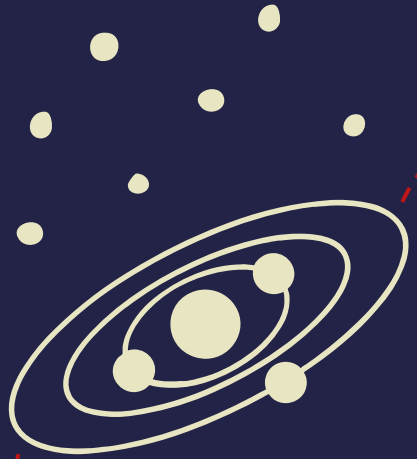

# IN SEARCH OF EVIDENCE OF FLARES IN T TAURI STARS AS γ-RAY EMITTERS

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Fermi Summer School
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RÍO NEGRO UNIVERSIDAD NACIONAL

CONICET

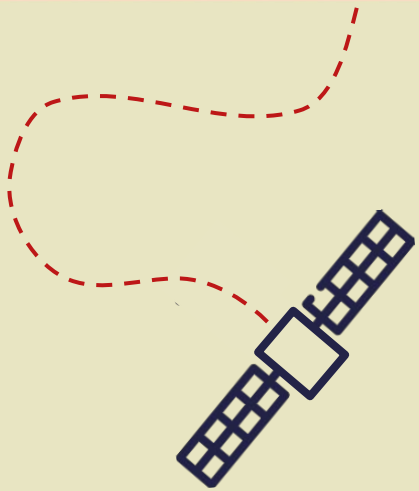
# FERMI GAMMA-RAY SPACE TELESCOPE

## LARGE AREA TELESCOPE (20 MeV – 300 GeV)

CATALOGS

- 1FGL — 1,451 sources
- 2FGL — 1,873 sources
- 3FGL — 3,033 sources
- 4FGL-DR4 — 7,194 sources

