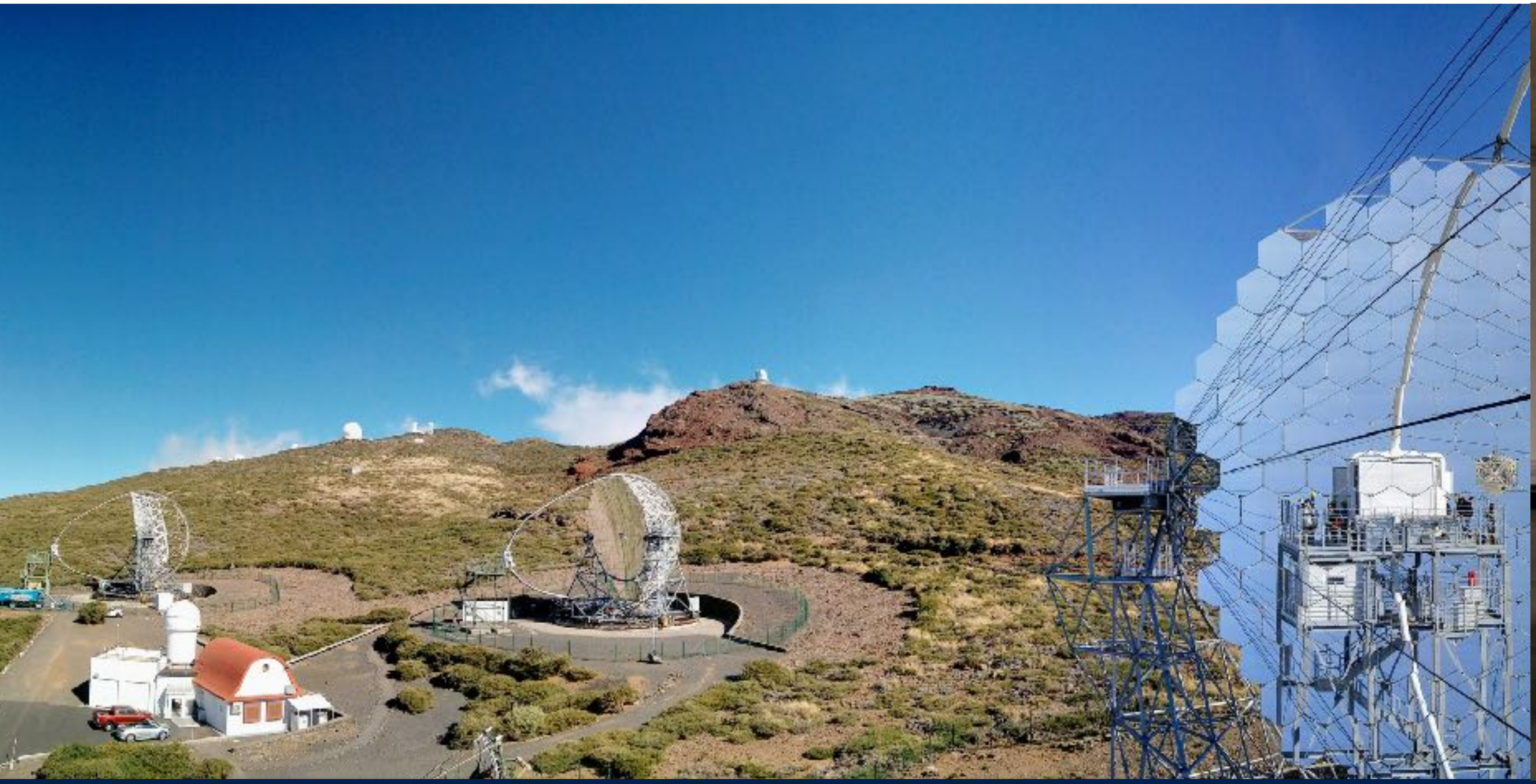
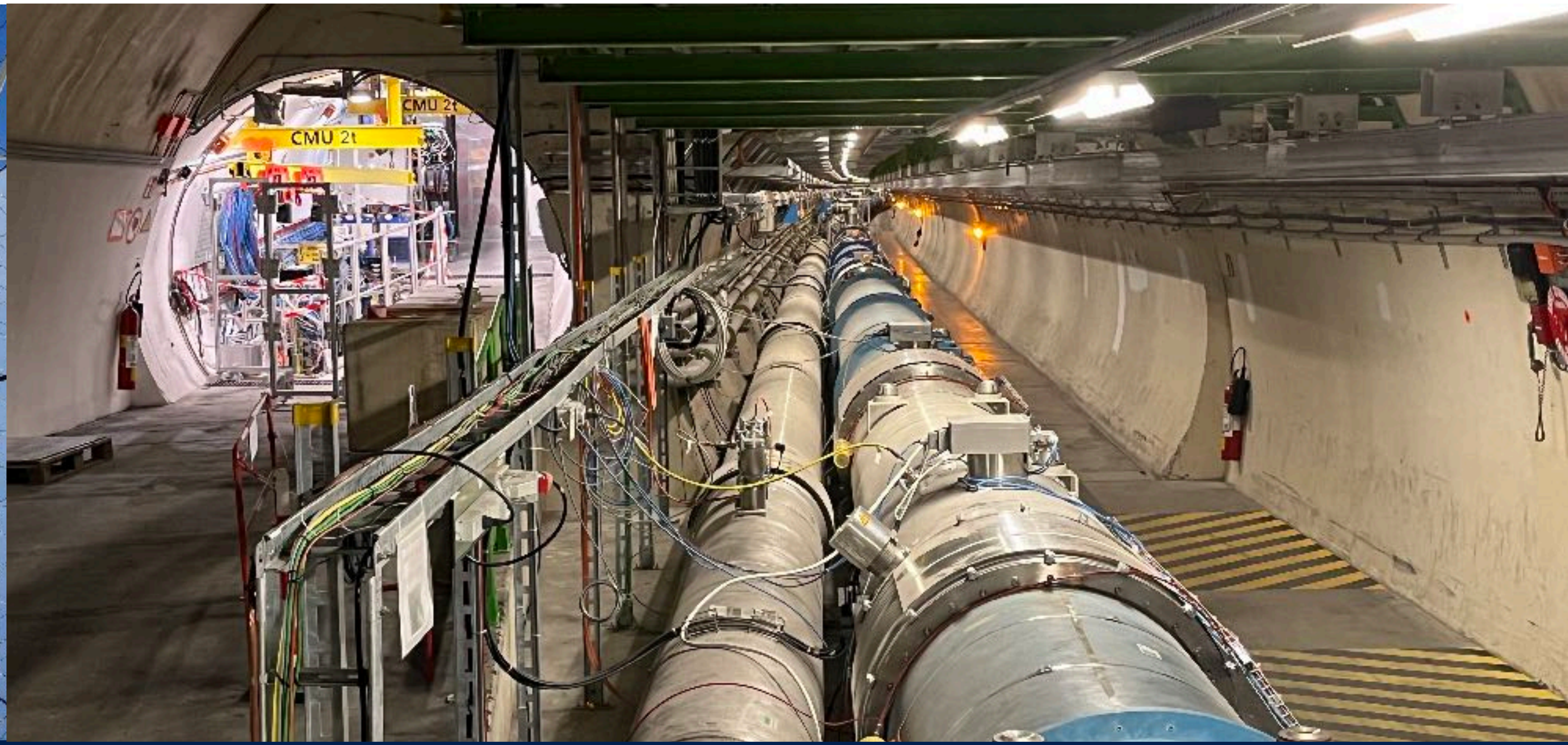
WIMP or WIMPless miracle? :

Searches for TeV-scale WIMPs Dark Matter with Gamma-ray telescopes and MeV-GeV Long-Lived Particles with the LHC forward beam

Tomohiro Inada

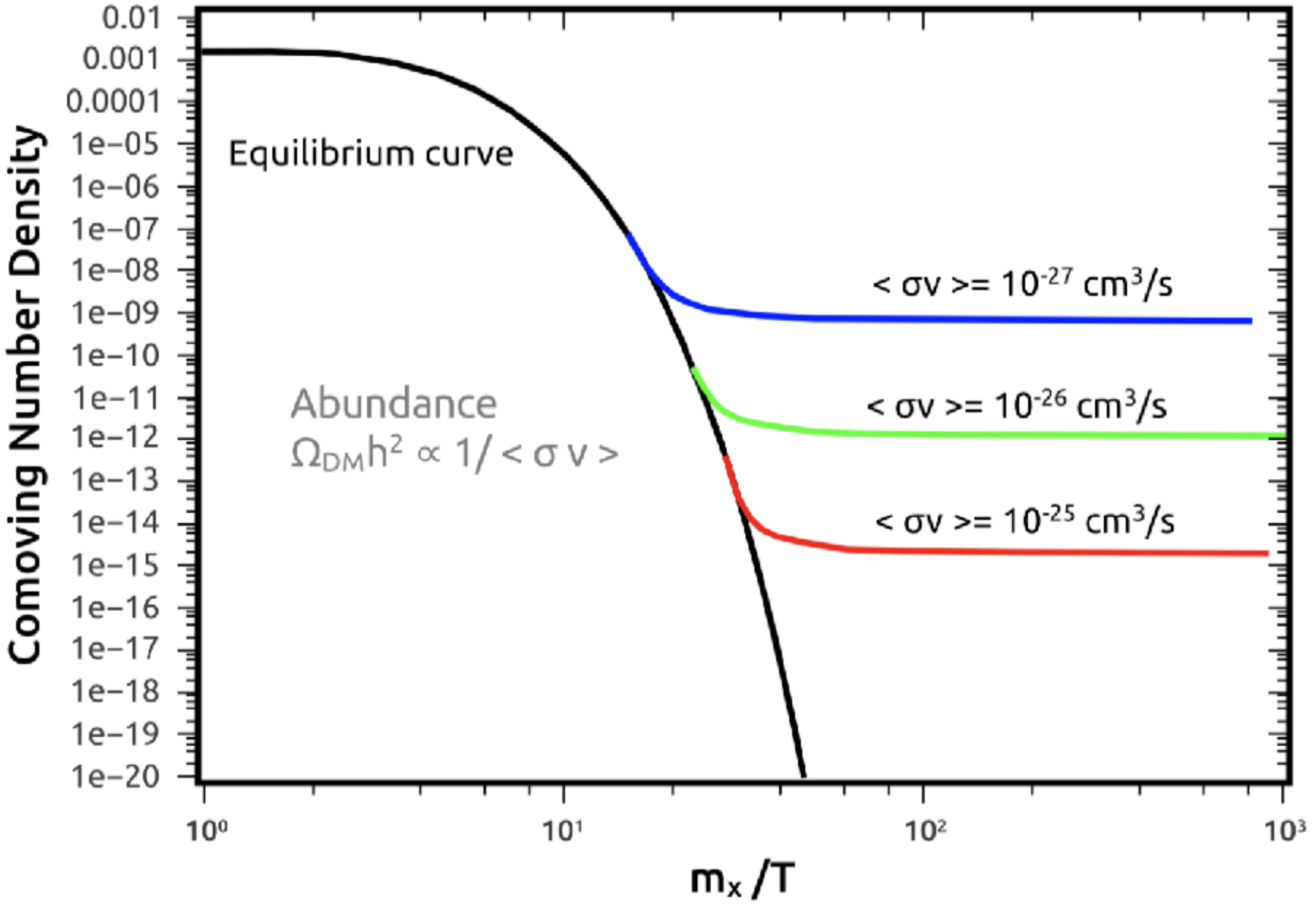
ICRR UTokyo and Tsinghua University

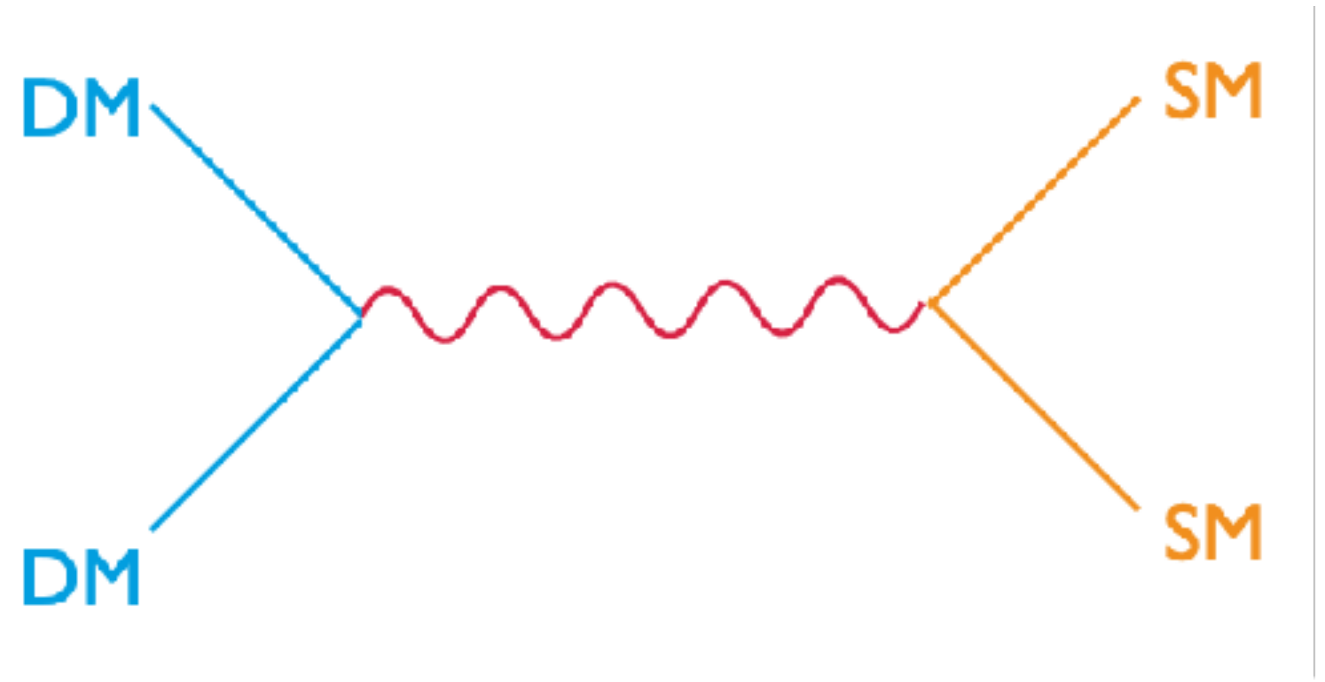




Motivation for Dark Matter

How dark matter was produced
in the early universe?





- DM is in thermal equilibrium.
- DM is diluted by the cosmic expansion
- DM cannot find each other and stop annihilation
- The DM number in comoving volume is **freeze-out**

Thermal freeze-out :

$$\Omega_{DM} \sim 1/\langle\sigma v\rangle \sim m^2/g^4$$

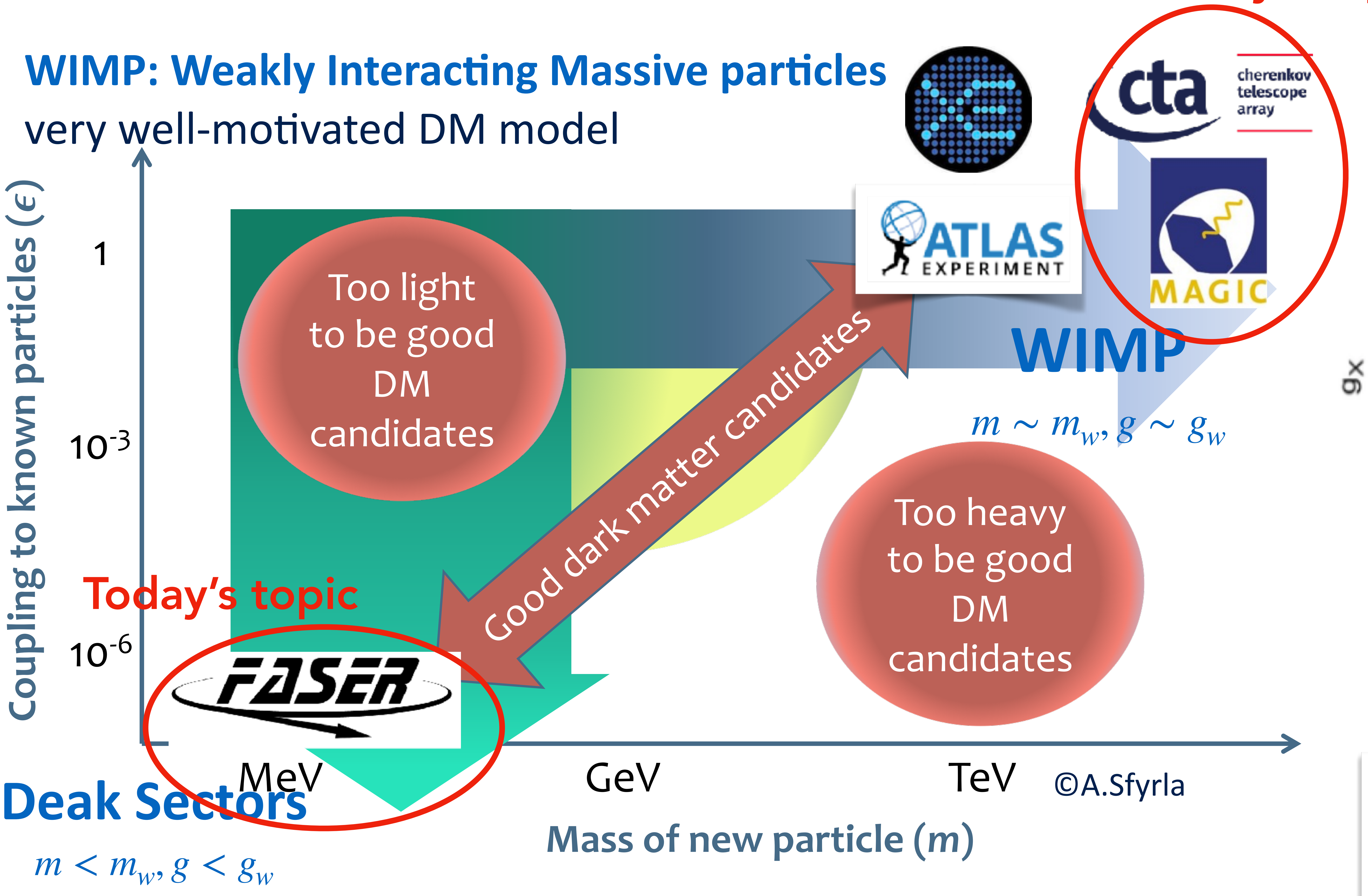
$\Omega_{DM} \sim 0.24$ (observable)
if, $m_{\rm DM} \sim m_{\rm EW}$ (100 GeV-1 TeV), $g \sim g_w$

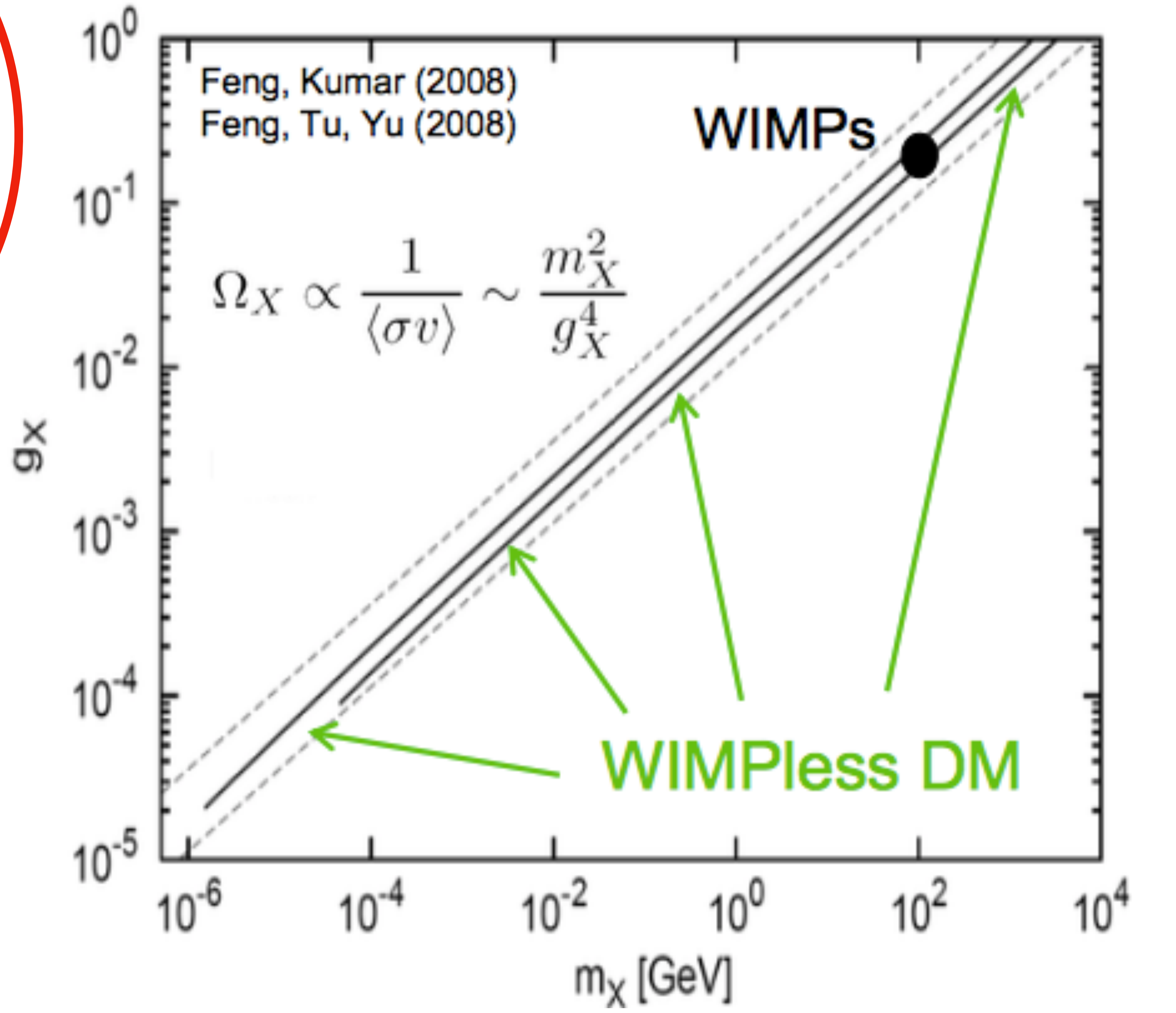
WIMP Miracle

WIMP or WIMPless miracle?

WIMP: Weakly Interacting Massive particles

very well-motivated DM model





The WIMPless Miracle: Dark Matter Particles without Weak-scale Masses or Weak Interactions

Jonathan L. Feng and Jason Kumar

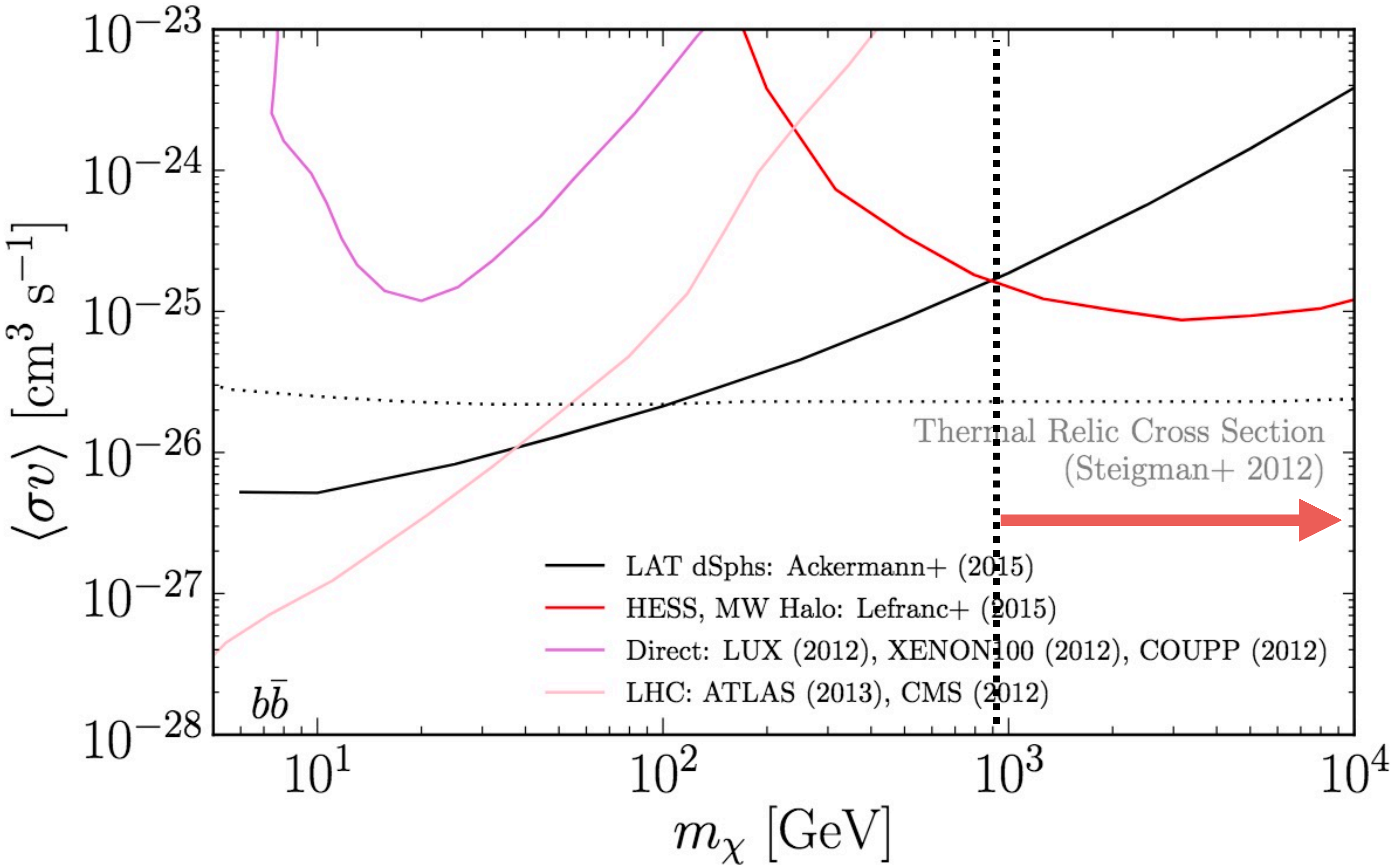
Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA

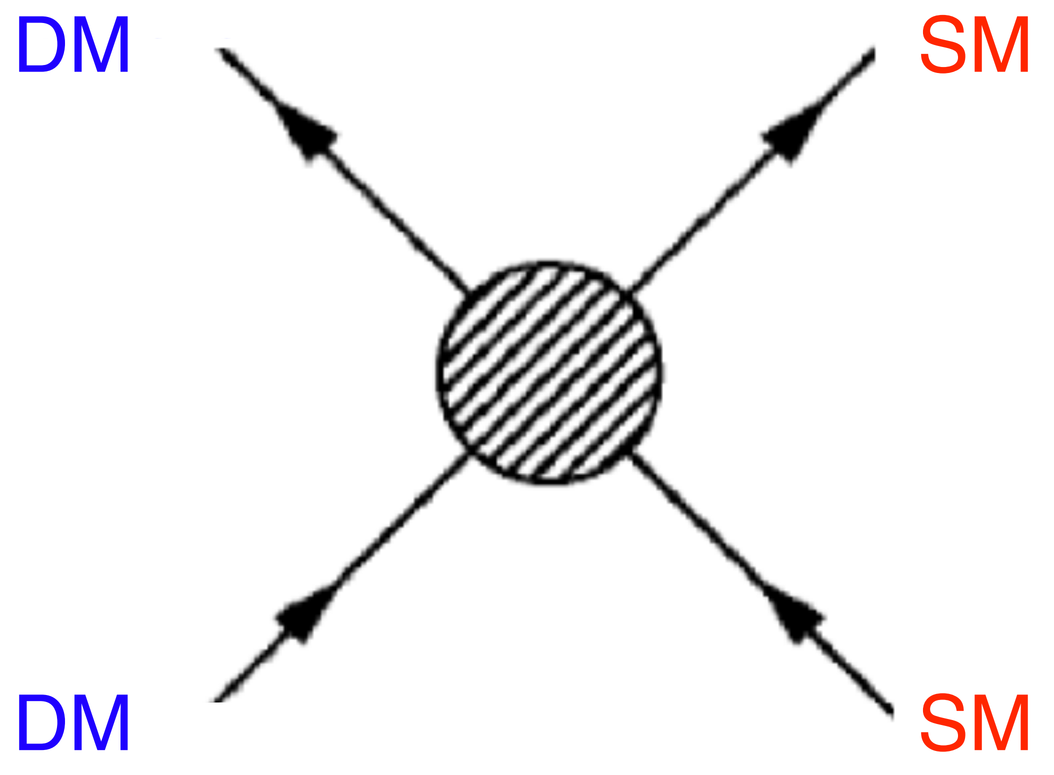
Phys.Rev.Lett.101:231301,2008

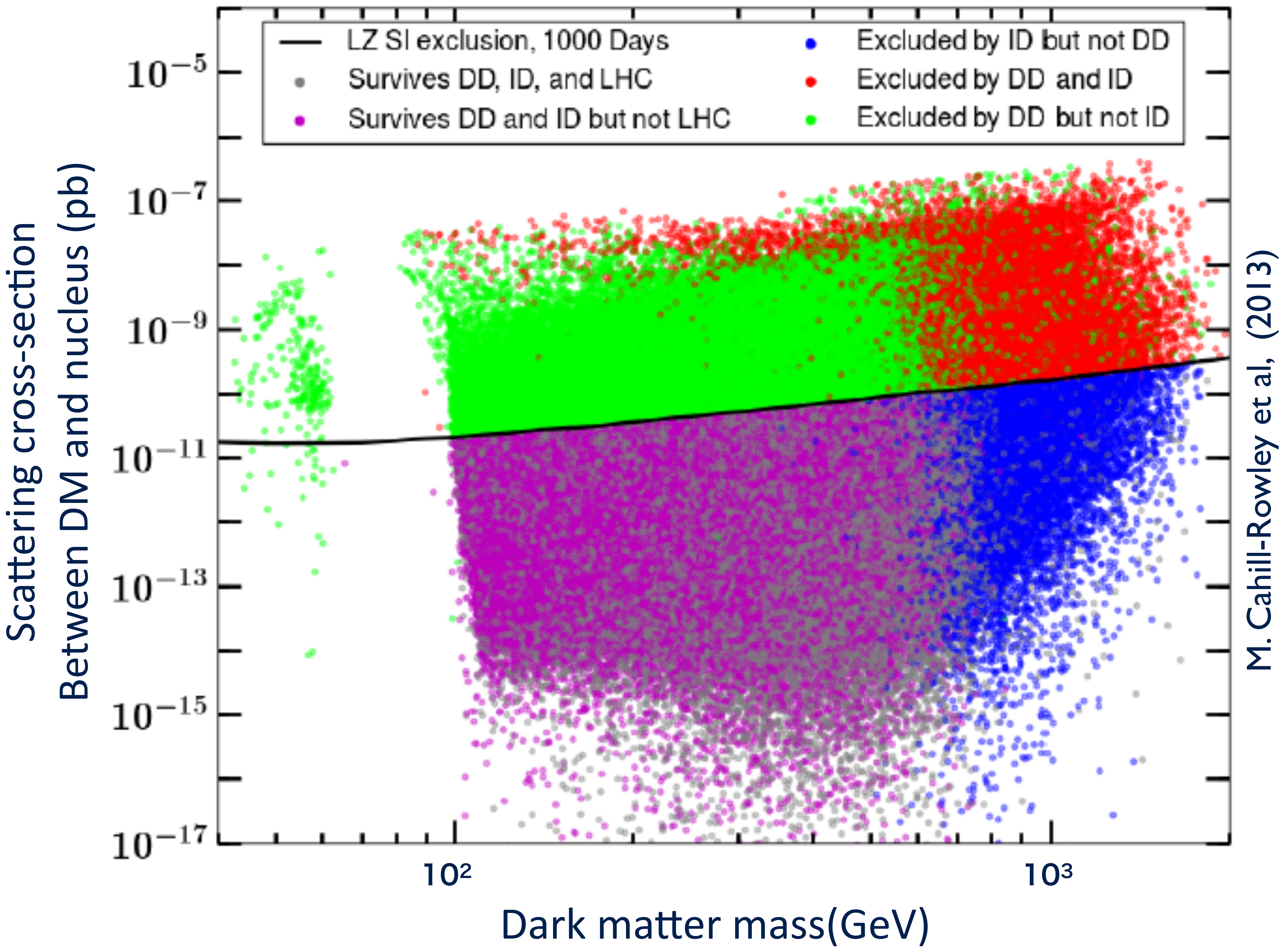
Let's try to search for DM in **the unexplored energy-scale!**

Complementarity of WIMP DM Searches

arXiv:1605.02016



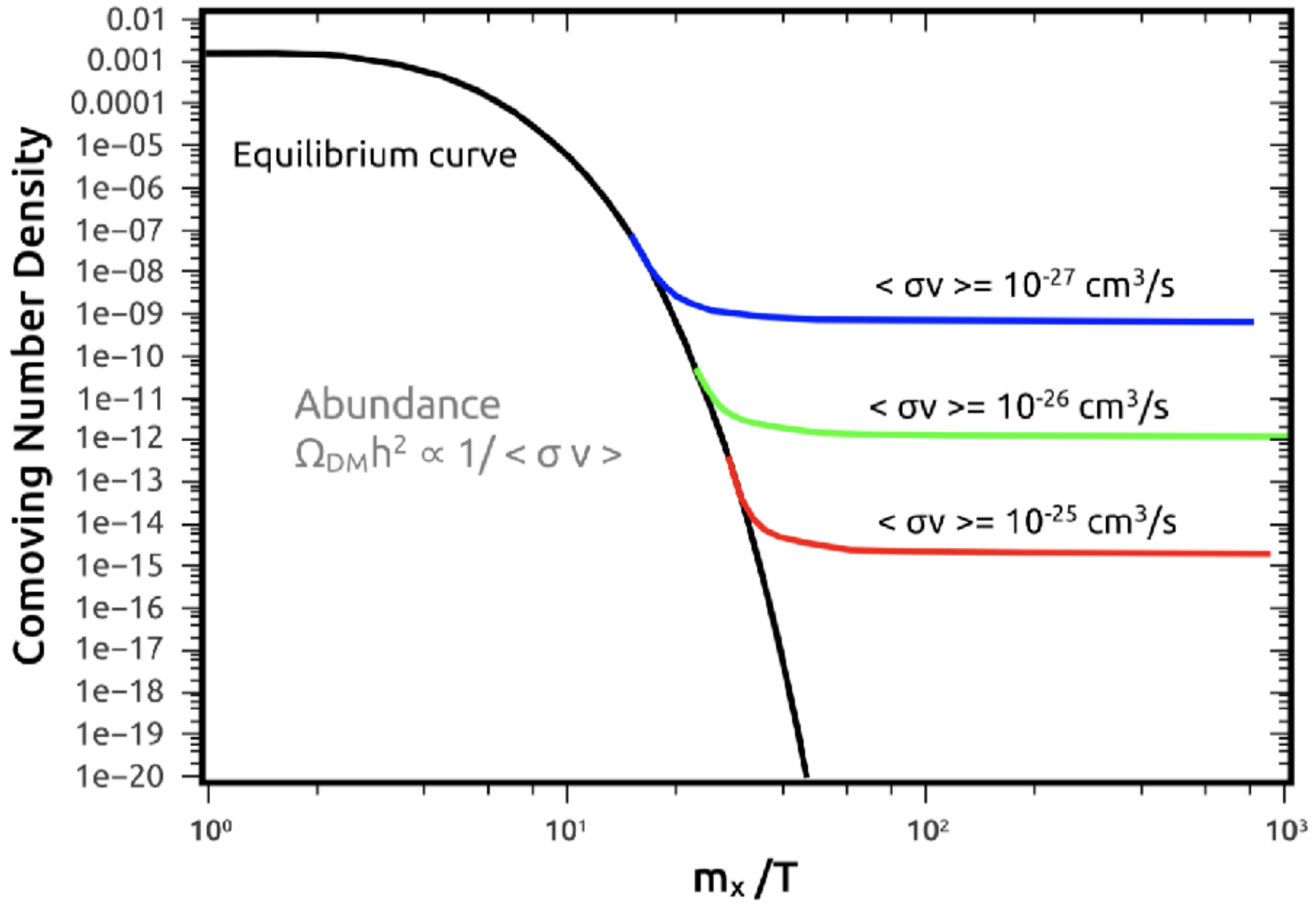




Imaging Atmospheric Cherenkov Telescopes (IACTs) would be useful to search for DM at **TeV-scale** due to the good sensitivity for high-energy gamma-ray

Why indirect way?

- **Test of particle DM**
  - information on the parameter (DM mass, a coupling constant…)
  - Complementary to direct detection and collider searches.
- **Test of DM production via thermal freeze-out (Unique!!)**
  - DM interaction rate equals the Hubble expansion rate of the universe.

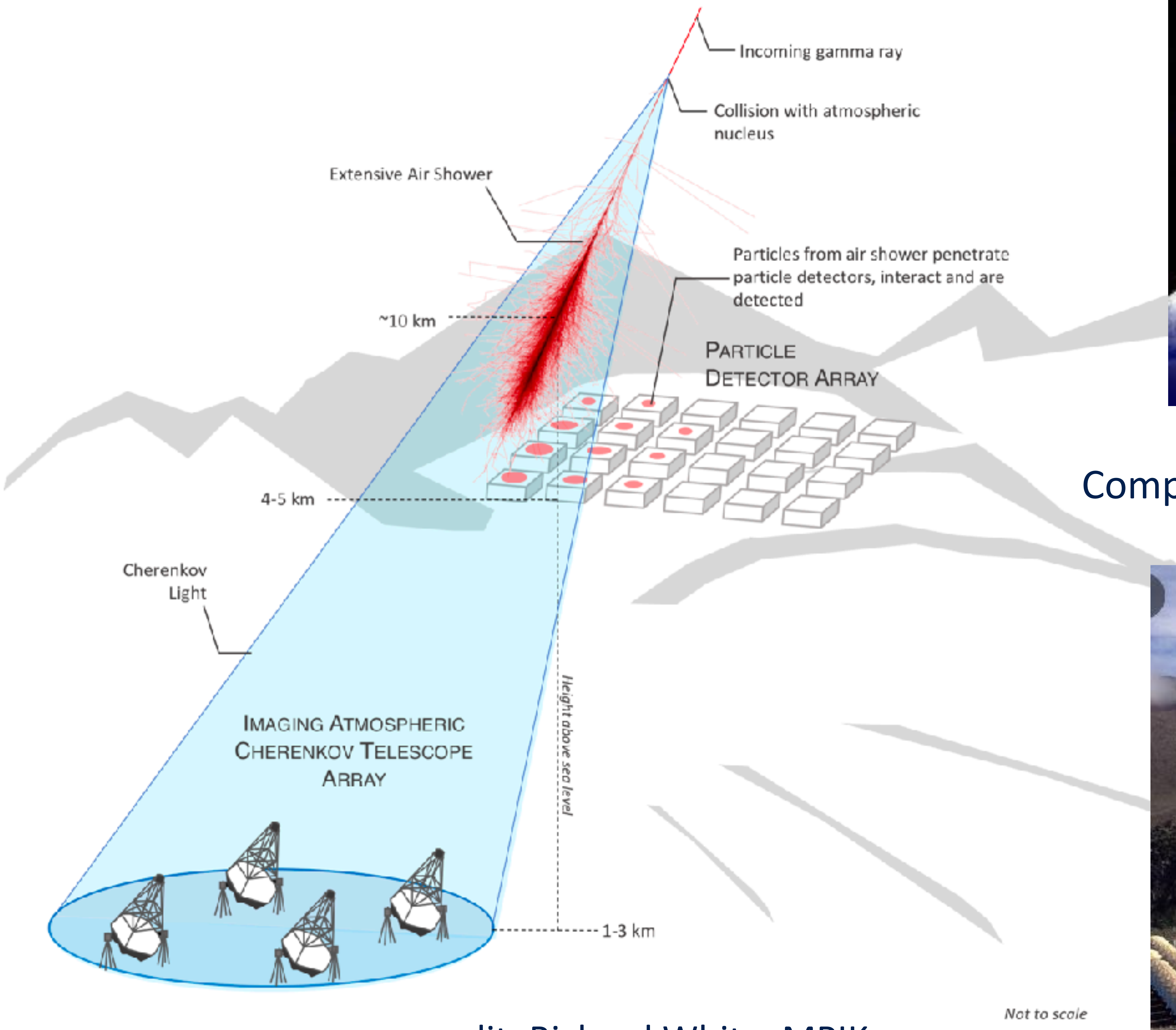


- DM is in thermal equilibrium.
- DM is diluted by the cosmic expansion
- DM cannot find each other and stop annihilation
- The DM number in comoving volume is **freeze-out**

$$\boxed{<\sigma v> \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}}$$

So-called **“thermal relic” cross-section**

Gamma-ray detectors

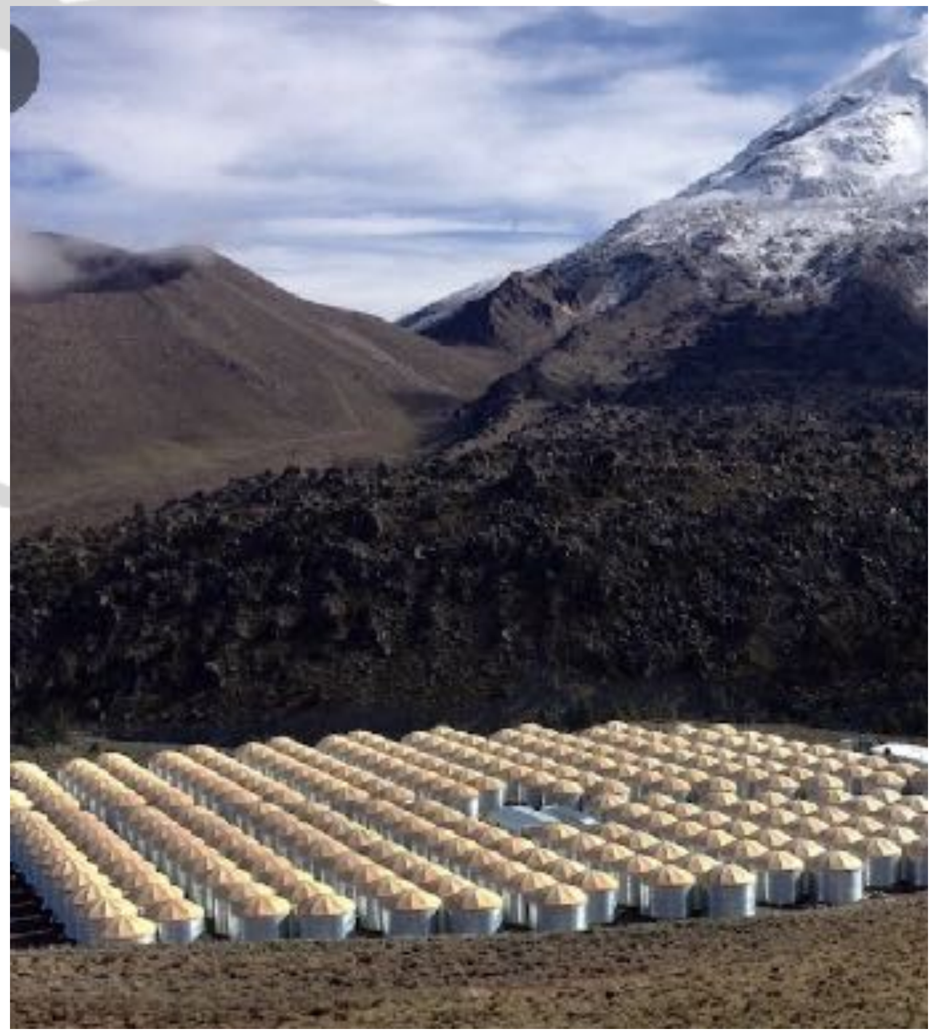


credit: Richard White, MPIK

MeV-GeV range
Satellite-borne detectors

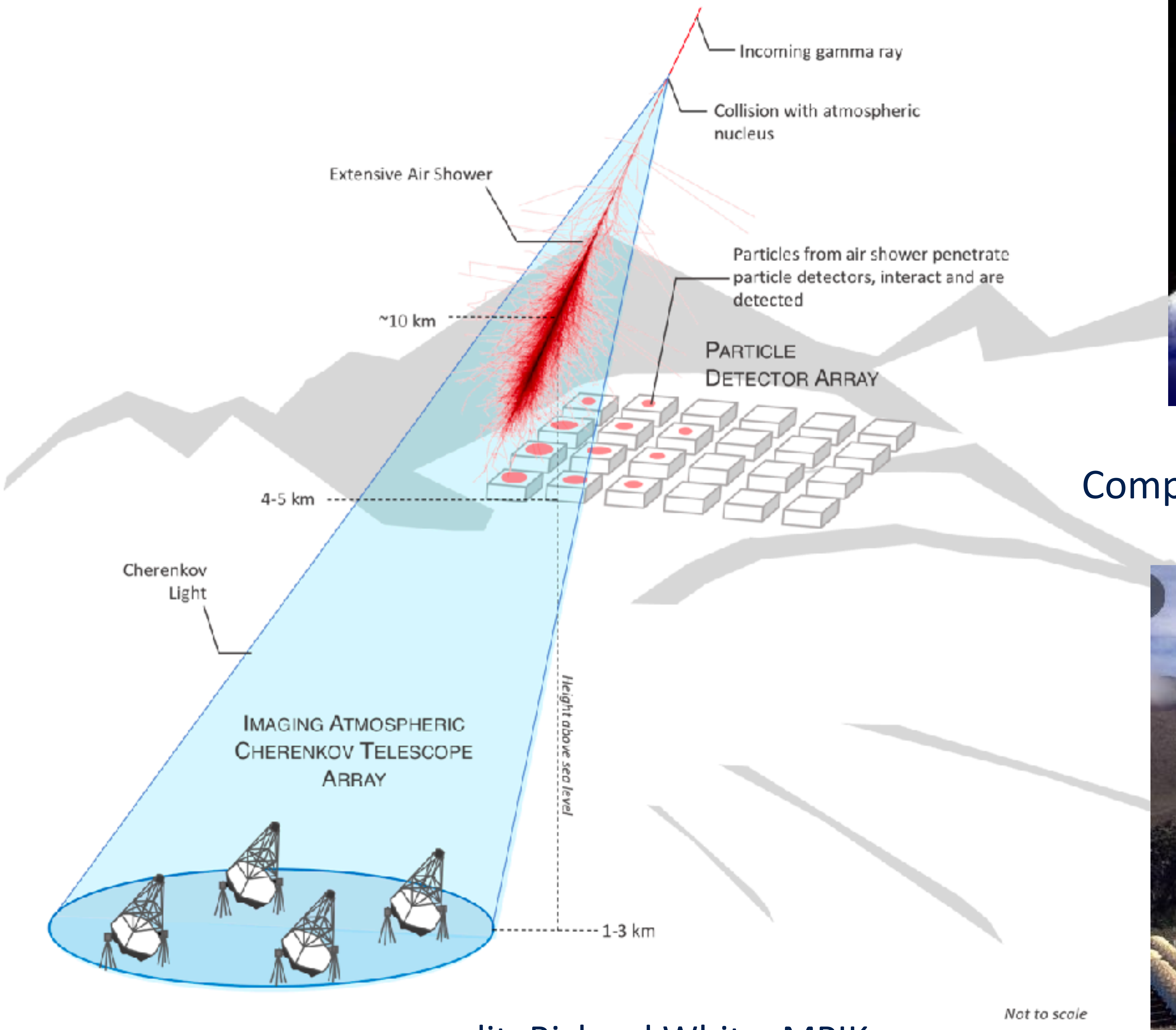
TeV range
Ground-based detectors (light)

TeV-PeV range
Compact Ground based detectors (particles)



>PeV range
Wide Ground-based detectors (particles)

Gamma-ray detectors



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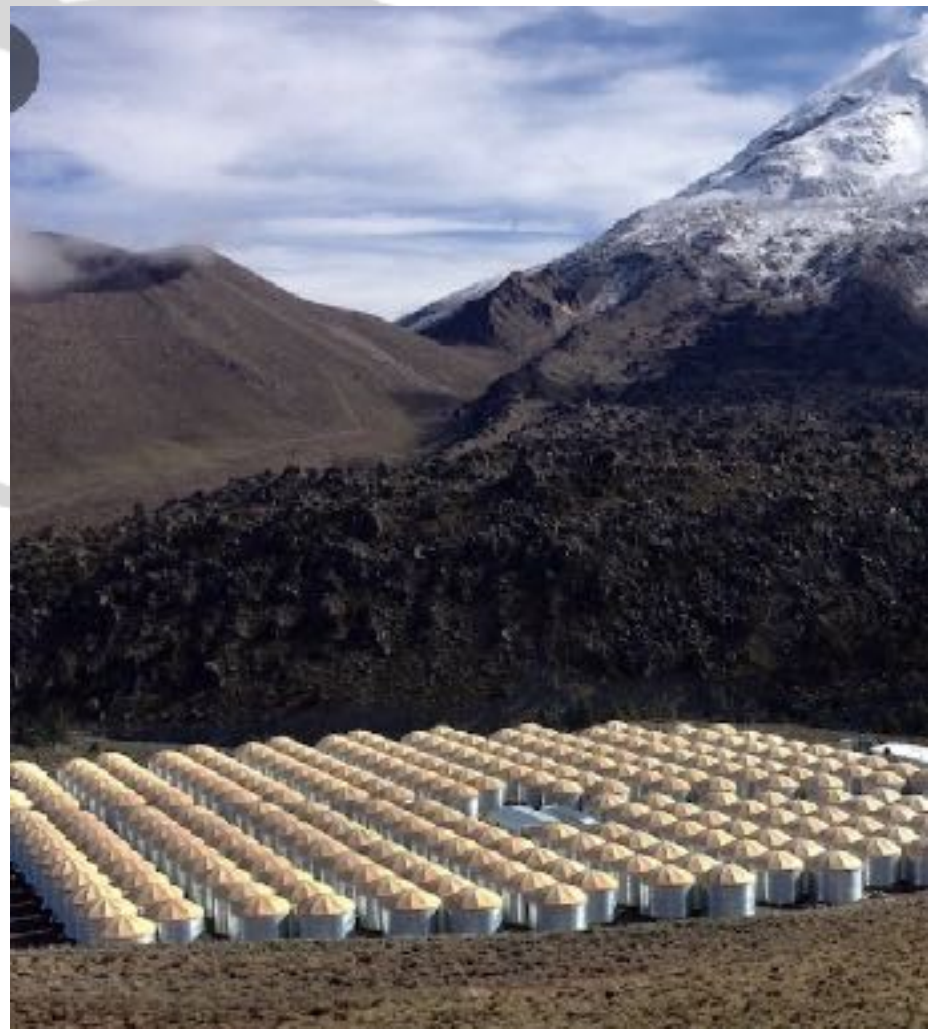


>PeV range
Wide Ground-based detectors (particles)

Imaging Atmospheric Cherenkov Telescopes

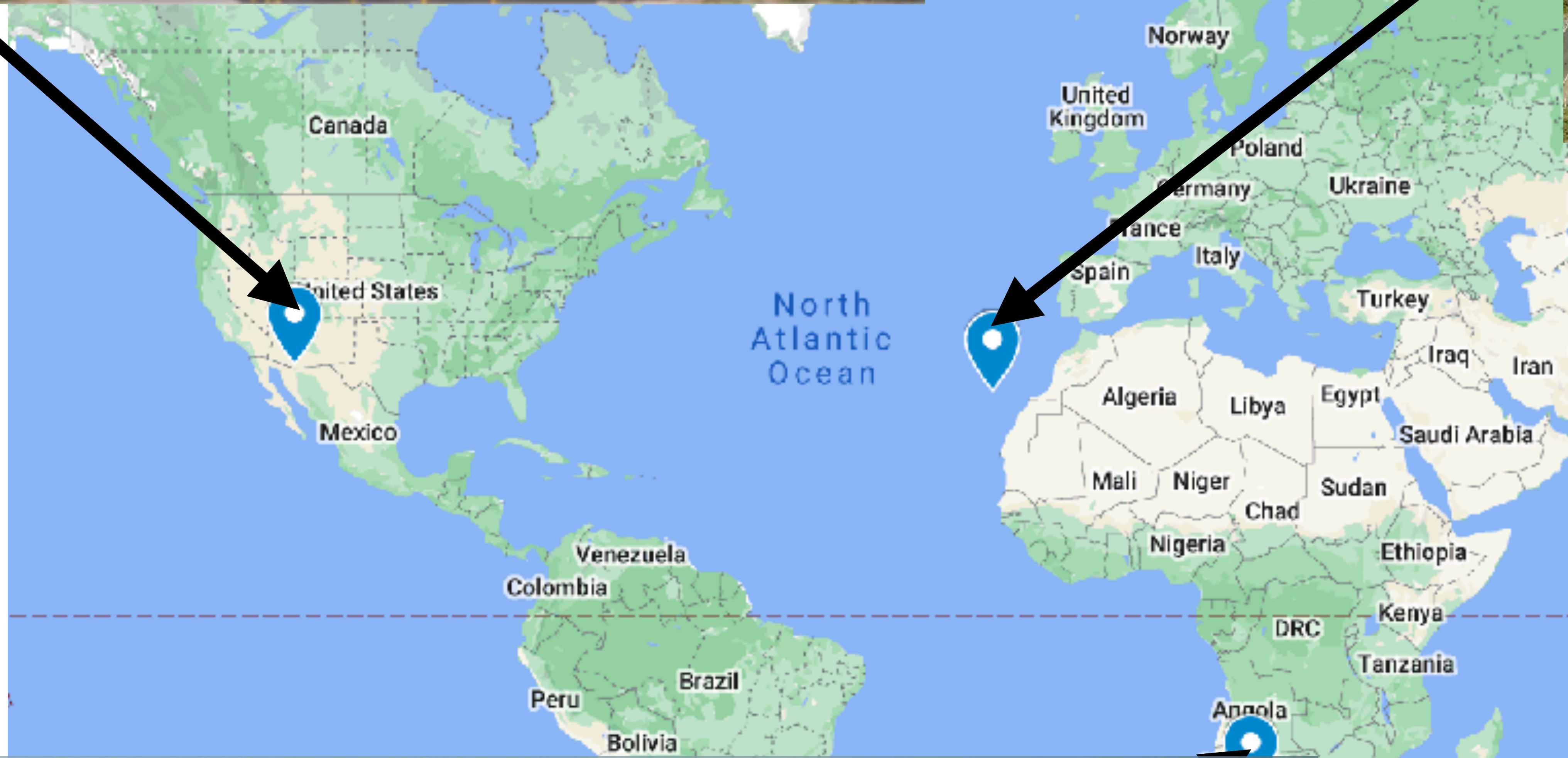
Imaging Atmospheric Cherenkov Telescopes (IACTs)

Imaging Atmospheric Cherenkov Telescopes (IACTs)

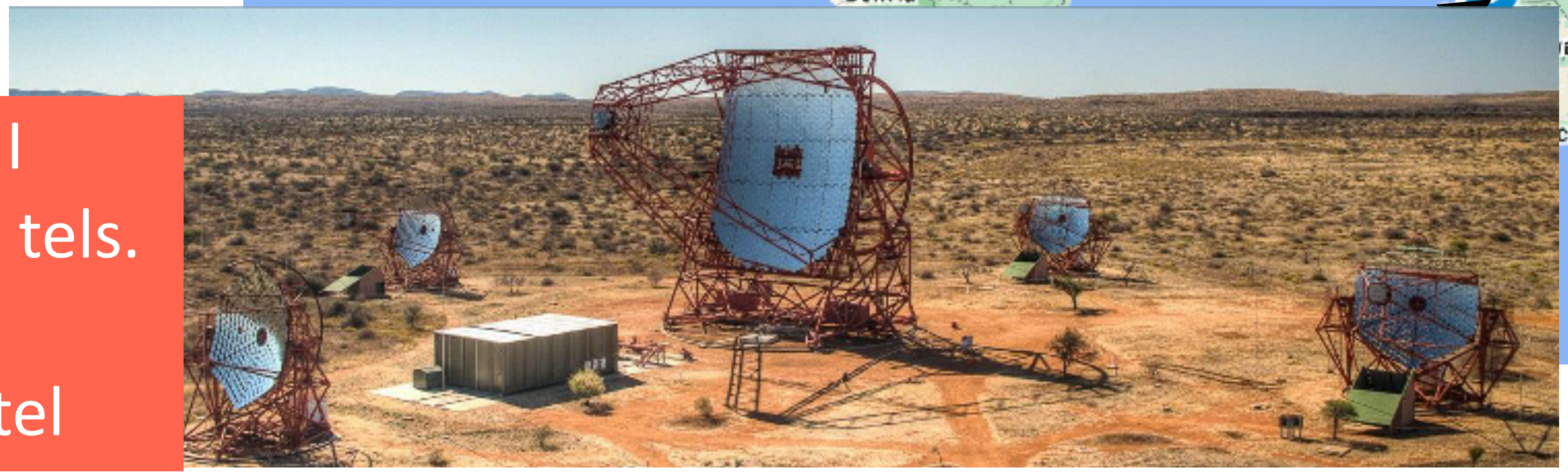
VERITAS
Dia. 12m × 4 tels.

