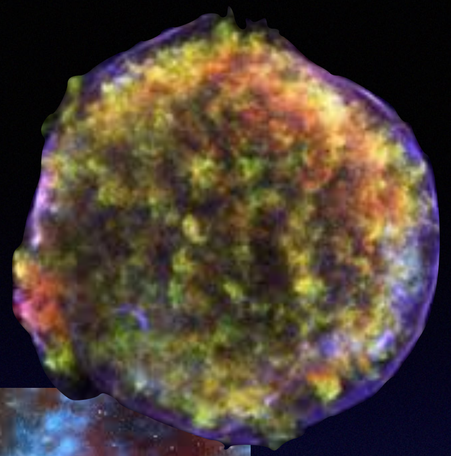
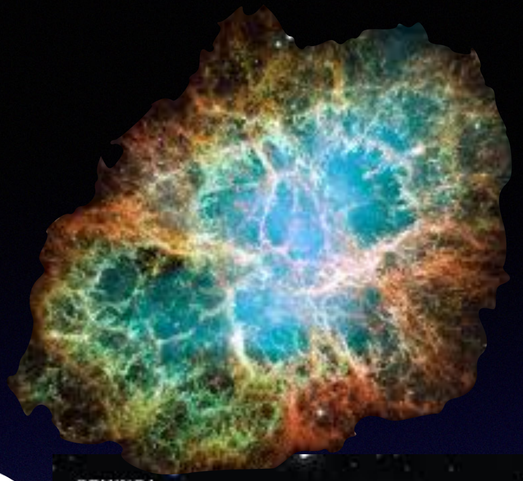
CRACHEN

Cosmic **R**ay **AC**celerators unveiled by
High **EN**ergy astrophysical observations

RESEARCH PROGRAM





THE BIG QUESTIONS

ORIGIN OF CRs

IMPACT OF CRs ON THE ISM AND IGM

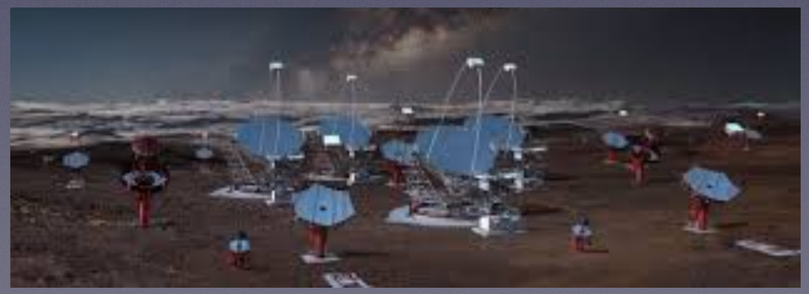
HOW TO ANSWER

HIGH ENERGY ASTROPHYSICAL OBSERVATIONS

X-RAYS

GAMMA-RAYS

VHE GAMMA-RAYS

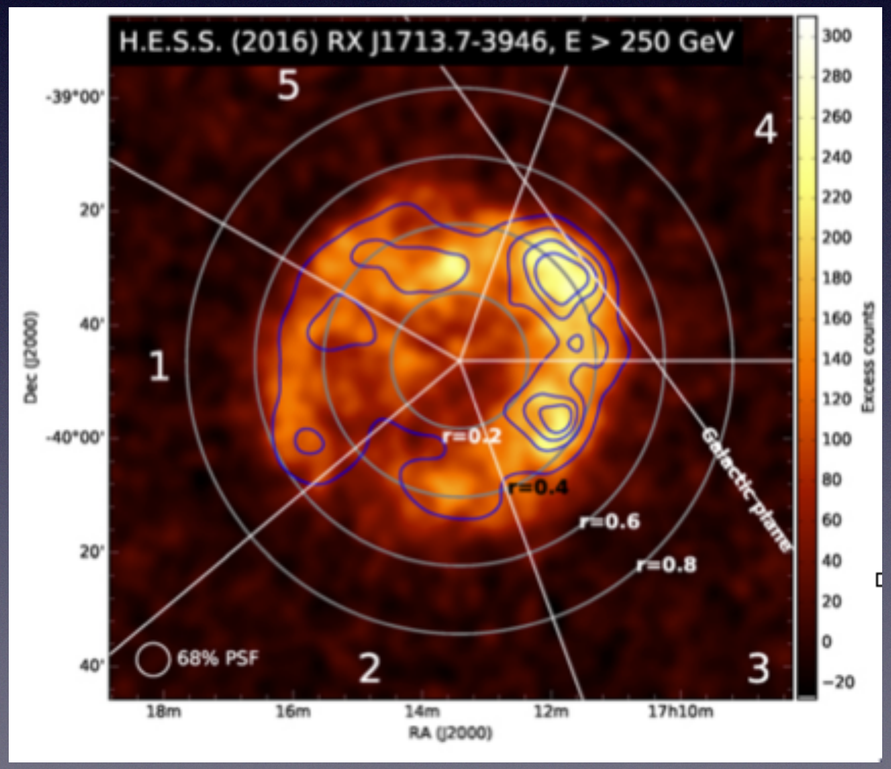


HADRONIC PEVATRONS

PROBLEMS

SNRs OBSERVATIONS

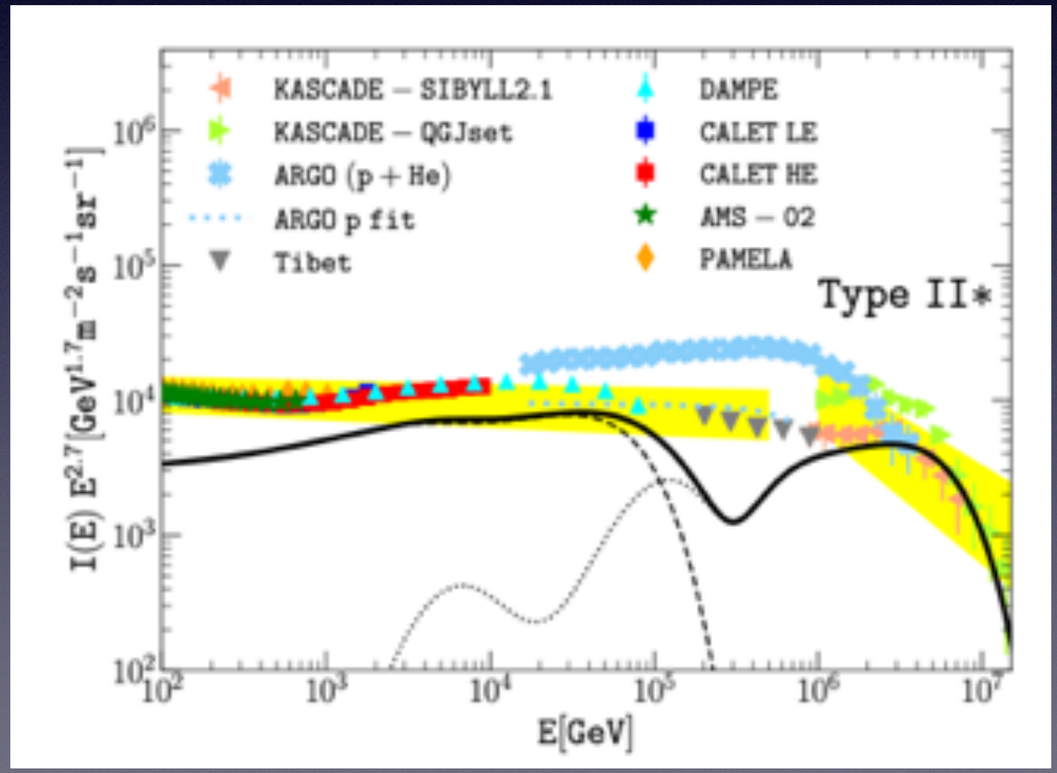
NO YOUNG GALACTIC SNR OBSERVED
BEYOND FEW 10s TeV



