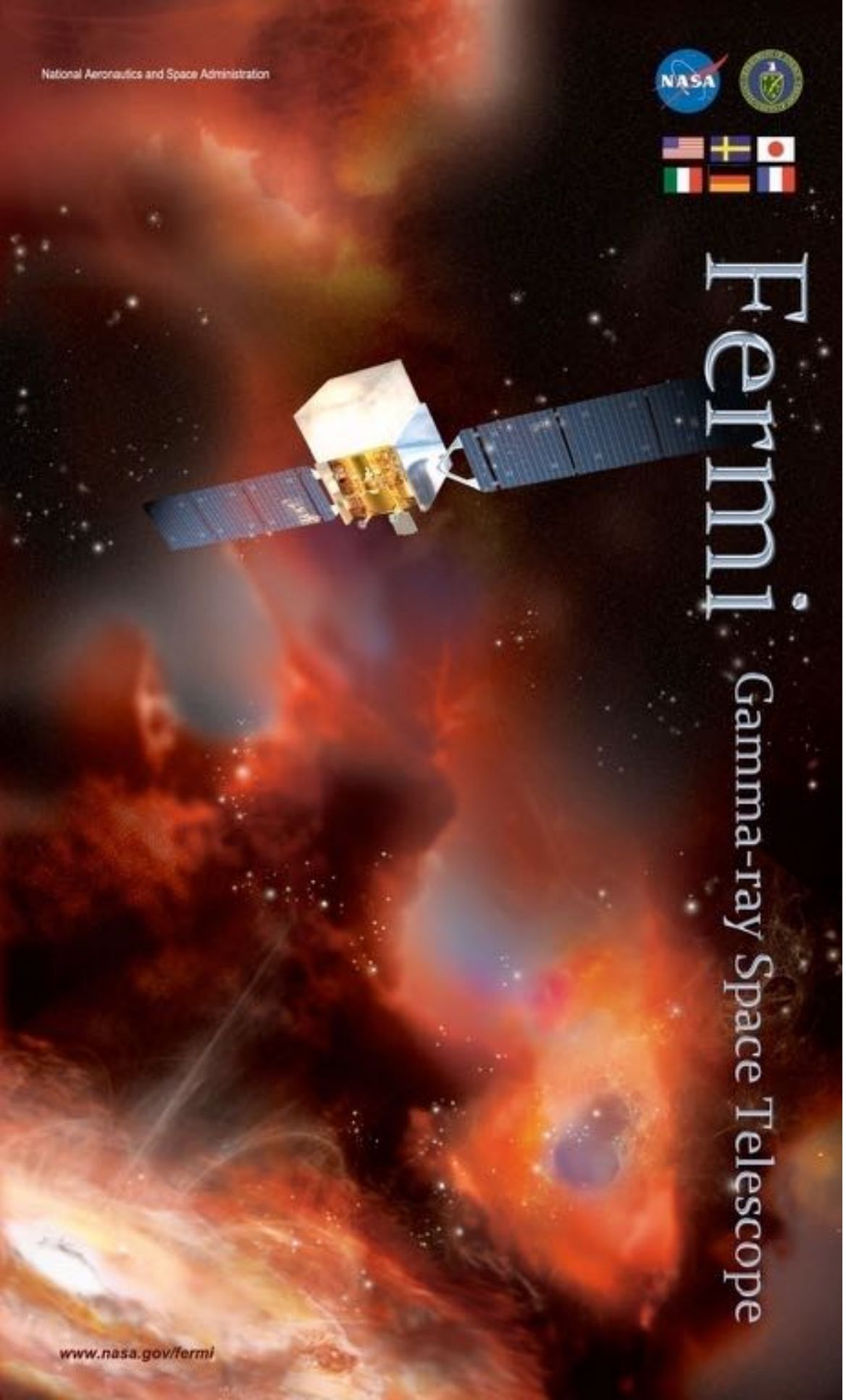
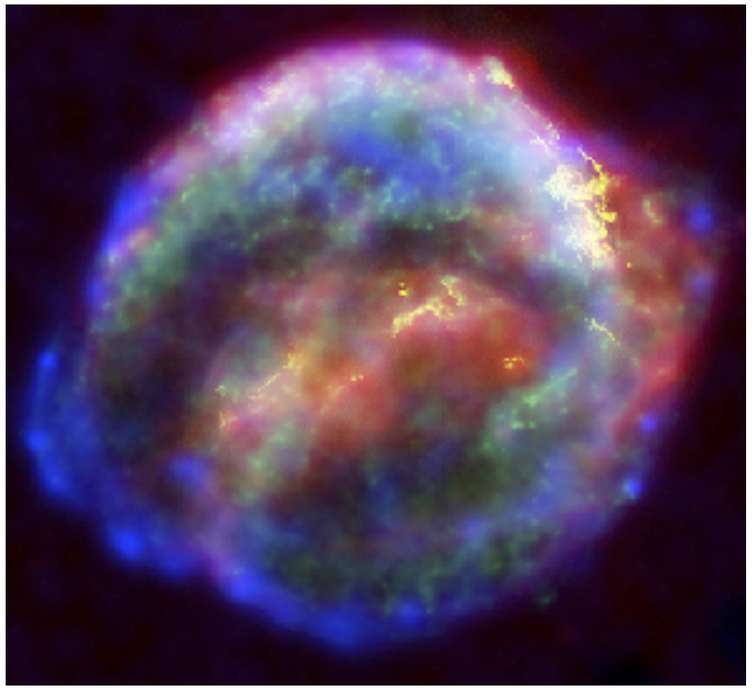


