Fermilab

Unraveling Geminga TeV halo with CTA

Elena Pinetti

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Unraveling TeV Halos with the Cherenkov Telescope Array

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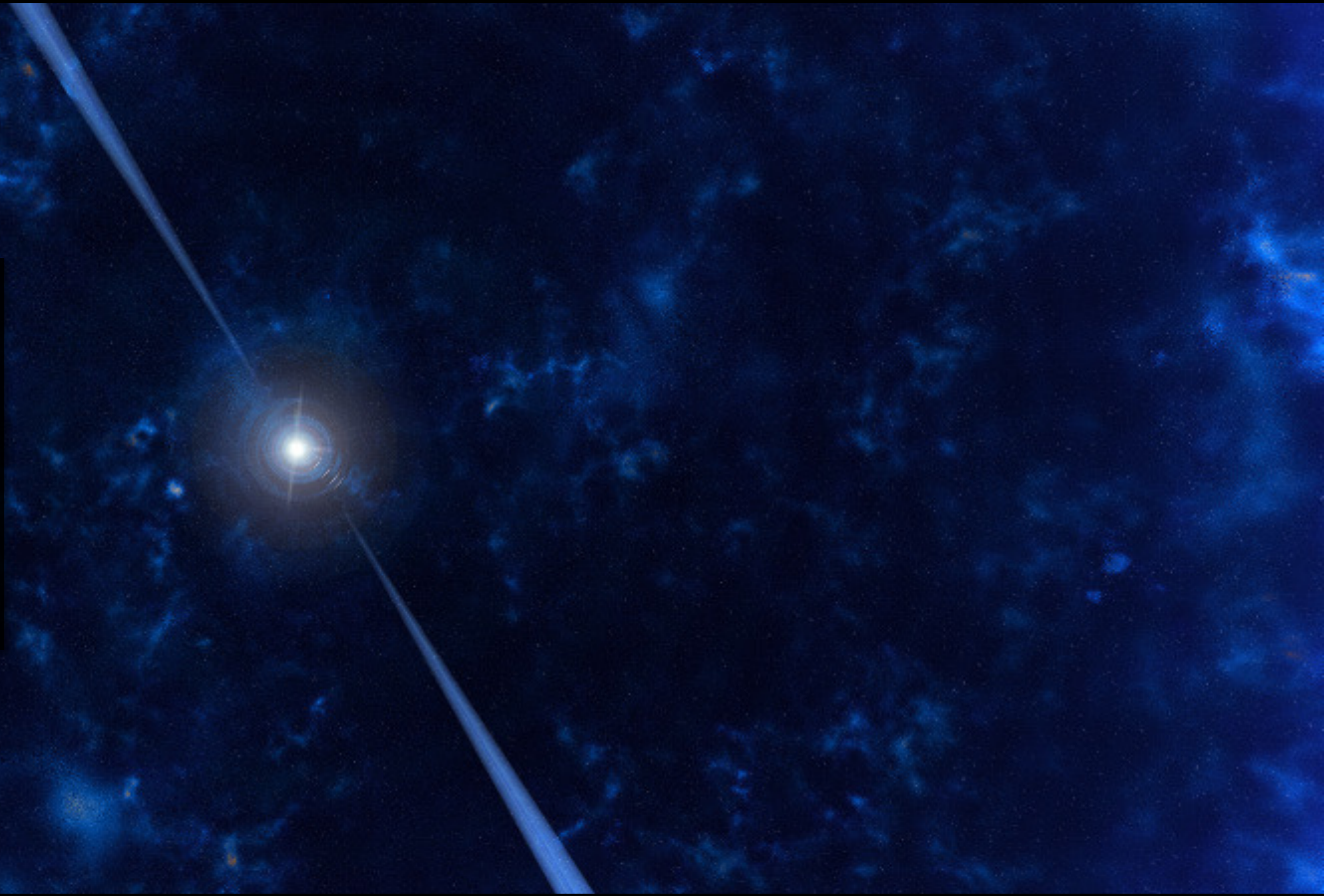
Reasons to be excited about TeV halos

- New discovery method to detect "invisible pulsars"
- Evolution and properties of pulsars
- Diffusion of cosmic rays in the Milky Way
- Origin of positron and Galactic Center excess?

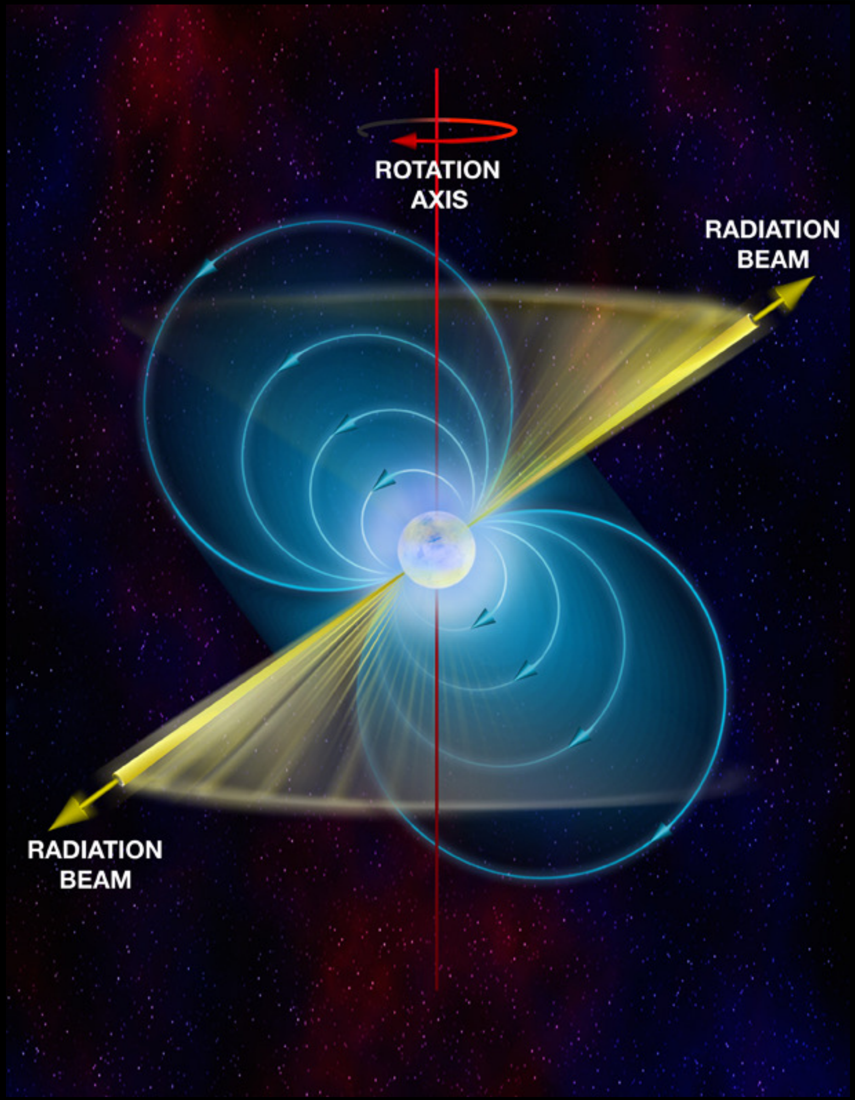
Outline

- ❑ Pulsars and TeV halos
- ❑ Theoretical modelling
- ❑ Preliminary results



Pulsars: "Pulsating Stars"

Neutron stars Fast-rotating Highly magnetised



Fun facts:

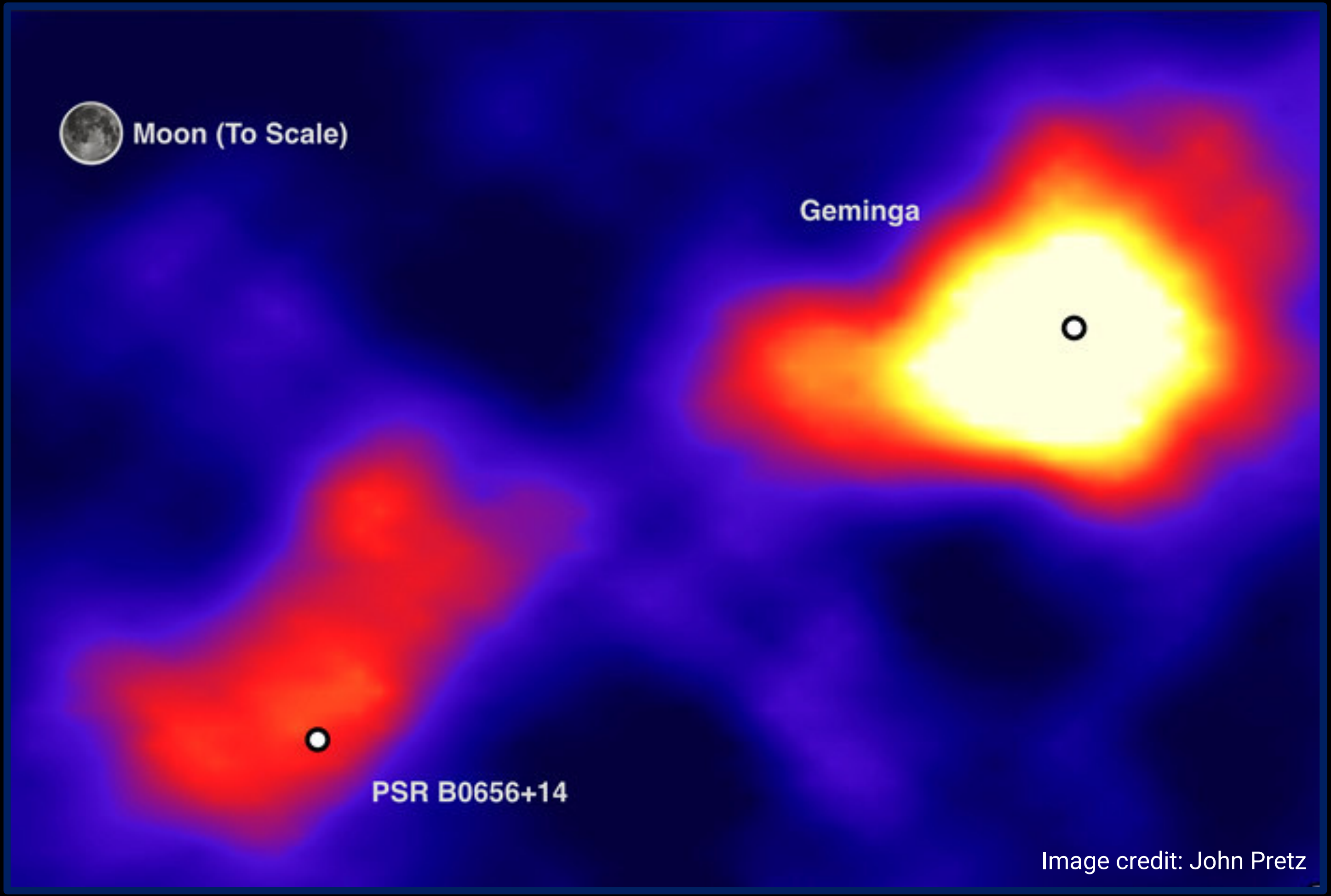
- Discovered in 1967 by the grad student Jocelyn Bell
- 3000 pulsars, mostly radio pulsars
- Their periods span 4 orders of magnitude:
  9.435 s to 1.395 ms

Discovery of TeV halos

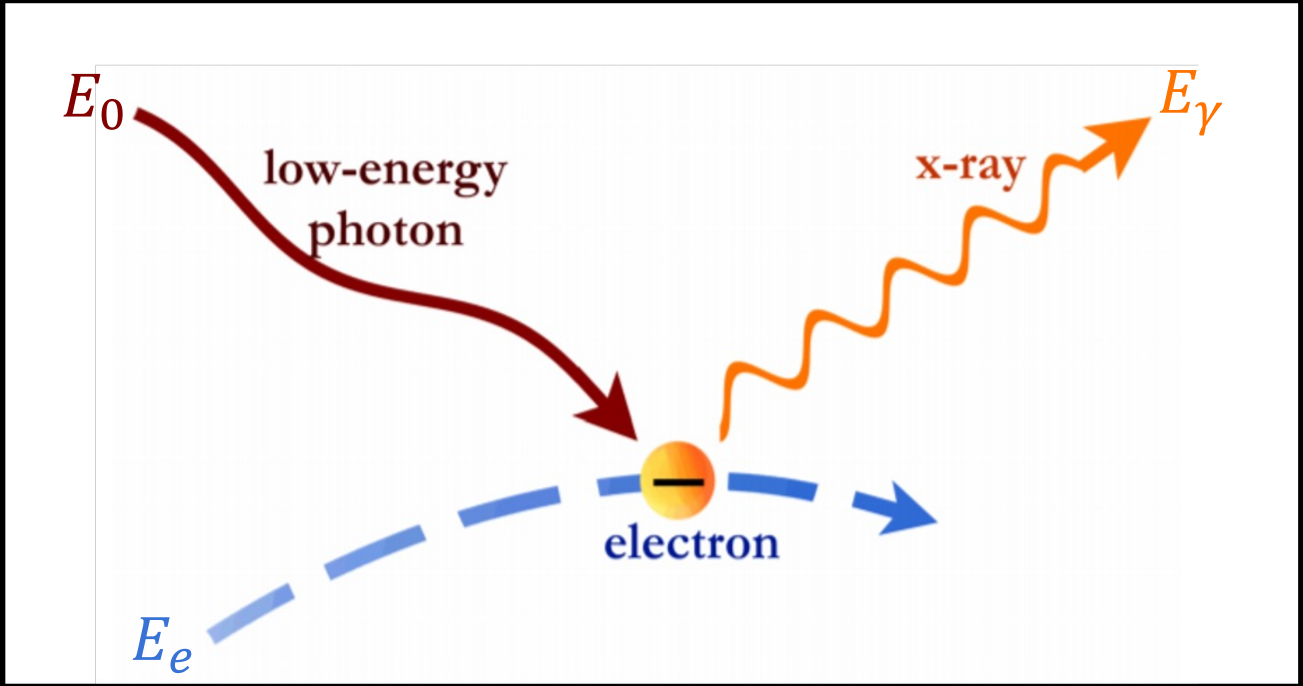
In 2017, HAWC Observatory discovered a bright gamma-ray emission around Geminga

Key observations:

- Bright (10^{32} erg/s)
- TeV gamma-rays
- Spatially extended



Inverse Compton scattering



$$\frac{d\phi}{dE\,dt\,dV} = \int dE_e \frac{dn_e}{dE_e}\frac{dN_\gamma}{dE_\gamma}$$

Electron number density

Photon distribution

Transport Equation

$$\frac{\partial}{\partial t}\frac{dn_e}{dE_e}(E_e,\vec{r},t) - \vec{\nabla}\cdot\left[D(E_e,\vec{r})\vec{\nabla}\frac{dn_e}{dE_e}(E_e,\vec{r},t)\right] + \frac{\partial}{\partial E_e}\left[b_{tot}(E_e,\vec{r})\frac{dn_e}{dE_e}(E_e,\vec{r},t)\right] = Q(E_e,\vec{r},t)$$