[EA & Casanova 2021]

THEORY

- ONLY RARE (1 / FEW 10^4 yr) EXTREME (10^{52} erg) SN
- IF PeV THEN ALSO DOMINANT AT 10^2-10^4 GeV



[Cristofari, Blasi, EA 2020]

HADRONIC PEVATRONs: WP1

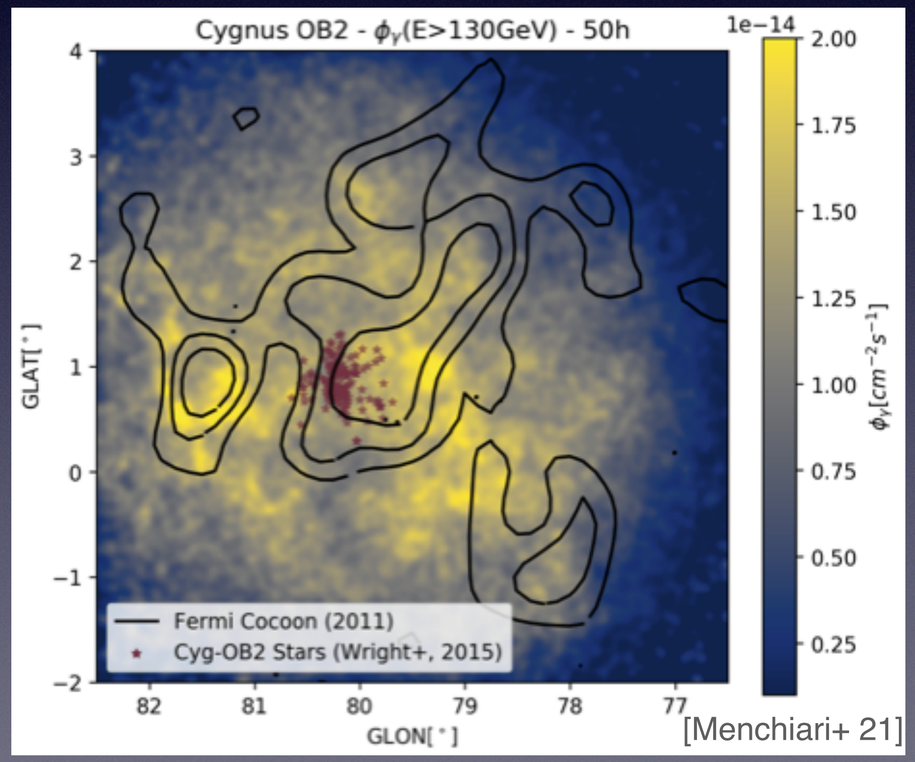
PROPOSED ANSWERS

STAR FORMING REGIONS

NO CUT-OFF BEYOND 100 TeV [Aharonian et al. 2019]

PEV COULD BE REACHED:

- INSIDE THE CLUSTER [Bykov et al. 2020]
- AT THE TERMINATION SHOCK [Morlino et al. 2020]
- IN MASSIVE STAR WINDS [OAA + OAPa]



[Menchiari+ 21]

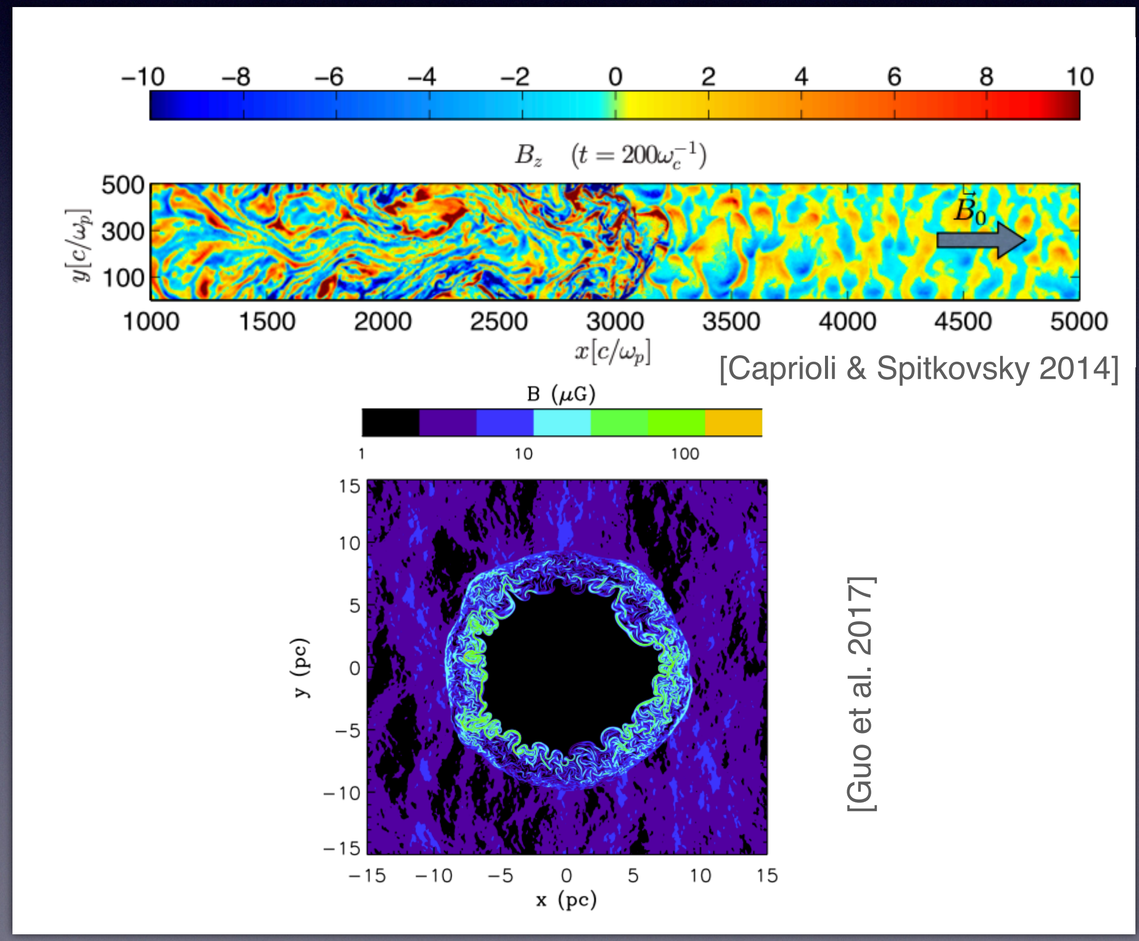
Simulation for CTA: 50 hr of observation

