CTA: GALACTIC SCIENCE

BARBARA OLMI

INAF -OAA

CTA – GALACTIC KSP

(1) GALACTIC PLANE SURVEY

SURVEY OF THE GP IN FEW GEV – 300 TEV RANGE, WITH UNPRECEDENTED RESOLUTION/SENSITIVITY

SYNTHETIC GPS:

- MANY DIFFERENT SYNTHETIC POPULATIONS (SNR + ISNR, PWNE, GAMMA-RAY BINARIES)
- DIFFUSE EMISSION
- KNOWN SOURCES – FROM GAMMA-CAT, 3FHL, 3HWC, LHAASO (REFINED TEMPLATES)
- SAMPLE OF KNOWN PULSAR/BINARIES –TEMPORAL PROFILES

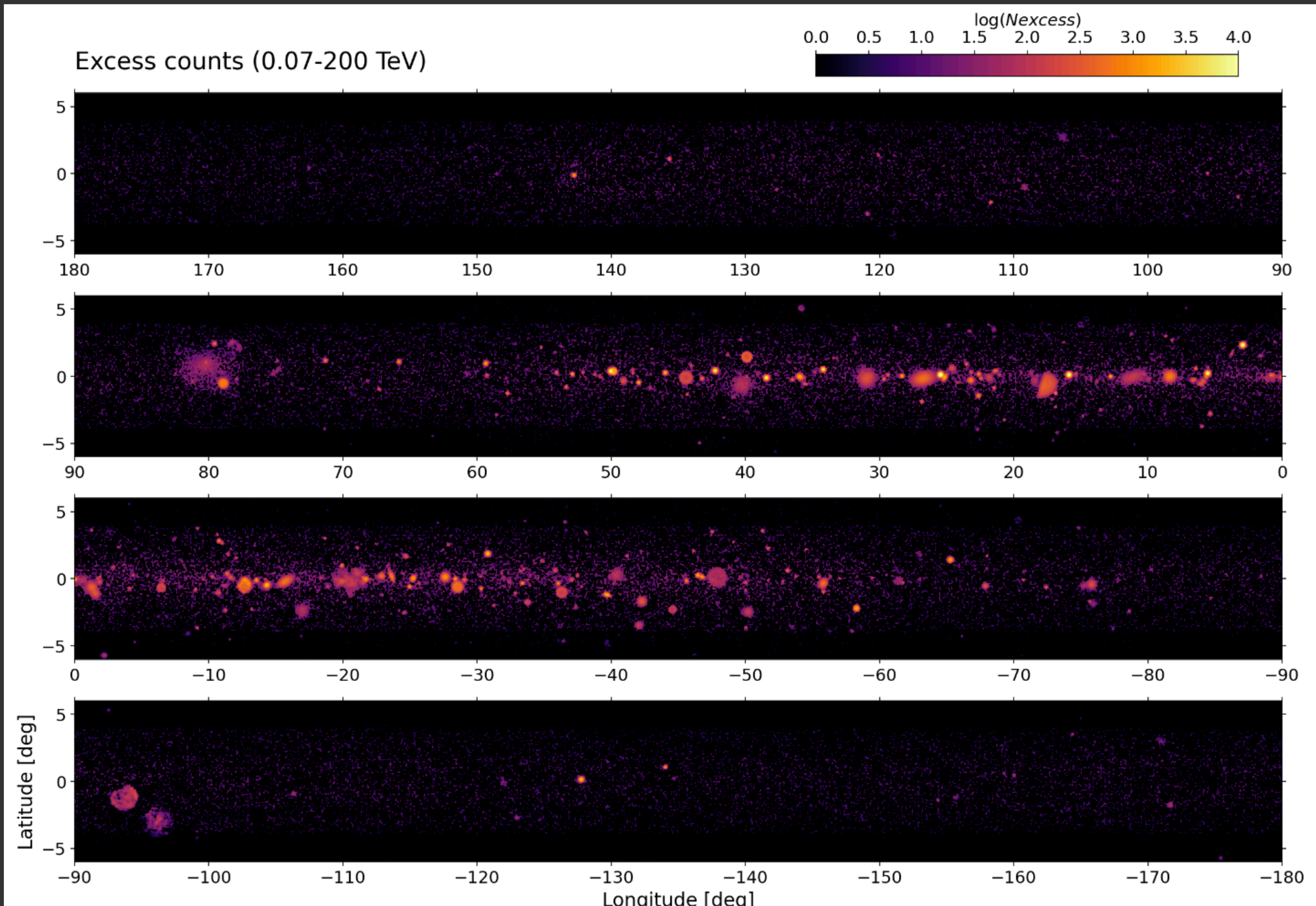
(2) PEVATRONS

KSP DEFINED BEFORE LHAASO (DATED BACK TO 2018) –> UPDATES UNDER DISCUSSION

PEVATRONS PAPER –> FOCUS ON HADRONIC PEVATRONS AND THEIR HE SPECTRAL SIGNATURES

- DEFINITION OF SELECTION CRITERIA BASED ON CUT-OFF IDENTIFICATION

(1) GPS SYNTHETIC GALACTIC PLANE SURVEY



Q. REMY ET AL. 2021

OF SOURCES WITH
TS > 25 IN 0.07–200 TEV

TYPE	#DETECTABLE	#DETECTED
PWN	294	241–257
SNR	37	16–31
ISNR	24	20–14
BINARY	10	10
KNOWN	134	111–122

UP TO 500 SOURCES DETECTABLE ~ x6 HESS-GPS, 3HAWKC

DOMINANT POPULATIONS

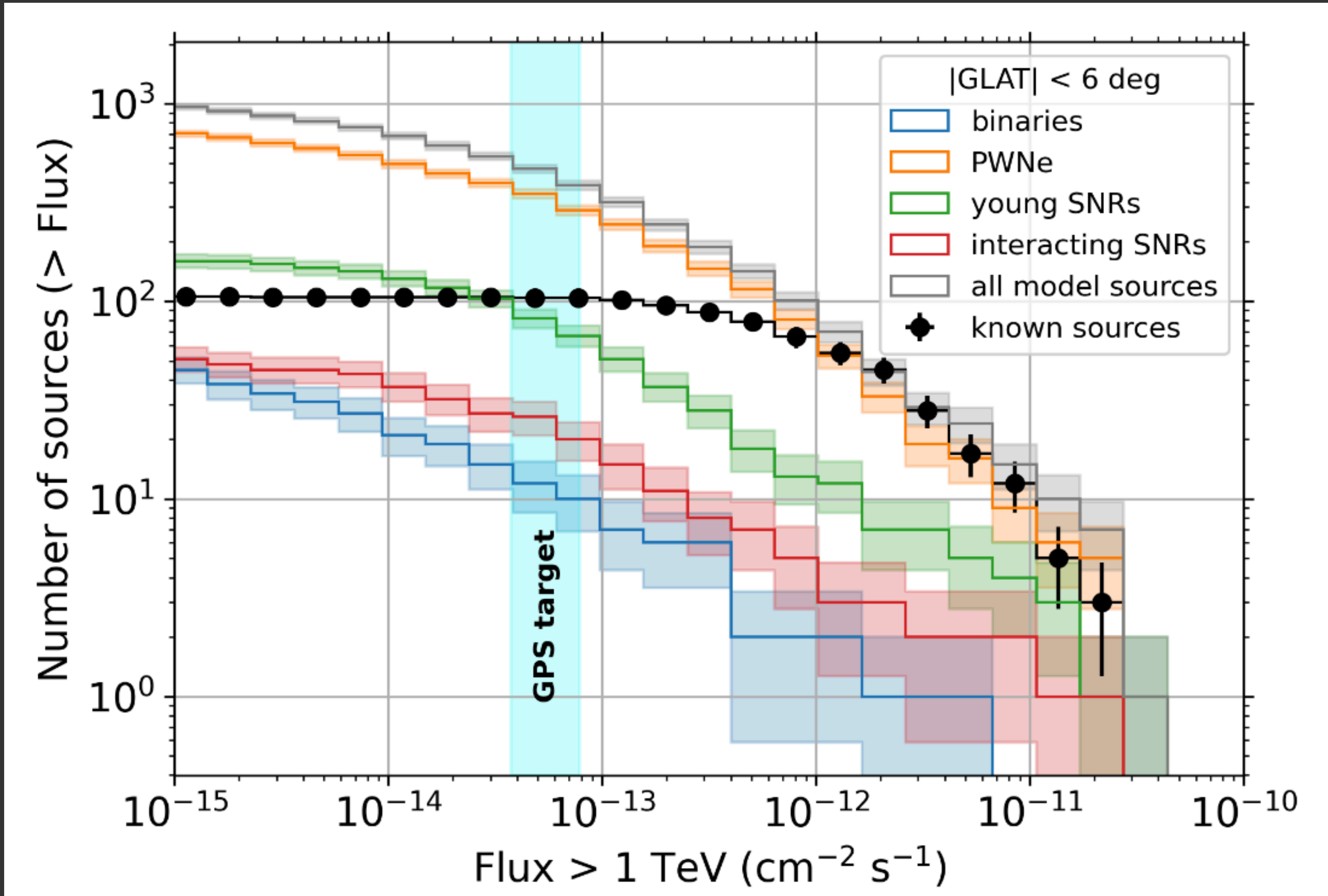
~ 60% PWNe –> ~ 250 NEW DETECTIONS EXPECTED

≲ 10% SNRs –> ~ x2 FACTOR IN DETECTED SNRS

SYNTHETIC MODELS

PARAMETERS OF THE POPULATIONS TUNED TO REPRODUCE THE OBSERVED logN-logS DISTRIBUTION AT HIGH ENERGIES

CAVEAT: UNIDENTIFIED SOURCES ARE SUPPOSED TO BE MOSTLY PWNE



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PWN – THE LARGEST CLASS

THEIR MODELING IS FUNDAMENTAL FOR THE INTERPRETATION OF UPCOMING DATA

INGREDIENTS TO GENERATE THE POPULATION:

- DISTRIBUTION OF CORE-COLLAPSE SNRS IN THE GALAXY
- PULSAR POPULATION (SPATIAL DISTRIBUTION, P_0, $\dot{E}_0$, B)

INITIAL POPULATION (T=0 YR)

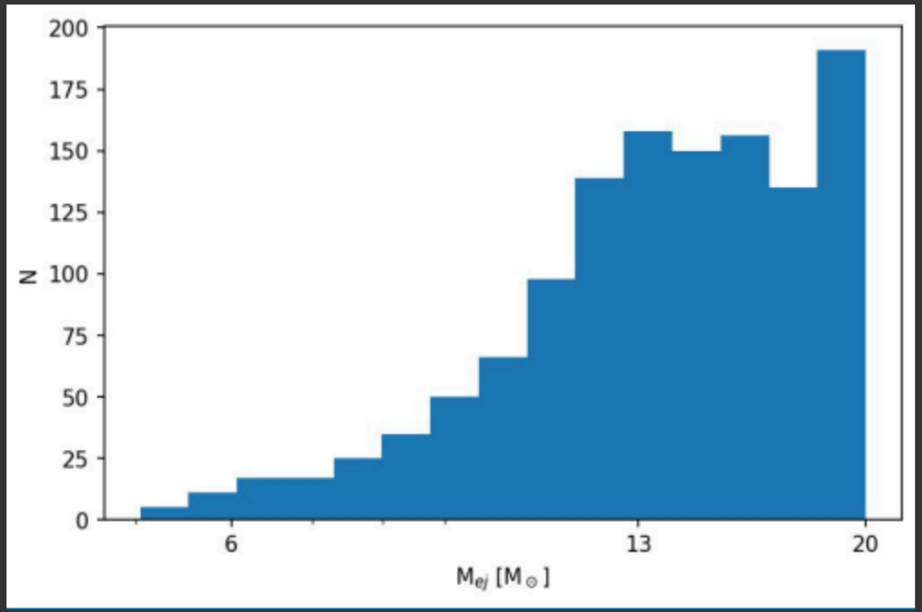
- EVOLVE THE POPULATION

1. SIMULATE DYNAMIC EVOLUTION OF EACH SNR/PWN FOR LONG TIMES (T_{FINAL} FOR GPS $=10^5$ YR)
2. SIMULATE RADIATIVE EVOLUTION OF SINGLE SPECTRA AT MULTI-WAVELENGTH

FINAL POPULATION ($T=T_{FINAL}$)