- **< 73%** Identified sources
- **> 27%** Unidentified sources

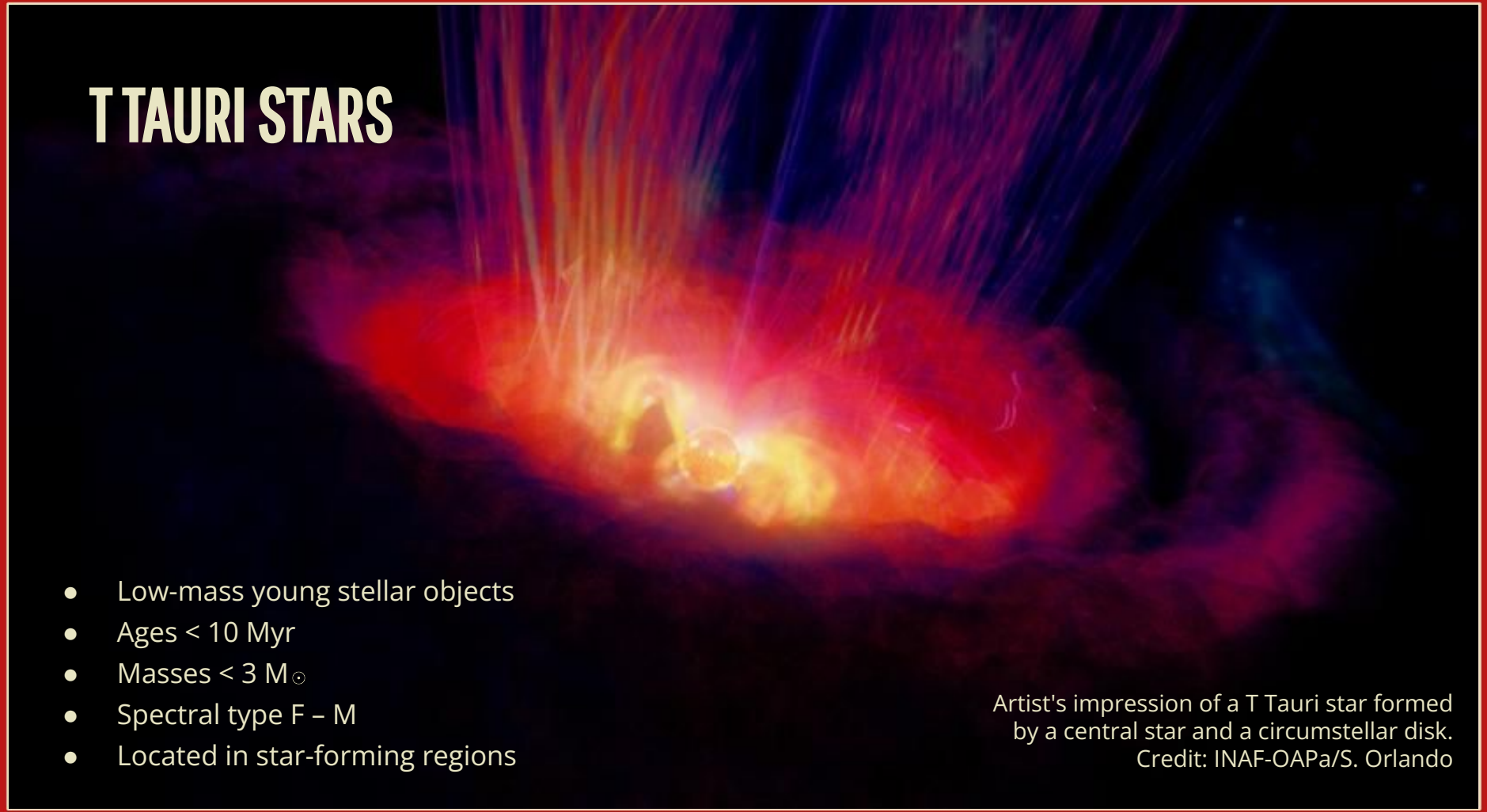


# γ-RAY EMITTERS

- PULSARS
- STARBURSTS
- SUPERNOVA REMNANTS
- AGNs
- GALAXY CLUSTERS
- COLLIDING-WIND BINARY SYSTEMS
- MICROQUASARS
- T TAURI STARS?

(del Valle M. V. et al., 2011, ApJ, 738, 115)

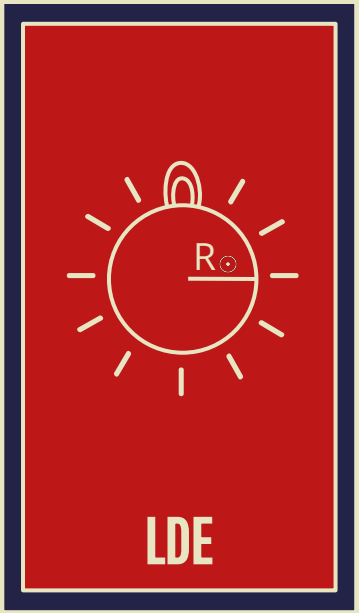
# T TAURI STARS



- Low-mass young stellar objects
- Ages < 10 Myr
- Masses < 3 $M_\odot$
- Spectral type F – M
- Located in star-forming regions

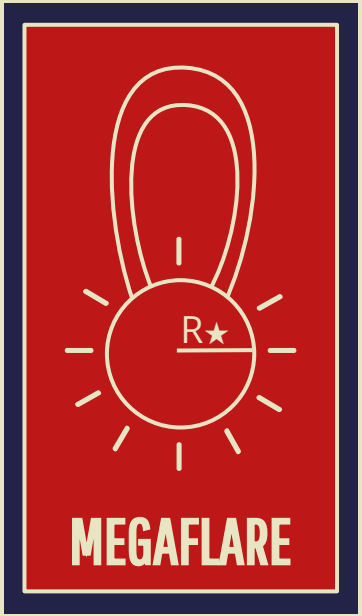
Artist's impression of a T Tauri star formed by a central star and a circumstellar disk.
Credit: INAF-OAPa/S. Orlando

