Wind-fed GRMHD simulations of Sagittarius A*: tilt and alignment of jets and accretion discs, electron thermodynamics, multiscale modelling of the rotation measure

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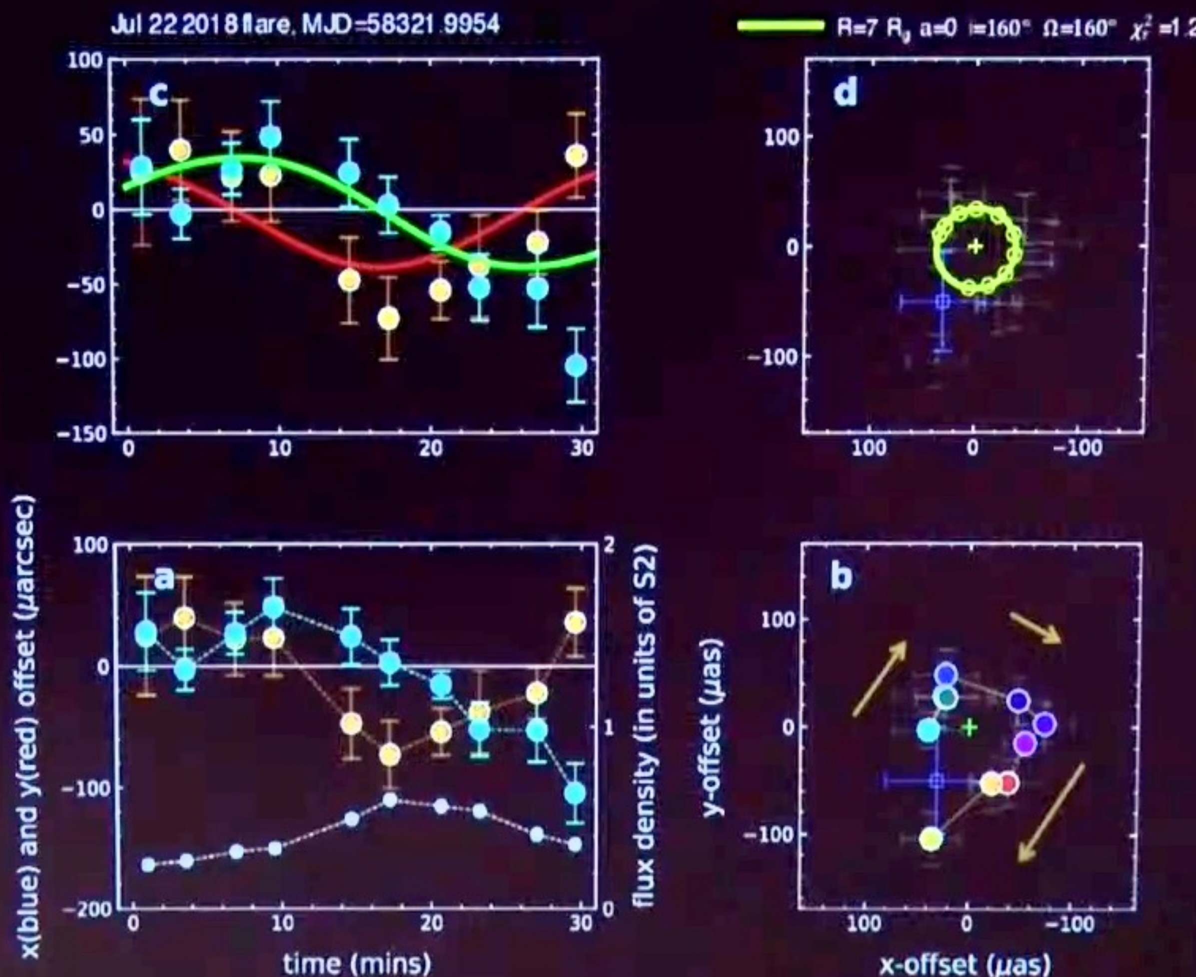
(Several slides taken from talk given by Ressler at ITC, Harvard University)