CORE-COLLAPSE SNRS

SPATIAL DISTRIBUTION + MODEL OF THE GALAXY FROM FAUCHER-GIGUERE & KASPI 2006

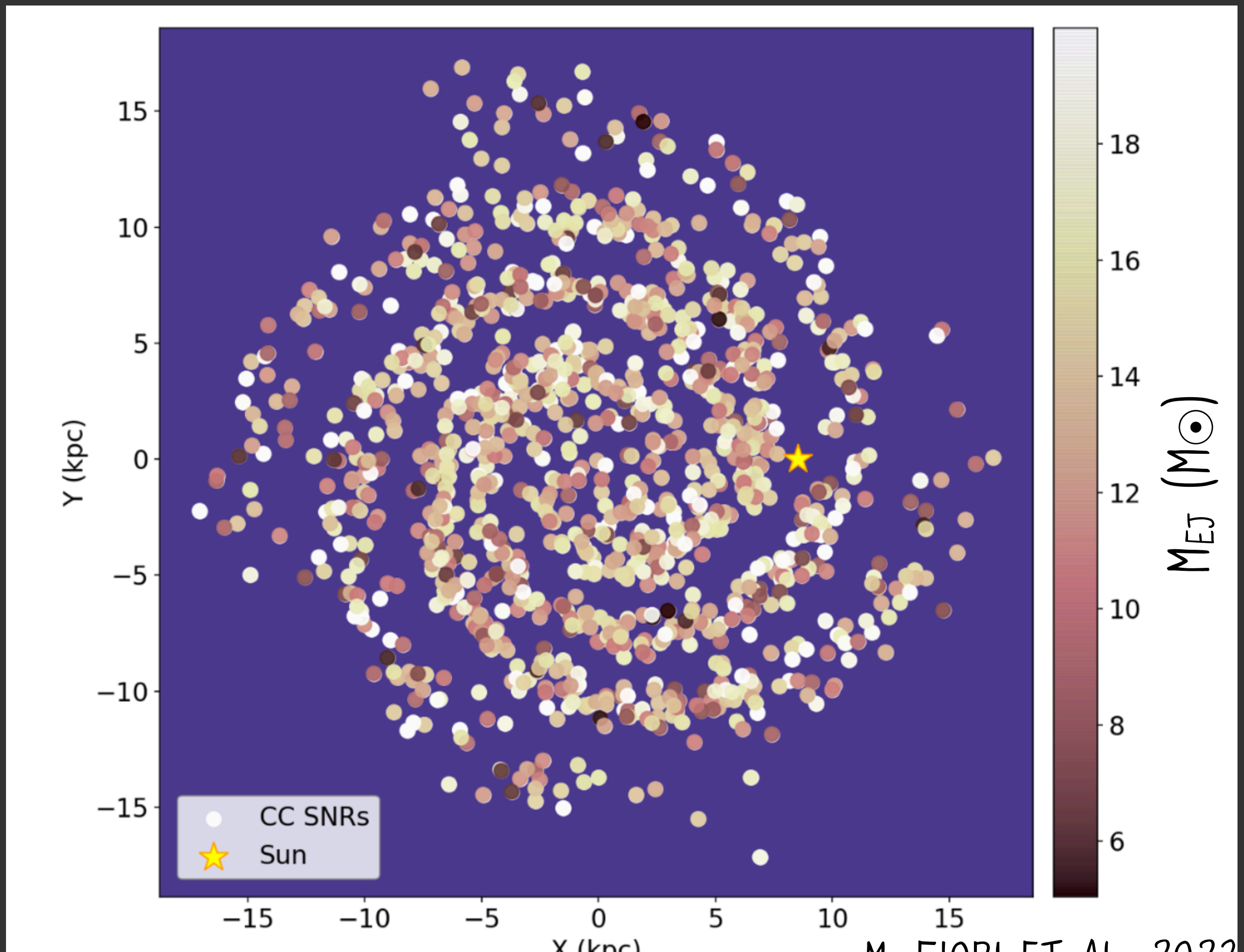


DISTRIBUTION OF MASS IN THE EJECTA
(ASSUMED RANGE 5-20 $M_\odot$ –SMARTT ET AL. 2009)

NORMAL DISTRIBUTION WITH:
$\langle M_{EJ} \rangle$=13 $M_\odot$

$\sigma_{M_{EJ}}$=3 $M_\odot$

TRUNCATED AT 20 $M_\odot$



M. FIORI ET AL. 2022

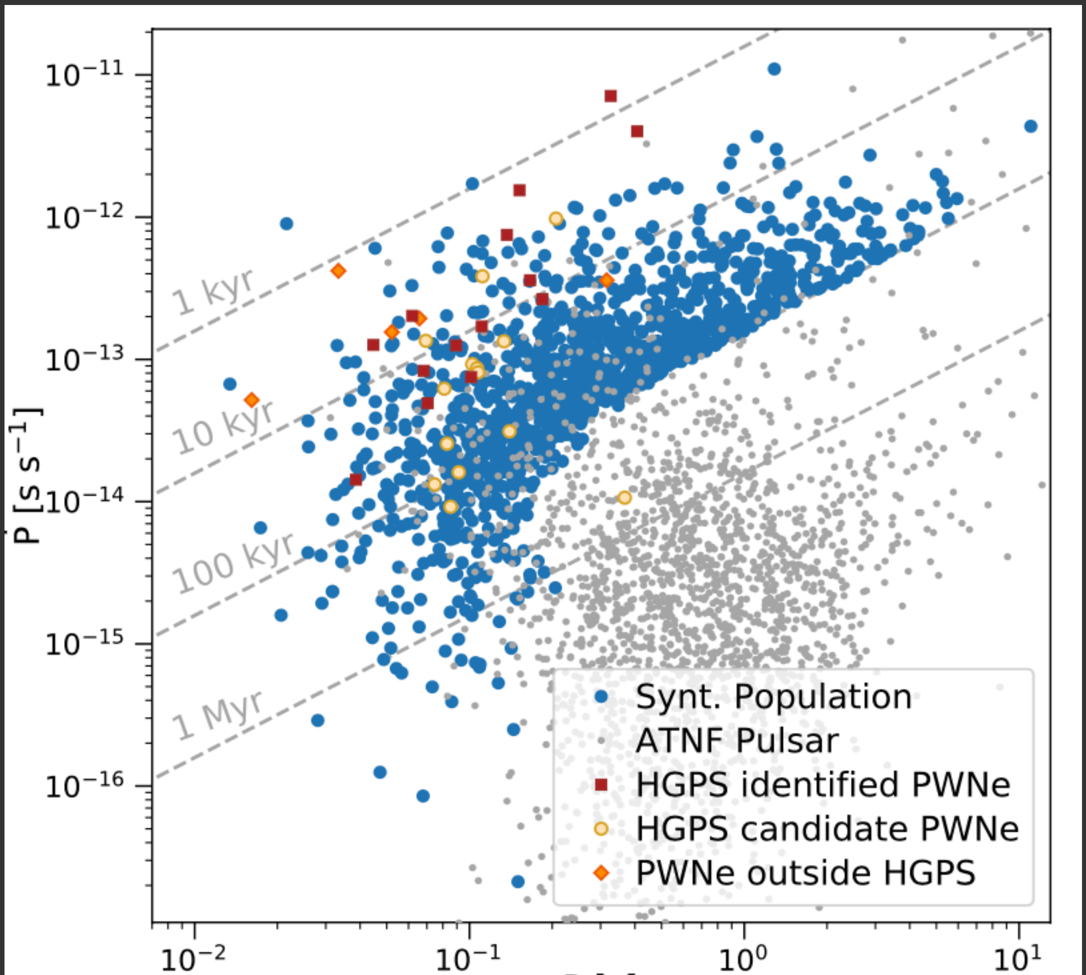
SNR MODELED AS IN CRISTOFARI ET AL. 2017

GENERATING PULSAR WIND NEBULAE

PULSAR POPULATION FROM WATTERS & ROMANI 2011 (GAMMA-RAY PULSARS)
CHARACTERIZED BY:

- FIXED BRAKING INDEX (PURE DIPOLE): n=3
- MAGNETIC FIELD: logNormal with <logB>=12.65, $\sigma_{<logB>}$=0.55
- INITIAL SPIN-DOWN PERIOD: $<P_0>$ = 50 ms, $\sigma_{<P0>}$=50 ms (truncated at 10 ms)
- PULSAR KICK VELOCITY: DOUBLE SIDED EXP WITH <V>= 380 km/s

SAMPLE OF ~ 1300 OBJECTS



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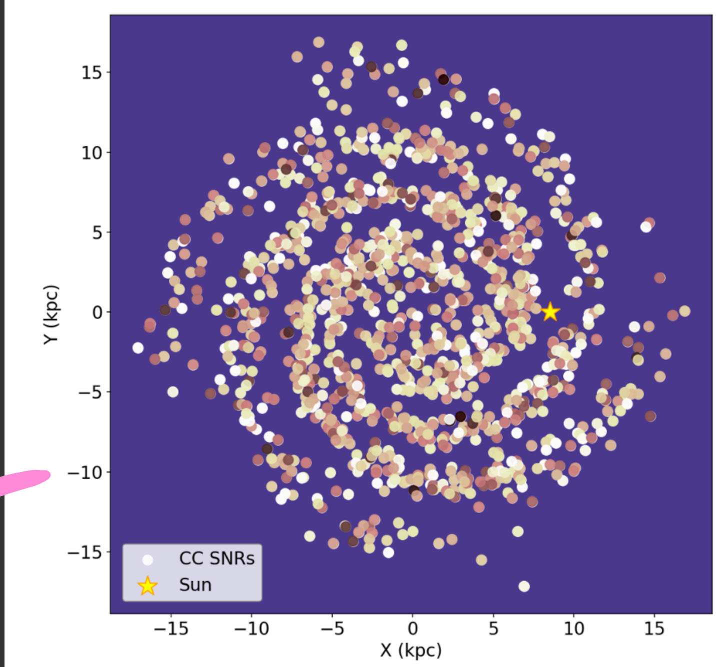
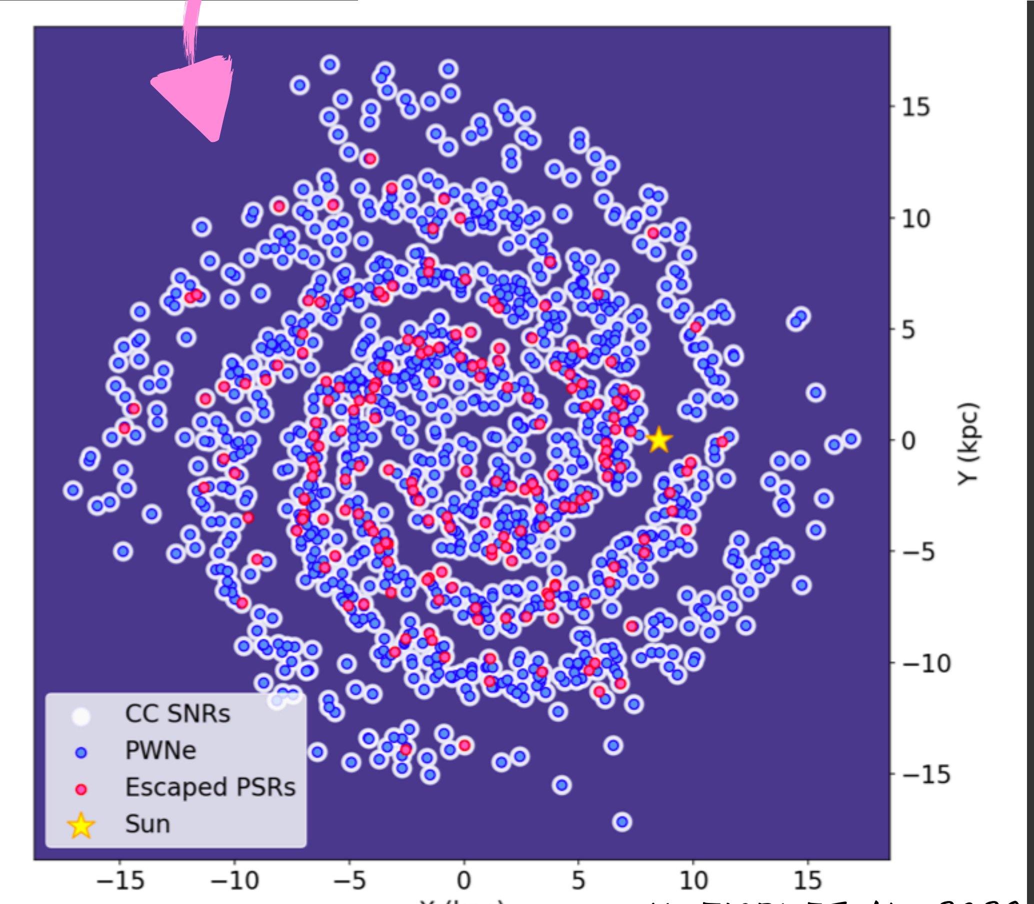
RANDOM ASSOCIATION
SNR – PULSAR