Electron number density

Diffusion

Energy losses

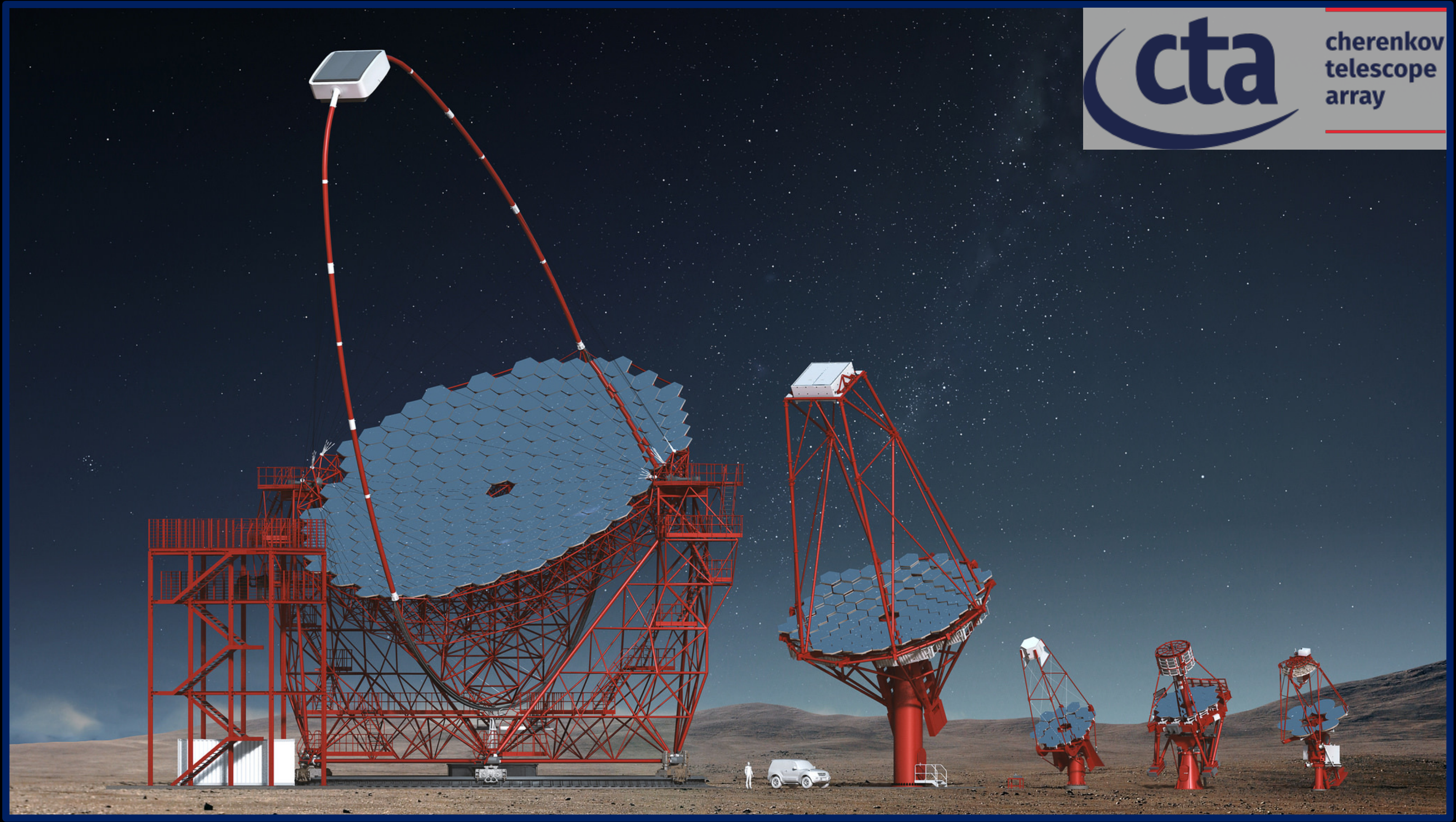
Source term

Models

1 Diffusion model

2 Injection spectrum

3 Time evolution

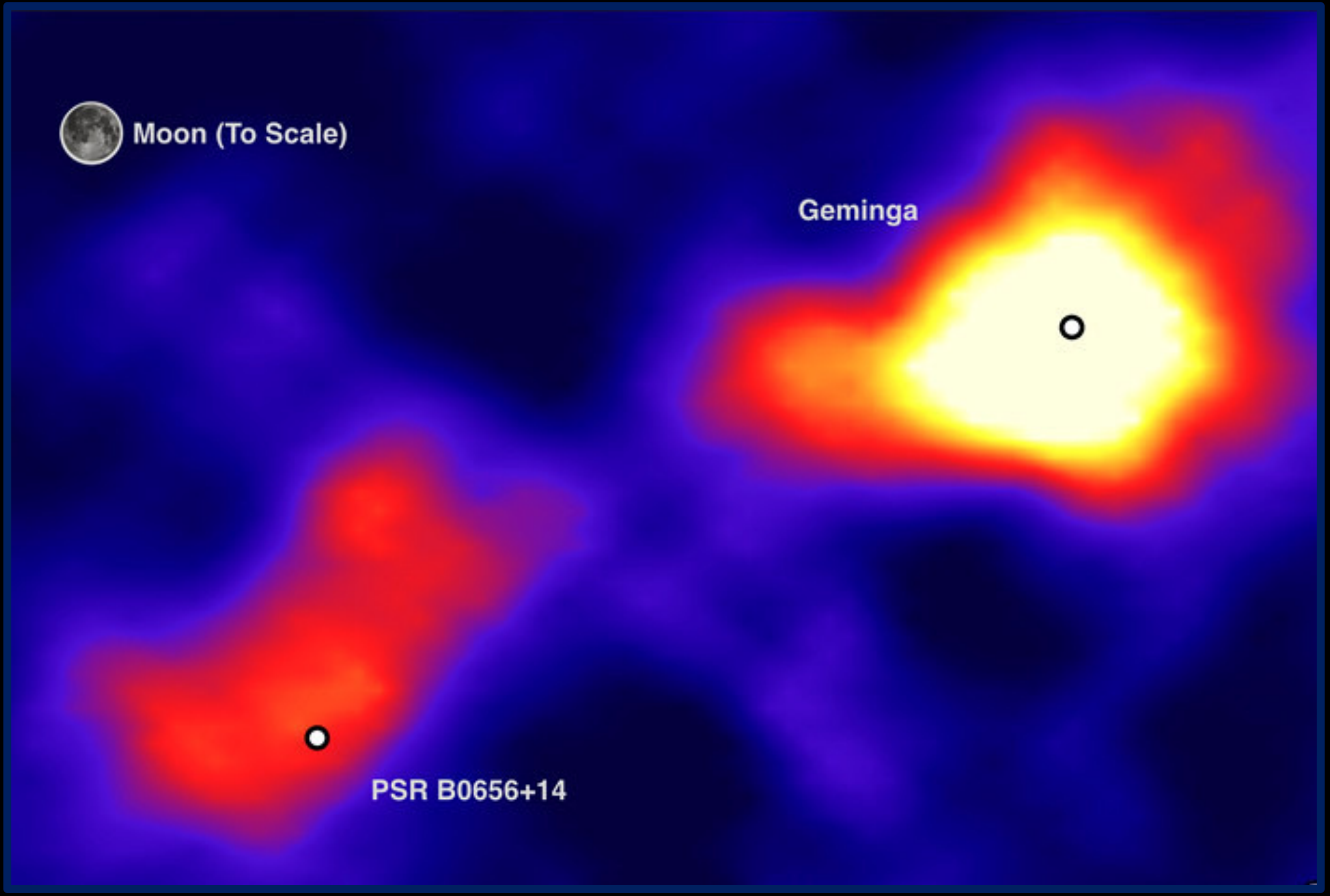


Diffusion models

See Tim Linden's talk!

