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Gravitational instability in a planet-forming disk

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The canonical theory for planet formation in circumstellar disks proposes that planets are grown from initially much smaller seeds[1–5]. The long-considered alternative theory proposes that giant protoplanets can be formed directly from collapsing fragments of vast spiral arms[6–11] induced by gravitational instability (GI)[12–14] – *if* the disk is gravitationally unstable. For this to be possible, the disk must be massive compared to the central star: a disk-to-star mass ratio of $1/10$ is widely held as the rough threshold for triggering GI, inciting significant non-Keplerian dynamics and generating prominent spiral arms[15–18]. While estimating disk masses has historically been challenging[19–21], the motion of the gas can reveal the presence of GI through its effect on the disk velocity structure[22–24]. Here we present kinematic evidence of gravitational instability in the disk around AB Aurigae, using deep observations of ^{13}CO and C^{18}O line emission with the Atacama Large Millimeter/submillimeter Array (ALMA). The observed kinematic signals strongly resemble predictions from simulations and analytic modeling. From quantitative comparisons, we infer a disk mass of up to $1/3$ the stellar mass enclosed within $1''$ to $5''$ on the sky.

・概要
ALMAによりAB Aur円盤を13CO, C18O J=2-1で高感度観測し、ガスの詳細な速度構造を求めた。観測結果を流体シミュレーションと解析モデルと比較して、円盤は重力不安定であり、直径156 au-780 au以内に星の質量の最大1/3の質量をもつ円盤が存在することを示した。

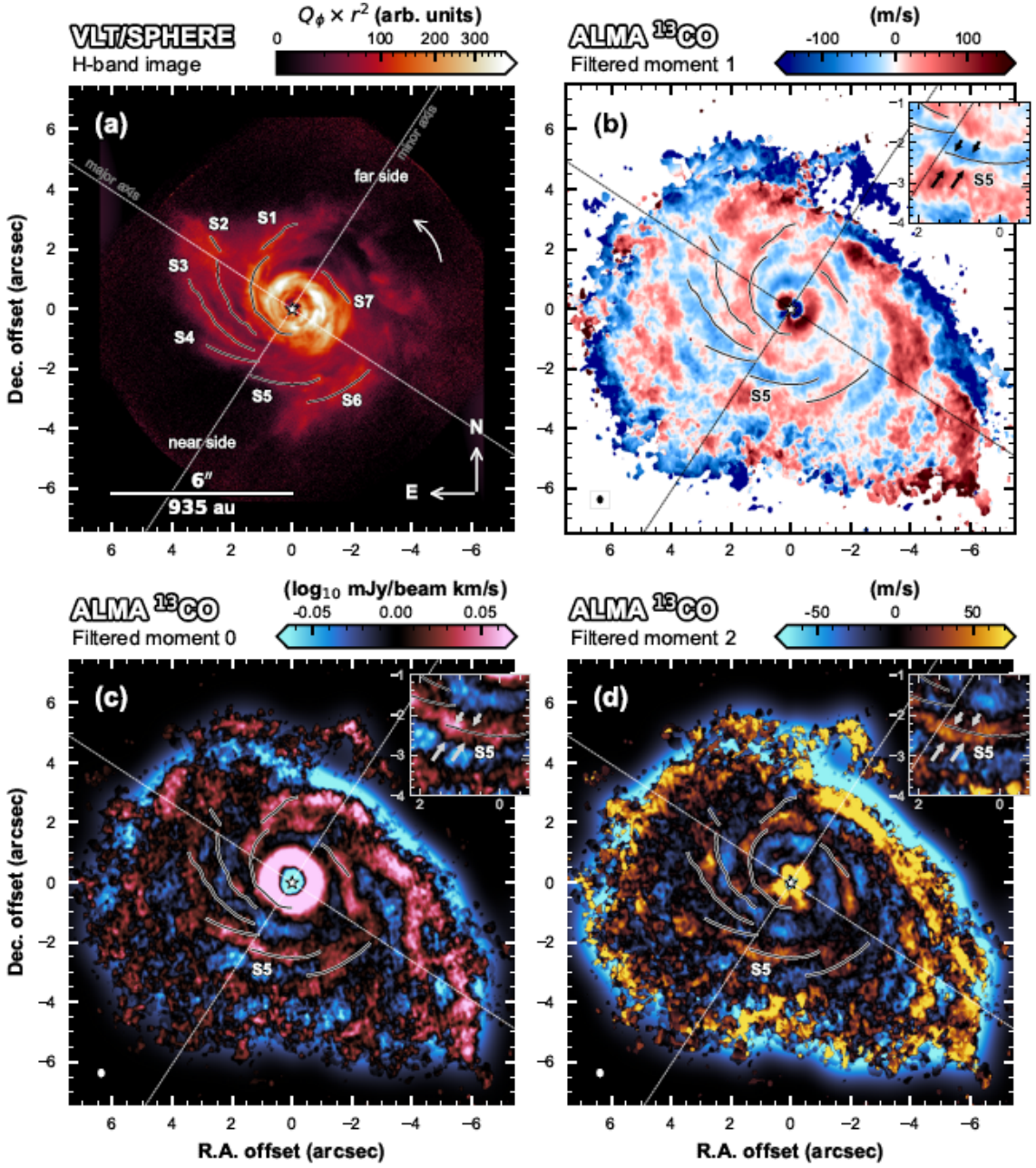
・AB Aur: M_*=2.4M_{sun}, 2.5-4.4 Myr, d=156pc

・観測: beam size: 0.237” x 0.175” (37 x 27 au), Δv=42m/s (13CO), 84m/s (C18O),
on-source time: 5.75 hrs