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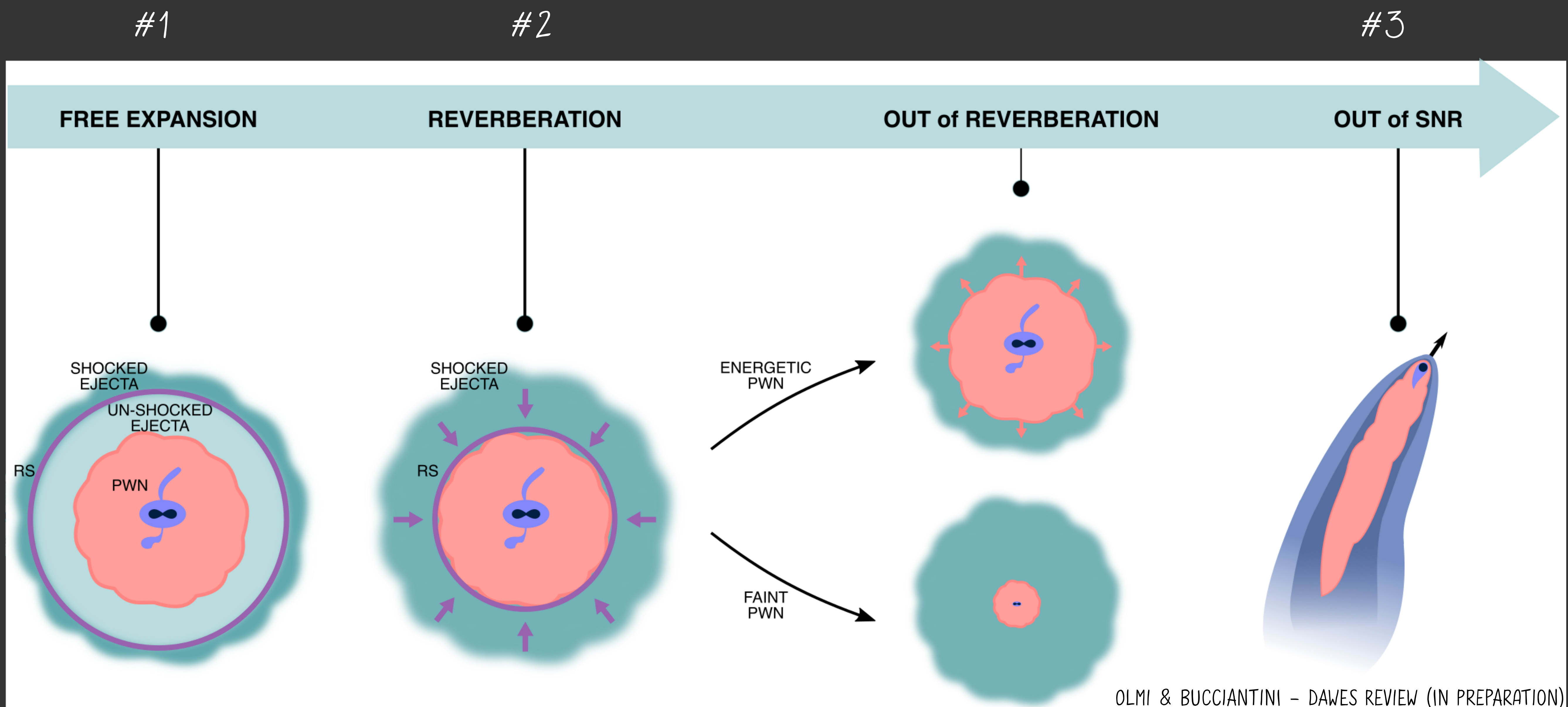
EVOLVING PULSAR WIND NEBULAE

THE DIFFERENT PHASES OF PWN EVOLUTION



OLMI & BUCCIANTINI – DAWES REVIEW (IN PREPARATION)

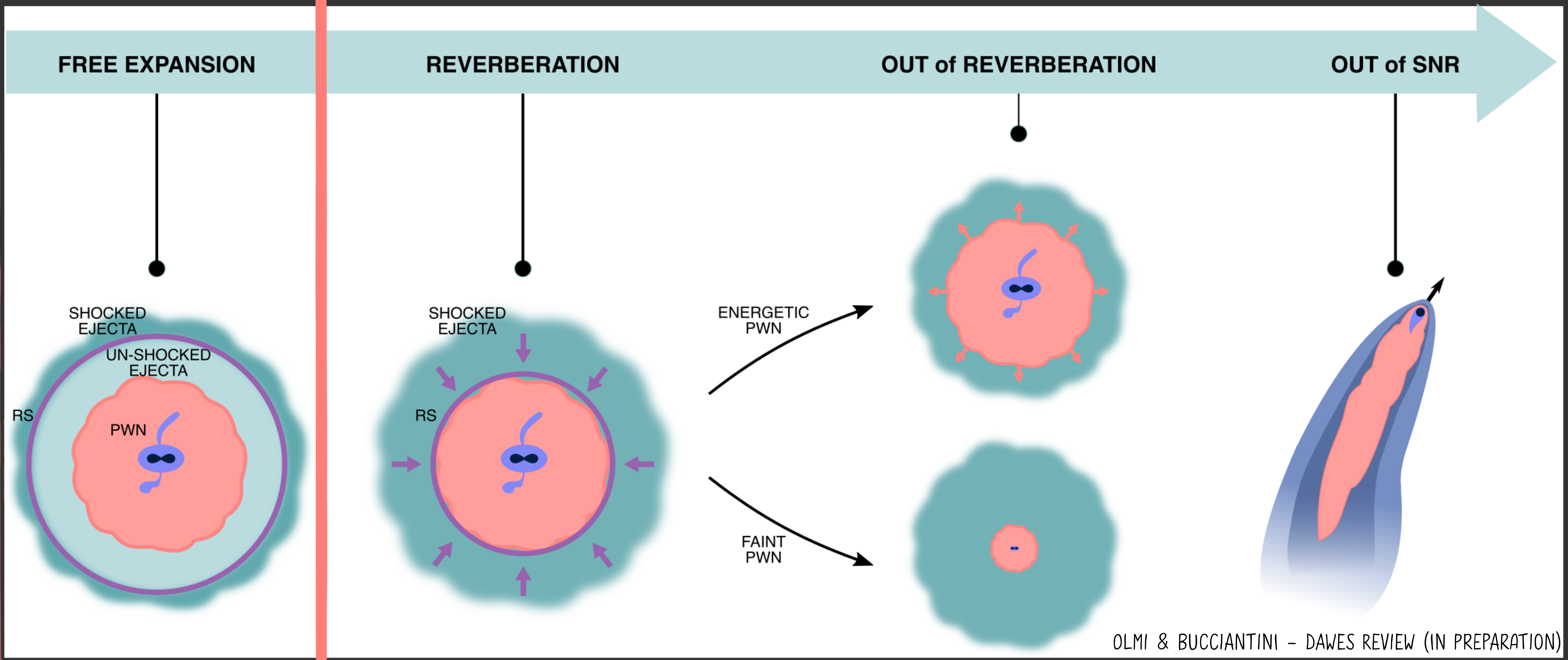
EVOLVING PULSAR WIND NEBULAE

THE DIFFERENT PHASES OF PWN EVOLUTION

#1

#2

#3



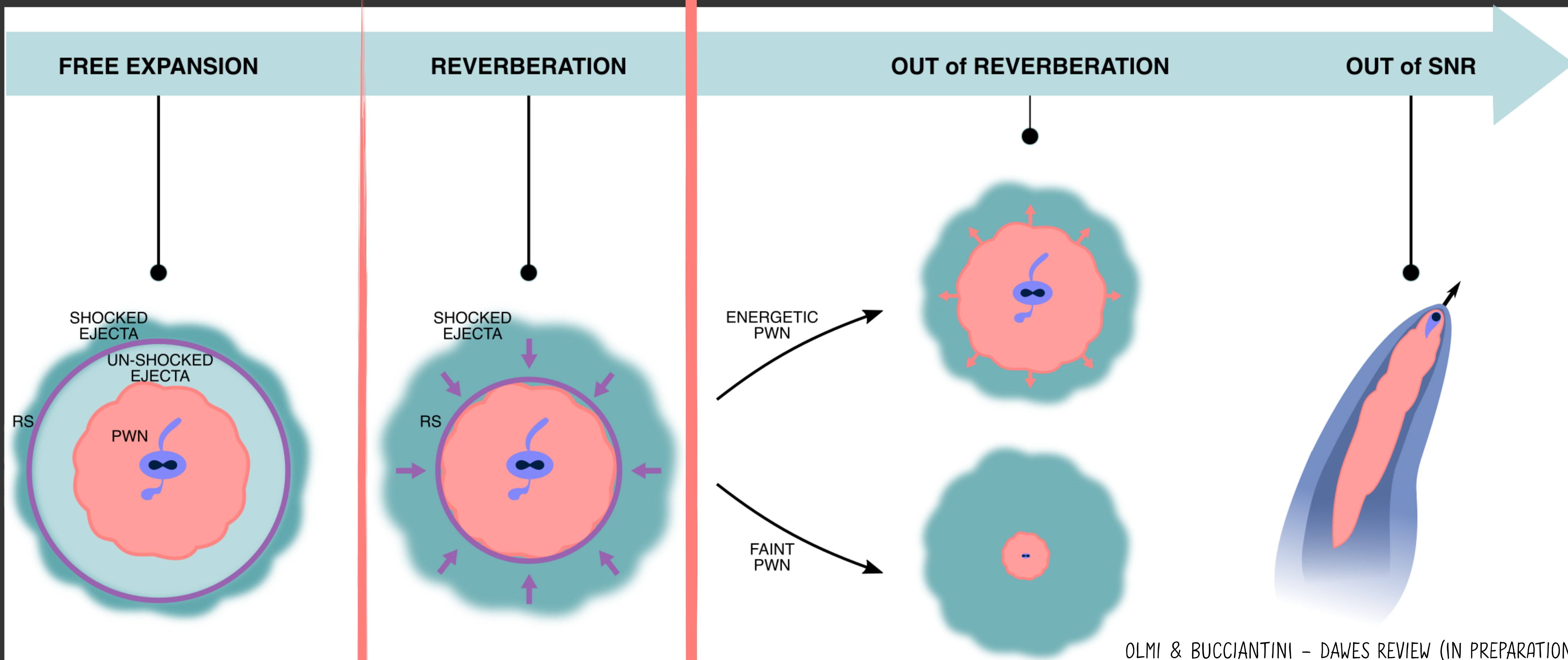
ONE ZONE MODELS
GOOD DESCRIPTION

(GELFAND ET AL. 2009,
BUCCIANTINI ET AL. 2011,
MARTIN ET AL. 2012)

EVOLVING PULSAR WIND NEBULAE

THE DIFFERENT PHASES OF PWN EVOLUTION

#1 #2 #3



CRITICAL

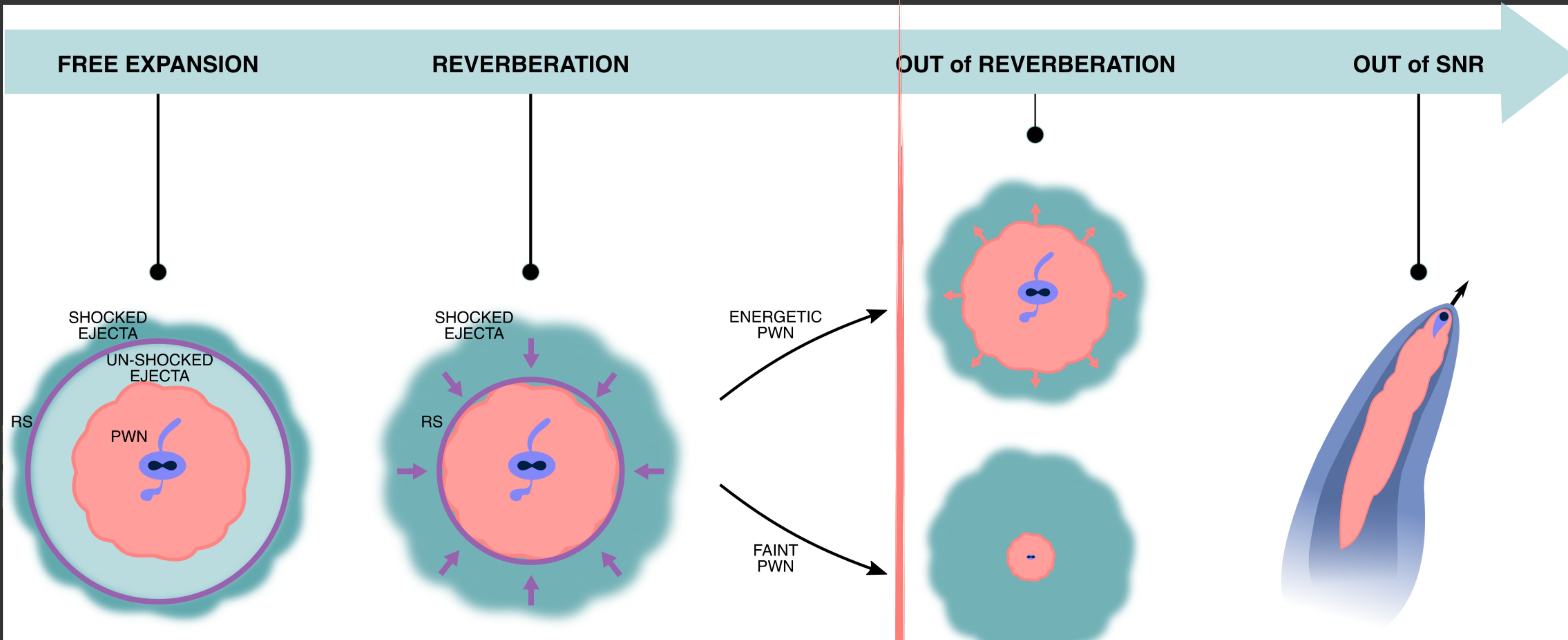
NOT PROPERLY ACCOUNTED FOR IN THE PAST

(FIRST ATTEMPT IN FIORI ET AL. 2022)