Fermi
Gamma-ray
Space Telescope

Kepler SNR : The last historic SNR to be detected in gamma-rays

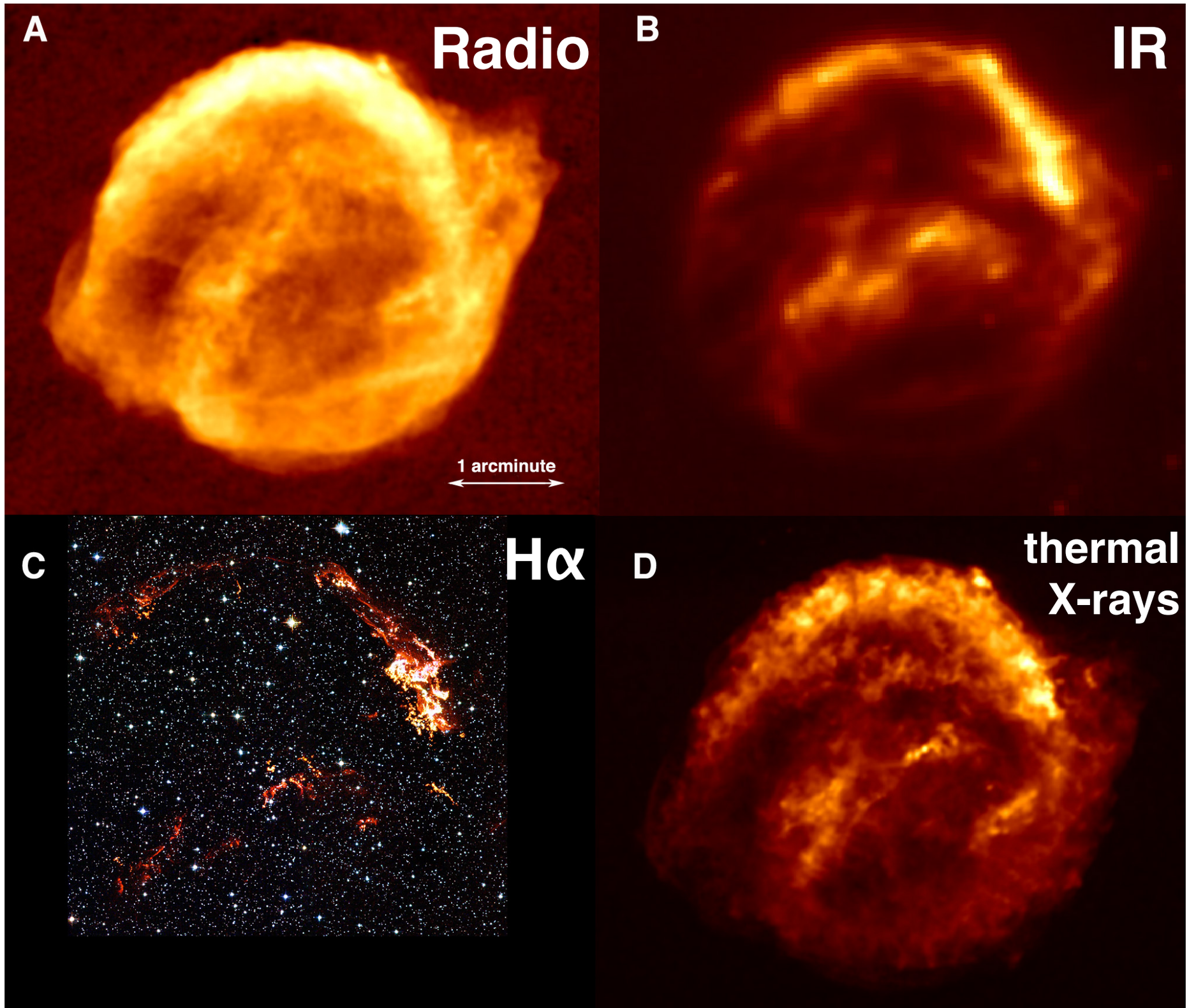


F. Acero[1], M. Lemoine-Goumard[2], J. Ballet[1]
1) DAp/AIM, CEA-Saclay
2) CENBG, Bordeaux

Astroparticle Symposium, October 2021

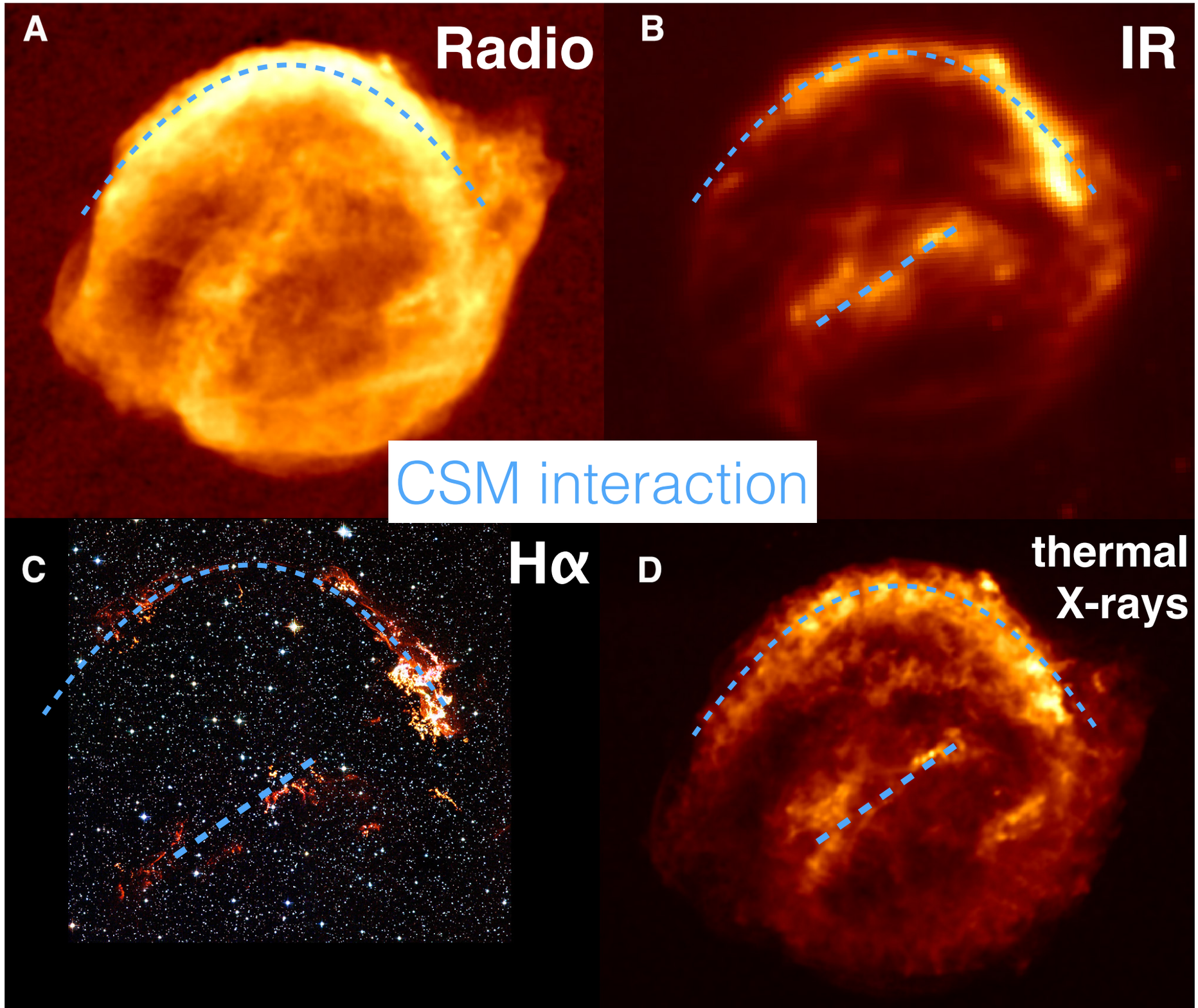
SN 1604: a Type Ia with circumstellar interaction

- **Thought to be a runaway single degenerate Type Ia SN**



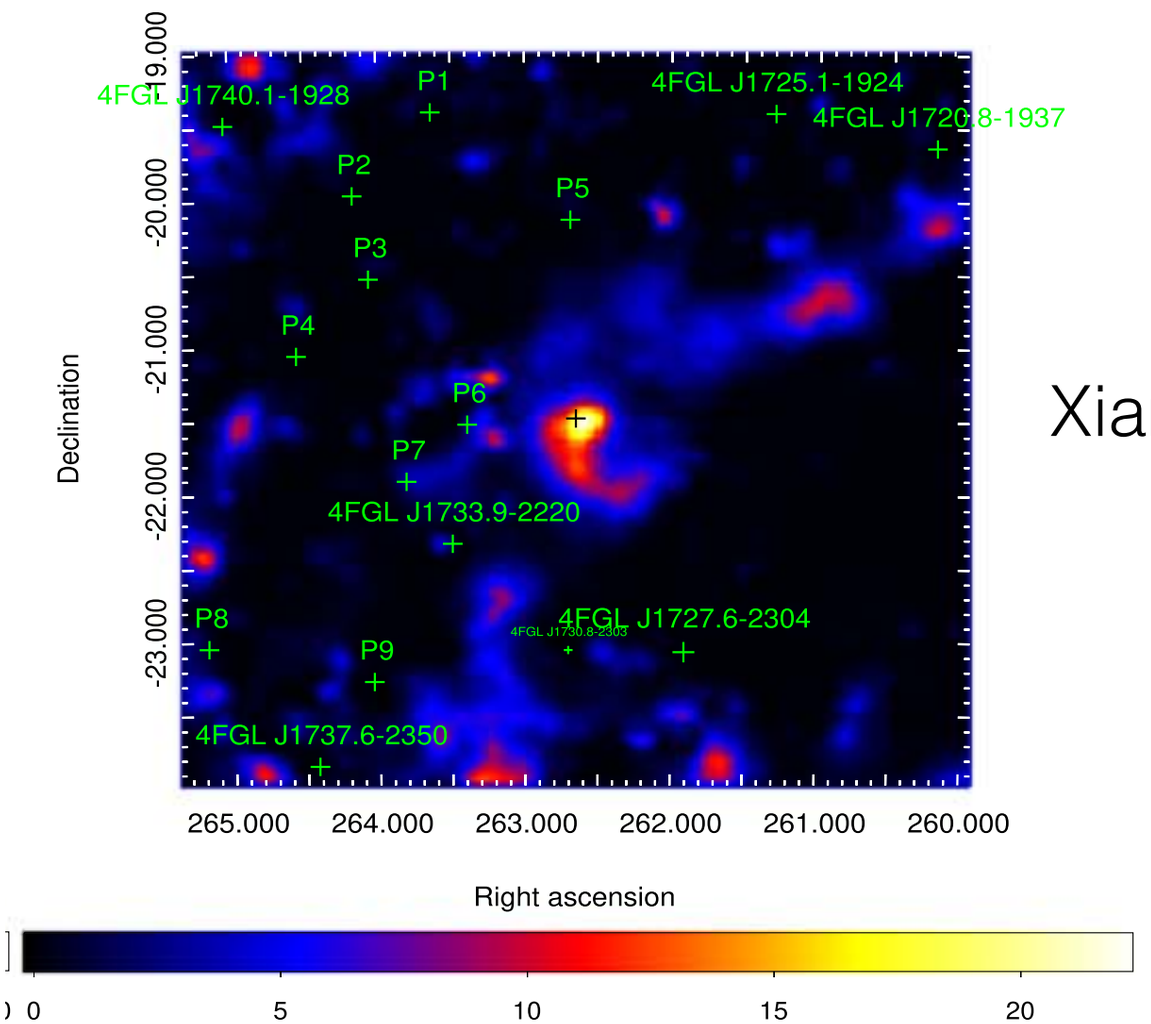
SN 1604: a Type Ia with circumstellar interaction

