Structure of a protobinary system: an asymmetric circumbinary disk and spiral arms

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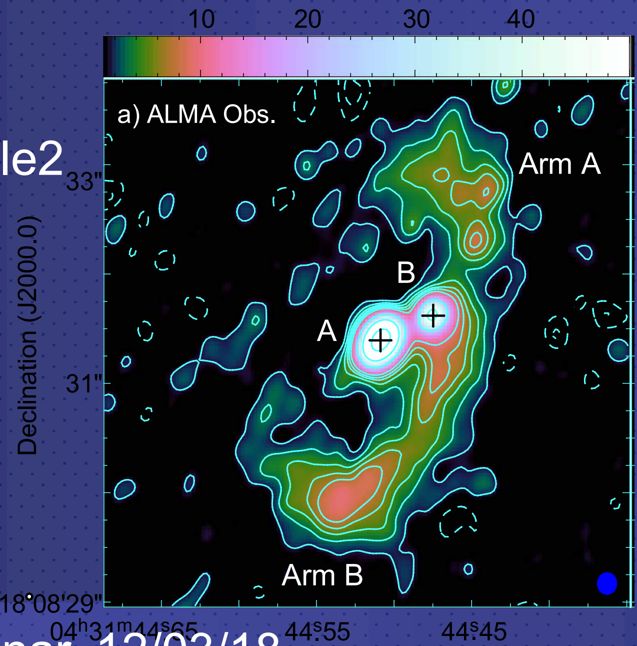
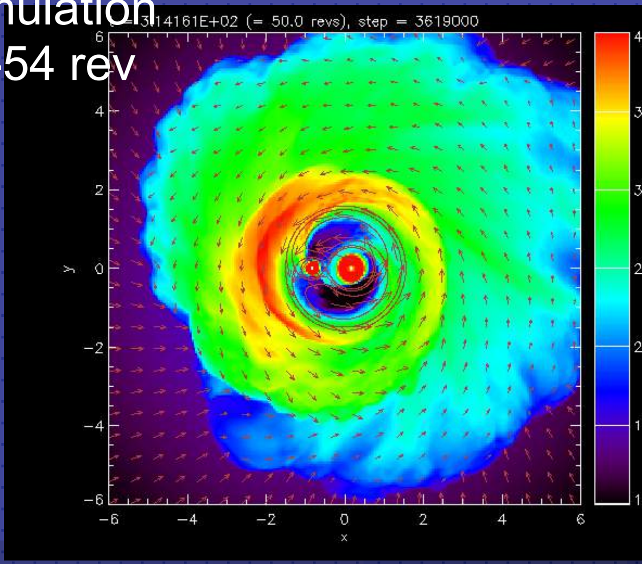
L1551 NE
ALMA Cycle2



Simulation
50-54 rev



EAO Informal seminar, 12/03/18

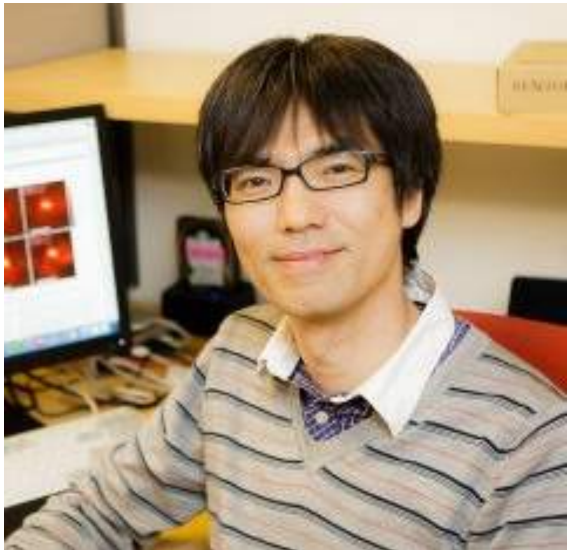
Topics on protobinary L1551 NE

- ALMA Cycle 0 + numerical simulations + synthetic observations
  - Takakuwa et al. 2014, ApJ, 796, 1
  - Takakuwa, Shigehisa; Saito, Masao; Saigo, Kazuya; Matsumoto, Tomoaki; Lim, Jeremy; Hanawa, Tomoyuki; Ho, Paul T. P.

- ALMA Cycle 2 + numerical simulations + synthetic observations
  - Takakuwa et al. 2017, ApJ, 837, 86
  - Takakuwa, Shigehisa; Saigo, Kazuya; Matsumoto, Tomoaki; Saito, Masao; Lim, Jeremy; Hanawa, Tomoyuki; Yen, Hsi-Wei; Ho, Paul T. P.

- Numerical simulatins: understanding gas dynamics
  - Matsumoto, Saigo, Takakuwa 2018, submitted to ApJ

Core members



Tomoaki Matsumoto
(Hosei U. / Princeton U.)

Numerical simulations

Shigehisa Takakuwa
(Kagoshima U. / ASIAA)

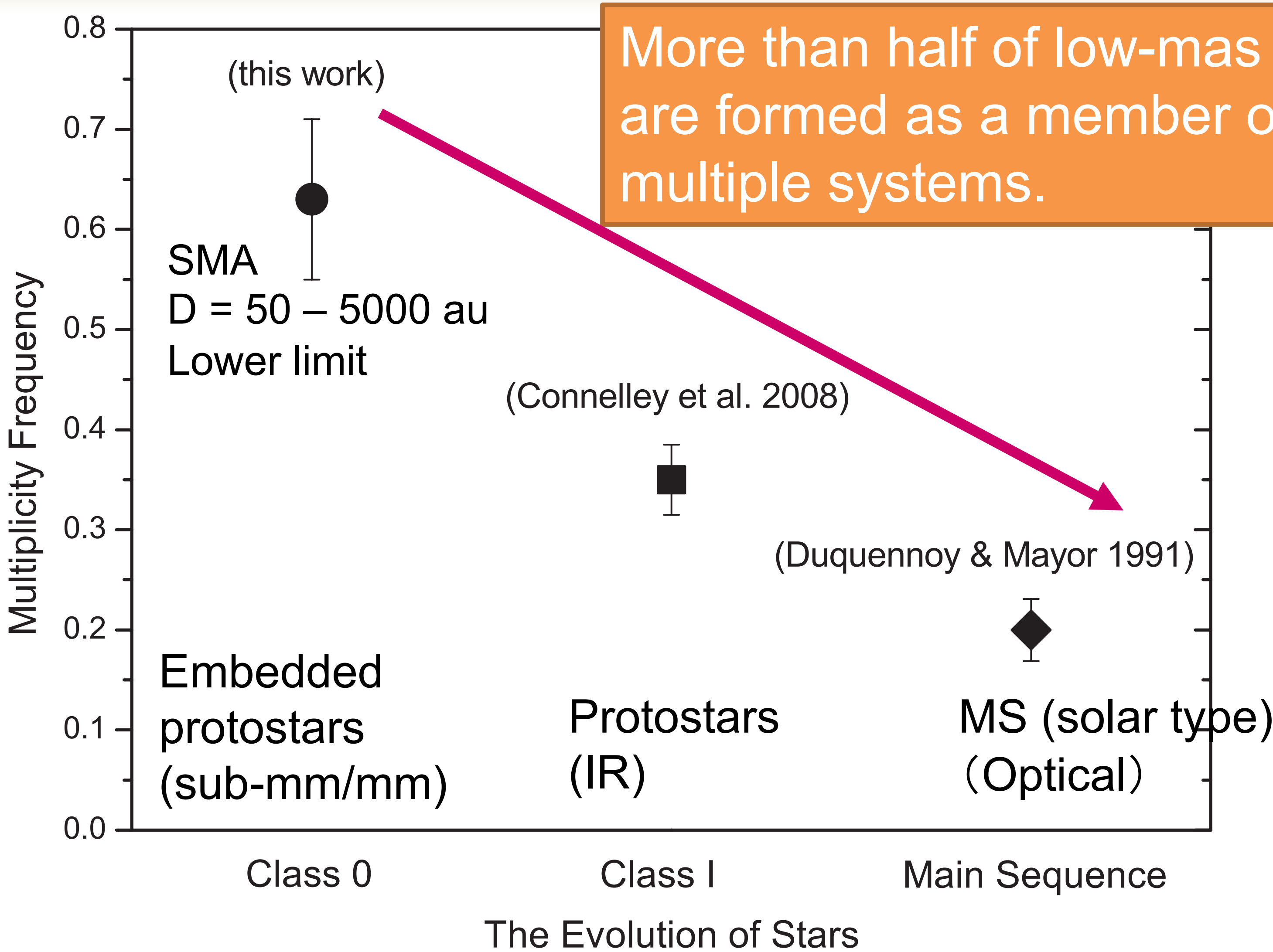
Radio observations

Kazuya Saigo
(NAOJ)

Synthetic observations

Evolution of multiple frequency of low mass stars

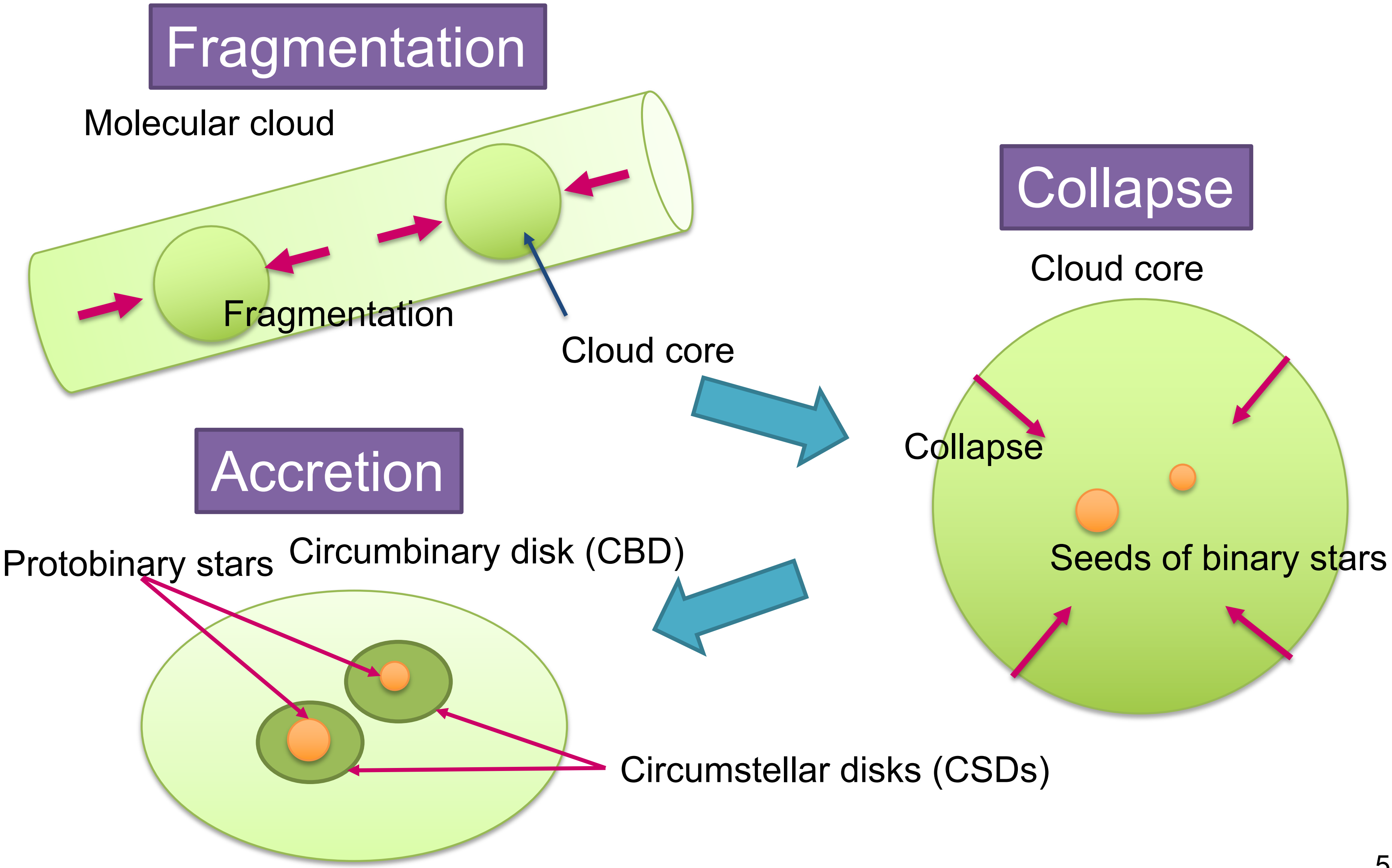
More than half of low-mas stars are formed as a member of multiple systems.

