Sep. 04-08th, 2017 @ Cagliari, Italy
Astrophysical Masers in IAU Symp. 336

Long-term and highly frequent monitor of 6.7 GHz methanol masers

to statistically research period flux variations around high-mass protostars using Hitachi 32-m

Koichiro Sugiyama[1,2]

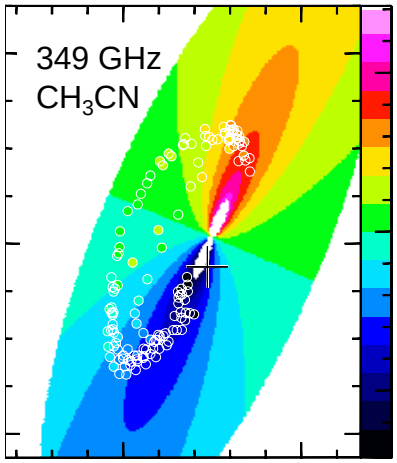
1: Mizusawa VLBI Observatory, NAOJ
2: Ibaraki University

Collaborators: Y. Yonekura[2], K. Motogi[3], Y. Saito[2], T. Yamaguchi[2], M. Momose[2], M. Honma[1], T. Hirota[1], M. Uchiyama[4], N. Matsumoto[1], K. Hachisuka[1], K. Inayoshi[5], K.E.I. Tanaka[6], T. Hosokawa[7], and K. Fujisawa[3]
Institution: 3. Yamaguchi Univ., 4. NAOJ, 5. Columbia Univ., 6. Univ. of Florida, 7. Kyoto Univ.

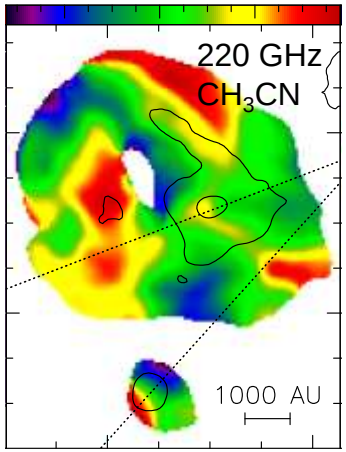
Periodic flux variations around high-mass protostars

1. Motivations

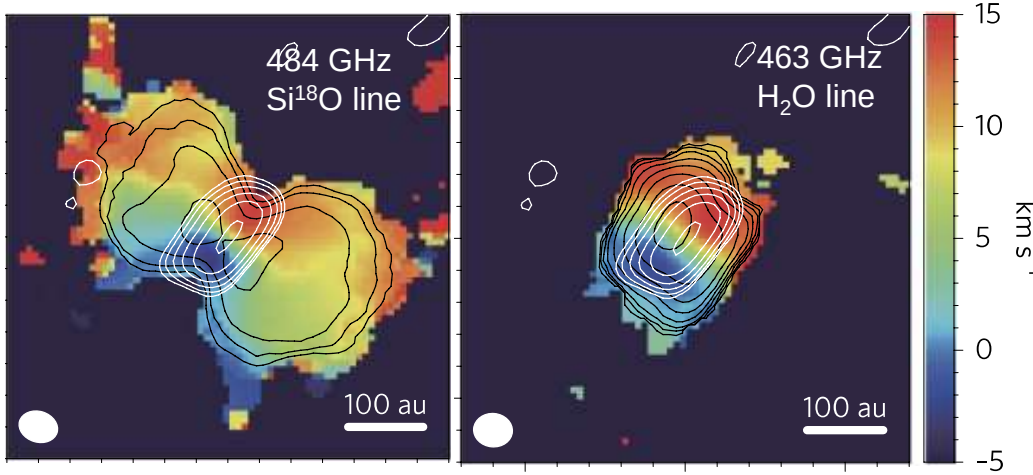
High-mass (HM) star formation



Disk in G 35.20-0.74N (**B-type**) (Sanchez-Monge+ 13)



Disk in G 345.50+0.35 (**O-type**) (Cesaroni+ 17)



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

Can be a **Scaled-Up** version of low-mass star formation

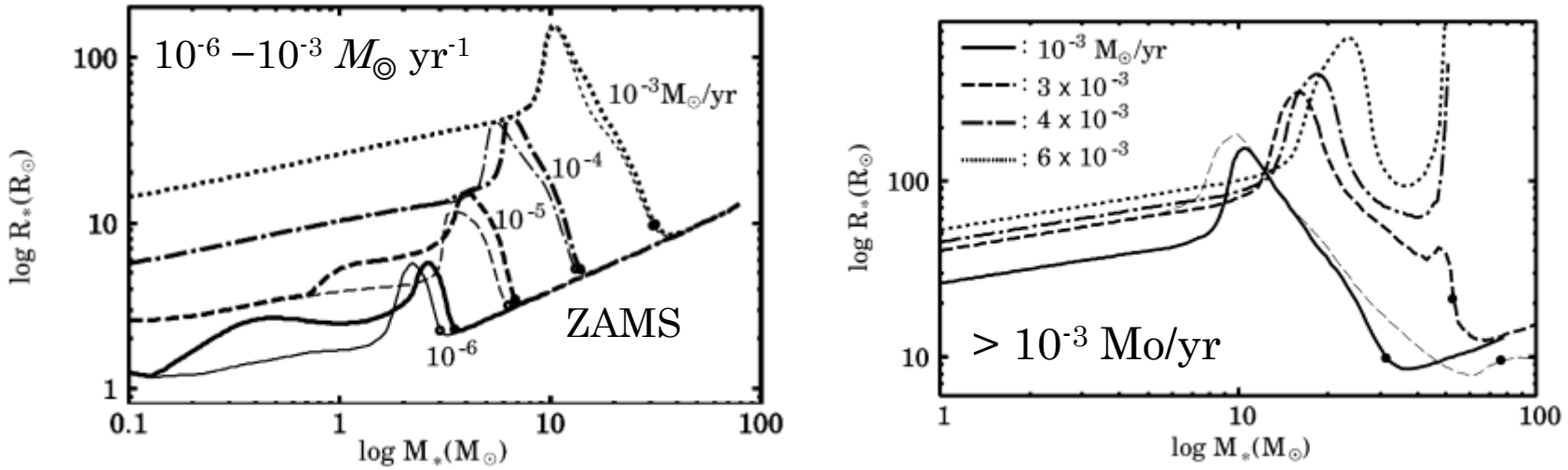
- **Disk** around **B-/O-type** (proto)stars (e.g., Sanchez-Monge+ 13; Cesaroni+ 17)
- **Disk-outflow** system (e.g., Hirota+17)
- Growth through **mass accretion** from disk (e.g., Beltran+ 06; Hosokawa+ 10)
- Magnetic field structure with **hourglass** shape (e.g., Tang+ 09)
- **Accretion burst** (Fujisawa+ 15; Caratti o Garatti+ 17; Hunter+ 17; Moscadelli+ 17)

Evolution of HM protostars (PSs)

Theoretically, it is determined by the **accretion rate onto the stellar surface** (Hosokawa & Omukai 2009)

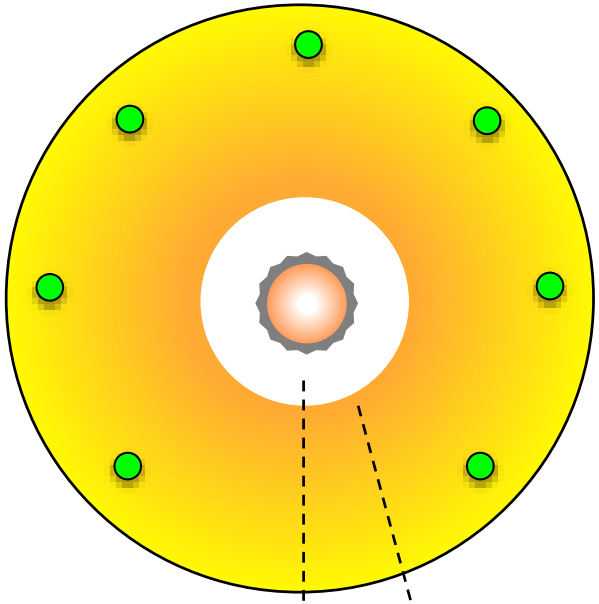
- Radii must be expanded to be 10-100 $R_\odot$ just before ZAMS
- Spatial scale **≦ 0.1 au-scale**

Somehow measure the accretion rates onto the surface …



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

Spatial scale : HMPSs vs instruments



❑ HMPSs scale : ≦ 0.1 au

(**≦ 0.1 mas @ ≧ 1kpc**)

✕ VLTI, ALMA, SMA, etc …

✕ VLBI: maser locates 100-1000 au

△ ext-ALMA: in most cases …

Maser

HMPO

rotation/accretion disk

envelope

≦ 0.1 au
Ext.-ALMA ??

~10-1000 au
VLTI, ALMA, SMA, VLBI

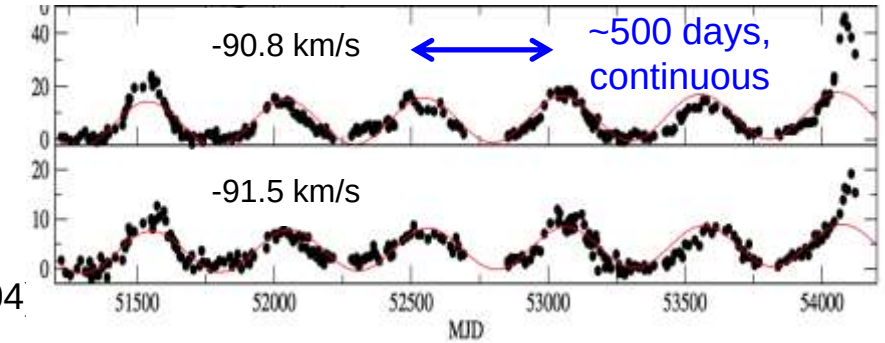
~10000 au (~0.1 pc)
NRO, Mopra, etc …

Periodic flux variation around HMPSs

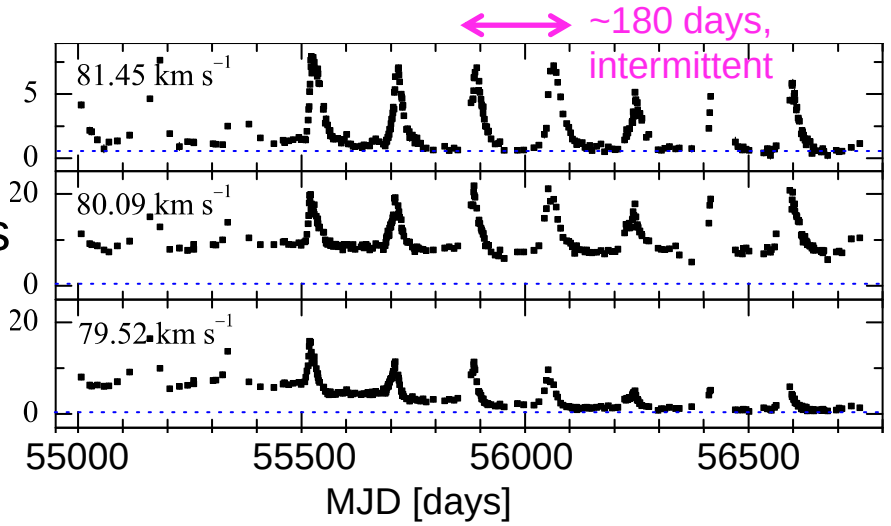
Discovered in G 9.62+0.20E of 6.7/12.2 GHz methanol masers with a period of 246 d (Goedhart+ 03)

- So far, 20 sources (e.g., Goedhart+ 04
- Periods: ~30–670 d
- Pattern: Continuous/Intermittent
- Synchronized in multi-spectral components
- Synchronized with other masers (Araya+10; Green+ 12; Szymczak+ 16)

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



G 331.13-00.24: Continuous (Goedhart+ 07)

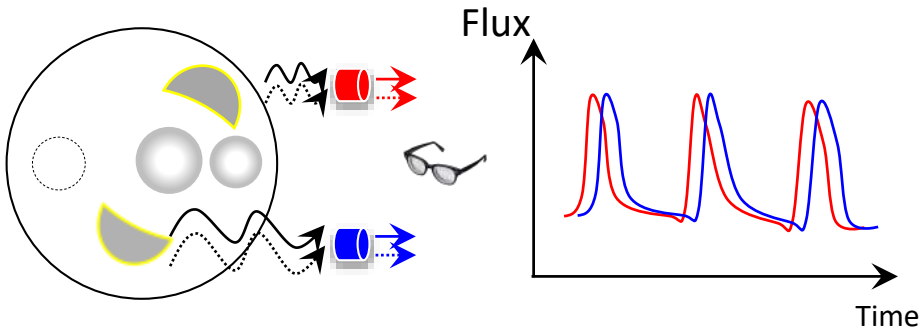


G 22.357+0.066: Intermittent (Szymczak+15)

