Expanding the Gaia legacy:
the role of Spanish ground-based facilities

Barcelona, 18 February 2020

CTA and its synergies with Gaia

Marc Ribó (mribo@ub.edu)

On behalf of the CTA-Spain community

cta cherenkov telescope array

Universitat de Barcelona

ICCUB Institut de Ciències del Cosmos

Excelencia María de Maeztu

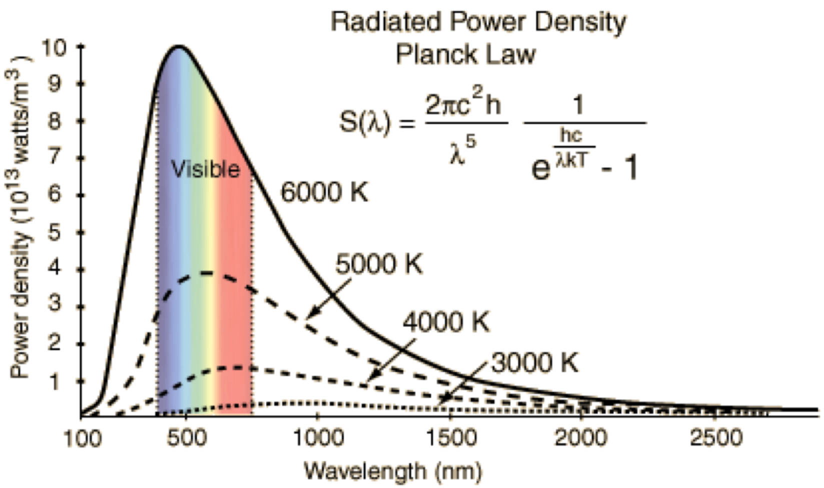
IEEC

OUTLINE

1. Introduction
2. Cherenkov Telescope Array
3. CTA Key Science Projects
4. CTA-Gaia Synergies
5. Conclusions

Introduction

Thermal processes: Maxwellian distribution of particle *E*, characterized by *T*.
Thermal spectrum: **black body emission**.



Introduction

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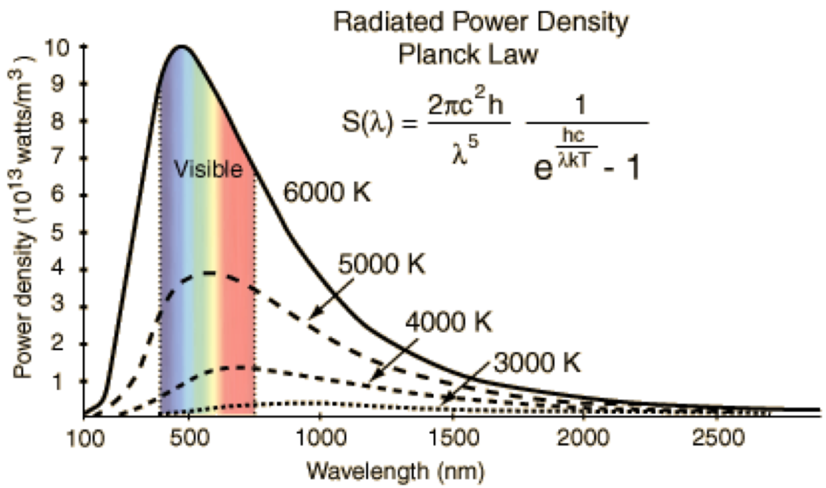
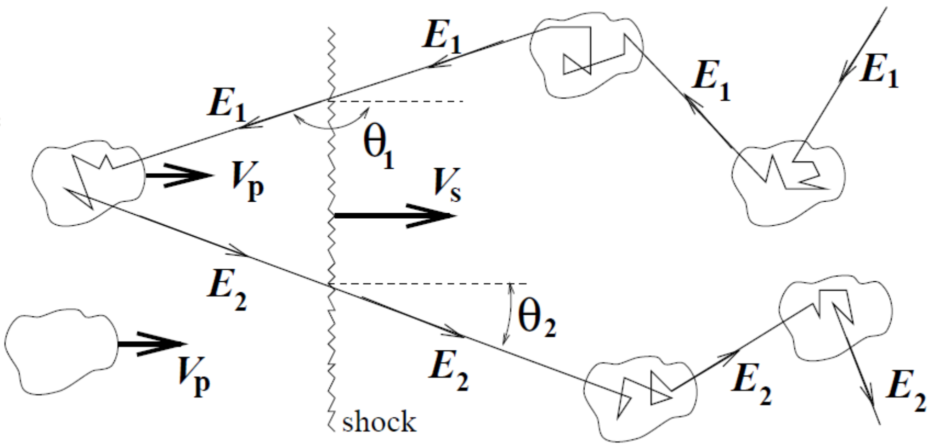


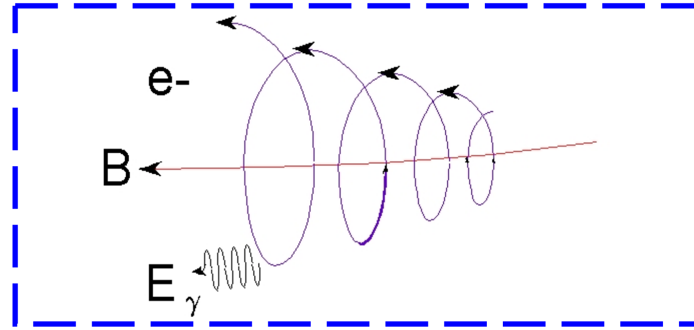


Non-thermal processes: particle acceleration → power-law distr. of particle *E*.
Non-thermal spectra: **very different**, depending on physical parameters.

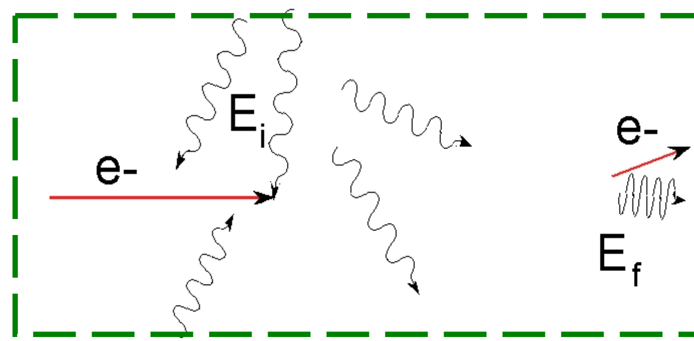
Introduction

➢ **Electromagnetic Processes**:

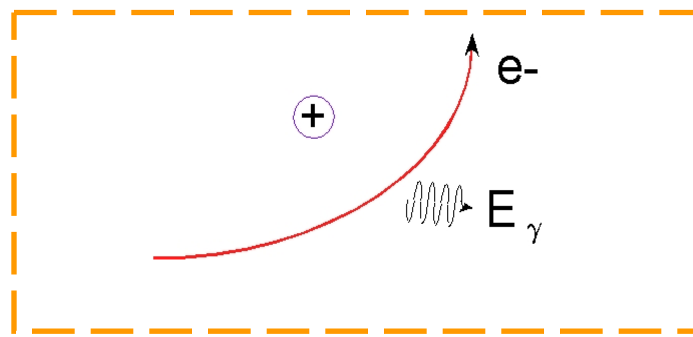
Synchrotron Emission:
Probes Magnetic Field, Electron Energy



Inverse Compton Scattering:
Probes Photon Field, Electron Energy



Bremmstrahlung:
Probes Matter Density, Electron Energy

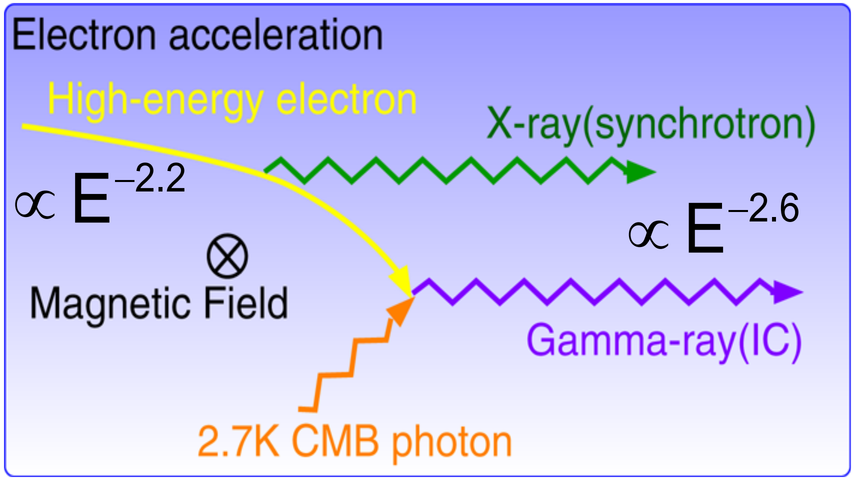


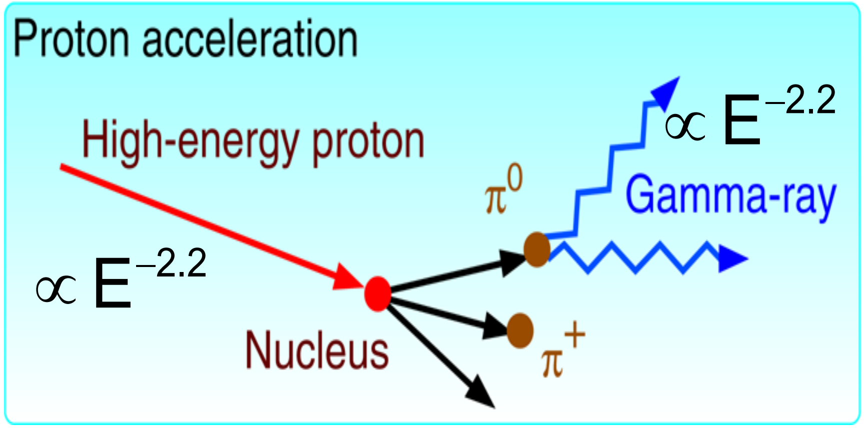
➢ **Hadronic Cascades**:

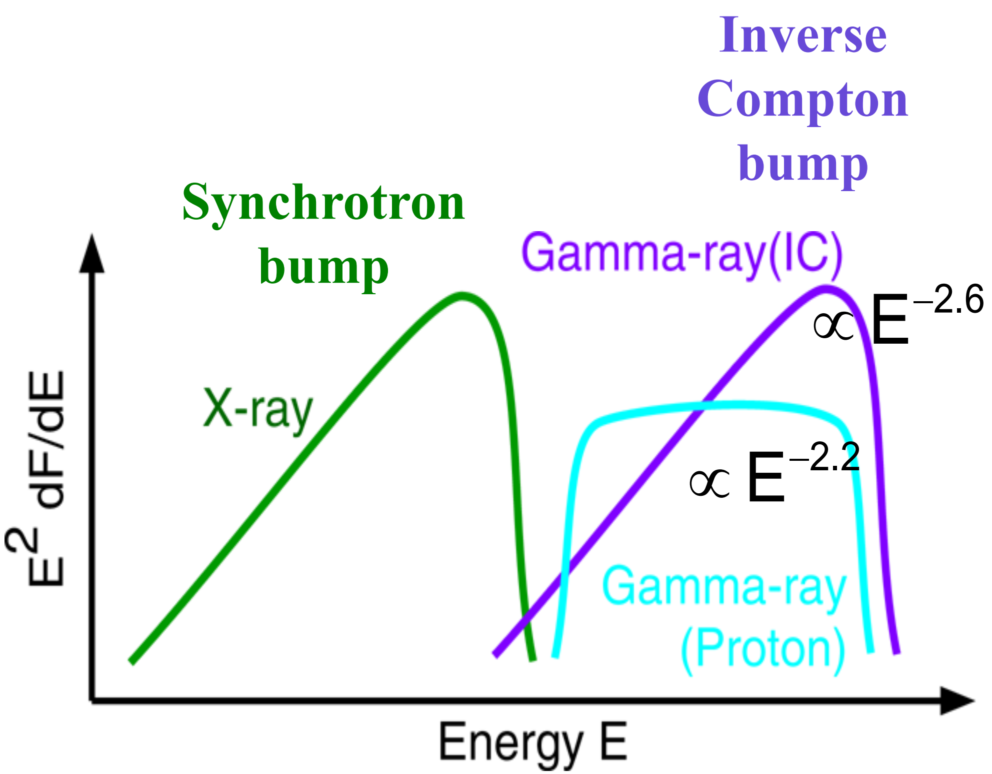
$$p + \gamma \rightarrow \pi^{\pm} + \pi^{o} + \ldots \rightarrow e^{\pm} + \nu + \gamma + \ldots$$
$$p + p \rightarrow \pi^{\pm} + \pi^{o} + \ldots \rightarrow e^{\pm} + \nu + \gamma + \ldots$$

Introduction

Gamma-ray emission processes

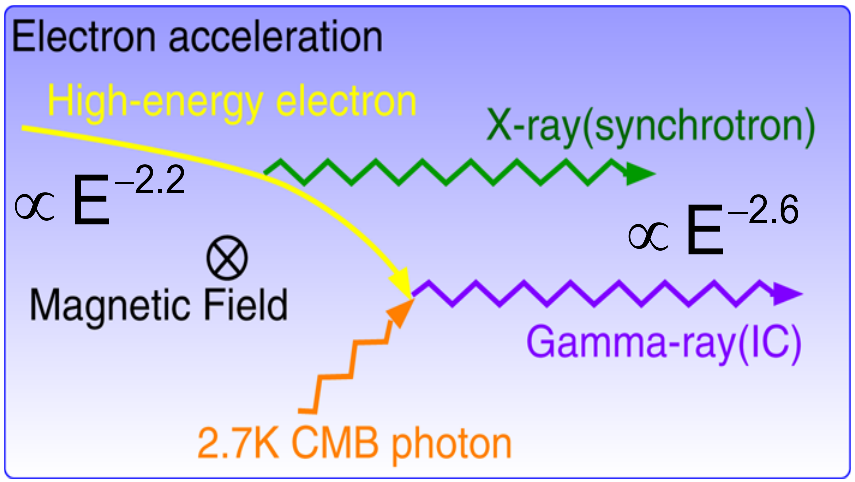


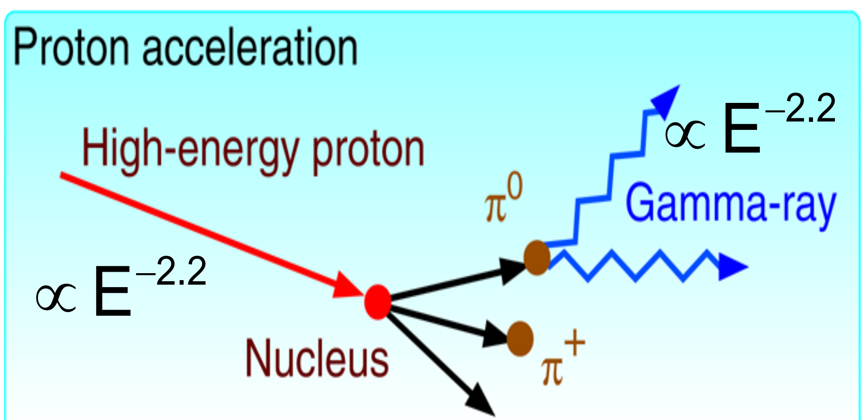


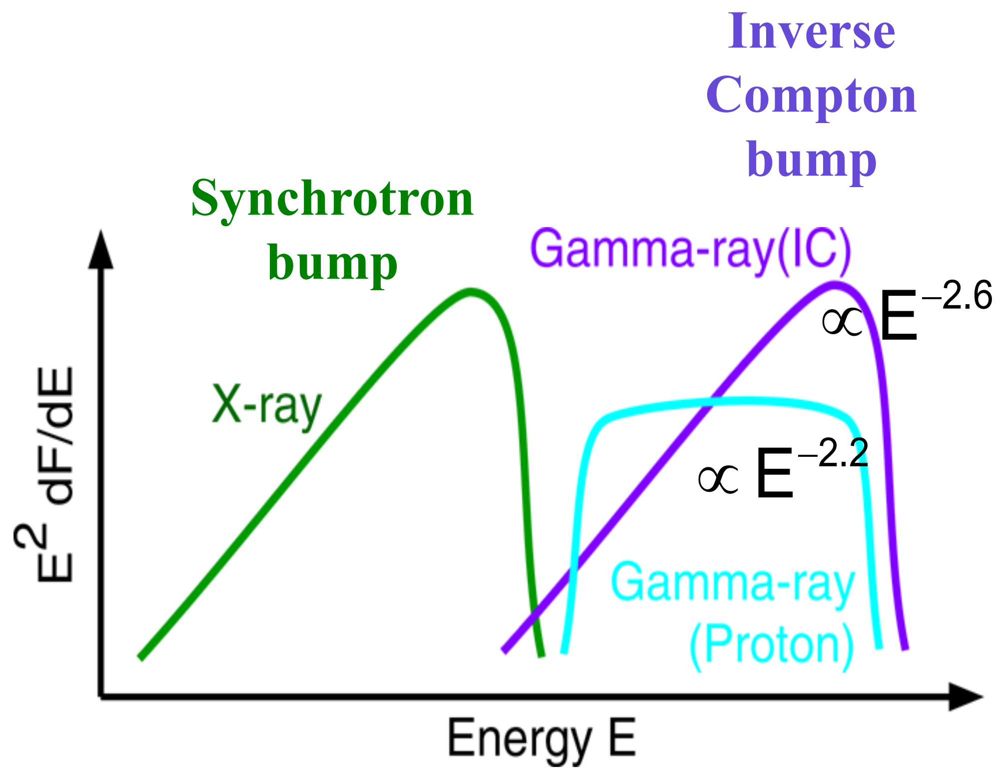


Introduction

Gamma-ray emission processes







Gamma rays

0.1-1 MeV soft *INTEGRAL*/IBIS

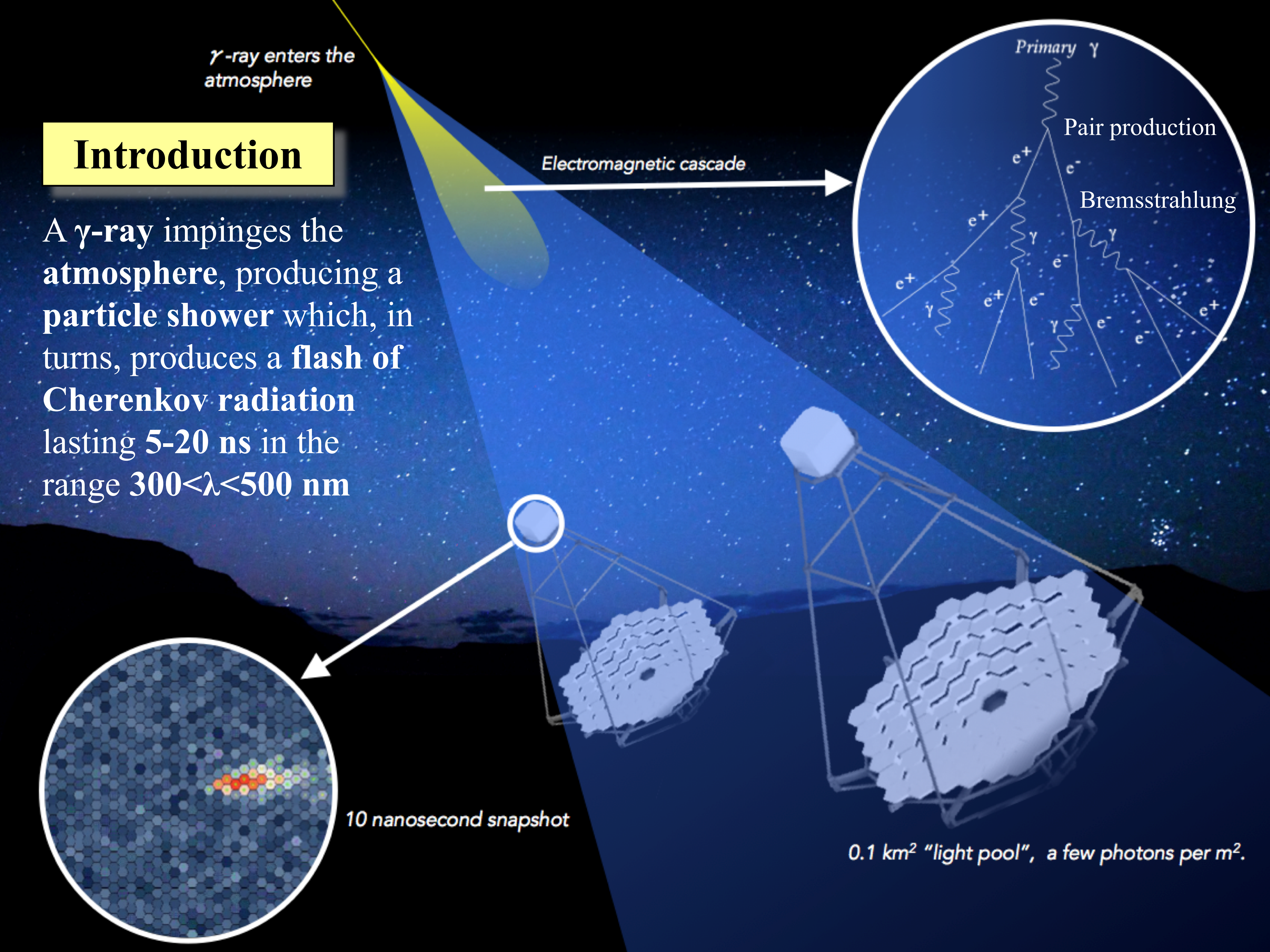
1-100 MeV *CGRO*/COMPTEL

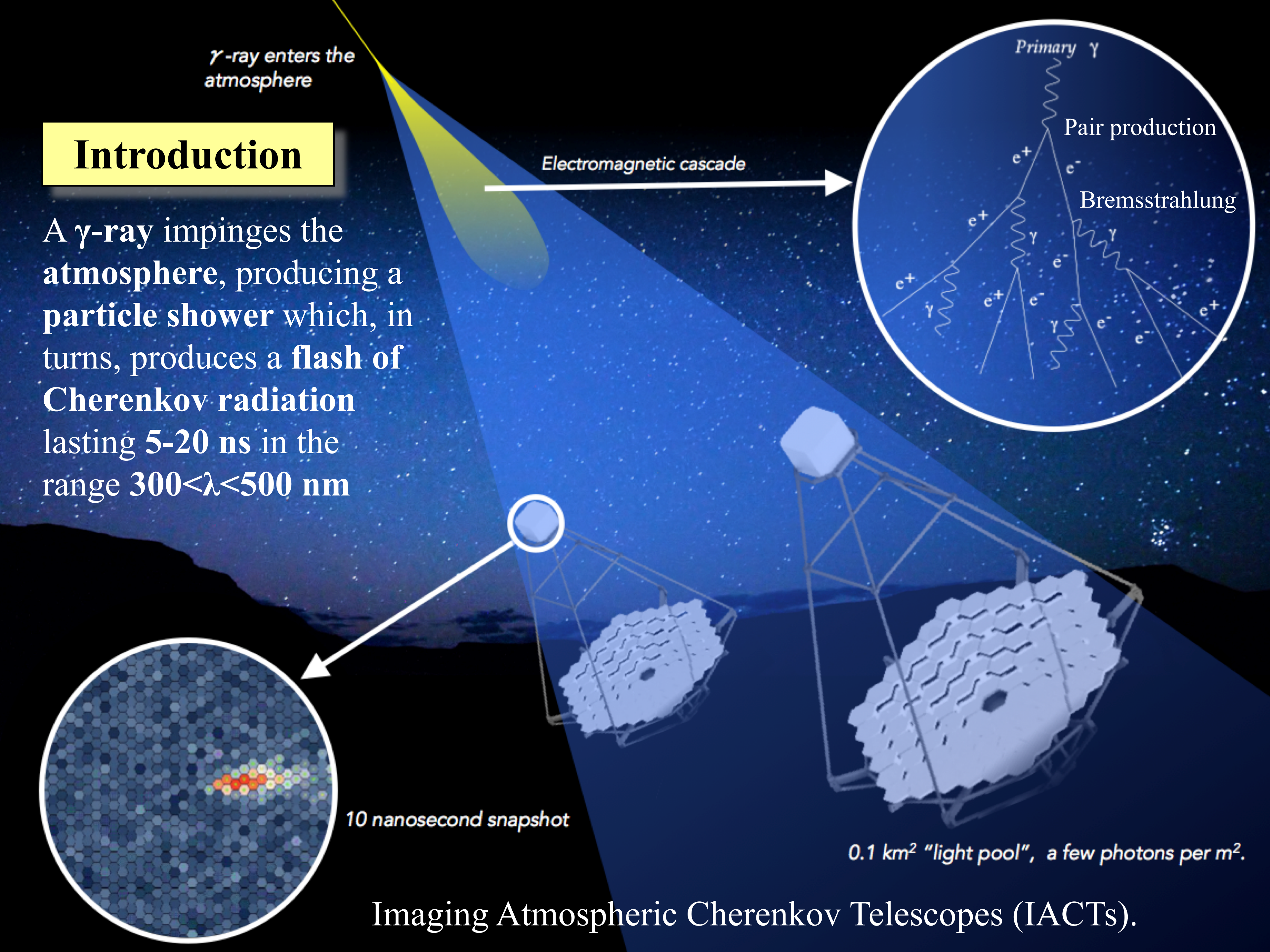
0.1-50 GeV **High Energy** (HE)
AGILE, *Fermi*/LAT

>50 GeV **Very High Energy** (VHE)
HESS, MAGIC, VERITAS, HAWC

Introduction

A **γ-ray** impinges the **atmosphere**, producing a **particle shower** which, in turns, produces a **flash of Cherenkov radiation** lasting **5-20 ns** in the range **300<λ<500 nm**

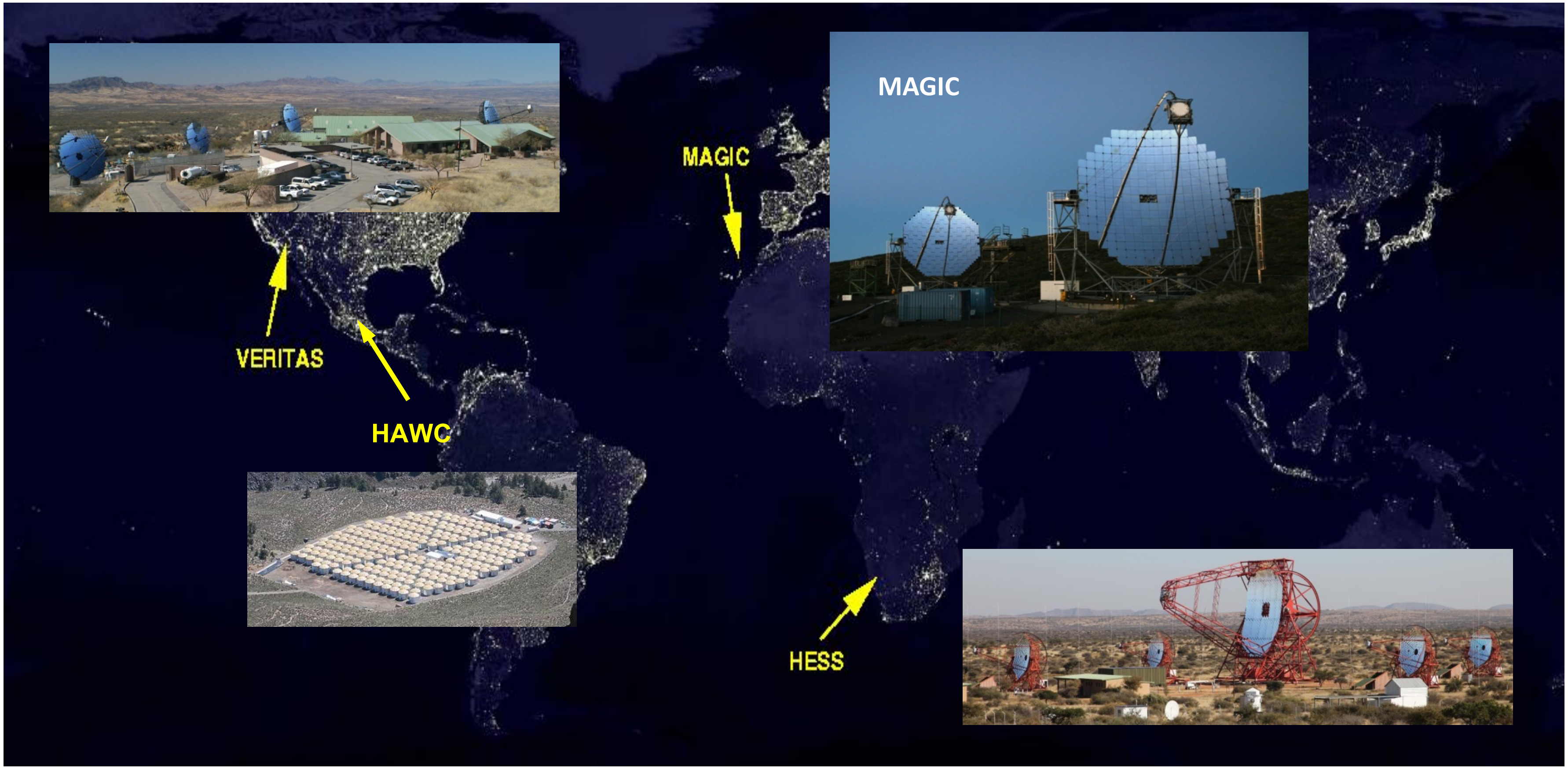



γ -ray enters the atmosphere
Introduction
A γ-ray impinges the atmosphere, producing a particle shower which, in turns, produces a flash of Cherenkov radiation lasting 5-20 ns in the range 300<λ<500 nm
Electromagnetic cascade
Primary γ
Pair production
Bremsstrahlung
e+
e-
γ
10 nanosecond snapshot
0.1 km² "light pool", a few photons per m².
Imaging Atmospheric Cherenkov Telescopes (IACTs).