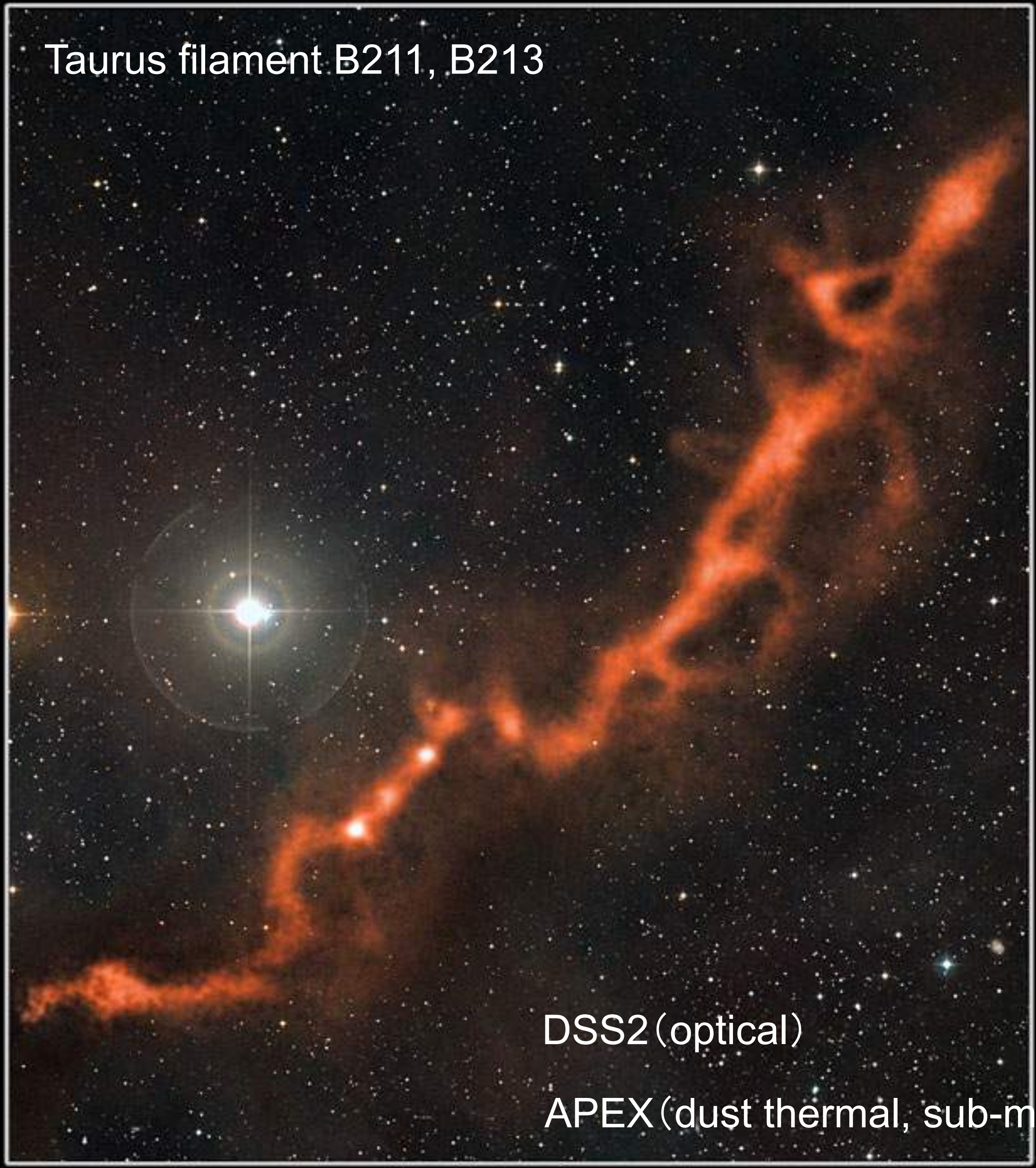


$$\text{multiplicity frequency (MF)} = \frac{B + T + Q}{S + B + T + Q},$$

Chen+ 2013

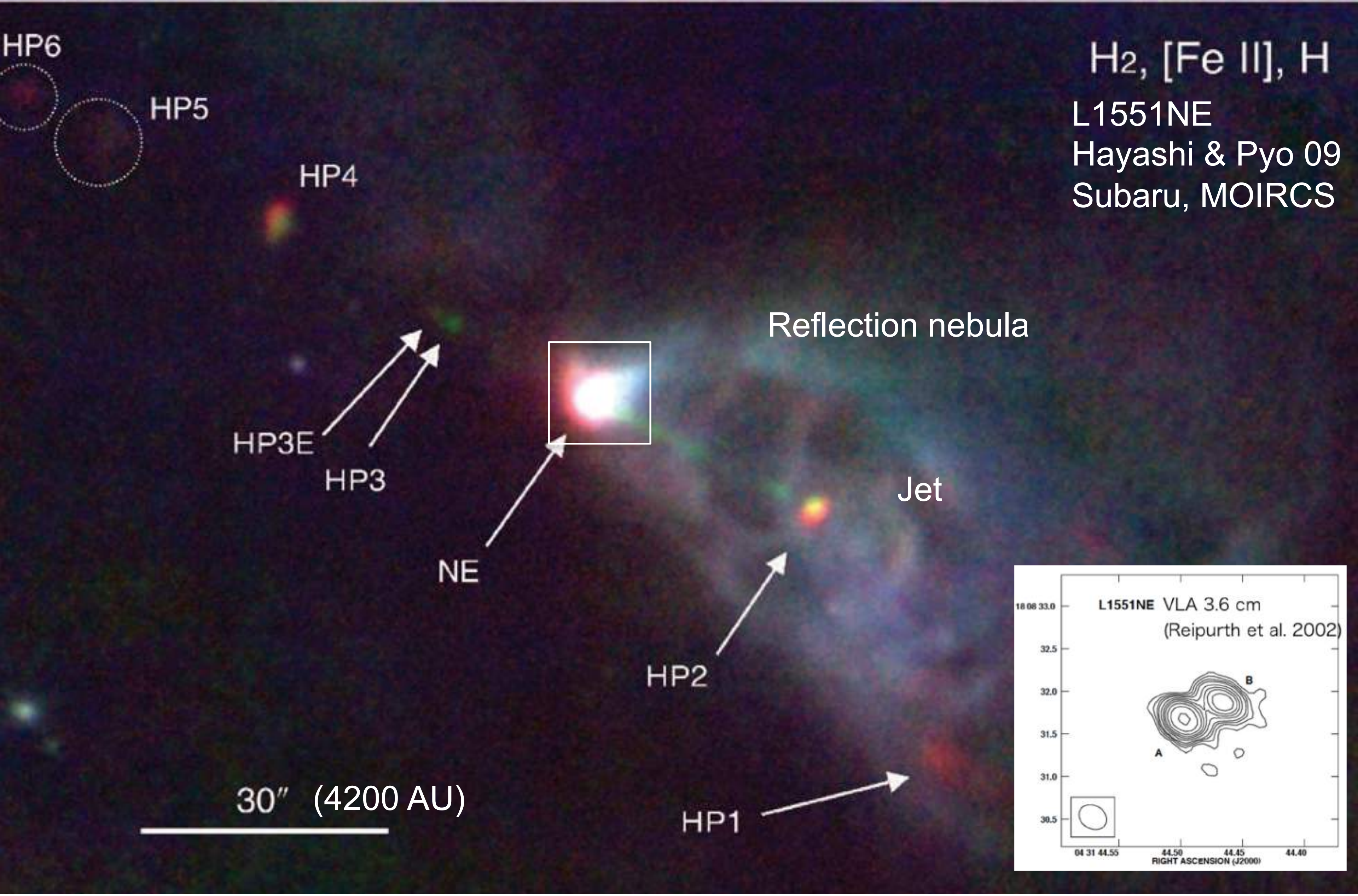
Scenario of binary/multiple star formation





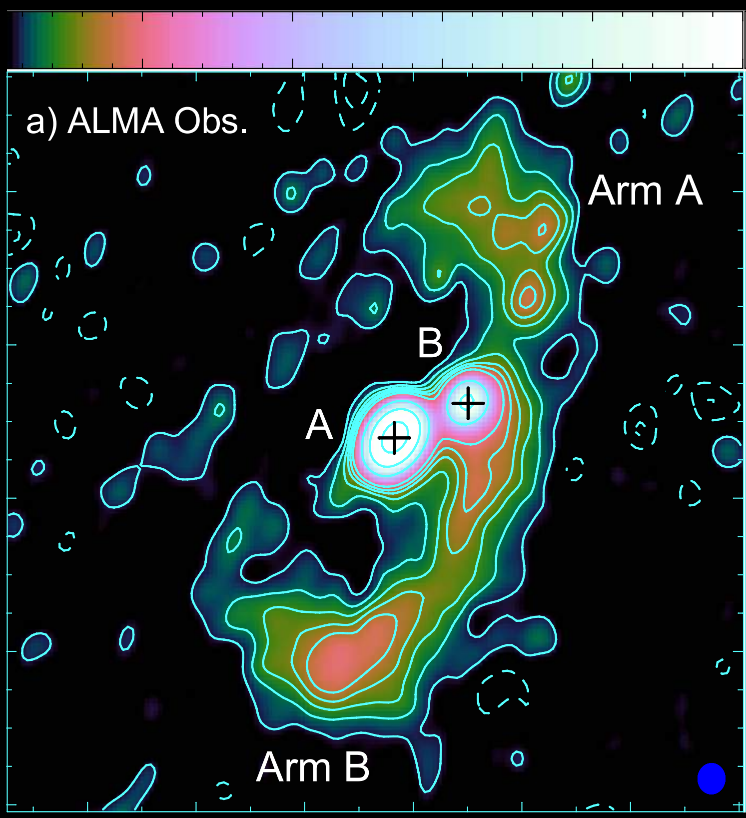
Taurus filament B211, B213
DSS2（optical）
APEX（dust thermal, sub-mm）