Candidates to cause periodicity

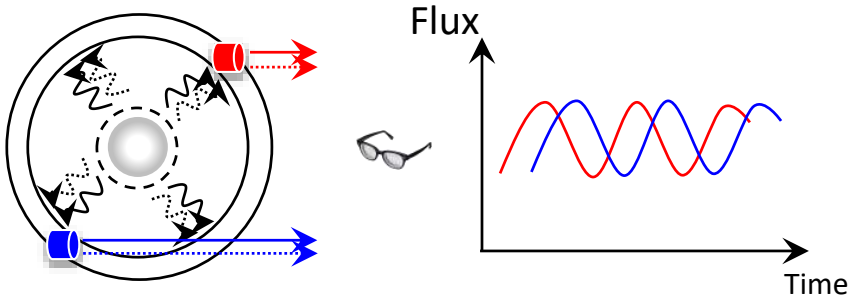
- Colliding wind binary
  (van der Walt+ 09; van der Walt 11)
- Stellar pulsation instability
  (Inayoshi+ 13; Sanna+ 15)
- Spiral shock heating in a circum-binary disk (Parfenov & Sobolev 14)

Seed photon; Intermittent



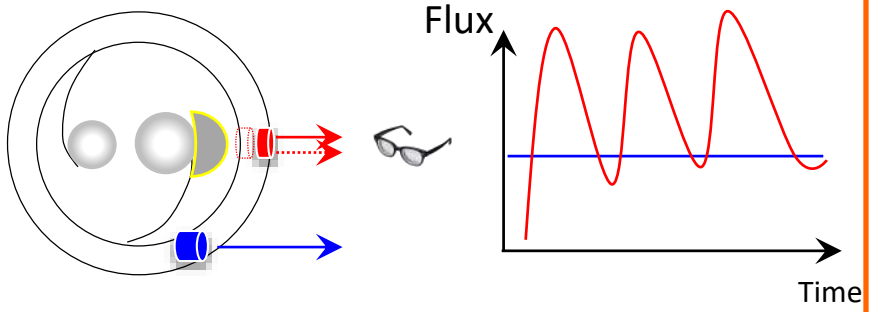
Colliding wind binary

Dust temperature; Continuous



Stellar pulsation instability

Classification by van der Walt+ (16)



Spiral shock heating in circumbinary disk

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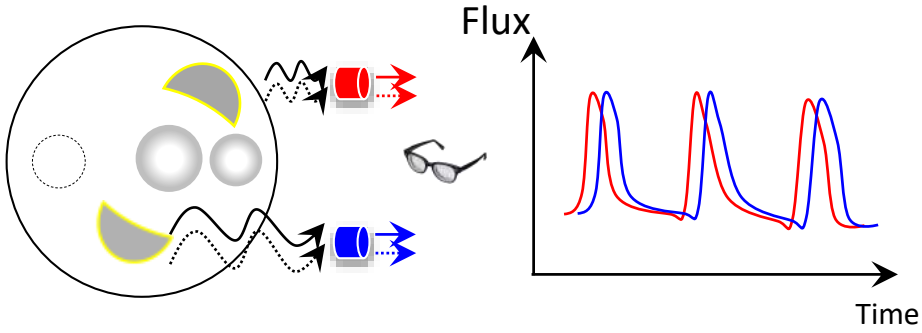
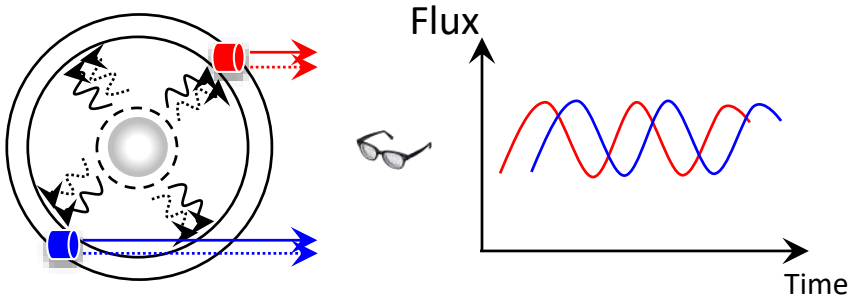


Colliding wind binary

Dust temperature; **Continuous**



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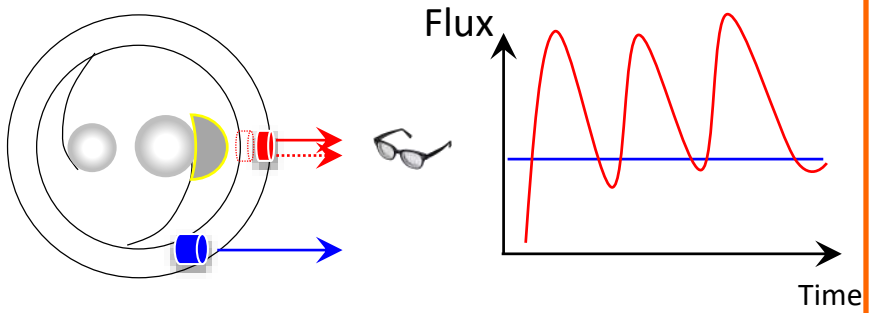
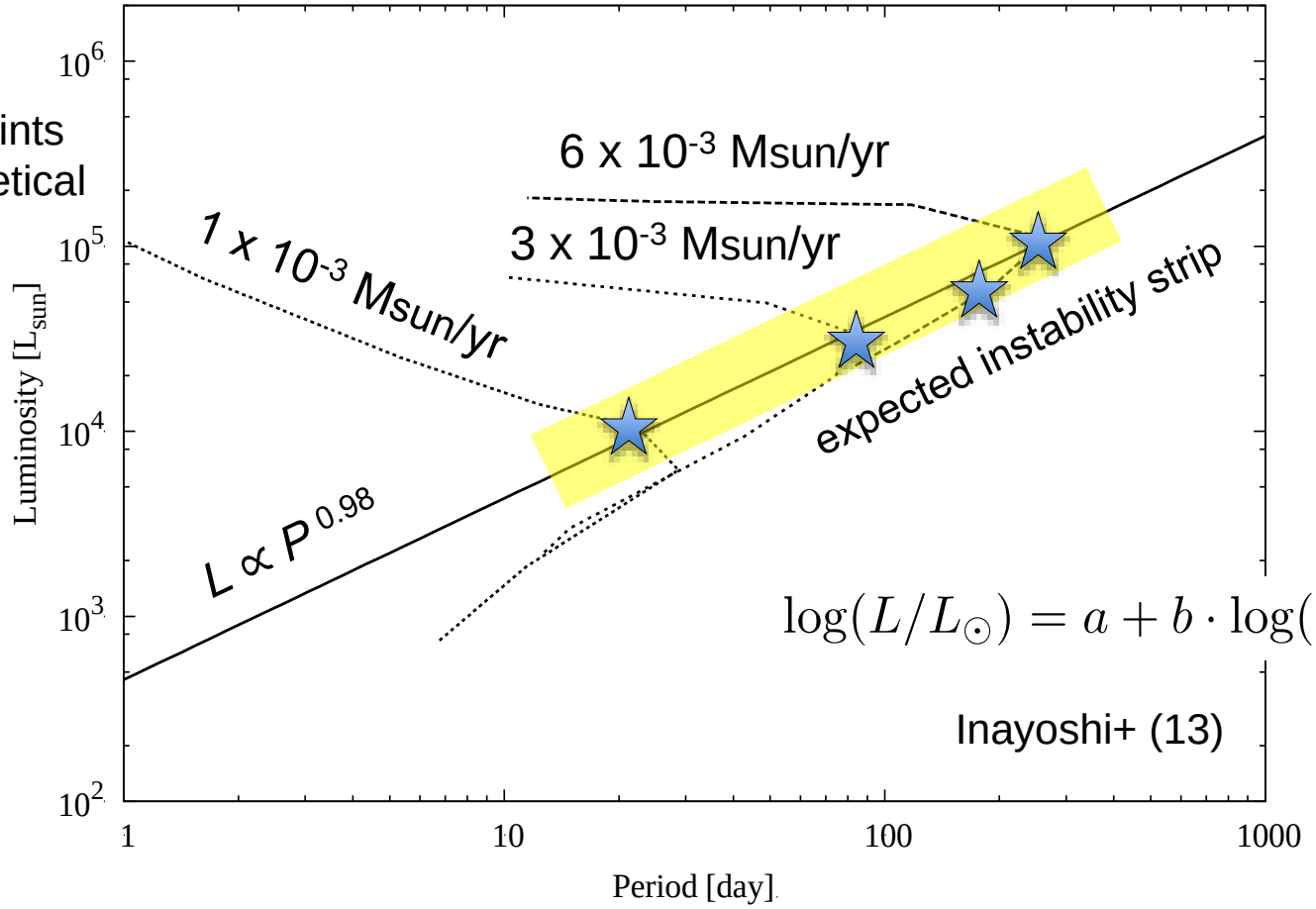


Spiral shock heating in circumbinary disk

Period-Luminosity relation:
expected from pulsational instability model

Unstable points
In the theoretical
calculations



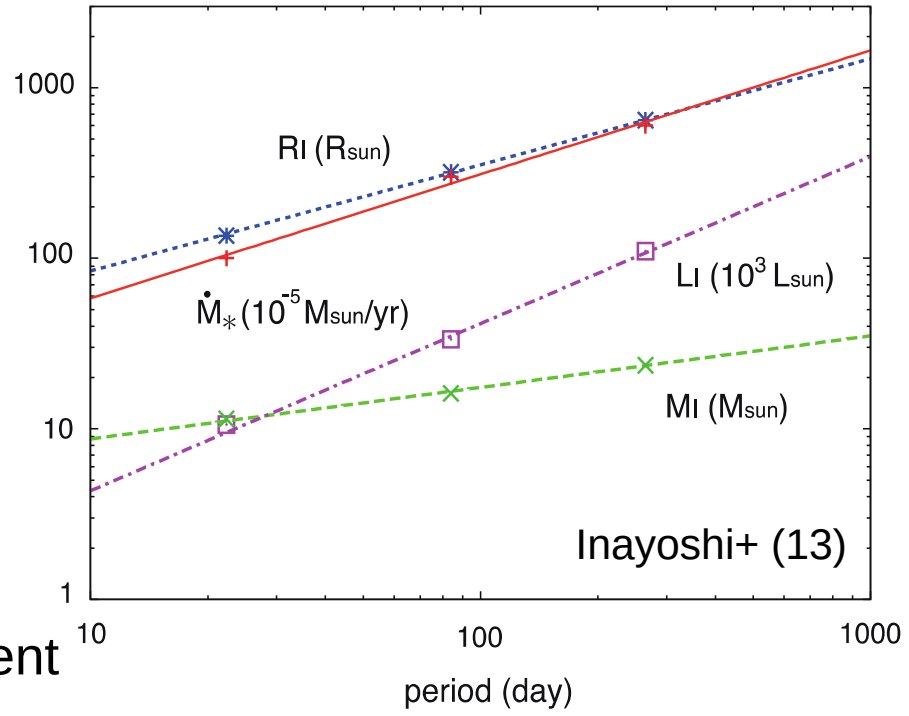
$$\log(L/L_\odot) = a + b \cdot \log(P/100 \text{ days})$$

Inayoshi+ (13)

Period-Luminosity relation: related to physical properties

- Expected to measure physical properties on HMPSs, indirectly from the equation $t_{accretion} \sim t_{KH}$
  - Luminosity
  - Mass
  - Radius
  - Accretion rate onto stellar surface

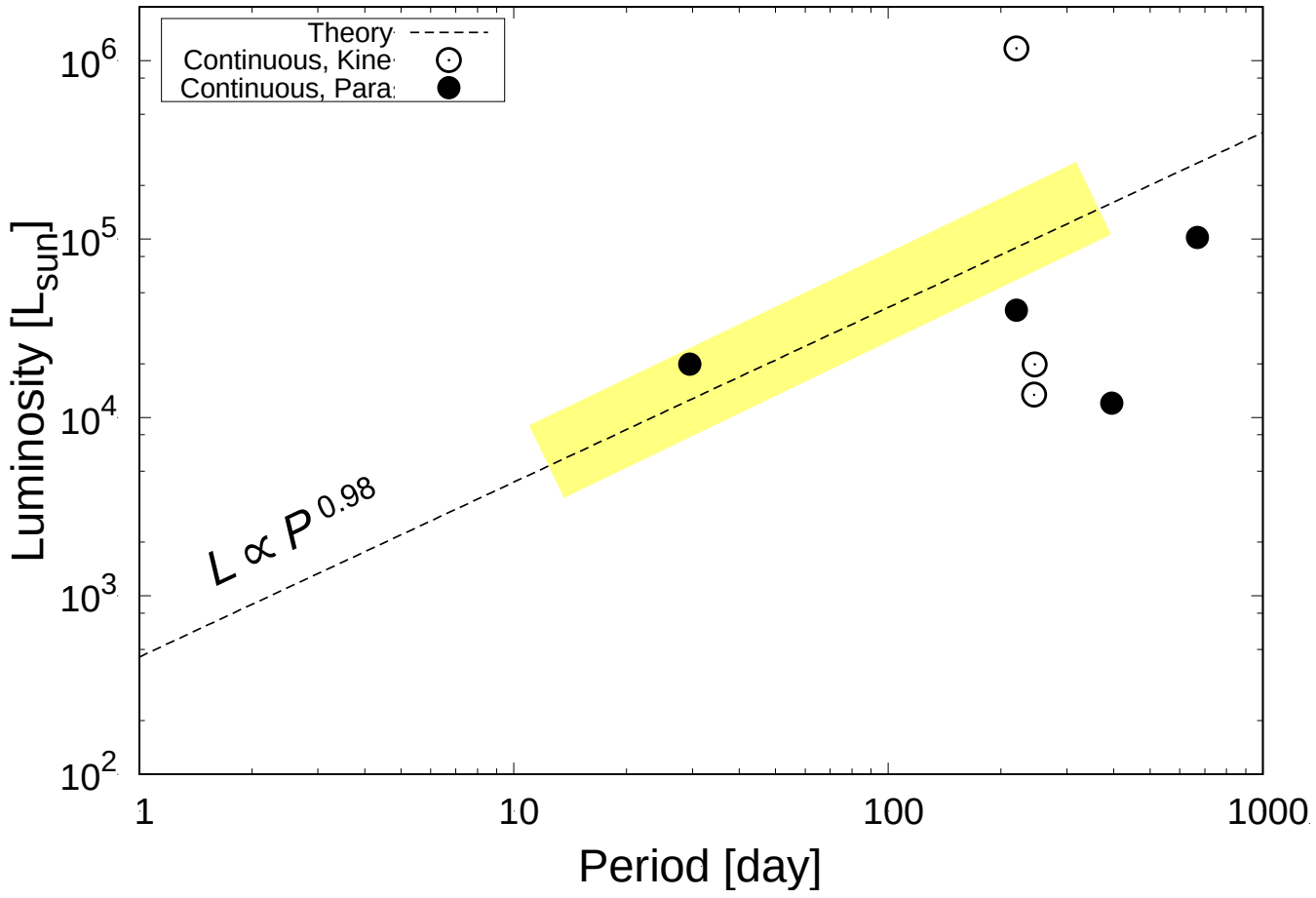
※ $t_{acc} = M / M_{dot}$; $t_{KH} = G M^2 / L R$