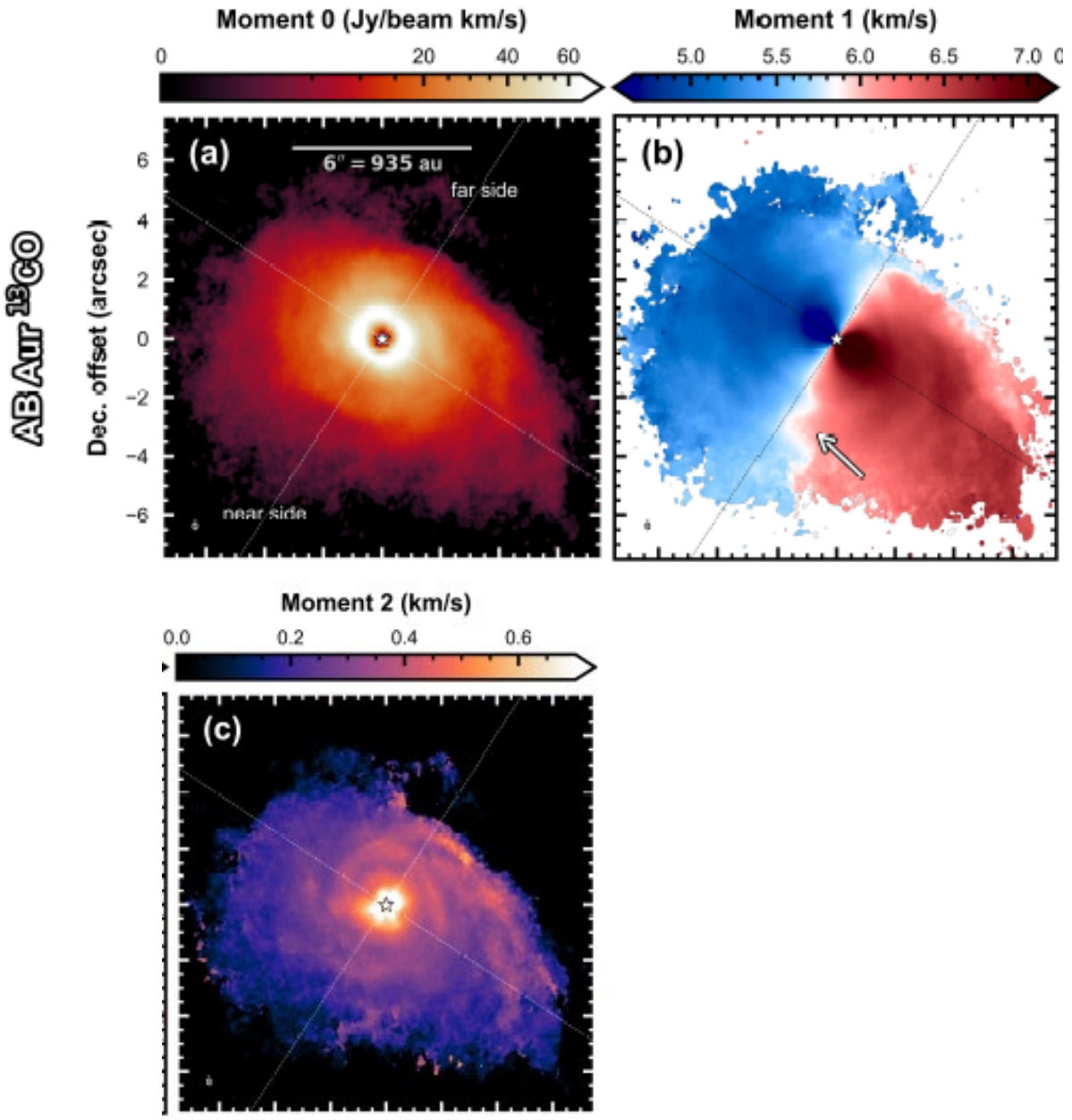
・結果: high-pass filterを用いて解析をした結果、VLT/SPHERE観測と同様の７本のspiral armsを13CO lineのmoment 0,1,2 mapsに見出した

・3D SPHシミュレーション(PHANTOM)：1M SPH particles
initial gas mass: 0.7 M_{sun} (M_{disk}/M_*=0.29), $\Sigma \propto r^{-1.0}$, $c_s \propto r^{-0.25}$
$t_{cool}=0.1\Omega_{Kep}^{-1}$→観測されたspiral armsを再現する結果が得られた

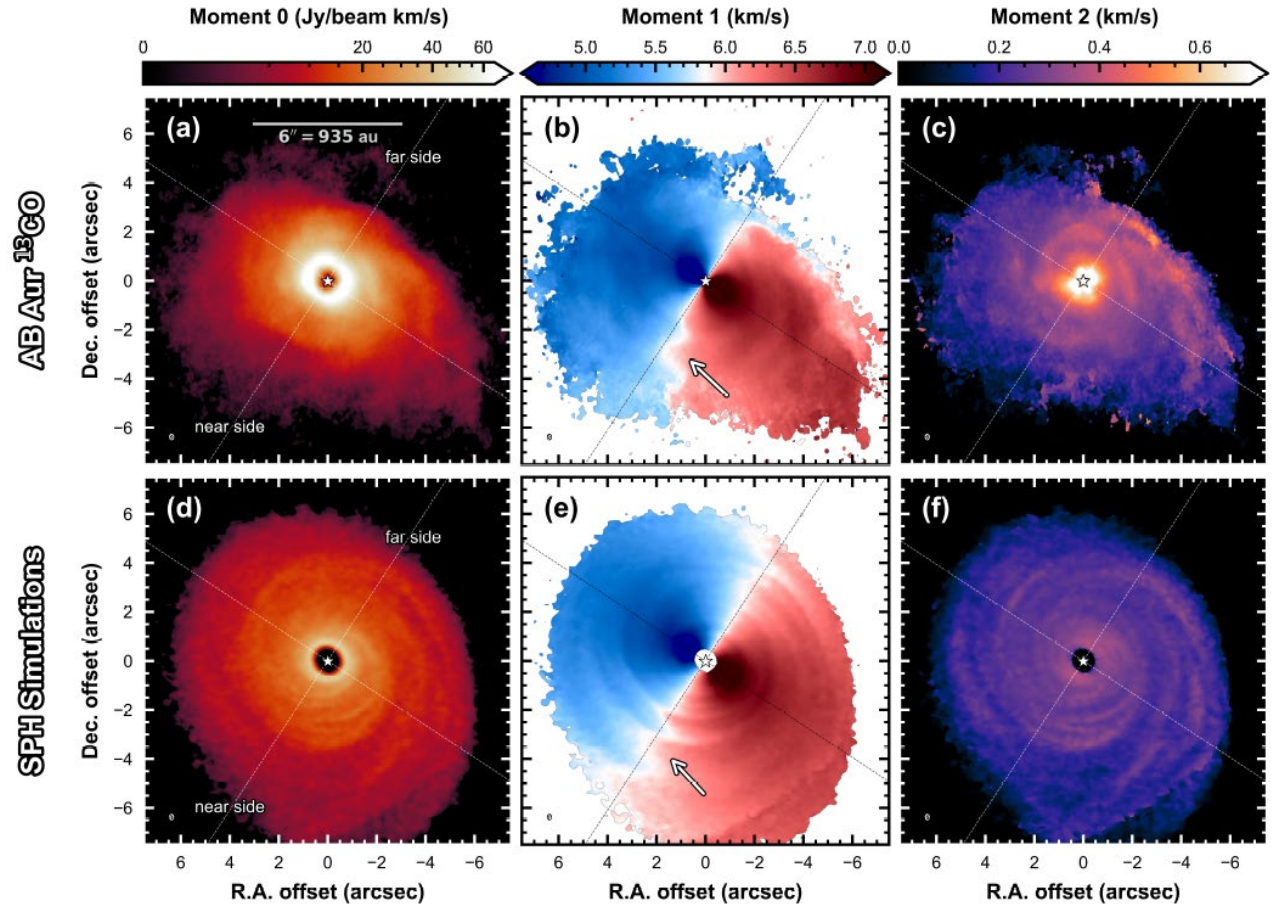
・VLT観測とALMA観測(ケプラー回転からのずれ)