CRs accelerated at the cluster TS

SUPERNOVA REMNANTS

CR INDUCED INSTABLITIES [OAA + GSSI]

MHD INSTABLITIES [OAA + OAPa]



[Caprioli & Spitkovsky 2014]

[Guo et al. 2017]

HADRONIC PEVATRONs: WP1

WP1 – PeVatrons

1.1

Acceleration in SNII
+
Diagnostics
(thermal/non-thermal)

OAA
OAPa

1.2

Acceleration in young
star winds
(interacting/non-interacting)

OAA
OAPa

1.3

Acceleration at TS of
young stellar clusters
+
turbulent acceleration
+
compare with observations
(Cygnus,Westerlund 1)
+
Predictions for ASTRI/CTA North

OAA
OAB
GSSI

1.4

MHD instability in
young SNRs
+
magnetic field amplification
and E_{max} increase

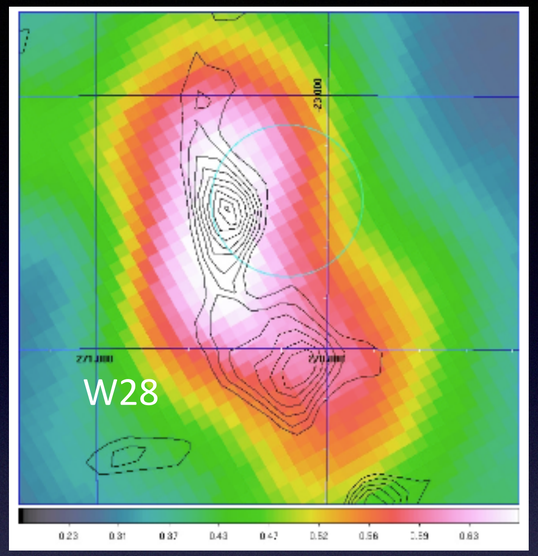
OAA
OAPa

1.5

Hadronic/leptonic
PeVatrons
+
HAWC sources
modelling (>100 TeV)
+
multi-messenger

OAA
OAB

NEAR SOURCE TRANSPORT: WP2

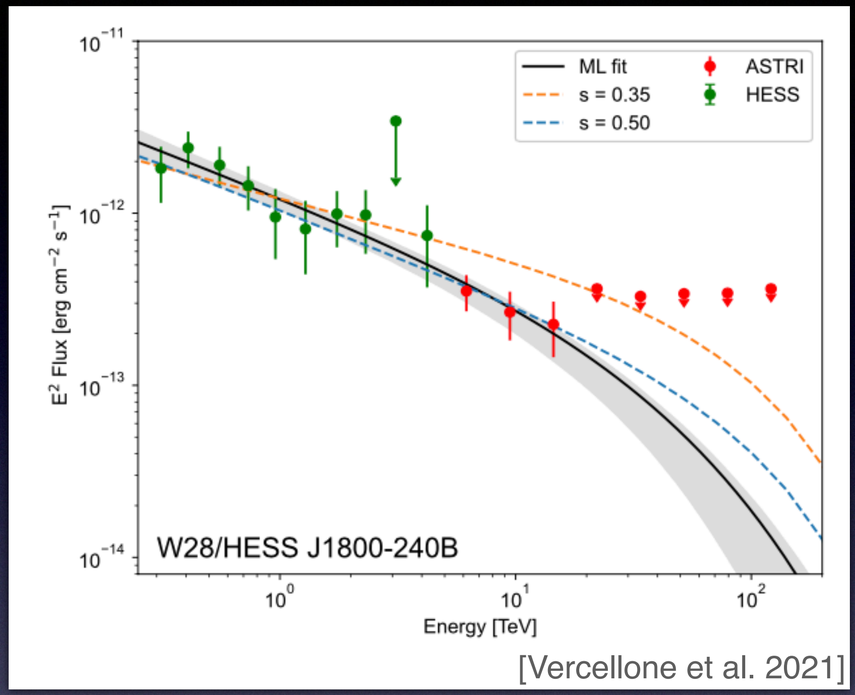


[Giuliani et al. 2010]

REDUCED DIFFUSIVITY AROUND SOURCES
[Giuliani et al. 2010, Abeysekara et al. 2017]

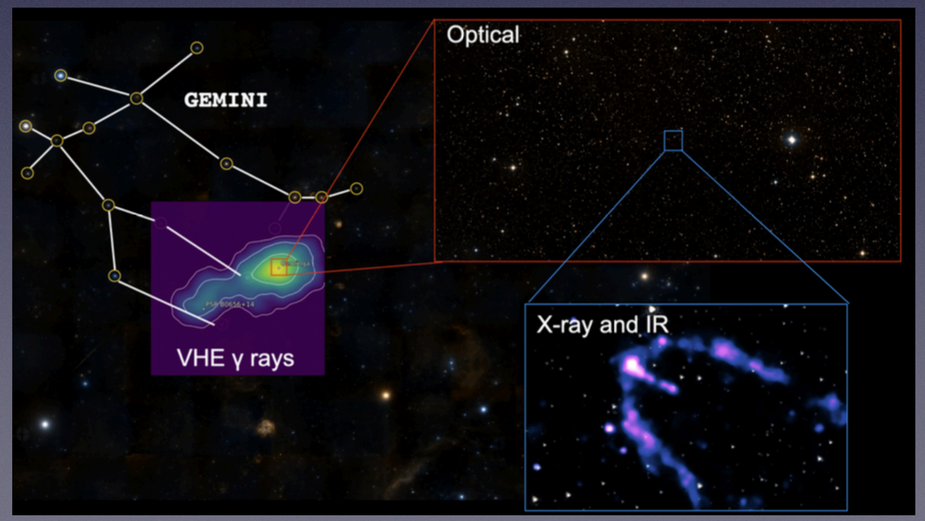
SELF-GENERATED INSTABILITIES
AND MULTI-MESSENGER SIGNATURES

LEARN ABOUT SOURCES AND MAYBE FIND PEVATRONS



[Vercellone et al. 2021]

[Lopez-Coto et al. 2021]



