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A new mode change in the variable gamma-ray pulsar PSR J2021+4026

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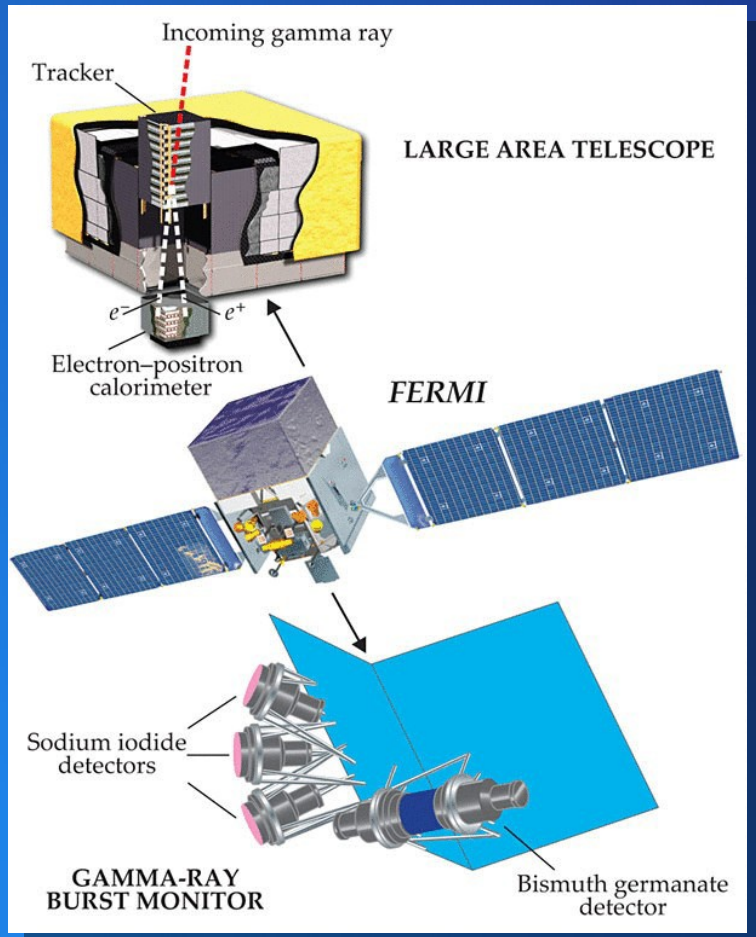
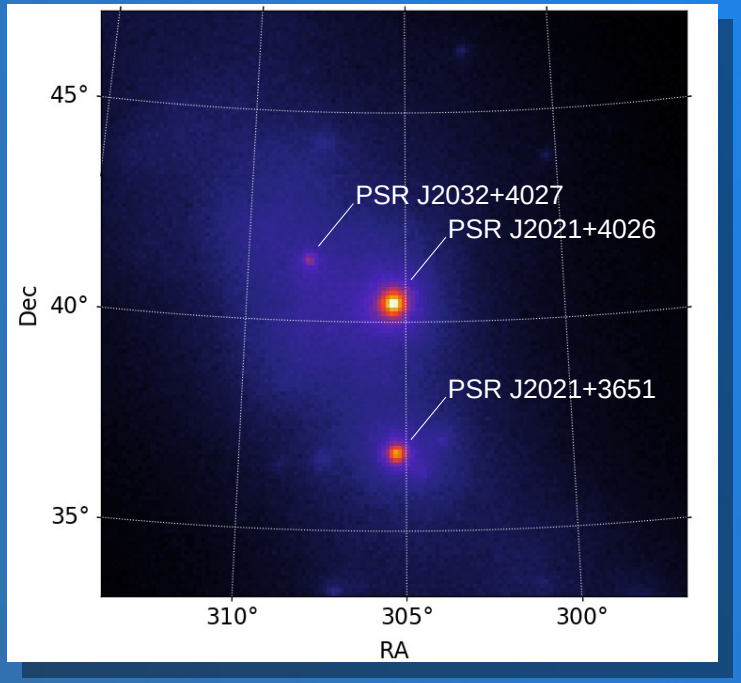
The *Fermi* Large Area Telescope

