Observing Axion Gegenschein with FAST

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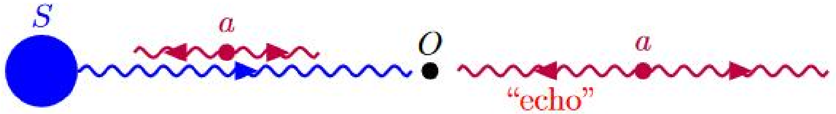
Outline

1. Axion gegenschein theory

- **axion gegenschein (Ghosh et al. 2020)**

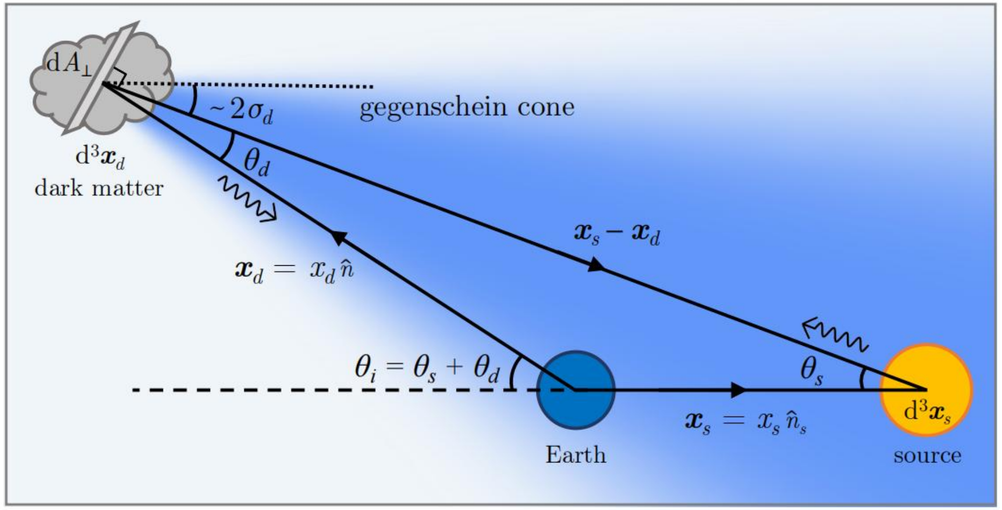


Buen-Abad et al. 2022

$$S_g = \frac{\hbar c^4 g_{a\gamma\gamma}^2}{16} \int_0^{\frac{t_0 c}{2}} S_\nu(\nu_a, x_d)\rho(x_d)\mathrm{d}x_d$$

- $g_{a\gamma\gamma}$: axion-photon coupling strength
- S_ν: flux density of primary source
- ρ: dark matter density in Milky Way

NFW profile $\rho(r) = \frac{\rho_0}{\frac{r}{r_s} \cdot \left(1 + \frac{r}{r_s}\right)^2}$