L1551 NE : Class I Protobinary stars

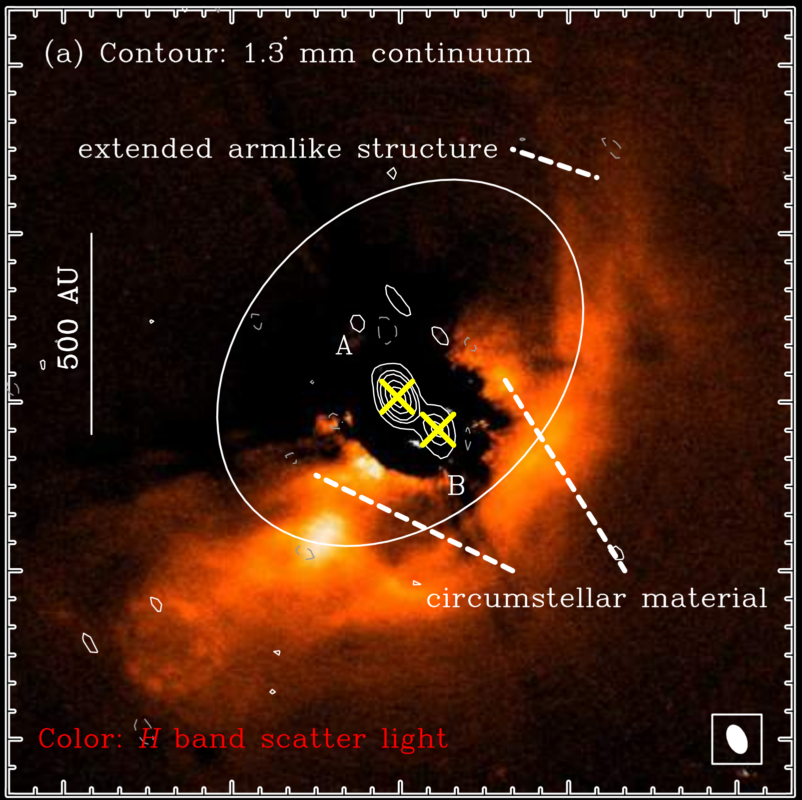


Observed asymmetry in CBDs

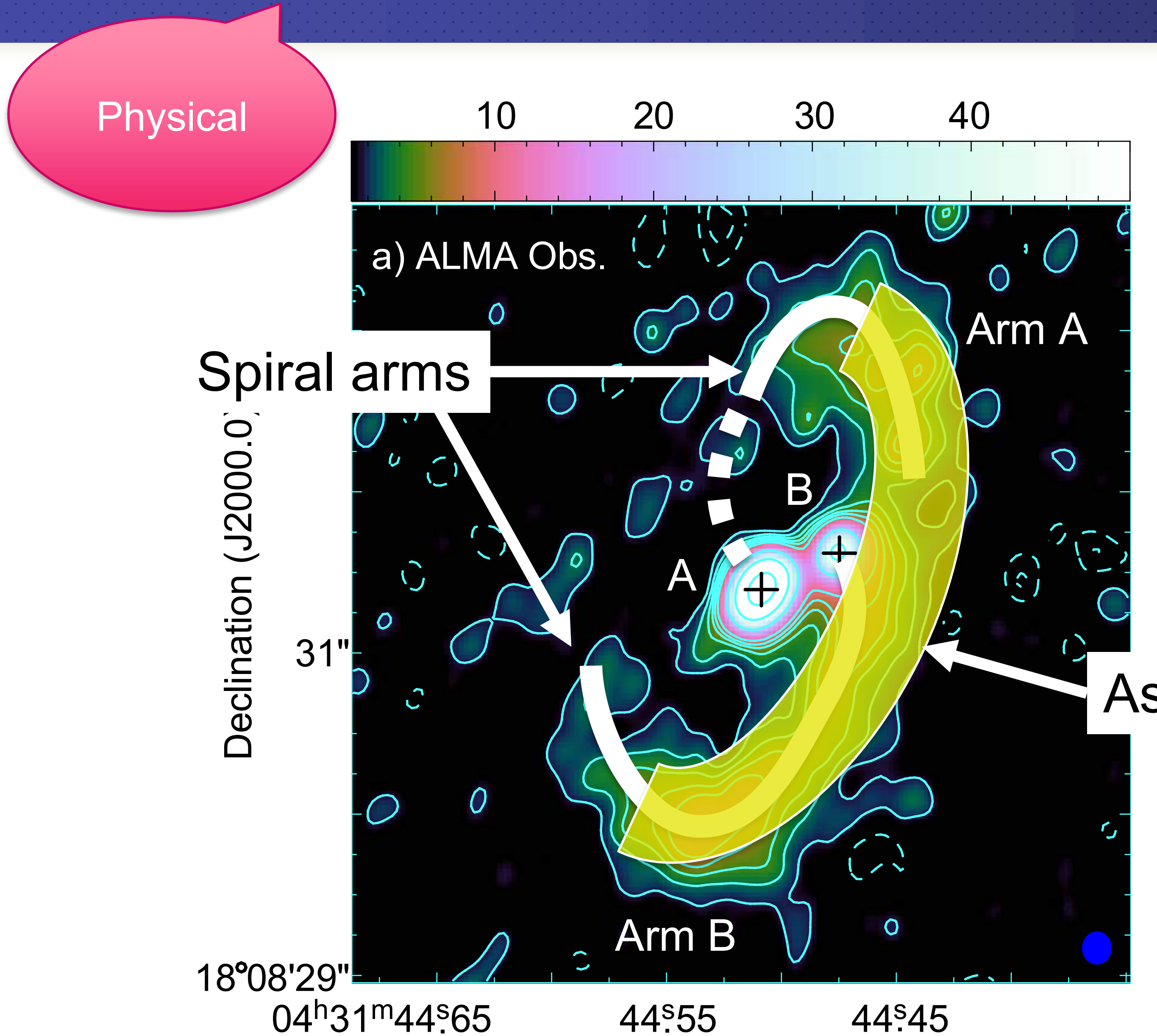
L1551 NE (Takakuwa+ 17)
ALMA Cycle-2

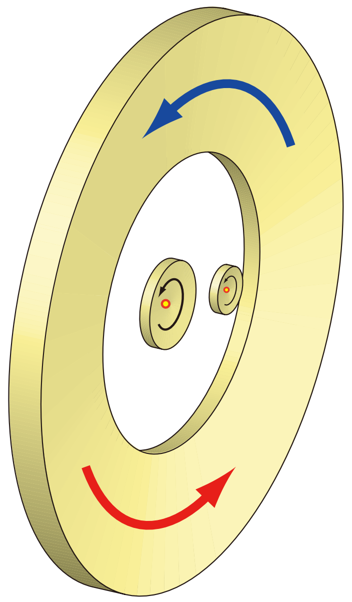


UY Aur (Tang+ 14, Hioki+ 07)
SUBARU H-band



Questions: origin of spiral arms and asymmetry



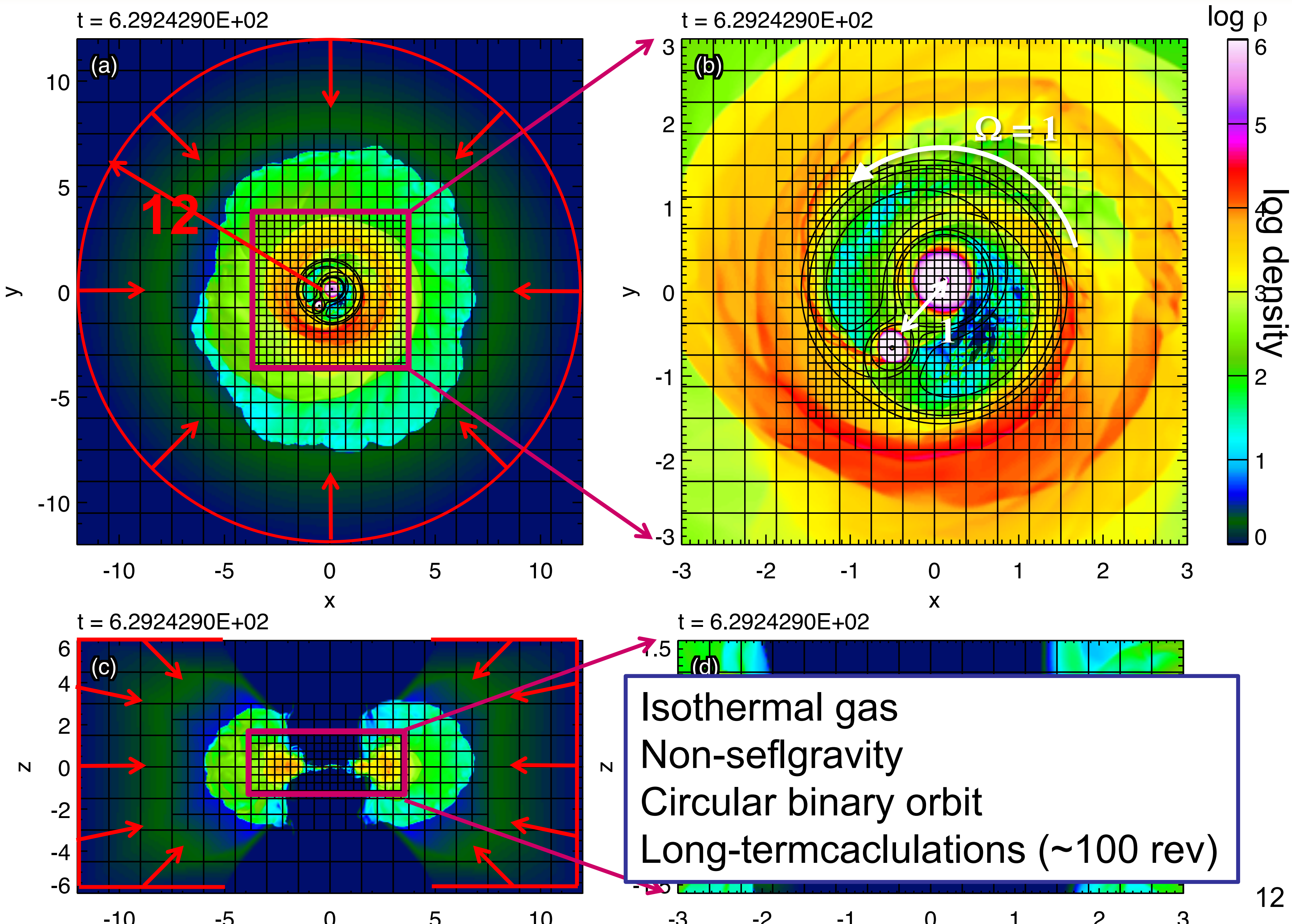


Summary of L1551 NE

- Class I protobinary
  - Main accretion phase, outflows from primary
- d = 140 pc
- M1 = 0.68 M_sun, M2 = 0.13 M_sun, q = 0.19
- Separation = 145 au (3D), 70 au (proected)
- Radius of CBD ~ 300 au
- Mass of CBD = 0.009 – 0.076 M_sun
- Mass of CSD = 0.005 – 0.043 M_sun (primary)
- Mass of CSD = 0.0019 – 0.015 M_sun (secondary)
- Rotation period = 1.9 x 10^3 years