- Main instrument of the *Fermi* Gamma-ray Space Telescope
- NASA mission, operative since June 2008
- **Pair-conversion** telescope (Atwood et al., 2009)
- Sensitive to gamma rays **above 20 MeV**
- **>5000 gamma-ray sources** detected (4FGL-DR2; Abdollahi et al., 2020)
- **~300 gamma-ray pulsars** *

* https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars/pulsars



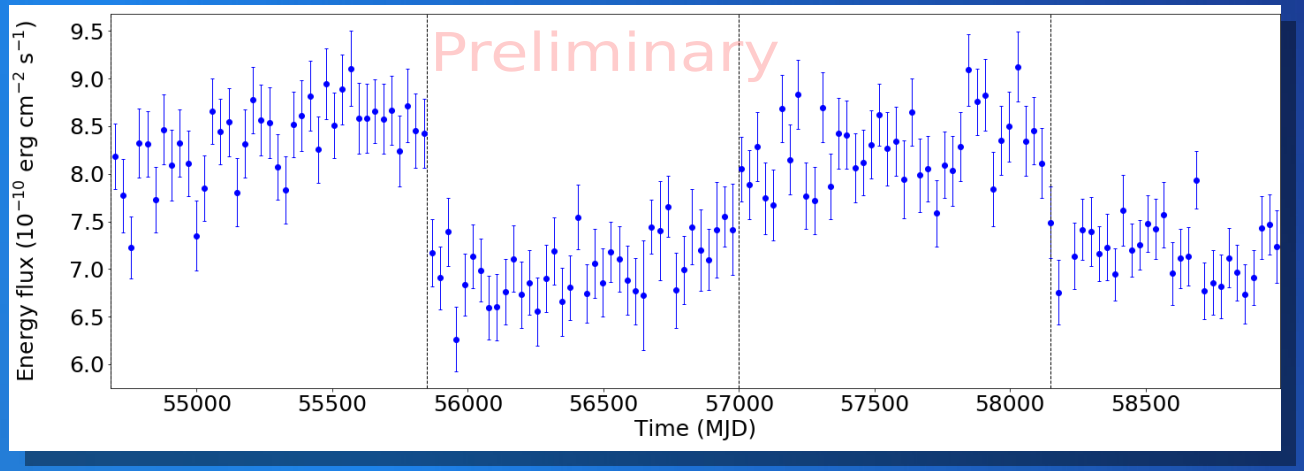
The variable PSR J2021+4026



- **Isolated, radio-quiet** gamma-ray pulsar in the Gamma Cygni SNR
- First discovered with *Fermi* LAT with period **~ 265 ms** (Abdo et al. 2009)
- X-ray counterpart (Weisskopf et al. 2011) and pulsations (Lin et al. 2013)
- Abrupt and simultaneous **flux** and **spin-down variations** (Allafort et al. 2013)
- **Repeated mode changes** (once every few years)

Previously observed events

- **Flux** from likelihood fit to 30-day intervals
- Switching between **two states** with different flux levels
- Recovery delayed by ~ 3.5 years



- **Continuous monitoring ...**

August 2008

October 2011

December 2014

February 2018

May 2020

Analysis setup

Maximum likelihood fit with summed LAT PSF components and photon weights *

Data Selection

T start:	MJD 54683 (Aug 5, 2008)
T stop:	MJD 59493 (Oct 6, 2021)
RA center:	305.805°
DEC center:	40.444°
ROI radius:	10°
Pixel size:	0.1°
Energy range:	100 MeV – 300 GeV
Energy bins:	35

Model

Includes 4FGL sources within 20°

Free parameters:

- Distance < 3.5°
- Variable sources in the field
- PSR J2021+3651

Fixed parameters:

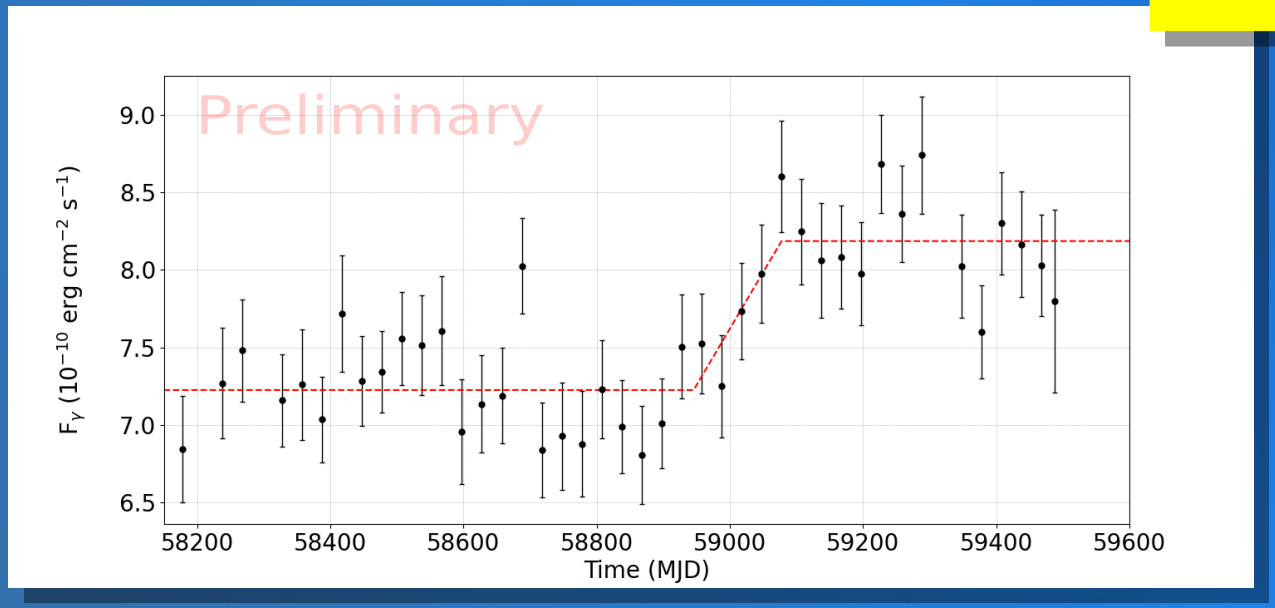
- Faint sources (< 5σ)

* https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/weighted_like.pdf

A new mode change!

- **Recovery** of the February 2018 flux drop
- Located around **June 2020** (earlier than expected)

$$F_\gamma(T) = \begin{cases} F_0 & \text{if } T < T_0 \\ F_0 + \frac{(F_1 - F_0)}{(T_1 - T_0)}(T - T_0) & \text{if } T_0 \leq T < T_1 \\ F_1 & \text{if } T \geq T_1 \end{cases}$$



- Results from a best fit:

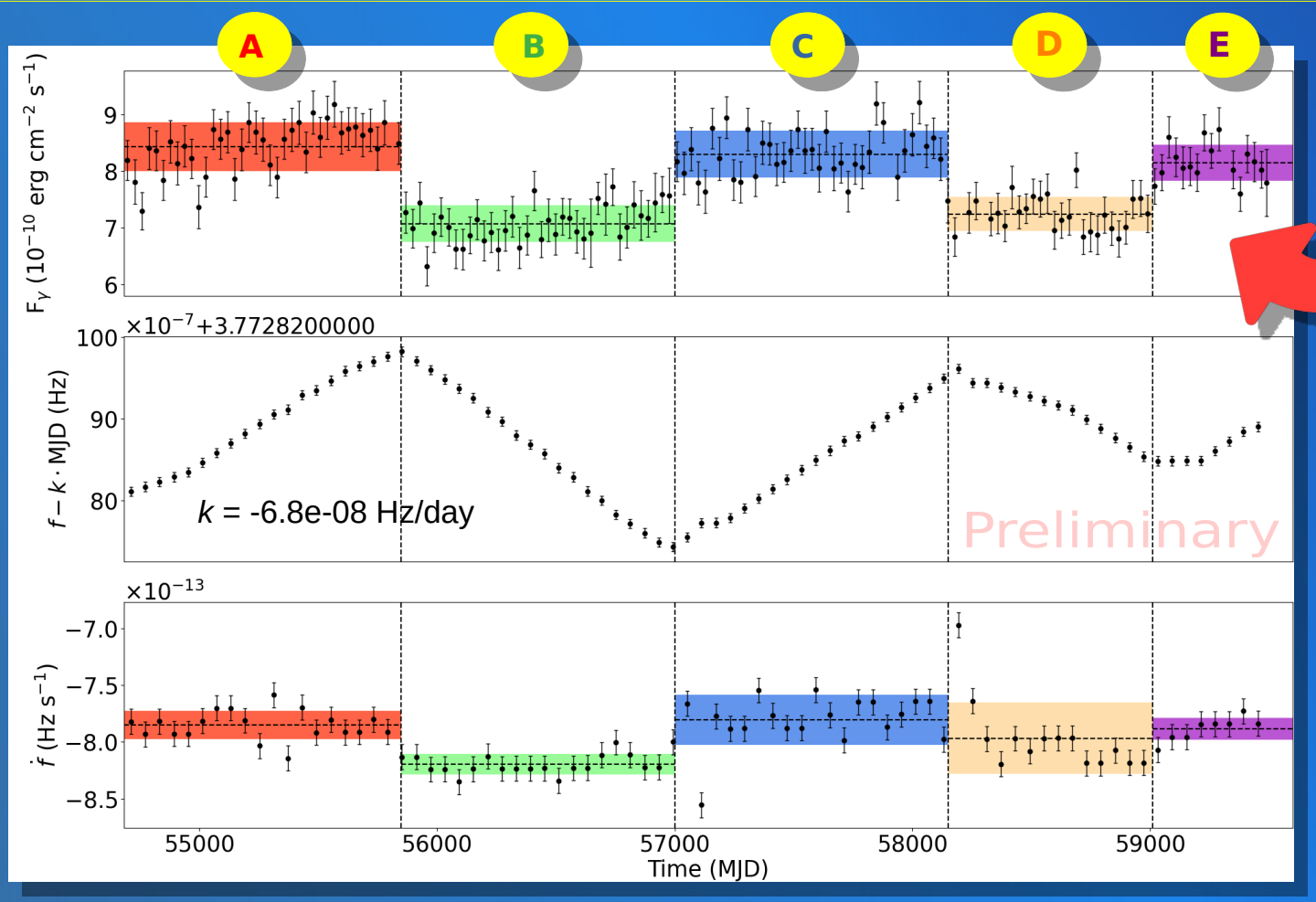
  $\Delta F_\gamma / F_\gamma$ = (12 ± 2) %

  T_0 = MJD 58950 ± 40

  T_1 = MJD 59080 ± 50

- Event centered in ~ **MJD 59010** (Jun 10, 2020)

Evolution of flux and spin-down



Latest event
(~ June 2020)

