銀河系中心ブラックホール Sgr A* 周りを運動するガス雲が近点通過時に起こすフレア現象

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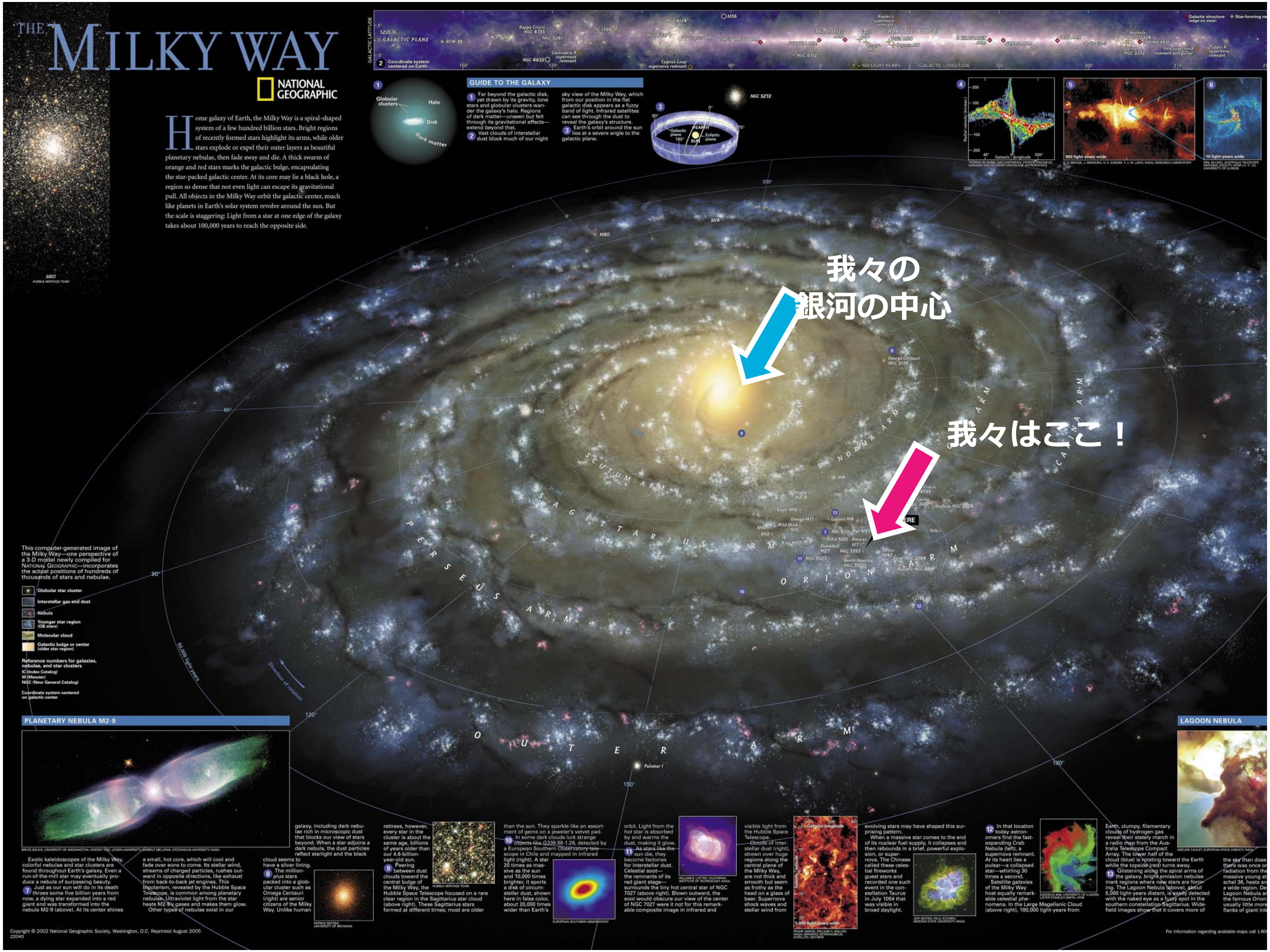
THE MILKY WAY
NATIONAL GEOGRAPHIC
Home galaxy of Earth, the Milky Way is a spiral-shaped system of a few hundred billion stars. Bright regions of recently formed stars highlight its arms, while older stars explode or expel their outer layers as beautiful planetary nebulae, then fade away and die. A thick swarm of orange and red stars marks the galactic bulge, encapsulating the star-packed galactic center. At its core may lie a black hole, a region so dense that not even light can escape its gravitational pull. All objects in the Milky Way orbit the galactic center, much like planets in Earth's solar system revolve around the sun. But the scale is staggering: Light from a star at one edge of the galaxy takes about 100,000 years to reach the opposite side.
GUIDE TO THE GALAXY
我々の
銀河の中心
我々はここ！
SCUTUM ARM
SAGITTARIUS ARM
PERSEUS ARM
NORMA ARM
CARINA ARM
ORION ARM
OUTER ARM
PLANETARY NEBULA M2-9
LAGOON NEBULA
This computer-generated image of the Milky Way—one perspective of a 3-D model newly compiled for National Geographic—incorporates the actual positions of hundreds of stars and nebulae.
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LETTER

5/Jan/2012 *Nature*

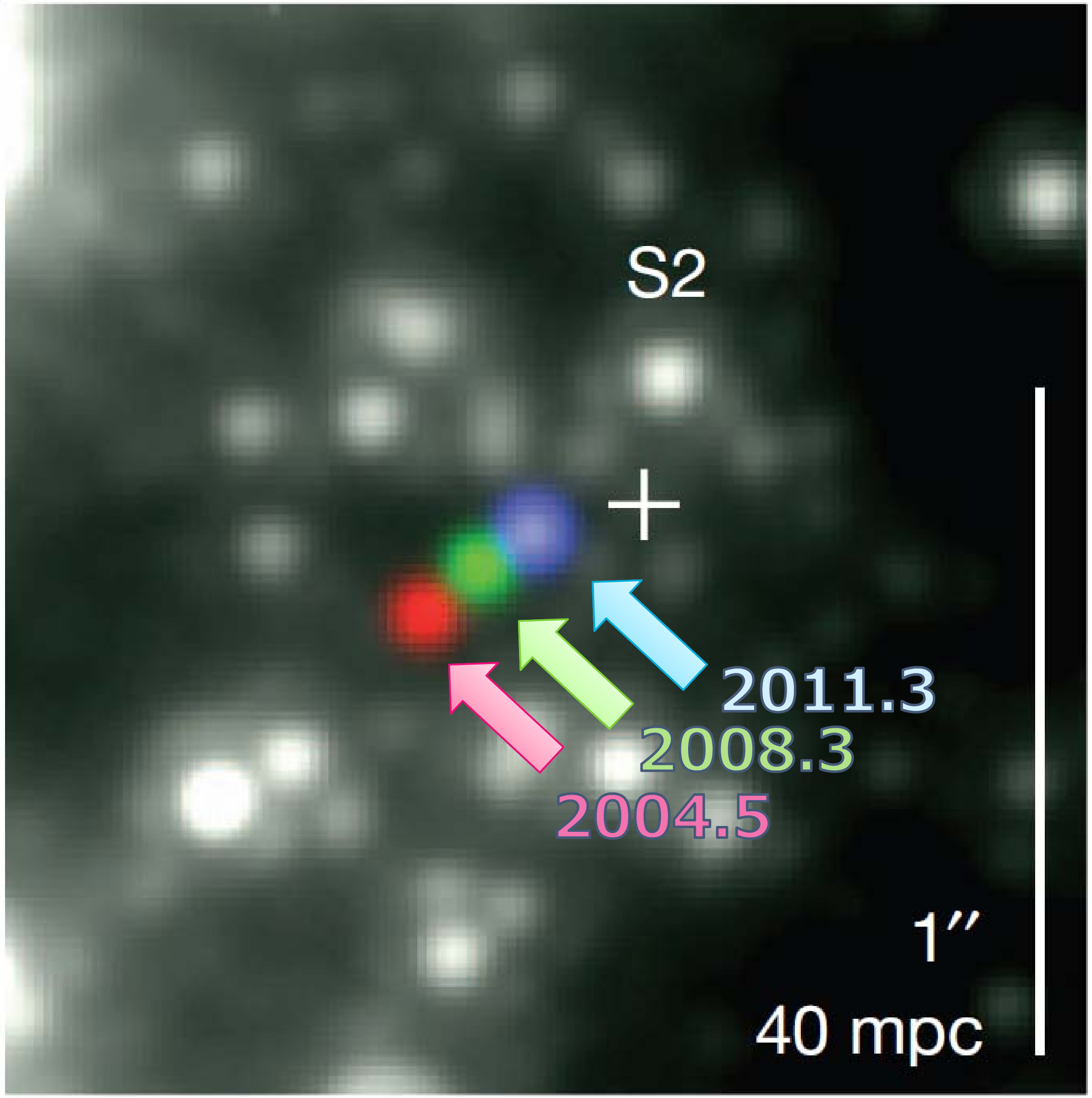
doi:10.1038/nature10652

A gas cloud on its way towards the supermassive black hole at the Galactic Centre