$$D = \begin{cases} D_0 E^{\delta} & r < r_h \\ D_{ISM} E^{\delta_{ISM}} & r > r_h \end{cases}$$

D_{ISM} [cm^2/s]	D_0 [cm^2/s]	δ	δ_h	r_h
10^{28}	10^{26}	0.4	1/3	30 pc



Injected spectrum

$$Q(E_e) \sim E_e^{\alpha} \exp\left(-\frac{E_e}{E_{co}}\right)$$

Energy spectrum

Energy cutoff

Time evolution

$$P = P_0 \left(1 + \frac{t}{\tau_0}\right)^{\frac{1}{n-1}}$$

Initial period

Spindown timescale

Braking index

$$\text{2 regimes:} \begin{cases} t \ll \tau_0 \\ t \gg \tau_0 \end{cases}$$

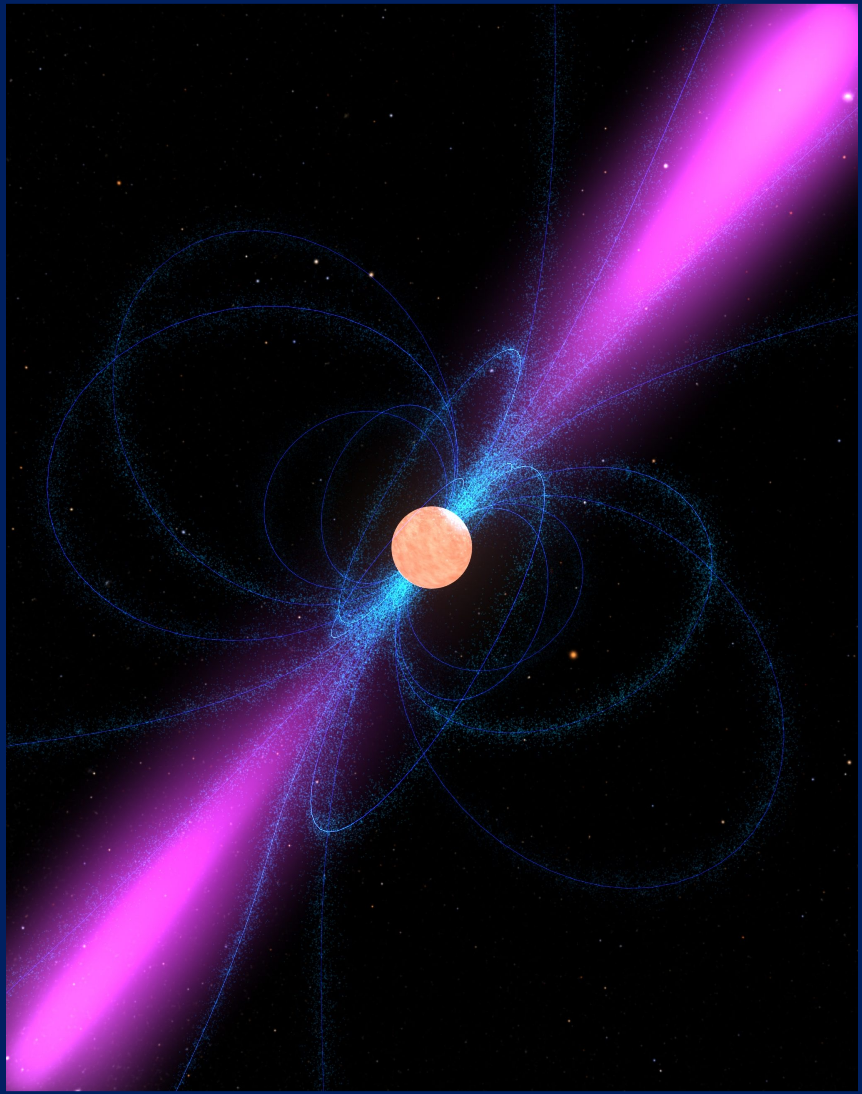
What do we measure?

