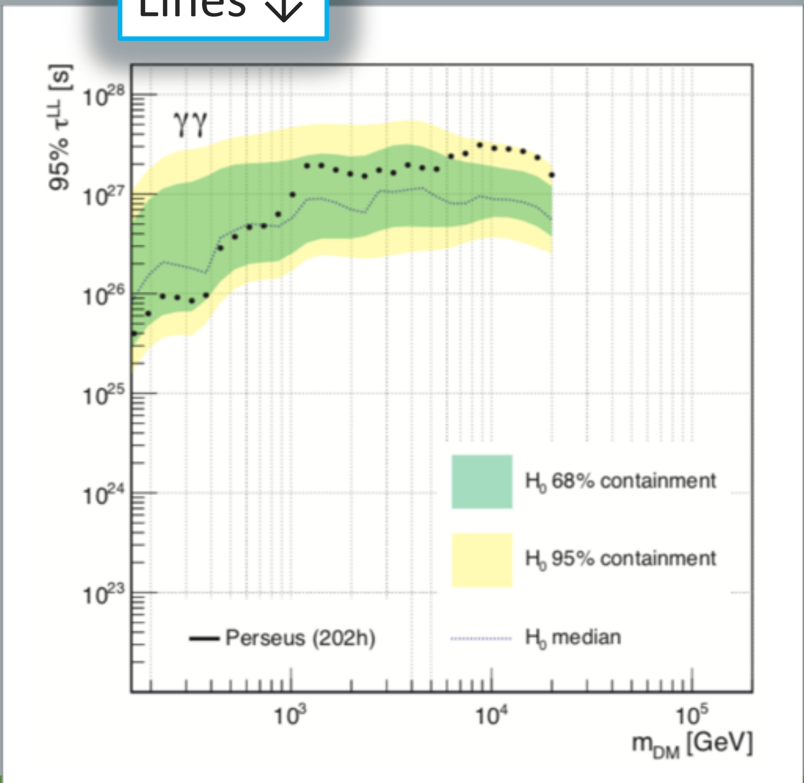


Decaying DM

Continuum→



Lines ↓



Then, so far, a big effort from IACTs

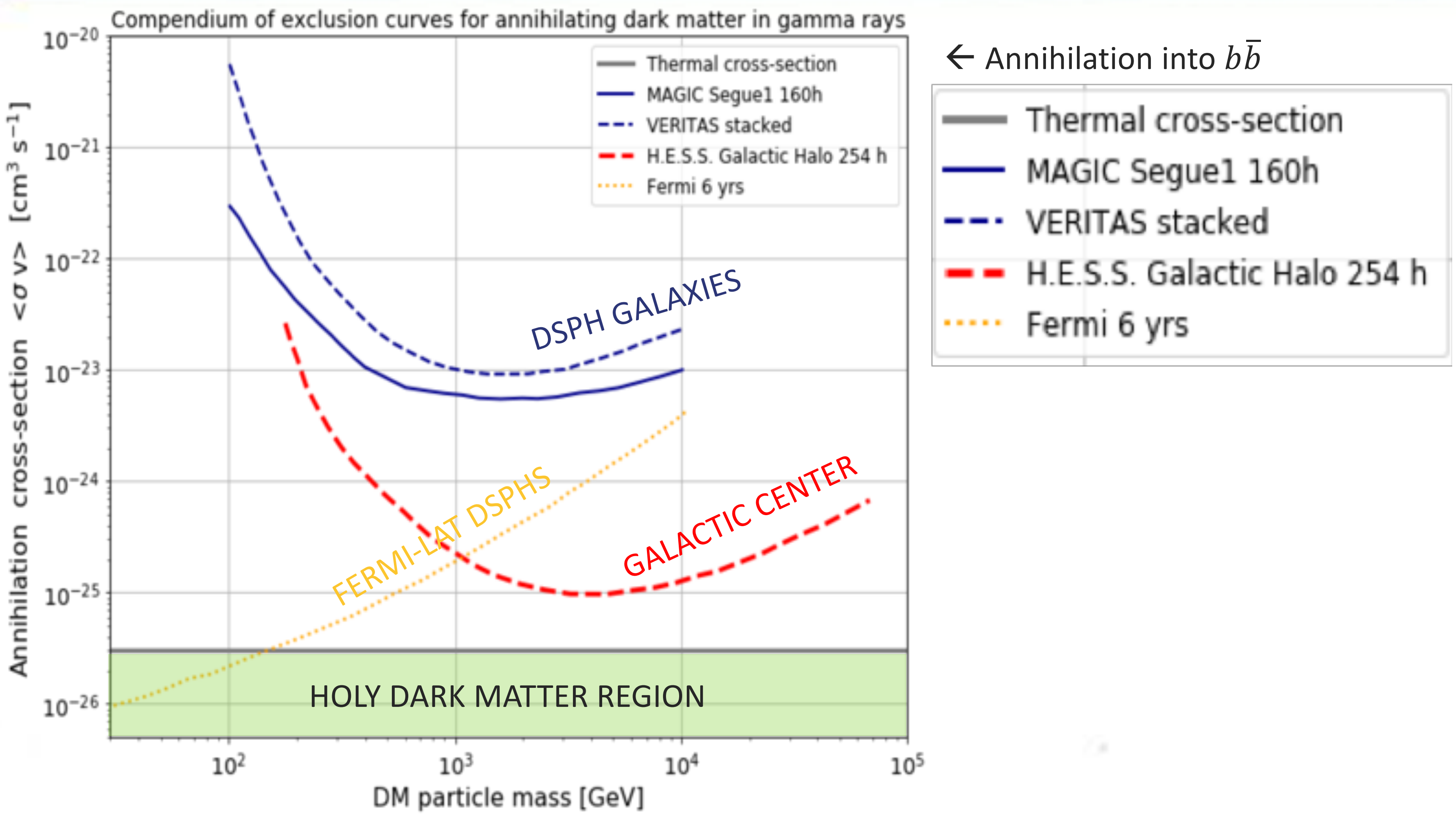
Target	Year	Time	Experiment
Globular Clusters			
M15	2002	0.2	Whipple
	2006 – 2007	15.2	H.E.S.S.
M33	2002 – 2004	7.9	Whipple
M32	2004	6.9	Whipple
NGC 6388	2008 – 2009	27.2	H.E.S.S.
Dwarf Satellite Galaxies			
Draco	2003	7.4	Whipple
	2007	7.8	MAGIC
	2007	18.4	VERITAS
Ursa Minor	2003	7.9	Whipple
	2007	18.9	VERITAS
Sagittarius	2006	11	H.E.S.S.
	–	–	H.E.S.S.
Canis Major	2006	9.6	H.E.S.S.
Willman 1	2007 – 2008	13.7	VERITAS
	2008	15.5	MAGIC
Sculptor	2008	11.8	H.E.S.S.
Carina	2008 – 2009	14.8	H.E.S.S.
	2008 – 2012	23	H.E.S.S.
Segue 1	2008 – 2009	29.4	MAGIC
	2010 – 2011	48	VERITAS
	2010 – 2013	158	MAGIC
Boötes	2009	14.3	VERITAS
Coma Berenices	2010 – 2013	8.6	H.E.S.S.
Fornax	2006? – 2012?	6	H.E.S.S.
Ursa Major 2	2014 – 16	95	MAGIC

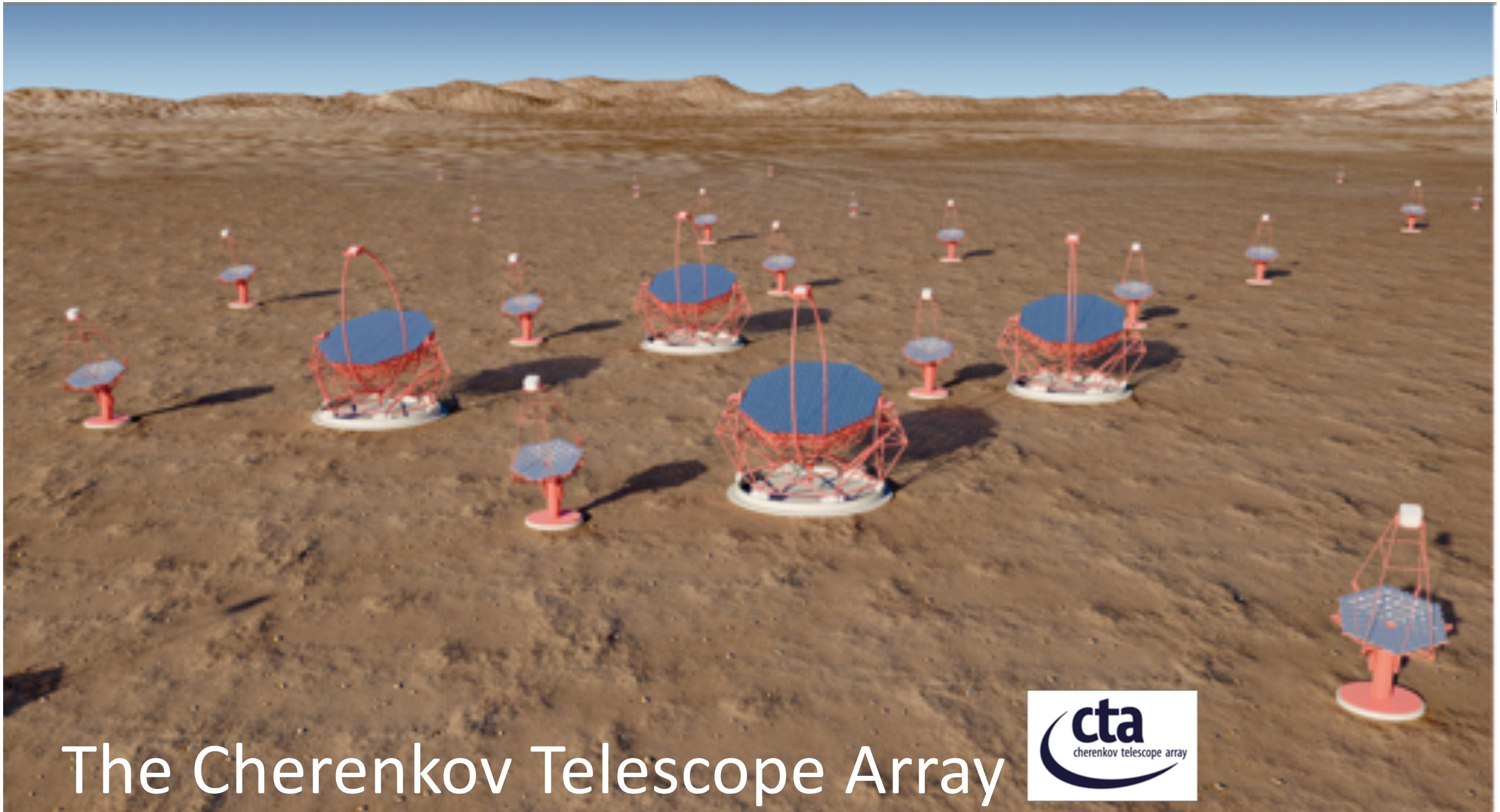
Target	Year	Time	Experiment
Galaxy Clusters			
Abell 2029	2003 – 2004	6	Whipple
Perseus	2004 – 2005	13.5	Whipple
	2008	24.4	MAGIC
	2009 – 2017	202	MAGIC
Fornax	2005	14.5	H.E.S.S.
Coma	2008	18.6	VERITAS
The Milky Way central region			
MW Center	2004	48.7	H.E.S.S.
MW Center Halo	2004 – 2008	112	H.E.S.S.
	2004 – 2014	254	H.E.S.S.
Line searches			
Lines	2004 – 2008	112	H.E.S.S.
	2010 – 2013	158	MAGIC
	2004 – 2014	254	H.E.S.S.
Other searches			
IMBH	2004 – 2007	400	H.E.S.S.
	2006 – 2007	25	MAGIC
UFOs	–	–	MAGIC
	–	–	VERITAS
Particles searches			
All-electron	2004 – 2007	239	H.E.S.S.
	xx	xx	VERTIAS
	2009 – 2010	14	MAGIC
Moon-shadow	–	–	MAGIC