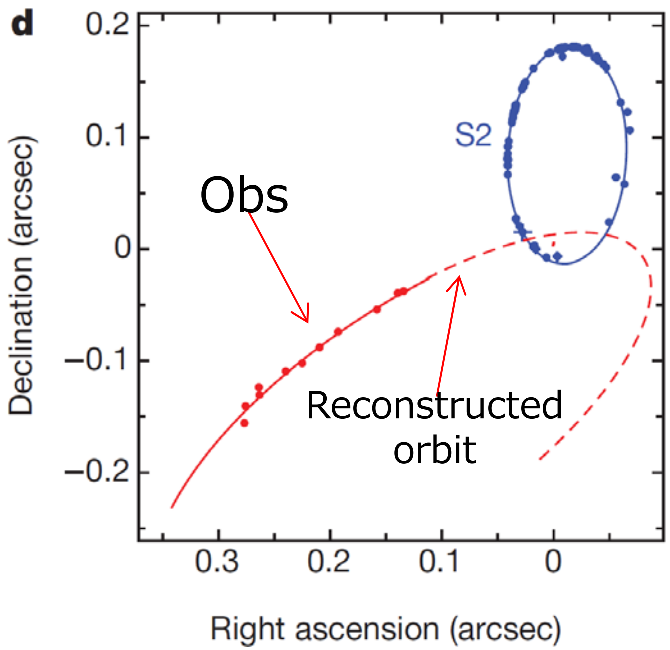
S. Gillessen[1], R. Genzel[1,2], T. K. Fritz[1], E. Quataert[3], C. Alig[4], A. Burkert[4,1], J. Cuadra[5], F. Eisenhauer[1], O. Pfuhl[1], K. Dodds-Eden[1], C. F. Gammie[6] & T. Ott[1]

Measurements of stellar orbits[1–3] provide compelling evidence[4,5] that the compact radio source Sagittarius A* at the Galactic Centre is a black hole four million times the mass of the Sun. With the exception of modest X-ray and infrared flares[6,7], Sgr A* is surprisingly faint, suggesting that the accretion rate and radiation efficiency near the event horizon are currently very low[3,8]. Here we report the presence of a dense gas cloud approximately three times the mass of Earth that is falling into the accretion zone of Sgr A*. Our observations tightly constrain the cloud's orbit to be highly eccentric, with an innermost radius of approach of only ~3,100 times the event horizon that will be reached in 2013. Over the past three years the cloud has begun to disrupt, probably mainly through tidal shearing arising from the black hole's gravitational force. The cloud's dynamic evolution and radiation in the next few years will probe the properties of the accretion flow and the feeding processes of the supermassive black hole. The kilo-electronvolt X-ray emission of Sgr A* may brighten significantly when the cloud reaches pericentre. There may also be a giant radiation flare several years from now if the cloud breaks up and its fragments feed gas into the central accretion zone.

- 3 Earth mass cloud was found in the Galactic center
- Rperi~270 au/Tperi~ 2013 Summer
- Giant radiation flare would be observed due to the mass accretion onto the Sgr A*

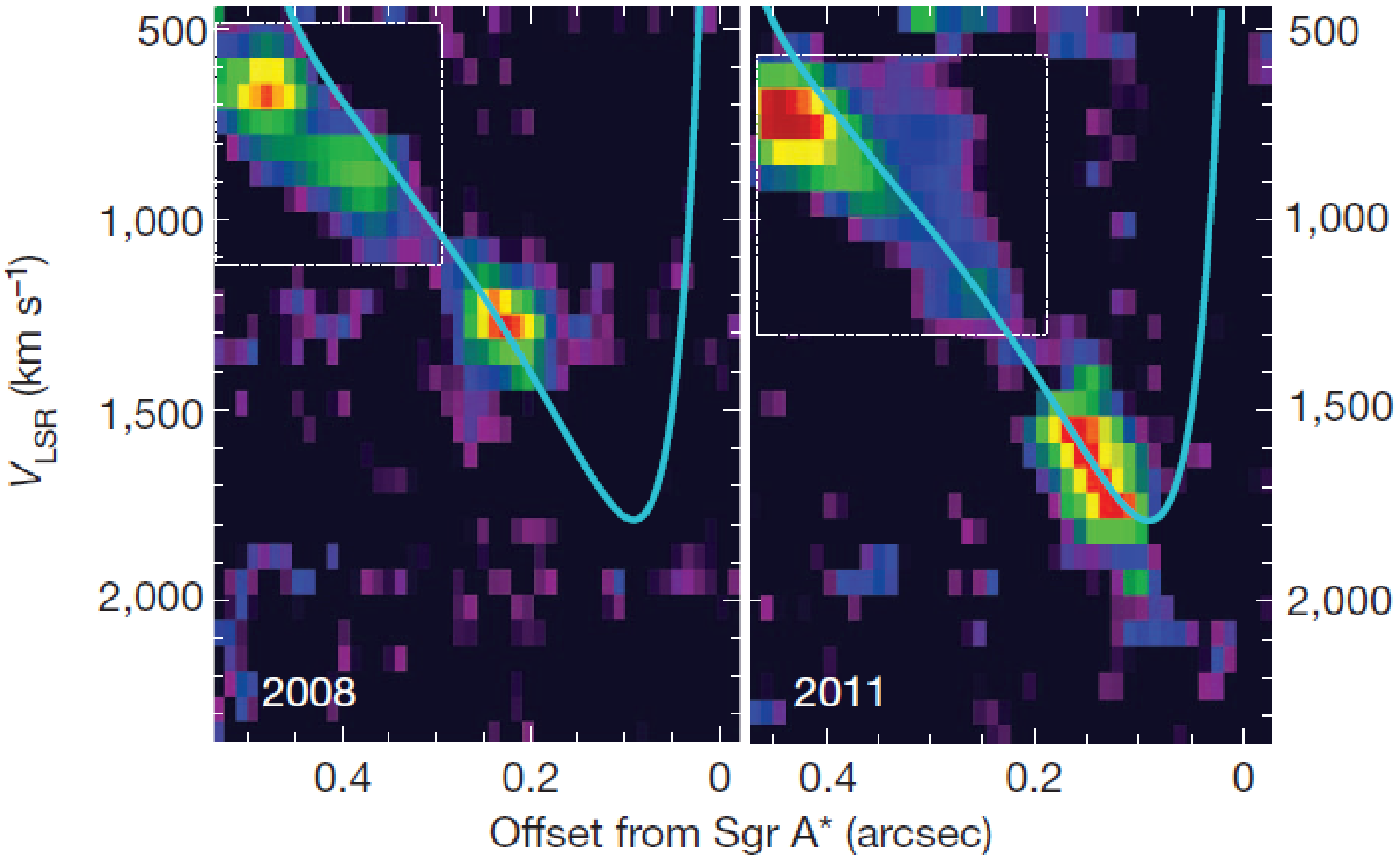


IR band images by VLT



Gillessen et al. 2012

P-V diagrams



- すでに引き延ばされた構造が観測されている

Gillessen et al. 2012

Cloud’s and orbital properties

- 質量：**~3地球質量**
- サイズ(Effective R):~15mas **~125 AU**

Table 1 | Orbit parameters of the infalling cloud

Parameters of Keplerian orbit around the $4.31 \times 10^6 M_{\odot}$ black hole at $R_0 = 8.33$ kpc	Best-fitting value
Semi-major axis, *a*	521 ± 28 mas
Eccentricity, *e*	0.9384 ± 0.0066
Inclination of ascending node, *i*	106.55 ± 0.88 deg
Position angle of ascending node, Ω	101.5 ± 1.1 deg
Longitude of pericentre, ω	109.59 ± 0.78 deg
Time of pericentre, t_{peri}	2013.51 ± 0.035
Pericentre distance from black hole, r_{peri}	$4.0 \pm 0.3 \times 10^{15}$cm = 3,140$R_S$
Orbital period, t_o	137 ± 11 years