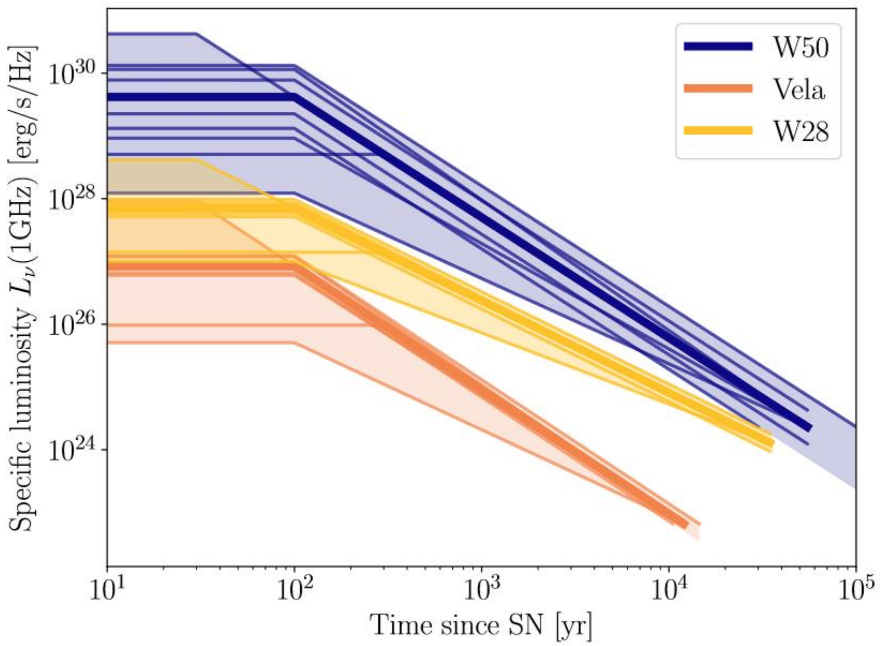


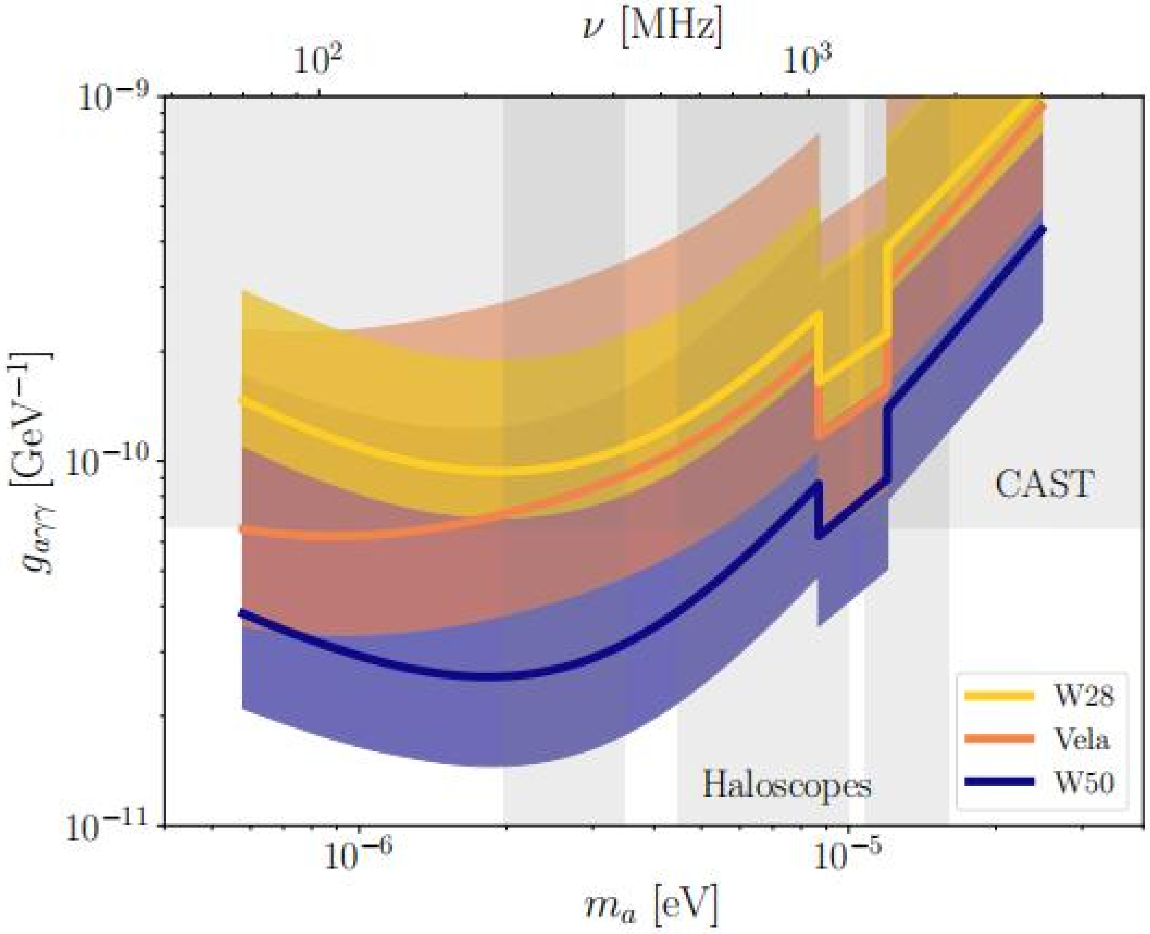
Sun et al. 2022

$$\theta_i \sim \theta_d \frac{x_{ds}}{x_s}, \quad \theta_i \ll 1$$

1. Axion gegenschein forecasts

- supernova remnants
- W50, Vela, W28
- 100h observation with FAST



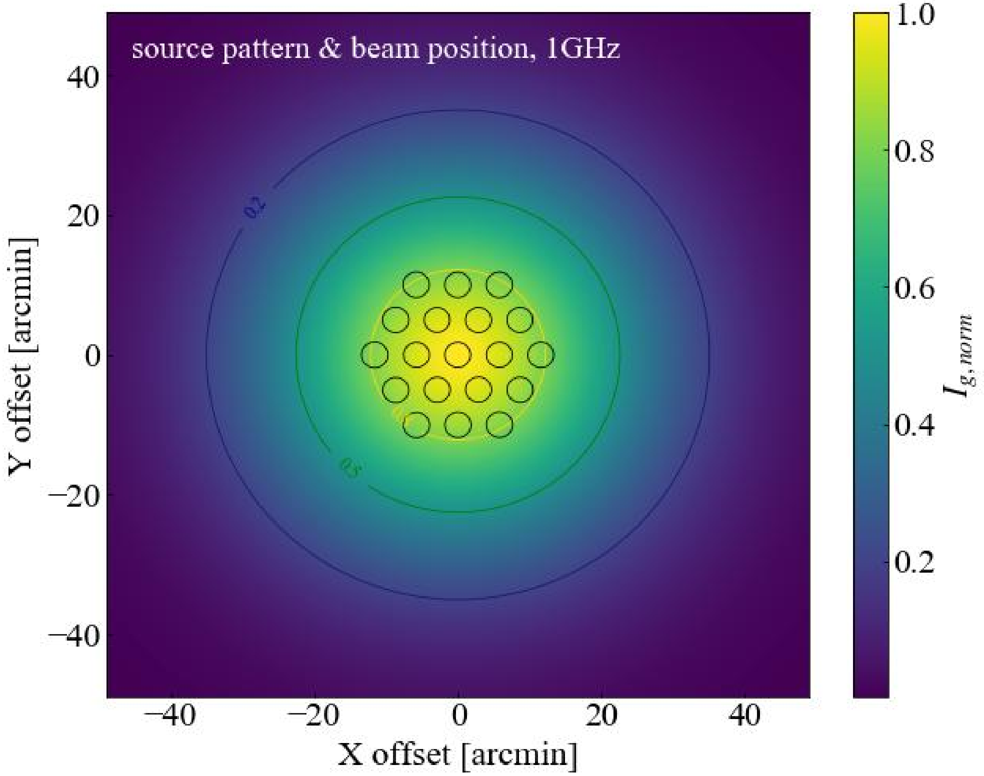


forecasts for constraints of $g_{a\gamma\gamma}$
Sun et al. 2022

1. Axion gegenschein   Vela SNR

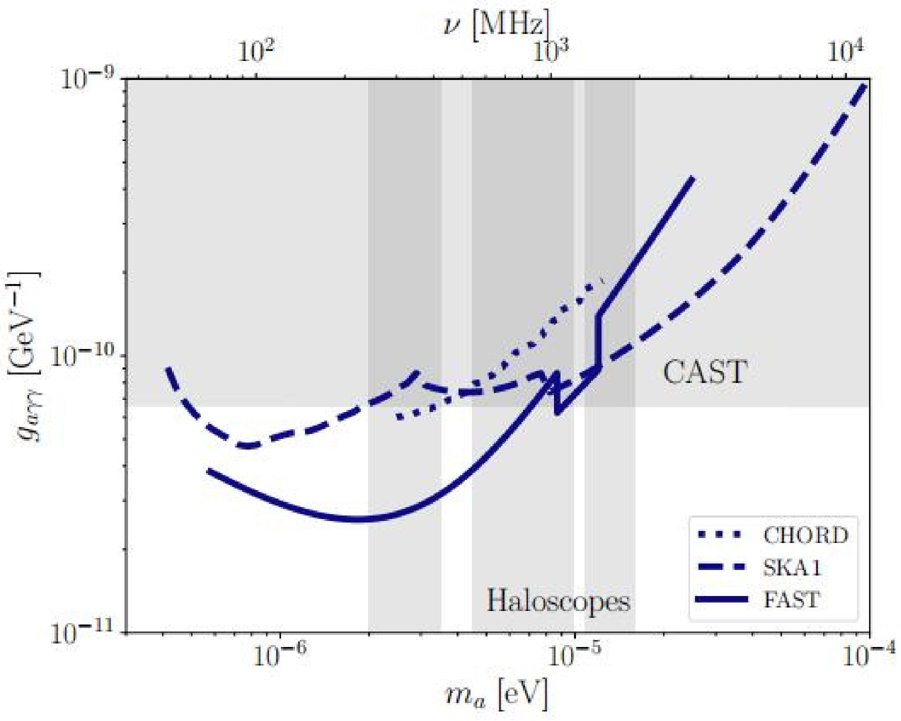
- Vela SNR gegenschein
- RA: 20h35m20.66s DEC: +45d10m35.20s
- FAST sky coverage: -15° ~ 65°

Parameters	Symbol	Fiducials	Error (or other model)
Position	(l, b)	$(263.55°, -2.79°)$	-
Distance	x_s	287 pc	+19 / -17 pc
Age	t_0	1.2×10^4 years	$\pm 2 \times 10^3$ years
MFA time	$t_{\rm MFA}$	100 years	+200 / -70 years
Spectral index	α	0.74	$\pm$ 0.04
Electron model	S_ν	$S_\nu \propto t^{-4p/5}$	$S_\nu \propto t^{-2(p+1)/5}$



1. Axion gegenschein forecasts

- **FAST (single dish telescope)**
  - D_{illu}=300m, A_{illu}=70700m^2, η_A=0.7, T_{sys}=20K
  - 70MHz - 3GHz (19beams in 1-1.5GHz)
- **CHORD (compact mapping interferometers)**
  - 24×22 rectangular array, D=6m, A_{illu}=14400m^2
  - η_A = 0.5, T_{sys}=30K
  - 300 MHz to 1500 MHz
- **SKA1 (long-baseline interferometers)**
  - SKA1-low: 131000 antennas, 50-350 MHz
  - SKA1-mid: 197 dishes, 350 MHz-15.3 GHz



100h observation of W50
(Sun et al. 2022)