SO FAR

SEMI-ANALYTICAL MODELING OF

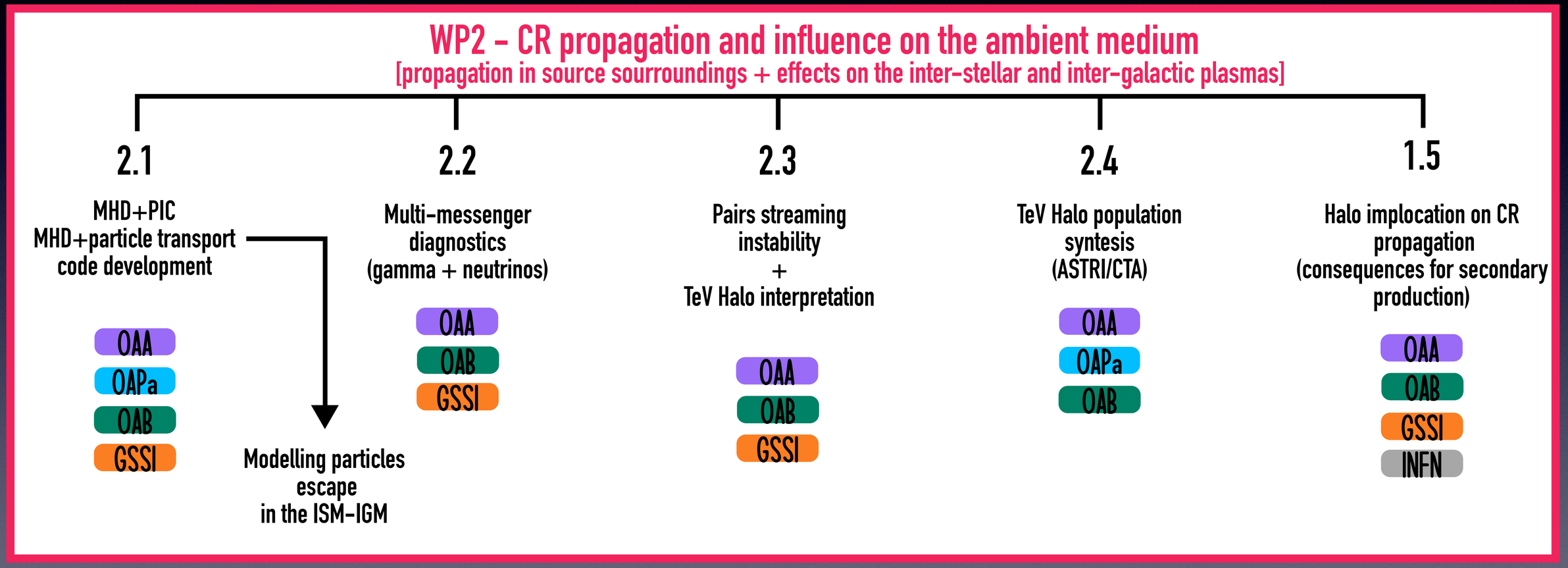
- SNRs [Nava et al. 2016, 2019; D'Angelo et al. 2016, 2018]
- PWNe [OAA + OAB]
- ESCAPE FROM GALAXIES [Blasi & EA 2015, 2019]

NEXT STEP:

NUMERICAL MODELING OF TRANSPORT

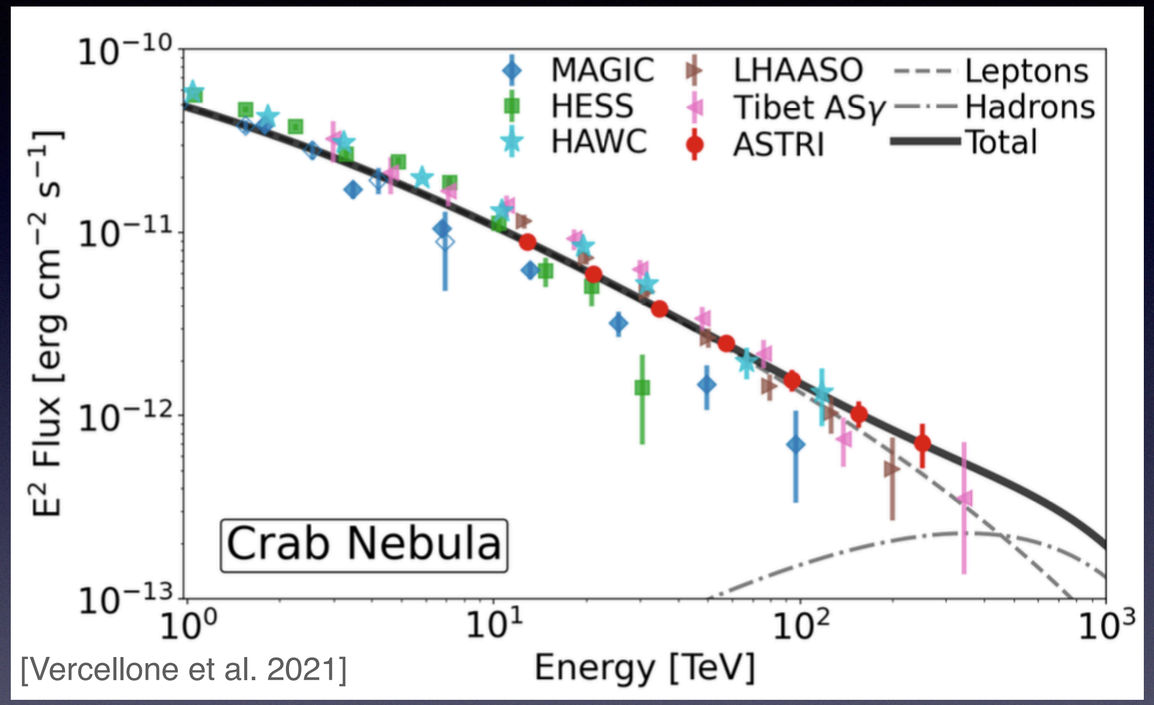
COMPLEX MULTI-SCALE PROBLEM

CR TRANSPORT and IMPACT: WP2



LEPTONIC PEVATRONS: WP3

PWNe: THE MOST NUMEROUS GALACTIC TeV SOURCES



[Vercellone et al. 2021]

THE CRAB NEBULA REACHES PEV ENERGIES

[Abdo et al. 2011, Tavani et al. 2011, Cao et al. 2021]

> NOT CLEAR HOW [e.g. EA 2019]

> NOT CLEAR IF ALSO HADRONS [e.g. EA & Arons 2006]

PSRs IN ALL FIELDS DETECTED BY HAWC BEYOND 100 TeV

[Abeysekara et al. 2020] AND BY LHAASO AT PeV [Cao et al. 2021]

SO FAR:

LONG STORY OF PWN MODELING:

- ONE-ZONE [Bucciantini et al. 2011]
- MHD FROM 1D [EA et al. 2000] TO 3D [e.g. Olmi et al. 2016]
- PIC SIMULATIONS OF SHOCK ACCELERATION [EA & Arons 2006]

NEXT STEPS:

- LONG TERM PWN EVOLUTION
- FIRST RELIABLE ASSESSMENT OF REVERBERATION
- HADRONS AND THEIR SIGNATURES

ACCELERATION in RELATIVISTIC PLASMAs: WP3

WP3 – Acceleration in relativistic plasmas

3.1

Modelling
PWNe+SNRs
(from young to BSPWNe)

OAA
OAPa

3.2

Observability predictions
+
population synthesis (ASTRI/CTA)

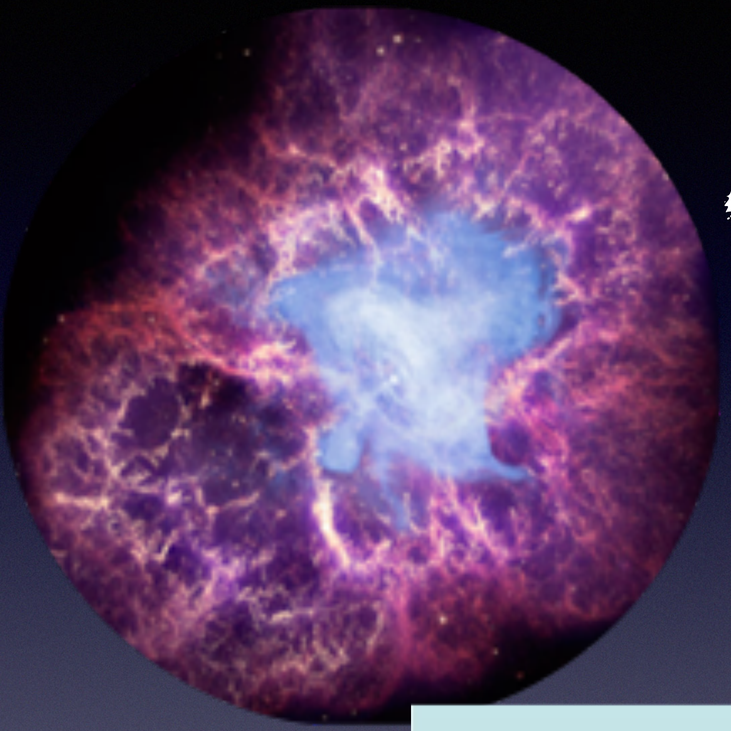
OAA
OAPa

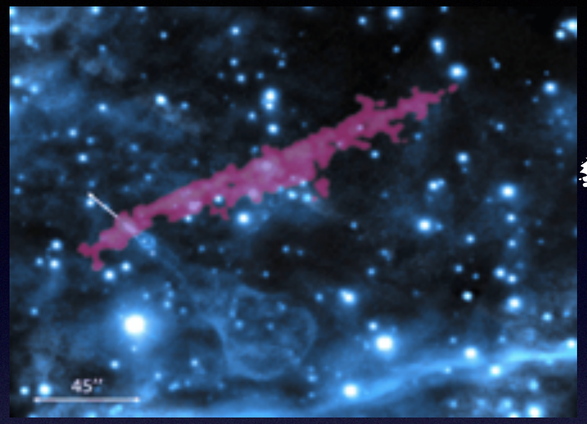
3.3

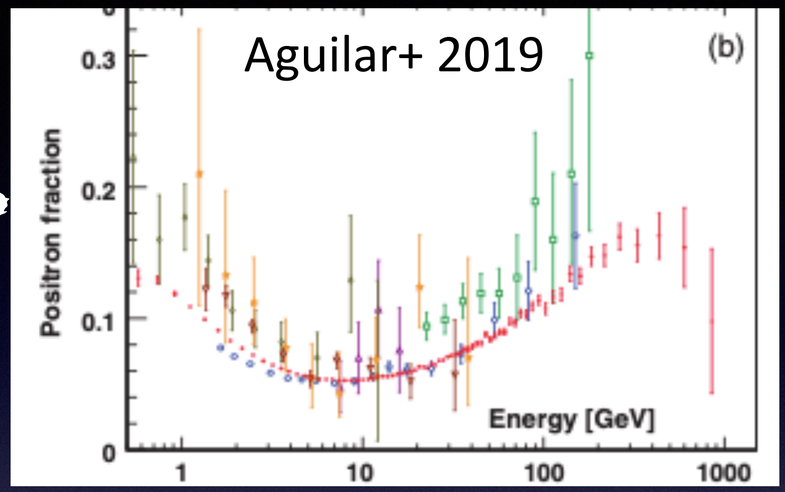
PWNe = PeVatrons?
(search for hadronic candidates)