観測のまとめ

- **3地球質量**のガス雲G2が銀河中心で見つかった
  - このガス雲は Sgr A* へ接近しており、**2013年夏**に**近点(~270 au)**を通過する
- Sgr A* 周りにある高温ガス成分との相互作用でクラウドが破壊される(see also Burkert +2012)?
  - Sgr A* の活動性が上がるかも！？
- **非常に注目されているイベント**
  - **41** citations (2013年3月5日)

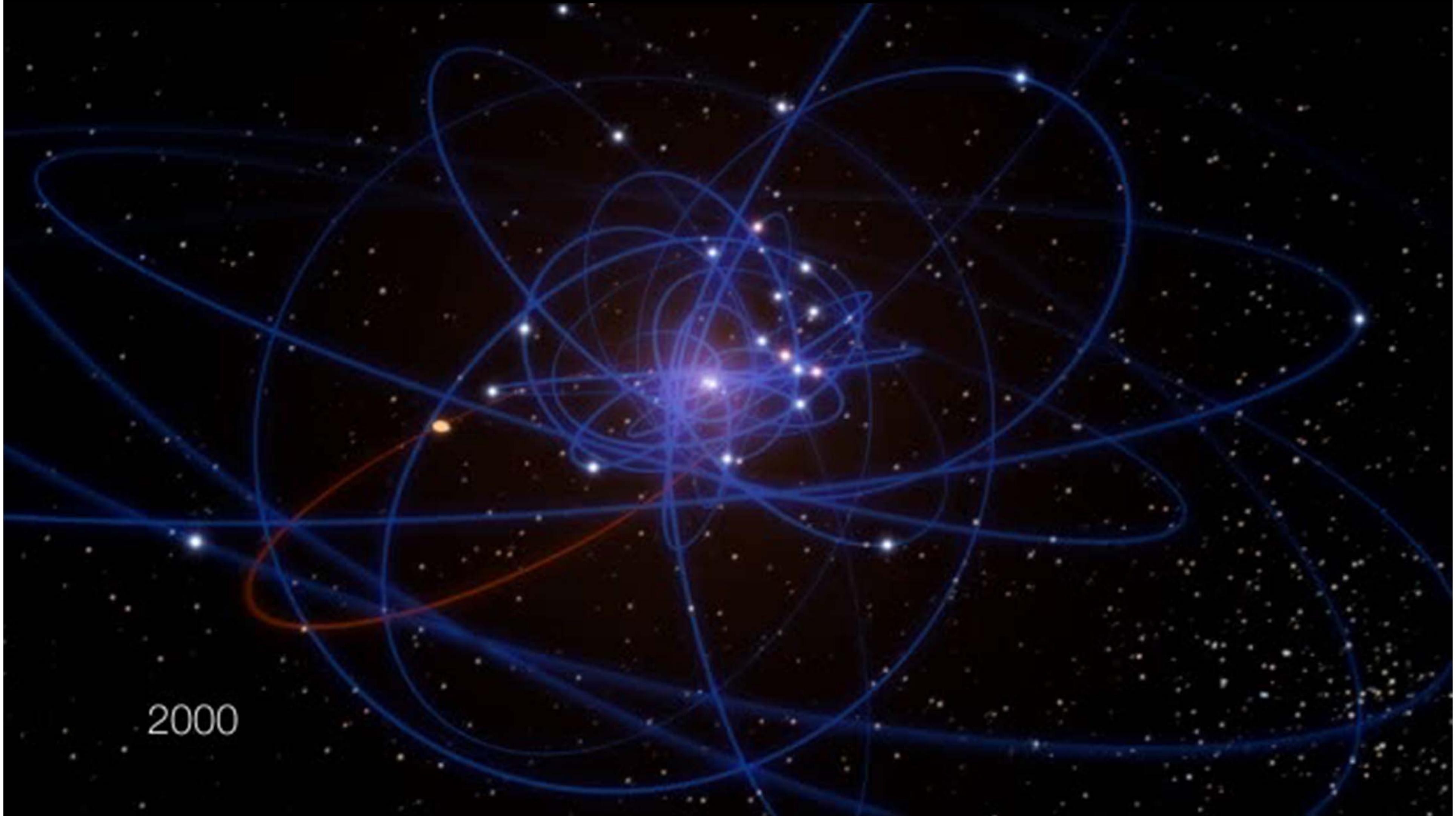
戦略プロ

Observing proposals 2013

PI	Band	Instrument	Title	Allocated Time	Strategy	UT observing dates
Ott	cm	VLA	Molecular Absorption Survey against the G2 Cloud Sgr A* Accretion Event	10h	Spectrum across multiple bands	triggered at a flux >6Jy, rms tau ~10^-3
Reid	cm	VLBA	Astrometry of Sgr A*: Preparing for the Infall of a Gas Cloud	2 x 2 x 6h	Pre-encounter 22 and 43 GHz astrometry	February 2013
public NRAO	radio	VLBA	Angular size measurements and astrometry of SgrA*	1 full track @ 2 bands	single, pre-encounter, baseline measurement	beginning of semester 2013A, eNews letter
public NRAO	radio	VLA	Continuum monitoring	13 x 2hrs x 8 bands	initially bimonthly, then monthly monitoring	eNews letter
Yusef-Zadeh	mm	VLBA	Joint VLBA/Chandra/EVLA Monitoring of the Gas Cloud G2 as it Encounters Sgr A*	6 x 7h	3mm monitoring with Chandra/VLA	May 2013
Marrone	millimeter	SMA	Polarization monitoring	5 x 7hrs	monthly monitoring of polarization and RM, Jan-May 2013 (to be reproposed for next semester)	
Haggard	radio	EVLA	Joint Chandra/XMM/EVLA Monitoring of the Gas Cloud G2 as it Encounters Sgr A*	6 x 7hrs	Roughly monthly sampling near pericenter, simultaneous w/ Chandra obs	
Bower	millimeter	ALMA	The G2 Gas Cloud Encounter with Sagittarius A*: Accretion Structure on Scales of 3000 to 1 Schwarzschild Radii	10 x 1hrs x 2 bands	monthly monitoring beginning in 2013	
Ott	(sub)millimeter	ALMA	Molecular Absorption Survey against the G2 Cloud Sgr A* Accretion Event	3.4h	Spectrum across multiple bands	triggered at a flux >6Jy, rms tau ~10^-3
Martin	(sub)millimeter	ALMA	Fuelling the Galactic center super massive black hole			
Ho	(sub)millimeter	ALMA	Proper Motions of Gas in the Immediate Vicinity of the Galactic Supermassive Black Hole			
Eckart	submm	APEX	Differential L'-band spectroscopy of the Dusty S-cluster Object (DSO/G2) approaching SgrA*	56h		
Gillessen	NIR	SINFONI/VLT	Watching a gas cloud disrupt [...]	70h	Two epochs of deep integral field spectroscopy to follow evolution of line shape	
Gillessen	NIR	NACO/VLT	Watching a gas cloud disrupt [...]	20h	ToO: If SgrA* changes in 2013, get multi-band lightcurves	
Ghez	NIR	Keck/OSIRIS & NIRC2	A LGS-AO Study of our Galaxy's Central Black Hole and its Environs	18 x half-nights (~80 hours)	Deep Imaging & Spectroscopy of the central arcsec	
Eckart	NIR	NACO/VLT	Nature of variable SgrA* X-ray and polarized NIR flares: Probing the accretion stream and source variability during the passage of DSO/G2	20h		
Nishiyama	NIR/MIR	IRCS, HiCIAO, COMICS/Subaru	Gas Cloud Accretion onto the SMBH SgrA*	15h		ToO: NIR spectroscopy, NIR polarimetry, or MIR imaging
Baganoff	X-ray	Chandra	Monitoring the Tidal Disruption of a Gas Cloud Approaching Sgr A*	6 x 20ksec	Roughly monthly sampling around pericenter time	Chandra schedule
Ponti	X-ray	Chandra / HETG	X-ray monitoring of Sgr A* during outburst	280ksec	ToO: If SgrA* gets brighter than Lx = 10^36 erg/s	
Haggard	X-ray	Chandra	Joint Chandra/XMM/EVLA Monitoring of the Gas Cloud G2 as it Encounters Sgr A*	6 x 50ksec	Roughly monthly sampling around pericenter time	Chandra schedule
Haggard	X-ray	XMM	Joint Chandra/XMM/EVLA Monitoring of the Gas Cloud G2 as it Encounters Sgr A*	1 x 30ksec	Single obs. near pericenter	
Ponti	X-ray	XMM	Capturing a major accretion event of Sgr A*	230ks	ToO: If Sgr A* becomes brighter than 10^35 erg/s	
Ponti	X-ray	XMM	Monitoring Sgr A*	100ks	Monitoring the cloud-SgrA* interaction	2x50ks
Grosso	X-ray	XMM		150ks		3x50ks
Degenaar	X-ray	Swift	Swift/XRT monitoring observations of the Galactic Center region	82ks	Bi-weekly monitoring (1ks/obs)	April 1, 2012 - March 31, 2013
Degenaar	X-ray	Swift	Continuing a Swift legacy: the monitoring campaign of the Galactic Center	248ks	Daily monitoring (1ks/obs)	April 1, 2013 - March 31, 2014
Haggard	X-ray	Swift	Swift Monitoring of the Encounter Between Sgr A* and the Gas Cloud G2	68ks	Monitoring weekly, then twice weekly, then daily near pericenter (1ks/obs)	April 1, 2013 - March 31, 2014
Morris	X-ray	Suzaku	Capturing a major accretion event of Sgr A*	200ks	ToO: if Swift > 5 x 10^35 erg/s	
Sunyaev	Gamma	INTEGRAL	Forthcoming major outburst of Sgr A*? Once in a life-time chance for INTEGRAL	2000 ksec	ToO	
Wilms	Gamma	INTEGRAL	Observing the Galactic Center Region with INTEGRAL	1000 ksec		
Kuulkers	Gamma	INTEGRAL	Regular and frequent INTEGRAL monitoring of the Galactic Bulge region	479 ksec		
Yusef-Zadeh	Gamma	Fermi	The Gamma-ray Variability of Sgr A* Induced by an Infalling Cloud	duration of flare	ToO: LAT flux >5×10^{-6} ph/cm^2/s or enhanced Lx	