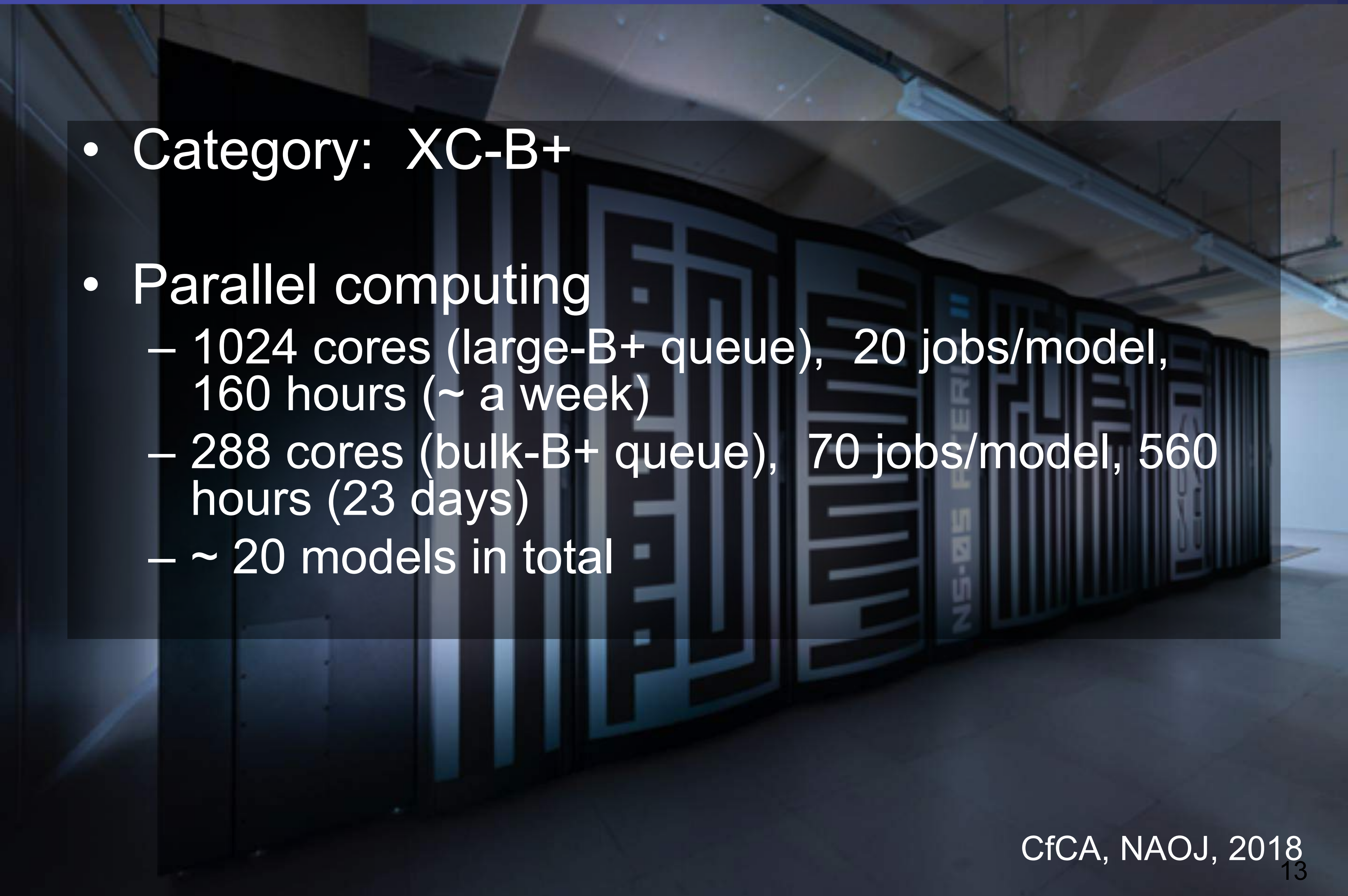
Numerical Method

SFUMATO AMR code



Isothermal gas
Non-seflgravity
Circular binary orbit
Long-termcaclulations (~100 rev)

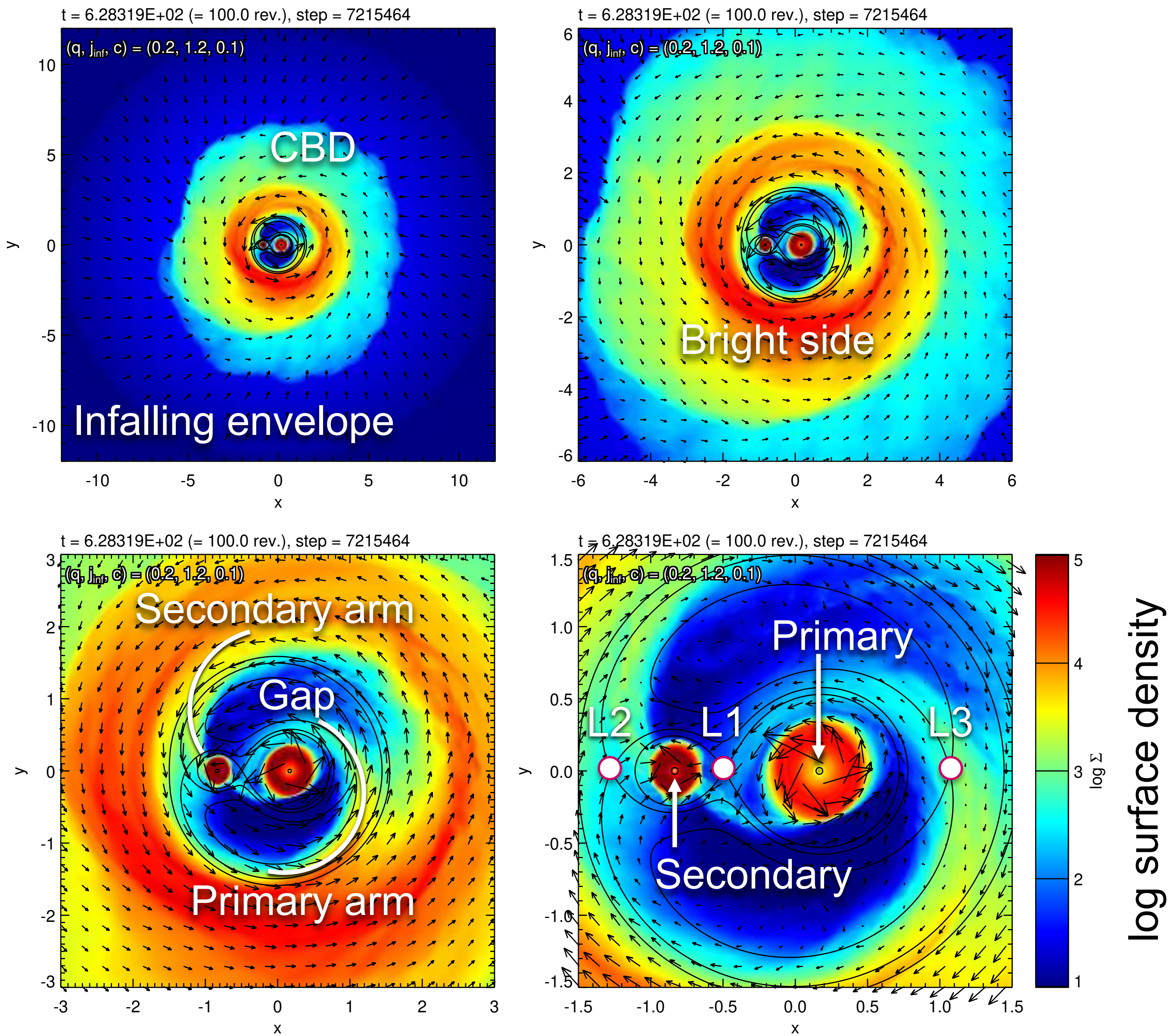
Super Computer ATERUI I/II



- Category: XC-B+
- Parallel computing
  - 1024 cores (large-B+ queue), 20 jobs/model, 160 hours (~ a week)
  - 288 cores (bulk-B+ queue), 70 jobs/model, 560 hours (23 days)
  - ~ 20 models in total

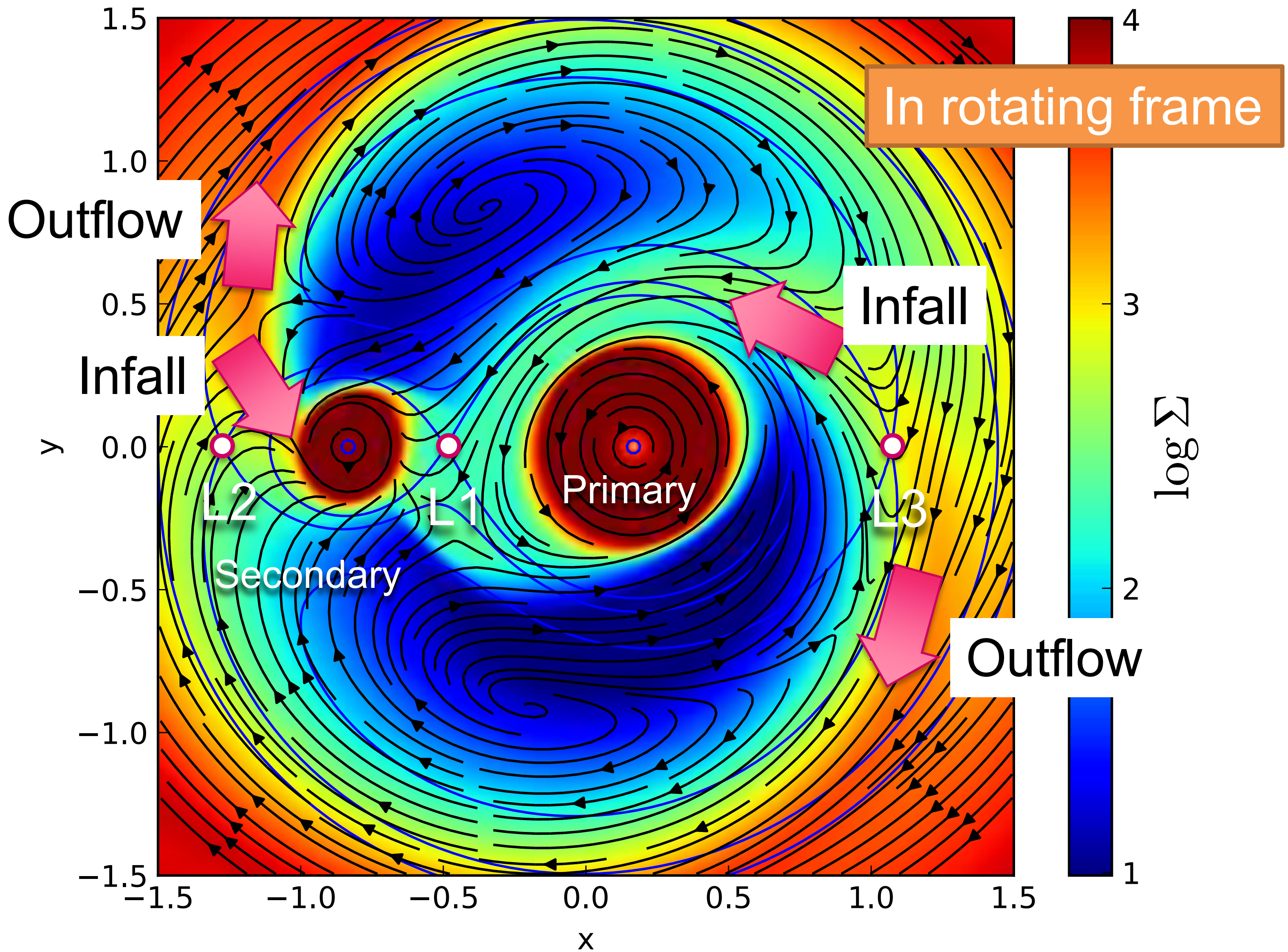
CfCA, NAOJ, 2018

Surface density distribution (fiducial model)