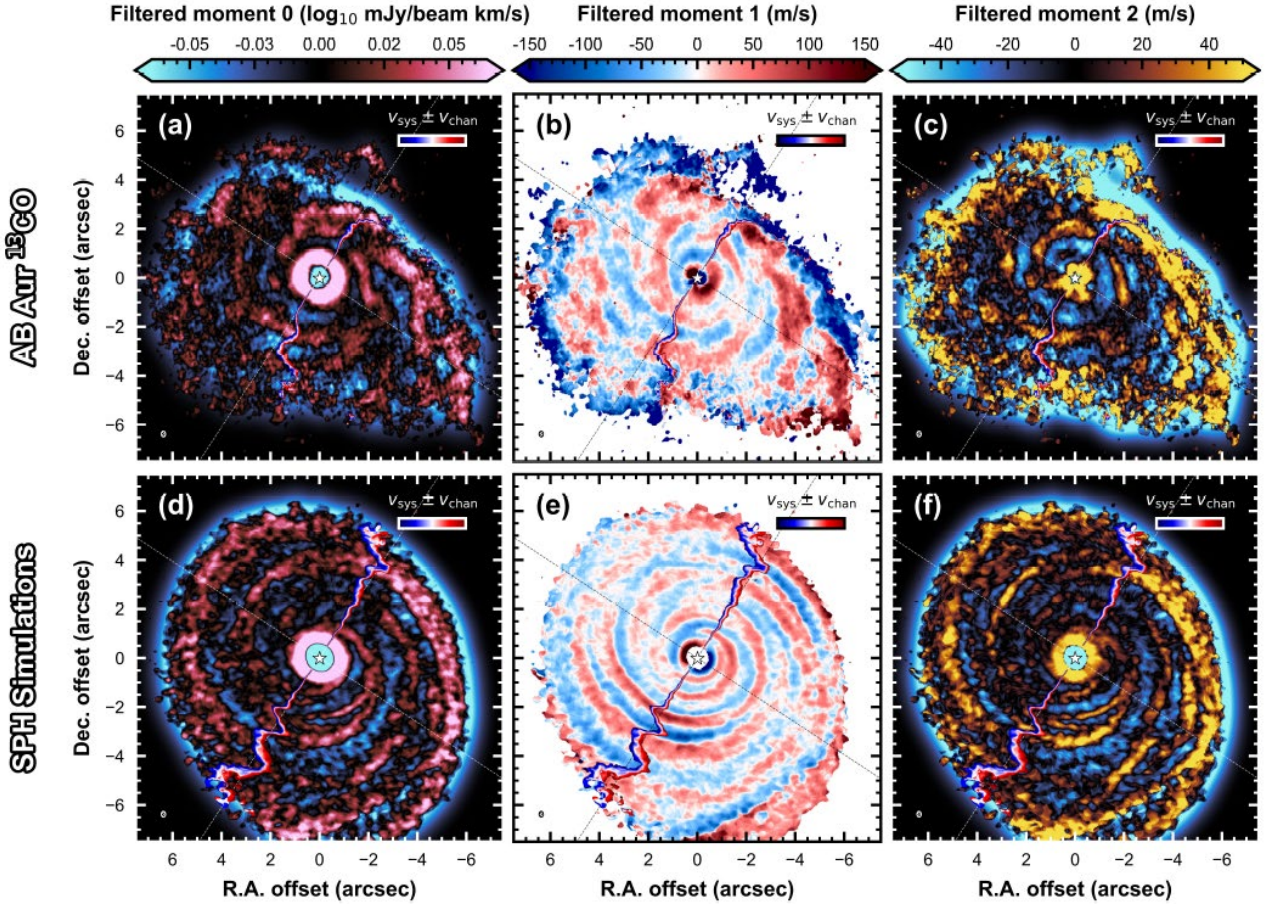


・ALMA観測の元データ

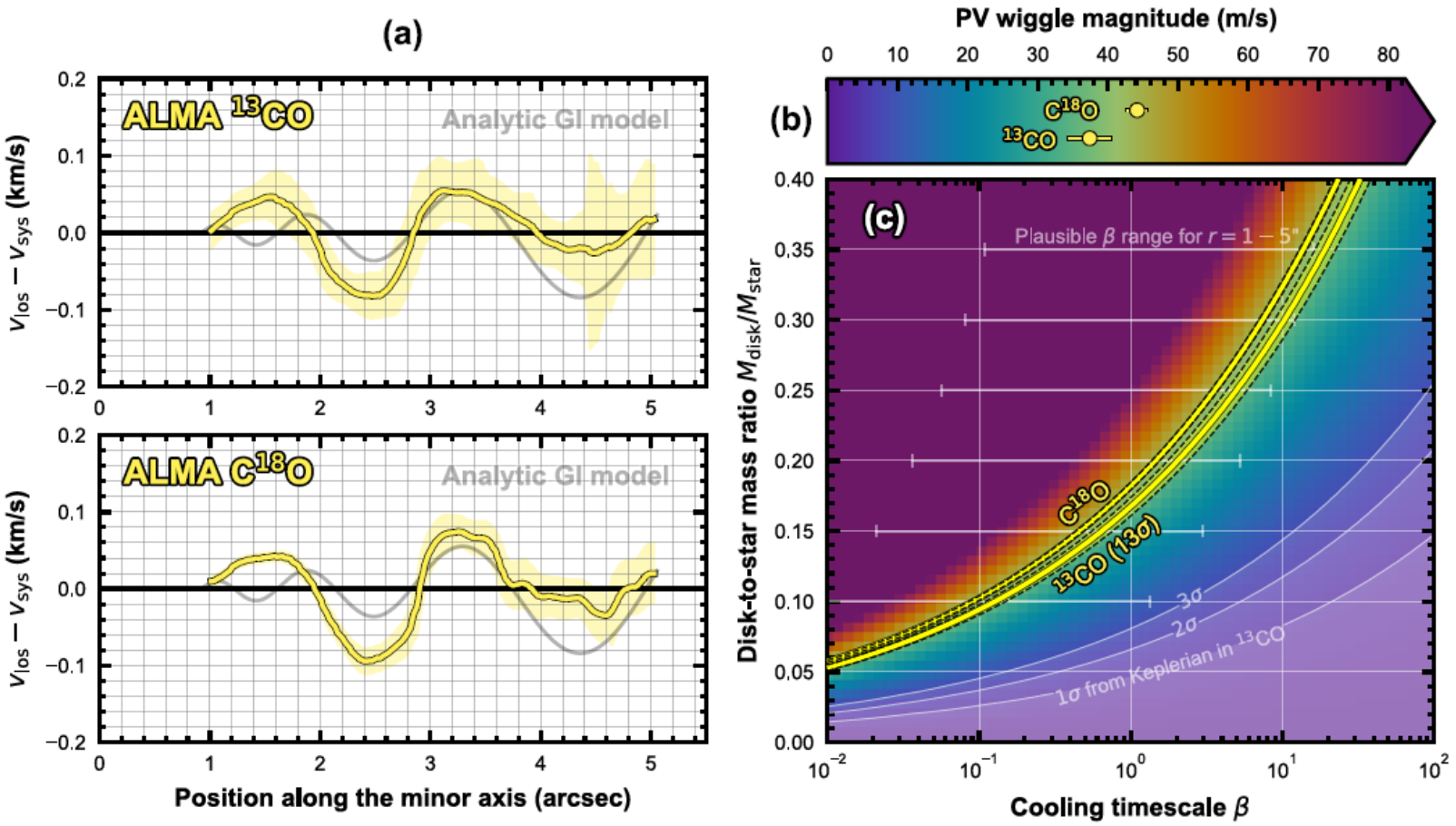


・ALMA観測とシミュレーション結果





・GI wiggleの解析(PV図)



wiggleの強さは、Mdisk/Mstarとcooling timescaleに敏感

$$A_{v_r}(r) = 2jm\chi\beta^{-1/2}\left(\frac{M_{\rm disk}(r)}{M_\star}\right)^2 v_{\rm Kep}(r)\,,$$

観測を再現するには、
0.1<Mdisk/Mstar<0.3
　for 0.1<β<10
この質量は、spiral armsの角度の観測値などとも良い一致。

Cooling が速ければ(β<3)
GIによるfragmentationで惑星が形成される可能性があるし、coolingが遅ければ(β>5)spiral arms中でダストが集積することで惑星が形成される可能性がある。

Accretion versus core-filament collision

Accepted by A&A Letter

Implications for streamer formation in Per-emb-2

Fumitaka Nakamura[1,2,3], Quang Nguyen-Luong[4,5,6], Kousuke Ishihara[1,2], Aoto Yoshino[1,3]

Context. Recent millimetre and sub-millimetre observations have unveiled elongated and asymmetric structures around protostars. These structures, referred to as streamers, often exhibit coherent velocity gradients, seemingly indicating a directed gas flow towards the protostars. However, their origin and role in star formation remain uncertain.
Aims. The protostellar core Per-emb-2, located in Barnard 1, has a relatively large streamer of 10^4 au that is more prominent in emission from carbon-chain molecules. We aim to unveil the formation mechanism of this streamer.
Methods. We conducted mapping observations towards Per-emb-2 using the Nobeyama 45 m telescope. We targeted carbon-chain molecular lines such as CCS, HC_3N, and HC_5N at 45 GHz.