December 20, 2023

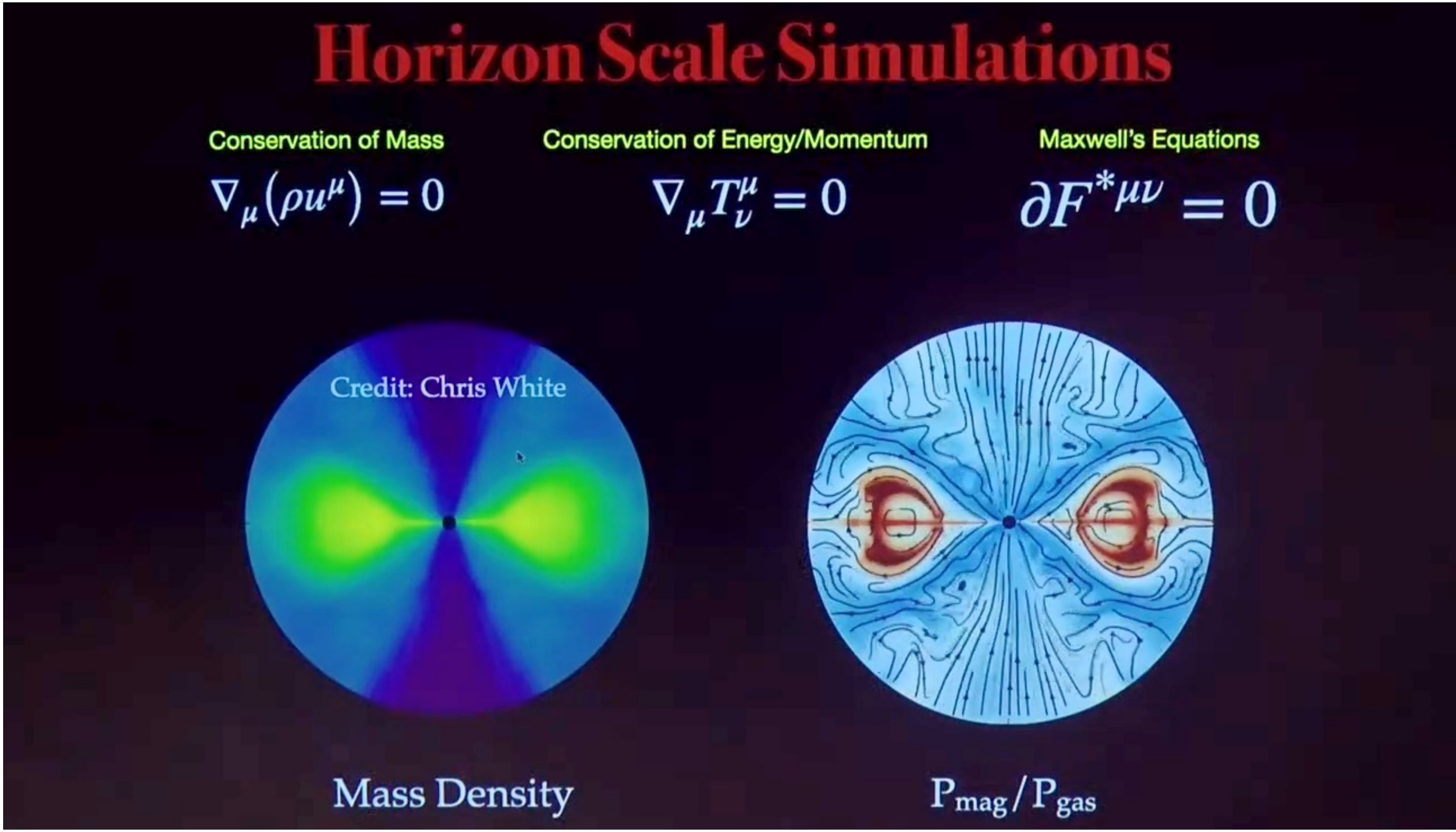

Image Credit: Event Horizon Telescope Collaboration 2022
Sagittarius A* at 230 GHz

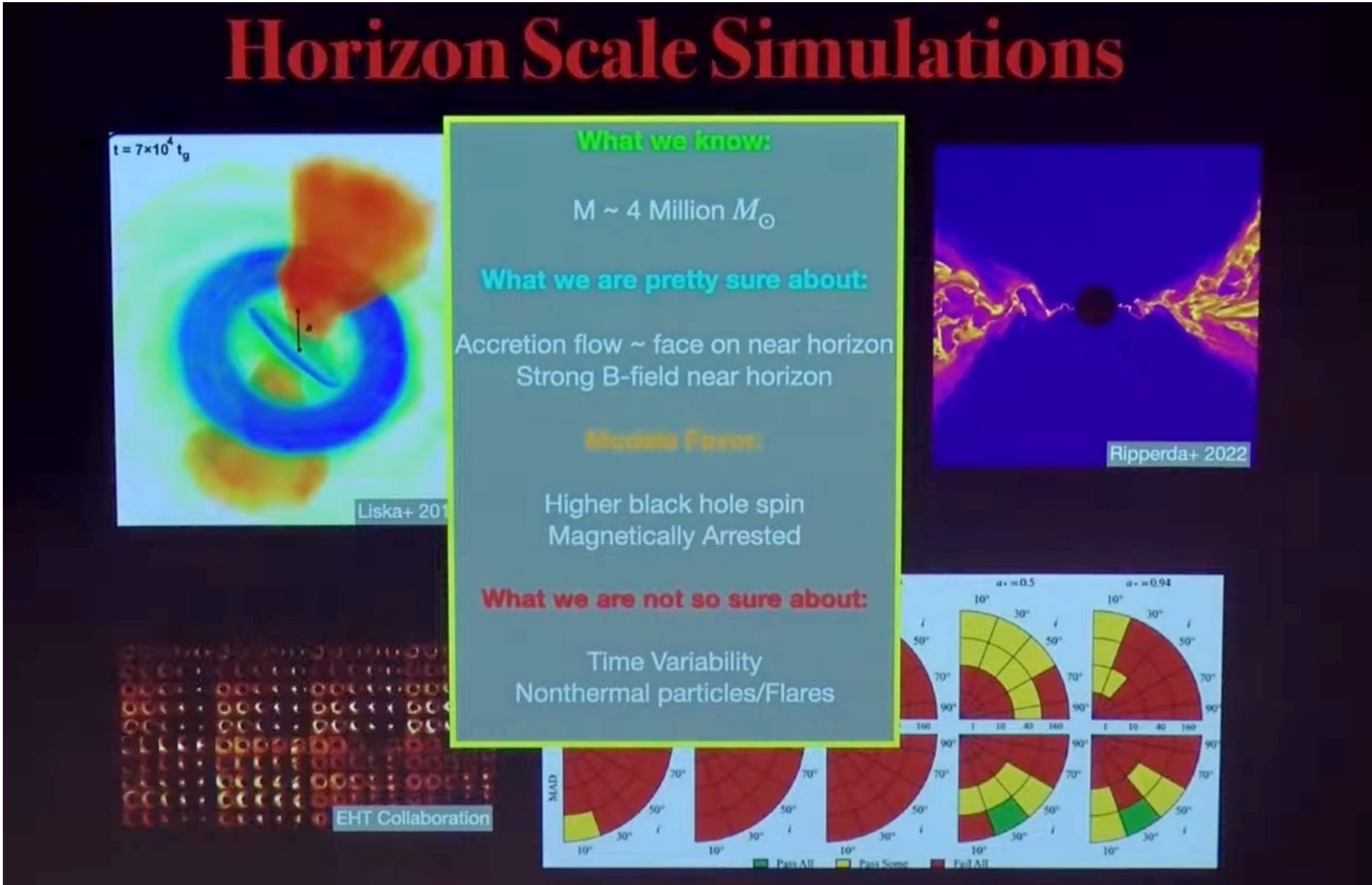
GRAVITY (NIR)

