Hrvatska zaklada za znanost

VHE Gamma- ray astronomy - tool for fundamental physics

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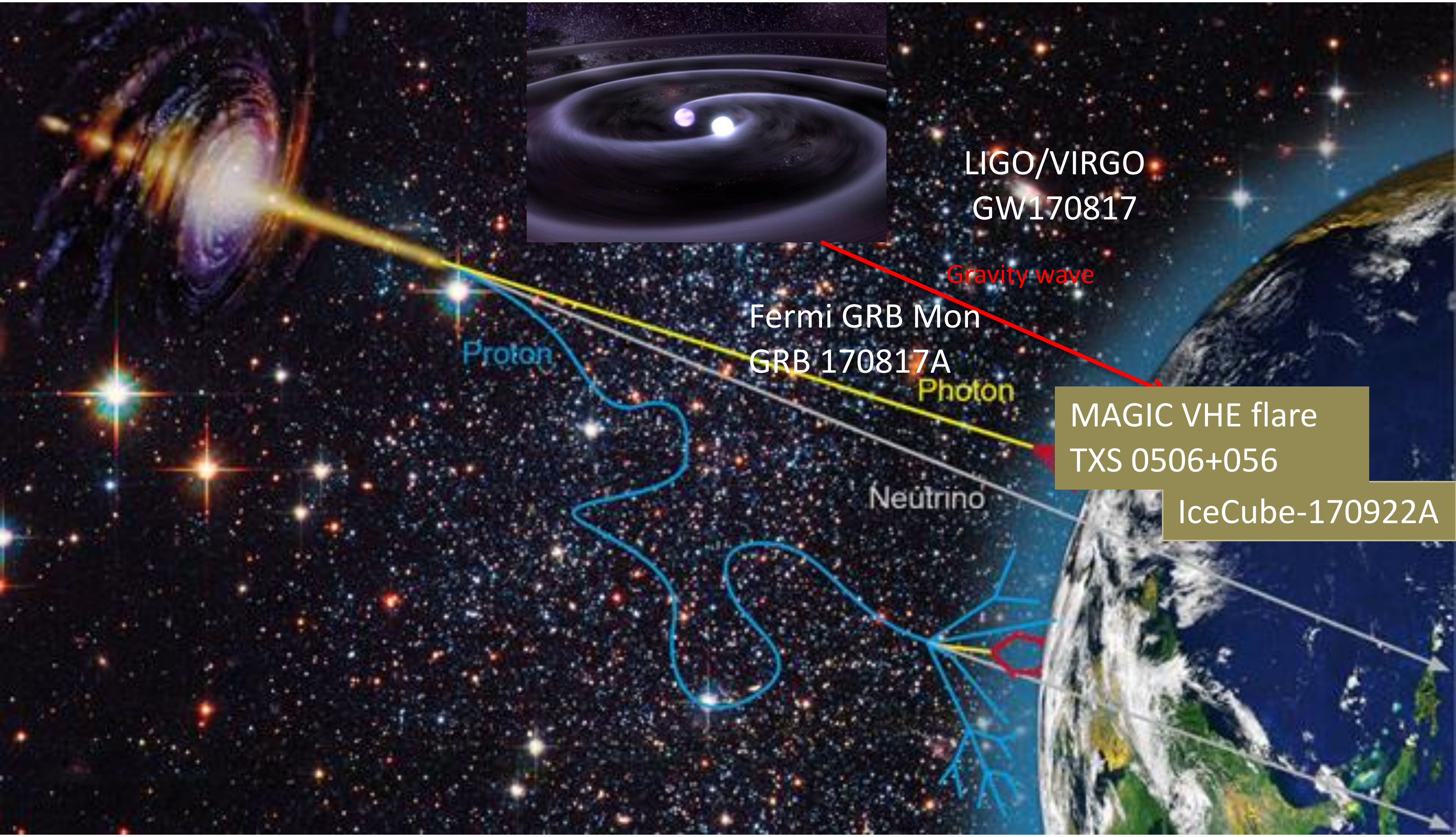
Outline

- Gamma-ray telescopes/detector
  - IACT (H.E.S.S.,MAGIC,VERITAS (50 GeV – 100TeV)
  - Satelite (Fermi, AGILE) (20 MeV – 300 GeV)
- Fundamental physics probed by gamma-rays
  - **Dark mattter search**
  - **Lorentz inavriance violation**
  - Extraglactic background light
  - Origin of cosmics ray
- Future prospects

Messangers from space



Multimessanger astronomy is on stage

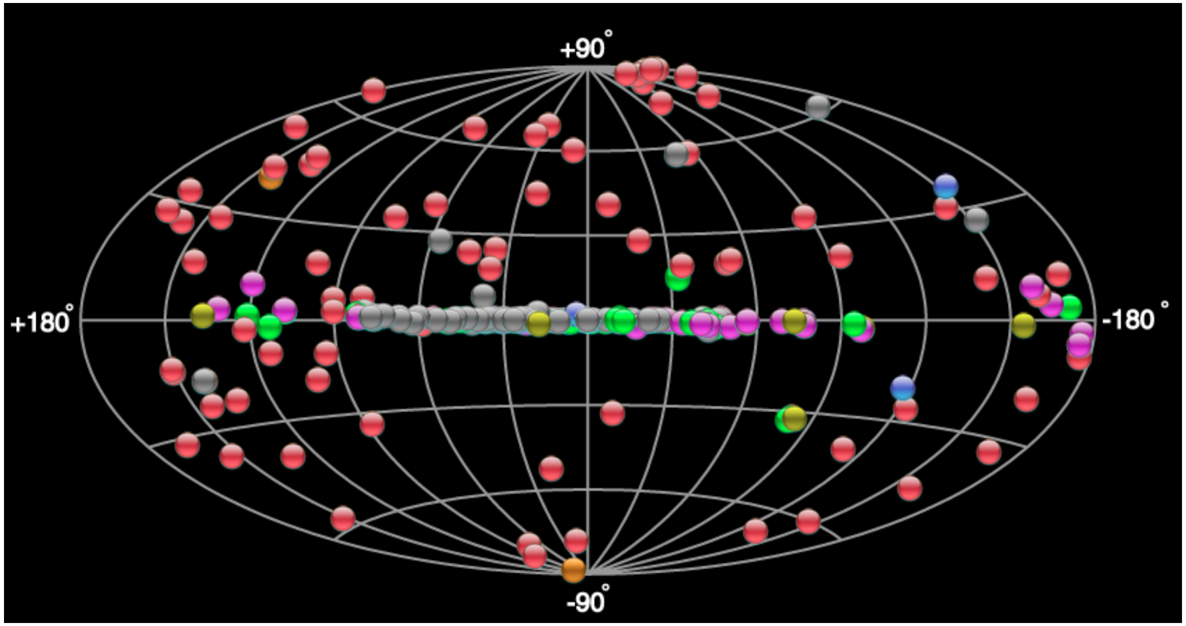
Fermi (LAT & GRB Monitor)

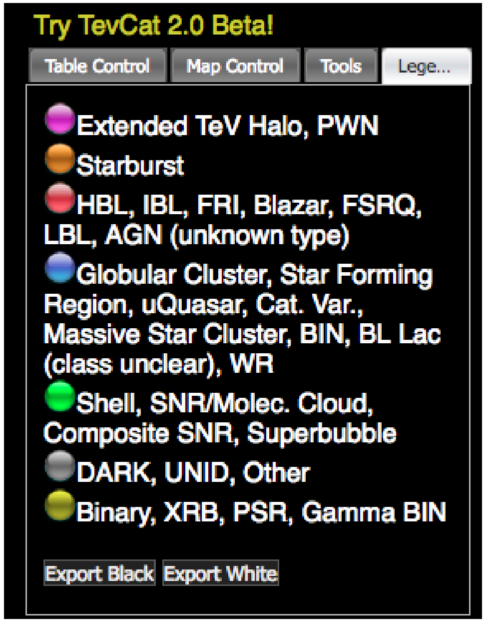
Large Area Telescope	Gamma-ray Burst Monitor
Pair-production instrument	NaI and BGO scintillators
Energy range: 20 MeV to > 300 GeV	Energy range: 8 keV to 40 MeV
Field of view: 2.4 steradians	Field of view: 9.5 steradians
Single photon angular resolution: <1° at 1 GeV	Gamma-ray burst localization: typical 3°
Timing accuracy: 1 microsecond	Timing accuracy: 2 microseconds
LAT Web site: https://www-glast.stanford.edu/instrument.html	GBM Web site: http://f64.nsstc.nasa.gov/gbm/instrument/

Current IACT telecopes for VHE gammas

VERITAS

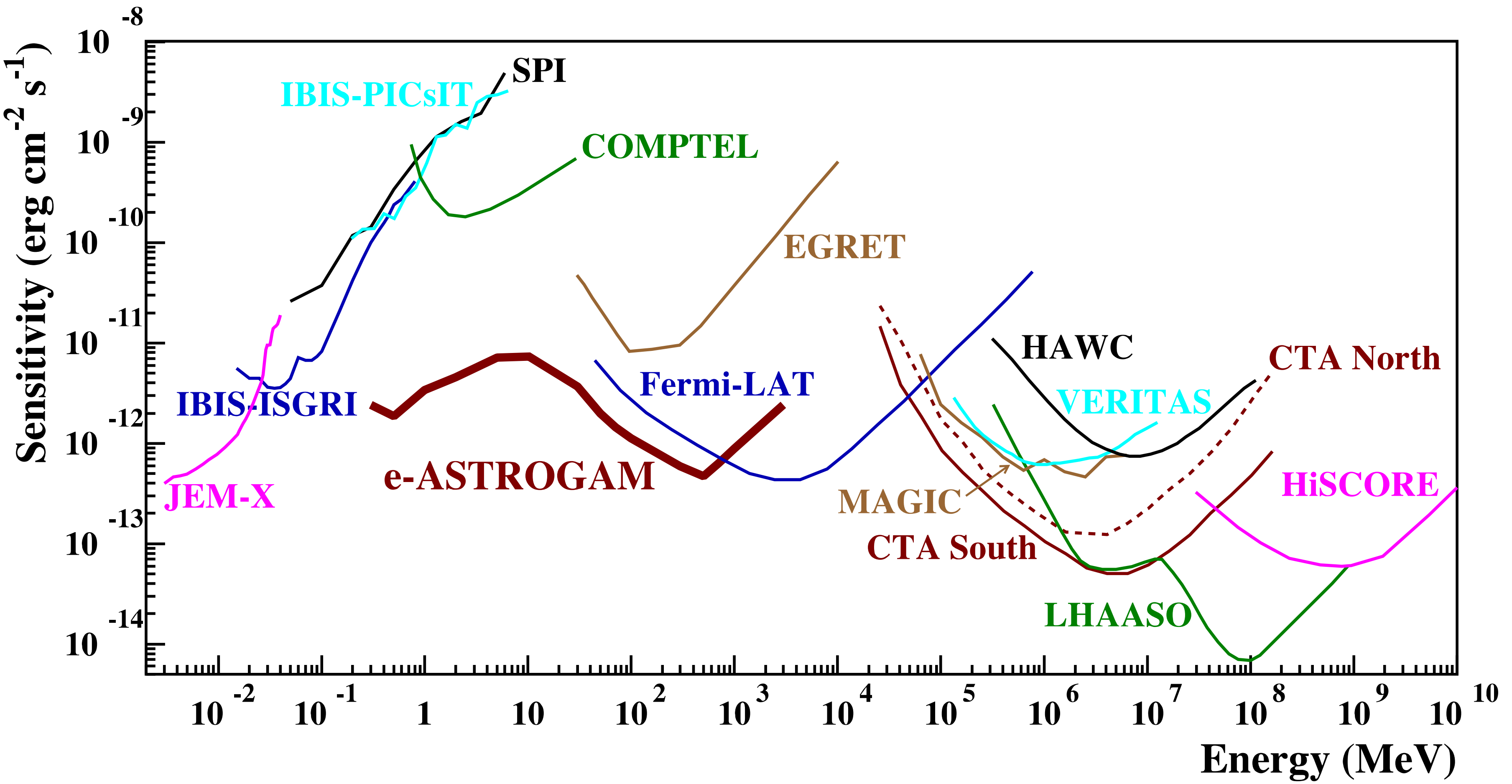
1989 Crab nebula, standard candle E > 1TeV, flux=2 × 10^{-7} m^{-2} s^{-1} (“standard candle”)