EVOLVING PULSAR WIND NEBULAE

THE DIFFERENT PHASES OF PWN EVOLUTION

#1 #2 #3



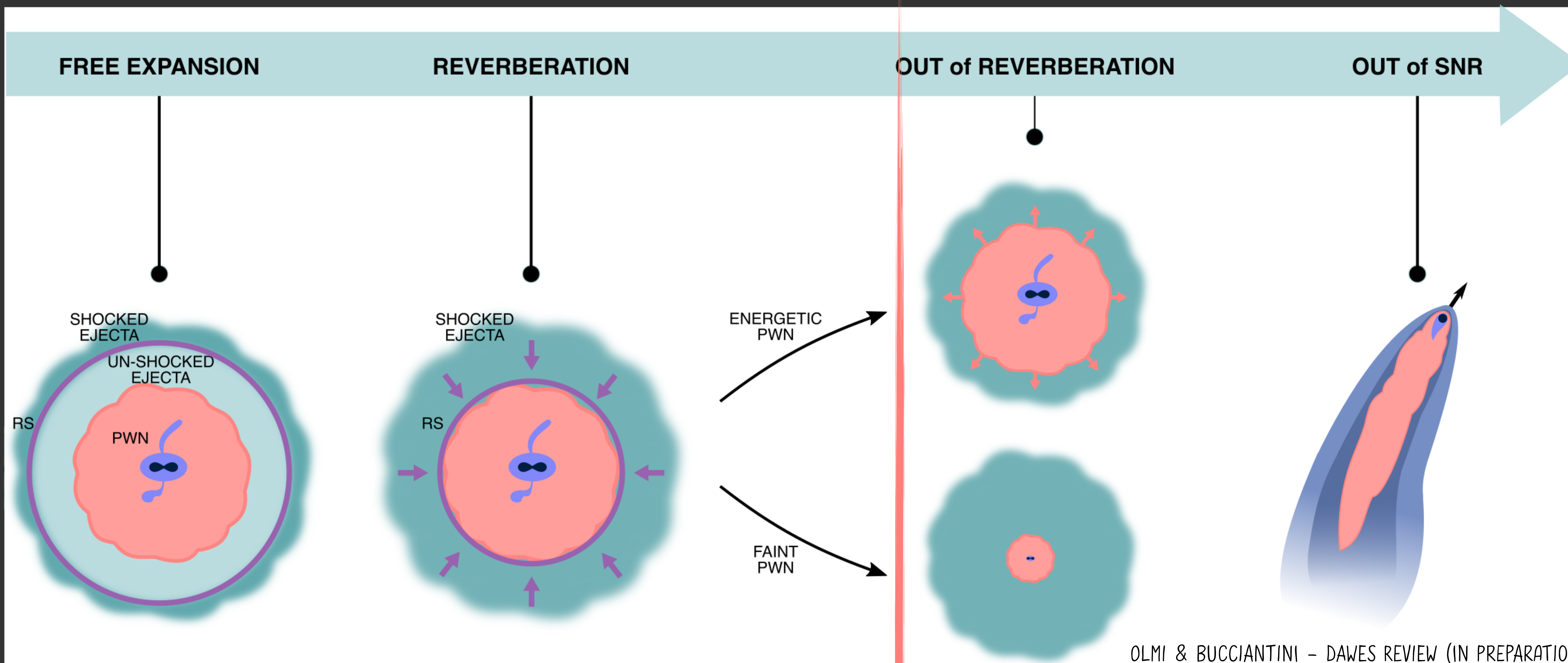
OLMI & BUCCIANTINI – DAWES REVIEW (IN PREPARATION

TRANSITION (COMPLEX PHASE)
+ OLD SYSTEMS (BOW SHOCKS)

EVOLVING PULSAR WIND NEBULAE

THE DIFFERENT PHASES OF PWN EVOLUTION

✓ GAMMA RAYS — #1
✓ GAMMA RAYS — #2
✗ GAMMA RAYS — #3



EVOLVED SYSTEMS NOT DETECTED AT GAMMA-RAYS SO FAR

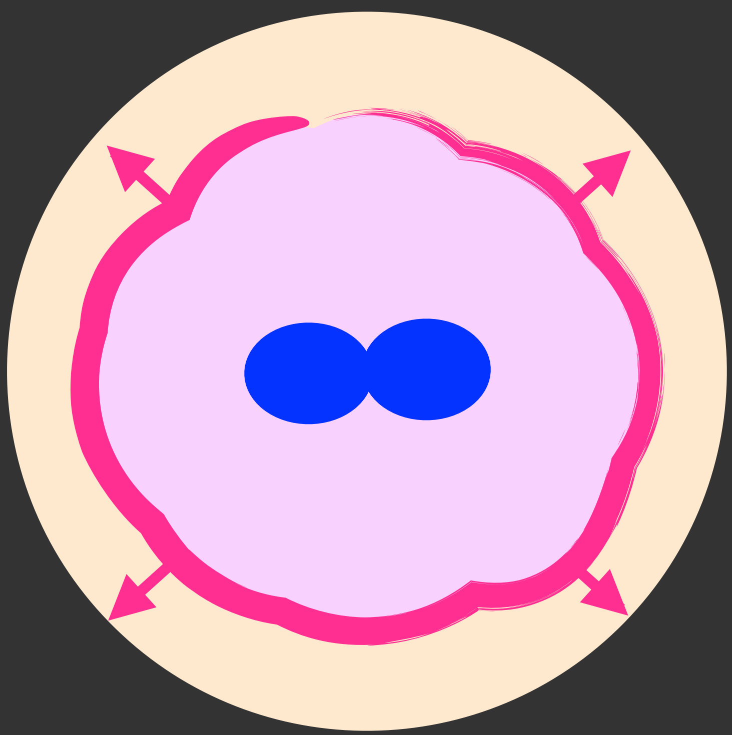
DIRECT CONTRIBUTION CAN BE NEGLECTED

BUT CONNECTION WITH INTERESTING FEATURES (TEV HALOS + X-RAY TAILS)

WHAT IS REVERBERATION?

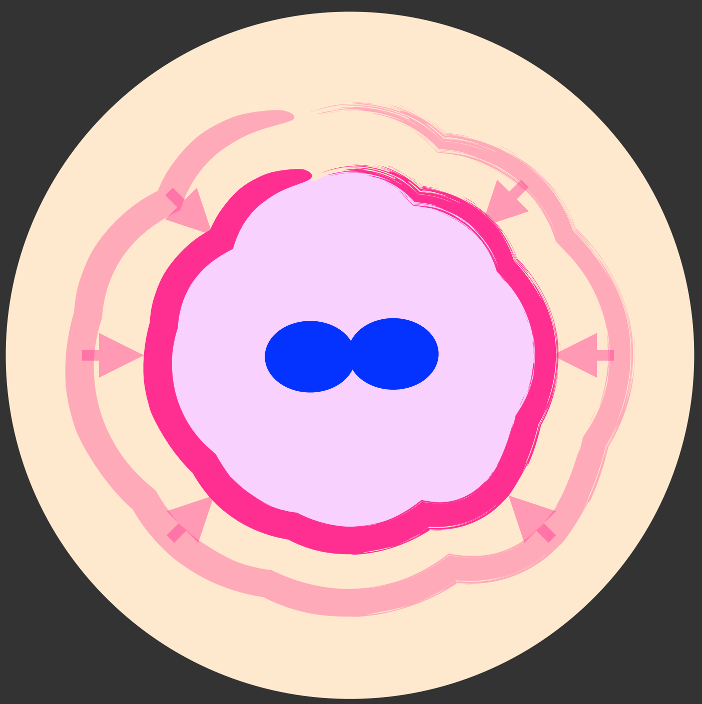
STARTS WITH THE REVERSE SHOCK BOUNCING ON THE PWN

POWERFUL PWN

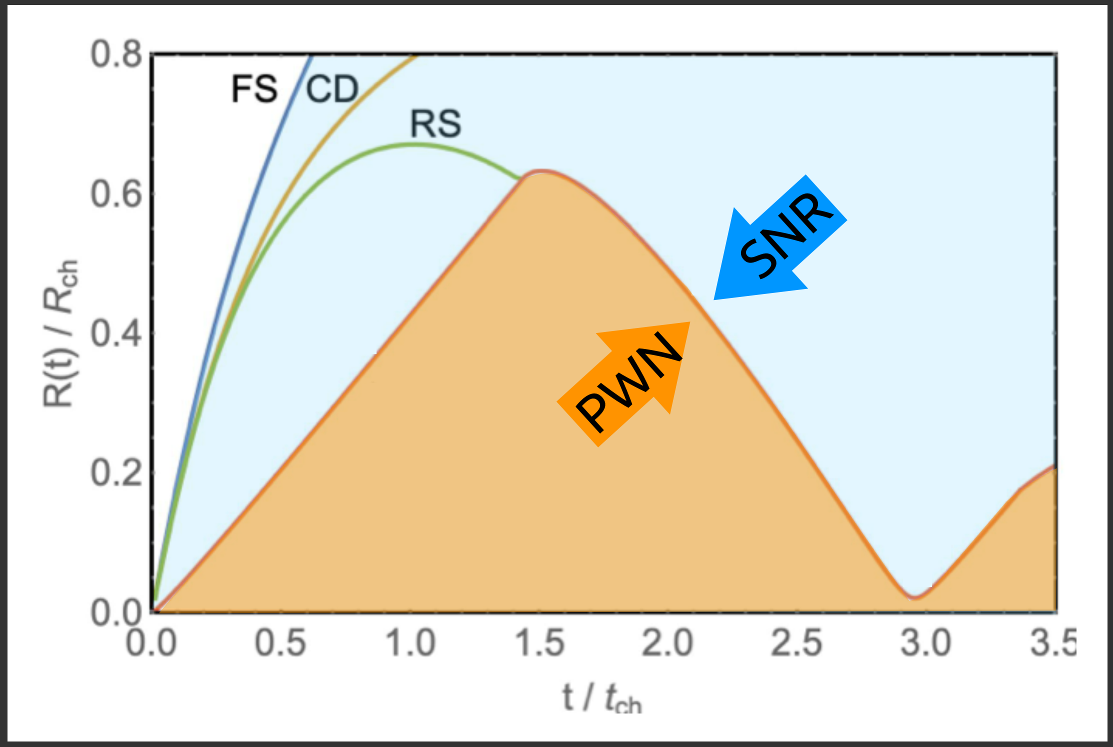


~NO COMPRESSION

FAINT PWN



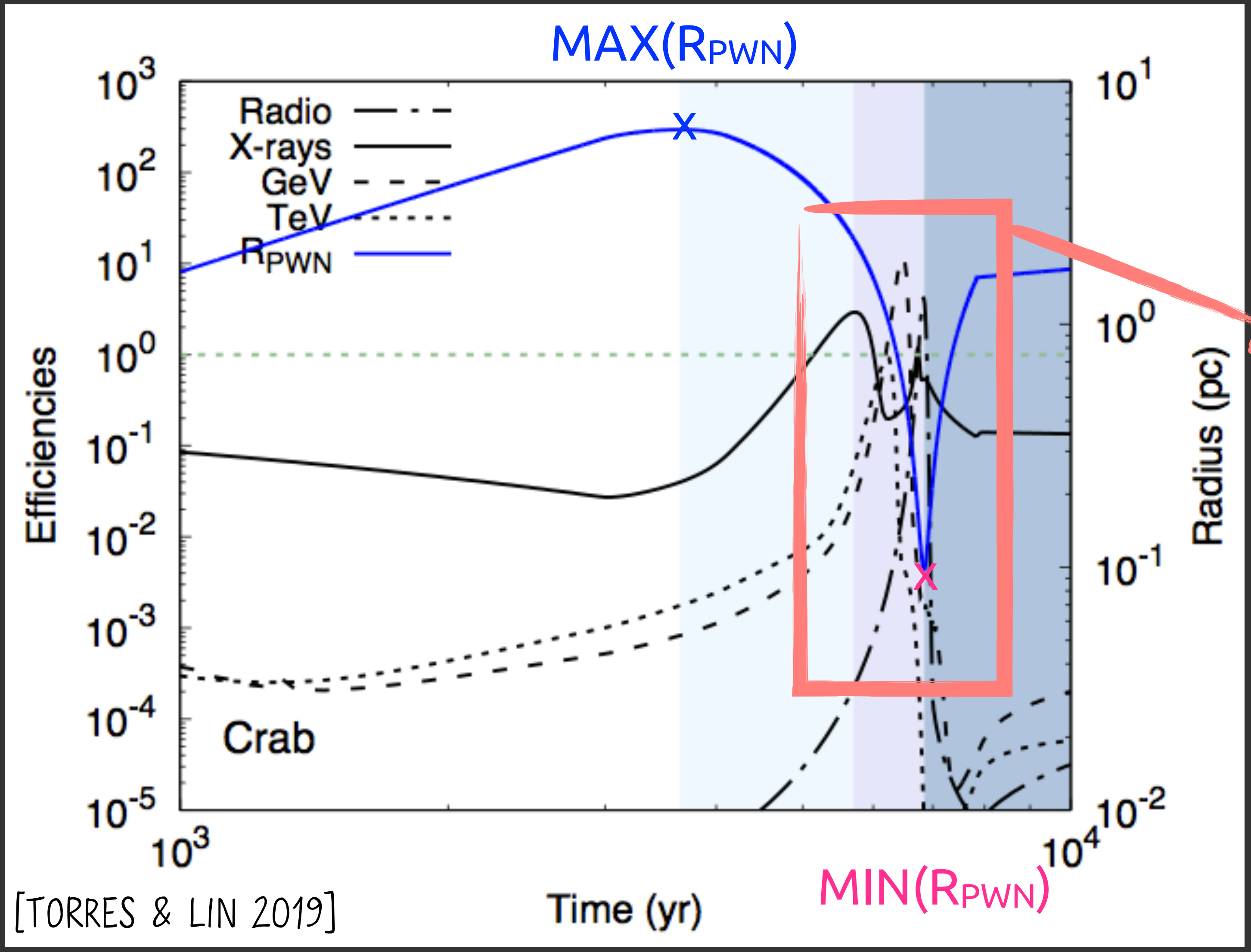
COMPRESSION (EVEN EXTREME)



WHAT DEFINITELY SHAPES THE EVOLUTION IS THE BALANCE BETWEEN THE INTERNAL (PWN) PRESSURE AND EXTERNAL (SNR) ONE

WHY IS REVERBERATION CRITICAL?