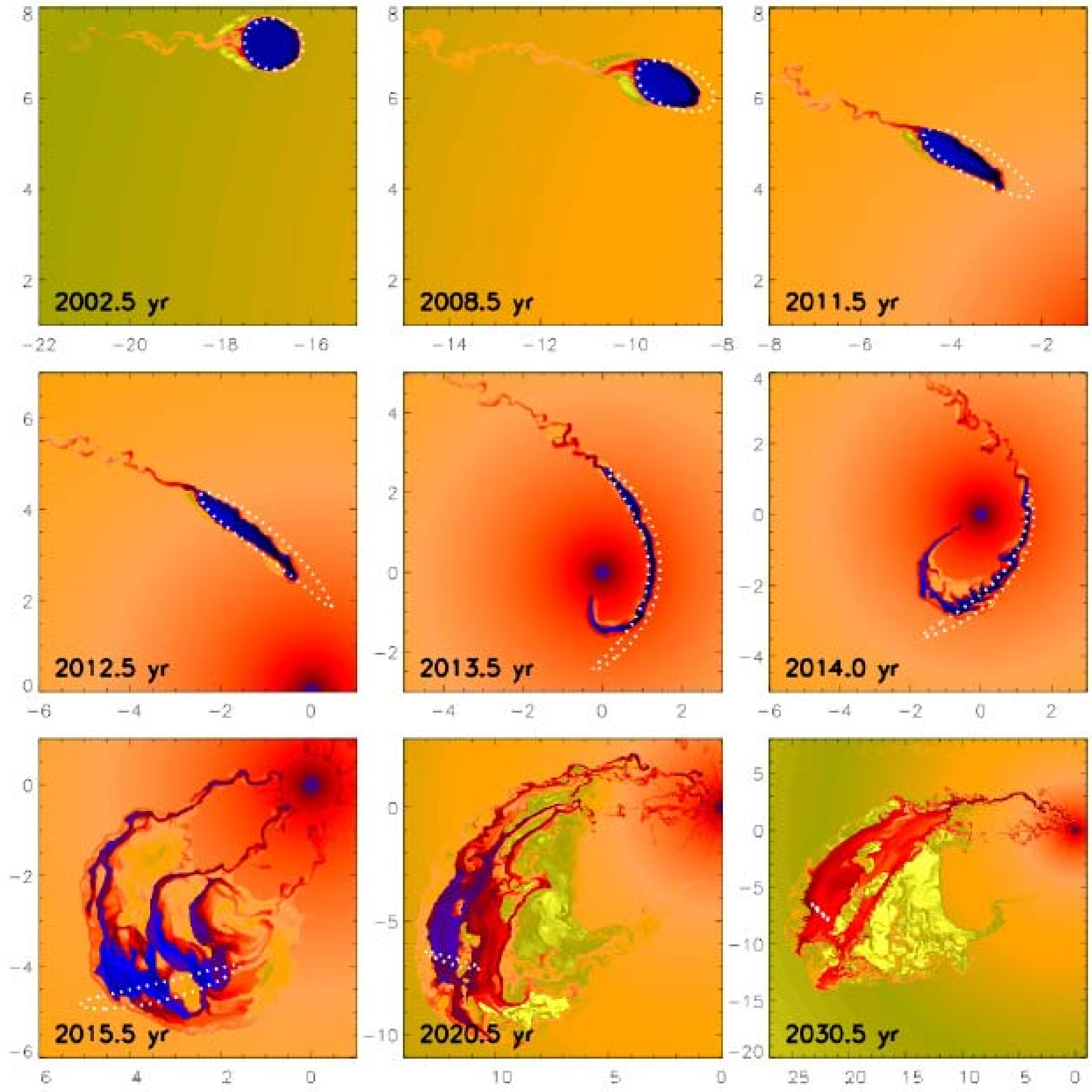
Gas Cloud Wiki
https://wiki.mpe.mpg.de/gascloud/FrontPage
28 Jan 2013