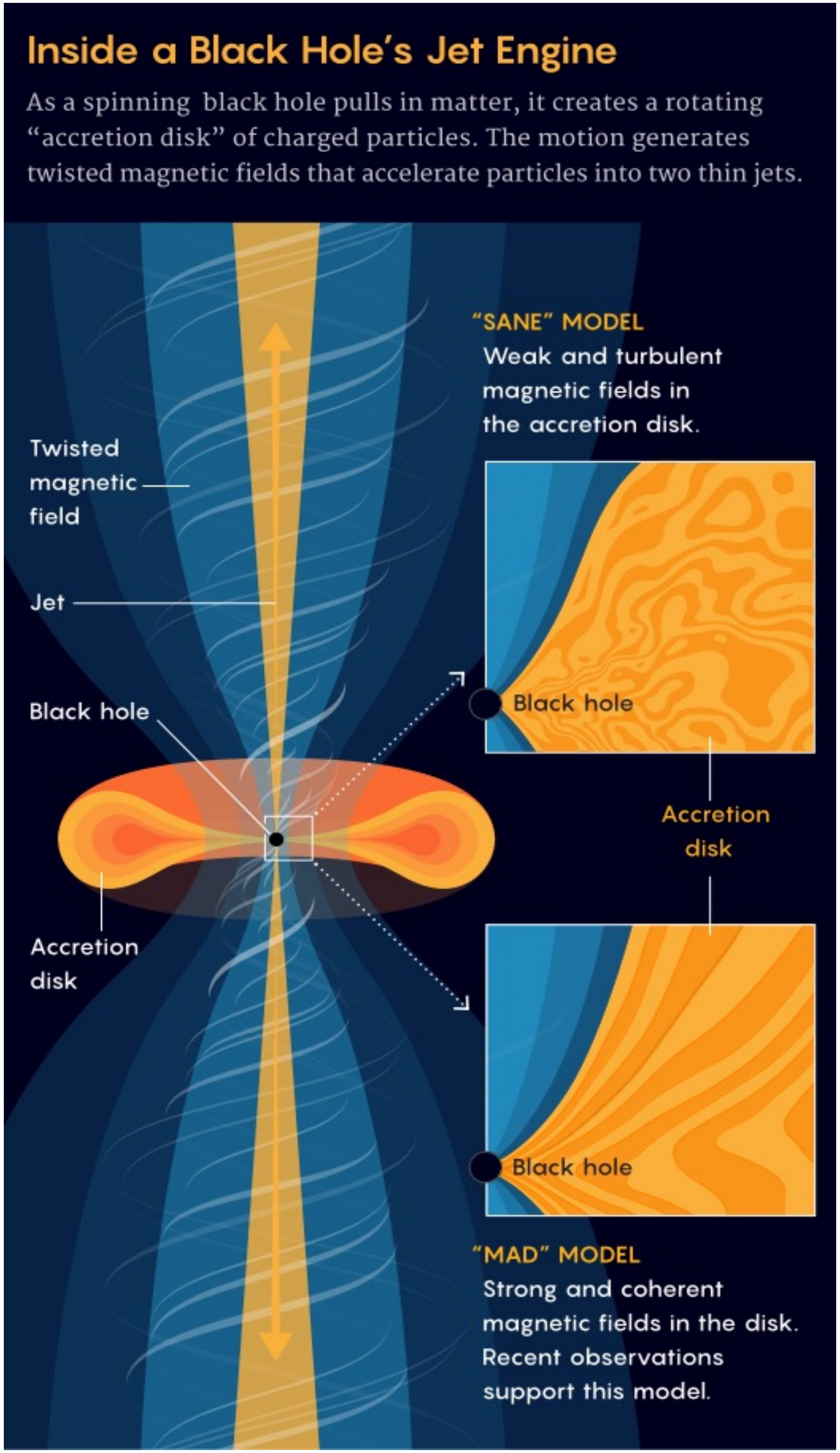
Flare motion
at ~ 5 r_s



GRAVITY
Collaboration 2018


Horizon Scale Simulations
Conservation of Mass
$\nabla_\mu(\rho u^\mu) = 0$
Conservation of Energy/Momentum
$\nabla_\mu T^\mu_\nu = 0$
Maxwell's Equations
$\partial F^{*\mu\nu} = 0$
Credit: Chris White
Mass Density
P_{mag} / P_{gas}

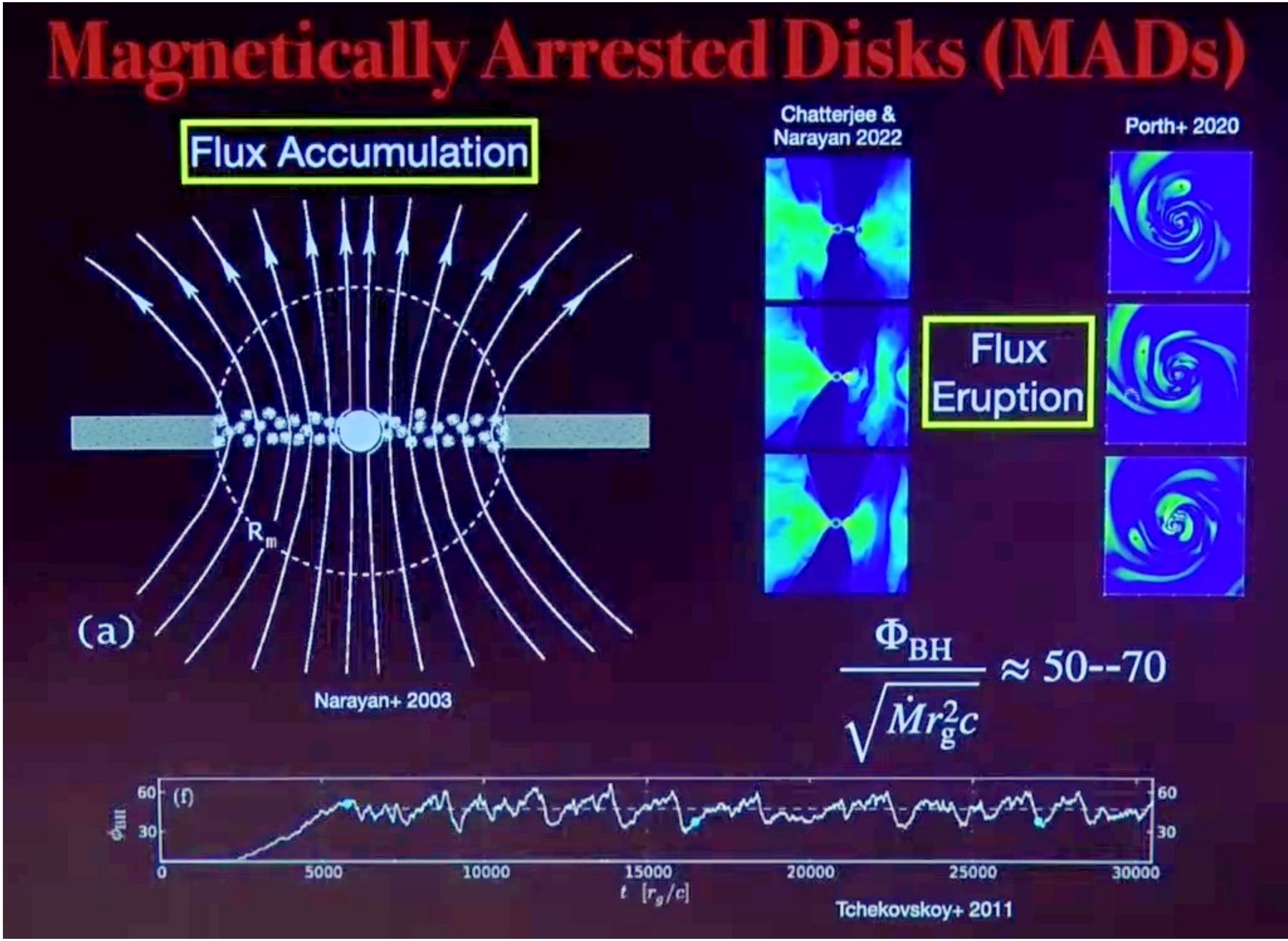

Horizon Scale Simulations
t = 7×10⁴ t_g
What we know:
M ~ 4 Million $M_\odot$
What we are pretty sure about:
Accretion flow ~ face on near horizon
Strong B-field near horizon
Higher black hole spin
Magnetically Arrested
What we are not so sure about:
Time Variability
Nonthermal particles/Flares
Ripperda+ 2022
EHT Collaboration
MAD
Pass All
Pass Some
Fail All