APPEARANCE OF "SUPER-EFFICIENCY" FOR EXTREME COMPRESSIVE SYSTEMS



AT THE MAXIMUM COMPRESSION THE EMITTED LUMINOSITY EXCEEDS L_{PWN}

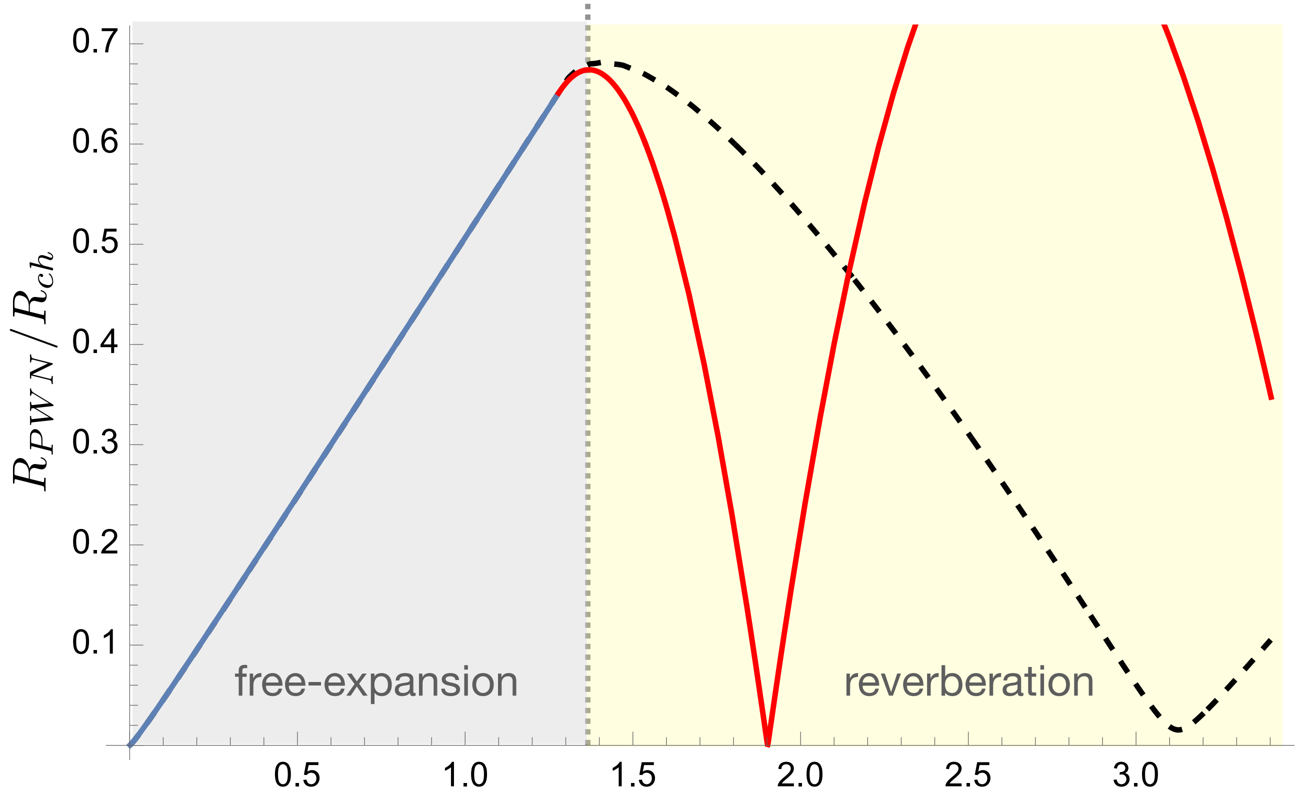
IF LARGE PART OF THE POPULATION UNDERGO SUPER-EFFICIENT PHASE, IT MIGHT DRASTICALLY CHANGE THE SED AT ALL WAVELENGTHS AND THE OUTCOME OF REVERBERATION

BIAS IN POPULATION STUDIES!

STANDARD MODELS AND EXTRA-COMPRESSION

"STANDARD" ONE-ZONE MODELS ASSUME P_{SNR} = 0.3-1 P_{SEDOV}

COMPARISON OF A STANDARD ONE ZONE MODEL AND 1D HD SIMULATION



1D-HD

1zone
(P_{SNR}=Sedov)

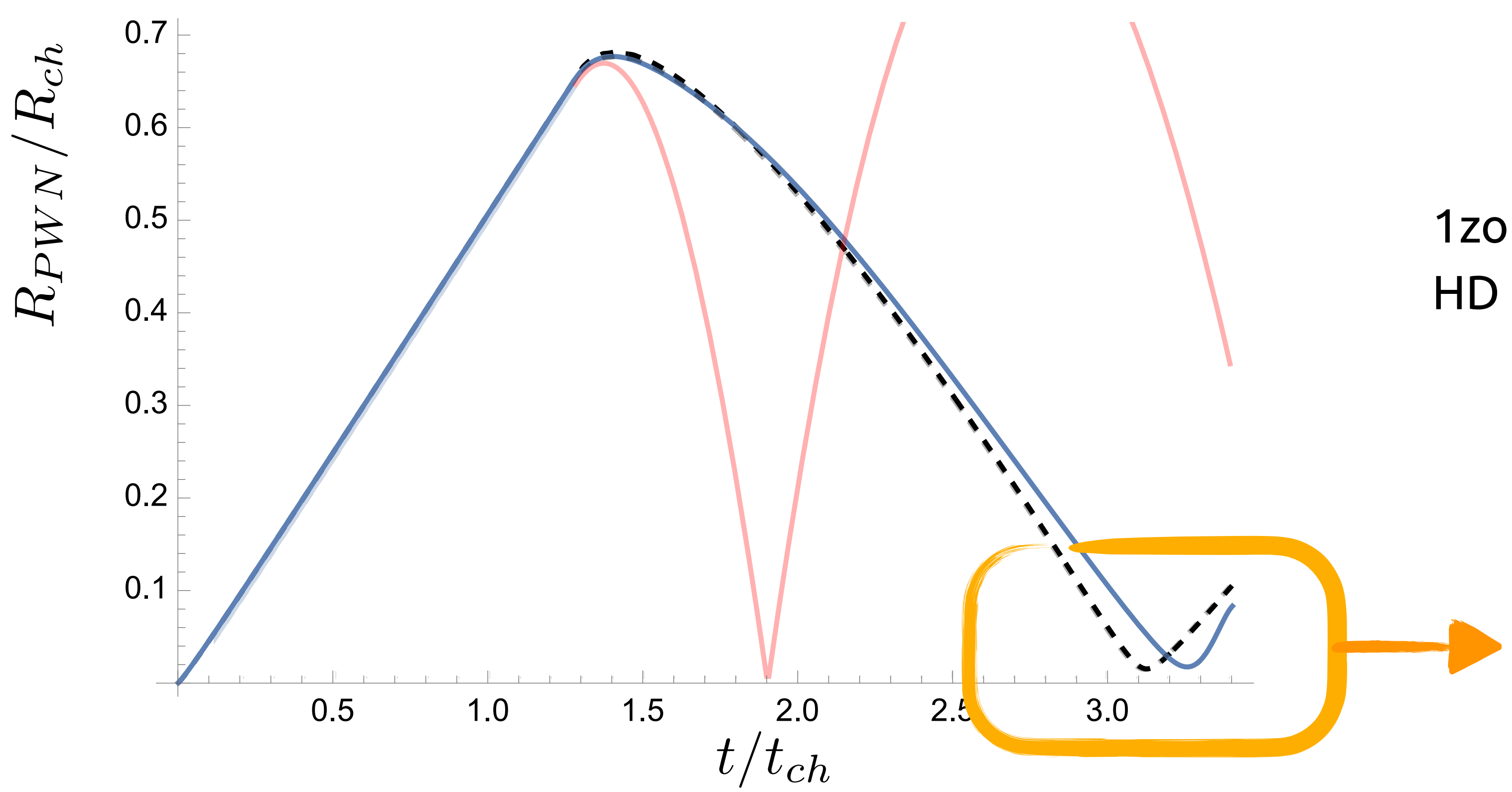
MAX(R_{PWN})/MIN(R_{PWN})

0.67/0.0007~960

0.67/0.015~45

factor 20 difference!

COMPARISON WITH A PHYSICALLY INFORMED ONE ZONE MODEL



1zone
HD informed

difference <%

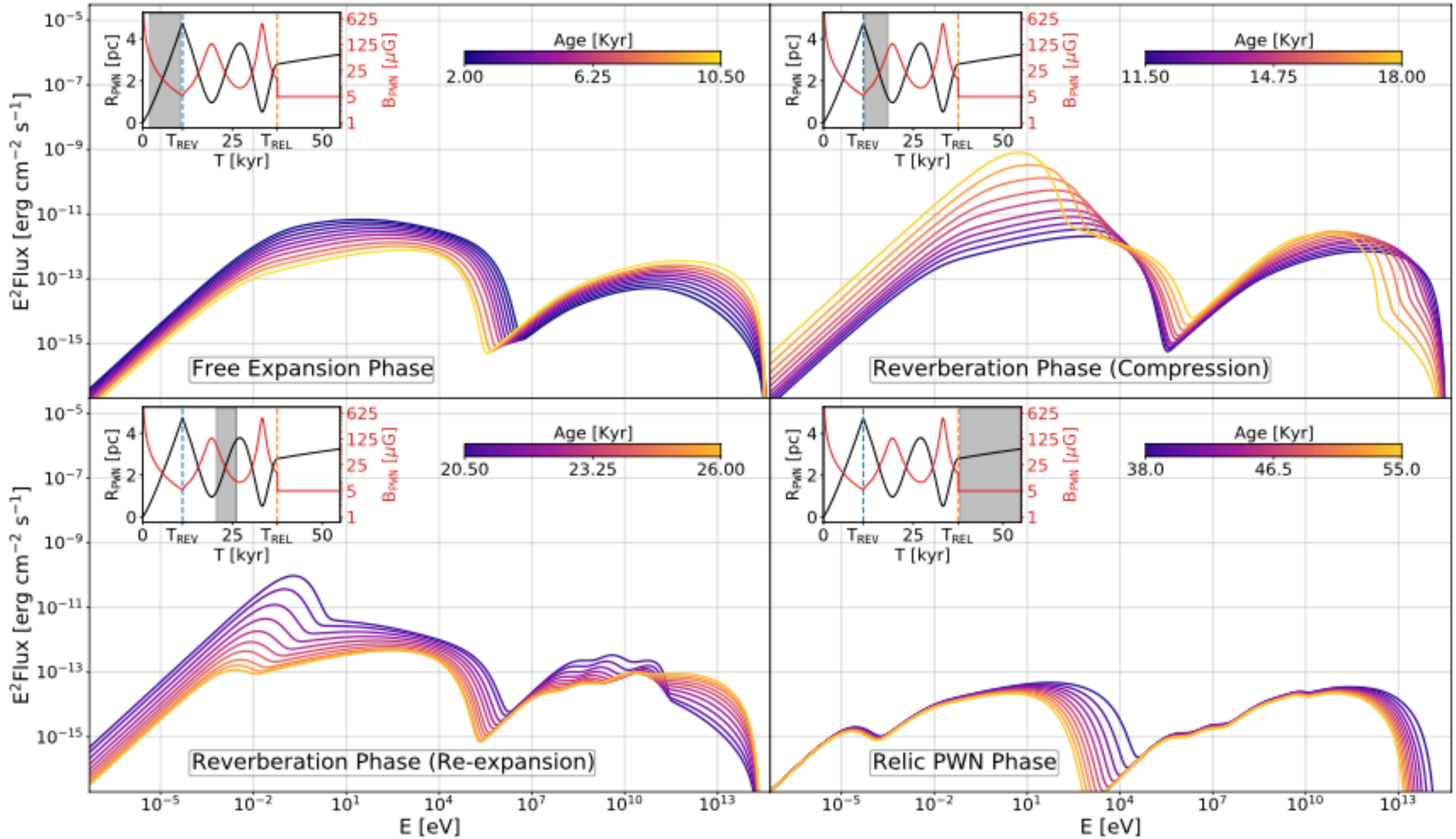
[BANDIERA ET AL. IN PREPARATION]