2. Observation strategy

- **ON-OFF**

  A: ~20h ON-source, ~100min OFF-source, 10 days

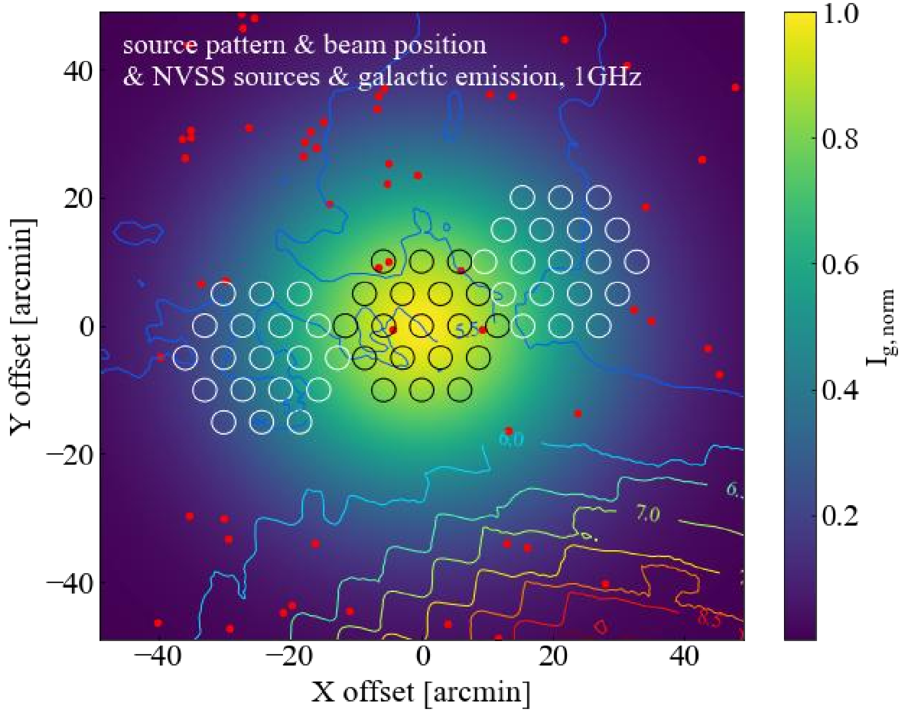
  B: ~320min ON-source, ~320min OFF-source, switch in every 10 minutes, 5 days

- **noise diode**: ~1K

  A: noise injected for 81.92μs in every 196.608μs

  B: noise injected for ~1s in every ~8s

- **sky calibrator**: 3C409, MultiBeamCalibration mode, ~20min(~20s per beam) each day



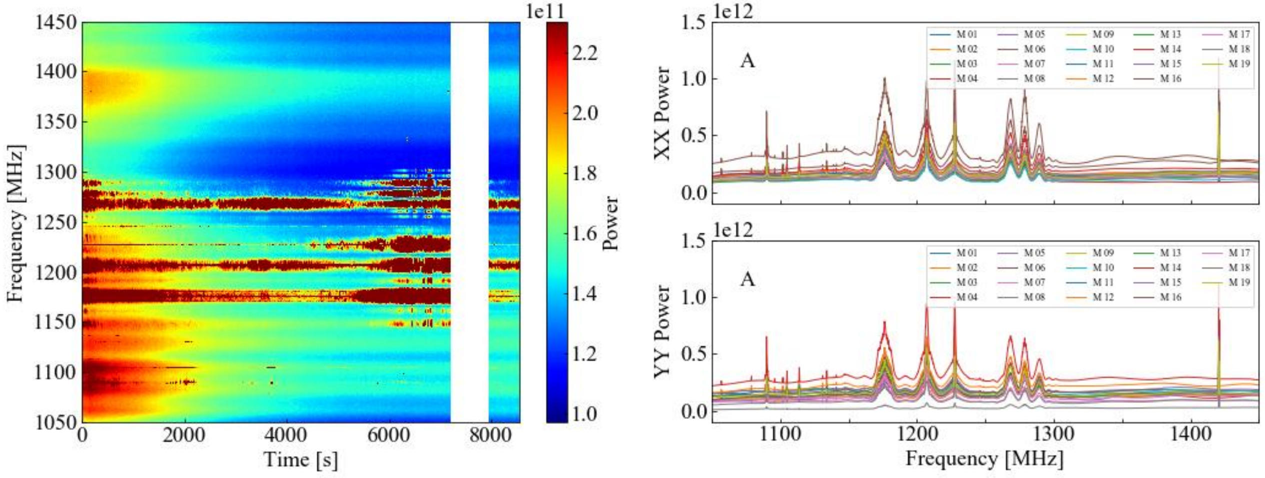
2. Observation data

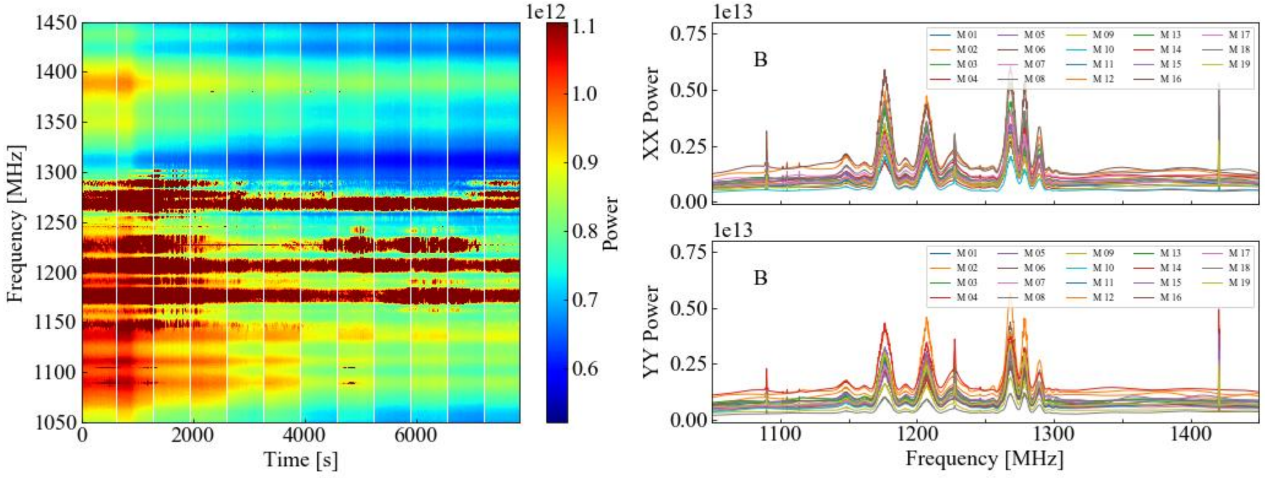
- **A**
- Δt ≈ 0.2s, Δν ≈ 7.6kHz (spec backend)
- Δt ≈ 98μs, Δν ≈ 122kHz (pulsar backend)

- **B**
- Δt ≈ 1.0s, Δν ≈ 7.6kHz

- **19 beams, 4 polarizations** (only 2 used)
- **Frequency bands**: 1050-1140MHz, ~~1140-1310MHz~~, 1310-1450MHz
- rebin: Δν ≈ 122kHz