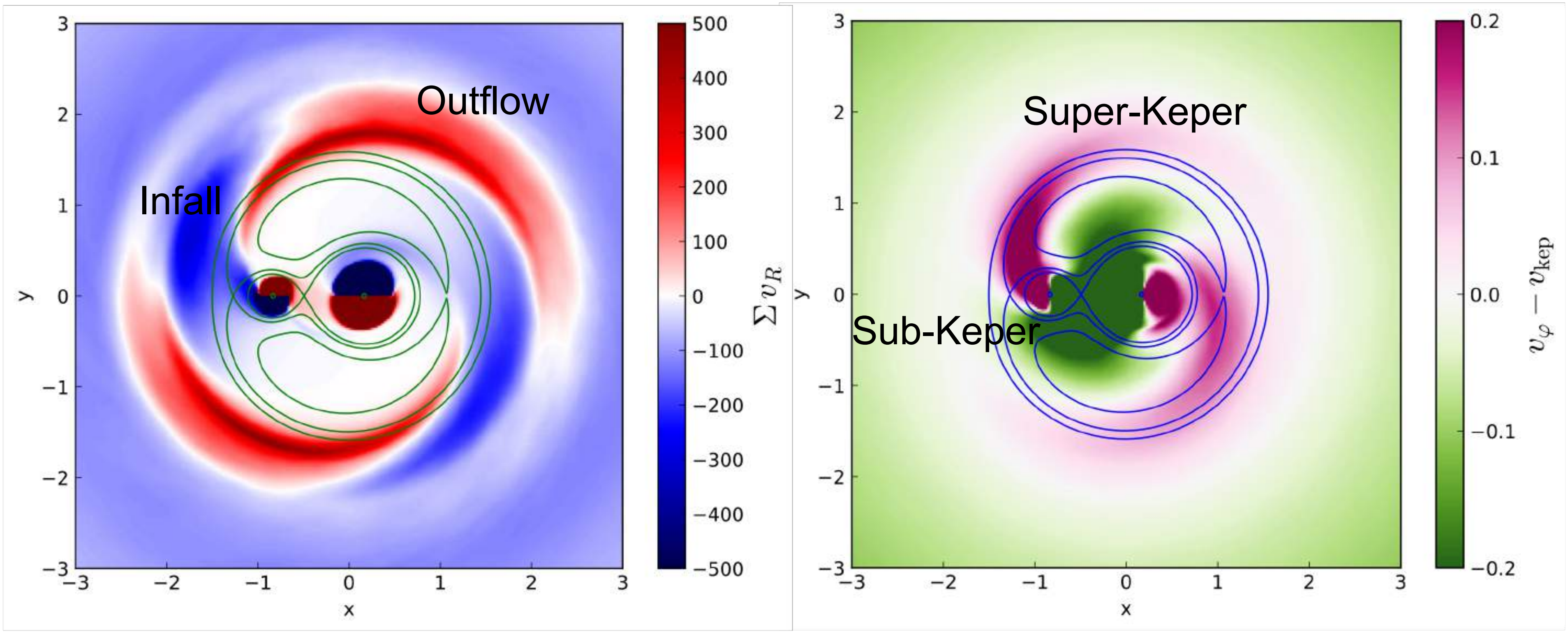


Gas flow along spiral arms

Temporal average to see long-lived structures



Temporal averages (80-100 rev)



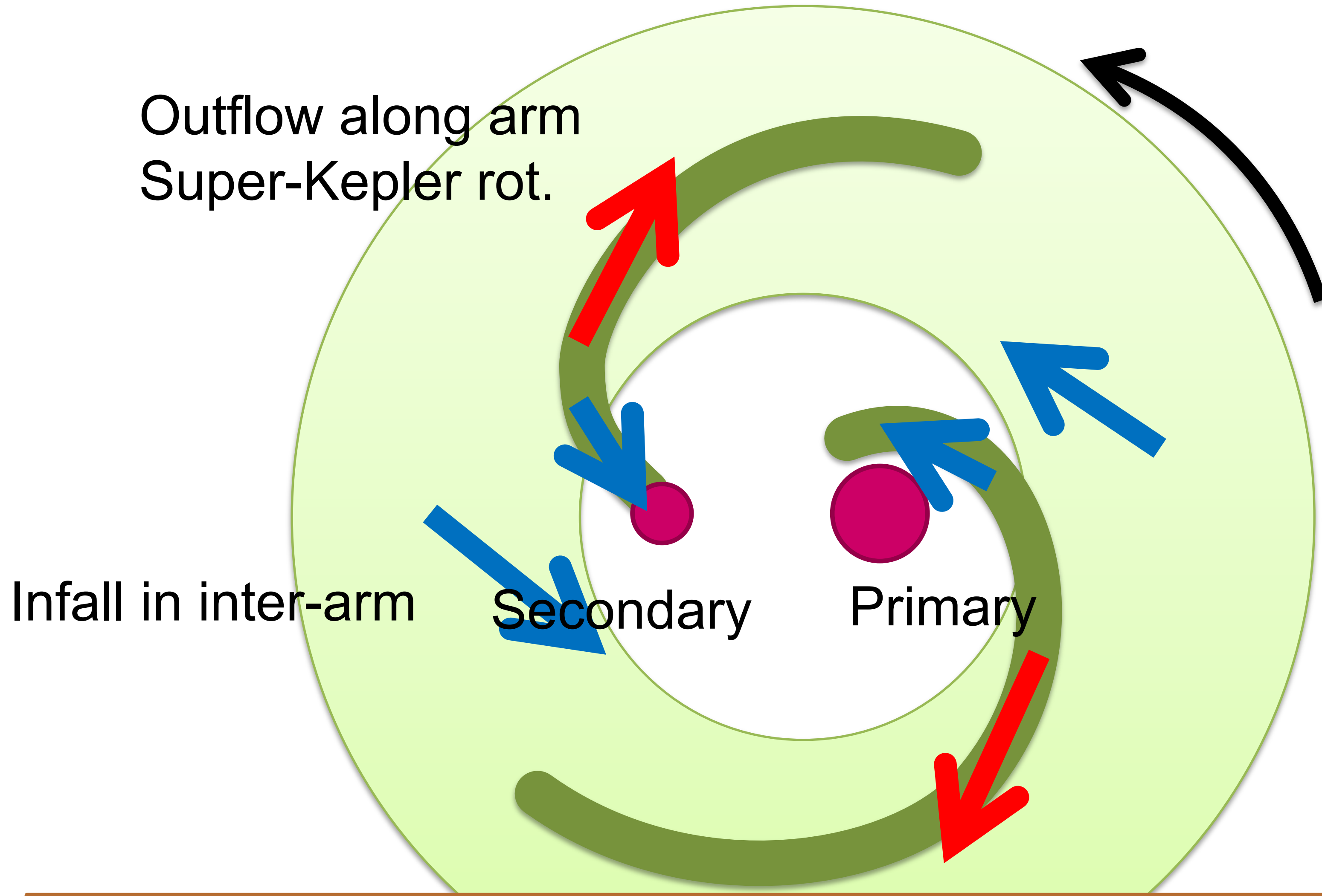
Mass flux, $\Sigma\ v_R$

Positive (red) : outflow
Negative (blue): infall

Rotation excess from Kepler rotation
c.f., swing-by of of a satelitte

Gravitational torque -> fast/slow rotation (super/sub-Kepler) -> outflow/infall
Gravity of stars -> infall onto stars

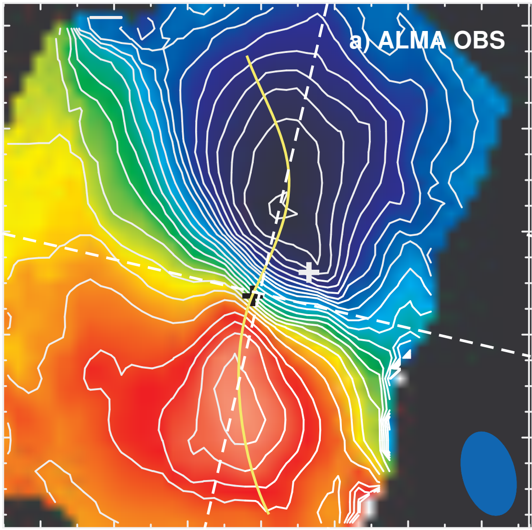
Summary of gas flow in rotating frame



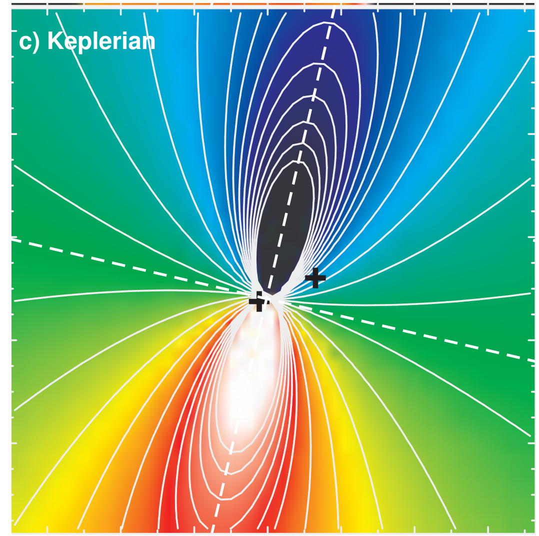
Gas flow is due to gravitational torque from binary stars.
Detection of the flow is a direct evidence of grav. torque.