VHE gammas - tool to study the most violen proces and to probe fundamental physics

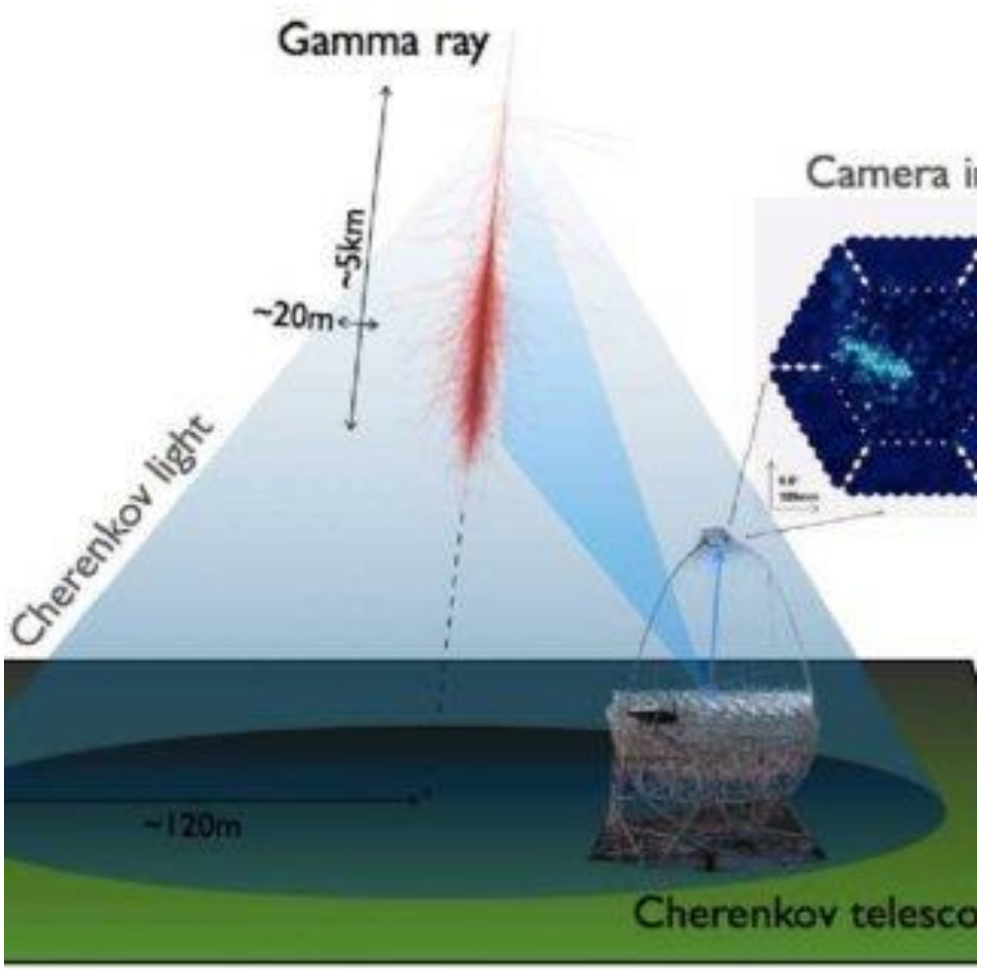
Points source sensitivity of gamma detector

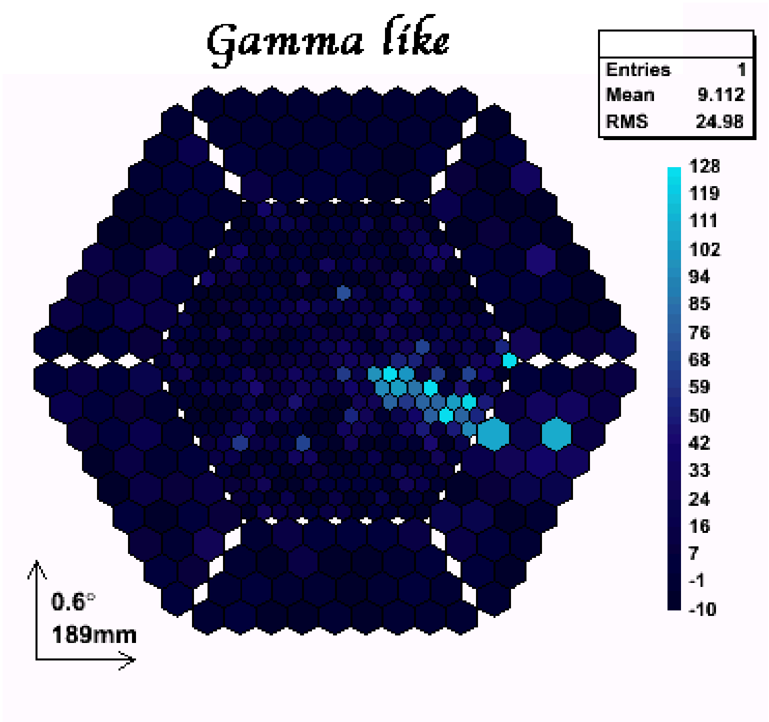


Future detector: CTA very soon, e-ASTROGRAM, HiSCORE

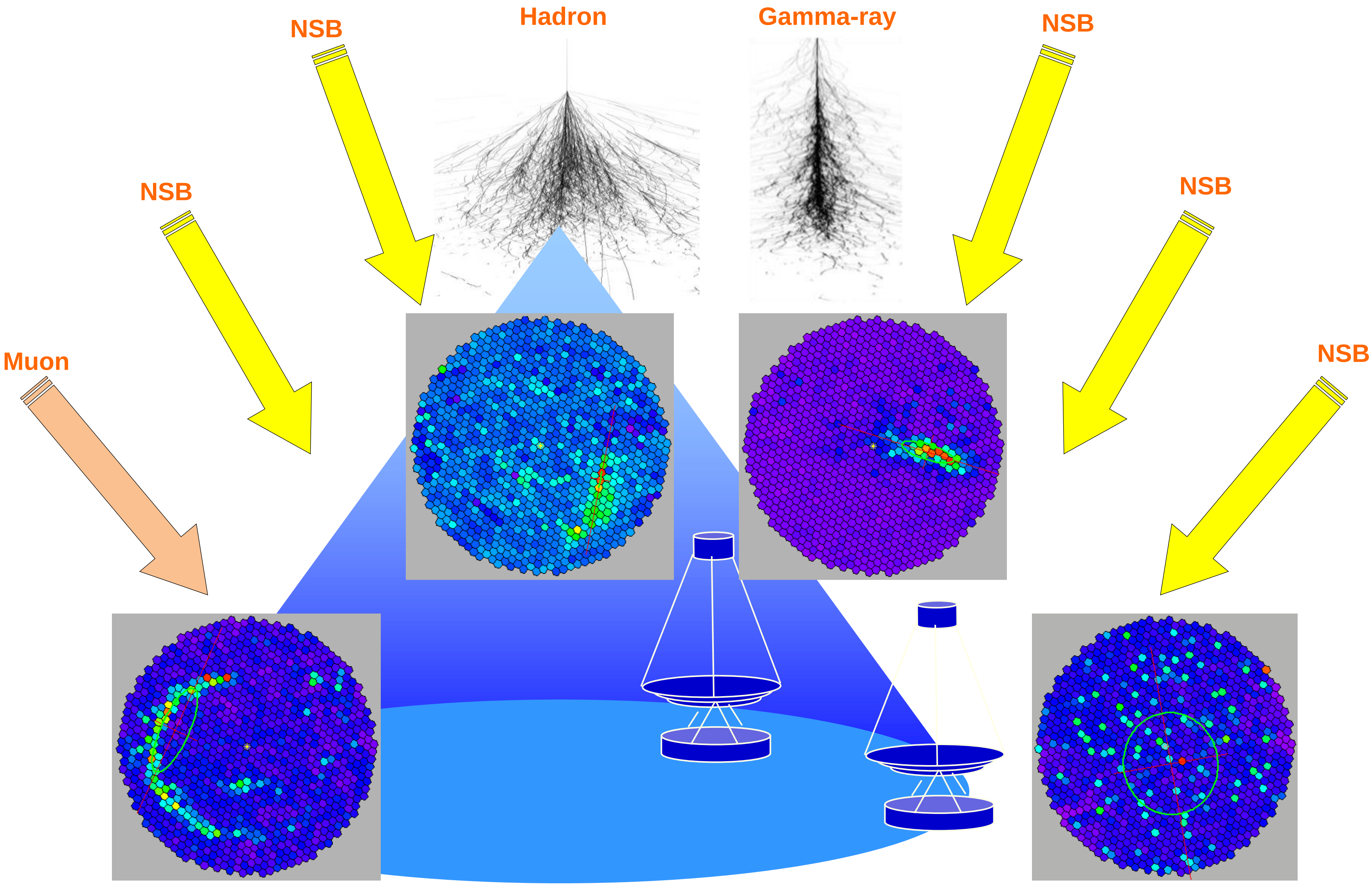
Imaging Air Cherenkov Tecnque

- 1989 Whipple Collaboration discovered 1th source of VHE gamma-ray
- (T. C.Weekes et. al., ApJ 342,(379-395) 1989):
- Crab nebula, standard candle E > 1TeV, flux=2 × 10^{-7} m^{-2} s^{-1} (“standard candle”)





