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nao.ac.jp

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Long-term and high frequent monitor of the 6.7 GHz methanol masers to research period flux variations using Hitachi 32-m

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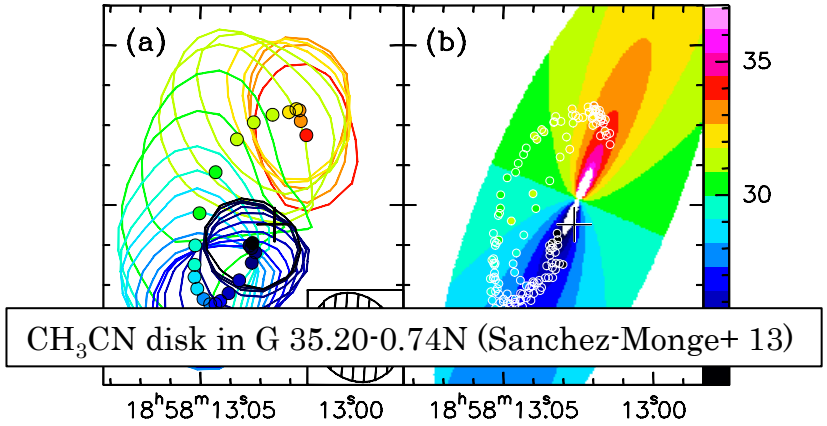
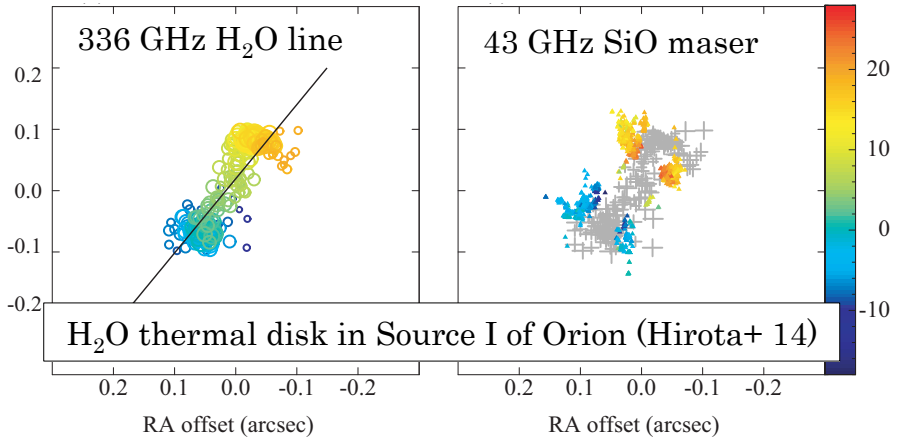
Periodic flux variations around high-mass protostars

1. Motivations

High-mass (HM) star formation

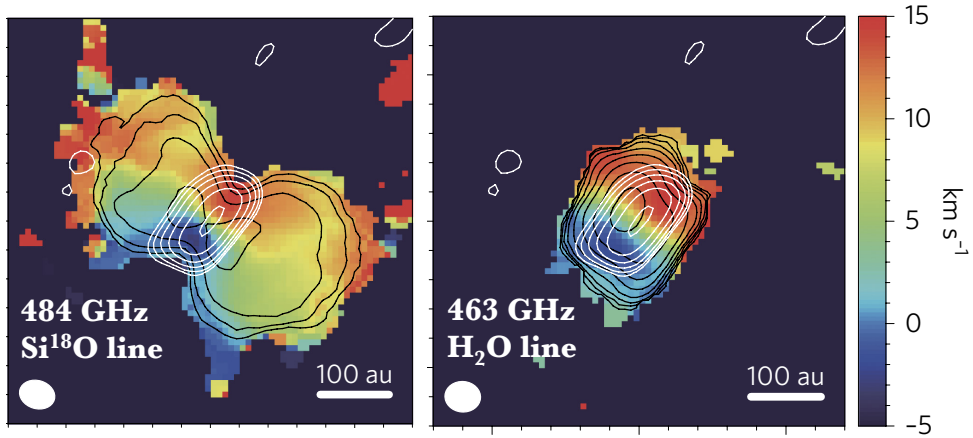


CH_3CN disk in G 35.20-0.74N (Sanchez-Monge+ 13)



H_2O thermal disk in Source I of Orion (Hirota+ 14)

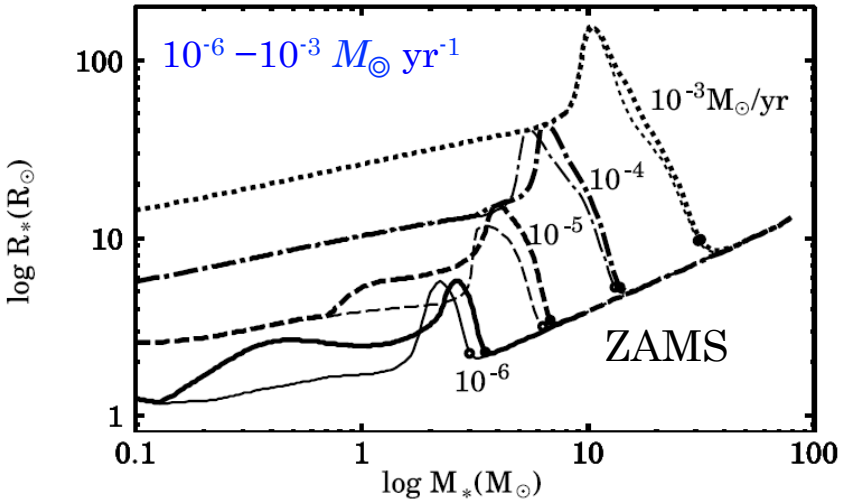
- Could be a **Scaled-Up** ver. of low-mass star formation!
  - **Disk-outflow** system (e.g., Hirota+17)
  - Growth through **mass accretion** from disk (e.g., Hosokawa+ 10)
  - Magnetic field structure with **hourglass** shape (e.g., Tang+ 09)
  - **Accretion burst** (Fujisawa+ 15; Caratti o Garatti+ 16)

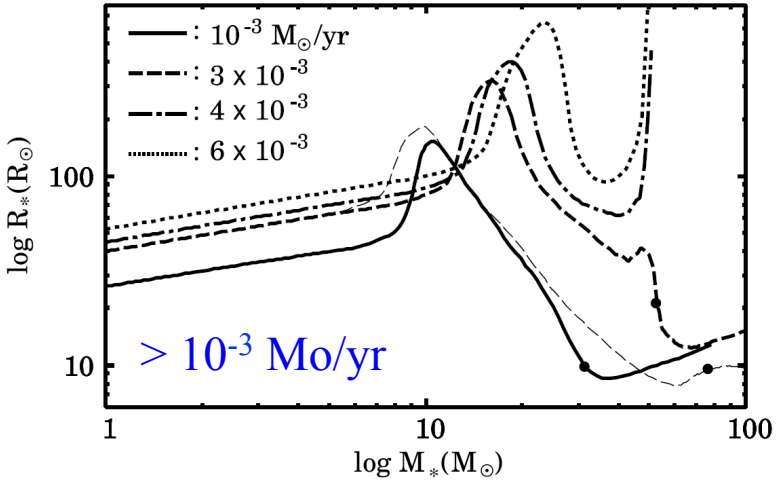


Disk-driven rotating bipolar outflow observed in Orion Source I (Hirota+ 17)

Evolutionary tracks depends on accretion rate onto the surface of HM proto-stars (≦ 0.1 au-scale)