# COMPARATIVE HIGHEST FLARING ACTIVITY




SUN

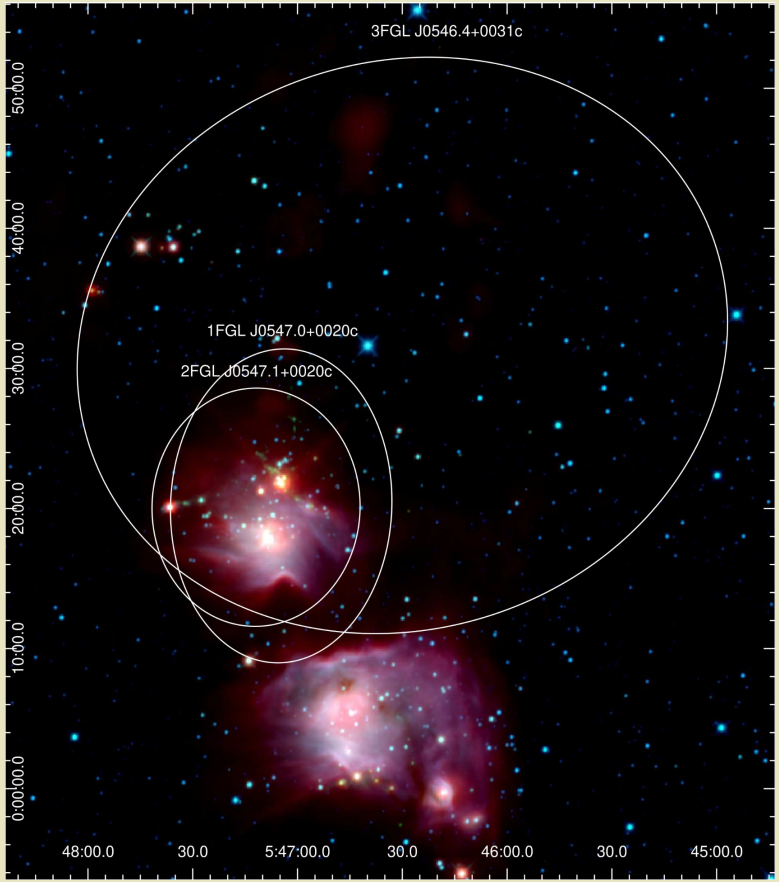
| | | |
|---|---|---|
| < 0.5 $R_\odot$ | LENGTH | < 4 $R_\odot$ |
| $10^{30-32}$ erg | X-RAY ENERGY RANGE | $10^{36.2-38}$ erg |
| < 3 hs | DURATION | < 30 hs |




T TAURI

# NGC 2071

- SFR located in the northern part of Orion B at a distance of 390 pc.
- Hα emission line stars, Herbig–Haro objects, T Tauri stars, high-mass young stellar objects.
- Positionally coincides with three **unidentified** γ-ray sources observed at different time intervals.
- No source was detected in the 4FGL catalog and its data releases.