Big time-investment

*← Edited from MD, NIM A 742 (2014), to appear in Mukherjee, Zanin **„The Science Program of the Third Generation of IACTs for exploring cosmic gamma rays“***

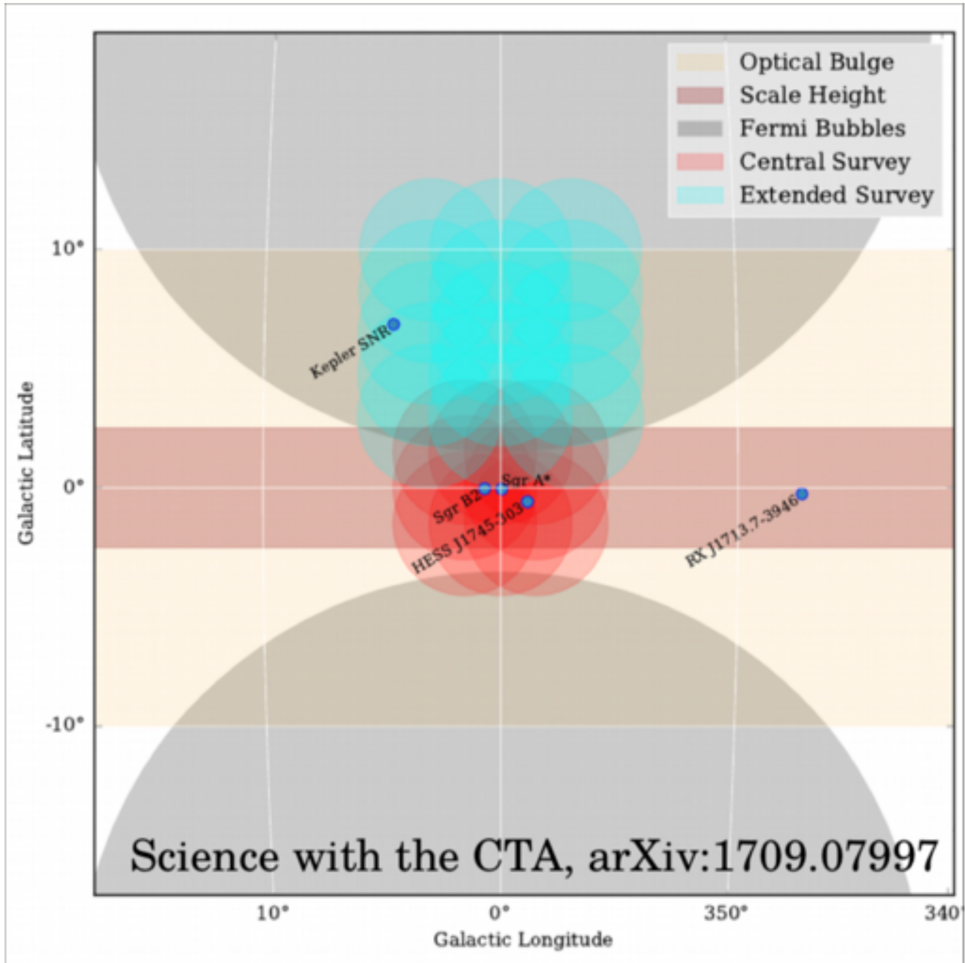
Where are we now? Where to go?