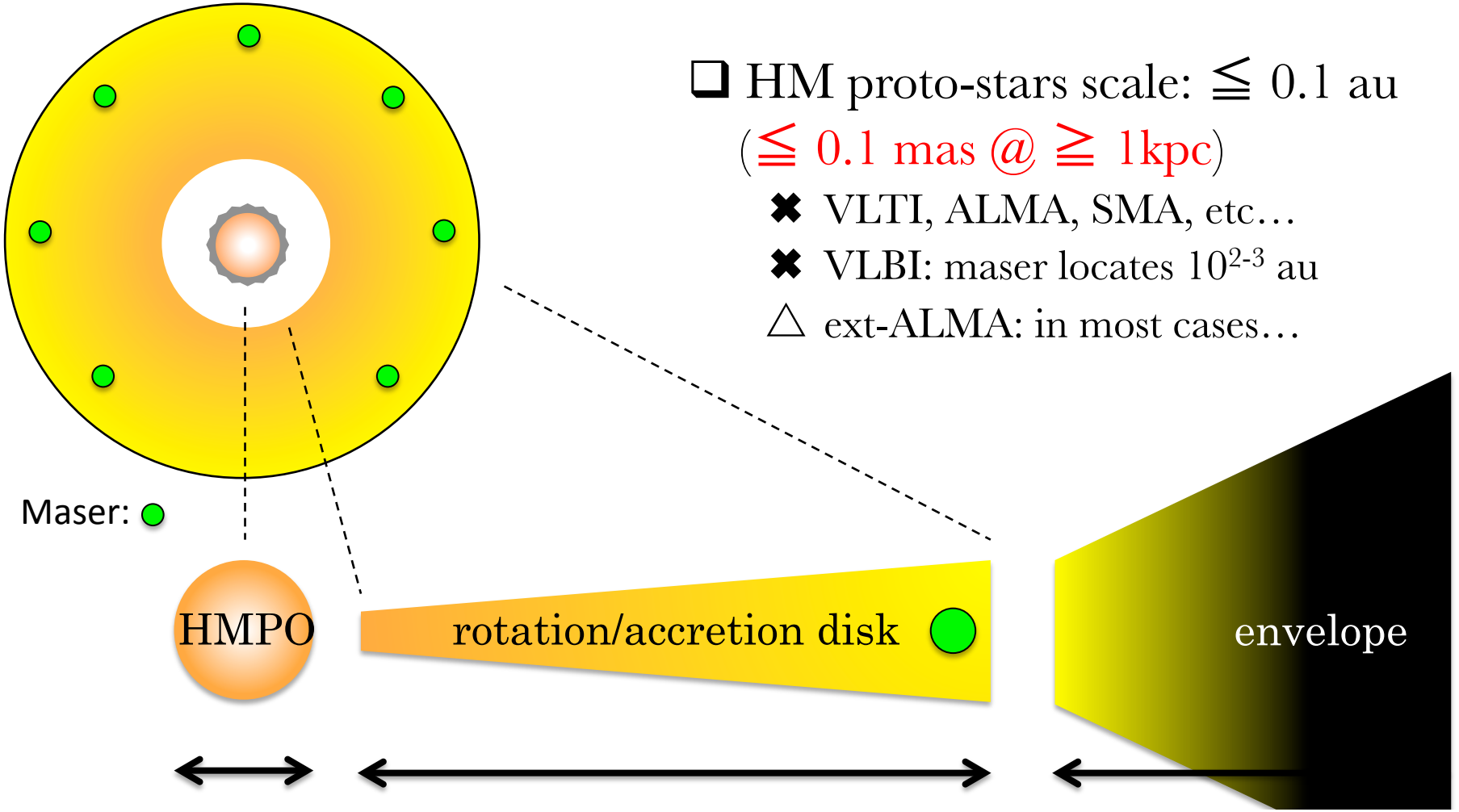
- Theoretical calculation suggested that evolutionary tracks of HM proto-stars are determined by an accretion rate onto the stellar surface of ones (Hosokawa & Omukai 2009)
  - Must be expanded just before ZAMS to be 10-100 $R_{\odot}$
  - Spatial scale ≦ 0.1 au-scale
- We need to measure the accretion rates onto the surface (tiny area) to understand the evolution of HM proto-stars





Evolutionary tracks depending on accretion rates onto the surface of HMPSs (Hosokawa & Omukai 09)

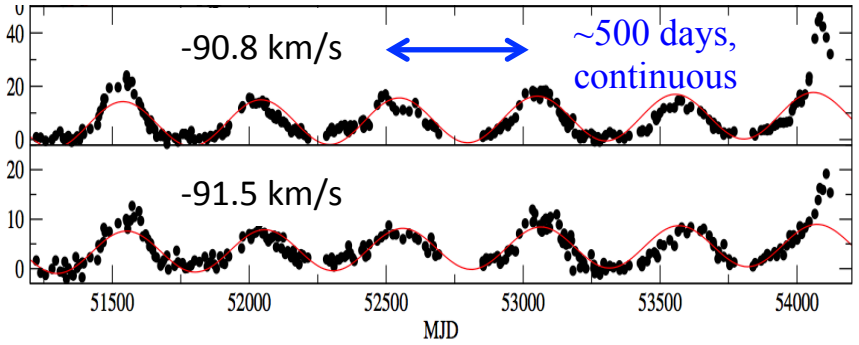
Spatial scale around the HM proto-stars (PSs) vs instruments



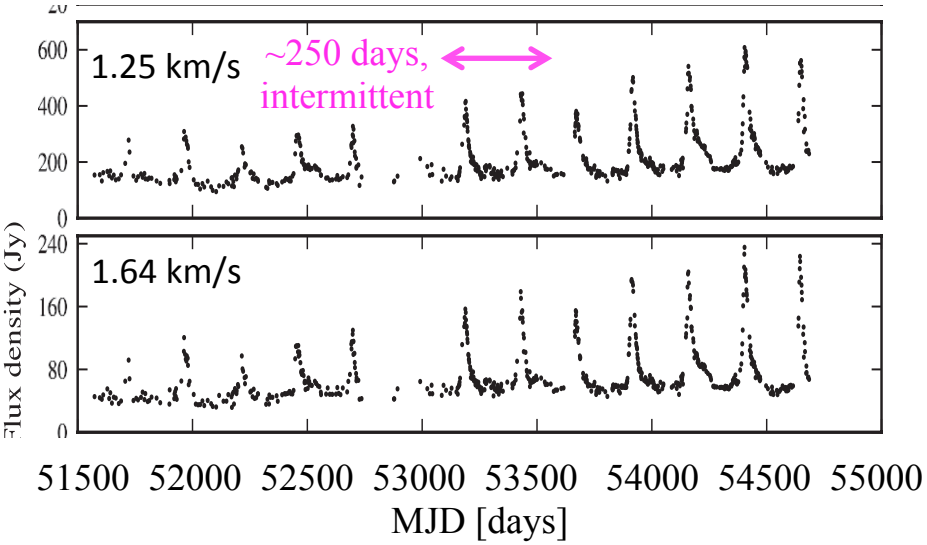
Periodic flux variations around HMPSs

- (Potentially) discovered in the 86 GHz SiO maser of Orion-KL (Ukita+ 81)
- Verified in the 6.7 GHz CH_3OH maser of G 009.62+00.20 E with a period of 246 d (Goedhart+ 03)
  - So far, in 20 sources (e.g., Goedhart+ 04)
- Characteristics
  - Periods: ~**30–670 d**
  - Pattern: Continuous / Intermittent
  - **Synchronized** in multiple spectral components

Possibly caused by central engine in tiny spatial scales of ~0.1-1 au (expected from Keplerian rotation)



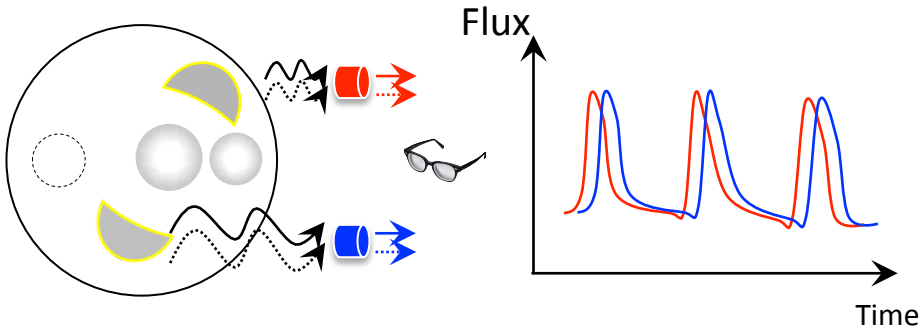
↑: Periodic methanol maser sources, G 331.13-00.24 (Goedhart+ 07), ↓: G 009.62+00.20 E (Goedhart+ 14).