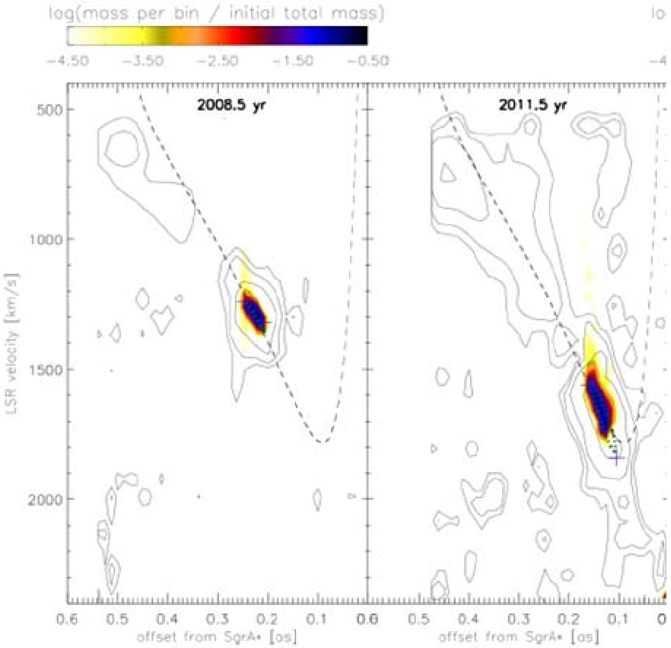
ESO animation

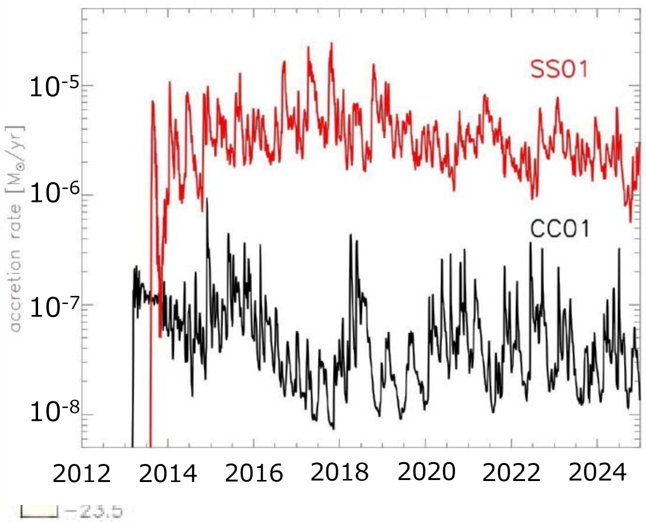


Simulation (Schartmann+2012)

- 2D, PLUTO(AMR)
- 2つのシナリオ
  1. コンパクトクラウド
  2. 球状シェルガス雲
- 状態方程式：等温ガス、断熱
- Sgr A* を取り巻く高温ガス
  - Radiatively Inefficient Accretion Flow (RIAF)
    - 温度密度分布:~1/r (Yuan+2003)
  - プロファイルは(ほぼ)固定







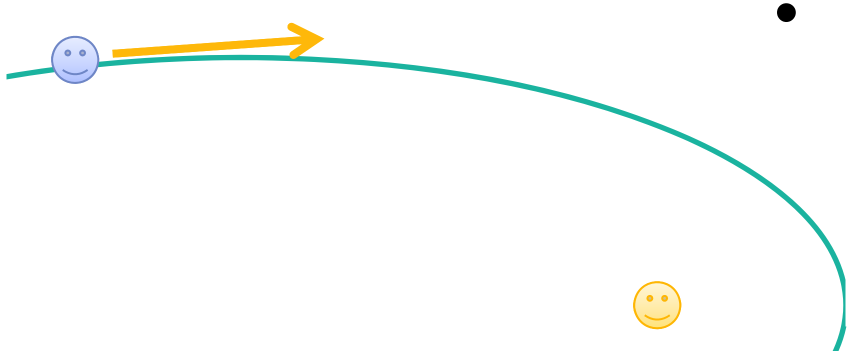
Schartmann+2012

気になるところ

- 軌道面2Dのシミュレーションでいいのか？
  - 潮汐力による軌道面に沿った方向の延びは表現できても、軌道面に垂直な方向への圧縮は表現できない
  - 近点通過速度は～5000km/s、これの数パーセントでも圧縮に使われると相当のエネルギーが近点通過時に放射で出るはず
- 形成の諸説には踏み込まず今のG2の形状を表していると思われるコンパクトシナリオを採用し、近点通過前後の主に軌道面に対して鉛直方向の運動に注目する

3次元 G2 シミュレーション

- G2、Sgr A*、ホットガスの3成分を N体/SPH法で3次元シミュレーション
  - 重力、流体、放射冷却(optically tin)を考慮
  - Sgr A* は sink 粒子
- 3次元一様密度クラウド
  - $3M_{\mathrm{Earth}}$, 半径 125AU
- 軌道パラメータ：Gillessen+2012
  - 近点通過時刻: A.D. 2013.5
- Since A.D. 1995 to A.D. 2033



- 高温ガス(RIAF)分布

$$\rho_{\mathrm{hot}}(r) = 1.7 \times 10^{-21} f_{\mathrm{hot}} \left(\frac{1.0 \times 10^{16} \mathrm{cm}}{r} \right) \mathrm{g\ cm^{-3}}$$

$$T(r) = 2.1 \times 10^{8} \left(\frac{1.0 \times 10^{16} \mathrm{cm}}{r} \right) \mathrm{K},$$