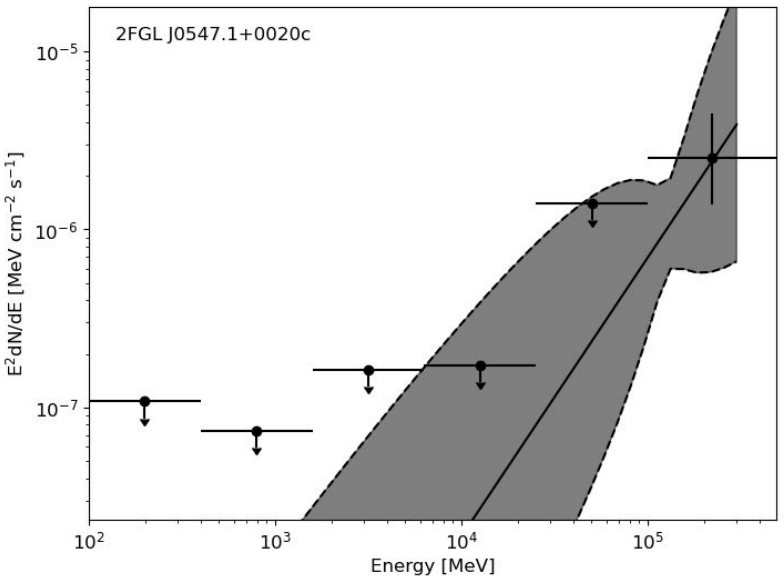

NGC 2071 obtained with the *WISE* using the 22 μm (red), 4.6 μm (green), and 3.4 μm (blue) bands. Ellipses in white are the 3σ significance *Fermi* error ellipses that positionally coincide with NGC 2071.

# γ-RAY ANALYSIS

(Filócomo A. et al., 2023, MNRAS, 525, 1726)

## Fermi data from Aug 2008 to Jul 2010

(observation time of the 2FGL catalog)

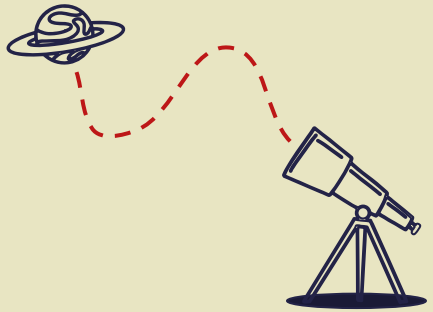



**Significance** = 3.2σ

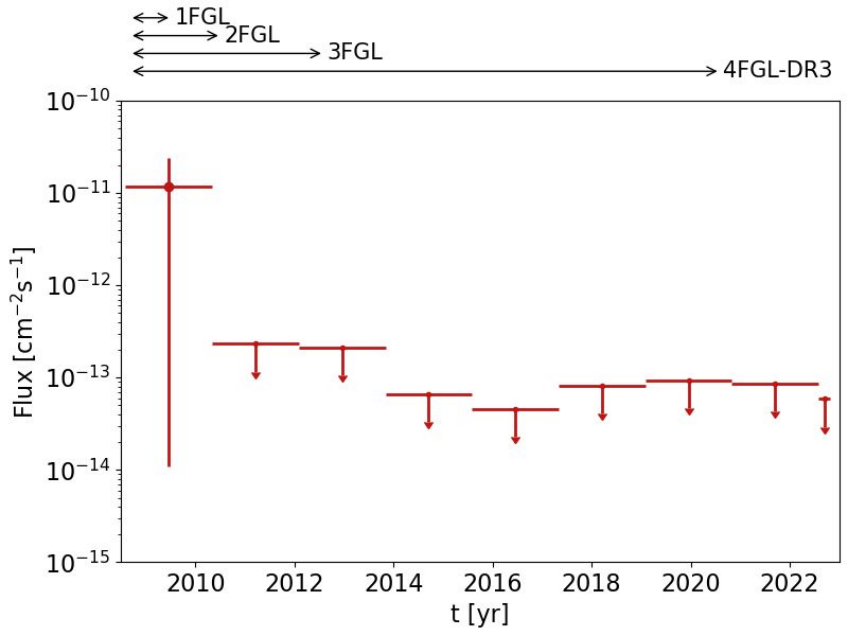
**Emission** significant at E > 100 GeV

Computed SED in the energy range **100 MeV – 300 GeV**.