Candidates to cause period variations

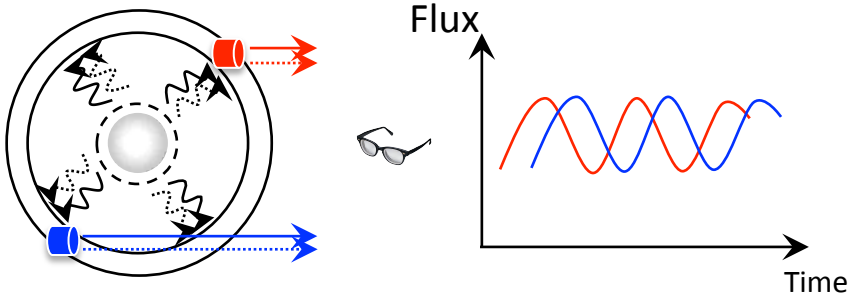
- **Colliding wind binary** (van der Walt+ 09; van der Walt 11)
- **Stellar pulsation instability** (Inayoshi+ 13; Sanna+ 15)
- **Spiral shock heating in a circum-binary disk** (Parfenov & Sobolev 14)

Seed photon

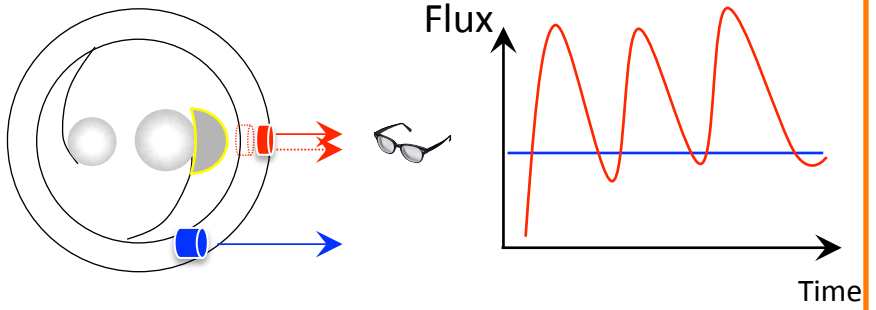


Colliding wind binary

Dust temperature



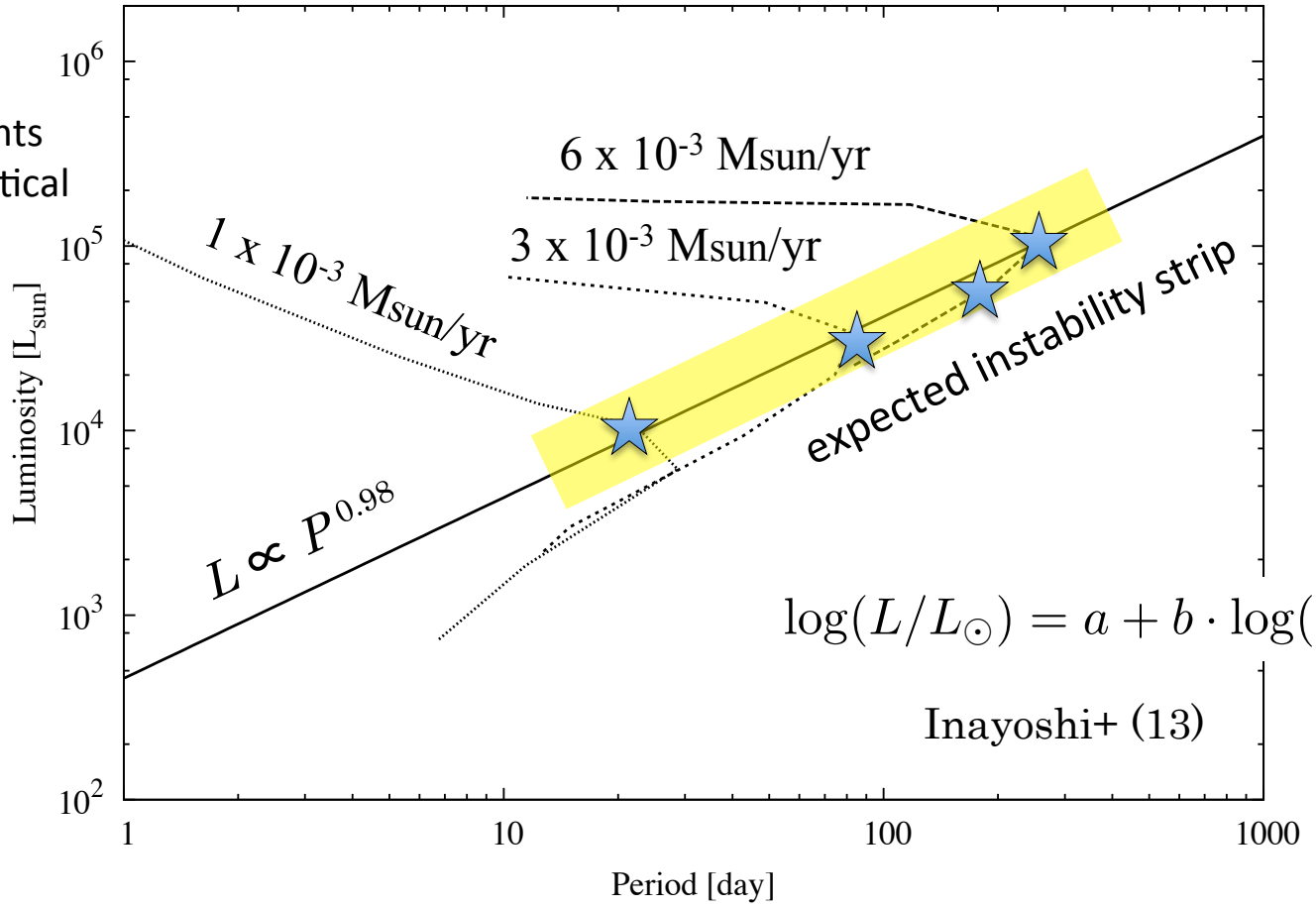
Stellar pulsation instability (Continuous / sinusoidal)