- **Thought to be a runaway single degenerate Type Ia SN**

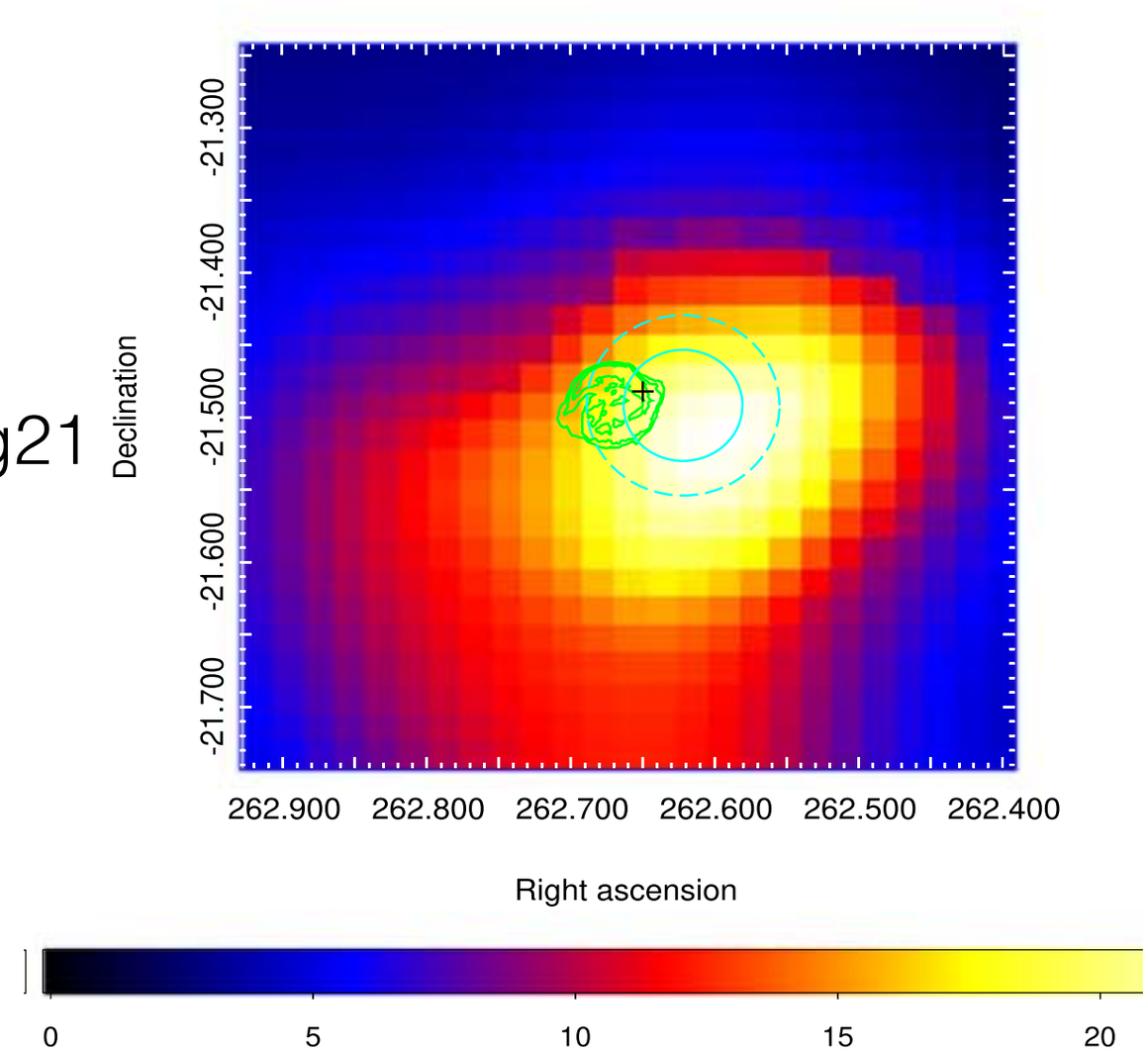


Kepler: the last historic SNR without gamma-rays

- **Upper-limits reported in LAT SNR catalog (3 yrs of P7 data)**
- **Upper-limits reported by HESS (13 hours)** → **New ICRC detection**
- **Paper by Xiang&Jiang (February21) but:**
  - **reported TS~21 (~3.8 sigma;12 yrs)**
  - **no study of the morphology and simple SED modeling**



Xiang21



Why doing a re-analysis ?

- **The TS=21 detection is ~3.8 sigma with 4 d.o.f. + impact of systematics ?**
  - **Analysis configuration can be optimized (Summed LL, bin size, …)**
    - **We revisit the same dataset with a more optimized analysis**

- **Peak in the TSmap is slighlty outside of the SNR and Xiang paper suggests an escaping CRs interpretation**
  - **Is the gamma-ray emission statistically compatible with arising from the Kepler SNR ? (not clear in Xiang)**
    - **Compare TS with MWL templates (radio, IR, X)**

- **Modeling in Xiang does not use the wealth of info known for Kepler (CSM interaction, densities, V_{shock}, …)**
  - **Propose a new SED modeling assuming CSM interaction**
    - **A self-consistent modeling with only 4 d.o.f. (B, Γ, W_e, W_p) fixing all other parameters to known values for Kepler**

Why doing a re-analysis ?

- **The TS=21 detection is ~3.8 sigma with 4 d.o.f. + impact of systematics ?**
  - **Analysis configuration can be optimized (Summed LL, bin size, …)**
    - **We revisit the same dataset with a more optimized analysis**

Abstract

A likely detection of γ-ray emission from the region of Kepler's Supernova Remnant (SNR) is reported by analyzing $\sim$12 yr of Pass 8 data of the Fermi Large Area Telescope. Its photon flux is $(4.85 \pm 0.60) \times 10^{-10}$ ph cm^{-2} s^{-1} with $\sim 4\sigma$ significance in 0.2–500 GeV. Moreover, our results show that there is no significant variability in the light curve of $\sim$12 yr, and its position can well overlap with the observation result of Chandra in hard X-ray band with a good spatial resolution of 0.″5, so the source is likely to be the GeV γ-ray counterpart of Kepler's SNR. The spectral energy distribution of γ-rays from Kepler's SNR favors a hadronic origin in GeV band. Through analyzing multi-band data from radio to γ-ray and surveying the distribution from the surrounding CO molecules cloud, we found that if this γ-ray emission is from Kepler's SNR, then it may originate from interactions between the relativistic protons escaping from the shock of Kepler's SNR and surrounding CO gas molecules. However, more observation data are necessary to firmly confirm the association between the γ-ray source and Kepler's SNR in the future.