MAGIC
Dia. 17m × 2 tels.

CTA-LST
Dia. 23m × 4 (1) tels.



H.E.S.S. II
Dia. 12m × 4 tels.
+
Dia. 28m tel



Typical performance

- Energy range: 20 GeV - 100 TeV
- Energy resolution: 10 - 15 %
- Angular resolution: 0.1 deg
- Field of view: 3 - 5 deg
- Duty cycle: about 10 - 20 %
  - dark time: about 1000 h/year

Sky coverage

Sky coverage depends on telescope location

- Northern hemisphere: MAGIC and VERITAS
  - e.g. Crab Nebula
- Southern hemisphere: H.E.S.S.
  - e.g. The Galactic Center

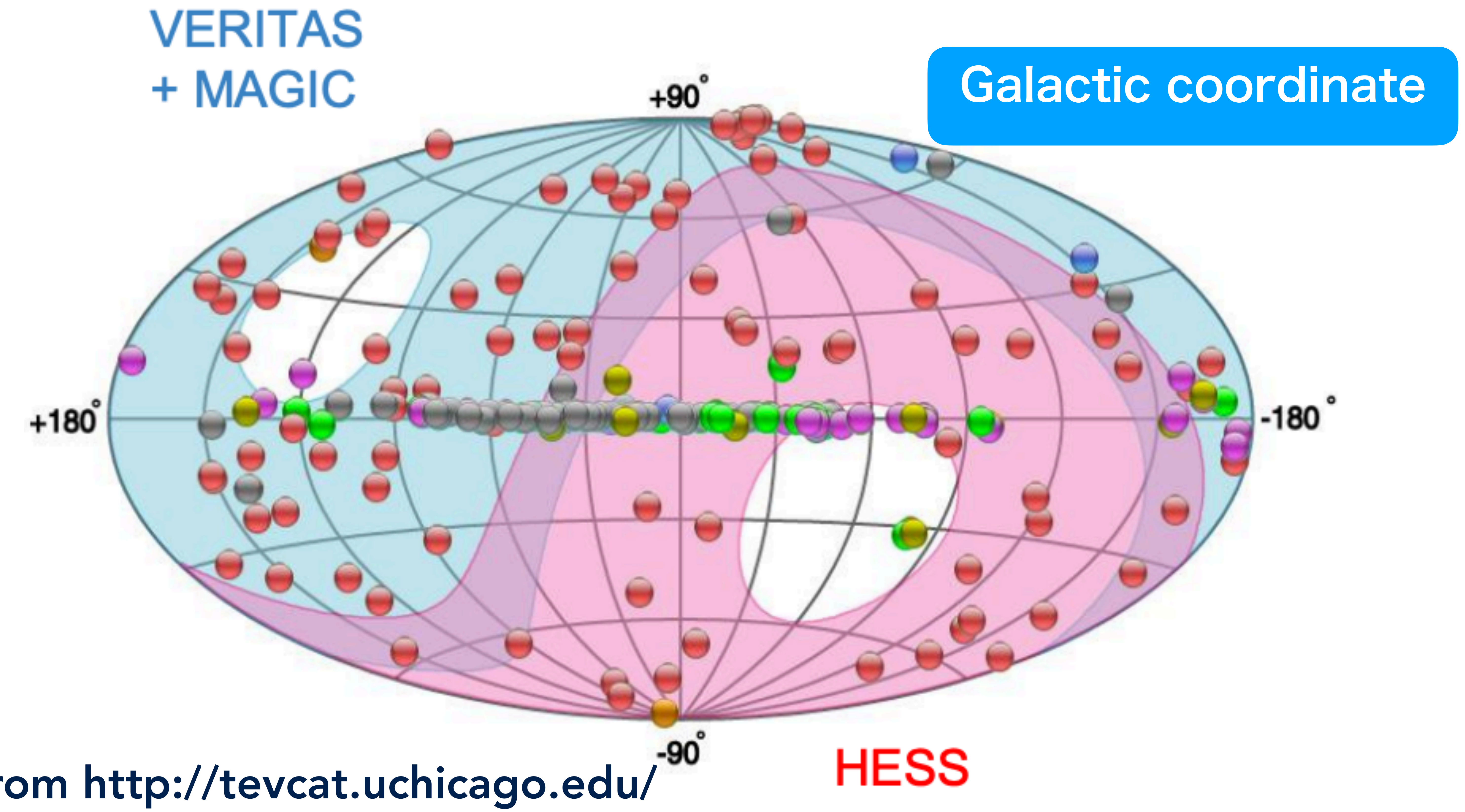


Figure from http://tevcat.uchicago.edu/

VERITAS site
N 31° 40′30″
W 110°57′07

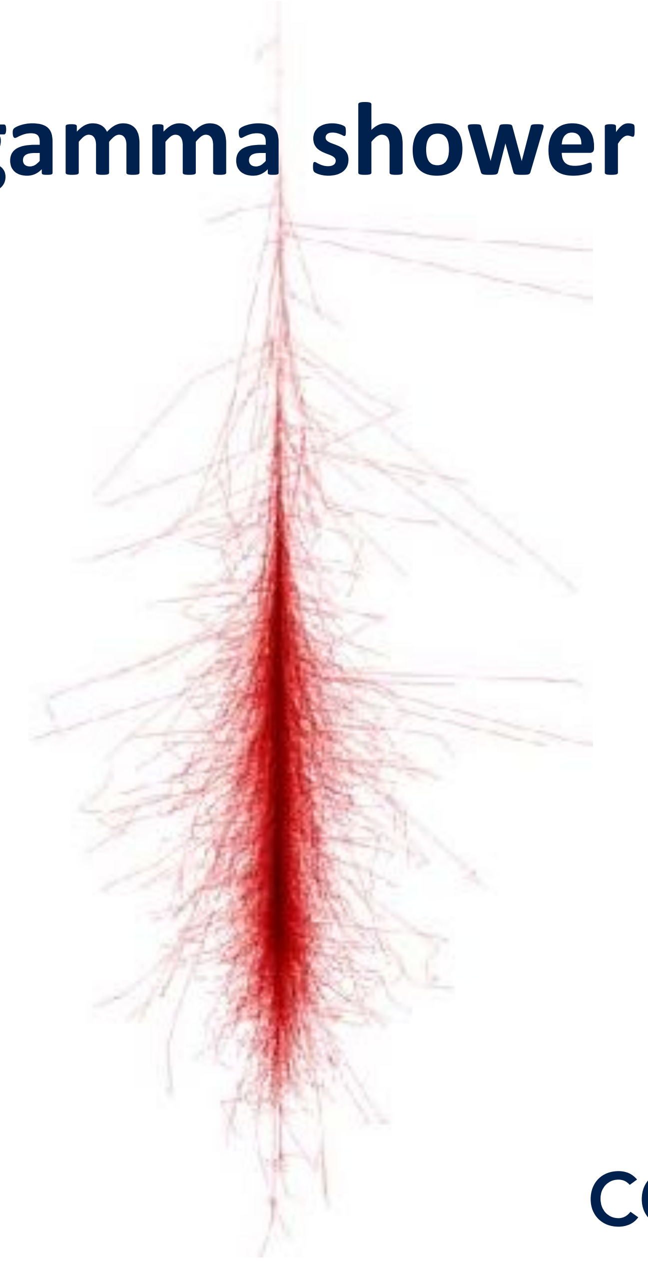
MAGIC site
N 28° 45′43″
W 17°53′24″

H.E.S.S. site
S 23° 16′18″
E 16°30′00″

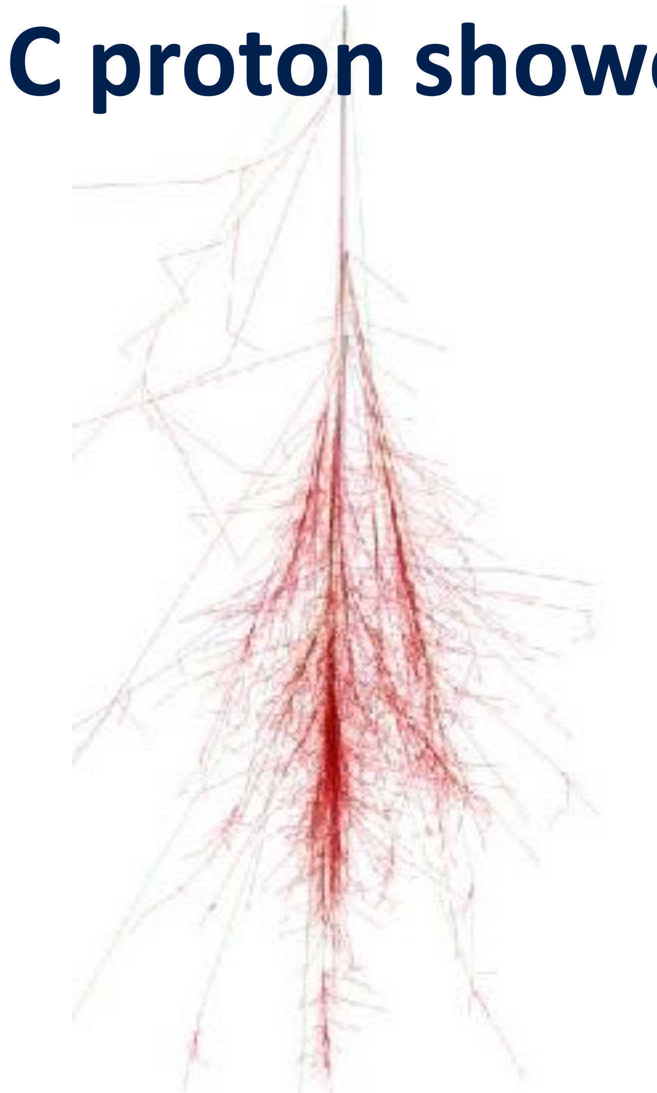
IACT technique

Gamma/Hadron = 1:10^3-10^4
very huge background at trigger level

MC gamma shower

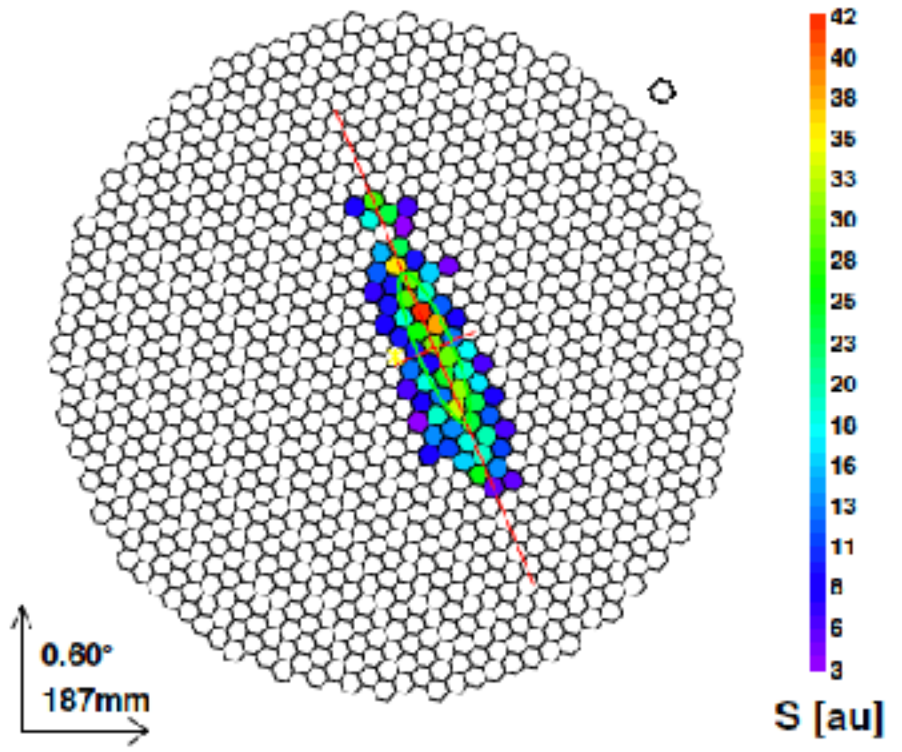


MC proton shower

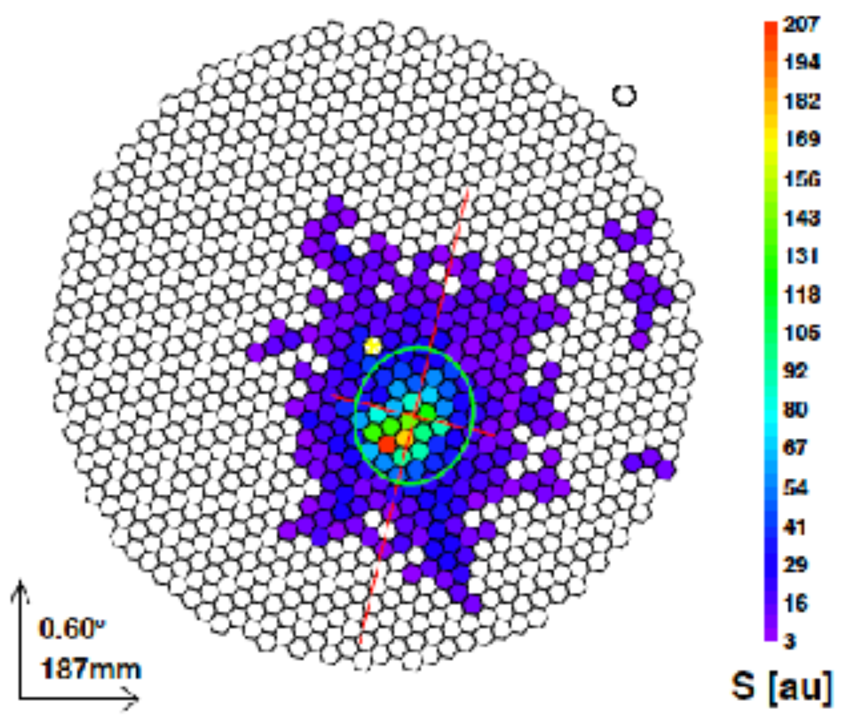


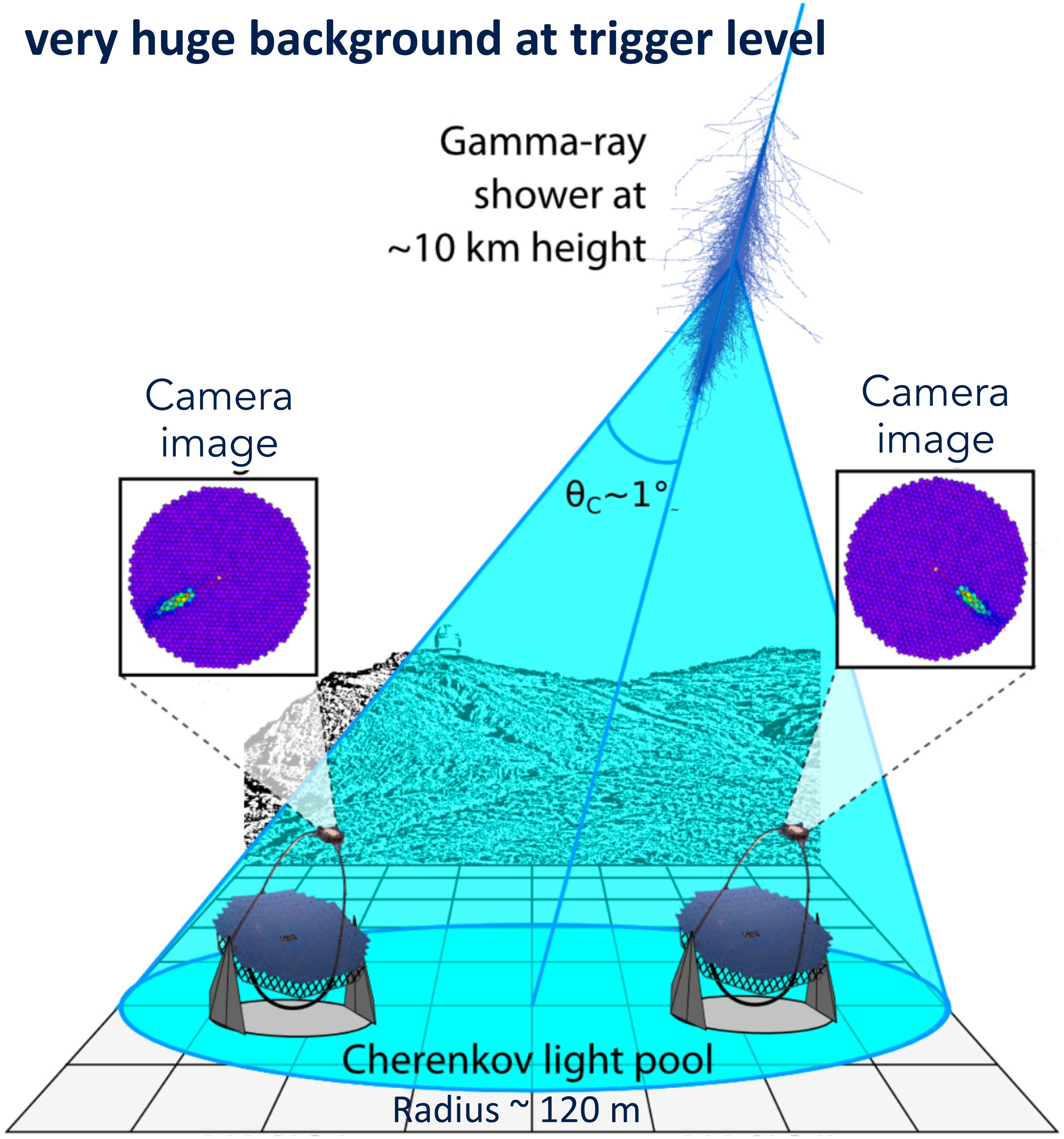
CORSIKA simulation

Gamma (signal)



Hadron(background)





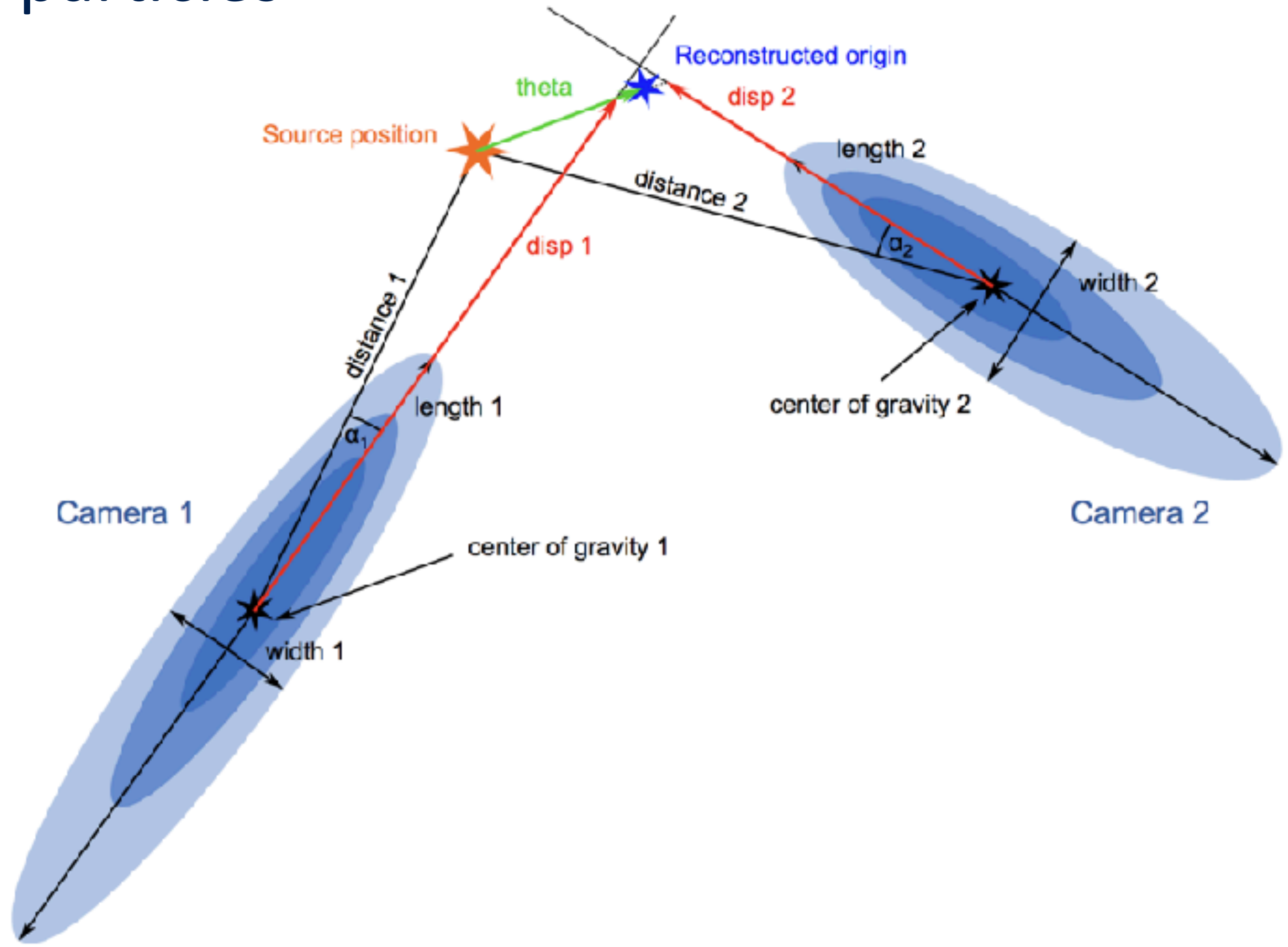
IACT technique

Image analysis with shower images

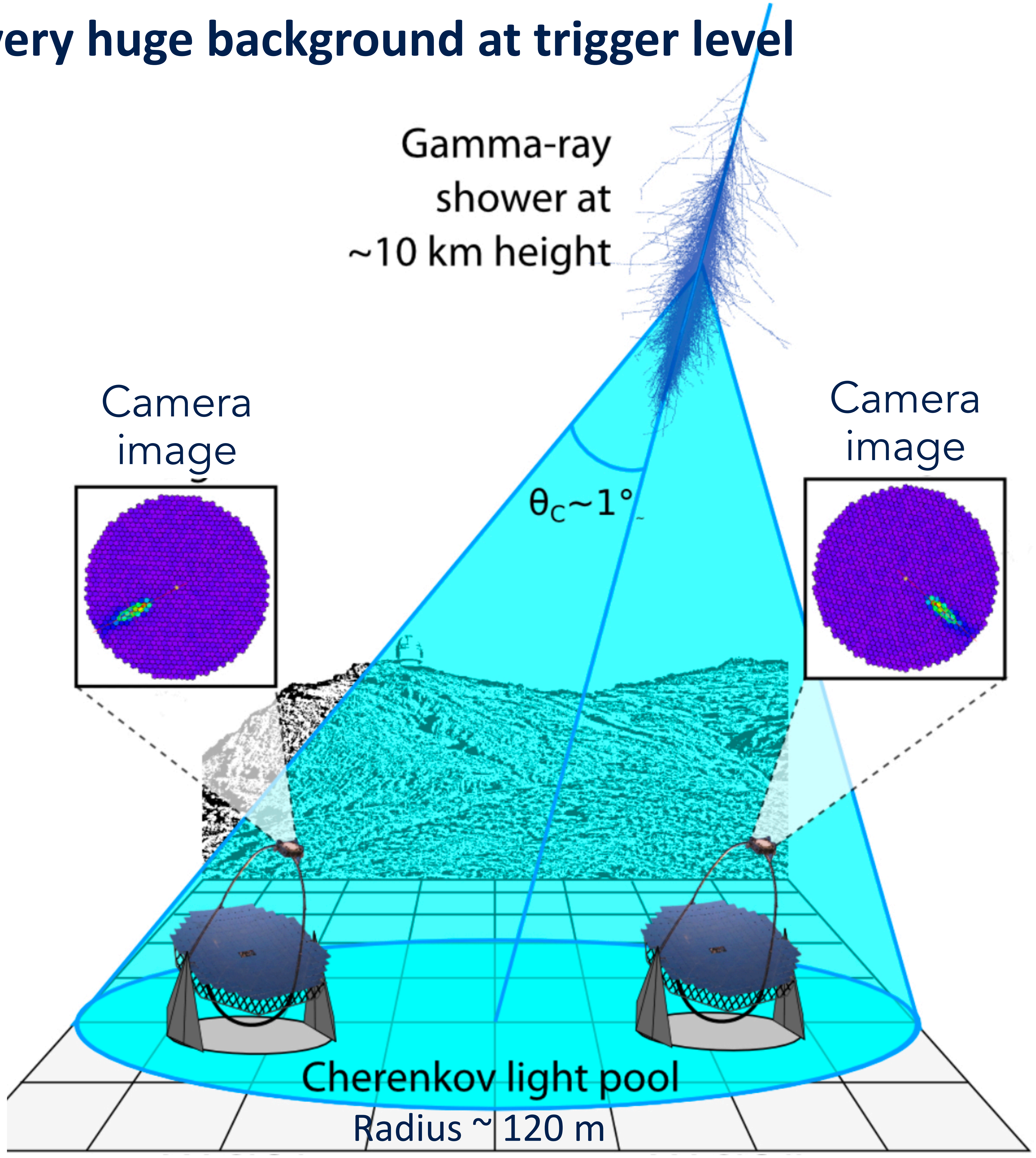
- Orientation
- Size/length/width
- Time gradient

Output on primary particles info

- Energy, direction, arrival time
- Types of particles



Gamma/Hadron = 1:10^3-10^4
very huge background at trigger level



IACT technique

Gamma/Hadron = $1:10^3$-10^4
very huge background at trigger level

Image analysis with shower images

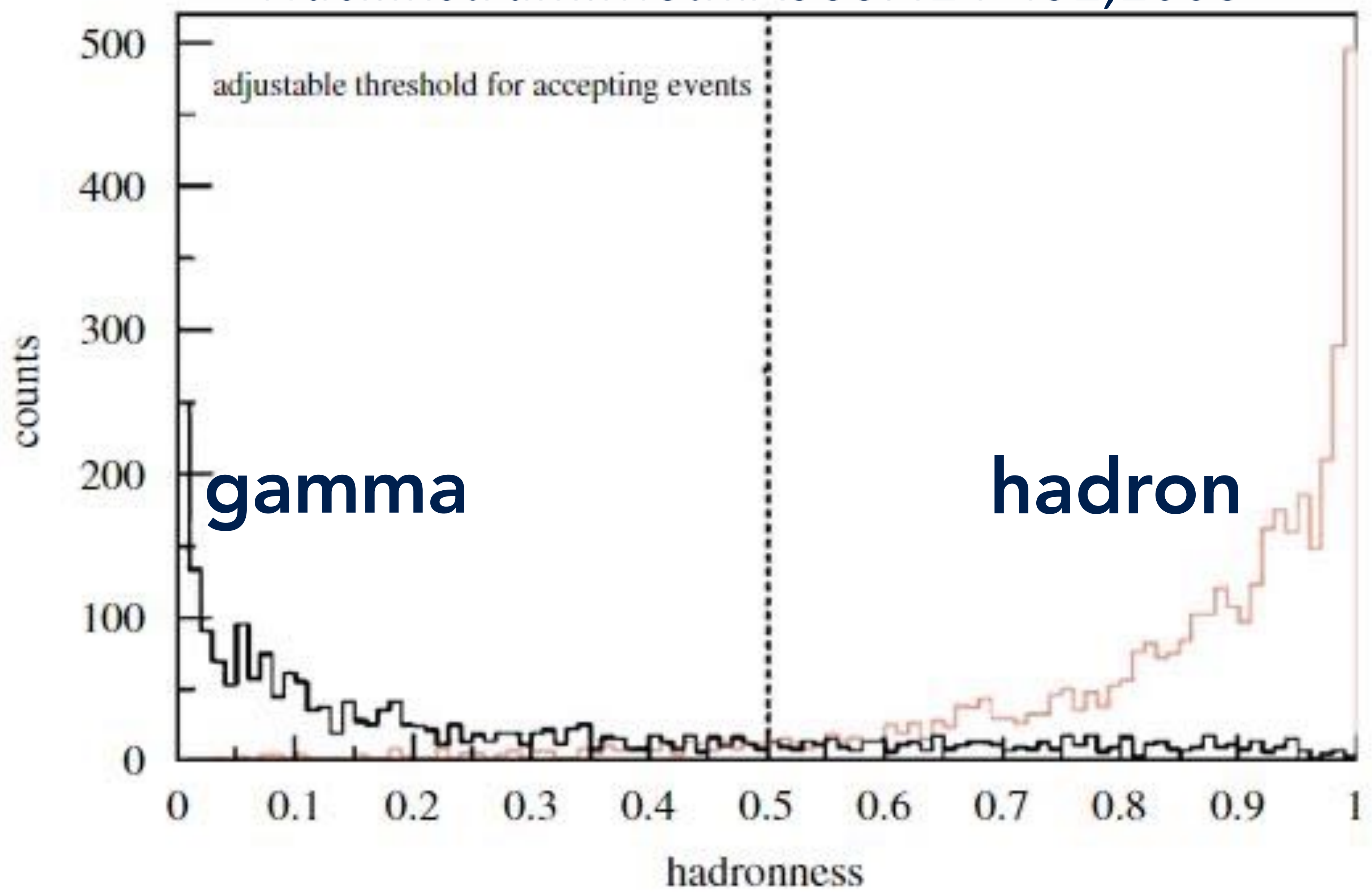
- Orientation
- Size/length/width
- Time gradient

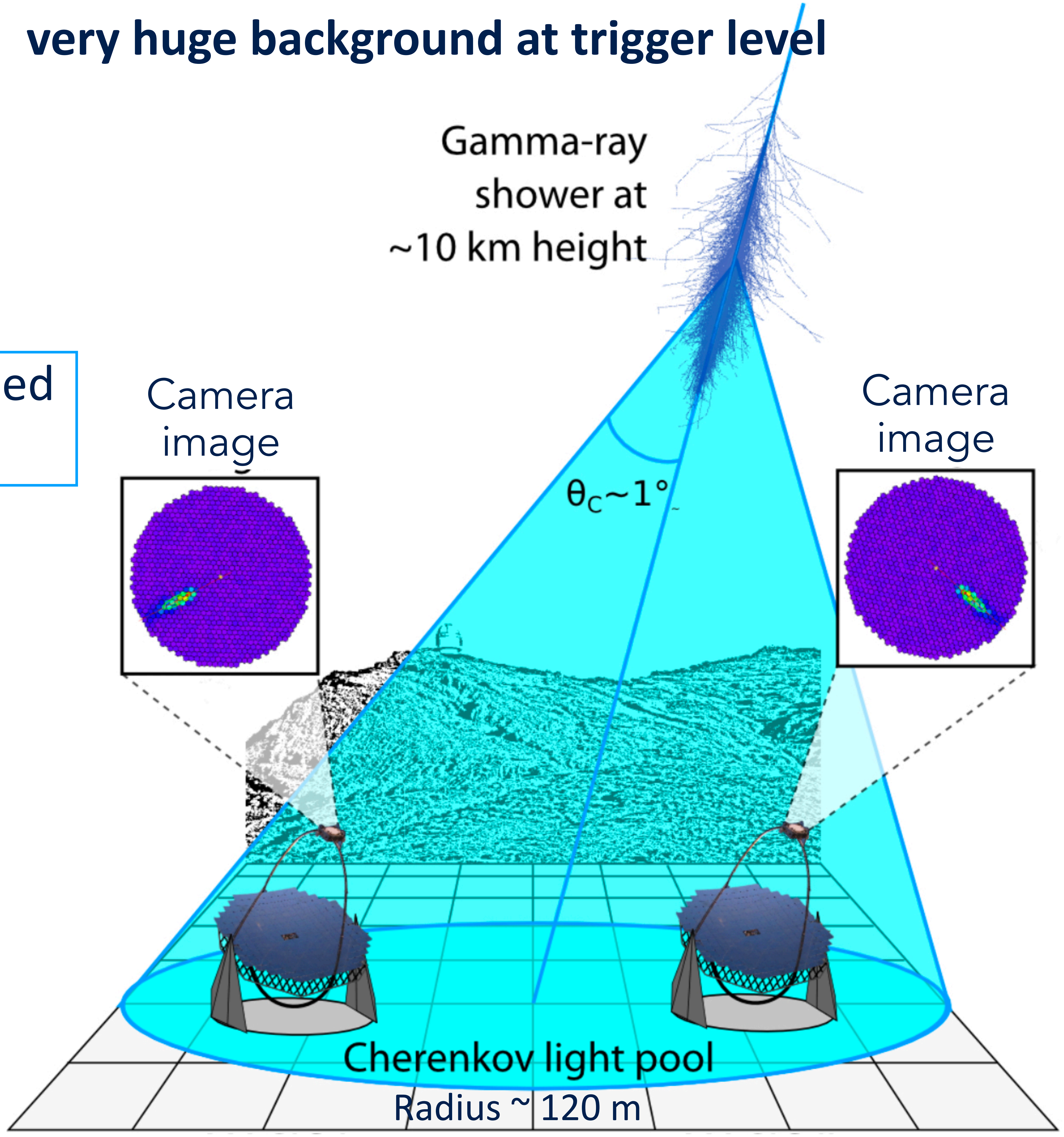
Output on primary particles info

- Energy, direction, arrival time
- Types of particles

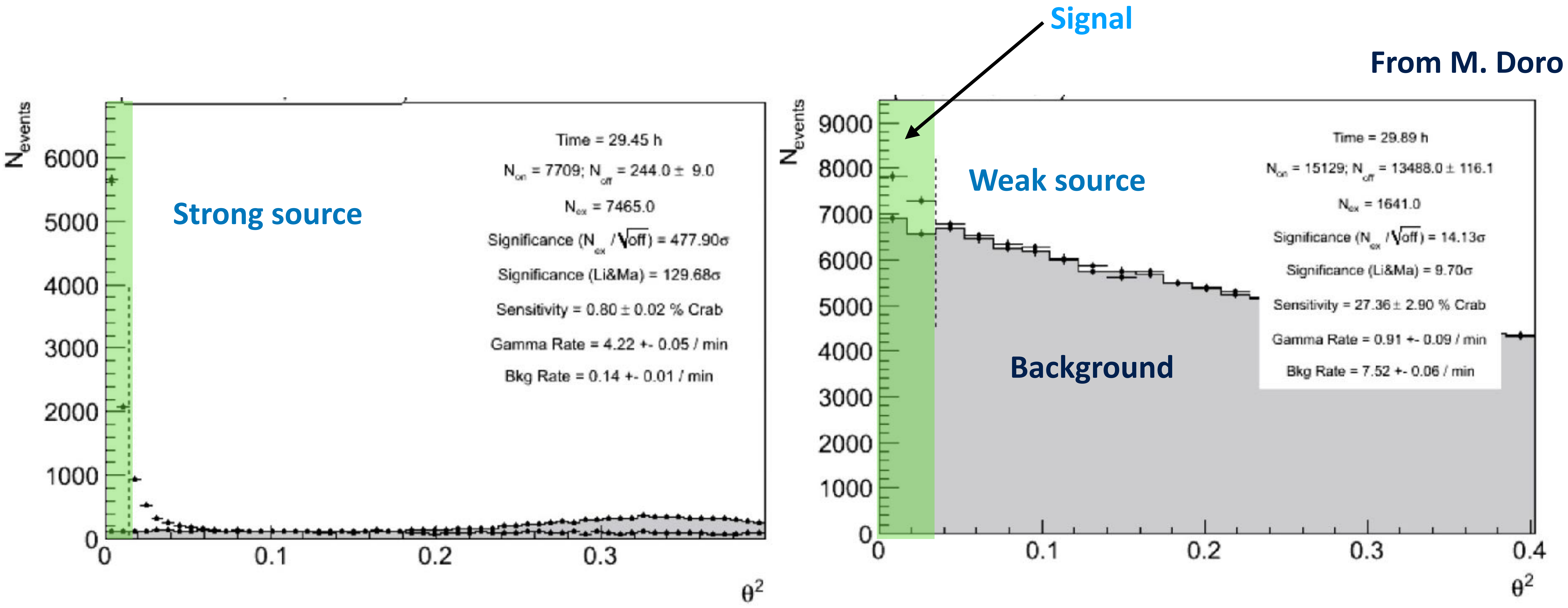
Machine learning based classification

Nucl.Instrum.Meth.A588:424-432,2008





Source detection on huge bkg



For IACT observations, always **huge proton background** exists (except for transient sources like Gamma-ray burst)
Note that this is difference from **analysis with satellites (e.g. Fermi-LAT)**

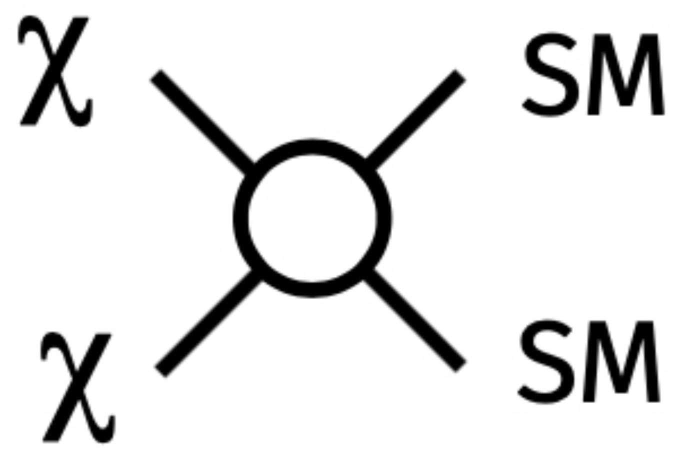
- **γ-ray event list ≠ photon list**

Current dark matter searches with IACTs

Expected gamma-ray flux from DM annihilation/decay

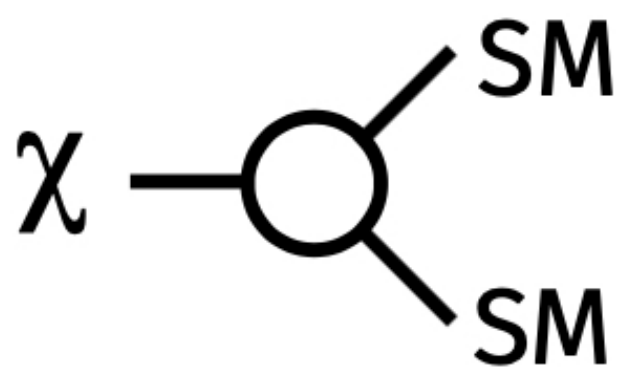
Annihilation

$$\frac{d\Phi^{ann.}}{dE_\gamma} = \frac{1}{4\pi}\frac{\boxed{\sigma v}}{2m_\chi^2} \times \sum_i Br_i \frac{dN_\gamma^i}{dE} \times \int_{\Delta\Omega}\int_{los} ds\ \rho^2(s,\ \Omega)$$



Decay

$$\frac{d\Phi^{dec.}}{dE_\gamma} = \frac{1}{4\pi}\frac{1}{m_\chi \boxed{\tau_\chi}} \times \sum_i Br_i \frac{dN_\gamma^i}{dE} \times \int_{\Delta\Omega}\int_{los} ds\ \rho(s,\ \Omega)$$



Particle physics term

σv : annihilation cross-section, τ : lifetime

mχ : Mass of DM particle

BR_i : branching ratio of each channel

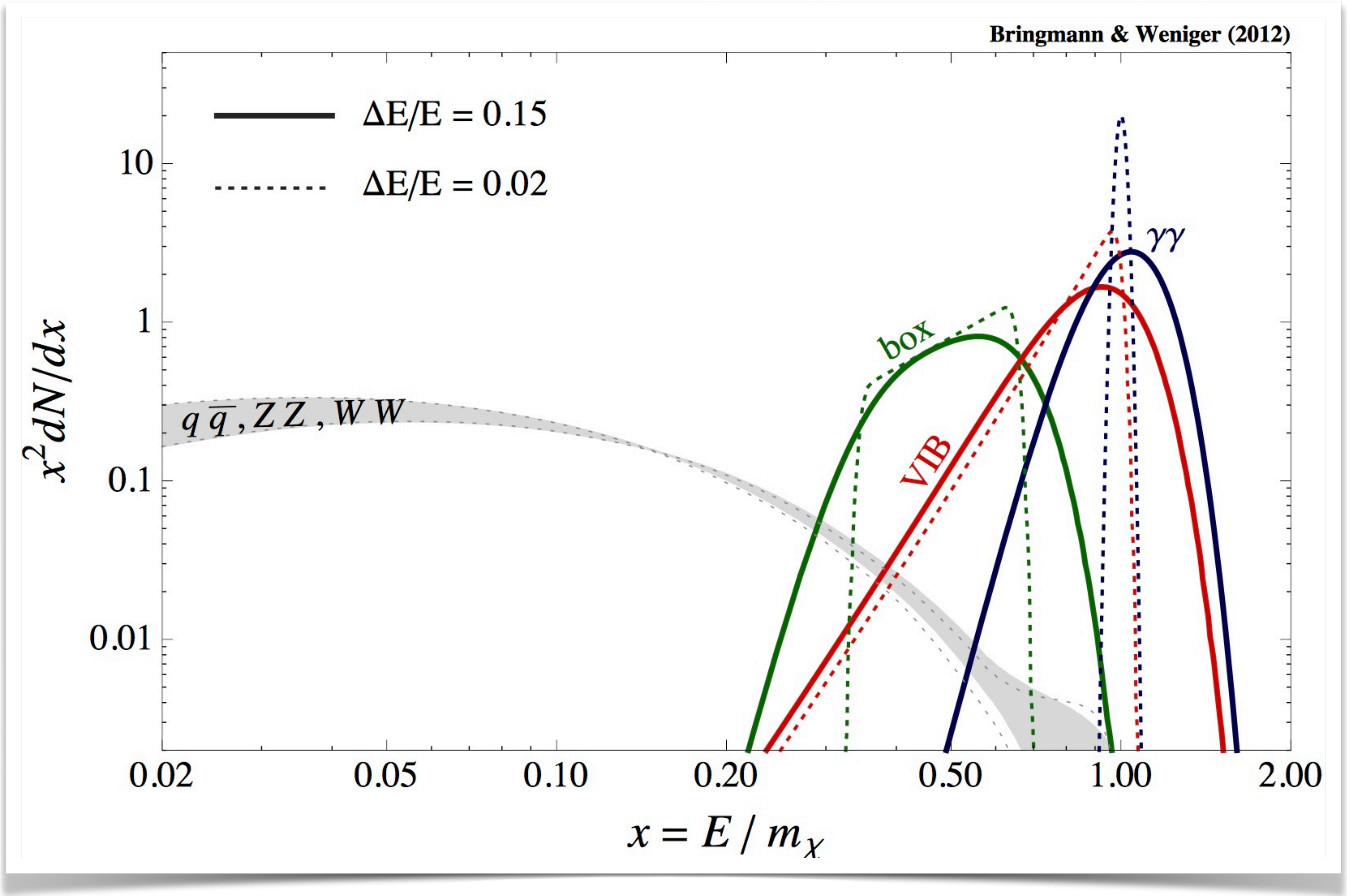
dN^i/dE : differential gamma-ray yield of each channel

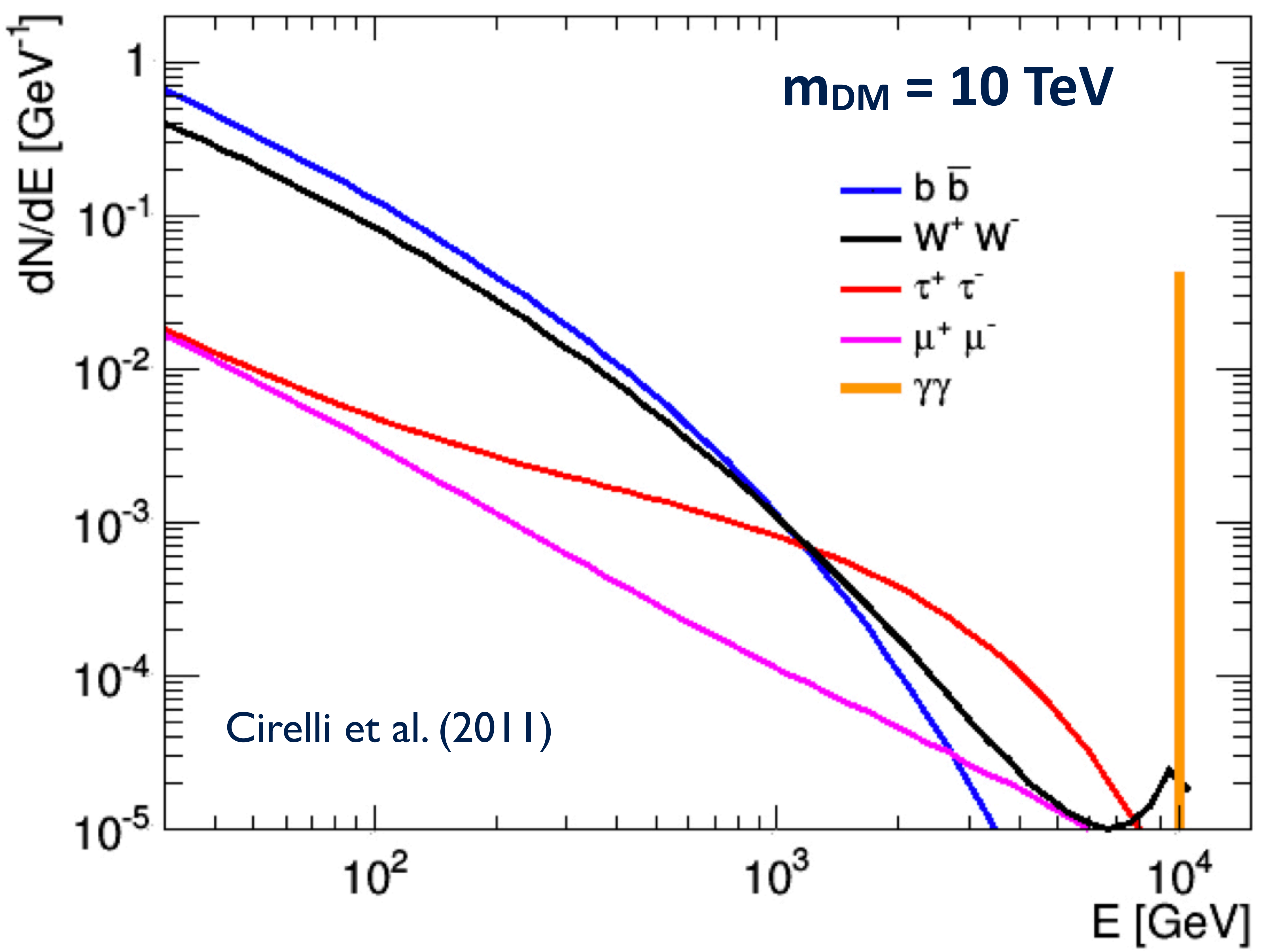
Astrophysics term

ρ : dark matter density

J-factor : Integrated DM density along the line of sight

Gamma-ray spectra from DM





Continuum spectra

- Sharp cut off at DM masses

Line-like emission

- clear peak, no contamination astrophysical component

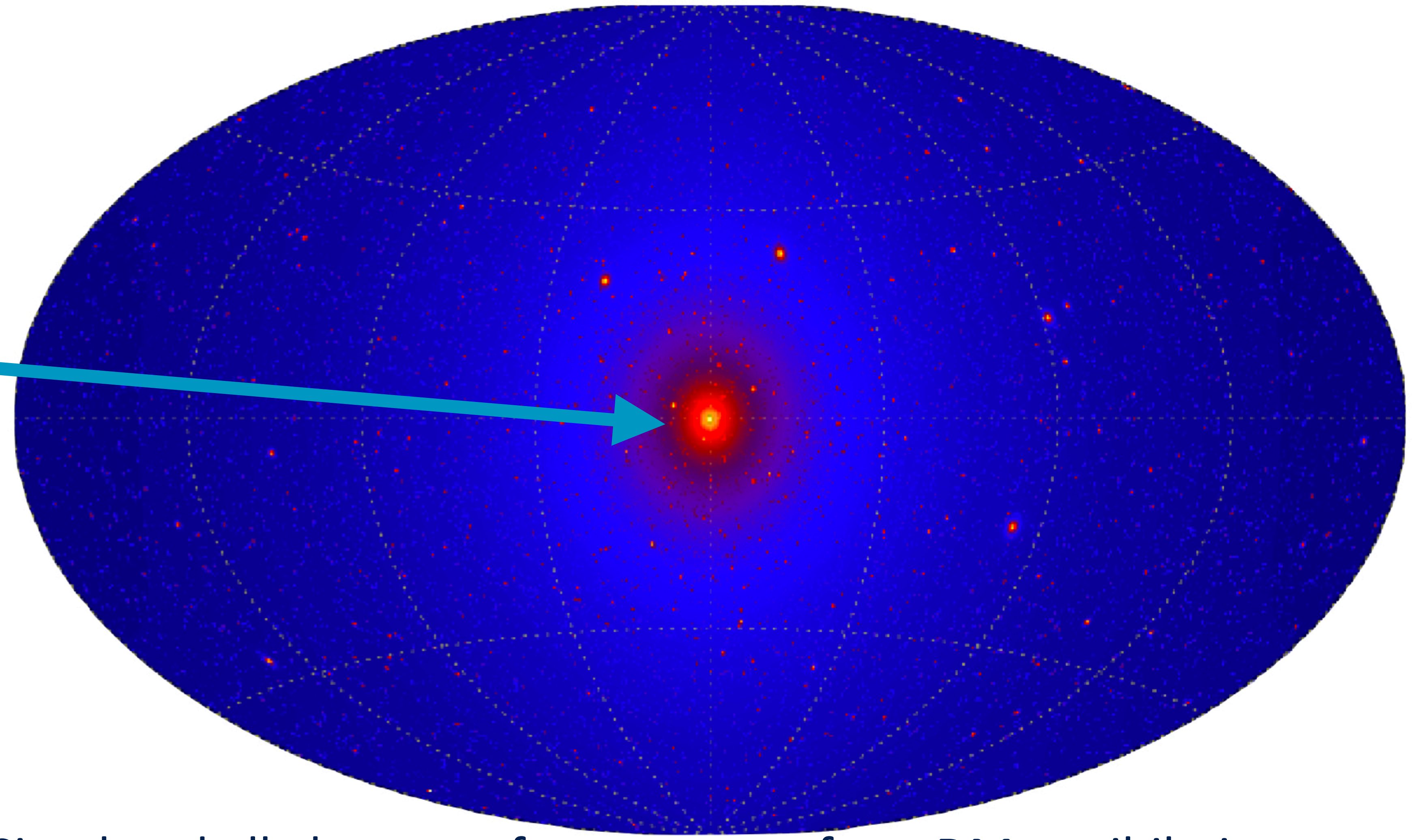
TeV DM particles: most energy deposited in **GeV-TeV final state** particles:

→High energy astronomy regime

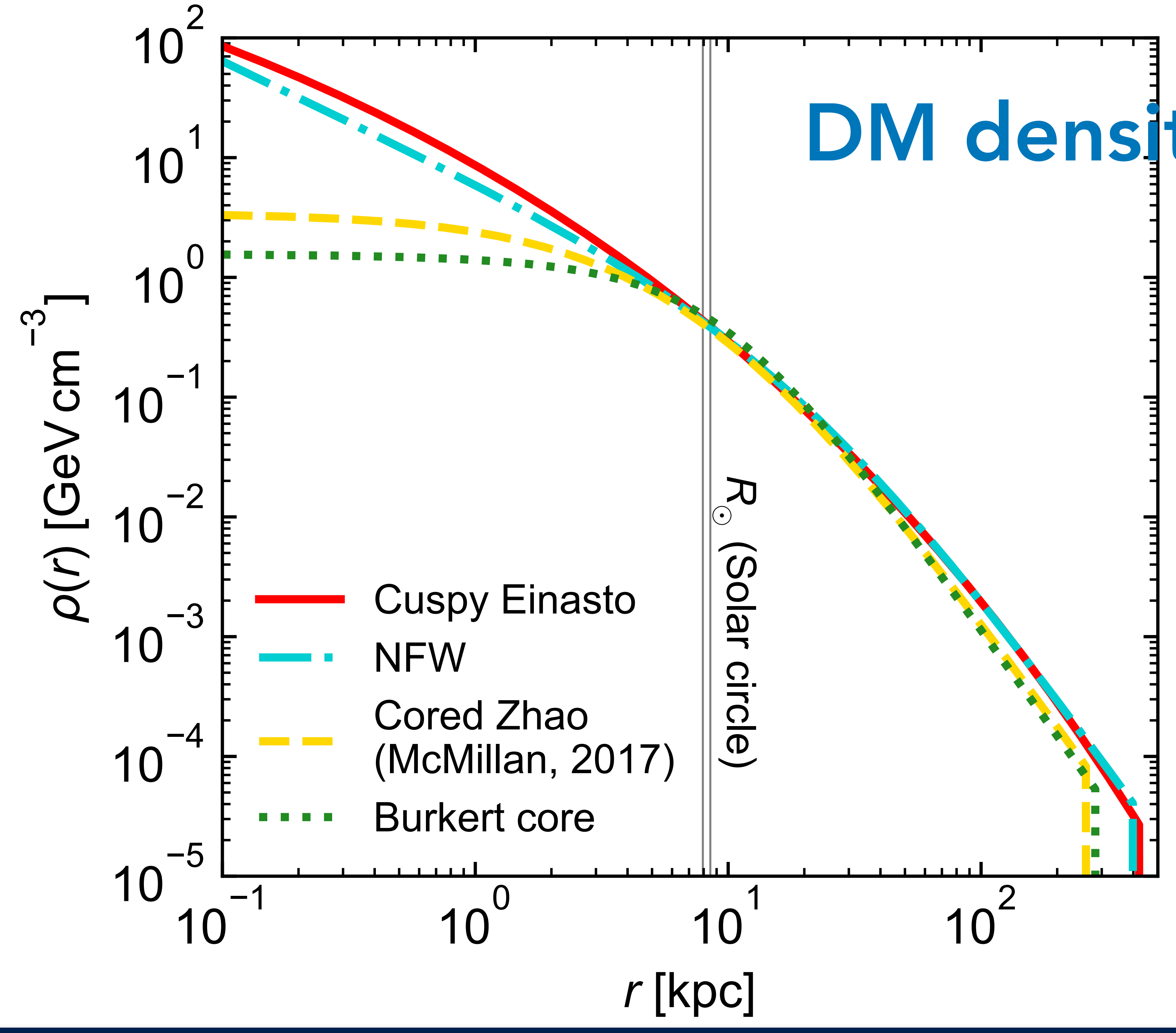
Observational targets

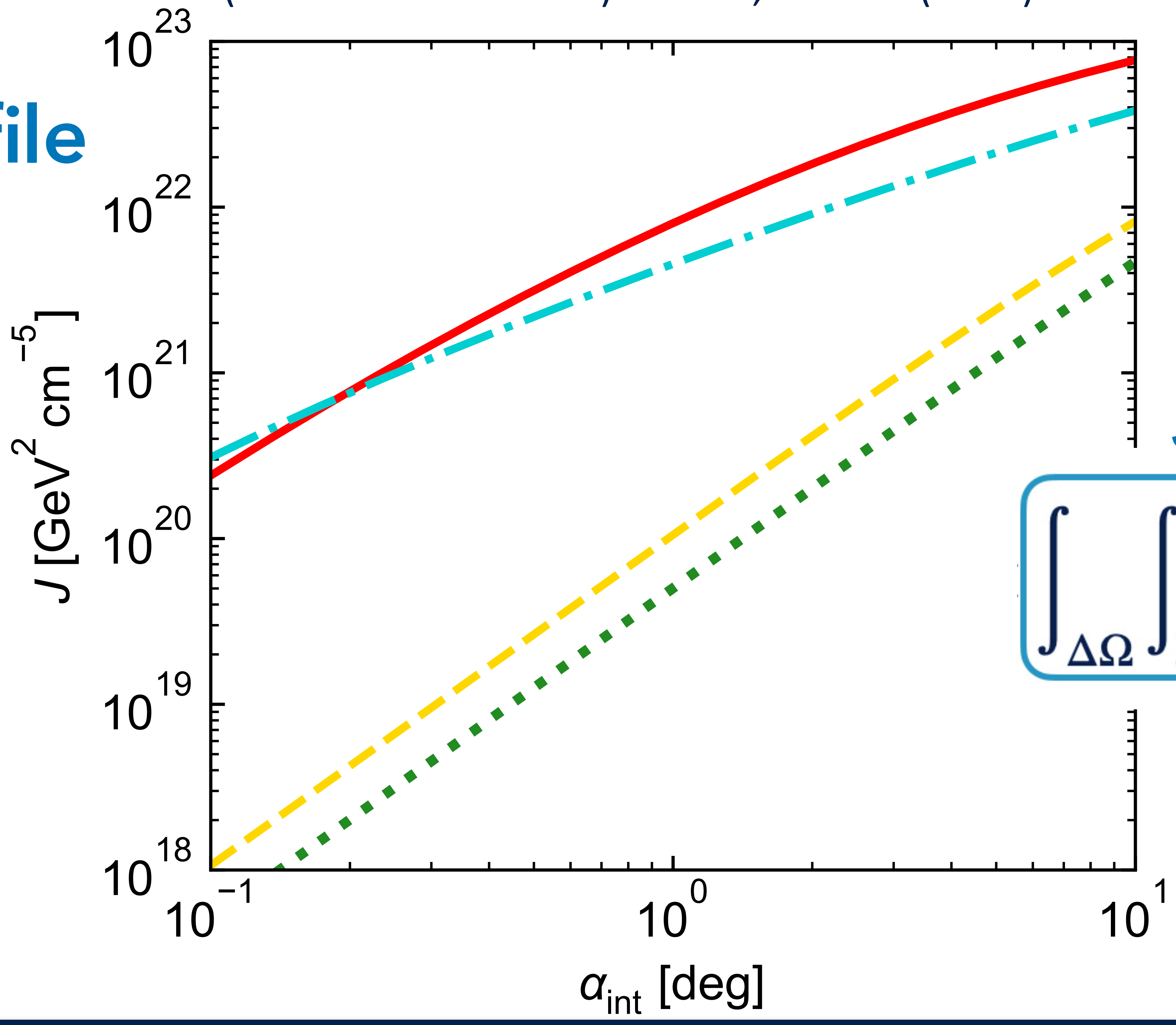
<u>Galactic Center and Halo</u>

- **The largest J-factor**
- Extended
- src confusion, diffuse bkg and **Cuspy/core differences in DM profiles**



Simulated all-sky map of gamma-rays from DM annihilation (Galactic coordinates) PRD 83, 023518 (2011)



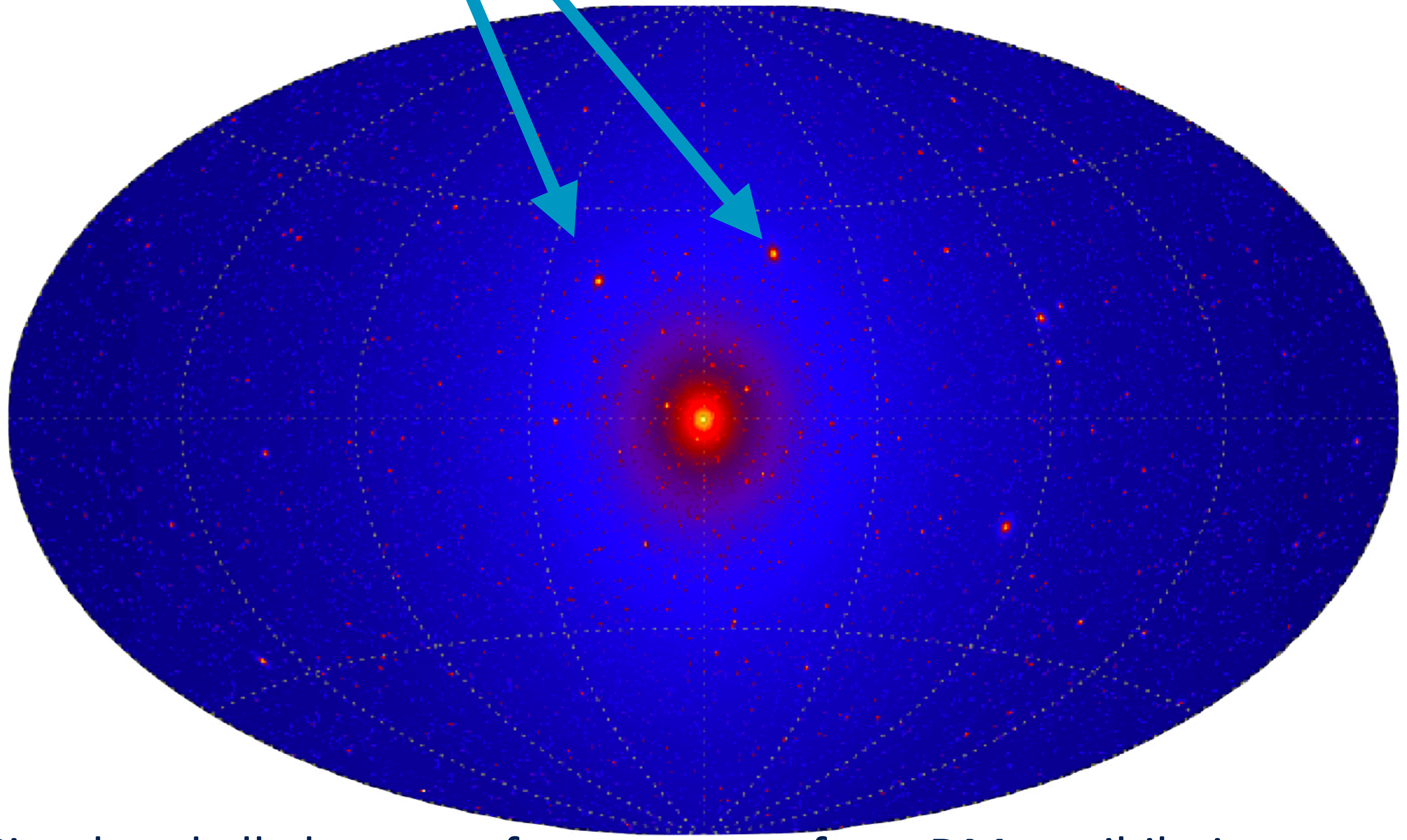


$$\int_{\Delta\Omega}\int_{los} ds\ \rho(s,\Omega)$$

Observational targets

Dwarf Galaxies (dSph)

- DM dominated system
  - less bkg, low J-factor,small extension
  - Lower uncertainties in J-factor



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J-factor

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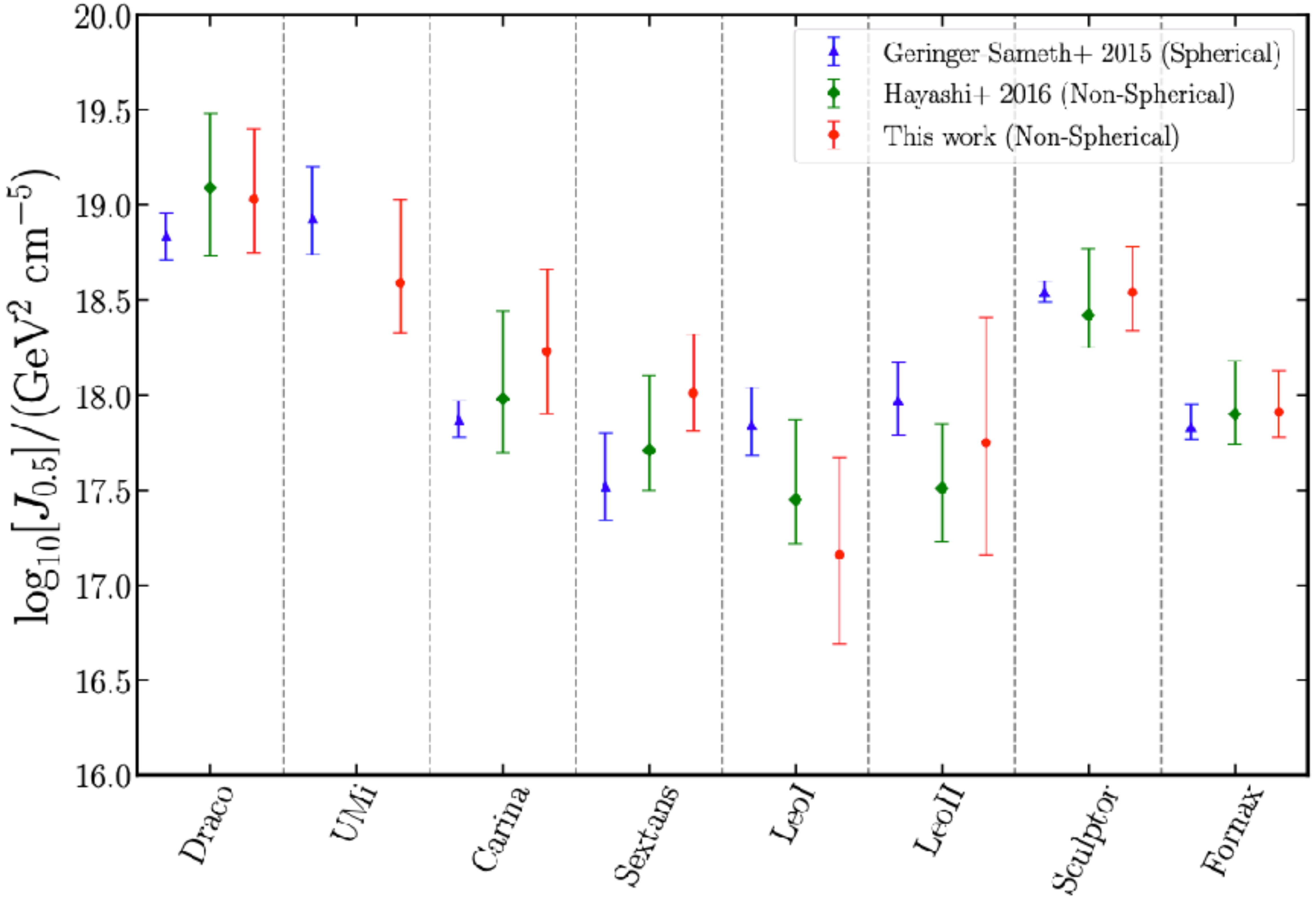
K. Hayashi et al (2020) ApJ 904 45

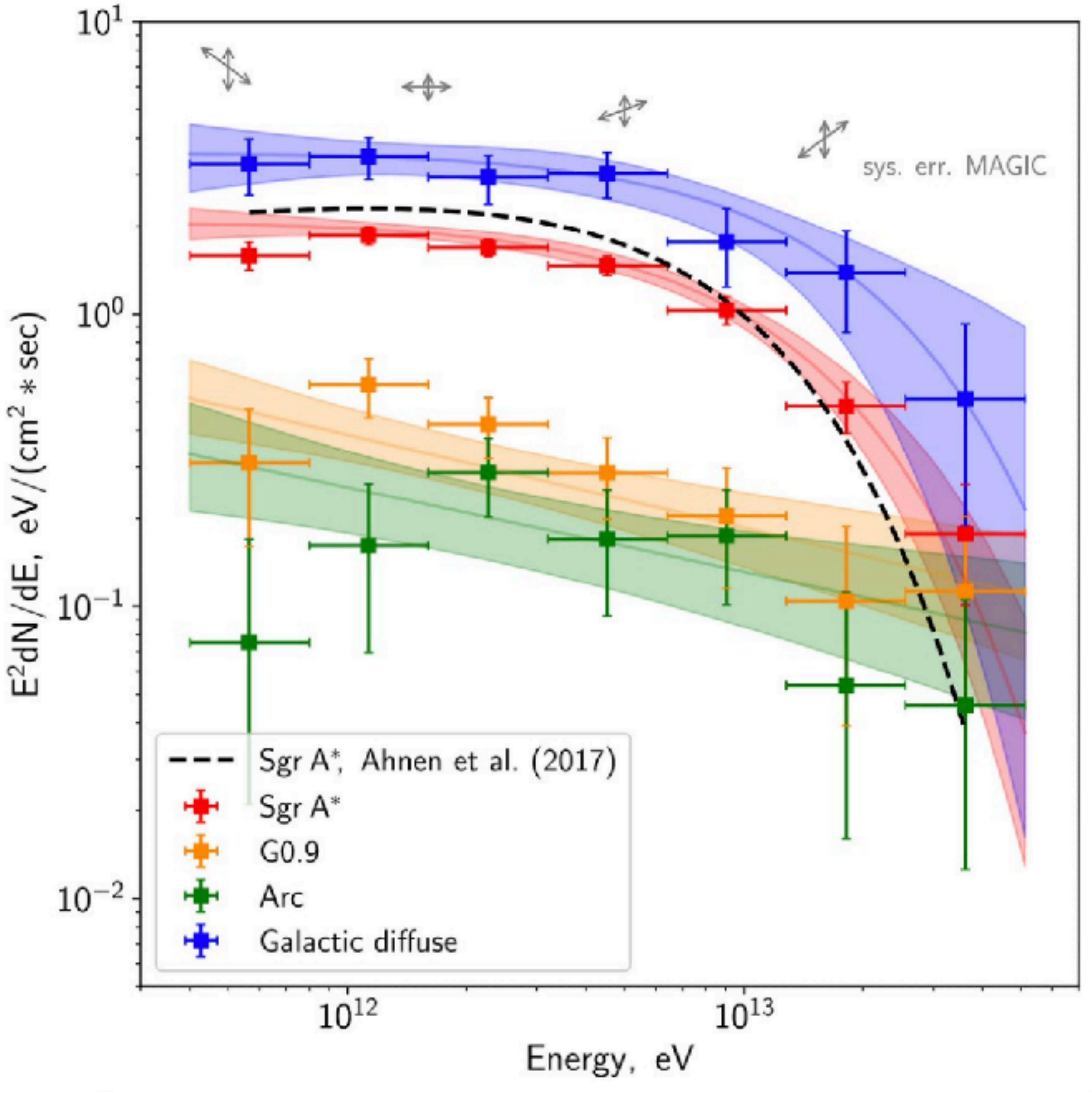


The Galactic Centre case

The Galactic Centre

The most complex source

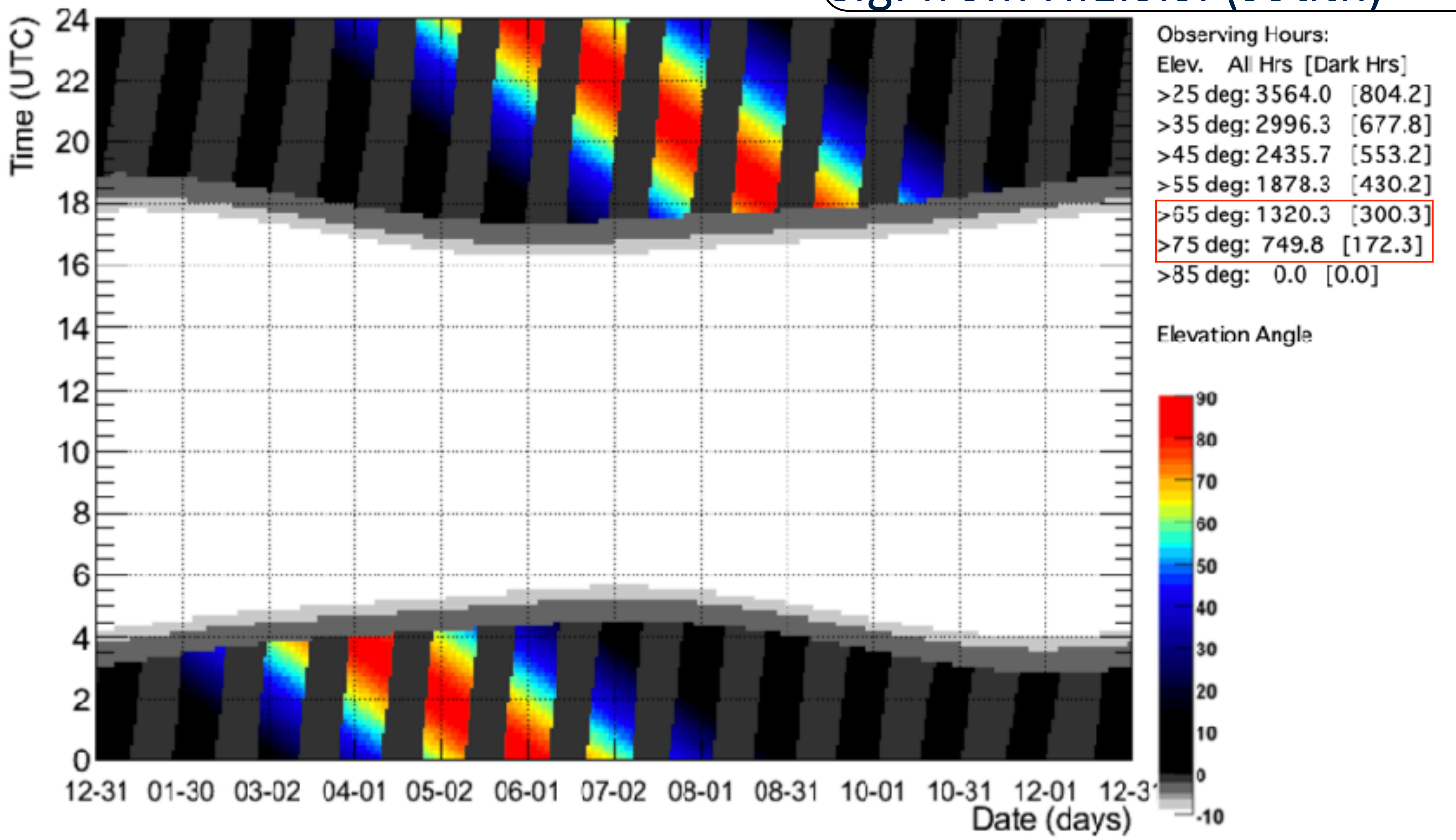
- many bright sources
- different obs. conditions between S and N
- the largest DM density expected



A&A 642, A190 (2020)

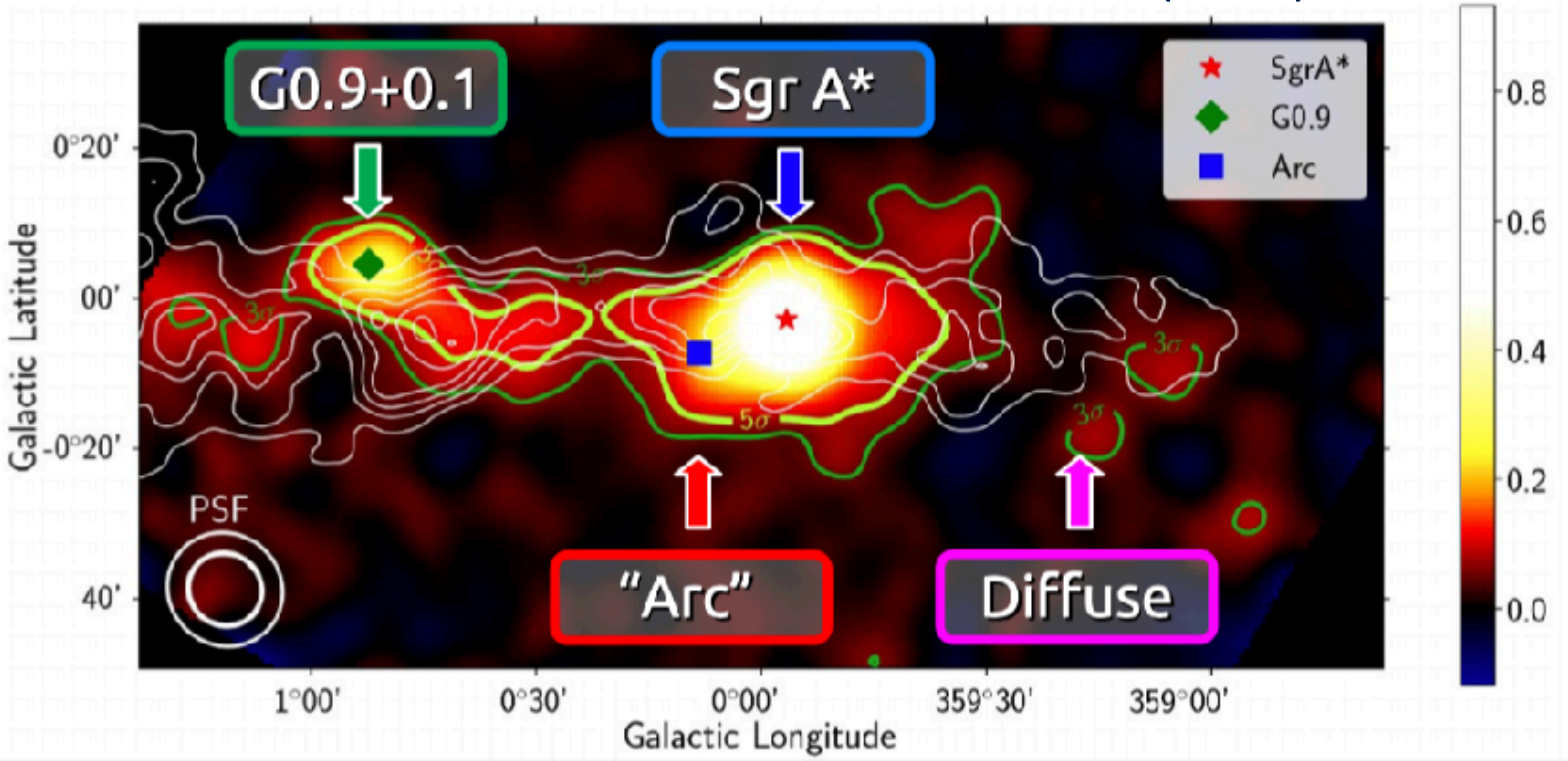
Galactic Centre

visible very close to the zenith
e.g. from H.E.S.S. (south)



http://tevcat.uchicago.edu

MAGIC collaboration A&A 642, A190 (2020)



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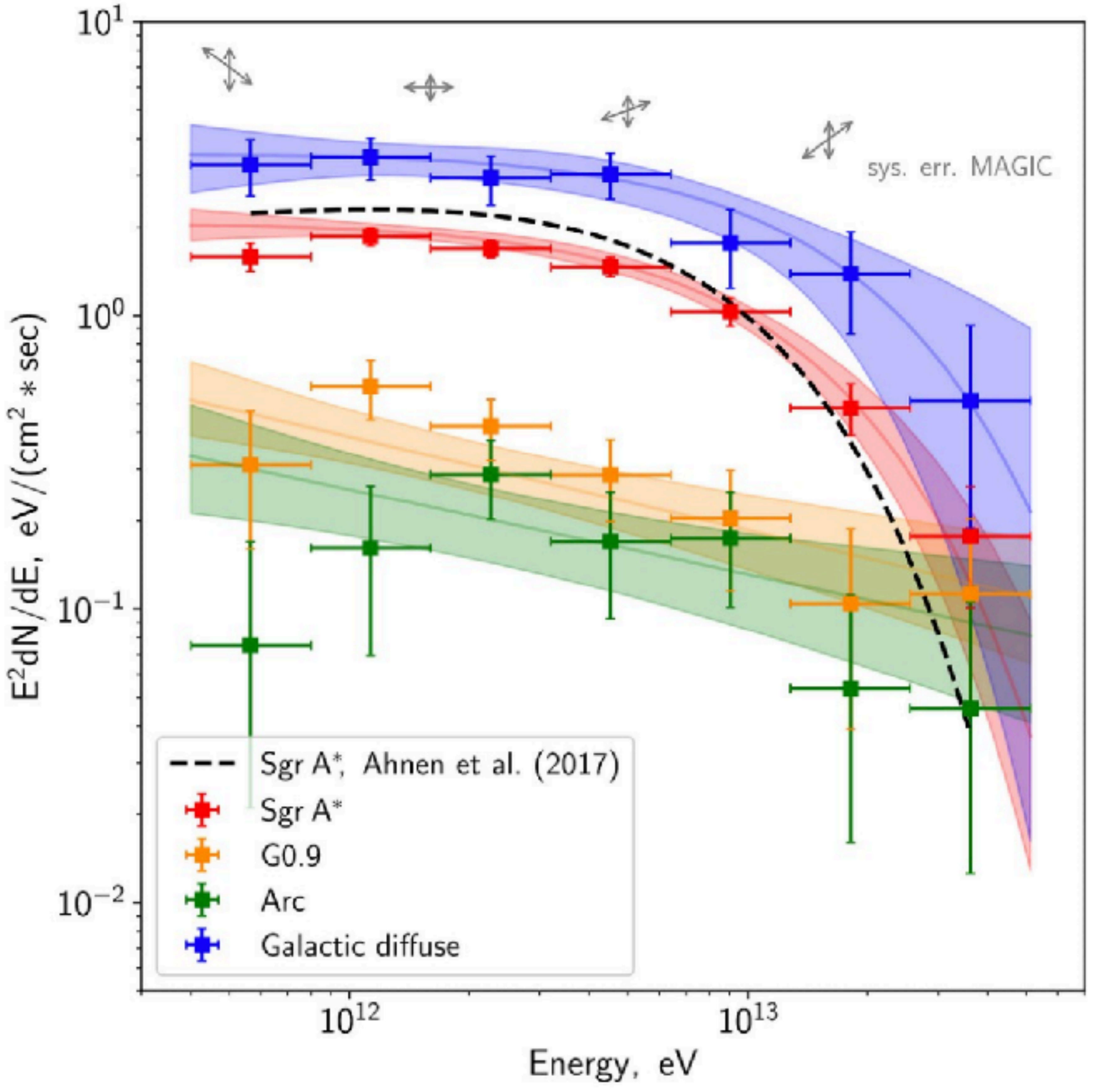

A&A 642, A190 (2020)

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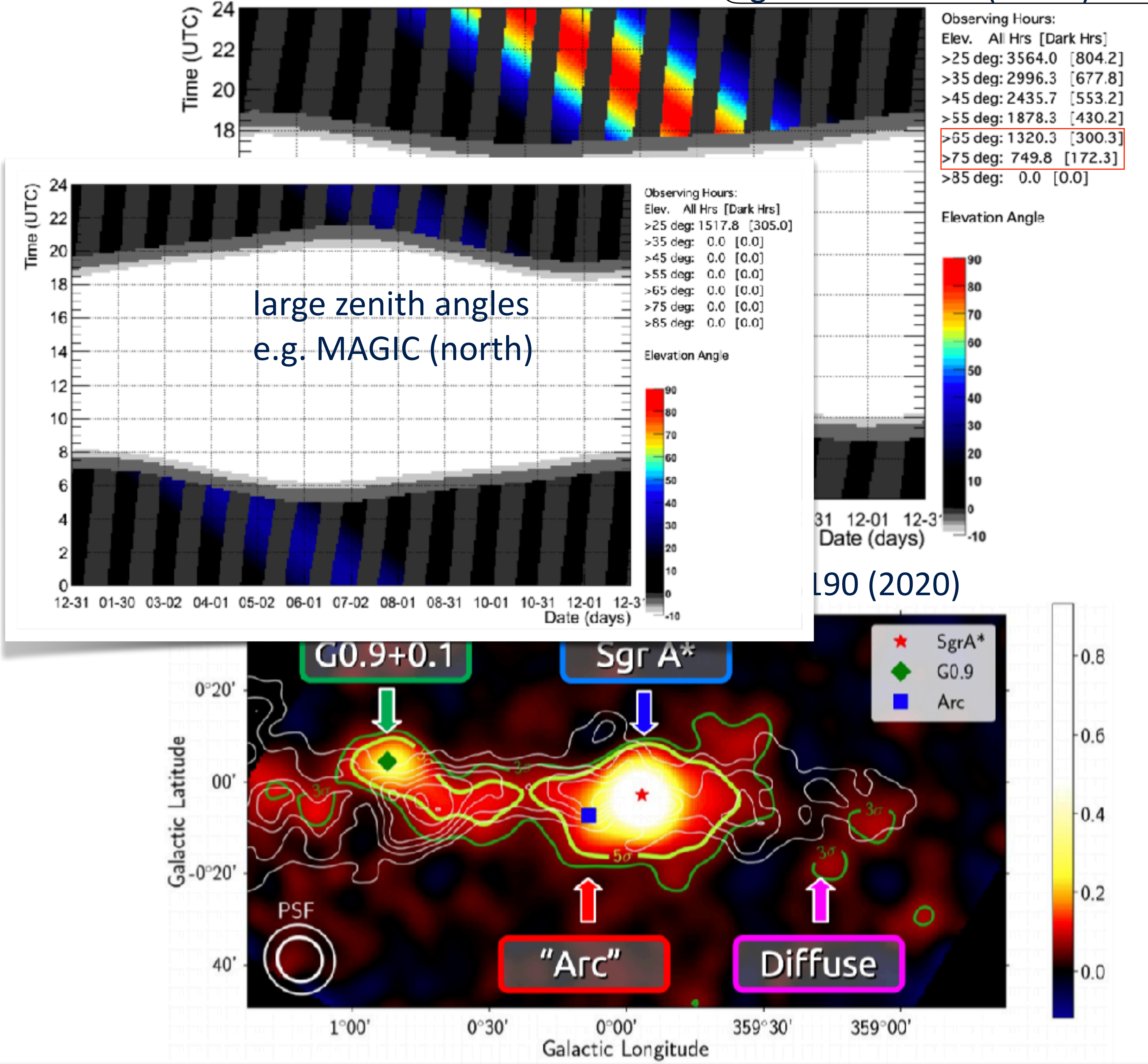


large zenith angles
e.g. MAGIC (north)

A&A 642, A190 (2020)

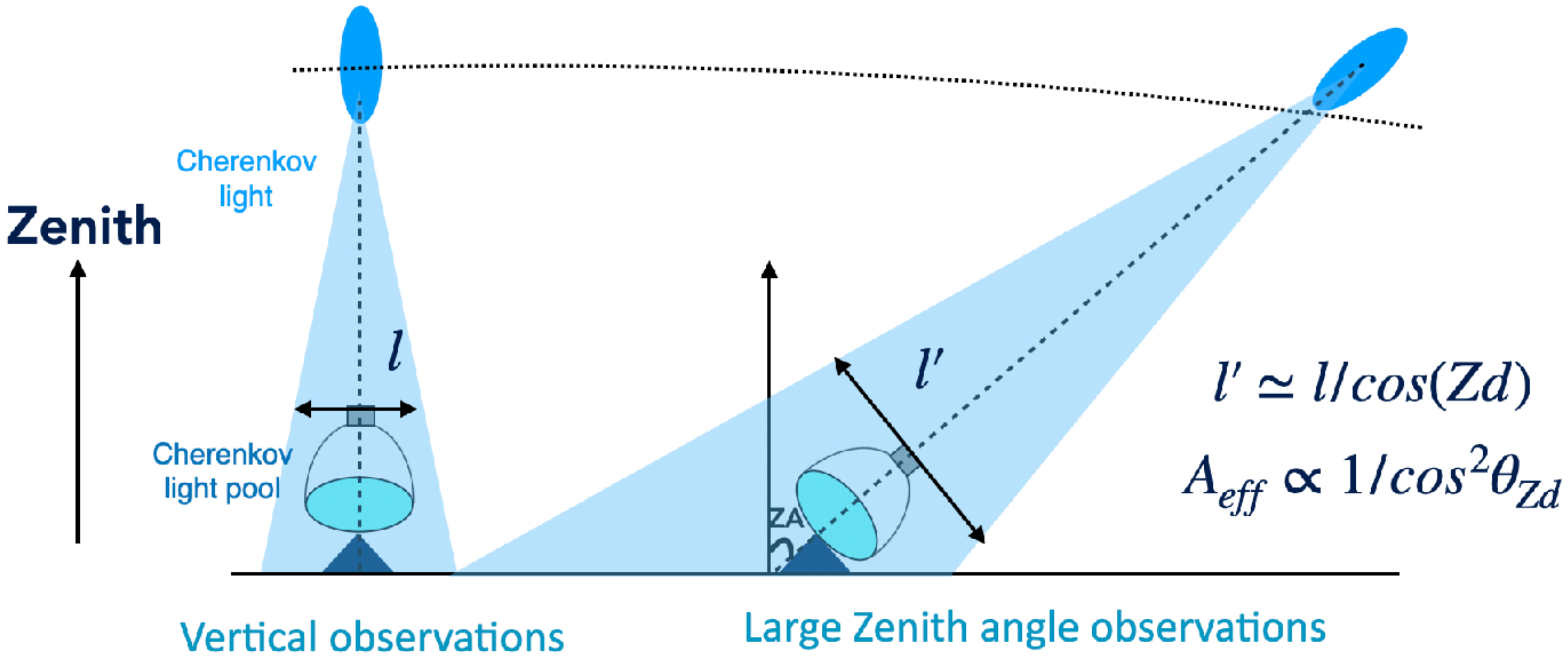
http://tevcat.uchicago.edu

The Galactic Centre

Key experimental fact:

- IACT performance depends on zenith angles
  - because of difference in a shower distance

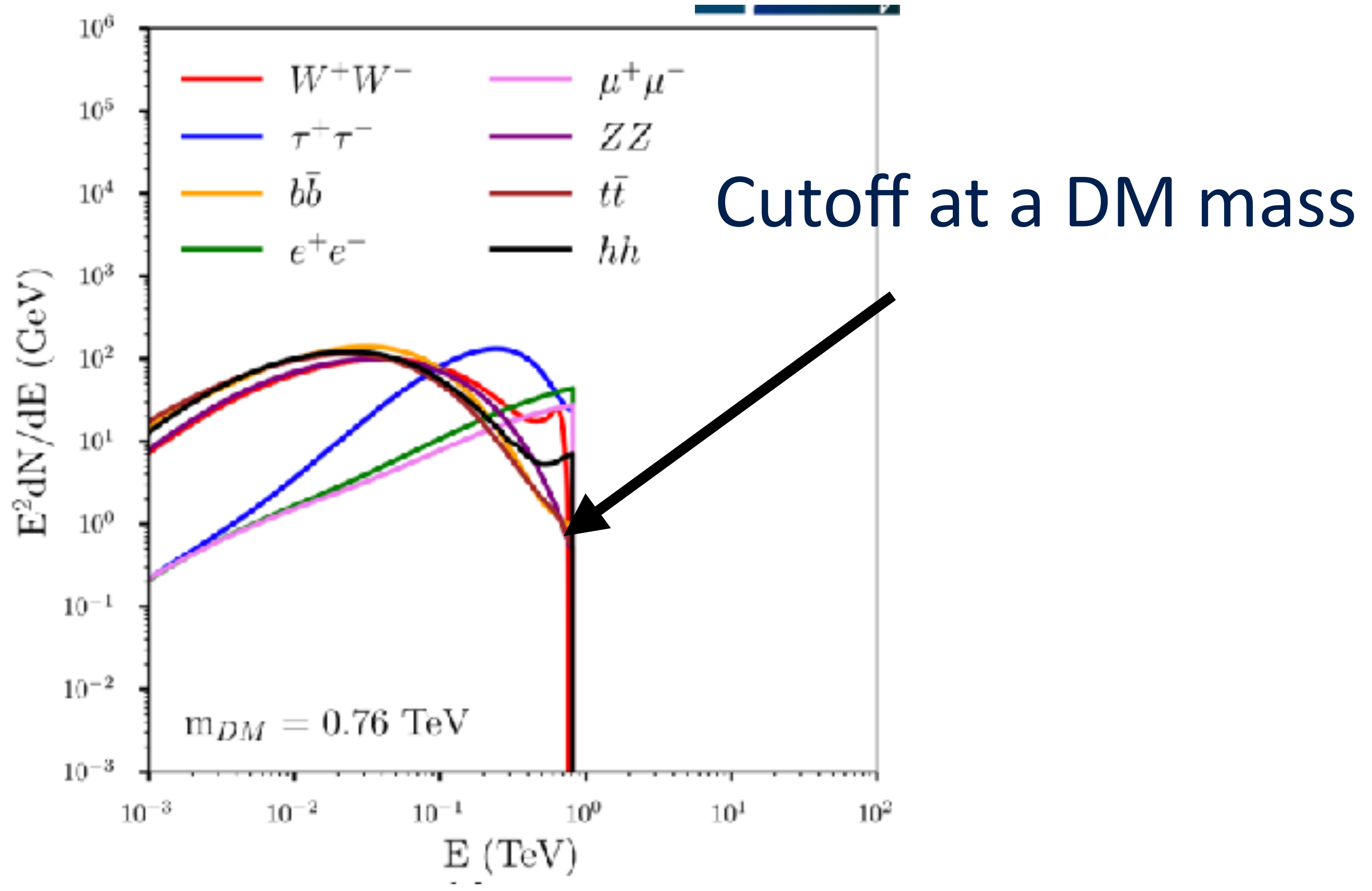
- Nominal setup: vertical observation
- Large zenith angle observation
  - energy threshold ↑
  - energy resolution ↑
  - **Effective collection area ↑**
    - good for higher energetic events



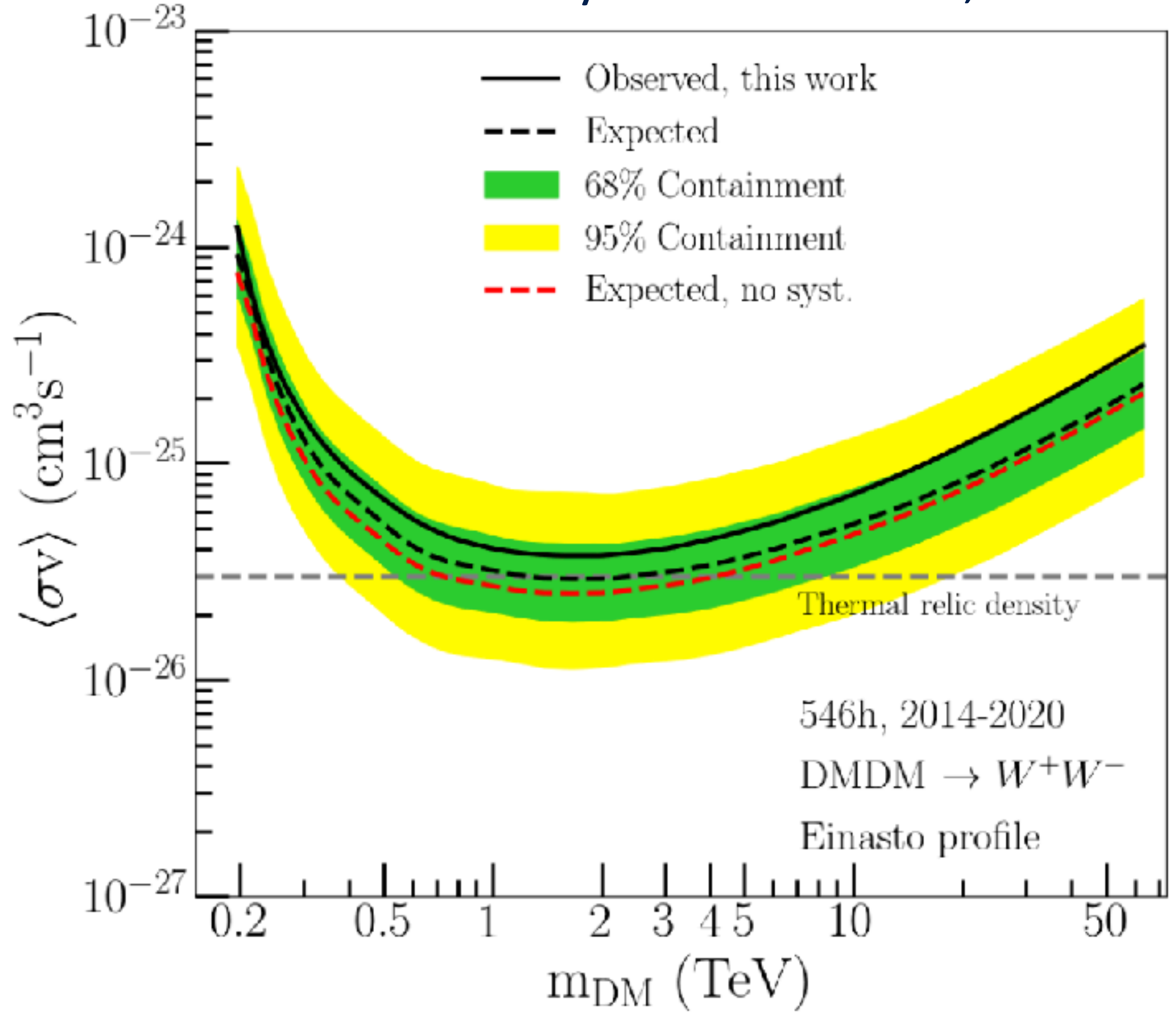
The Galactic Centre (Continuum spectra)

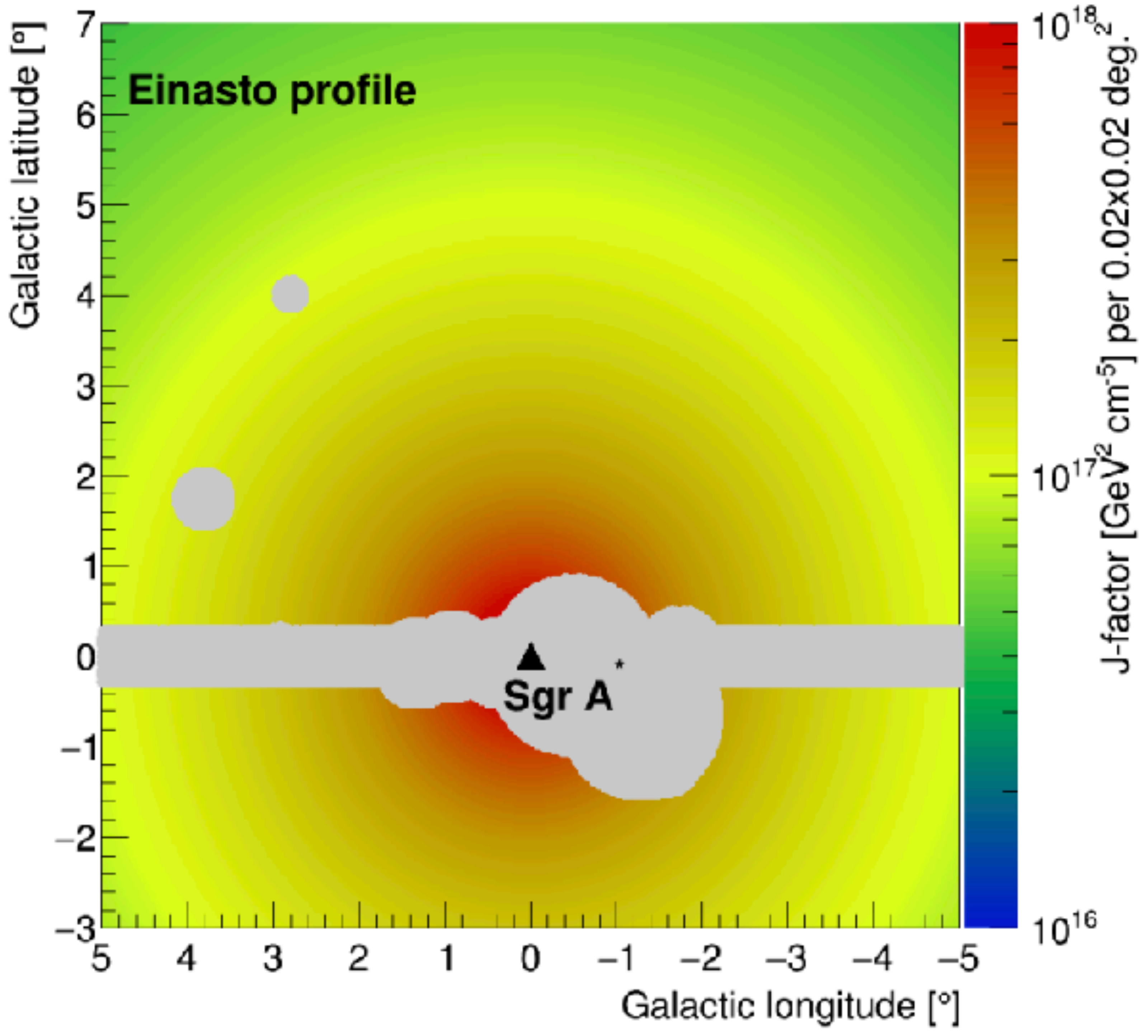
Continuum spectra

- Currently, only provided by H.E.S.S.
- Very close to the thermal cross-section
  - Good sensitivity with Einasto profile



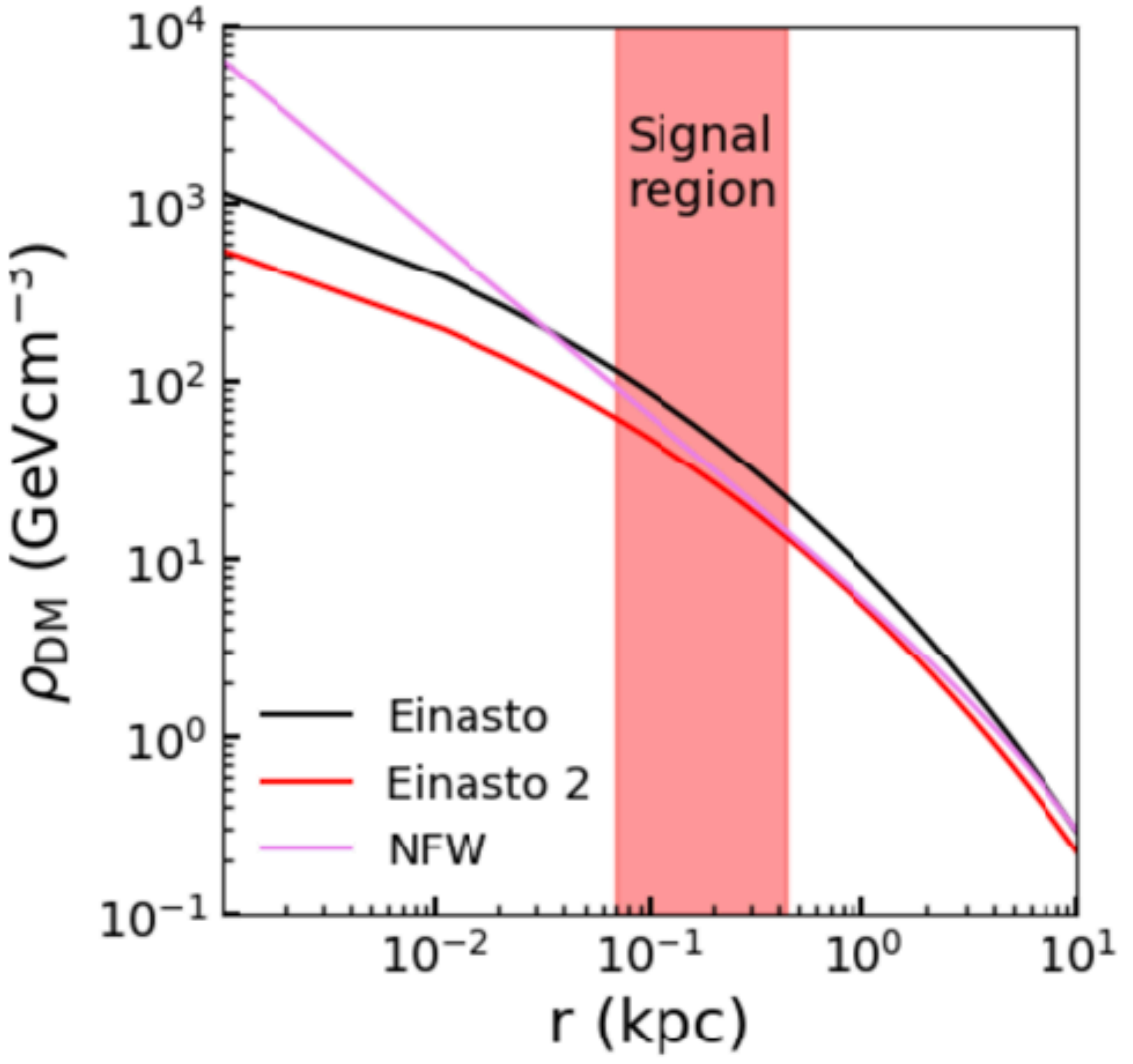
Phys. Rev. Lett. 129, 111101 (2022)