Spiral shock heating in circumbinary disk

Period-Luminosity relation:
expected from pulsational instability model

Unstable points
In the theoretical
calculations



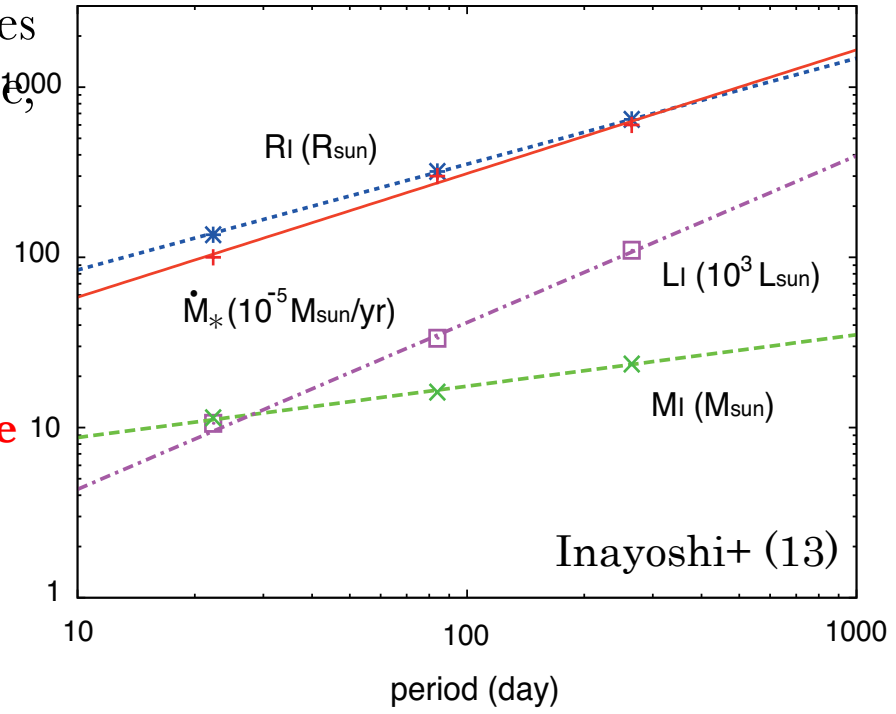
$$\log(L/L_\odot) = a + b \cdot \log(P/100 \text{ days})$$

Inayoshi+ (13)

Period-Luminosity relation: related to physical properties

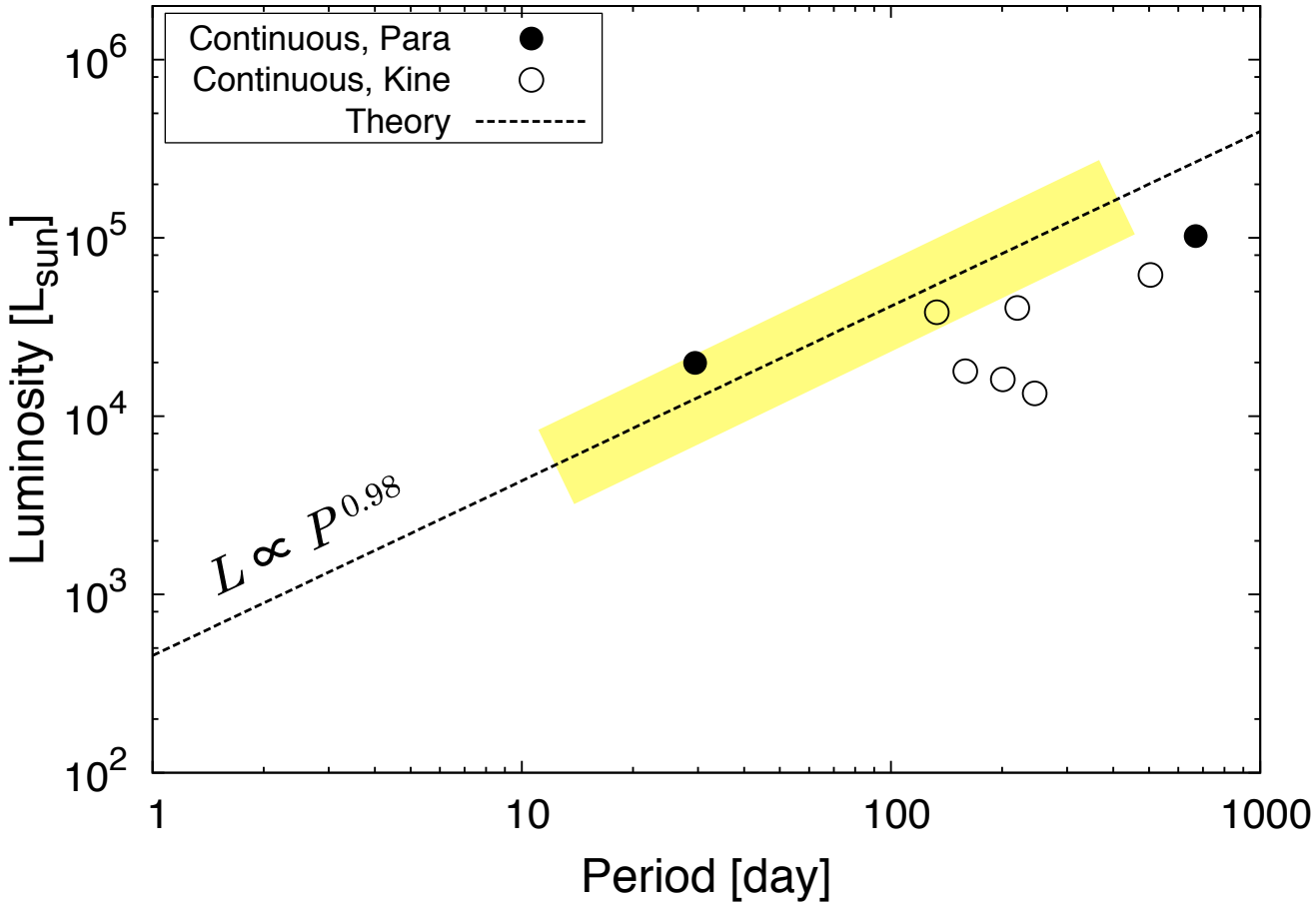
- Expected to measure physical properties on HM proto-stars at protostellar phase, indirectly from $t_{accretion} \sim t_{KH}$
  - Luminosity
  - Mass
  - Radius
  - **Accretion rate onto stellar surface**

※ $t_{acc} = M / M_{dot}$; $t_{KH} = G M^2 / L R$



- Achieve the measurement **at sub-au scale** using single-dish low-angular resolution instrument observations !
- Should be verified and established by observations

Period-Luminosity (P-L) relation:
based on observed data so far



Period-Luminosity (P-L) relation:
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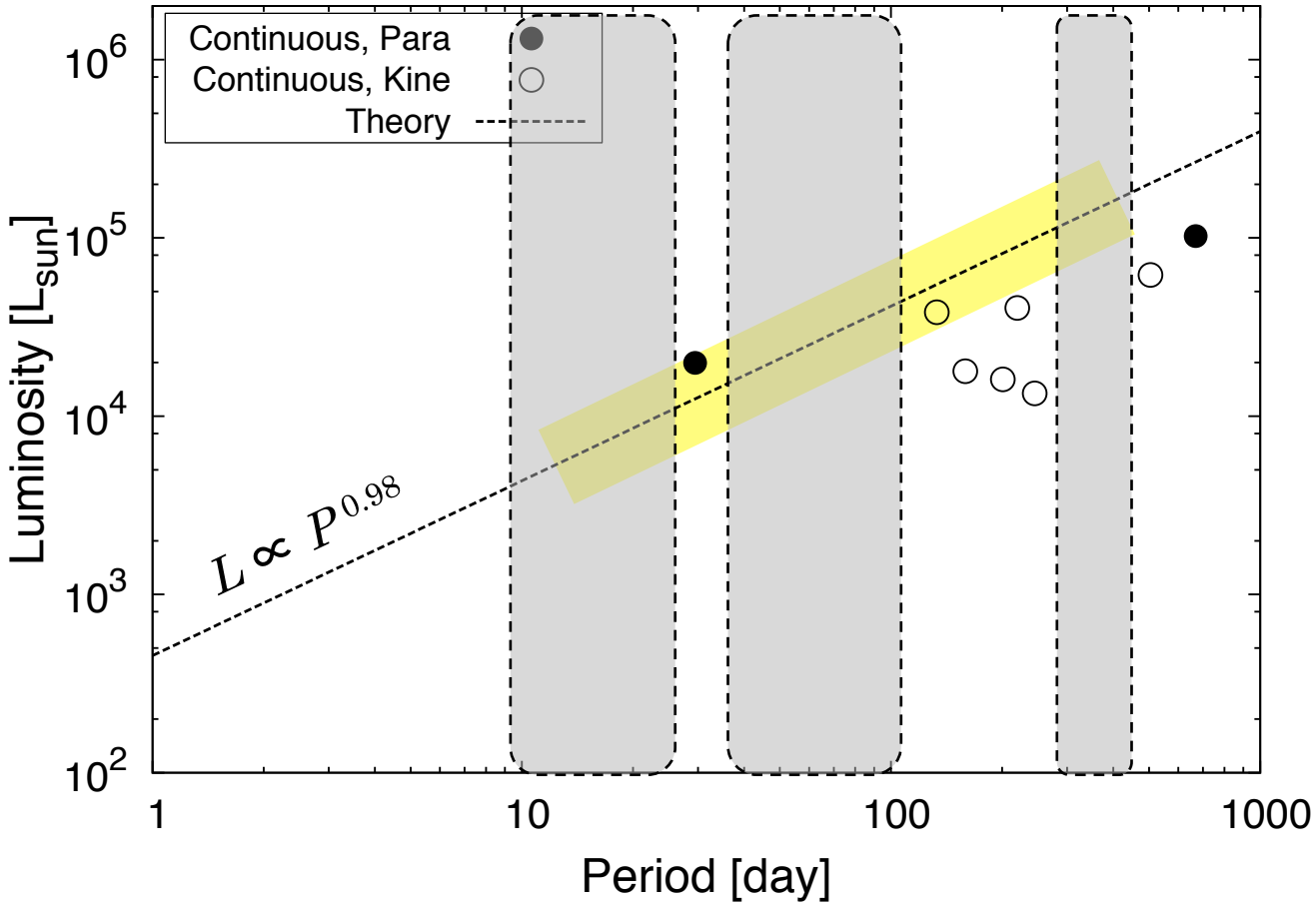