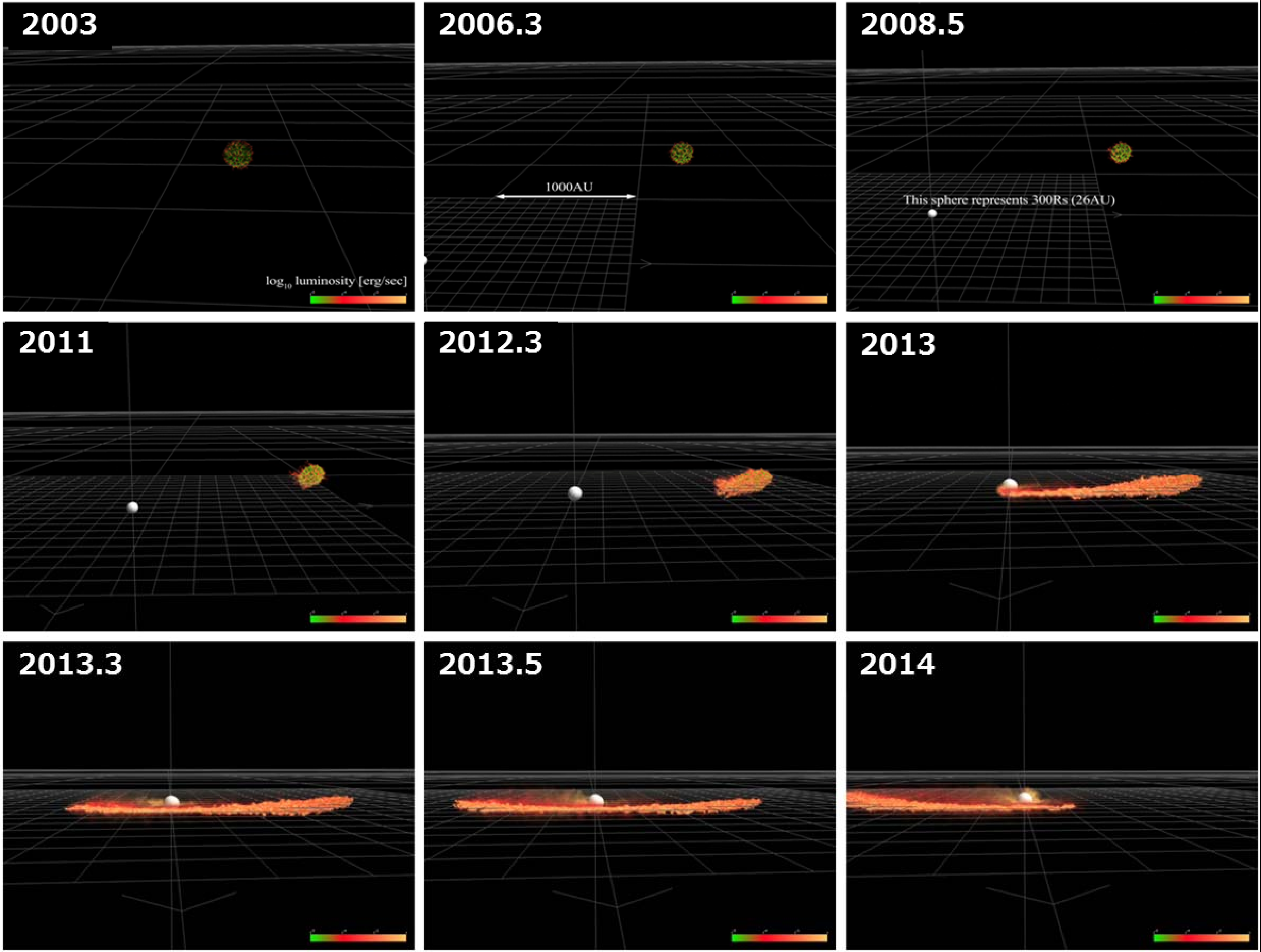
Run parameters

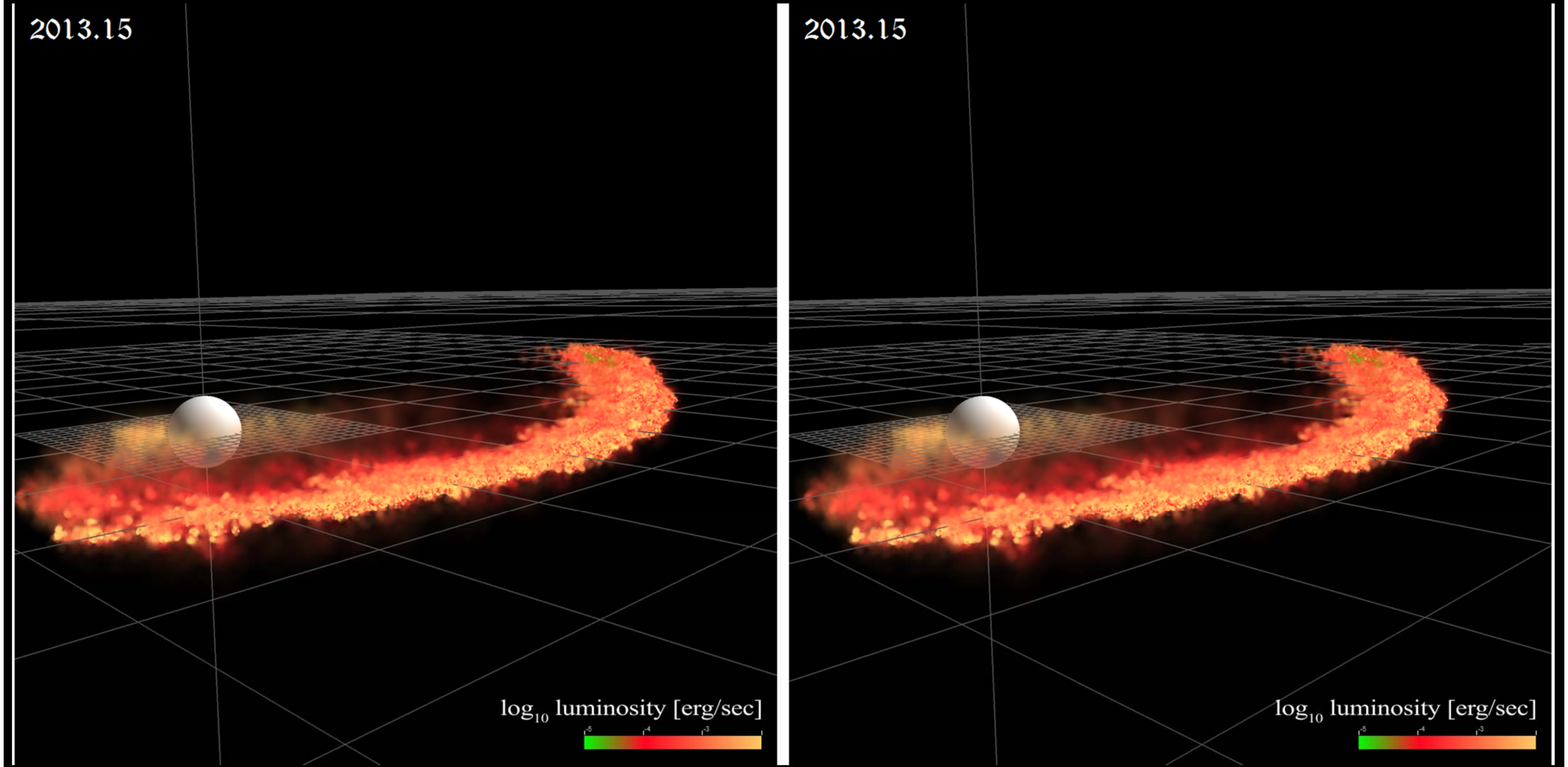
- 三つの f_{hot}
  - f_{hot}=1 : Run 1
  - f_{hot}=0.1 : Run 2
  - f_{hot}=0 : Run 3

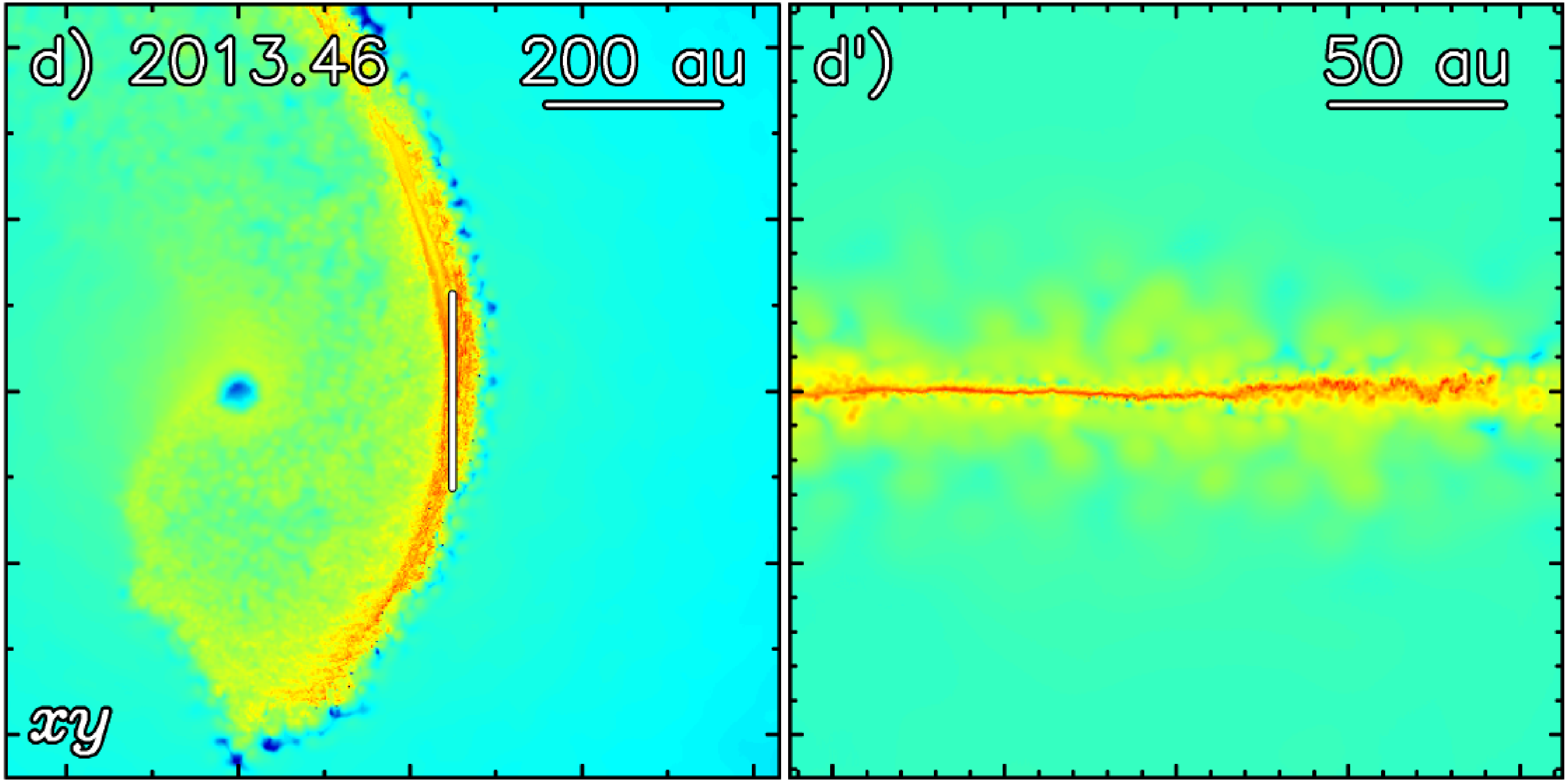
Component	Number of particles	Mass of particles	Softening length
Cloud (Run 1)	1×10^6	$3 \times 10^{-6}\ M_\oplus$	0.43 au
Cloud (Run 2)	3×10^5	$1 \times 10^{-5}\ M_\oplus$	0.65 au
Cloud (Run 3)	10^7	$3 \times 10^{-7}\ M_\oplus$	0.20 au
Hot gas (Run 1)	1×10^7	$2.8 \times 10^{-5}\ M_\oplus$	0.92 au
Hot gas (Run 2)	3×10^6	$9.4 \times 10^{-5}\ M_\oplus$	0.63 au
Hot gas (Run 3)	N/A	N/A	N/A
SMBH (Run 1,2,3)	1	$4.31 \times 10^6\ M_\odot$	10 au