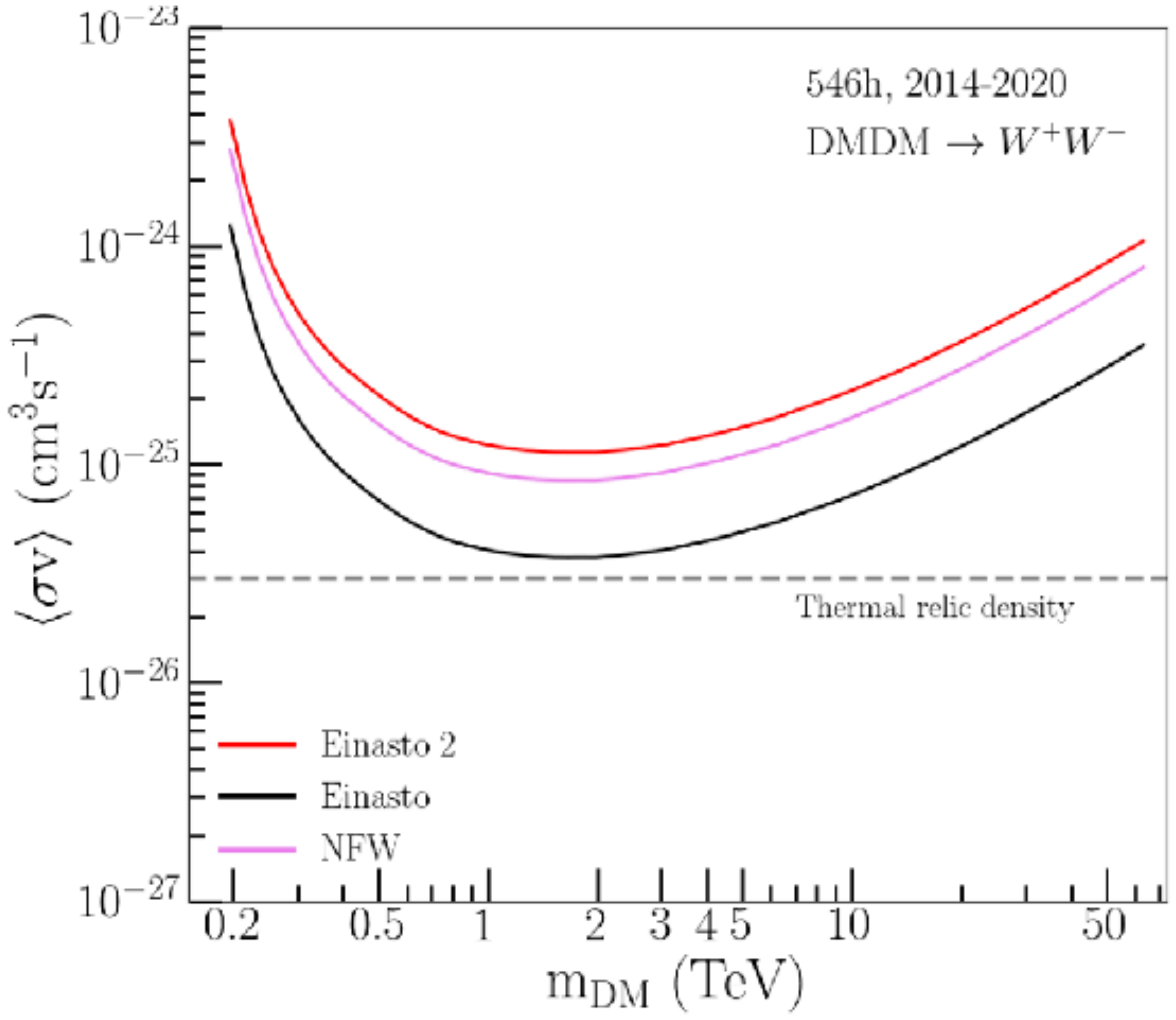


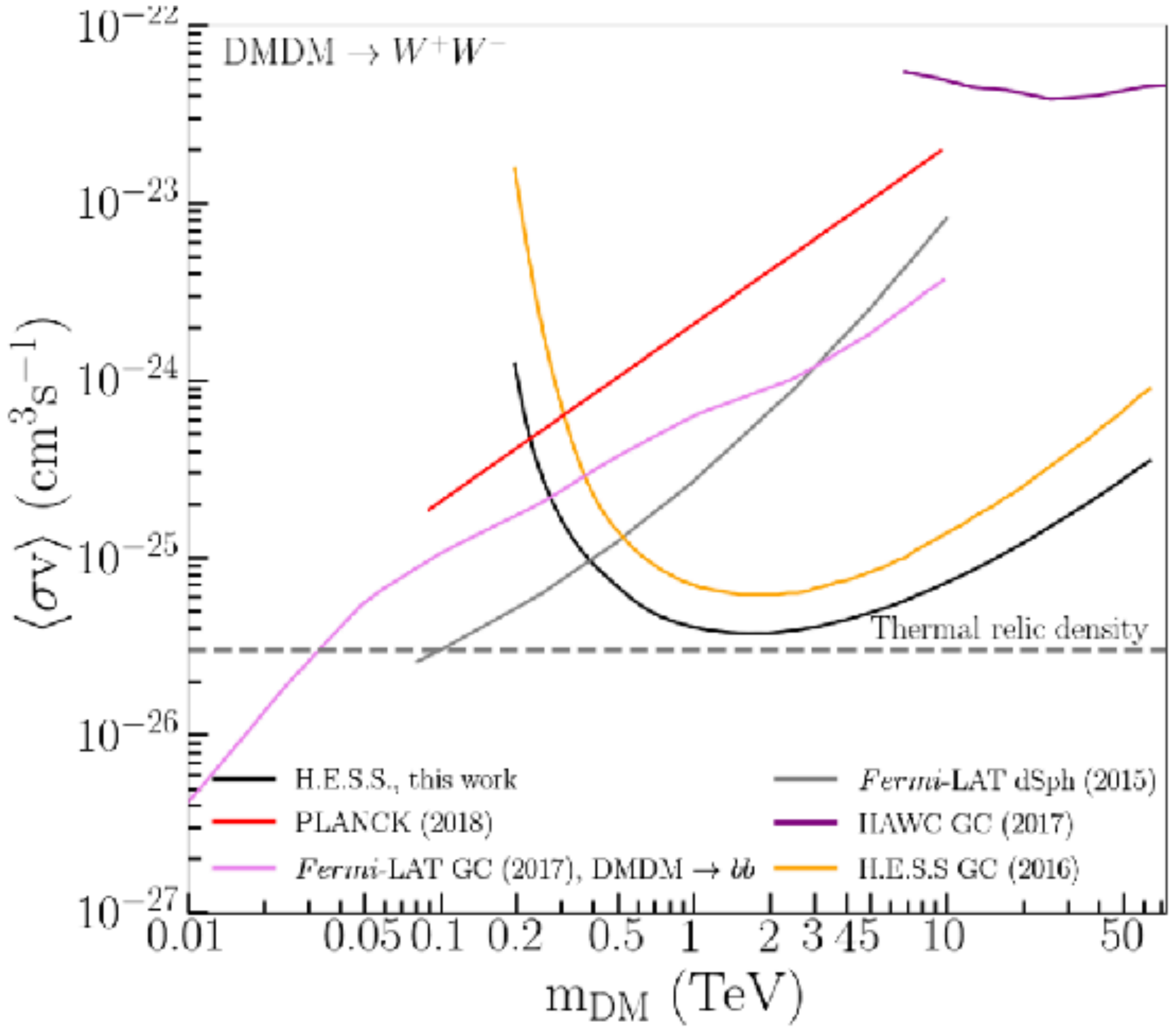
The Galactic Centre (Continuum spectra)

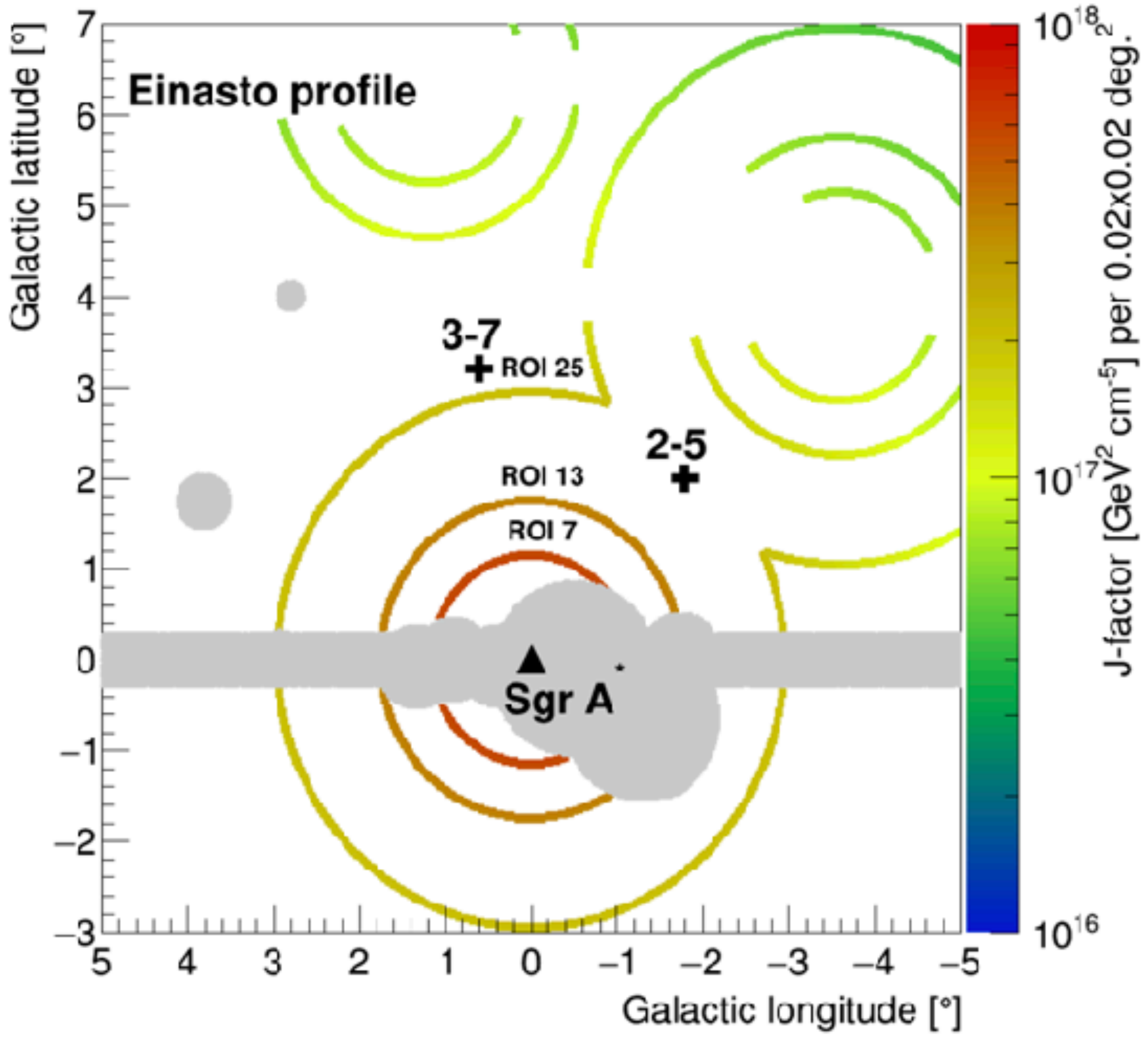
- key analysis technique: ON-OFF analysis
  - gradient of DM slope is used for signal extraction
    - make use of cuspy profile, difficult for cored one
  - assume isotropic background and foreground components



$$\mathcal{L}_{ij}(\mathbf{N}^{S},\mathbf{N}^{B}|\mathbf{N}_{ON},\mathbf{N}_{OFF}) = \frac{[\beta_{ij}(N^{S}_{ij}+N^{B}_{ij})]^{N_{ON,ij}}}{N_{ON,ij}!} e^{-\beta_{ij}(N^{S}_{ij}+N^{B}_{ij})} \frac{[\beta_{ij}(N^{S'}_{ij}+N^{B}_{ij})]^{N_{OFF,ij}}}{N_{OFF,ij}!} e^{-\beta_{ij}(N^{S'}_{ij}+N^{B}_{ij})} e^{-\frac{(1-\beta_{ij})^2}{2\sigma^2_{\beta_{ij}}}}$$

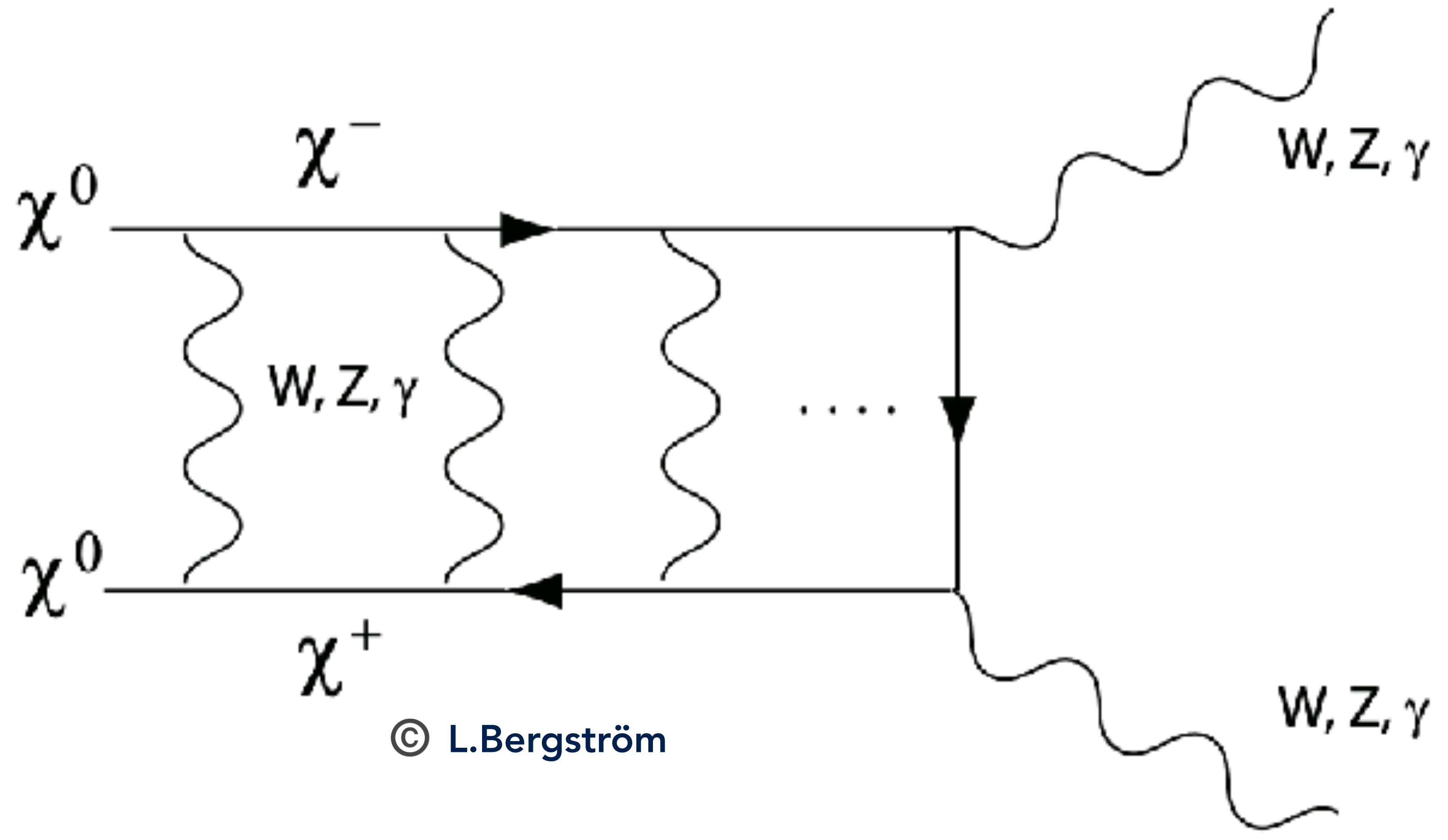


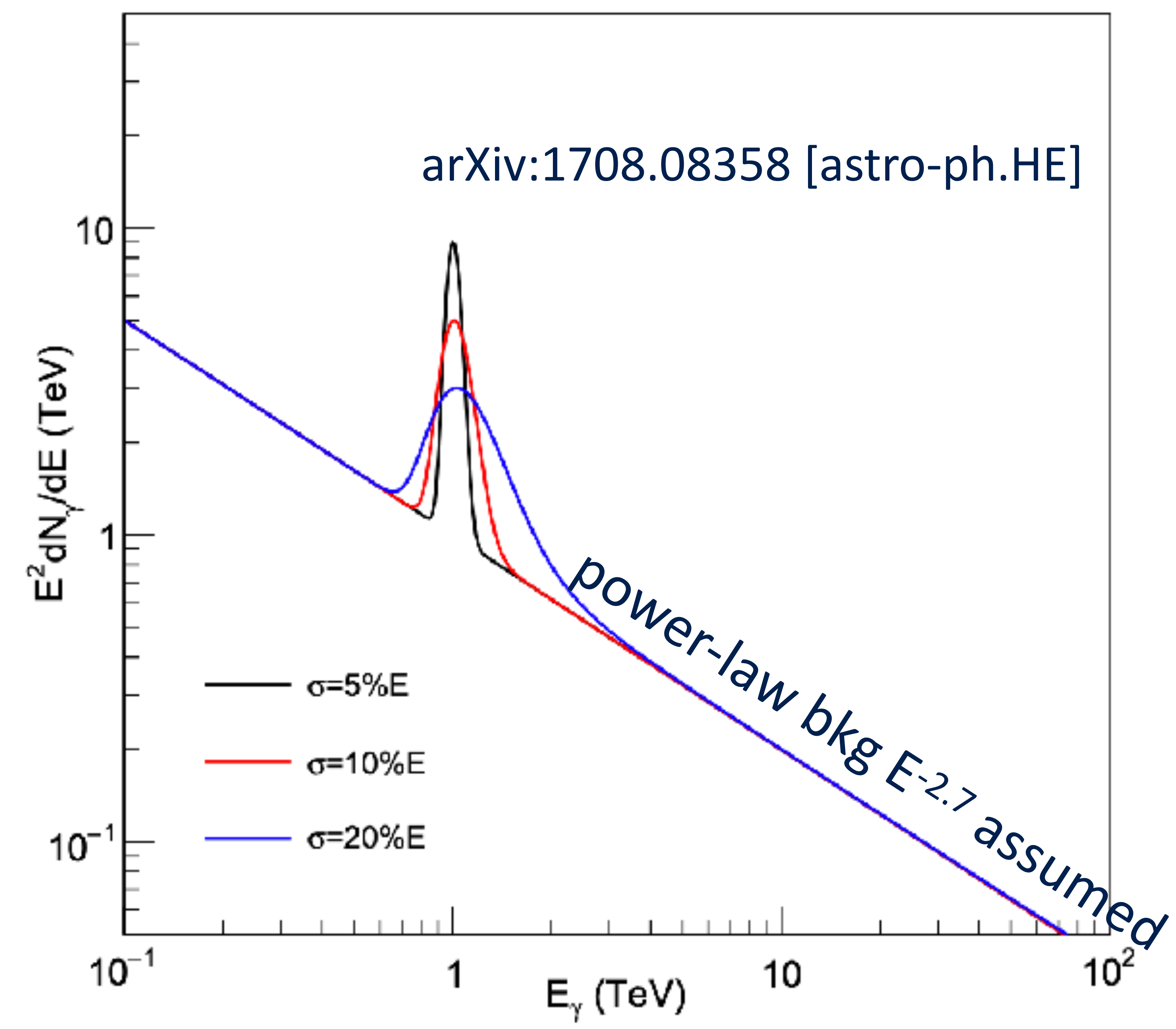


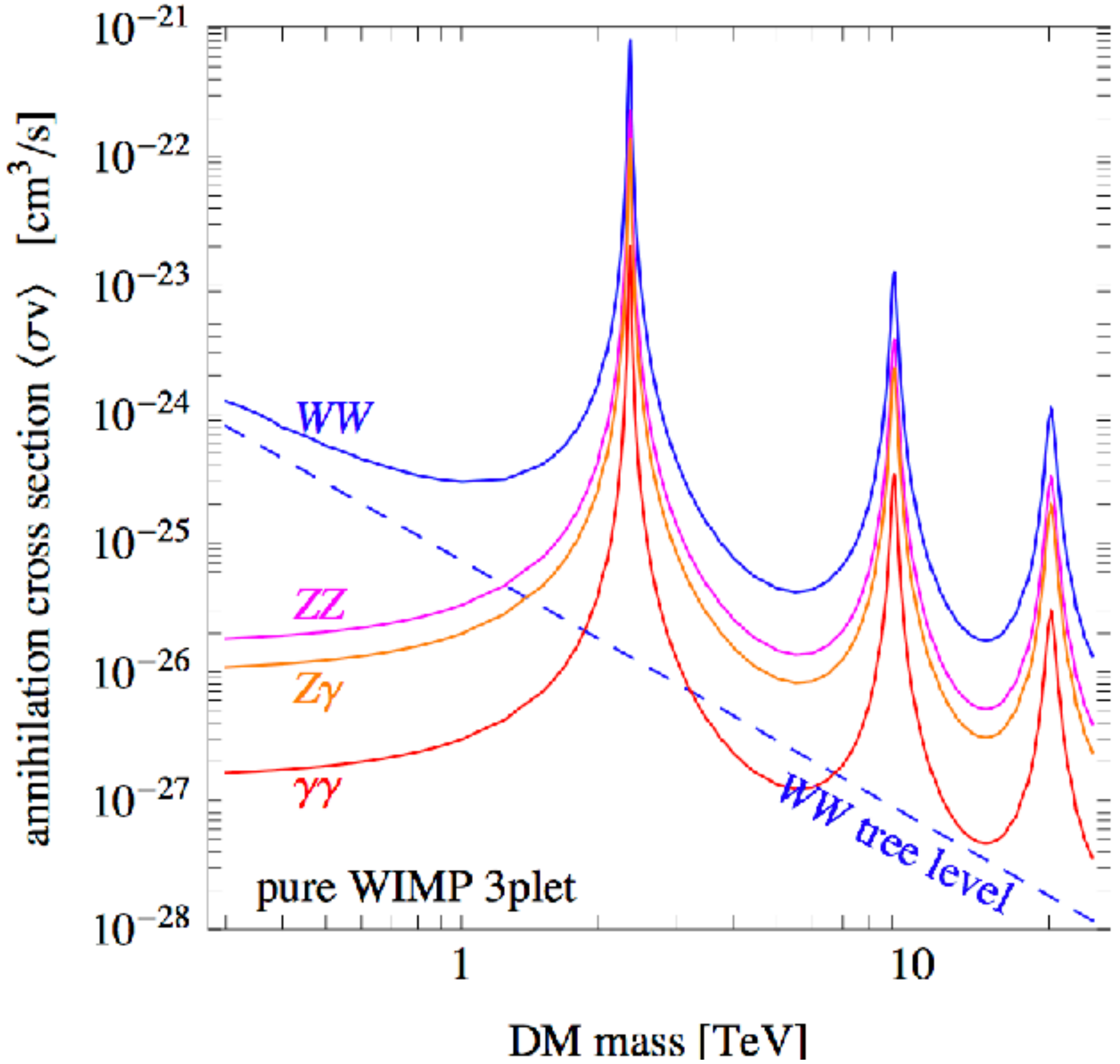


The Galactic Centre (Line search)

- clear signal, no contamination
- less flux expected than continuum spectra, in general
  - due to loop-suppression
- Some heavy DM (e.g. SUSY) models enhance their annihilation rate
  - Sommerfeld enhancement





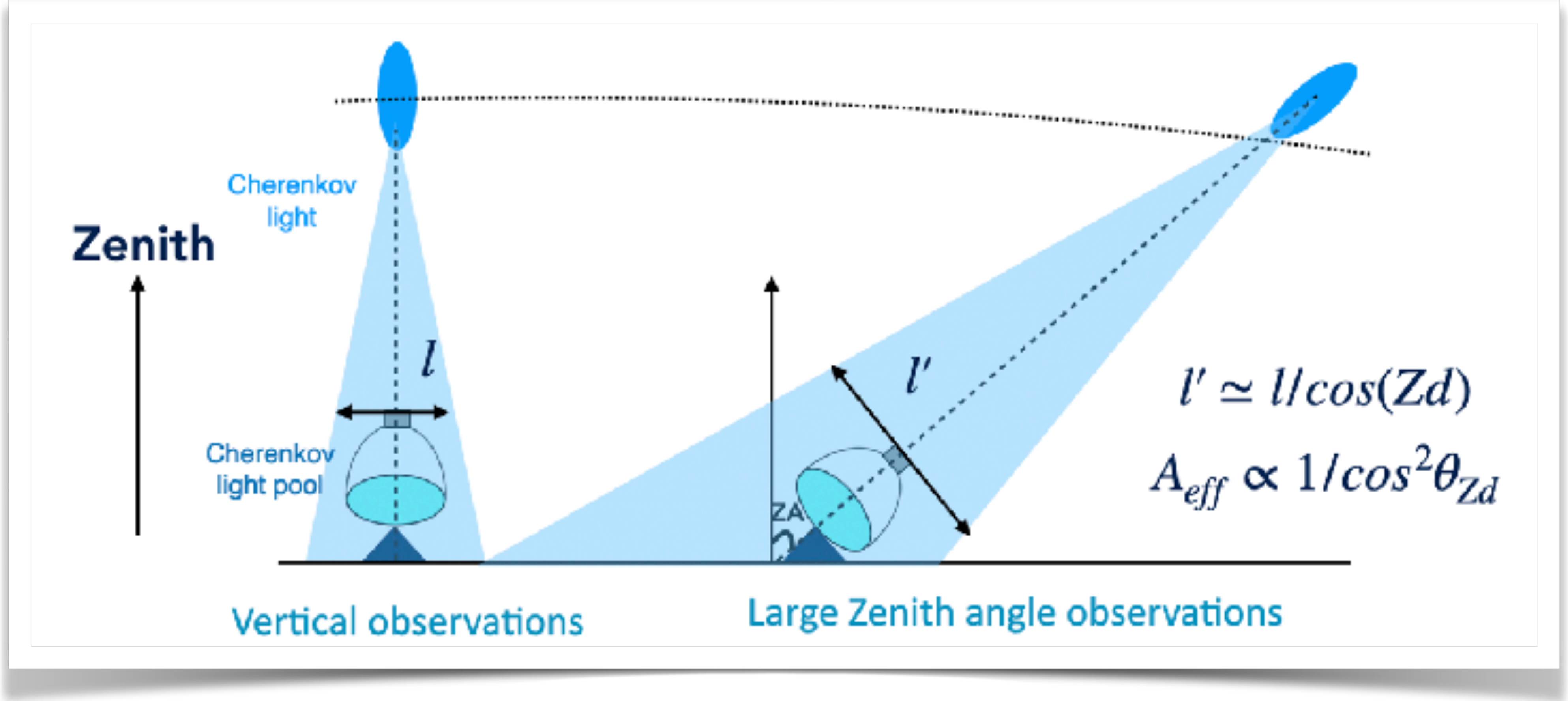


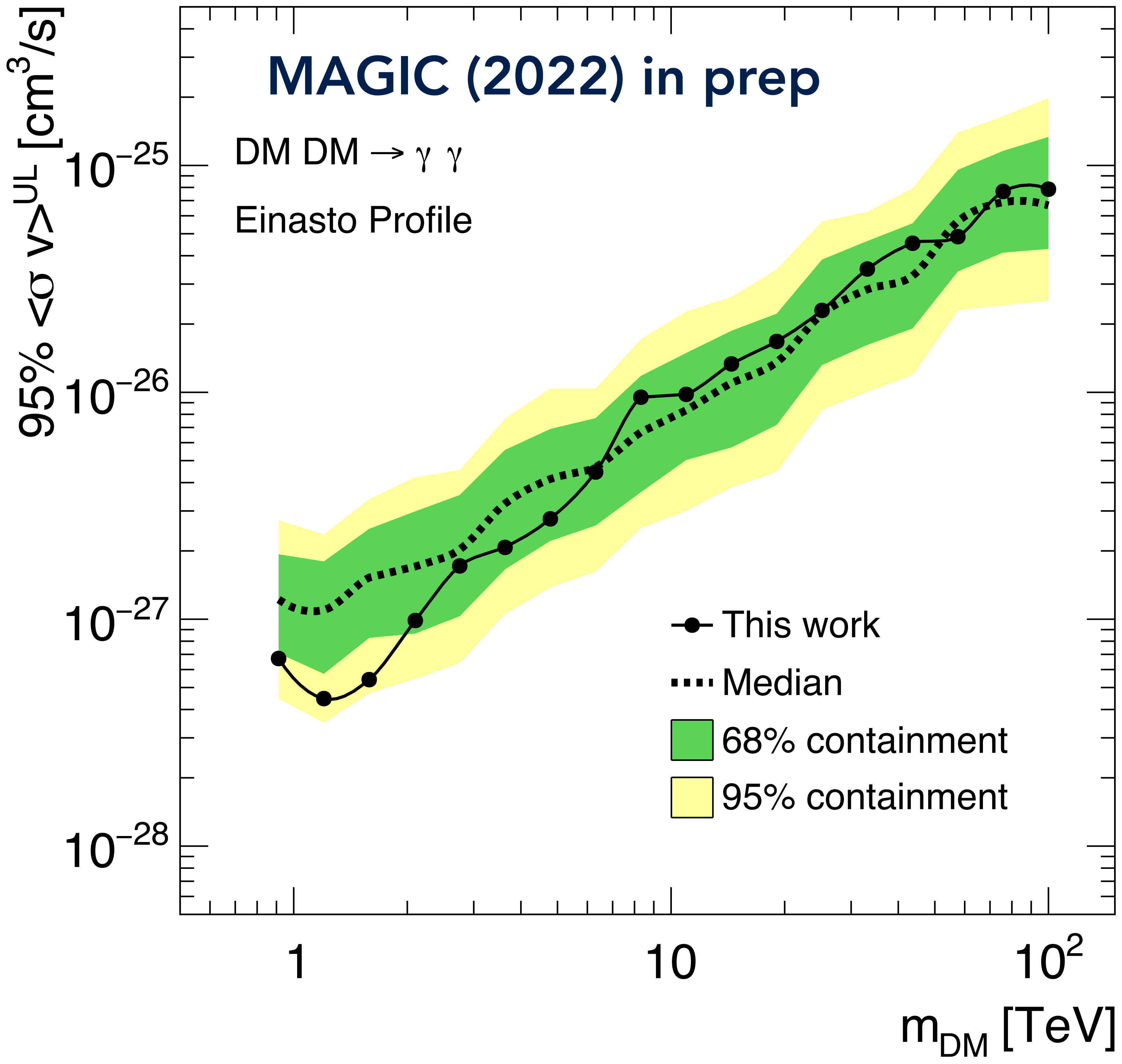
J. Hisano, S. Matsumoto, M. M. Nojiri and O. Saito 2005
M. Cirelli, N. Fornengo and A. Strumia (2006)
H. E.S.S. collaboration JCAP11(2018)

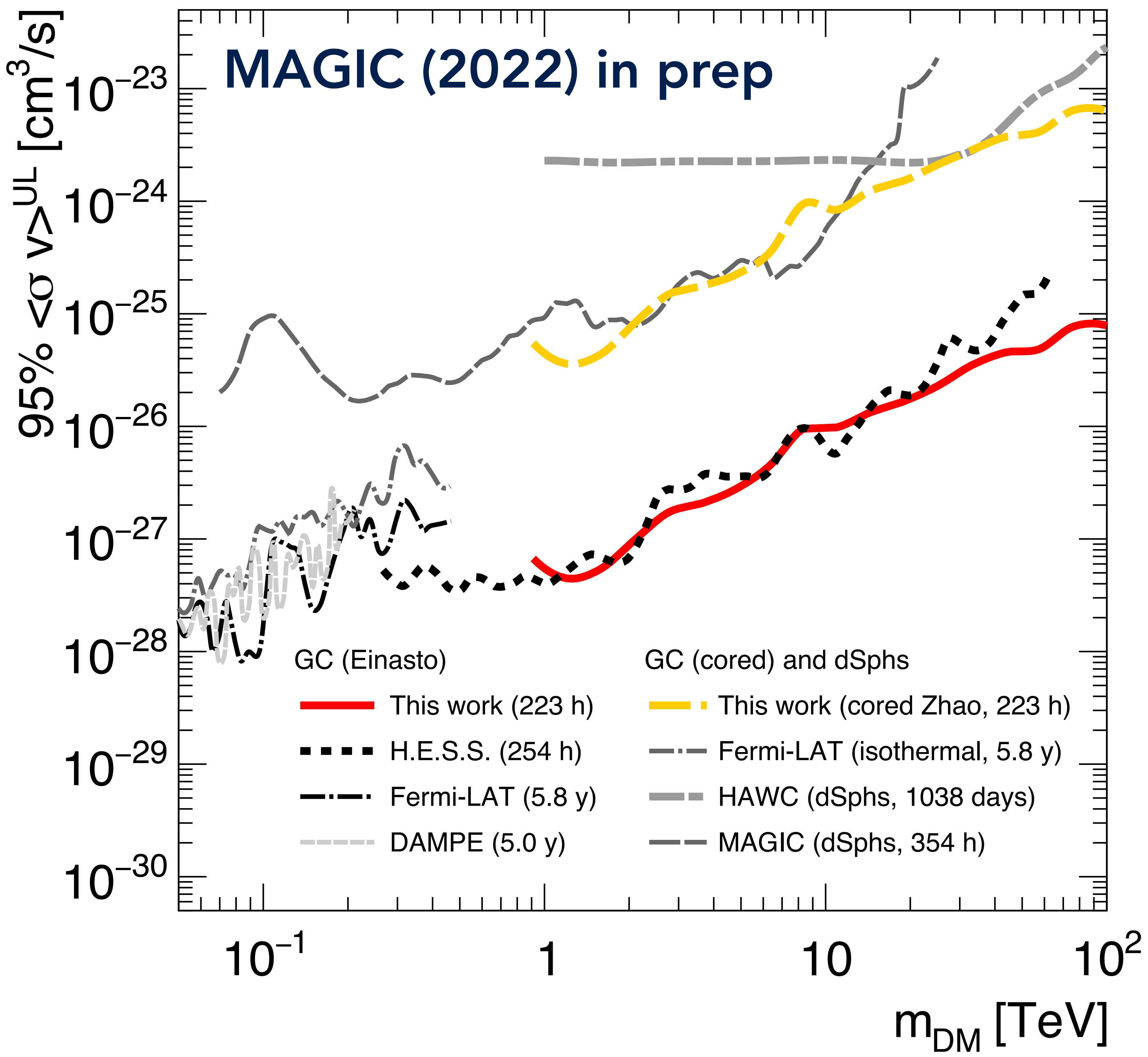
The Galactic Centre (Line search)

H.E.S.S. (cuspy) and MAGIC (core and cuspy)

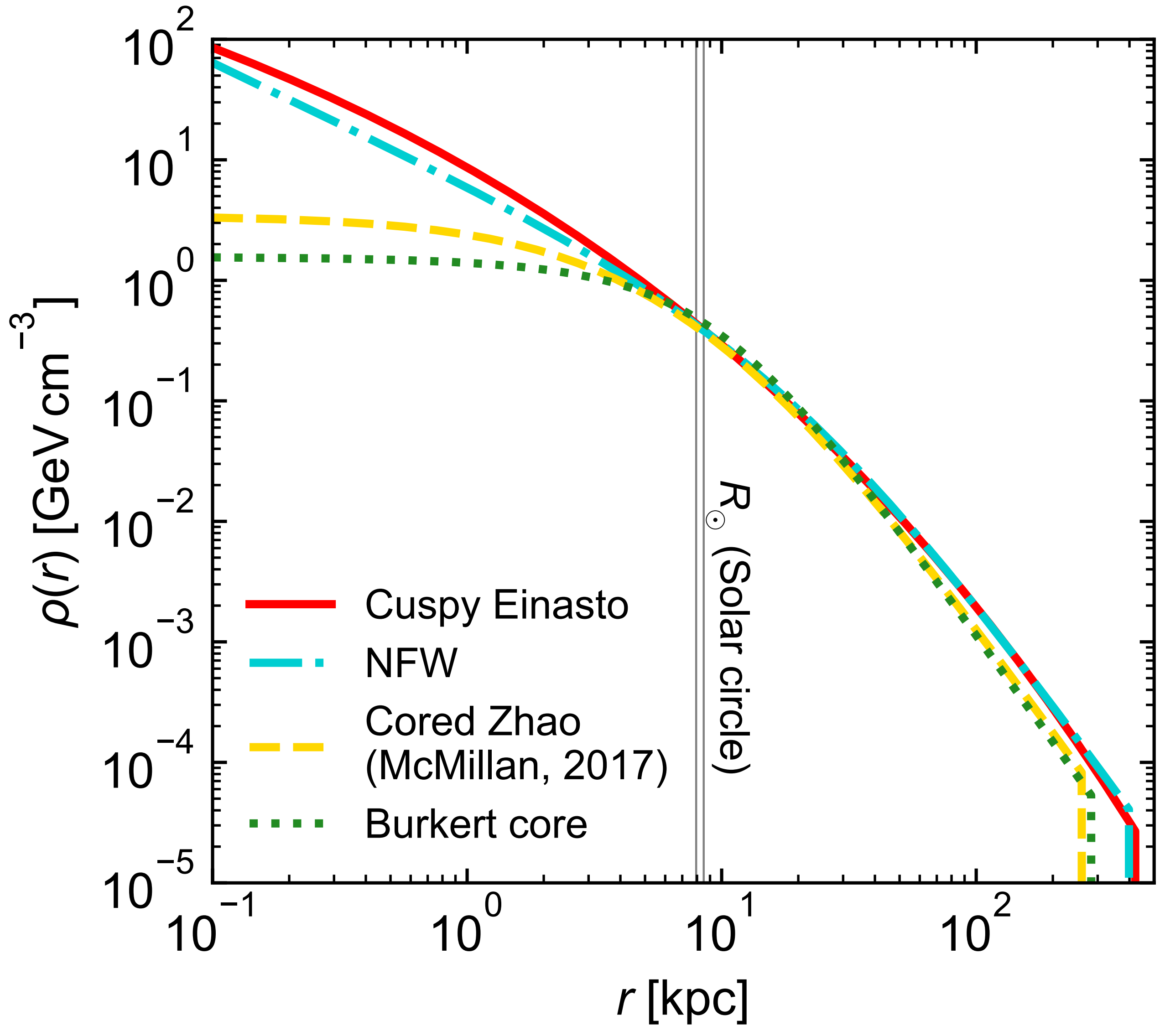
- MAGIC shows the best sensitivity beyond about 10 TeV (cuspy)
- comparable results with dwarf (core)



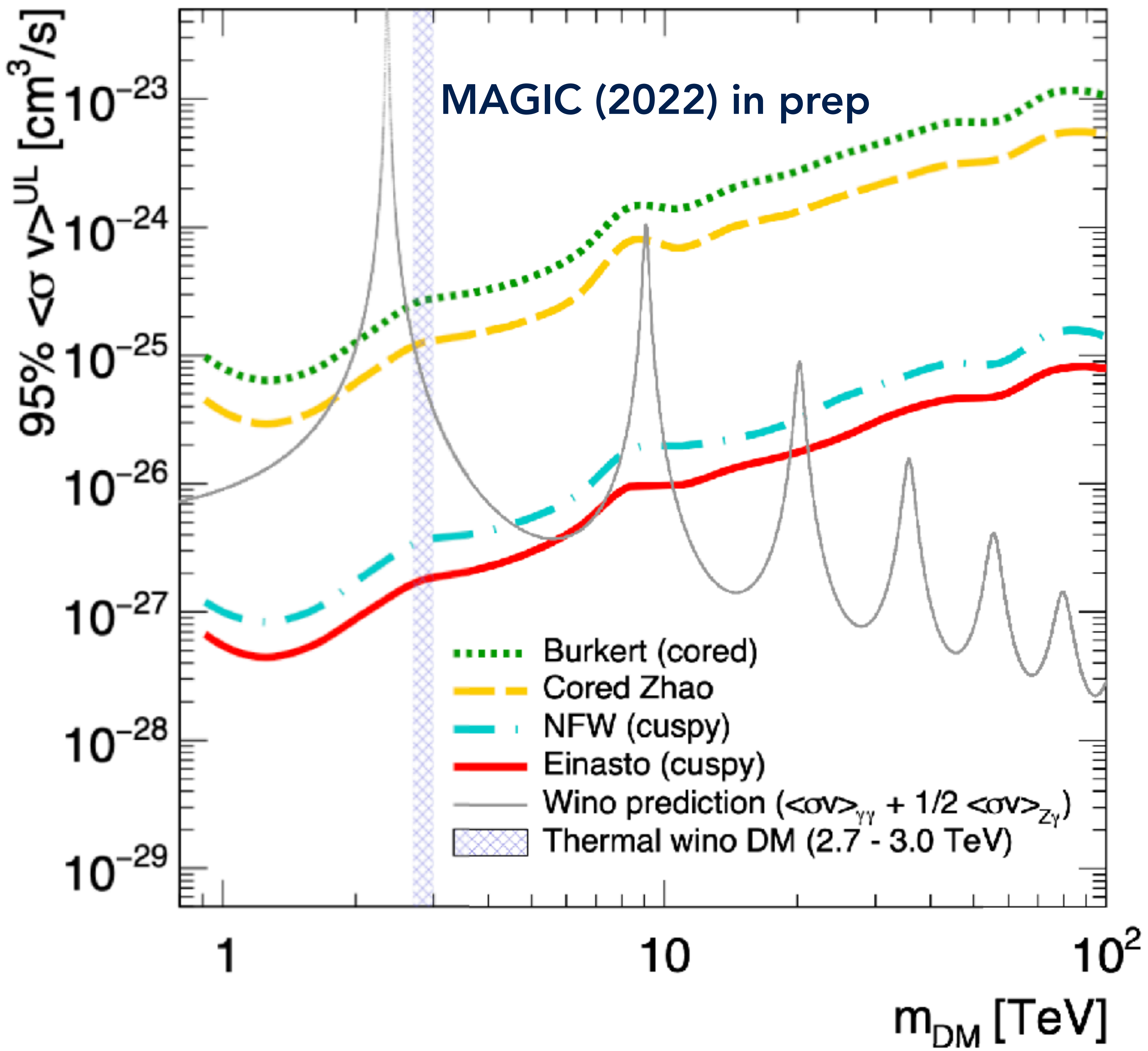


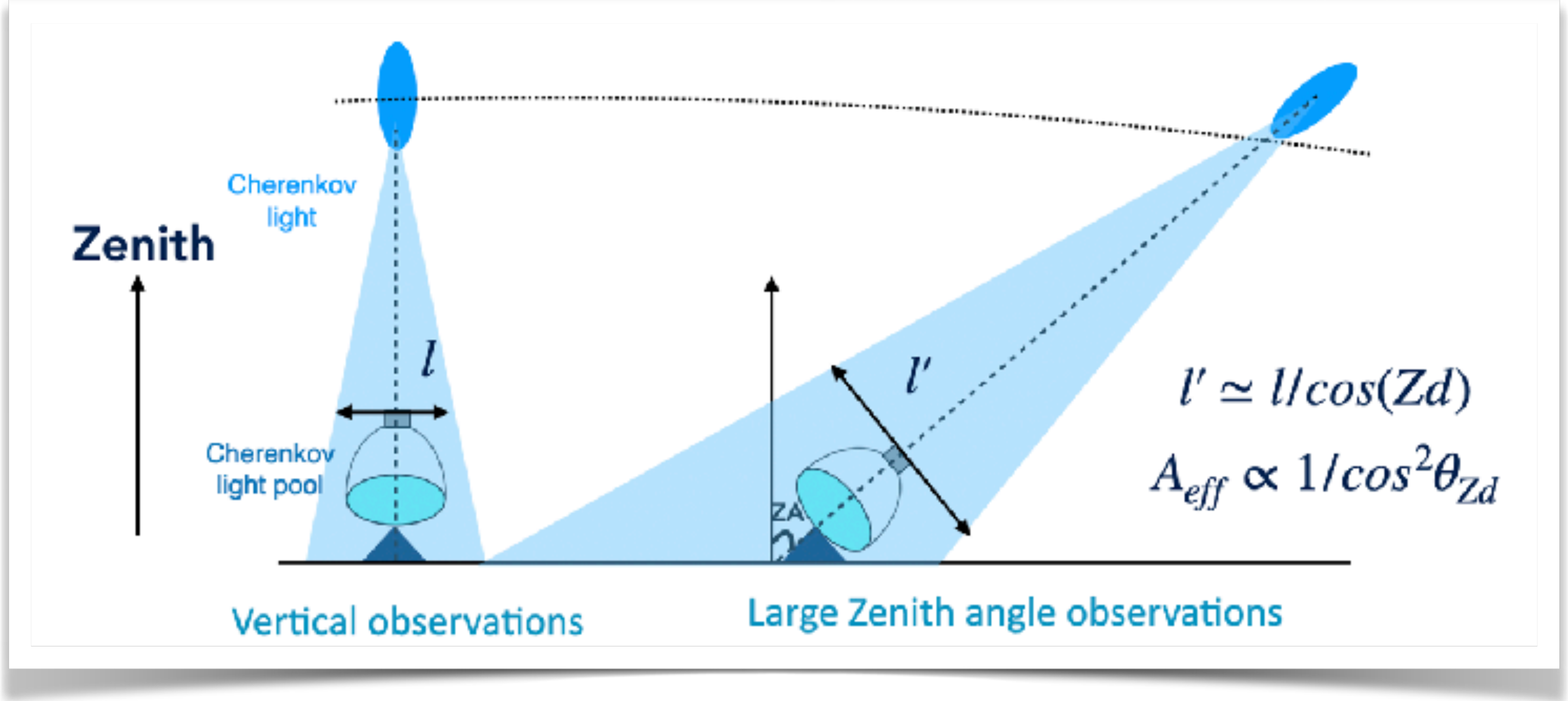


assumed DM density profile



Constraints on SUSY-Wino with DM line

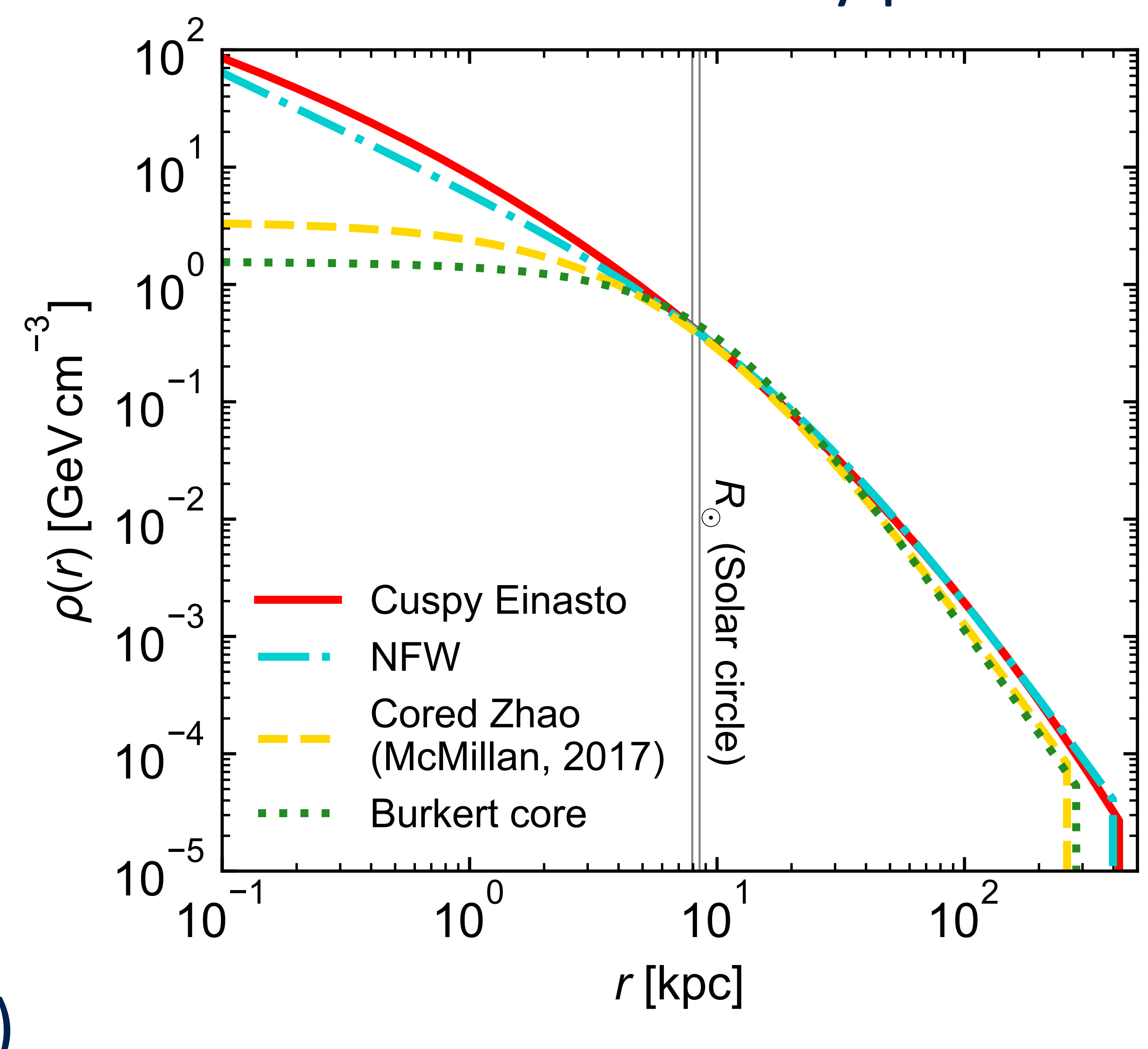




- H.E.S.S. (cuspy) and MAGIC (core and cuspy)
- Exclude well-motivated SUSY-Wino models
  - with both cuspy and core
- Thermal higgsino DM $\langle \sigma v \rangle$ = 1.0×10^{-28} $cm^3\,s^{-1}$@1 TeV would be the next target

e.g. Phys. Rev. D 103, 023011 (2021)

assumed DM density profile



Dwarf galaxies (dSphes) case

IACT observations at dSphs

arXiv:2111.01198 [astro-ph.HE]

Dwarf Satellite Galaxies					
Draco	2003	7.4	Whipple	Ann.	Wood et al. (2008)
	2007	7.8	MAGIC‡	Ann.	Albert et al. (2008b)
	2007	(18.4)	VERITAS	Ann.	Acciari et al. (2010)
	2007 – 2013	(49.8)		Ann.	Archambault et al. (2017)
	2007 – 2018	114		–	Kelley-Hoskins (2018)
	2018	52.6	MAGIC	Ann.	Maggio et al. (2021)
Ursa Minor	2003	7.9	Whipple	Ann.	Wood et al. (2008)
	2007	(18.9)	VERITAS	Ann.	Acciari et al. (2010)
	2007 – 2013	(60.4)		Ann.	Archambault et al. (2017)
	2007 – 2018	161		–	Kelley-Hoskins (2018)
Sagittarius	2006	(11.0)	H.E.S.S.	Ann.	Aharonian et al. (2008)
	2006 – 2012	90		Ann.	Abramowski et al. (2014)
	2006 – 2012	(85.5)		Ann.	Abdalla et al. (2018a)
Canis Major	2006	9.6	H.E.S.S.	Ann.	Aharonian et al. (2009a)
Willman 1	2007 – 2008	13.7	VERITAS	Ann.	Acciari et al. (2010)
		(13.6)		Ann.	Archambault et al. (2017)
	2008	15.5	MAGIC‡	Ann.	Aliu et al. (2009)
Sculptor	2008	(11.8)	H.E.S.S.	Ann.	Abramowski et al. (2011)
				Ann.	Abdalla et al. (2018a)
	2008 – 2009	12.5		Ann.	Abramowski et al. (2014)
Carina	2008 – 2009	(14.8)	H.E.S.S.	Ann.	Abramowski et al. (2011)
	2008 – 2009	(12.7)		Ann.	Abramowski et al. (2014)
	2008 – 2010	22.9		Ann.	Abdalla et al. (2018a)
Segue 1	2008 – 2009	29.4	MAGIC‡	Ann.	Aleksić et al. (2011)
	2010 – 2011	(47.8)	VERITAS	A.+D.	Aliu et al. (2012)
	2010 – 2013	(92.0)		Ann.	Archambault et al. (2017)
	2010 – 2013	157.9	MAGIC	A.+D.	Aleksić et al. (2014)
				Ann.	Ahnen et al. (2016b)
	2010 – 2018	184	VERITAS	–	Kelley-Hoskins (2018)
Boötes 1	2009	14.3	VERITAS	Ann.	Acciari et al. (2010)
		(14.0)		Ann.	Archambault et al. (2017)
Coma Berenices	2010 – 2013	(8.6)	H.E.S.S.	Ann.	Abramowski et al. (2014)
	2010 – 2013	10.9		Ann.	Abdalla et al. (2018a)
	< 2018	37	VERITAS	–	Kelley-Hoskins (2018)
	2018	50.2	MAGIC	Ann.	Maggio et al. (2021)
Fornax	2010	6.0	H.E.S.S.	Ann.	Abramowski et al. (2014)
				Ann.	Abdalla et al. (2018a)
Ursa Major II	2014 – 2016	94.8	MAGIC	Ann.	Ahnen et al. (2018a)
Triangulum II*	2014 – 2016	62.4	MAGIC	Ann.	Acciari et al. (2020)
	< 2018	181	VERITAS	–	Kelley-Hoskins (2018)
Segue II	< 2018	19	VERITAS		Kelley-Hoskins (2018)
Canes Ven I	< 2018	14	VERITAS	–	Kelley-Hoskins (2018)
Canes Ven II	< 2018	14	VERITAS	–	Kelley-Hoskins (2018)
Hercules	< 2018	13	VERITAS	–	Kelley-Hoskins (2018)
Sextans	< 2018	13	VERITAS	–	Kelley-Hoskins (2018)
Draco II	< 2018	10	VERITAS		Kelley-Hoskins (2018)
Leo I	< 2018	7	VERITAS	–	Kelley-Hoskins (2018)
Leo II	< 2018	16	VERITAS	–	Kelley-Hoskins (2018)
Leo IV	< 2018	3	VERITAS	–	Kelley-Hoskins (2018)
Leo V	< 2018	3	VERITAS	–	Kelley-Hoskins (2018)
Reticulum II	2017 – 2018	18.3	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Tucana II	2017 – 2018	16.4	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Tucana III*	2017 – 2018	23.6	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Tucana IV*	2017 – 2018	12.4	H.E.S.S.†	Ann.	Abdalla et al. (2020)
Grus II*	2018	11.3	H.E.S.S.†	Ann.	Abdalla et al. (2020)

- about 30 sources observed for 15 years
- total observation time: more than 1000 hours
- the deepest observation: 158 hours

Combination of dSph results: five experiments

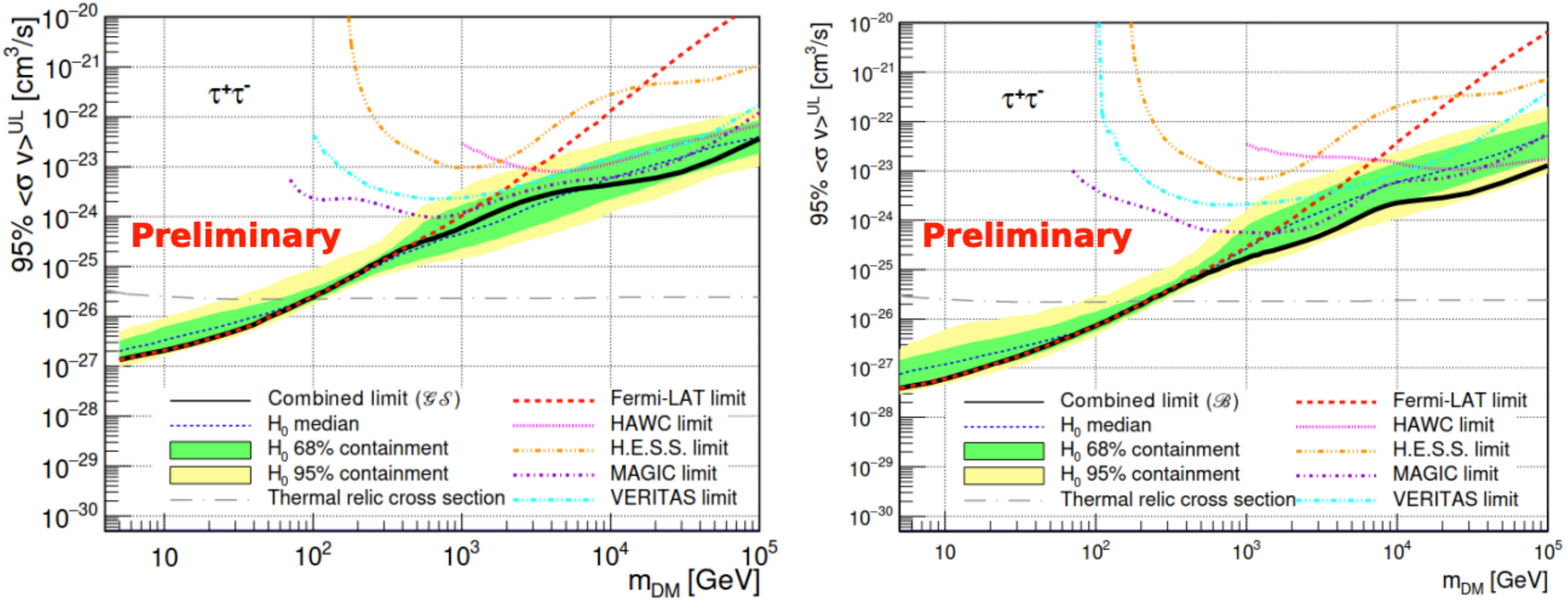
Source name	Experiments	Distance (kpc)	$\log_{10} J$ $\log_{10}(\mathrm{GeV^2 cm^{-5} sr})$
Bootes I	*Fermi*-LAT, HAWC, VERITAS	66	$18.24^{+0.40}_{-0.37}$
Canes Venatici I	*Fermi*-LAT	218	$17.44^{+0.37}_{-0.28}$
Canes Venatici II	*Fermi*-LAT, HAWC	160	$17.65^{+0.45}_{-0.43}$
Carina	*Fermi*-LAT, H.E.S.S.	105	$17.92^{+0.19}_{-0.11}$
Coma Berenices	*Fermi*-LAT, HAWC, H.E.S.S., MAGIC	44	$19.02^{+0.37}_{-0.41}$
Draco	*Fermi*-LAT, HAWC, MAGIC, VERITAS	76	$19.05^{+0.22}_{-0.21}$
Fornax	*Fermi*-LAT, H.E.S.S.	147	$17.84^{+0.11}_{-0.06}$
Hercules	*Fermi*-LAT, HAWC	132	$16.86^{+0.74}_{-0.68}$
Leo I	*Fermi*-LAT, HAWC	254	$17.84^{+0.20}_{-0.16}$
Leo II	*Fermi*-LAT, HAWC	233	$17.97^{+0.20}_{-0.18}$
Leo IV	*Fermi*-LAT, HAWC	154	$16.32^{+1.06}_{-1.70}$
Leo T	*Fermi*-LAT	417	$17.11^{+0.44}_{-0.39}$
Leo V	*Fermi*-LAT	178	$16.37^{+0.94}_{-0.87}$
Sculptor	*Fermi*-LAT, H.E.S.S.	86	$18.57^{+0.07}_{-0.05}$
Segue I	*Fermi*-LAT, HAWC, MAGIC, VERITAS	23	$19.36^{+0.32}_{-0.35}$
Segue II	*Fermi*-LAT	35	$16.21^{+1.06}_{-0.98}$
Sextans	*Fermi*-LAT, HAWC	86	$17.92^{+0.35}_{-0.29}$
Ursa Major I	*Fermi*-LAT, HAWC	97	$17.87^{+0.56}_{-0.33}$
Ursa Major II	*Fermi*-LAT, HAWC, MAGIC	32	$19.42^{+0.44}_{-0.42}$
Ursa Minor	*Fermi*-LAT, VERITAS	76	$18.95^{+0.26}_{-0.18}$

arXiv:2108.13646v1

- combination of 20 dSph observations
  - 20 from Fermi-LAT: 10 yrs
  - 9 from IACTs: 500+ hrs
  - 12 from HAWC: 1000+ days
- 5 exp. covers 5 GeV to 100 TeV of DM masses