Problems to be solved

- Lack of samples
  - < 20% (~170 sources) monitored enough to investigate periods
  - Mainly toward bright sources

☞ Long-term, high-frequent, and unbiased monitor toward large samples!

- Inaccurate luminosity
  - Inaccurate source distance (kinematic distances: 6/8 sources)
  - Low-spatial resolution FIR data

- Comparison with a monitor at NIR band
  - Need to investigate a change of dust temperature due to the luminosity variation of a central exciting source

2. Observations

Hitachi 32-m monitor project: obs. parameters


Hitachi 32-m (Credit: NAOJ)

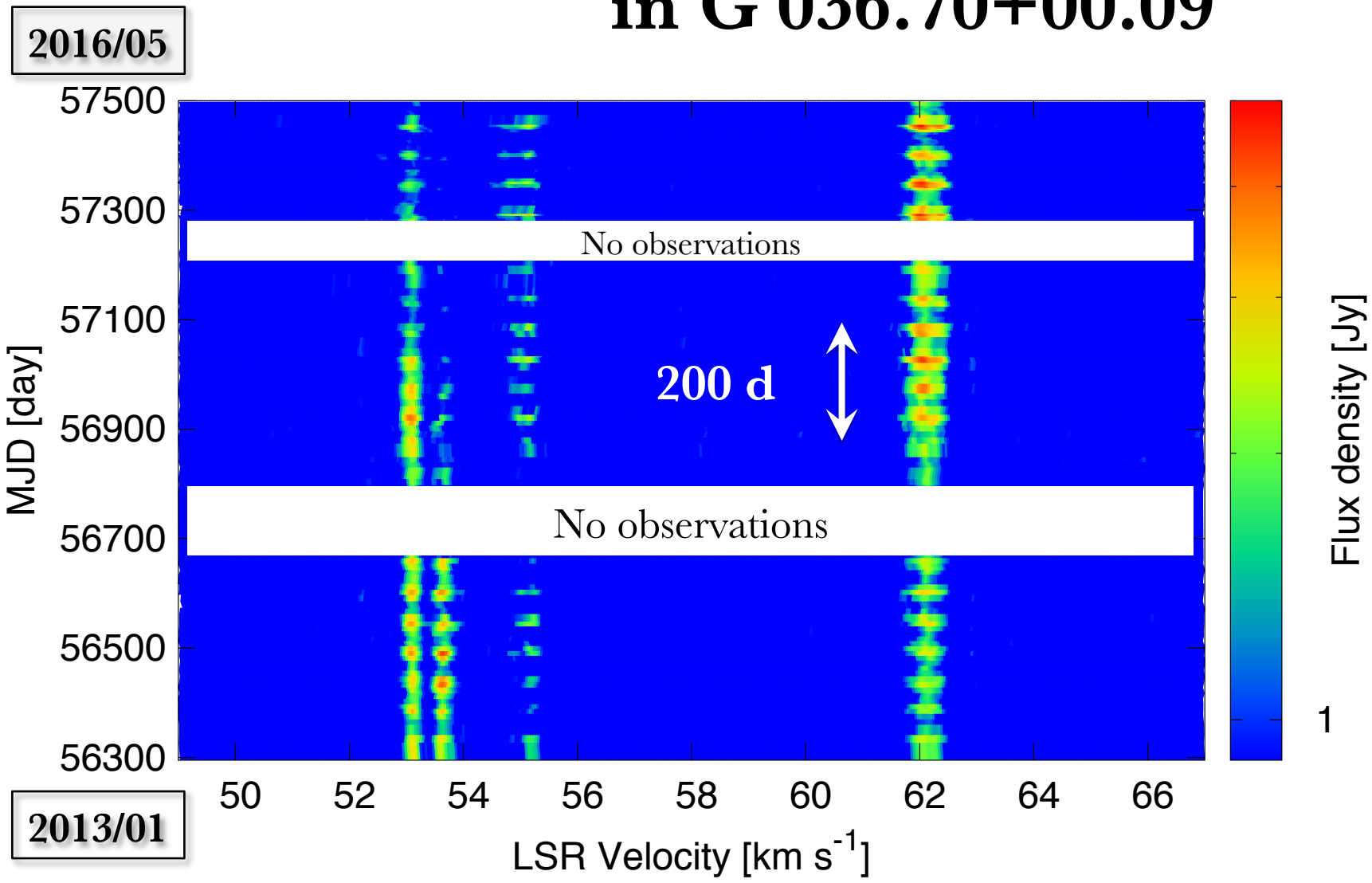
- Target sources : **442 sources** in total
  - Dec > -30 deg from the methanol maser catalog till in 2012/Dec
- Initiated from 2012/Dec/30 using Hitachi 32-m telescope

Parameter / Session	1st & 2nd	3rd
Telescope, beam size	Hitachi (Ibaraki) 32-m, 4.6 arcmin @6.7GHz	
Duration	2012/12/30 – 2014/01/10 2014/05/07 – 2015/08/24	2015/09/18 – 2017/02/19
Observational interval	9-10 days^{-1} / source	4-5 days^{-1} / source
Radio frequency	6664 – 6672 MHz	
Channel	8,192 (binned from 2,097,152 channels)	
Velocity resolution	0.044 km s^{-1}	
Sensitivity (3 σ) with 5 min	~0.9 Jy	