# TIME VARIABILITY ANALYSIS



## Fermi data from Aug 2008 to Oct 2022

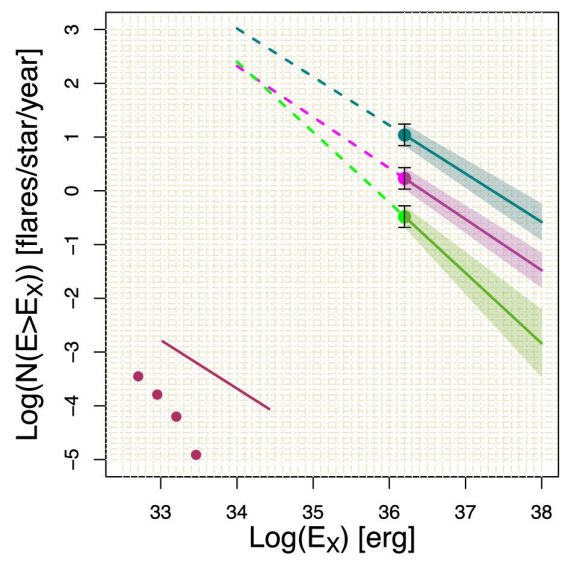



Detected only in the **first bin** with a significance of 3σ

Light curve with a 1.75-yr size bin for the source detected within 14.23 yr of *Fermi*-LAT observations.

# Frequency of X-ray flares as a function of their X-ray energy and the mass of the star

(Getman K. V., Feigelson E. D., 2021, ApJ, 916, 32)




Stars with M < 1M$_\odot$ (teal), M > 1 M$_\odot$ (green), M = 0.1–150 M$_\odot$ (magenta). The colored bands represent the observed power-law megaflare distribution, and the dashed lines extrapolate these relations to lower energies. Frequencies from older solar-type stars are in maroon.

Frequency of flares with $E_X > 10^{36.2}$ erg (M < 1 M$_\odot$):

$0.3^{+0.2}_{-0.1}$ flares/star/year

# Frequency of megaflares in NGC 2071

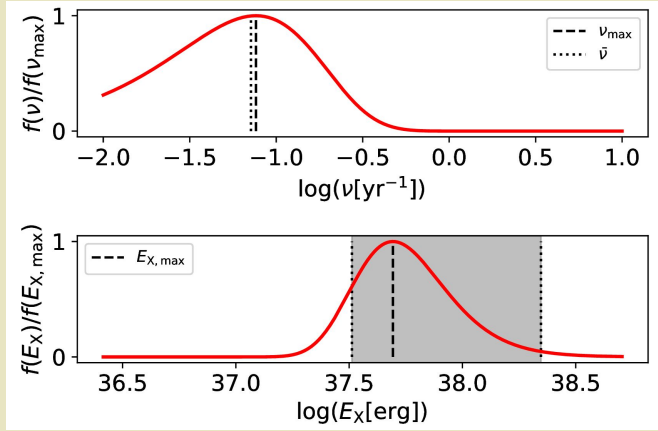
$f(\nu|D)$ is the PDF that represents the degree of belief in the proposition that the true value of the frequency lies in $[\nu, \nu+d\nu]$ given the data $D$:

- Estimation of the true frequency (value that maximizes $f$) and estimation of the **minimum energy of the flares**:

$$\nu_{max} = 0.076\ \mathrm{yr}^{-1} \dashrightarrow E_{X,max} = 5 \times 10^{37}\ \mathrm{erg}$$

(Megaflare: $10^{36.2} < E_X < 10^{38}$ erg)

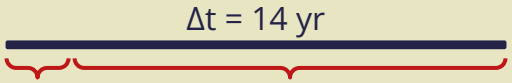
- 90% credible region for $E_X$ = $[0.33, 2.22] \times 10^{38}$ erg




Behavior of $f(\nu|D)$ and $f(E_X|D)$.