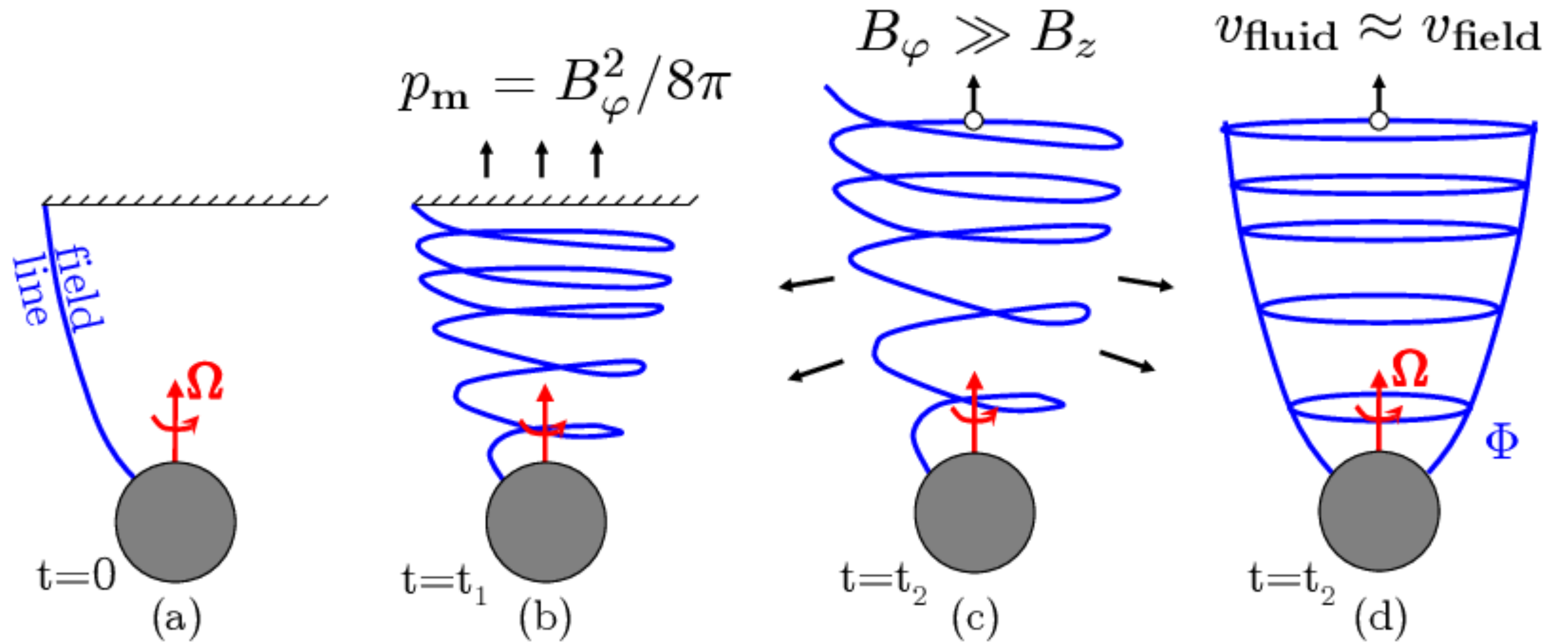
Standard And Normal Evolution (SANE)

Magnetically Arrested Disk (MAD)

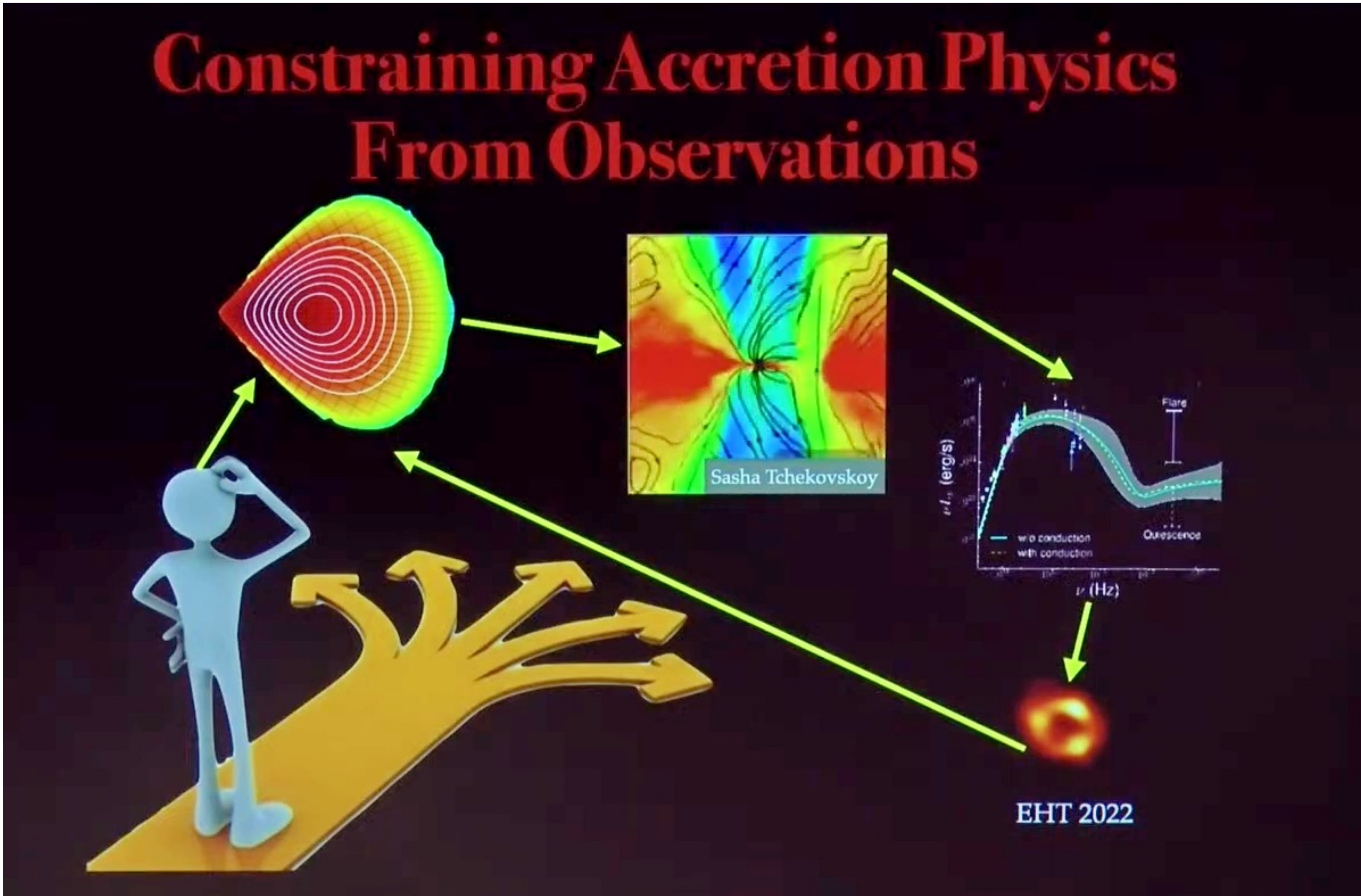
Image credit: Quanta Magazine


Magnetically Arrested Disks (MADs)
Flux Accumulation
R_m
(a)
Narayan+ 2003
Chatterjee & Narayan 2022
Porth+ 2020
Flux Eruption
$\frac{\Phi_{BH}}{\sqrt{\dot{M} r_g^2 c}} \approx 50\text{--}70$
(f)
ϕ_{BH}
60
30
0
5000
10000
15000
20000
25000
30000
t $[r_g/c]$
Tchekovskoy+ 2011