- Achieve **sub-au scale** measurement 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



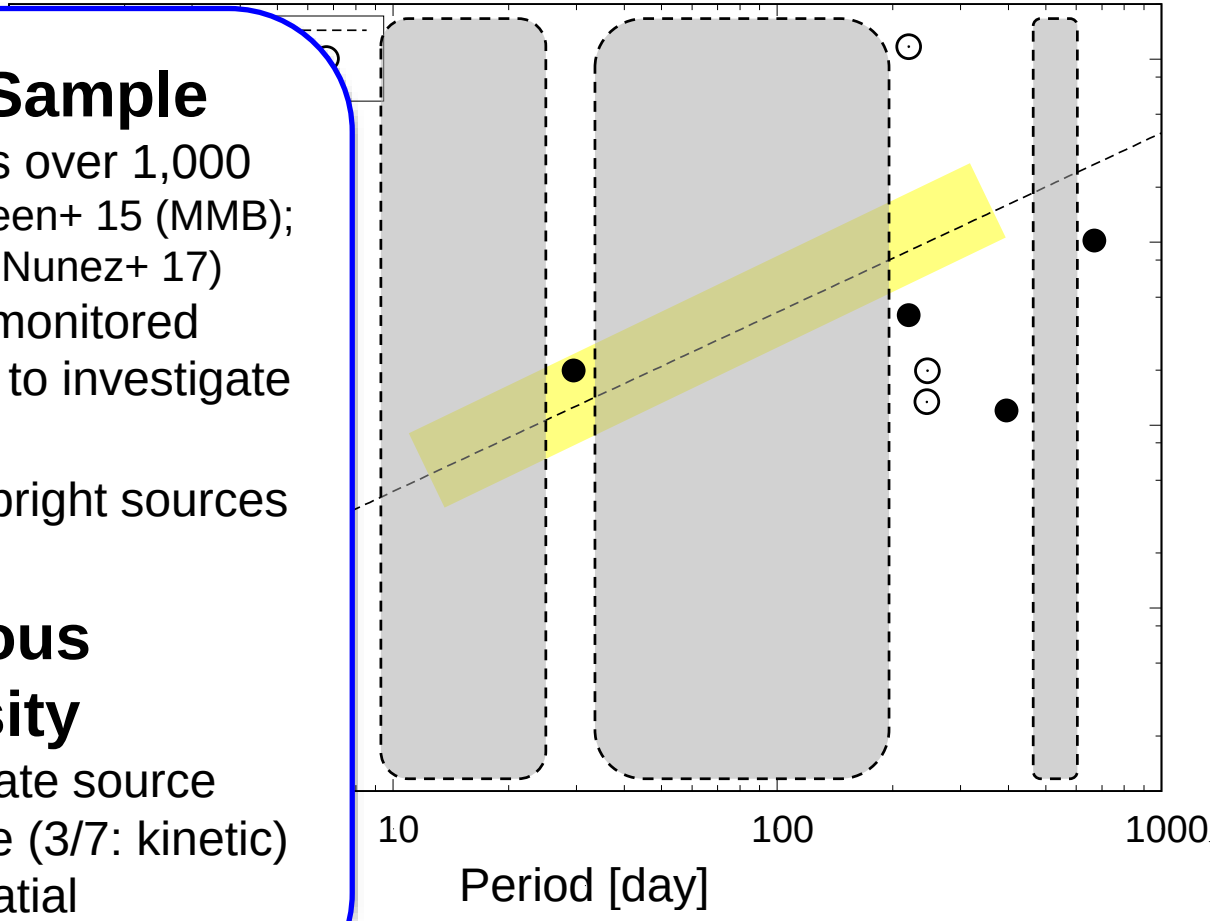
Period-Luminosity (P-L) relation:
based on observed data so far

1. Lack of Sample

- Sources over 1,000 (e.g., Breen+ 15 (MMB); Quiroga-Nunez+ 17)
- < 20% monitored enough to investigate periods
- Mainly bright sources

1. Ambiguous Luminosity

- Inaccurate source distance (3/7: kinetic)
- Low-spatial resolution FIR data



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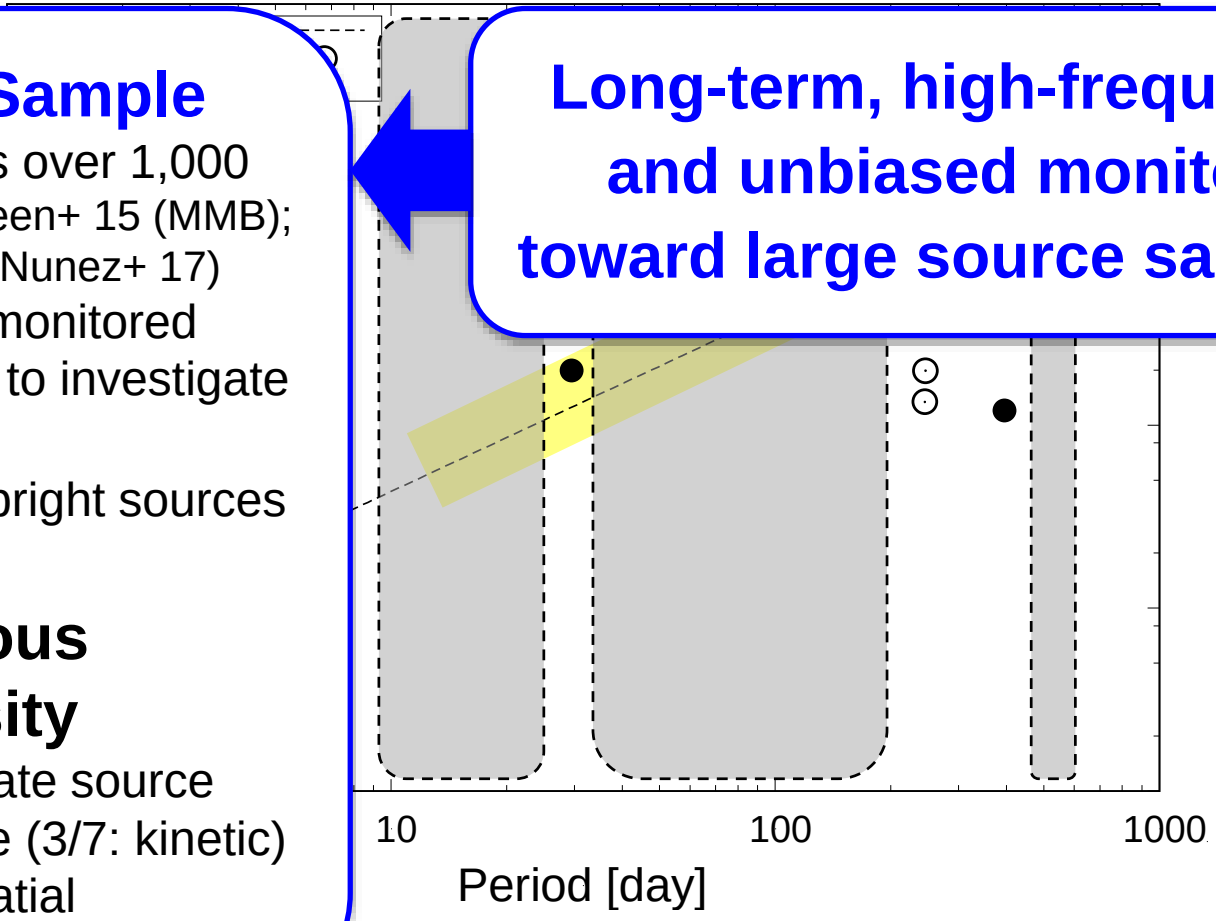
Long-term, high-frequent, and unbiased monitor toward large source sample



2. Observations

Hitachi 32-m monitor project: obs. parameters (Yonekura+ 16)


Hitachi 32-m (Credit: NAOJ)

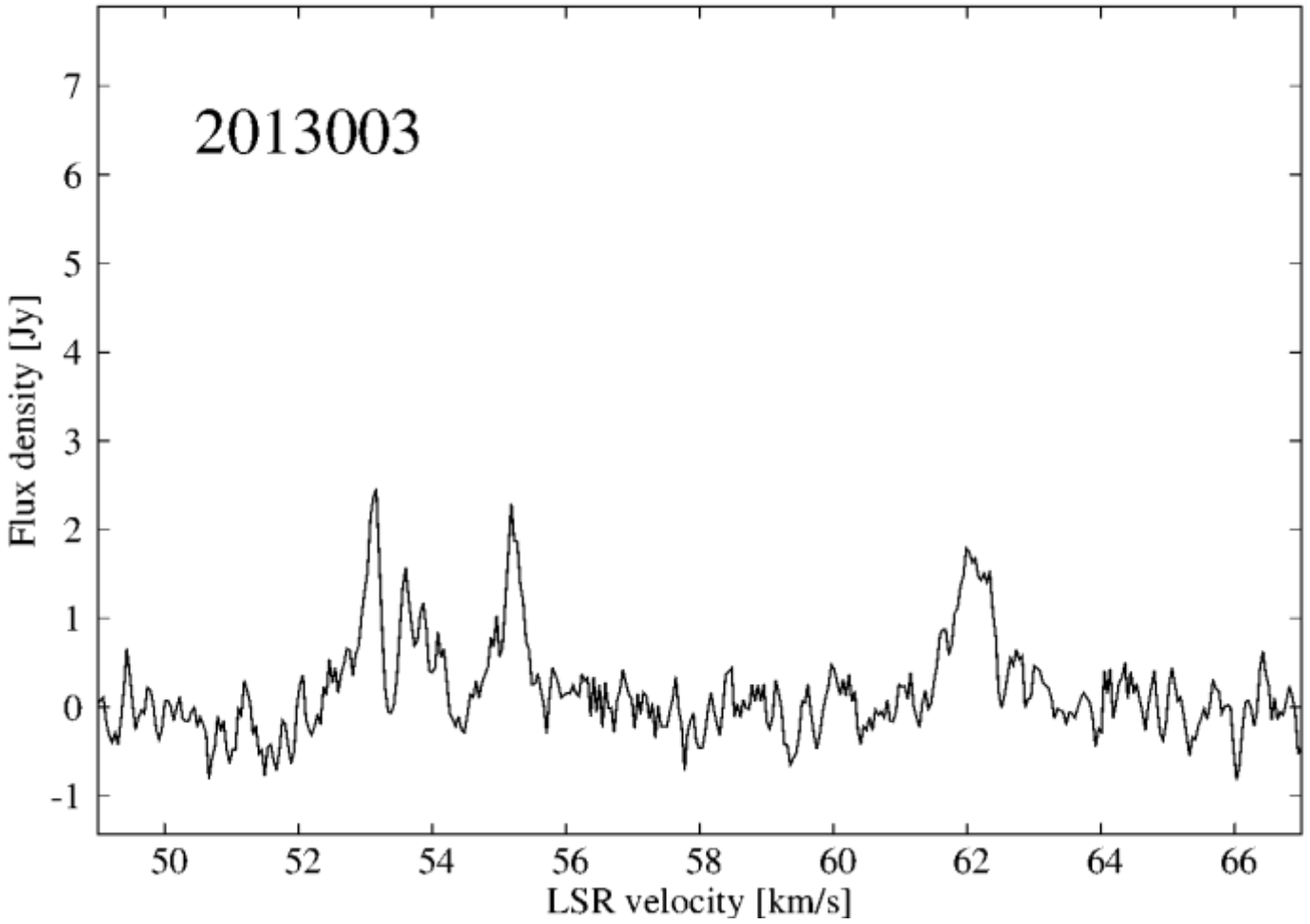
- ❑ Target sources : **442 sources** in total
  - Dec > -30 deg from the methanol maser catalog by 2012/Dec
- ❑ Initiated from Dec. 30th, 2012 using Hitachi 32-m telescope