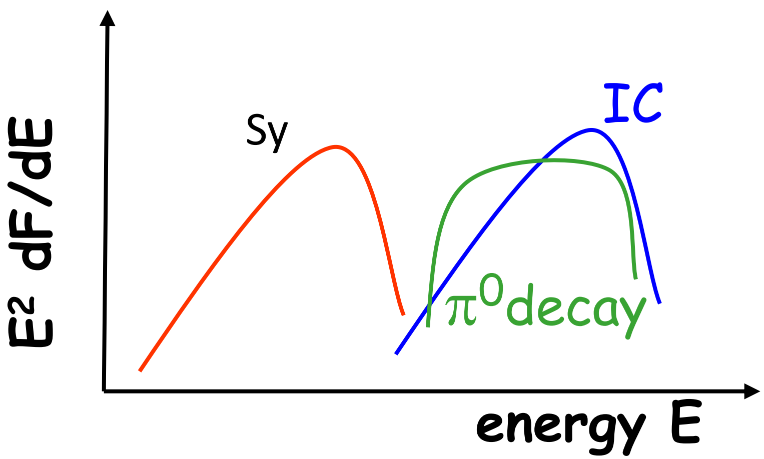
A lot of background



Generation of VHE gamma ray

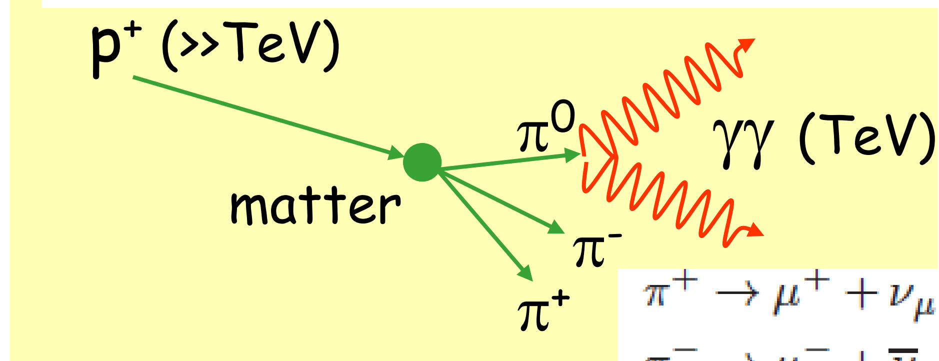
- Hadronic model of emission
- Leptonic model of emission

▸ Disentangle hadronic from leptonic gamma ray origin
=> shape of spectrum



Hadronic model of γ emission

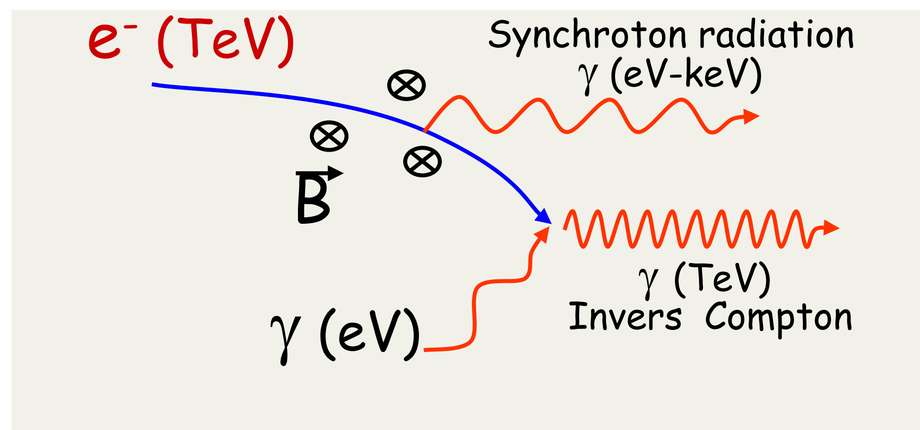
$$E_{\rm min}^{\rm max} = \frac{1}{2}(\gamma m_\pi \pm \beta\gamma m_\pi) = \frac{1}{2}E_\pi(1 \pm \beta)$$



$$\pi^+ \to \mu^+ + \nu_\mu$$

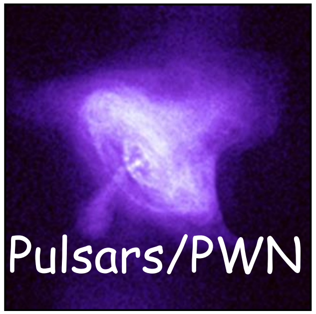
$$\pi^- \to \mu^- + \overline{\nu}_\mu$$

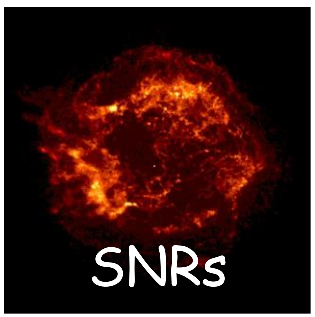
Leptonic model γ emission

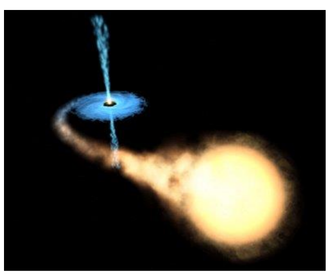


Scientific scope of VHE gamma astronomy

Galactic

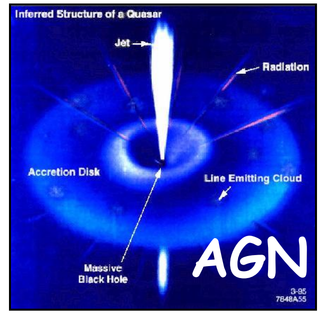


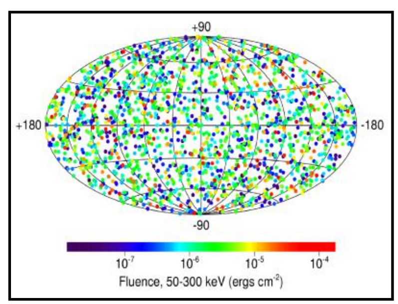




Binary systems

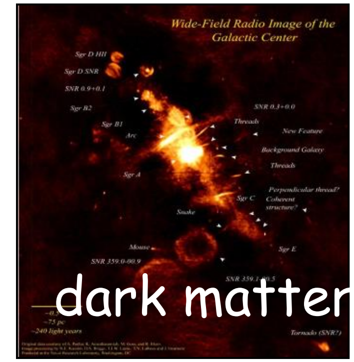
Extragalactic

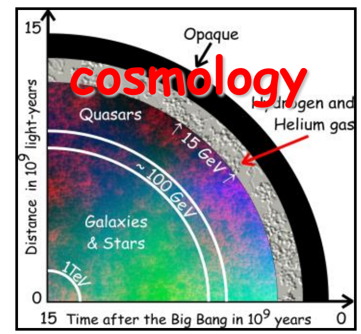


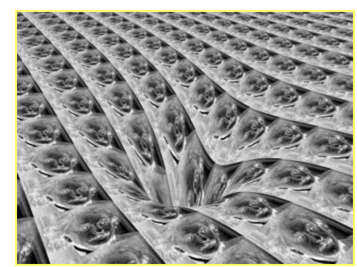


GRBs

Fundamental





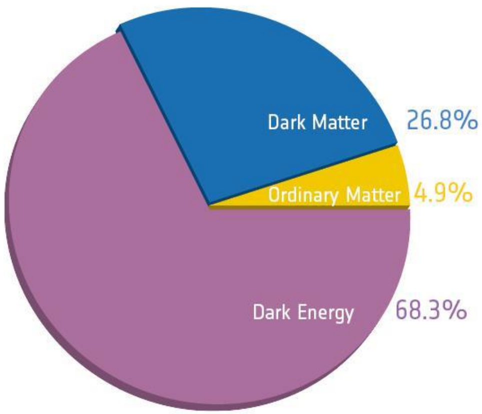


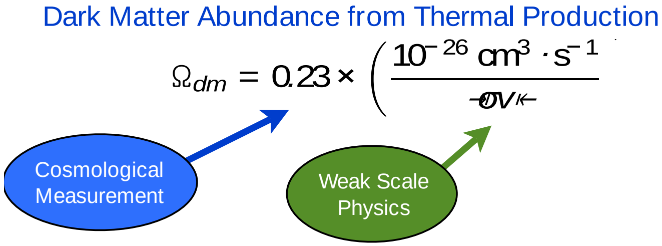
Qantum Gravity Effect

Dark matter and VHE gamma ray

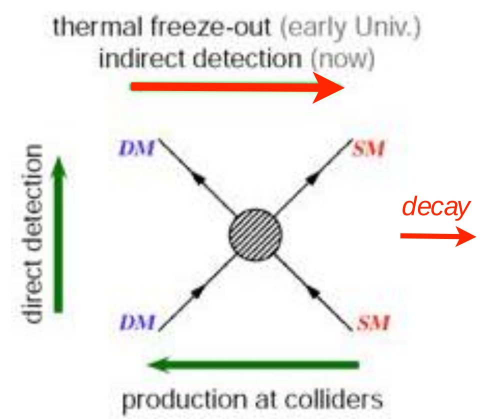
Evidence for DM and search method

- Overwhelming evidence for a Dark Mater component in the Universe
- Particle candidates in-line with observations: Weakly Interacting Massive Particles (WIMPs). Several BSM theories predict WIMPs (SUSY, Extra dimensions, ...)
- WIMPs mass range: O(10) GeV – O(100) TeV
- Indirect DM searches aimed at detectingng secondary SM products (**including gamma-rays**) from annihilation or decay of DM particles
- **Gamma-rays as final states are of major interest because:**
  - trace back to abundance /distributioon of DM
  - show peculiar spectral features (smocking guns)
- Indirect Dark Matter searches are needed to confirm signals in direct and/or accelerator searches are **THE** Dark Matter





$\langle \sigma v \rangle \sim 10^{-26}\ cm^3 s^{-1}$



Strategy for indirect DM serach

- Find the source/region of high density dark matter
  - As close as possible
  - Low astophycical background
- Model the measured gamma-ray flux for the selecetd DM anihillation process in order to be able to find out mass of DM if you are lukcy or in case of non-detection of gamma rays to put the upper limit <σv>

$$< \sigma v >^{95\%CL} = \frac{8\pi}{< J(\Delta\Omega) >} \times \frac{N_{\gamma}^{95\%CL}\, m_{DM}^{2}}{T_{OBS}\int_{0}^{m_{DM}} A_{eff}(E)\frac{d^{3}\Phi_{\gamma}}{dEdAdt}dE}$$

Dark matter annihilation signal

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

Particle phsyics terma

Astrophysical terma

$$\frac{d\Phi^{PP}}{dE} = \frac{1}{4\pi}\frac{\langle\sigma_{\mathrm{ann}}v\rangle}{2m_\chi^2}\frac{dN}{dE}$$