Results. Using `astrodendro`, we identified one protostellar and four starless cores, including three new detections, on the *Herschel* column density map. The starless and protostellar cores are more or less gravitationally bound. We discovered strong CCS and HC_3N emissions extending from the north to the south, appearing to bridge the gap between the protostellar core and the starless core to its north. This bridge spans 3×10^4 au with velocities of 6.5 to 7.0 km s^{-1}. The velocity gradient of the bridge is opposite that of the streamer. Thus, the streamer is unlikely to be connected to the bridge, suggesting that the former does not have an accretion origin.
Conclusions. We propose that a collision between a spherical core and the filament has shaped the density structure in this region, consequently triggering star formation within the head-tail-shaped core. In this core-filament collision scenario, the collision appears to have fragmented the filament into two structures. The streamer is a bow structure, while the bridge is a remnant of the shock-compressed filament. Thus, we conclude that the Per-emb-2 streamer does not significantly contribute to the mass accumulation towards the protostar.

・概要

Per-emb-2に付随するStreamerを Nobeyama 45mを用いて、CCS, HC3N, HC5Nで観測した。

ハーシェルのダスト放射の観測データにastrodendroを適用して、原始星1つと4つの星なしコアを発見した。

原始星と星なしコアを繋ぐ3x10^4 auの長さのブリッジ構造を、CCS と HC3Nで発見した。その速度構造はStreamerと逆向きであり、この構造は、Streamerとは別物である。

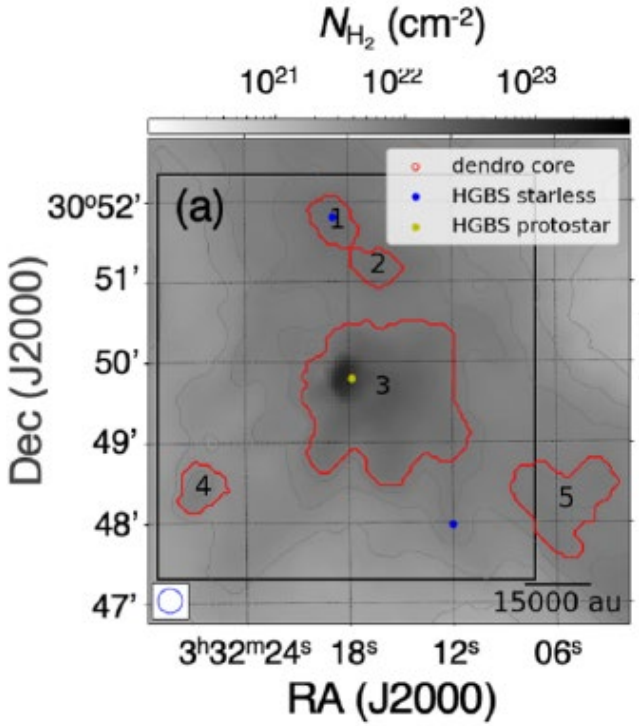
この構造は、コアとフィラメントの衝突により生じたものであり、このstreamerを通じた原始星への質量降着は小さい。