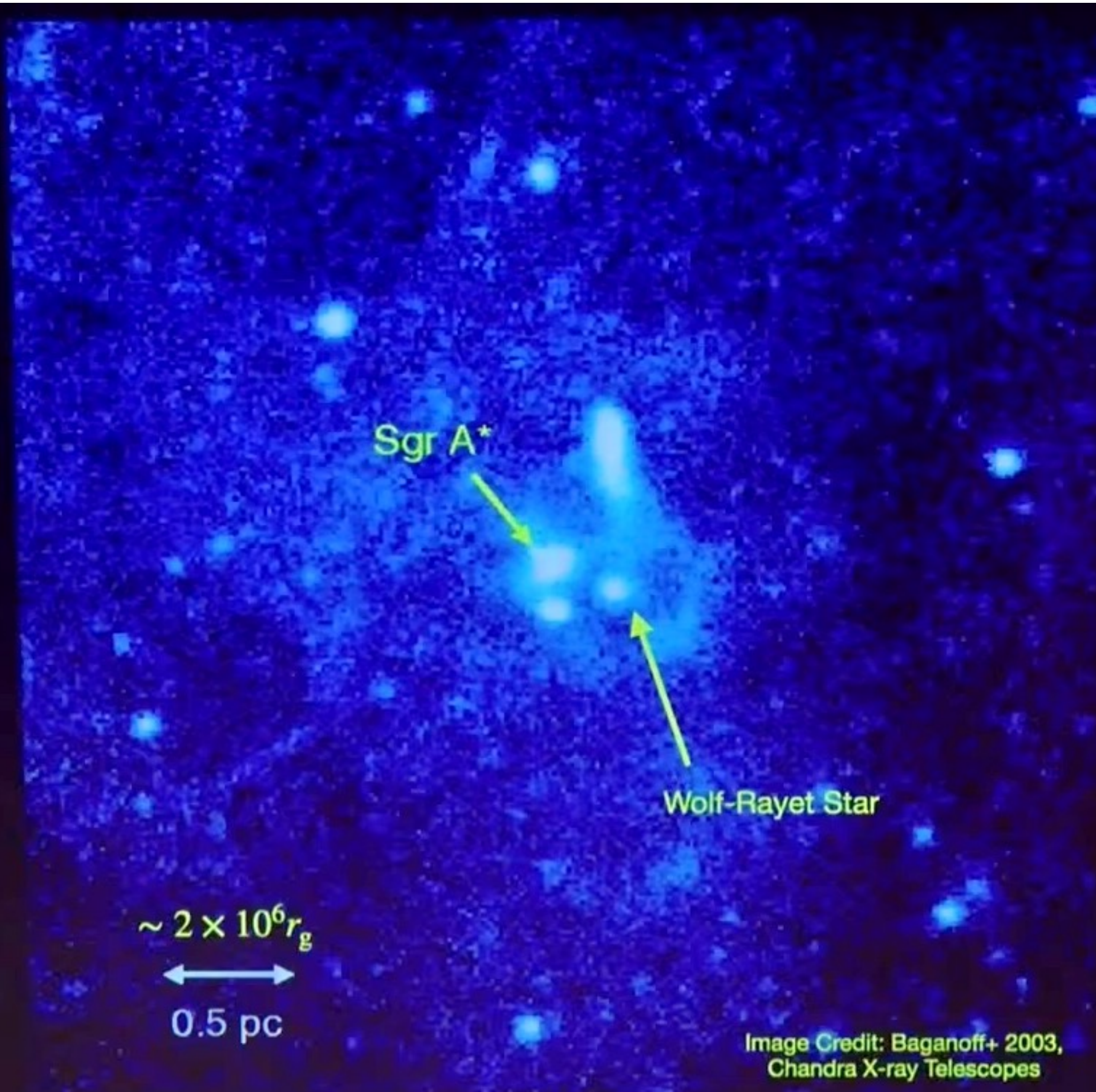
Blandford-Znajek (BZ) process for spinning black hole
(Davis & Tchekhovskoy, ARAA, 2020)



4: Illustration of jet formation by magnetic fields. (a) Consider a purely


Constraining Accretion Physics
From Observations
Sasha Tchekovskoy
Flare
w/o conduction
with conduction
Quiescence
ν (Hz)
νL_ν (erg/s)
EHT 2022