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

Particle physics term:

- thermally-averaged velocity-weighted annihilation cross section $\langle\sigma v\rangle$
- m_χ-dark matter mass
- Differential gamma ray yield per annihilation **dN/dE** summed over all the n possible channels that produce photons

$$\frac{dN}{dE} = \sum_{i=1}^{n}\mathrm{Br}_i\frac{dN_i}{dE}$$

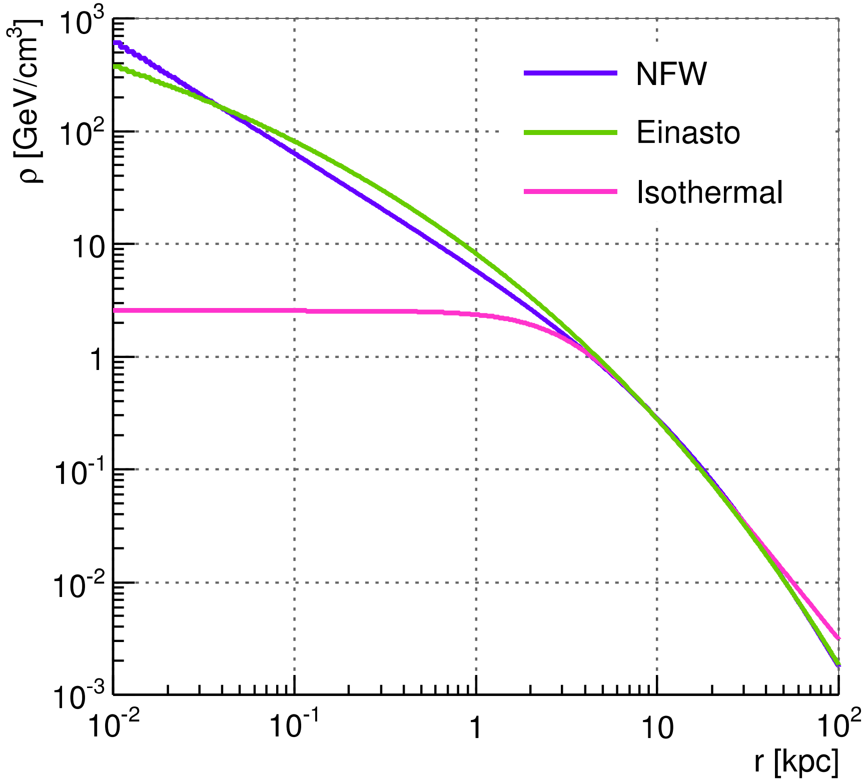
with:

l -position along the line of sight,
ΔΩ - observed solid angle,
ρ - DM density profile

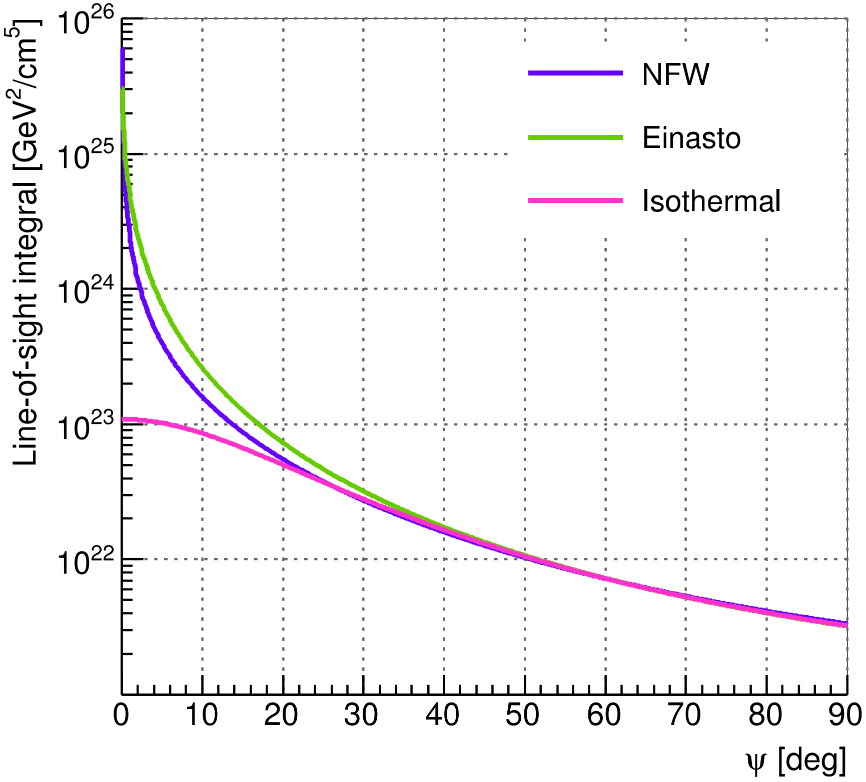
Integral flux

$$\Phi(>E_0,\Delta\Omega) = \frac{1}{4\pi}\frac{\langle\sigma_{\mathrm{ann}}v\rangle}{2m_\chi^2}\int_{E_0}^{m_\chi}\frac{dN}{dE}dE\int_{\Delta\Omega}\int_{los}\rho^2(l,\Omega)\,dl\,d\Omega.$$

DM density profile

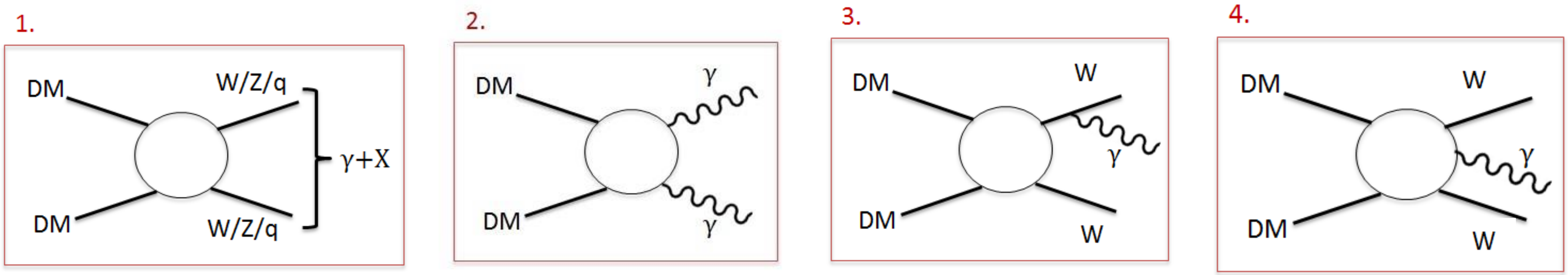


Line-of-sight integral (J/ΔΩ) as a function of the angle ψ from the center of the halo.



Dark matter annihilation signals in gamma-rays

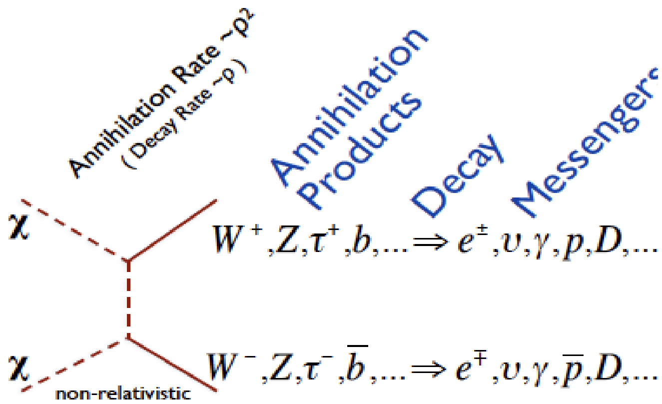
1. Continuum: hadronization and/or decay of W/Z, quarks, leptons…
2. Line from prompt annihilation in two photons
   not at tree level: suppressed ⟶ but clear signature at DM mass !
3. Final state radiation
4. Virtual internal bremsstrahlung

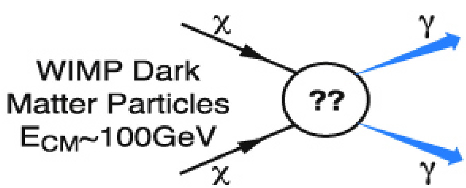


Thermal relic cross section for WIMPs:

- For the continuum signal : $\langle \sigma v \rangle \sim 3 \times 10^{-26}\,\mathrm{cm^3 s^{-1}}$
- For the prompt line signal : $\langle \sigma v \rangle \sim 10^{-29}\,\mathrm{cm^3 s^{-1}}$

