中国科学院国家天文台
NATIONAL ASTRONOMICAL OBSERVATORIES, CAS

The HI absorption line & anomalous dispersion in pulsar emission

JIANG Jinchen (NAOC postdoc)

SPSS 2024
Kunming

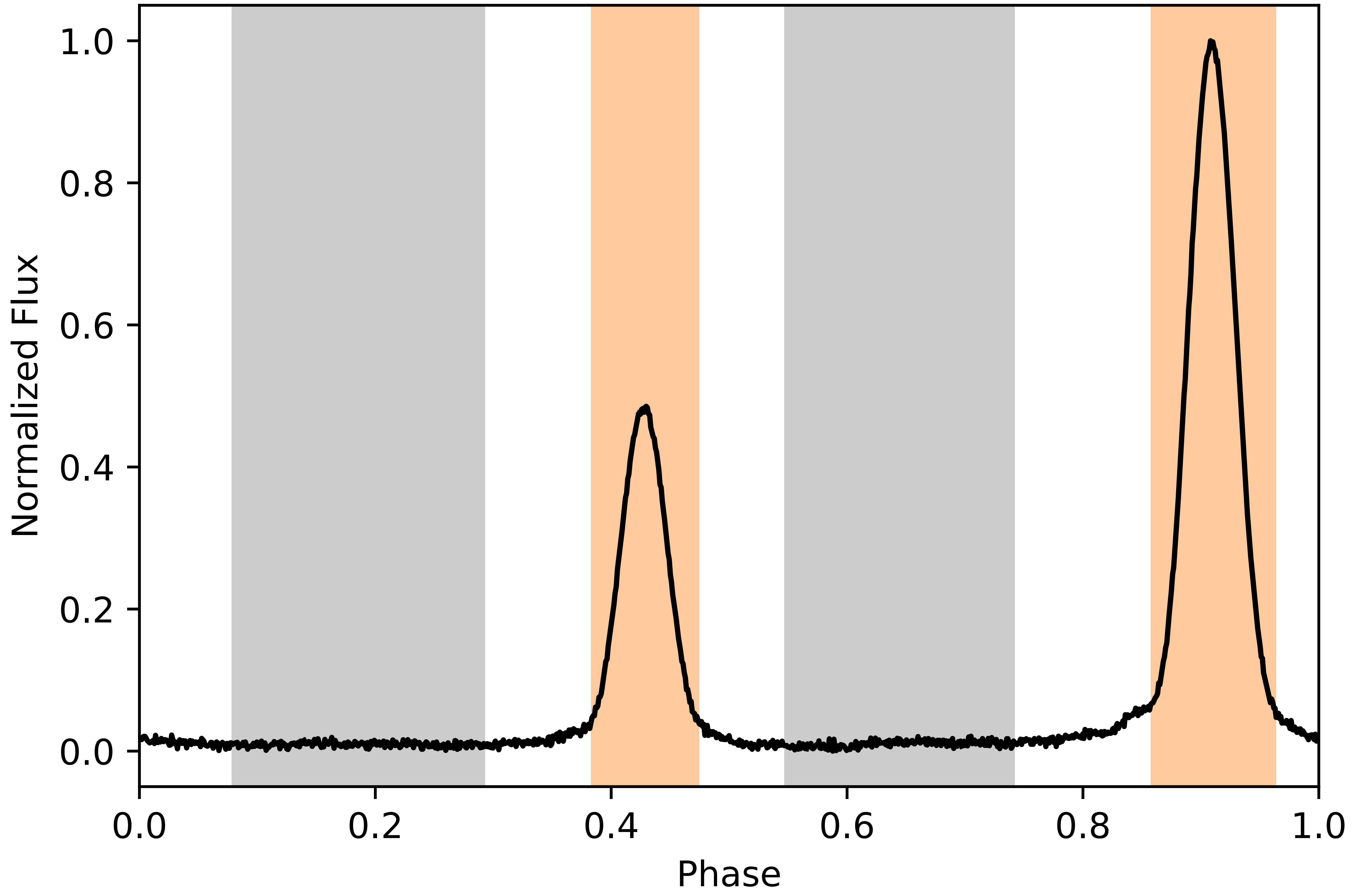
HI absorption line

- Radiative transfer equation

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = j_\nu - \alpha_\nu I_\nu$$