Bondi Radius Resolved



Hot gas from Wolf-Rayet Stars and other point sources

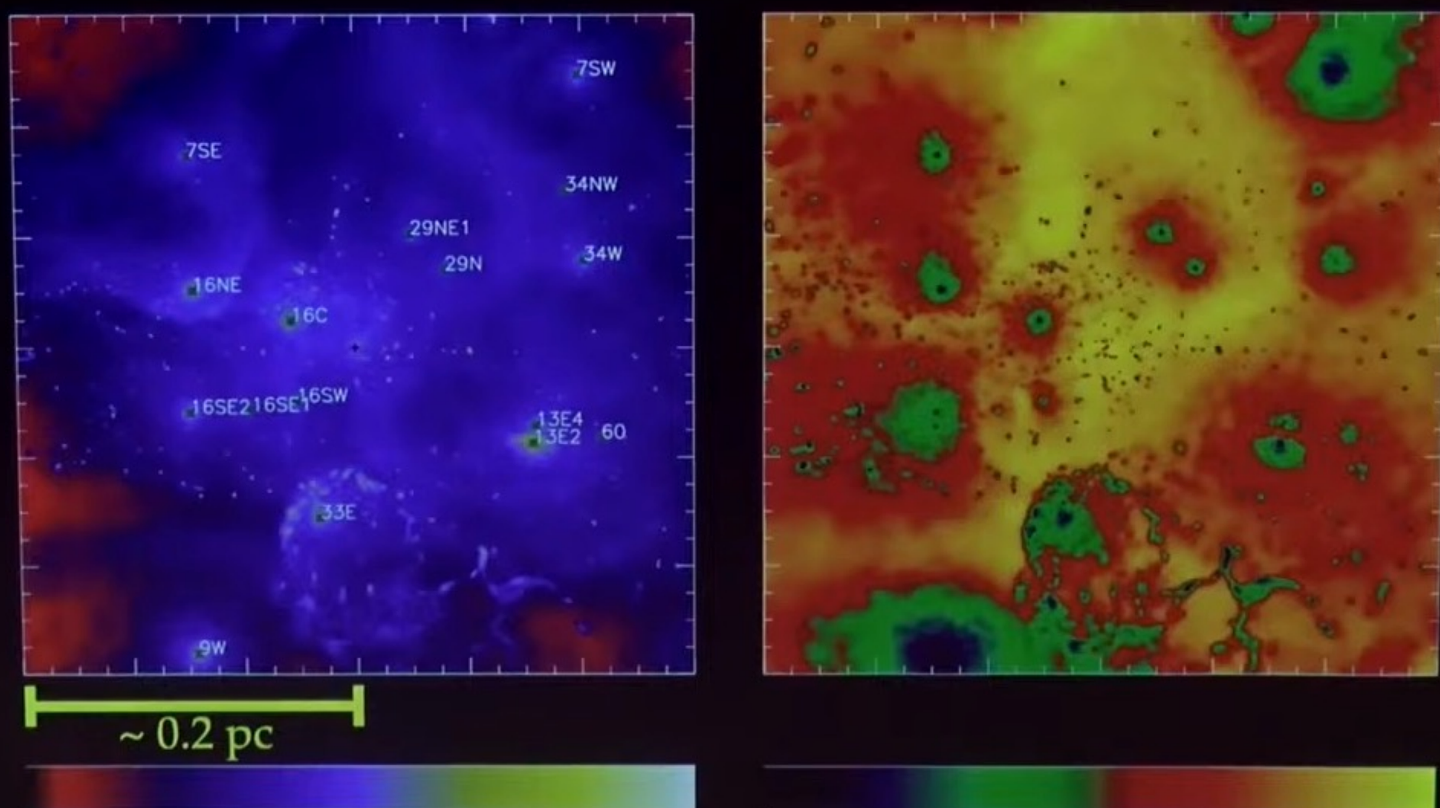
$T \sim 1.3$ keV

$n_e \sim 26\ \mathrm{cm}^{-3}$

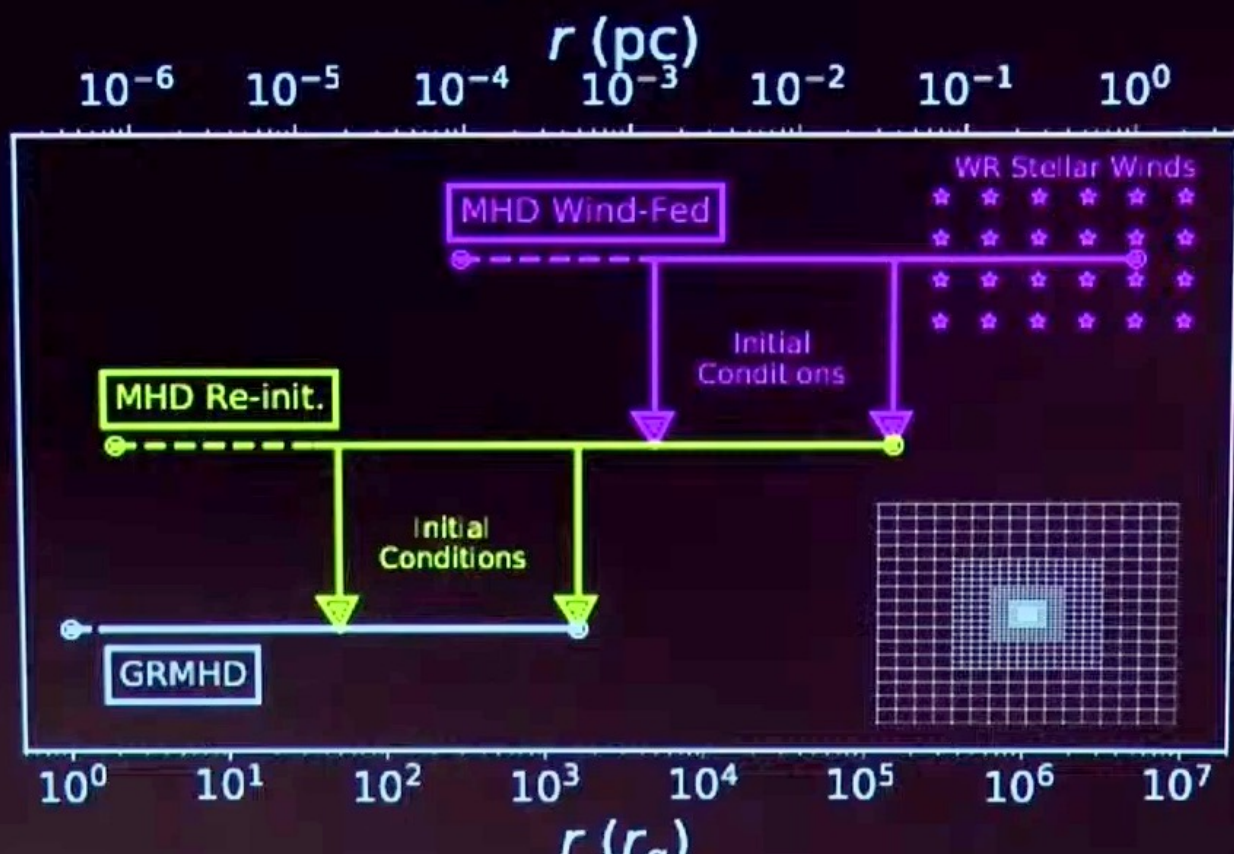
$\dot{M}_{\rm Bondi} \sim 10^{-6} M_\odot/\mathrm{yr}$