1 Period

2 Period derivate

→ Age of the pulsar
Spindown luminosity
Surface magnetic field

3 Flux → Size of the halo
Injected spectrum



Energy flux

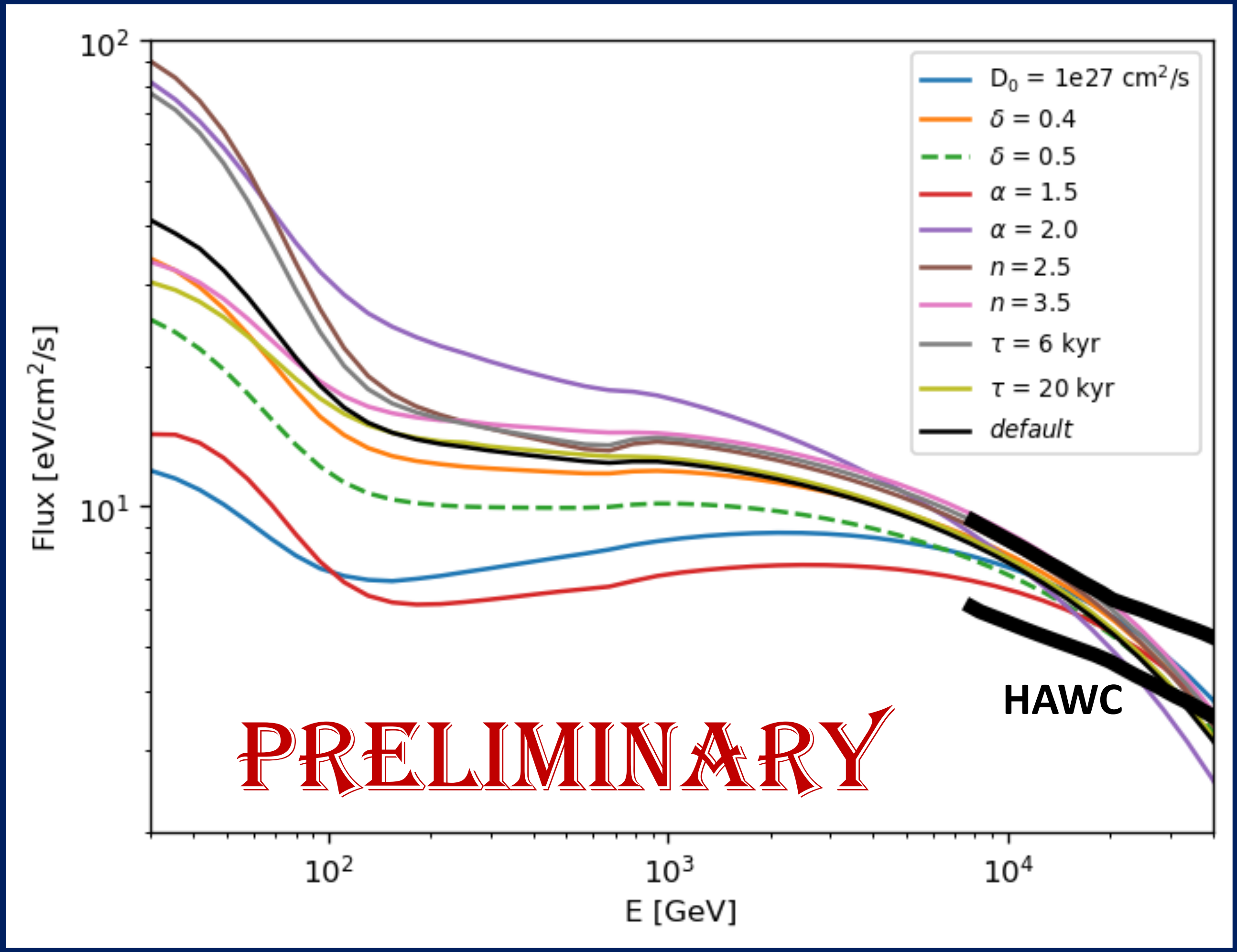
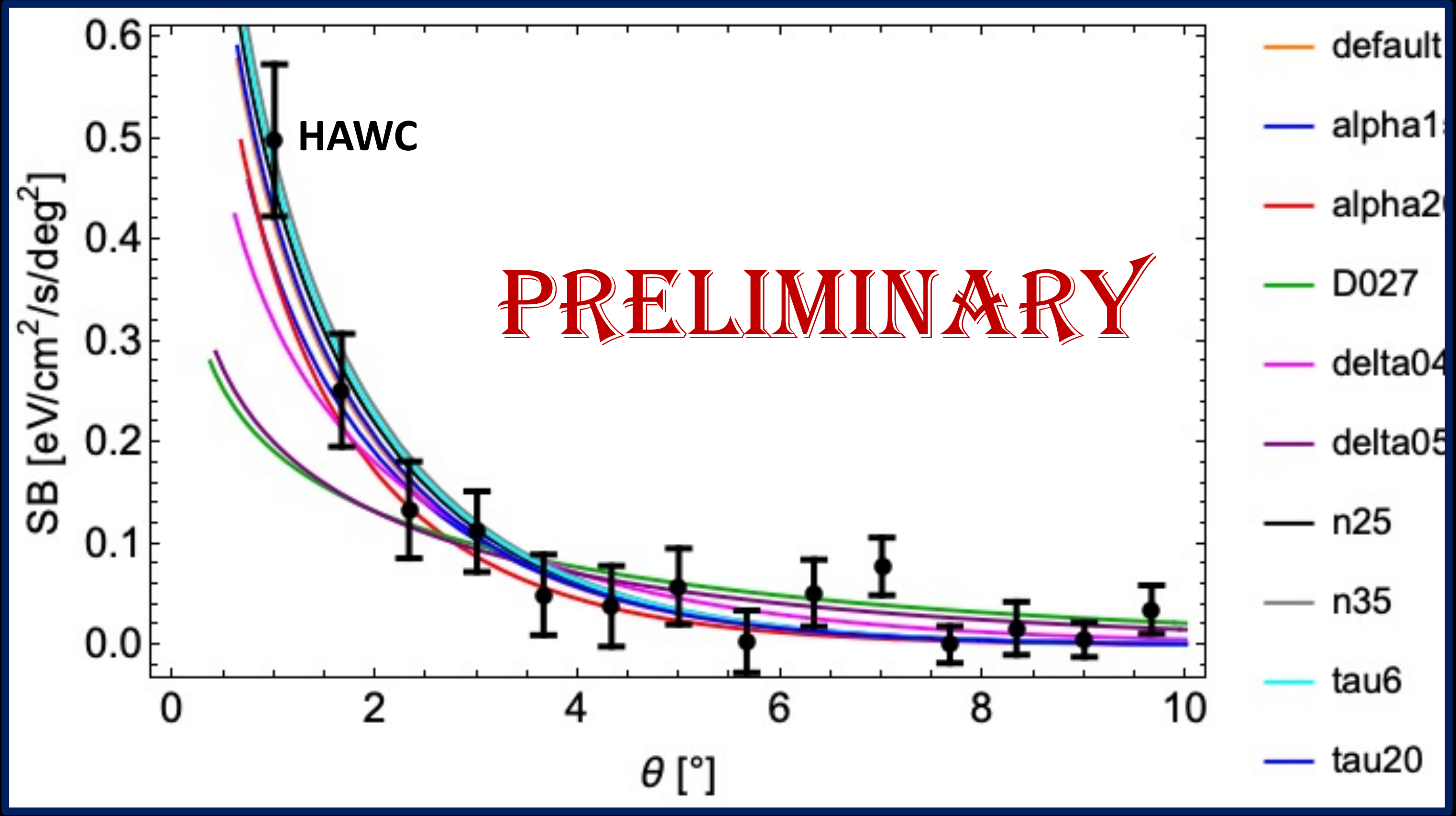


Table 1. Default configuration.

α	D_0	δ	$E_{\rm cut}$	n	r_b	τ
1.8	10^{26} cm/s	1/3	500 TeV	3	30 pc	12 kyr

Surface brightness



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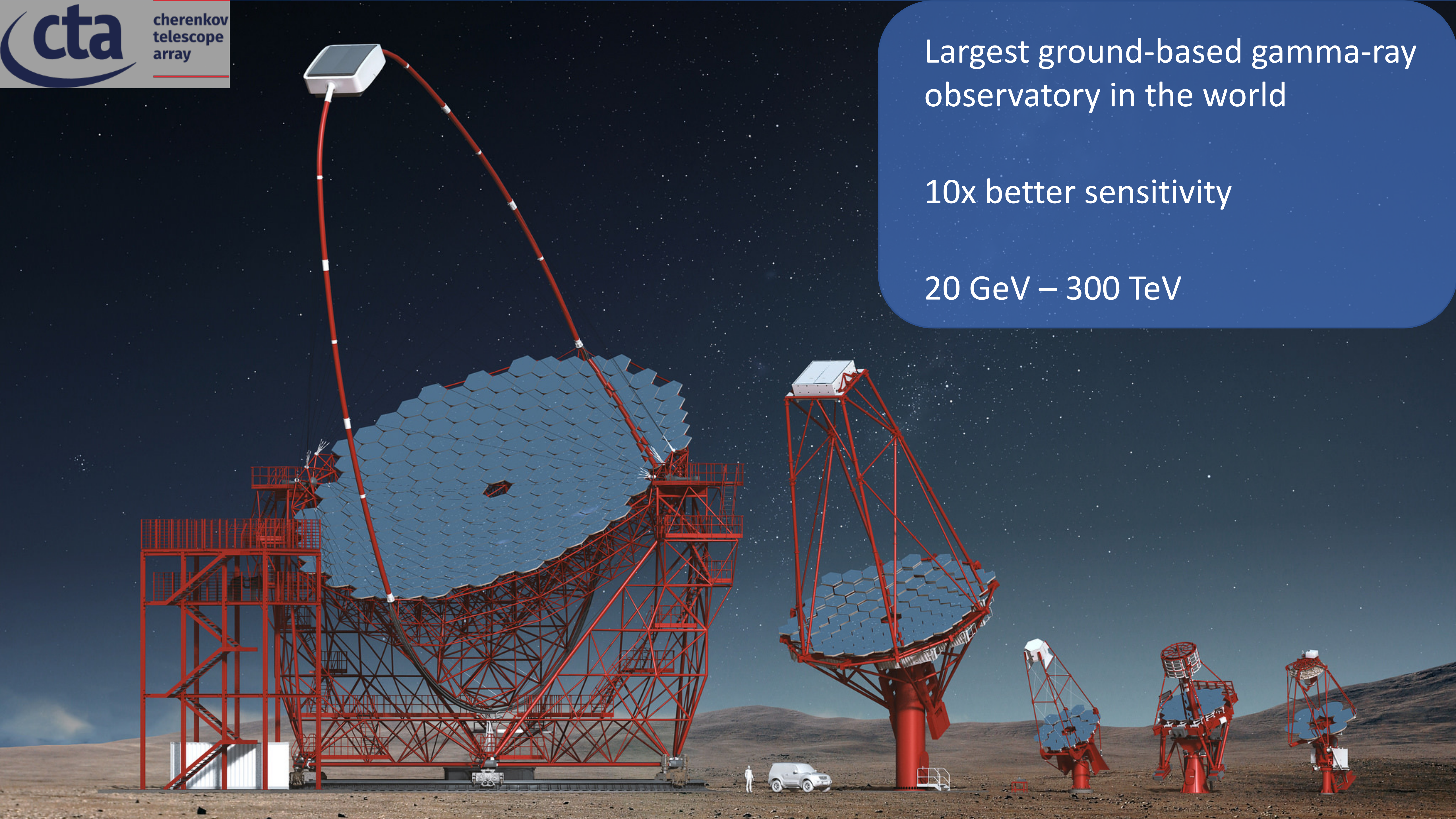
cta cherenkov telescope array