$$I_\nu = \boxed{I_{\nu,0}e^{-\tau_\nu}} + S_\nu(1 - e^{-\tau_\nu})$$

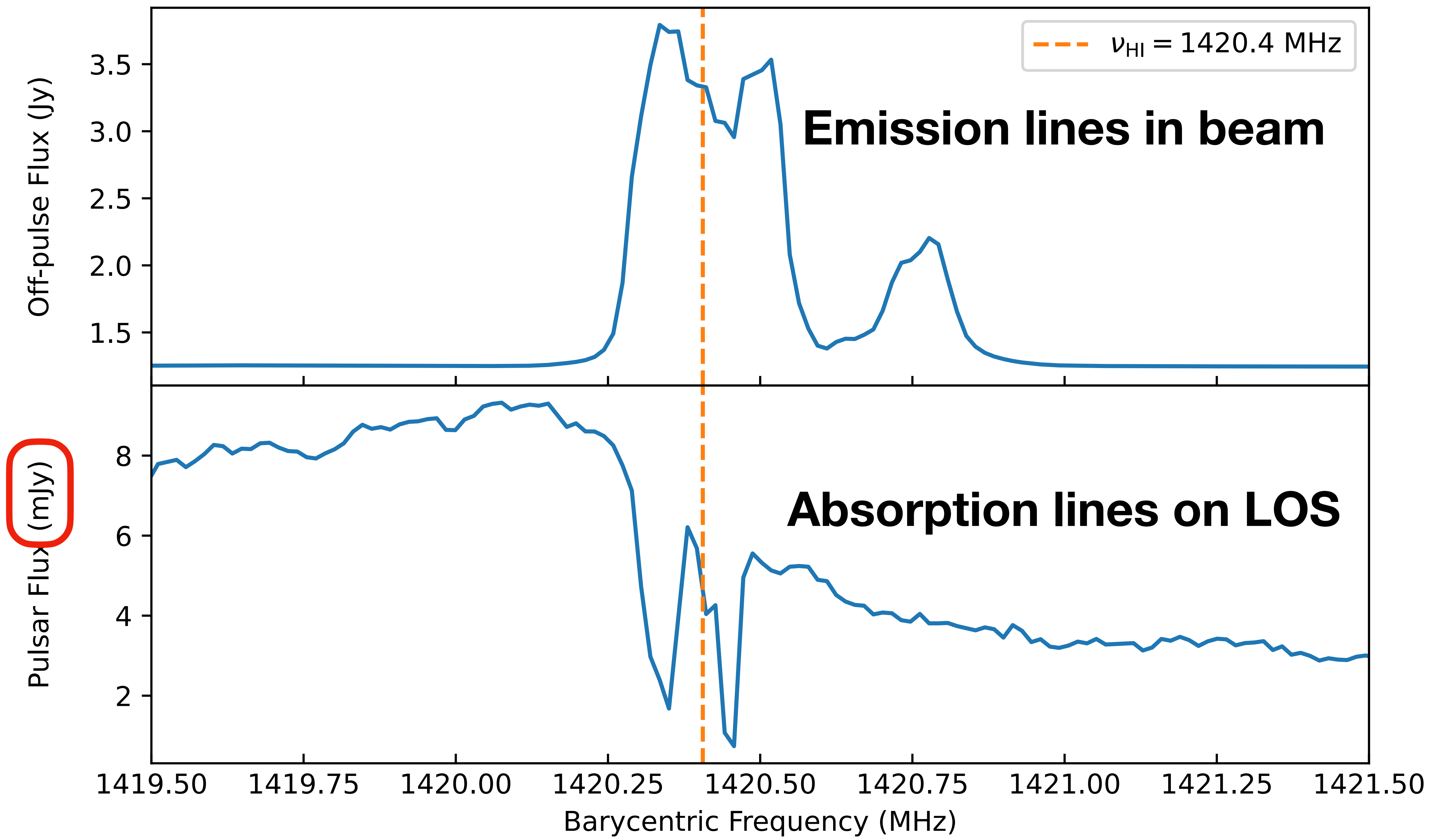
- On-Off observation
  angular resolution
  time resolution: pulsar



- PSR B1937+21 (J1939+2134)
  P = 1.56 ms
  bright

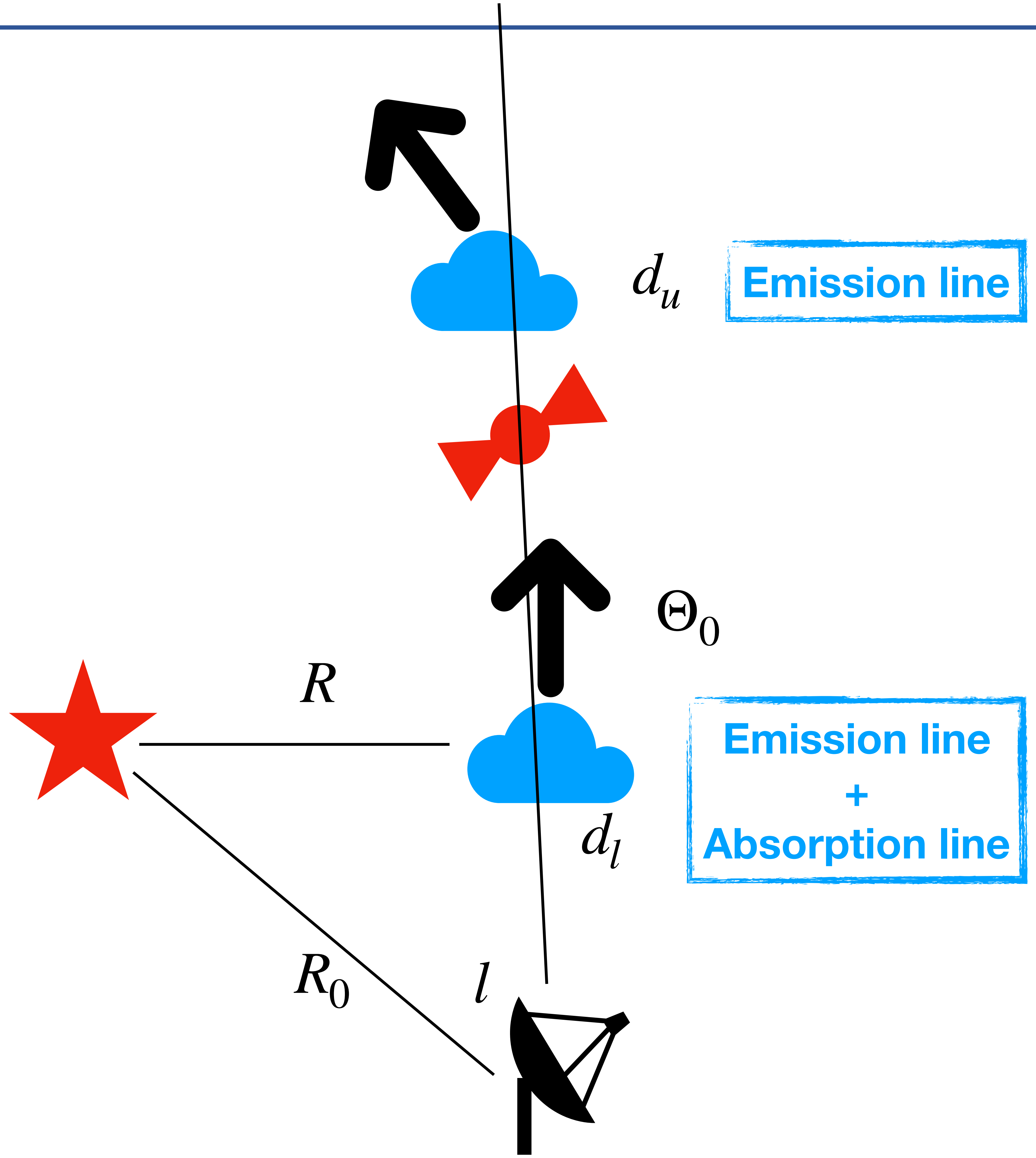
- DSPSR
  CPU off-line
  500 MHz/32768 chan = 15 kHz/chan