A: ON OFF

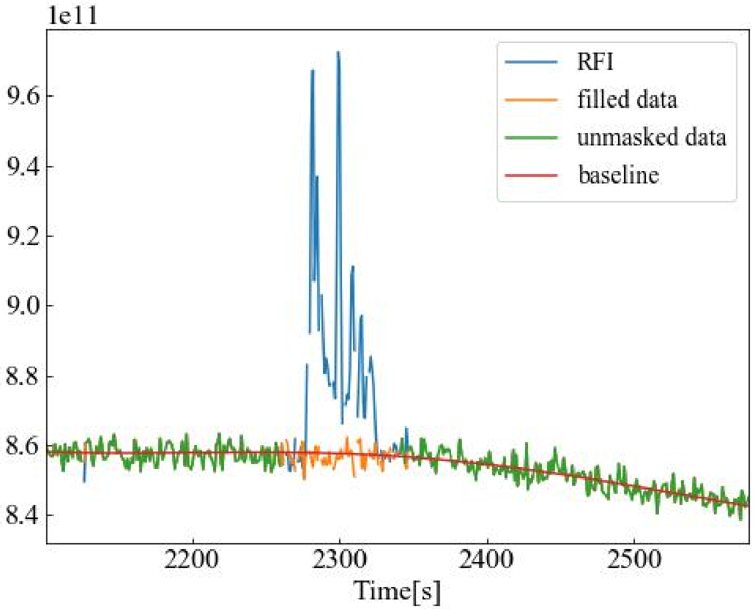




B: ON - OFF - ON - OFF...

3. Data processing

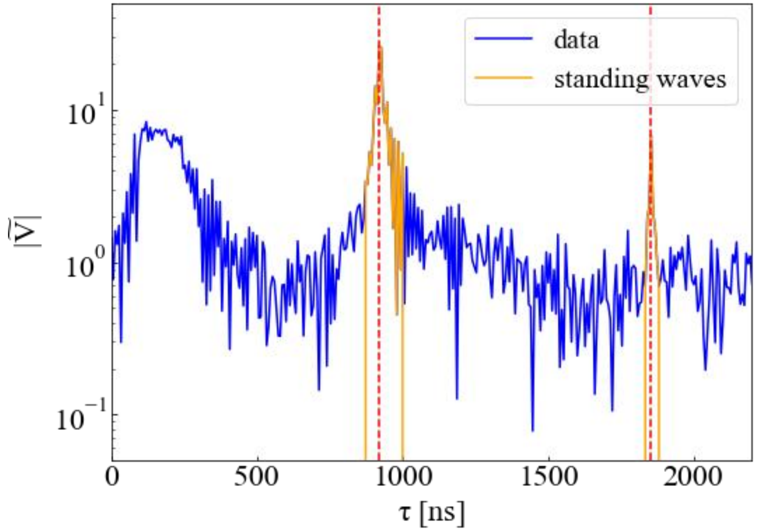
- **(1) temporal RFI flagging**



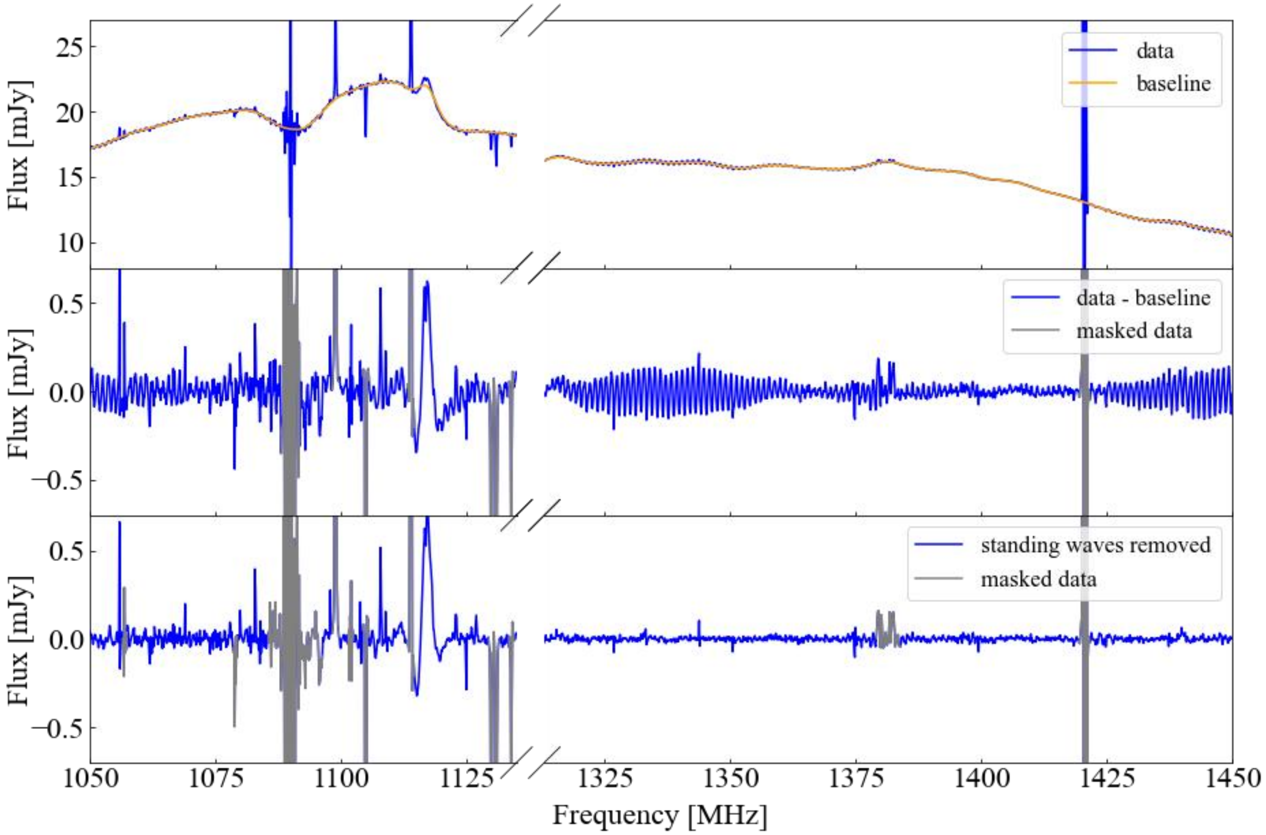
- **(2) bandpass and temporal fluctuation calibration**
  - bandpass $$bp(\nu) = \frac{\langle V_{\rm on}(\nu,t) - V_{\rm off}(\nu,t)\rangle_t}{\frac{t_{\rm on}}{t_{\rm samp}} \cdot T_{\rm ND}(\nu)}$$
  - temporal fluctuation $$g(t) = \left\langle \frac{V_{\rm spec,on}(\nu,t) - V_{\rm spec,off}(\nu,t)}{bp_{\rm spec}(\nu)} \right\rangle_\nu$$
  - calibrated data $$T_{\rm cal}(\nu,t) = \frac{V_{\rm spec}(\nu,t)}{bp_{\rm spec}(\nu) \cdot g(t)}$$
- **(3) absolute flux calibration**
  - 3C409 $$S_{\rm 3C409}(\nu)B(r) = \frac{T_{\rm 3C409}(\nu)}{\eta(\nu, \theta_{\rm ZA,0}) \cdot G_0}$$
  - flux $$S(\nu,t) = \frac{T_{\rm cal}(\nu,t)}{\eta(\nu,t) \cdot G_0}$$