MODIFIED THIN-SHELL MODEL FOR THE GPS

EVOLUTION OF A RANDOM SOURCE

FREE-EXPANSION: STANDARD ONE-ZONE MODEL

REVERBERATION: RECIPE FOR SNR P FROM 1D-HD



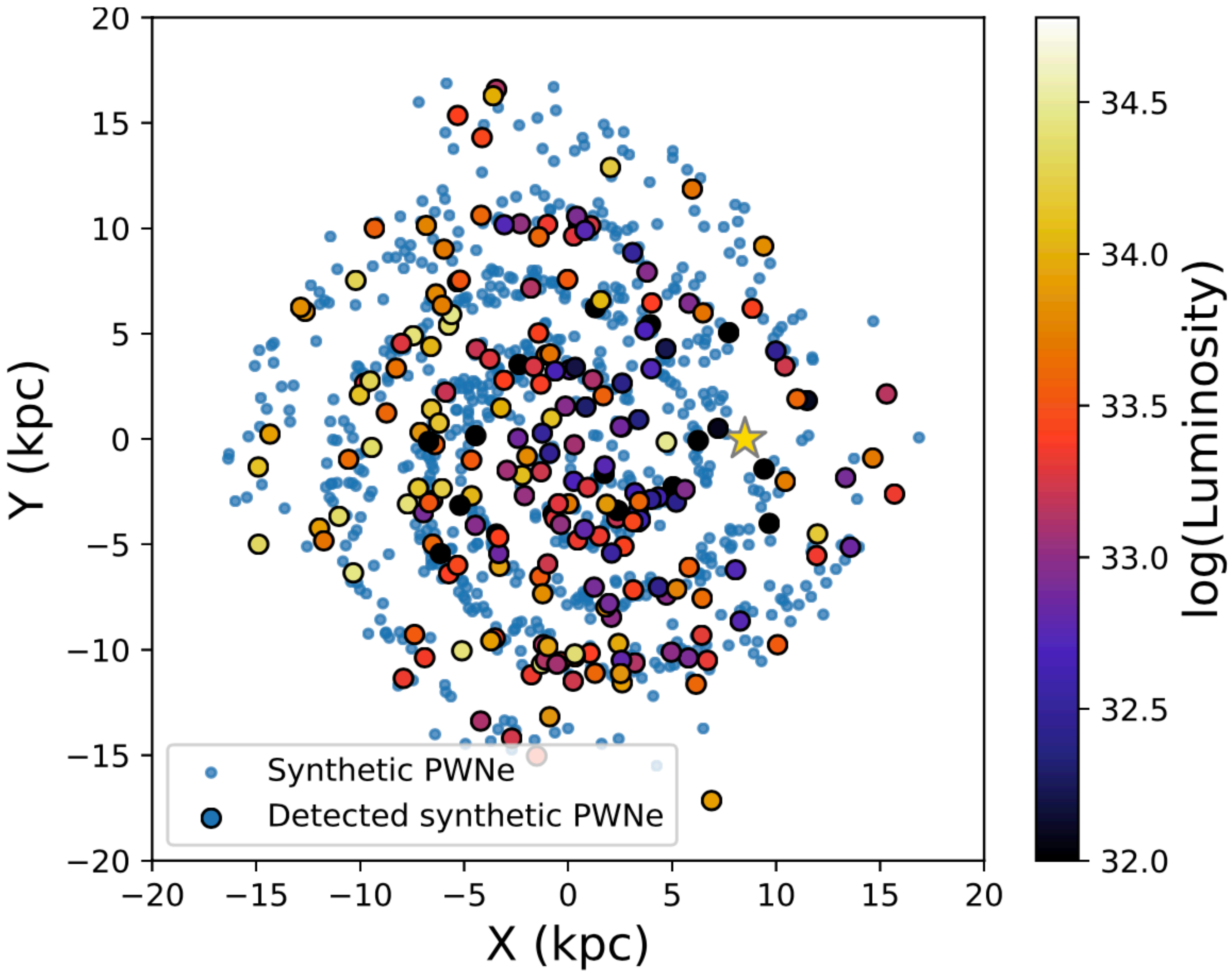
RELIC: ADIABATIC EXPANSION

RADIATIVE EVOLUTION PERFORMED WITH GAMERA LIBRARY

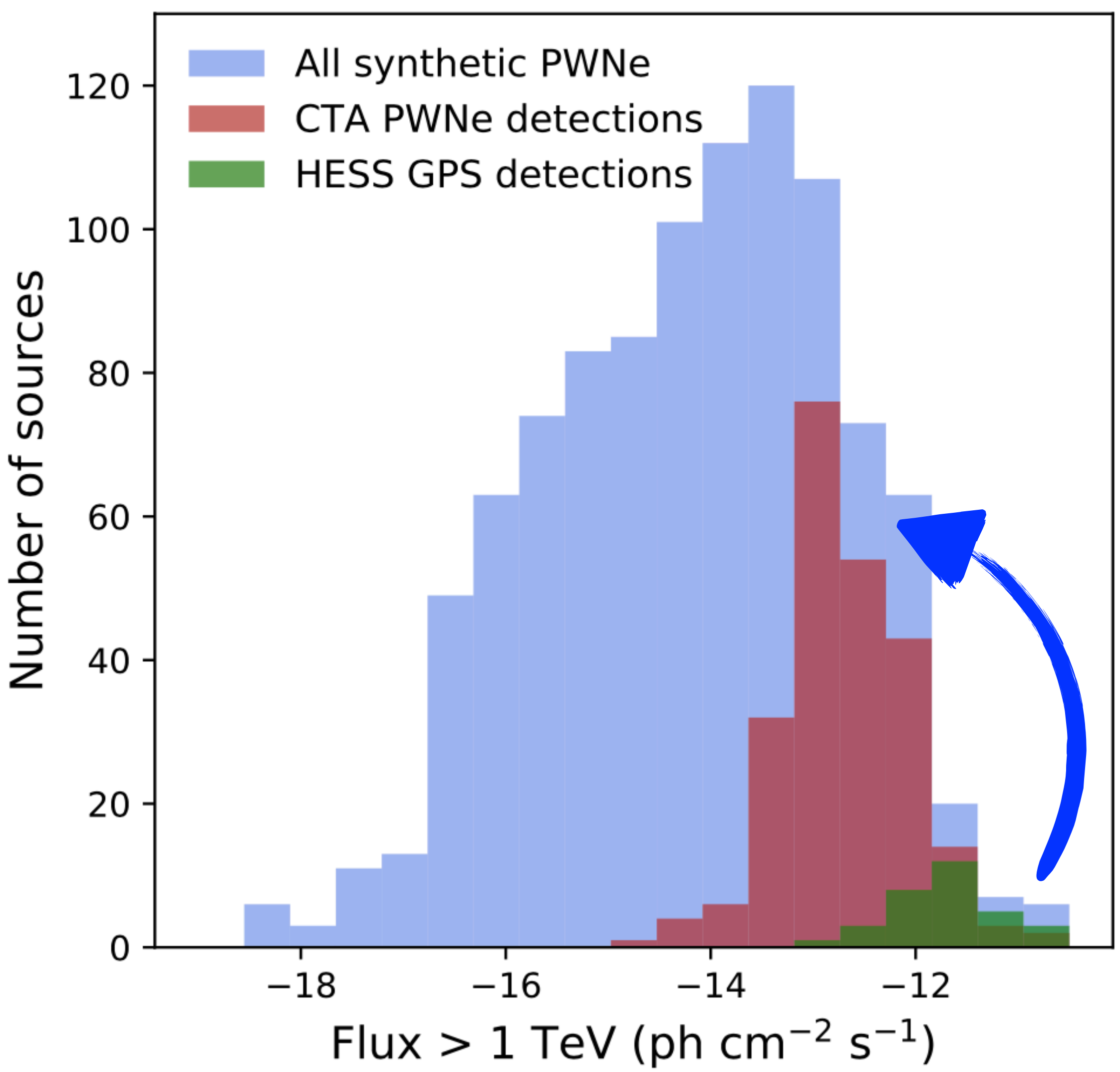
[M. FIORI ET AL. 2022]

RESULTS FOR THE PWN SURVEY

DISTRIBUTION OF DETECTED PWN IN THE GALAXY



DETECTIONS VS ENTIRE POPULATION +
CFR WITH HESS-GPS DETECTIONS



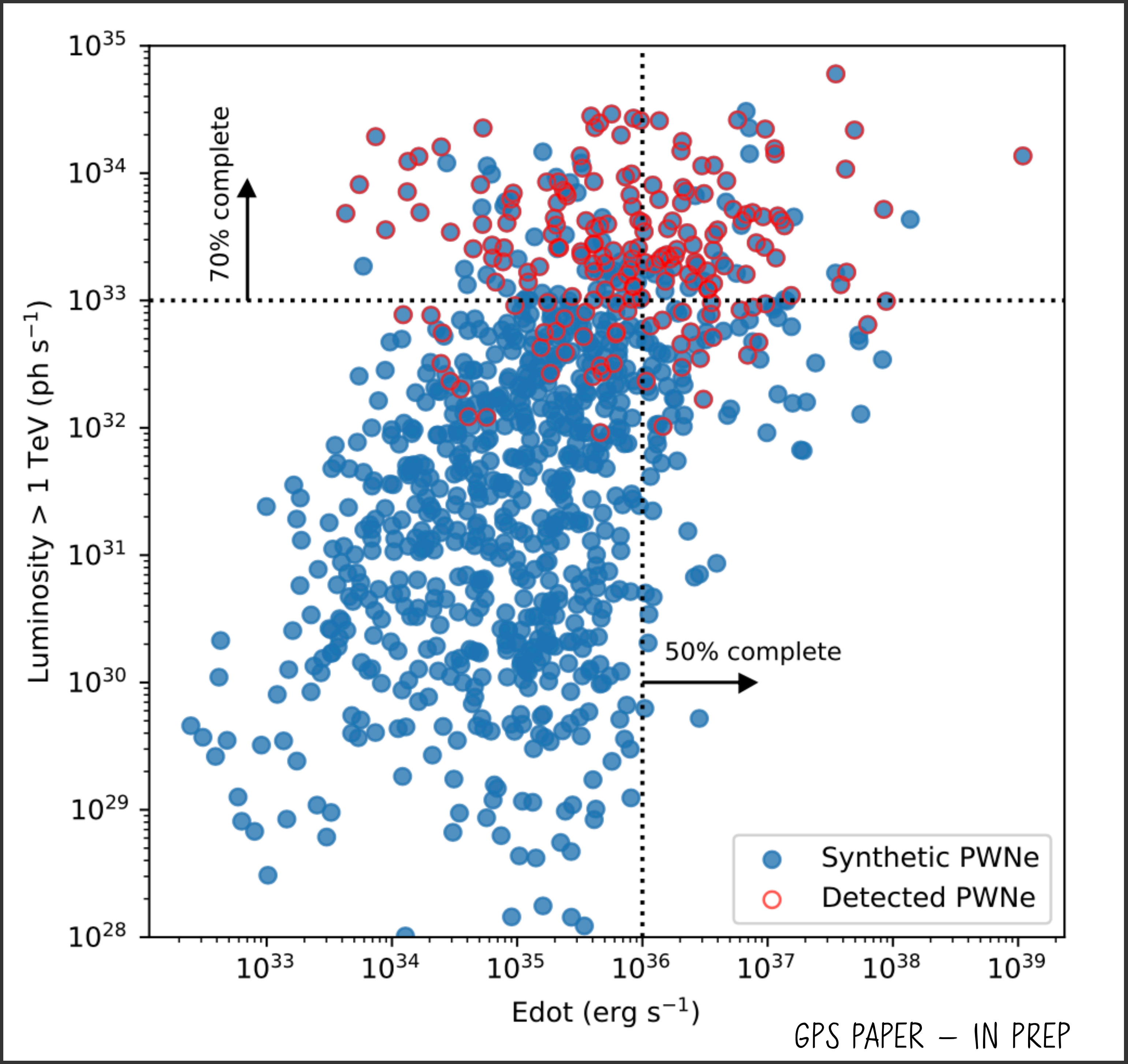
GPS PAPER – IN PREP

DETECTED 1/2 OF PWN POWERED BY POWERFUL ($L_{PSR} \geq 10^{36}$ erg/s)