The Cherenkov Telescope Array

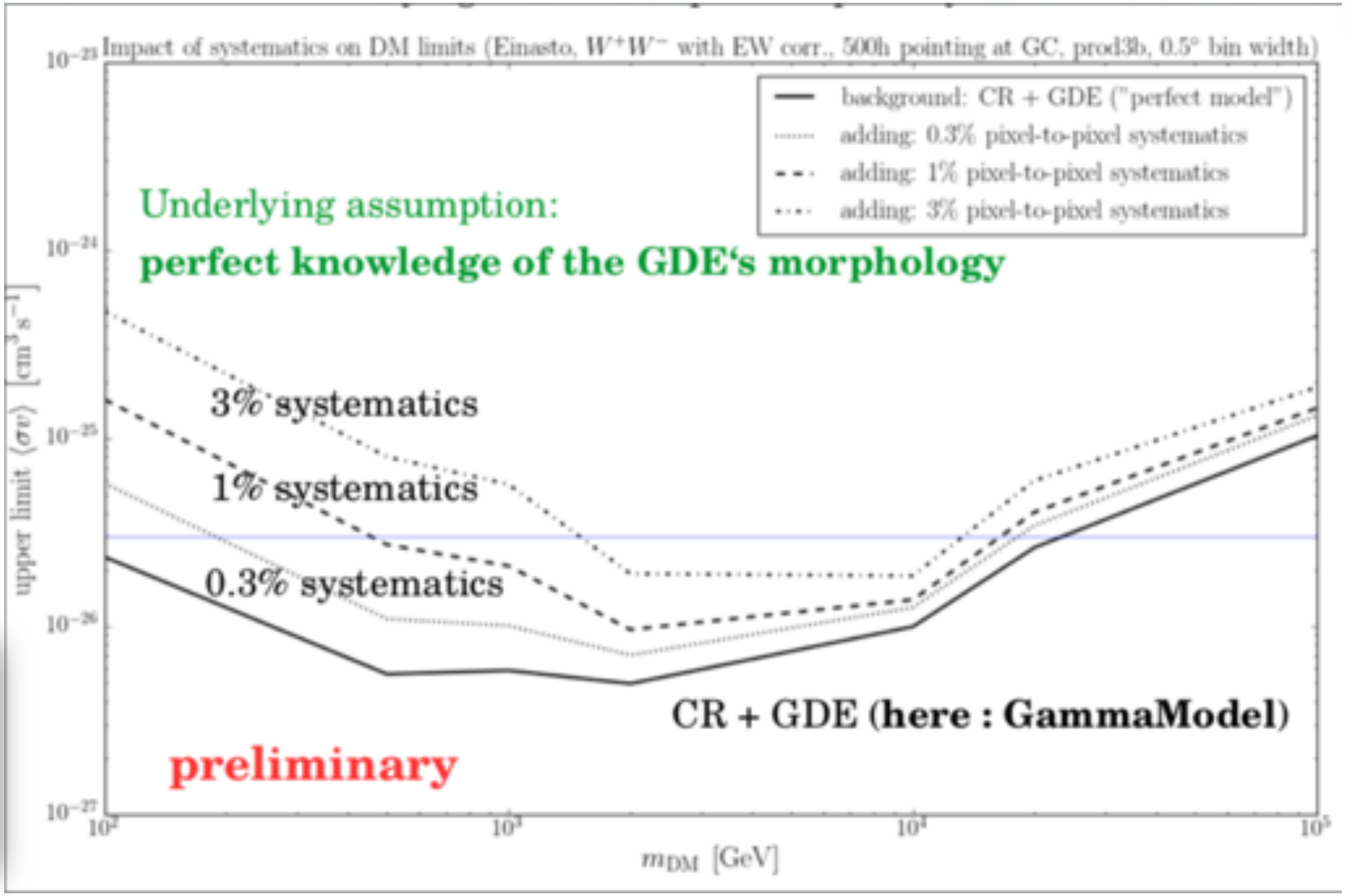
CTA DM strategy outlined



500h

Galactic Center: sytematics

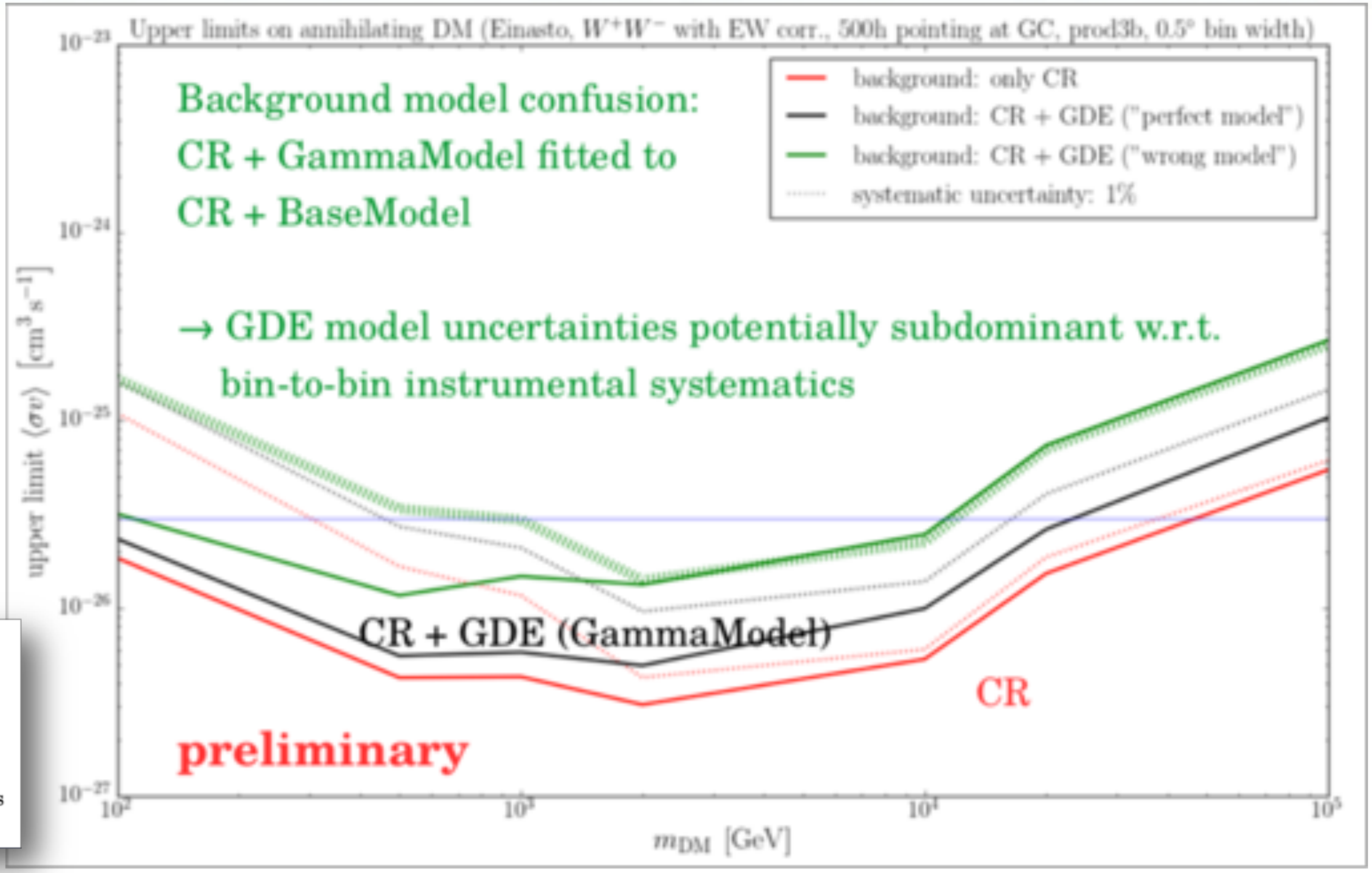
Systematics matter
Over long observations



TeV Particle Astrophysics Conference 2018
27 – 31 August 2018
Berlin, Germany

Speaker: Christopher Eckner
T. Bringmann, A. Sokolenko, L. Yang and G. Zaharijas
for the CTA Consortium

Diffuse components



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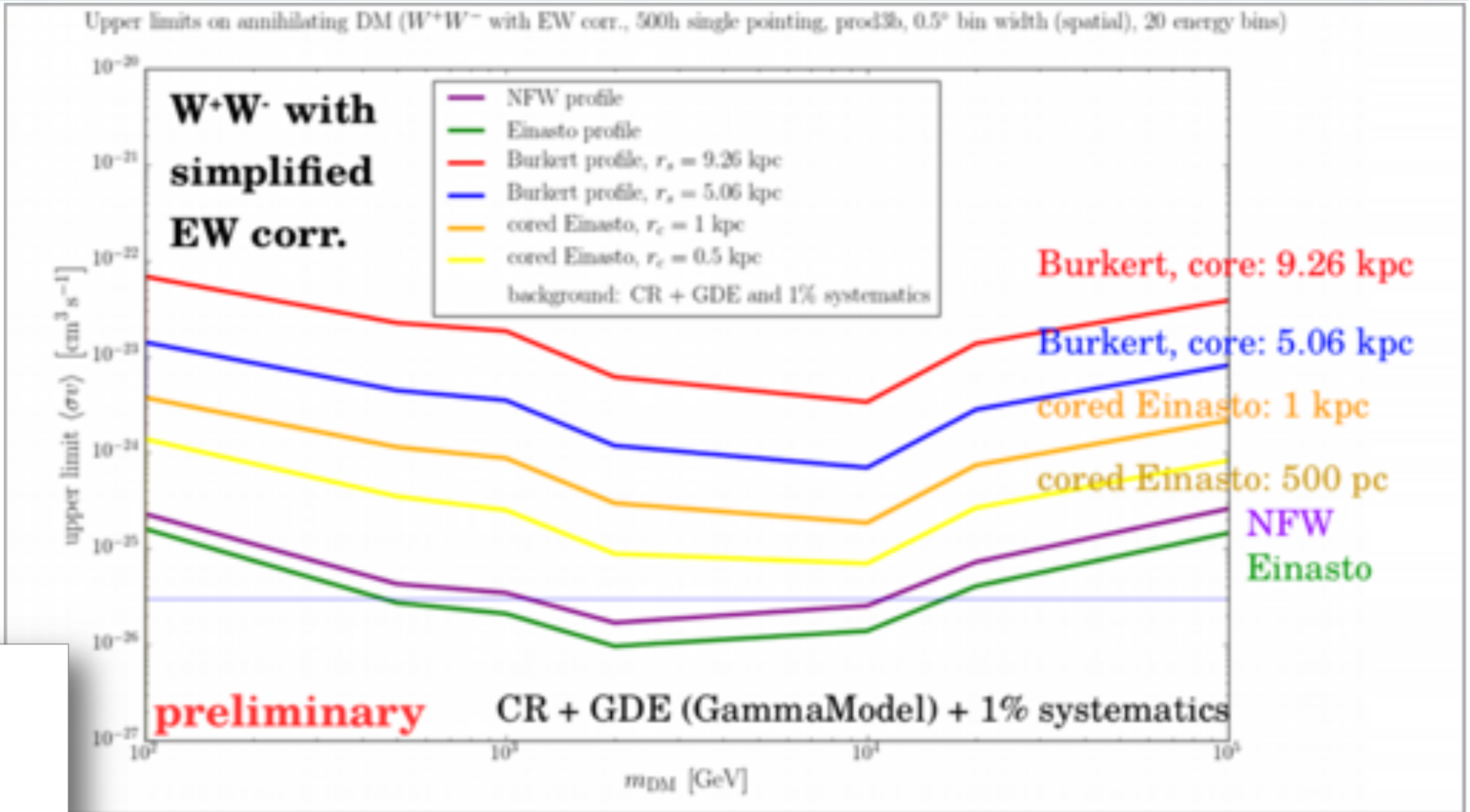
DM profile



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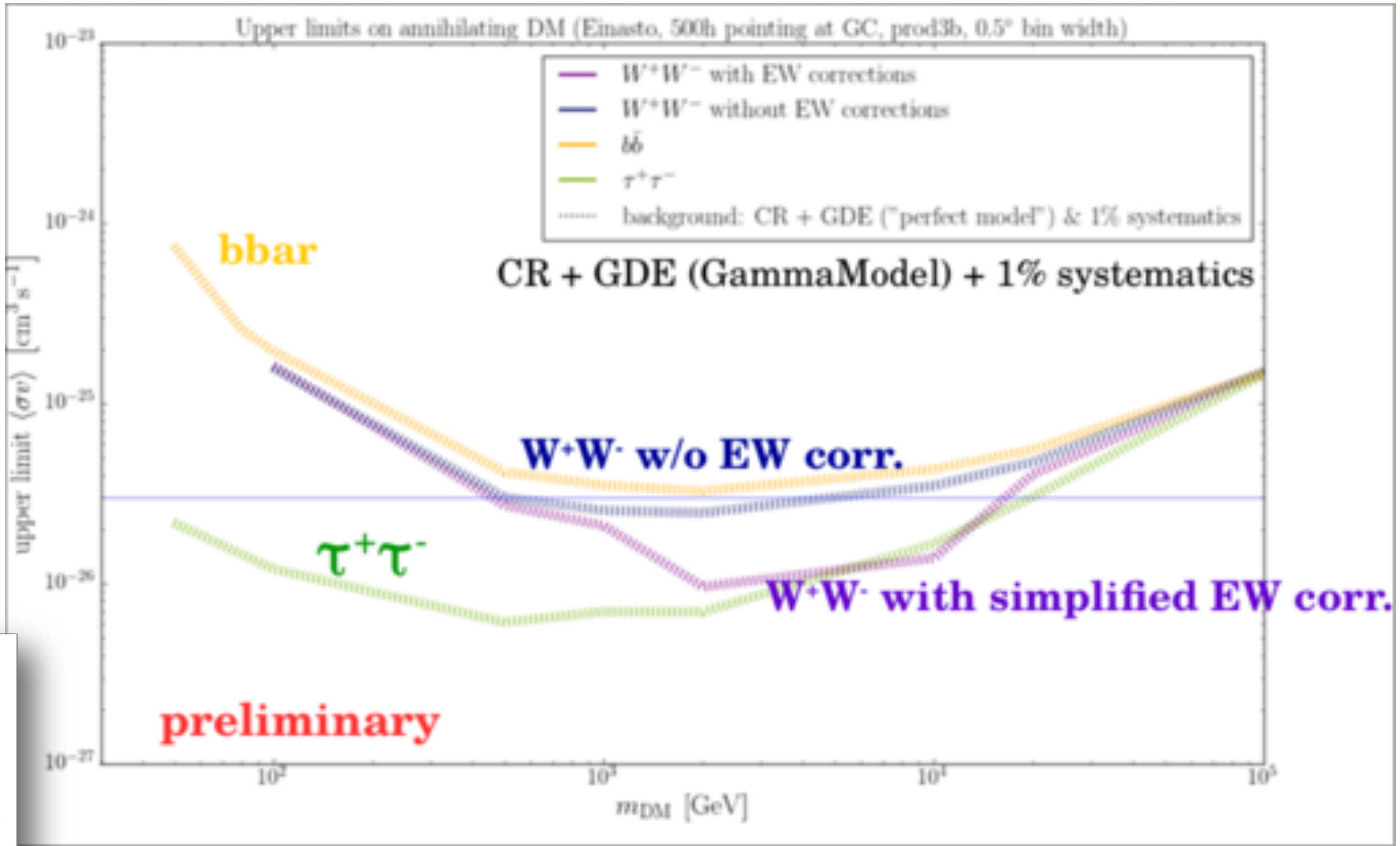
Summary:

Enter the parameter space < 30 TeV



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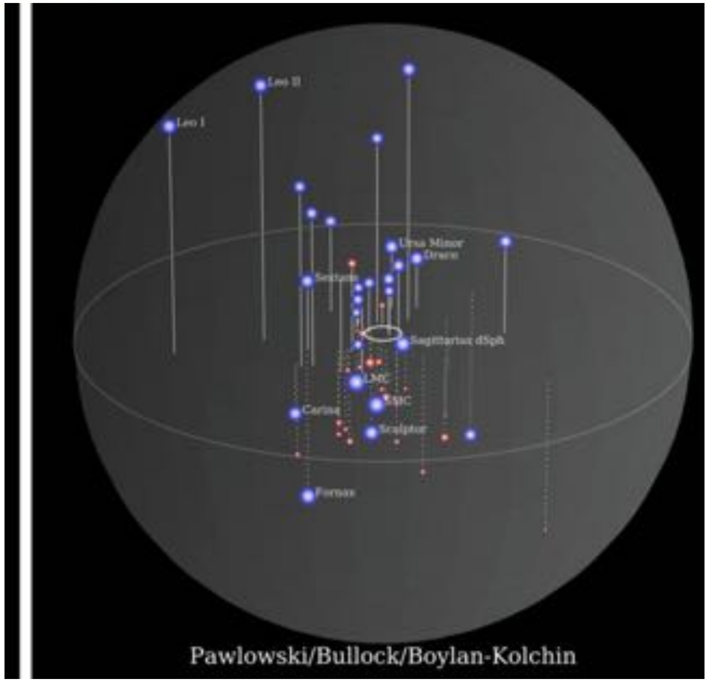
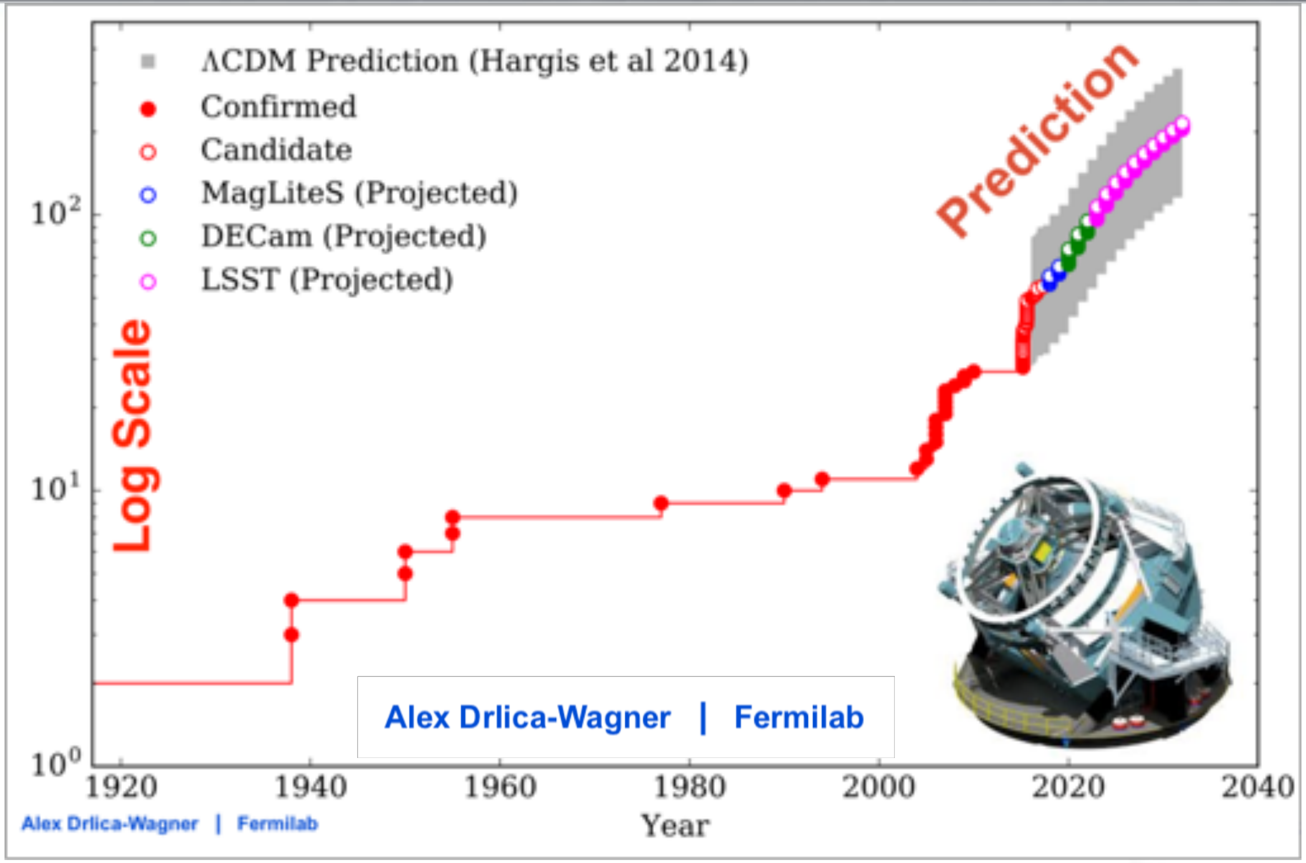
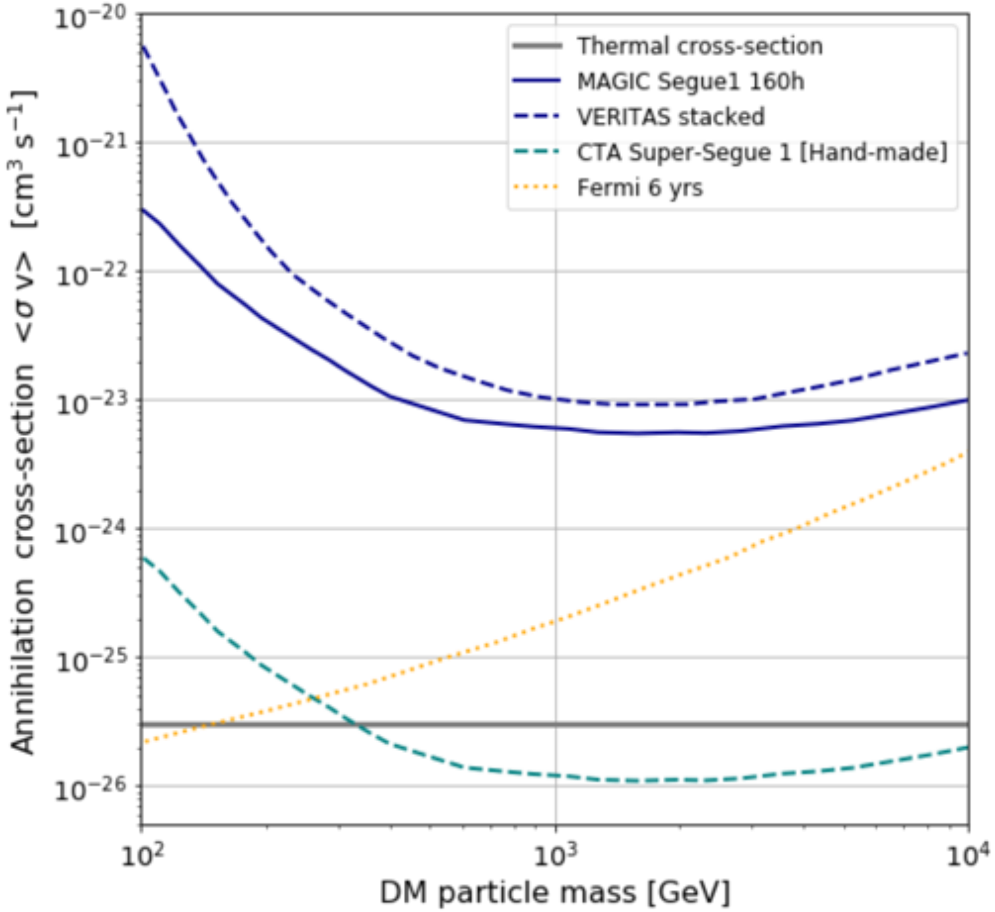
More visible dSphs coming