DM decay to gamma - spectral features

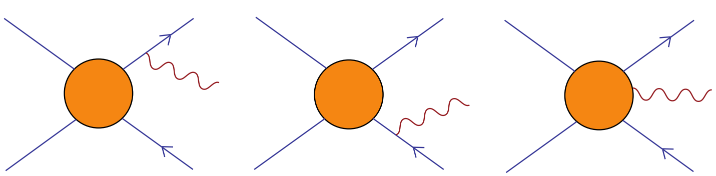




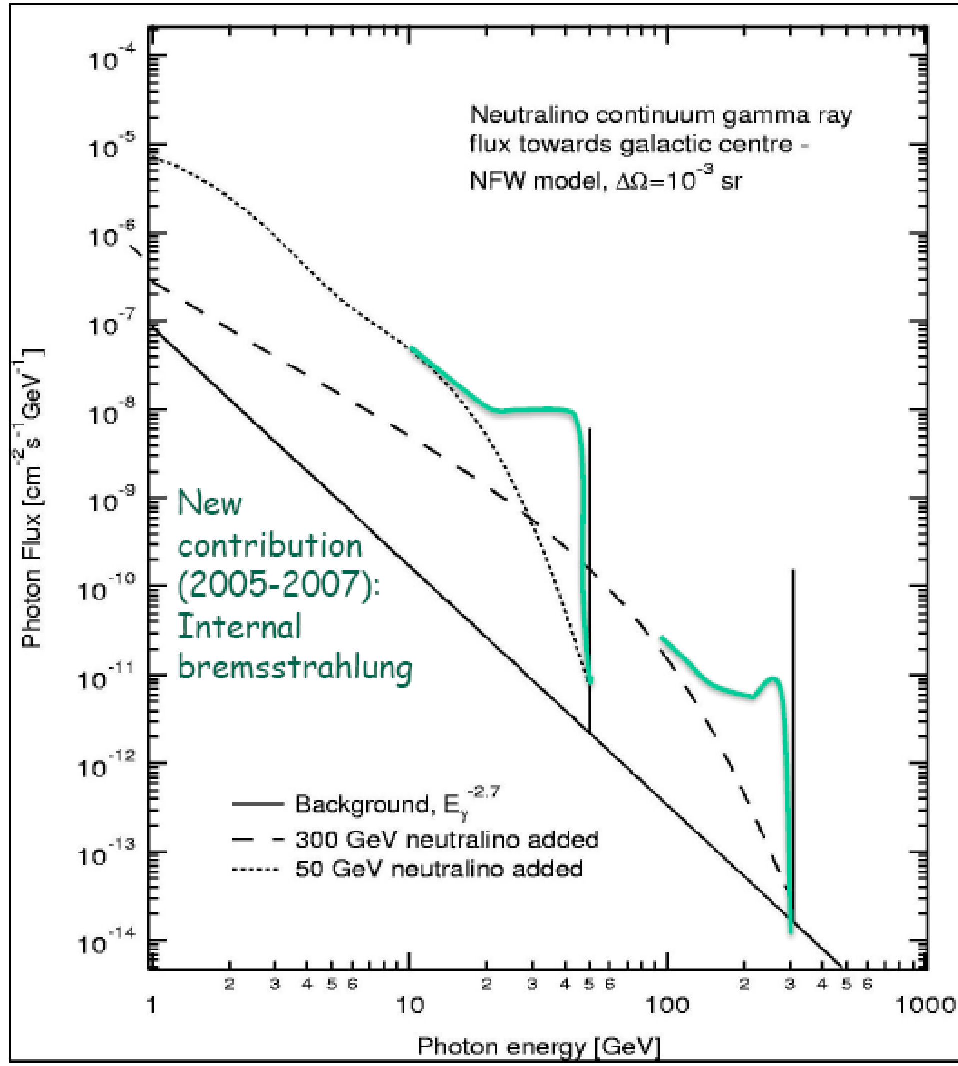
X γ, Z H

Line spectral features
but loop susspresd

$$E_\gamma = m_\chi[1 - m_X^2/4m_\chi^2]$$



(a) (b) (c)



L.B., P.Ullio & J. Buckley 1998

T. Bringmann, L.B., J. Edsjö, 2007

Dark matter targets for VHE gamma-ray searches

- DM density profile matters
- Astrophysical background matters as well

Where to look for Dark Matter

- ***Galactic centre***

  \+ Highest *J-factor*

  − High astroph. bkg

  − Uncertainties on inner DM distribution

  (Southern Hemisphere)

- ***Galactic halo***

  \+ High J-factor

  − Not fully-free from astro. Bkg.

  − Extended

  (Southern Hemisphere)

- ***Galaxy Clusters?***

  \+ Huge amount of DM

  − High astroph. bkg

  − Distant

  − Extended

  − Uncertainties *J-factors*

- ***DM Clumps***

  \+ Free from astroph. kg.

  \+ Neraby and numerous

  − To be found

  − Bright enough

- ***Dwarf Galaxies***

  \+ DM dominated (high M/L ratios)

  \+ Free from astroph. bkg

  \+ Close (<~100 kpc)

  \+ Slightly extended at most

  \+ **~20 new optimal dSphs discovered**

  \+ Less uncertainties on on *J-factors*

  − *J-factors* ~100 lower than for GC

Wisely choose /balance between
pro and contra parameters for DM search

MAGIC & Fermi Combined analysis

Due to expected universality of DM properties, a joint likelihood function $\mathcal{L}$ can be constructed as a product of the particular likelihood function for each of the data samples and instruments.

$$\mathcal{L}_{iM}(\langle\sigma v\rangle; J_i, \mu_{iM} | \mathcal{D}_{iM}) = \prod_{k=1}^{N} \mathcal{L}_{iMk}(\langle\sigma v\rangle; J_i, \mu_{iMk} | \mathcal{D}_{iMk})$$

$$\mathcal{L}_{iF}(\langle\sigma v\rangle; J_i, \mu_{iF} | \mathcal{D}_{iF}) = \prod_{k=1}^{NE\text{-}bins} \mathcal{L}_{iFk}(\overline{E\Phi}_k \langle\sigma v\rangle; J_i)$$

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

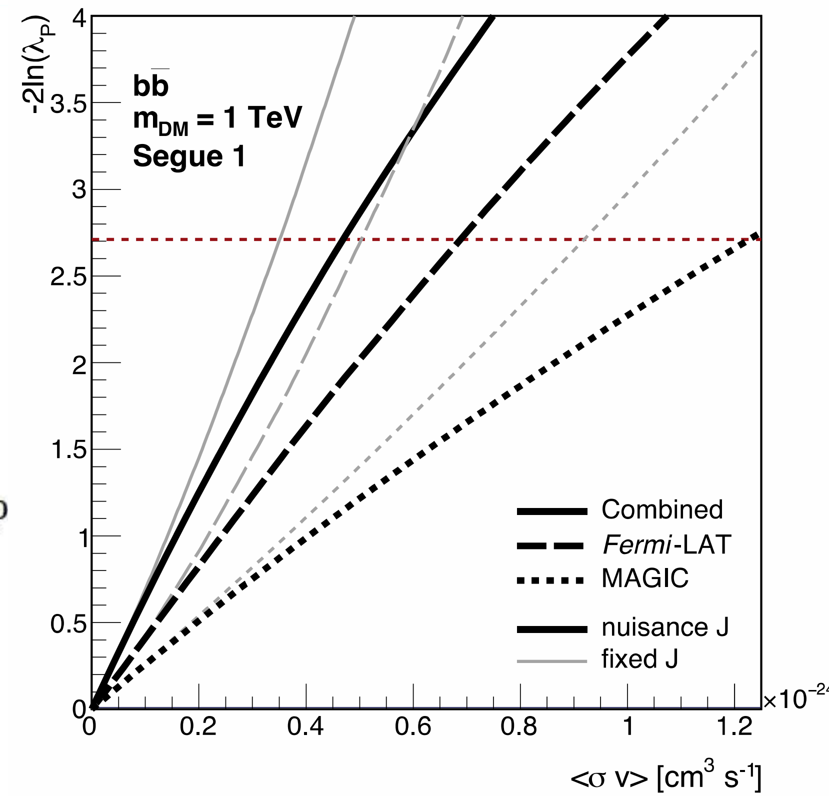
Likelihood ratio as a function of $\langle\sigma v\rangle$ for significance test of DM hyp

$$\lambda p = \mathcal{L}(\langle\sigma v\rangle; \hat{\hat{\nu}} | \mathcal{D}) / \mathcal{L}(\widehat{\langle\sigma v\rangle}; \hat{\nu} | \mathcal{D})$$

Computation one-side 95% confidence level upper limits by

$$-2 \ln \lambda p(\langle\sigma v\rangle | \mathcal{D}) = 2.71$$

IRF of each experiments and event list do not need to be comabined and average

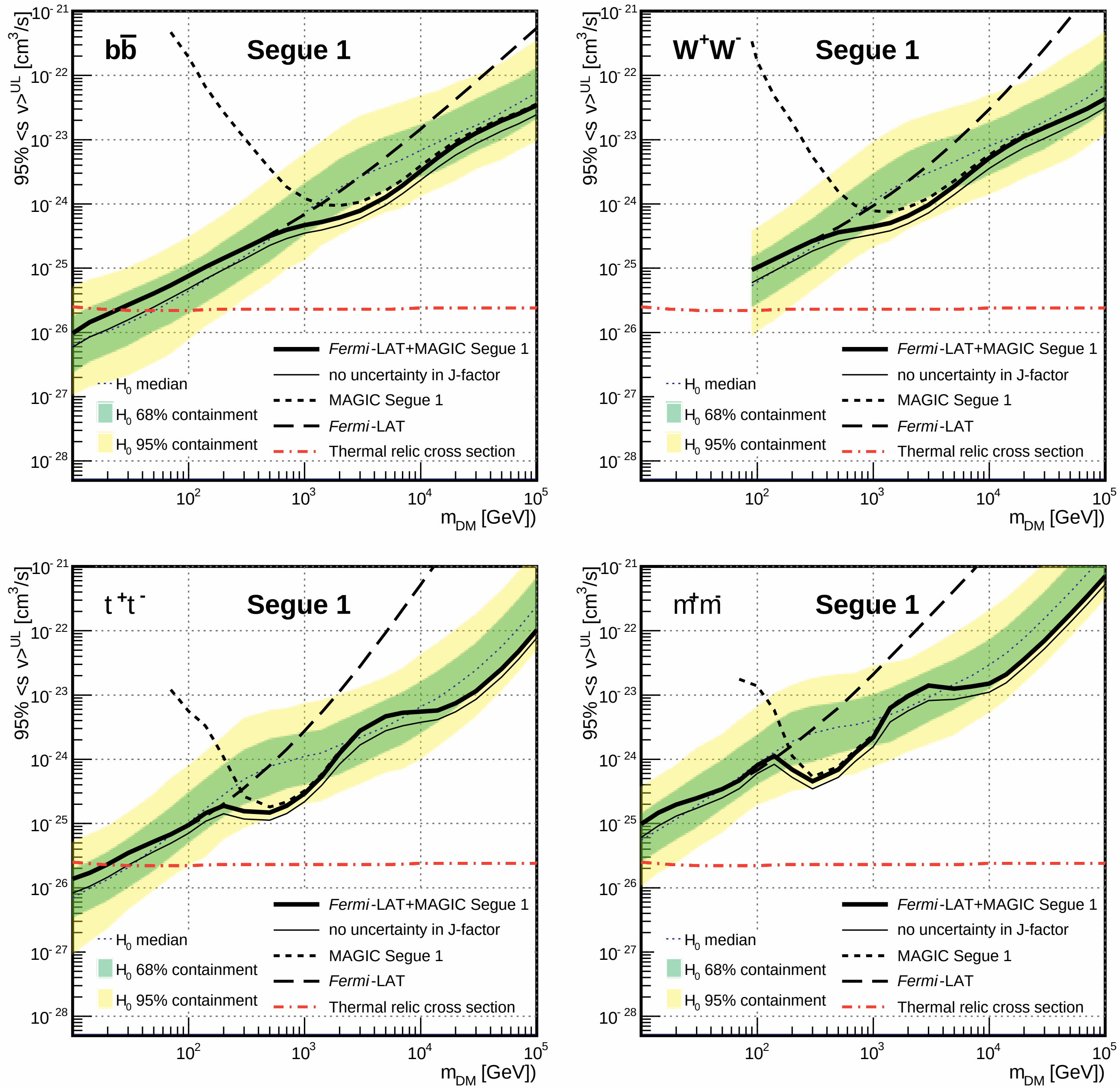


Combination improves sensitivity

See also: J. Aleksić, J. Rico, M. Mar=nez JCAP 10 (2012) 032 and M.L. Ahnen et al. JCAP 02 (2016) 039