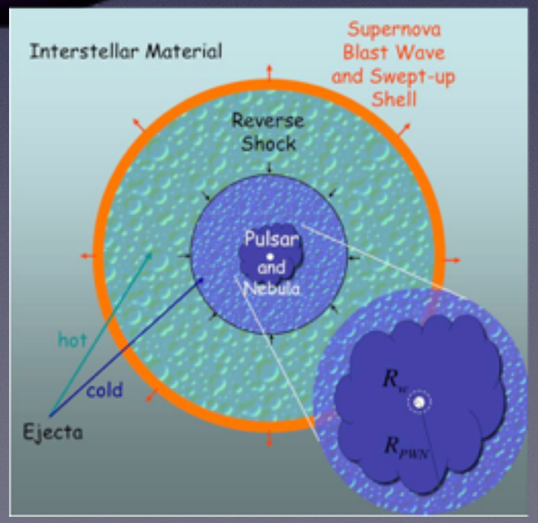
OAA
OAPa

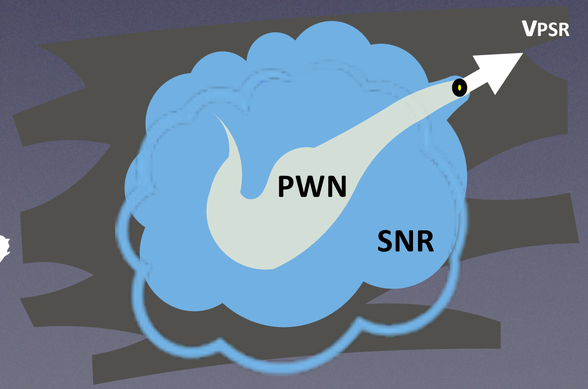
ORIGIN OF COSMIC LEPTONS: WP4



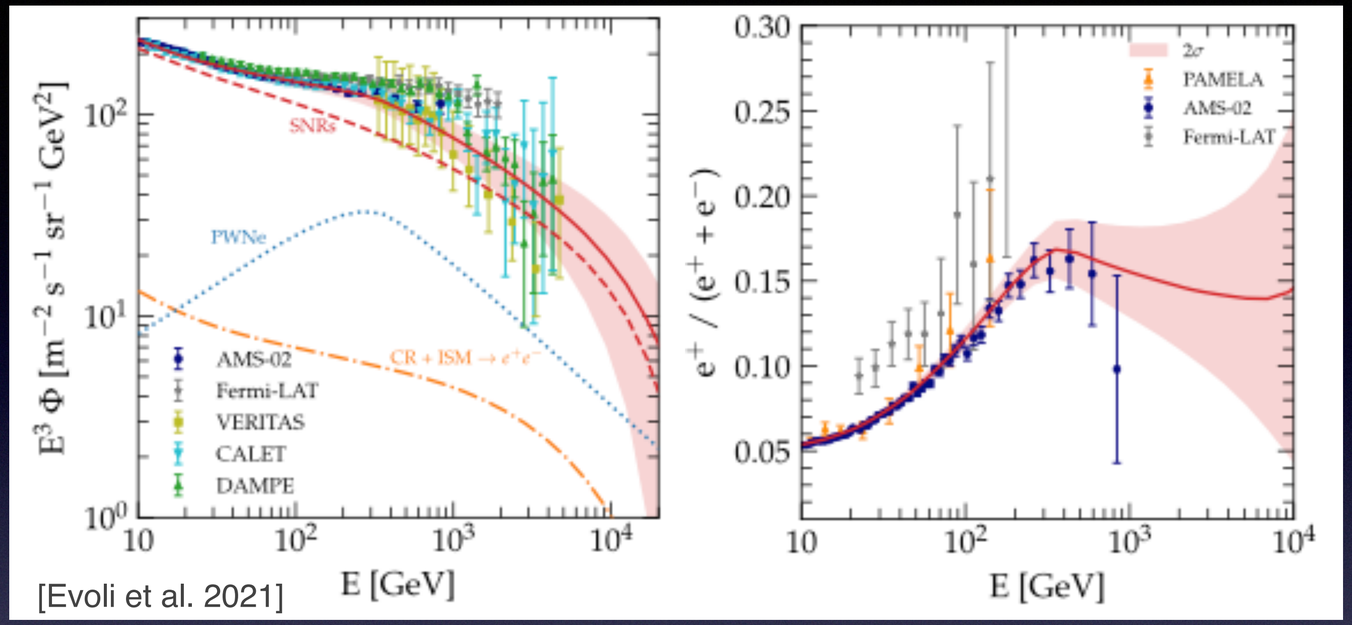




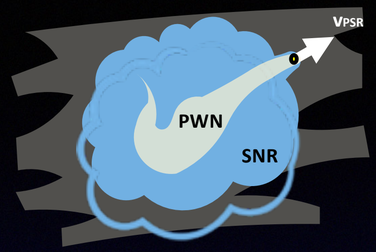




ORIGIN OF COSMIC LEPTONS: WP4

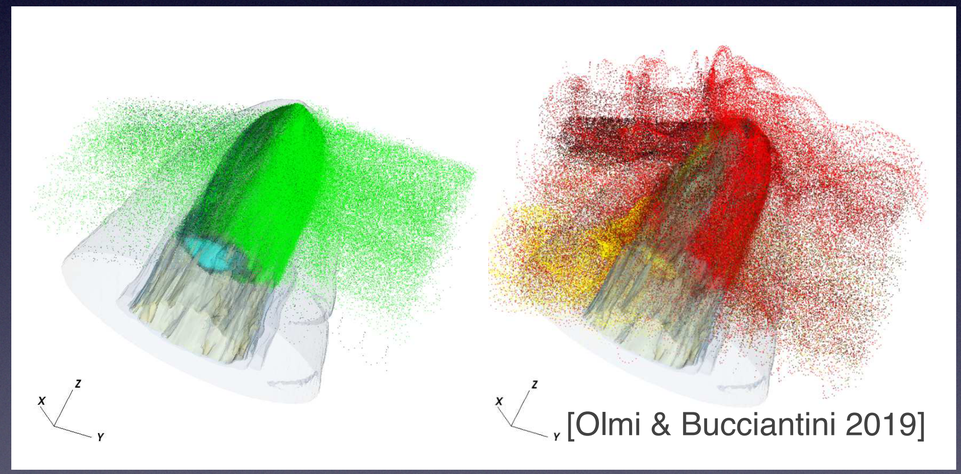


[Evoli et al. 2021]



SO FAR:

EVOLVED PWNe MAJOR CONTRIBUTIONS OF CR POSITRONS [e.g. Evoli et al. 2021] BUT…


[Olmi & Bucciantini 2019]

NEXT STEPS

- ROLE OF PARTICLE ENERGY LOSSES NEVER ASSESSED [Olmi & Torres 2020, OAA + OAPa]
- HALOS TO BE TAKEN INTO ACCOUNT [OAA + GSSI]
- ORIGIN OF HALOS IMPORTANT TO ASSESS HOW COMMON [Evoli, Linden, Morlino 2018; Lopez-Coto et al. 2021]
- RECENT WORK [Olmi & Bucciantini 2019] OPENS POSSIBILITIES OF CURRENT DRIVEN INSTABILITIES [OAA + GSSI]

LEPTONIC PEVATRONS: WP4

WP4 – Origin of cosmic leptons

4.1

Energetic evolution of nebular plasmas
(from the acceleration at the TS to the release in ISM)