Residual from Kepler rotation (C18O)

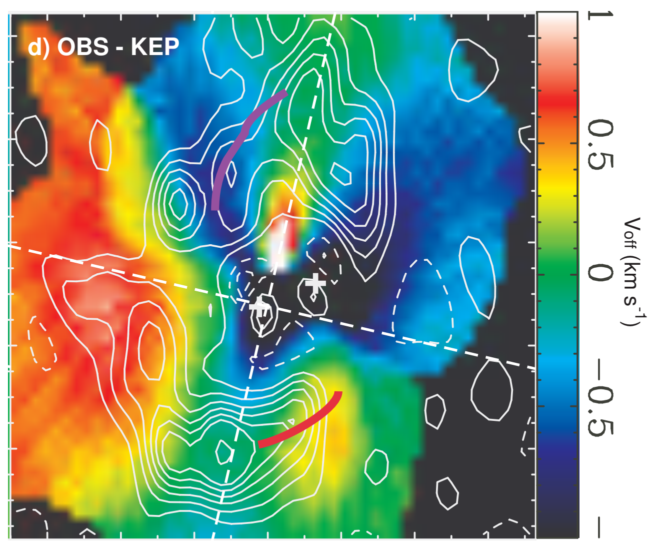
Observation (moment 1)



Keplerian rotation (model)

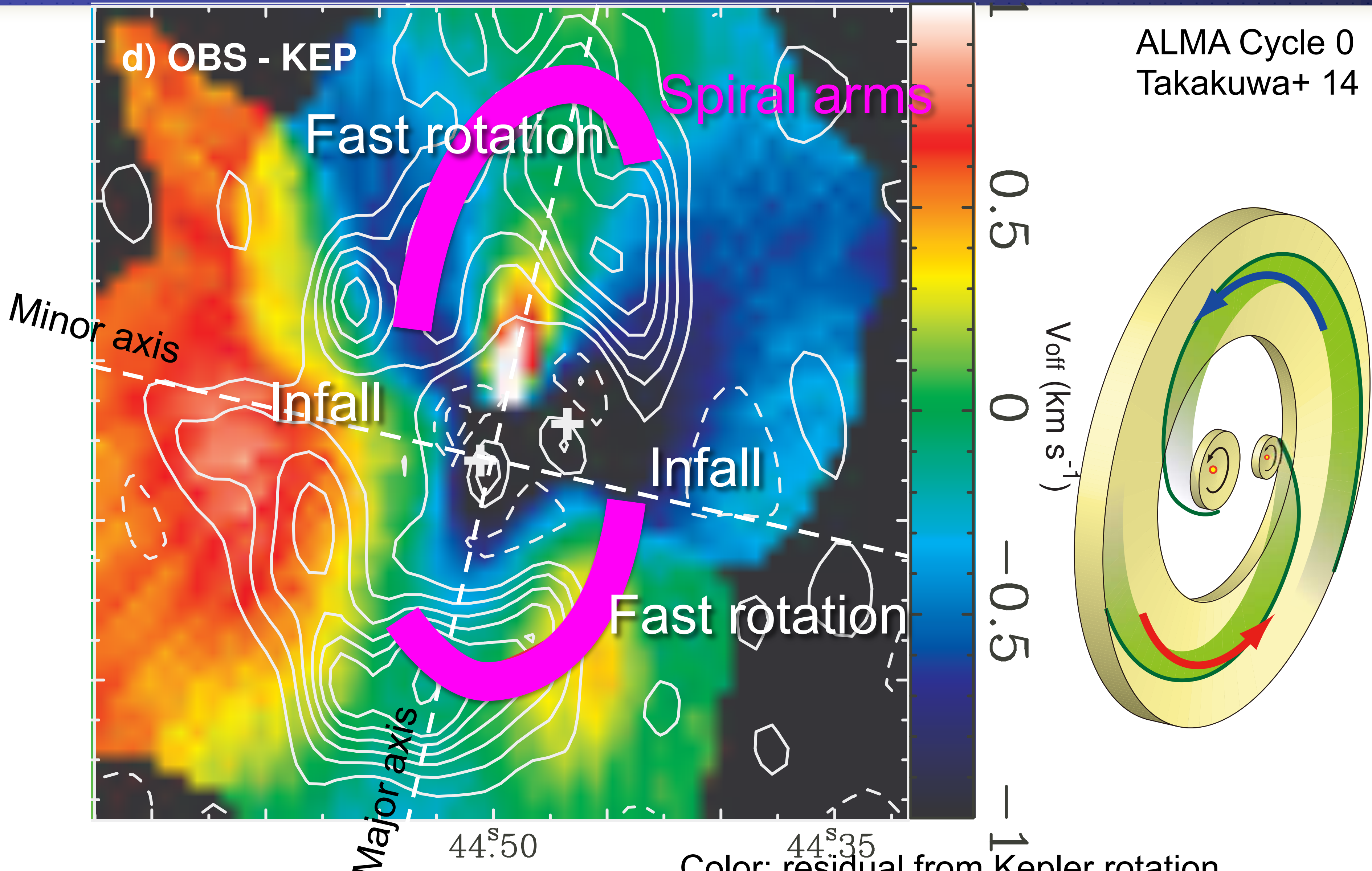


Residual



ALMA Cycle 0
Takakuwa+ 14

Residual from Kepler rotation (C18O)



ALMA Cycle 0
Takakuwa+ 14

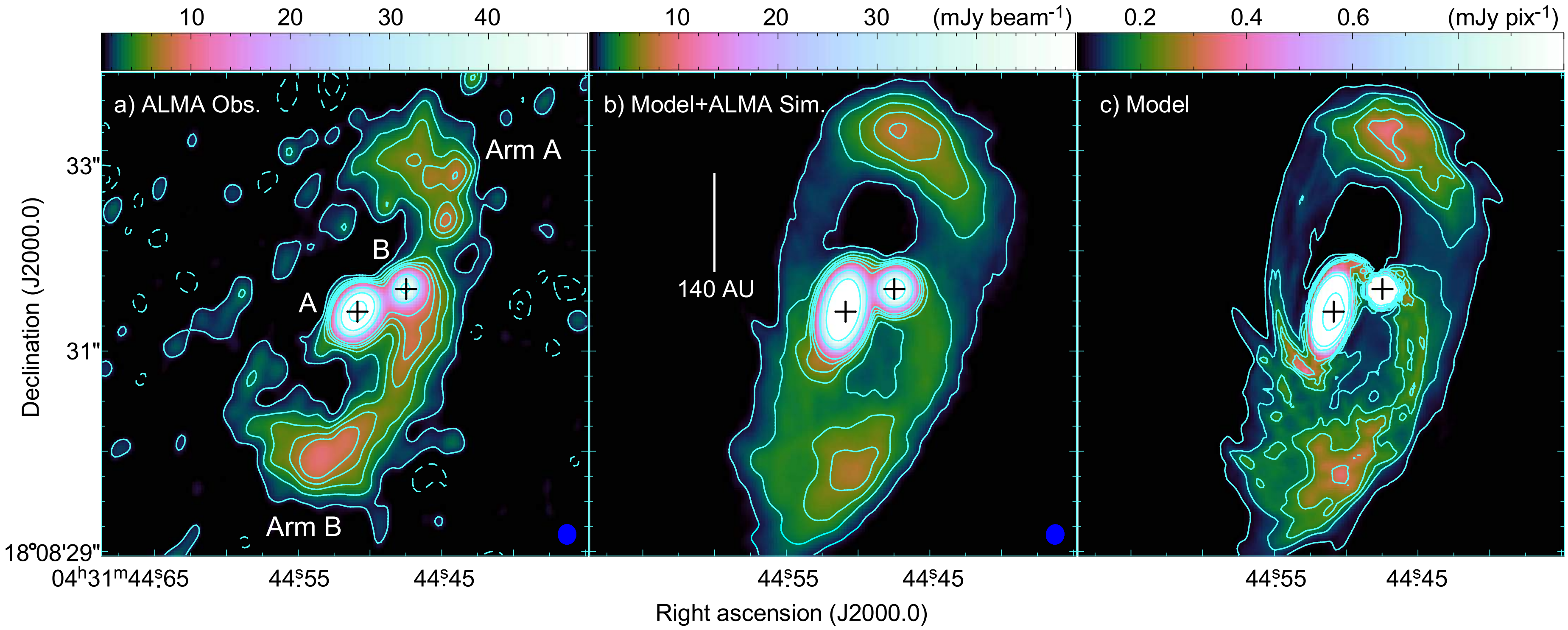
Color: residual from Kepler rotation.
Contour: dust emission