Comparison of the limits with 2 sets of J-factors

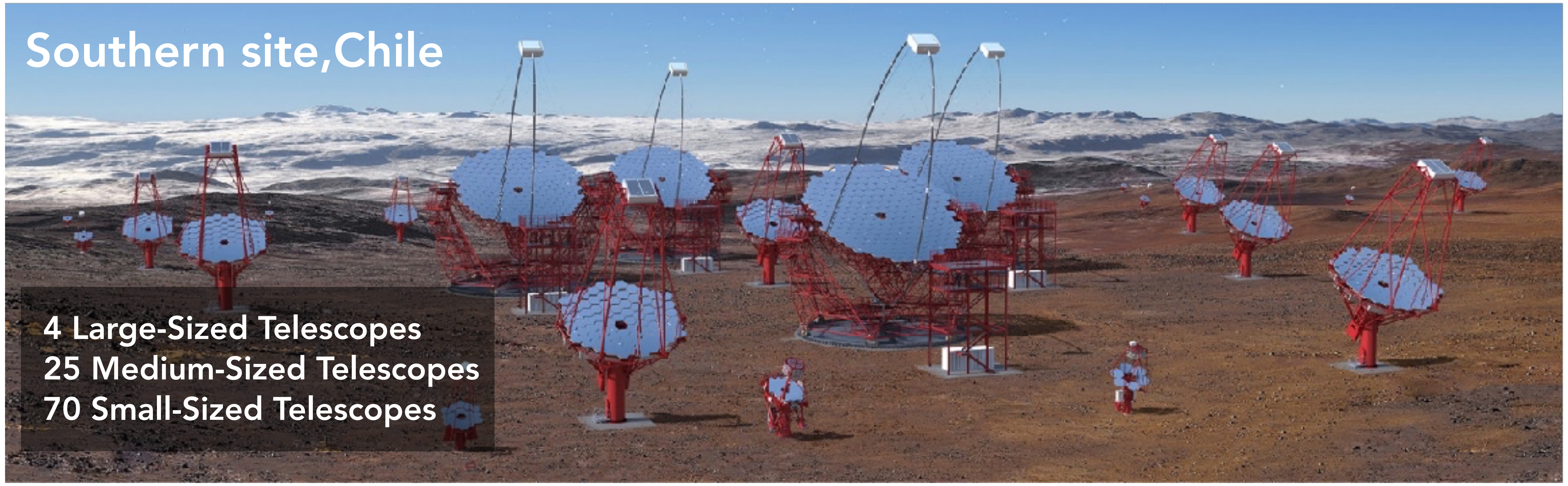
Plots are from D. Kerszberg's talk at γ2022



- Limits **2-6× more constraining** with the J-factors of Bonnivard et al.
- Below 10 TeV - DM limits largely dominated by Fermi-LAT
- above 10 TeV - IACTs and HAWC take over

Future prospects

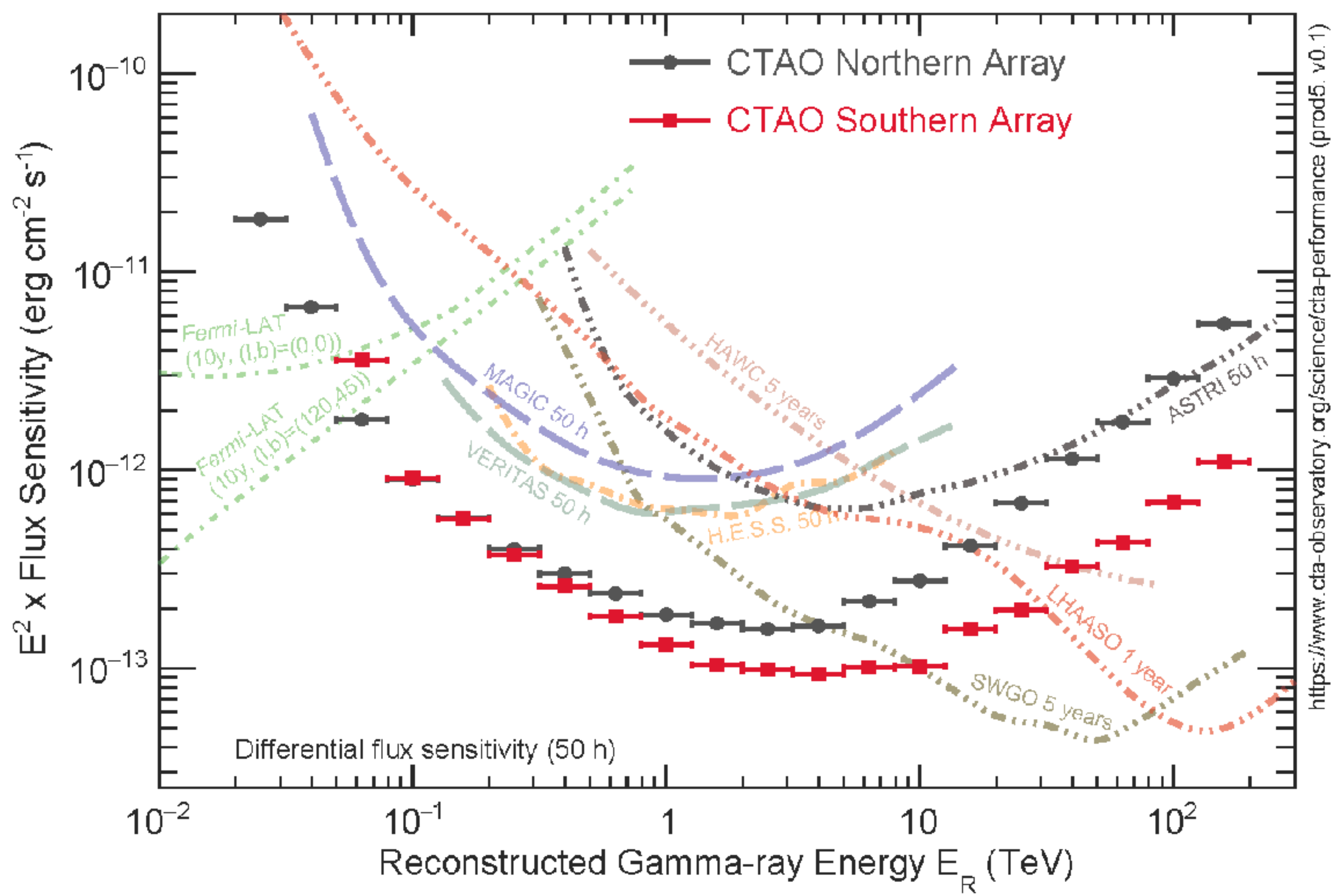
Cherenkov Telescope Array

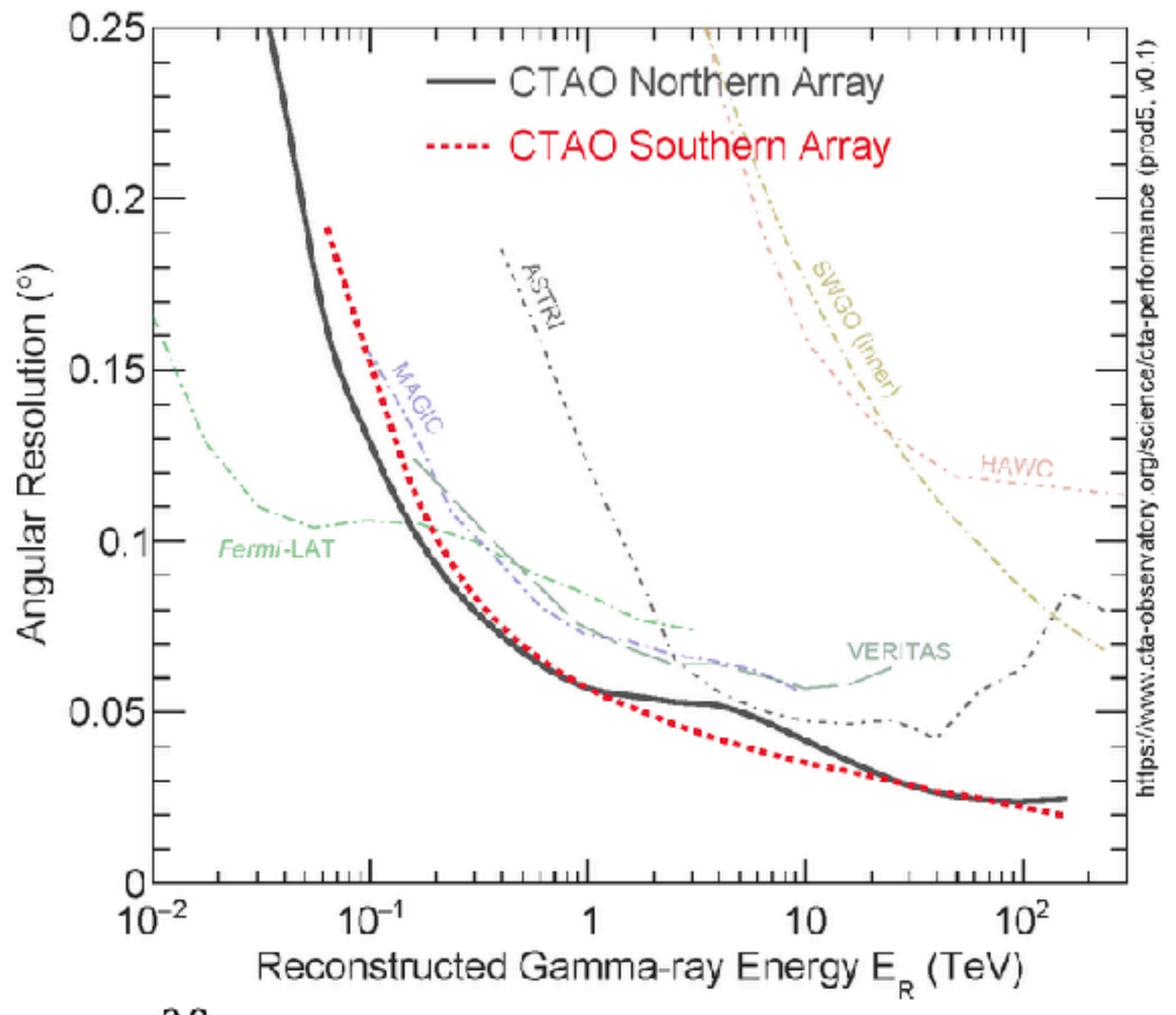


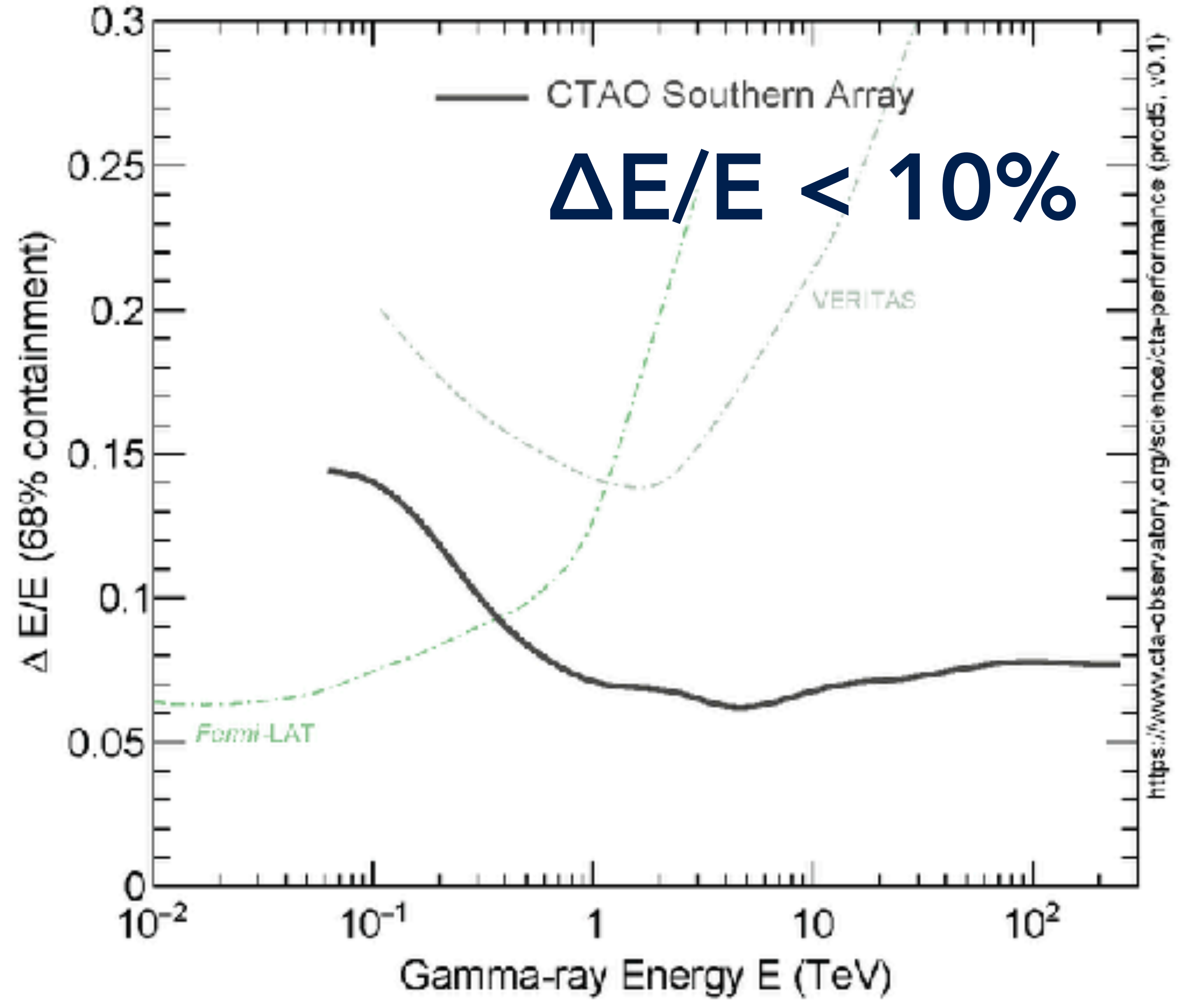
Next generation ground-based gamma-ray telescope: Two arrays of Cherenkov telescopes in **Chile/ La Palma**

- Over 100 telescopes
- About 1500 scientists and engineers
- About 200 institutes

Sensitivity



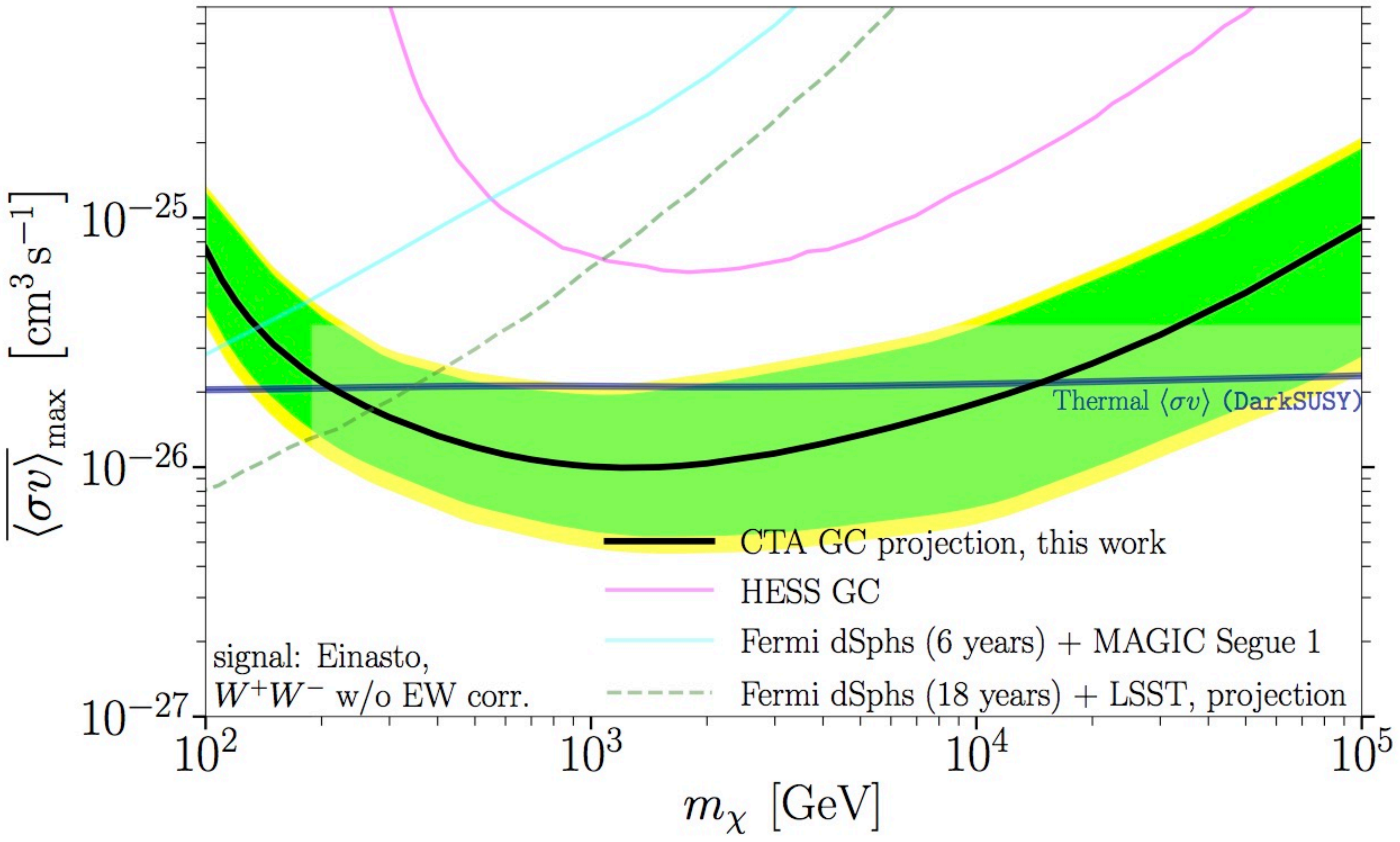


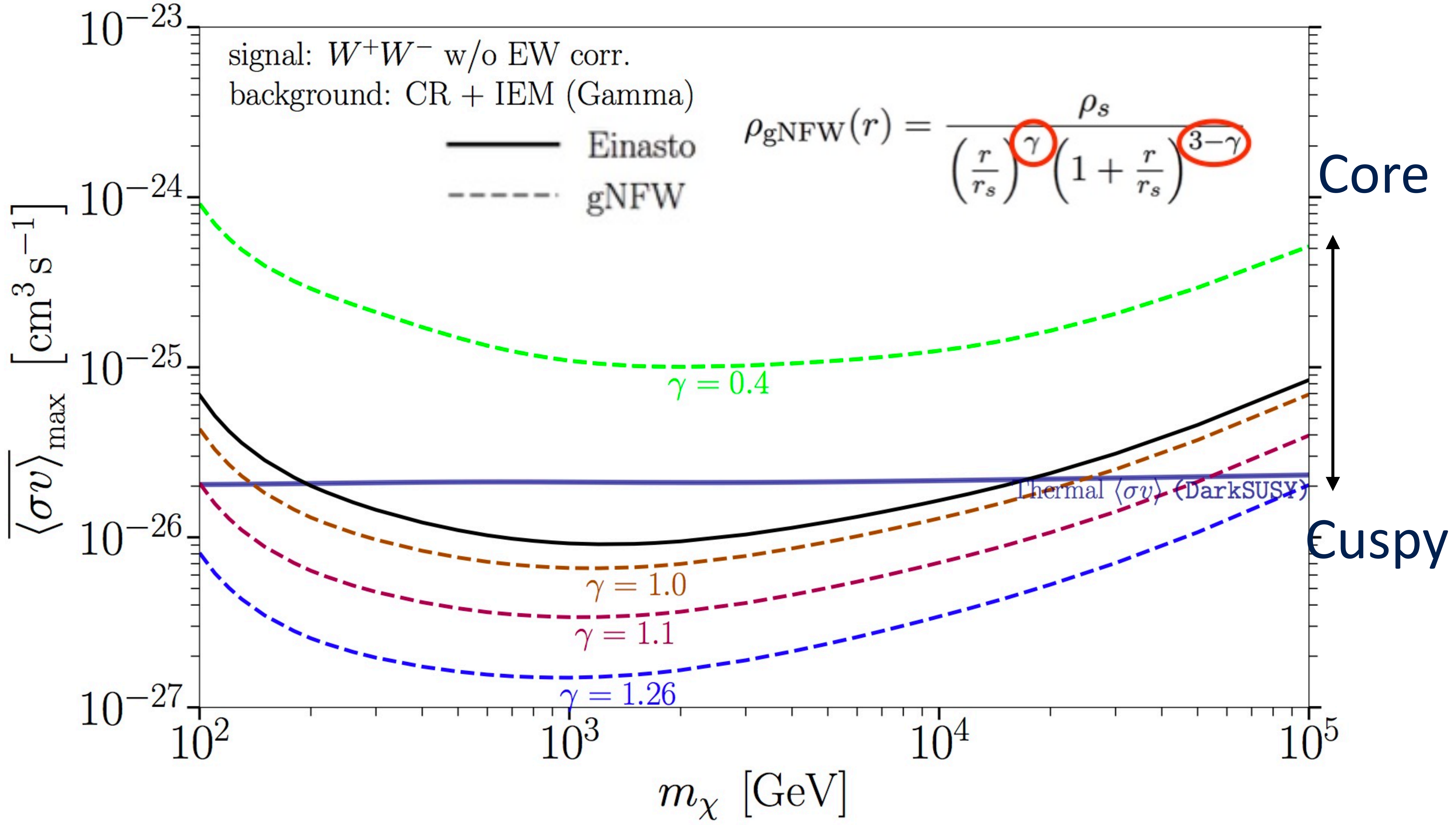


ΔE/E < 10%

Energy range: 20 GeV – 300 TeV

CTA: Sensitivity to DM signal from Galactic Center





Galactic center observations with CTA can

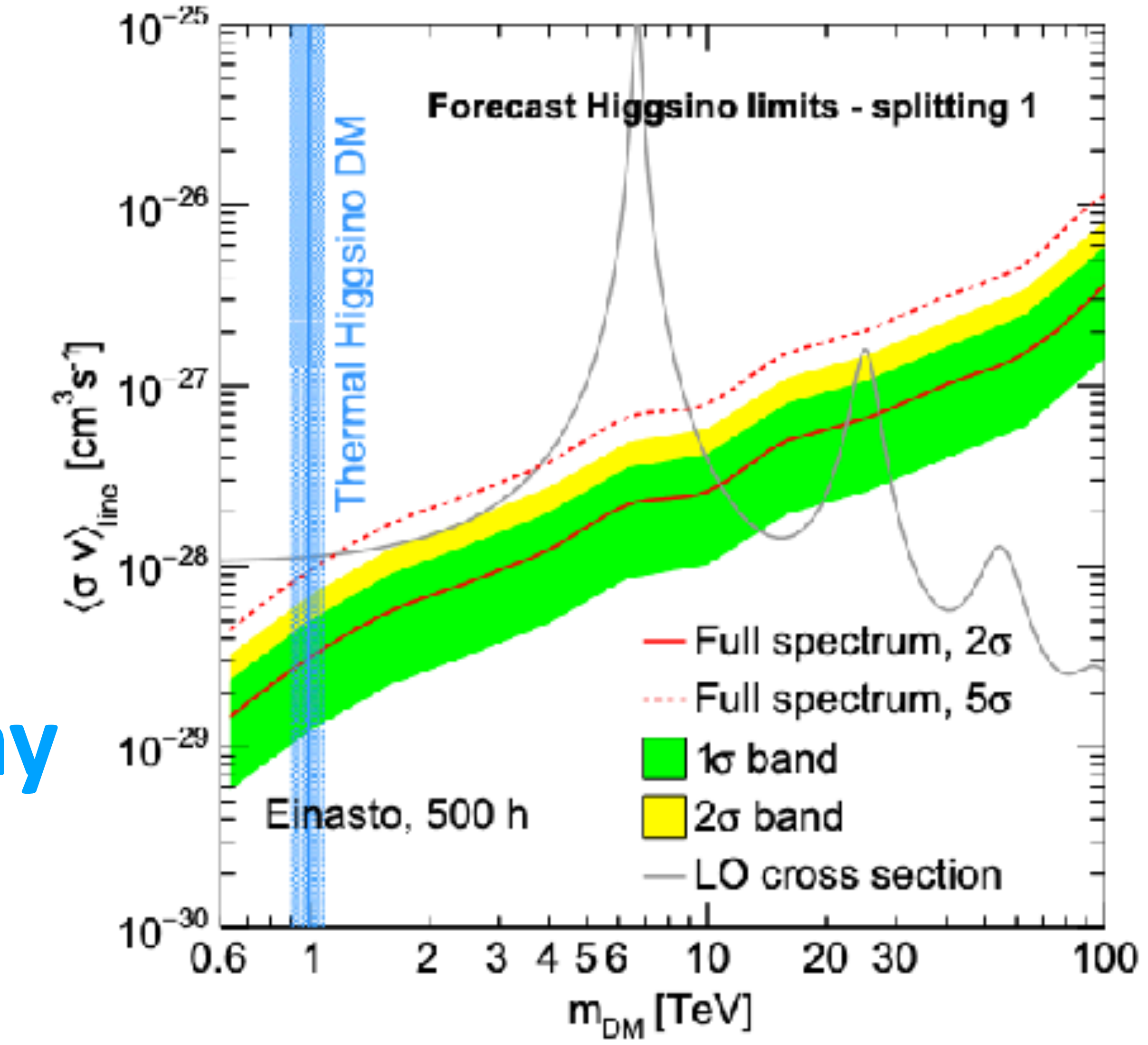
test the thermal relic cross section of **500 GeV - 10 TeV WIMPs**

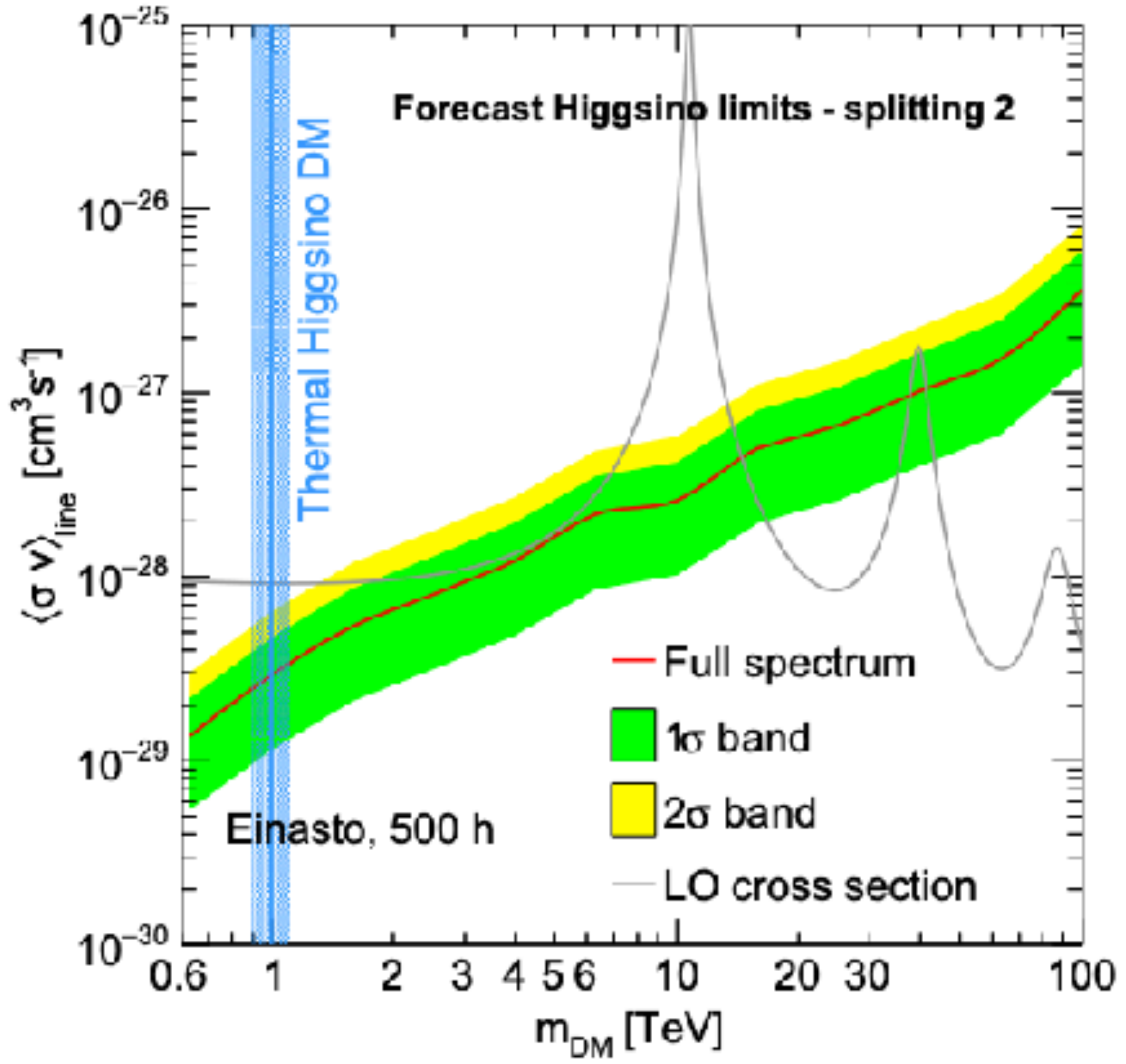
CTA: Sensitivity to popular SUSY models with the GC

Phys. Rev. D 103, 023011 (2021)

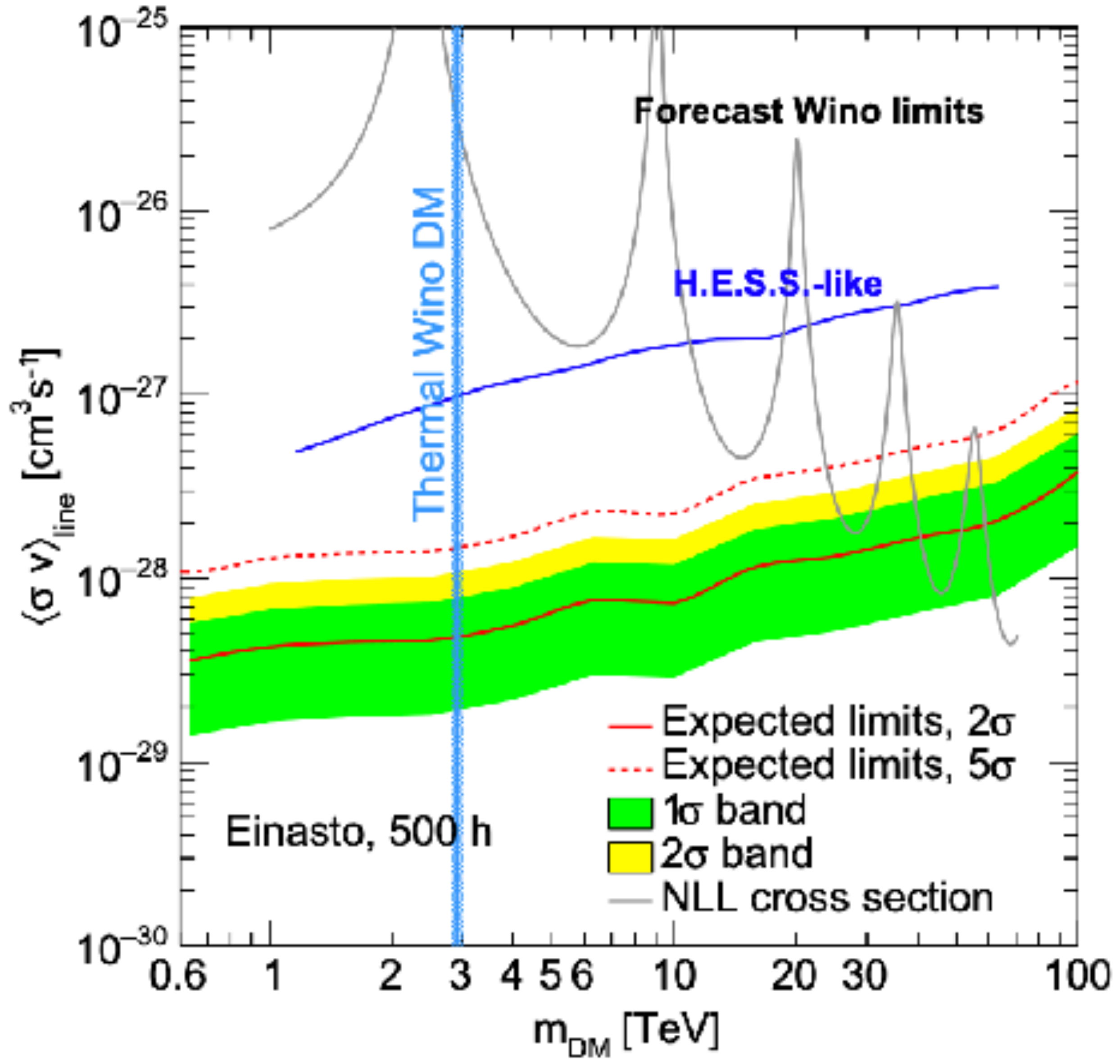
- CTA with the GC can constrain **SUSY-Wino, Higgsino**
  - **Wino@3 TeV: with both core and cuspy**
  - **Higgsino@1 TeV: with up to 1kpc core size**
  - The channel considered, mainly
    - **line emission** + **continuum spectra from W, Z decay**

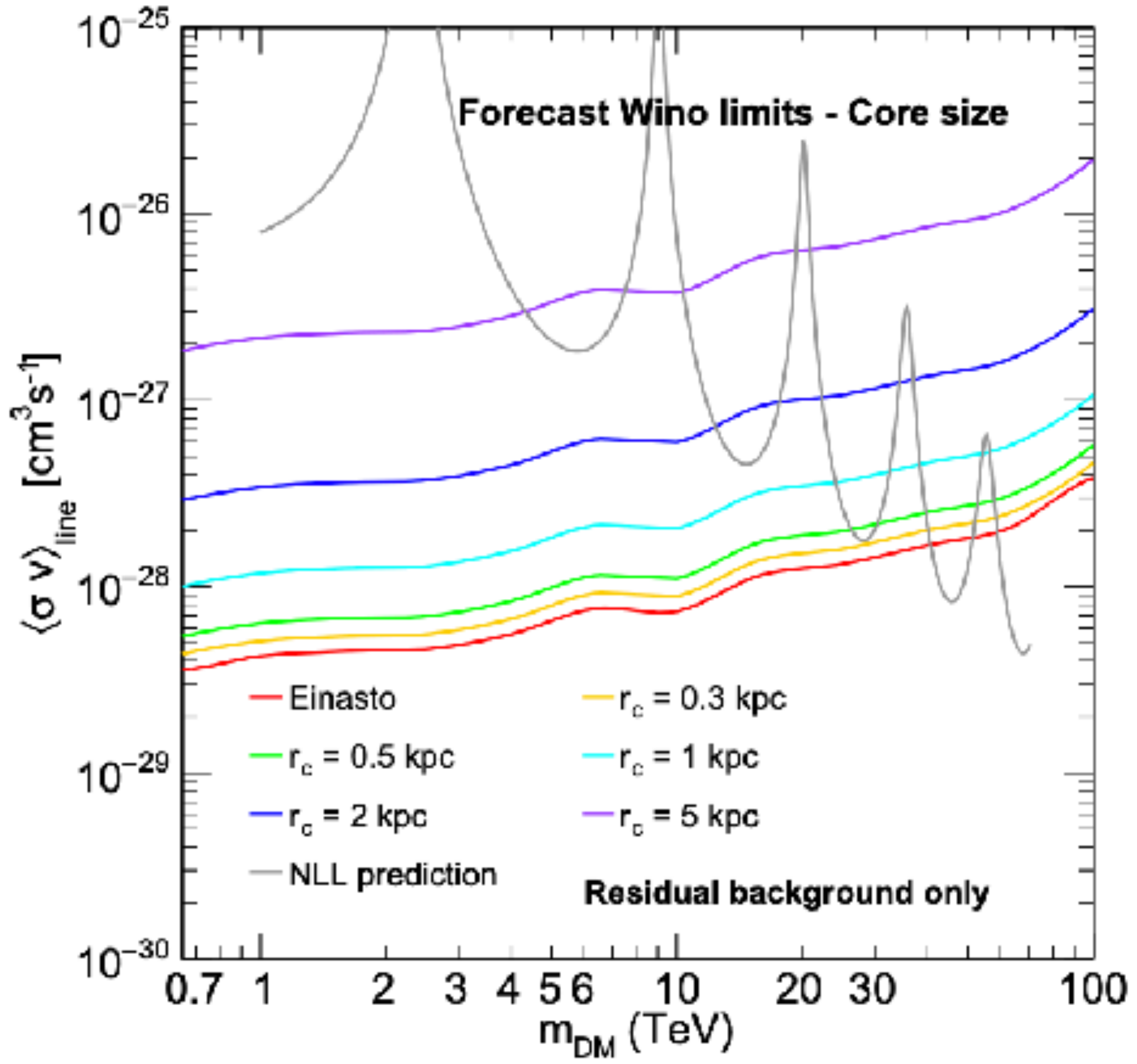
Higgsino

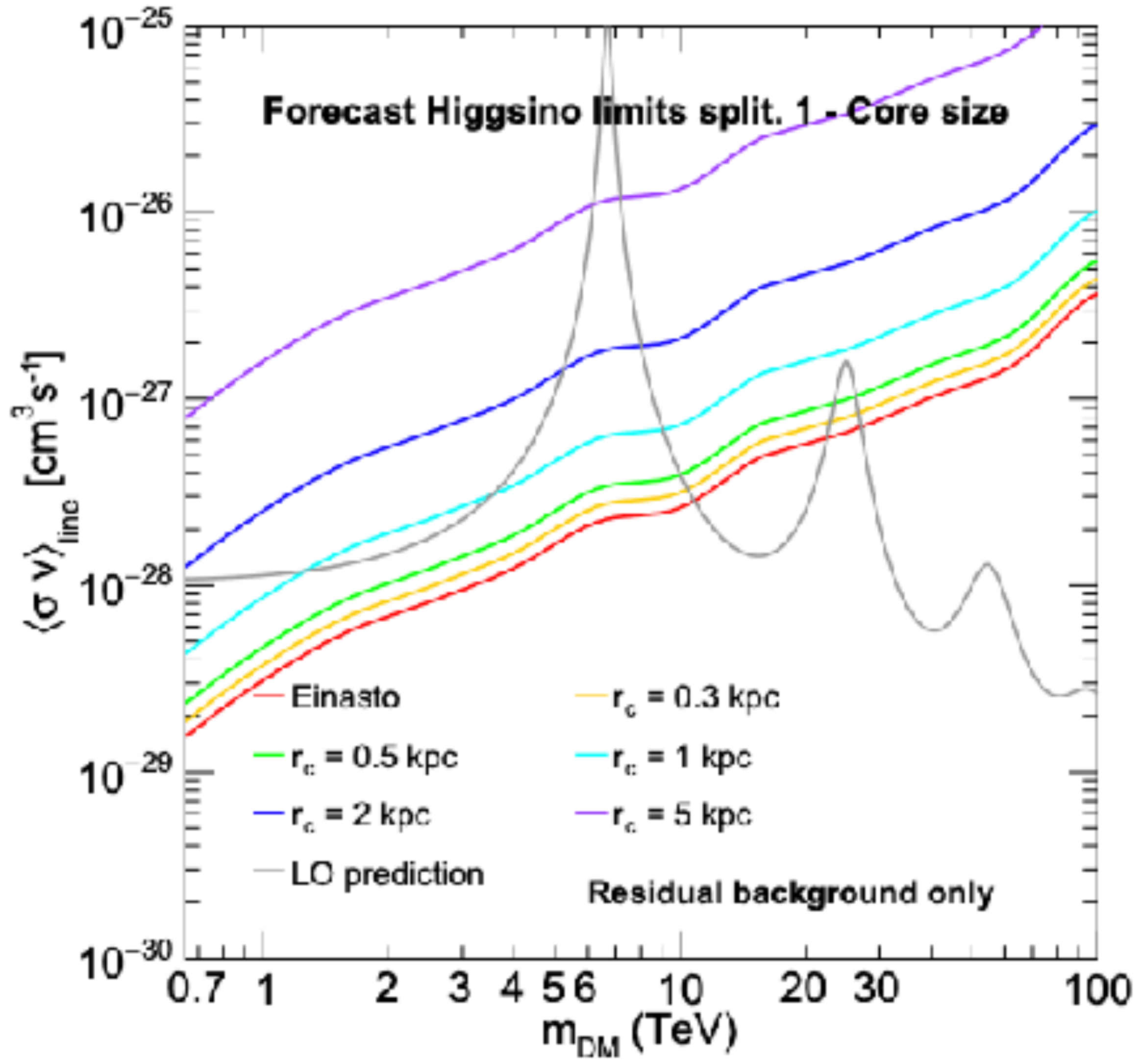


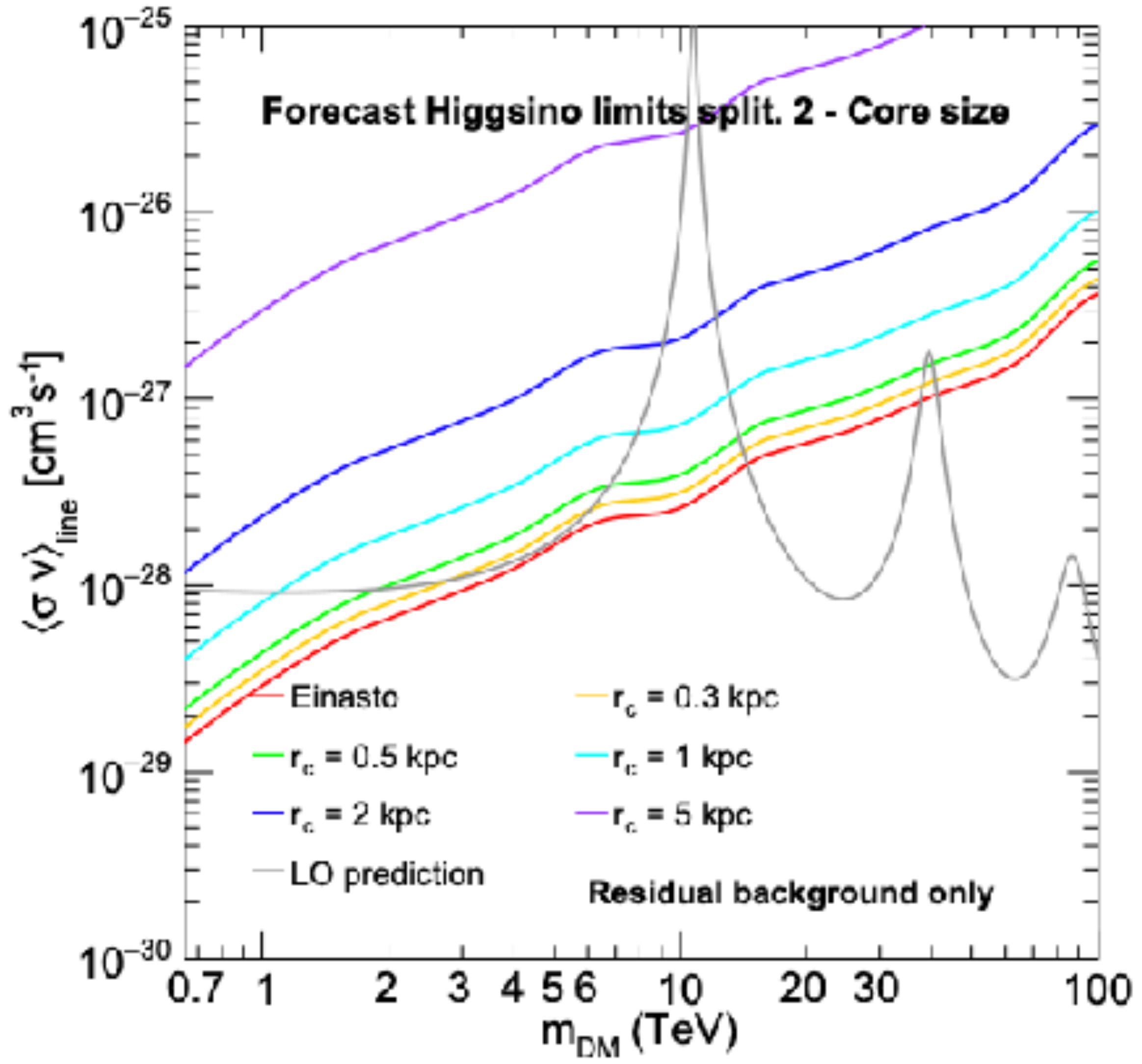


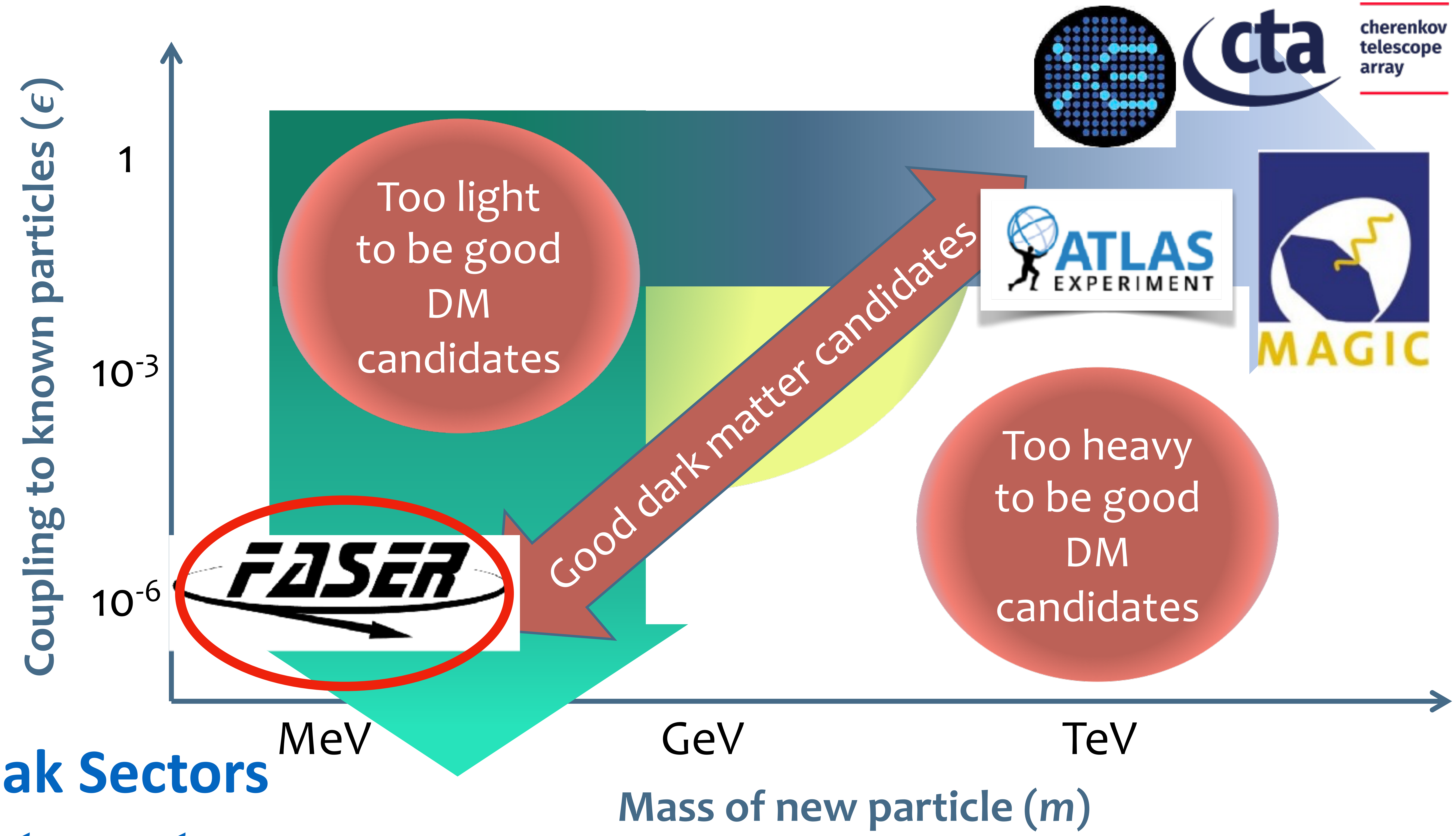
Wino











Deak Sectors

$m < m_w, g < g_w$

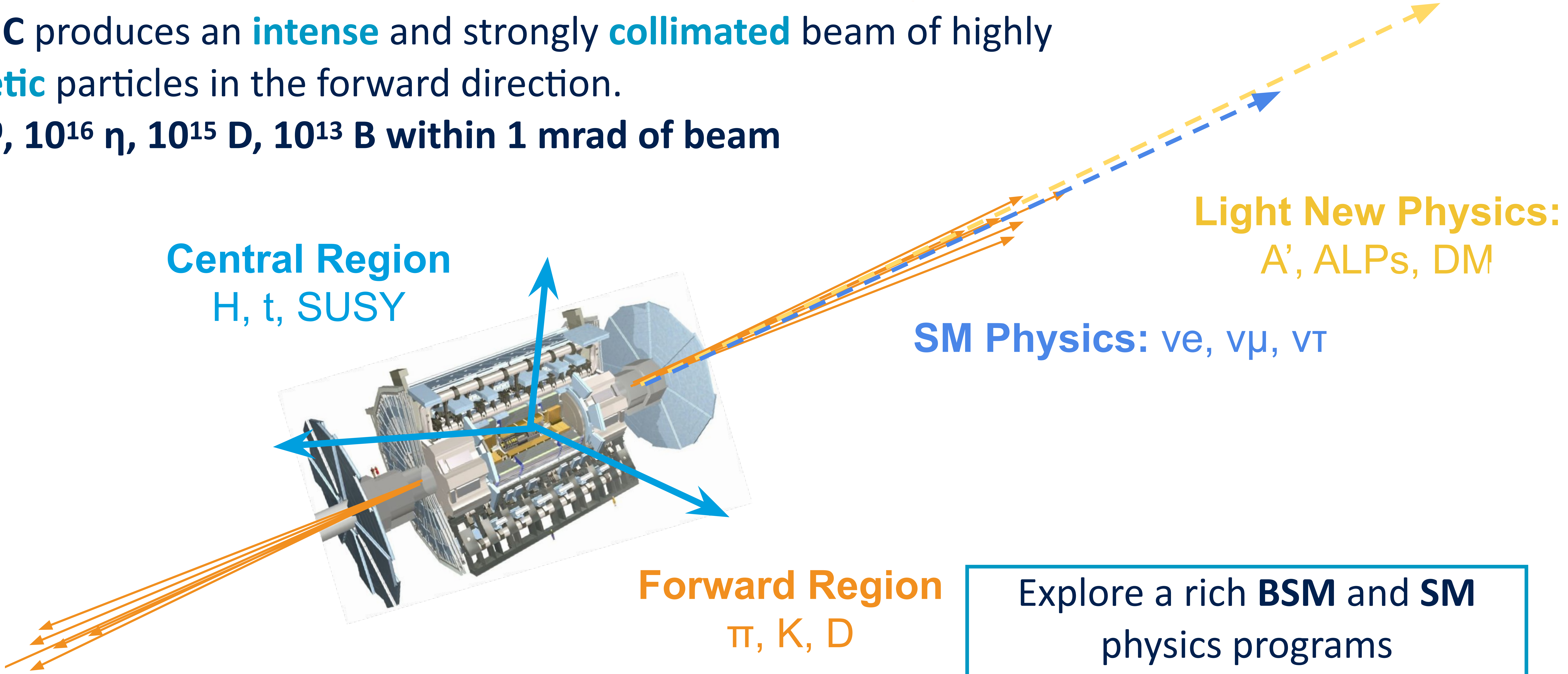
FASER - New experiment from the LHC Run3

FASER joined the LHC family

Idea and Motivation

The LHC produces an **intense** and strongly **collimated** beam of highly **energetic** particles in the forward direction.