Parallel *N*-body/SPH code : ASURA

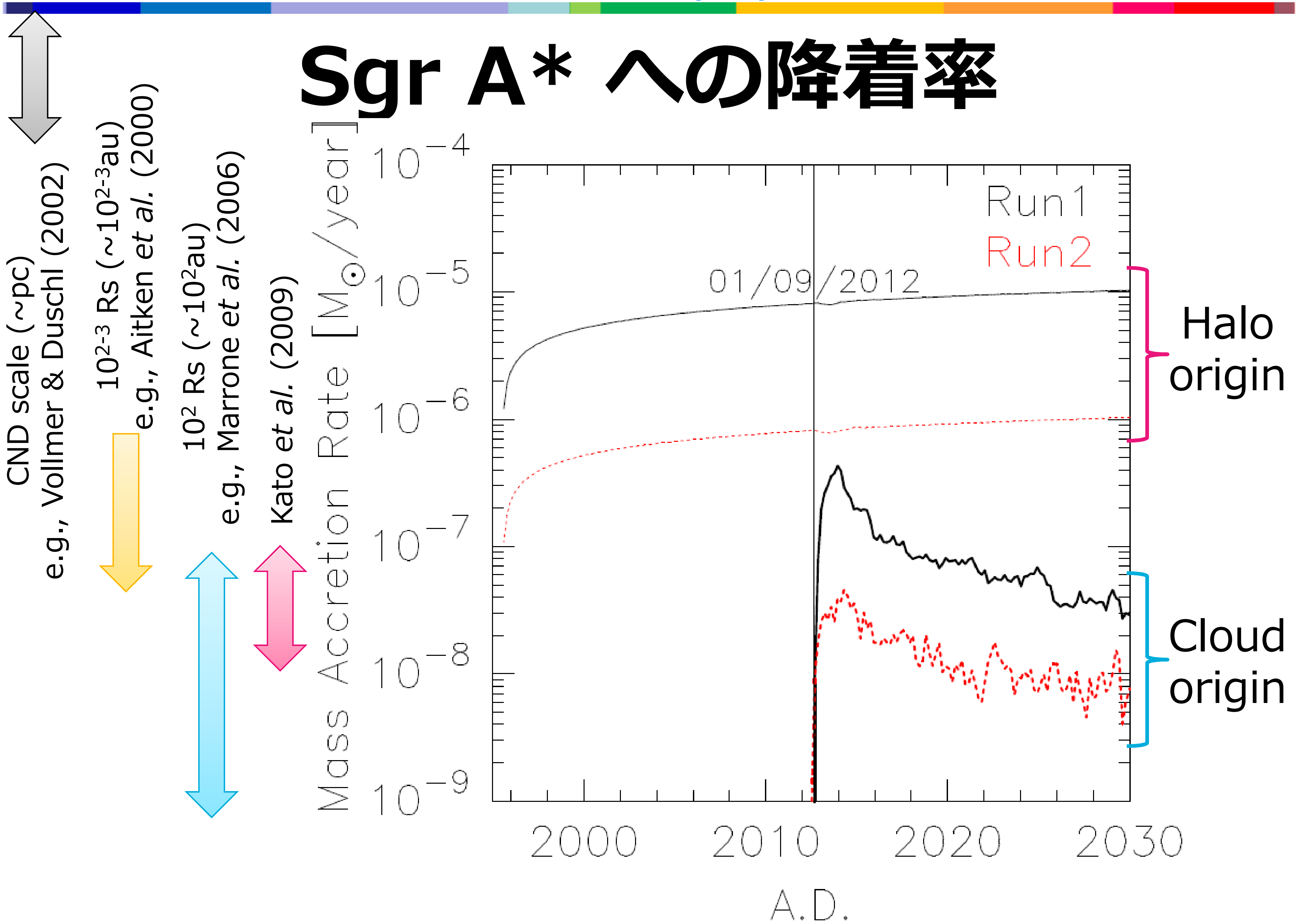
- C (C99) + MPI
- Domain decomp.:Orthogonal Recursive Bisection
- Gravity: Parallel Tree+GRAPE
  - Hardware accelerators : GRAPE-5/GRAPE-6A/GRAPE-7/GRAPE-DR
  - Software accelerator : Phantom-GRAPE
    - Assembler tuned software library!!
  - Symmetrized Plummer Potential (Saitoh&Makino 2012a)
- Hydro : Density Independent SPH (Saitoh&Makino 2012b)
- Time integrator: Leap-frog
  +Individual time steps
  +Time-step limiter (Saitoh&Makino 2009)
  +FAST (Saitoh&Makino 2010)


2003
log10 luminosity [erg/sec]
2006.3
1000AU
2008.5
This sphere represents 300Rs (26AU)
2011
2012.3
2013
2013.3
2013.5
2014

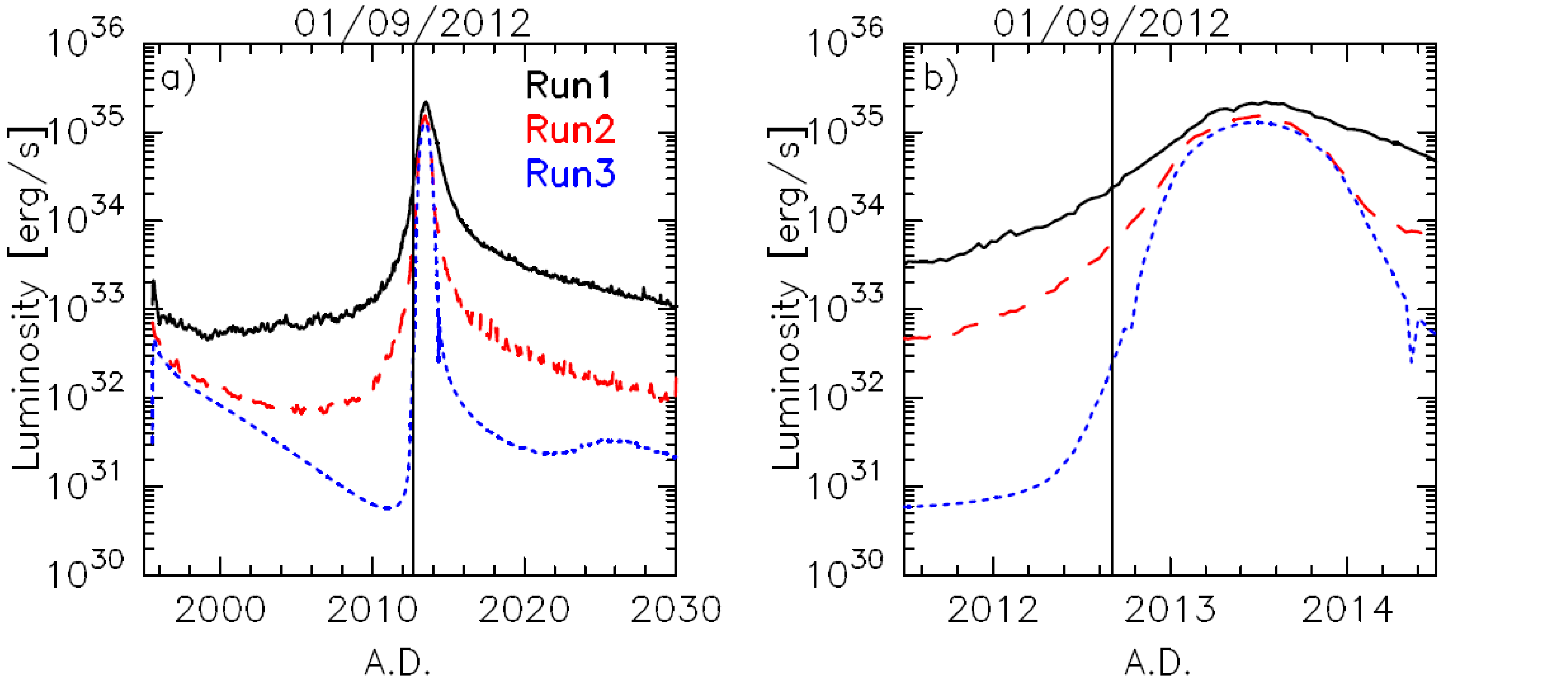

2013.15
log10 luminosity [erg/sec]
2013.15
log10 luminosity [erg/sec]