Bondi Scale Simulations

Cuadra+ 2005, 2006, 2008
Calderon+ 2019
Russell+ 2019



Bridging the Gap

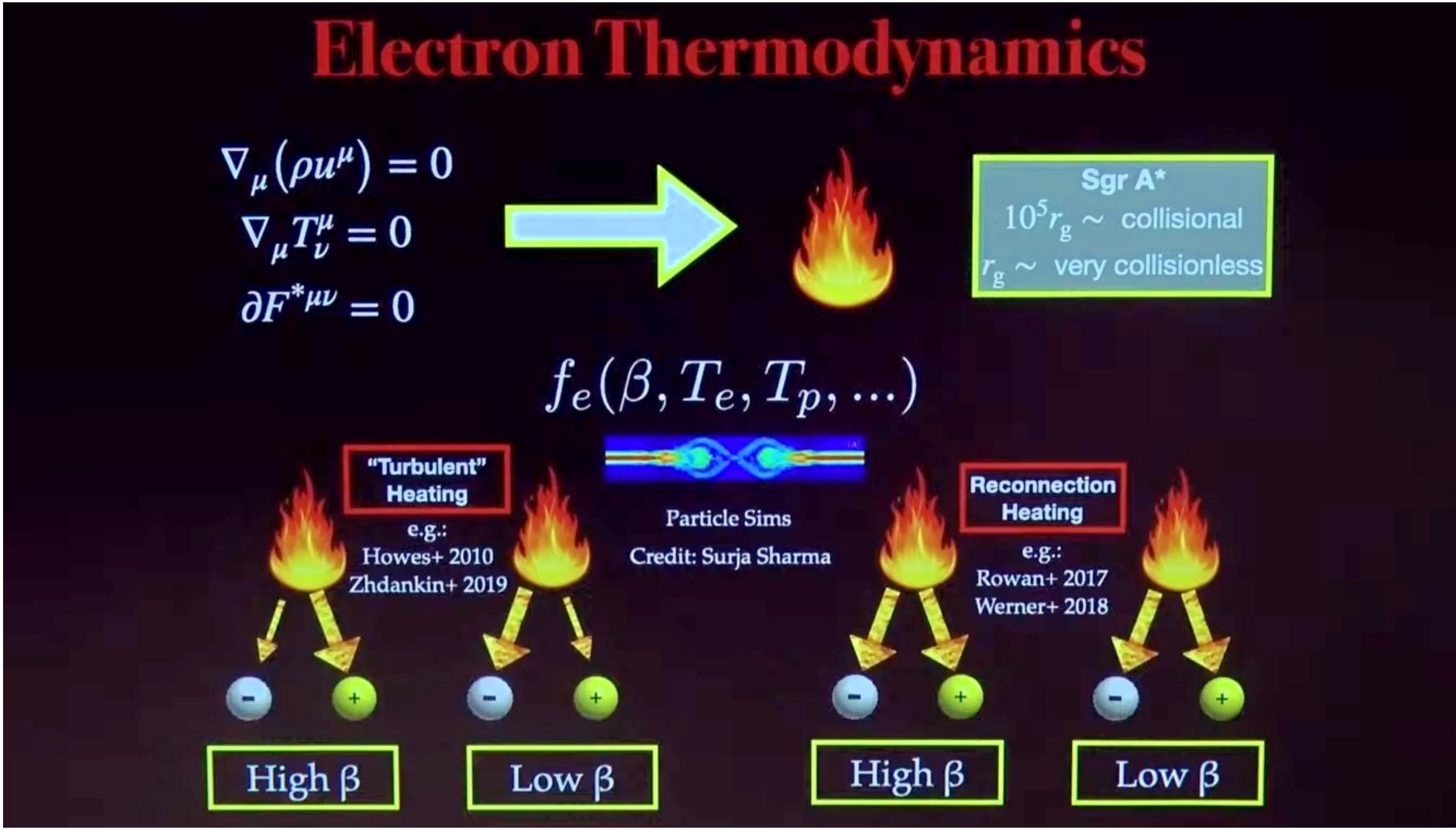


Main Parameters of the Model

$$\beta_w \equiv \frac{P_{ram}}{P_{mag}}$$

$t_{restart}$

$$f_e = f_e(\beta, T_e/T_i, \sigma, \ldots)$$



Electron Thermodynamics
$\nabla_\mu(\rho u^\mu) = 0$
$\nabla_\mu T^\mu_\nu = 0$
$\partial F^{*\mu\nu} = 0$
Sgr A*
$10^5 r_g \sim$ collisional
$r_g \sim$ very collisionless
$f_e(\beta, T_e, T_p, \ldots)$
"Turbulent" Heating
e.g.:
Howes+ 2010
Zhdankin+ 2019
Particle Sims
Credit: Surja Sharma
Reconnection Heating
e.g.:
Rowan+ 2017
Werner+ 2018
High β
Low β
High β
Low β