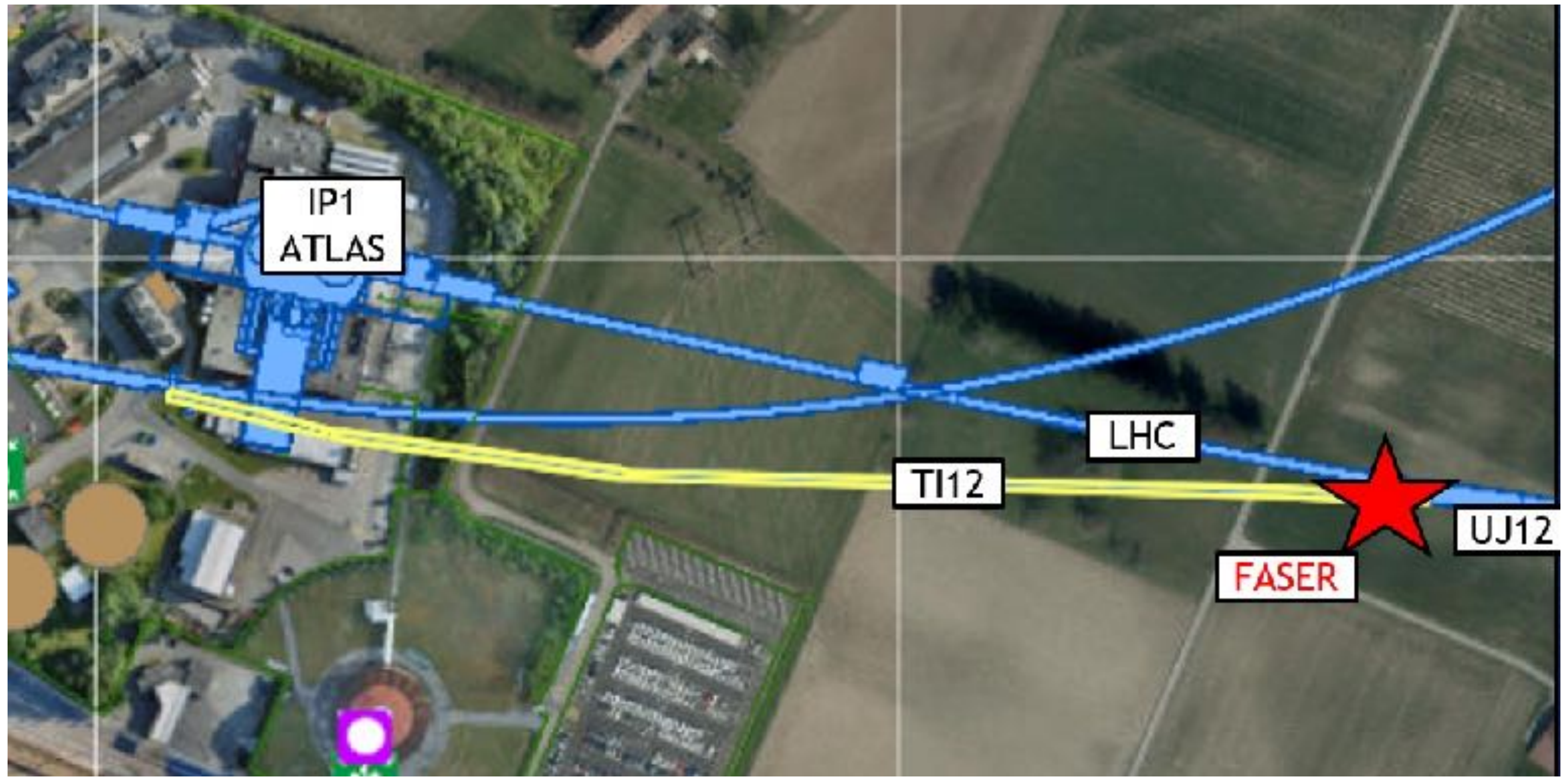
10^{17} π^0, 10^{16} η, 10^{15} D, 10^{13} B within 1 mrad of beam



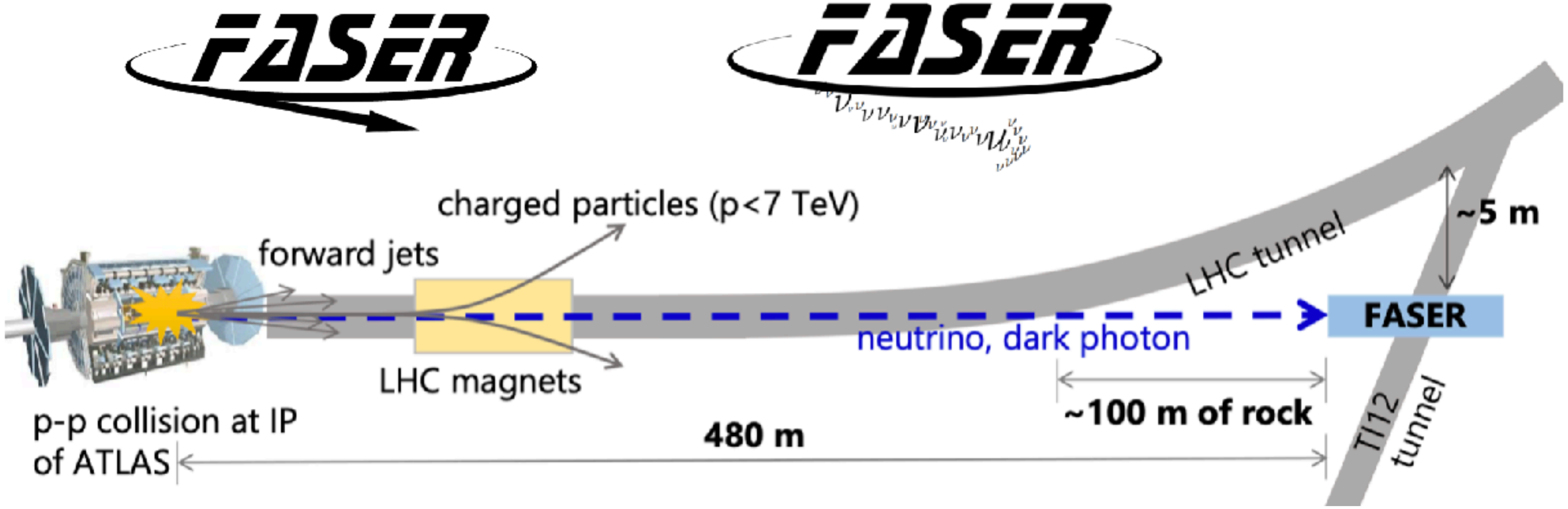
Explore a rich **BSM** and **SM** physics programs
in the far farward region

FASER

- **ForwArd Search ExpeRiment (FASER) at the LHC**
  - Placed **480 m downstream of the ATLAS IP** on the beam axis
  - Started the **operation** from the beginning of the **LHC Run3**



- **Physics motivation**
  - New long-lived particle search in **MeV-GeV masses**
  - **All flavors of neutrinos** at the **TeV-energy frontier**



- **Favorable location**
  - **Very low background from collision**
    - **Only high-energy muon** at about $1/cm^2/sec$
  - **Low radiation level from the LHC**
    - 4×10^6 1-MeV $neutron/cm^2/year$

FASER collaboration

75 members from 22 institutions and 9 countries

FASER history

The first theoretical proposal in 2017

[Submitted on 30 Aug 2017 (v1), last revised 14 Jun 2018 (this version, v3)]

FASER: ForwArd Search ExpeRiment at the LHC

Jonathan L. Feng, Iftah Galon, Felix Kling, Sebastian Trojanowski

Submitted LOI to CERN in Nov. 2018 -> Approved in Mar. 2019

[Submitted on 26 Nov 2018]

Letter of Intent for FASER: ForwArd Search ExpeRiment at the LHC

FASER Collaboration, Akitaka Ariga, Tomoko Ariga, Jamie Boyd, David W. Casper, Jonathan L. Feng, Iftah Galon, Shih-Chieh Hsu, Felix Kling, Hidetoshi Otono, Brian Petersen, Osamu Sato, Aaron M. Soffa, Jeffrey R. Swaney, Sebastian Trojanowski

Submitted LOI for Neutrino program in Dec. 2019 -> Approved

[Submitted on 9 Jan 2020]

Technical Proposal: FASERnu

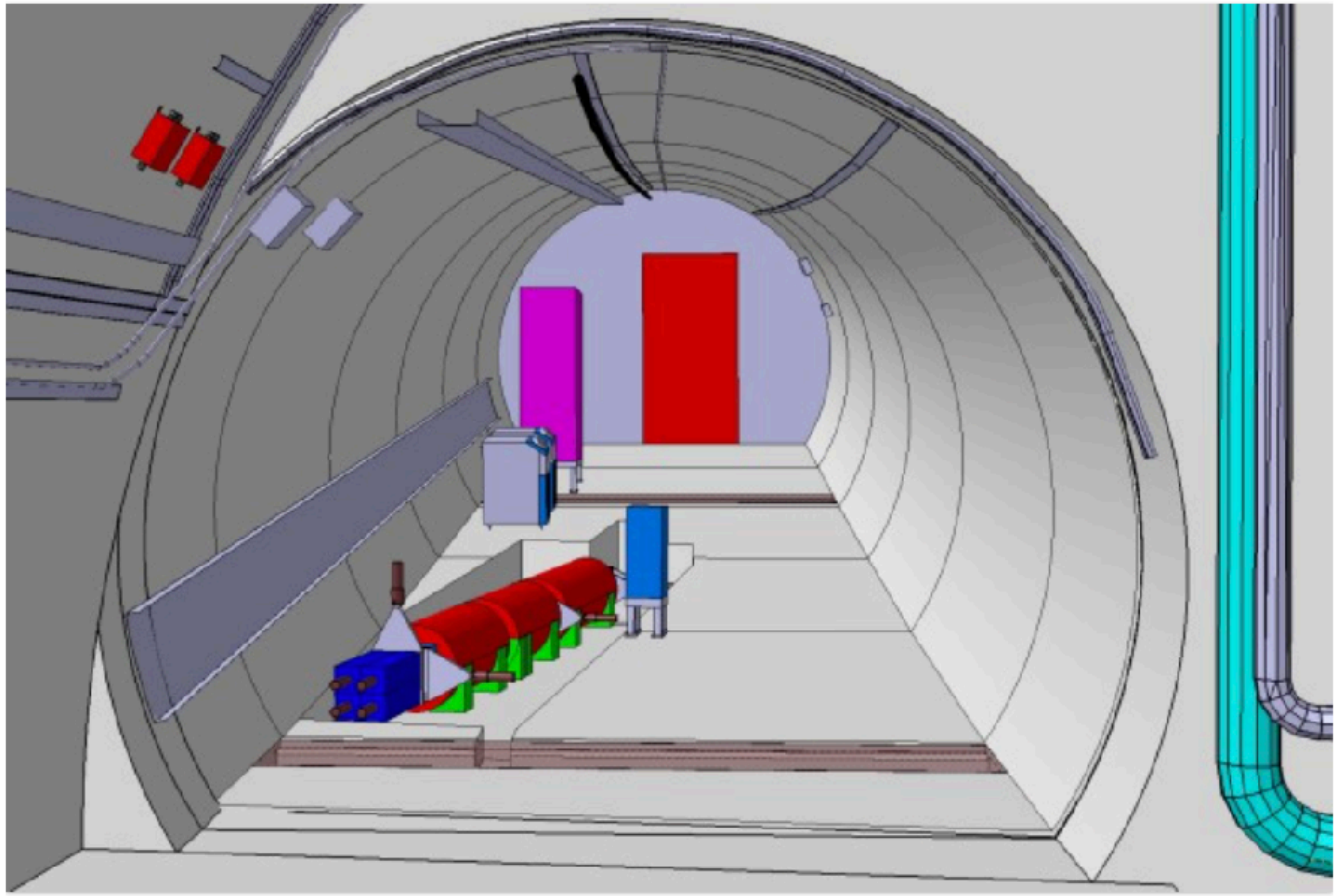
FASER Collaboration: Henso Abreu, Marco Andreini, Claire Antel, Akitaka Ariga, Tomoko Ariga, Caterina Bertone, Jamie Boyd, Andy Buckley, Franck Cadoux, David W. Casper, Francesco Cerutti, Xin Chen, Andrea Coccaro, Salvatore Danzeca, Liam Dougherty, Candan Dozen, Peter B. Denton, Yannick Favre, Deion Fellers, Jonathan L. Feng, Didier Ferrere, Jonathan Gall, Iftah Galon, Stephen Gibson, Sergio Gonzalez-Sevilla, Shih-Chieh Hsu, Zhen Hu, Giuseppe Iacobucci, Sune Jakobsen, Roland Jansky, Enrique Kajomovitz, Felix Kling, Umut Kose, Susanne Kuehn, Mike Lamont, Helena Lefebvre, Lorne Levinson, Ke Li, Josh McFayden, Sam Meehan, Dimitar Mladenov, Mitsuhiro Nakamura, Toshiyuki Nakano, Marzio Nessi, Friedemann Neuhaus, John Osborne, Hidetoshi Otono, Serge Pelletier, Brian Petersen, Francesco Pietropaolo, Michaela Queitsch-Maitland, Filippo Resnati, Marta Sabate-Gilarte, Jakob Salfeld-Nebgen, Francisco Sanchez Galan, Pablo Santos Diaz, Osamu Sato, Paola Scampoli, Kristof Schmieden, Matthias Schott, Holger Schulz, Anna Sfyrla, Savannah Shively, Jordan Smolinsky, Aaron M. Soffa, Yosuke Takubo, Eric Torrence, Sebastian Trojanowski, Serhan Tufanli, Dengfeng Zhang, Gang Zhang

FASER: CERN approves new experiment to look for long-lived, exotic particles

The experiment, which will complement existing searches for dark matter at the LHC, will be operational in 2021

The project was just approved 3.5 years ago

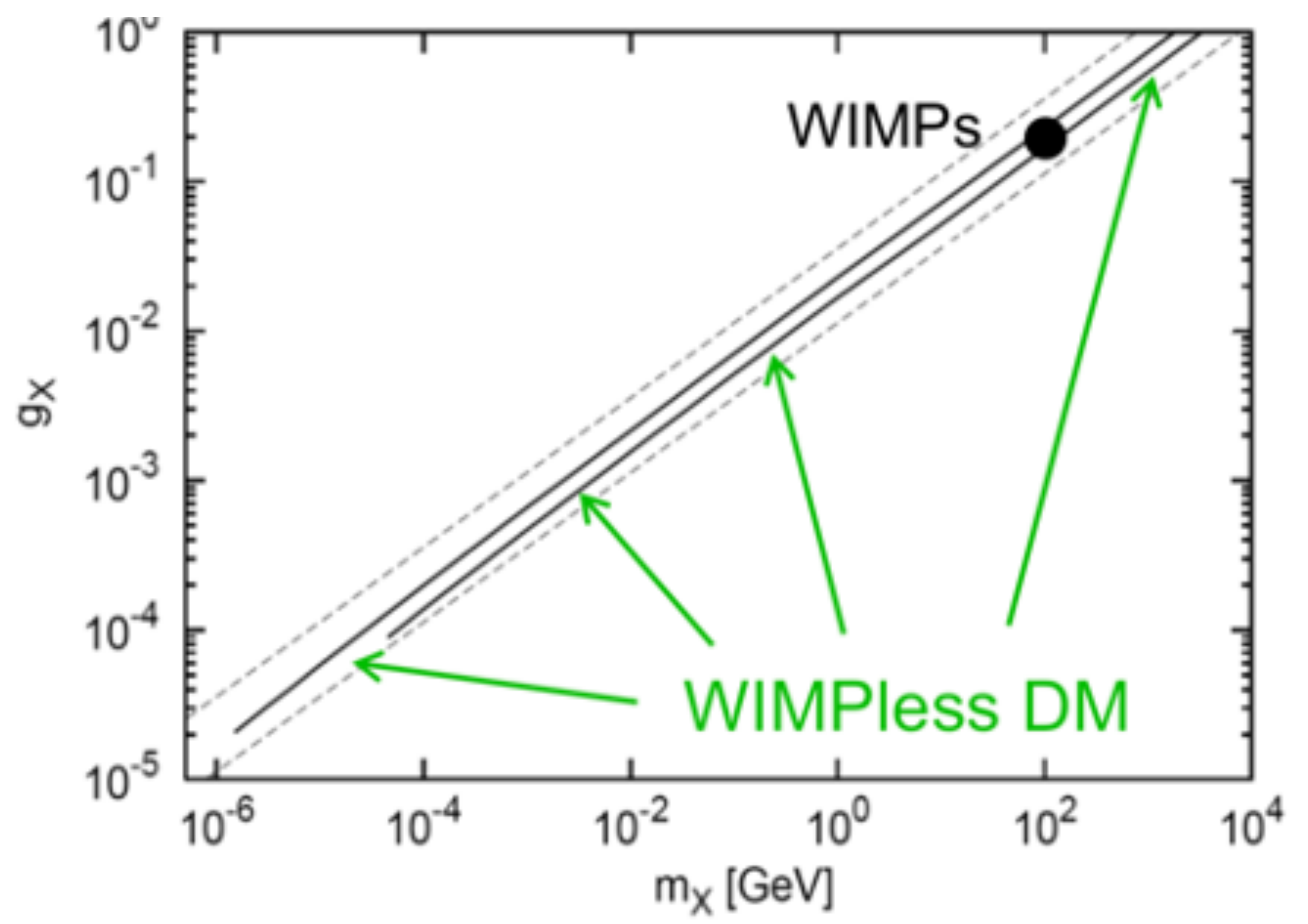
7 MARCH, 2019 | By Cristina Agrigoroae



Search for new light weakly-coupled partciles

How to explain the DM relic density? $\Omega_X \sim \langle \sigma_A v \rangle^{-1} \sim \frac{m_X^2}{g_X^4}$

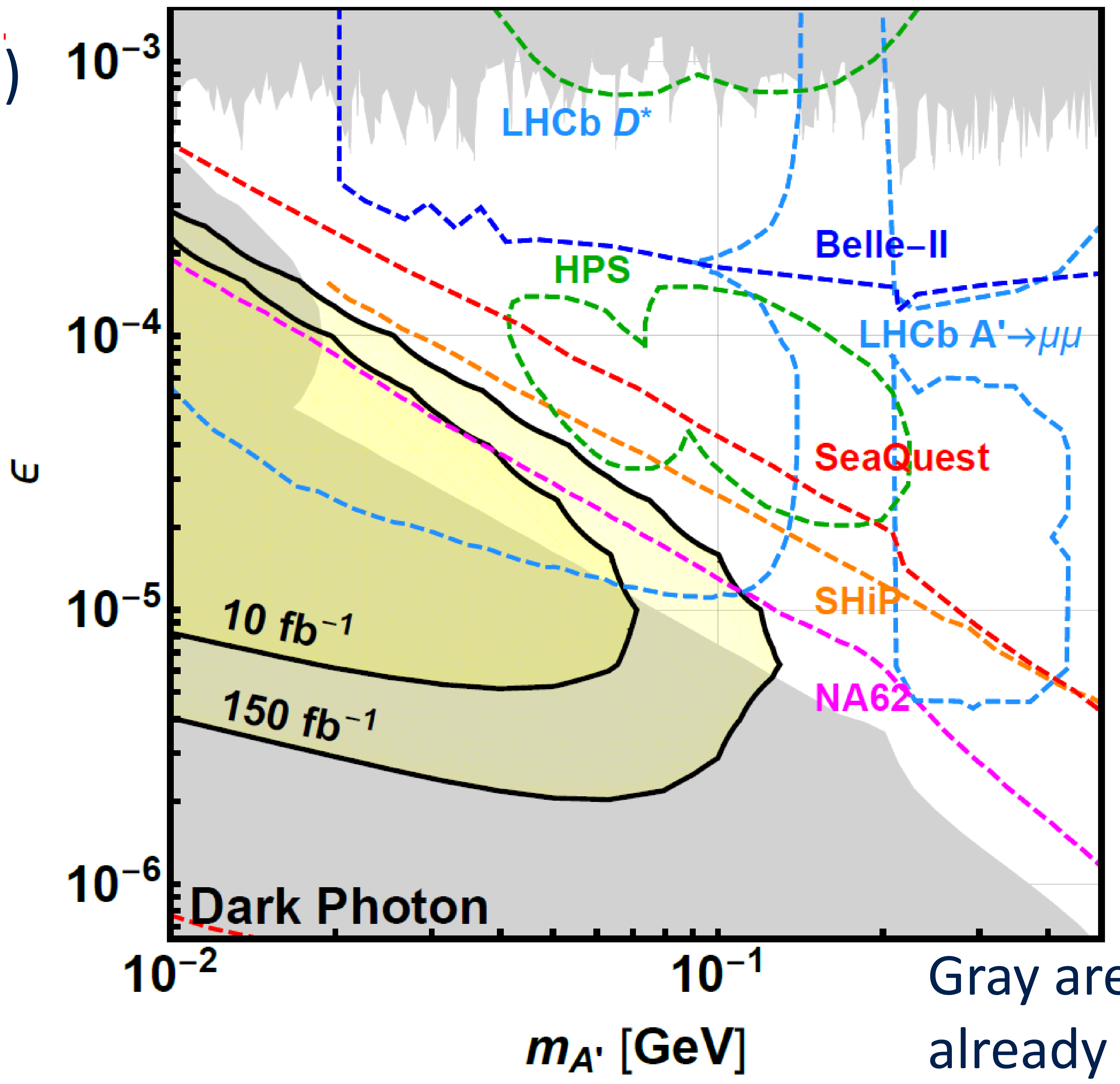
- **WIMP**: $m_\chi \sim m_w, g_\chi \sim g_w$
  - no signal yet
- **WIMPless DM:** m is free and $g_\chi \neq g_w$
  - **dark sector:** $m_\chi < m_w, g_\chi < g_w$ (long-lived with weak g_χ)



Phys.Rev.Lett.101:231301,2008

FASER is the first dedicated far-detector collider experiment for long-lived particle search

- with already **10 fb^{-1}** (LHC luminosity) starting to explore unconstrained space
- Significant discovery potential **with 150fb-1**
  - **Expected Run-3 dataset**



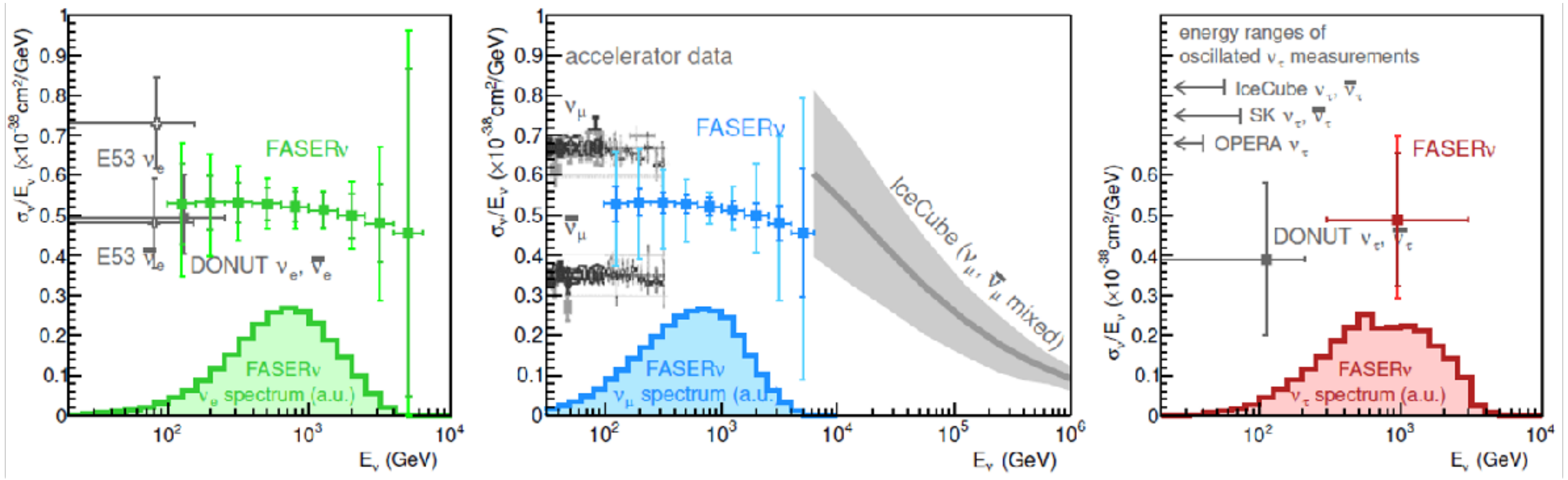
Gray area: already constrained

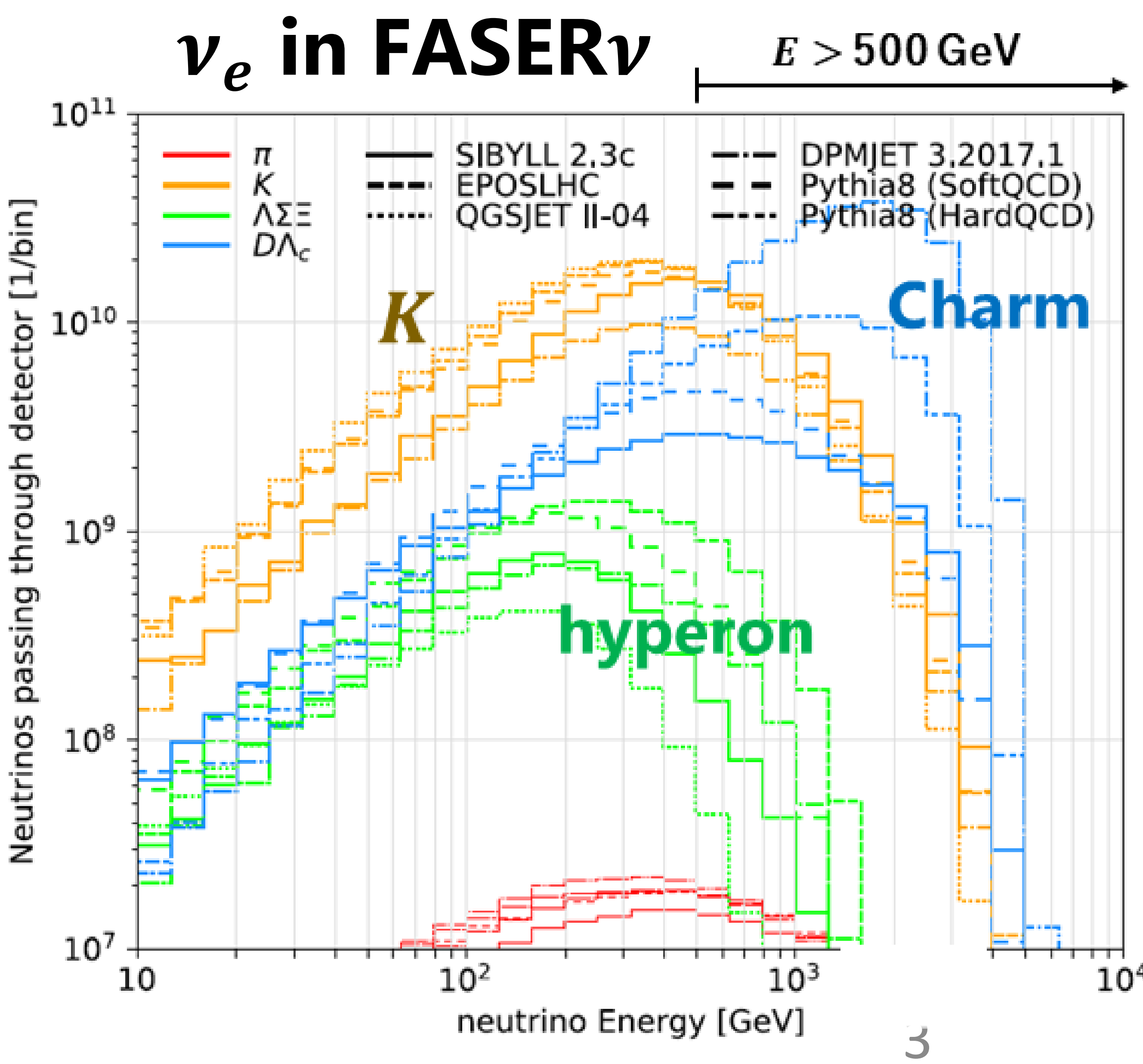
Exploring neutrinos at the TeV-energy frontier

- **High-energy neutrino interactions**
  - Cross-section measurements of **different flavors at TeV energies**
  - **NC measurements,** constraining neutrino nonstandard interactions
  - Neutrino CC interaction with **charm production** ($\nu s \to lc$) and **heavy (e.g. *beauty*) quark production**

- **Forward particle production**
  - **Neutrinos produced in the forward direction** at the LHC **originate from the decay of hadrons,** mainly pions, kaons, and charmed mesons.
  - **Neutrinos from charm decay** is relevant for **neutrino telescopes (such as IceCube)** for understanding the **prompt atmospheric neutrino** production.

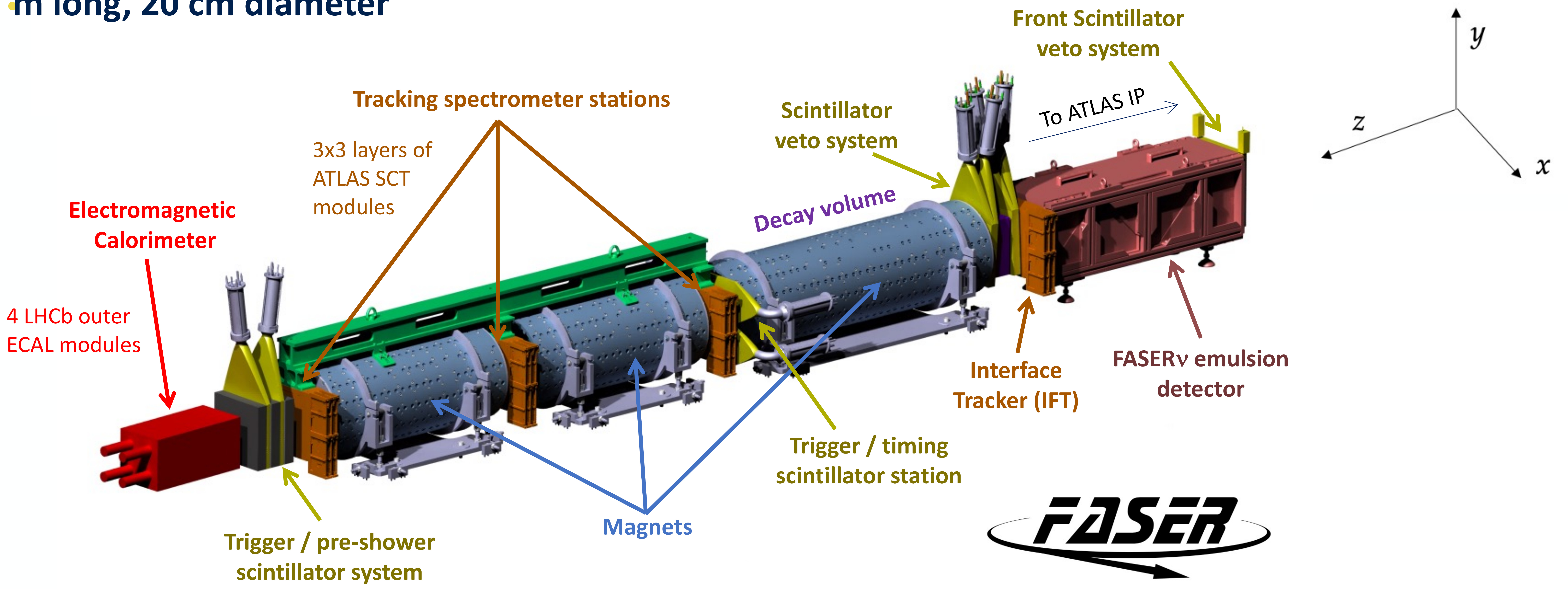
    $\sqrt{s} = 13.6$ TeV $\rightarrow \sim$ **100 PeV** in lab. frame energy

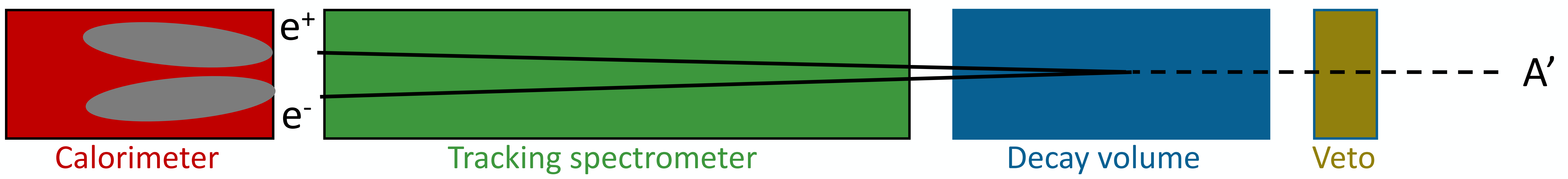




FASER detector

7 m long, 20 cm diameter

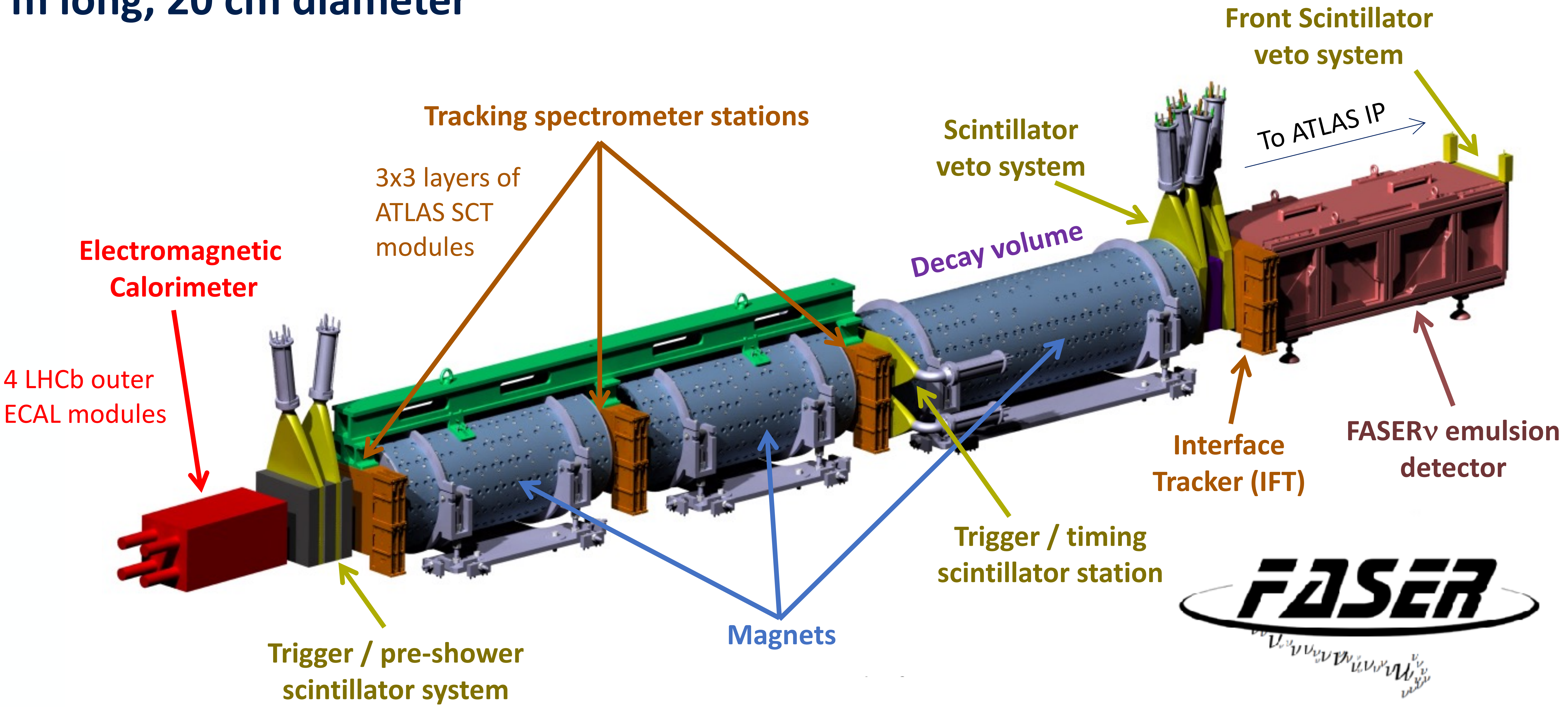


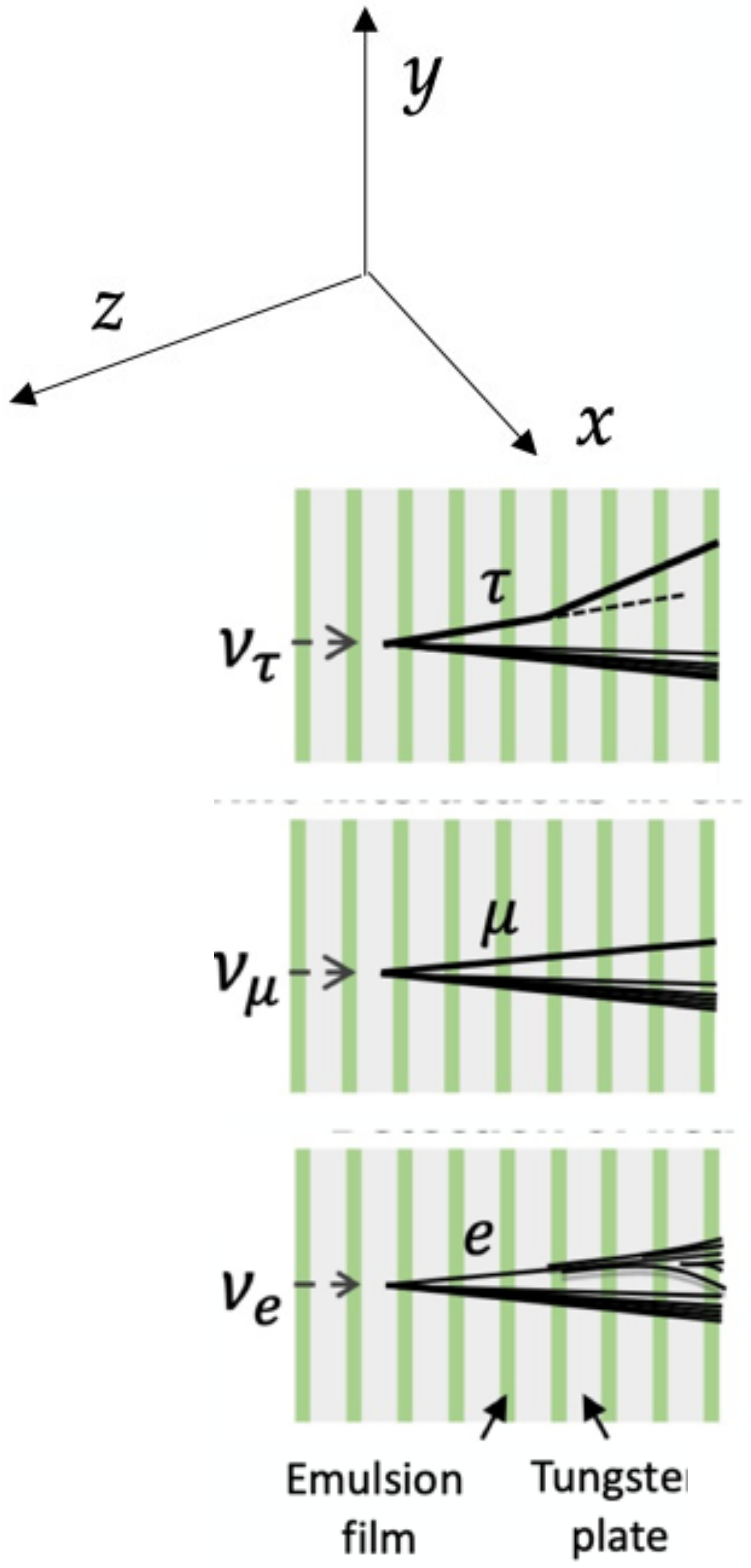


FASER signature for LLPs

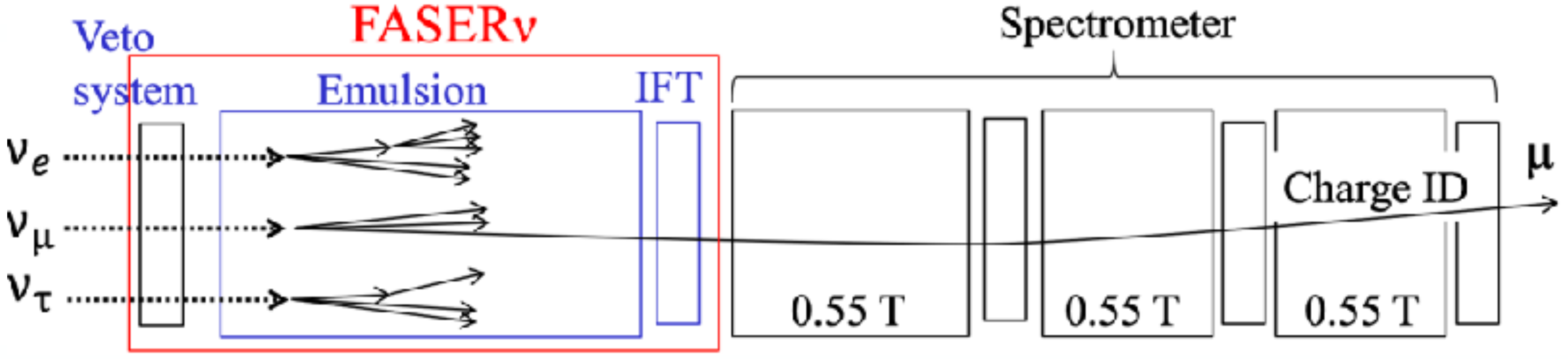
FASER detector

7 m long, 20 cm diameter

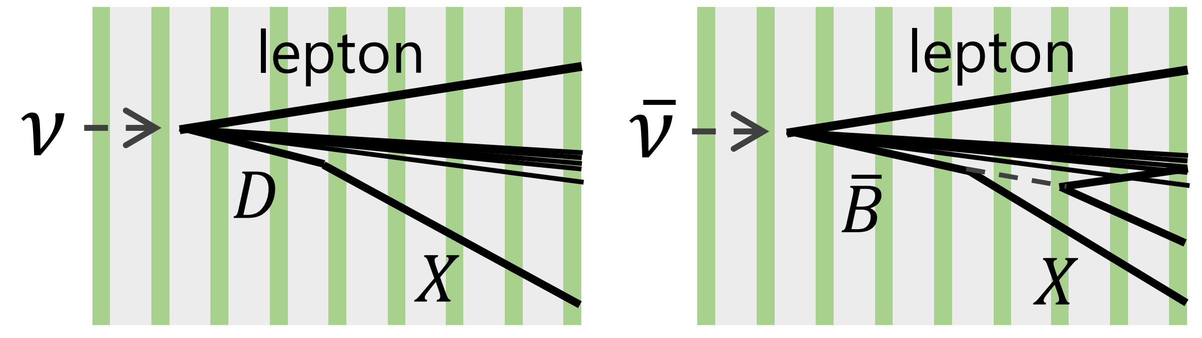




FASERν signatures for high energy neutrinos



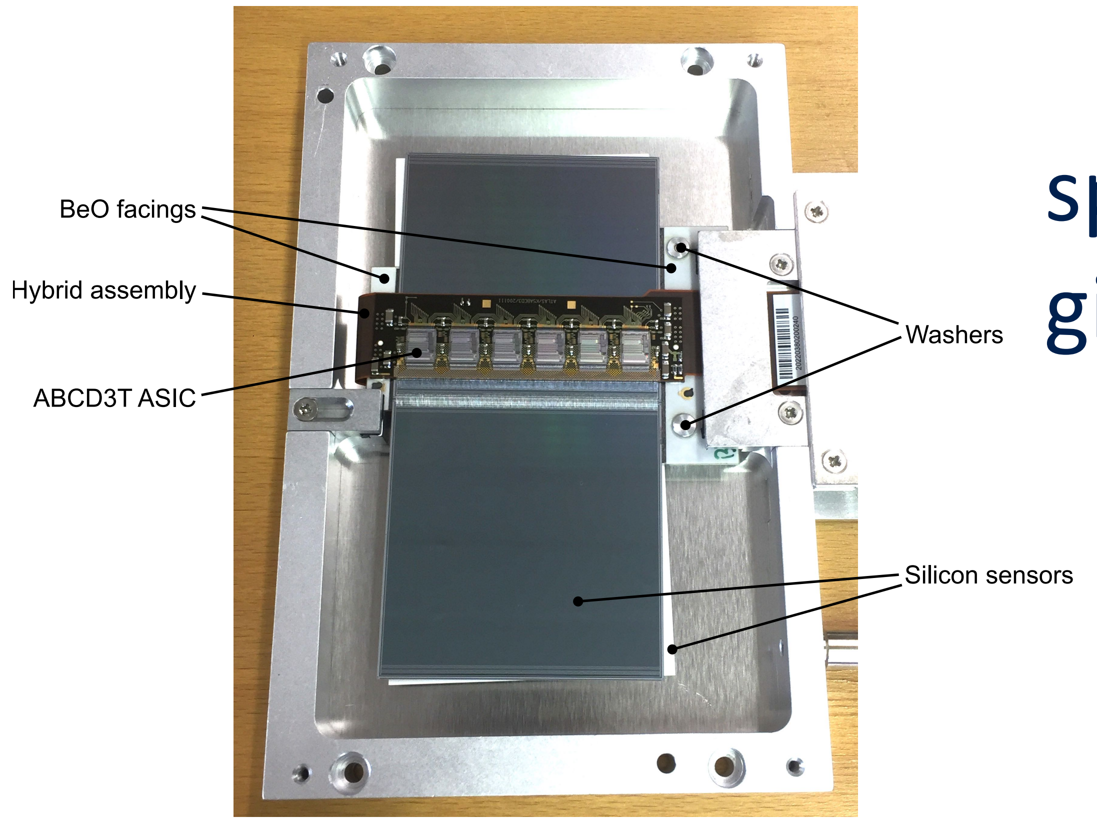
CC heavy quark production



FASER Tracking components

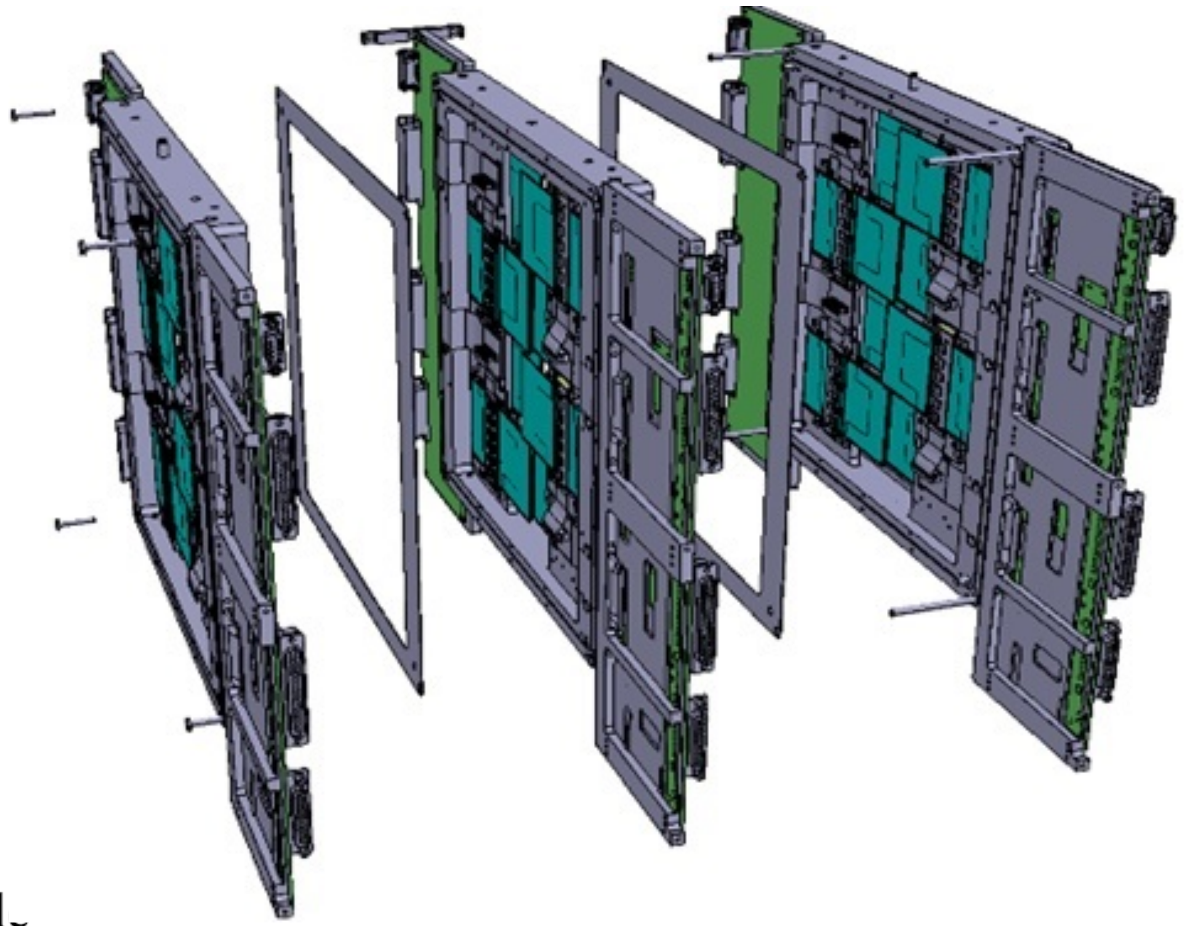
3 tracker stations + Interface tracker placed after the FASERν emulsion detector

Semiconductor Tracker (SCT) modules
→8 modules per tracker plane

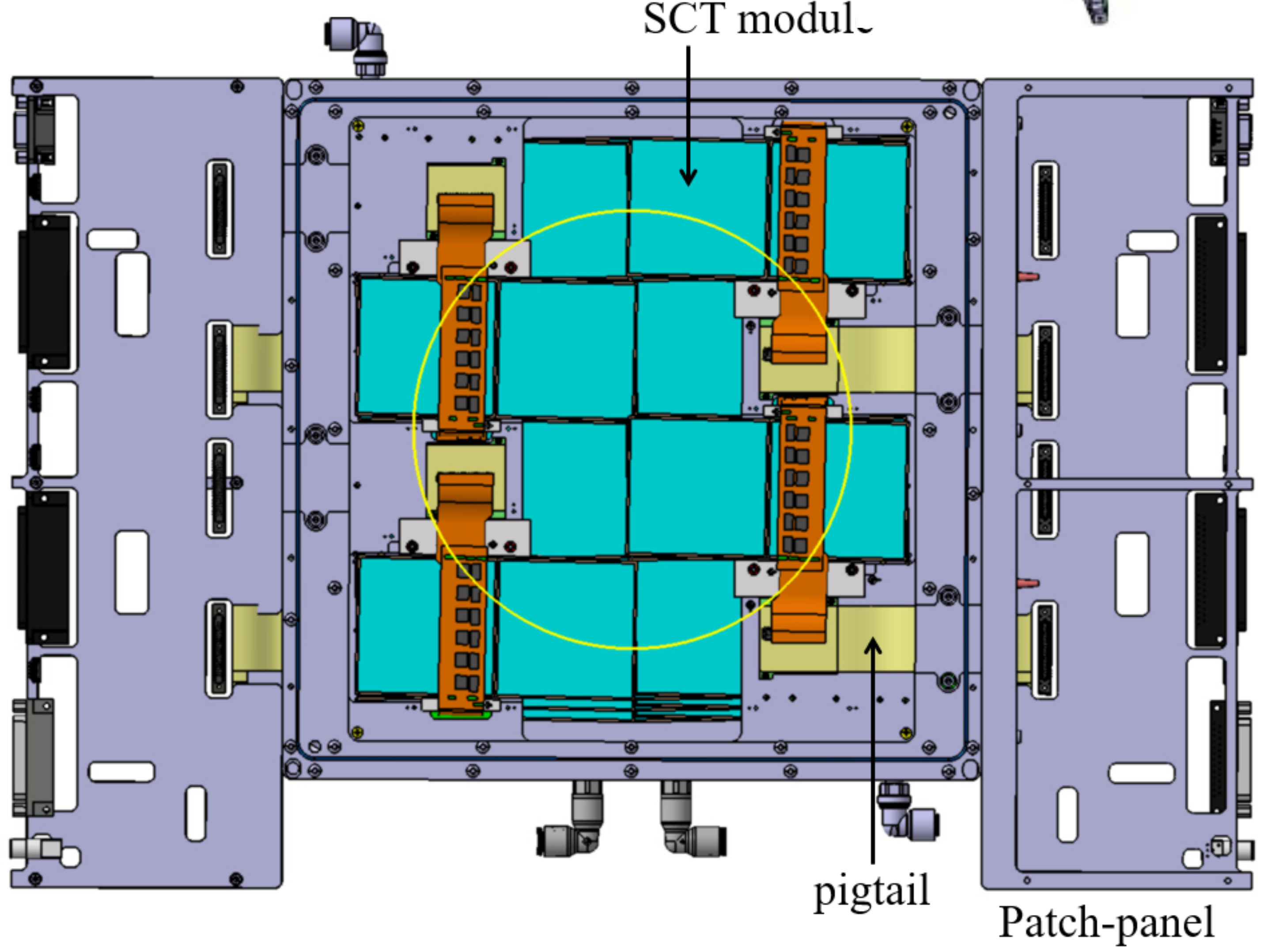


spare modules given by ATLAS

Tracker Station



Tracker Plane



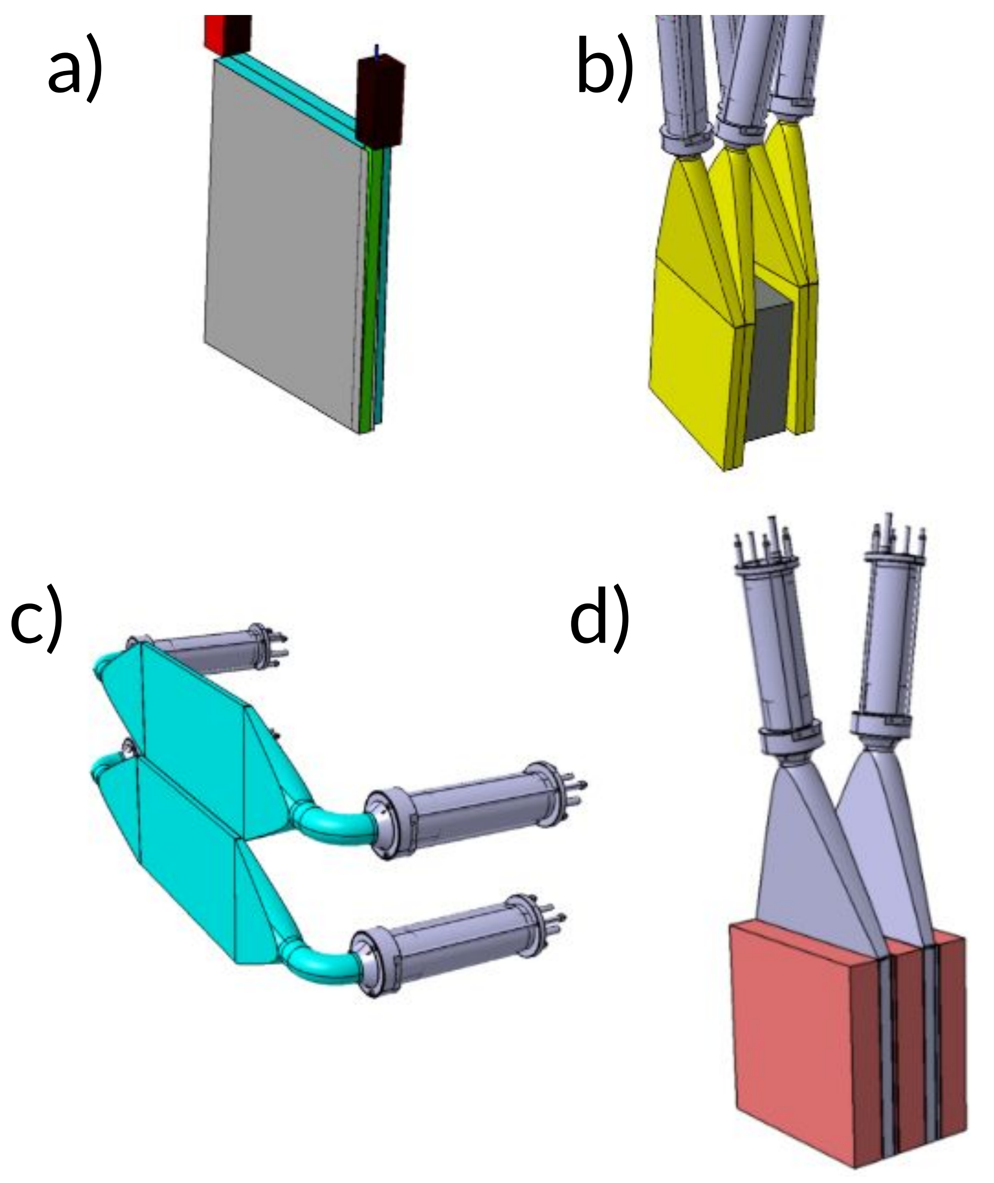
3 Tracker planes per station (12 in total)