Introduction

Current TeV instrumentation

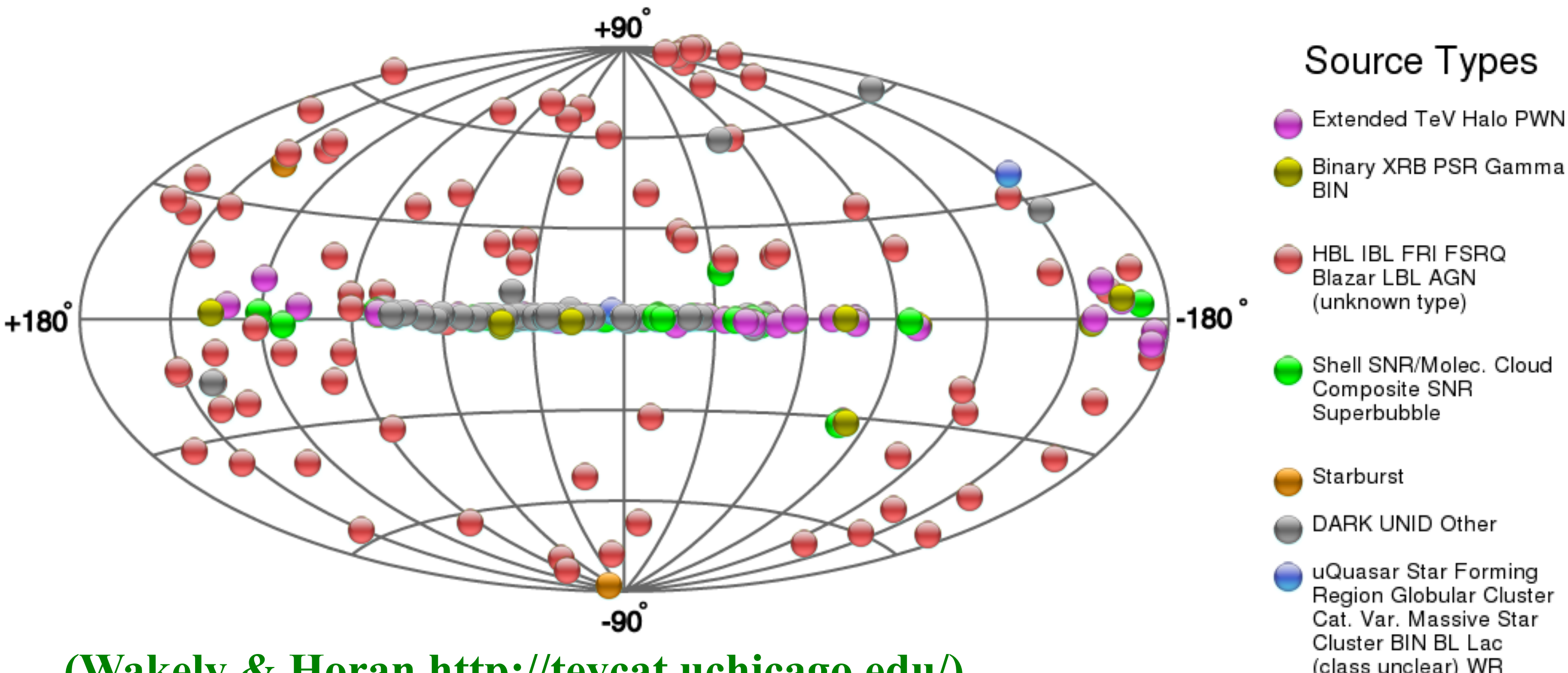
Sensitivity **<1% of Crab** Nebula flux in 50 h, energy range **~0.05-100 TeV**, energy resolution ~10% (**$\Delta E/E$ ~0.1**), angular resolution **<0.1º**, wide **FoV 3-5º**.



Introduction

This instrumentation allows us to conduct **surveys**, **morphological** studies, **spectro-morphological** studies, detect **faint and diffuse emission**, detect **variability**, or conduct **phase-resolved spectroscopy** of variable sources.

2020 Feb: **226** sources known! **~35%** extragalactic, **~40%** galactic, **~25%** unid.



(Wakely & Horan http://tevcat.uchicago.edu/)

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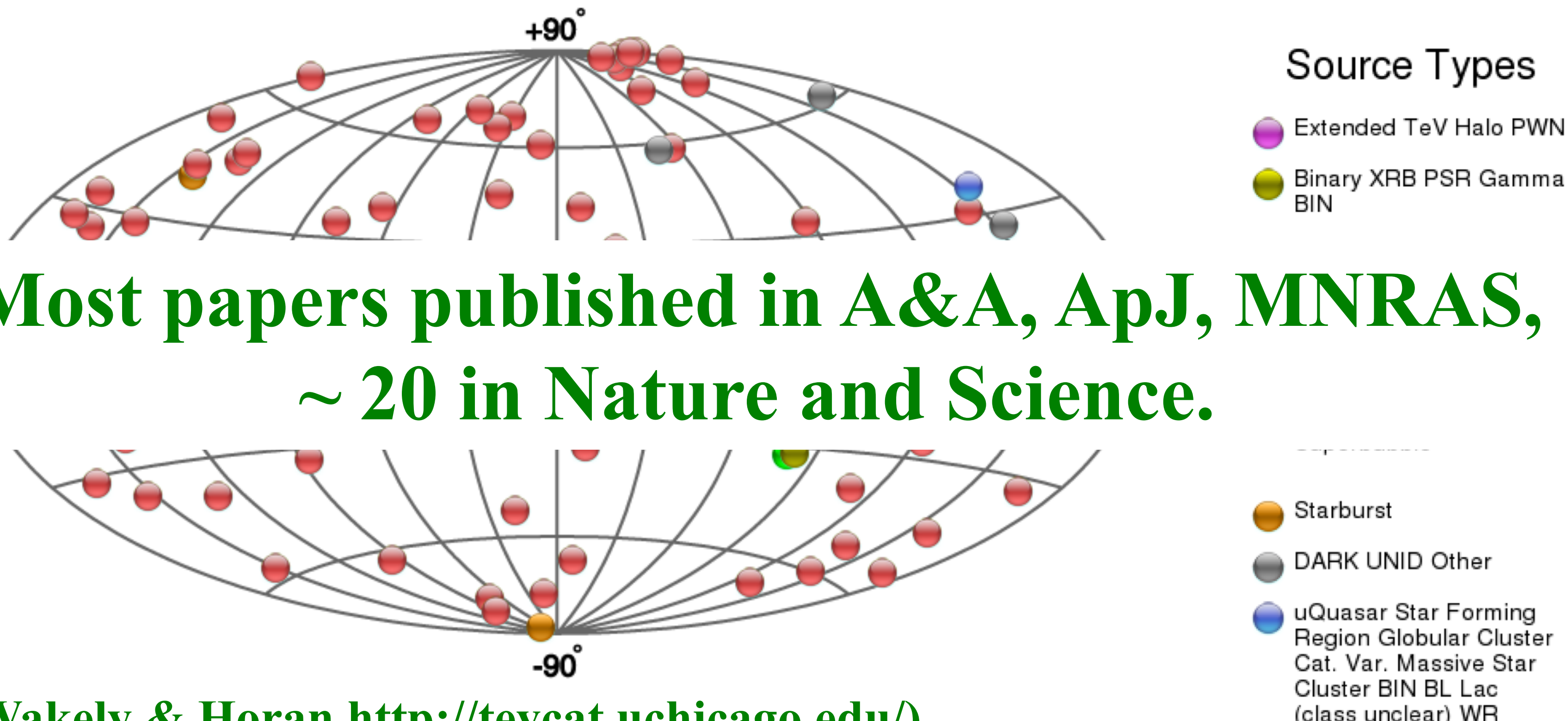
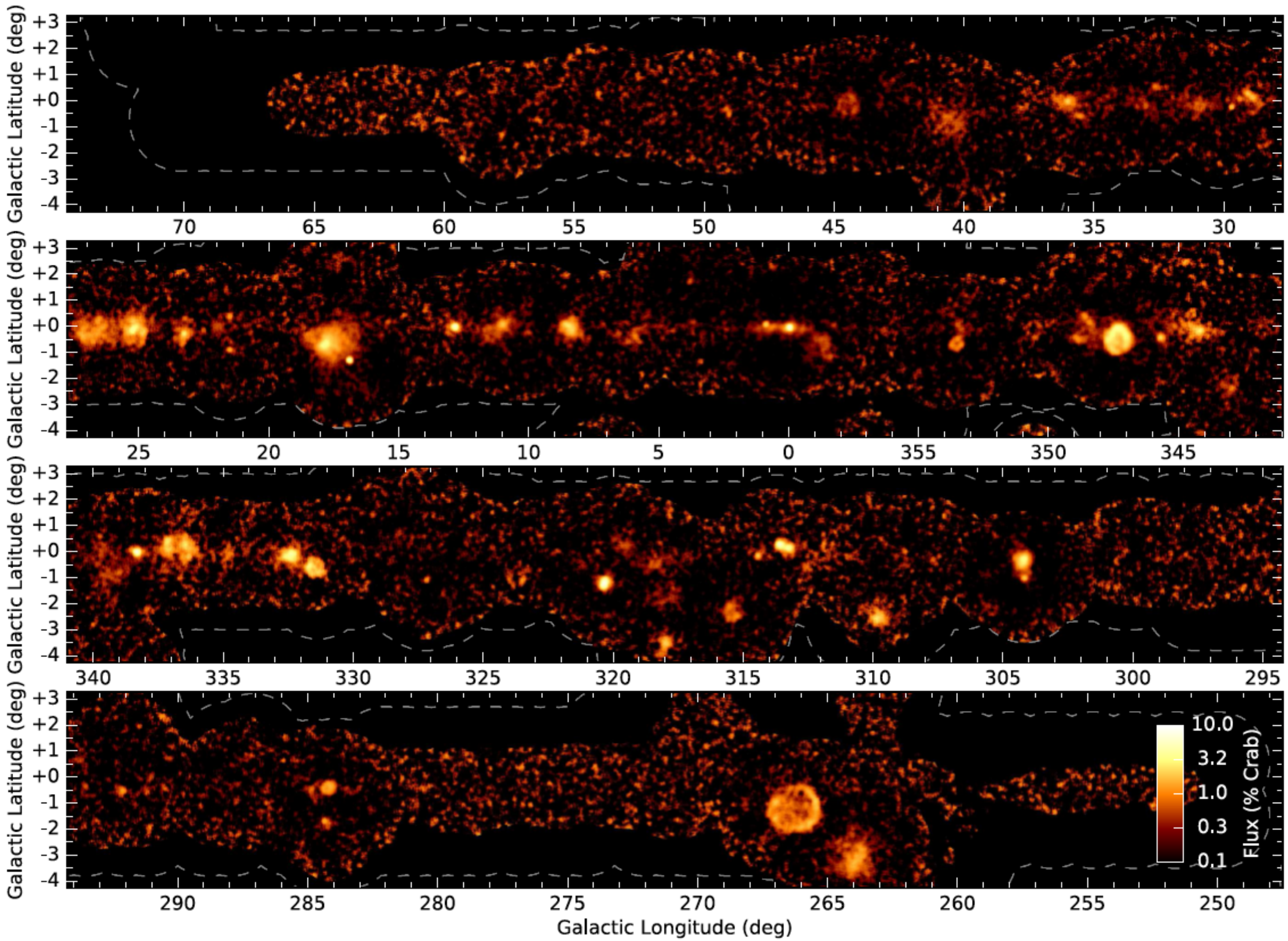


Most papers published in A&A, ApJ, MNRAS, ~ 20 in Nature and Science.

(Wakely & Horan http://tevcat.uchicago.edu/)

Introduction

Survey of the southern Galactic plane
(HESS Collaboration 2018).



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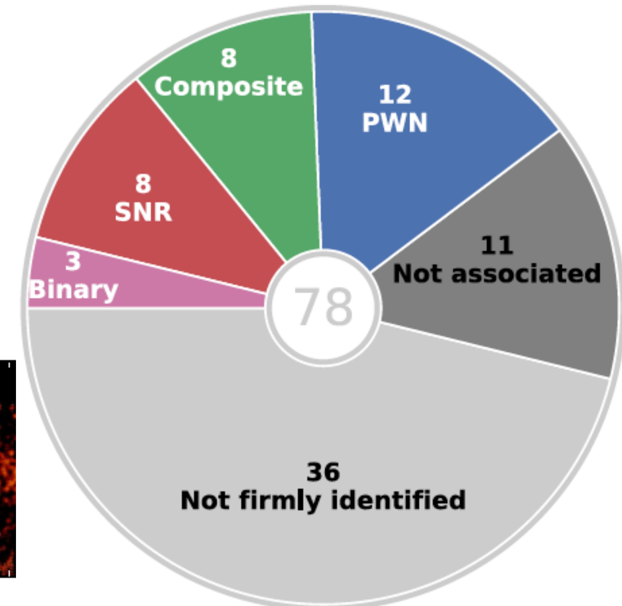
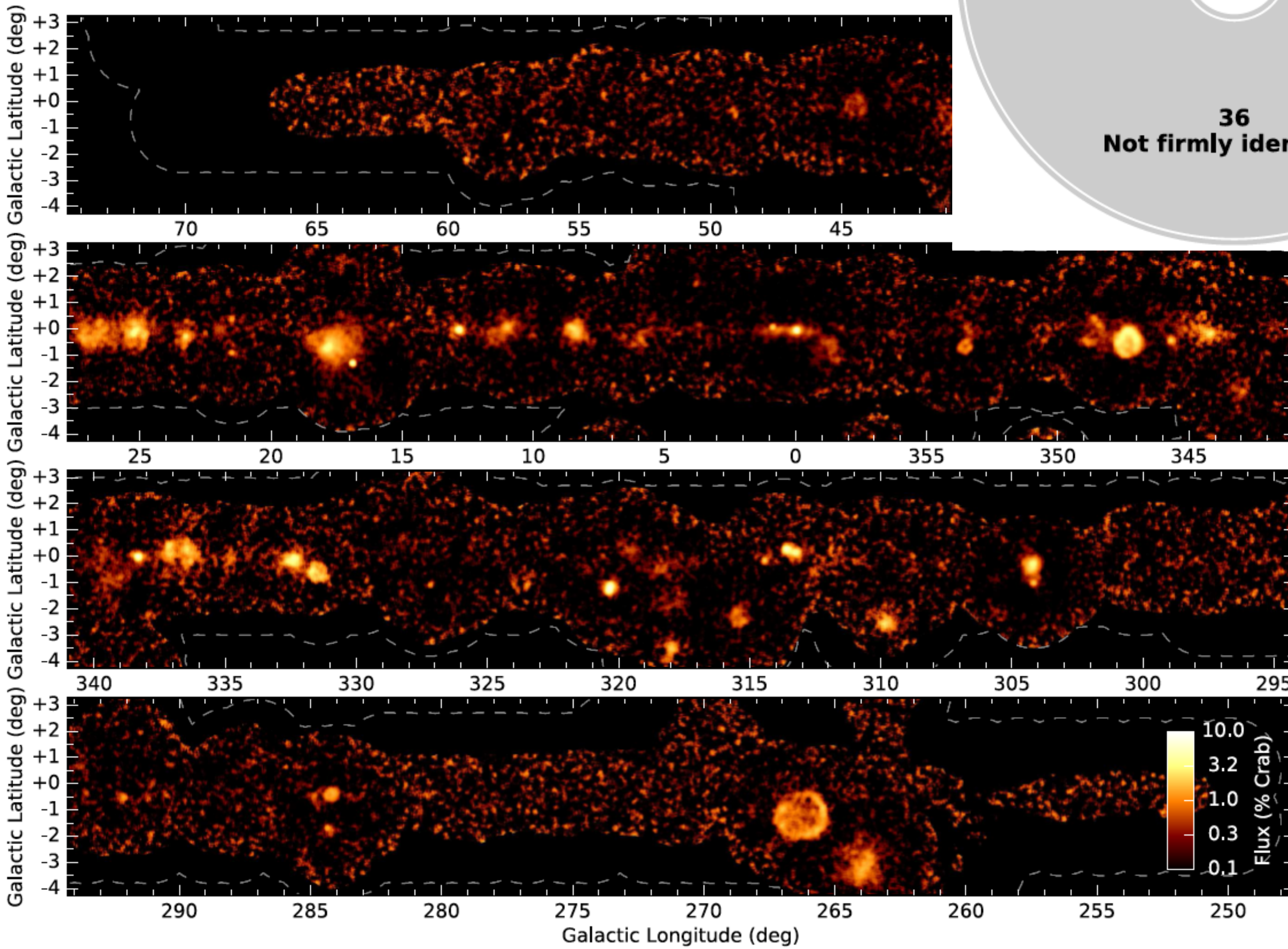
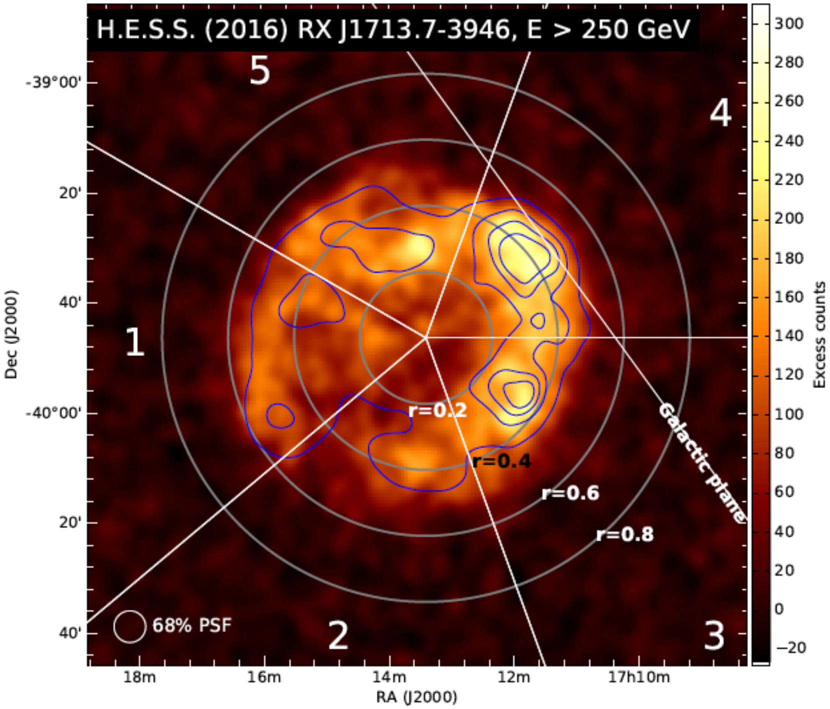


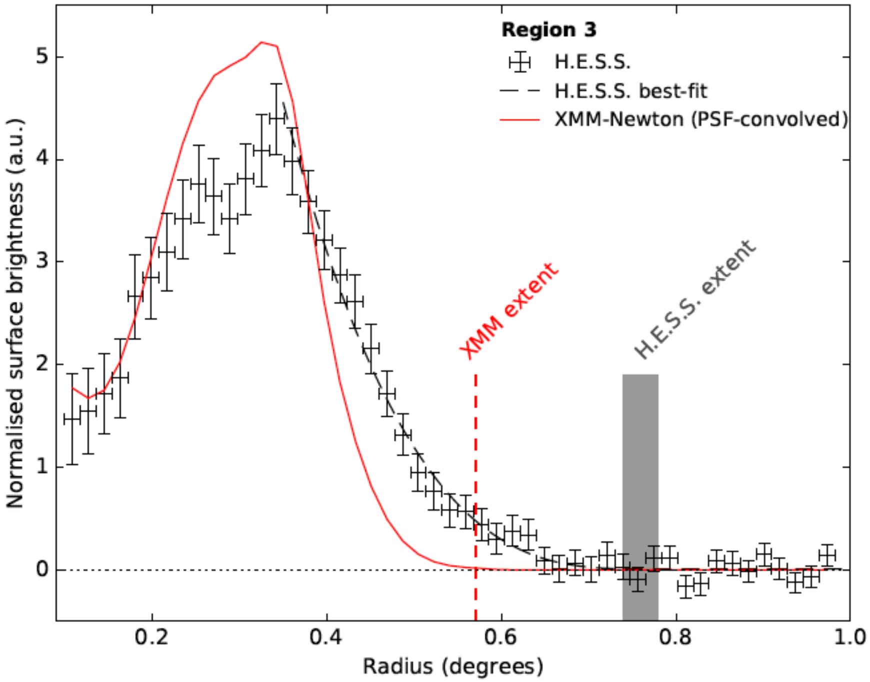


Introduction

SNR RX J1713.7–3946 (HESS Collaboration et al. 2018).
Evidence for gamma-ray emission extending beyond the X-ray emitting shell.

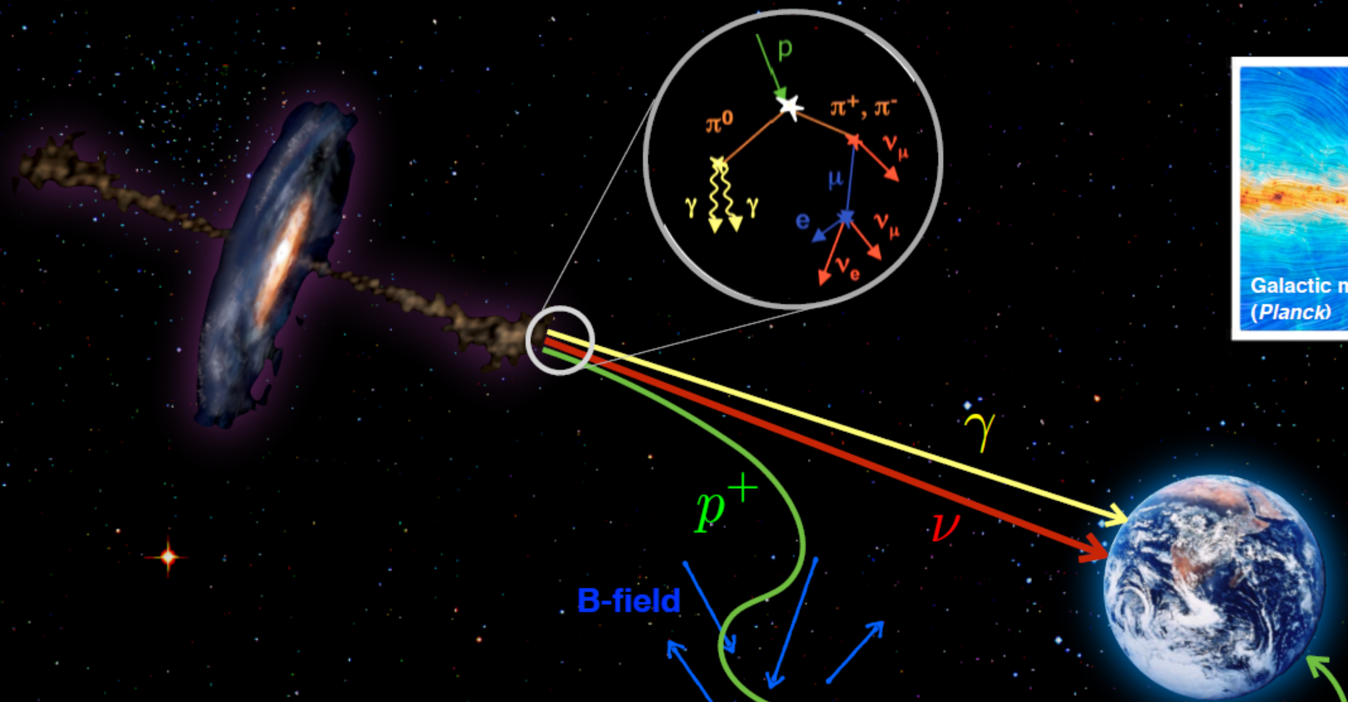
- First indication for particles in the process of leaving the acceleration shock.
- **Leptonic** processes could dominate in the shell and central part.
- **Hadronic** processes could contribute in the outer regions.

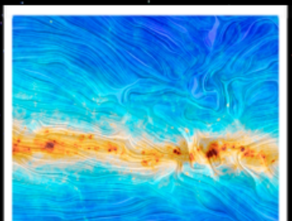




Introduction

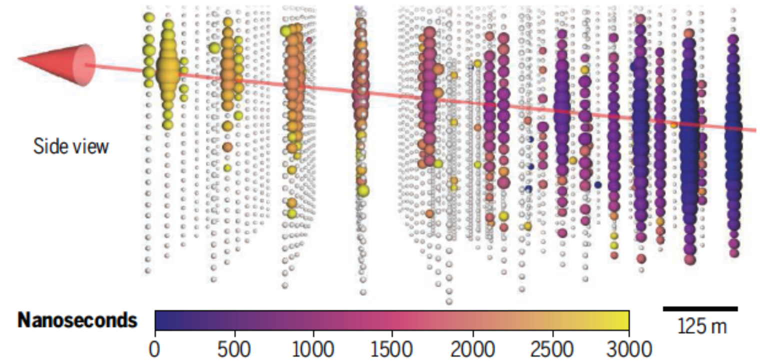
Multi-messenger astronomy



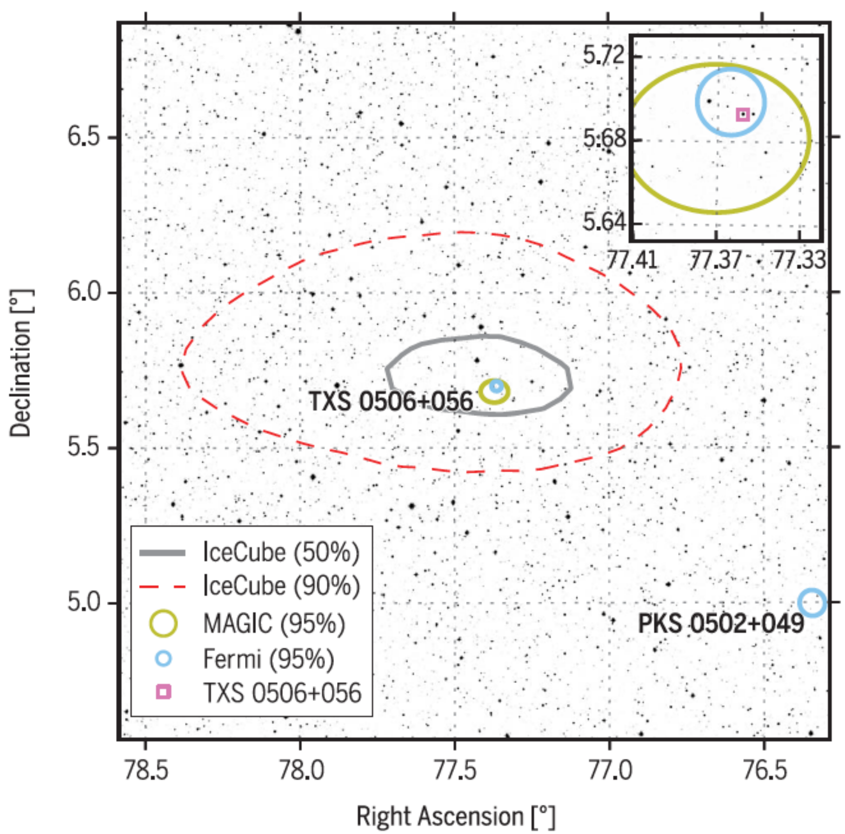

Galactic magnetic field (*Planck*)

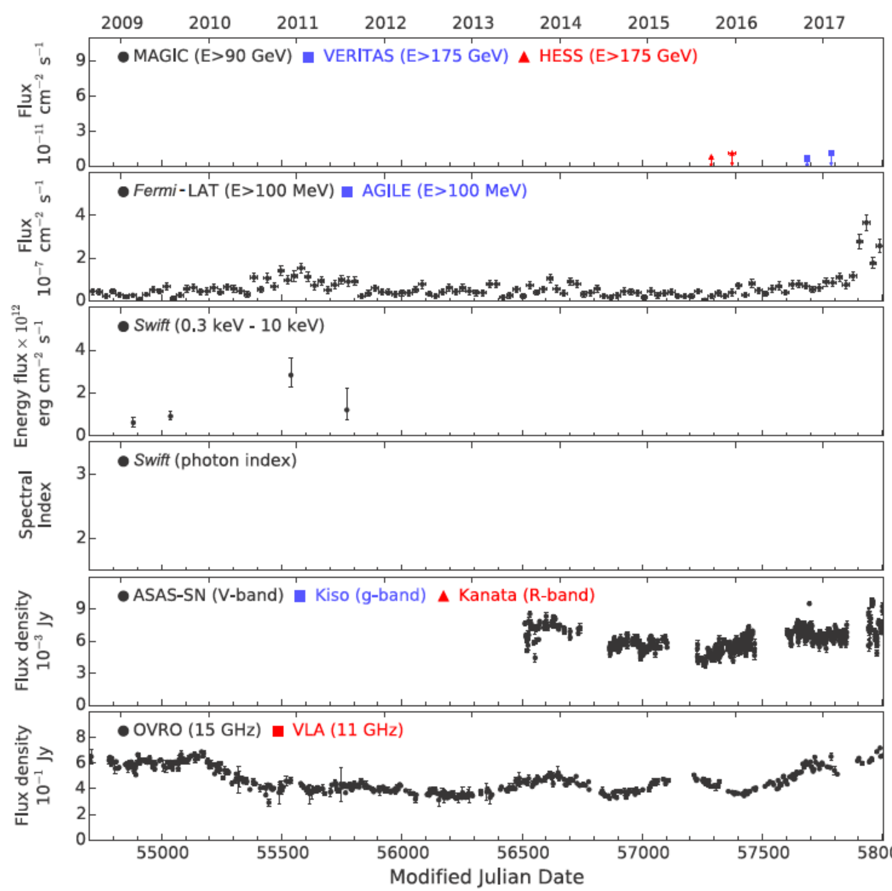
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$ **(oscillates to ~1:1:1)**

Introduction



Counterpart of an **Extremely High Energy neutrino** of 290 TeV in 2017 September 22.
Origin of **Ultra-High Energy Cosmic Rays**?
(Icecube, Fermi/LAT, MAGIC et al. 2018, Science).