- Scintillation

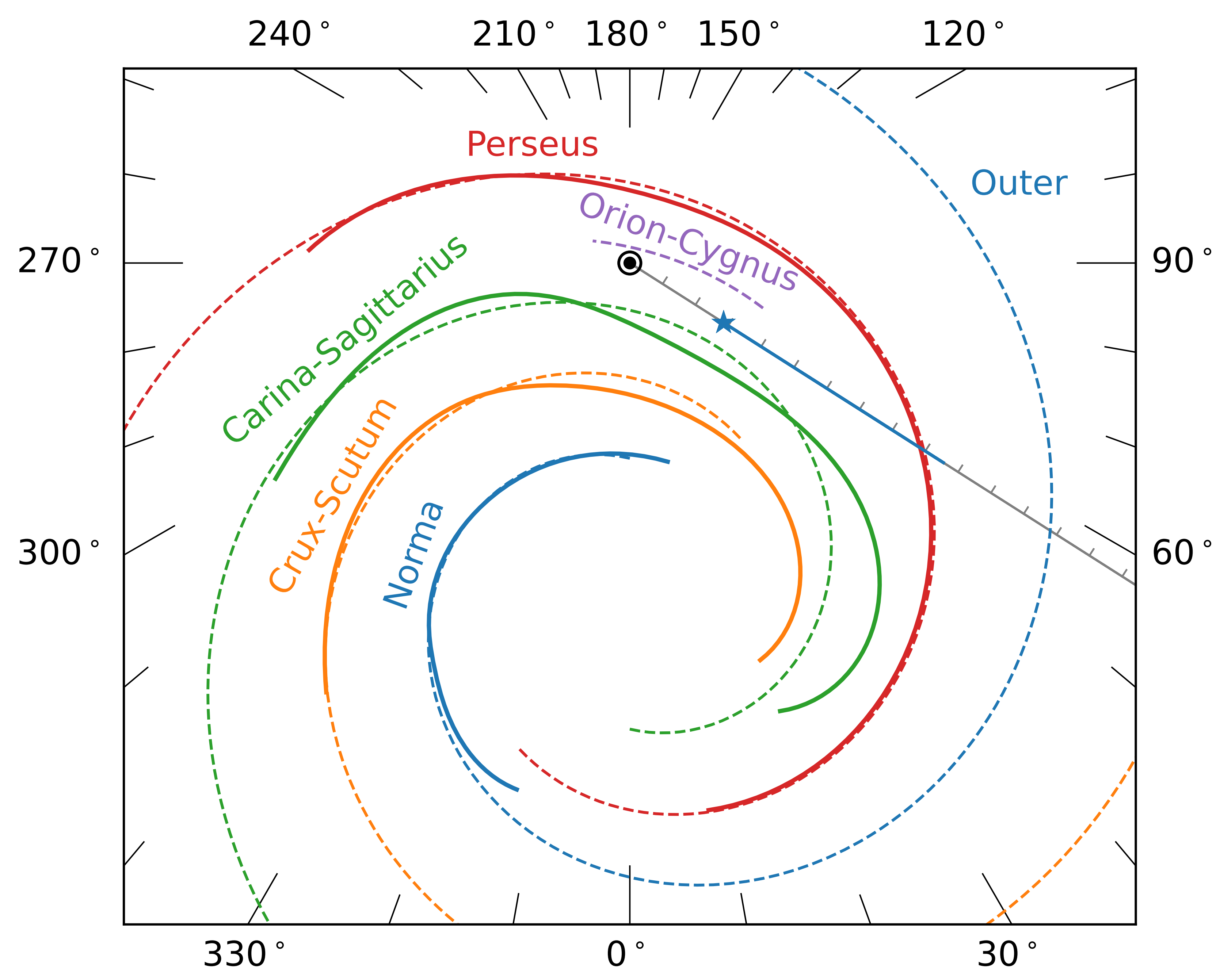


Kinematic distance

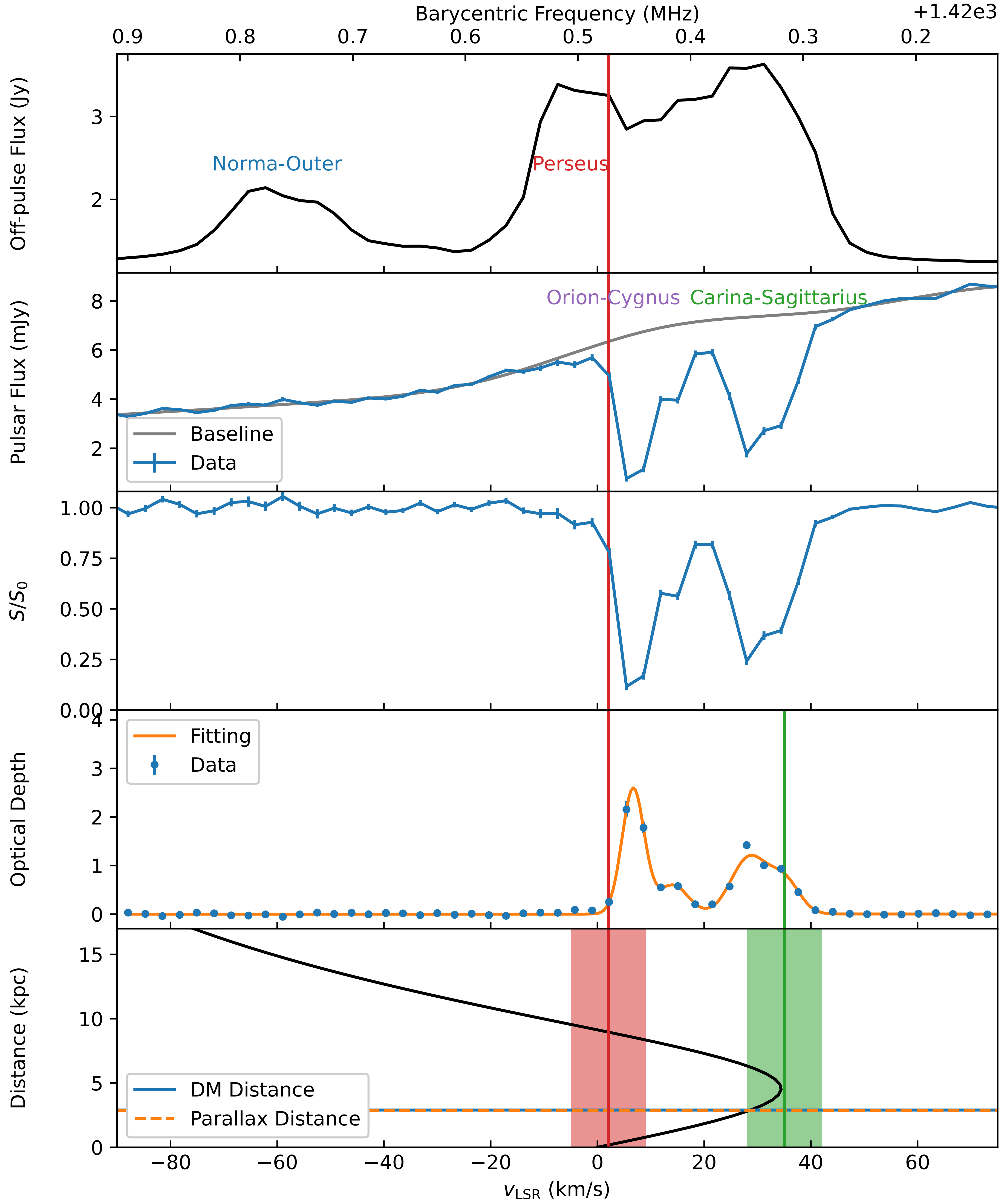
- Galactic rotation curve
  $R_0 = 8.5\,\mathrm{kpc},\ \Theta_0 = 220\,\mathrm{km/s}$
- Radial velocity of HI cloud
  $R^2 = R_0^2 + d^2 - 2R_0 d\cos l$
  $v_r = R_0(\omega - \omega_0)\sin l \cos b$
  Local Standard of Rest (LSR)
  streaming & random motion: $\sim 7\,\mathrm{km/s}$
  (Fich et al. 1989, Frail et al. 1990)
- Lower bound of pulsar distance
  furthermost cloud with absorption
- Upper bound of pulsar distance
  nearest cloud without absorption