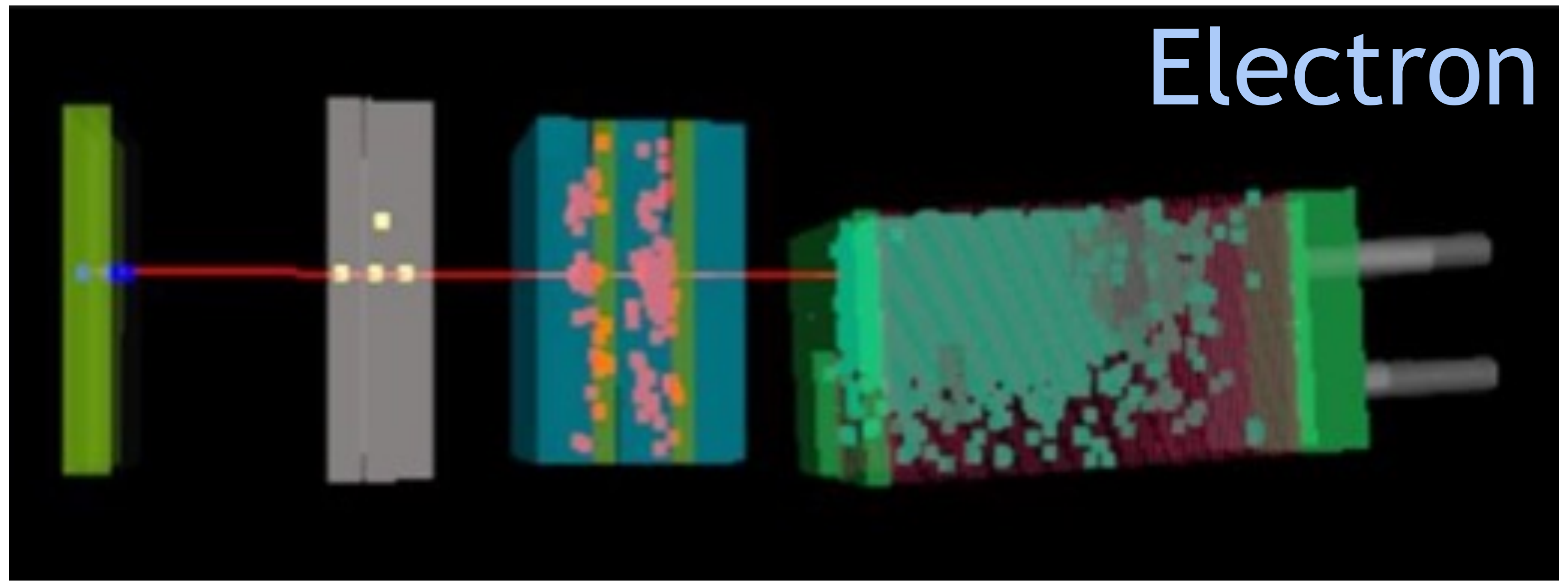
- 80µm strip pitch, 40mrad stereo angle (17µm / 580µm resolution)
  - precision measurement in bending (vertical) plane
  - 8 SCT modules give a 24cm x 24cm tracking layer

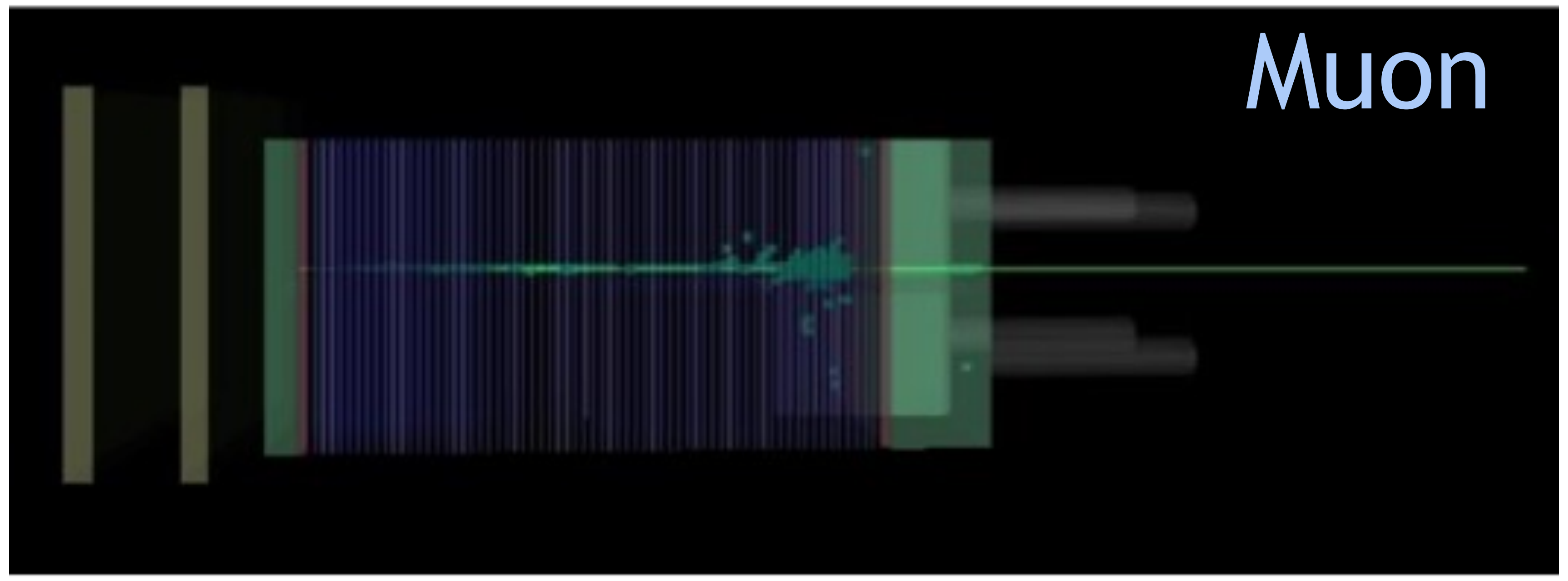
FASER calorimeter, pre-shower and scintillator systems

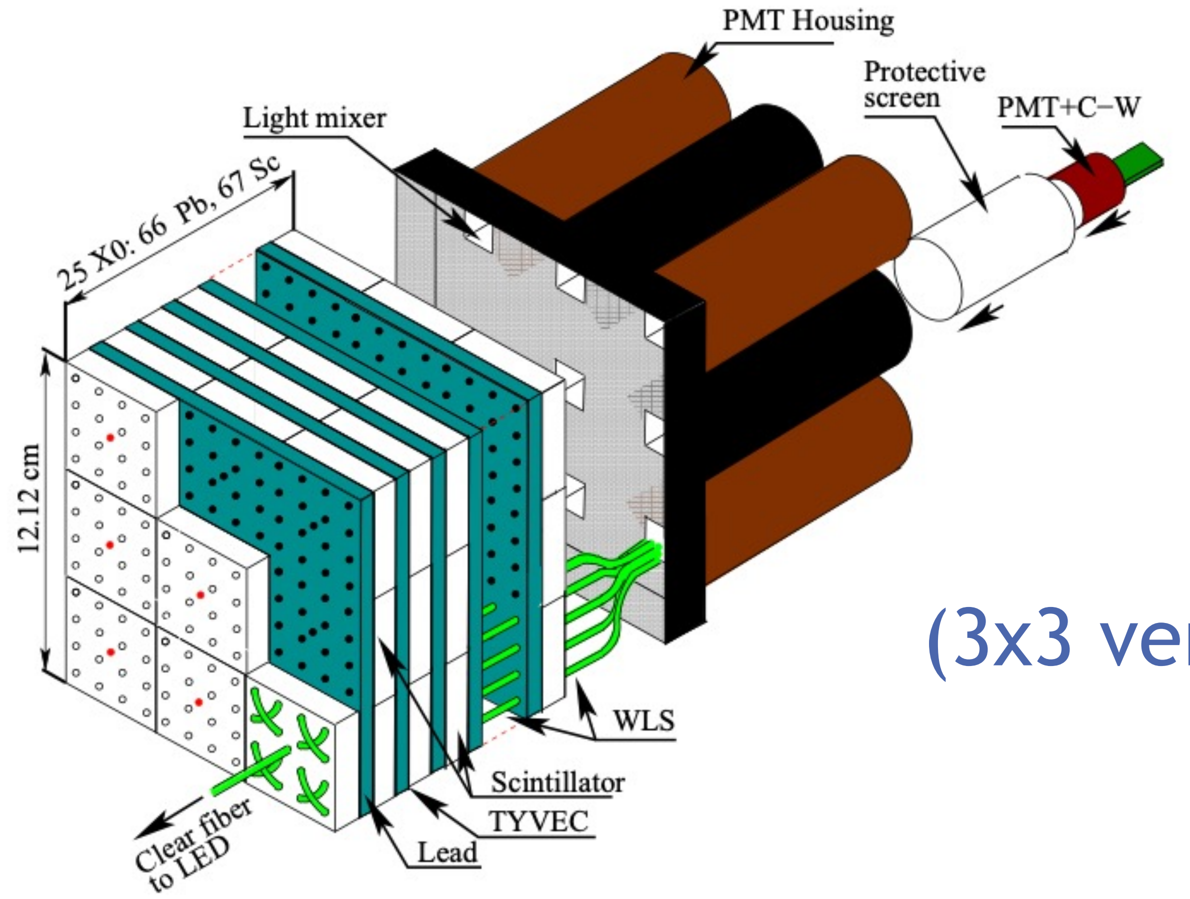
- **Four scintillator stations**
  - (a) FASERν (b) Interface Veto, (c) Timing, & (d) Preshower
  - **>99.98 % efficiency**, sufficient to **veto all incoming muons**
  - photo-multiplier tubes to detect the scintillation signals.

- **Electromagnetic calorimeter** made of spare **LHCb modules**
  - 66 layers of lead-scintillator plates read by 2x2 array of PMTs
  - 12 cm x 12 cm (25 X_0)
  - Simulated deposits for electrons and muons









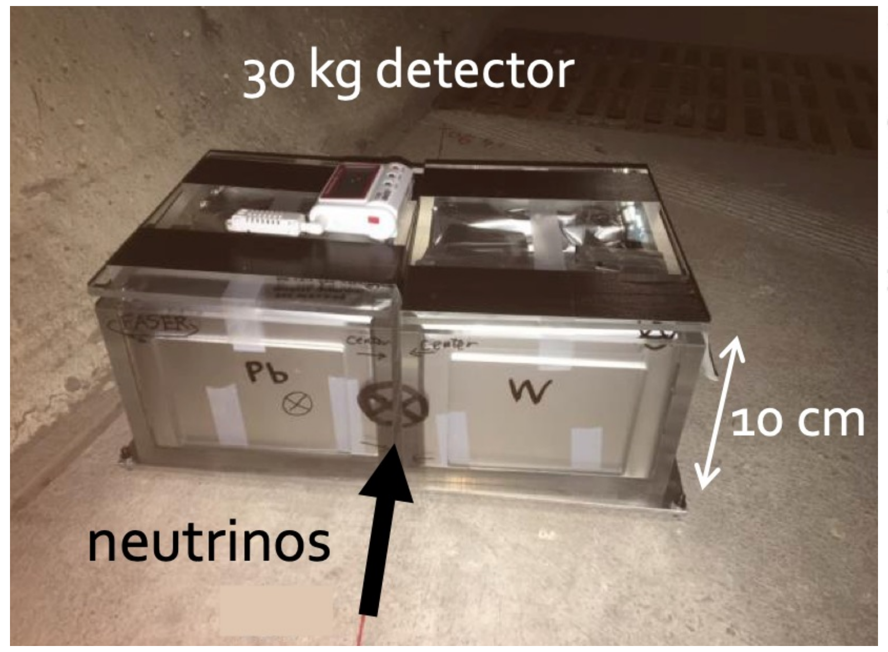
LHCb
(3x3 version)

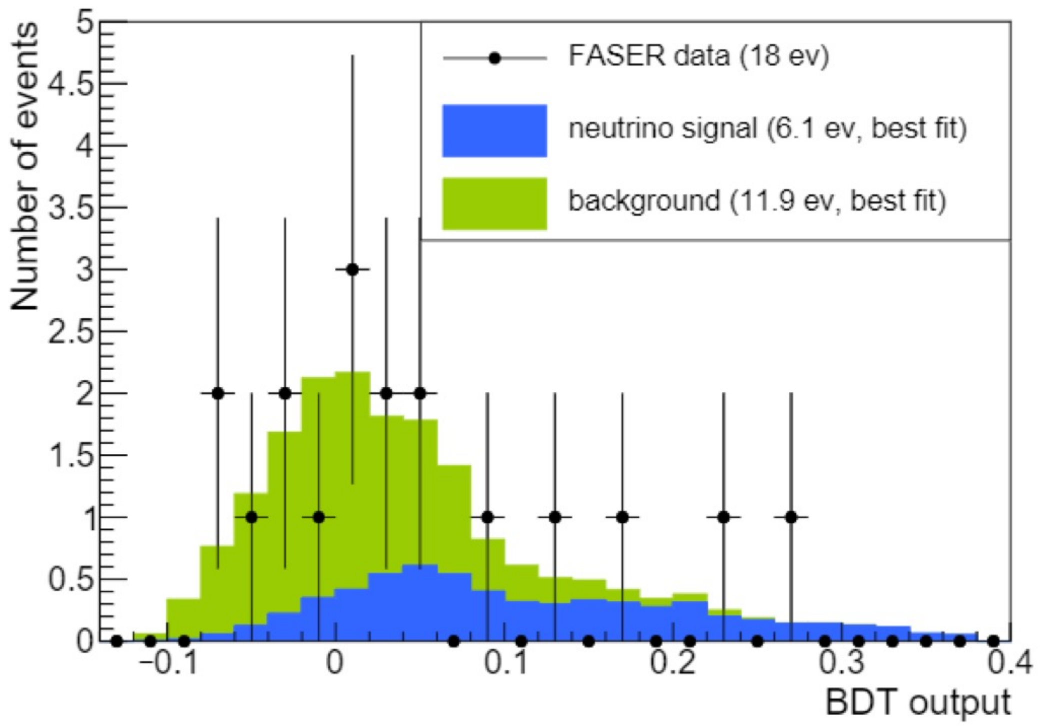
FASERν Emulsion/Tungsten detector

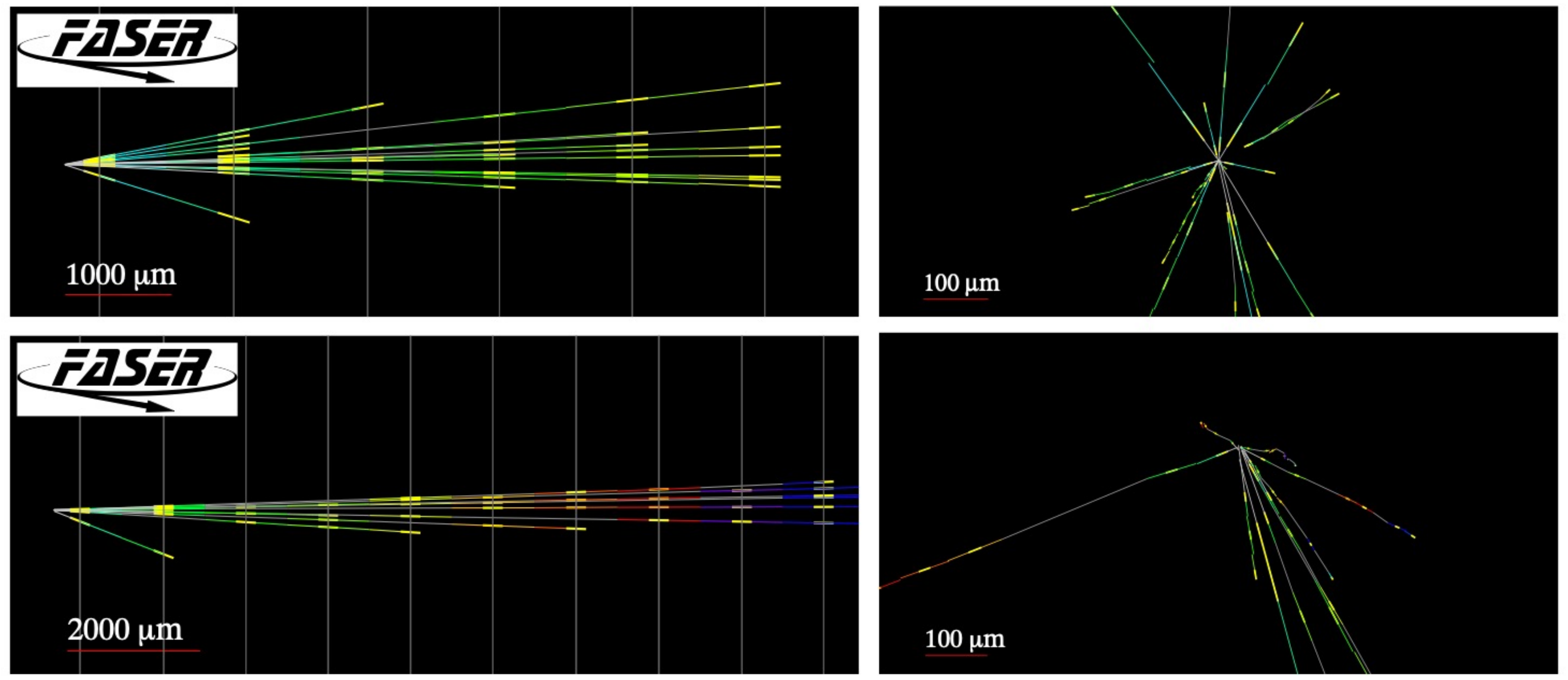
- **730 layers of an emulsion film and 1.1 mm tungsten plate**
  25 cm × 30 cm × 1.1 m, **1.1 tons**, 220 X_0

- In 2018, pilot detector (30 kg) exposed in TI18 for 1.5 month
  - **Observed (2.7σ) first collider neutrino candidates!**

- FASERν will be exchanged frequently during Run 3
  - Partial detector (~30% films): 15th March - 26 th July
  - First full detector (TS1): 26 th July – 13 th Sept
  - Second detector (TS2): 13 th Sept – 8 th Nov
- Regularly exchanged (∼**every 3 months**) to keep a manageable occupancy







Emulsion Film Production → Detector Assembly → Exposure → Development → Full Area Readout → Reconstruction

Ship to CERN | Install in Ti12 | Disassemble | Ship to Japan

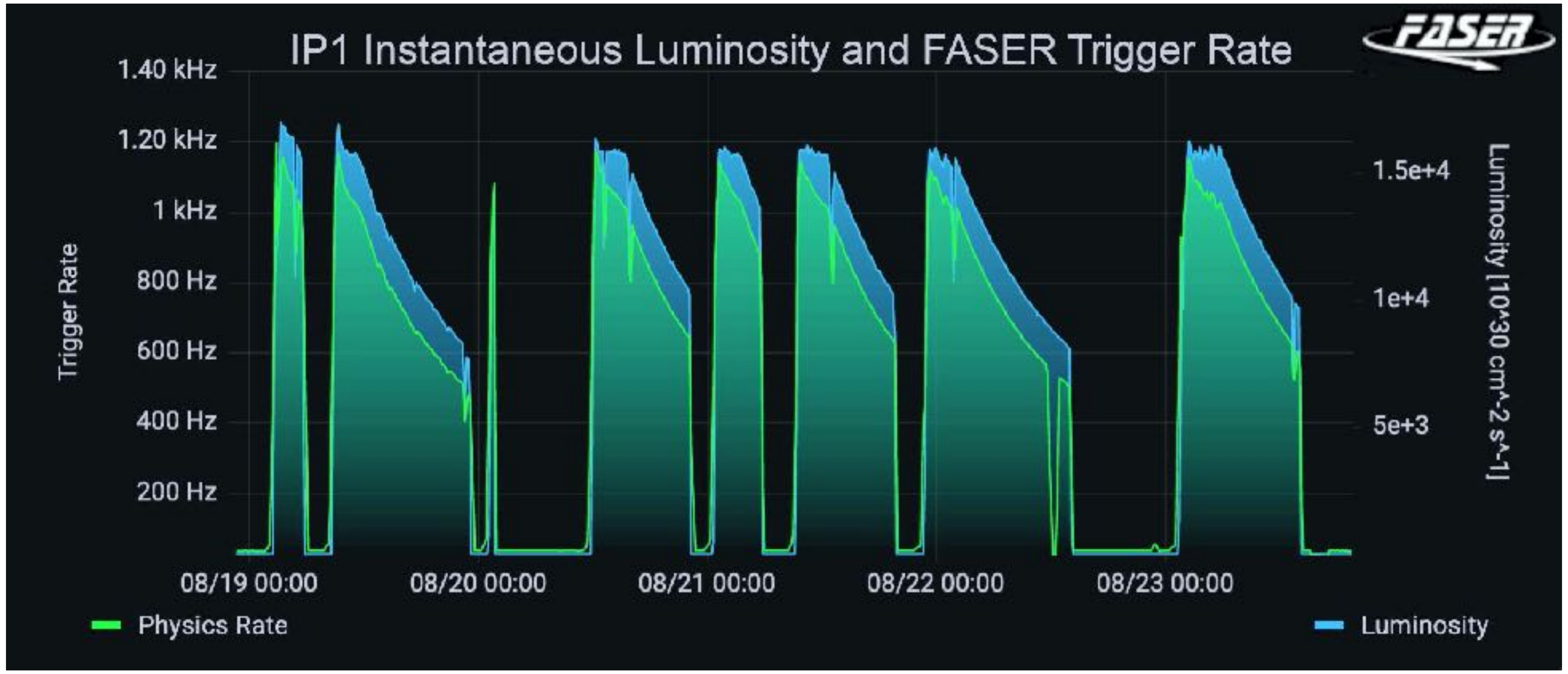
All detector components are successfully installed in T12 in March 2022

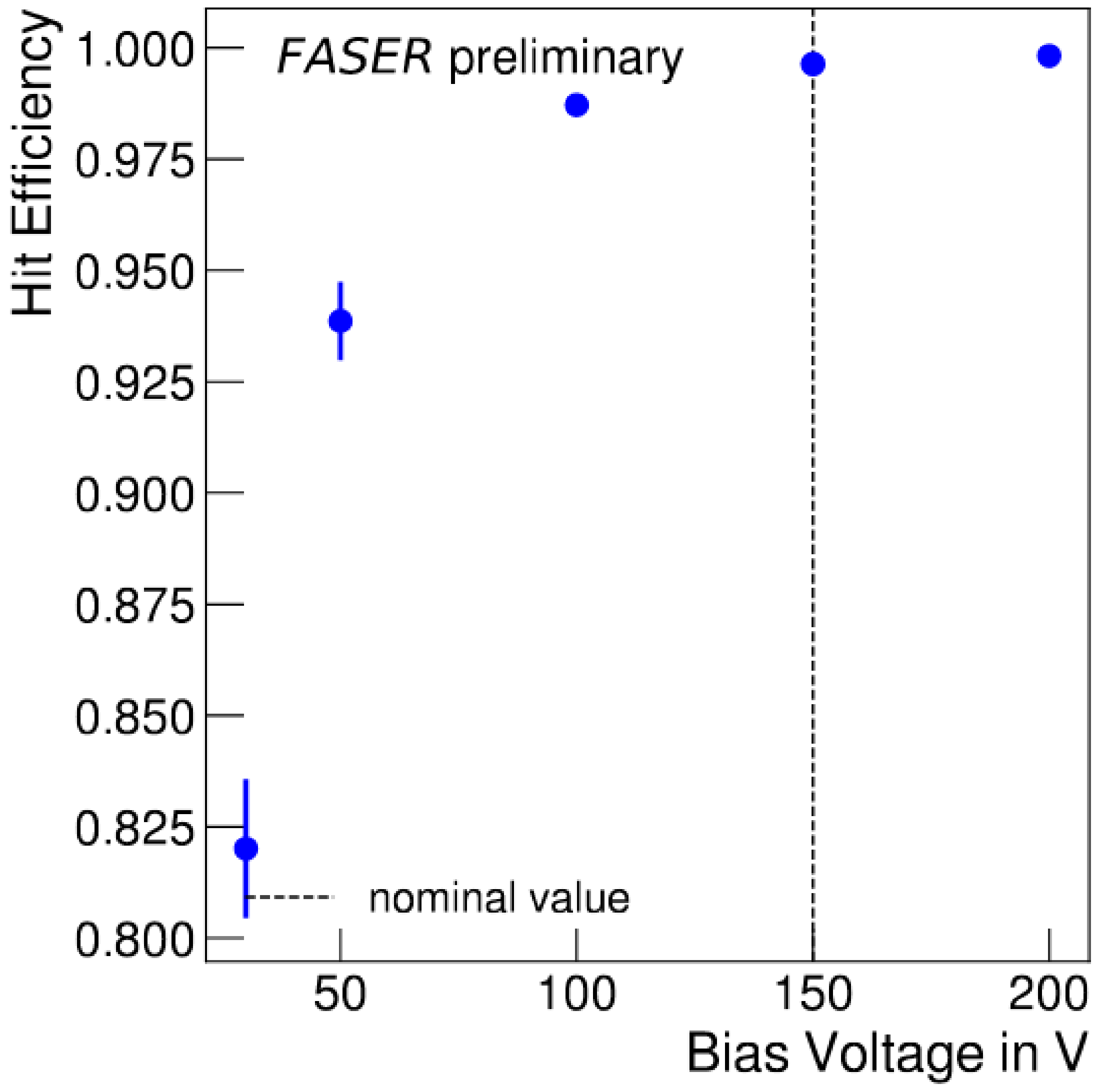
Particles from ATLAS

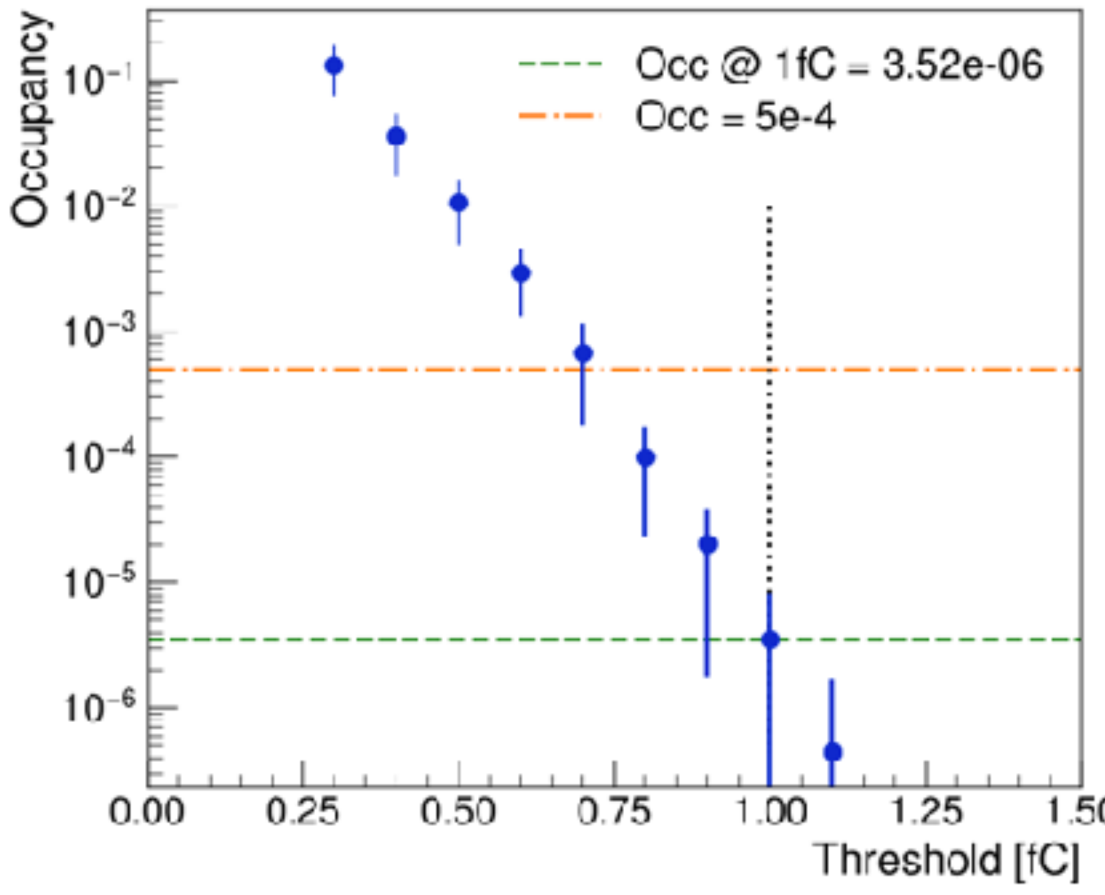
Run 3 data-taking and early performace

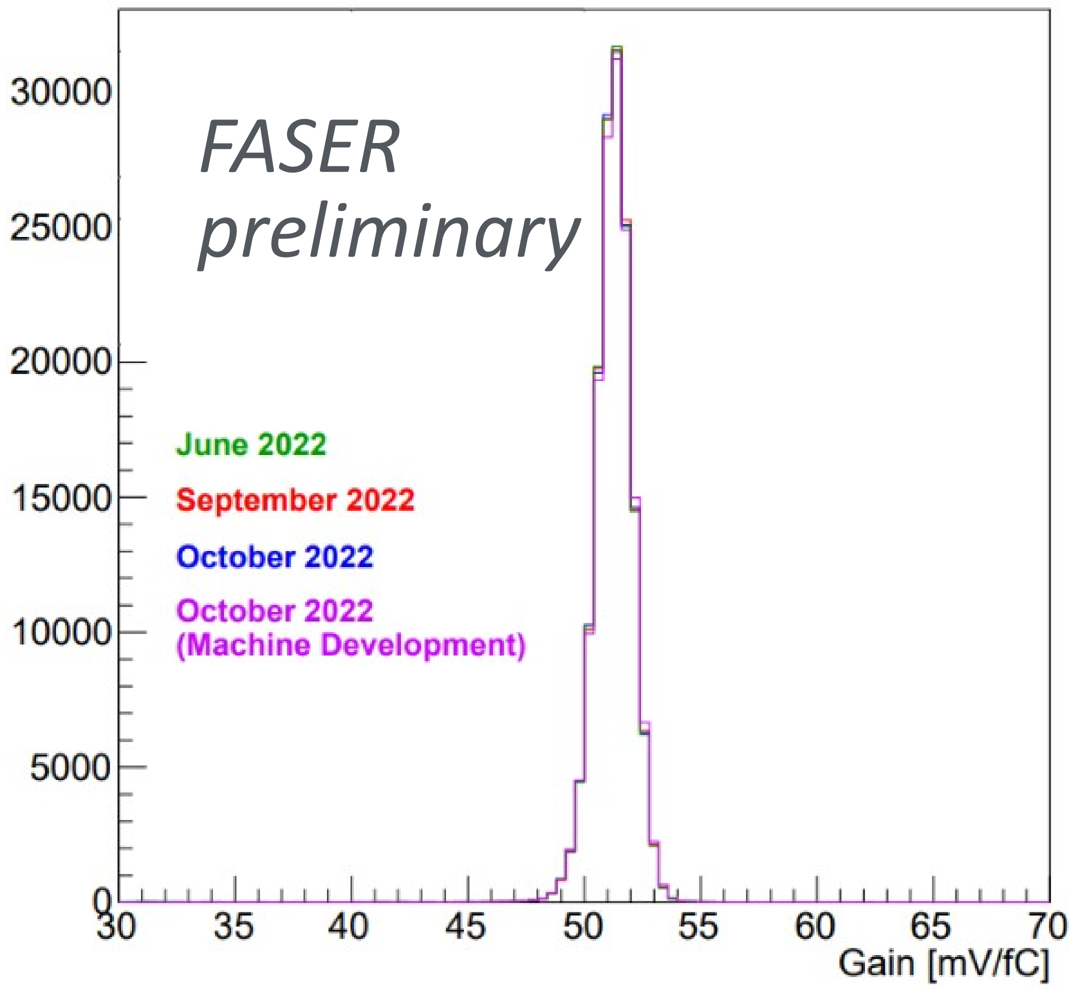
Since July 2022 $\sqrt{s}$ = 13.6 TeV collision data has been collected

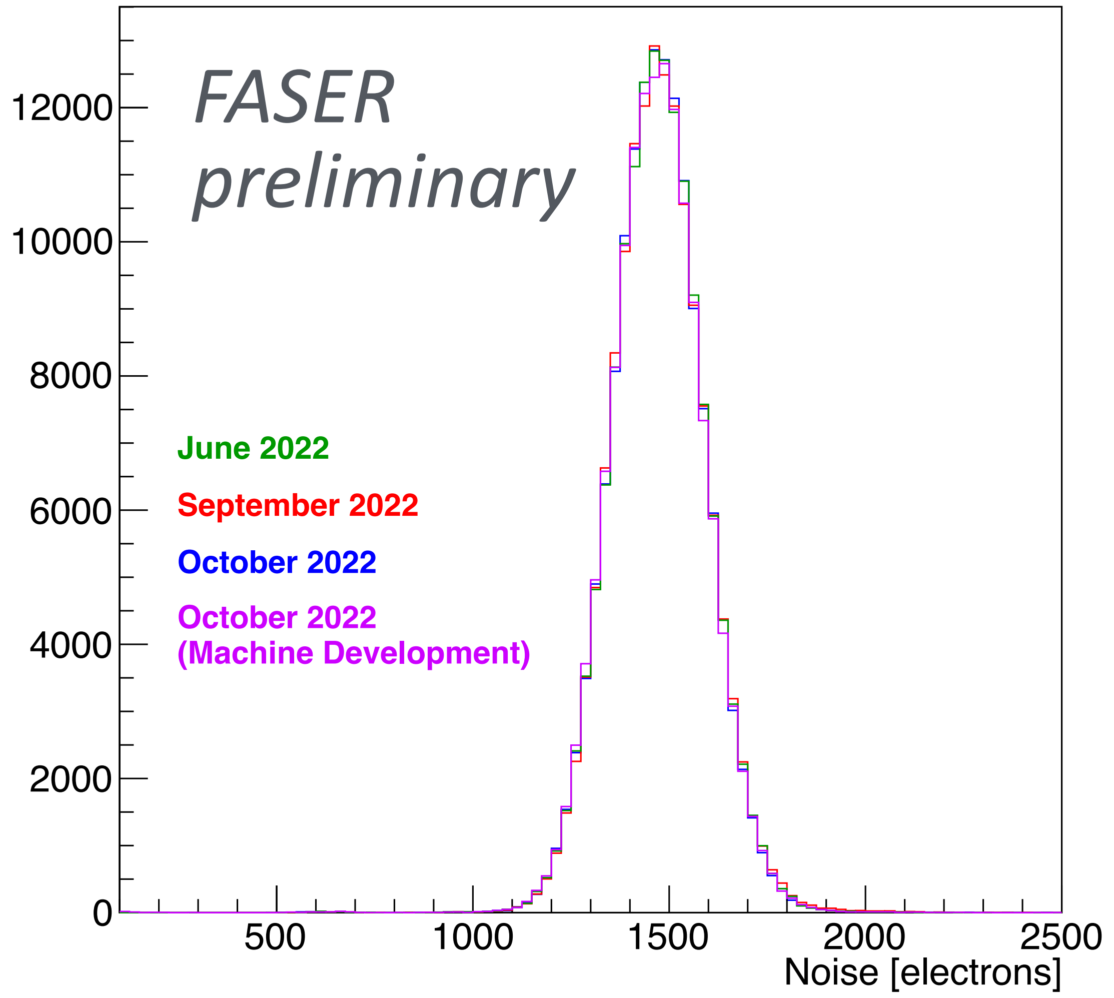
- More than L_{int}= 24 fb^{-1} data has been recorded to date
- Maximum trigger rate is about 12 kHz
- **With early data**, trying to check the detector performance
  - **Finalize the configuration** for the detector operation
- **Keep monitoring** the performance **by regular calibration runs**
  - very stable operation since the data-taking started



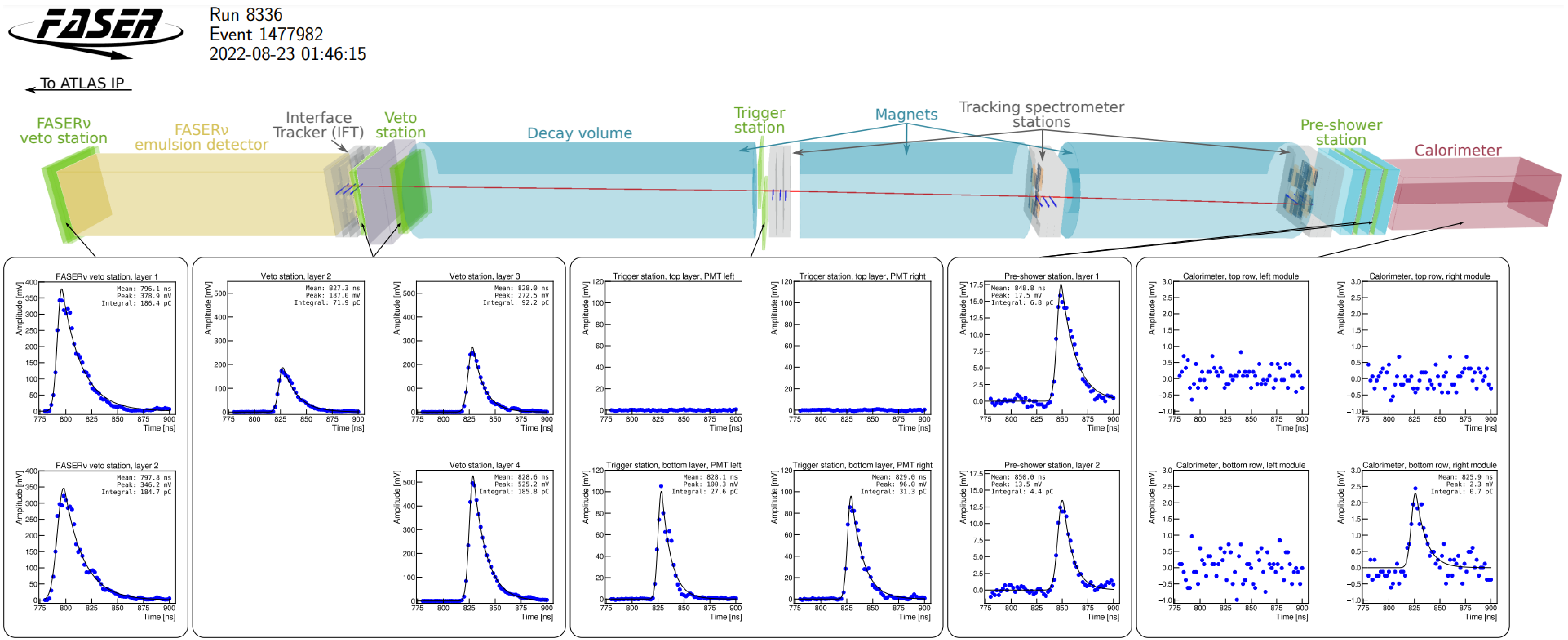








Run 3 Data: August 2022 Event Displays



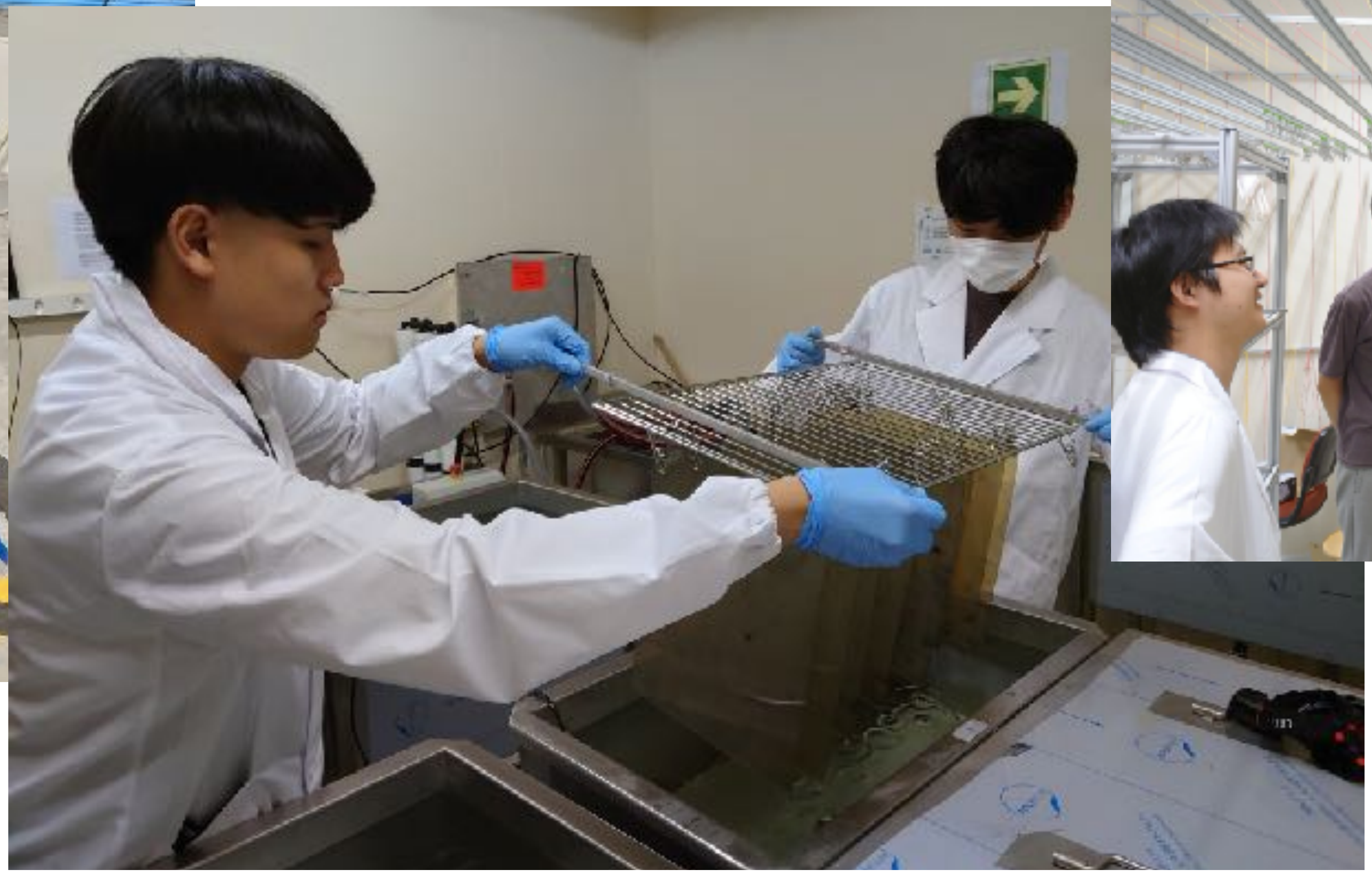
Waveform fits consistent with MIP

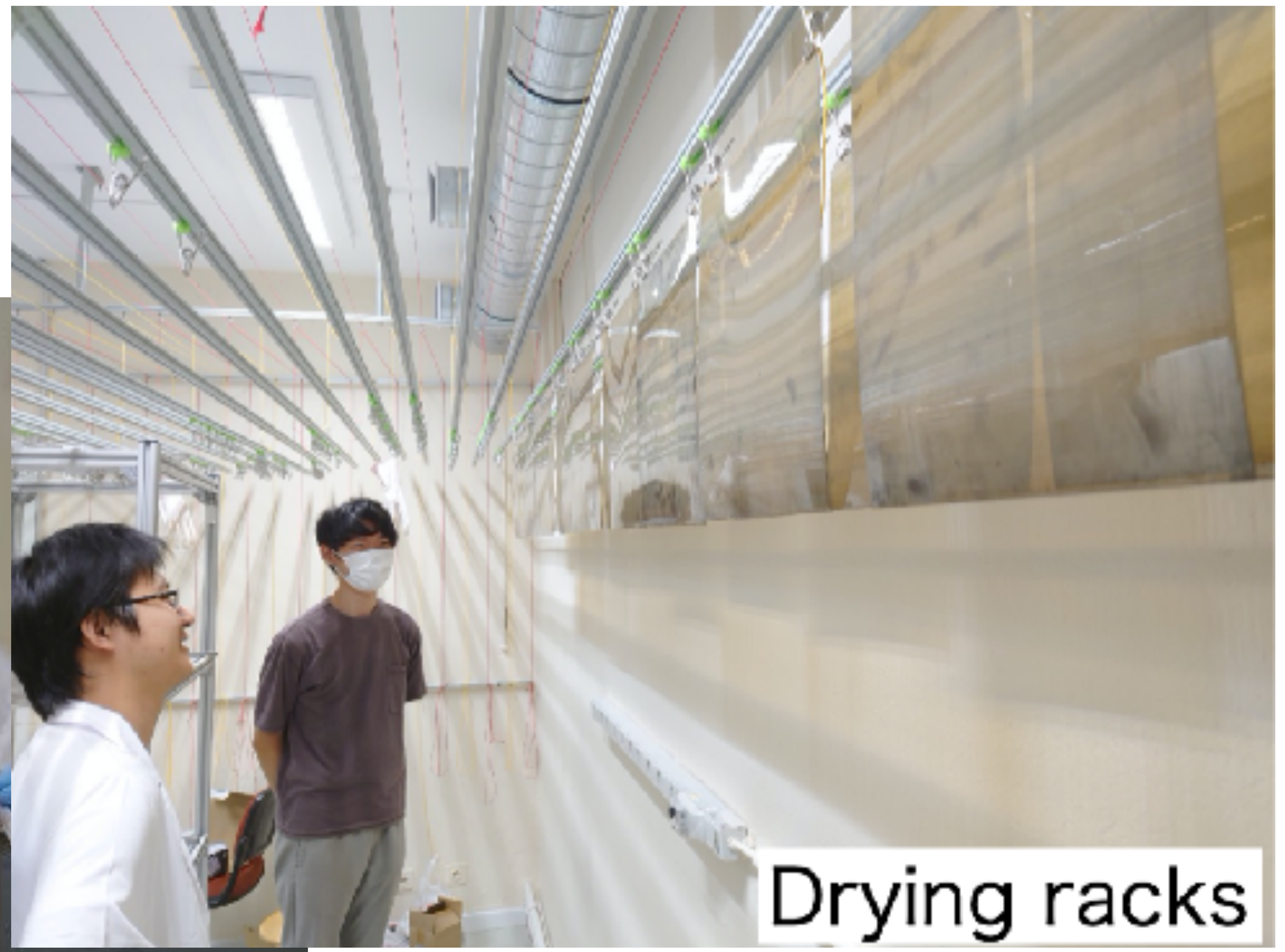
FASERν installation, operation and readout

Since March 2022, we keep collecting data with FASERν

- Detector is assembled in dark room **at the emulsion facility in CERN**
- Installation to TI12 can be done within a single day
- After exposures, **films are developed and dried at CERN**
- **Scanning films** are performed by the facility at Nagoya University in Japan after transportation

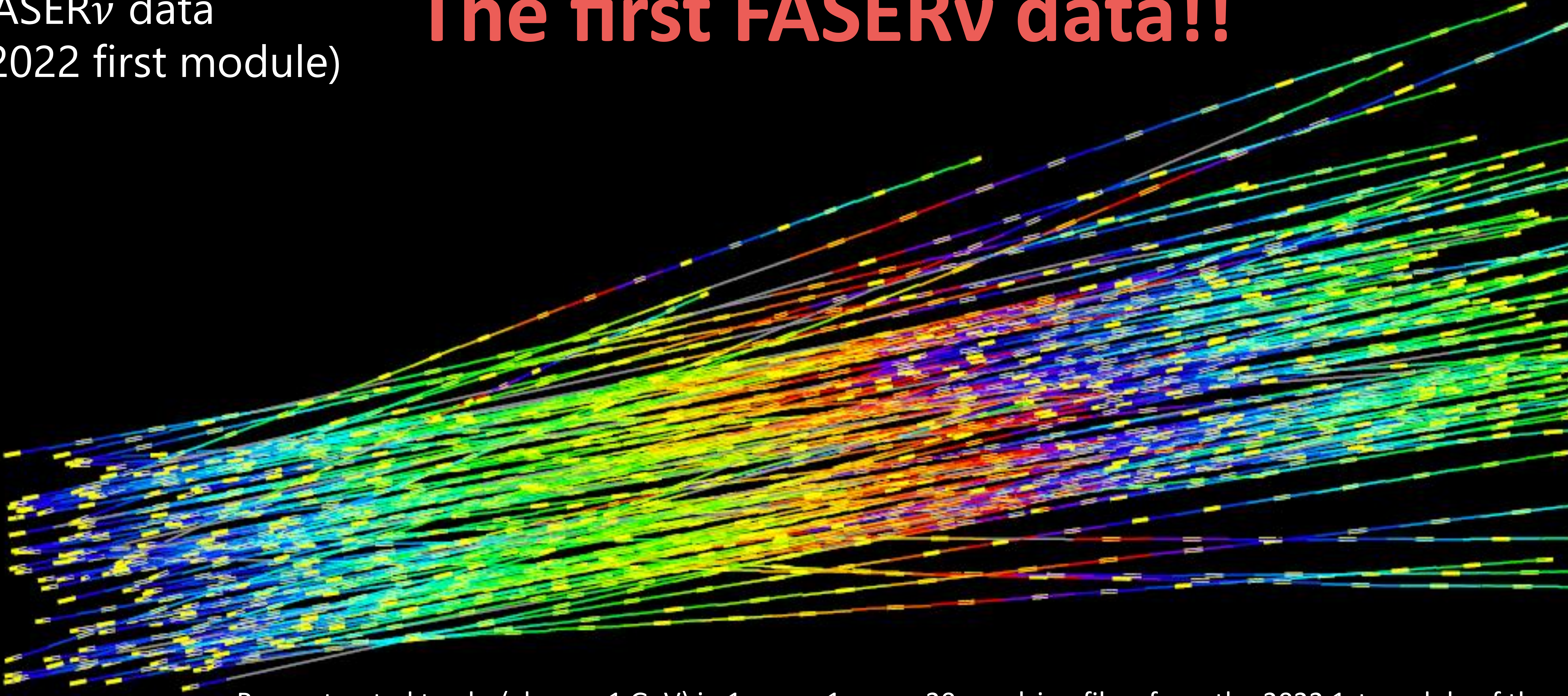
		Integrated luminosity per module (fb^{-1})	N ν int. expected
2022 1st module	Mar 15 – Jul 26	0.5	~7
2022 2nd module	Jul 26 – Sep 13	10.6	~530
2022 3rd module	Sep 13 – Nov 29	(~20)	(~1000)





FASERν data
(2022 first module)

The first FASERν data!!



500 μm

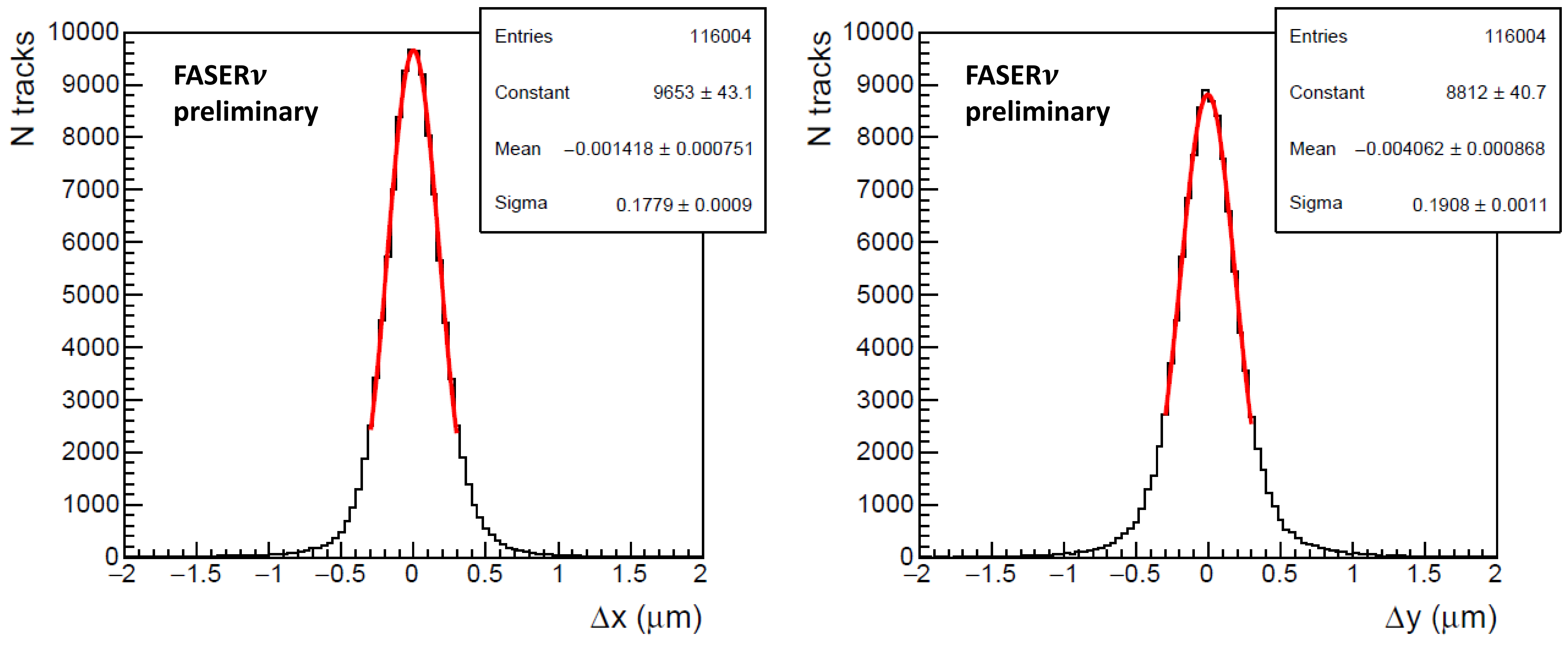
Reconstructed tracks (above ~1 GeV) in 1 mm × 1 mm × 20 emulsion films from the 2022 1st module of the FASERν detector, which collected 0.5 fb^{-1} of data.