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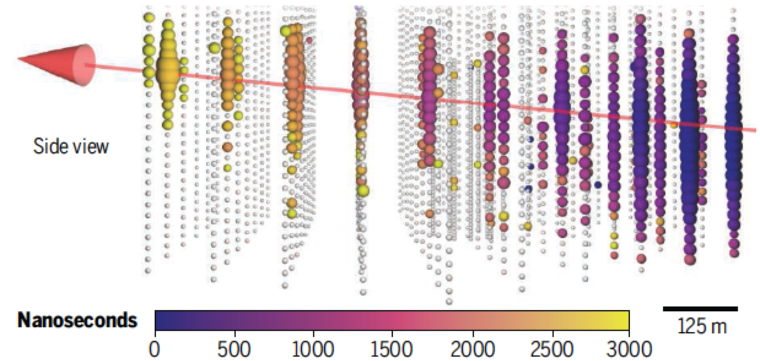
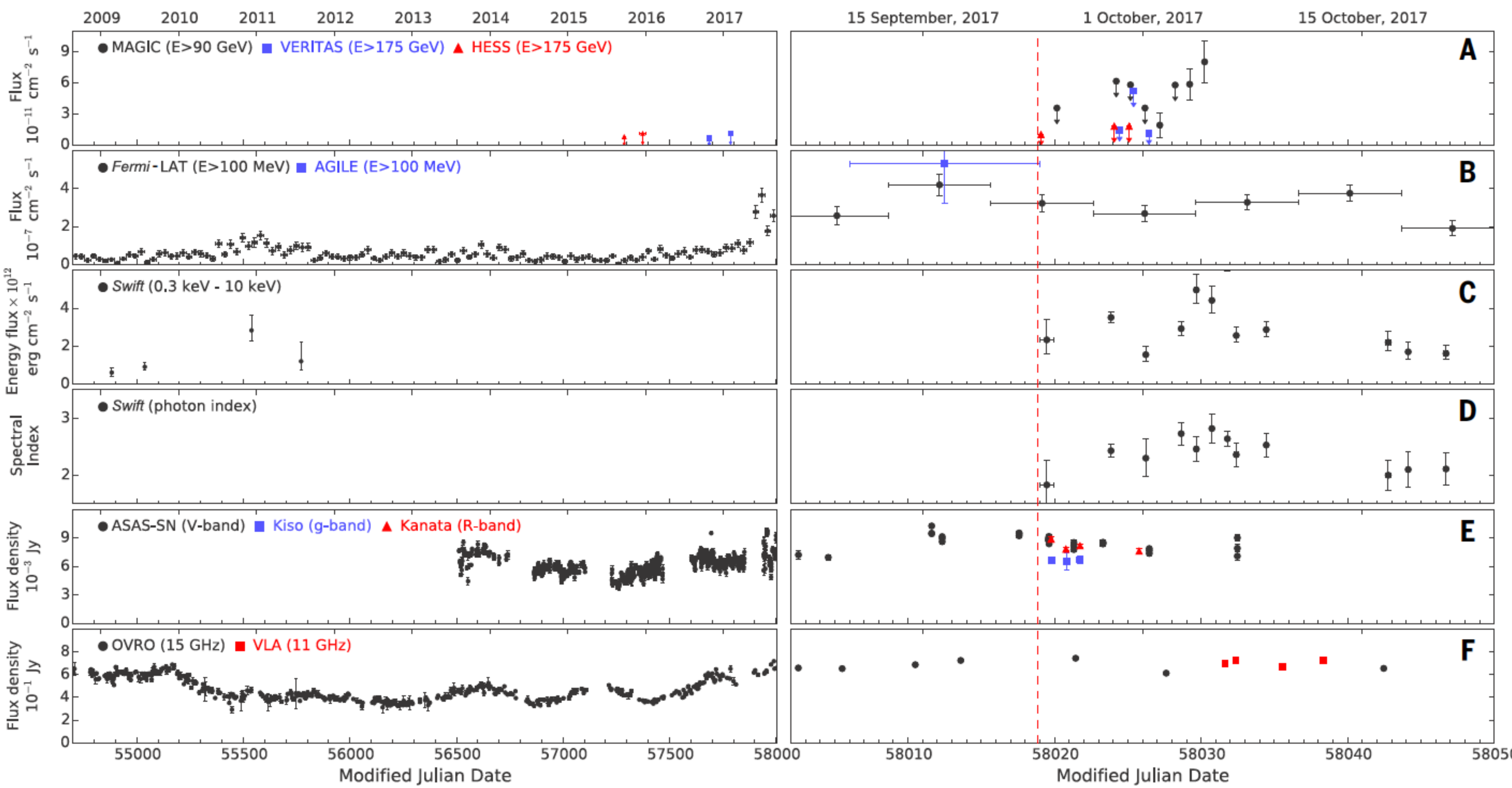
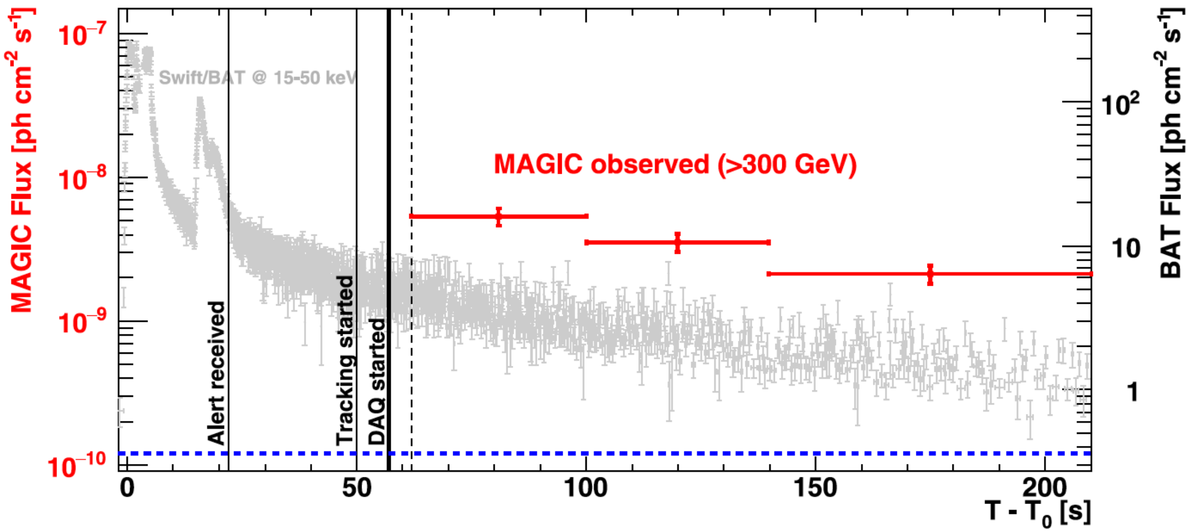
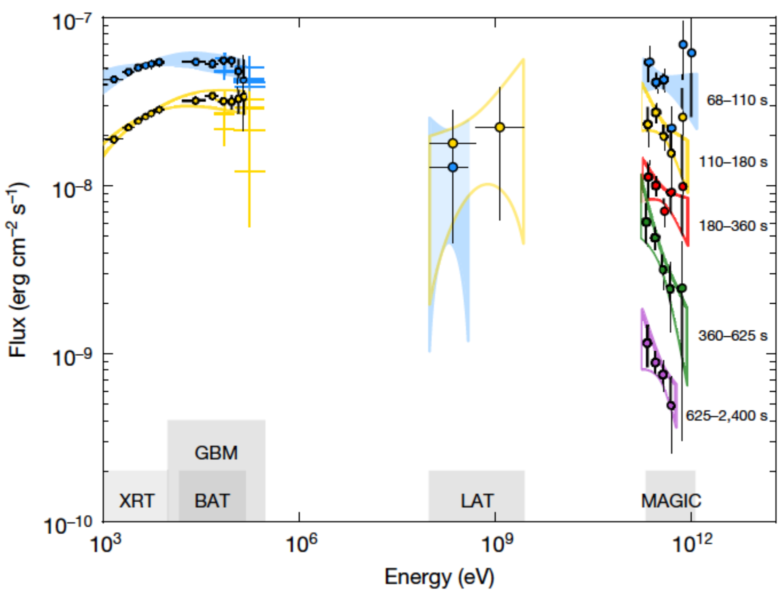


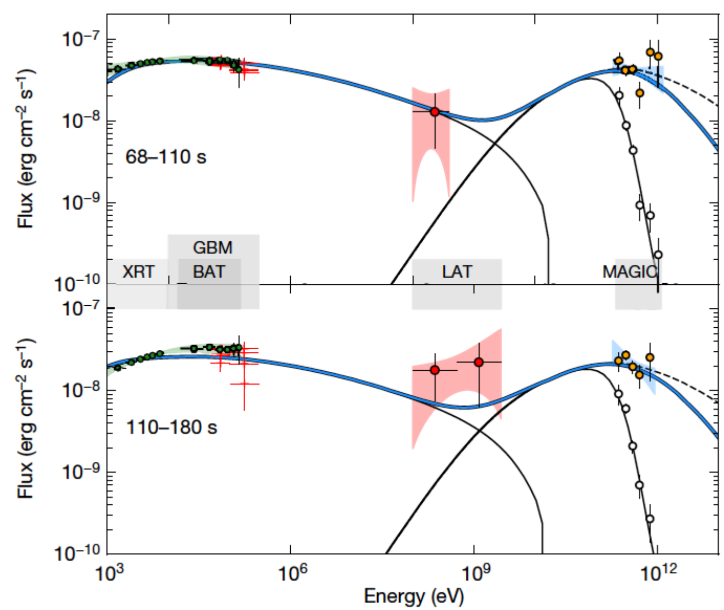


Introduction

First GRB reported at TeV energies. IC component. (MAGIC Collaboration 2019 & MAGIC Collaboration et al. 2019).

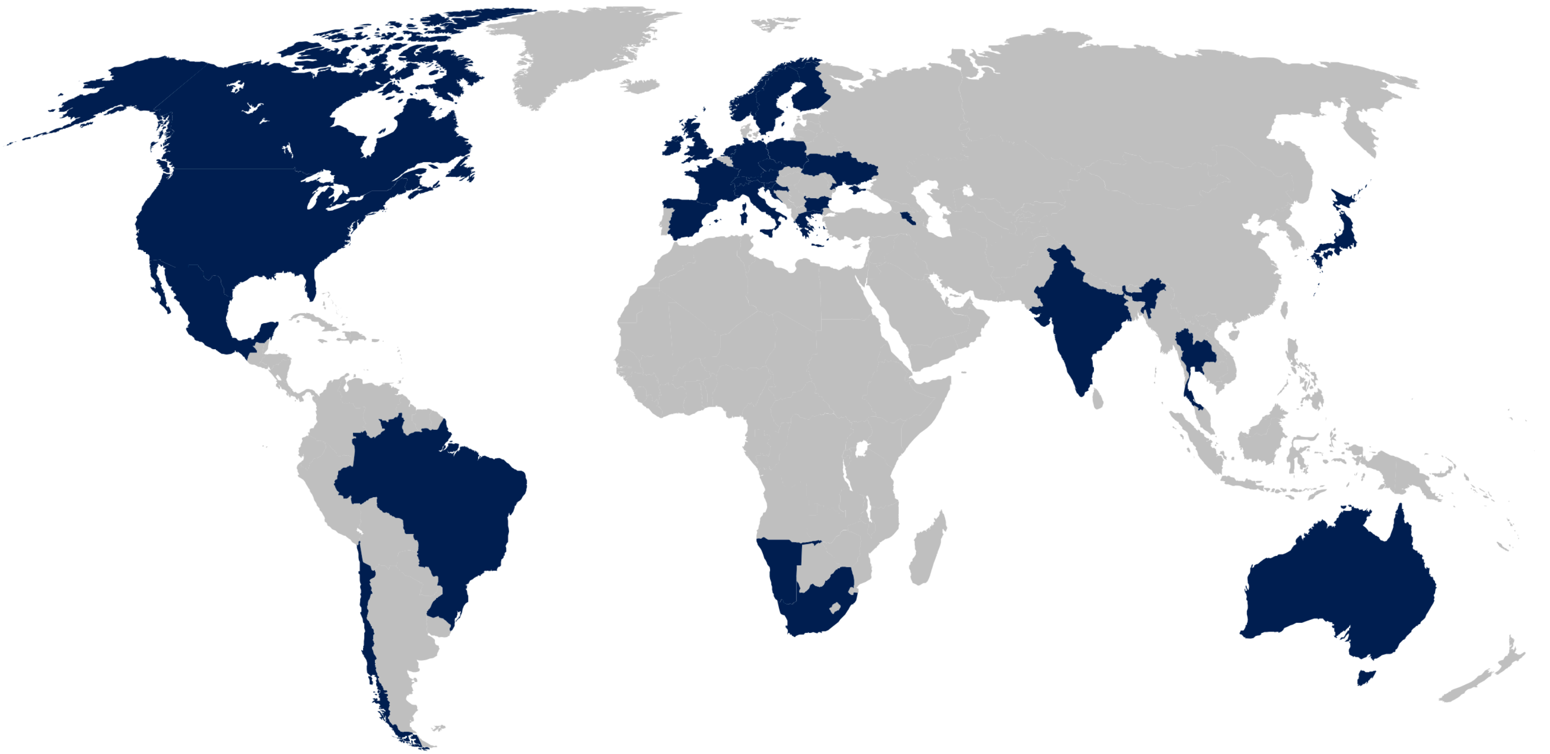






Cherenkov Telescope Array

CTA science goals and design is being developed by the **CTA Consortium**:
> 1.400 scientists and engineers from about **200 institutes in 31 countries**.
http://www.cta-observatory.org/



Spain involved since the beginning (~2008); **http://observatorio-cta.es/**

Cherenkov Telescope Array

CTA-Spain: coordinated effort by all the Spanish groups working for CTA:

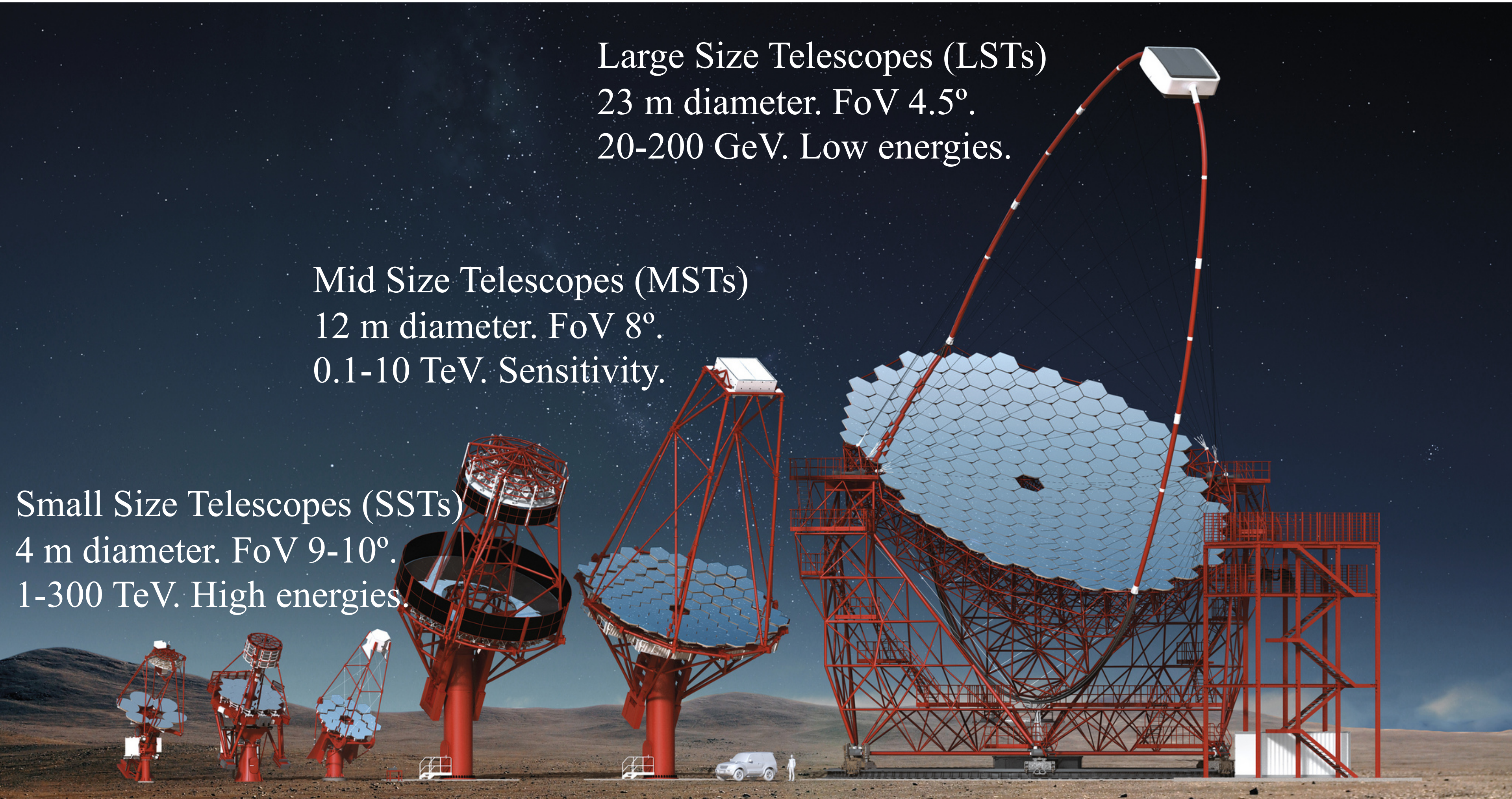
- **IAC** → Astrophysics (R. García-López)
- **ICE-CSIC** → Astrophysics (D.F. Torres)
- **UJA** → Astrophysics (J. Martí)
- **IAA** → Astrophysics (I. Agudo)
- **ICCUB** → Astroparticle Physics (M. Ribó) + Astrophysics (J.M. Paredes)
- **IFAE** → Astroparticle Physics (M. Martinez)
- **UCM-GAE** → Astroparticle Physics (J.L. Contreras)
- **CIEMAT** → Astroparticle Physics (C. Delgado)
- **IFT** → Astroparticle Physics (M.A. Sánchez-Conde)
- **UAB** → Radiation Physics (Ll. Font)
- **UCM-ELEC** → Applied electronics (J.M. Miranda)
- **PIC** → Computing (M. Delfino)

A truly coordinated effort of 12 groups (so far) from different fields.

There is a Working Group of Red de Infraestructuras de Astronomía about CTA.

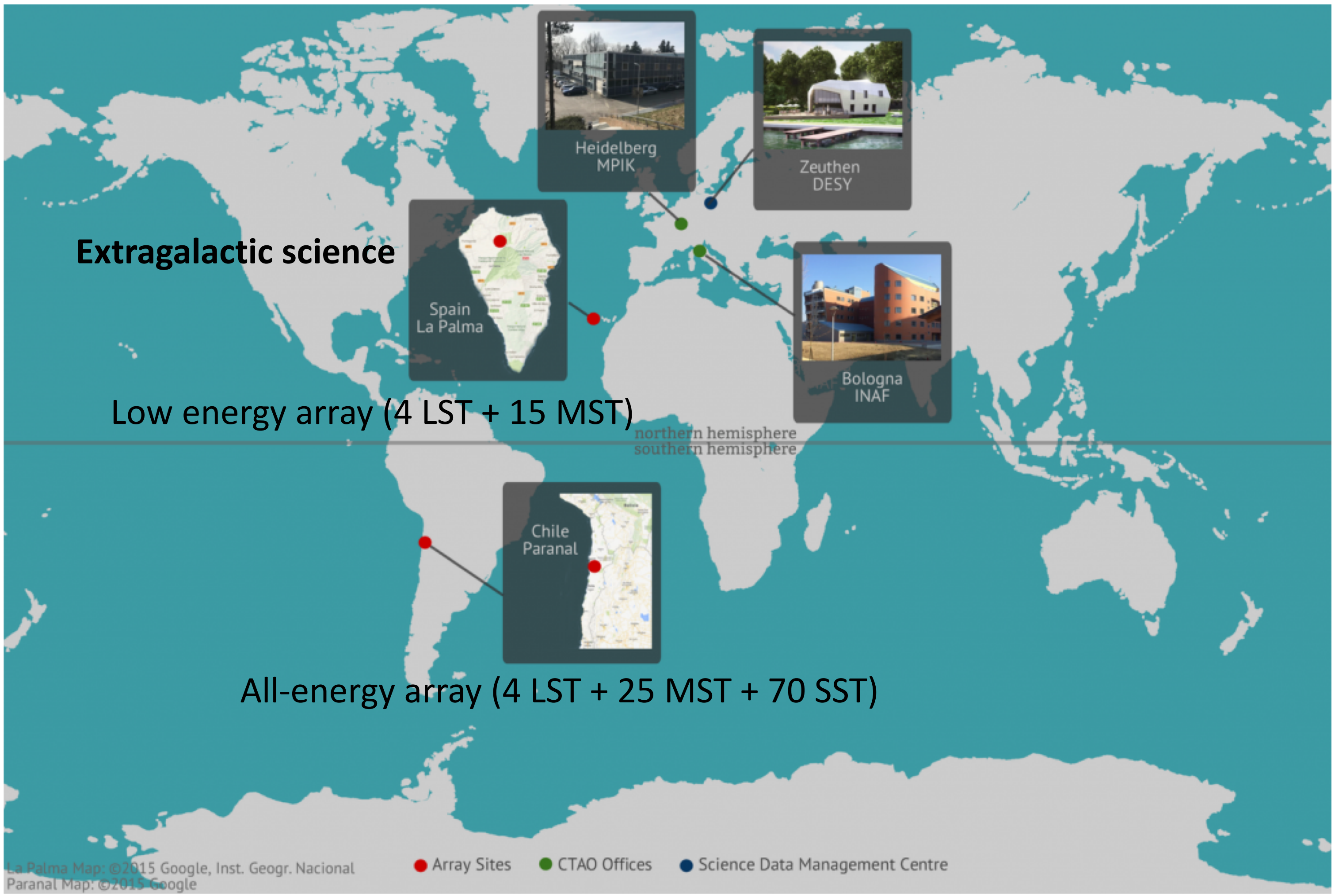
Cherenkov Telescope Array

Different telescope **sizes** for different **energy ranges**.
Slightly different technologies.

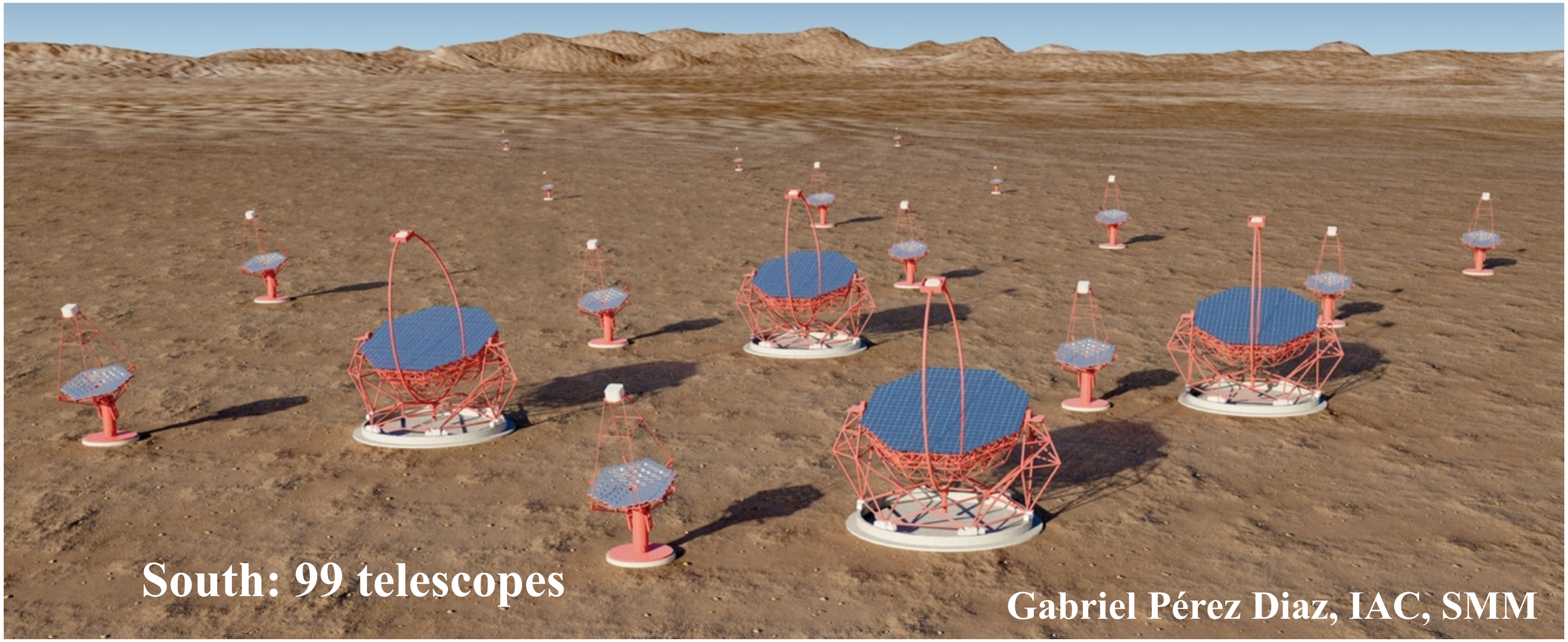


Cherenkov Telescope Array

One observatory, 2 sites for full sky coverage.



Cherenkov Telescope Array

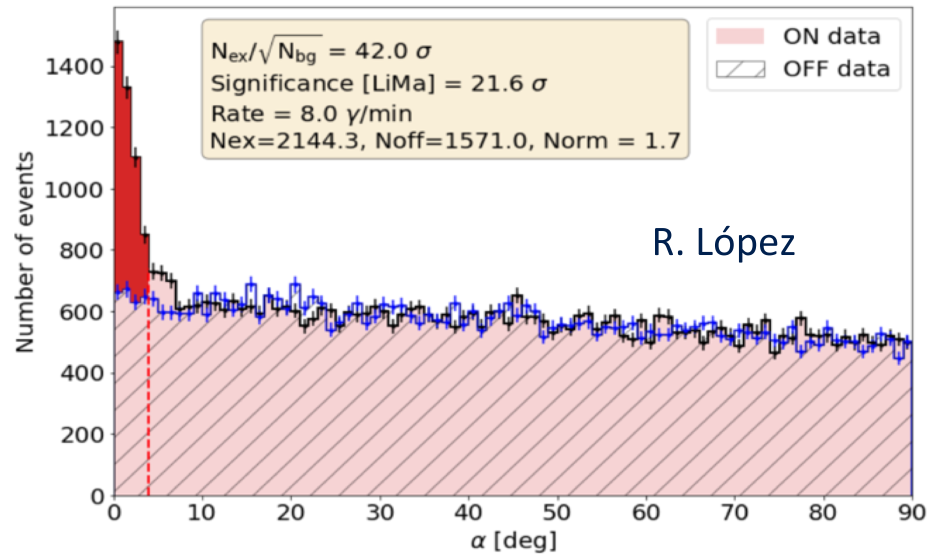


Cherenkov Telescope Array

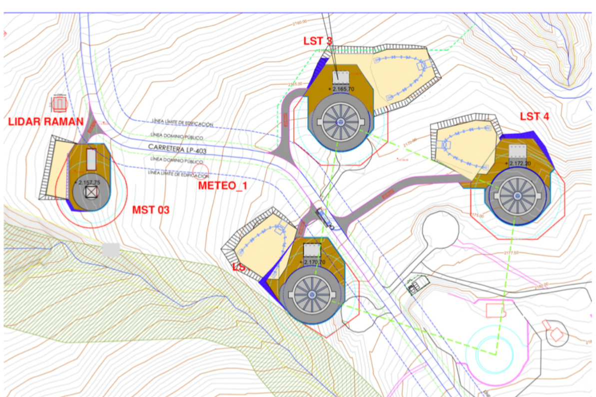
Cherenkov Telescope Array

Commissioning ongoing.
Many improvements taking place.
Targeting June for first complete telescope requirement verification.

First detection of Crab Nebula with LST1 (quick analysis using 4.5 hours November 2019).