- Lower bound
  2.8 - 6.3 kpc
  Carina-Sagittarius Arm

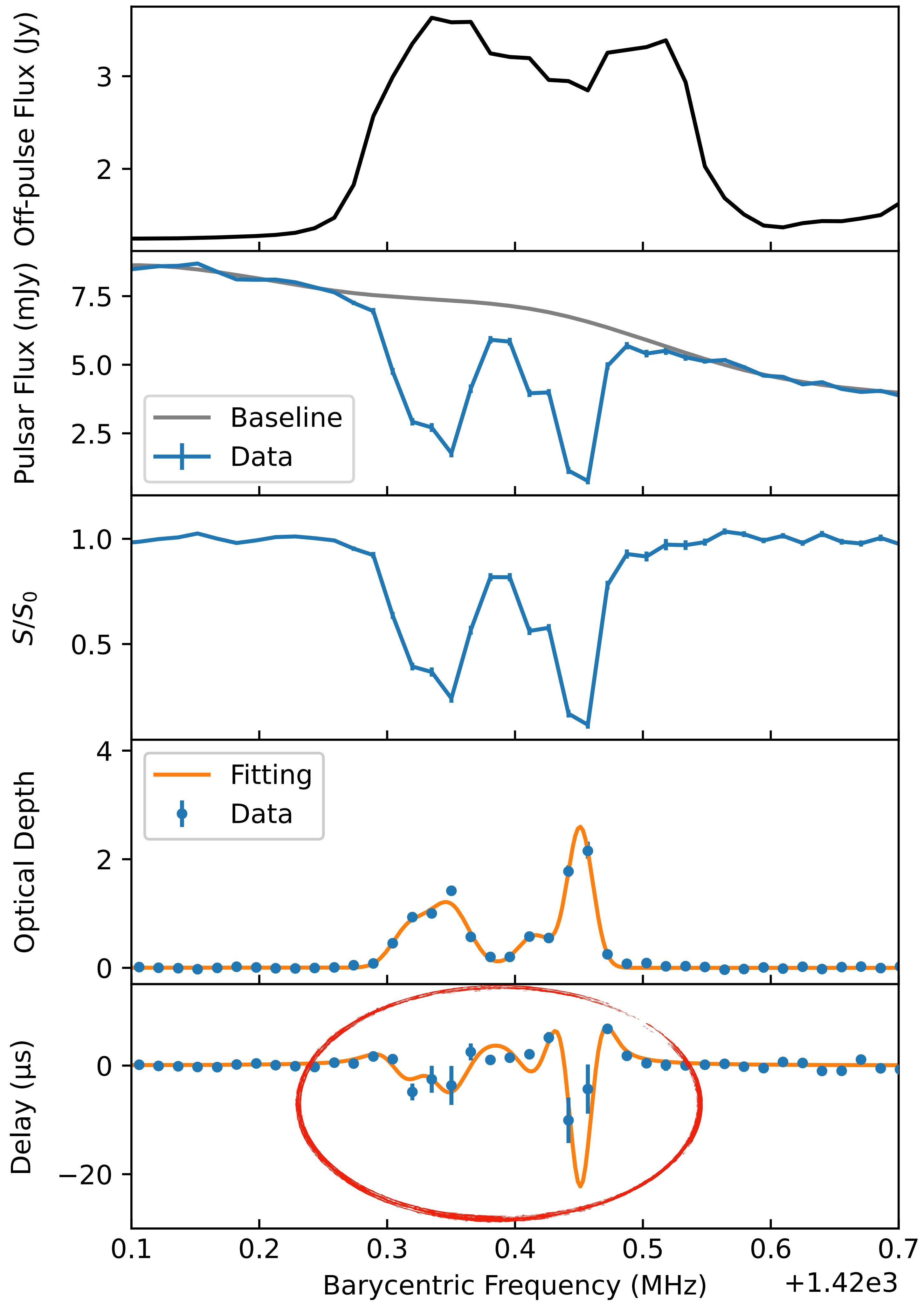


- Upper bound
  8.3 - 9.6 kpc
  Perseus Arm

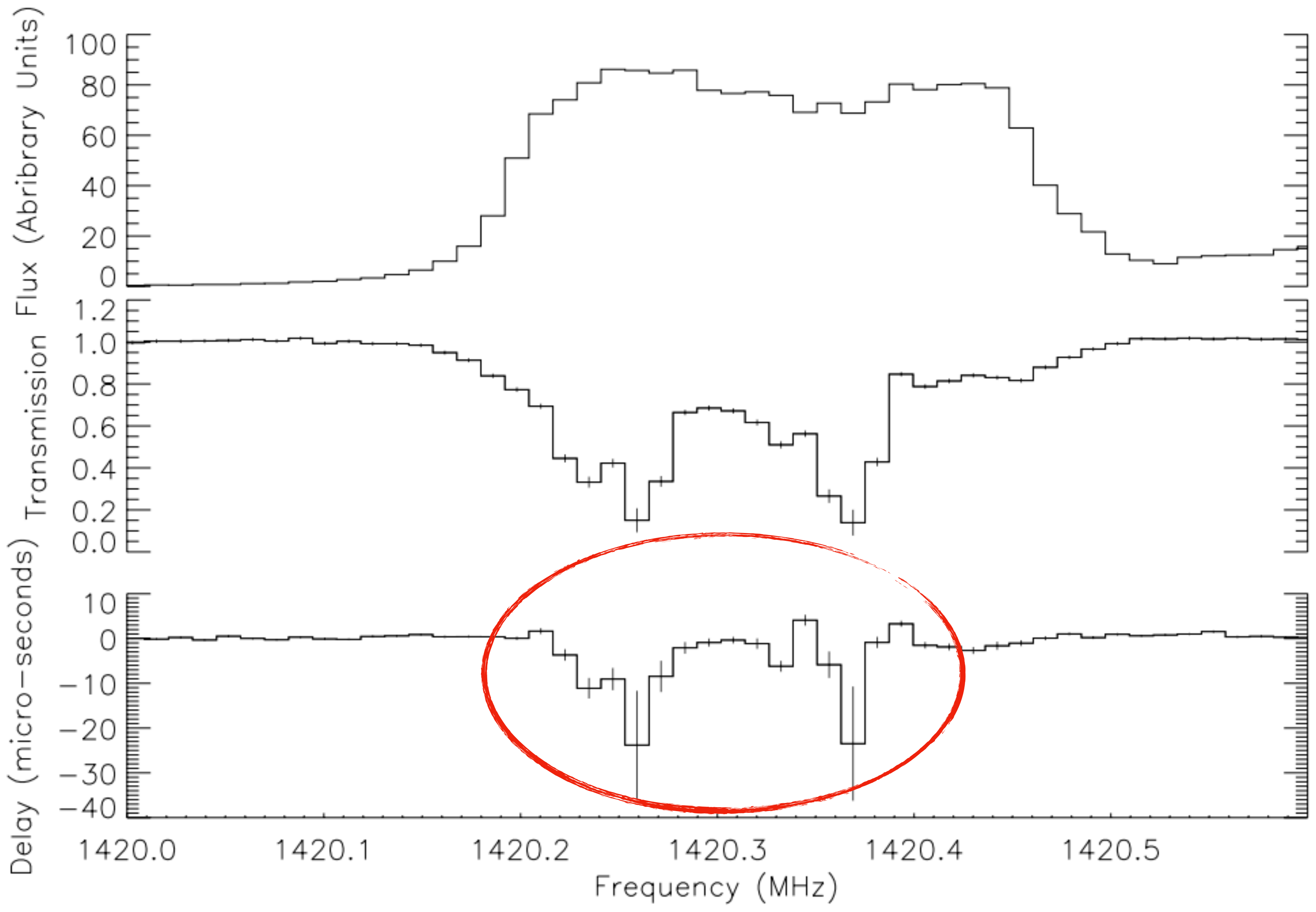


- Previous results
  DM distance: 2.9 kpc (YMW16)
  VLBI distance: 2.6 kpc (Ding et al. 2023)
  kinematic distance: $d_l = 4.6$ kpc, $d_u = 14.8$ kpc (Weisberg et al. 2008)

Timing at HI absorption line



FAST result



Arecibo result
Jenet et al. 2010

What about causality?