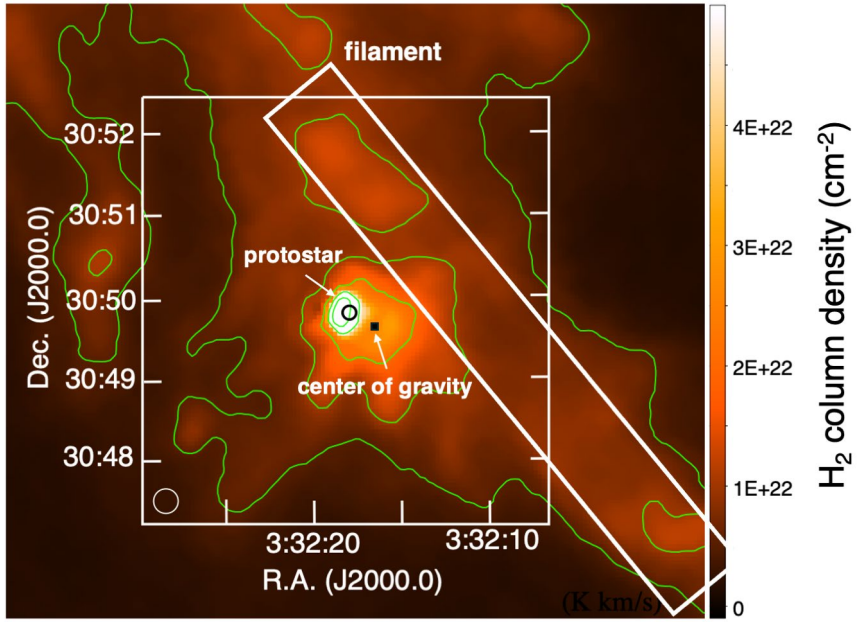
・観測: NRO 45m, Z45 receiver, mapping observations (5’ x 5’ box)
CCS (4_3-3_2), HC3N (5-4), HC5N (17-16) @ ~45 GHz
角分解能: 49” @ 43GHz (0.07pc @ 300pc), 速度分解能 Δv~25m/s
ダスト連続波: Herschel Gould Belt Survey (Andre+2010) (ang. res. ~18”)

・結果:

- ダスト連続波：astrodendroにより１つの原始星と４つの星なしコアを同定

Number	Peak R.A. (J2000)	Peak Dec. (J2000)	M_{core} $M_\odot$	R_{core} pc	$\langle N \rangle$ 10^{22} cm^{-2}	$\langle n \rangle$ 10^5 cm^{-3}	$\langle T_{dust} \rangle$ K	σ_{CCS} km s^{-1}	$\alpha_{vir}(\alpha_{BE})$	type / HGBS
1	3:32:19.13	30:51:44.67	0.508	0.0148	1.28	5.4	12.7	0.37	1.422 (0.565)	starless/449
2	3:32:16.36	30:51:08.40	0.398	0.0077	1.25	29.6	12.6	0.41	1.014 (0.377)	starless/new
3	3:32:18.50	30:49:50.63	9.723	0.0884	1.97	0.5	12.1	0.84	1.077 (0.176)	protostellar/447
4	3:32:26.94	30:48:21.45	0.200	0.0130	0.64	3.1	13.8	–	– (1.265)	starless/new
5	3:32:06.46	30:47:55.46	1.083	0.0565	0.86	0.2	12.7	0.45[a]	2.954 (1.013)	starless/new
HGBS 442	3:32:12.04	30:47:59.0	0.105	0.0300	0.25	0.05	0.02	10.4	(3.9)	starless