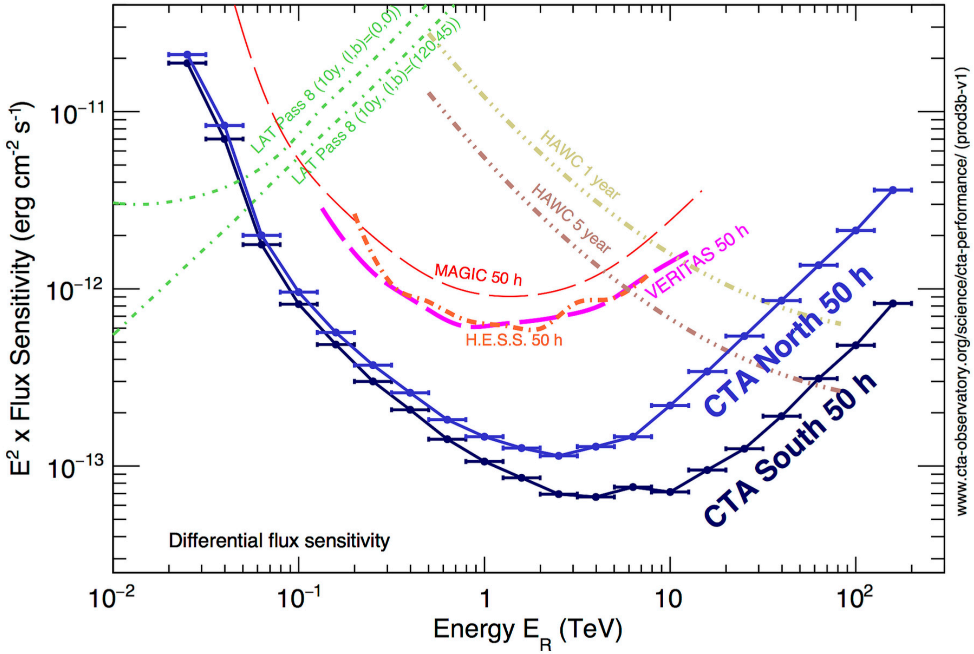


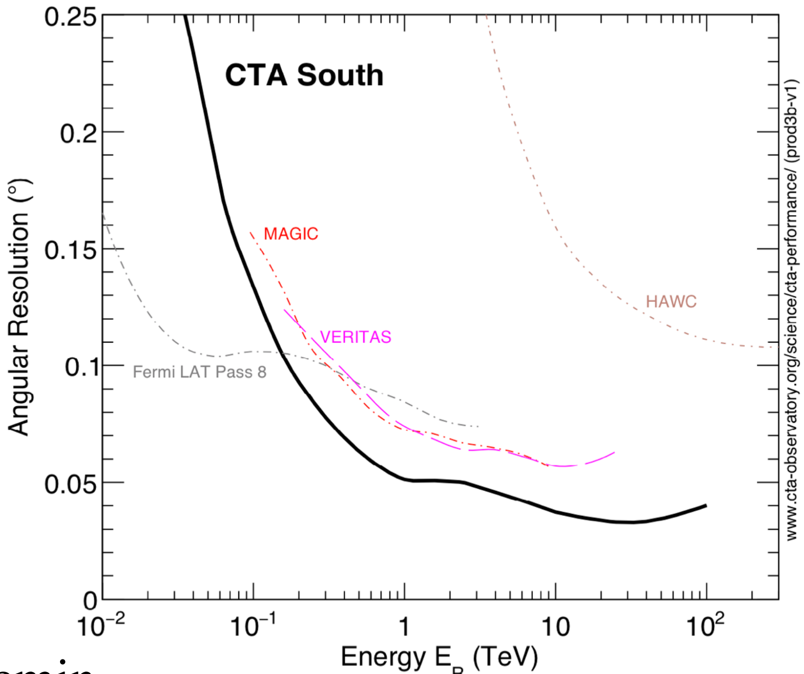
Production of next 3 LSTs ongoing.



Cherenkov Telescope Array

CTA **sensitivity**: a factor 5-20 better than current facilities (energy dependent).





Angular resolution: down to 0.03 deg. or 2 arcmin.

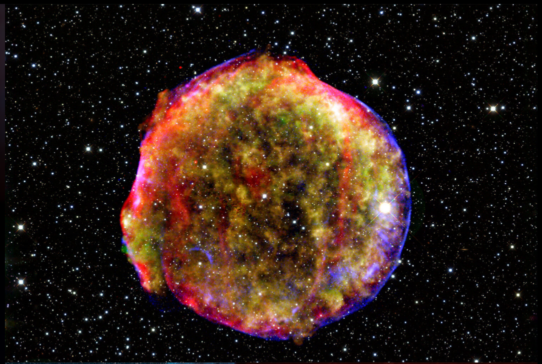
Energy resolution: 5-10% above 100 GeV.

CTA Key Science Projects

CTA Main Scientific Themes:

Theme 1: Cosmic Particle Acceleration

- How and where are particles accelerated?
- How do they propagate?
- What is their impact on the environment?

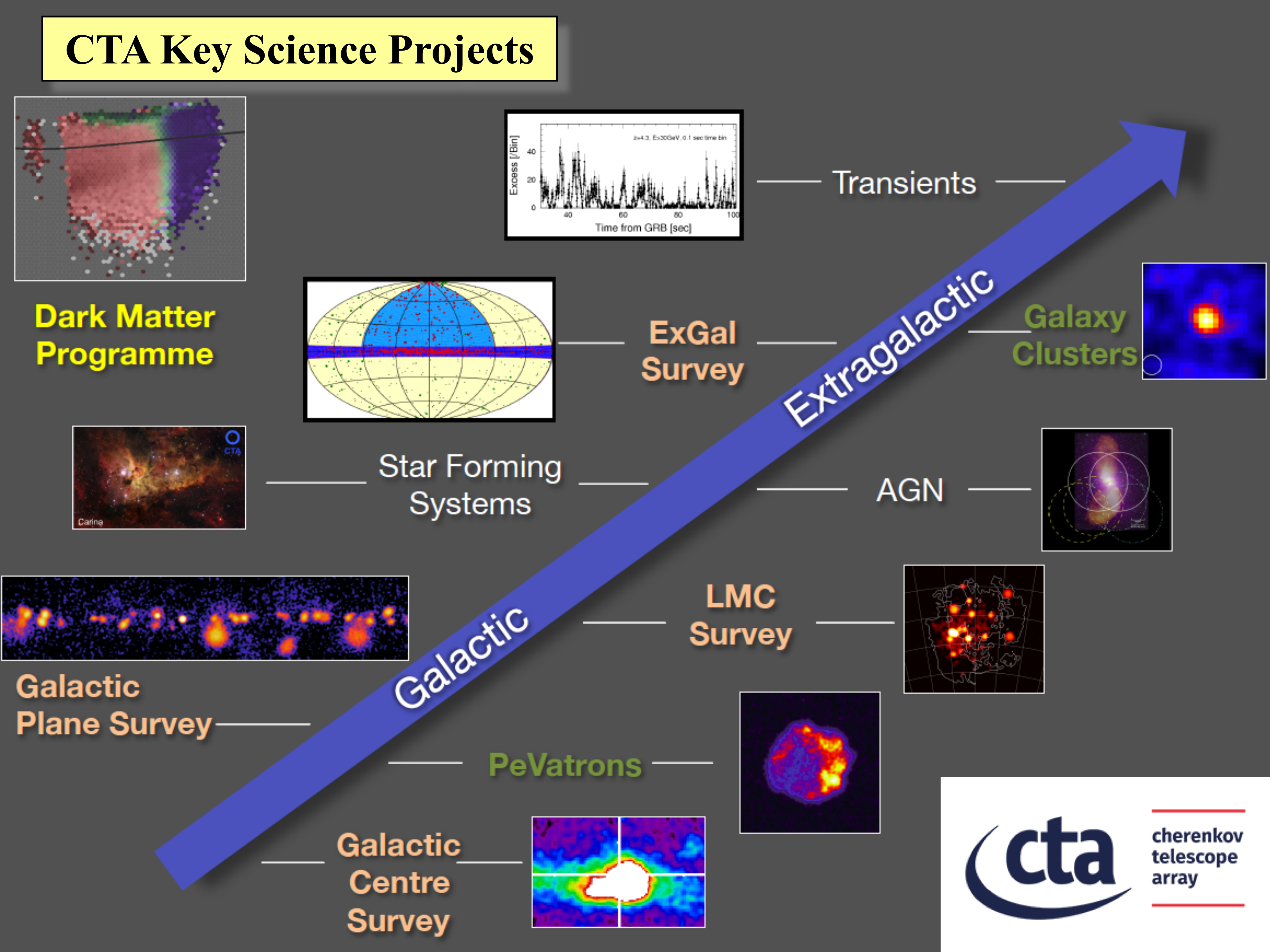


Theme 2: Probing Extreme Environments

- Processes close to neutron stars and black holes?
- Processes in relativistic jets, winds and explosions?
- Exploring cosmic voids

Theme 3: Physics Frontiers – beyond the SM

- What is the nature of Dark Matter? How is it distributed?
- Is the speed of light a constant for high energy photons?
- Do axion-like particles exist?


CTA Key Science Projects
Dark Matter Programme
Excess [/Bin]
Time from GRB [sec]
Transients
ExGal Survey
Galaxy Clusters
Extragalactic
Carina
Star Forming Systems
AGN
LMC Survey
Galactic Plane Survey
Galactic
PeVatrons
Galactic Centre Survey
cta
cherenkov telescope array

CTA Key Science Projects

Science with CTA: +200 pages describing CTA science goals

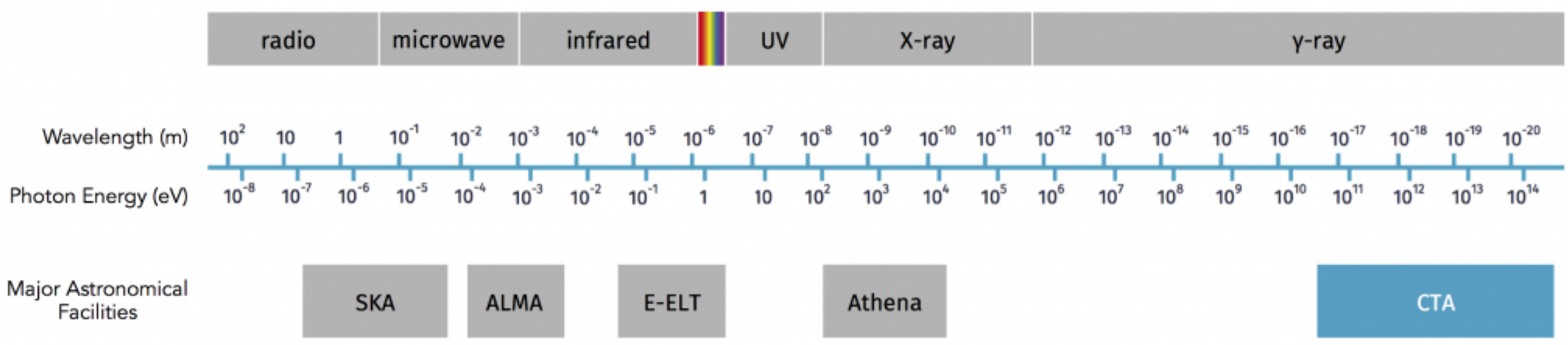
The CTA Consortium
arXiv:1709.07997

Published in 2019 as a book and open-access online version by World Scientific Publishing Co. Pte. Ltd. ISBN #9789813270091

CTA-Gaia synergies

cherenkov telescope array

Gaia: 2-3 eV. CTA: 20 GeV-300 TeV. → ~10-14 orders of mag. difference.



Thermal optical emission from stars.

Non-thermal synchrotron optical emitting electrons from different sources.

CTA-Gaia synergies

cherenkov telescope array

From the CTA Science book:

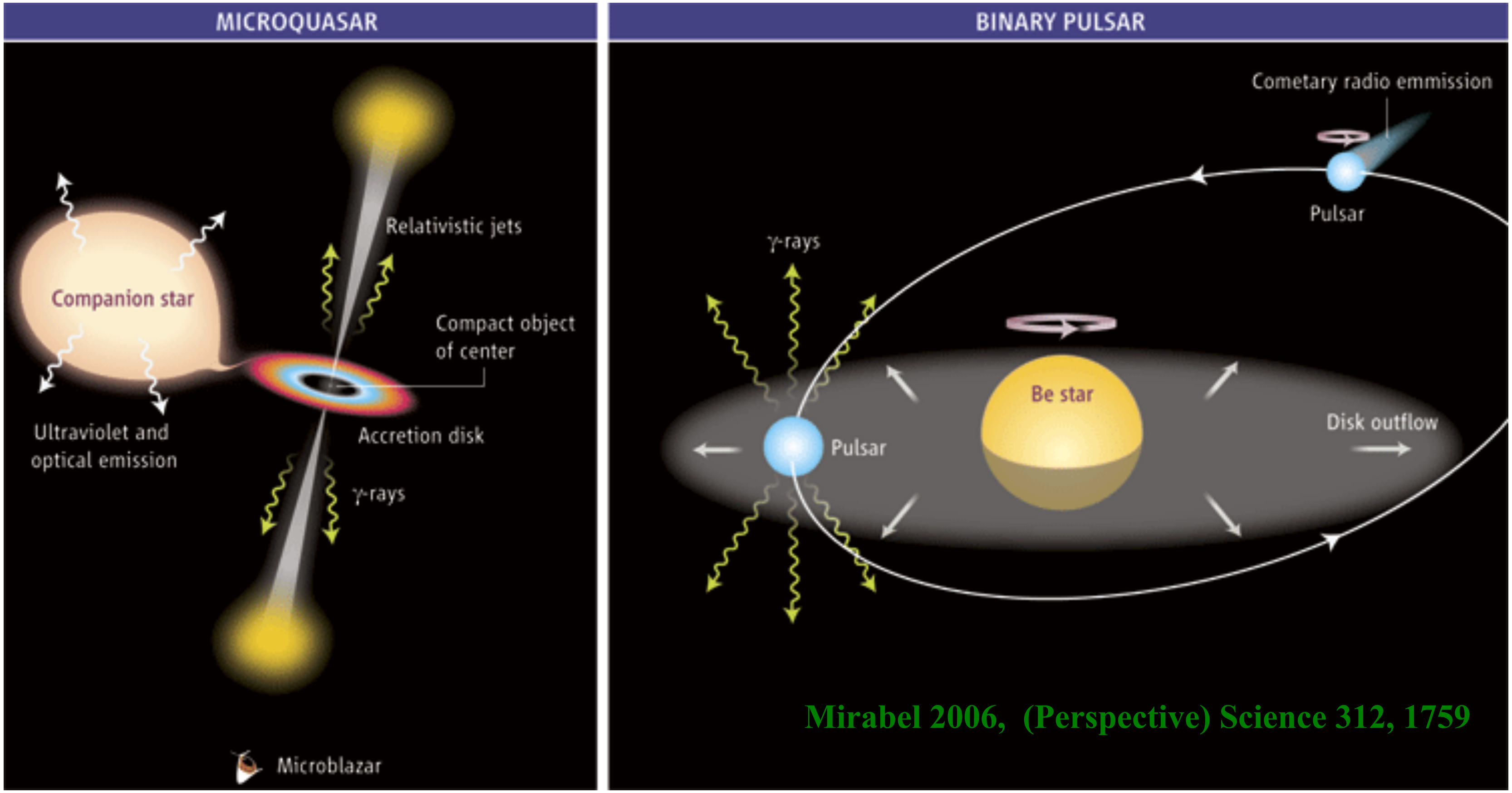
- 4. **Dark Matter Programme**
  - 4.2.1 **Milky Way**. The interpretation of CTA observations requires tighter observational constraints from microlensing and large scale radial velocity surveys. Kinematic surveys such as … **Gaia**… are collecting samples of thousands of radial velocities which will be used to map the dynamical structure of the bulge and bar regions. Together, the microlensing and kinematic data have the potential to provide improvements on the constraints in the mass profile of the inner Galaxy.
  - 4.2.3 **Large Magellanic Cloud**. It is the **Gaia** satellite that promises the next major step in understanding by mapping out the proper motion velocity field in much greater detail. **With 3D velocities, it may become possible to unravel the inner dark halo slope**, although considerable further modelling effort for the stellar and gas components will be needed.

CTA-Gaia synergies

From the CTA Science book:

- 6. **Galactic Plane Survey**
    - Identification of Transient sources in the Galactic Plane.
- 9. **Transients**
    - New and upcoming optical **transient factories** such as **Gaia**, Pan-STARRS, iPTF, ZTF, and LSST, as well as radio transient factories such as SKA and its pathfinders LOFAR, MeerKAT, MWA, and ASKAP [293] (see details in Chapter 2) guarantee a revolution in our physical understanding of the transient universe

Binary systems. X-ray binaries (microquasars) vs. gamma-ray binaries.



Cygnus X-3, Cygnus X-1

LS 5039 ?
LS I +61 303 ?
HESS J0632+057 ?
1FGL J1018.6−5856 ?
4FGL J1405.1-6119 ? **LMC P3 ?**

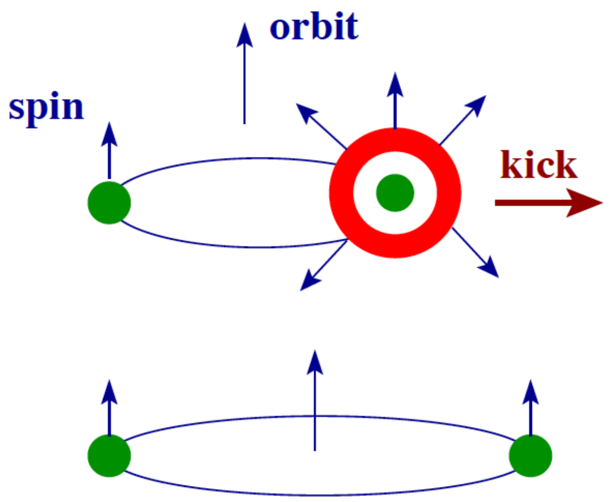
PSR B1259−63
PSR J2032+4127

Kicks during SN explosion (from Podsiadlowski).

Kicks and Binary Orbits

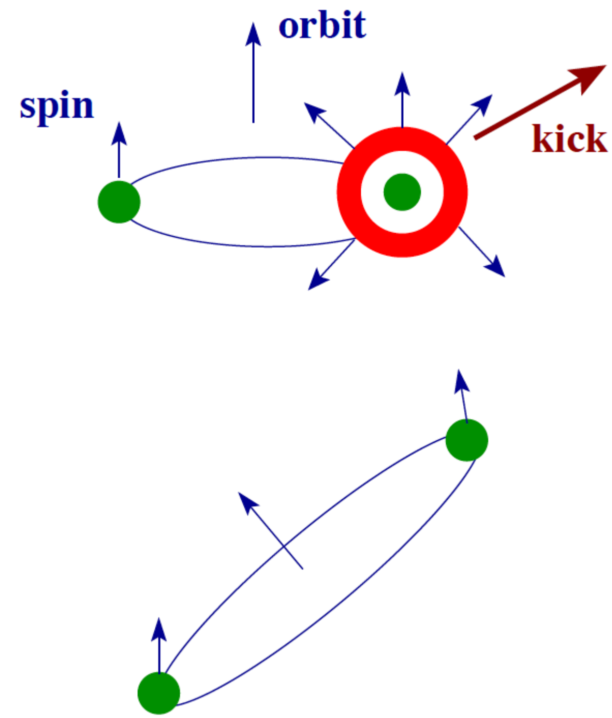
Blaauw Kick

- only due to supernova mass loss



- orbit increases
- spin + orbit remain aligned
- disruption if more than half the mass is lost

Asymmetric Explosion



- orbit increases or decreases
- spin/orbit misalignment (retrograde orbits possible)
- system can remain bound that could not otherwise

Note: if kick along spin axis → retrograde orbits impossible

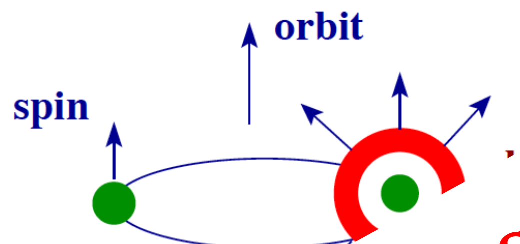
Kicks during SN explosion (from Podsiadlowski).

Some massive runaway stars might be in gamma-ray binaries

Kicks and Binary Orbits

Blaauw Kick

- only due to supernova mass loss



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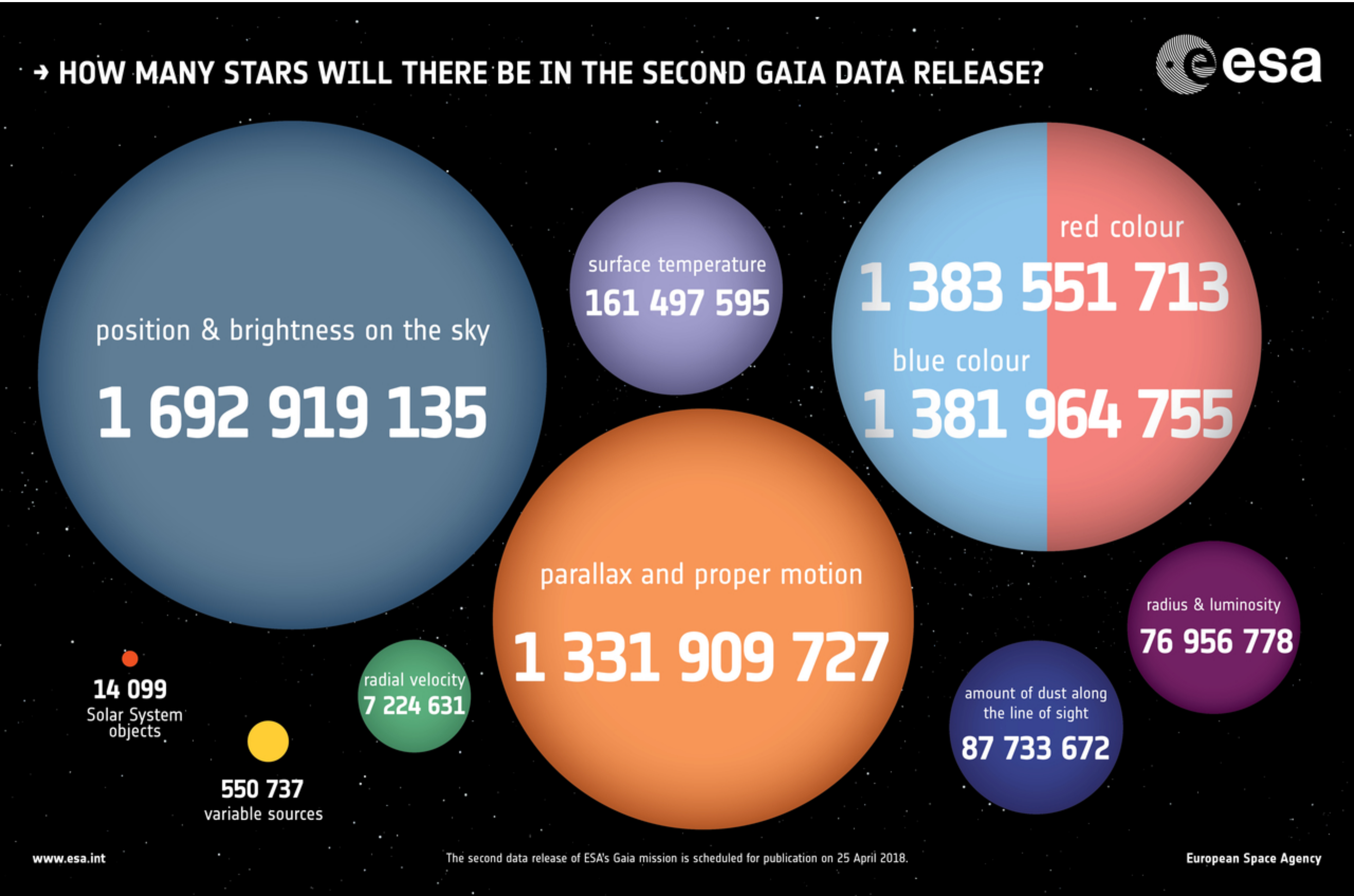
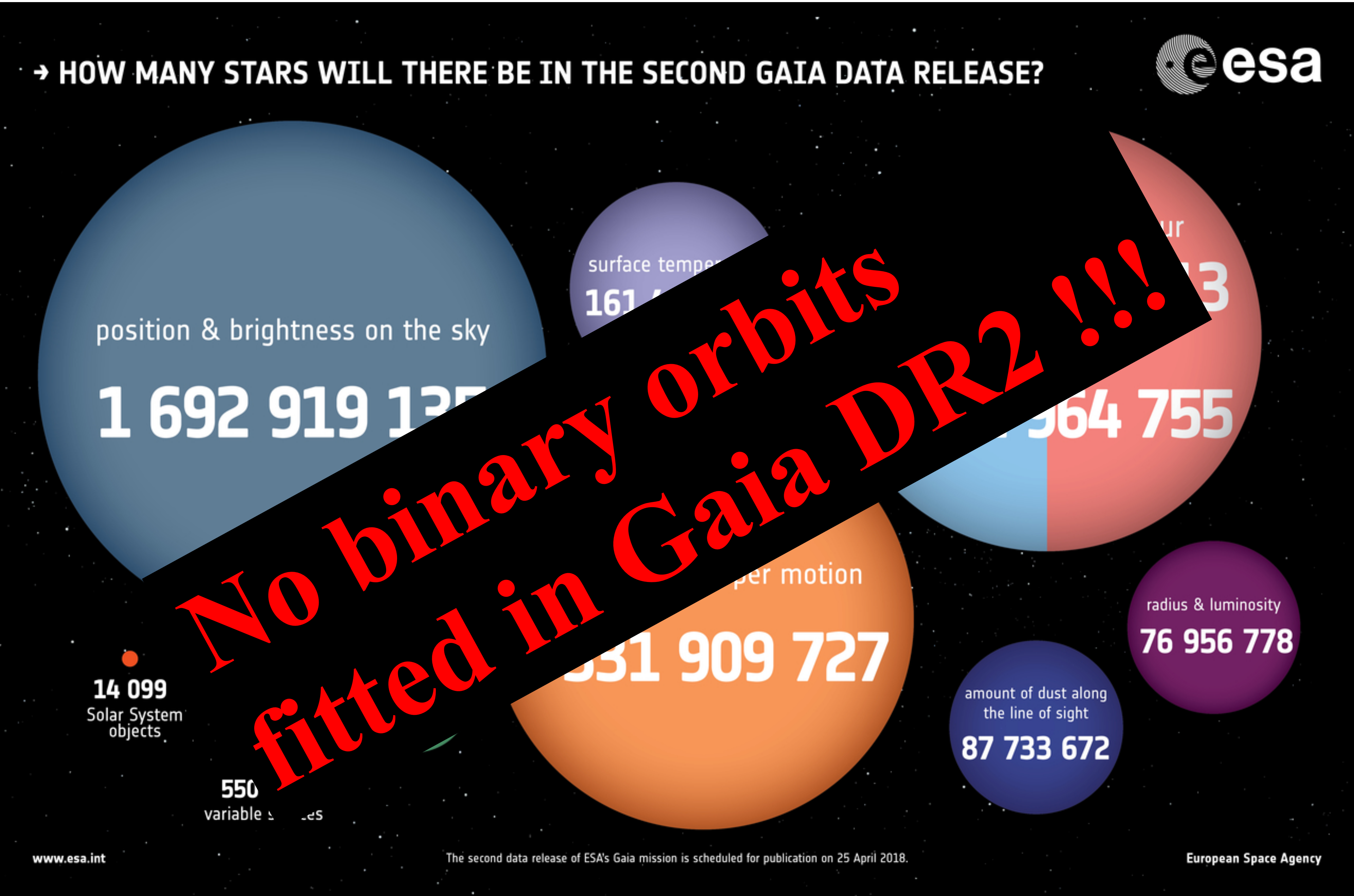
Gaia DR2.