(CSM interaction, densities, V_{shock}, …)

- **Propose a new SED modeling assuming CSM interaction**
  - **A self-consistent modeling with only 4 d.o.f. (B, Γ, W_e, W_p) fixing all other parameters to known values for Kepler**

Different analysis configuration

- **We report a TS=38.3 above 100 MeV and 34 above 700 MeV**

Xiang config: 22.9 above 700 MeV

Table 2. Results of the fit of the LAT data between 700 MeV and 1 TeV using different analysis configurations.

Configuration number	Summed analysis	Spatial bin size (°)	Region size (°)	TS TS
1	Yes	0.05	15	33.9
2	No	0.05	15	30.6
3	No	0.1	15	23.2
4	No	0.1	20	21.4

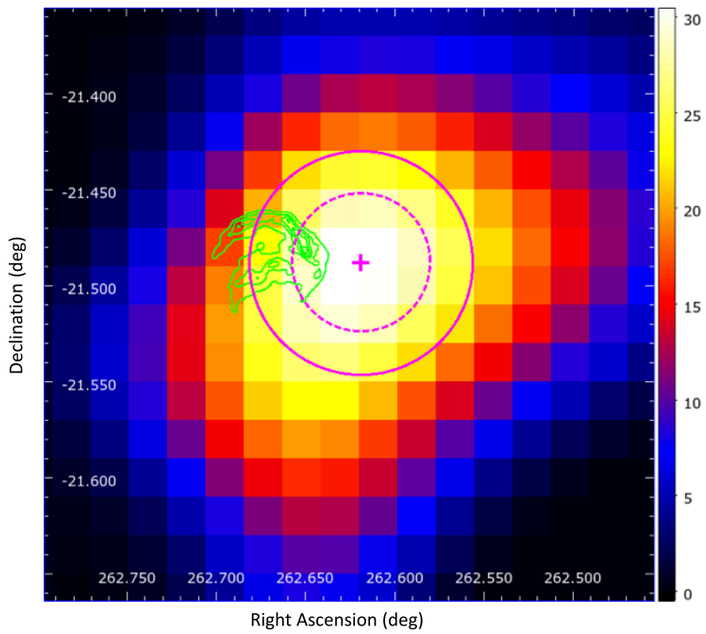
Xiang config

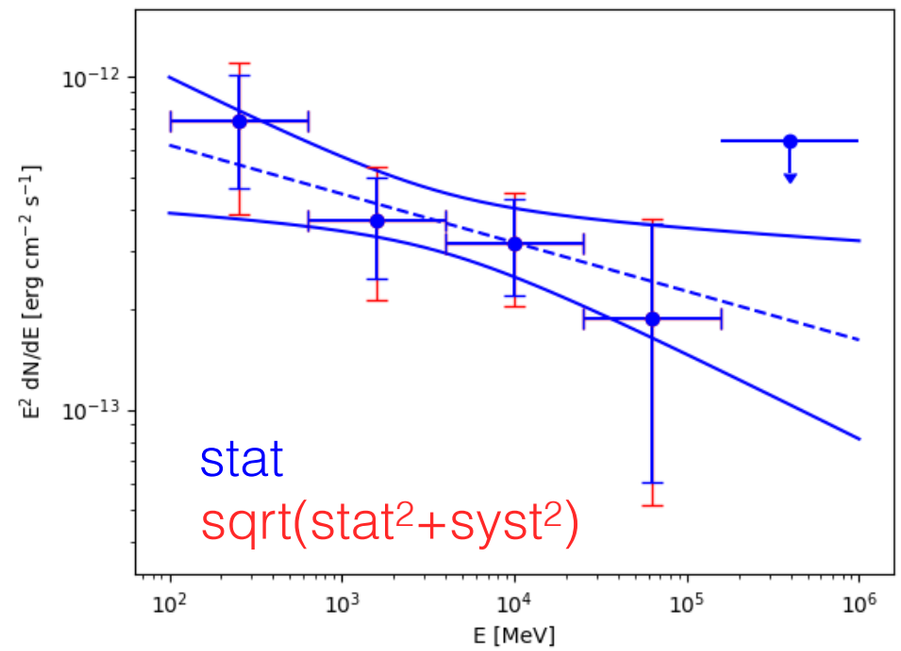
Analysis comparison

Zoomed TS map

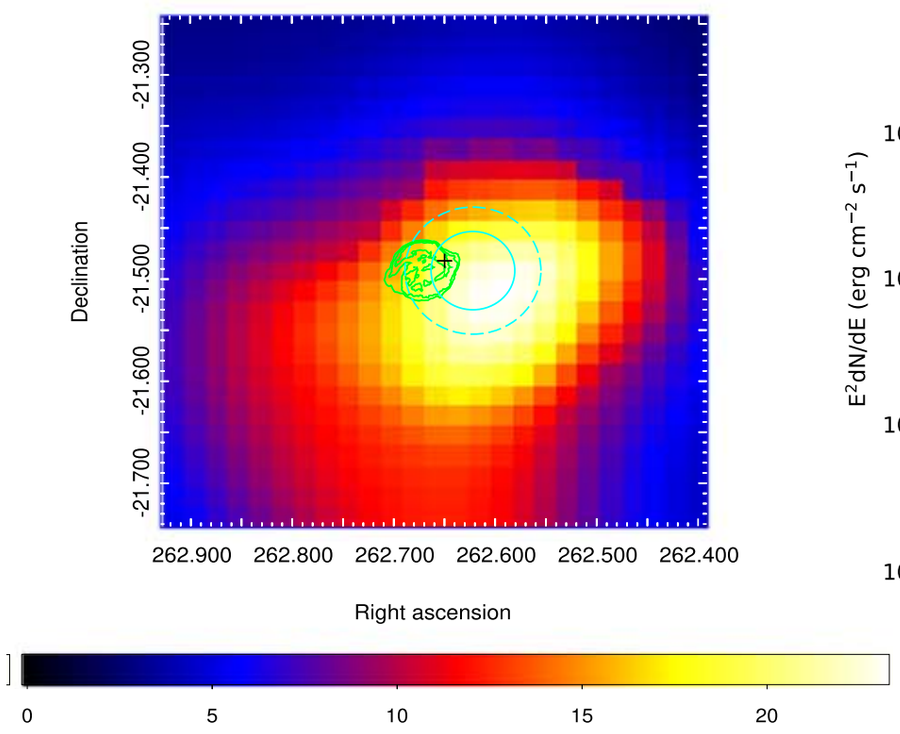
SED