$$\Delta F_\gamma / F_\gamma \sim 15\%$$
$$\Delta \dot{f} / \dot{f} \sim 5\%$$

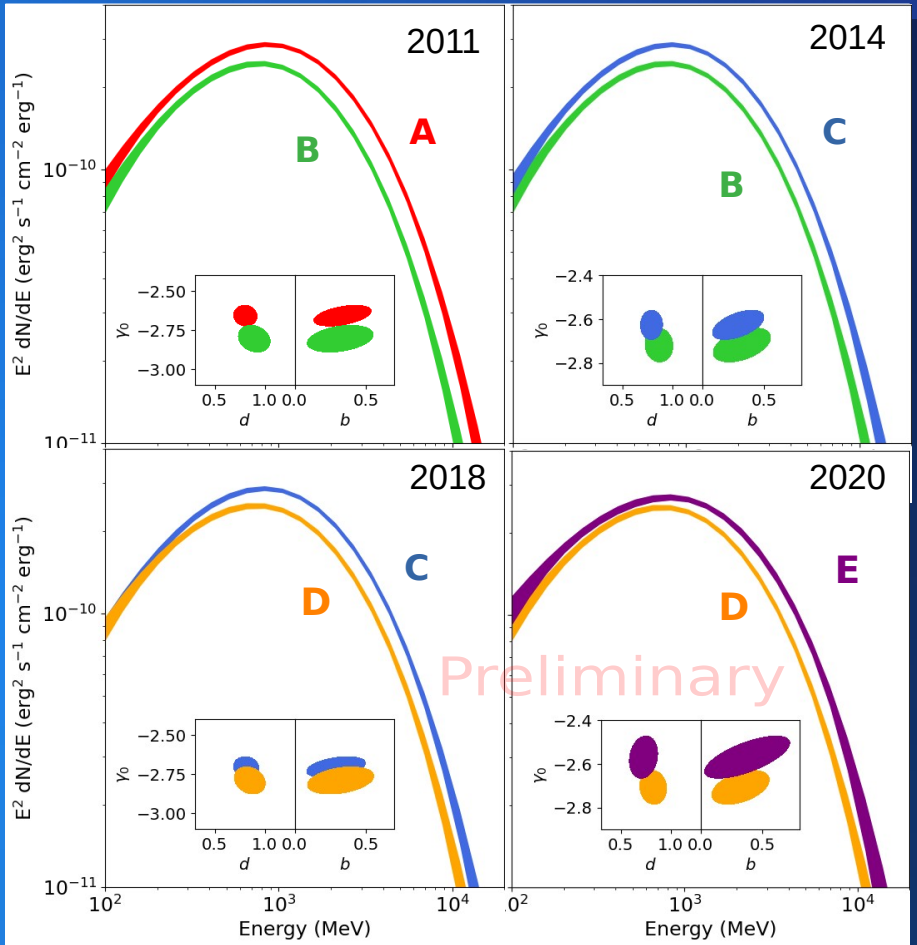
Timing parameters from **H-test** to 60-day intervals (de Jager and Busching. 2010)

Spectral variability

$$\frac{dN}{dE} \propto \begin{cases} \left(\frac{E}{E_0}\right)^{\gamma_0 - \frac{d}{2}\ln\frac{E}{E_0} - \frac{db}{6}\ln^2\frac{E}{E_0} - \frac{db^2}{24}\ln^3\frac{E}{E_0}} & \text{if } |b\ln\frac{E}{E_0}| < e^{-2} \\ \left(\frac{E}{E_0}\right)^{\gamma_0 - \frac{d}{b}} \exp\left[\frac{d}{b^2}\left(1 - \left(\frac{E}{E_0}\right)^b\right)\right] & \text{otherwise} \end{cases}$$

$E_0 =$ 2 GeV

- Maximum likelihood fit to intervals between events
- **Softer spectrum** when the flux is low ($\Delta\gamma/\gamma \sim 5\%$)
- Variability with **~3 sigma** significance