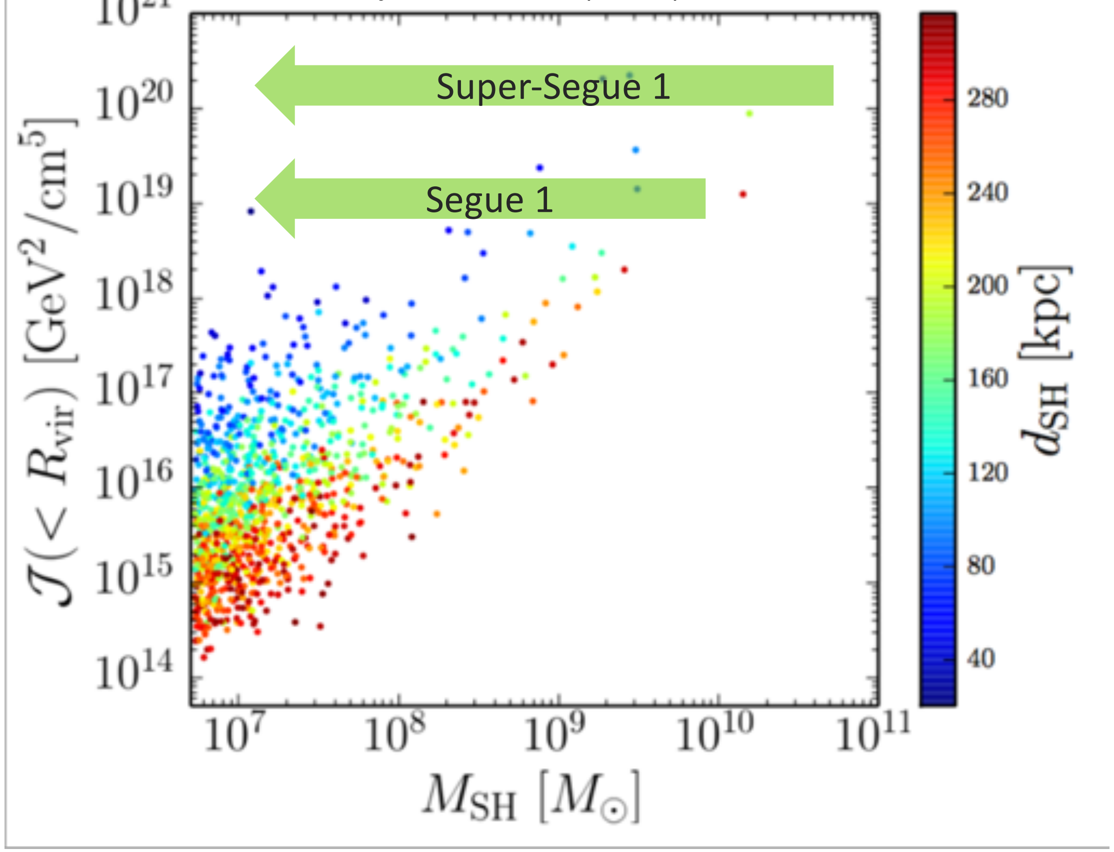


At the time of CTA, possibly *all* dSph will be discovered

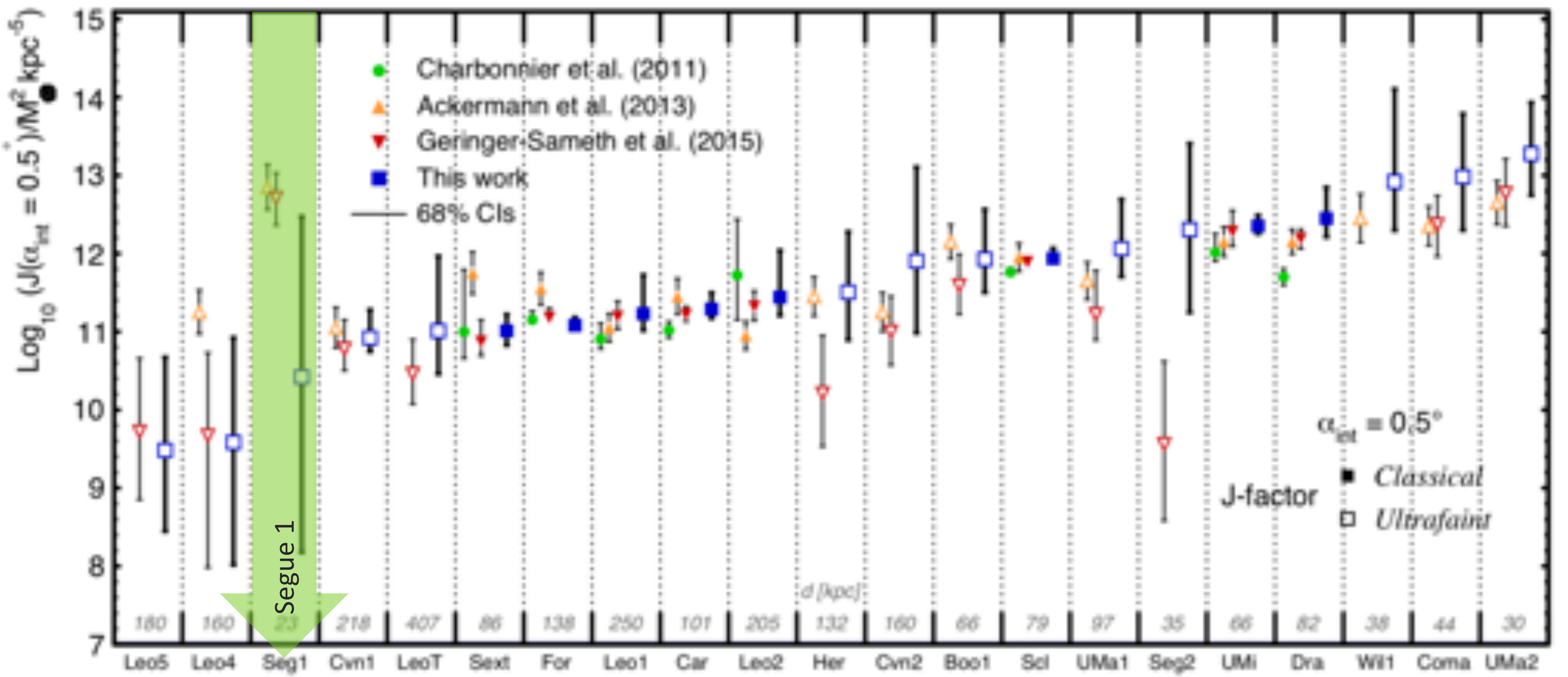
Need a high J-factor



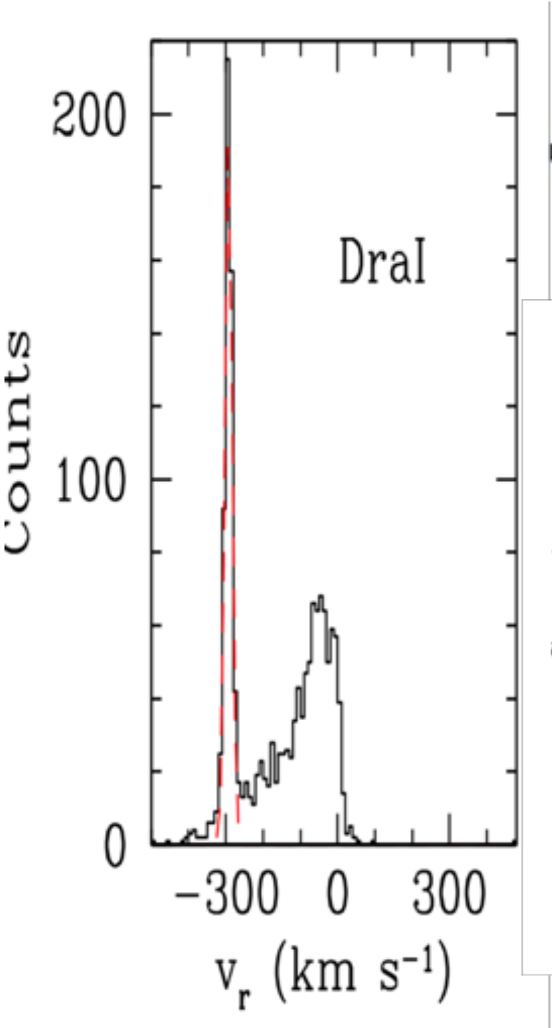
Calore+ Phys.Rev. D96 (2017) no.6, 063009



Need accurate J-factors!