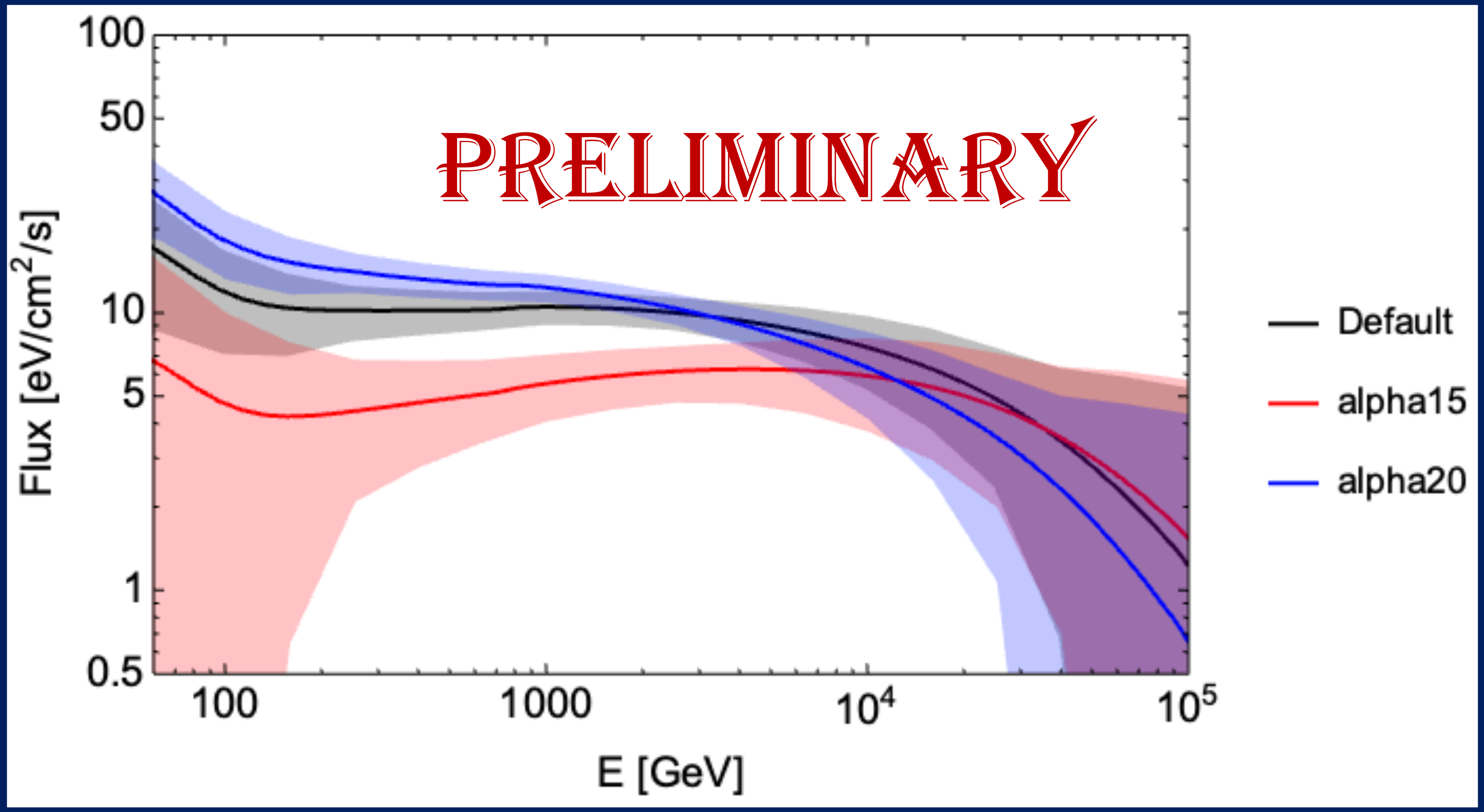


Largest ground-based gamma-ray observatory in the world

10x better sensitivity

20 GeV – 300 TeV

Models



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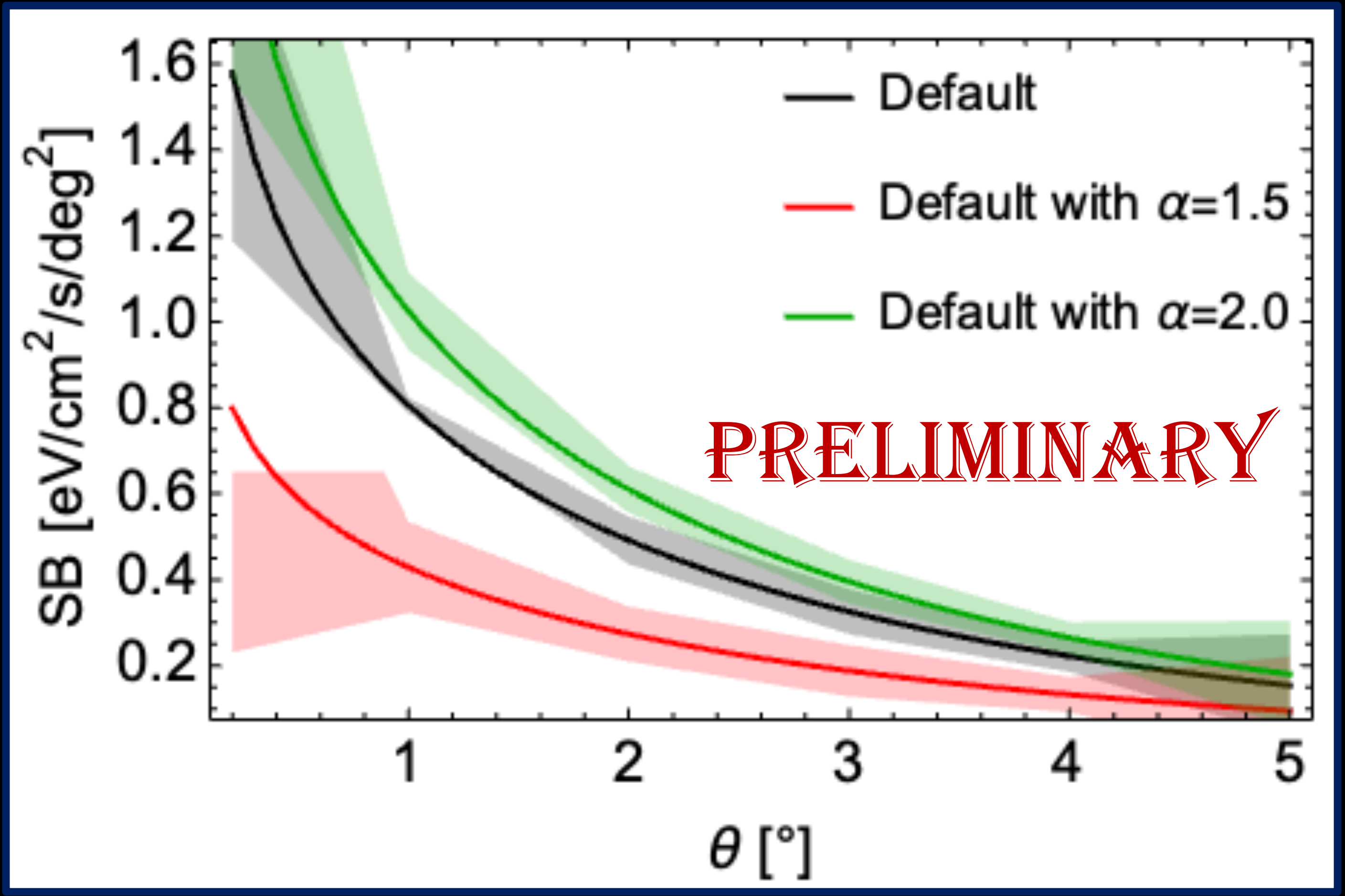