The track density measured in the data sample is 1.2×10^4 /cm^2, corresponding to 2.3×10^4 /cm2 /fb^{-1}

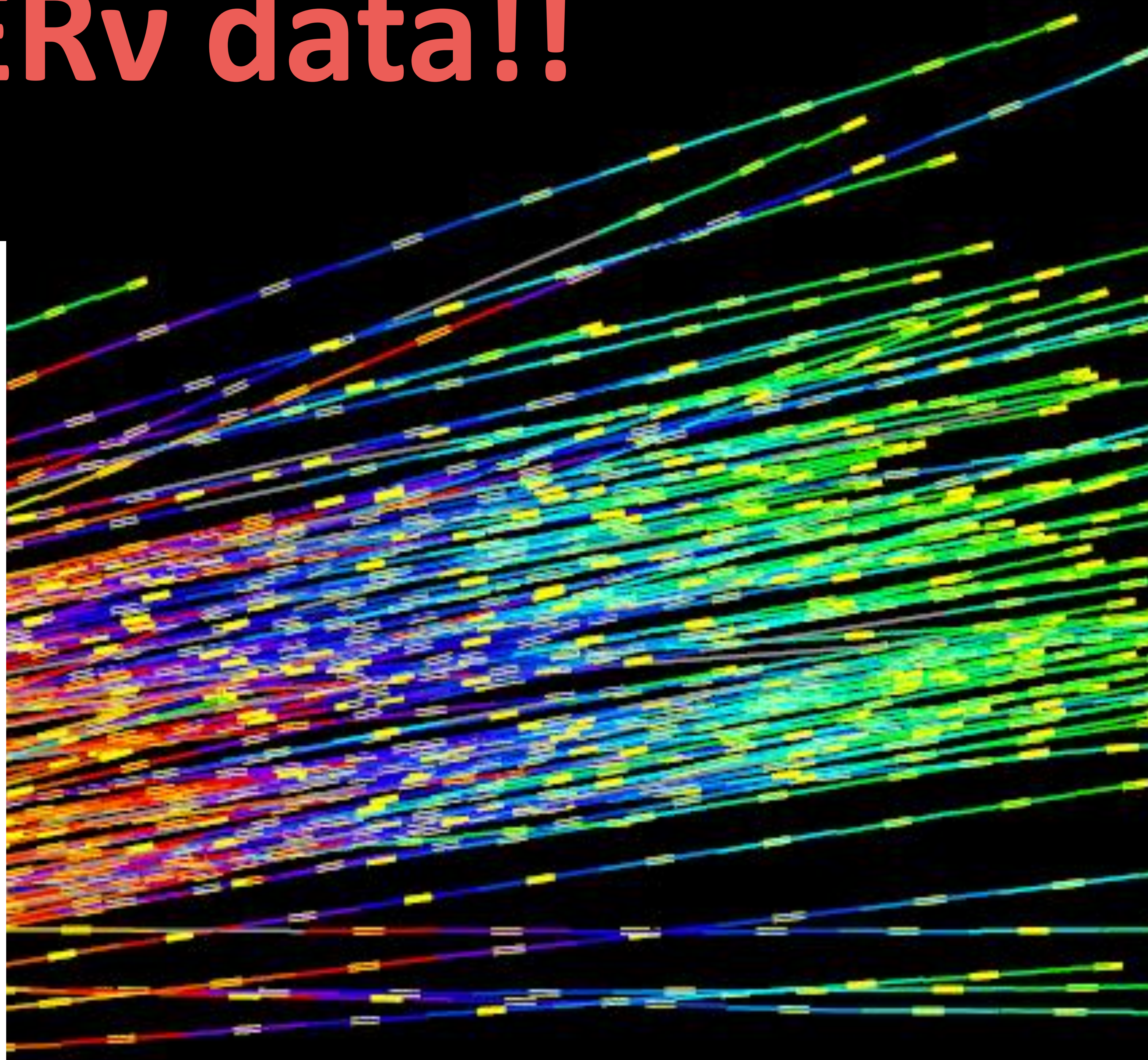
The first FASERν data!!

FASERν data
(2022 first module)

First data: Position deviation



~**0.2 μm** for the case dedicated alignment is applied to 10 emulsion films

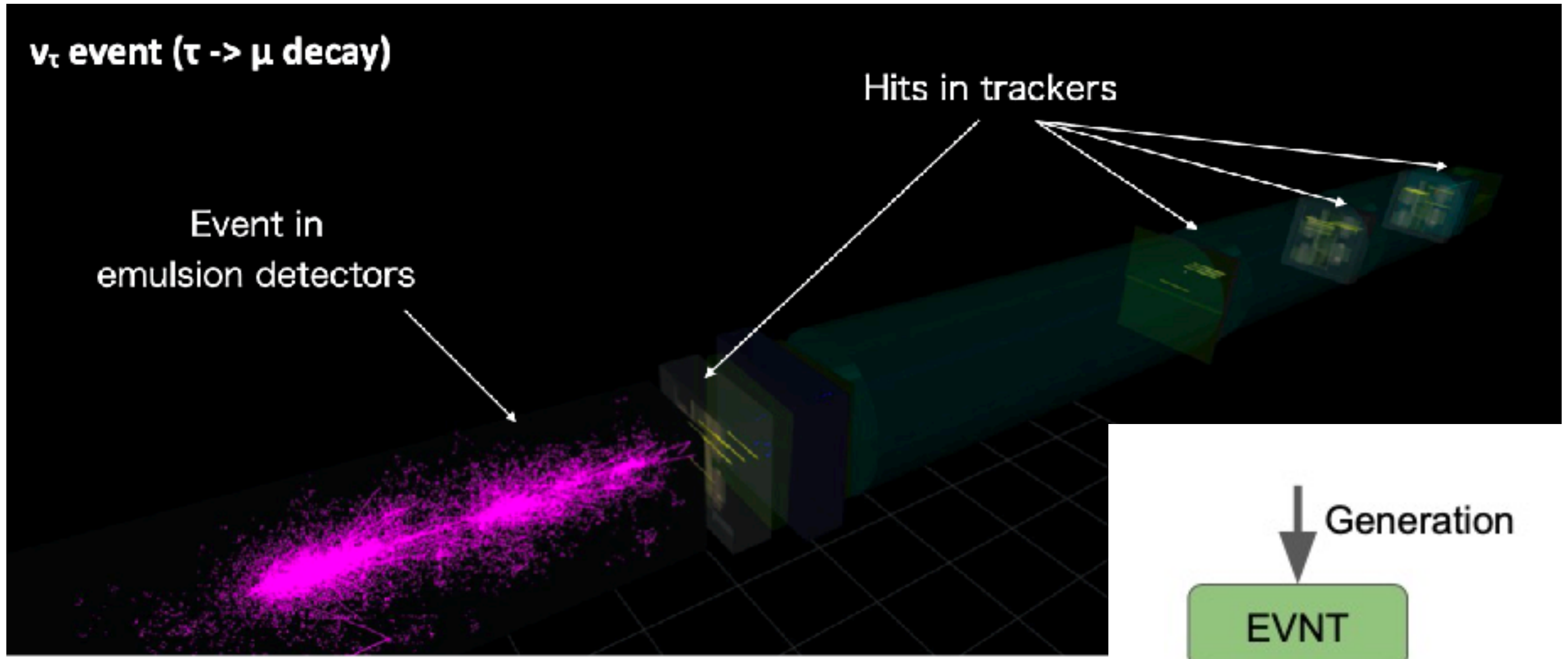


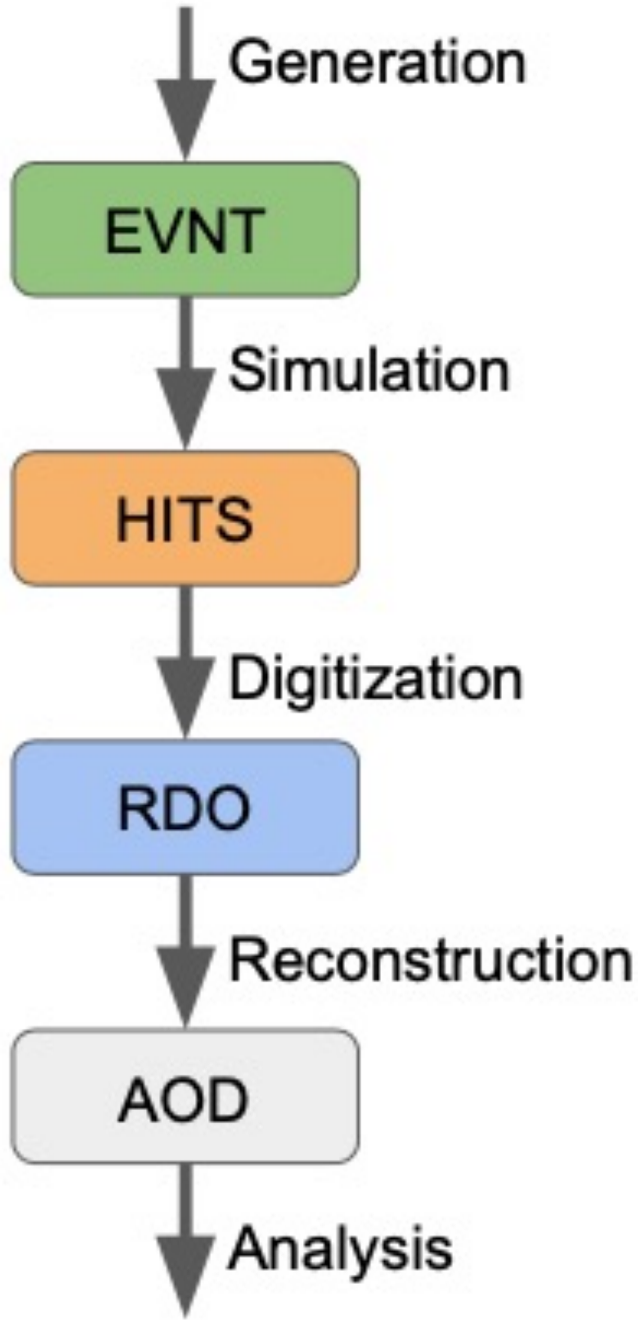
Reconstructed tracks (above ~1 GeV) in 1 mm × 1 mm × 20 emulsion films from the 2022 1st module of the FASERν detector, which collected 0.5 fb^{-1} of data.

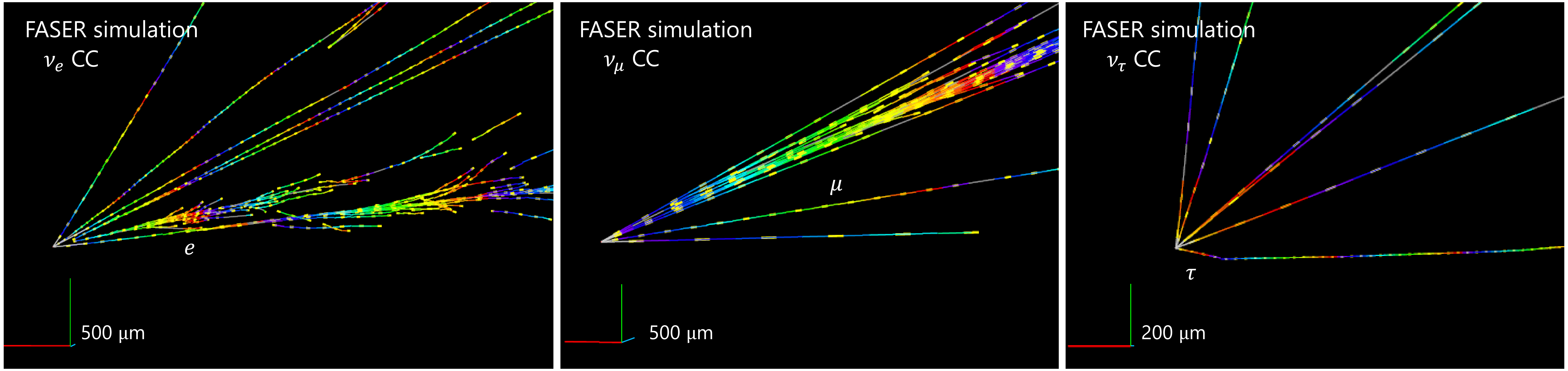
The track density measured in the data sample is 1.2×10^4 /cm², corresponding to 2.3×10^4 /cm2 /fb^{-1}

Readiness of data analysis

- **FASER offline analysis software, Calypso**
  - Based on "Athena" for ATLAS offline reco.
    - Enable to test several types of **generators**
    - **Genie & FLUKA** used for **neutrinos** studies and **muon-induced background**
  - The geometry is validated and analysis pipeline is fully ready.



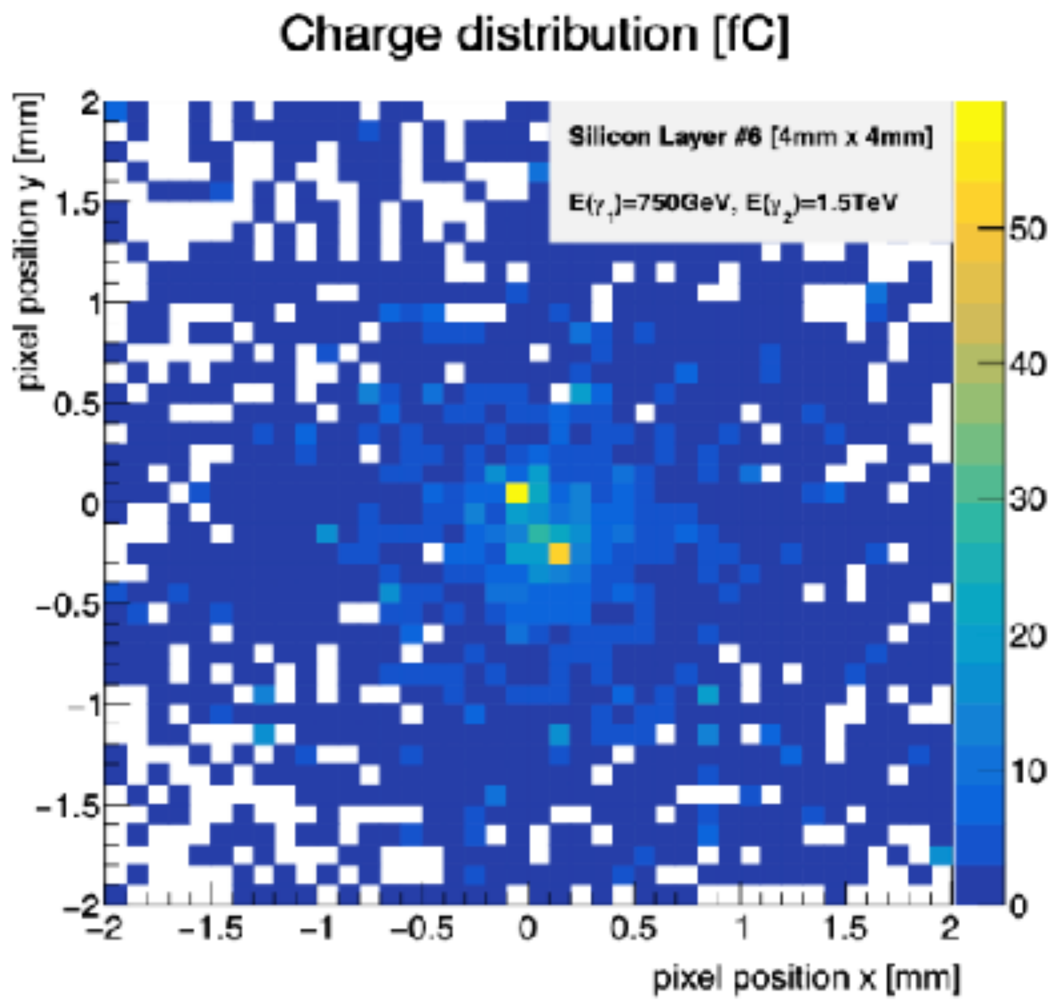


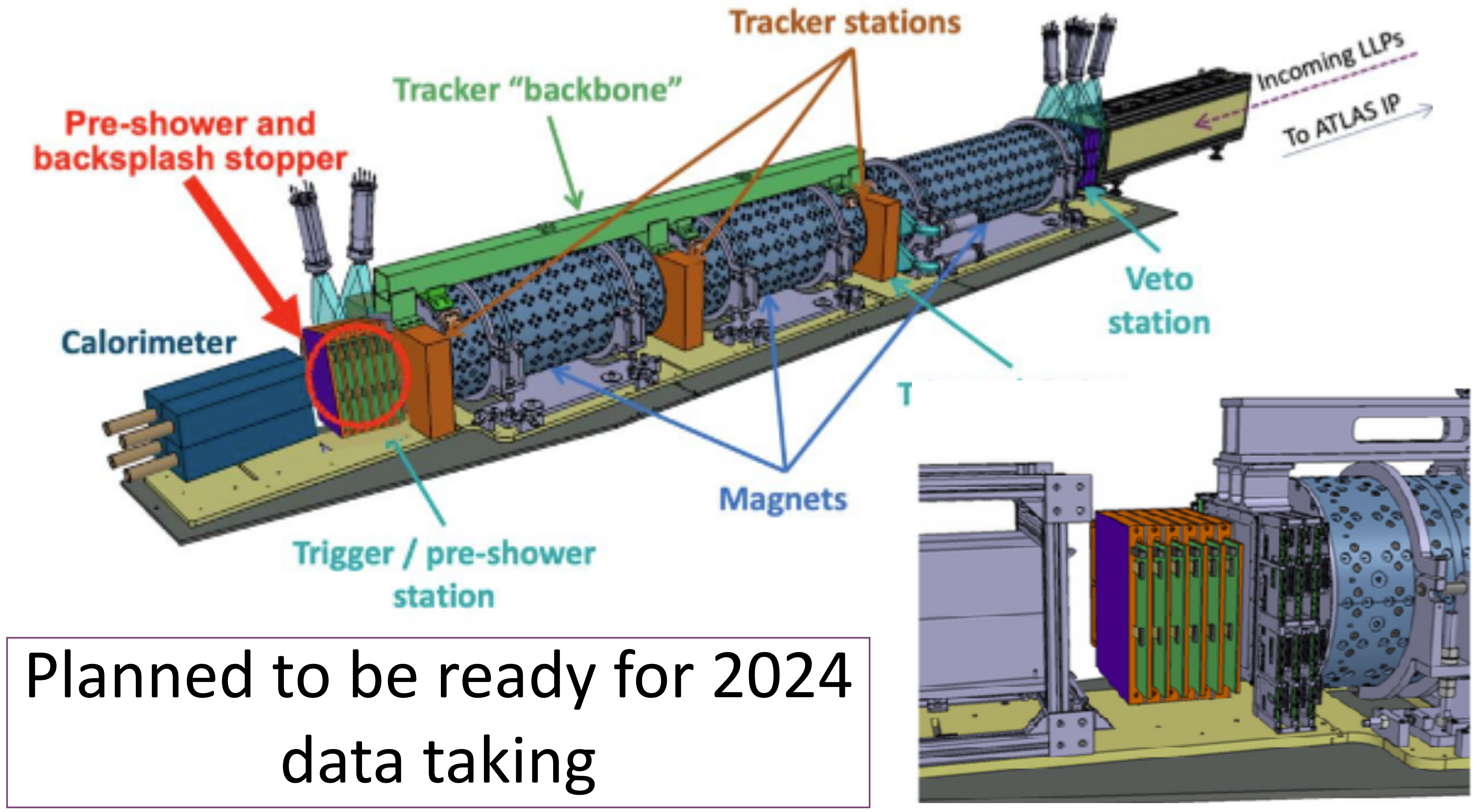


Future upgrade plan

- **Upgrade to enable 2-γ physics**
  - enable to measure Axion Like Particles and long live particles decaying into two photons
  - **current preshower to be replaced with a high-resolution silicon pre-shower detector using monolithic pixel ASICs**
    - hexagonal pixels of 65 µm side

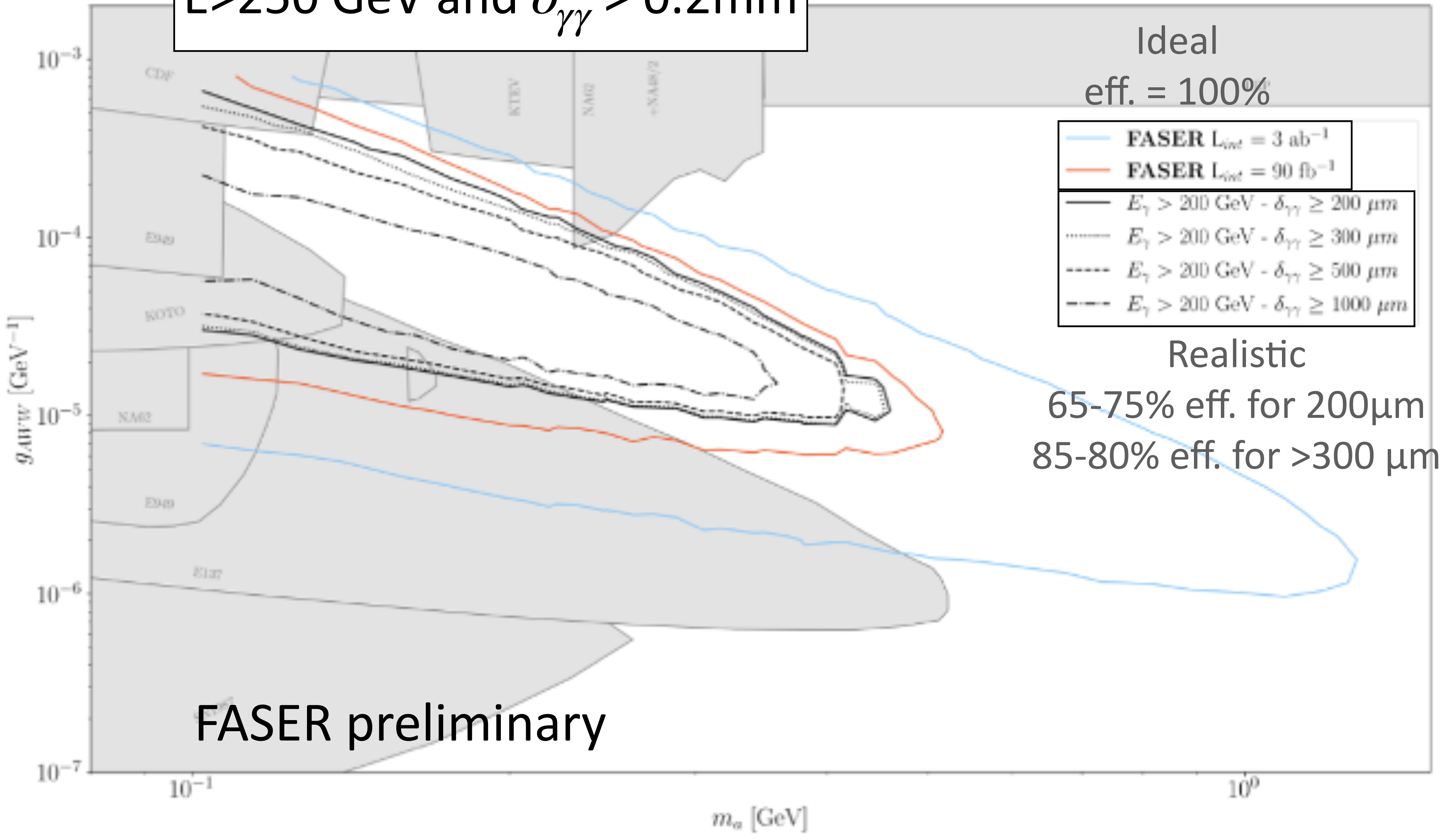
200 µm between two photons
Distinguishable





Planned to be ready for 2024 data taking

2-photon pairs with
E>250 GeV and $\delta_{\gamma\gamma}$ > 0.2mm



Physics Beyond Colliders

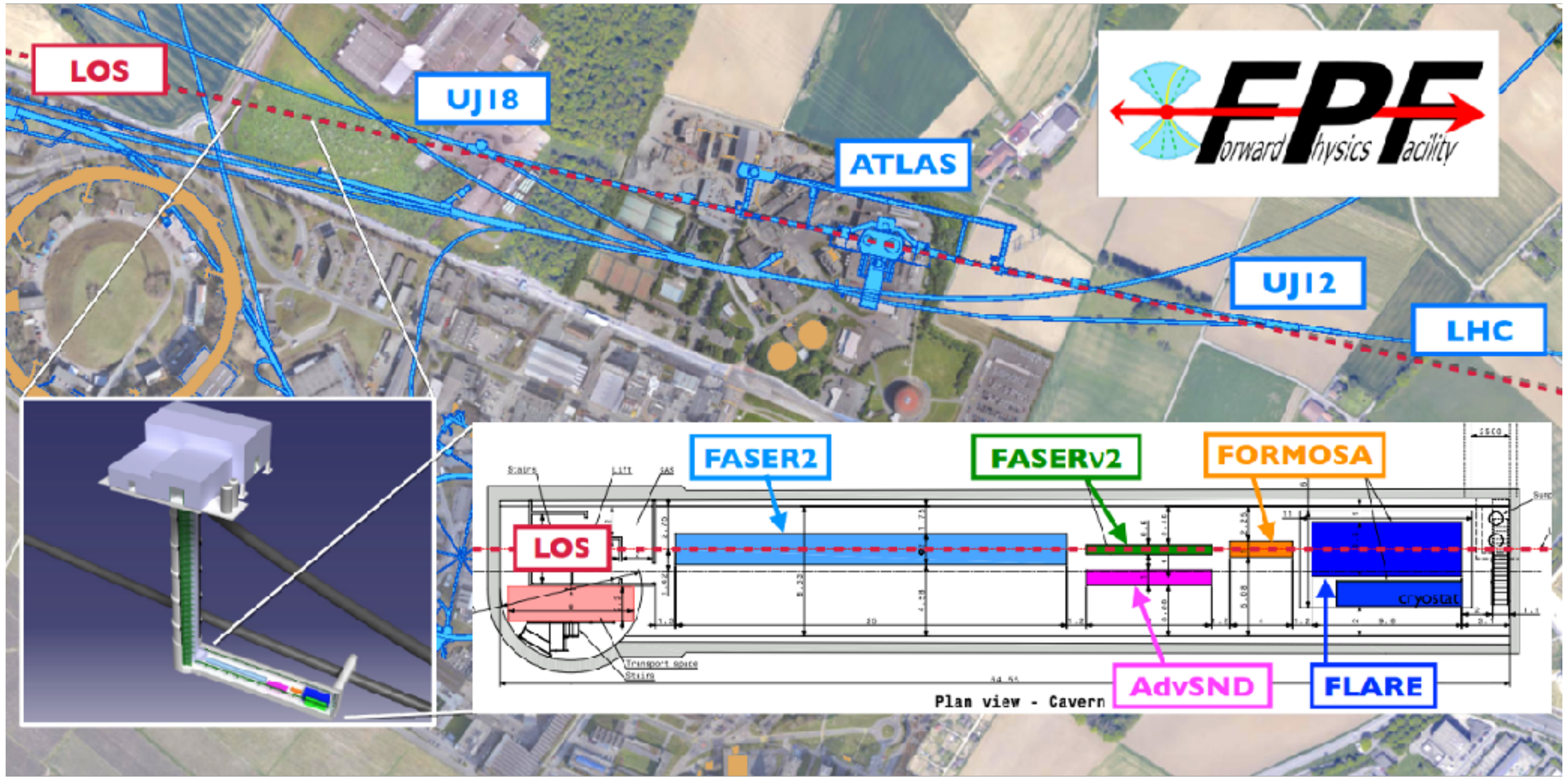
FPF

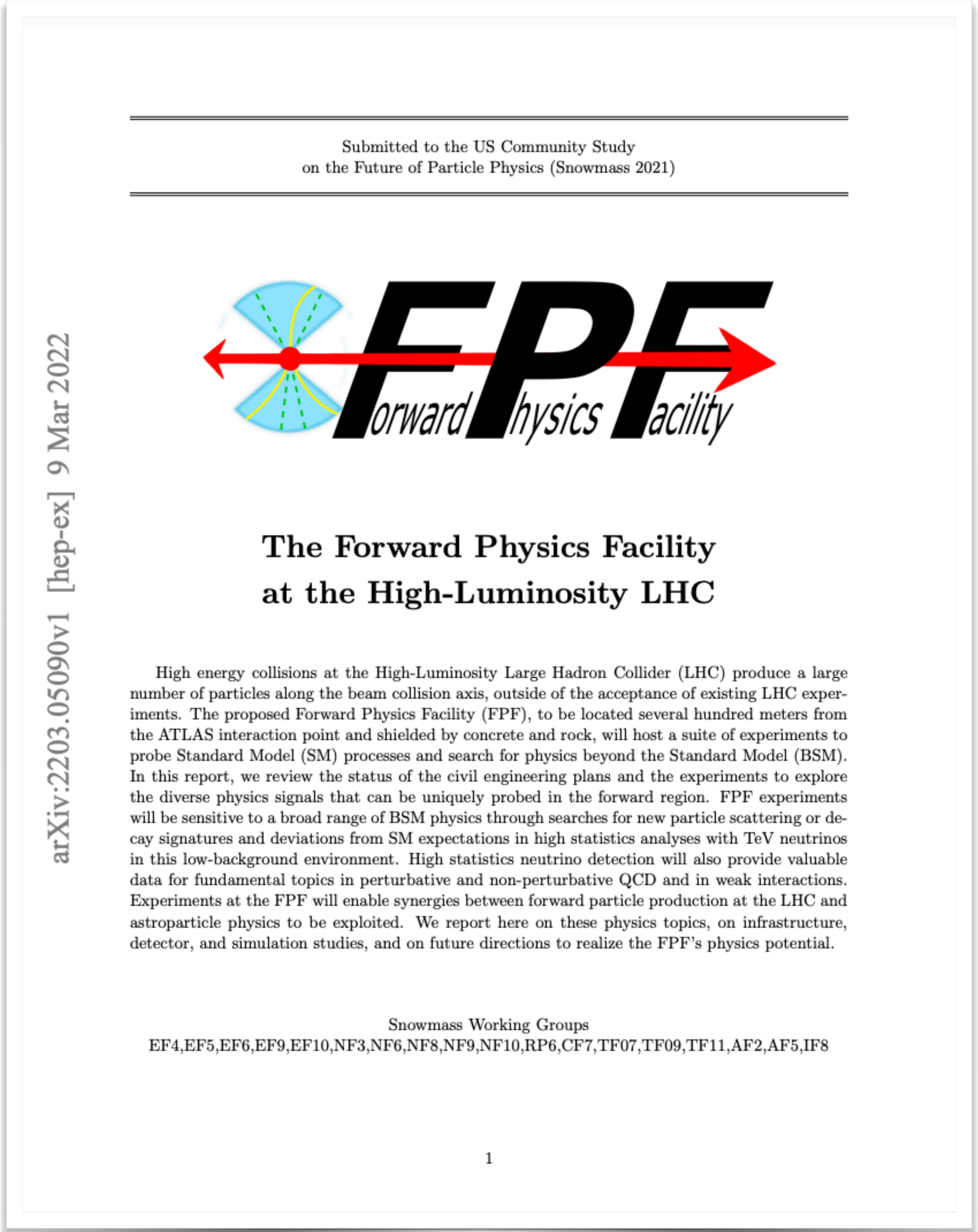
Forward Physics Facility

Forward Physics Facility in the HL-LHC era

Forward Physics Facility

- submitted white Paper(>400 pages!!) towards snowmass
  - 236 authors, 156 endorsers
- **Aimed at physics with the LHC forward beam**
  - increase statistics **(×20 Run3, 150 fb^{-1}) in HL-LHC era**
  - **Plan to have a new experimental cavern**





arXiv:2203.05090v1 [hep-ex] 9 Mar 2022

Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Forward Physics Facility

The Forward Physics Facility
at the High-Luminosity LHC

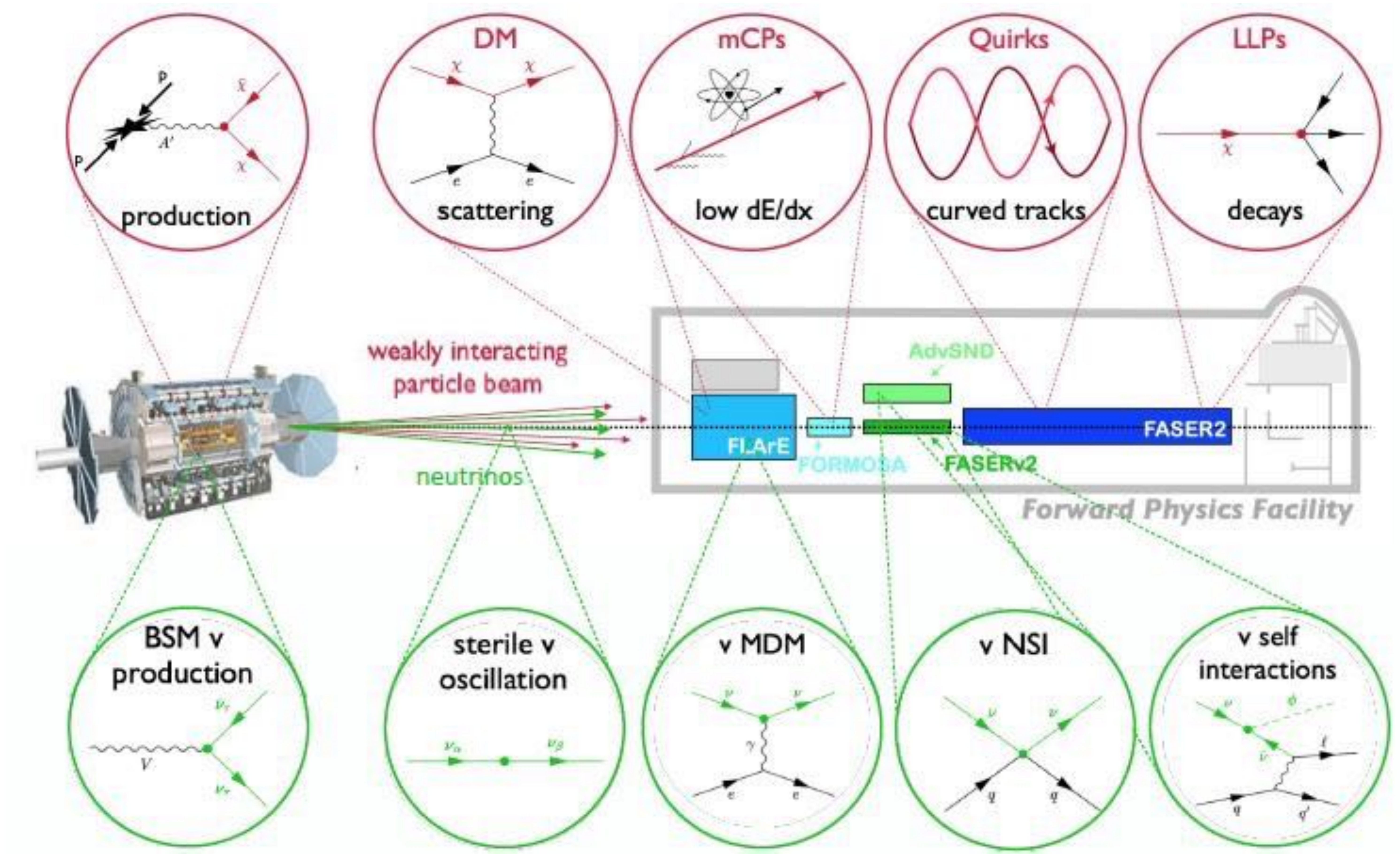
High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments. The proposed Forward Physics Facility (FPF), to be located several hundred meters from the ATLAS interaction point and shielded by concrete and rock, will host a suite of experiments to probe Standard Model (SM) processes and search for physics beyond the Standard Model (BSM). In this report, we review the status of the civil engineering plans and the experiments to explore the diverse physics signals that can be uniquely probed in the forward region. FPF experiments will be sensitive to a broad range of BSM physics through searches for new particle scattering or decay signatures and deviations from SM expectations in high statistics analyses with TeV neutrinos in this low-background environment. High statistics neutrino detection will also provide valuable data for fundamental topics in perturbative and non-perturbative QCD and in weak interactions. Experiments at the FPF will enable synergies between forward particle production at the LHC and astroparticle physics to be exploited. We report here on these physics topics, on infrastructure, detector, and simulation studies, and on future directions to realize the FPF's physics potential.

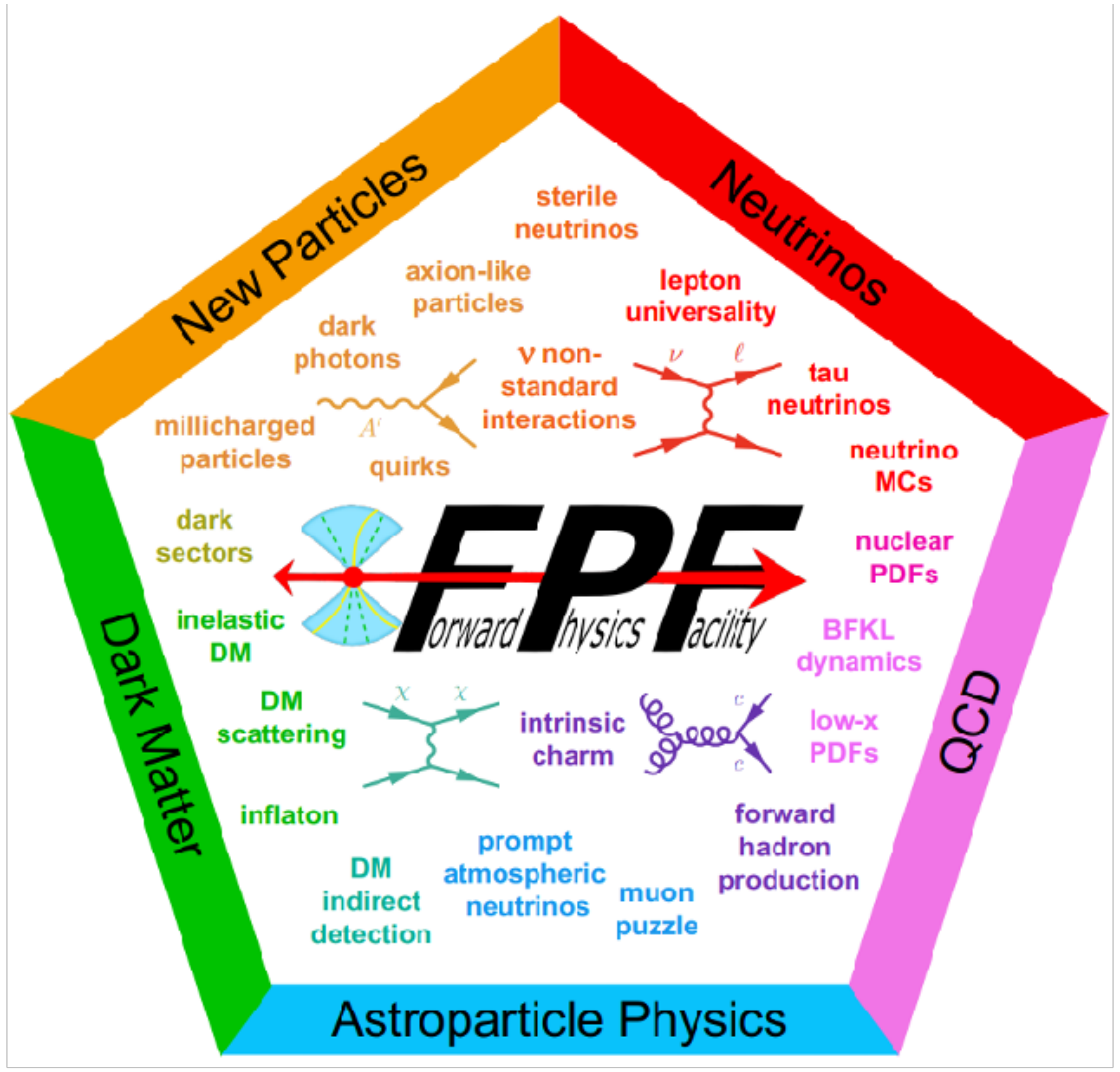
Snowmass Working Groups
EF4,EF5,EF6,EF9,EF10,NF3,NF6,NF8,NF9,NF10,RP6,CF7,TF07,TF09,TF11,AF2,AF5,IF8

1

http://arxiv.org/abs/2203.05090

Forward Physics Facility in the HL-LHC era





http://arxiv.org/abs/2203.05090

Allow us to access variety of physics with unexplored the LHC forward beam region!!

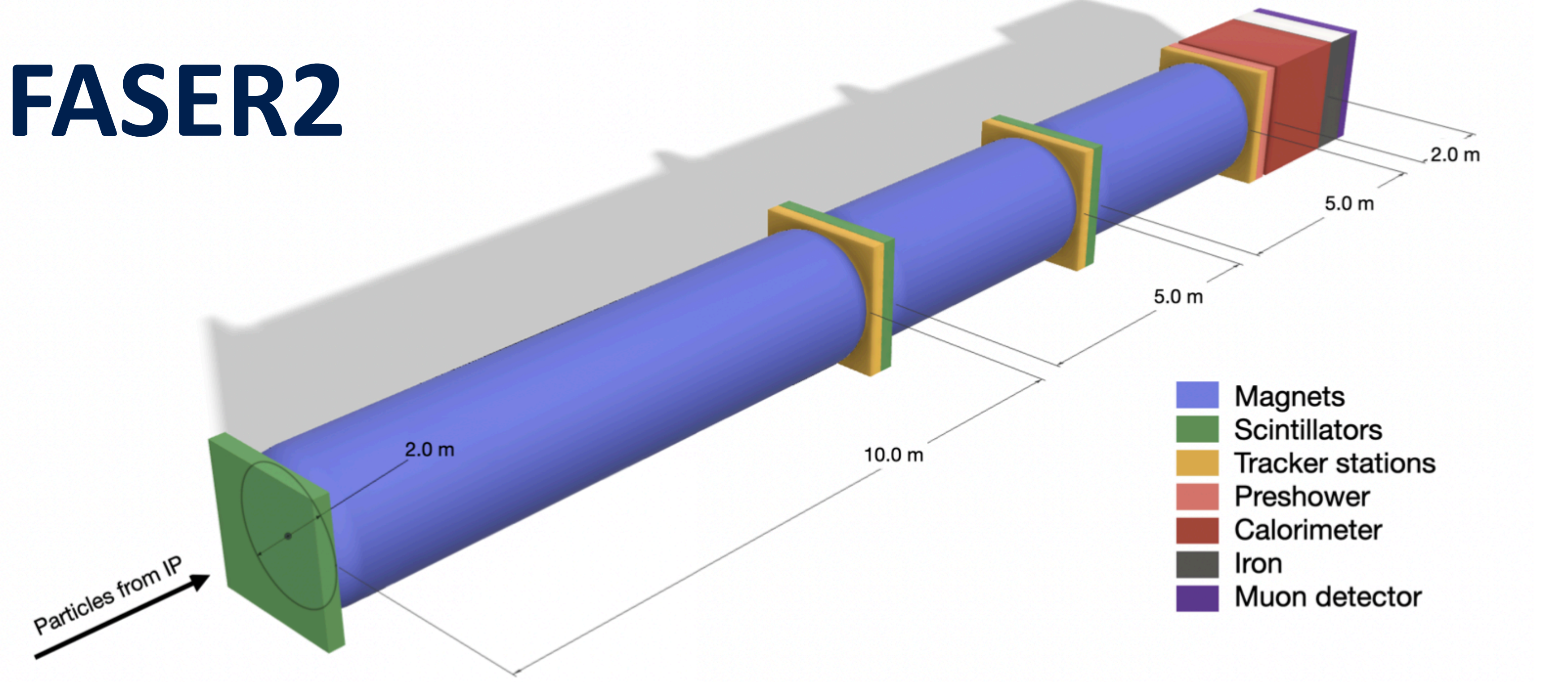
The Forward Future: FASER(ν)2

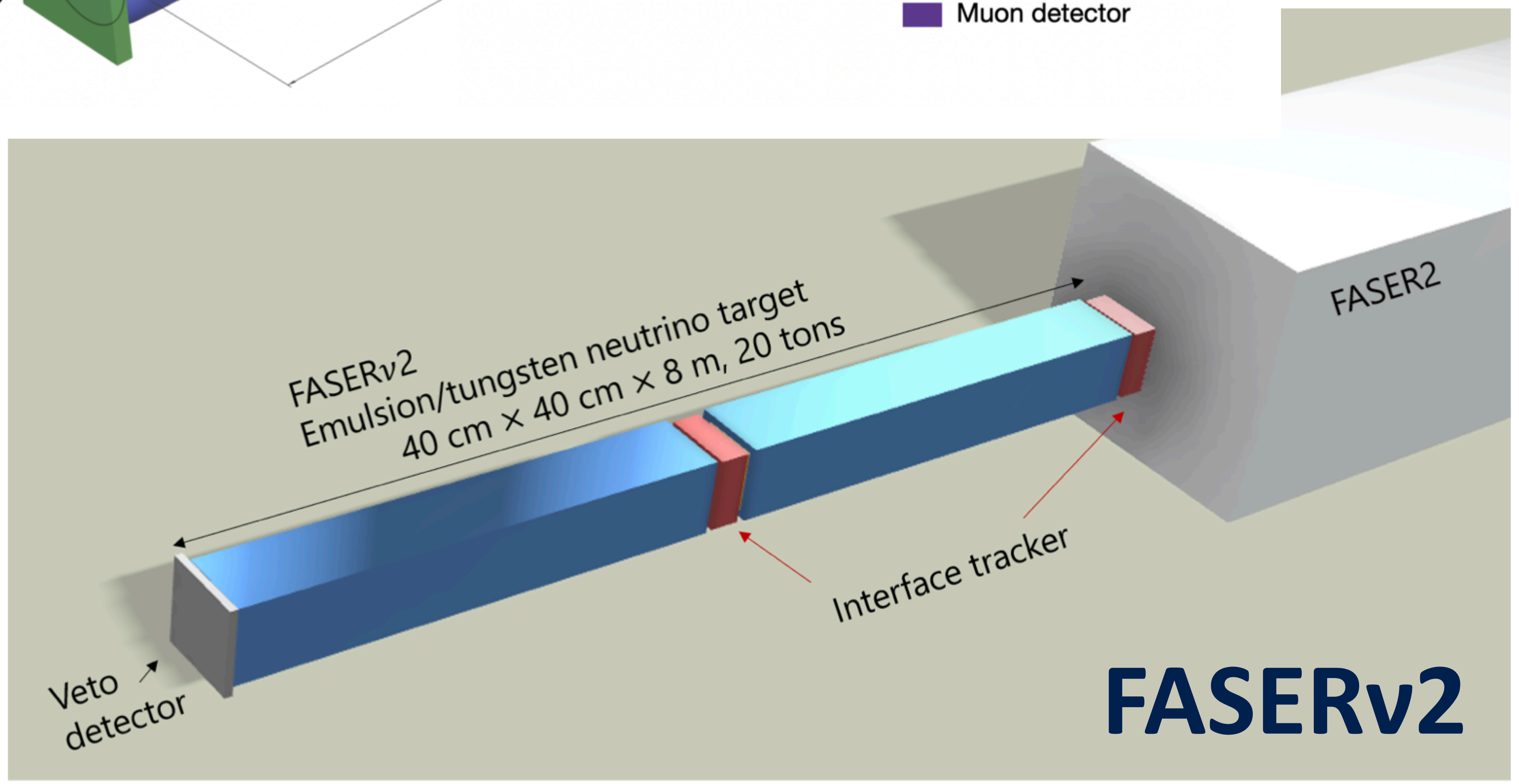
In HL-era, it is expected to increase statistics
(×20 Run3, 150 fb^{-1}) in HL-LHC era

e.g. Expected Neutrino Flux

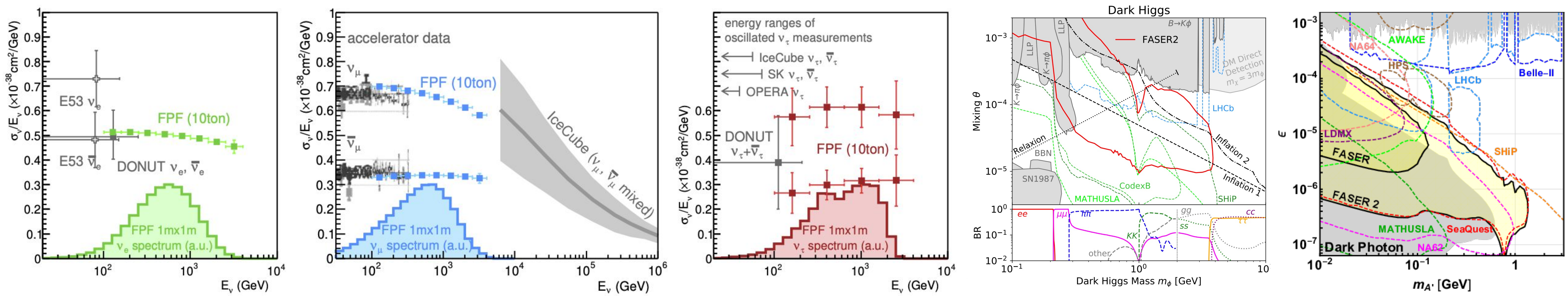
	Detector			Number of CC Interactions		
	Name	Mass	Coverage	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
LHC Run3	FASERν	1 ton	$\eta \gtrsim 8.5$	1.3k / 4.6k	6.1k / 9.1k	21 / 131
	SND@LHC	800kg	$7 < \eta < 8.5$	180 / 500	1k / 1.3k	10 / 22
HL-LHC	FASERν2	20 tons	$\eta \gtrsim 8$	178k / 668k	943k / 1.4M	2.3k / 20k
	FLArE	10 tons	$\eta \gtrsim 7.5$	36k / 113k	203k / 268k	1.5k / 4k
	AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	6.5k / 20k	41k / 53k	190 / 754

FASER2





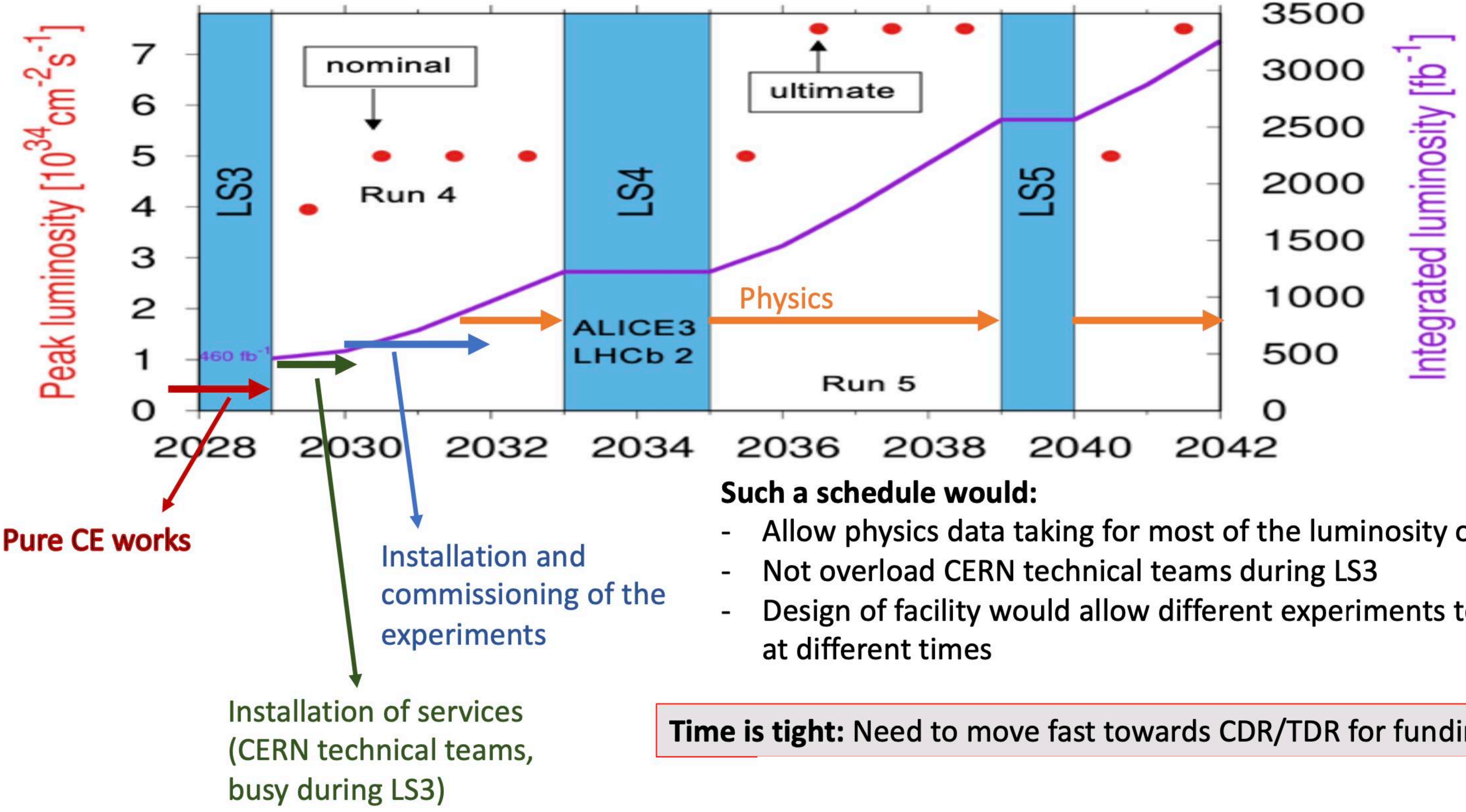
FASERν2



Possible FPF schedule

Slide from M.Diwan and A. De Roeck

https://indico.cern.ch/event/1137276/contributions/4950688/attachments/2542150/4378787/FPF_PBCworkshop_Nov22.pdf



Such a schedule would:

- Allow physics data taking for most of the luminosity of the HL-LHC
- Not overload CERN technical teams during LS3
- Design of facility would allow different experiments to come online at different times

Time is tight: Need to move fast towards CDR/TDR for funding and approval

Summary

- Indirect DM searches with gamma-ray is complementary with other WIMP searches
  - In particular, good tool to access **heavy DM models**
- **Ground-based Gamma-ray telescopes (IACTs)** has a good sensitivity on TeV gamma-ray
  - constrain WIMPs with variety of targets
    - **the Galactic Centre**: the most progressive
      - constrain on SUSY models with **different DM density profiles**
    - **dSphs**: the robust
      - all gamma-ray instruments are combined for the legacy result
  - Current IACTs generation are making **legacy results.**
- Next generation: **Cherenkov Telescope Array**
  - **The first Large-Sized Telescope is in operation**

- FASER is the new exeperiment from LHC-Run3
  - Explore **the LHC forward physics**
- Physics potential: covering multi-energy scales
  - Long-lived particle searches in **MeV-GeV masses**
  - All flavors' neutrino cross-section measurement in **TeV-scale**
- LHC Run3 got started. Data-taking is ongoing very well
  - Until now the integrated luminosity from the LHC is about $20 fb^{-1}$. Analysis is ongoing.
- Started design studies **for Forward Physics Facility in HL-LHC era from 2028**

Thank you so much for your attention!

Back

Up