FERMI & MAGIC DM for Segue 1

No evidence for
DM annihilation
10 GeV – 100 TeV



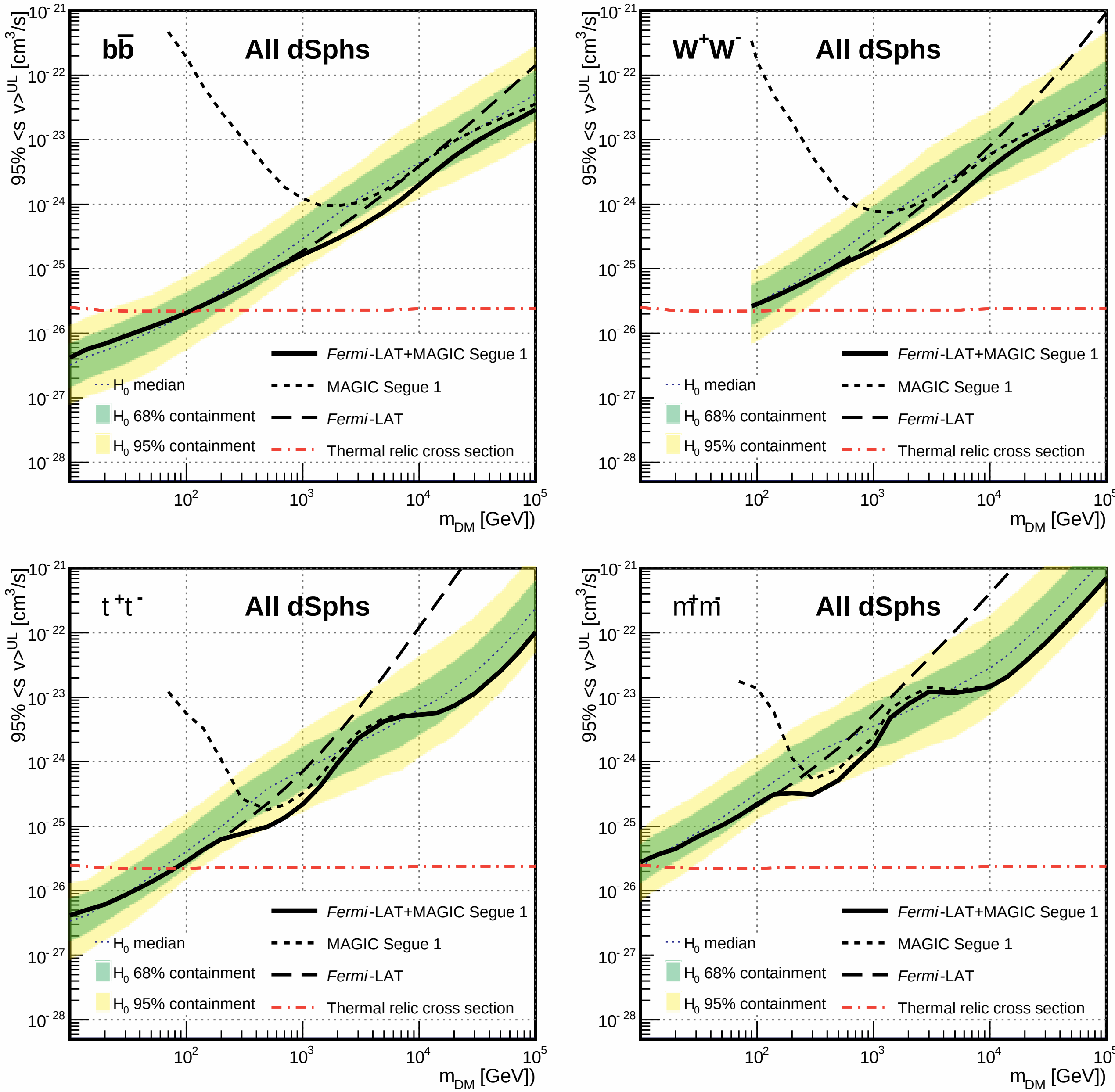
FERMI & MAGIC DM from dSphs

No evidence for
DM annihilation
10 GeV – 100 TeV
Widest range covered by
single gamma ray analysis

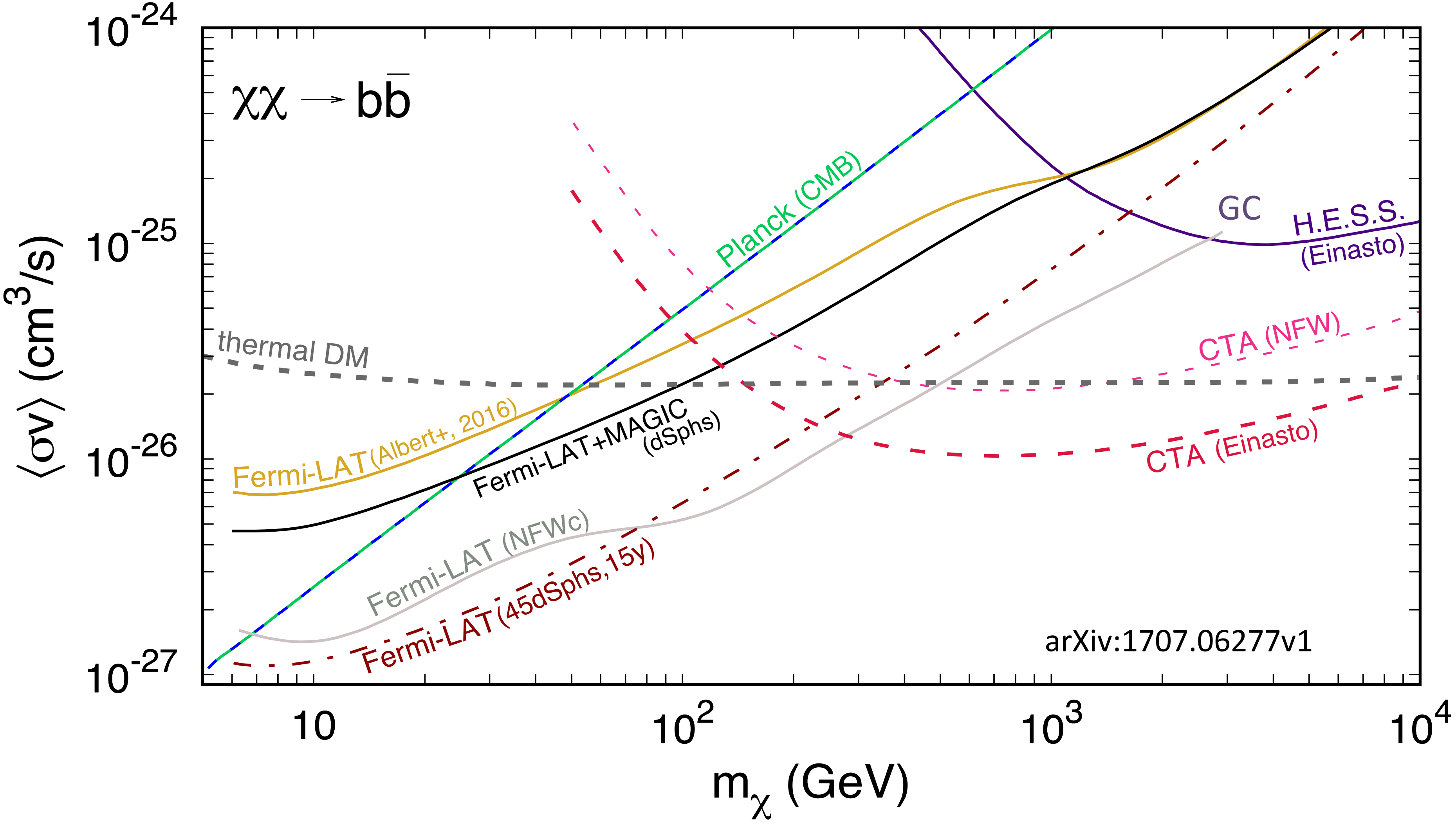
Combined results provide
factor 2 stronge
constraints

Analysis method is generic
and can be easily extented
to include data from more:
targets, instruments and/or
messenger

Future: combine DM
search for dSphs including
data: Fermi-LAT, MAGIC,
H.E.E.S., VERITAS,
HAWC, Antares, IceCube,
SuperKamiokande

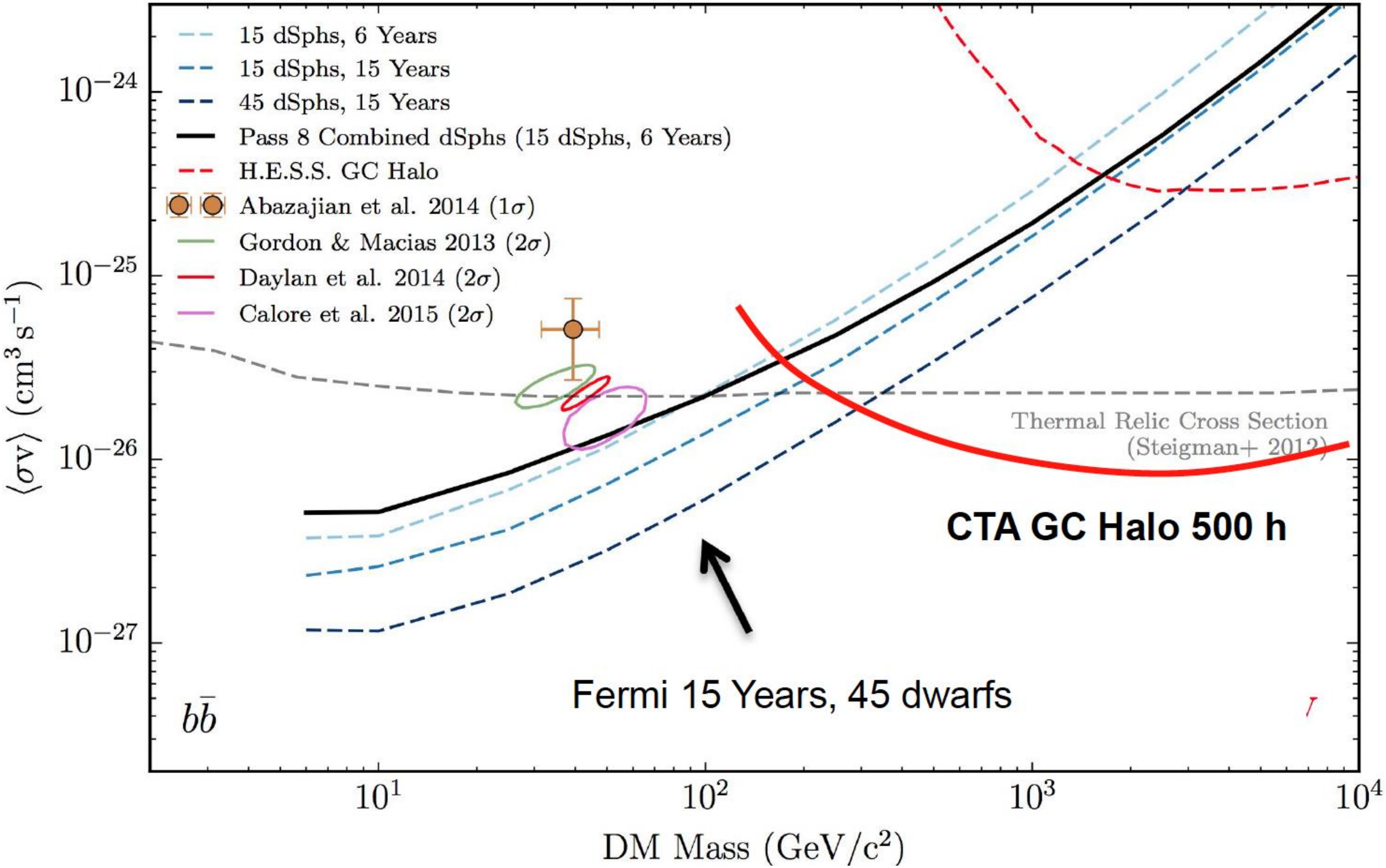


Current limits on DM annihilation cros section (FERMI + IACT)