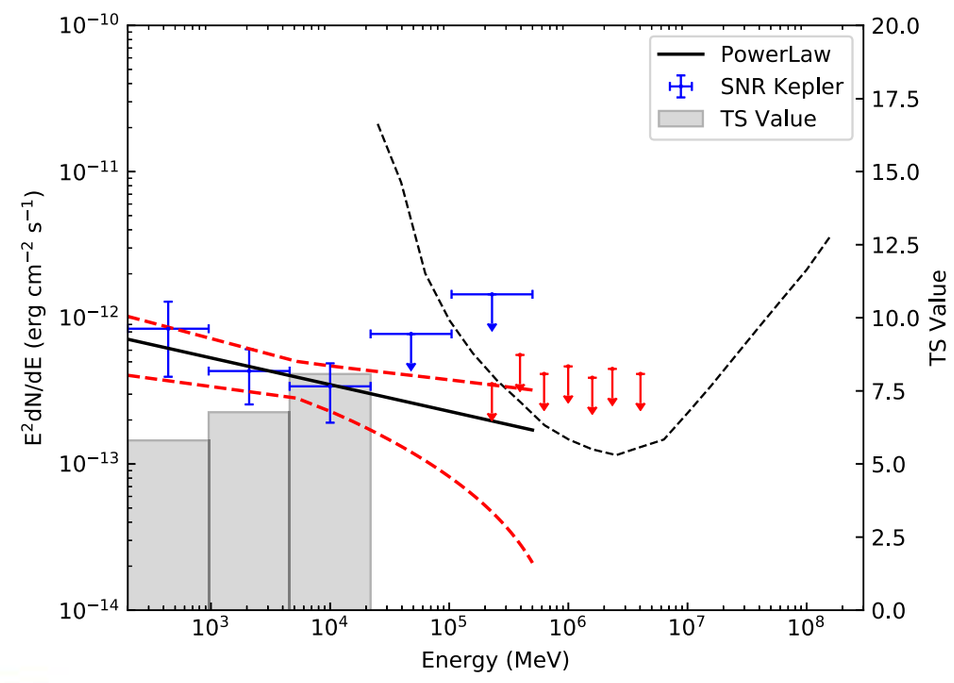
This work





Xiang21





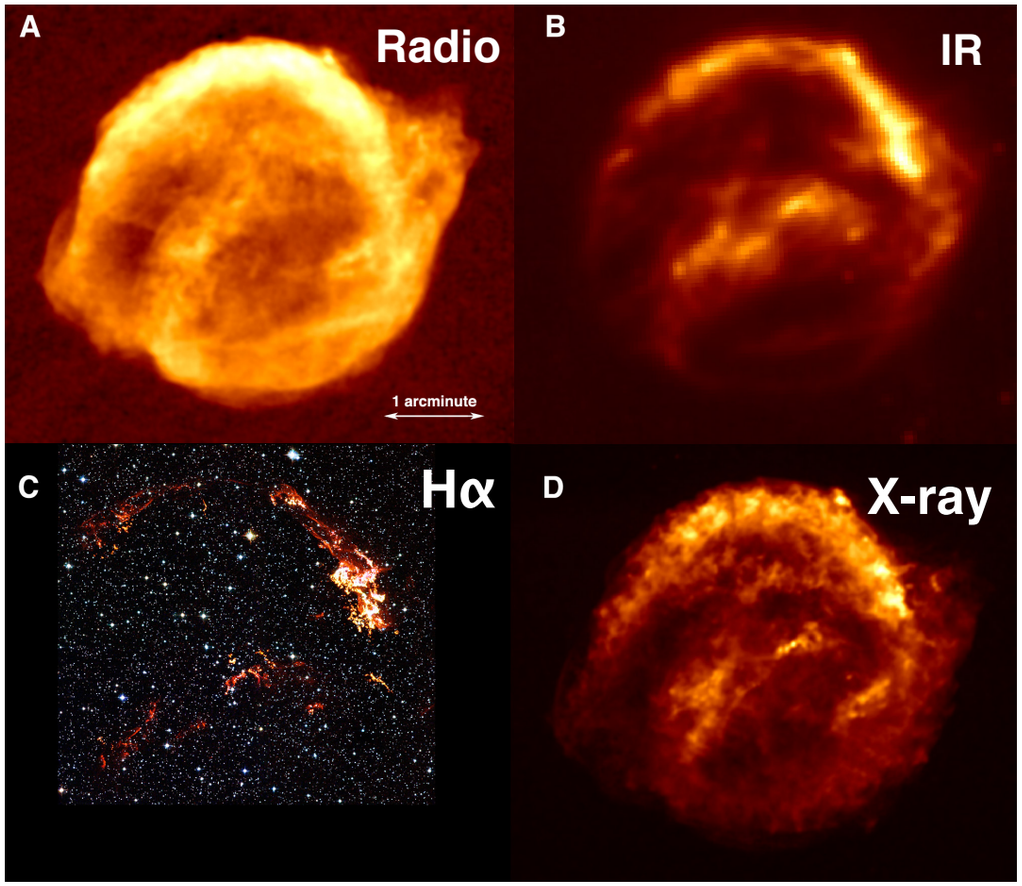
Is the emission compatible with Kepler : YES

- **No significant difference between best-fit point source and MWL**
- **Source not significantly extended: TS_{ext}=0.3**

Table 1. Results of the fit of the LAT data between 1 GeV and 1 TeV using different spatial models

Spatial model	TS	k	ΔAIC
X-ray template	28.6	2	-24.6
Radio template	28.8	2	-24.8
Infra-red template	29.7	2	-25.7
Best point source (PS)	32.1	4	-24.1

MWL templates and point source give comparable significance



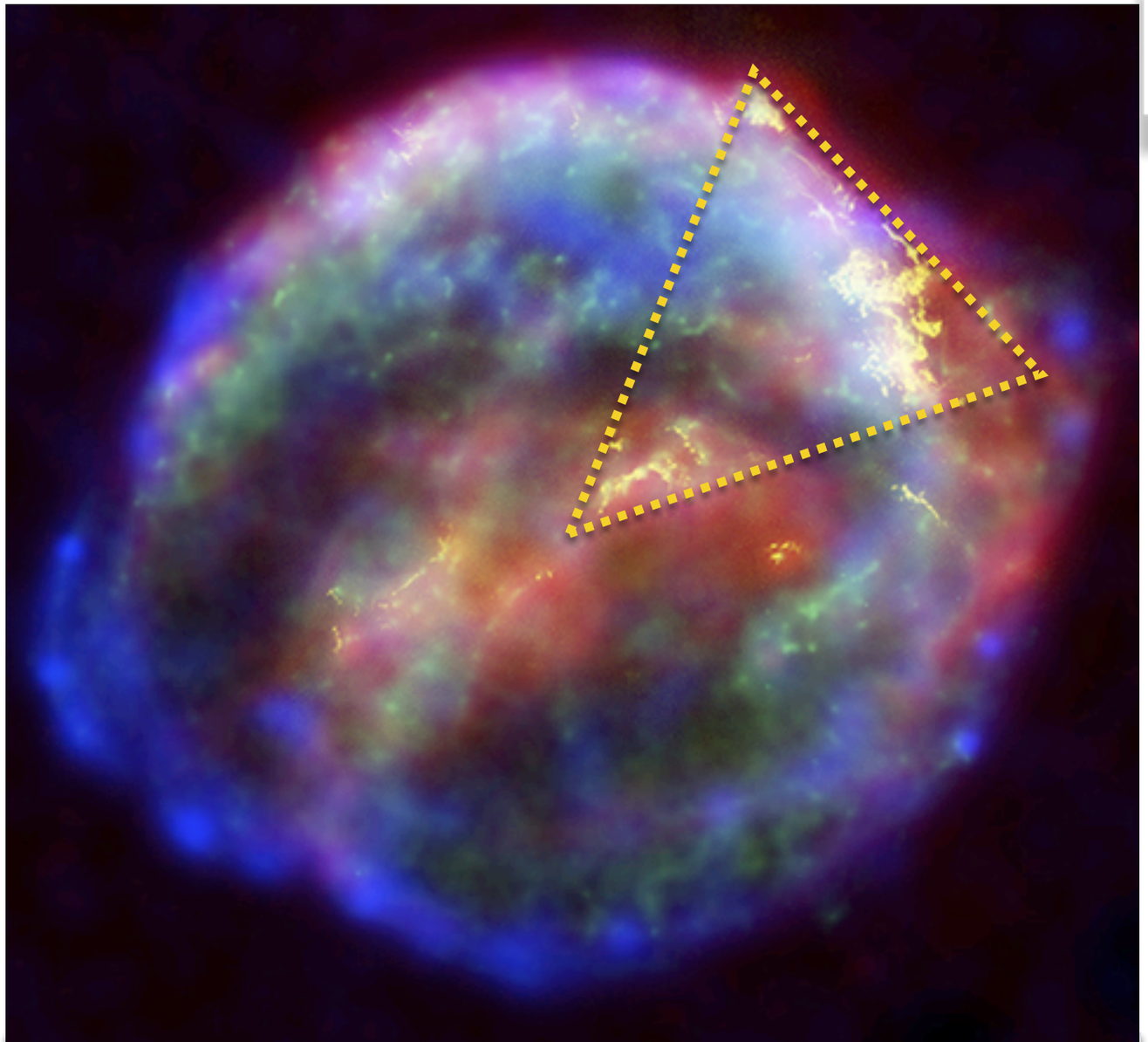
Modeling rationale

Gamma-ray stems from the NW interaction region where density is high (n_0~8 cm^{-3} from optical). Now distance well measured = 5.1 ± 0.8 kpc