3. Data processing

- **(4) baseline and standing waves removing**
- weighted averaging data from different beams and OFF-source points →



delay spectrum



3. Data processing

- **(5) signal searching**
- **Features of axion gegenschein signal:**
- position: determined by axion mass, $h\nu_a = m_a c^2/2$
- shape: **Gaussian**
- width: related to Doppler broadening, $\Delta\nu/\nu \sim 2\sigma_d/c$, $\sigma_d \sim 116km/s$ $\Rightarrow$ $\boldsymbol{\Delta\nu \sim 1MHz}$
- detection: **2 polarization, 19 beams, all time**
- **Searching method**
- **matched-filtering** and interation
- template: Gaussian, 0.3MHz < σ < 0.6MHz

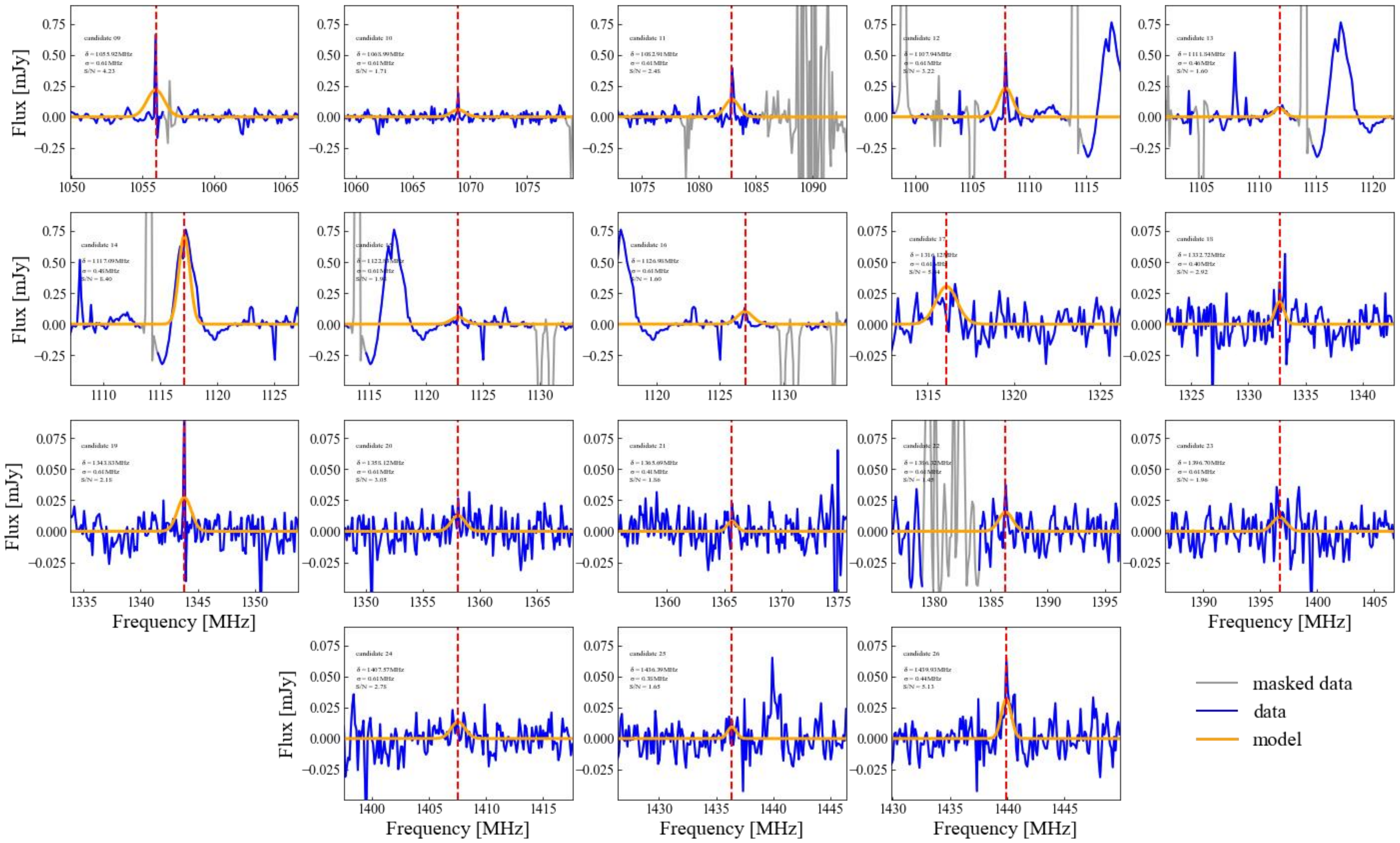
matched-filtering method:

signal: $s(x)$ template function: $\alpha t(x-\delta;\sigma)$

minimize $\chi^2 = \sum_{x=1}^{N} [\alpha t(x-\delta;\sigma) - s(x)]^2$

$\Leftrightarrow$ maximize $c(\delta) = s(x) * t(x-\delta;\sigma)$

4. Results candidates



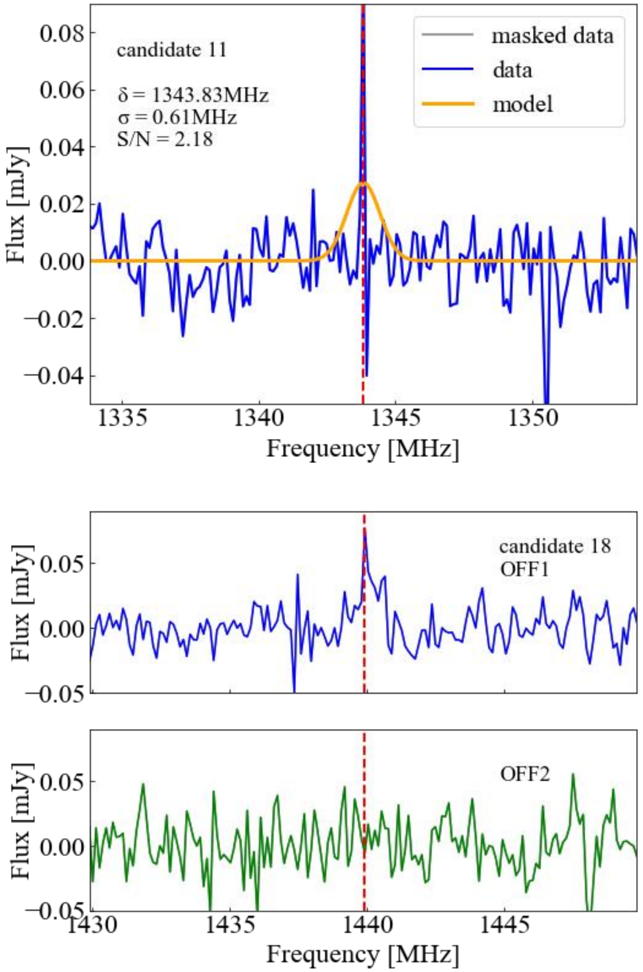
4. Results candidates

● candidates selection：

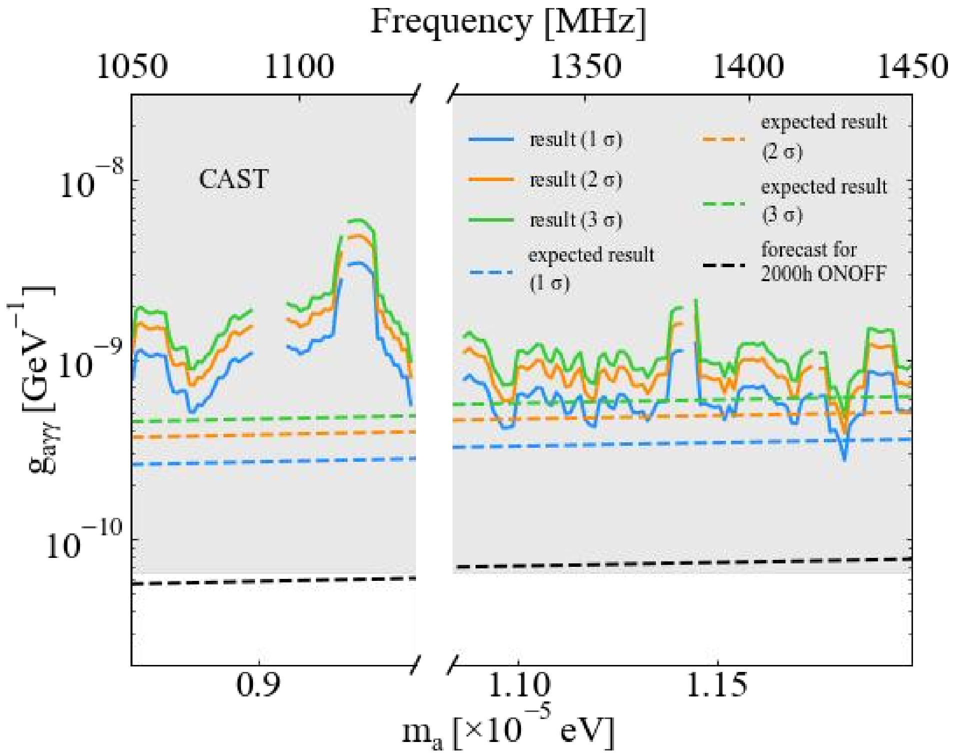
• (1) exclude too narrow/wide

• (2) divide data into 2 groups and compare S/N, shape and peak flux in each group

- polarizations
- beams
- OFF-source points
- time



4. Results constraint



$$S_g = \frac{\hbar c^4 g_{a\gamma\gamma}^2}{16} S_{\nu,0}(\nu_a) \int_0^{\frac{(t_0 - t_{MFA})c}{2}} \left(\frac{t_0 - \frac{2x_d}{c}}{t_0} \right)^{-\frac{4p}{5}} \rho(x_d) dx_d$$

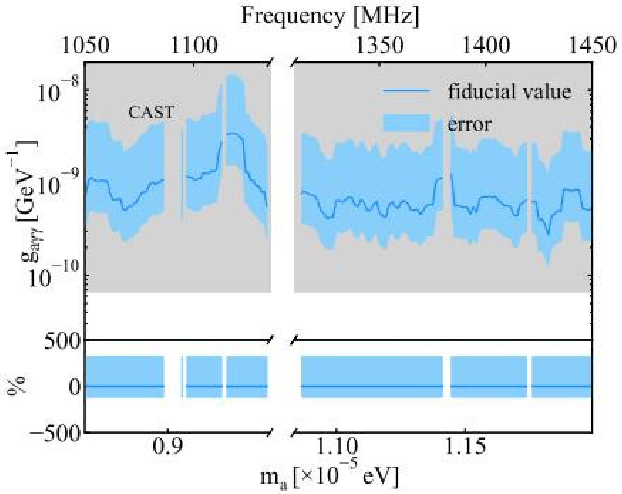
$$+ \frac{\hbar c^4 g_{a\gamma\gamma}^2}{16} S_{\nu,0}(\nu_a) \int_{\frac{(t_0 - t_{MFA})c}{2}}^{\frac{t_0 c}{2}} \left(\frac{t_{MFA}}{t_0} \right)^{-\frac{4p}{5}} \rho(x_d) dx_d$$