Kramers-Kronig relation

- Causality in Green's function of $\epsilon(\omega)$

  $G(\tau < 0) = 0$

  $$\epsilon(\omega)/\epsilon_0 = 1 + \int_0^{\infty} G(\tau) e^{i\omega\tau} \mathrm{d}\tau$$

  $\epsilon(\omega)$ is analytic in the upper half-ω-plane.

- Kramers-Kronig relation

  $$\mathrm{Re}[\epsilon(\omega)/\epsilon_0] = 1 + \frac{1}{\pi}\mathscr{P}\int_{-\infty}^{+\infty} \frac{\mathrm{Im}[\epsilon(\omega')/\epsilon_0]}{\omega' - \omega} \mathrm{d}\omega'$$

  $$\mathrm{Im}[\epsilon(\omega)/\epsilon_0] = -\frac{1}{\pi}\mathscr{P}\int_{-\infty}^{+\infty} \frac{\mathrm{Re}[\epsilon(\omega')/\epsilon_0]}{\omega' - \omega} \mathrm{d}\omega'$$

  absorption $\Longleftrightarrow$ dispersion

- Lorentz dispersion model

  Damped harmonic oscillator

  $$m_e \ddot{\mathbf{x}} + m_e \gamma \dot{\mathbf{x}} + m_e \omega_0^2 \mathbf{x} = - e\mathbf{E}_0$$

  $$\frac{\epsilon(\omega)}{\epsilon_0} = 1 + \frac{Ne^2}{\epsilon_0 m_e} \sum_i \frac{f_i}{\omega_i^2 - \omega^2 - i\omega\gamma_i}$$