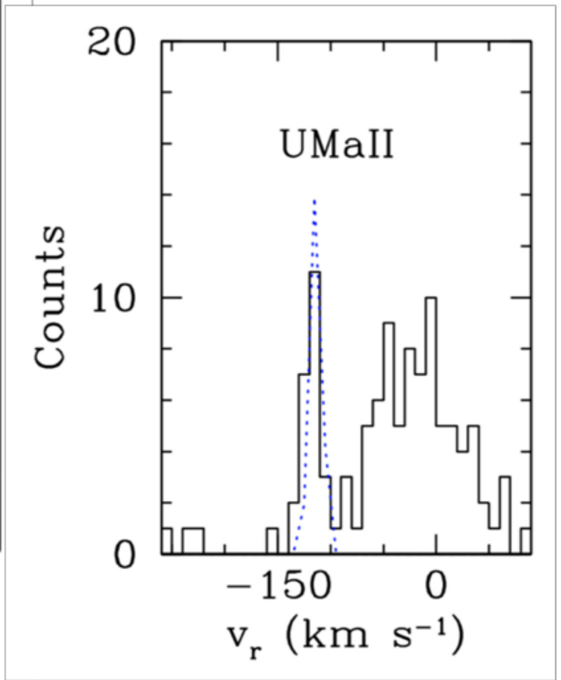


Bonnivard+ MNRAS 453 (2015) 849-867



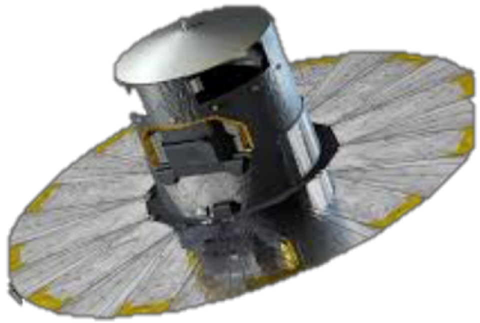
Assessing J-factors

← ↓ F.G. Saturni



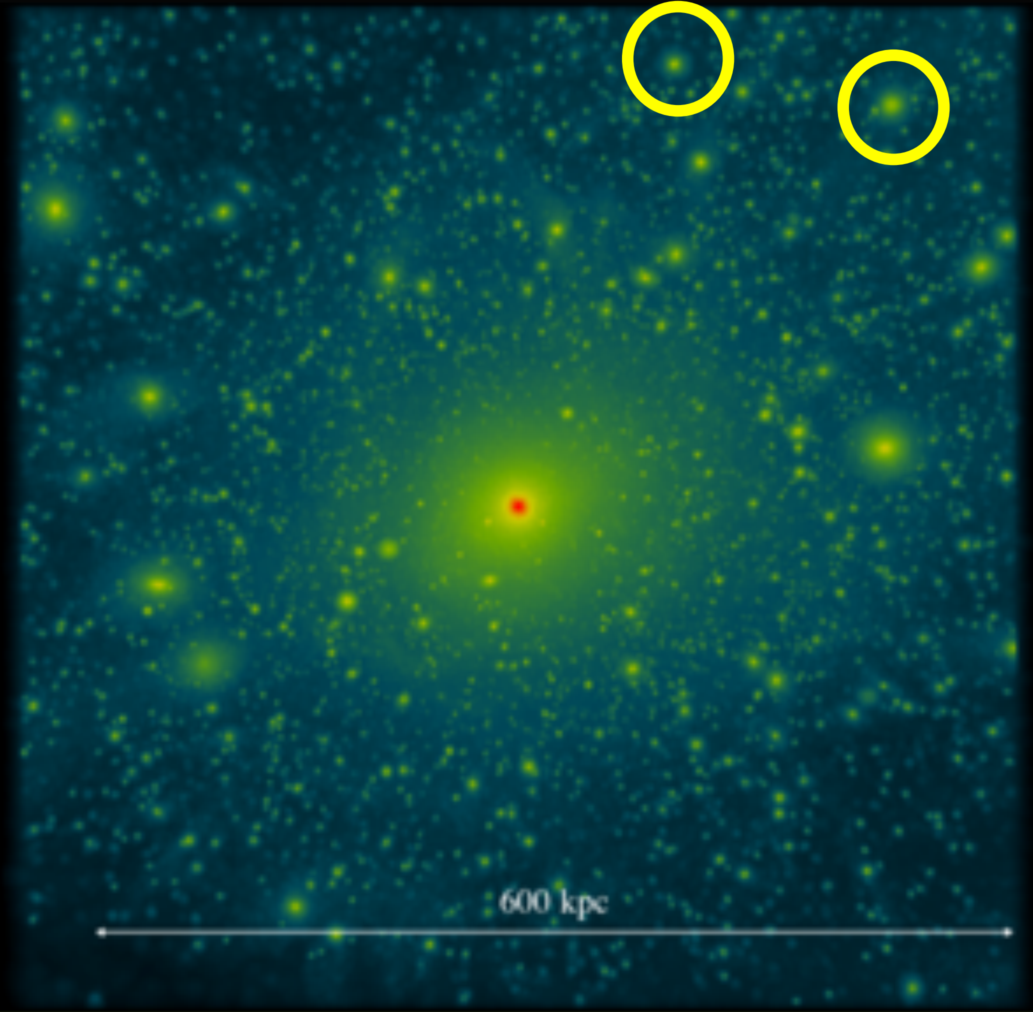
Advanced spectroscopy follow-ups of LSST targets→

Remove foreground stars with GAIA→



Close interaction between communities needed!

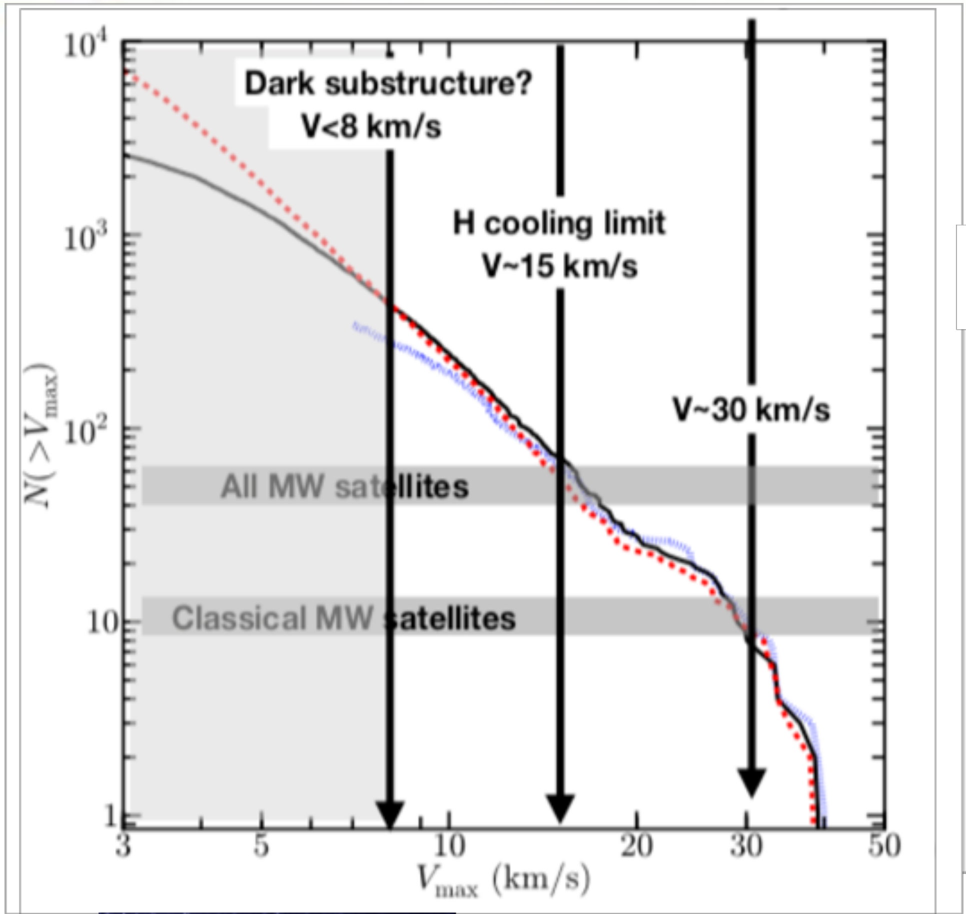
dSph



Garrison-Kimmel et al. 2018

Not all subhalos are necessarily optically bright!

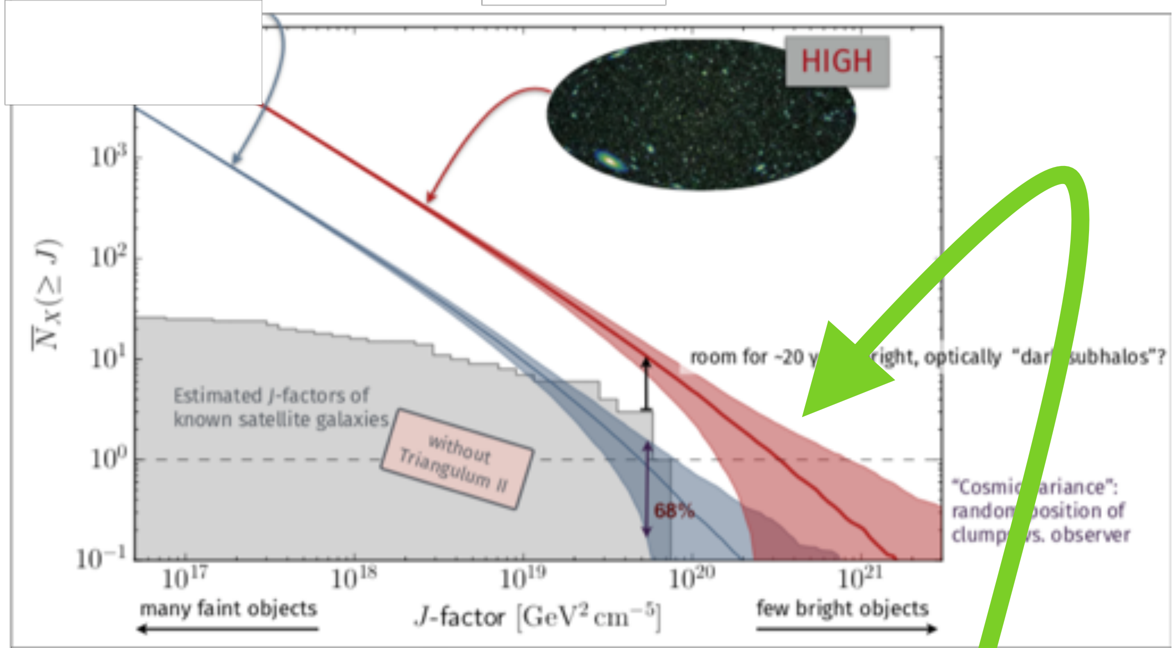
Dark subhaloes?