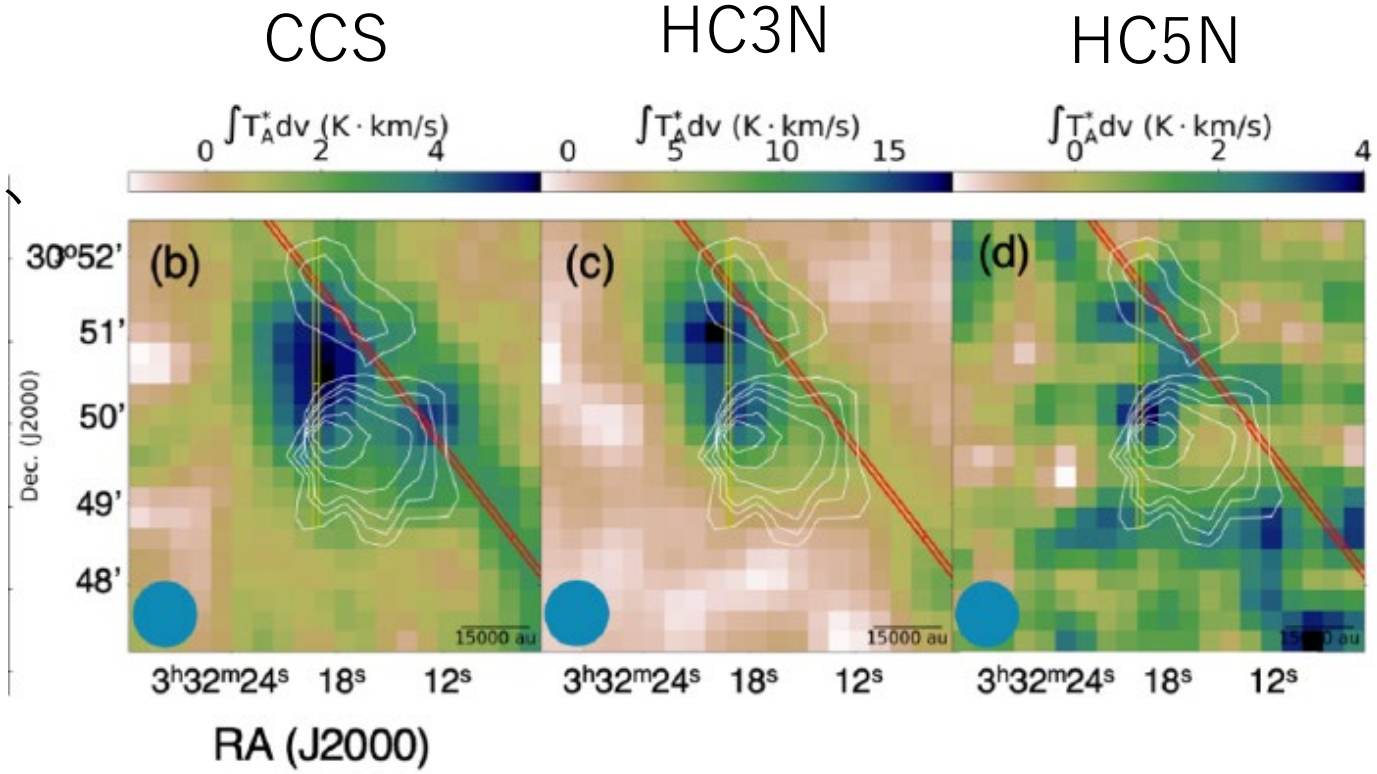


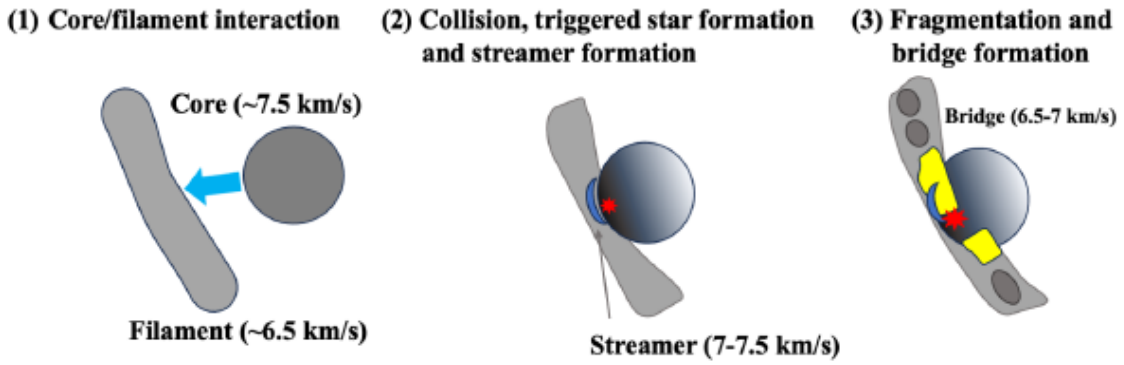


・結果(続き)

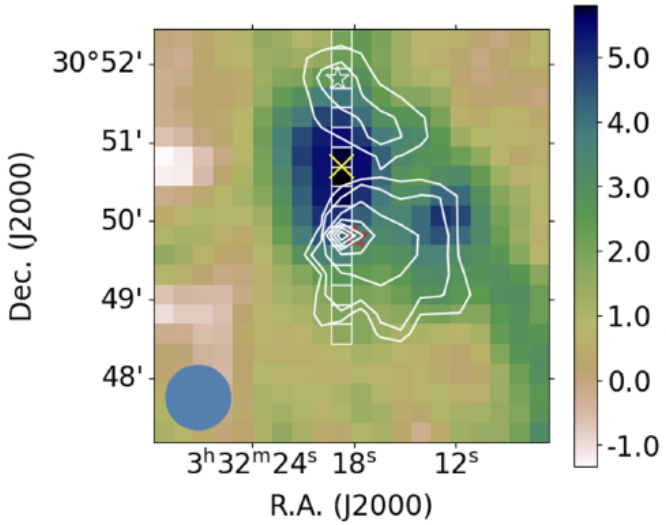
Core 5はビリアル・パラメータが高い。また、外圧の影響を調べたところ、
Core 5は高く、周囲からの圧力により、重力収縮していると考えられる。
他のコアは、ほぼ平衡状態と考えられる。
原始星コアはhead-tail構造を持っており、重力中心がoff-setしている。
周囲のinfall gasから角運動量が運び込まれた形跡はない。