Synchrotron + IC

Electron emission coming from fast shocks (Southern hemisphere)

V_{shock} ~5000 km/s
n_0~10^{-2} cm^{-3}

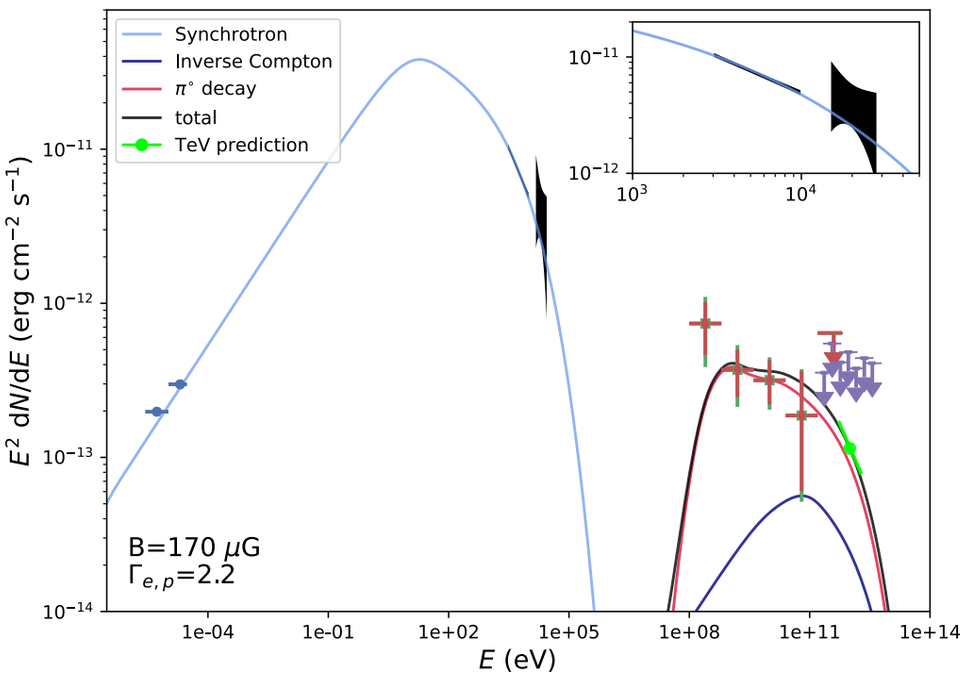


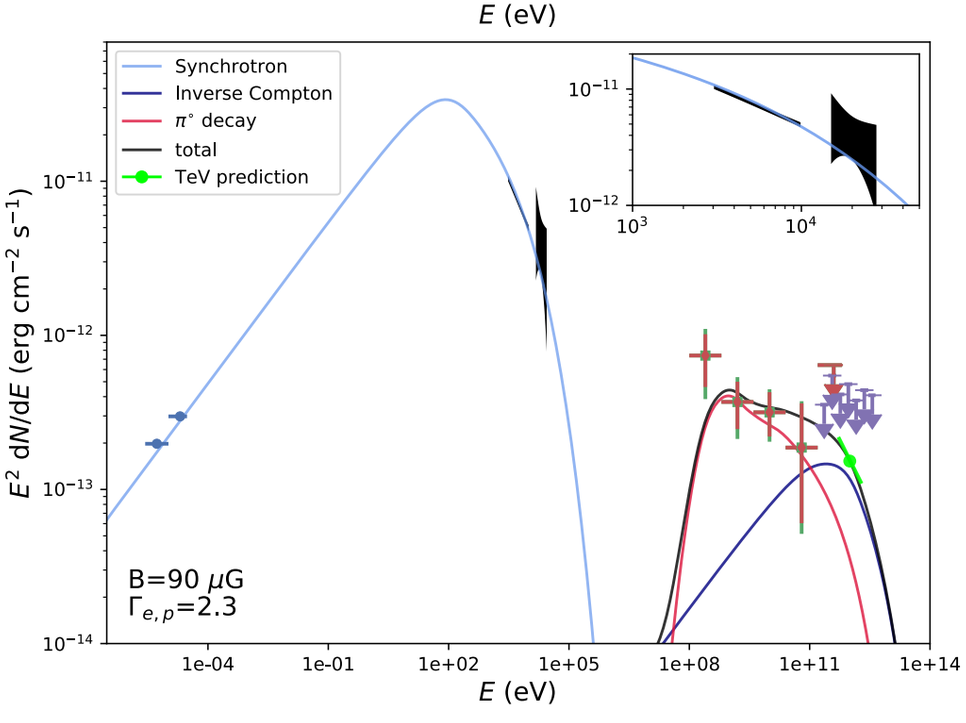
IR (24 μm Spitzer) Hα synchrotron (X)

Hadronic emission

Interaction with the CSM with ~8 cm^{-3}
Lower shock speed ~1700 km/s

SED modeling





B μG	n_0 cm^{-3}	$V_{\rm sh,e}$ km s^{-1}	$V_{\rm sh,p}$ km s^{-1}	$\Gamma_{e,1}/\Gamma_{e,2}$	$E_{\rm break,e}$ TeV	$E_{\rm max,e}$ TeV	Γ_p	$E_{\rm max,p}$ TeV	W_e erg	W_p erg
170	[8]	[5000]	[1700]	2.2/[3.2]	[1.1]	[18.4]	2.2	[21.2]	1×10^{47}	5.6×10^{48}
90	[8]	[5000]	[1700]	2.3/[3.3]	[3.9]	[25.3]	2.3	[11.2]	2.8×10^{47}	5.6×10^{48}

Only 4 d.o.f. B and Γ shape param (linked ?)