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 s) with 5 min	~0.9 Jy	

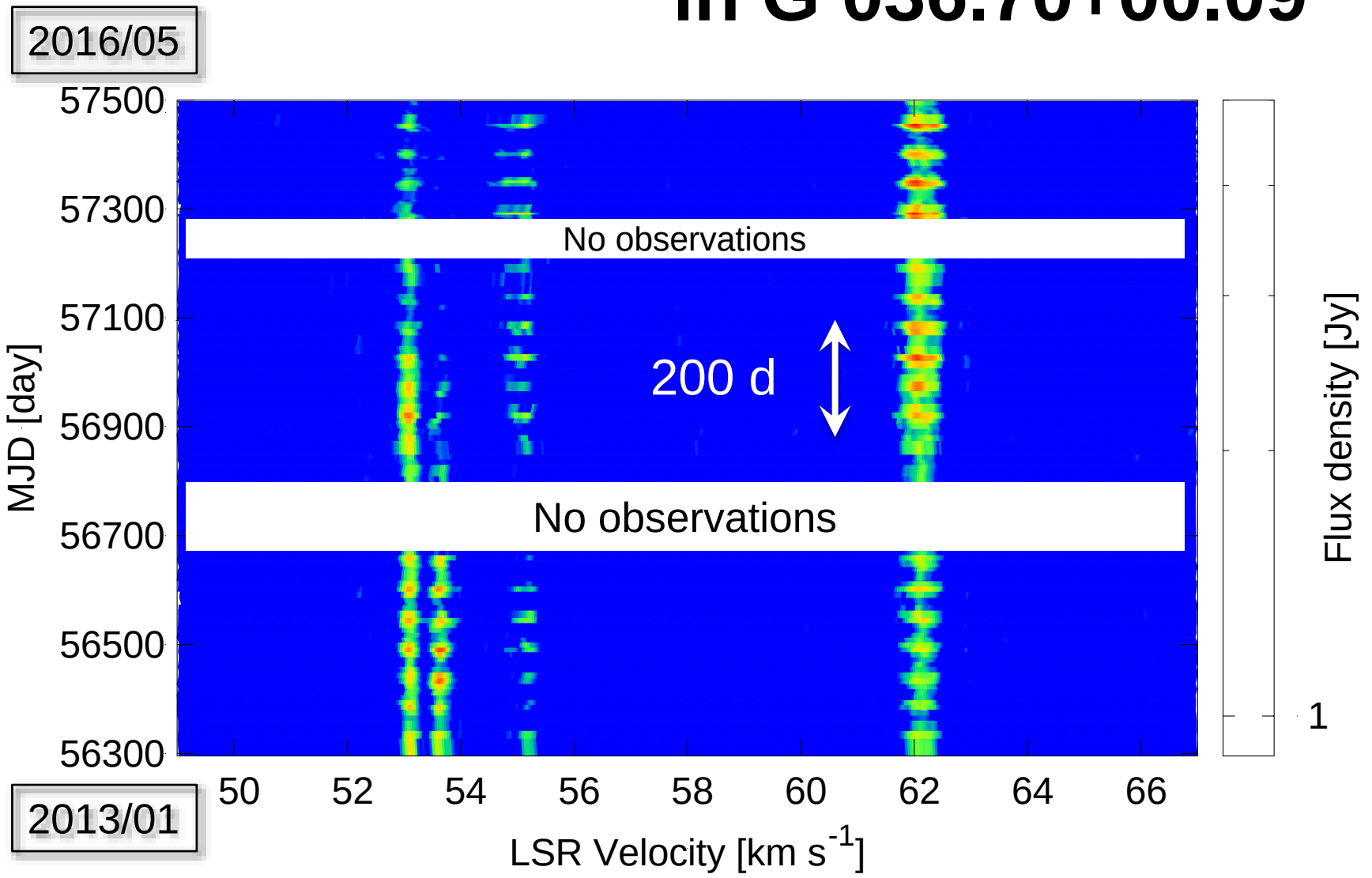
Ibaraki（Hitachi・Takahagi）32-m radio telescopes (from HP of Center for Astronomy, Ibaraki Univ.)

3. Results

e.g., Flux variations in G 036.70+00.09 (Sugiyama+ 15)



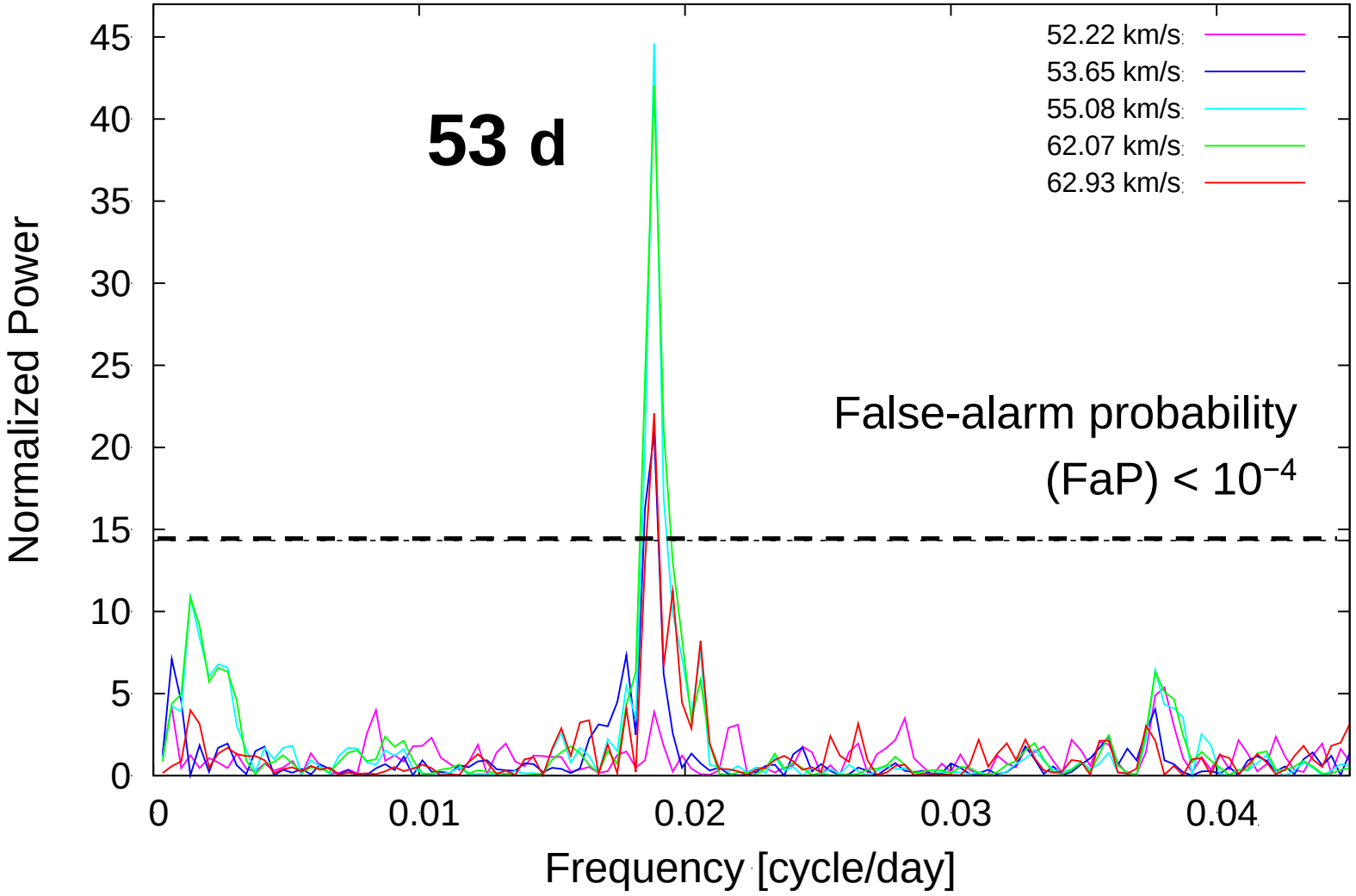
e.g., Dynamic spectrum in G 036.70+00.09



New detections of periodic variations

- Lomb-Scargle periodogram（Lomb 76; Scargle 82）
  - The most sensitive method to search for periodicity (Goedhart+ 14)
  - Programmed by Y. Yasui (Ibaraki M2 in 2015) based on Numerical Recipe

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



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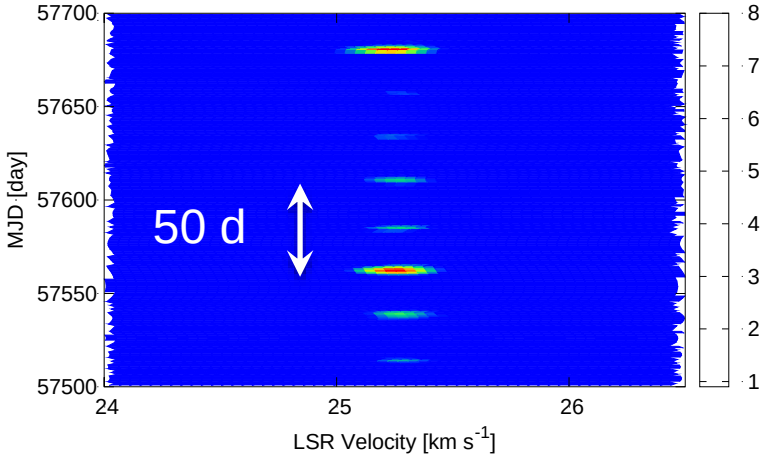
- How to judge periodic sources
  - ① False-alarm probability（FaP）**< 10^{-4}**（confidence of **99.99 %**）
  - ② Detectable **at least 3 periodic cycles**
  - ③ **S/N >= 7** at the maximum timing

in 42 sources, identified as periodic variations

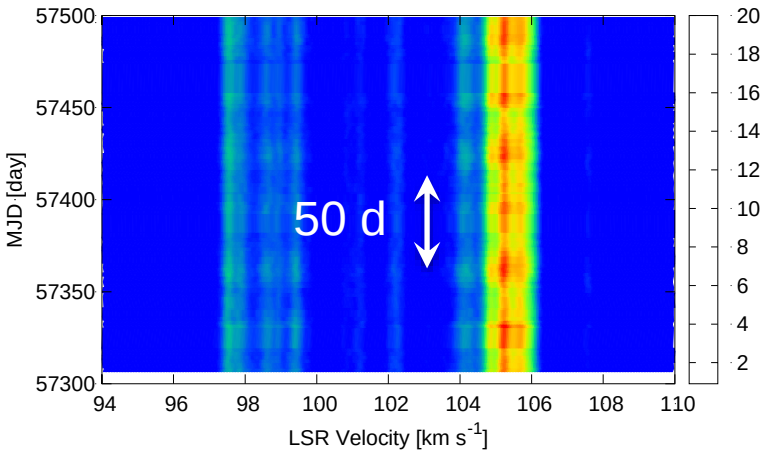
Newly detected: **31 sources** (periods: 22-409 d)

Other sources showing periodicity

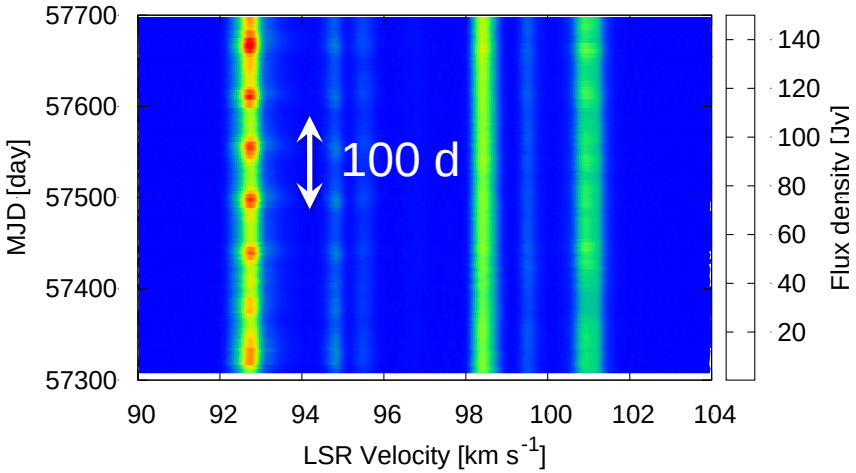
G 014.23-00.50 : 24 d, intermittent
(Sugiyama+ 17)