Garrison-Kimmel+2014

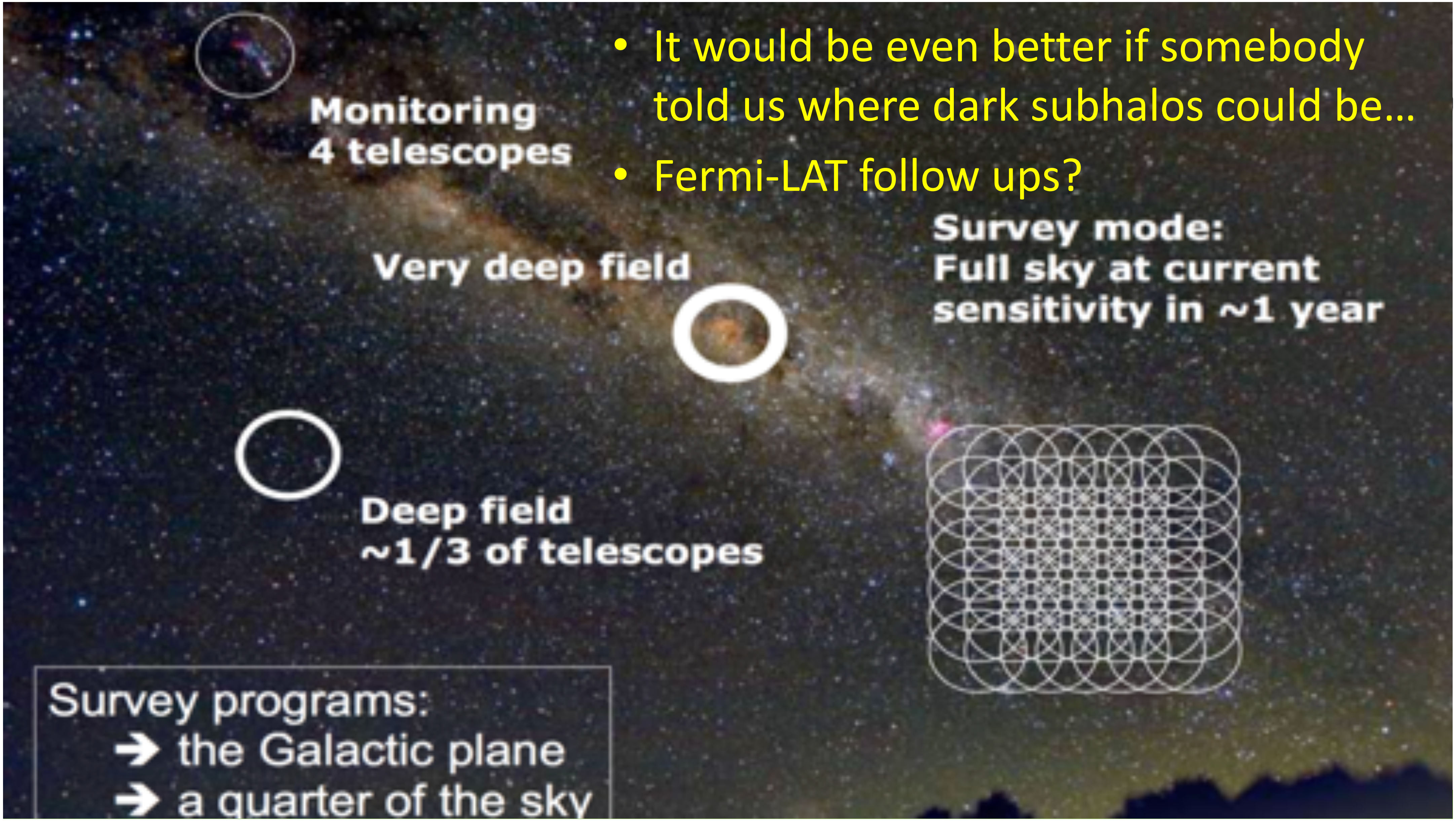
- + superclean targets
- – unknown location
- ? Fluxes, uncertainty

Lake (1990), ... , Zechlin et al. (2012), Schoonenberg et al. (2016), ... Hütten et al. (JCAP, 2016)



Room for 1-20 g-ray bright, optically dark subhalos!

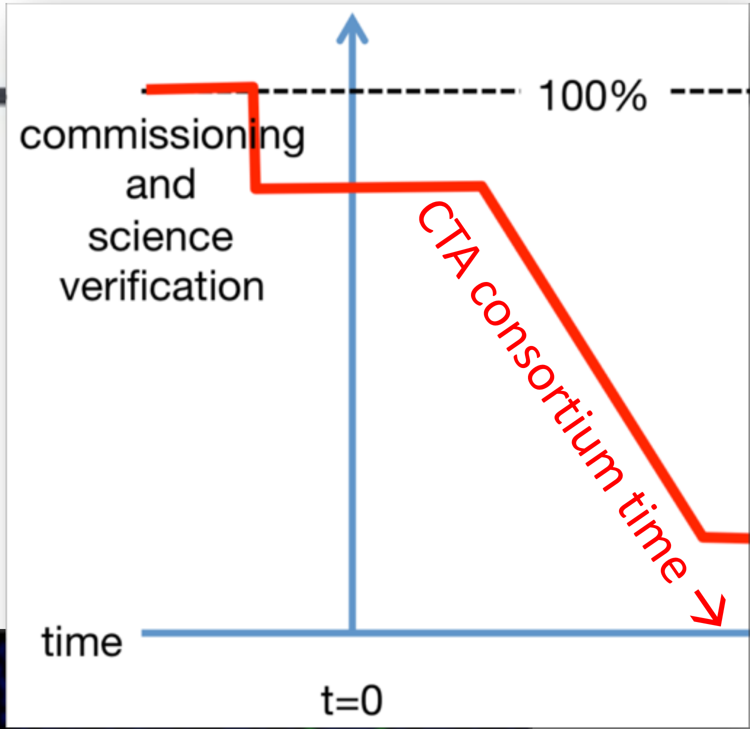
- It would be even better if somebody told us where dark subhalos could be…
- Fermi-LAT follow ups?