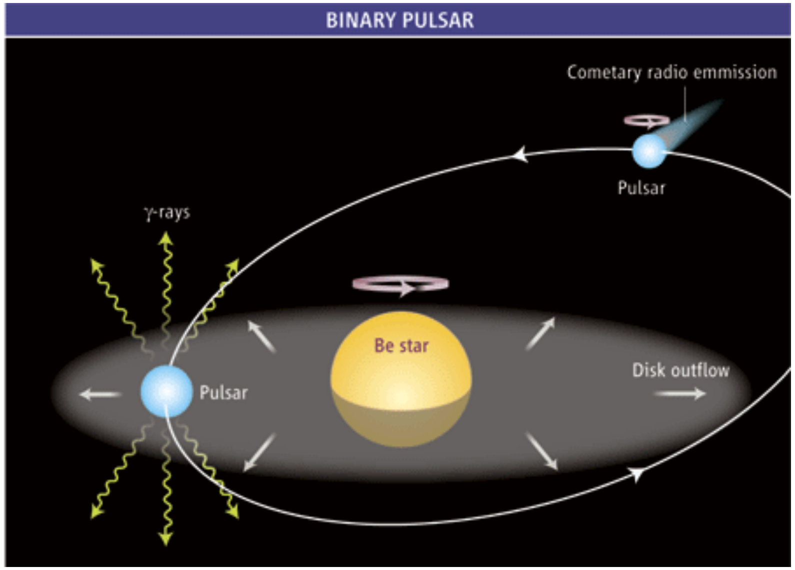


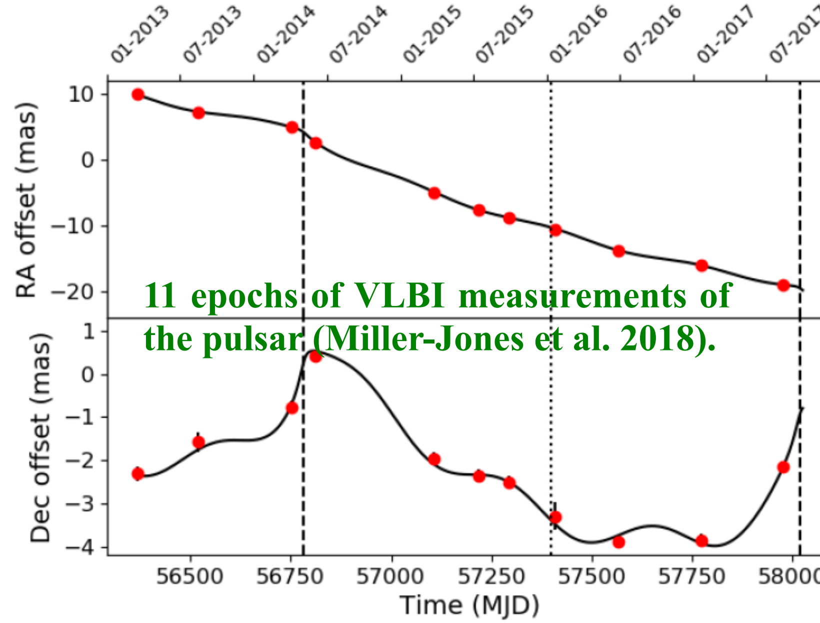
→ HOW MANY STARS WILL THERE BE IN THE SECOND GAIA DATA RELEASE?
esa
position & brightness on the sky
1 692 919 135
surface temperature
161 497 595
red colour
1 383 551 713
blue colour
1 381 964 755
parallax and proper motion
1 331 909 727
radius & luminosity
76 956 778
amount of dust along the line of sight
87 733 672
radial velocity
7 224 631
14 099
Solar System objects
550 737
variable sources
www.esa.int
The second data release of ESA's Gaia mission is scheduled for publication on 25 April 2018.
European Space Agency

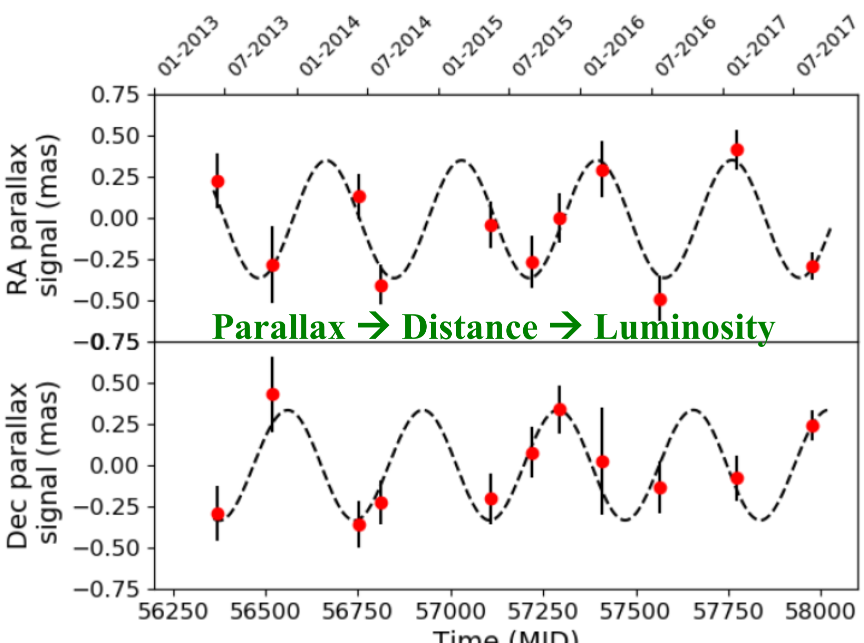
Gaia DR2.

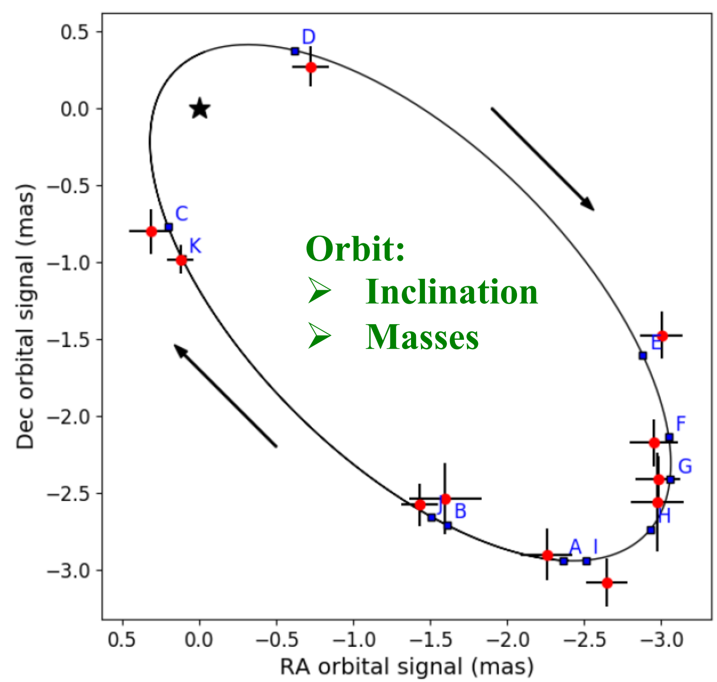

→ HOW MANY STARS WILL THERE BE IN THE SECOND GAIA DATA RELEASE?
esa
position & brightness on the sky
No binary orbits fitted in Gaia DR2 !!!
radius & luminosity
76 956 778
amount of dust along the line of sight
87 733 672
14 099
Solar System objects
www.esa.int
The second data release of ESA's Gaia mission is scheduled for publication on 25 April 2018.
European Space Agency

Gaia DR2 results on gamma-ray binaries. PSR B1259-63 (Miller-Jones et al. 2018).



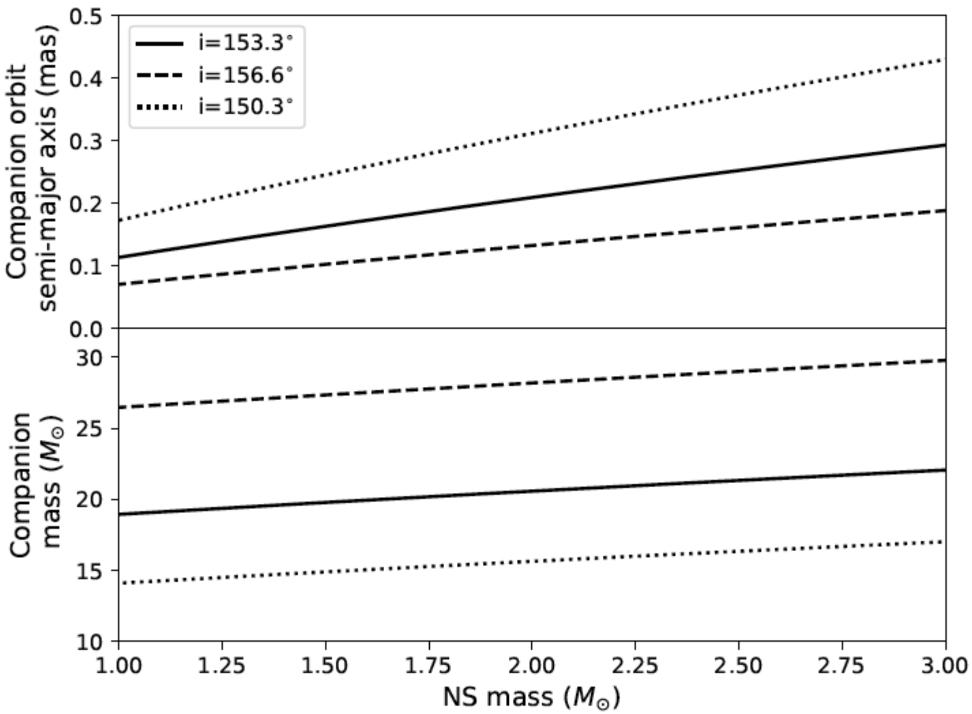


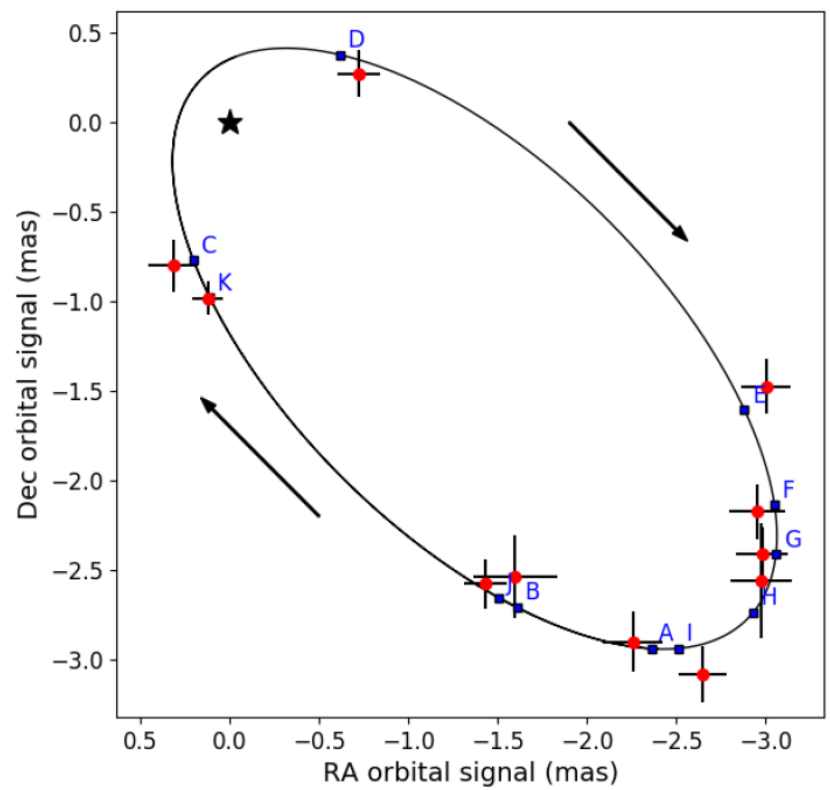




	Parameter	Symbol	Value
VLBI	Reference position in R.A. (J2000)	α_0	$13^{h}02^{m}47\overset{s}{.}638337^{s} \pm 0.000012$
	Reference position in Dec. (J2000)	δ_0	$-63°50'8.628585'' \pm 0.000008$
	Proper motion in R.A. (mas yr^{-1})	$\mu_\alpha \cos\delta$	-7.010 ± 0.030
	Proper motion in Dec. (mas yr^{-1})	μ_δ	$-0.532^{+0.033}_{-0.032}$
	Parallax (mas)	π	$0.387^{+0.047}_{-0.049}$
	Inclination angle (°)	i	$153\overset{\circ}{.}3^{+3\overset{\circ}{.}2}_{-3\overset{\circ}{.}0}$
	Longitude of the ascending node (° E of N)	Ω	$189\overset{\circ}{.}2 \pm 1.7$
Pulsar timing	Orbital period (days)	P	1236.724526 ± 0.000006
	Epoch of periastron (MJD)	T_0	$53071.2447290 \pm 0.0000007$
	Eccentricity	e	$0.86987970 \pm 0.00000006$
	Projected semi-major axis (lt-s)	$a \sin i$	1296.27448 ± 0.00014
	Argument of periastron	ω	$138\overset{\circ}{.}665013 \pm 0\overset{\circ}{.}000011$

(Miller-Jones et al. 2018)





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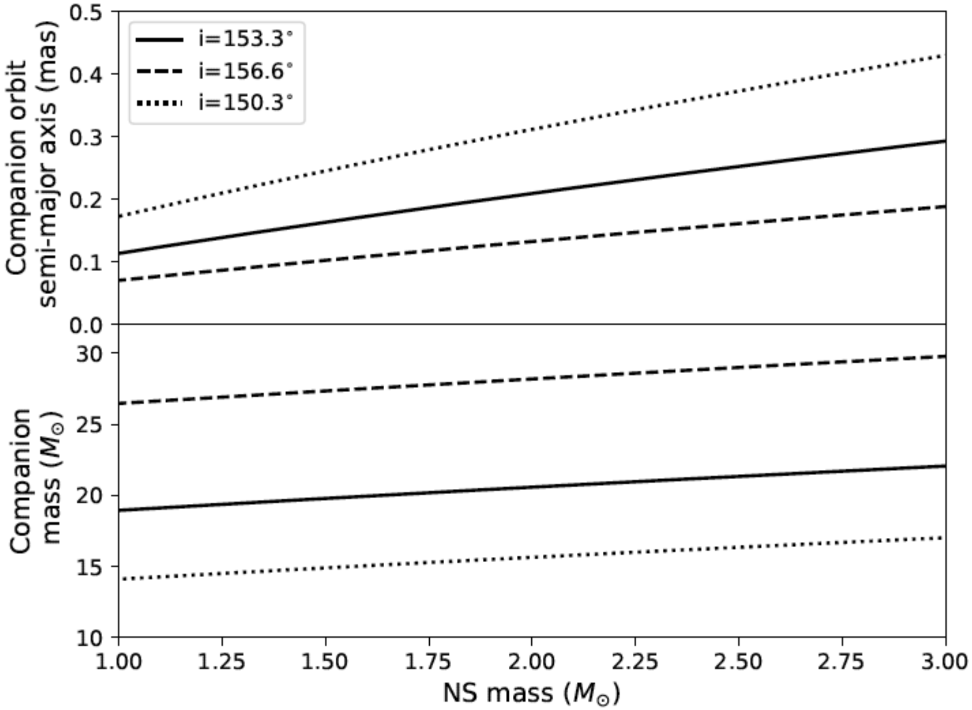

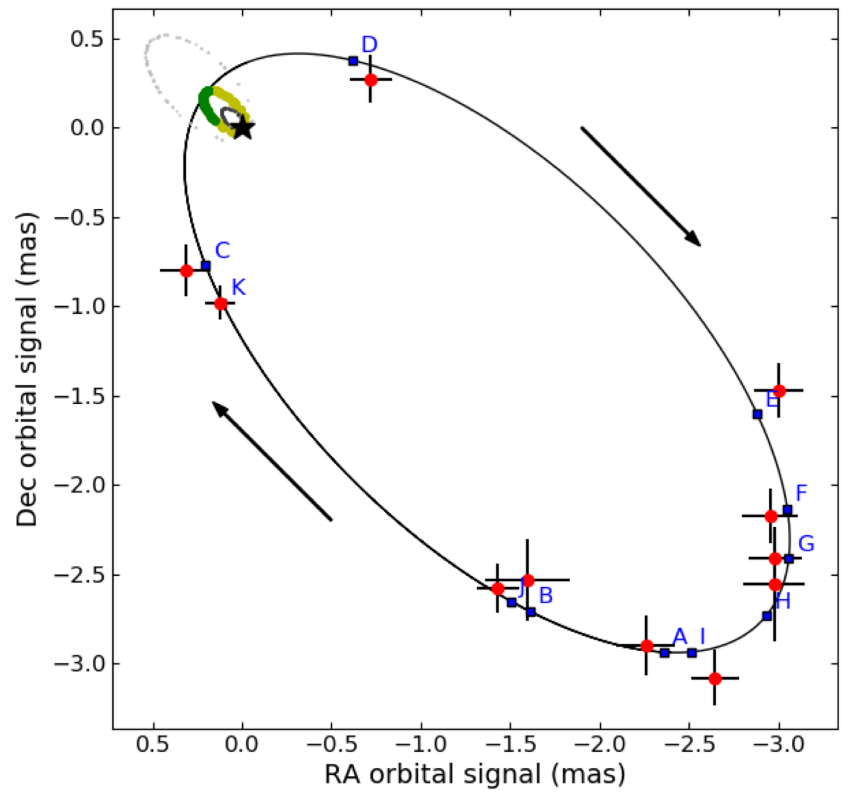

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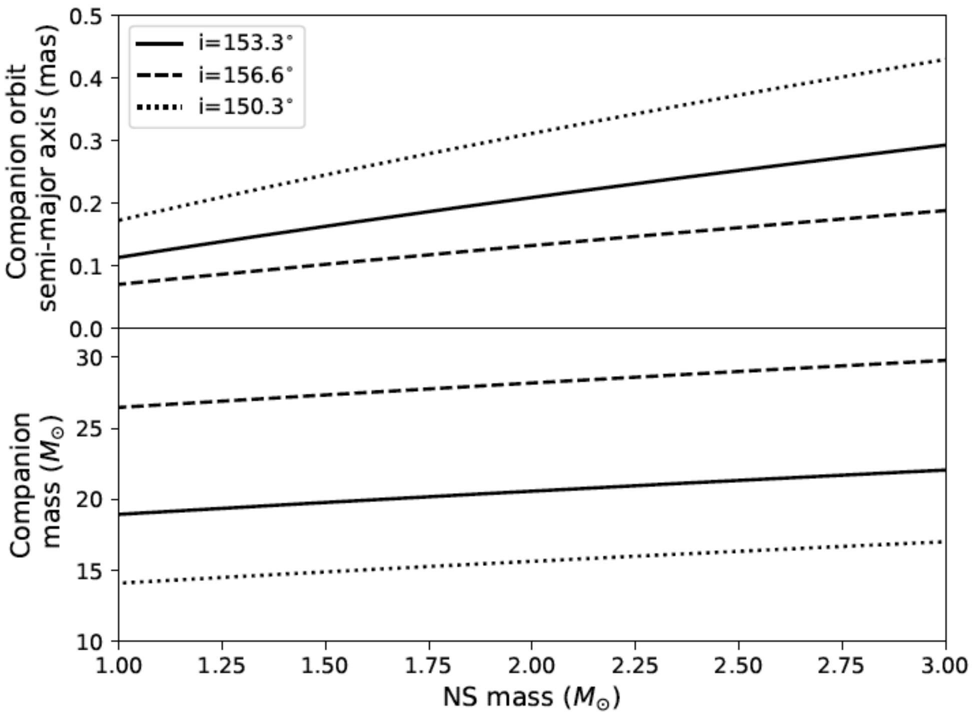
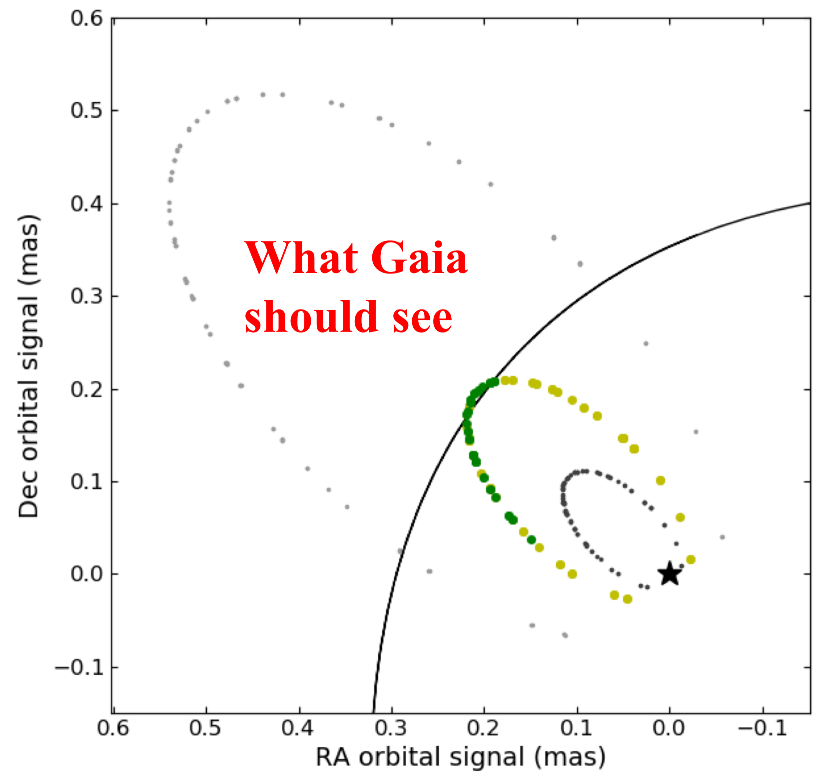
Gaia DR2:
-6.986 +/- 0.043 mas/yr
-0.416 +/- 0.044 mas/yr
0.4181+/-0.0308

(Miller-Jones et al. 2018)





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Projected semi-major axis (lt-s)	$a \sin i$	1296.27448 ± 0.00014
Argument of periastron	ω	$138^\circ.665013 \pm 0^\circ.000011$

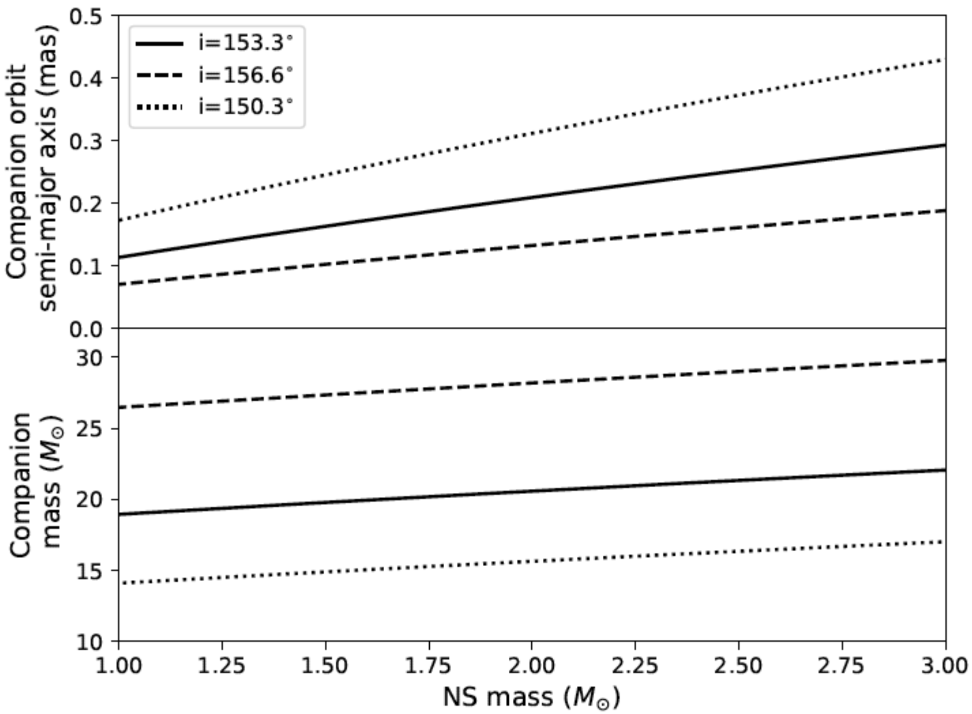
VLBI (reference position through longitude of the ascending node)

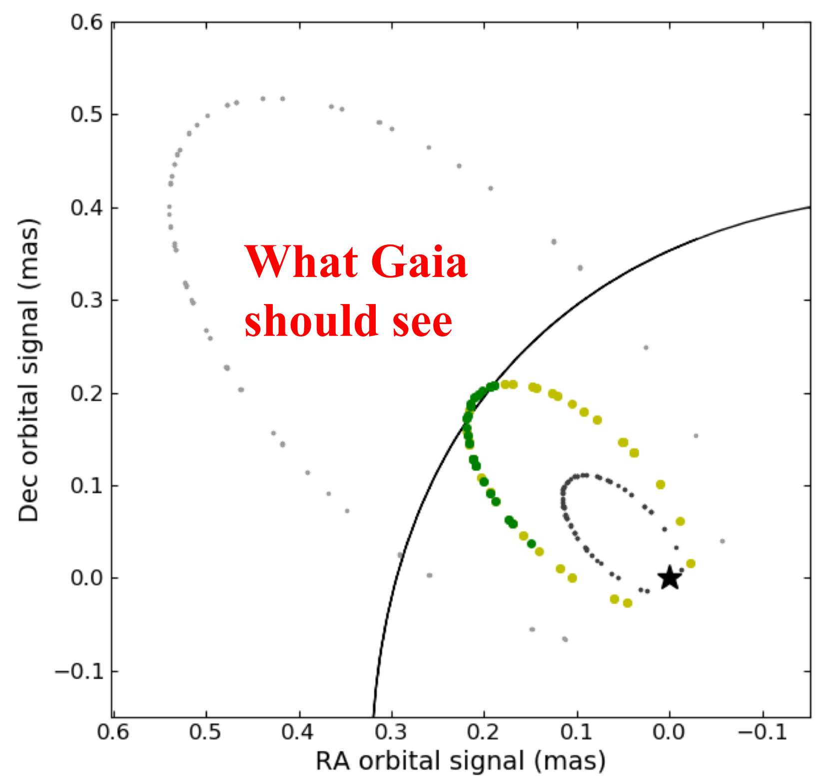
Pulsar timing (orbital period through argument of periastron)

Gaia DR2:
-6.986 +/- 0.043 mas/yr
-0.416 +/- 0.044 mas/yr
0.4181+/-0.0308

GOF of 8, bad !!

(Miller-Jones et al. 2018)





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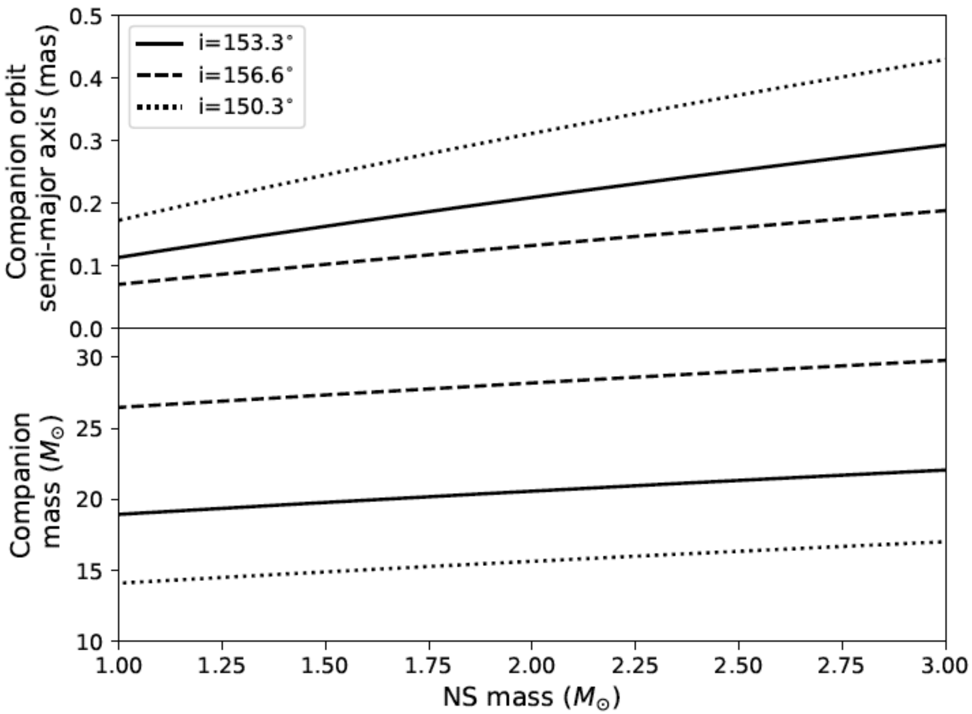
	Parallax (mas)	π	$0.387^{+0.047}_{-0.049}$
	Inclination angle (°)	i	$153.3°^{+3.2°}_{-3.0°}$
	Longitude of the ascending node (° E of N)	Ω	$189.2° \pm 1.7$
Pulsar timing	Orbital period (days)	P	1236.724526 ± 0.000006
	Epoch of periastron (MJD)	T_0	$53071.2447290 \pm 0.0000007$
	Eccentricity	e	$0.86987970 \pm 0.00000006$
	Projected semi-major axis (lt-s)	$a \sin i$	1296.27448 ± 0.00014
	Argument of periastron	ω	$138.665013° \pm 0.000011°$

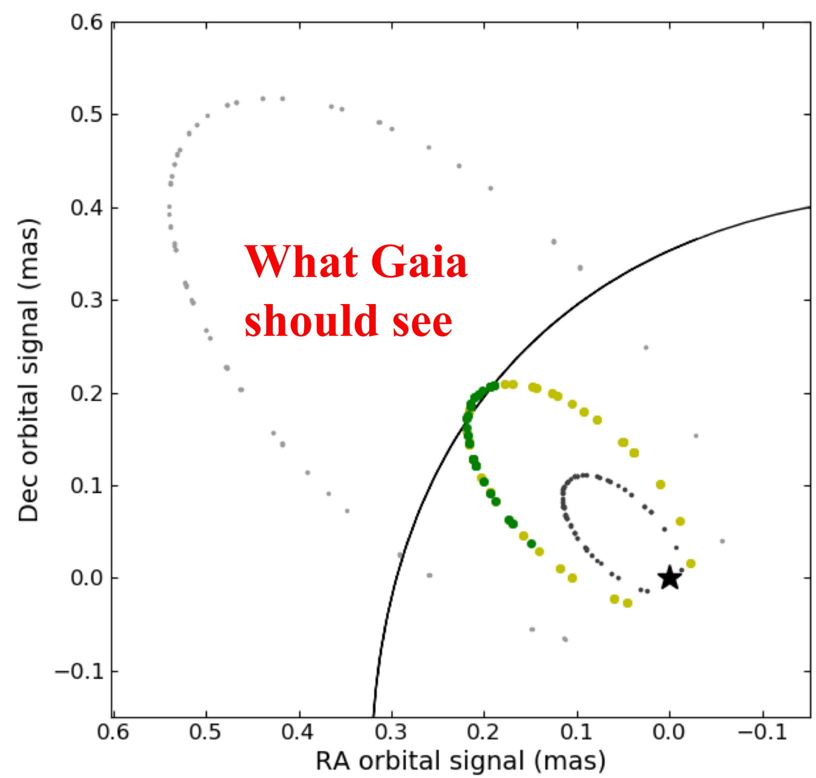
Gaia DR2:
-6.986 +/- 0.043 mas/yr
-0.416 +/- 0.044 mas/yr
Differences in pm:
0.024 +/- 0.052 mas/yr
0.116 +/- 0.055 mas/yr

Measuring a_* allows obtaining NS mass

Potential new targets for CTA, etc.