Comparison btw ALMA and simulation

ALMA Cycle 2

Synthetic observation

Hydrodynamical simulation

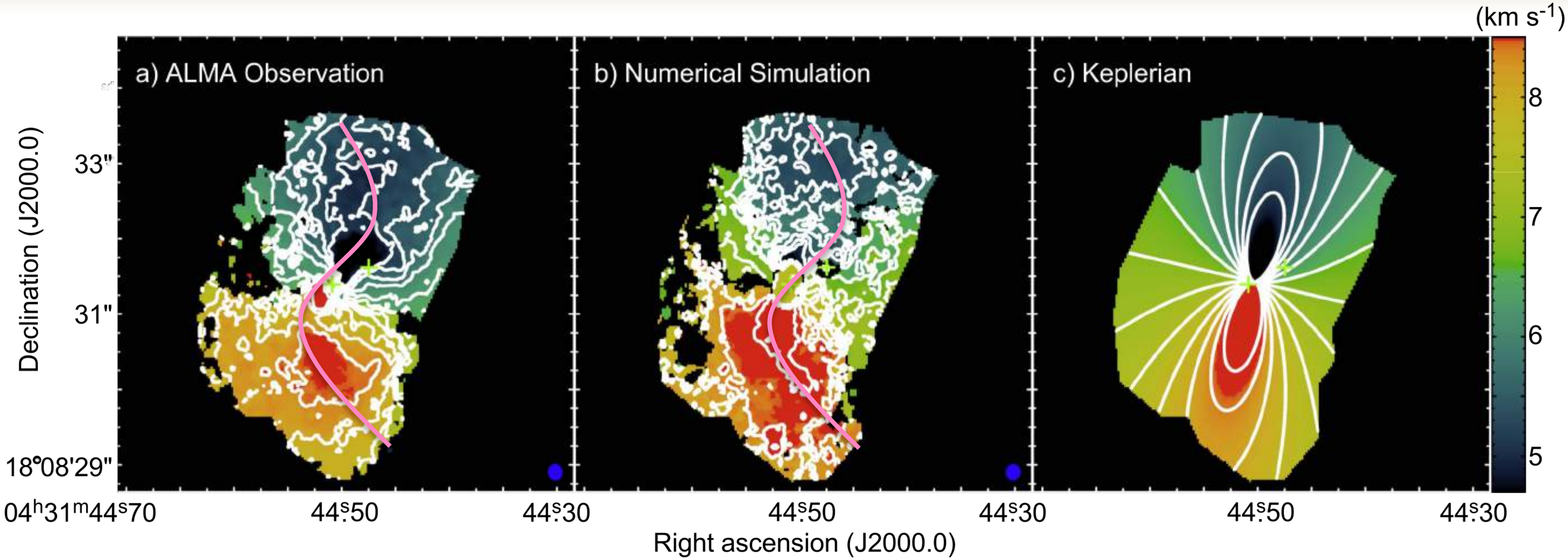


w/ CASA

Radiation transfer

Takakuwa+17

Moment 1 maps of obs and sim

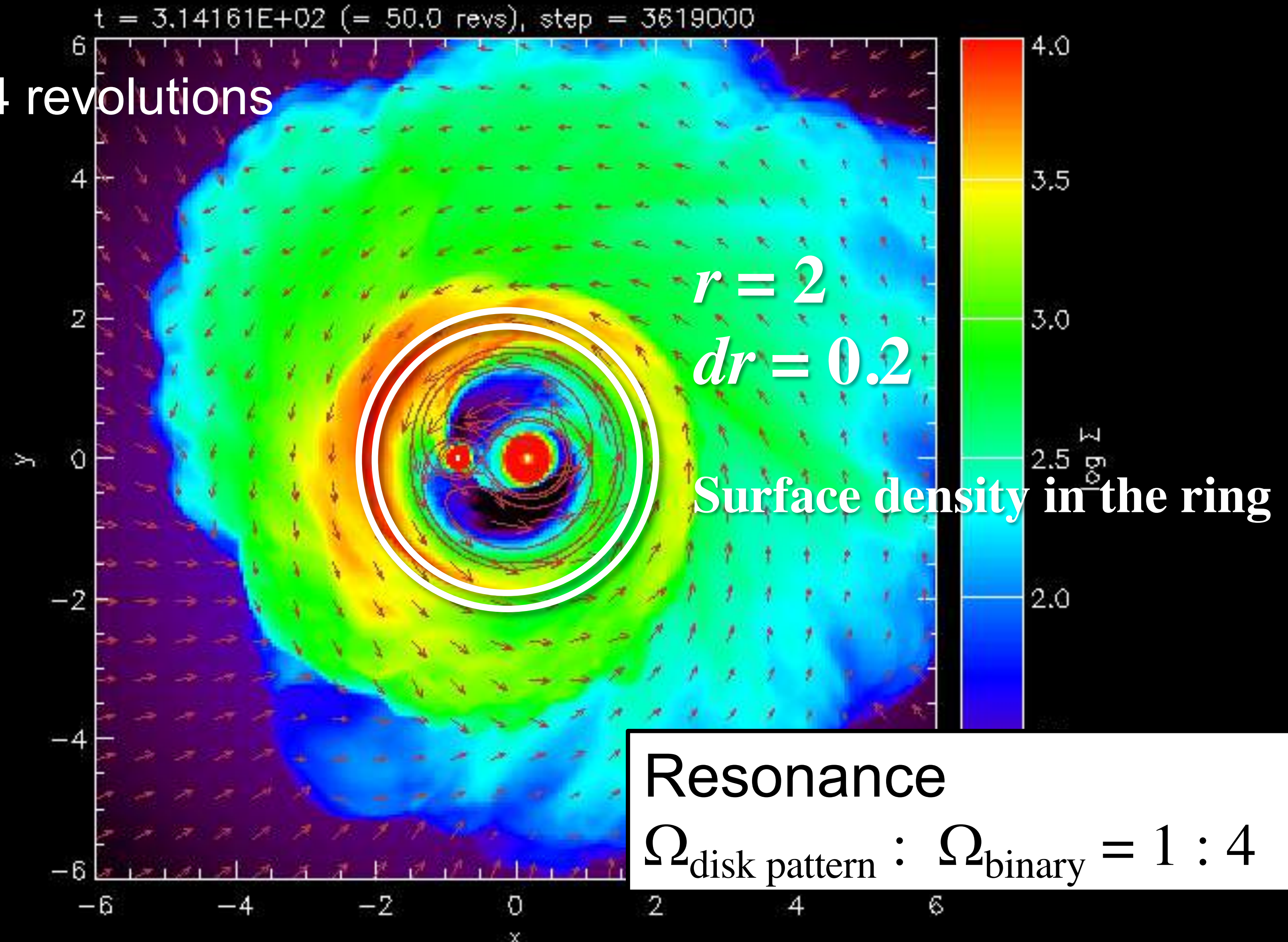


ALMA Cycle 2
Takakuwa+ 17

S-shaped moment 1 map is reflected by gravitational torque.

Asymmetry of CBD

Non-axisymmetric pattern 1 rev. when binary stars 4 rev（commensurability）

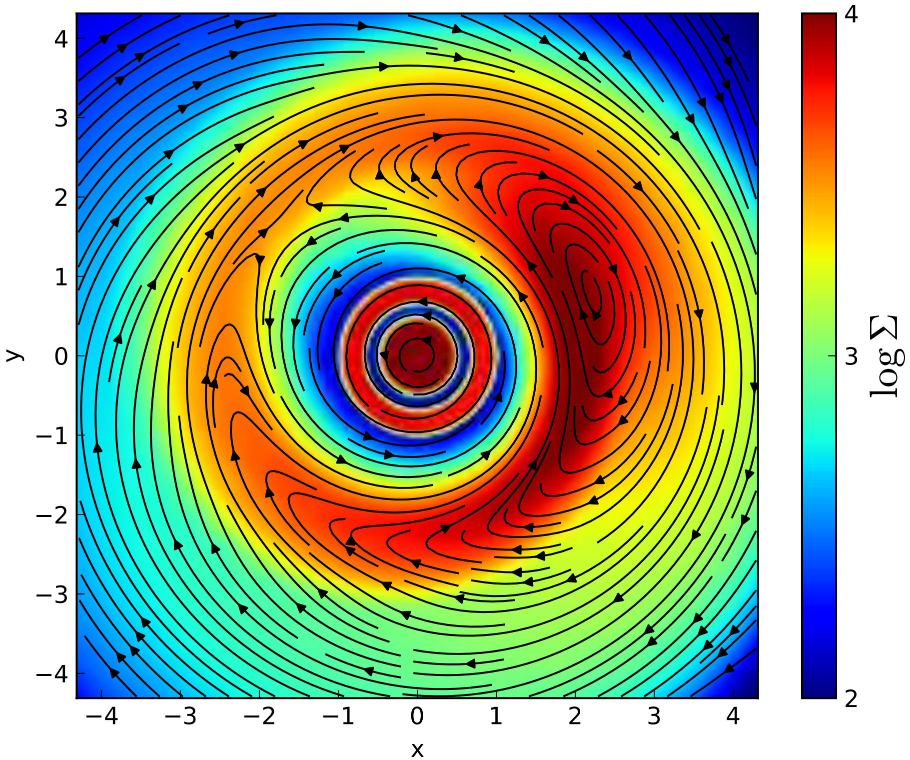


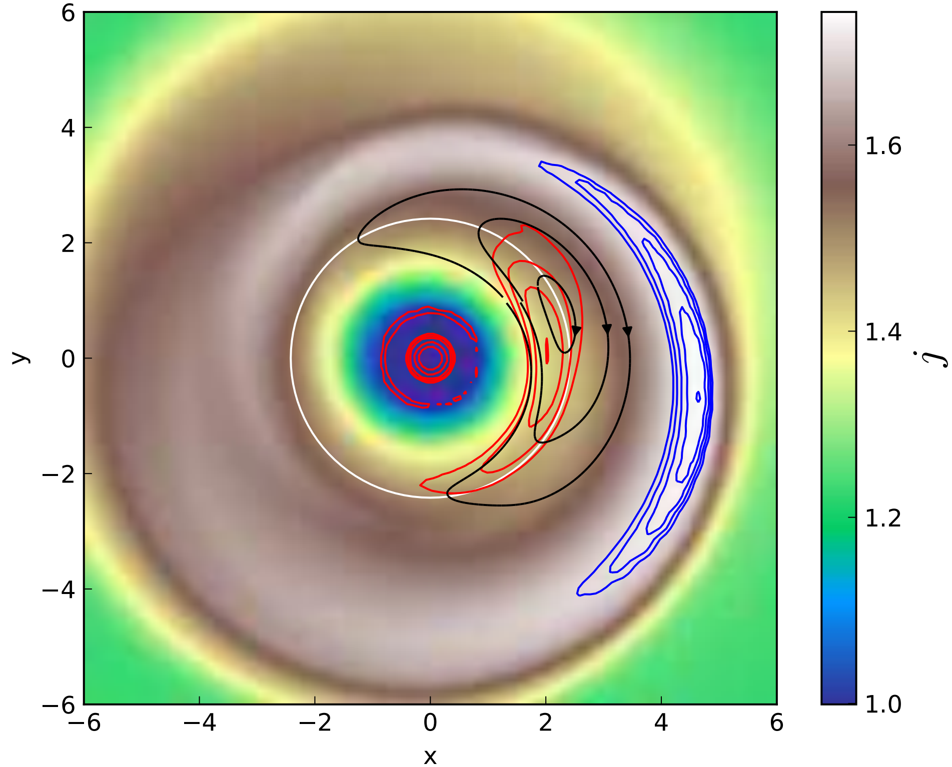
Resonance

$\Omega_{\text{disk pattern}} : \Omega_{\text{binary}} = 1 : 4$

Vortex in CBD

Time average btw 80-100 rev in the rotating frame with Ω_p (rotation with pattern)





Gravitational torque
-> j increases
-> exchange radial position
-> vortex
-> density bump (e.g., RWI)
-> asymmetry

Blue cont: specific angular mom.
Red cont: surface density
Black : stream lines
White: centrifugal radius with Ω_p

Summary

- Comparison between ALMA observations with high-resolution simulations is a powerful tool.
- We found that an evidence of gravitational torque acting on the CBD of L1551NE in gas motion.
  - inflow / outflow, super-sub Kepler rotation.
- Asymmetry in circumbinary disks are explained by the numerical simulation. It is caused by resonance between Kepler rotation and gravitational torque.
- Spiral arms and asymmetry are natural outcome of interaction between binary stars and CBD.