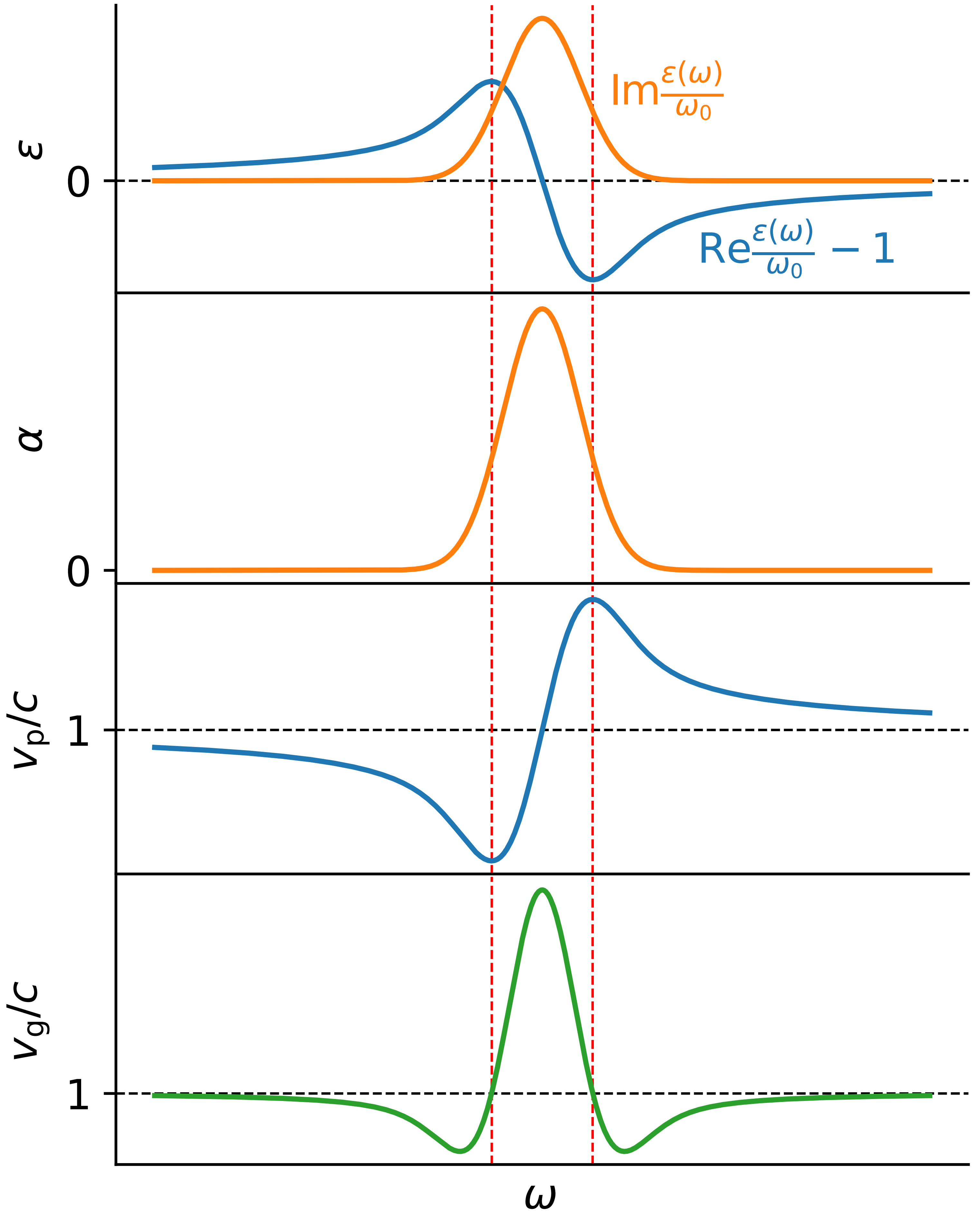
Anomalous dispersion

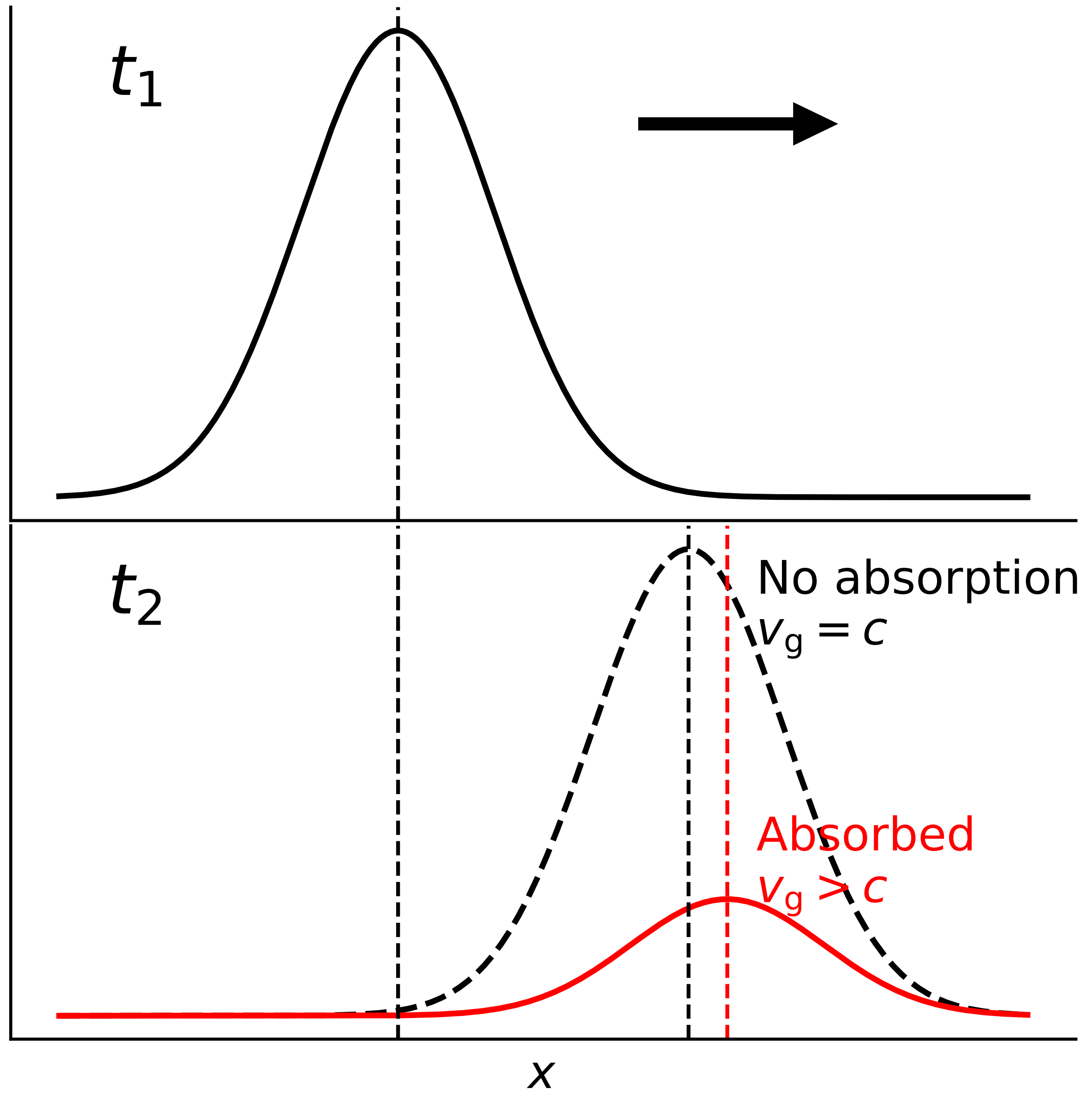
- Normal dispersion
  n increases with ω

- Anomalous dispersion
  n decreases with ω

- Phase velocity $v_\mathrm{p} = \omega/k = c/n$
  Group velocity $v_\mathrm{g} = \mathrm{d}\omega/\mathrm{d}k$
  $$v_\mathrm{g} = \frac{c}{n(\omega) + \omega\frac{\mathrm{d}n}{\mathrm{d}\omega}}$$
  $v_\mathrm{g} > c$ around absorption lines