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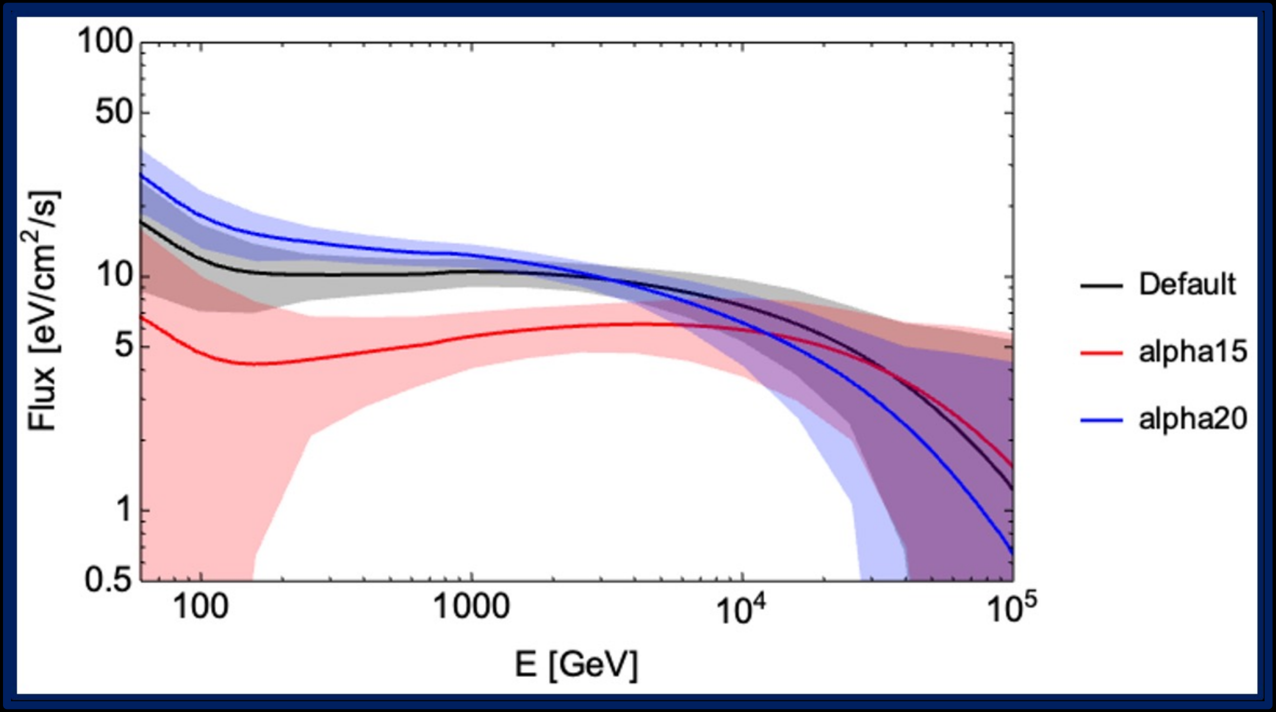
Conclusions

1. TeV halos opens a new window in understanding the properties of pulsars

2. Energy and angular fluxes provide complementary information

3. CTA will be able to better constrain the diffusion, injection spectrum and time evolution of pulsars



Conclusions

Thank you for your attention!

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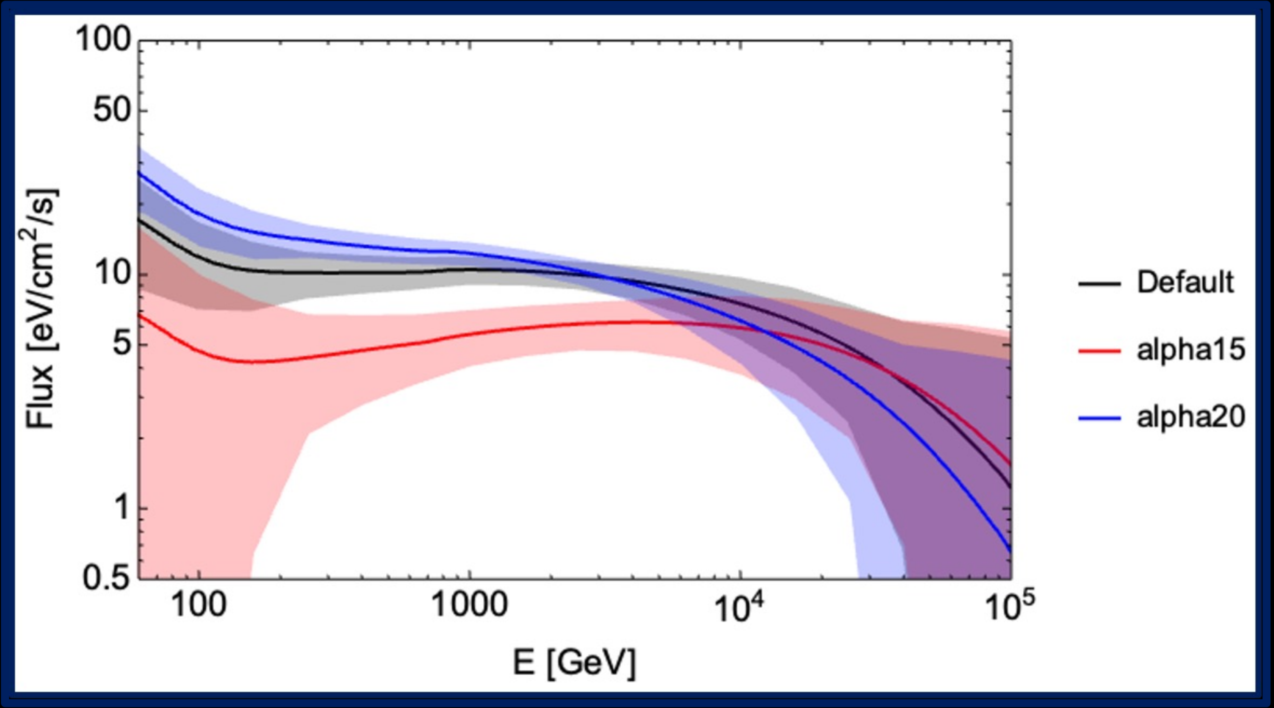