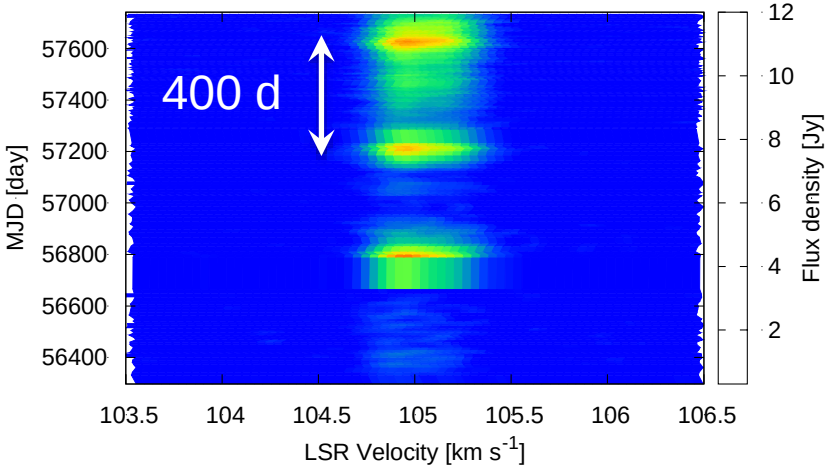
G 033.39+00.01 : 31 d, continuous



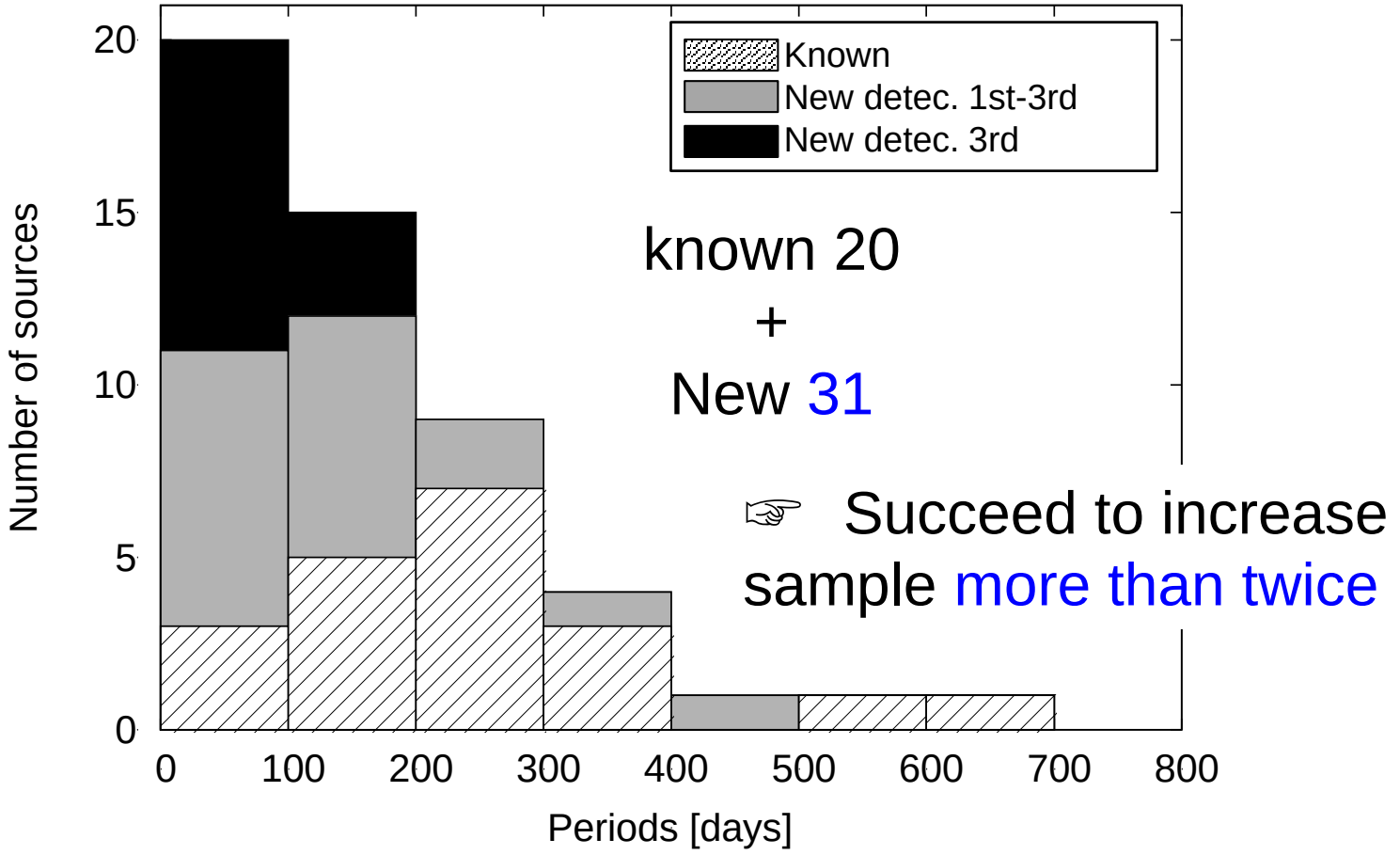
G 032.04+00.05 : 56 d, a part of (conti.)



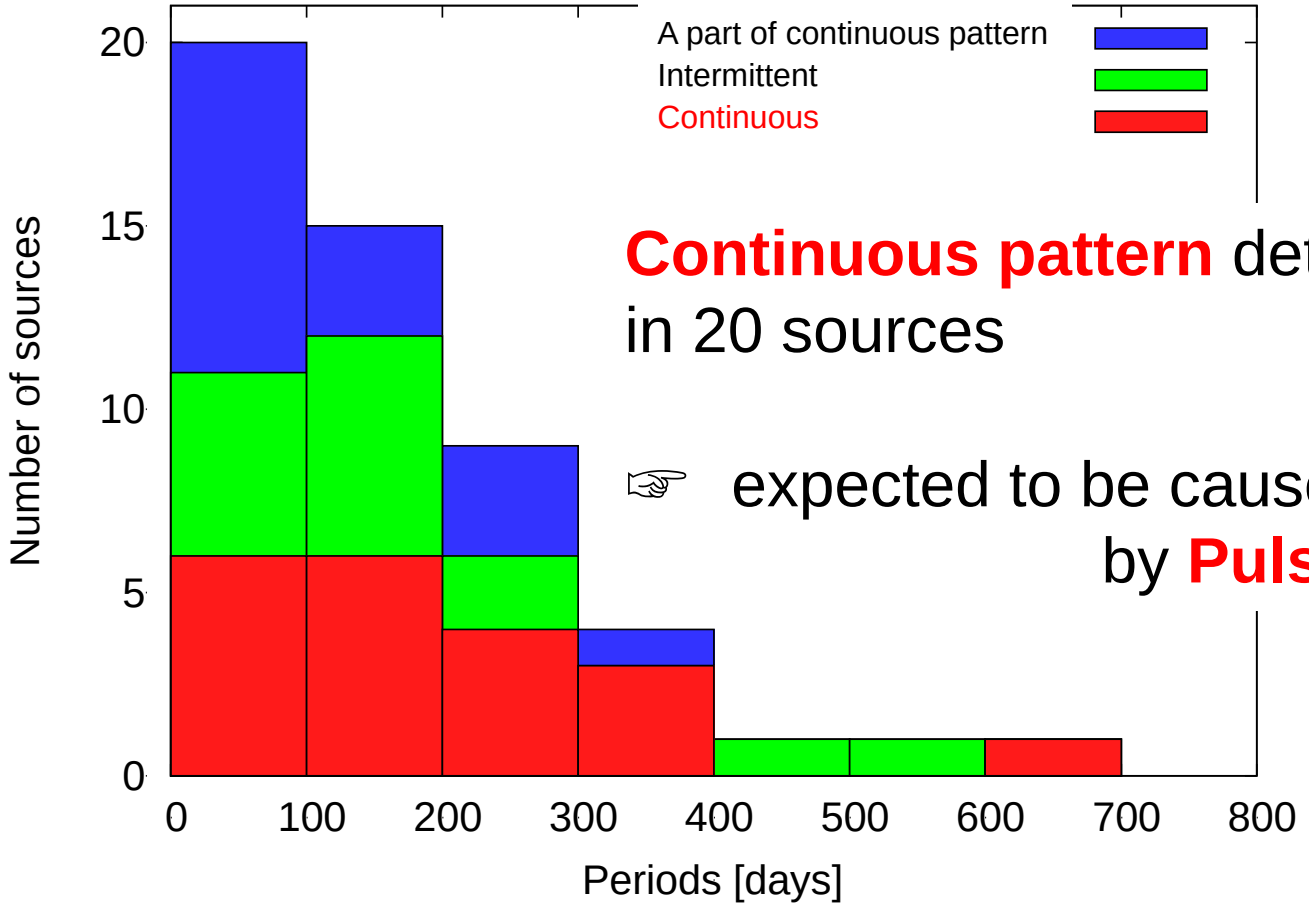
G 028.86+00.06 : 409 d, continuous



Histogram of periodic sources



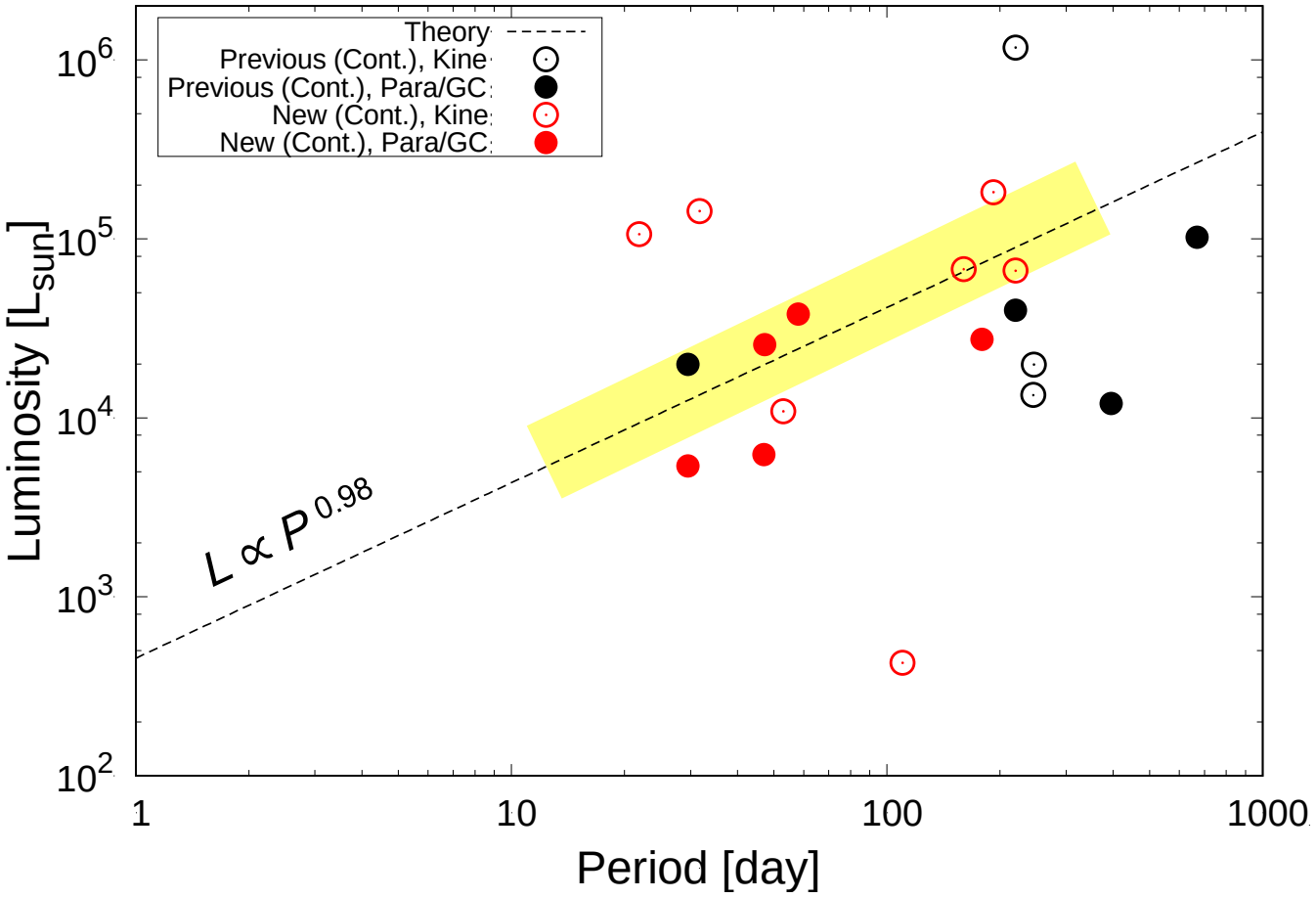
Histogram classified by pattern of periodic flux variation



Continuous pattern detected in 20 sources

☞ expected to be caused by **Pulsation**

The latest P-L relation



For Completion of P-L relation

- **Parallax** measurements to ambiguous distance sources
  - 2 sources have been observed as VERA17A-124
    - Observed in Feb. (epoch 1), Apr. (epoch 2), Jun (epoch 3) 2017
    - 1/2 source, succeeded a phase-referencing with ~40 μas accuracy
  - Other sources will be initiated by using also VERA

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

4. Summary

Summary

- **Periodic flux variability** could be an unique probe to measure physical properties on high-mass protostars (HMPSs) indirectly
  - Accretion rate onto the surface measured through P-L relation, which is a key parameter to determine evolutionary tracks of HMPSs

- Ibaraki (Hitachi) 32-m monitor project
  - Initiated since Dec. 30th, 2012 – 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)

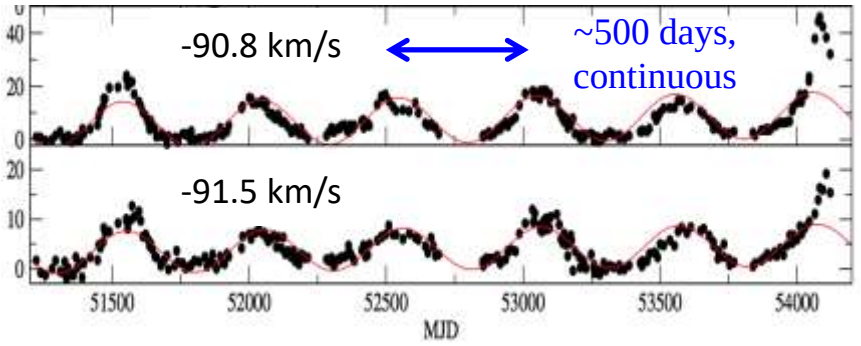
- To complete establishment of the P-L relation on HMPSs
  - **Source distance measurements** with high-positional accuracy by **Parallax**
  - **Completion for longer periodic sources than 1-2 yrs** by combining proceeding with archival data obtained using the Hitachi 32-m

Grazie for your attention!