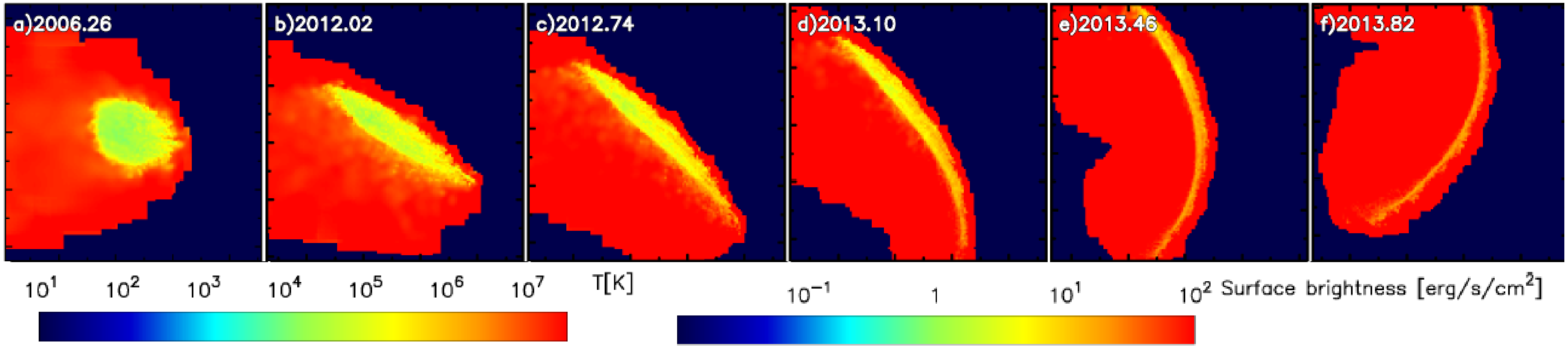

d) 2013.46
200 au
xy
d')
50 au

Sgr A* への降着率


CND scale (~pc)
e.g., Vollmer & Duschl (2002)
10^{2-3} Rs (~10^{2-3}au)
e.g., Aitken *et al.* (2000)
10^2 Rs (~10^2au)
e.g., Marrone *et al.* (2006)
Kato *et al.* (2009)
Mass Accretion Rate [$M_\odot$/year]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
Run1
Run2
01/09/2012
Halo origin
Cloud origin
2000
2010
2020
2030
A.D.

光度進化


01/09/2012
a)
Run1
Run2
Run3
Luminosity [erg/s]
10^{36}
10^{35}
10^{34}
10^{33}
10^{32}
10^{31}
10^{30}
2000
2010
2020
2030
A.D.
01/09/2012
b)
2012
2013
2014
A.D.


a)2006.26
b)2012.02
c)2012.74
d)2013.10
e)2013.46
f)2013.82
10^1 10^2 10^3 10^4 10^5 10^6 10^7 T[K]
10^{-1} 1 10^1 10^2 Surface brightness [erg/s/cm^2]

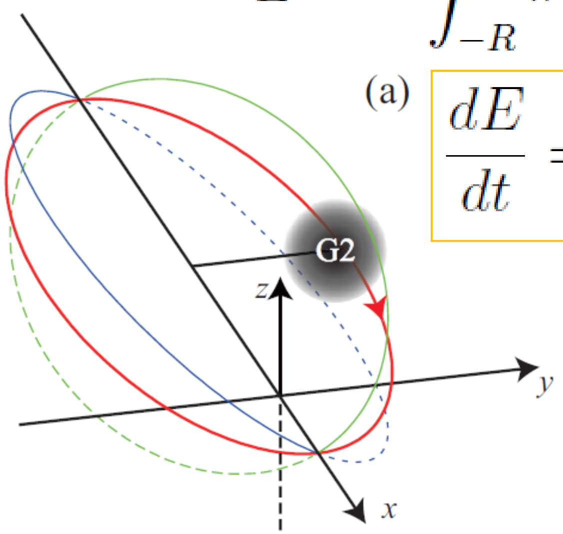
解析的な光度進化の見積もり

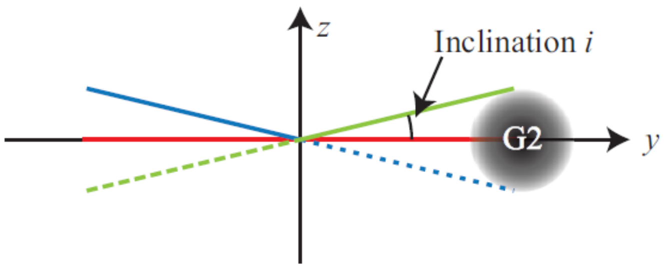
- 次の仮定をする…
  1. すべてのガス成分が同じ ascending node を共有した楕円軌道をもつ
  2. ガス雲のサイズが 125 au : ascending node からもっとも離れたところで
  3. すべてのエネルギーが近点通過時に解放

$$E = \int_{-R}^{R} \pi (R^2 - h^2) \rho V_z^2 dh = 3.5 \times 10^{43} \left(\frac{m}{3M_\oplus}\right) \left(\frac{R}{125\ \mathrm{AU}}\right)^2 \mathrm{erg}.$$

$$\frac{dE}{dt} = 1.1 \times 10^{36} \left(\frac{m}{3M_\oplus}\right) \left(\frac{R}{125\ \mathrm{AU}}\right)^2 \left(\frac{1\ \mathrm{year}}{\tau}\right) \mathrm{erg/s},$$

(a)





ラム圧の影響

- ラム圧： $P(r) = \rho_{\rm hot}(r) v_{\rm c}(r)^2,$
- 単位時間あたりのエネルギー

$$\frac{dE_{\rm ram}}{dt} = CP(r)\sigma_{\rm c} v_{\rm c}(r) = C\rho_{\rm hot}(r) v_{\rm c}(r)^3 \sigma_{\rm c}$$

- Hot ambient profile と軌道の情報(r-v_c; Burkert+2012)を入れると:

$$\frac{dE_{\rm ram}}{dt} = 7.5 \times 10^{33} C f_{\rm hot} \left(\frac{6 \times 10^{16}\ {\rm cm}}{r}\right) \left\{\left(\frac{6 \times 10^{16}\ {\rm cm}}{r}\right) - 0.48\right\}^{3/2} \left(\frac{\sigma_c}{\pi (125\ {\rm AU})^2}\right)\ {\rm erg\ s^{-1}}$$

1. A.D.2000,r_{2000}=6x10^{16}cm、σ=π(125AU)^2、dE/dt $\simeq 7.5 \times 10^{33} C f_{\rm hot}\ {\rm erg\ s^{-1}}.$
2. A.D.2013.5,$r_{2013.5}$=4x10^{15}cm,σ<1AUx40 AU=40AU^2、dE/dt $\leq 5.1 \times 10^{33} C f_{\rm hot}\ {\rm erg\ s^{-1}}.$

まとめ

- Sgr A* 周りを運動する3地球質量ガス雲 G2の3次元シミュレーションを行った
- 潮汐力により軌道面鉛直方向に強く圧縮され、2013年に **~10^{35} erg/s** のエネルギー放出
  - 10^4Kまで加熱されたガスからの再結合線
  - 銀河中心のダストに邪魔されない近赤外線
  - 放出のエネルギーは、ガス雲のサイズ、質量、密度分布などによる➔今後の観測のデータとの突き合わせで、より詳細な情報が構築できる
  - **天文学としてはまれな答え合わせのできる研究**