The betting odds of observing more than one flare in $\Delta t_1$ against observing exactly one flare are:

- **93.5%** one flare
- **6.5%** more than one flare




$\Delta t_1 = 1.75$ yr, $k_1 > 0$ $\quad$ $\Delta t_2 = 12.25$ yr, $k_2 = 0$

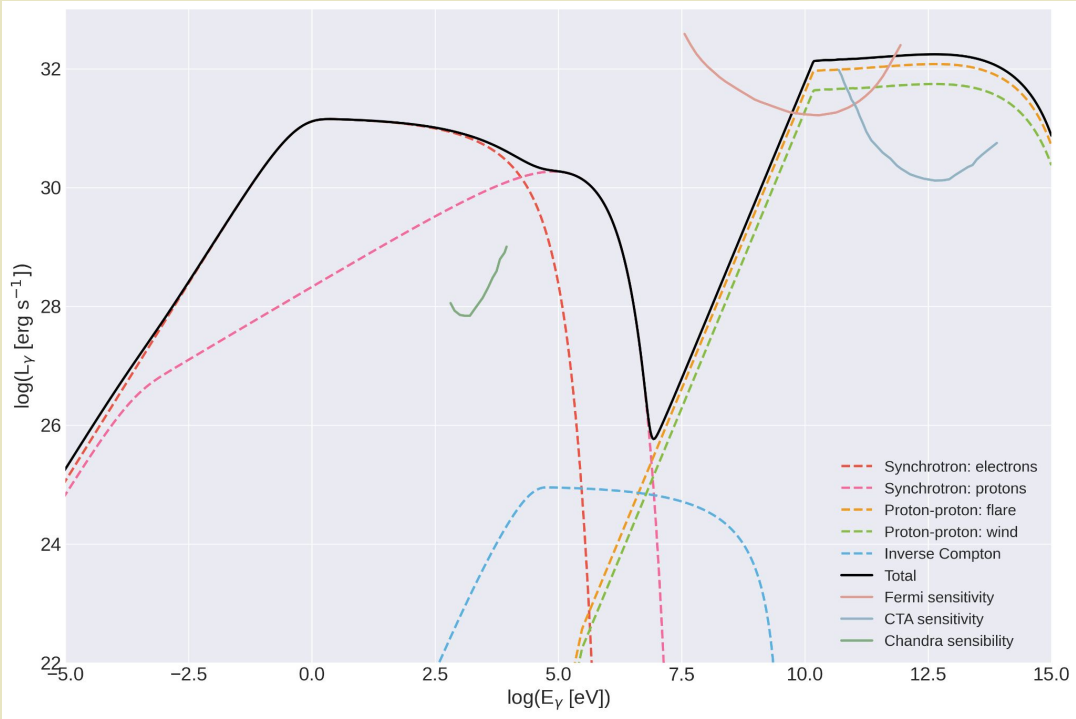
$k_i$ = number of events in $\Delta t_i$

# THEORETICAL MODEL

(Filócomo A. et al., in progress)

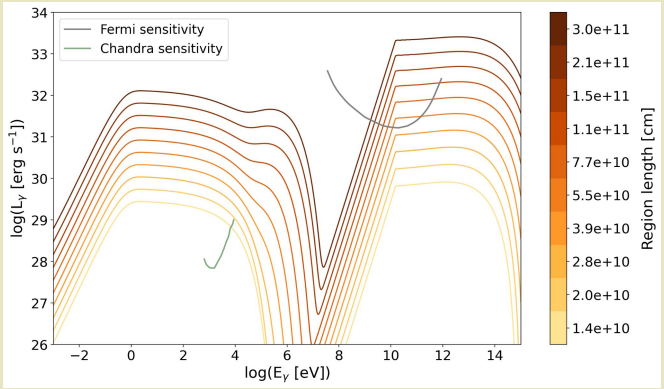
| FIDUCIARY MODEL | |
|---|---|
| Region length | $1.4\,R_{\odot}$ |
| Magnetic field | $2.5\times10^{3}$ G |
| Plasma density | $5\times10^{11}$ cm$^{-3}$ |
| Injection index | 2.0 |
| Wind velocity | $1.5\times10^{7}$ cm s$^{-1}$ |
| Mass loss rate | $10^{-8}\,M_{\odot}$ yr$^{-1}$ |

Lepto-hadronic non-thermal emission model of a megaflare in a T Tauri star.