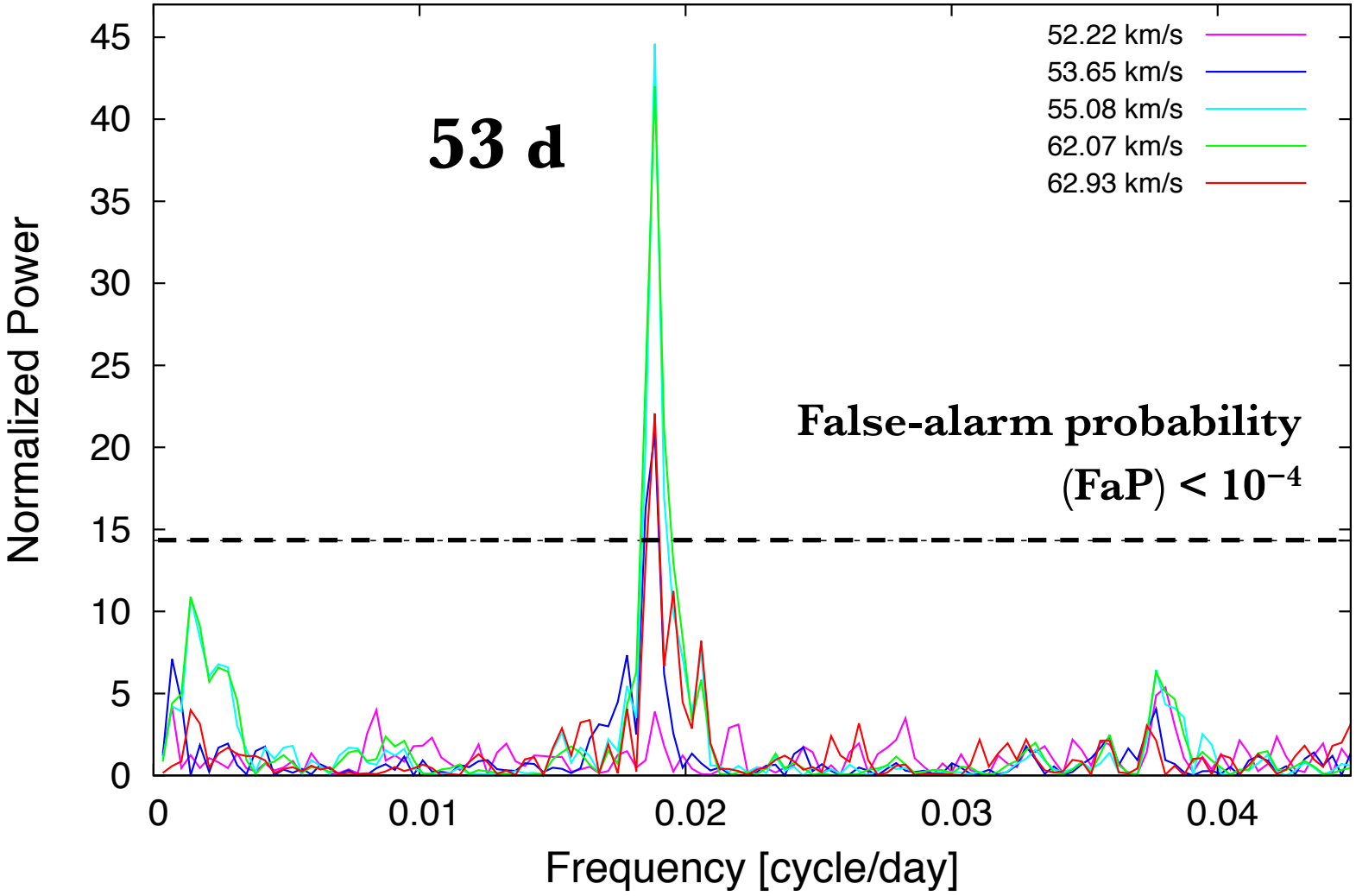
Ibaraki (Hitachi・Takahagi) 32-m radio telescopes (from HP of Center for Astronomy, Ibaraki Univ.)

3. Results

e.g., Dynamic spectrum in G 036.70+00.09



e.g., Lomb-Scargle periodgram in G 036.70+00.09



New detections of periodic variations

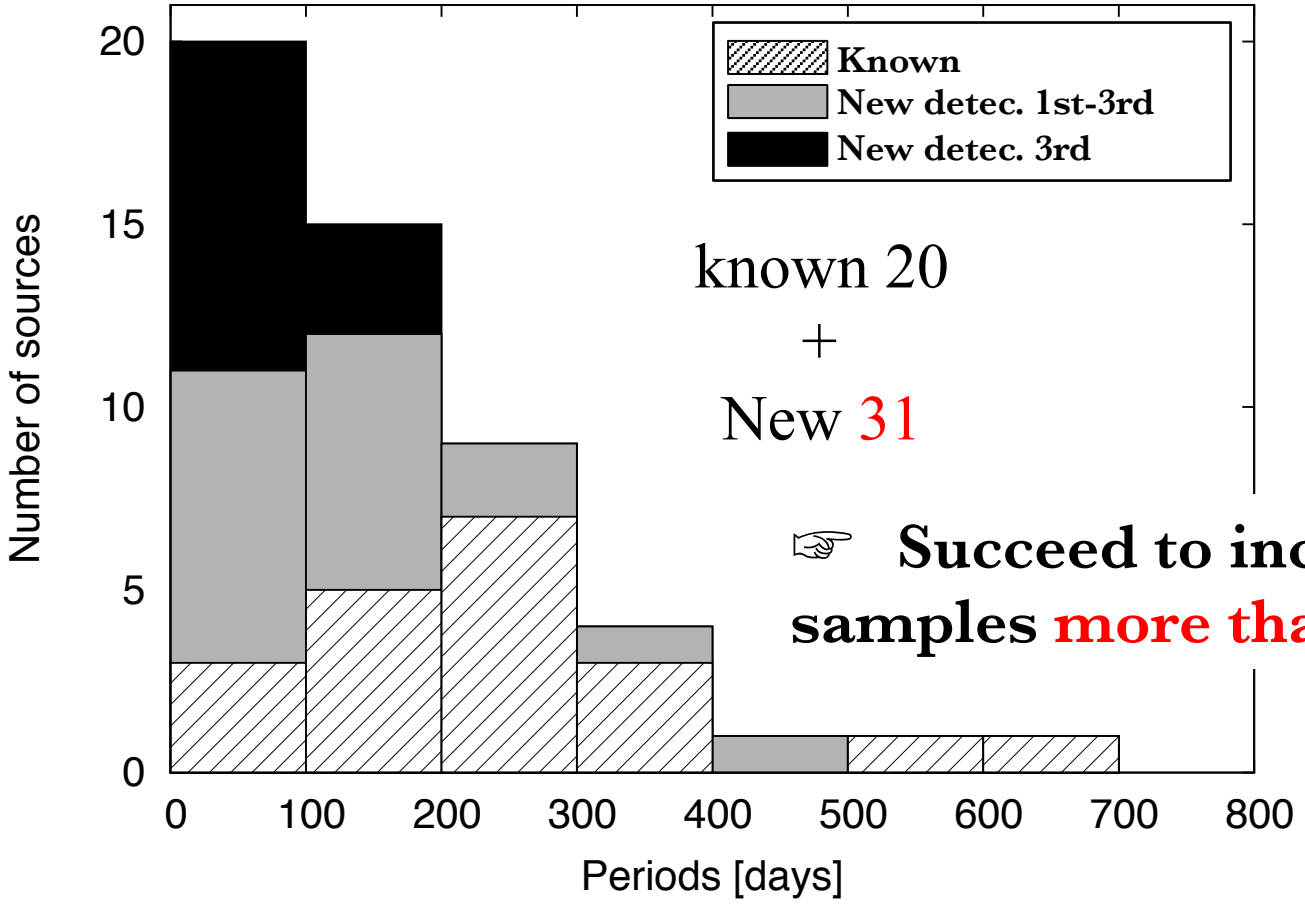
- Lomb-Scargle periodogram (Lomb 76; Scargle 82)
  - Programmed by Y. Yasui (Ibaraki M2 in 2015) based on Numerical Recipe

- How to judge periodic sources
  - ① False-alarm probability (FaP) **< 10^{-4}** (confidence of **99.99 %**)
  - ② Detectable **at least 3 periodic cycles**
    - ➢ e.g., ~450 d at maximum during 1st-3rd season of ~1400 d
  - ③ **S/N >= 7** at the peak timing