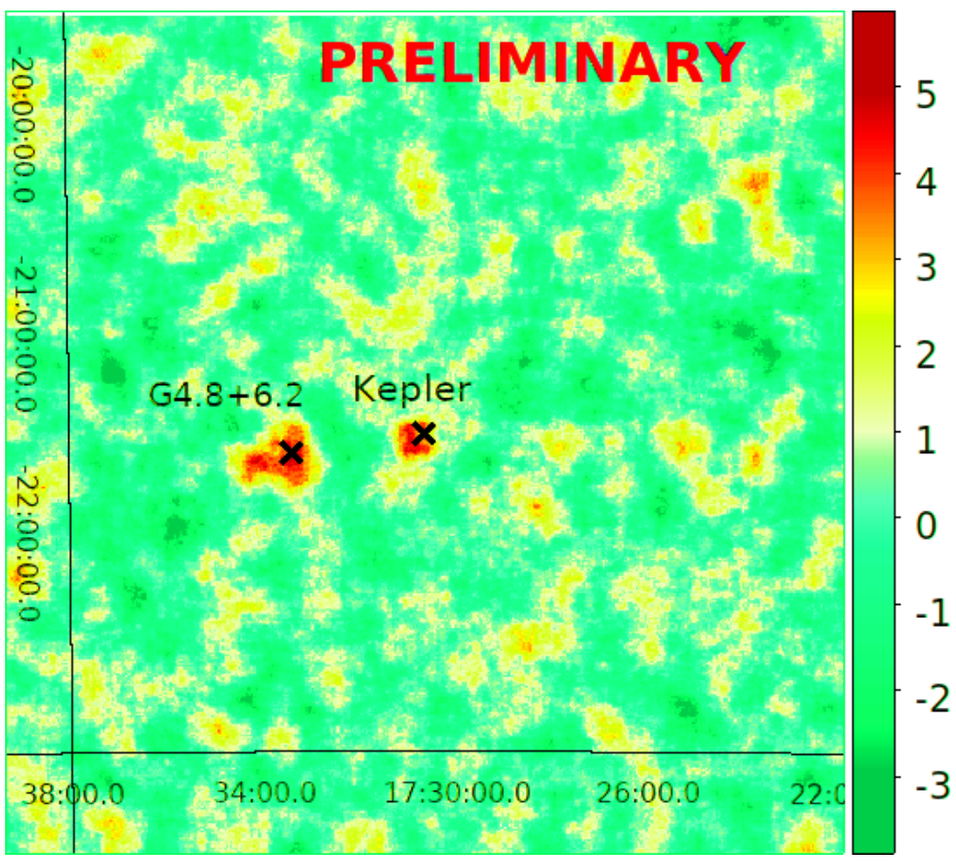
- **Most parameters are fixed from theory or literature**
- **$V_{sh,e}$ from Chandra X-ray synchrotron rims motion**
- **$V_{sh,p}$ from Hubble Hα motion**
- **Density from Hα**
- **Electrons are cooling limited => $E_{max,p}$ & E_{break}**
  - **Exponentially Cutoff BrokenPowerLaw with a change of slope after Ebreak to Γ2=Γ1+1.**
- **Proton acceleration is age limited =>$E_{max,p}$**
- **With an opening angle of 45° (filling factor 15%)**
  - **Local proton budget ~ 4% of E_{51}**

New : ICRC 2021 HESS Kepler detection

PROCEEDINGS OF SCIENCE

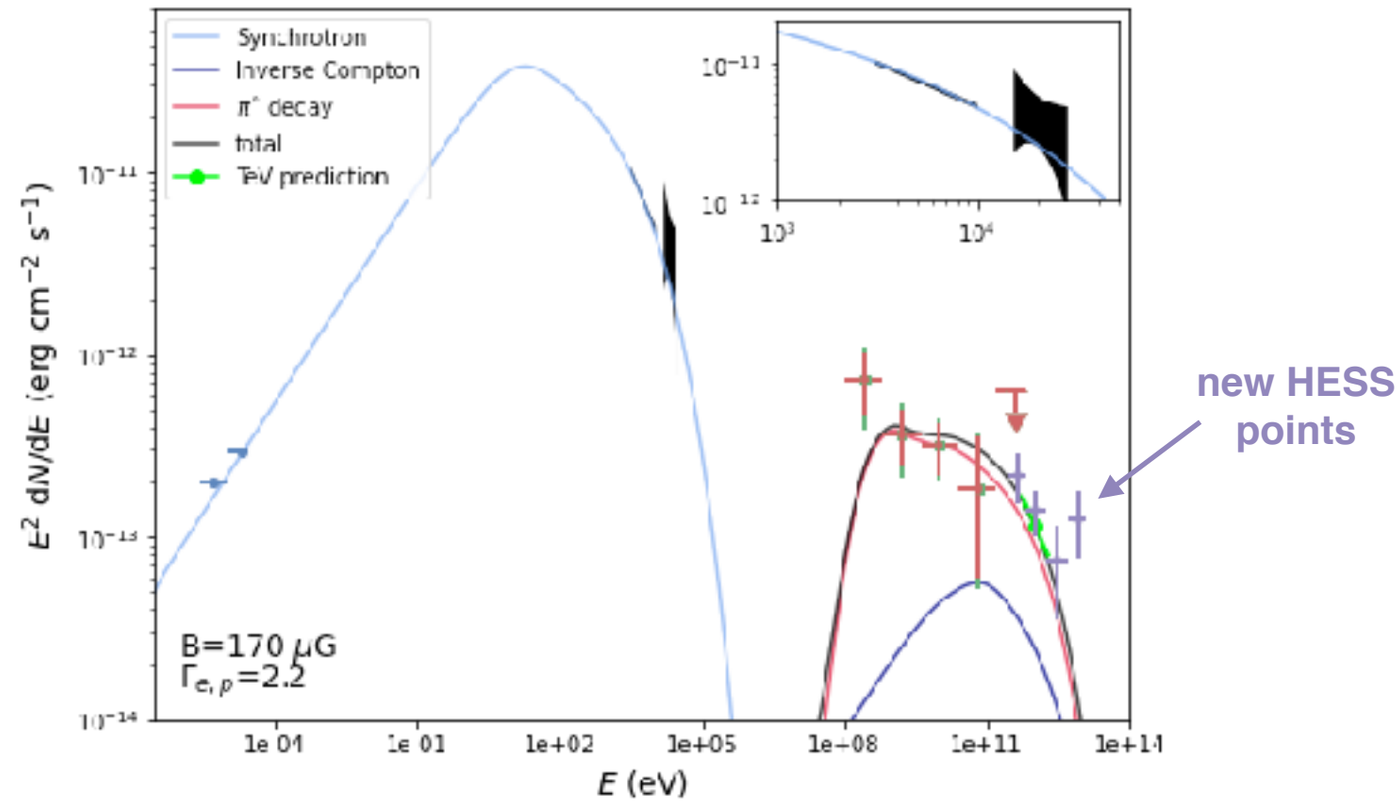
ONLINE ICRC 2021

Deep observations of Kepler's SNR with H.E.S.S.