CCS, HC3Nは同様の分布をしており、
ダスト連続波のフィラメント構造
(赤線)に沿って分布している。

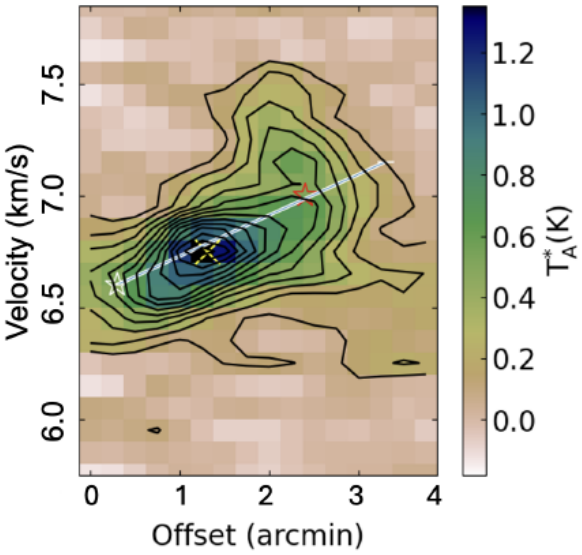




CCS



PV図



・結果：CCSのPV図

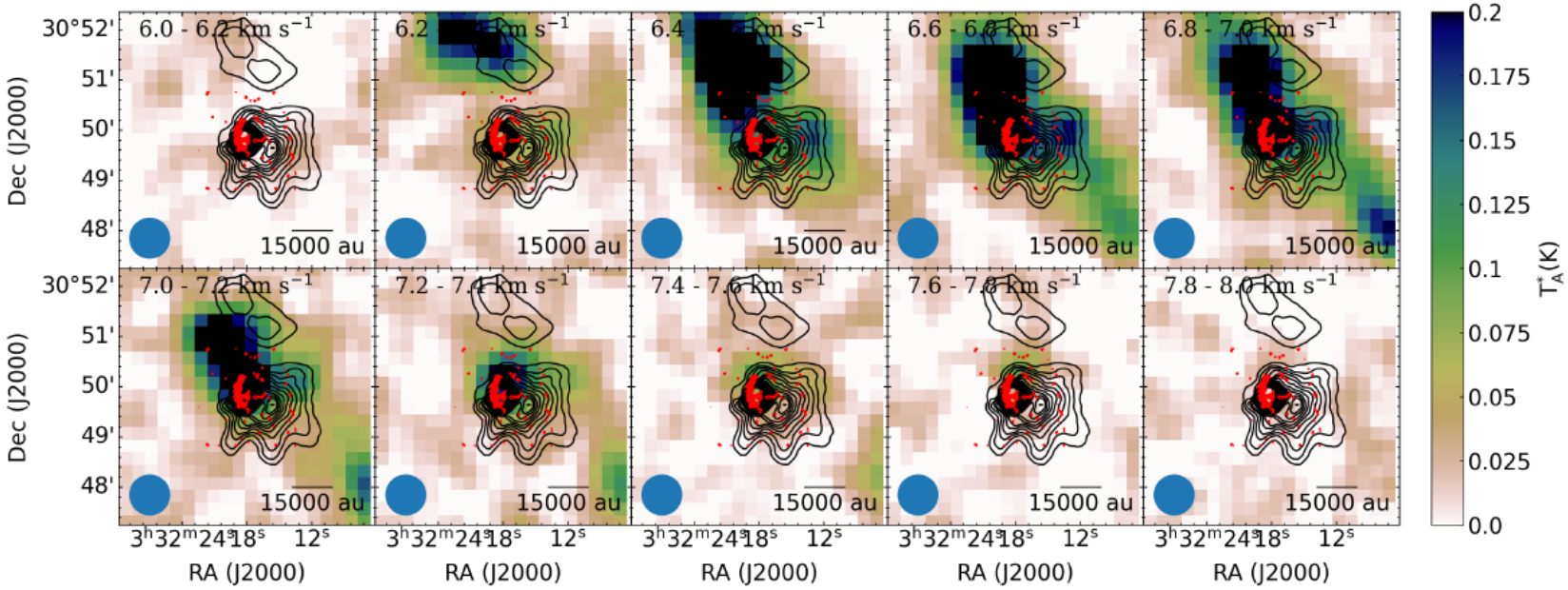
CCSのPV図が示す速度の向きは、Streamer(右の図、赤)と逆向き。Streamerの速度勾配はより急である。

コア・フィラメント衝突による構造形成を提案。

(大きなエンベロープが付随しているので)

Streamerによる降着の寄与は大きくないだろう。

Color：HC3N, 今回の野辺山観測
赤：CCSのNOEMA観測の積分強度(Pineda+2020)



Accepted

An Earth-Mass Planet and a Brown Dwarf in Orbit Around a White Dwarf

Keming Zhang[1,2,3], Weicheng Zang[4,5], Kareem El-Badry[6], Jessica R. Lu[3], Joshua S. Bloom[3], Eric Agol[7], B. Scott Gaudi[8], Quinn Konopacky[1], Natalie LeBaron[3], Shude Mao[4], Sean Terry[3,9,10]

Terrestrial planets born beyond 1–3 AU have been theorized to avoid being engulfed during the red-giant phases of their host stars. Nevertheless, only a few gas-giant planets have been observed around white dwarfs (WDs) — the end product left behind by a red giant. Here we report on evidence that the lens system that produced the microlensing event KMT-2020-BLG-0414 is composed of a WD orbited by an Earth-mass planet and a brown dwarf (BD) companion, as shown by the non-detection of the lens flux using Keck Adaptive Optics (AO). From microlensing orbital motion constraints, we determine the planet to be a 1.9 ± 0.2 Earth-mass ($M_\oplus$) planet at a physical separation of 2.1 ± 0.2 au from the WD during the event. By considering the system evolutionary history, we determine the BD companion to have a projected separation of 22 au from the WD, and reject an alternative model that places the BD at 0.2 au. Given planetary orbital expansion during the final evolutionary stages of the host star, this Earth-mass planet may have existed in an initial orbit close to 1 au, thereby offering a glimpse into the possible survival of planet Earth in the distant future.

・概要

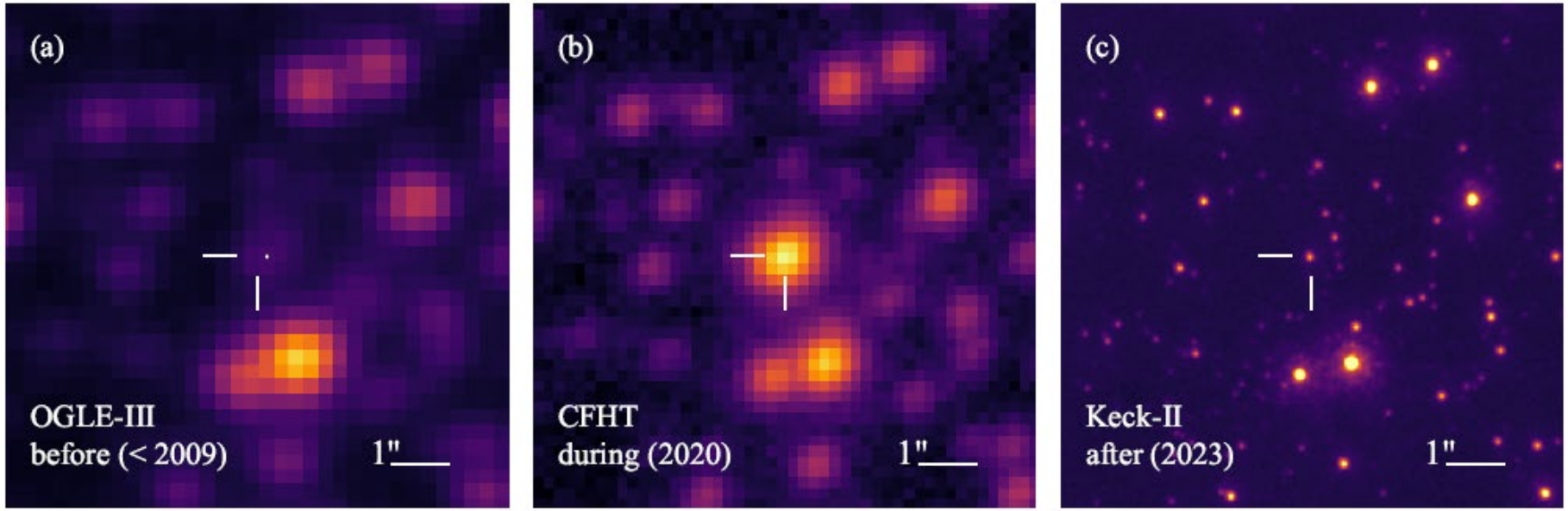
マイクロレンズ法により、白色矮星に付随する地球型惑星と褐色矮星を検出した。

地球型惑星の質量は1.9M_E, 白色矮星との距離は2.1 auであった。

褐色矮星と白色矮星の距離は22 auと推定される。

恒星の進化(赤色巨星段階)を考えると、地球型惑星はかつて1 auの軌道長半径だったかもしれず、地球の将来の姿を見ているのかもしれない。

・観測: Keck II望遠鏡 with laser-guide-star AOにより、2020年のマイクロレンズ・イベントをフォローアップ観測した。→主星の性質と褐色矮星の位置に制限を与えた。