☞ in **42 sources, identified periodic variations**

- Known : 11 sources
- New ! : **31 sources** with periods of 22-409 d

Histogram of periodic sources



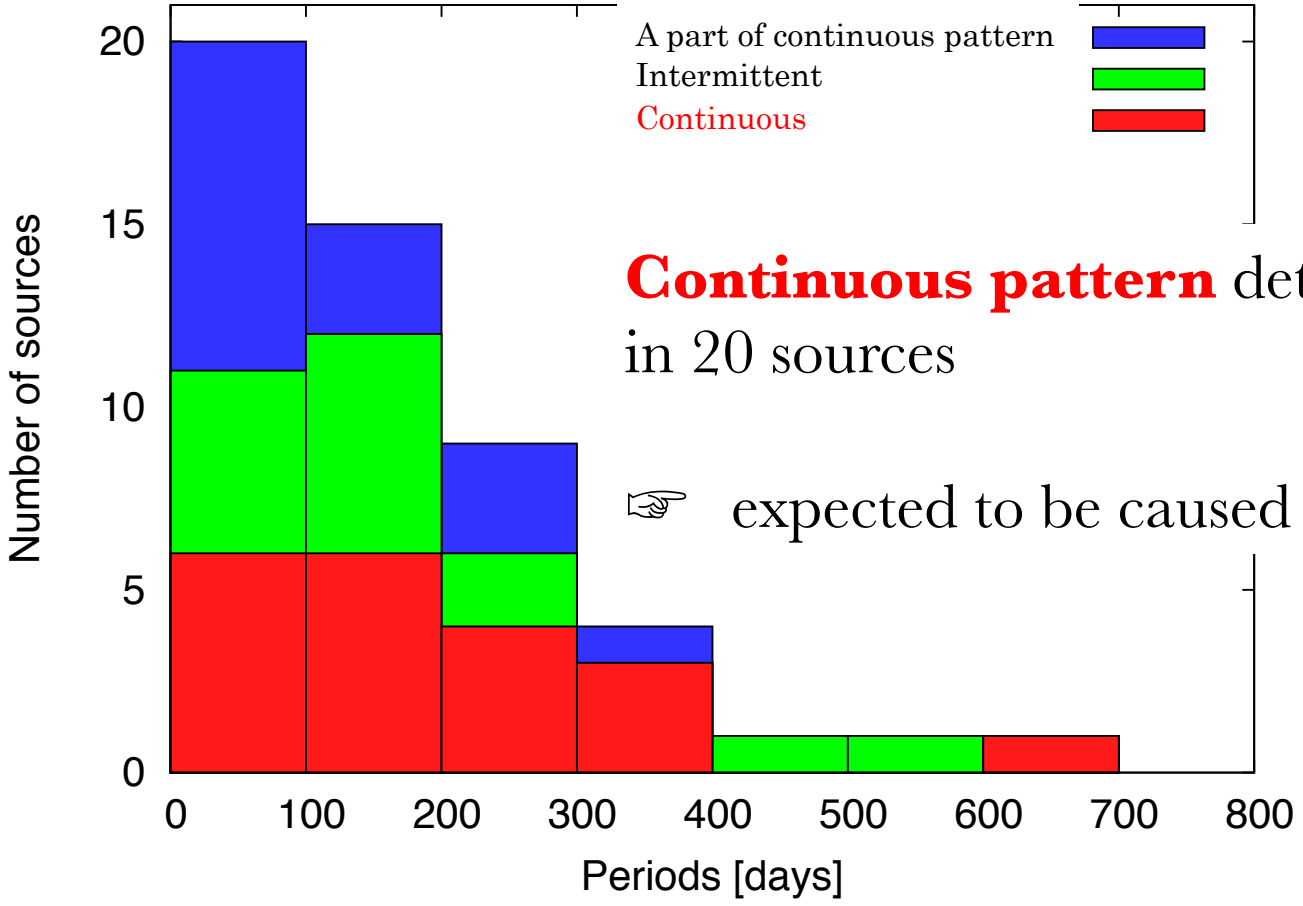
known 20

+

New 31

☞ **Succeed to increase samples more than twice!**

Histogram classified by pattern of periodic flux variation



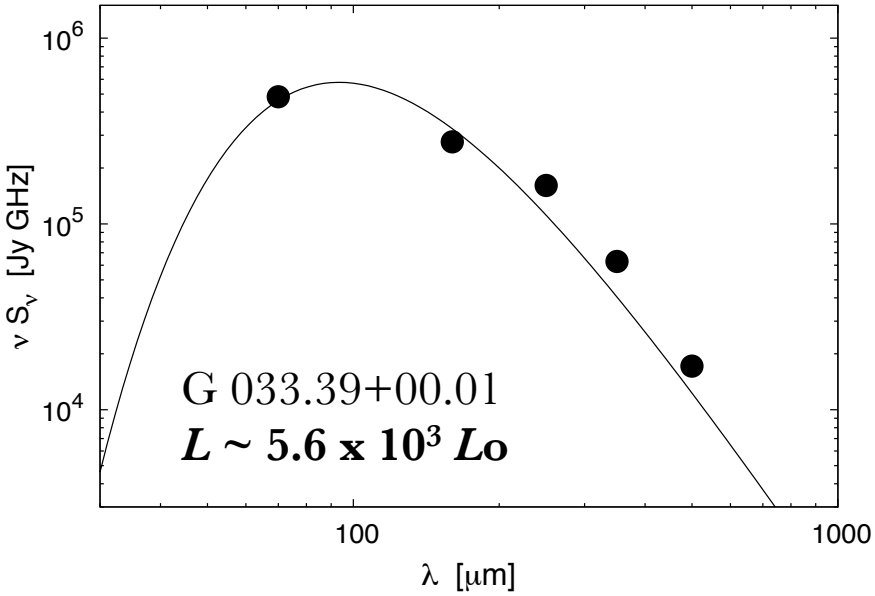
Continuous pattern detected in 20 sources