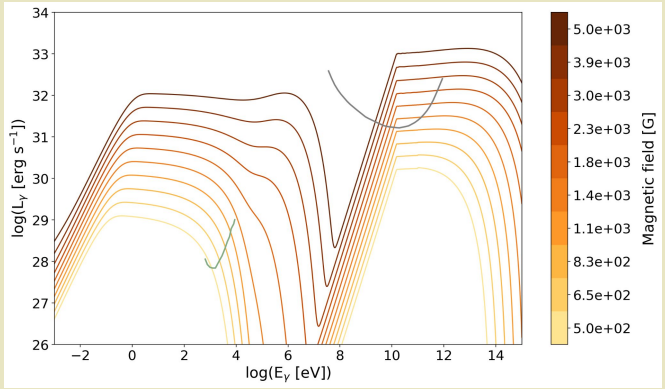



Luminosity of the spectral energy distribution for the fiduciary model.

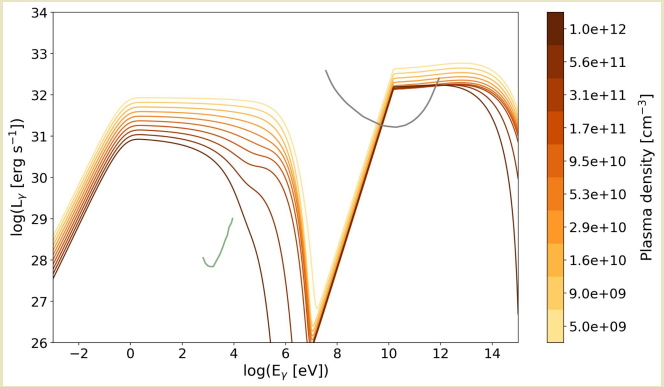
## **Region length** ($0.2\ R_\odot < L < 4\ R_\odot$)



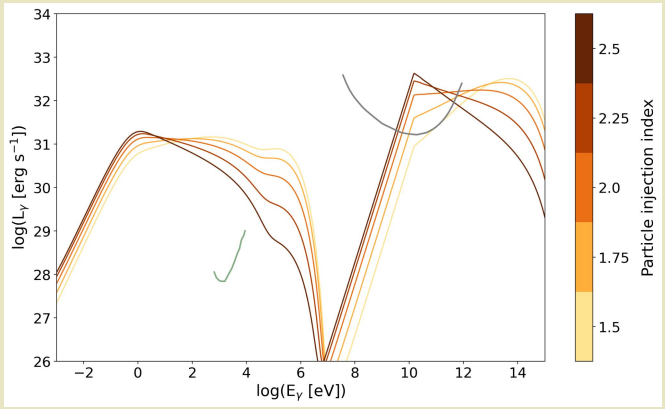

## **Magnetic field** ($5\times10^2\ G < B < 5\times10^3\ G$)

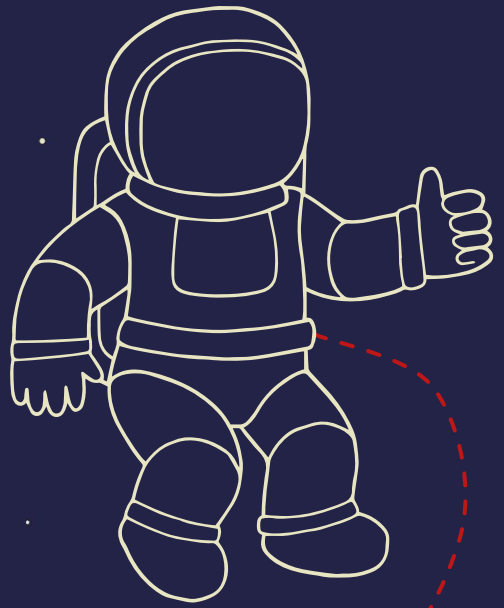



## **Plasma density** ($5\times10^9\ cm^{-3} < n < 10^{12}\ cm^{-3}$)




## **Particle injection index** ($1.5 < p < 2.5$)





# THANK YOU!

# Frequency of megaflares in NGC 2071

Using the fact that at least $N\star$ = 58 stars were classified as T Tauri stars within the 2FGL error ellipse, the frequency of flares with energy > $E_X$ is