$$S_{\rm obs} = f_\Delta \int I_g(\hat{n}) b(\hat{n}) \mathrm{d}\Omega$$

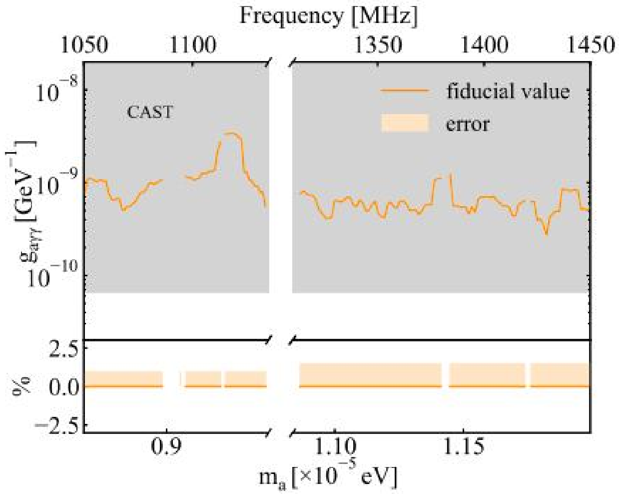
$$S/N < 1, 2, 3$$

5. Error estimation

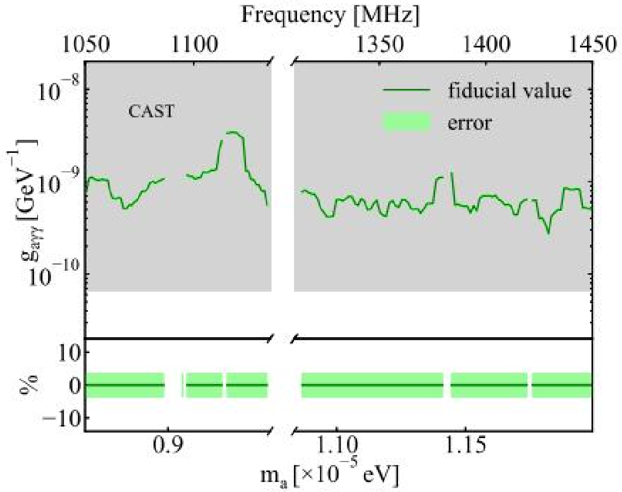
Vela SNR model



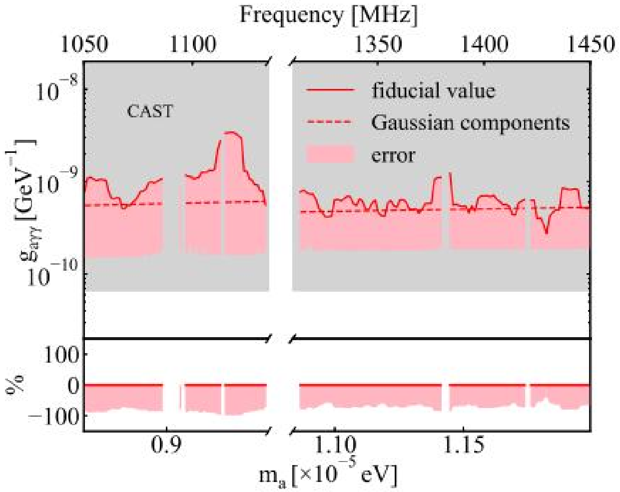
pointing error



calibration process



residual components

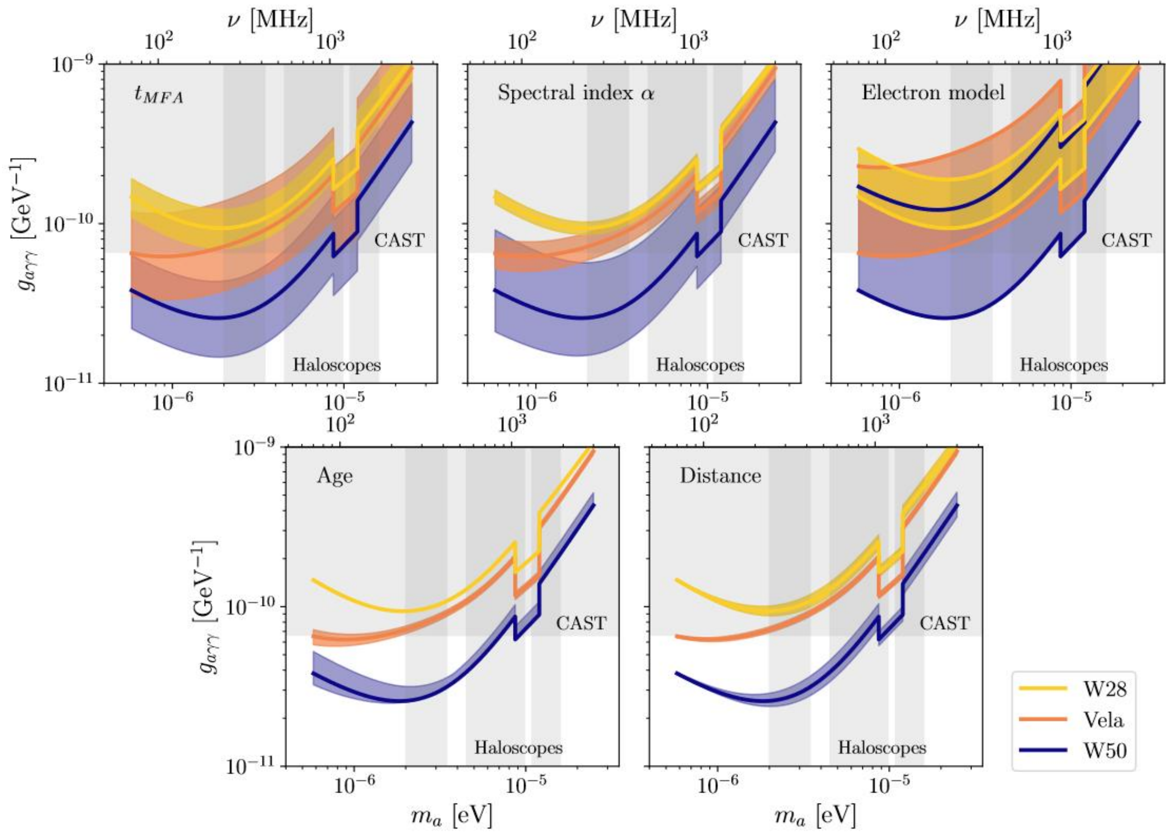


6. Summary

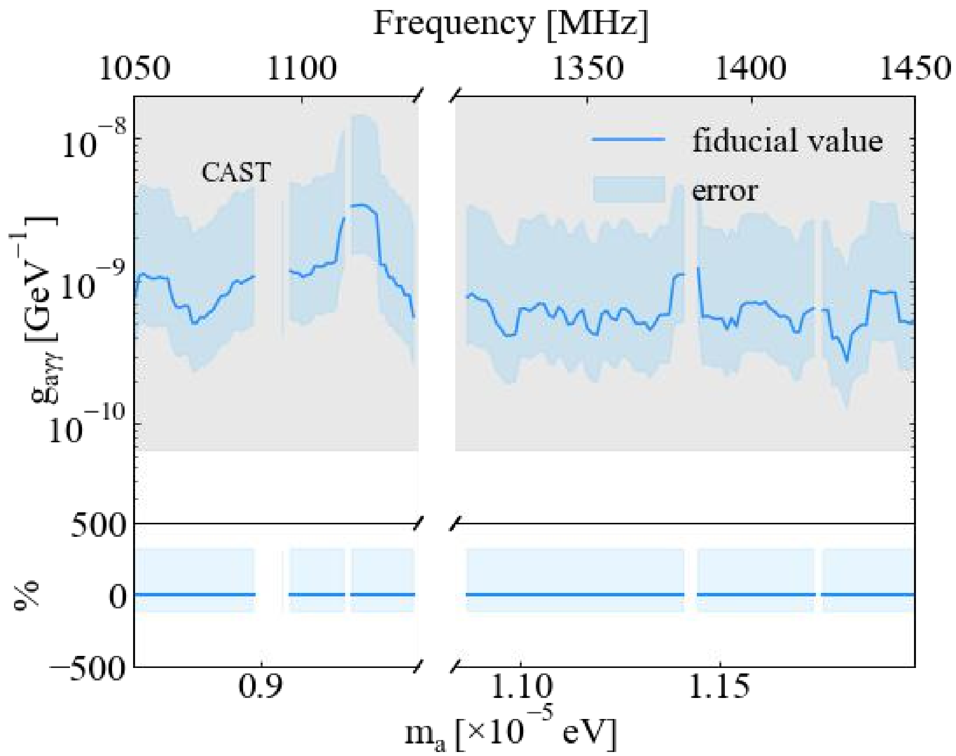
- a constraint of axion-photon coupling strength $g_{a\gamma\gamma}$ at m_a ~ 10μeV
- other experiments/approaches
- future improvements:
  - long integral time
  - better sources
  - accurate model of primary sources
  - more effective data processing methods for weak signals detection
  - better performance of telescopes

Thanks!