A Statistical Study of Massive Cluster-forming Clumps

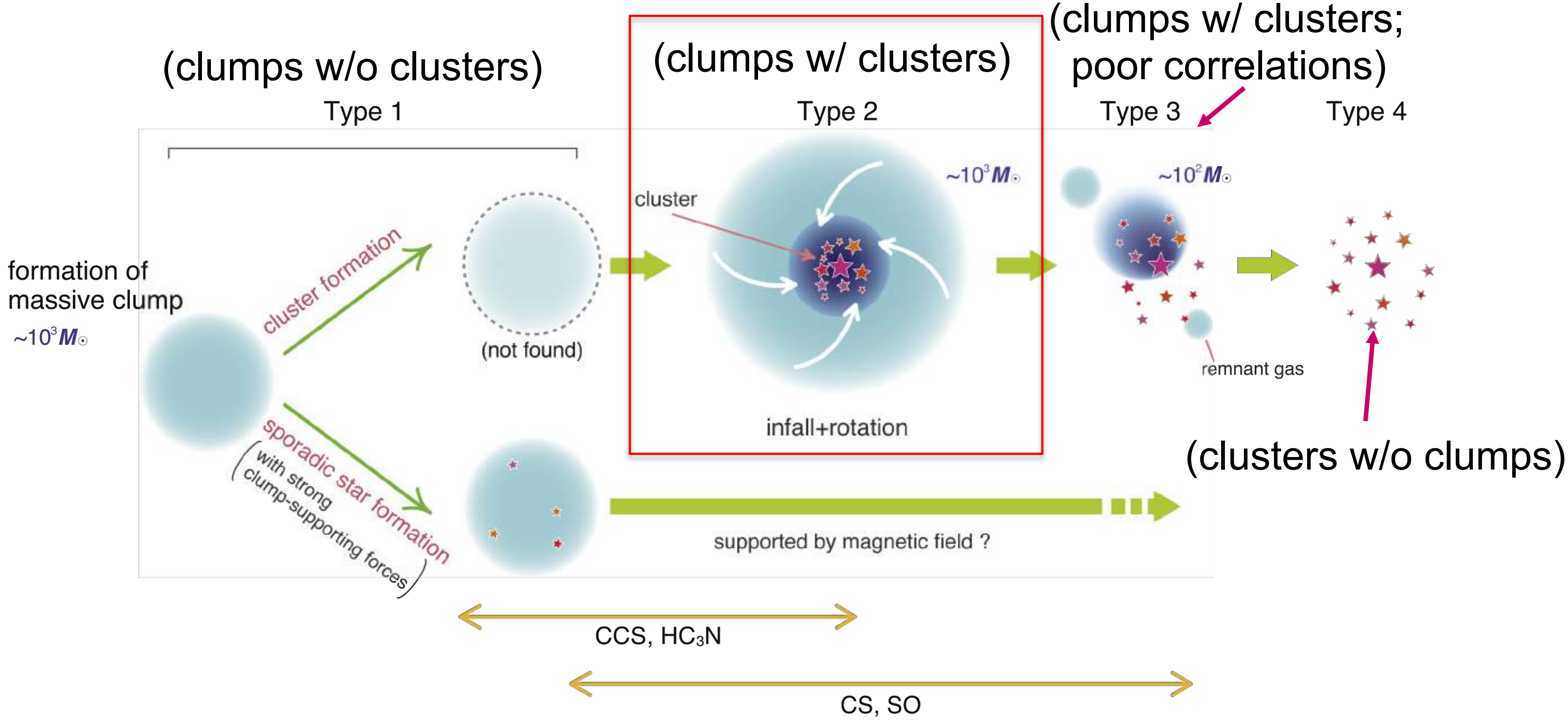
Shimoikura et al. 2018, ApJ, 855, 45

Shimoikura, Tomomi; Dobashi, Kazuhito; Nakamura, Fumitaka; Matsumoto, Tomoaki; Hirota, Tomoya

<- from Twitter @eao_jcmt

Scenario of cluster formation

JCMT observation (M18BP015)
Onset of cluster formation

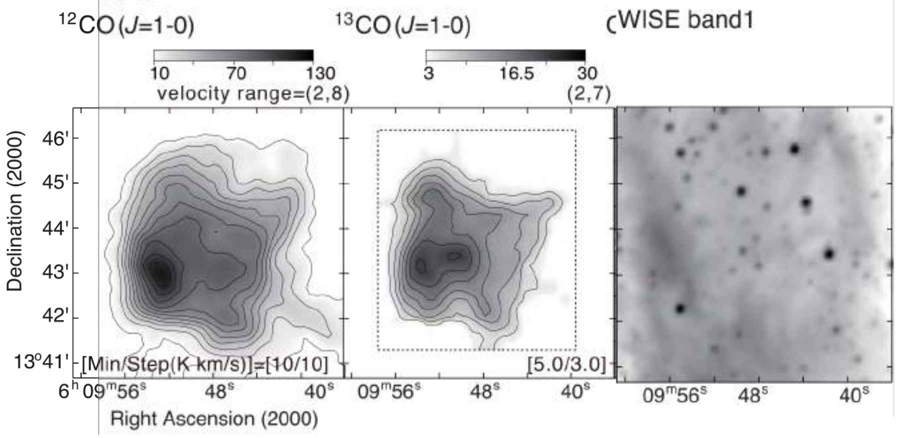


Shimoikura+ 18

Types of clumps and clusters; 15 regions and 24 clumps

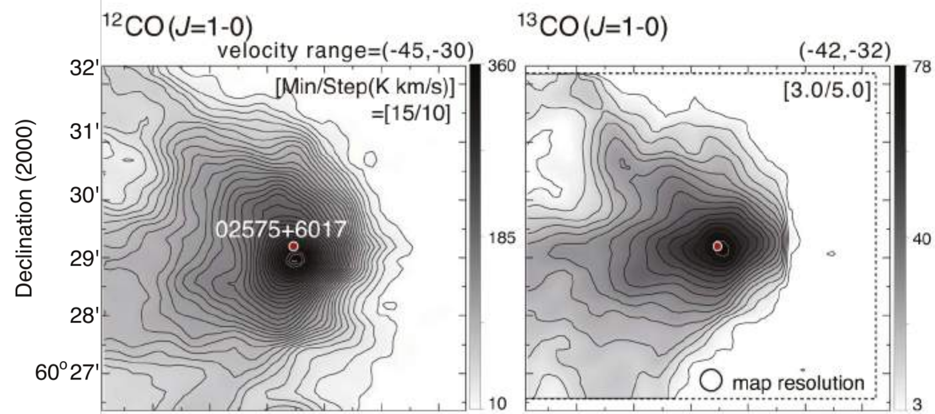
Type 1 (clumps w/o clusters)

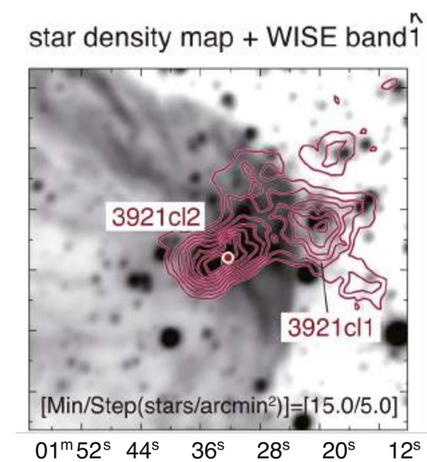
No. 4678



Type 2 (clumps w/ clusters)
Type 4 (clusters w/o clumps)

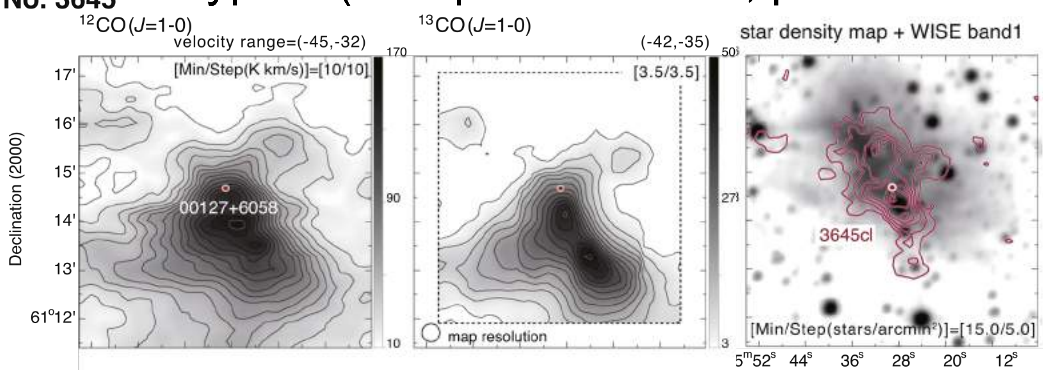
No. 3921





Type 3 (clumps w/ clusters; poor correlations)

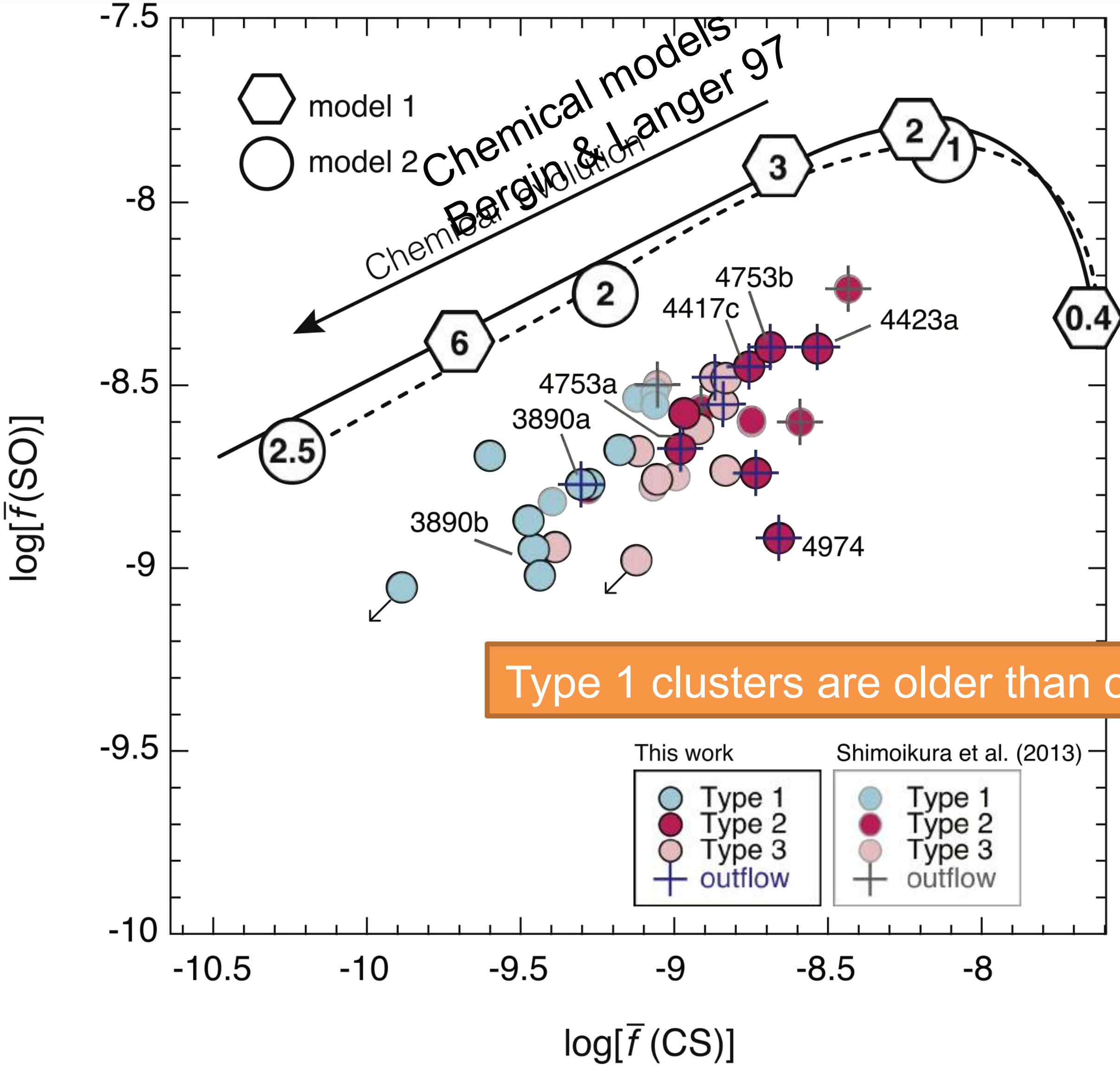
No. 3645



Observations: NRO 45m telescope

Shimoikura+ 18

Chemical evolution and types of clusters



Type 1 clusters are older than other types; long-lived.

Shimoikura+ 18

fractional abundance of molecules wrt H2