(Miller-Jones et al. 2018)





GOF, UWE and RUWE for gamma-ray binaries:

Most of the sources had a **bad GOF > 3** → **Promising discriminator** !!

After applying the recommended routines by **Lindegren et al. (2018)**, all of them turned out to have **“normal” values of UWE and RUWE around 1** !!!

Gamma-ray Binary System	Spectral Type	Orbital Period (days)	G	$G_{BP} - G_{RP}$	GOF	UWE	$RUWE$	Peculiar Velocity (km s^{-1})
LS 5039	O6.5V	3.9	10.8	1.5	−2.64	0.85	0.69	142 ± 40 (1)
1FGL J1018.6−5856	O6V	16.58	12.3	1.4	0.10	1.00	0.94	45^{+30}_{-9} (2)
LS I +61 303	B0Ve	26.49	10.4	1.3	3.30	1.13	0.91	16 (3)
HESS J0632+057	B0Vpe	315	8.9	0.9	3.15	1.19	0.88	–
PSR B1259−63	O9.5Ve	1236.7	9.6	1.2	7.87	1.33	1.11	26 ± 8 (4)
MT91 213	Be	8578	11.4	1.6	9.26	1.48	1.05	–

(1) Moldón et al. 2012, (2) Marcote et al. 2012, (3) Wu et al. 2017, (4) Millor-Jones et al. 2018.

Gaia DR2 results on gamma-ray binaries.
1FGL J1018.6-5856 (Marcote et al. 2018).

It is a runaway binary escaping from the Galactic Plane.

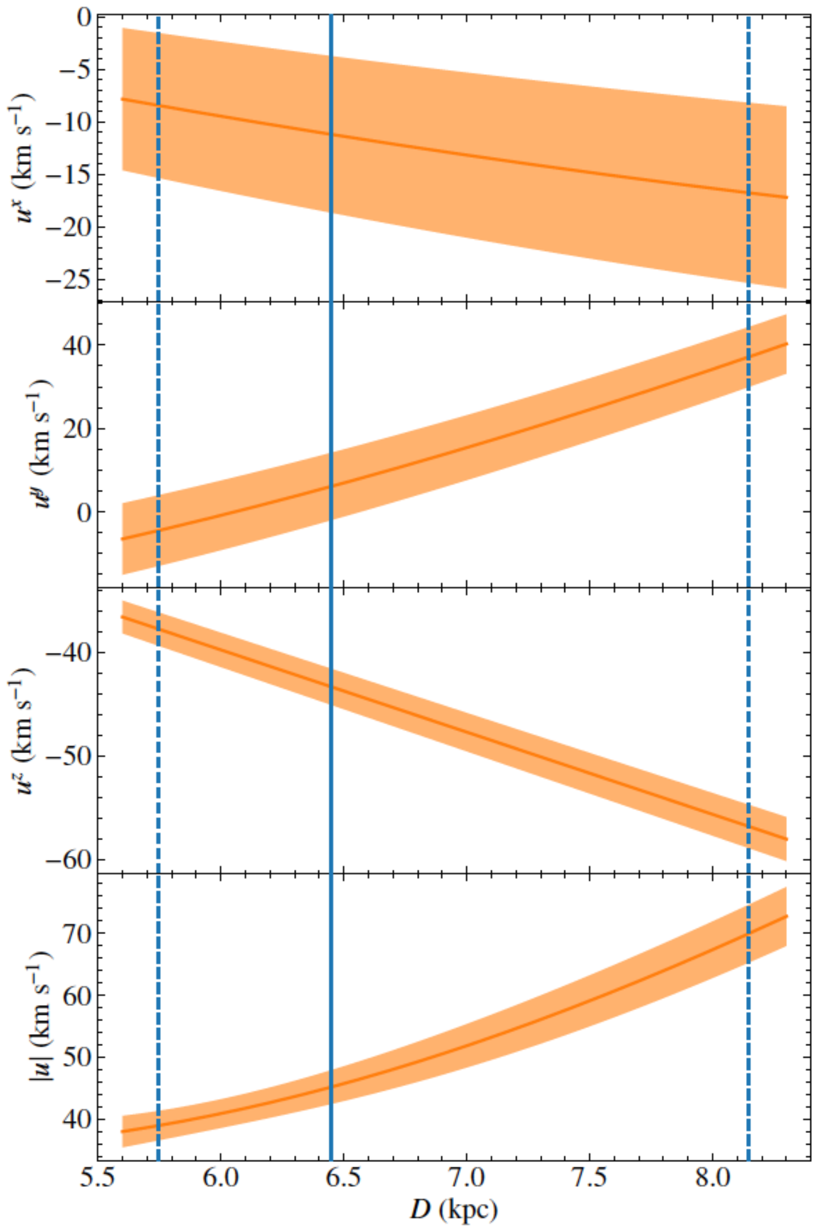
Similar to LS 5039
(Ribó et al. 2002, Moldón et al. 2012).

Goal:

➢ Search for new gamma-ray binaries using O and Be star catalogues

Methodology:

➢ Use Gaia DR2 on these stars to search for **runaway stars**



GOSC.

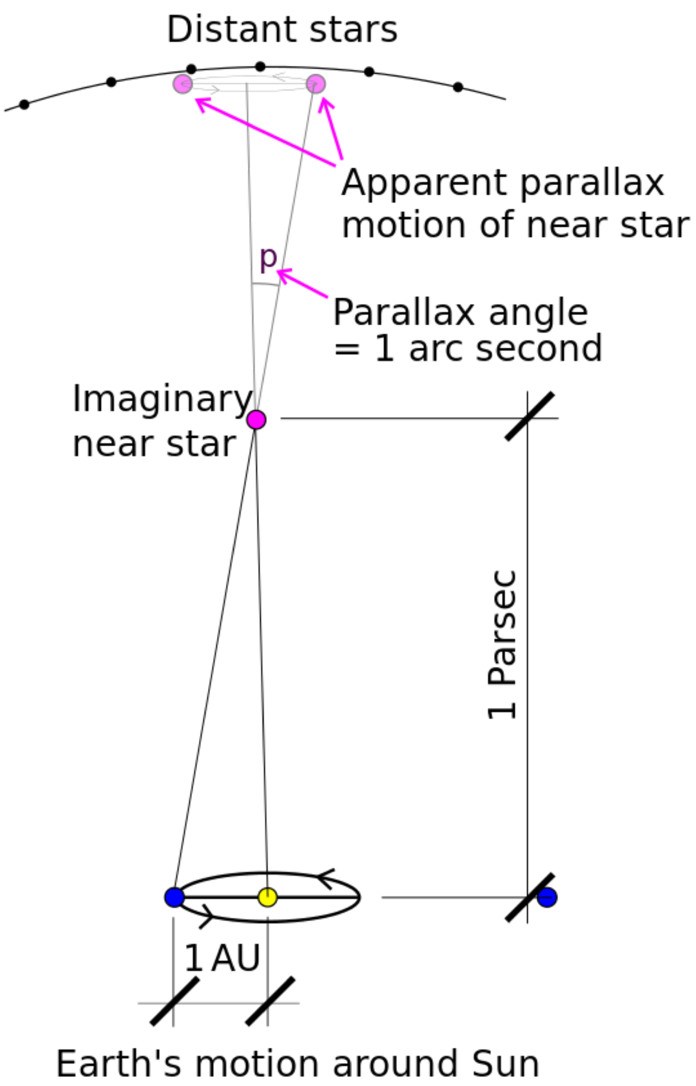
- Galactic O-Star Catalog **(Maíz Apellániz et al. 2004, 2013, 2018)**.
- Available at http://gosc.cab.inta-csic.es
- It contains **618** O and B0 stars.
- These authors detected 76 runaway stars (some of them not in GOSC).

BeSS.

- Catalog of Be stars.
- Available at http://basebe.obspm.fr/basebe/
- It contains **2251** classical Be stars.

Filters applied in Gaia DR2 data.

- G magnitude > 6 to avoid saturation.
- 5 parameters solutions: position, proper motion and parallax.
- Parallax over error > 5 to have distance uncertainties smaller than 20%.
- Visibility periods > 10 to avoid bad solutions or large uncertainties.



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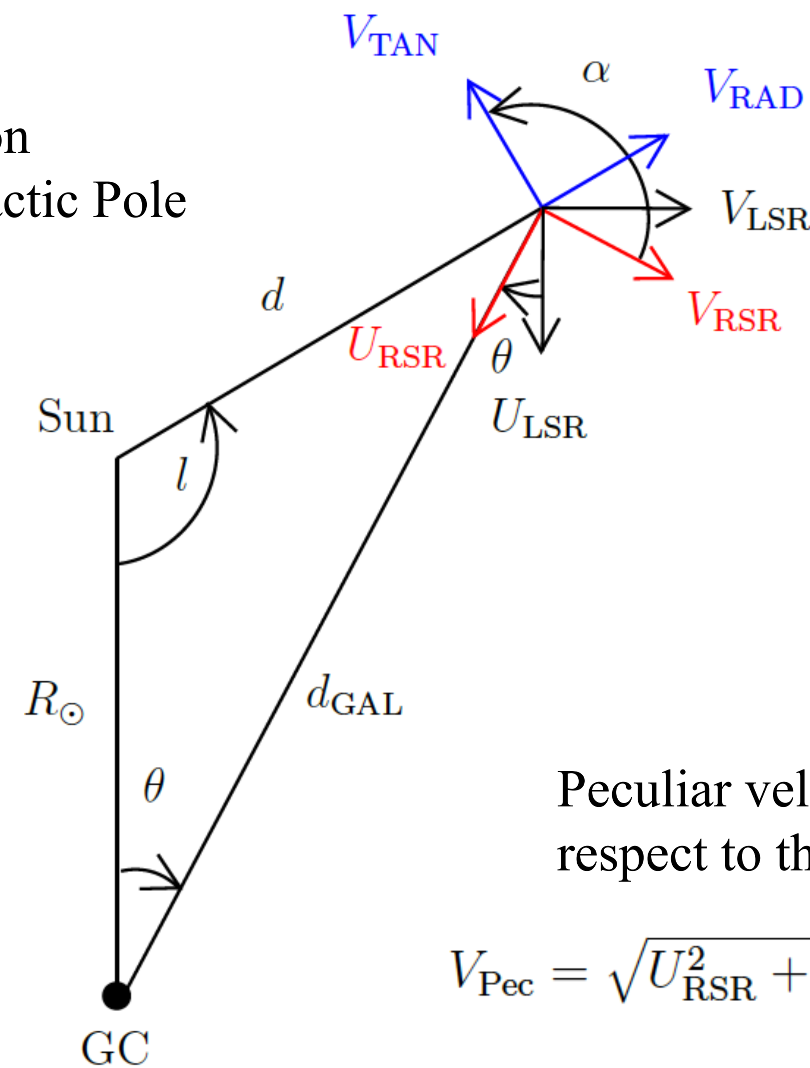
- Galactic O-Star Catalog **(Maíz Apellániz et al. 2004, 2013, 2018)**.
- Available at http://gosc.cab.inta-csic.es
- It contains **618** O and B0 stars.
- These authors detected 76 runaway stars (some of them not in GOSC).
- After several filters we work with an O-Gaia DR2 catalog of **370** objects.

BeSS.

- Catalog of Be stars.
- Available at http://basebe.obspm.fr/basebe/
- It contains **2251** classical Be stars.
- After several filters we work with a BeSS-Gaia DR2 catalog of **1399** objects.

The Local Standard of Rest and the Regional Standard of Rest.

Galactic velocities:
U towards the GC.
V towards Galactic rotation
W towards the North Galactic Pole

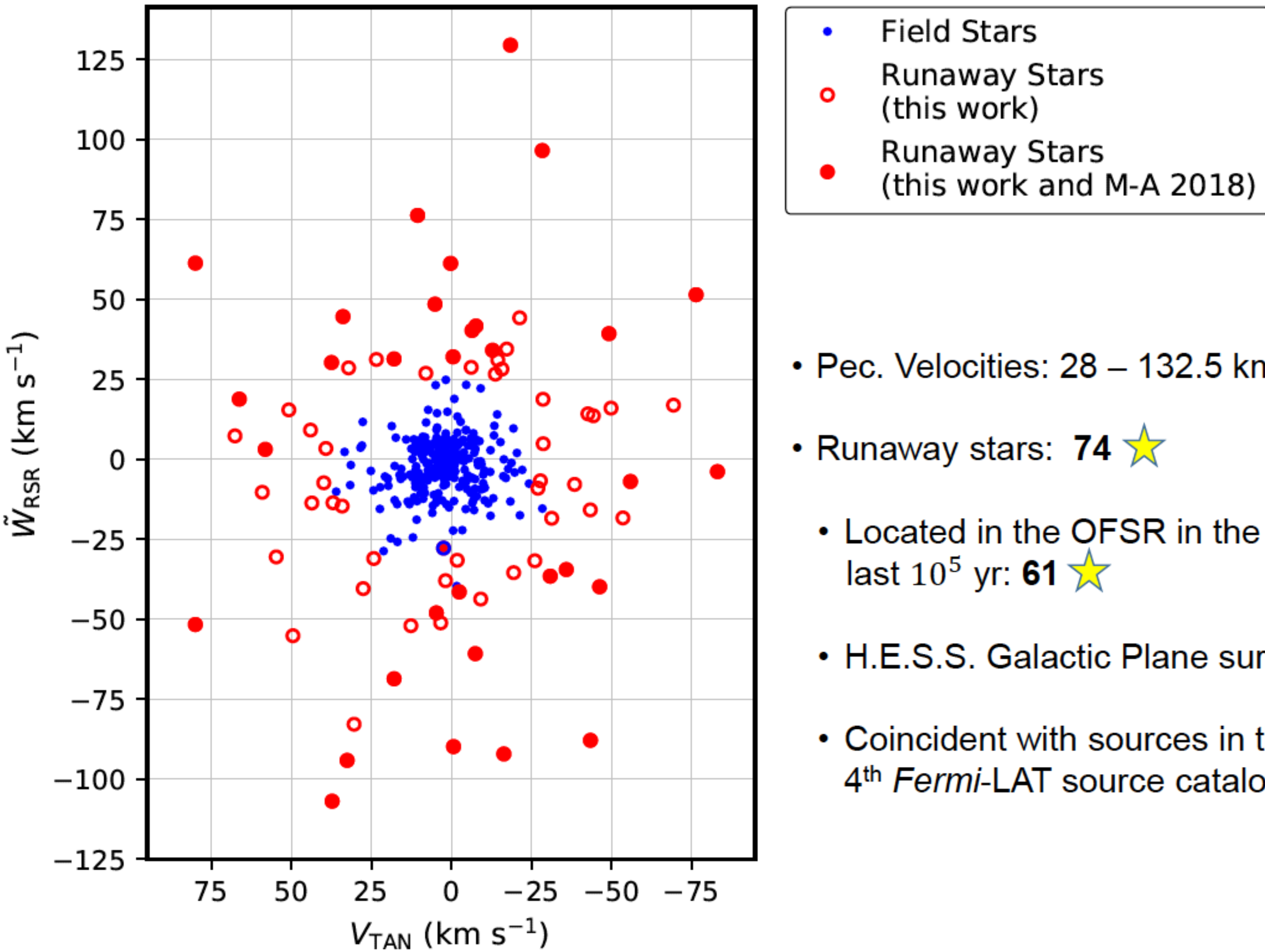


We use the Galactic rotation model of **Reid et al. (2014)**.

Peculiar velocity with respect to the RSR.

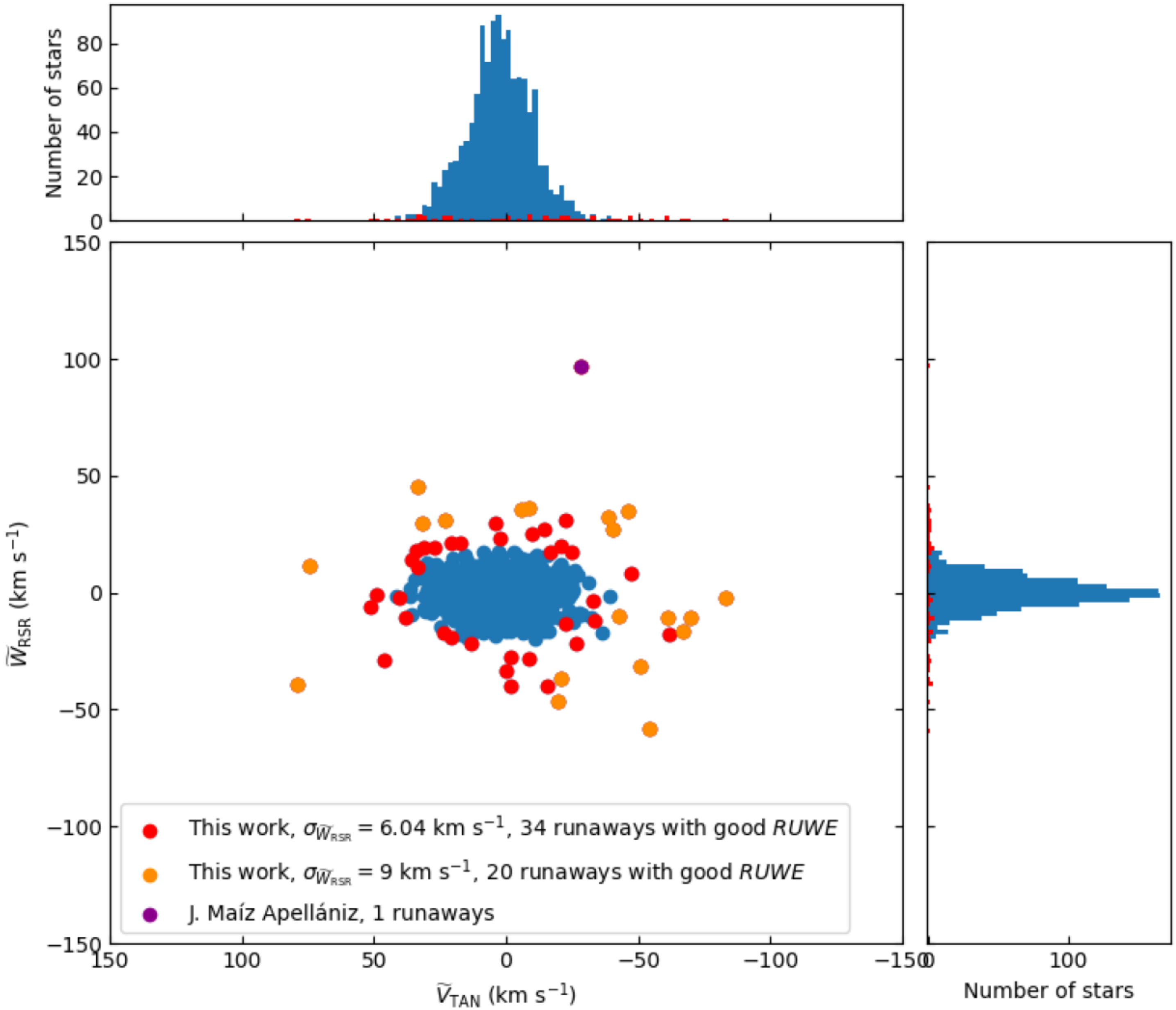
$$V_{\rm Pec} = \sqrt{U^2_{\rm RSR} + V^2_{\rm RSR} + W^2_{\rm RSR}}$$

Runaways in GOSC.



- Pec. Velocities: 28 – 132.5 km s^{-1}
- Runaway stars: **74**
  - Located in the OFSR in the last 10^5 yr: **61**
  - H.E.S.S. Galactic Plane survey : **24**
  - Coincident with sources in the 4th *Fermi*-LAT source catalog: **2**

Runaways in BeSS.



Gamma-ray binary candidates.

GOSC.

- Galactic O-Star Catalog **(Maíz Apellániz et al. 2004, 2013, 2018)**.
- Available at http://gosc.cab.inta-csic.es
- It contains **618** O and B0 stars.
- These authors detected 76 runaway stars (some of them not in GOSC).
- After several filters we work with an O-Gaia DR2 catalog of **370** objects.
- We have found **76 runaways, 42 more than Maíz Apellániz et al. (2018)**.
- 24 are in positions covered by the HESS GPS, 2 are 4th *Fermi*-LAT sources.

BeSS.

- Catalog of Be stars.
- Available at http://basebe.obspm.fr/basebe/
- It contains **2251** classical Be stars.
- After several filters we work with a BeSS-Gaia DR2 catalog of **1399** objects.
- We have found **54 new runaway stars**.
- Only 5 are in positions covered by the HESS GPS.

Future work.

- Make deep searches in MW catalogues.
- Conduct radial velocity studies to constrain 3-D velocities and search for binarity!

Conclusions

- **Multi-wavelength** and **multi-messenger** observations are needed to fully **understand the non-thermal Universe**.

- Every time we open a **new window**, like VHE gamma rays (MAGIC, etc.), neutrinos (Icecube) or GWs (LIGO) **we discover new types of sources**.

- **MAGIC**, **HESS** and **VERITAS** have made a significant change in VHE astrophysics: from detections to detailed studies with physical modeling.

- **CTA** is the future in the field, and will work as **an open observatory**. It promises to revolutionize astrophysics in the highest energy ranges.

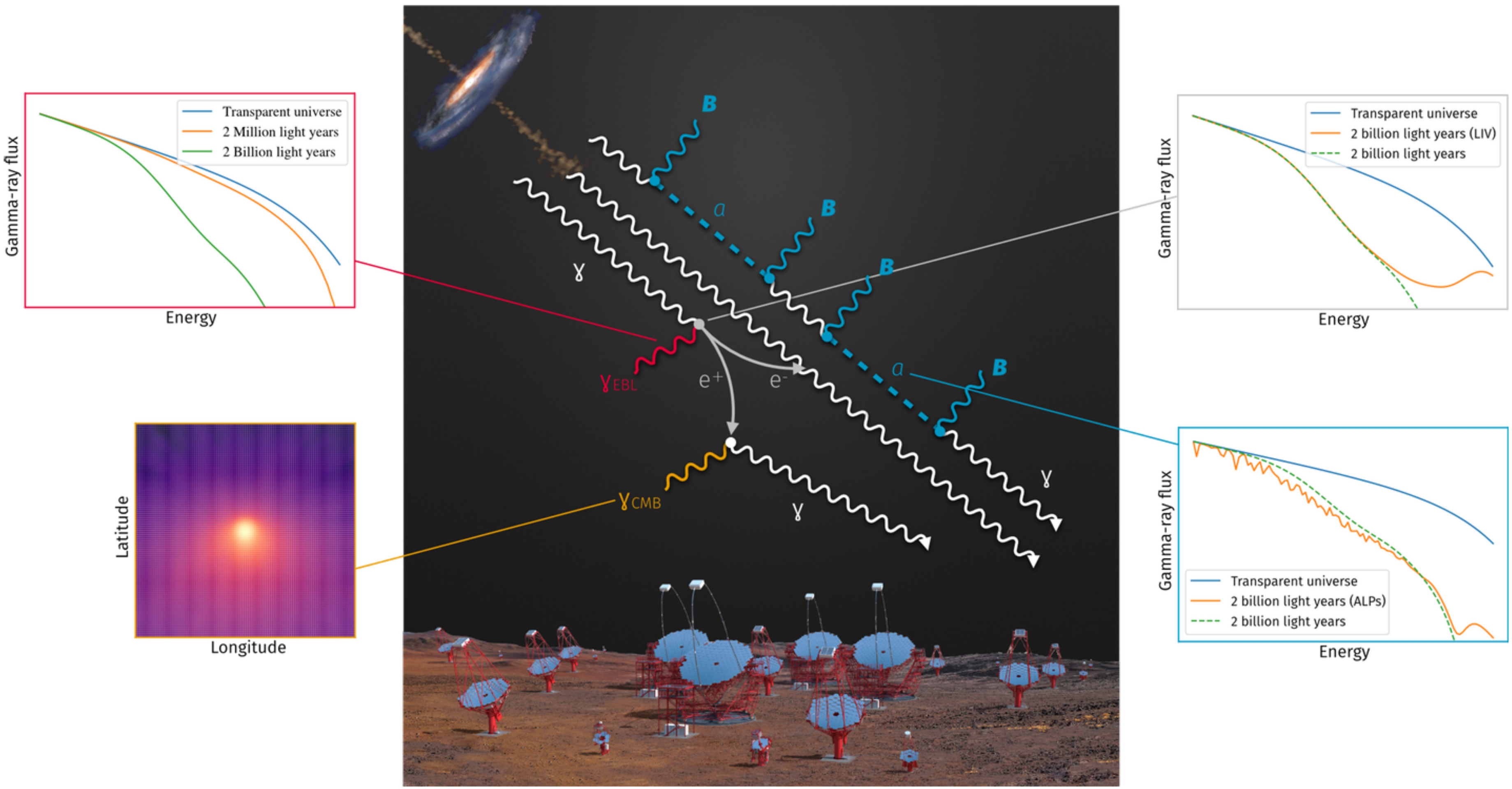
- **Gaia** has allowed a revolution in astrometric studies of Galactic sources, paving the road for future discoveries with **CTA** (e.g. gamma-ray binaries).

- The **future** in High-Energy Astrophysics is **bright**!

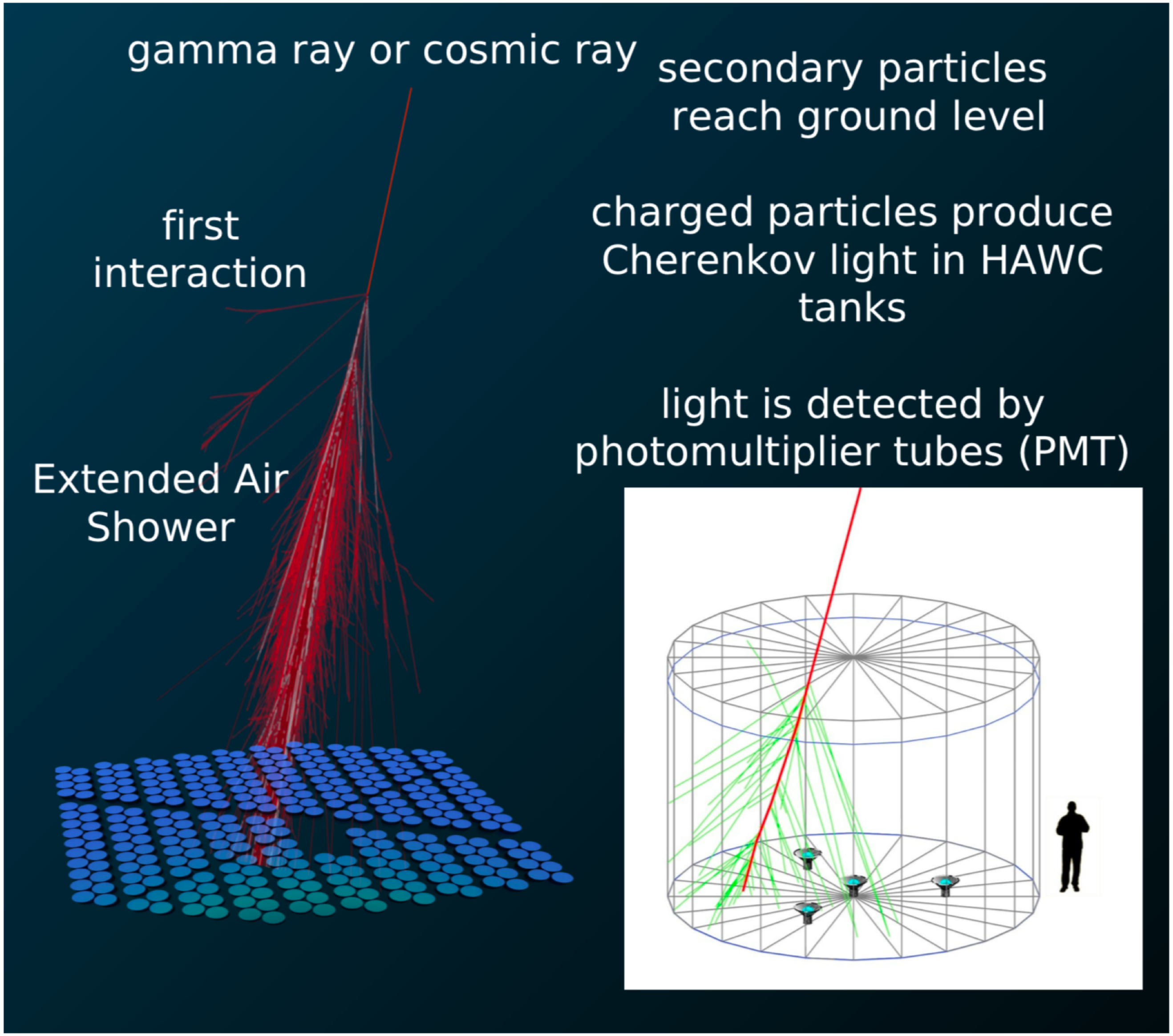
Read “CTA: estado actual” in Boletín de la SEA (38 Verano 2018).