・今回の観測前のマイクロレンズ・イベントの解

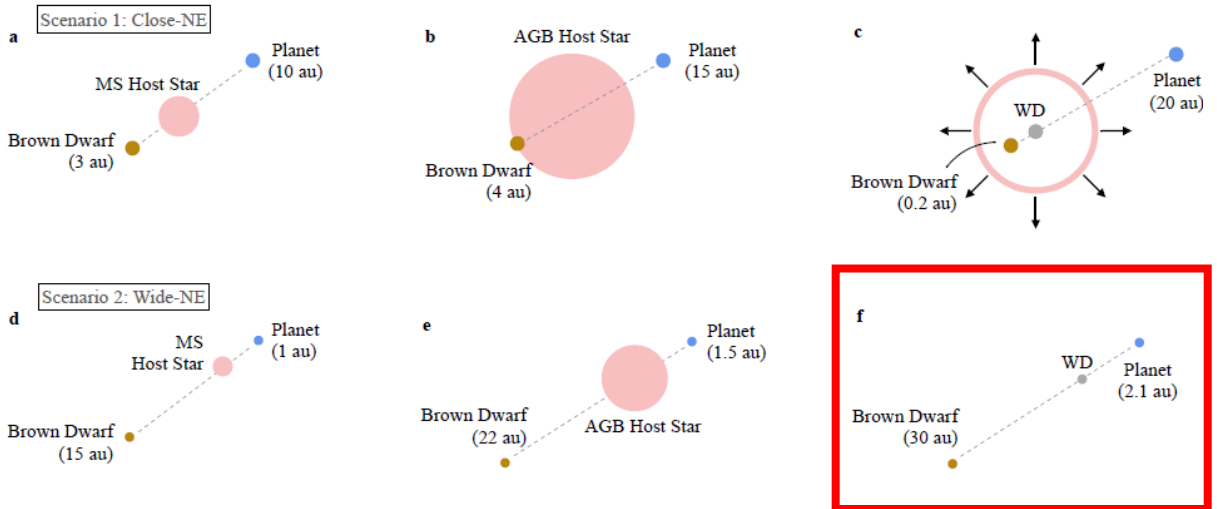
Parameter	Unit	North-East		South-East	
		Close	Wide	Close	Wide
Primary lens mass	$M_\odot$	$0.45^{+0.10}_{-0.08}$	$0.36^{+0.08}_{-0.06}$	$0.25^{+0.06}_{-0.03}$	$0.19^{+0.06}_{-0.04}$
Distance	kpc	$1.12^{+0.23}_{-0.19}$	$0.99^{+0.20}_{-0.17}$	$0.73^{+0.15}_{-0.09}$	$0.57^{+0.14}_{-0.09}$
Minimum MS lens brightness (K_s)	mag	$16.32^{+0.27}_{-0.26}$	$16.84^{+0.24}_{-0.34}$	$17.16^{+0.16}_{-0.18}$	$17.25^{+0.16}_{-0.19}$
Einstein radius	mas	$1.73^{+0.06}_{-0.06}$	$1.65^{+0.07}_{-0.06}$	$1.62^{+0.05}_{-0.04}$	$1.64^{+0.05}_{-0.04}$
Microlensing parallax	–	$0.45^{+0.10}_{-0.08}$	$0.54^{+0.12}_{-0.10}$	$0.76^{+0.12}_{-0.15}$	$0.99^{+0.21}_{-0.22}$
Source brightness (K_s)	mag	17.08 ± 0.06	16.99 ± 0.06	17.03 ± 0.06	16.95 ± 0.06
3-σ Excess brightness (K_s)	mag	18.63	19.06	18.88	19.34

・今回の観測結果

- 系のKs brightness: 16,99 mag : 白色矮星のモデルと一致
- ~0.3MsunのWD-WDの連星はレアと考えられるので、伴星はBDと考えられる。
- 赤色巨星段階を考えるとclose binaryは考えにくいので、wide binaryと考えられる

・今回の観測前のマイクロレンズ・イベントの解：３天体の質量

Parameter	Unit	Close-NE	Wide-NE
WD mass	$M_\odot$	$0.51^{+0.08}_{-0.05}$	$0.49^{+0.06}_{-0.03}$
Distance	kpc	$1.27^{+0.19}_{-0.12}$	$1.33^{+0.16}_{-0.12}$
WD flux (K_s)	mag	$23.8^{+0.7}_{-0.6}$	$24.0^{+0.6}_{-0.8}$
Proper motion	mas yr^{-1}	$7.74^{+1.52}_{-0.63}$	$7.77^{+1.29}_{-0.76}$
Proper motion direction	deg	$62.9^{+21.4}_{-21.7}$	$68.5^{+15.4}_{-20.2}$
Planet mass	$M_\oplus$	$1.75^{+0.31}_{-0.18}$	$1.87^{+0.27}_{-0.16}$
Planet projected separation	au	$2.17^{+0.30}_{-0.17}$	$2.07^{+0.22}_{-0.11}$
Planet physical separation ($e < 0.2$)	au	$\gtrsim 10$	$2.07^{+0.24}_{-0.09}$
BD mass	M_J	$32.4^{+4.8}_{-2.6}$	$27.0^{+4.0}_{-3.1}$
BD projected separation	au	$0.20^{+0.03}_{-0.02}$	$22.3^{+2.4}_{-1.5}$



惑星質量は1.87M_E, 白色矮星からの距離は2 au

* 主星のWDは、主系列星段階では~1Msunと考えられる。