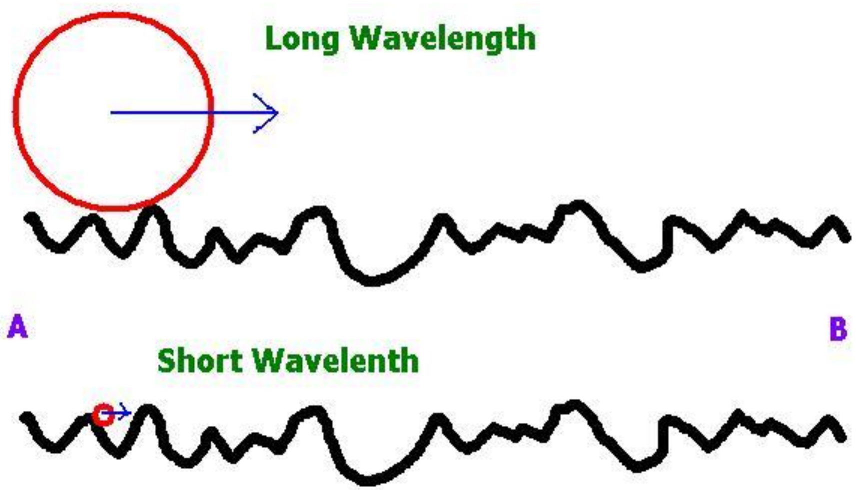


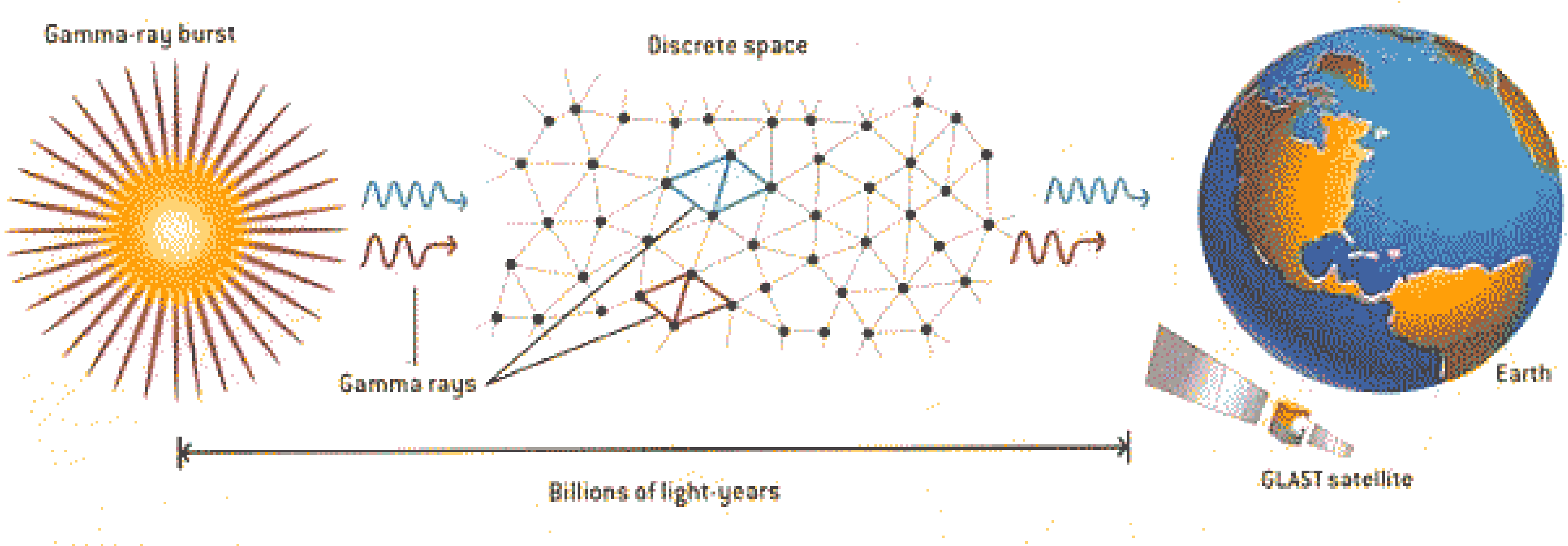
CTA – expected sensitivity

- Expected CTA DM sensitivity 2023



Lorentz Invariance Violation





Lorentz Invariance Violation

- QG effects may cause violations of Lorentz Invariance (LIV) → speed of light in vacuum may acquire a dependence on its energy → $v_\gamma(E_\gamma) \neq c$
- The Lorentz-Invariance violating terms are typically expanded using a series of powers of the photon energy E_γ over the *Quantum Gravity mass* $M_{QG,n}$:

$$c^2 p_\gamma^2 = E_\gamma^2 \left[1 + \sum_{n=1}^{\infty} s_n \left(\frac{E_\gamma}{M_{QG,n} c^2} \right)^n \right]$$

where $s_n=\{-1,0,+1\}$ is a model-dependent factor

- The Quantum-Gravity Mass M_{QG}
  - Sets the energy (mass) scale at which QG effects become important. Is expected to be of the order of the Planck Mass and most likely smaller than it

$$M_{QG} \lesssim M_{Planck} \equiv \sqrt{\hbar c/G} \simeq 1.22 \times 10^{19} GeV/c^2$$

Lorentz Invariance Violation

- Since $E_\gamma < M_{QG,n}c^2$, the sum is dominated by the lowest-order term (n) with $s_n \neq 0$, usually n=1 or 2 (“linear” and “quadratic” LIV respectively):

$$u_\gamma = \frac{\partial E_\gamma}{\vartheta p_\gamma} \simeq c \left[1 - s_n \frac{1+n}{2} \left(\frac{E_\gamma}{M_{QG,n}c^2} \right)^n \right]$$

s_n=+1 or -1 is for subluminal and superluminal respectively

- If the speed of light depends on its energy, then two photons with energies $E_h > E_l$ emitted simulatneously will arrive at different times. For s_n=+1 (speed retardation):

$$\Delta t = \frac{(1+n)}{2H_0} \frac{E_h^n - E_l^n}{(M_{\mathrm{QG},n}c^2)^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} dz'$$

- **We want to constrain LIV -> set lower limit on $M_{QG,n}$ by measuring the upper limit of Δt between photons of different energies**

Phenomenological Approach

- Need very fast transinet phenomena providing “time stamp” for the simultaneous emission of different gamma ray energies
  - Fast GRB
  - AGN flare
  - Regular pulsed emission (Crab pulsar)
- Figure of merrit: $\mathbf{M_{QG} \sim (L\ \Delta E)\ /(c\Delta t)}$
- $\Delta \boldsymbol{E}$ – the lever arm
  - for the instrument (instrumental limit)
  - for the observed energies (observing source)
- $\Delta \boldsymbol{t}$: the time resolution
  - time resolution of the instrument (instrumental limit)
  - the bining time to have enough statistics (observing source)
- ***L***: the typical distance of the source
- Measure ΔE and Δt from data and calculate QG scale E_{QG}
- The meaning of E_{QG} is the energy scale at which QG is effective ..

LIV & FERMI GRB 090510

- Even a tiny variation in photon speed, when accumulated over cosmological light-travel times, may be revealed by observing sharp features in γ-ray burst (GRB) light-curves
- **FERMI GRB 090510** emission up to ~31 GeV from the distant and short GRB 090510.
- No evidence for the LIV, a lower limit of $1.2E_{Planck}$ on the scale of a linear energy dependence is set

	t_{start} (ms)	Limit on $\|\Delta t\|$ (ms)	Reasoning for t_{start} or method used for setting the limits	E_l (MeV)	Valid for s_n +1	Confidence	Limit on $M_{QG,1}$ (M_{Planck})	Limit on $M_{QG,2}$ ($10^{10}GeV/c^2$)
. (a)	-30	< 859	start of any <MeV emission	0.1	+1	very high	> 1.19	> 2.99
. (b)	530	< 299	start of main<MeV emission	0.1	+1	high	> 3.42	>5.06
. (c)	630	< 199	start of main>0.1 GeV emission	100	+1	high	> 5.12	> 6.20
. (d)	730	< 99	start of main>1 GeV emission	1000	+1	medium	> 10.0	> 8.79
. (e)	–	< 10	association with<1 MeV spike	0.1	±1	low	> 102	> 27.7
. (f)	–	< 19	if 0.75GeV γ-ray from 1st spike		-1	low	> 1.33	> 0.54
. (g)	$\|\Delta t/\Delta E\| < 30ms/GeV$		Lag analysis of all LAT photons	–	±1	very high	> 1.22	–

Abdo et al. 2009, Nature 462, 331

- These results support Lorentz invariance and disfavor models in which a quantum nature of space-time alters the speed of light, giving it a linear dependence on photon energy

LIV & Crab Pulsar

- MAGIC has detected emission from the Crab Pulsar up to 0.5 TeV for the main pulse P1, and up to 1.5 TeV for the inter-pulse P2
- The spectrum of both pulses is consistent with a power-law, however a significant difference was found between the reconstructed spectral indices of P1 and P2, the latter being harder
- Maximum likelihood method is constructed containing two parameters $\lambda_1 \equiv 10^{19}\ \mathrm{GeV}/E_{QG_1}$ $\lambda_2 \equiv 10^{12}\ \mathrm{GeV}/E_{QG_2}$
- LIV produces mean phase delay

$$\Delta\phi_n = c_n \cdot \left(\lambda_n \cdot \left(\frac{E}{\mathrm{GeV}}\right)\right)^n$$

$$c_1 = \xi_1 \cdot \frac{d_{\mathrm{Crab}}}{c \cdot P_{\mathrm{Crab}}} \cdot 10^{-19} \quad (\mathrm{GeV}^{-1})$$

$$c_2 = \xi_2 \cdot \frac{3}{2} \frac{d_{\mathrm{Crab}}}{c \cdot P_{\mathrm{Crab}}} \cdot 10^{-24} \quad (\mathrm{GeV}^{-2})$$

c- speed of light, d_{Crab}- pulsar disatnce, P_{Crab}-pulsar period

LIV & Crab pulsar

Data samples used:

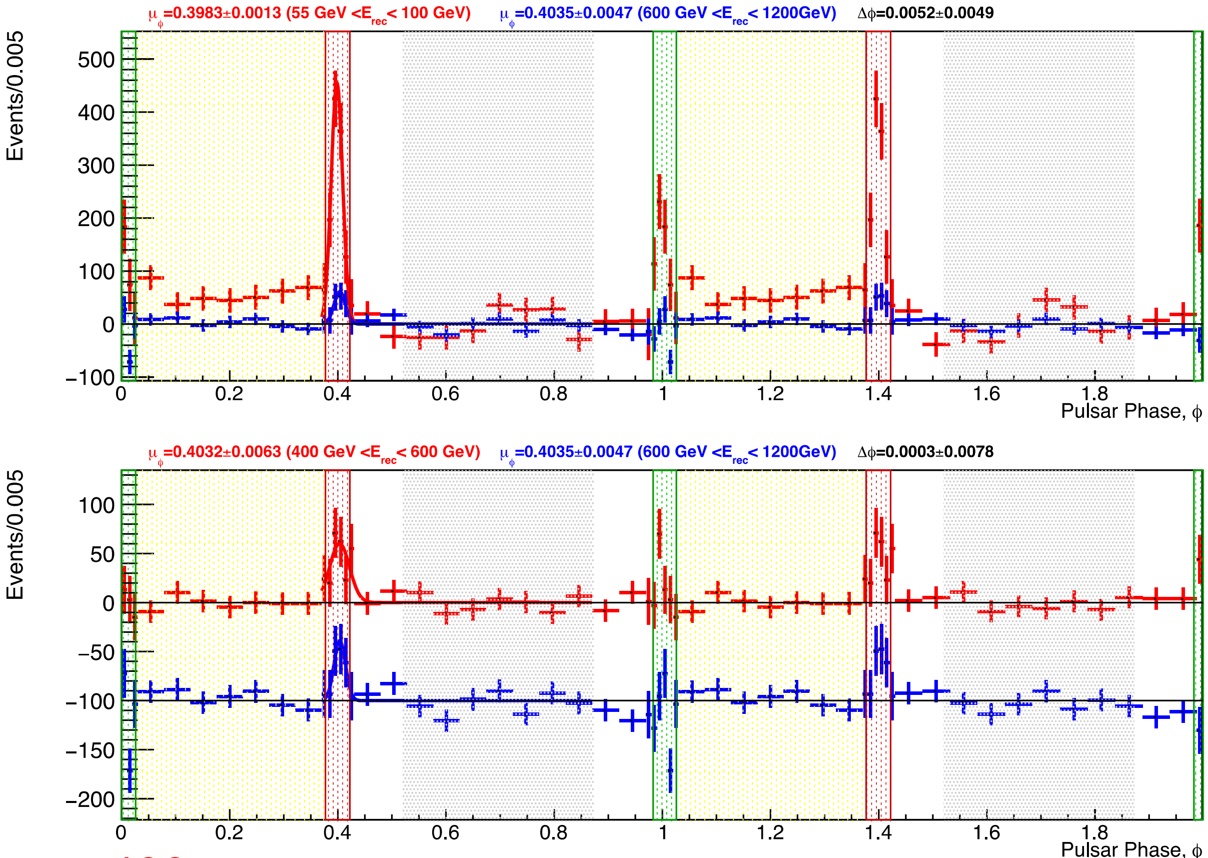
- **19 observation periods.**
- **19 different IRFs**
- **Systematic uncertanity studied and included in the limits**

A profile likehood analysis of pulsar events reconstructed for energies above 400 GeV finds no signficant variation in arrival time as the energy increase.

95 % CL lower limits are obatined on LIV energy scale are obatined (linear and quadratic)

Pulsar are useful to study time of flight diferences of energetic photons. Stable and continum emission ensure limits improvement over time.

55 Gev < E < 100 GeV 600 Gev < E < 1200 GeV



400 Gev < E < 600 GeV 600 Gev < E < 1200 GeV

case	95% CL limit (w/o systematic)	95% CL limit (incl. systematics)
$\xi_1 = +1$	$E_{QG_1} > 7.8 \cdot 10^{17}$ GeV	$E_{QG_1} > 5.5 \cdot 10^{17}$ GeV
$\xi_1 = -1$	$E_{QG_1} > 6.4 \cdot 10^{17}$ GeV	$E_{QG_1} > 4.5 \cdot 10^{17}$ GeV
$\xi_2 = +1$	$E_{QG_2} > 8.0 \cdot 10^{10}$ GeV	$E_{QG_2} > 5.9 \cdot 10^{10}$ GeV
$\xi_2 = -1$	$E_{QG_2} > 7.2 \cdot 10^{10}$ GeV	$E_{QG_2} > 5.3 \cdot 10^{10}$ GeV

Caveat in LIV search

How to disentangle propagation delays from source intrinsic delay?

- observe sources at different redshifts and check delay proportional to distance.

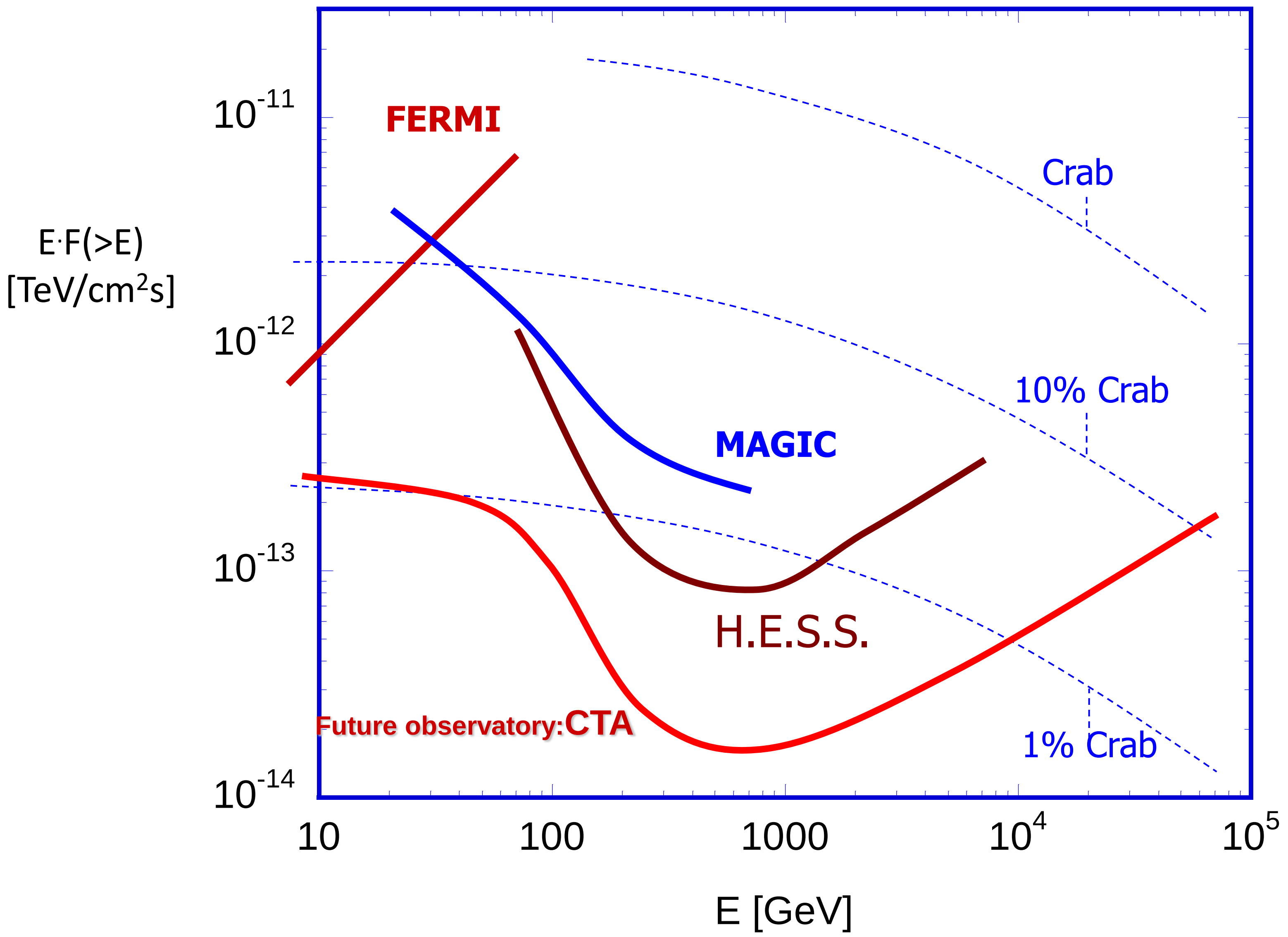
- use geometrical time stamps (pulsars).

CTA – LST (23 m diameter)


CTA Large Size Telescope, May 2018
Credits: T. Dettlaff

Ideal#geometry#for#common#observa1ons#

CTA sensitvity



Summary

- There is a clear interplay between gamma ray astrophysics and fundemental physics
  - Study the progattion of phootns over cosmological distances
  - Search for dark matter and new particles in phootn spectrum
  - Study physics of extreme enviroemnts
- VHE gamma ray astrophysics is exploring regions beyond the reach of accelerators
- CTA with factor ten better sensitivity than current IACTs is just around corner
- New instruments are planed (e-ASTROGRAM, COMPAIR) or going to be upgarde (HAWC, LHASSO) ...

Thanks

Indircet DM search

The gamma- ray flux from WIMP annihilation is proportional to:

- The number density squared of particles, i.e., ρ^2;
- The WIMP annihilation cross section today, σ;
- The mean WIMP velocity v;
- Volume of the sky observed within a solid angle Ω;
- Number of gamma-rays produced per annihilation at a given energy, also known

as the energy spectrum (dN/dE)

$$\overbrace{\frac{d\Phi}{d\Omega dE}}^{\text{Diff.Flux}} = \frac{\overbrace{\sigma v}^{\text{Anni. Cross Section}}}{8\pi m_\chi^2} \times \underbrace{\frac{dN}{dE}}_{\text{Energy Spectrum}} \times \overbrace{\int_{\text{l.o.s}} ds}^{\text{Line of Sight Integral}} \times \underbrace{\rho^2(\overrightarrow{r}(s,\Omega))}_{\text{DM Distribution}}$$

Therefore, after measuring the flux in gamma-rays from a given source, we compare that with background expectations. If no excess is observed, we can choose a DM density profile and select an annihilation final state needed for dN/dE, and then derive a limit on the ratio $\langle\sigma v\rangle/m_\chi^2$ according to equation above. This is the basic idea behind experimental limits.