☞ expected to be caused **Pulsation**

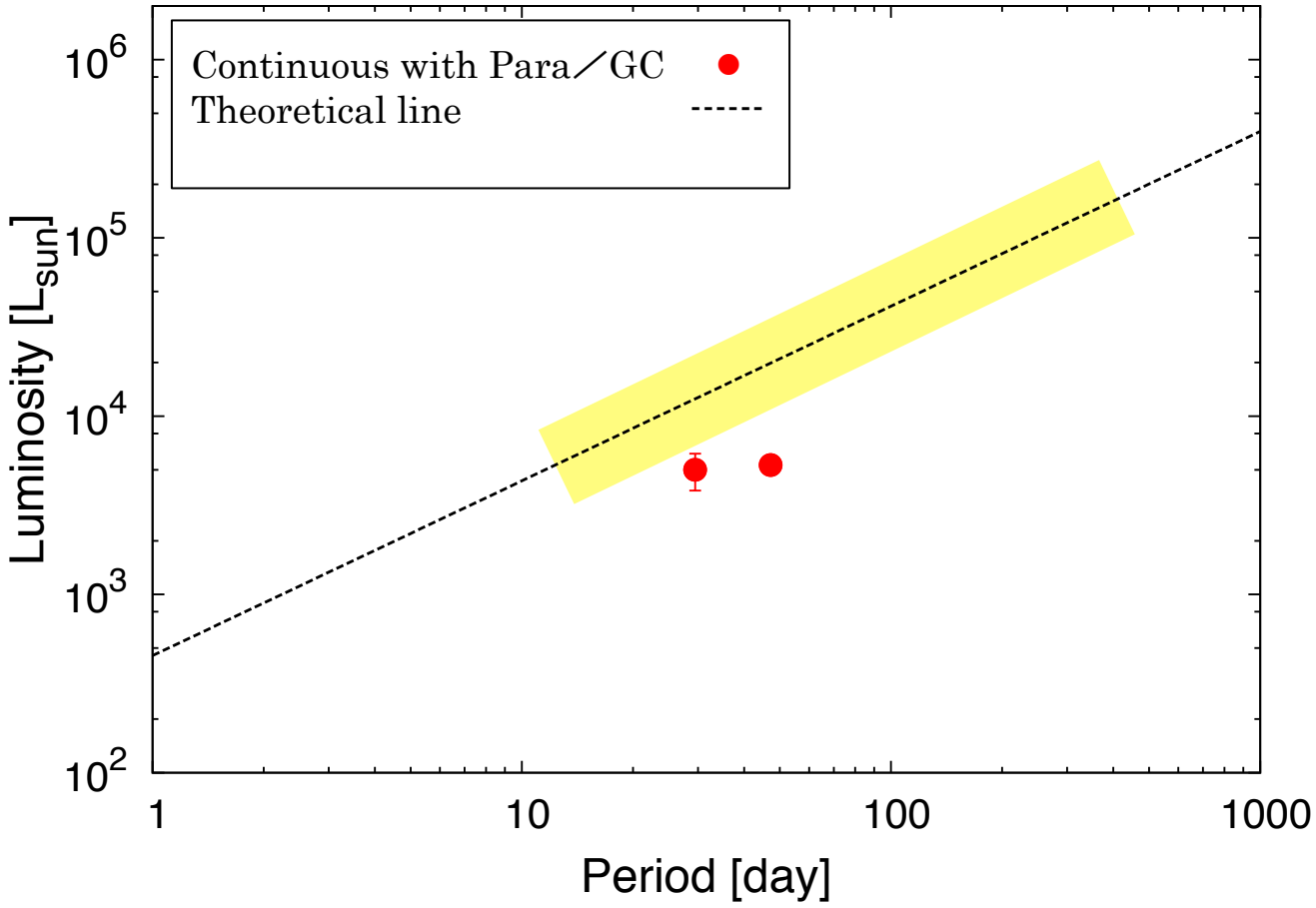
Luminosity estimated from Herschel PACS/SPIRE photometric data

- Total flux from MIR-FIR data
  - Herschel photometry (Molinari+ 16)
    - Freq.: 70, 160, 250, 350, 500 μm
    - PSF : 6, 12, 18, 24, 35 arcsec
    - Area : $-70° \leqq \boldsymbol{l} \leqq +68°$
  - SED fit with single black body

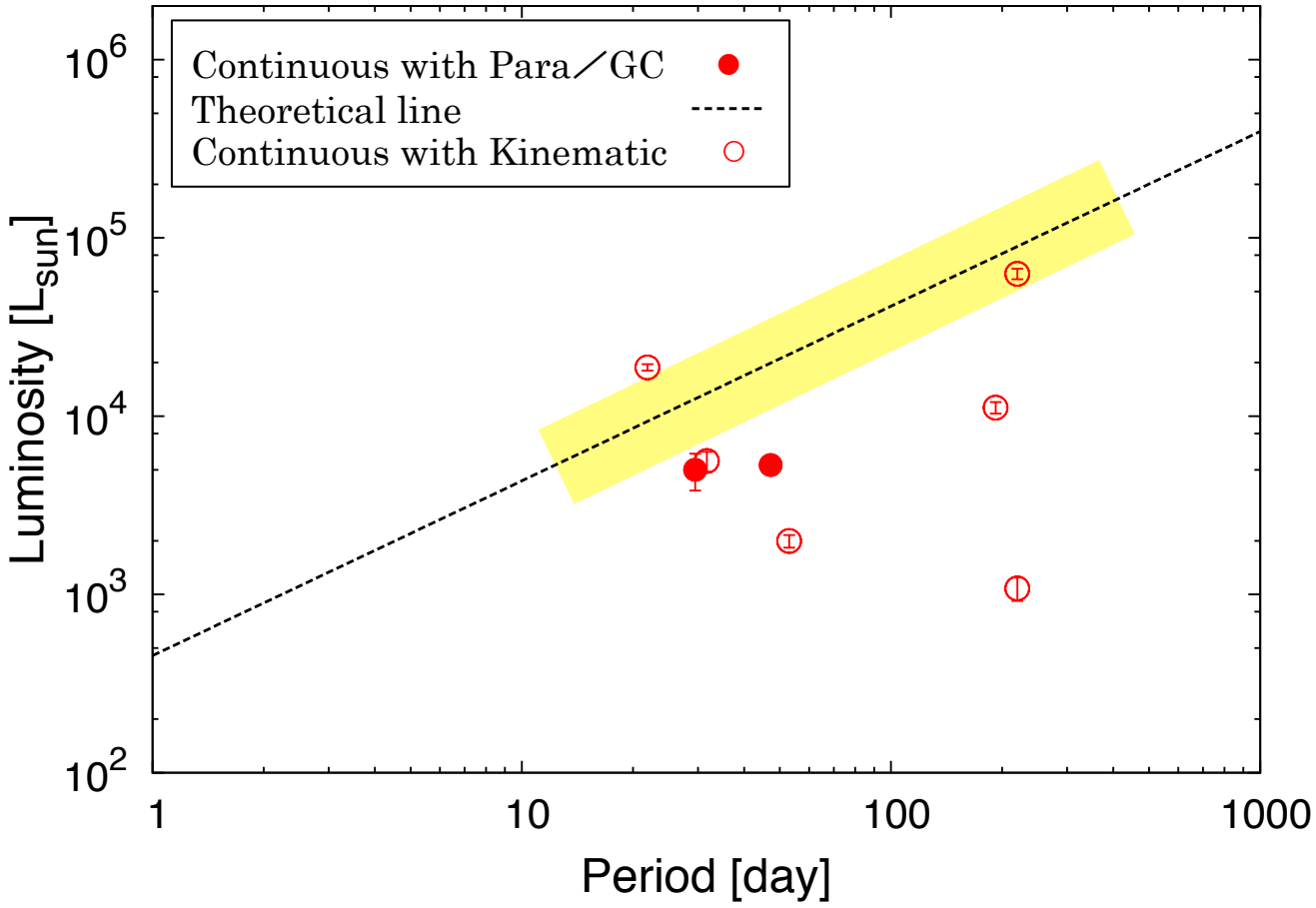
☞ applicable to **11 sources**



Updated P-L relation



Updated P-L relation



For completion of P-L relation verification

- **Parallax** measurements to ambiguous distance sources
  - 2 sources have been observed as VERA17A-124
    - Observed in Feb. (epoch 1), Apr. (epoch2) 2017
    - 1/2 source, succeeded a phase-referencing with ~40 μas accuracy

- **Completion of the periodic samples**
  - To complete longer periodic sources than 1-2 yrs, we have proceeded with the Hitachi monitor since Jun. 14 in 2017
    - will be discussed by combining it with the Hitachi archival data

4. Summary

Summary

- **Periodic flux variabilities** could be unique probe to measure physical properties on HM proto-stars indirectly
  - Accretion rate onto the surface measured through P-L relation, which is a key parameter to determine evolutionary tracks of HM proto-stars

- Ibaraki (Hitachi) 32-m monitor project
  - Initiated since 2012/Dec/30 – ongoing
  - Target: **442 sources** (all samples (as of 2012) observable from Ibaraki)
  - Obs. interval: **9-10 & 4-5 d/source**
  - Detected **Newly 31** sources : periods of **22 -409 days** (by L-S periodogram)

- To complete the verification of P-L relation on HM proto-stars
  - **Source distance measurements** with high-positional accuracy by **Parallax**
  - **Completion for longer period sources than 1-2 yrs** by combining proceeding with archival data obtained using the Hitachi 32-m