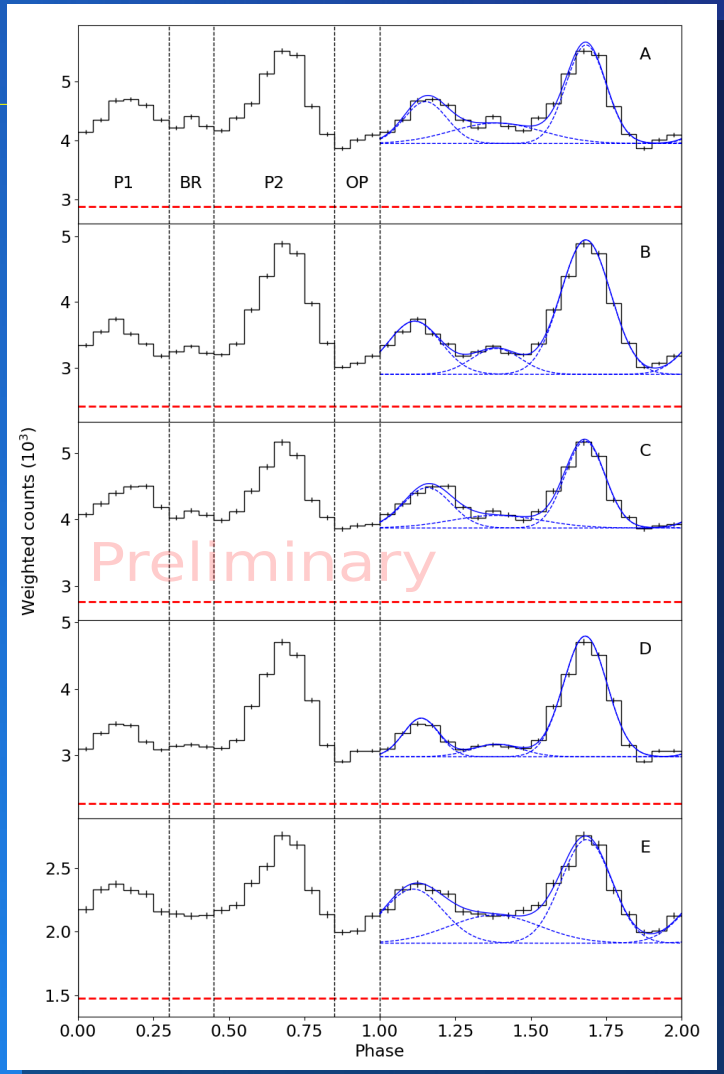


Pulse profile

- Phases computed with a full-mission timing solution (Ajello et al. 2021)
- **Maximum likelihood fit** with photon probabilities in different time intervals

$$N(\phi) = const + \sum_{i=1}^{3} A_i \exp\left[-\frac{(\phi-\mu_i)^2}{2\sigma_i^2}\right]$$

- Change in **pulsed-to-constant** components ratio
- Weak variations in the **relative peak amplitudes**
- Indications of a **gamma/X-ray phase shift** after the 2014 event (M. Razzano et al., in prep.)



The nature of PSR J2021+4026

Li et al. (2012)

$$\frac{L}{L_0} = 0.3 + 0.3\log(\sigma/\Omega)^2 + 1.2\sin^2\alpha\,,\ (\sigma/\Omega)^2 > 0.4;$$
$$\frac{L}{L_0} = 0.2 + 0.08\log(\sigma/\Omega)^2 + (1.3 + 0.2\log(\sigma/\Omega)^2)\sin^2\alpha,$$
$$0.004 < (\sigma/\Omega)^2 < 0.4. \qquad (9)$$

Pétri (2022)

$$\mathbf{j} = \rho_e \frac{\mathbf{E}\wedge\mathbf{B}}{E_0^2/c^2 + B^2} + (|\rho_e| + 2\,\kappa\, n_0\, e)\,\frac{E_0\,\mathbf{E}/c^2 + B_0\,\mathbf{B}}{E_0^2/c^2 + B^2}$$

$$\Delta\dot{f}/\dot{f} \sim 5\%$$
$$\Delta\sigma/\sigma \sim 8\%$$
$$\Delta k/k \sim 8\%$$

- Results suggest a variation of the whole magnetospheric structure
- Current pulsar models do not take account of variability
- Spin-down vs. conductivity and pair multiplicity from equations for **radiative magnetospheres**
- Non-linear relation between *k* and luminosity
- **PIC simulations** (Kalapotharakos et al. 2018) may produce the observed $\Delta F_\gamma / F_\gamma \sim 15\%$

Conclusions

- **First and only variable isolated gamma-ray pulsar**
- Maximum likelihood fit to Fermi-LAT fully characterizes the observed mode changes
- Theoretical discussion currently limited to semi-quantitative estimates
- **Continuous monitoring** may provide further information about variability in gamma-ray pulsars

To be continued…

References

Abdo et al. 2009. ApJ, 700, 1059.
Abdollahi et al. 2020. ApJS, 247, 33.
Ajello et al. 2021. ApJS, 256, 12.
Allafort et al. 2013. ApJL, 777, L2.
Atwood et al. 2009. ApJ, 697, 1071.
de Jager & Busching. 2010. A&A, 221,180.
Kalapotharakos et al. 2018. ApJ, 857, 23.
Li et al. 2012. ApJ, 746, 12.
Lin et al. 2013. ApJL, 770, L9.
Ng et al. 2016. ApJ, 825, 18.
Pétri 2022. MNRAS, 512, 2854.
Takata et al. 2020. ApJ, 890, 16.
Weisskopf et al. 2011. ApJ, 743, 74.

Thank you for listening!

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