- Group velocity is defined at Gaussian peak





Causality is preserved

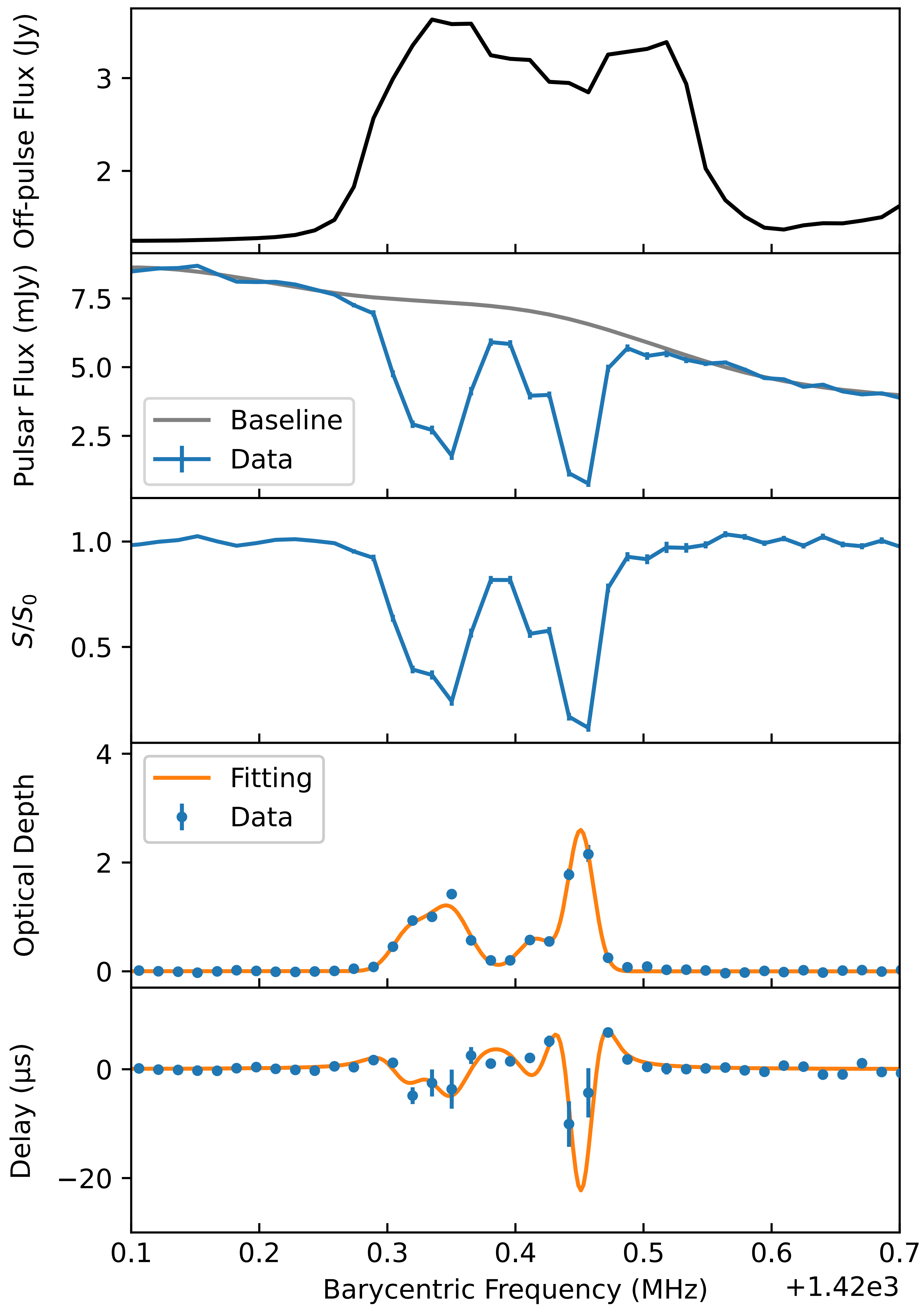
- Absorption lines
  4 Gaussian components in optical depth

$$\tau(f) = \tau_0 e^{-\frac{(f-f_c)^2}{2f_d^2}}$$

- Prediction of Lorentz model

$$\Delta t(f) = \tau_0 \left(\frac{f-f_c}{4\pi f_d^2}\right) \mathrm{Im}\left[w\left(\frac{f-f_c}{\sqrt{2}f_d}\right)\right] - \frac{\tau_0}{2\sqrt{2}\pi^{3/2}f_d}$$

  Faddeeva function $w(z) = e^{-z^2}\mathrm{erfc}(-iz)$
  (Janet et al. 2010)



Summary

- Kinematic distance of PSR B1937+21
  between 2 Galactic arms
- Anomalous dispersion
  $\sim 10\,\mu s$ faster-than-light
- Requires high S/N
  large telescopes (Arecibo, FAST and ???)
  bright pulsars (B1937+21 and ???)
  good luck (HI cloud, scintillation)
  new FAST proposal for more pulsars

Thanks!

Reference

- Ding H., Deller A. T., Stappers B. W., Lazio T. J. W., Kaplan D., Chatterjee S., Brisken W., et al., 2023, MNRAS, 519, 4982. doi:10.1093/mnras/stac3725

- Fich M., Blitz L., Stark A. A., 1989, ApJ, 342, 272. doi:10.1086/167591

- Frail D. A., Weisberg J. M., 1990, AJ, 100, 743. doi:10.1086/115556

- Jackson J. D., Zia R. K. P., 1977, PhT, 30, 61. doi:10.1063/1.3037637

- Jenet F. A., Fleckenstein D., Ford A., Garcia A., Miller R., Rivera J., Stovall K., 2010, ApJ, 710, 1718. doi:10.1088/0004-637X/710/2/1718

- Jing W. C., Han J. L., Hong T., Wang C., Gao X. Y., Hou L. G., Zhou D. J., et al., 2023, MNRAS, 523, 4949. doi:10.1093/mnras/stad1782

- Taylor J. H., Cordes J. M., 1993, ApJ, 411, 674. doi:10.1086/172870

- Wainscoat R. J., Cohen M., Volk K., Walker H. J., Schwartz D. E., 1992, ApJS, 83, 111. doi:10.1086/191733

- Weisberg J. M., Stanimirovic S., Xilouris K., Hedden A., de la Fuente A., Anderson S. B., Jenet F. A., 2008, ApJ, 674, 286. doi:10.1086/523345

- Yao J. M., Manchester R. N., Wang N., 2017, ApJ, 835, 29. doi:10.3847/1538-4357/835/1/29