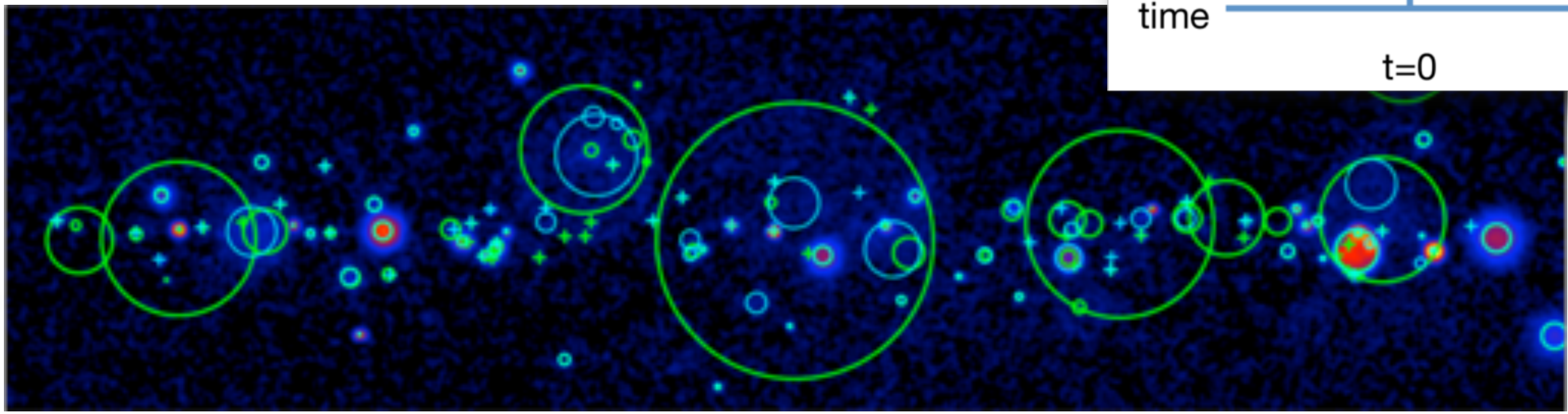


Guest and pipelines program

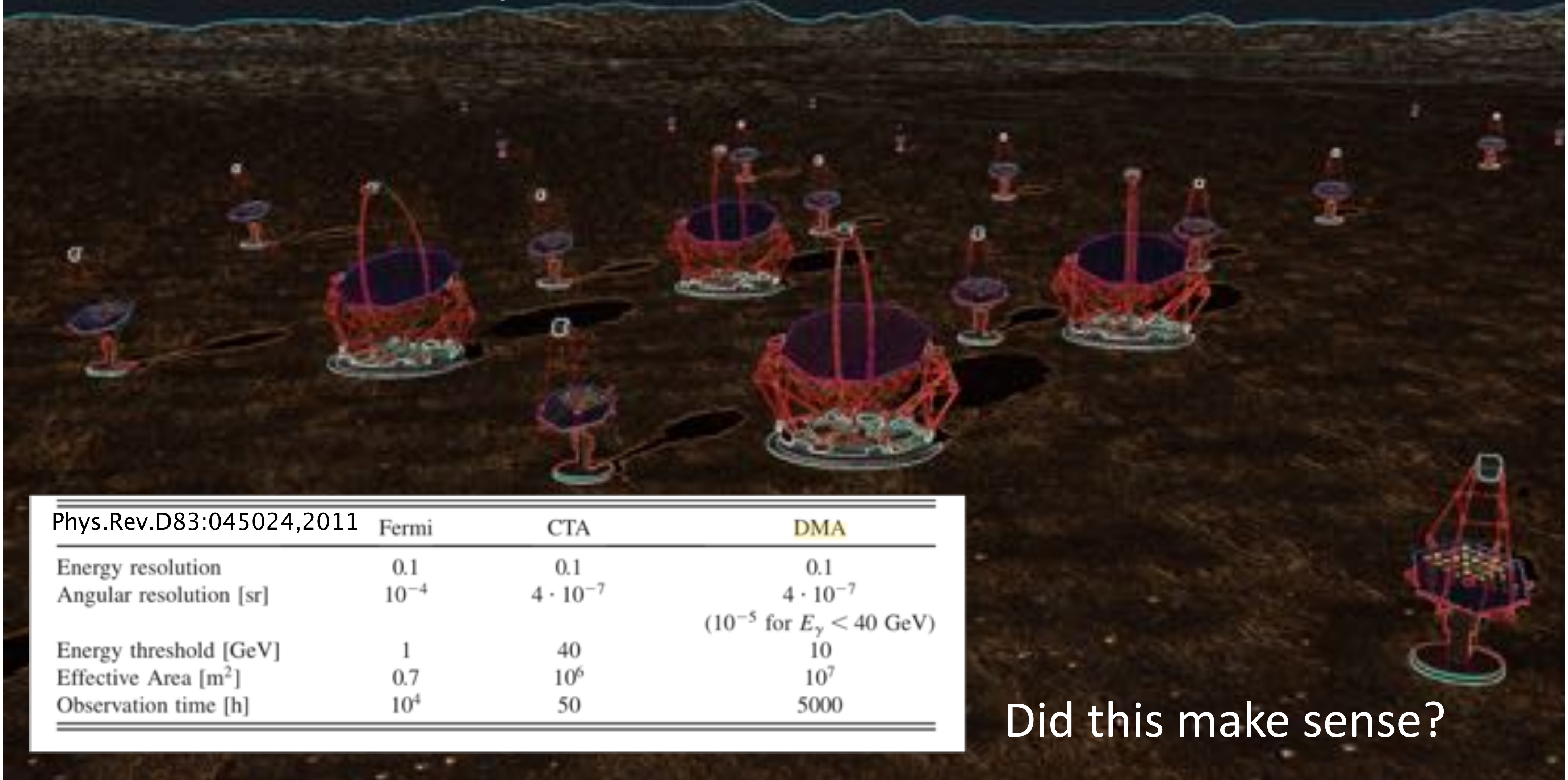
- Guest observation time >50%

- Public photon list
- Public analysis pipeline!



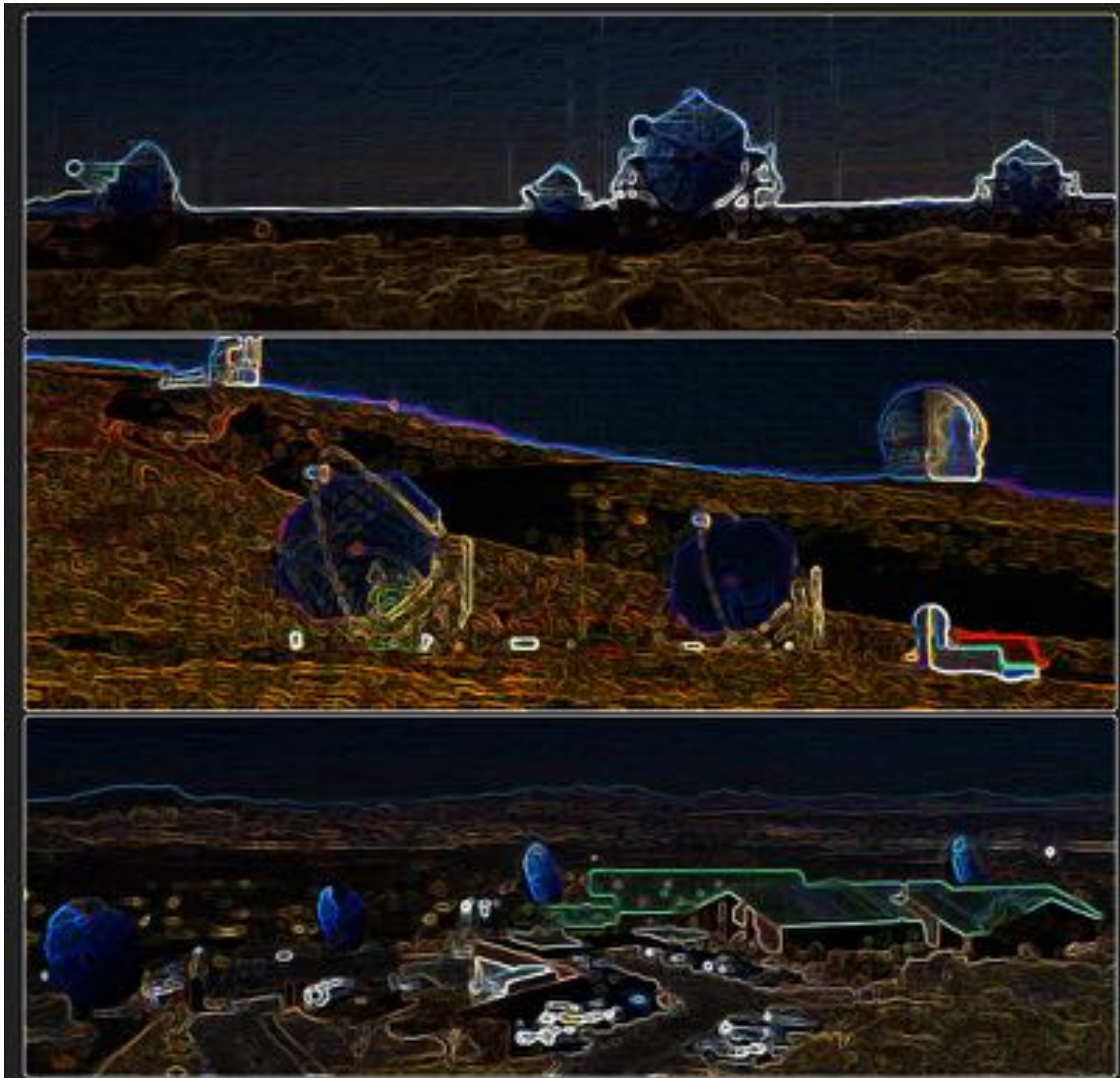


Dark Matter Array



Phys.Rev.D83:045024,2011	Fermi	CTA	DMA
Energy resolution	0.1	0.1	0.1
Angular resolution [sr]	10^{-4}	$4 \cdot 10^{-7}$	$4 \cdot 10^{-7}$ (10^{-5} for $E_\gamma < 40$ GeV)
Energy threshold [GeV]	1	40	10
Effective Area [m^2]	0.7	10^6	10^7
Observation time [h]	10^4	50	5000

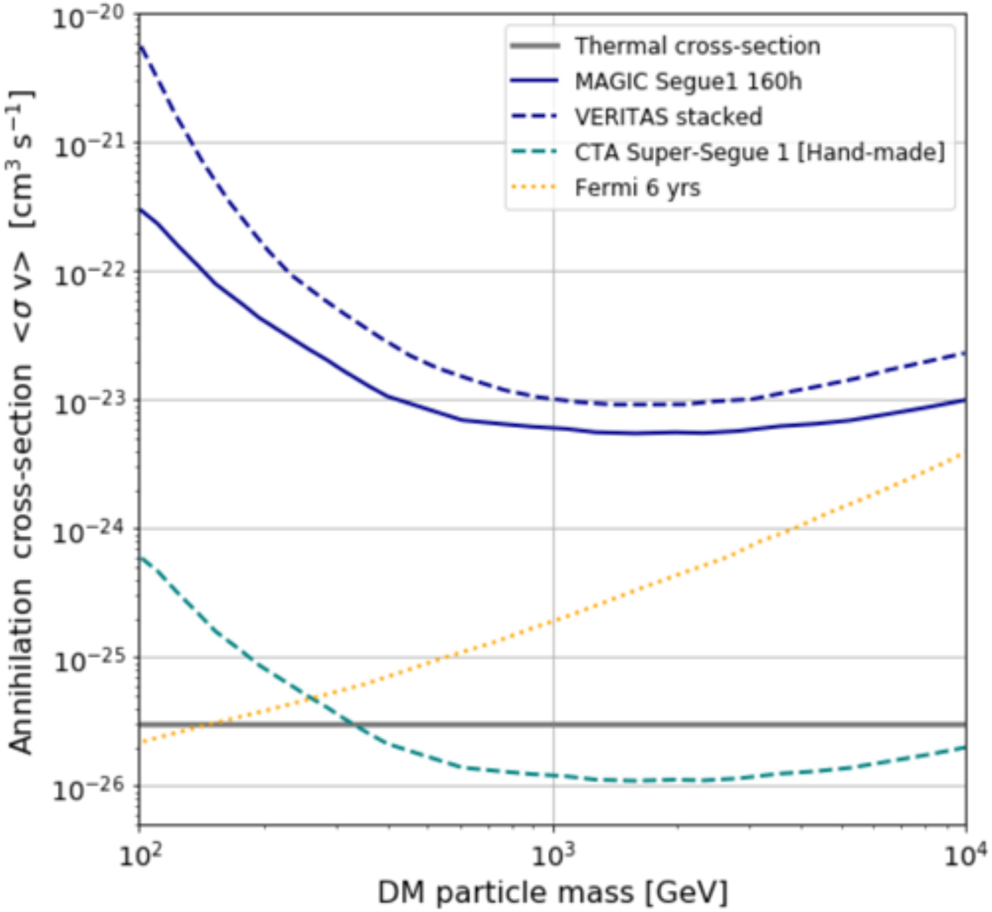
Did this make sense?



Before their death…

Use MAGIC VERITAS and HESS
for dSph deep field?

Conclusions



- CTA will dedicate important fraction of time for dark matter searches
- Galactic center obvious target + extragalactic scan
- Where else to point? One or many dSphs? How to improve chances?

Announcements

- Starting from this year **external scientists can apply for observation time with MAGIC.** Deadline for the call is set on November 2017: https://magic.mpp.mpg.de/outsiders/magicop/

- Some **MAGIC groups accepts PhD "affiliation":** If you interested in MAGIC data, phd can JOIN OUR SCIENCE PROGRAM without fees

Thanks!