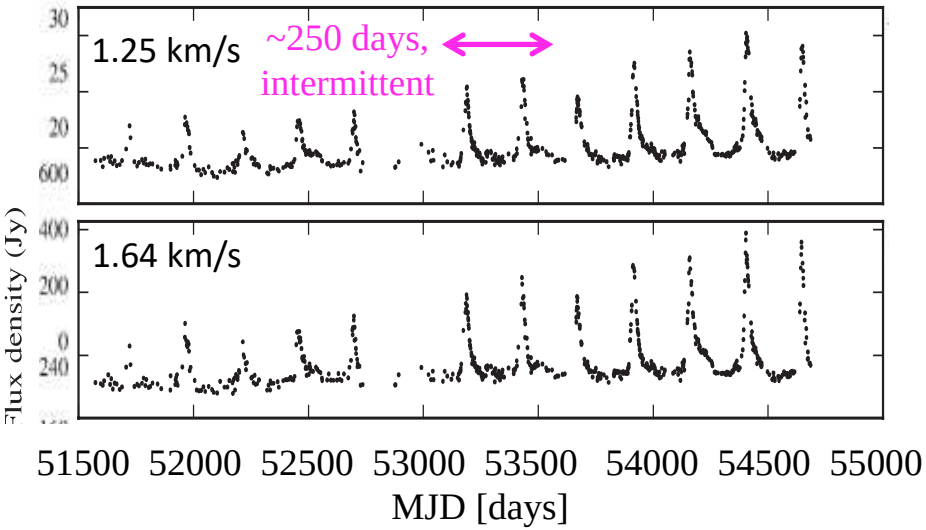
Periodic flux variations around HMPSs

- (Potentially) discovered in the 86 GHz SiO maser of Orion-KL (Ukita+ 81)
- Verified in the 6.7/12.2 GHz CH_3OH masers 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

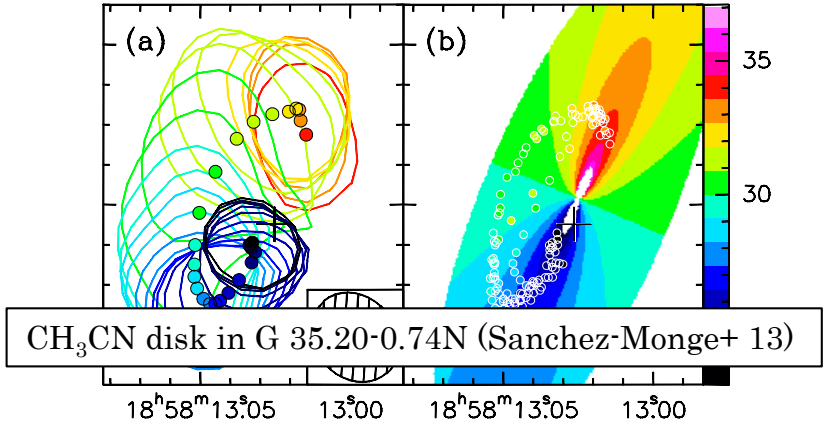
Possibly caused by central engine in tiny spatial scales of ~0.1-1 au (expected from Keplerian rotation)



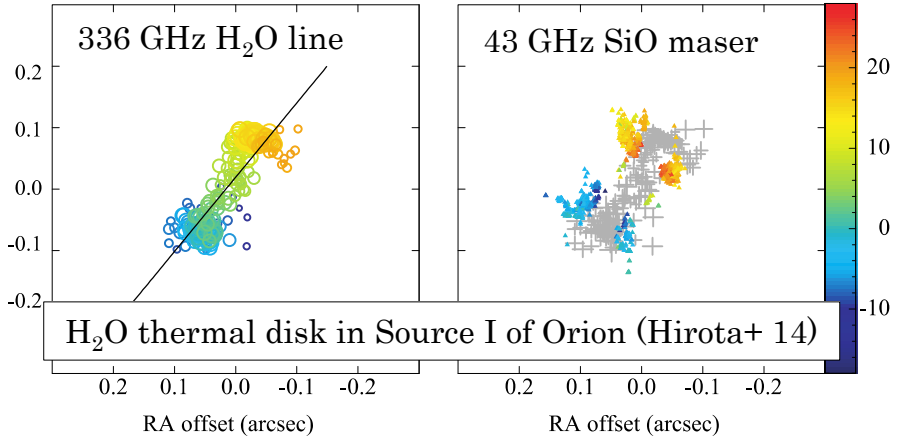
↑: Periodic methanol maser sources, G 331.13-00.24 (Goedhart+ 07), ↓: G 009.62+00.20 E (Goedhart+ 14).



High-mass (HM) star formation

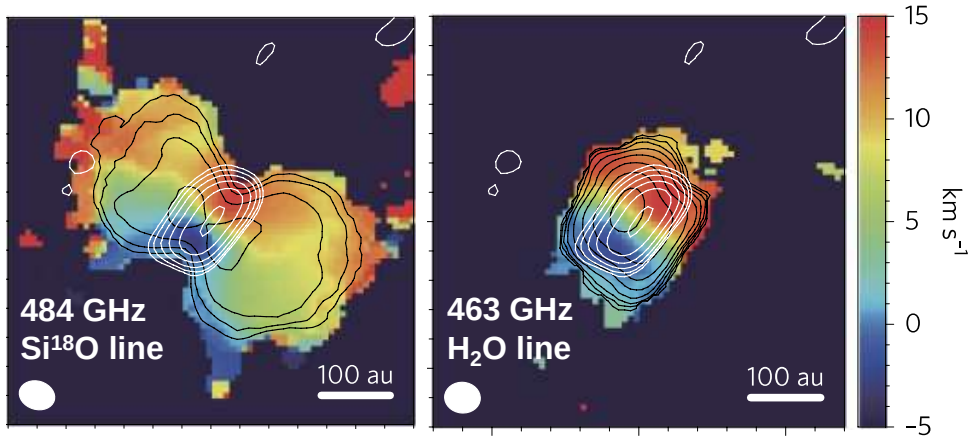


CH_3CN disk in G 35.20-0.74N (Sanchez-Monge+ 13)



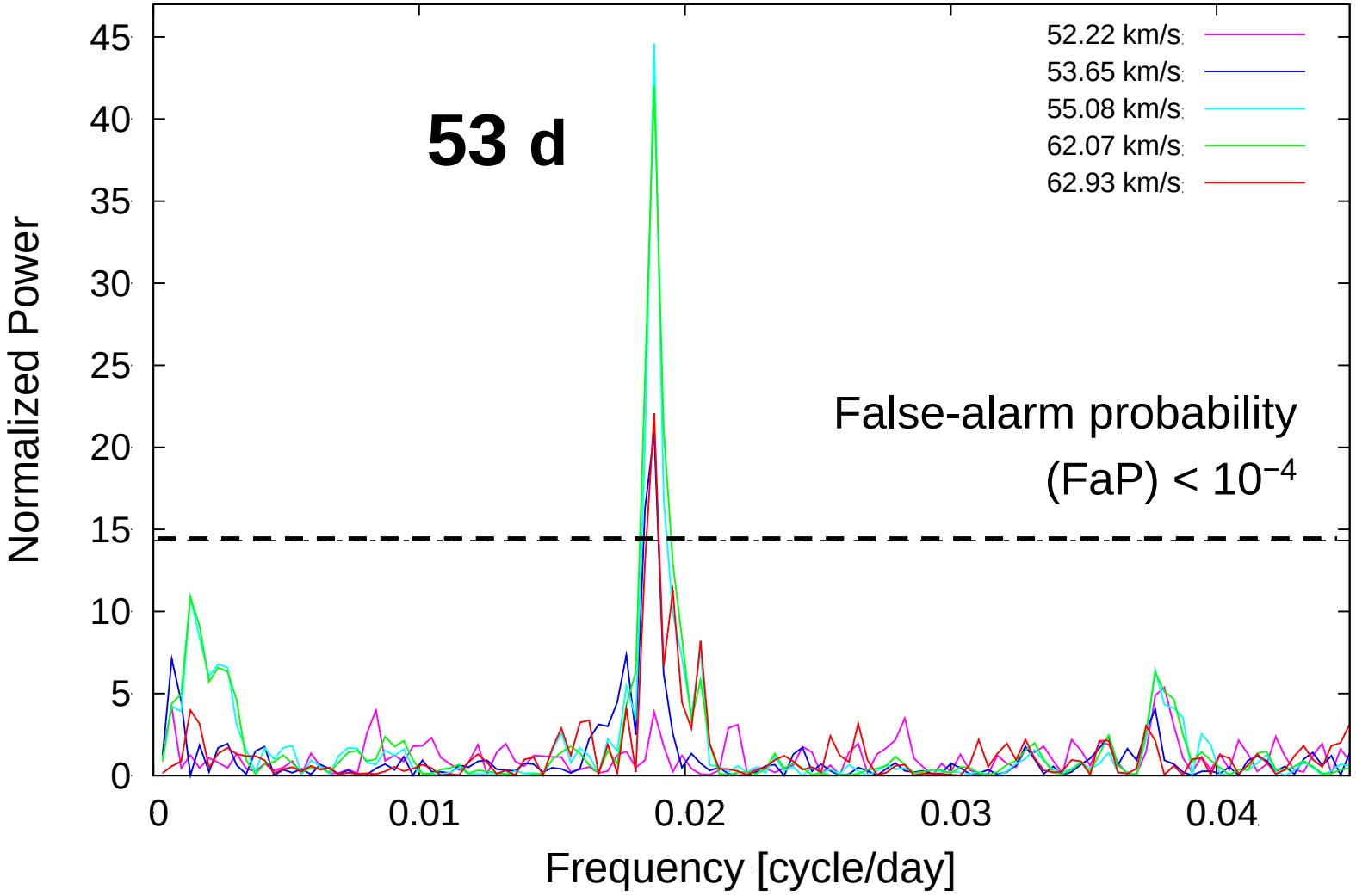
H_2O thermal disk in Source I of Orion (Hirota+ 14)

- 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; Hunter+ 17)



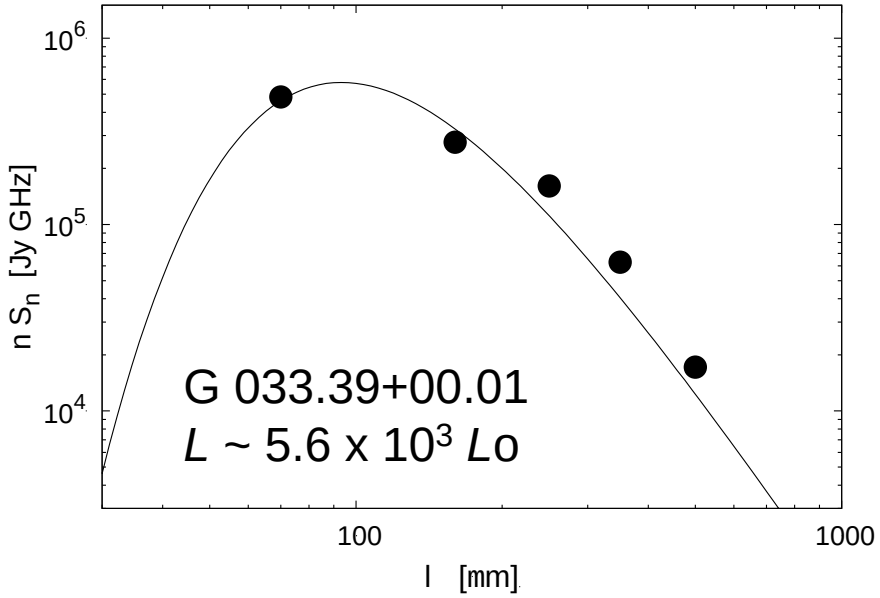
Disk-driven rotating bipolar outflow observed in Orion Source I (Hirota+ 17)