ENORMOUS JUMP IN POPULATION COVERAGE

CTA PWN SURVEY: COMPLETENESS

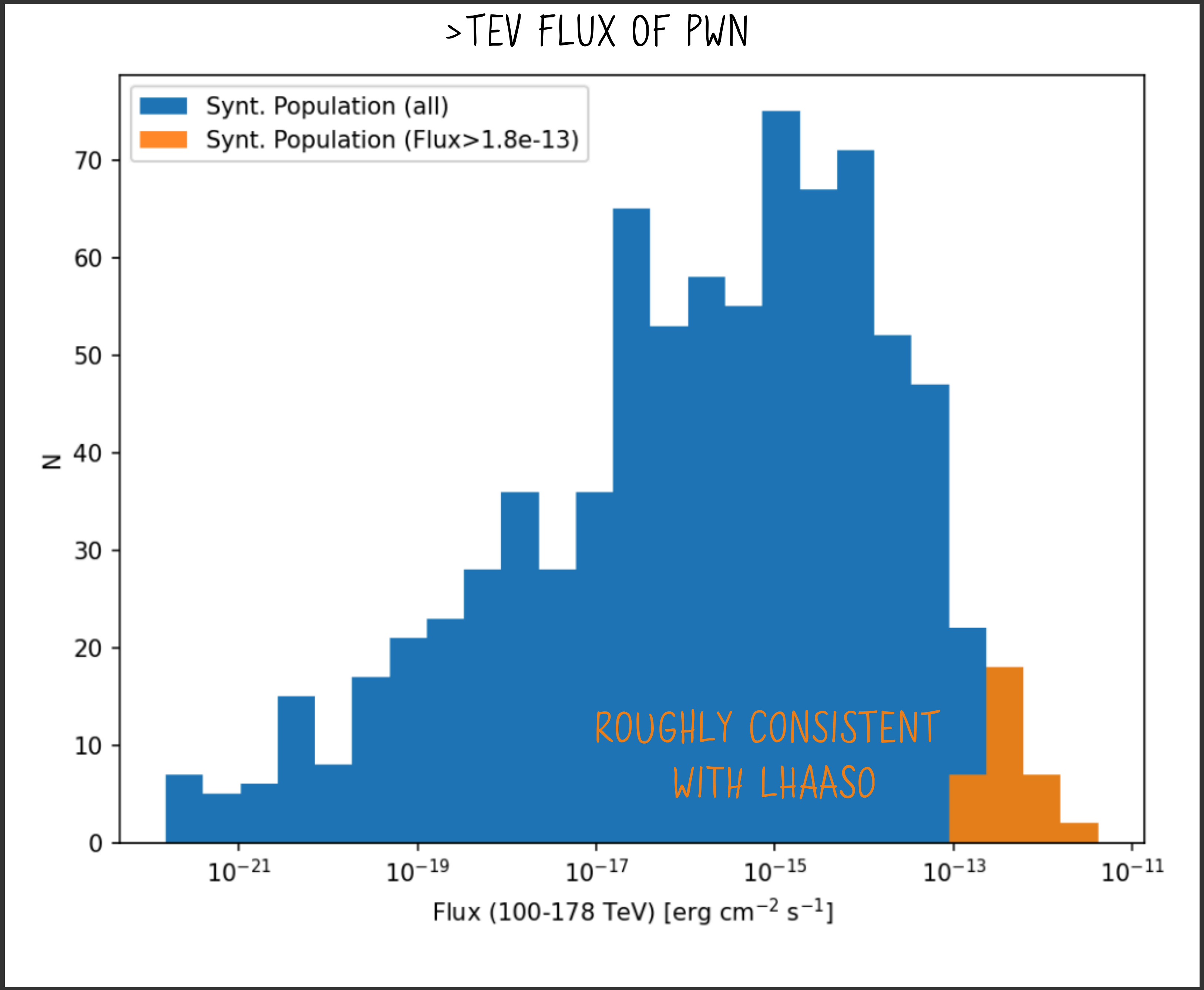
COMPLETENESS OF THE PWN SURVEY IN THE L_{PSR}–L_{PWN} PLANE



SOURCE CONFUSION + UNKNOWN UNDERLING POPULATION WILL MAKE DETECTION MORE DIFFICULT

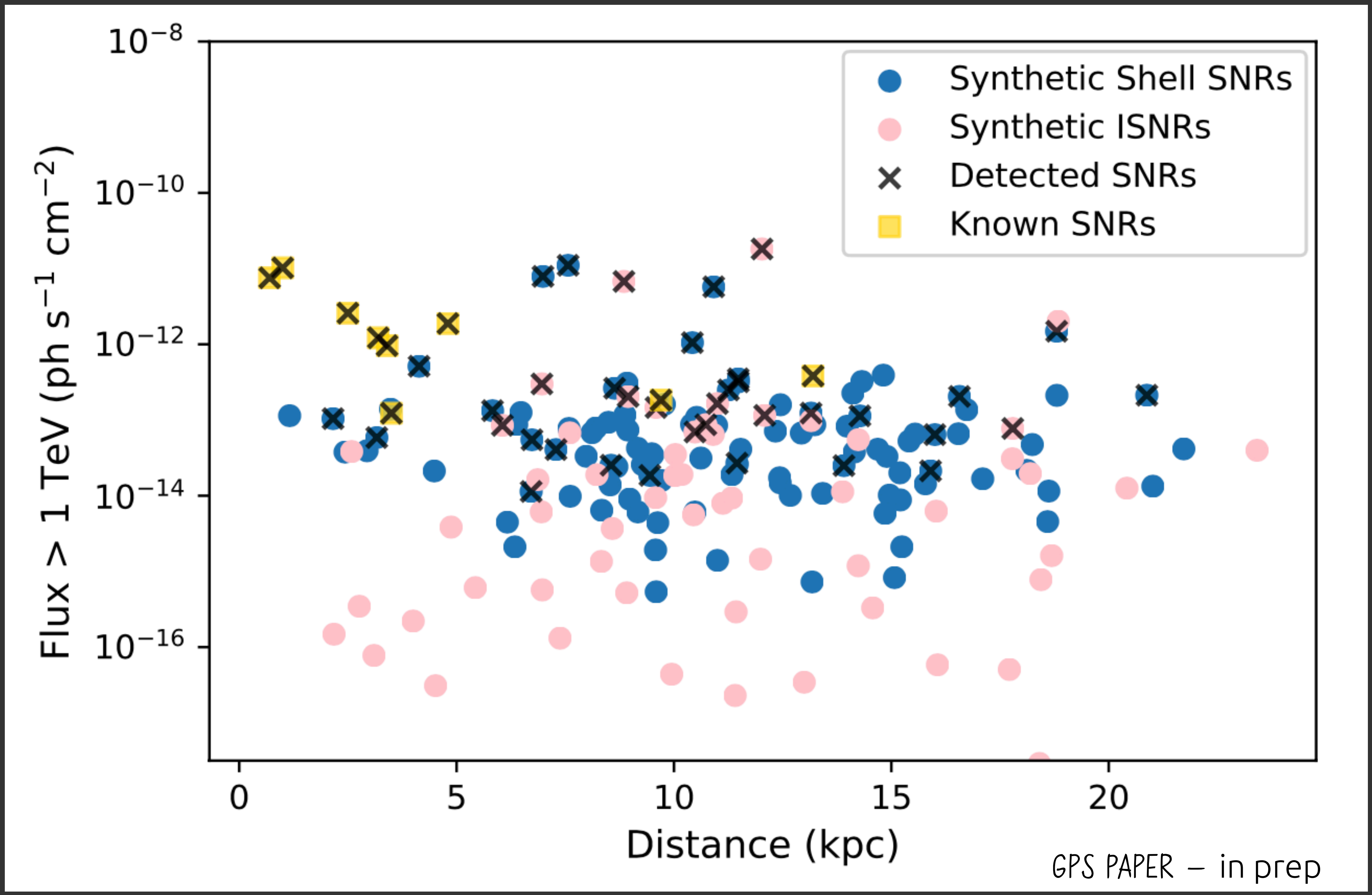
PRESENCE OF UHE SOURCES

THE SNR AND PWN SYNTHETIC POPULATIONS CONTAIN SOME UHE SOURCES



RESULTS FOR THE SNR SURVEY

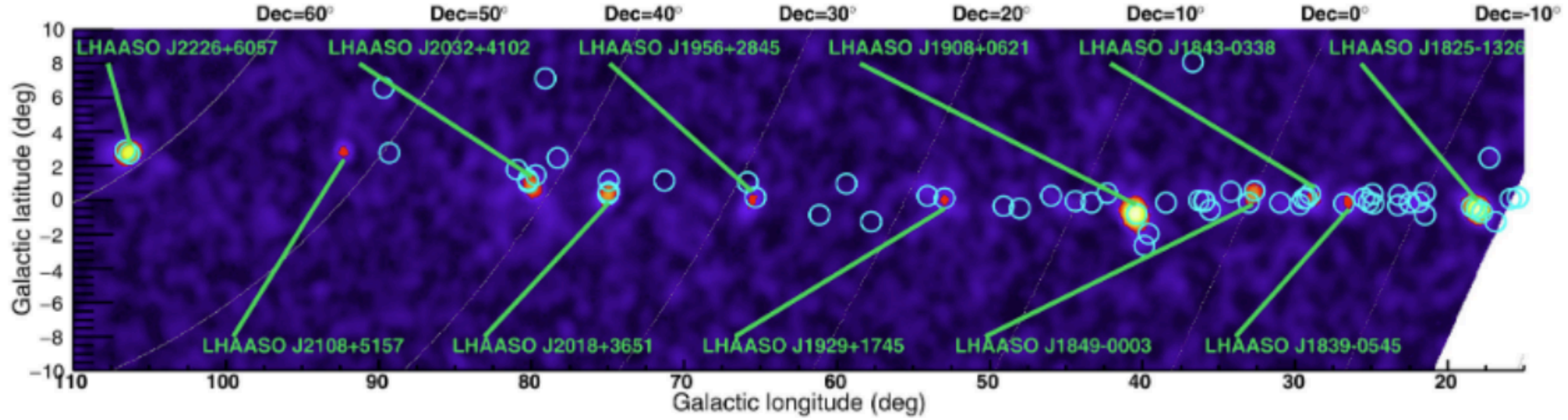
SHELL + INTERACTING SNRS



NEW OBJECTS CAN BE DETECTED UP TO A DISTANCE OF 20 KPC
AND DOWN TO A FLUX OF A FEW 10^{-14} photons/s

UPGRADE IN FLUX SENSITIVITY BY ~5-10 THAN CURRENT TEV SNRS SAMPLE

(2) PEVATRONS



Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV. The circles indicate the positions of known very-high-energy γ-ray sources.

LHAASO'S 12 PEVATRONS

TWO FUNDAMENTAL ASPECTS IN THE DEFINITION OF THE SCIENCE CASE:

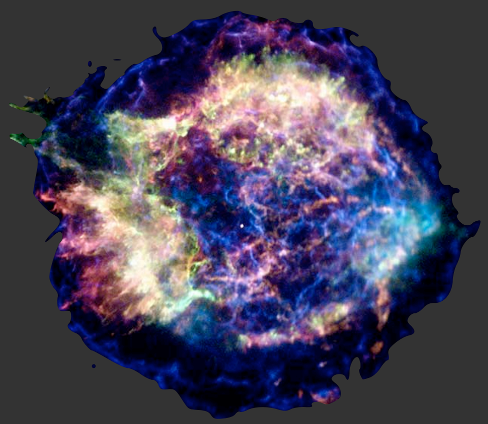
(1) PARTICLE ACCELERATION IN INDIVIDUAL OBJECTS UP TO PEV ENERGIES

SEARCH FOR EXTREME ACCELERATORS
DISTINGUISH BETWEEN LEPTONIC AND HADRONIC ACCELERATORS
—> NEED PRECISE MEASUREMENTS OF THE HE SPECTRAL SHAPE

(2) CR SPECTRUM $\gtrsim$ KNEE

REQUIRE DETAILED LOOK AT SOURCES TO UNDERSTAND THEIR POSSIBILITY TO ACCELERATE AT PEV, THEIR LOCATION (ONLY < 4KPC DISTANCE CAN PROVIDE CR AT EARTH), NUMBER

A POINT ON HADRONIC ACCELERATORS



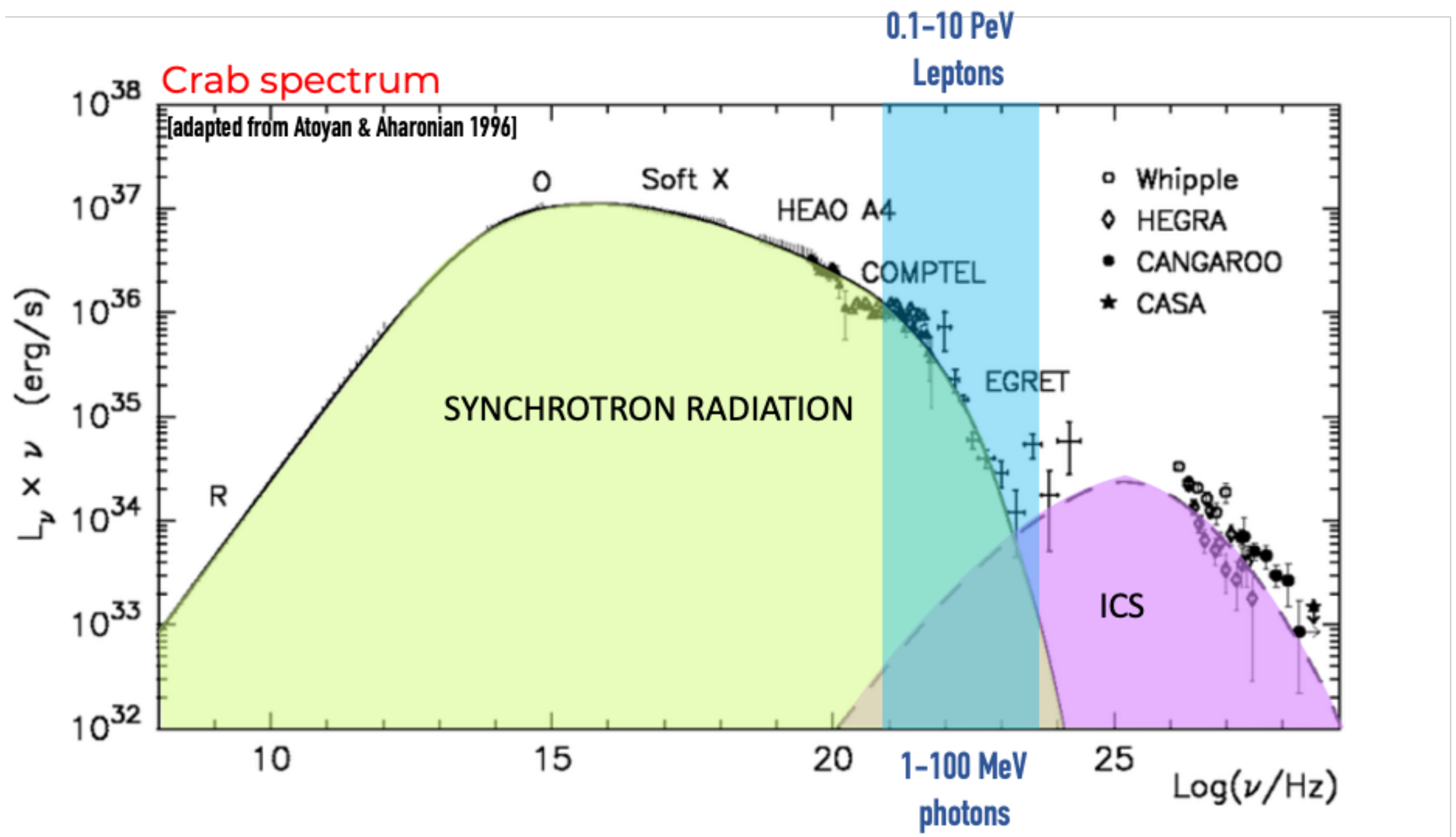
SNR MAYBE NOT BE THE PREFERRED CANDIDATES ANYMORE:

- NO CLEAR EVIDENCE OF ACCELERATION OF P @ E> 1 PEV
- EXPECT TO BE RARE + CAN SURVIVE AS PEVATRONS FOR SHORT TIMES (≲50 YR) –> MAYBE NOT VISIBLE (STRATEGY: LOOK AT INTERACTION OF ESCAPED PARTICLES WITH MOLECULAR CLOUDS?)