Backup

Introduction

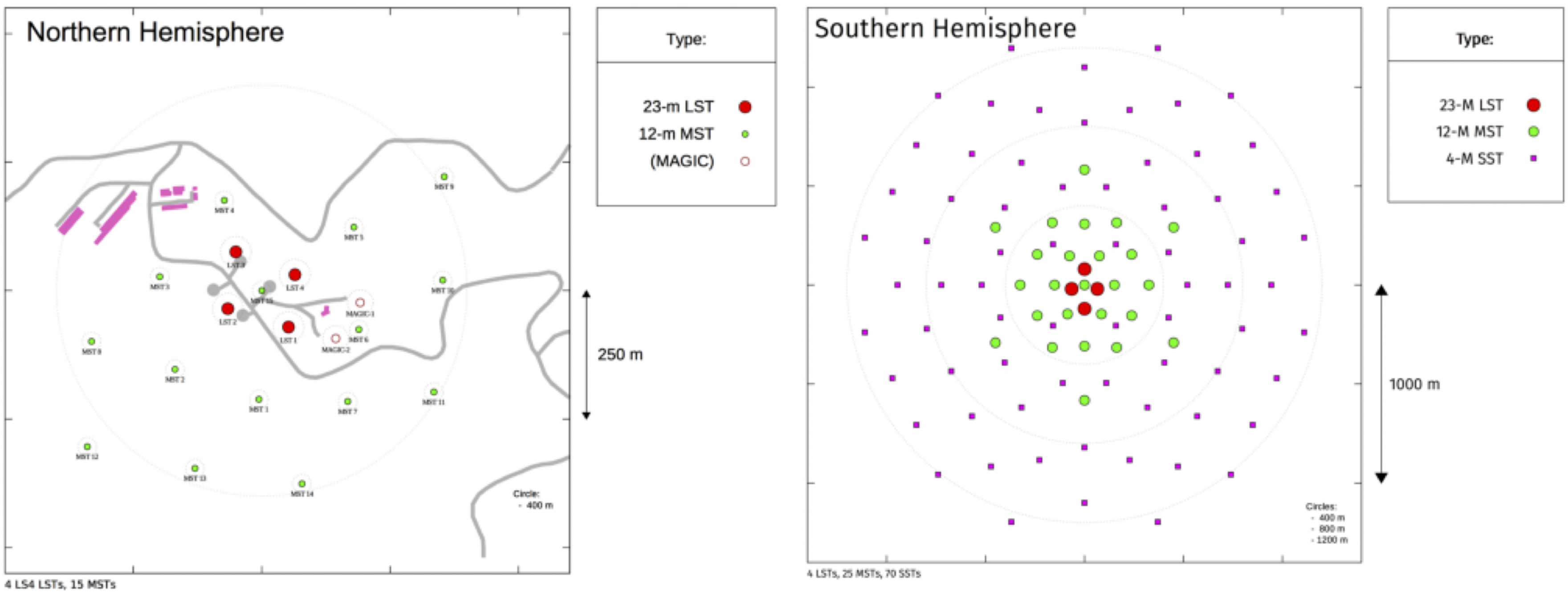


Introduction



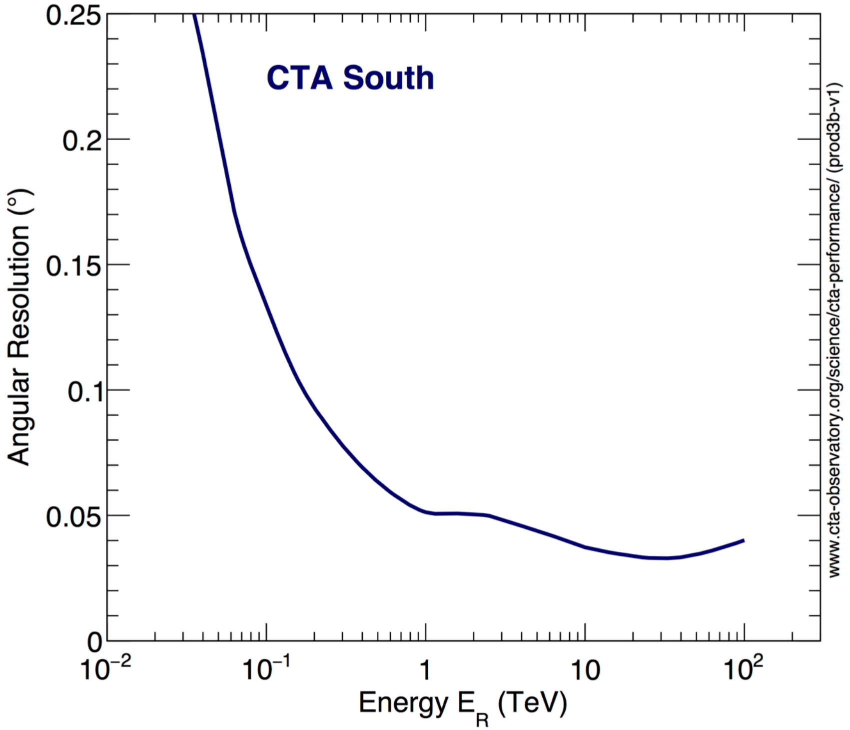
Cherenkov Telescope Array

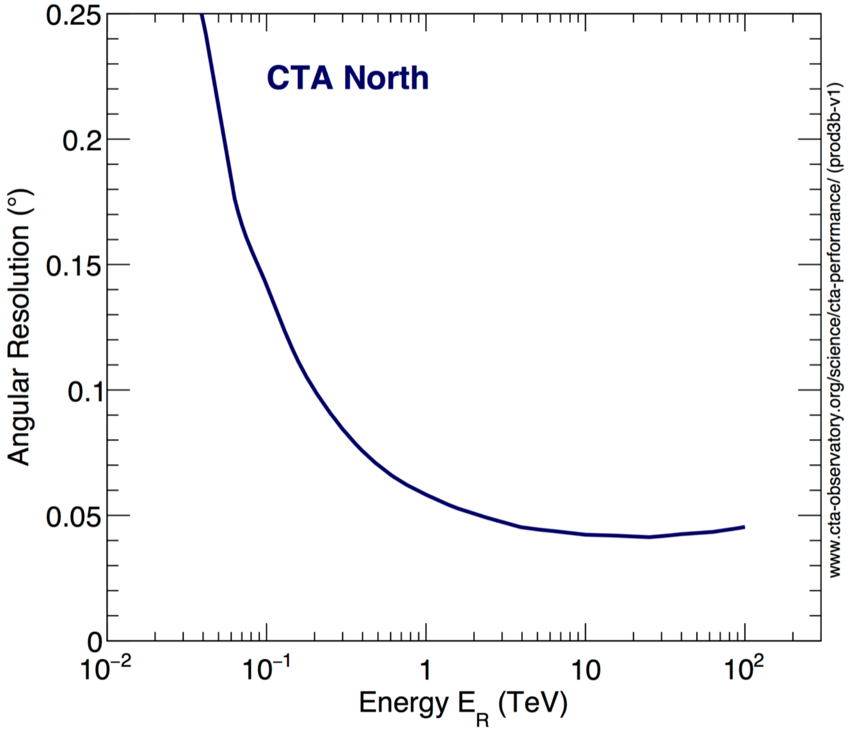
CTA array layout.



Cherenkov Telescope Array

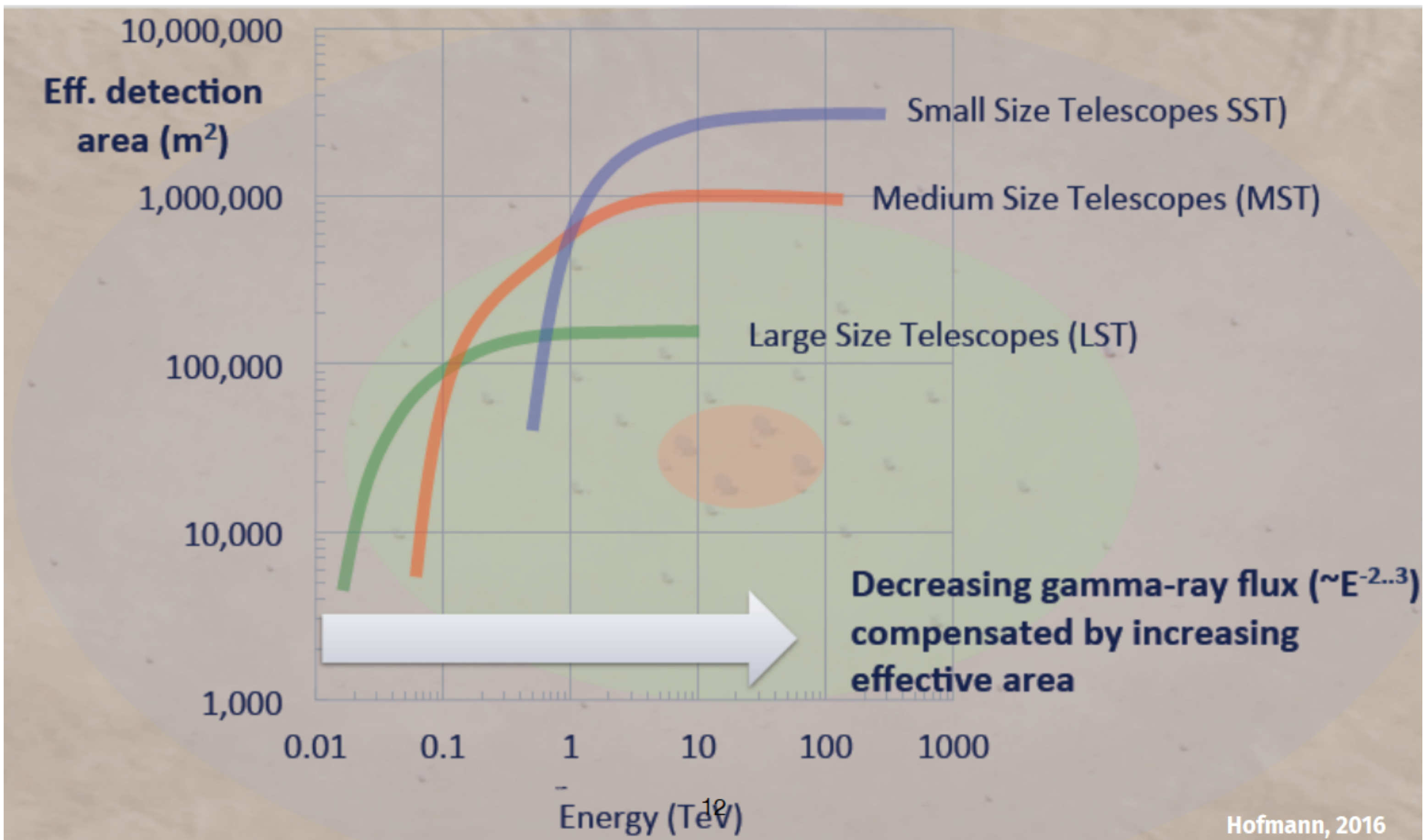
Angular resolution.





Cherenkov Telescope Array

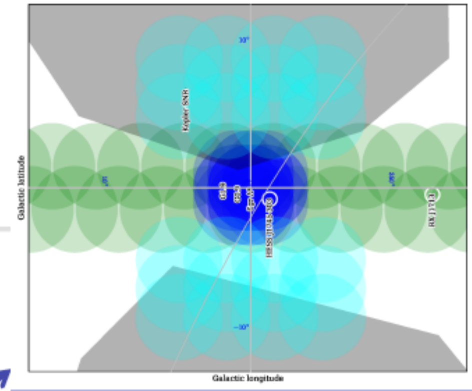
Effective area for gamma-ray detection



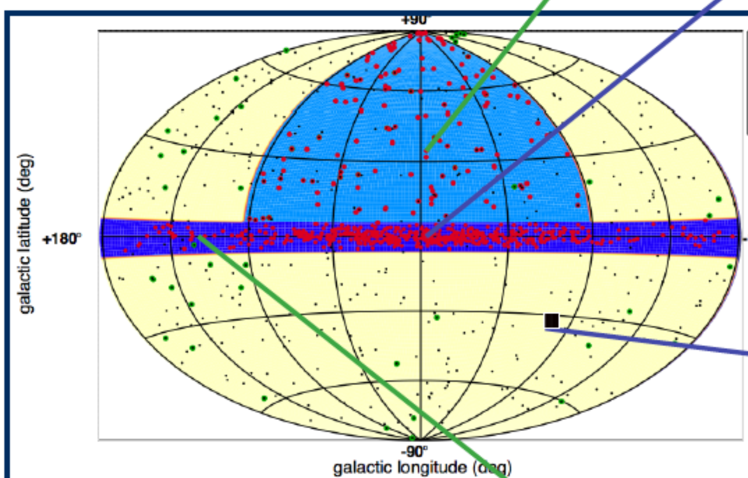
Cherenkov Telescope Array

CTA Key Science Projects

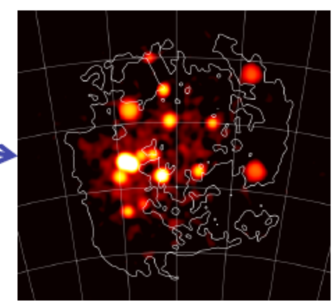
The Survey KSPs



Extragalactic Survey:
Unbiased survey of ¼ sky to ~6 mCrab
VHE population study, duty cycle
New, unknown sources; O(1000) h



Galactic Centre Survey:
ID of the central source
Spectrum, morphology of diffuse emission
Deep DM search; base of the Fermi Bubbles
Central exposure: O(525) h, 10°x10° : O(300) h

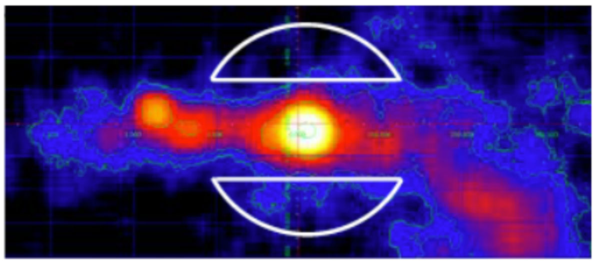


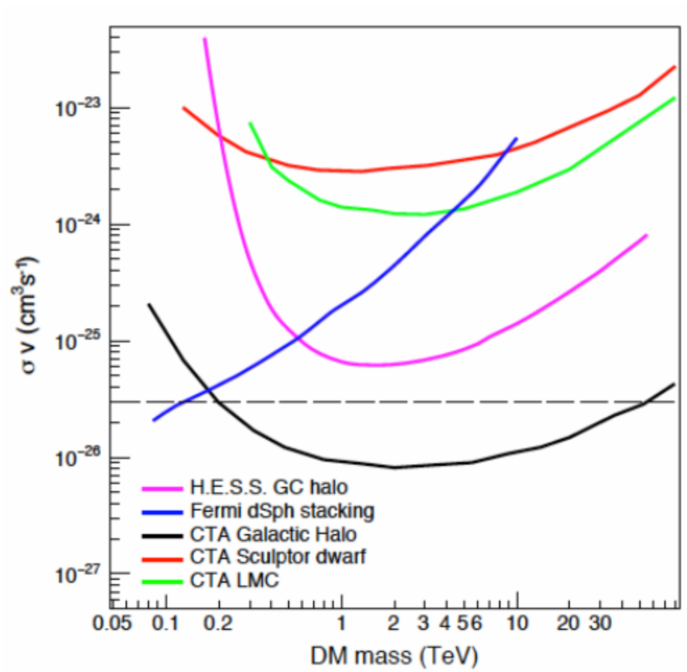
Galactic Plane Survey:
Survey of entire plane to ~2 mCrab
Galactic source population: SNRs, PWNe, etc.
PeVatron candidates, early view of GC, O(1620) h

Large Magellanic Cloud Survey:
Face-on satellite galaxy with high SFR
Extreme Gal. sources, diffuse emission (CRs)
DM search; O(340) h in six pointings

CTA Key Science Projects

The Dark Matter Programme





- **Key target: Galactic Centre halo**
  - Deep observation O(525 h) to reach canonical thermal cross-section for wide WIMP mass range
- **Complementary observations**
  - Dwarf Sph. Galaxies O(100 h)
  - LMC O(340 h)
  - Perseus Gal. Cluster O(300 h)
  - Expect strategy to evolve with new information

Viana (Fund. Physics)

CTA Key Science Projects

Table 9.1 – Summary table of proposed maximum observation times for follow-up targets in the Transients KSP. Observations of Galactic transients could be extended beyond Year 3 of regular operations if new source classes with fast variability are discovered. The early phase, prior to array completion, is assumed to last for two years.

		Observation times (h yr^{-1} $site^{-1}$)			
Priority	Target class	Early phase	Years 1–2	Years 3–10	Years 1–10
1	GW transients	20	5	5	
2	HE neutrino transients	20	5	5	
3	Serendipitous VHE transients	100	25	25	
4	GRBs	50	50	50	
5	X-ray/optical/radio transients	50	10	10	
6	Galactic transients	150	30	0(?)	
	Total per site (h yr^{-1} $site^{-1}$)	390	125	95	
	Total both sites (h yr^{-1})	780	250	190	
	Total in different CTA phases (h)	1560	500	1520	2020

Table 9.3 – Summary table of Galactic transients proposed within the Transient KSP during the early phase of CTA. The codes for the last column are: S (south), N (north, A (any), and B (both, if possible).

Follow-up priority	Target class	Detected @ HE	Trigger	Rate (yr^{-1})	Urgency	Activity duration	Obs. time (h) /night	Total time (h)	Site
1	Magnetar giant flares	–	MeV	0.1	1 min	1–2 d	Max. 1	10	A/B
2	PWN flares: Crab nebula	Y	HE	1	1 d	5–20 d (HE)	4	50	S&N
3	HMXB microquasars: Cyg X-3	Y	HE/X-ray	0.5	1 d	50–70 d (HE)	Max. 1	50	N
	Cyg X-1	Y	HE/X-ray	0.2	1 d	1–10 d ?	Max. 1	30	N
4	Unidentified HE transients	Y	HE	1	1 d	?	2	20	A/B
5	LMXB microquasars	?	X-ray/radio	1	1 d	Weeks	2	20	A/B
6	Novae	Y	HE/opt.	2	1 d	Weeks	2	20	A/B
7	Transitional pulsars	Y	Radio/opt.	0.5	1 d	Weeks	2	20	A/B
8	Be/X-ray binary pulsars	N	X-ray	1	1 d	Weeks	2	20	A/B

CTA Key Science Projects

cherenkov telescope array

Science program

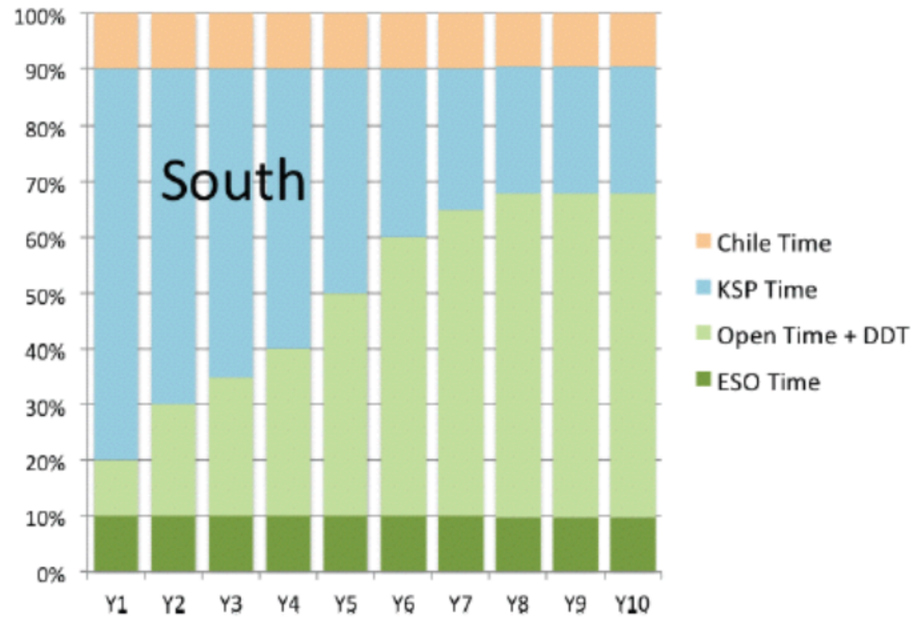
Key science projects

Science themes

Theme		Question	Dark Matter Programme	Galactic Centre Survey	Galactic Plane Survey	LMC Survey	Extra-galactic Survey	Transients	Cosmic Ray PeVatrons	Star-forming Systems	Active Galactic Nuclei	Galaxy Clusters
Understanding the Origin and Role of Relativistic Cosmic Particles	1.1	What are the sites of high-energy particle acceleration in the universe?		✔	✔✔	✔✔	✔✔	✔✔	✔	✔	✔	✔✔
	1.2	What are the mechanisms for cosmic particle acceleration?		✔	✔	✔		✔✔	✔✔	✔	✔✔	✔
	1.3	What role do accelerated particles play in feedback on star formation and galaxy evolution?		✔		✔				✔✔	✔	✔
Probing Extreme Environments	2.1	What physical processes are at work close to neutron stars and black holes?		✔	✔	✔			✔✔		✔✔	
	2.2	What are the characteristics of relativistic jets, winds and explosions?		✔	✔	✔	✔	✔✔	✔✔		✔✔	
	2.3	How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?					✔	✔			✔✔	
Exploring Frontiers in Physics	3.1	What is the nature of Dark Matter? How is it distributed?	✔✔	✔✔		✔						✔
	3.2	Are there quantum gravitational effects on photon propagation?						✔✔	✔		✔✔	
	3.3	Do Axion-like particles exist?					✔	✔			✔✔	

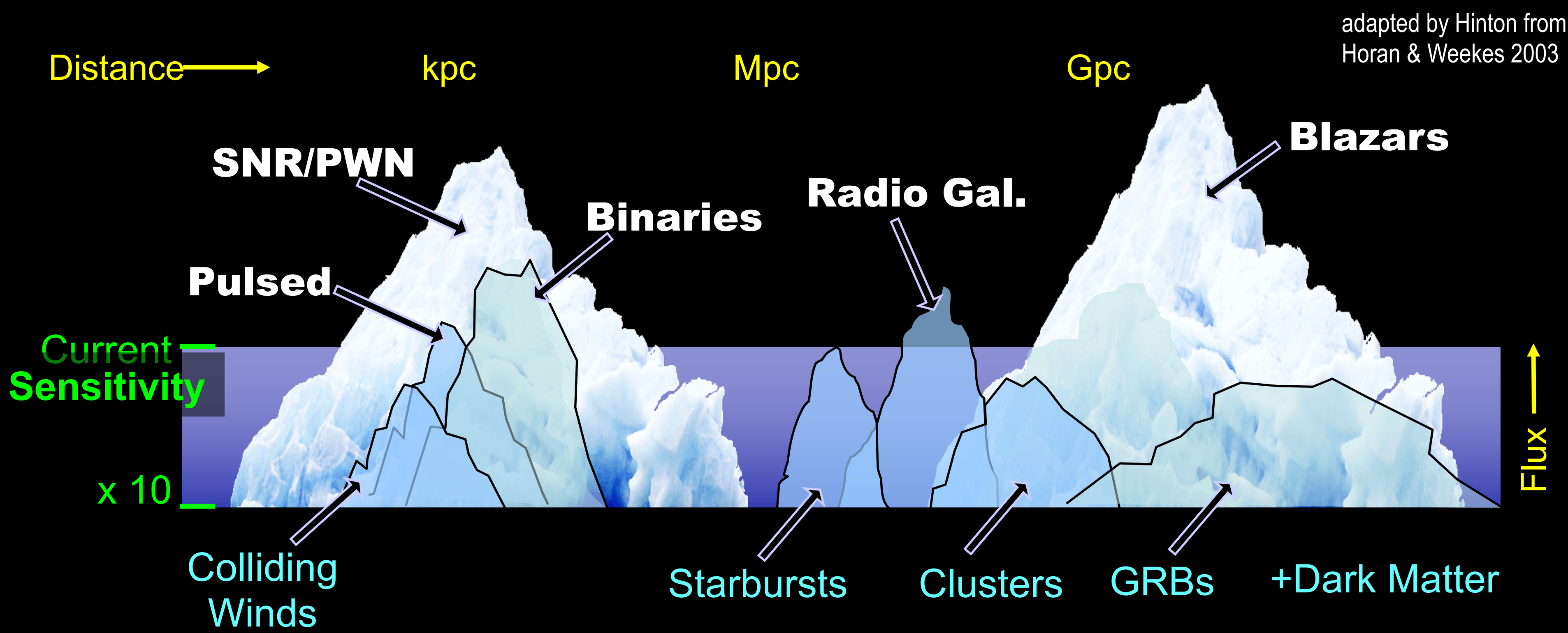
CTA Key Science Projects

Observing time



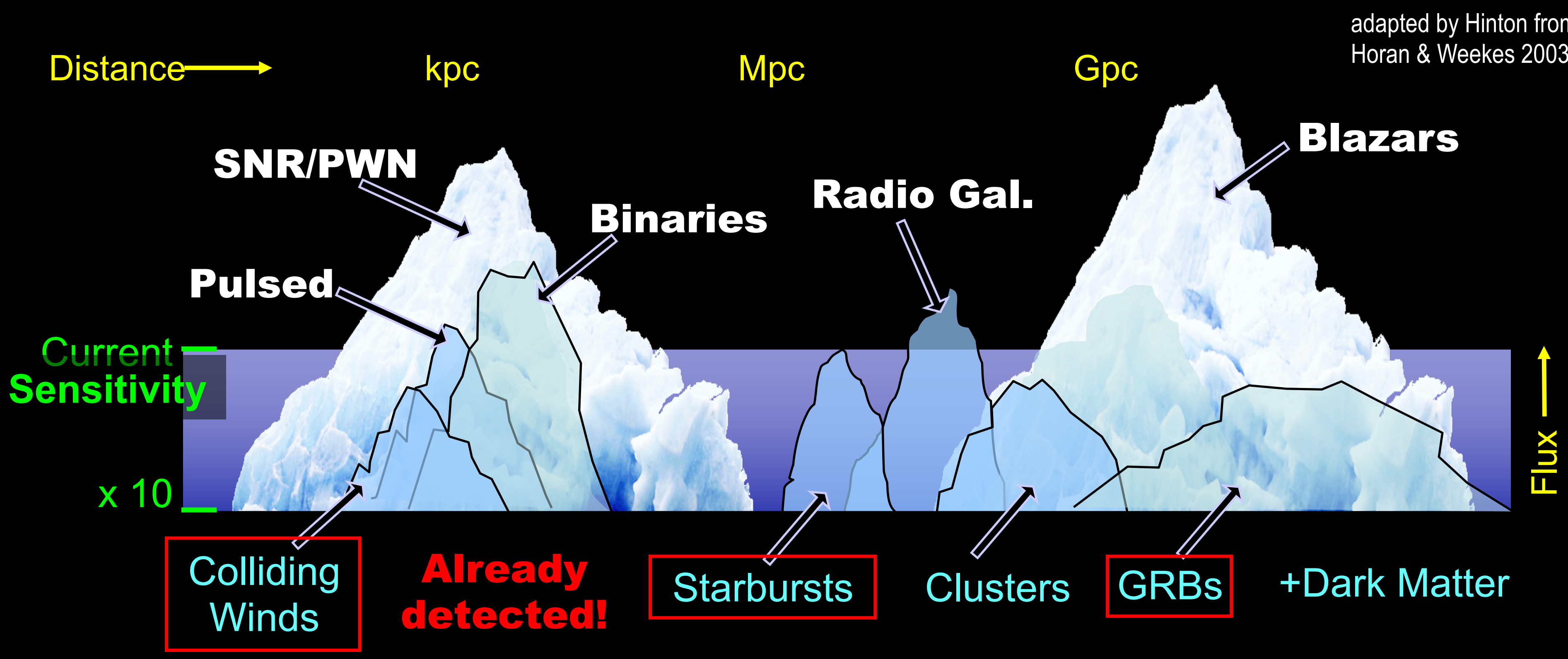
- Total ~1000-1300 hr/yr/site:
  - Key Science Programs (KSPs).
  - Open Time: Guest Observer proposals.
- All CTA science data products will be fully open after proprietary period.