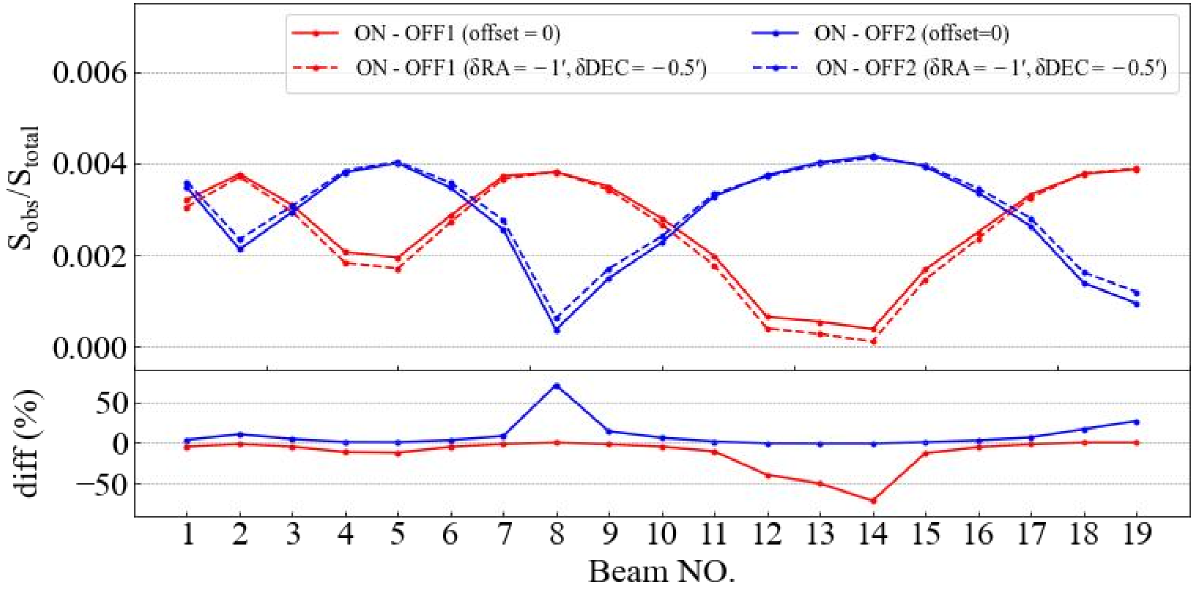
5. Error estimation Vela SNR model

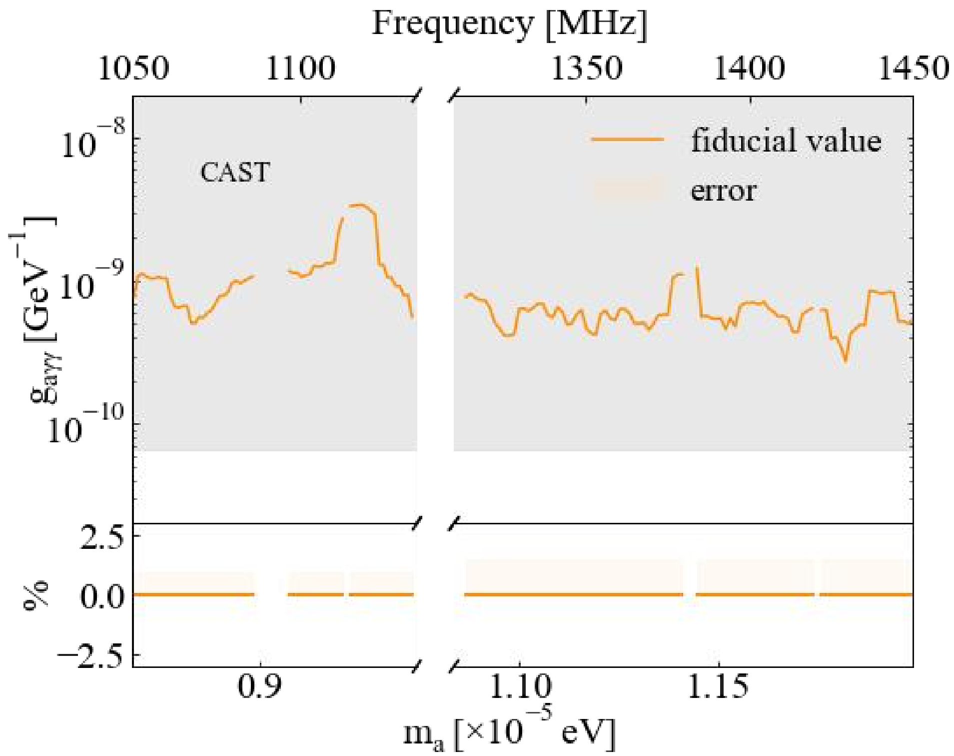


Sun et al. 2022



5. Error estimation pointing error



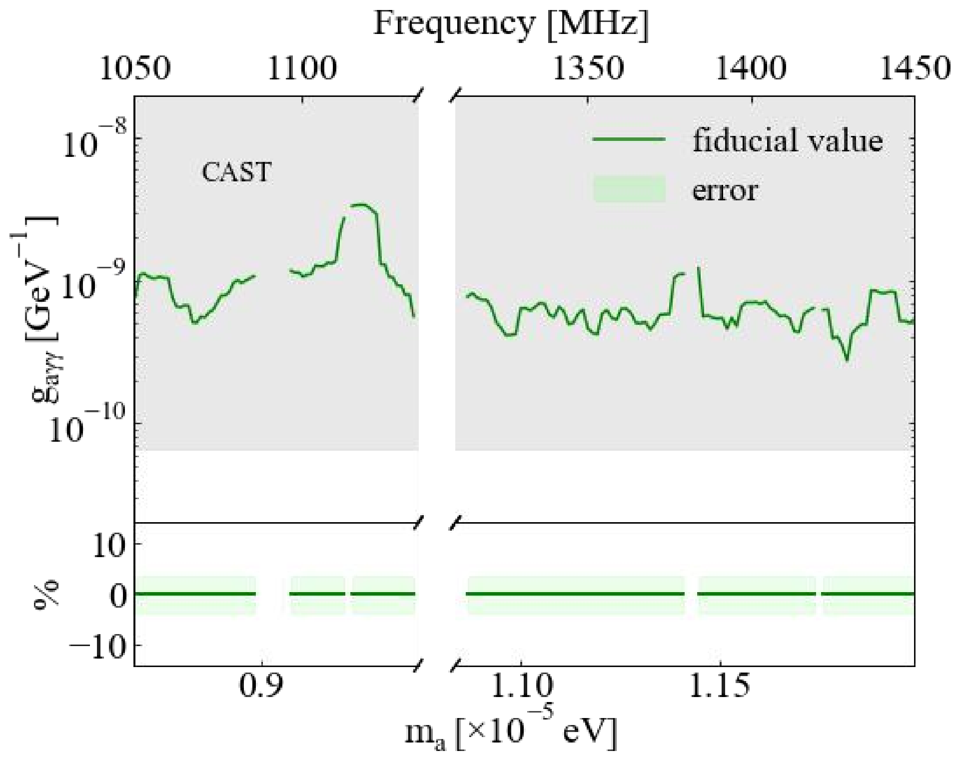


δRA = -1’, δDEC = -0.5’

5. Error estimation **calibration process**

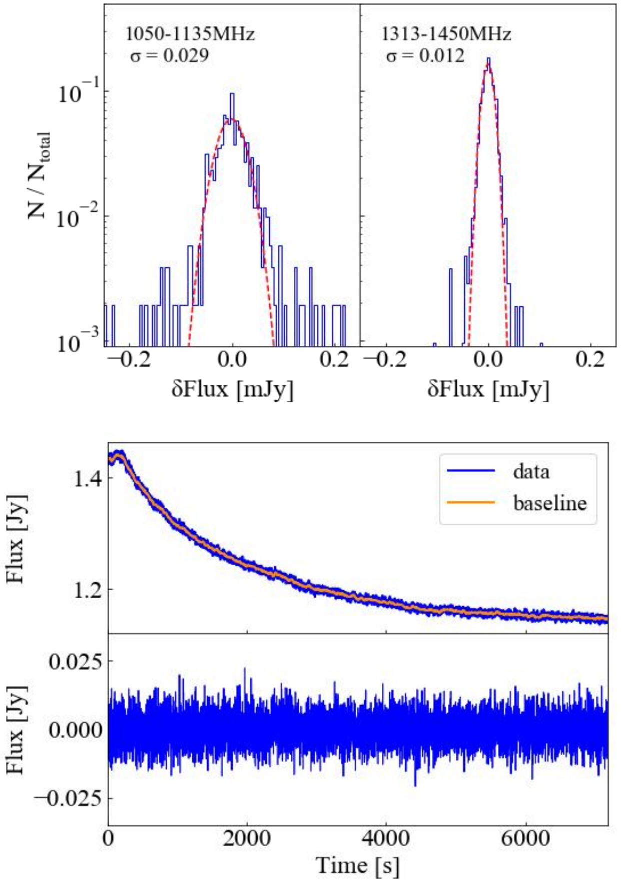
- noise diode
  - bandpass stability
- sky calibrator
  - flux
  - η(ν,za)
  - beam pattern

roughly assume a 7% error



5. Error estimation　residual components

- RFI, baseline, standing waves, ...
- (1) Gaussian/ non-Gaussian components



- (2) $\mathrm{rms}(v)_t/\sqrt{t_{samp}}$