OTHER POSSIBILITIES:

- CORE-COLLAPSE SNR
  - CAN PRODUCE PEV PARTICLES IN THE FIRST DAYS AFTER EXPLOSION (CONSORTIUM PUB. IN PREP. – CR WG)
- MASSIVE YOUNG STELLAR CLUSTERS
  - DETECTED AT GAMMA-RAYS, LHASSO OBSERVED 1.4 PEV PHOTONS FROM THE CYGNUS COCOON.
  - THEORETICAL MODELS NOT MUCH ADVANCED YET (CR WG)
- SUPER BUBBLES (EVOLVED STELLAR CLUSTERS)
- GALACTIC CENTER
  - GAMMA-RAYS DETECTED, SOURCE NOT CLEAR (SGR A*, STELLAR CLUSTERS?)

LEPTONIC ACCELERATORS: PSR AND PWN



THE CRAB IS THE UNIQUE FIRMLY IDENTIFIED LEPTONIC ACCELERATOR

KEEP IN MIND ACCELERATION LIMITS: MAXIMUM AVAILABLE ENERGY FROM PSR POTENTIAL DROP

$$\Phi_{PSR} = \left(\frac{\dot{E}}{c}\right)^{1/2}$$

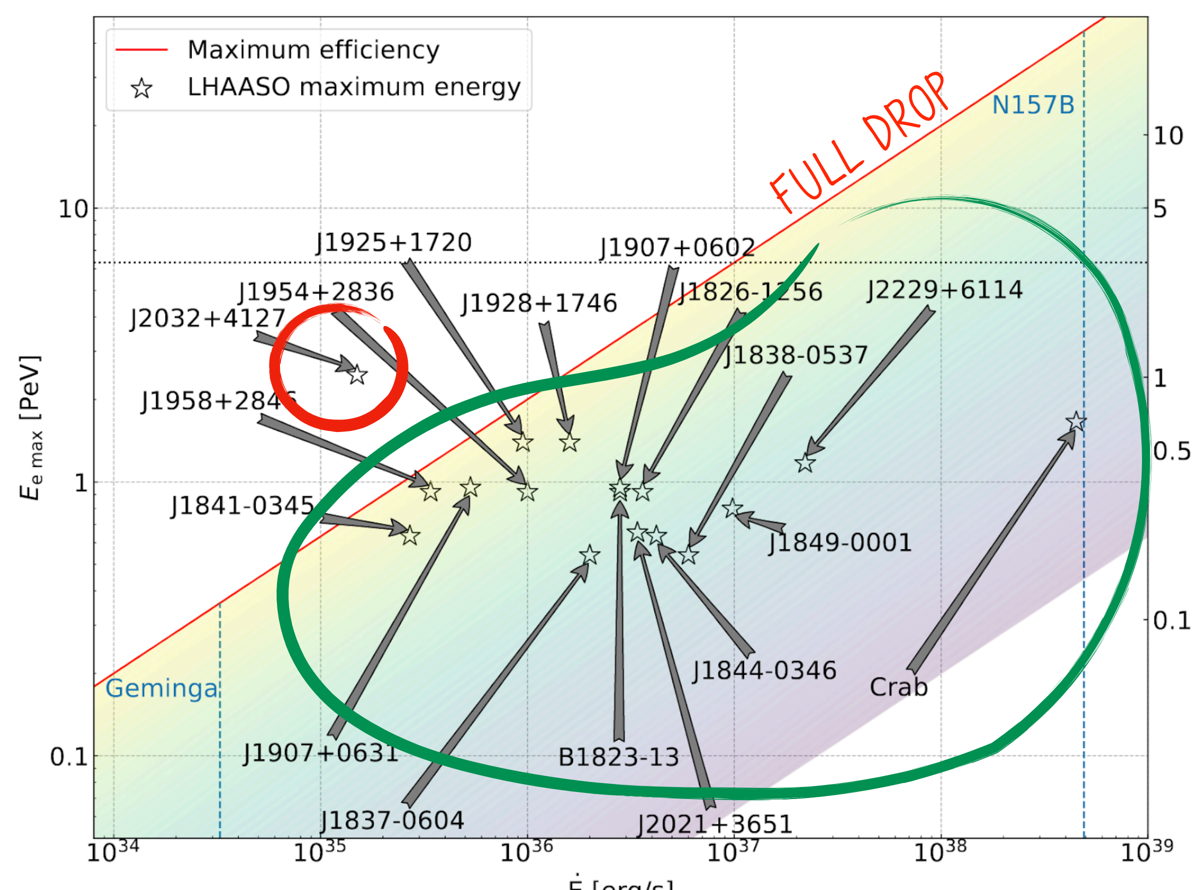
$$[\xi_E\ ,\ \xi_B] \leq 1$$

EFFICIENCY IN PARTICLES AND B FIELD

$$E_{max} \sim e\Phi_{PSR}$$

$$E_{max} \sim 2\xi_E \xi_B^{1/2} \left(\frac{\dot{E}}{10^{36}\ \mathrm{erg/s}}\right)^{1/2} \mathrm{PeV}$$ <-- LEPTONS

$$E_{max,\gamma} \sim 0.9\xi_E^{1/3}\xi_B^{0.65} \left(\frac{\dot{E}}{10^{36}\ \mathrm{erg/s}}\right)^{0.65} \mathrm{PeV}$$ <-- PHOTONS (CMB AS TARGET)

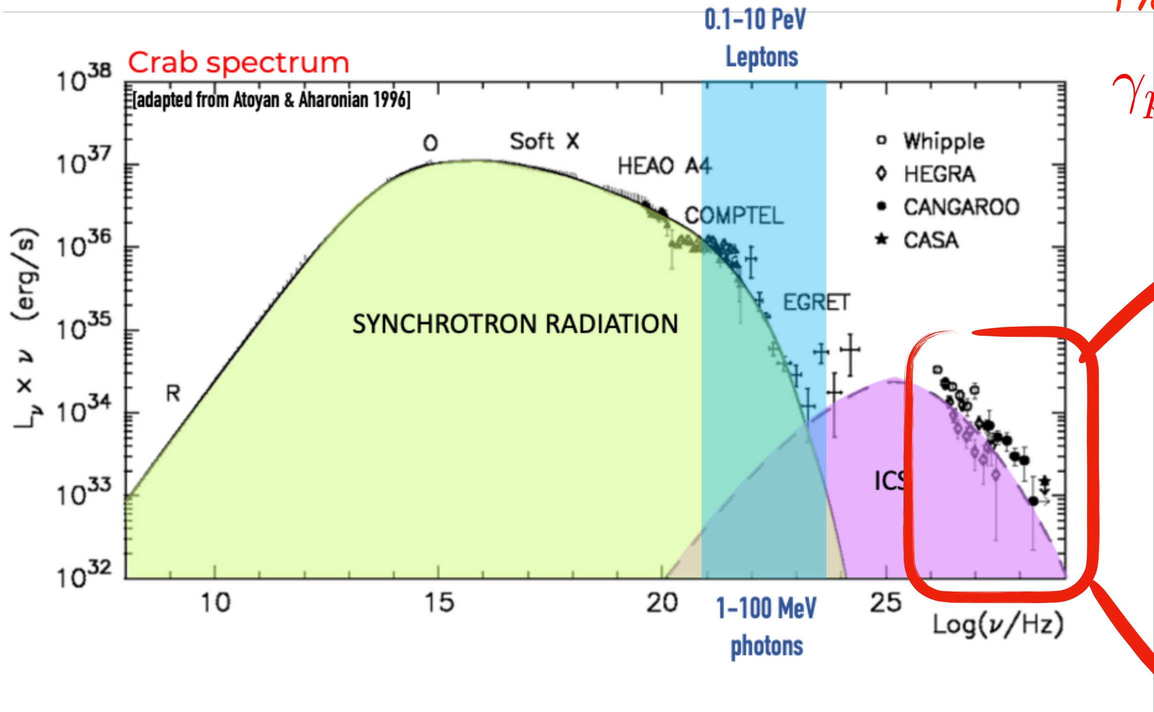


LOPEZ-COTO ET AL. 2022

ARE PWN ALSO HADRONIC ACCELERATORS?

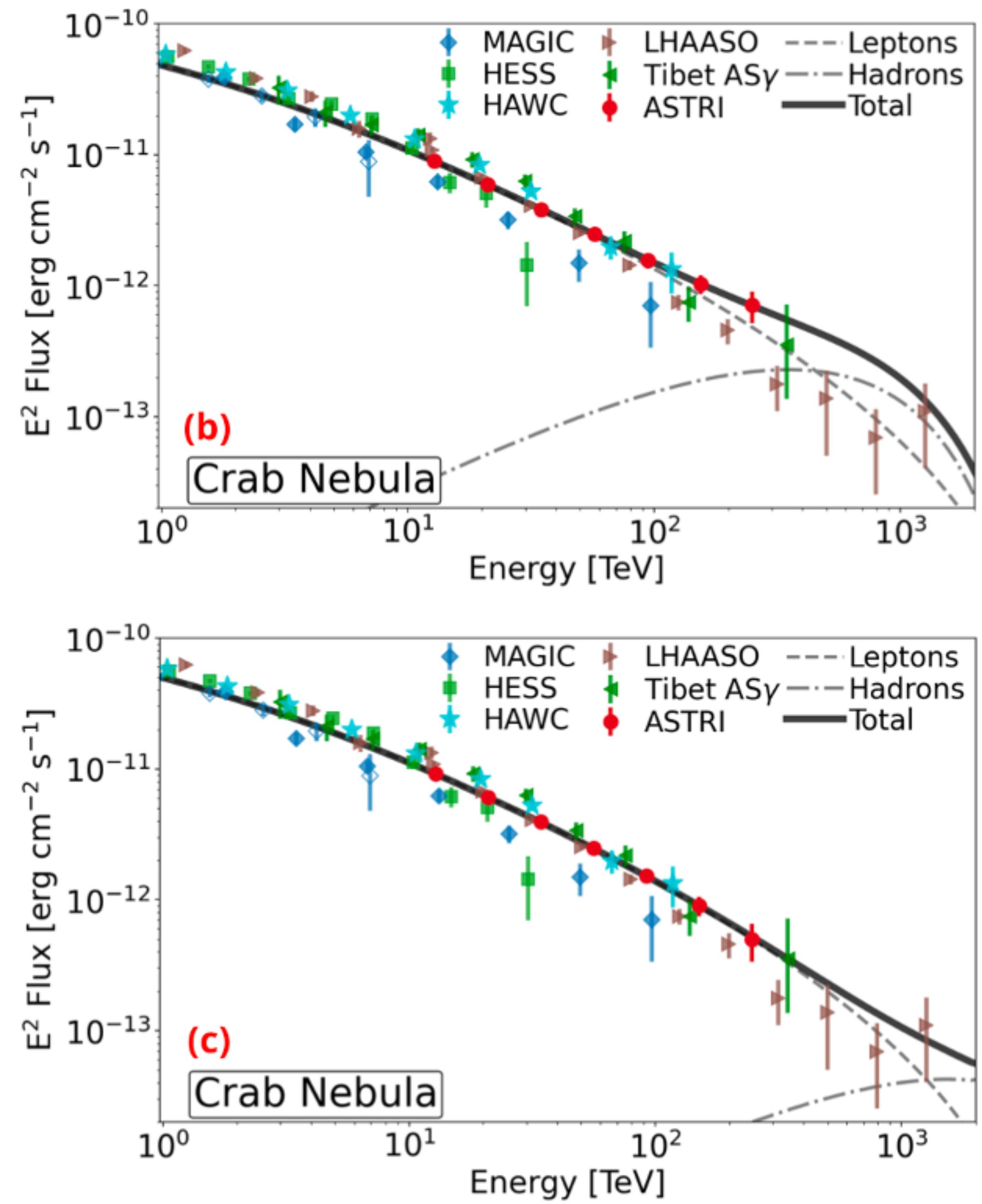
PRESENCE OF PROTONS IN THE PW NOT EXCLUDED THEORETICALLY [SEE E.G. GUEPIN ET AL. 2020]

-> CAN BE ONLY VISIBLE AT VHE WHERE IC IS KLEIN-NISHINA SUPPRESSED



4% PROTONS @ $\gamma_p = 5 \times 10^6$

4% PROTONS @ $\gamma_p = 2 \times 10^7$



GOOD VHE SPECTRAL DATA FUNDAMENTAL TO DISTINGUISH LEPTONIC/HADRONIC SCENARIO (ASTRI MINI ARRAY!)

VERCELLONE ET AL. 2022

KEY ROLE OF CTAO

THE GALACTIC PLANE SURVEY

WIDEN THE GAMMA-RAY CATALOGUE AND ADD MORPHOLOGICAL INFORMATION

- A FACTOR OF 6 MORE SOURCES EXPECTED COMPARED WITH HESS-GPS, 3HAWKC

  –> HUGE NUMBER OF PWN (SOURCE CONFUSION PROBLEM, DISTINGUISH PWN FROM HALOS?)

PEVATRONS PHYSICS

PEV SENSITIVITY << LHAASO BUT LARGE ENERGY COVERAGE + EXCELLENT ANGULAR/ENERGY RESOLUTION

–> CRUCIAL TO MAKE SENSE OUT OF LHAASO DETECTIONS:

- ANGULAR RESOLUTION = IDENTIFY POSITION, NATURE AND MORPHOLOGY OF THE SOURCE
- WIDE ENERGY COVERAGE = SPECTRAL SHAPE (LEPTONIC/HADRONIC)

–> BEST STRATEGY SEEMS: DEEP OBSERVATIONS OF SELECTED CANDIDATES (FROM LHAASO – ASTRI MA – THE GPS – FUTURE INSTRUMENTS)