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



Luminosity estimated from Herschel PACS/SPIRE photometric data

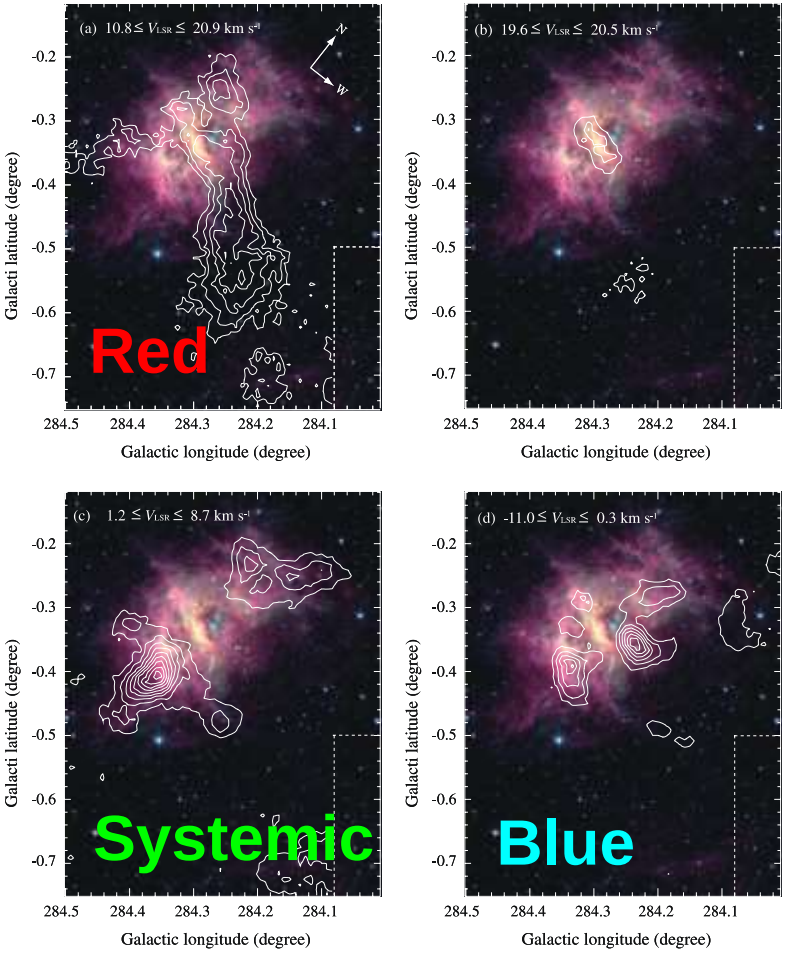
- Total flux from MIR-FIR data
  - Herschel photometry（Molinari+ 16）
    - Freq.: 70, 160, 250, 350, 500 μm
    - PSF ：6, 12, 18, 24, 35 arcsec
    - Area : −70° ≦ *l* ≦ +68°
  - SED fit with single black body



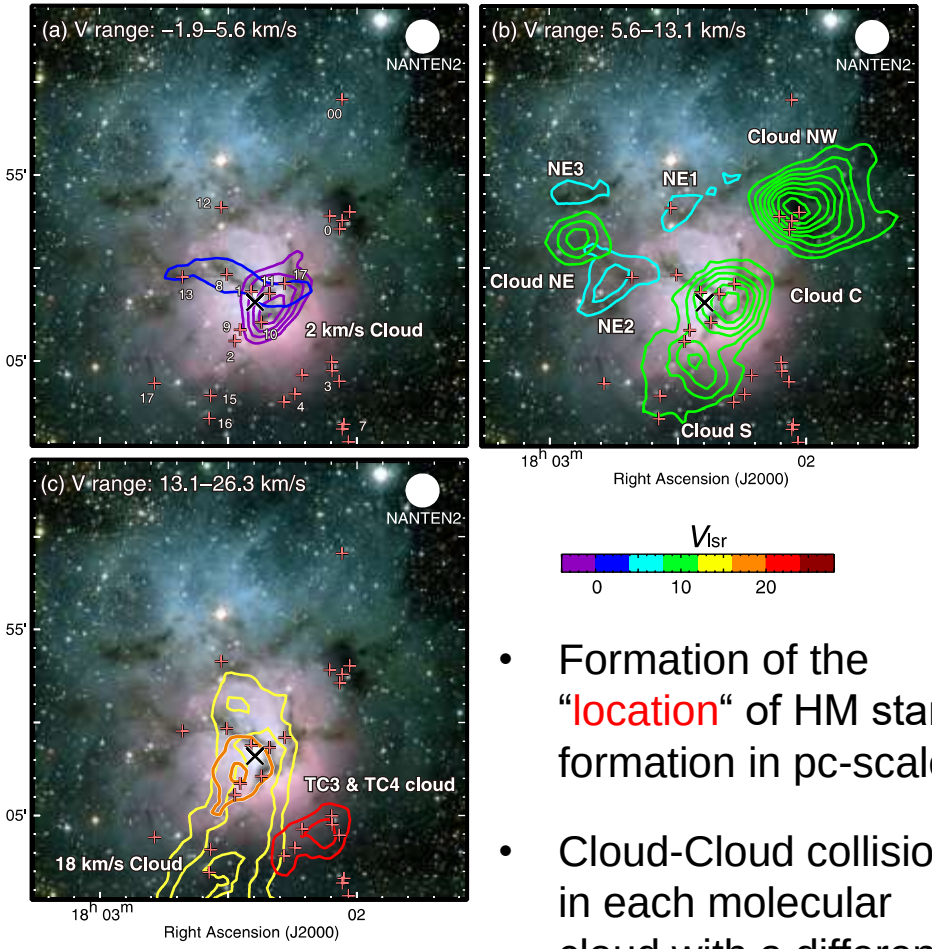
☞ applicable to **11 sources**

- Distance to selected sources（e.g., Honma+ 12; Reid+ 14; Green+ 11）
  - Parallax or GC：**2** sources
  - Kinematic：**7** (near/far distinguished by HI Self-Absorption method）

HM star formation : pc (~10^5 au)-scale



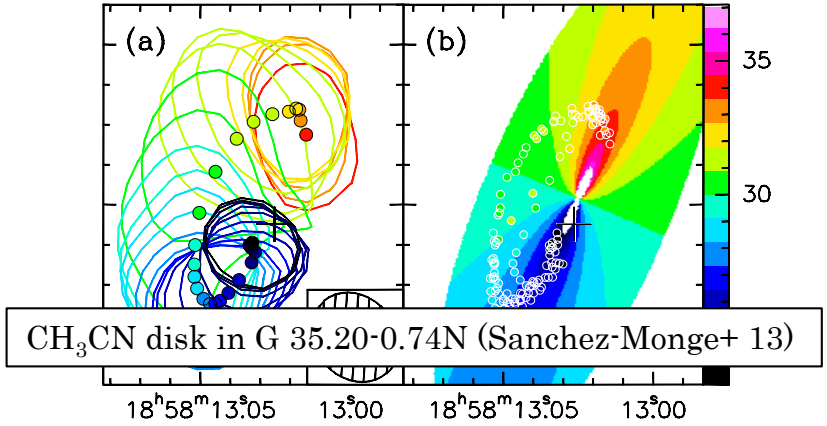
C-C Collision of RCW49 in Westerlund2 (Furukawa+ 09)



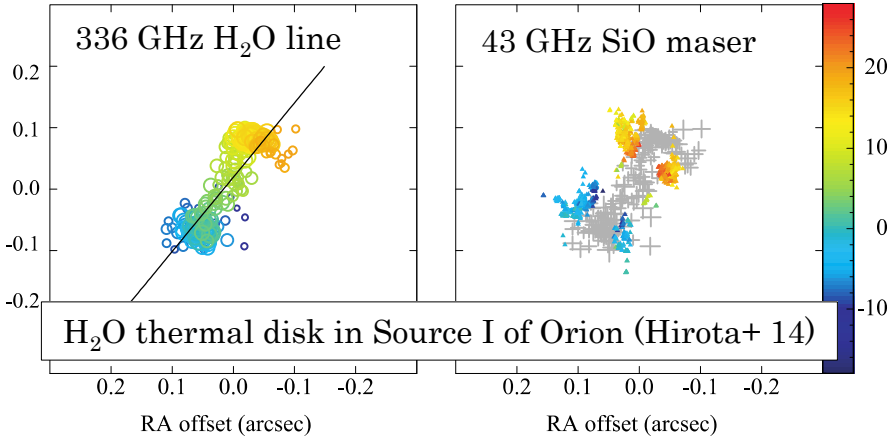
C-C Collision in M20 (Torii+ 11)

- Formation of the "location" of HM star formation in pc-scale
- Cloud-Cloud collision in each molecular cloud with a different velocity (Nagoya group)

High-mass (HM) star formation



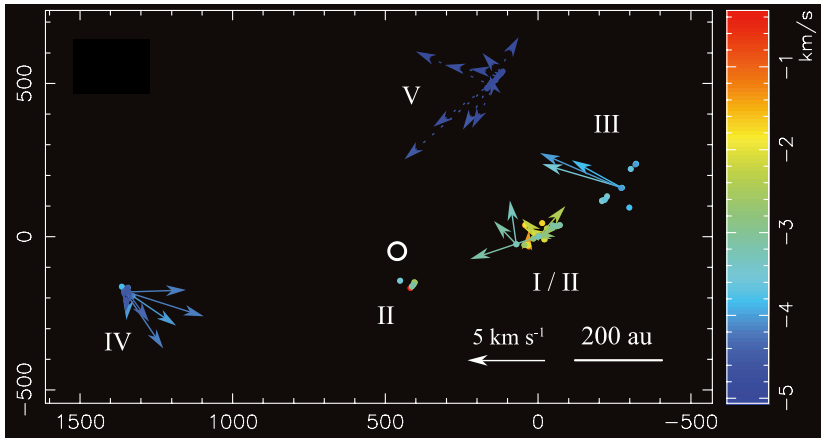
CH_3CN disk in G 35.20-0.74N (Sanchez-Monge+ 13)



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

mass accretion from surrounding disk

- Theory:
  - high-accretion rate (e.g., Nakano+00)
  - non-spherical (e.g., Krumholz+ 09)
- Observation:
  - rotating disk based on LSR vel. (e.g., Cesaroni+ 99; Hirota+14)
  - Accretion from disk/envelope based on 3-D vel. with VLBI (e.g., Goddi+ 11; Sugiyama+ 14)



Rotating and Infalling proper motions detected with JVN in HMPSs Cep A-HW2 (Sugiyama+ 14)

Summary

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

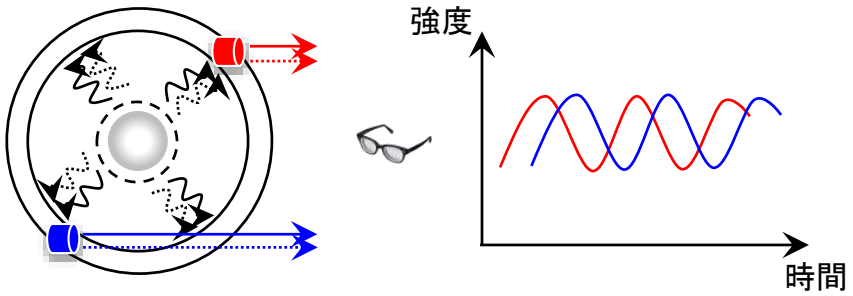
- Ibaraki (Hitachi) 32-m monitor project
  - Initiated since 2012/Dec/30 – ongoing
  - Toward all samples (as of 2012) observable from Ibaraki: 442 sources
  - Obs. interval: 4-5 or 9-10 $days^{-1}$ /source
  - Newly detected 14 sources : periods of 24 -220 days

- To improve the accuracy of P-L relation on HM proto-stars
  - Increasing samples with shorter and longer periods, Astrometry, NIR monitor, and spatial distribution in multi-epochs

Possible mechanisms to cause the periodic variations

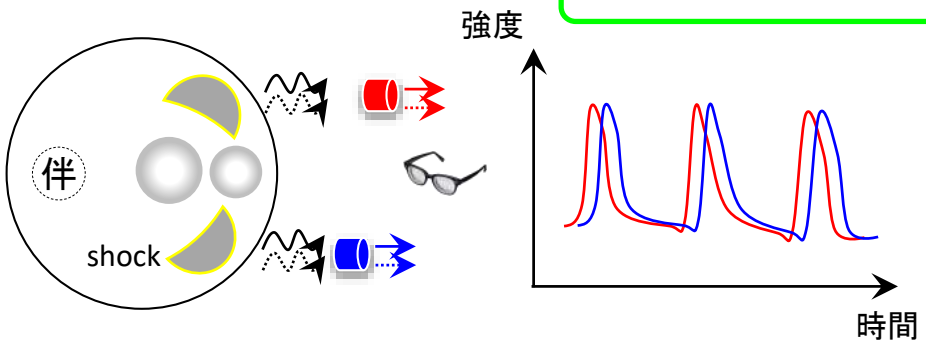
- 定量的な理論モデル
  - 原始星の脈動不安定（Inayoshi+ 13）
    - ZAMS直前の ~10^3 yrs
    - 高降着率下で成長: ≧ 10^{-3} Mo/yr
    - κ 機構に従い, 連続的なパターンを示す
  - Colliding wind binary（van der Walt 11）
  - 連星系円盤を通じたスパイラルショックの周期的生成（Parfenov & Sobolev 14）