Science Potential



- Current instruments have passed the critical sensitivity threshold and reveal a rich panorama, **but this is clearly only the tip of the iceberg**

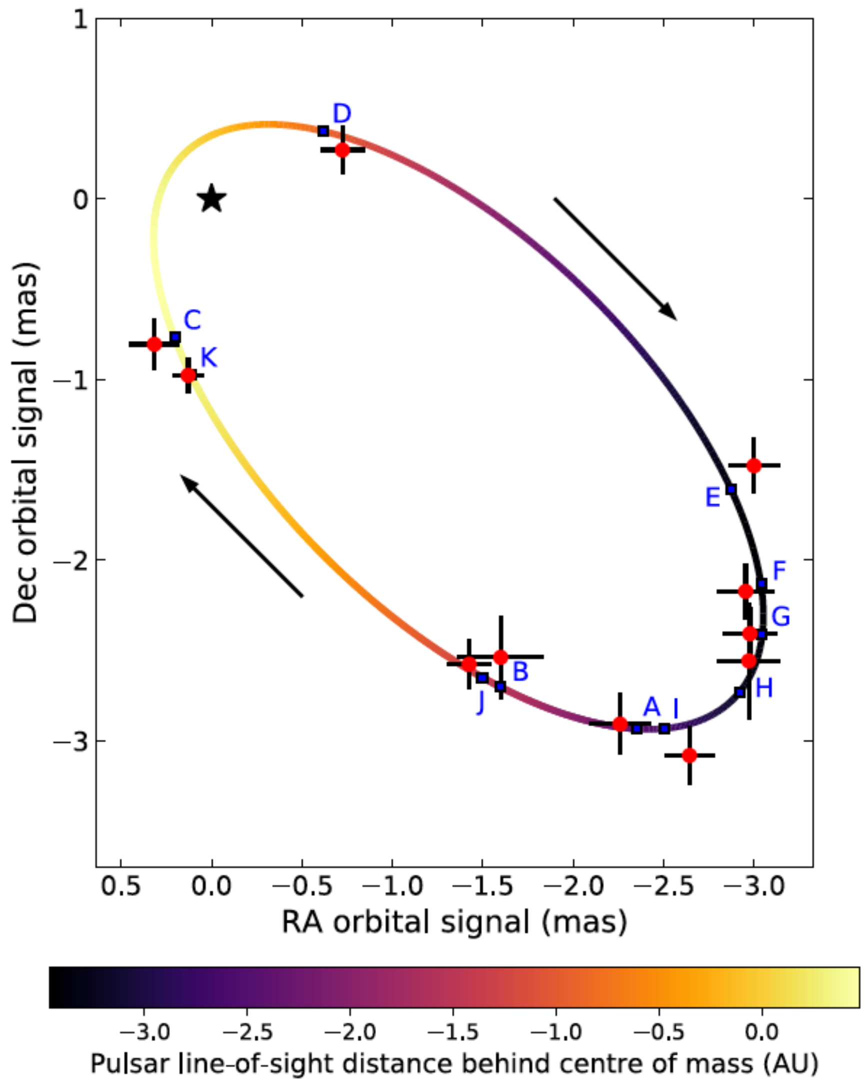
Science Potential

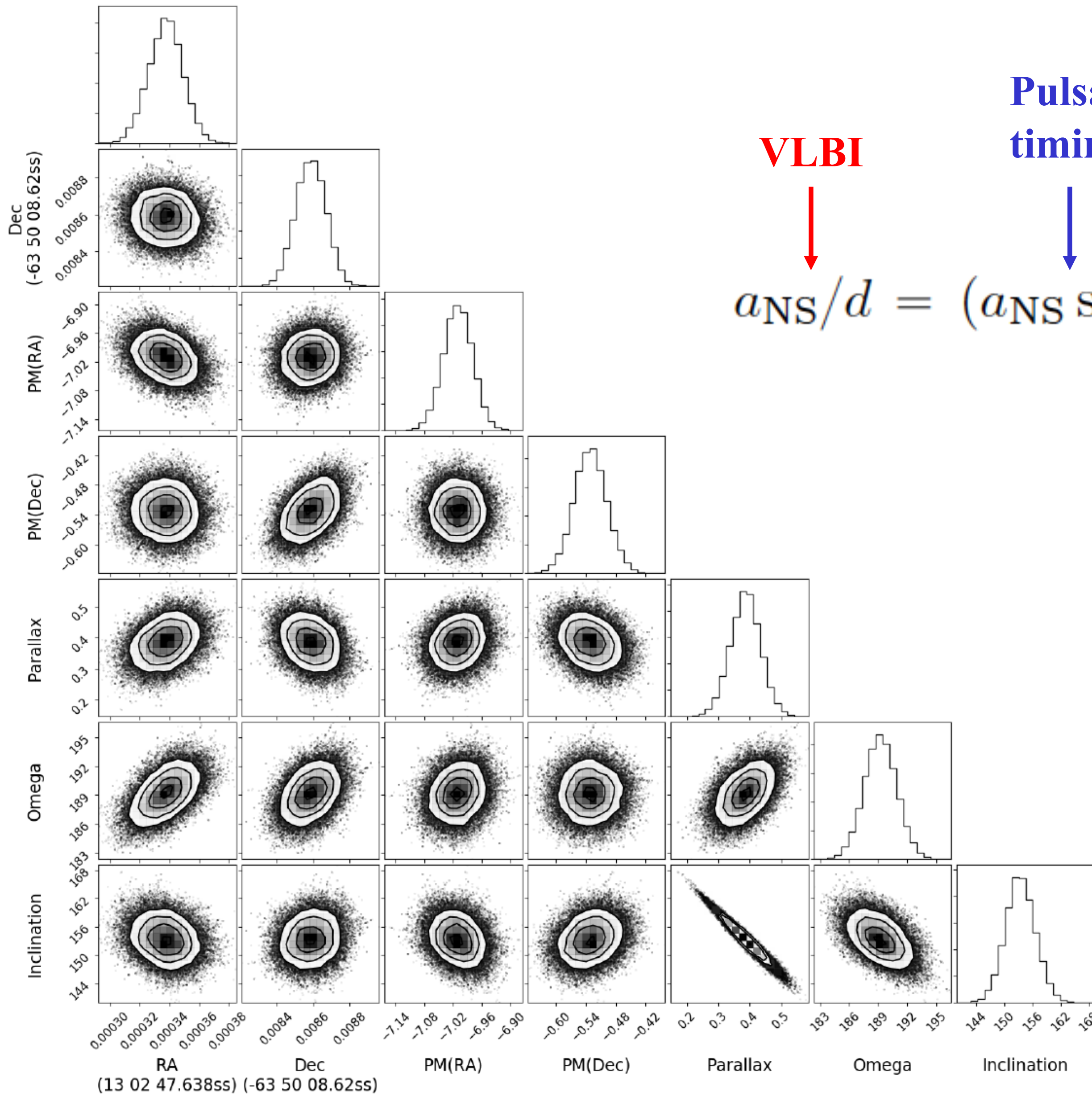


- Current instruments have passed the critical sensitivity threshold and reveal a rich panorama, **but this is clearly only the tip of the iceberg**

Backup

Gaia DR2 results on gamma-ray binaries. **PSR B1259-63** **(Miller-Jones et al. 2018)**.





Pulsar timing

VLBI

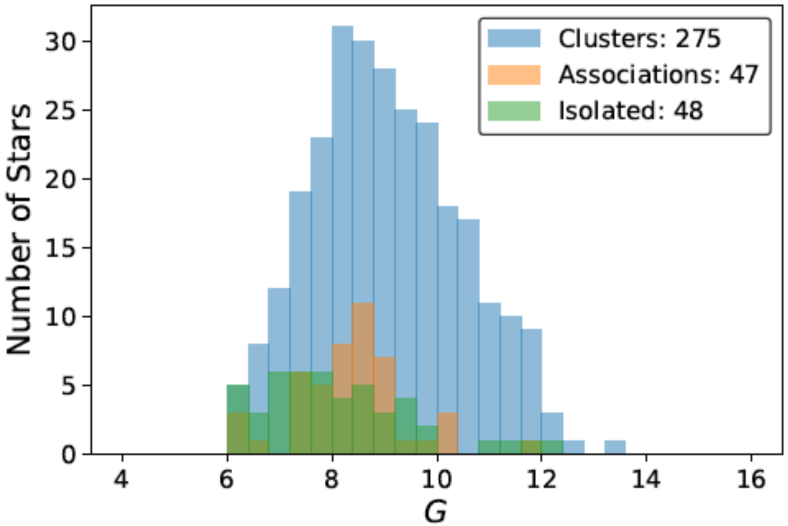
$$a_{\mathrm{NS}}/d \; = \; (a_{\mathrm{NS}} \sin i)/d \sin i$$

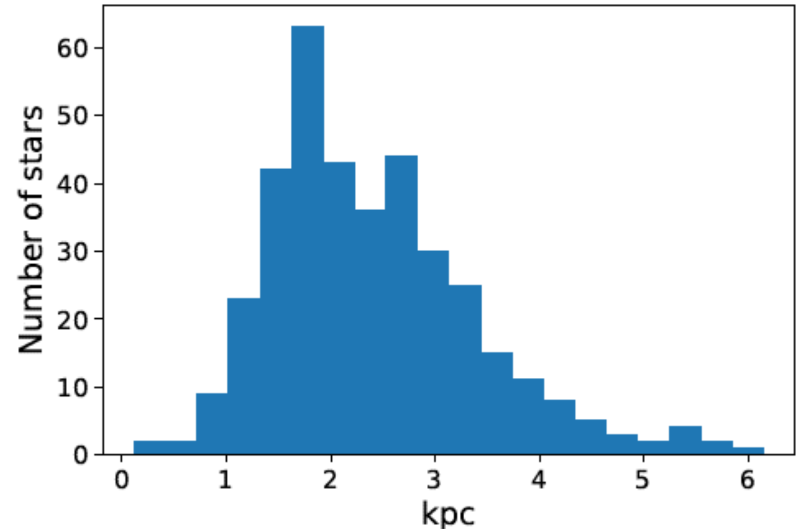
GOSC.

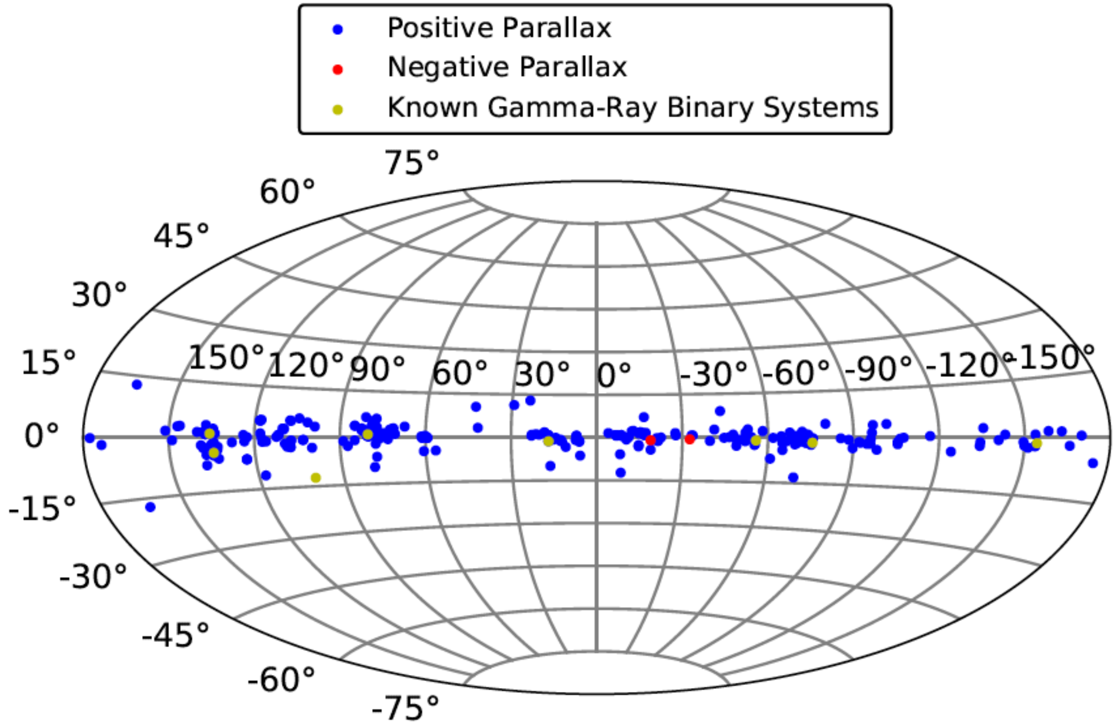
Table 4.1: Filters used to generate our GOSC-*Gaia* DR2 Catalog. The second column corresponds to the number of stars that satisfy the conditions of the first column considering all the stars that are cross-matched in GOSC and *Gaia* DR2. The third column is the number of stars that remain after applying the corresponding filter.

Filters	Number of stars	Final number of stars
Does not appear in Gaia	3	615
Duplicate `source_id`	10	605
A0 stars	1	604
Multiple component stars	70	535
5 parameter solution	598	530
$G \geq 6$	560	494
`mean_varpi_factor_al` $\in [-0.23, 0.32]$	602	489
`visibility_periods_used` ≥ 10	535	438
$\mid$ `parallax_over_error` $\mid \geq 5$	480	372
Negative Parallax	2	370

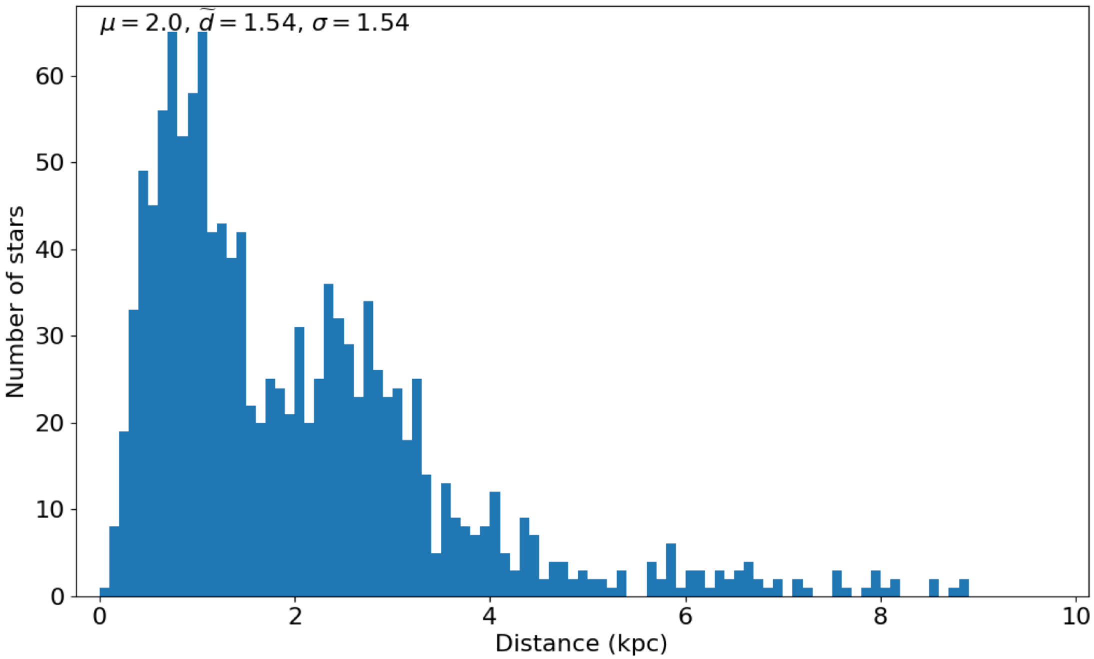
GOSC.


Clusters: 275
Associations: 47
Isolated: 48
Number of Stars
G
0
5
10
15
20
25
30
4
6
8
10
12
14
16

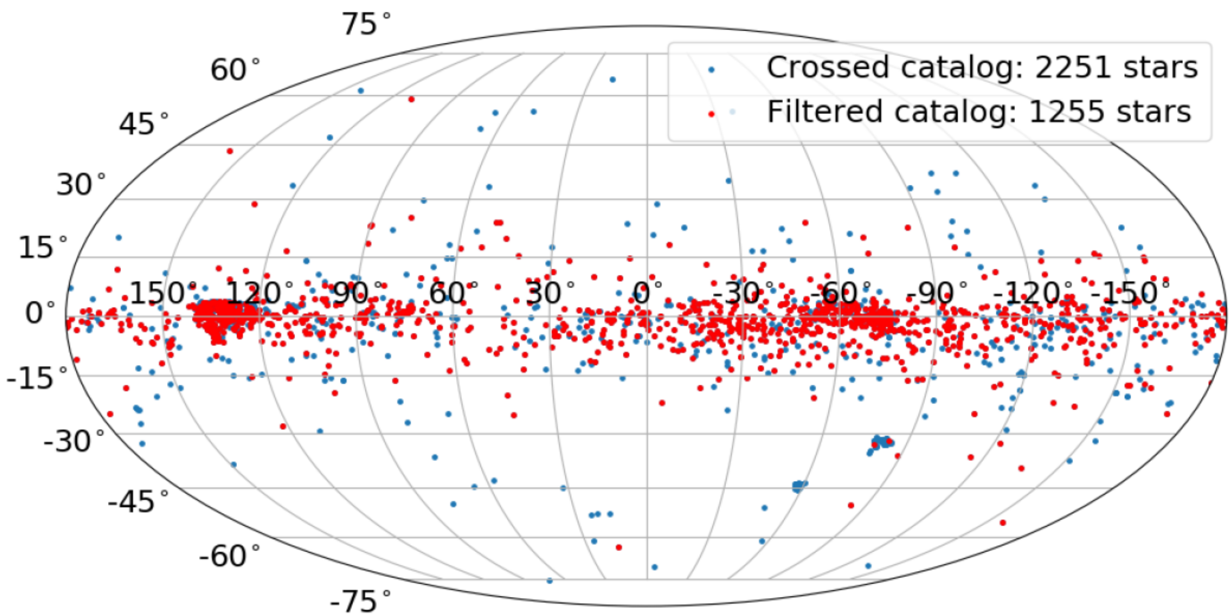

Number of stars
kpc
0
10
20
30
40
50
60
0
1
2
3
4
5
6


Positive Parallax
Negative Parallax
Known Gamma-Ray Binary Systems
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
150°
120°
90°
60°
30°
0°
-30°
-60°
-90°
-120°
-150°

BeSS.



$\mu = 2.0$, $\widetilde{d} = 1.54$, $\sigma = 1.54$
Number of stars
Distance (kpc)
0
10
20
30
40
50
60
0
2
4
6
8
10



Crossed catalog: 2251 stars
Filtered catalog: 1255 stars
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
150°
120°
90°
60°
30°
0°
-30°
-60°
-90°
-120°
-150°

Name	System type	Orbital period (d)	Radio structure (AU)	Multi-wavelength periodicity			
				Radio	X-ray	GeV	TeV
Emission line star companion							
PSR B1259−63	O9.5 Ve + NS	1237	Cometary tail ~ 120	P	P	P	P
LS I +61 303	B0 Ve + ?	26.5	Cometary tail ? $\sim 10 - 700$	P	P	P	P
HESS J0632+057	B0 Vpe + ?	320	Elongated ~ 60	V	P	P?	P
PSR J2032+057/MT91 213	Be + NS	40-50 yr	?	D	D	D	D
Non-Emission line star companion							
LS 5039	O6,5 V((f)) + ?	3.9	Cometary tail ? $10 - 1000$	p	P	P	P
1FGL J1018.6−5856	O6,5 V((f)) + ?	16.5	?	P	P	P	P
CXOU J053600.0−673507 (LMC P3)	O5 III + NS?	10.3	?	P	P	P	D

Note: P: Periodic emission, p: Persistent emission, V: Variable emission, D: Detected

(Paredes & Bordas 2018)

Some gamma-ray binaries are runaways:

Table 6.5: Known gamma-ray binaries and their parameters computated with our method. References: (1) Moldón et al. (2012), (2) Marcote et al. (2018), (3) Wu et al. (2017), (4) Miller-Jones et al. (2018), (5) Grudzinska et al. (2015).

Gamma-ray Binary System	Spectral Type	Classified as Runaway with our method	$V_{\rm TAN}$ (km s^{-1})	$\tilde{W}_{\rm RSR}$ (km s^{-1})	Our Peculiar Velocity (km s^{-1})	Peculiar Velocity Literature (km s^{-1})
LS 5039	06.5V	Y	-16.4 ± 7.1	-92.1 ± 11.0	93.6 ± 11.4	142 ± 40 (1)
1FGL J1018.6−5856	O6V	Y	-13.6 ± 14.1	-43.8 ± 9.0	45.9 ± 12.7	45^{+30}_{-9} (2)
LS I +61 303	B0Ve	N	5.0 ± 5.4	5.8 ± 1.3	7.7 ± 3.6	16 (3)
HESS J0632+057	B0Vpe	N	6.1 ± 6.5	3.6 ± 1.4	7.1 ± 5.6	–
PSR B1259−63	O9.5Ve	N	-2.7 ± 4.8	8.1 ± 1.0	8.5 ± 1.8	26 ± 8 (4)
MT91 213	Be	Y	17.4 ± 3.0	22.1 ± 1.1	28.1 ± 2.2	–

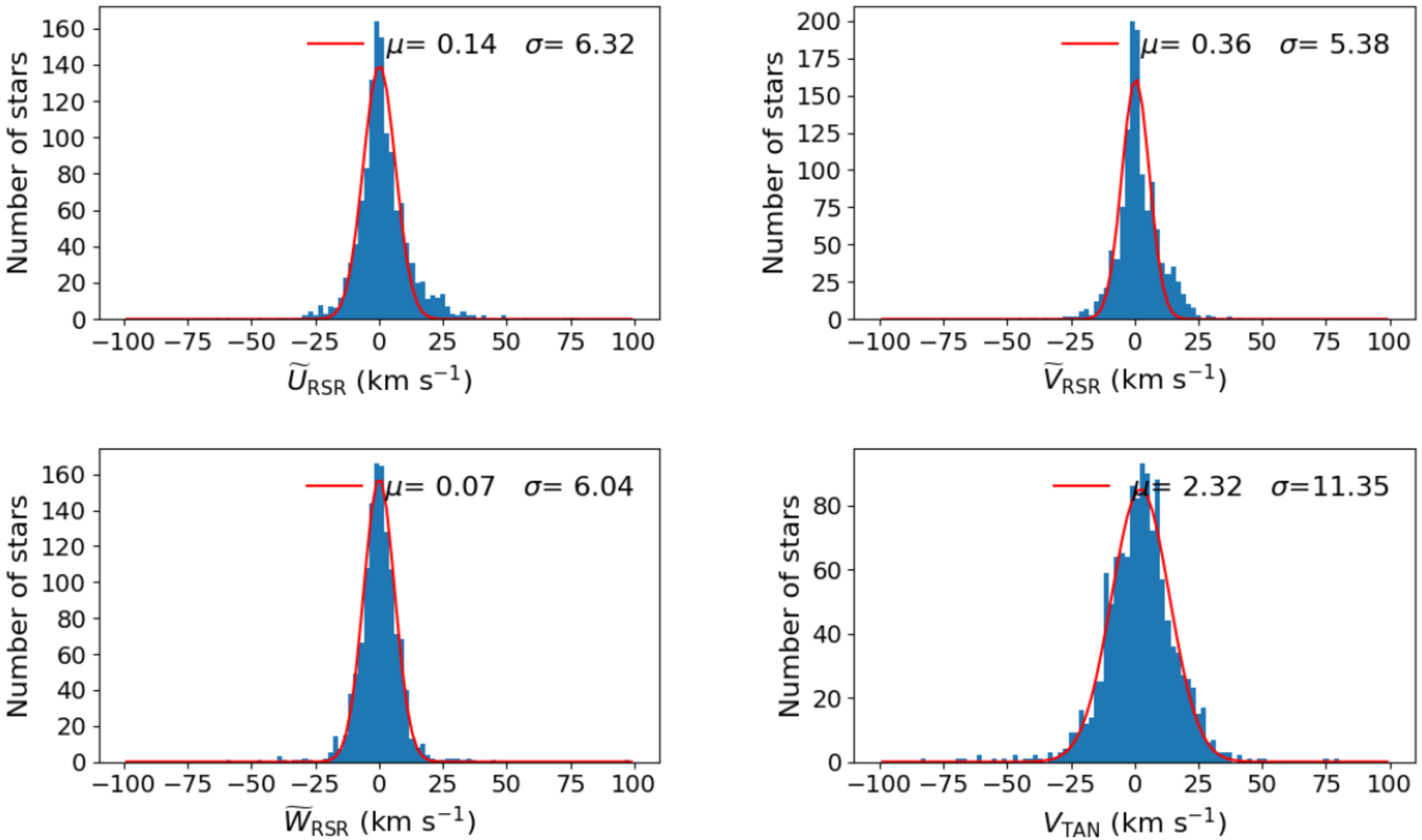
Some gamma-ray binaries are runaways:

Gamma Ray Binary System	Spectral Type	Runaway	Our Radial Velocity (km/s)	Radial Velocity from Literature (km/s)
1FGL J1018.6-5856	O6V	True	35.1 ± 0.1	33 ± 3
LS 5039	O6.5V	True	6.8 ± 0.1	17.2 ± 0.5
LS I +61 303	B0Ve	False	-36.7 ± 0.1	-40.2 ± 1.9
MWC 148	B0Vpe	False	41.1 ± 0.1	
PSR B1259-63	O9.5Ve	False	-22.4 ± 0.1	0 ± 0
MT91 213	Be	True	-13.8 ± 0.1	
MWC 656	Be	False	-29.6 ± 0.1	-14.1 ± 2.1
HD 13831	Be	False	-46.8 ± 0.1	

Table 3.1: Table showing the kinematics of six γ-ray binaries and two Be binaries. (*: star in BeSS)

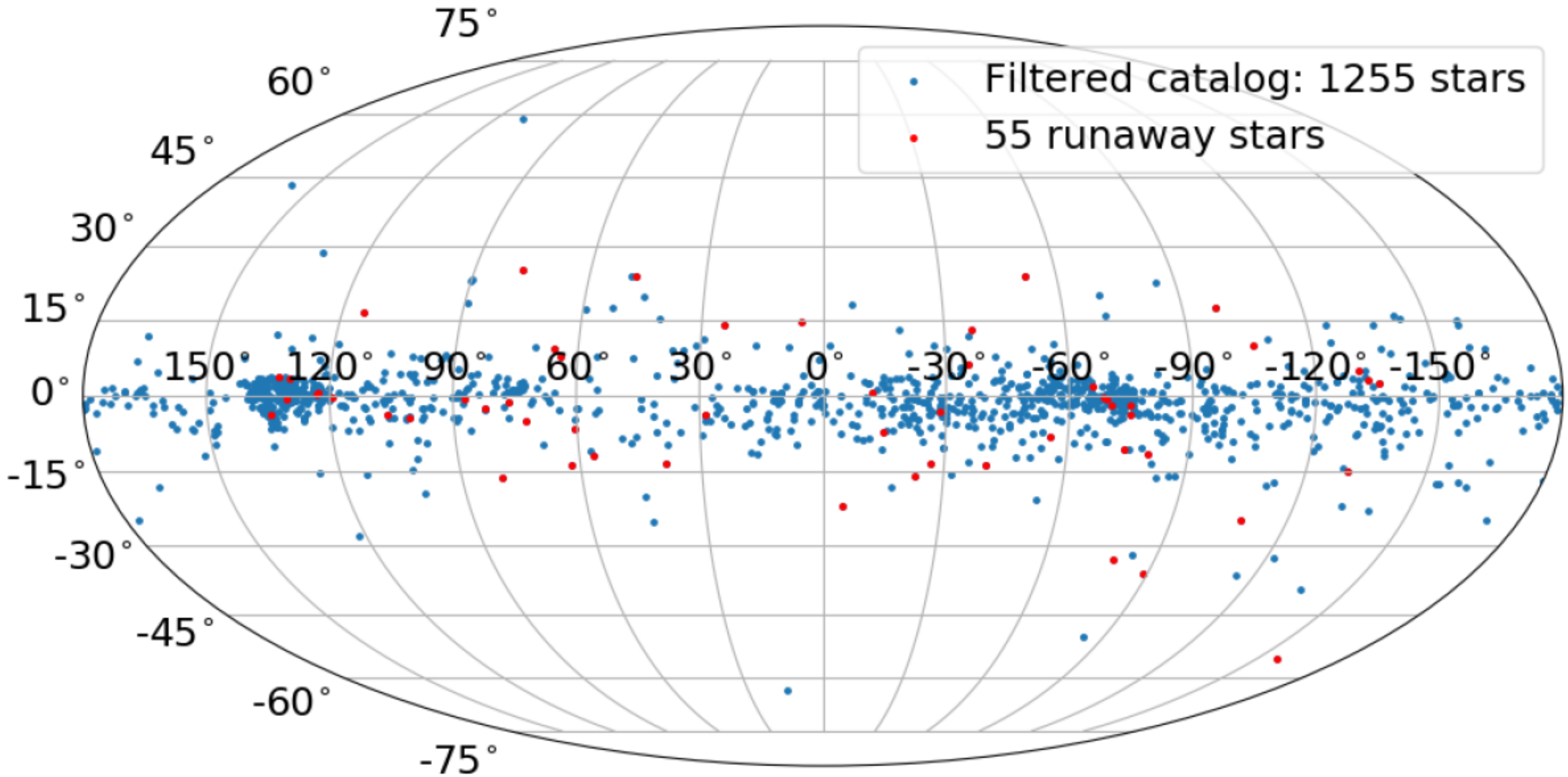
Binary	V_r	W_{RSR}	V_{TAN}	V_{PEC}	Runaway
LS 5039	17.2±0.5 (Moldón et al. 2012)	-92.3 ± 11.0	-16.4 ± 7.1	94.2 ± 11.0	yes
	6.8 ± 0.1	-92.1 ± 11.0	-16.4 ± 7.1	93.6 ± 11.4	yes
1FGL J1018.6-5856	35.5 ± 1.3 (Monageng et al. 2017)	-43.9 ± 9.0	-13.6 ± 14.1	45.9 ± 12.3	yes
	35.1 ± 0.1	-43.9 ± 9.0	-13.6 ± 14.1	45.9 ± 12.4	yes
LS I +61 303*	-40.2 ± 1.9 (Casares et al. 2005)	5.7 ± 1.3	5.0 ± 5.4	8.4 ± 5.1	no
	-36.7 ± 0.1	5.8 ± 1.3	5.0 ± 5.4	7.7 ± 5.4	no
HESS J0632+057*	41.1 ± 0.1	3.6 ± 1.5	6.1 ± 6.5	7.1 ± 5.6	no
PSR B1259-63*	0±0 (Miller-Jones et al. 2018)	7.7 ± 1.0	-2.7 ± 4.8	24.9 ± 6.1	no
	-22.4 ± 0.1	8.1 ± 1.0	-2.7 ± 4.8	8.5 ± 1.8	no
MT91 213	-13.8 ± 0.1	22.1 ± 1.1	17.4 ± 3.0	28.1 ± 2.2	no
MWC 656*	-14.1 ± 2.1 (Casares et al. 2014)	1.6 ± 1.4	-6.3 ± 3.1	17.5 ± 7.1	no
	-29.6 ± 0.1	4.9 ± 1.4	-6.3 ± 3.1	8.1 ± 2.9	no
HD 13831*	-46.8 ± 0.1	-16.9 ± 6.0	12.6 ± 6.0	21.1 ± 6.7	no

Runaways in BeSS.



Runaways in BeSS.

$\sigma_b = 6.5$ deg
$\sigma_b = 14.4$ deg



$\sigma_Z = 117$ pc
$\sigma_Z = 525$ pc