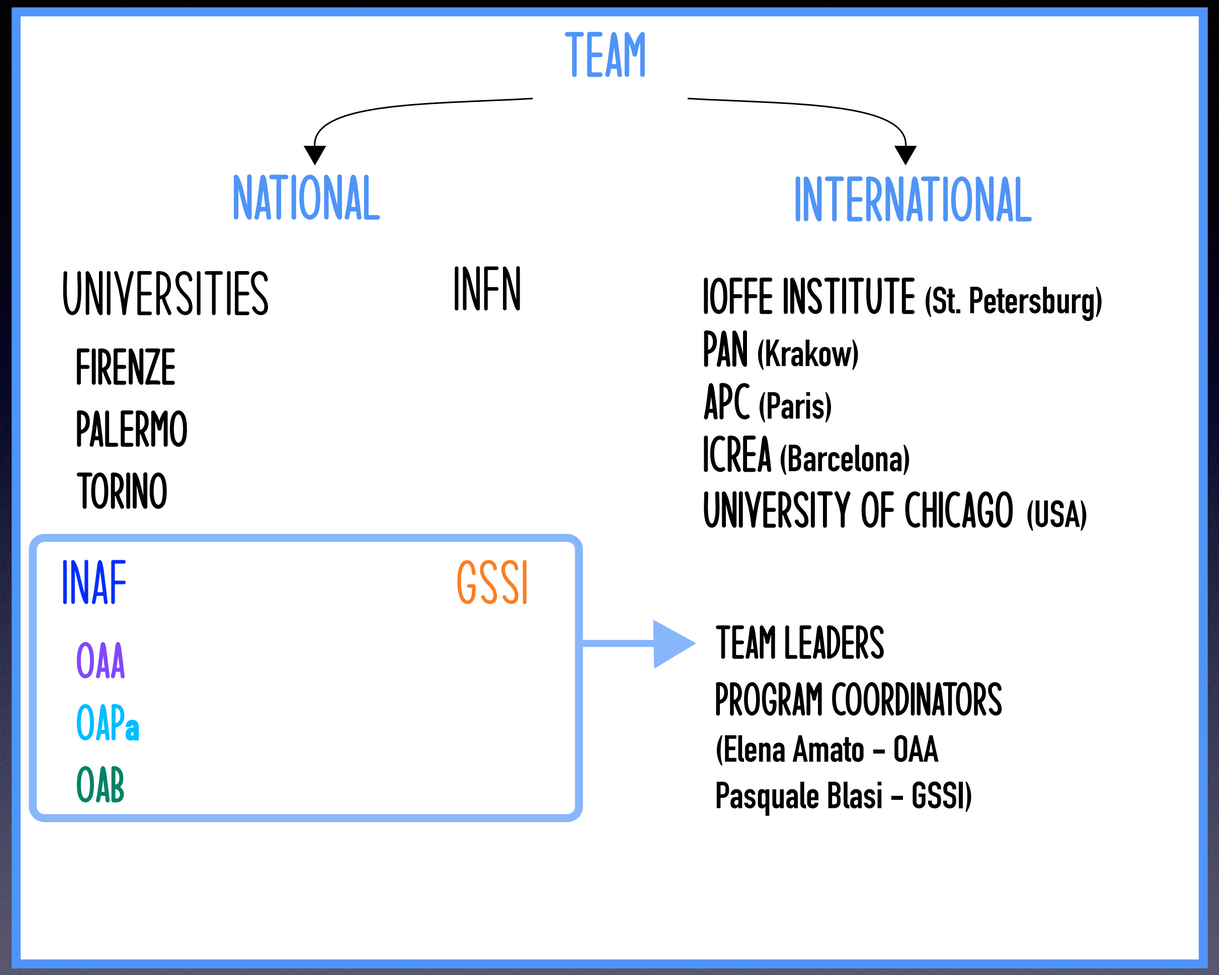
OAA
OAPa

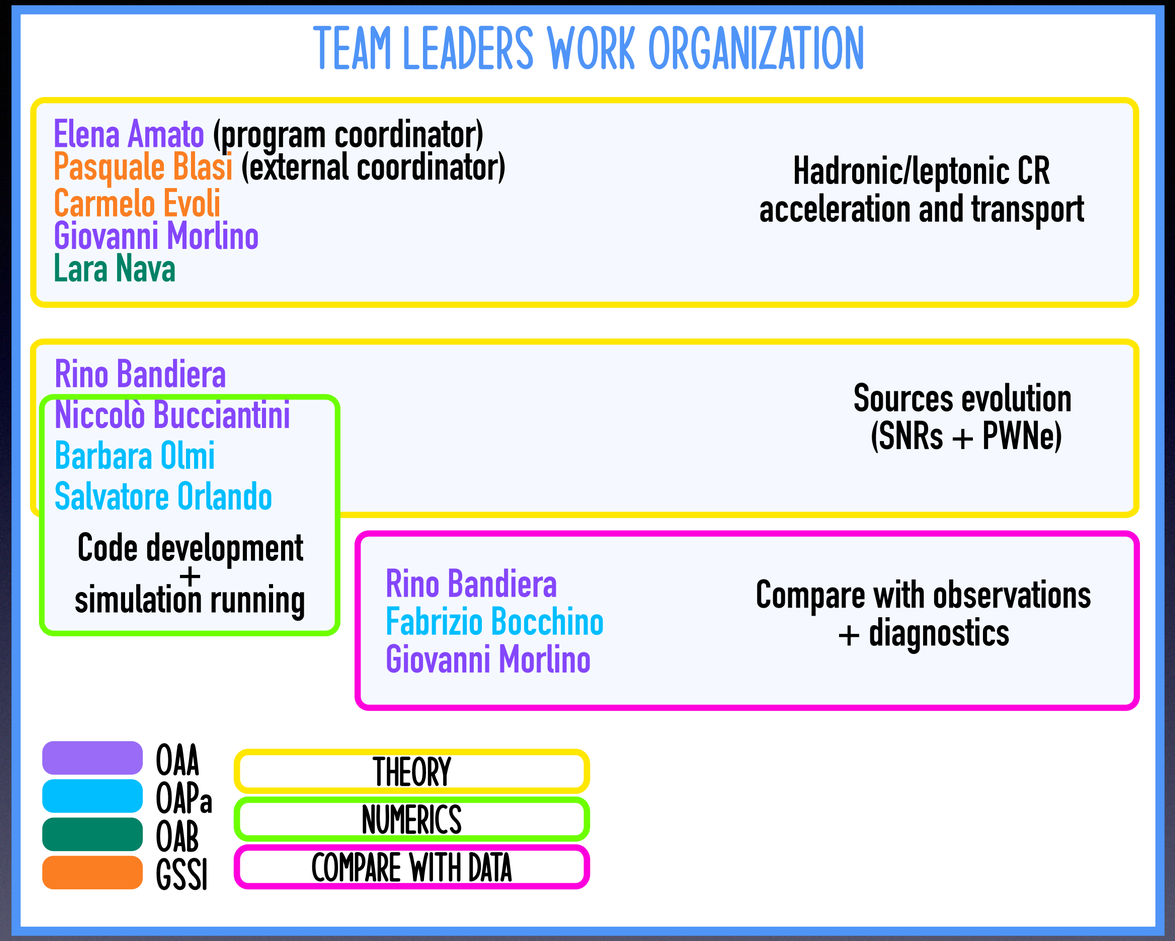
4.2

Leptons propagation in the ISM
+
PWNe contribution to cosmic leptons

OAA
GSSI

TEAM ORGANIZATION AND INAF LEADERSHIP





- CONSTANT FEEDBACK ON AND FROM THE ASTRI AND CTA COLLABORATIONS
- COORDINATION OF CTA SCIENCE WORKING GROUPS ON CRs (Amato former, Morlino current) AND GALACTIC SCIENCE (Olmi)
- MEMBERS OF THE EDITORIAL BOARD OF RELEVANT ASTRI AND CTA PUBLICATIONS

INAF TEAM COMPOSITION

OA ARCETRI

		FTE 21	FTE 22	FTE 23	TOT 21	TOT 22	TOT 23
TI	E. Amato	0,4	0,4	0,4	1,7	1,7	1,7
	R. Bandiera	0,4	0,5	0,3			
	N. Bucciantini	0,4	0,3	0,4			
	G. Morlino	0,5	0,5	0,6			
	M. Padovani	0	0	0			
	L. Del Zanna	0,2	0,2	0,2	0,2	0,2	0,2
TD	S. Menchiari	0,5	0,5	0,6	1,1	0,5	0,6
	J. Soldateschi	0,3					
	N. Tomei	0,3					
					3,0	2,4	1,9

OA PALERMO

		FTE 21	FTE 22	FTE 23	TOT 21	TOT 22	TOT 23
TI	S. Orlando	0,1	0,1	0,2	0,6	0,6	0,5
	F. Bocchino	0,1	0,1	0,2			
	B. Olmi	0,4	0,4	0,5			
	M. Miceli	0,1	0,1	0,2	0,1	0,1	
TD	E. Greco	0,1			0,25	0,1	0,6
	S. Ustamujic	0,15	0,1				
					0,95	0,8	0,5