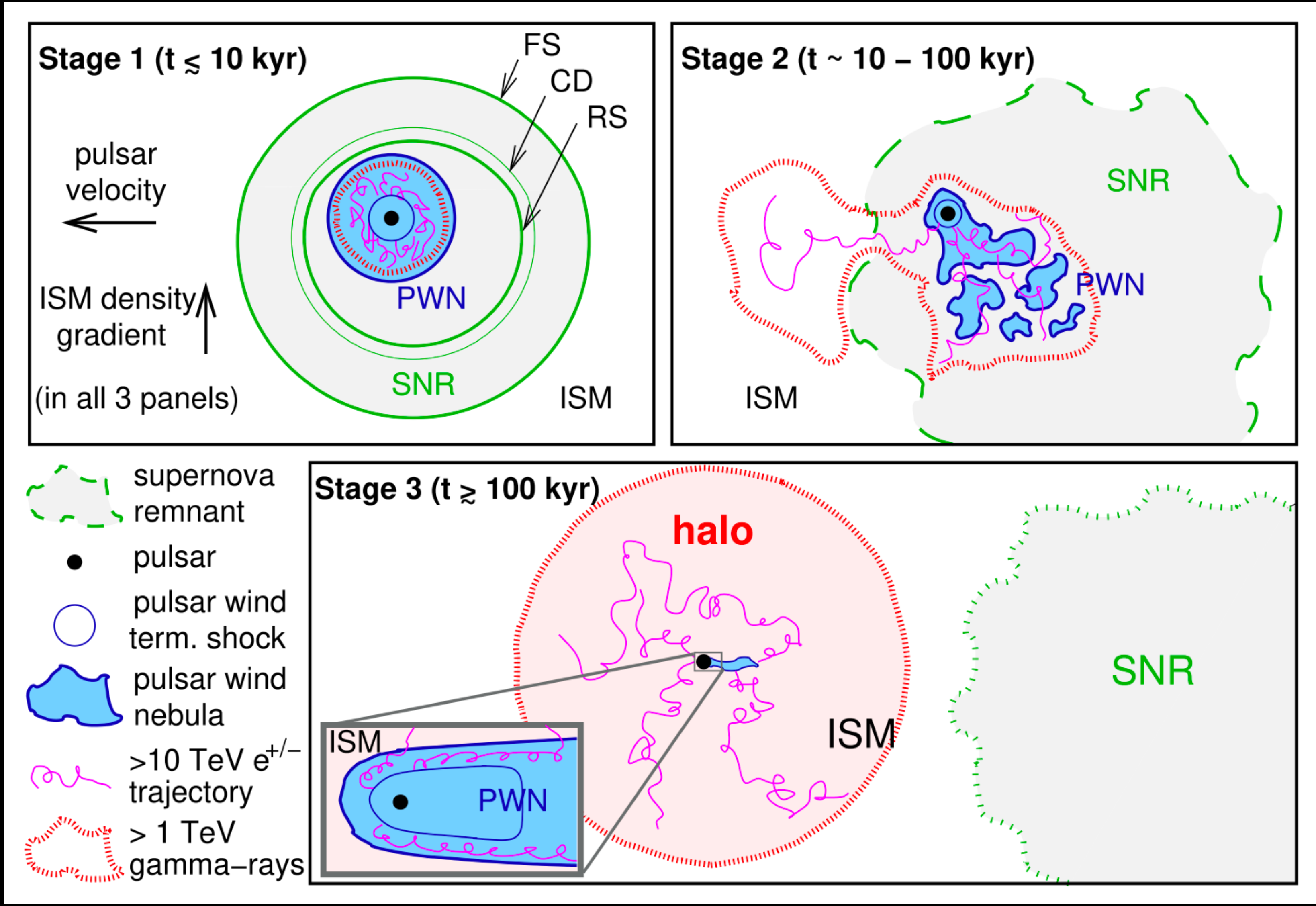
Back-up slides

PRELIMINARY

Models

	alpha_15	alpha_20	D0_1e27	default	delta_04	delta_05	n_25	n_35	tau_20kyr	tau_6kyr
alpha_15	χ^2_{red} p-value df	26.03 6.62e-36 7	$\chi^2_{th,\,total}$= =0.48 too low	13.11 5.27e-17 7	6.33 1.86e-07 7	1.49 2.16e-01 3	16.87 1.93e-22 7	16.75 4.22e-25 8	12.46 4.63e-16 7	16.53 6.03e-22 7
alpha_20	18.72 3.84e-25 7		19.16 8.66e-26 7	3.48 3.79e-03 5	7.02 1.76e-07 6	11.90 2.94e-15 7	4.18 2.17e-03 4	2.07 6.59e-02 5	3.73 2.23e-03 5	3.50 7.27e-03 4
D0_1e27	$\chi^2_{th,\,total}$= =0.49 too low	25.44 4.89e-35 7		11.51 1.76e-16 8	6.64 7.14e-08 7	1.18 3.17e-01 3	17.05 1.04e-22 7	16.51 1.05e-24 8	11.03 1.07e-15 8	14.71 1.01e-21 8
default	10.89 8.02e-14 7	4.58 3.50e-04 5	10.16 2.73e-14 8		3.37 1.77e-02 3	5.67 3.09e-07 8	1.91 1.48e-01 2	0.93 4.23e-01 3	$\chi^2_{th,\,total}$= =0.52 too low	1.54 2.14e-01 1
delta_04	5.40 3.31e-06 7	8.08 9.46e-09 6	5.58 1.88e-06 7	0.90 4.42e-01 3		2.85 1.41e-02 5	4.88 1.83e-04 5	3.43 1.13e-03 7	0.98 4.18e-01 4	3.03 5.80e-03 6
delta_05	2.02 1.08e-01 3	16.16 2.09e-21 7	2.01 1.09e-01 3	6.53 1.52e-08 8	3.67 2.56e-03 5		8.57 1.49e-10 7	11.03 1.06e-15 8	7.29 9.10e-09 7	7.85 1.31e-10 8
n_25	14.18 1.55e-18 7	7.03 1.19e-05 4	14.95 1.19e-19 7	4.62 9.84e-03 2	6.10 1.16e-05 5	9.21 1.90e-11 7		6.09 1.19e-05 5	6.06 2.34e-03 2	$\chi^2_{th,\,total}$= =1.02 too low
n_35	18.55 4.22e-28 8	5.57 3.93e-05 5	19.25 2.90e-29 8	3.19 2.26e-02 3	7.34 7.64e-09 7	13.13 3.90e-19 8	6.97 1.62e-06 5		5.27 5.13e-03 2	4.88 6.22e-04 4
tau_20kyr	8.67 1.11e-10 7	9.00 1.45e-08 5	9.15 1.13e-12 8	$\chi^2_{th,\,total}$= =0.52 too low	2.45 4.38e-02 4	6.21 2.68e-07 7	12.02 6.02e-06 2	4.02 1.80e-02 2		11.24 7.99e-04 1
tau_6kyr	15.32 3.44e-20 7	2.55 3.74e-02 4	13.83 2.78e-20 8	2.44 1.18e-01 1	5.39 1.41e-05 6	8.25 3.02e-11 8	$\chi^2_{th,\,total}$= =1.02 too low	3.38 9.07e-03 4	4.36 3.67e-02 1	

Pulsar's evolution



Liu, arXiv:2207.04011v1

Geminga

$$P = 237\ ms$$

$$\dot{P} = 1.1 \times 10^{14}$$

$$T = 340\ kyr$$

$$\dot{E} = 3.25 \times 10^{34}\ erg/s$$