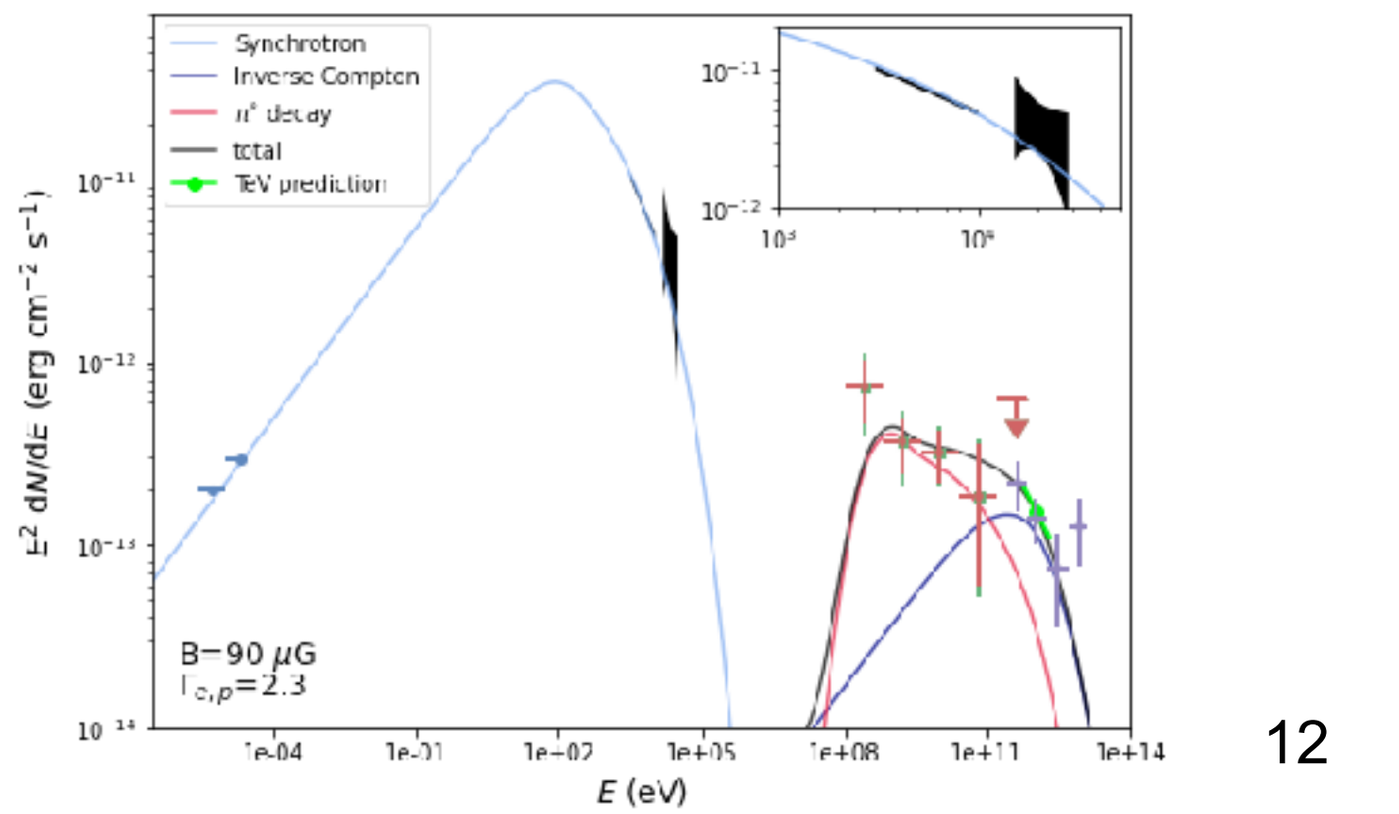


- **Very deep exposure: 152h !! (vs 13h before)**

same parameters as previous slide

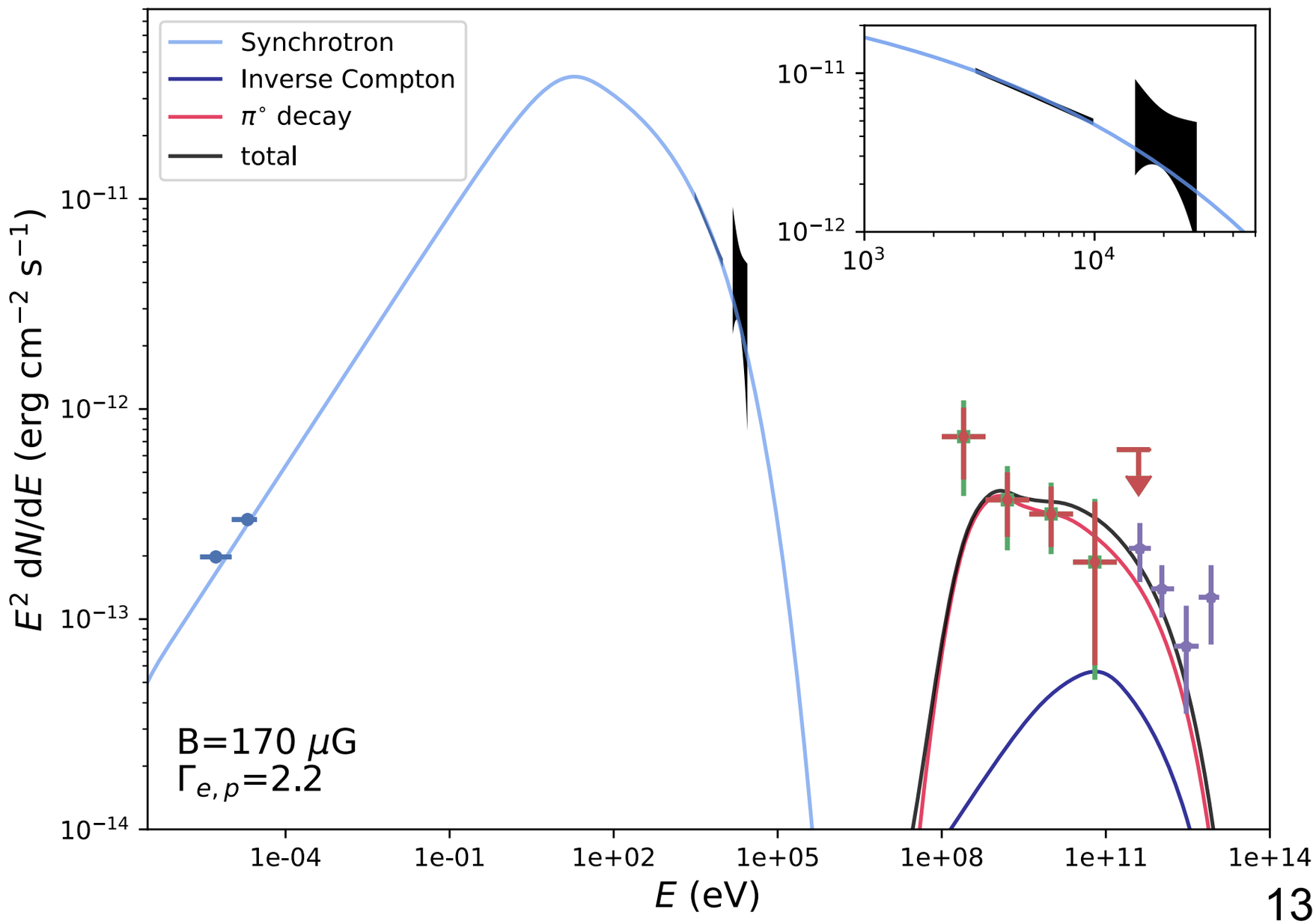


new HESS points



SED modeling

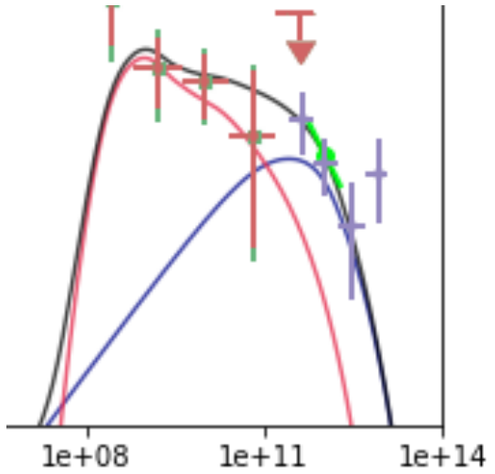
- **A high B implies a low Inverse Compton emission. Proton emission dominates.**
- **$E_{max,p}$ ~ 20 TeV for Vsh=1700 km/s (protons interacting with dense CSM)**
- **$E_{max,p}$ could be 170 TeV for Vsh=5000 km/s but low target density in South**



Conclusion

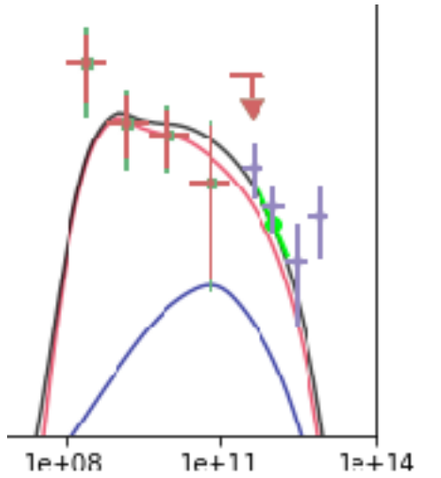
- Transform the candidate detection from TS=21 to TS~40 + stable to alt IEM
- Statistically compatible with the Kepler MWL templates (not outside)

- SED modeling assuming π^o from NW interaction. Fixing as many parameters as possible from the literature and theory.
- Requires a steep spectral slope of Γ=2.2-2.3.



- Compatible with the new HESS data points
- Depending on magnetic field, TeV dominated by:

  - ~100 μG : IC dominated and should arise from Southern fast shocks
  - >150 μG : π^o dominated and arising from NW interaction region



  - Angular separation of 0.05° at the limit of current IACT (=>CTA)