OA BRERA

		FTE 21	FTE 22	FTE 23	TOT 21	TOT 22	TOT 23
TI	L. Nava	0,25	0,25	0,25	0,35	0,35	0,35
	F. Tavecchio	0,1	0,1	0,1			
TD	C. Righi	0,2	0,2		0,2	0,2	
					0,55	0,55	0,35

OTHERS

		FTE 21	FTE 22	FTE 23	TOT 21	TOT 22	TOT 23
IRA BO	G. Brunetti		0,2	0,2	0,2	0,2	0,2
OA PD	M. Fiori	0,1	0,1	0,1			
OA TO	A. Mignone	0,1	0,1	0,1			
					0,2	0,2	0,2

INAF TOTAL 2016-2025: **40 FTE**

INAF TOTAL TI 2016-2025: 25 FTE

GRAND TOTAL 2016-2025: 60 FTE

RESULTS (in 2016-2020)

PUBLICATIONS

- ✓ 118 ARTICLES in PEER-REVIEWED INTERNATIONAL JOURNALS
- ✓ 25 CONFERENCE PROCEEDINGs

CONFERENCES

- ✓ 53 INVITED TALKs
- ✓ 26 CONTRIBUTED TALKs
- ✓ 20 PARTICIPATIONS in SOC of INTERNATIONAL CONFERENCEs

OUTREACH and EDUCATION

- ✓ UNIVERSITY and PHD COURSES @ UNIFI, UNISI, SISSA
- ✓ LECTUREs for HIGH SCHOOL STUDENTs and TEACHERs on HIGH ENERGY ASTROPHYSICs
- ✓ SCIENCE OUTREACH EVENTs on SN EXPLOSIONs, COSMIC RAYs, GAMMA RAYs
- ✓ ENRICHMENT of CR OUTREACH ACTIVITY of OAA (20 keuro private donation)

FUNDS

ORIGIN	SECURED 2021	SECURED 2022	SECURED 2023	PRESUMED 2021	PRESUMED 2022	PRESUMED 2023
ASI	11,5	0	0	0	0	0
INAF-MAINSTREAM	9,5	0	0	0	0	0
INAF PRIN 2019	20	16	0	0	0	0
MIUR	0	0	0	0	100	100
TOTAL	58			200		

INAF TOTAL 2016-2020: 130 kEURO

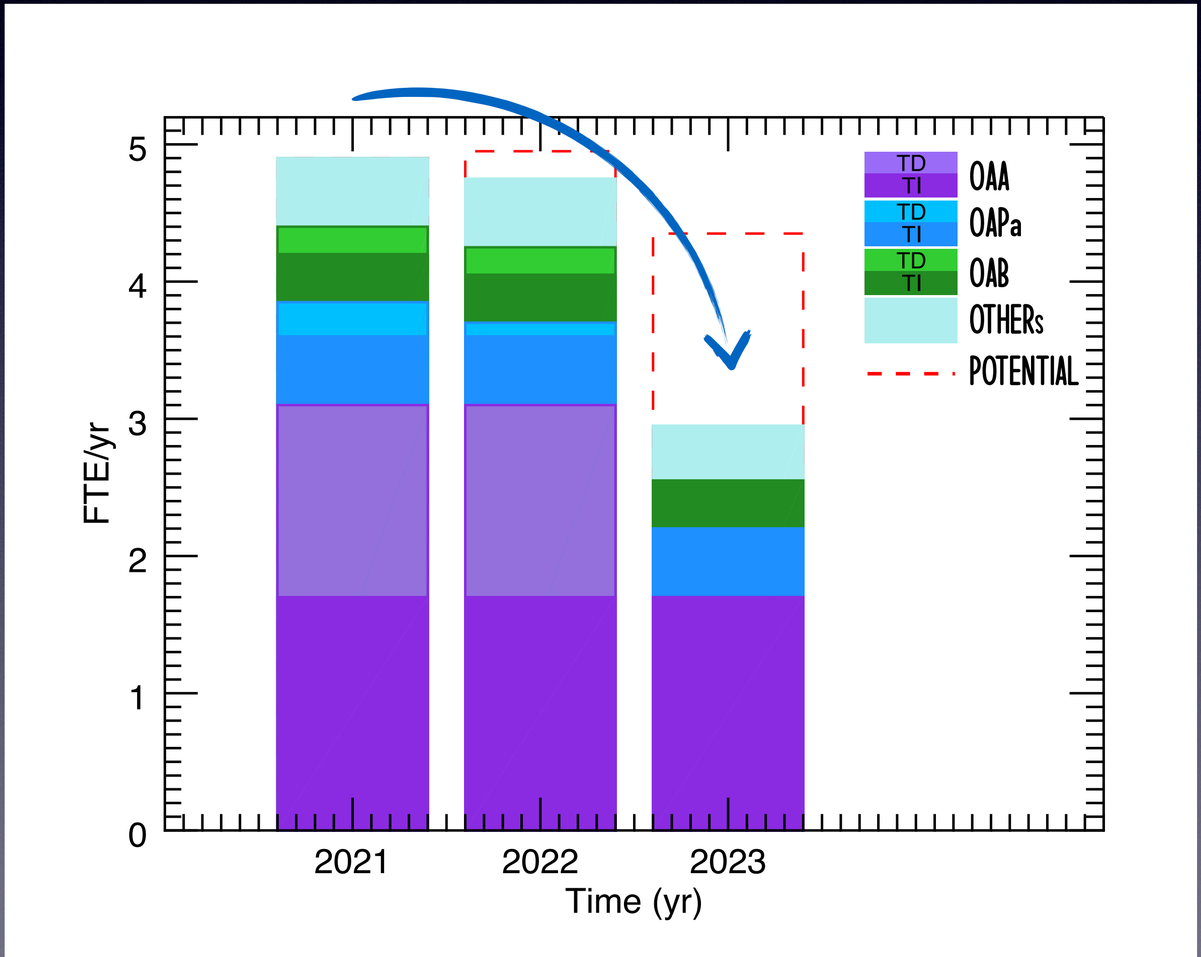
INAF TOTAL 2016-2025: **600 kEURO**

GRAND TOTAL 2016-2025: 1000 kEURO

NEEDS/CRITICALITIES

(1) MAN POWER, MAN POWER, MAN POWER!!!

FTE evolution 2021-2023



(2) SECURE-FREE-RAPID ACCESS to COMPUTATIONAL RESOURCES

(3) LARGE DATA STORAGE

PROSPECTS

CRs
PWNe
HIGH ENERGY OBSERVATIONS

RIGHT NOW
LIKELY THE BEST QUIPPED TEAM WORLDWIDE
TO MAKE SIGNIFICANT PROGRESS ON THESE QUESTIONS