$$\log\left[\frac{\nu(E_{\rm X})}{\rm yr^{-1}}\right] = \log\left[N_\star \frac{N(E>E_{\rm X})}{\rm yr^{-1}}\right] = \kappa' - \beta \log\left(\frac{E_{\rm X}}{\rm erg}\right),\ \kappa' = \kappa + \log N_\star = 48.70$$

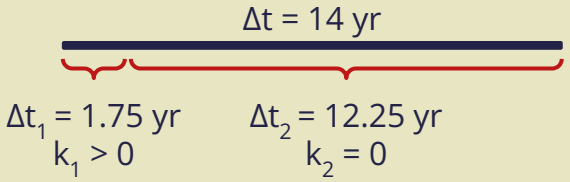
PDF that represents the degree of belief in the proposition that the true value of the frequency lies in [$\nu$, $\nu$+$d\nu$] given the data $D$:

$$f(\nu|D) = \frac{\mathcal{L}(D|\nu)g(\nu)}{\int_0^\infty \mathcal{L}(D|\nu)g(\nu)d\nu} \rightarrow \nu_{max}$$

Counting the number of flares $k$ in a time interval $\Delta t$ is a Poisson process.

$\mathcal{L}(D|\nu)$ is the probability of measuring the data $D$ given $\nu$:

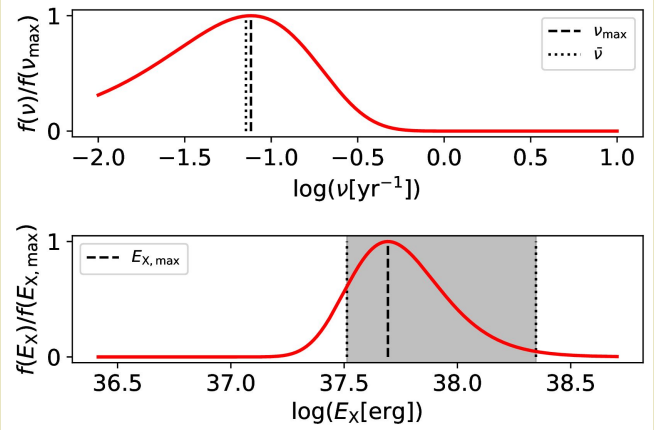
$$\mathcal{L}(D|\nu) = (1 - \mathrm{e}^{-\nu\Delta t_1})\mathrm{e}^{-\nu\Delta t_2}$$




$g(\nu)$ represents the degree of belief in $\nu$ before taking the data $D$:

$$g(\nu) = 1/\Delta\nu$$

Behavior of $f(\nu \mid D)$ and $f(E_X \mid D)$




- Estimation of the true frequency (value that maximizes *f*) and estimation of the minimum energy of the flares:

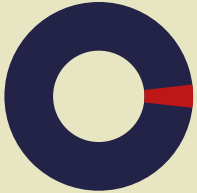
$$\nu_{max} = 0.076\ \mathrm{yr}^{-1} \dashrightarrow E_{X,max} = 4.89 \times 10^{37}\ \mathrm{erg}$$

(one event every 13.2 yr)

- 90% credible region for $E_X$ = $[0.33, 2.22] \times 10^{38}$ erg

The betting odds of observing more than one flare in $\Delta t_1$ against observing exactly one flare are:

$$q = \frac{P(k>1|k>0,\nu_{\max})}{P(k=1|k>0,\nu_{\max})} = \frac{1-e^{-\nu_{\max}\Delta t_1}(1+\nu_{\max}\Delta t_1)}{\nu_{\max}\Delta t_1 e^{-\nu_{\max}\Delta t_1}} = 0.069$$



- **93.5%** one flare
- **6.5%** more than one flare