連続的パターン

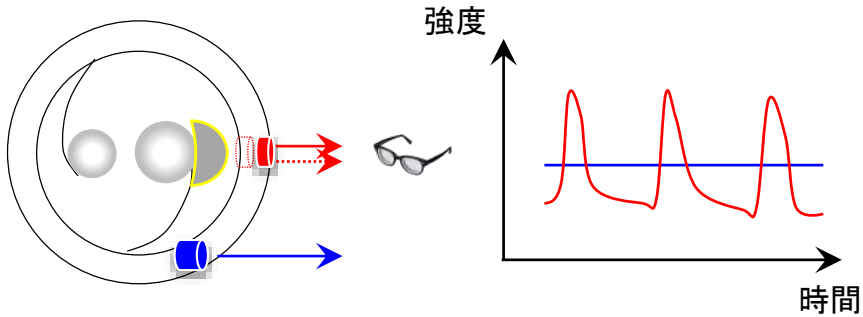


脈動不安定の模式図

間欠的パターン



Colliding wind binary の模式図



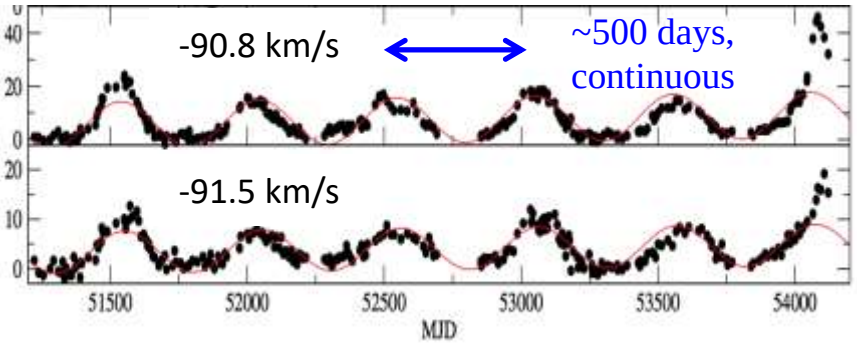
連星スパイラルショックの模式図

Characteristic flux variation: Periodic

- Discovered in the “methanol masers” around HM proto-stars
  - So far, in 20 source (e.g., Goedhart+ 04)
  - Periodicity: ~30–670日
  - Pattern: Continuous / intermittent
  - Synchronized in spectral components

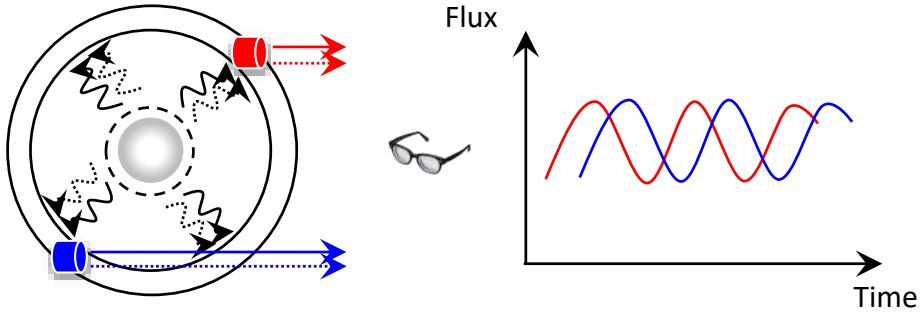
☞ **~0.1-1 au scales with Keplar**

☞ **Caused by central system??**



Periodic methanol maser sources, G 331.13-00.24 (Goedhart+ 07)

- Possible theoretical models
  - Stellar pulsation instability (Inayoshi+ 13)
    - Occurred at ~10^3 yrs just before ZAMS
    - Grow under high-accretion: ≧ 10^{-3} Mo/yr
    - κ mechanism present continuous pattern
  - Colliding wind binary (van der Walt 11)
  - Circumbinary spiral shock with periodic rotation (Parfenov & Sobolev 14)



Stellar pulsation instability model suggested for high-mass proto-stars (Inayoshi+ 13), and expected continuous (sinusoidal) pattern of flux variabilities.

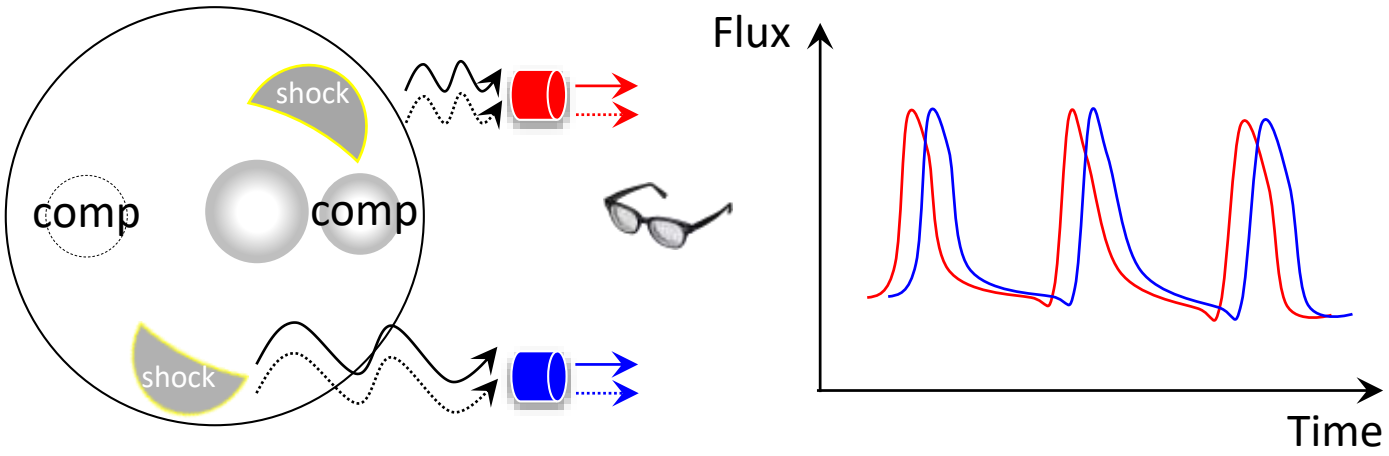
Possible theoretical models
(e.g., Goedhart+ 08)

- Stellar pulsational instability (Inayoshi+ 13)
  - Occur at unstable duration just before ZAMS
  - Periodic change of luminosity causes changes of dust temperature

- Colliding wind binary (van der Walt 11)
  - Occur at later phase forming an ultra-compact HII region
  - Colliding in each stellar wind at proximity point
  - Periodic pulse of ionizing radiation as the seed photon

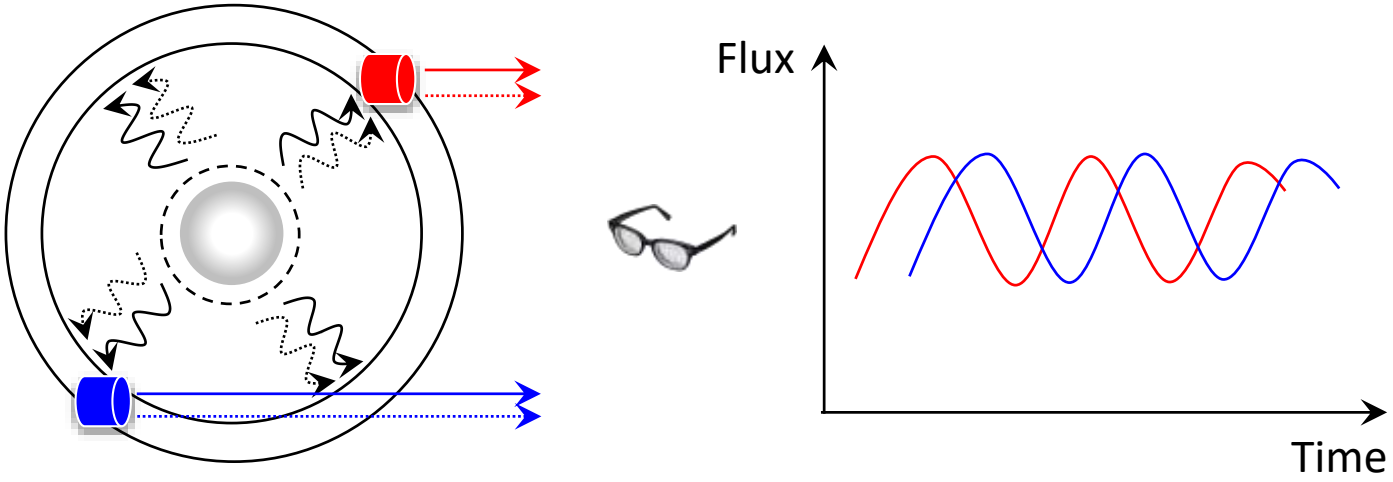
- Circumbinary spiral shock (Parfenov & Sobolev 14)
  - Occur at early evolutionary phase forming circumbinary disk
  - Periodic forming spiral shock locally heats dust at masing area

Colliding wind binary (CWB)
(van der Walt+ 09; van der Walt 11)



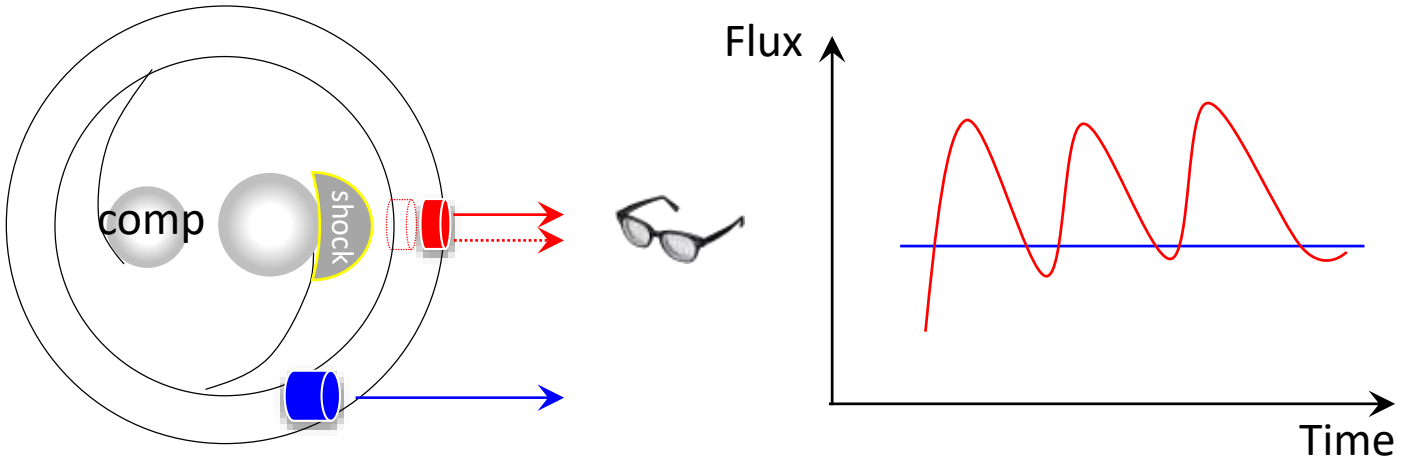
- Occur at later phase forming an UC HII region
- Colliding in each stellar wind at proximity point
- Periodic pulse of ionizing radiation as the seed photon
- Eccentricity present intermittent periodic pattern

Stellar pulsational instability
(Inayoshi+ 13; Sanna+ 15)



- Occur at unstable ~10^3 yr duration just before ZAMS
- Grow under high-accretion conditions > 10^{-3} Mo/yr
- Periodic change of luminosity causes changes of dust temperature
- □κ mechanism" present continuous periodic pattern

Spiral shock heating in a circum-binary disk (Parfenov & Sobolev 14)



- Occur at early phase forming circumbinary disk
- Periodic forming spiral shock locally heats masing area
- Eccentricity present intermittent periodic pattern
- As a result, flux density of the limited masers that column density is increased along l.o.s. could be changed

Lomb-Scargle periodgram (Lomb 76; Scargle 82)

- Equation

$$P_N(\omega) \equiv \frac{1}{2\sigma^2}\left\{\frac{\left[\sum_j (h_j - \bar{h})\cos\omega(t_j-\tau)\right]^2}{\sum_j \cos^2\omega(t_j-\tau)} + \frac{\left[\sum_j (h_j - \bar{h})\sin\omega(t_j-\tau)\right]^2}{\sum_j \sin^2\omega(t_j-\tau)}\right\}$$

$$\tan(2\omega\tau) = \frac{\sum_j \sin 2\omega t_j}{\sum_j \cos 2\omega t_j}$$

ω: Frequency
τ : Shift from "t"
(appropriate to isolated data)

- Confidence level
  - (False-alarm probability = significance level)

$$P(>z) \equiv 1 - (1 - e^{-z})^M$$