Smorgasbord of Models

$$\beta_w = 10^2, a = 0$$

3 different realizations

$$\beta_w = 10^2, a = 0.9375$$

2 different realizations

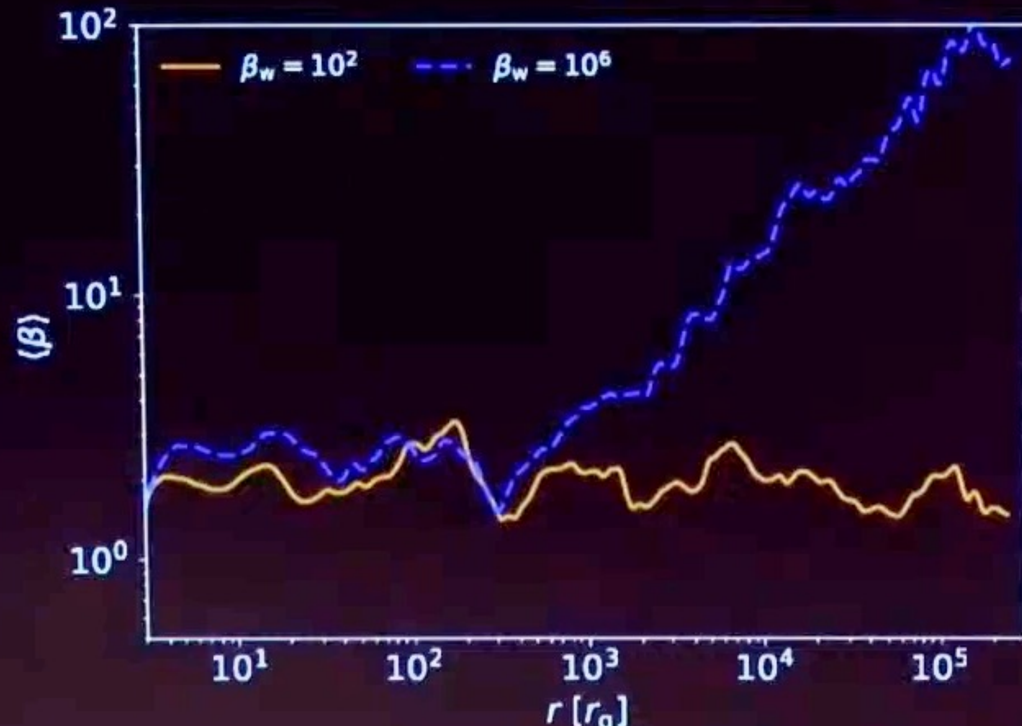
$$\beta_w = 10^6, a = 0$$

2 different realizations

$$\beta_w = 10^6, a = 0.9375$$

1 realization

Strongly Magnetized Flows Seem Inevitable

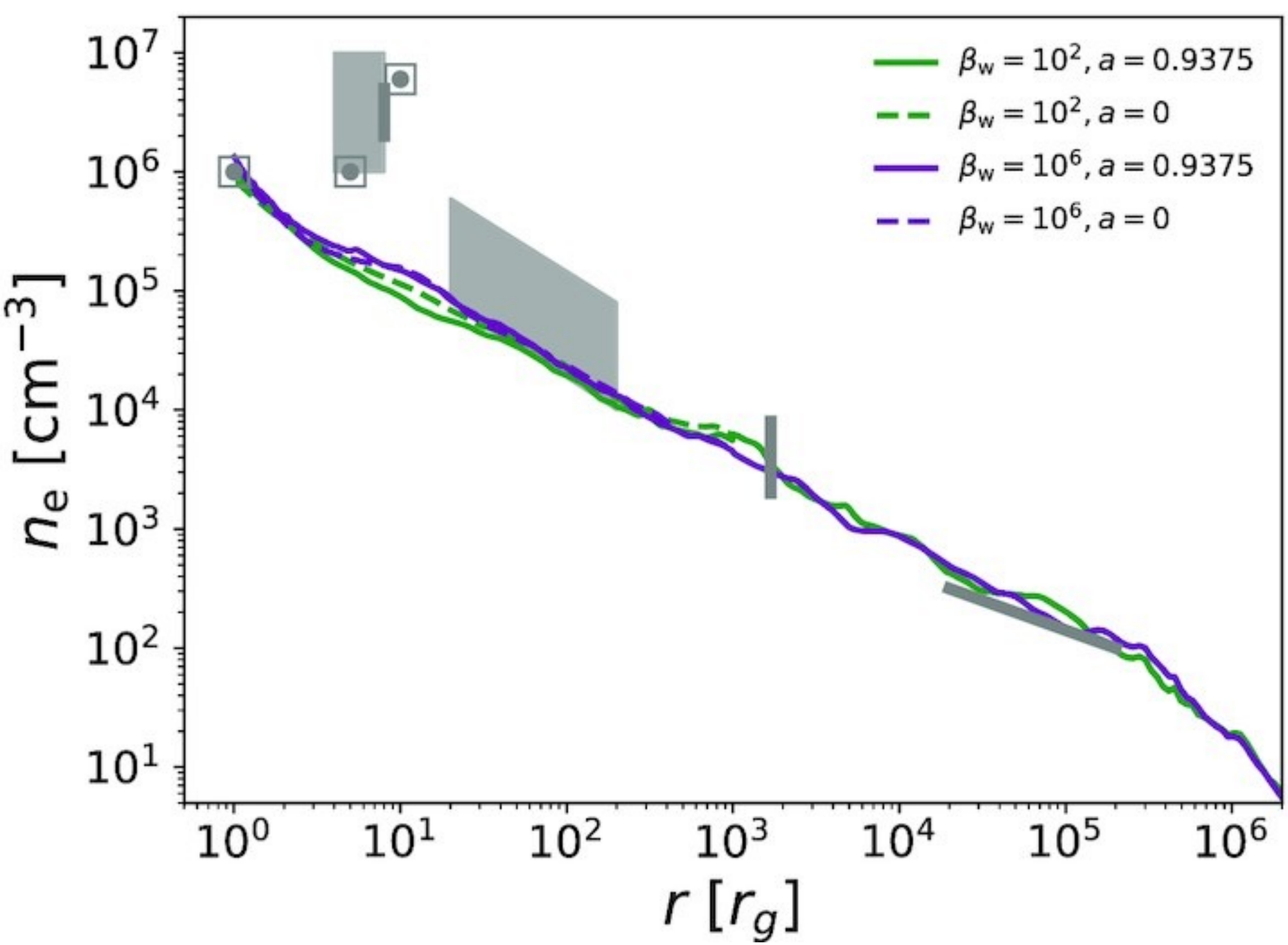


Weakly Magnetized Winds

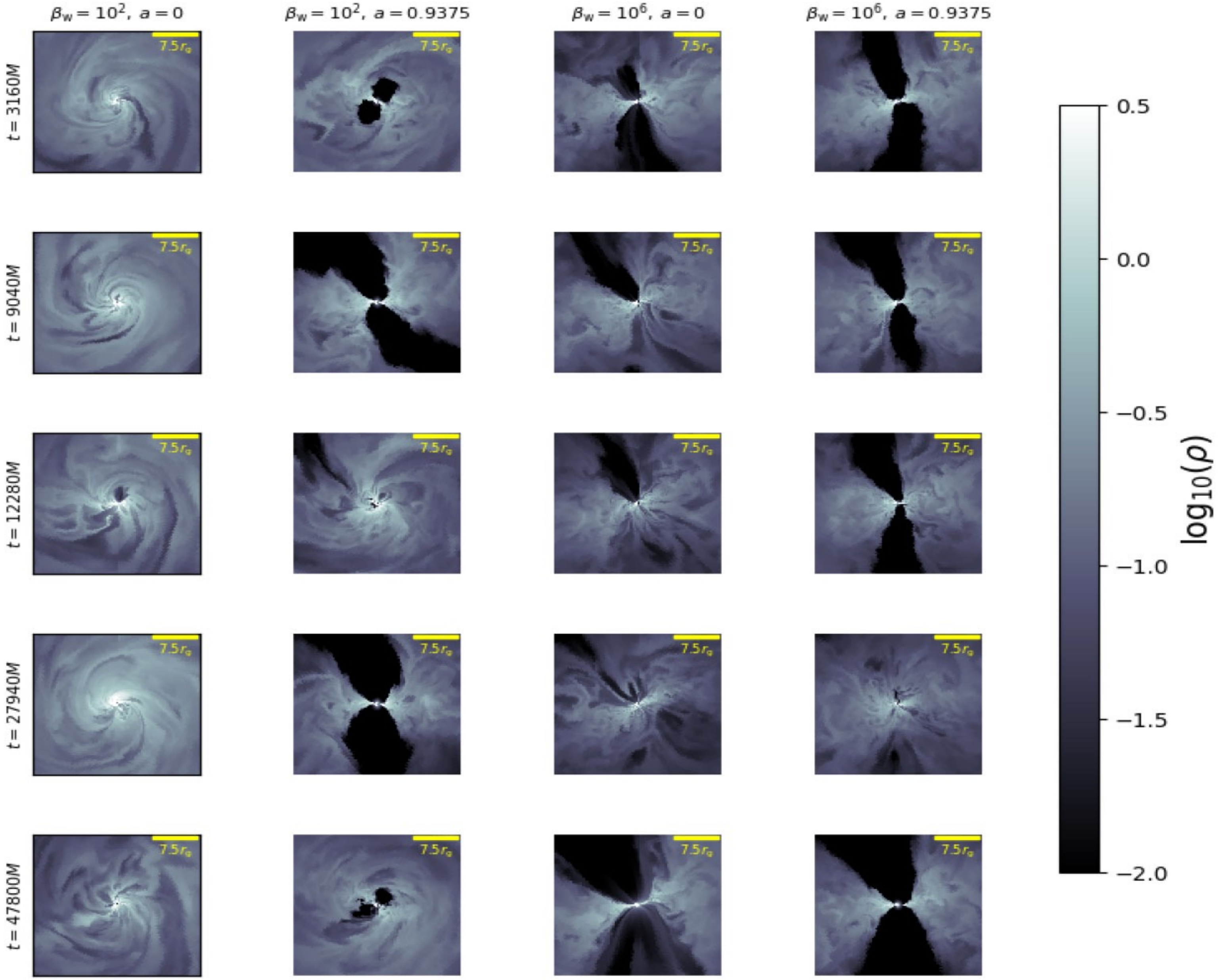
Strongly Magnetized Winds

$$\beta \equiv \frac{P_g}{P_{mag}}$$

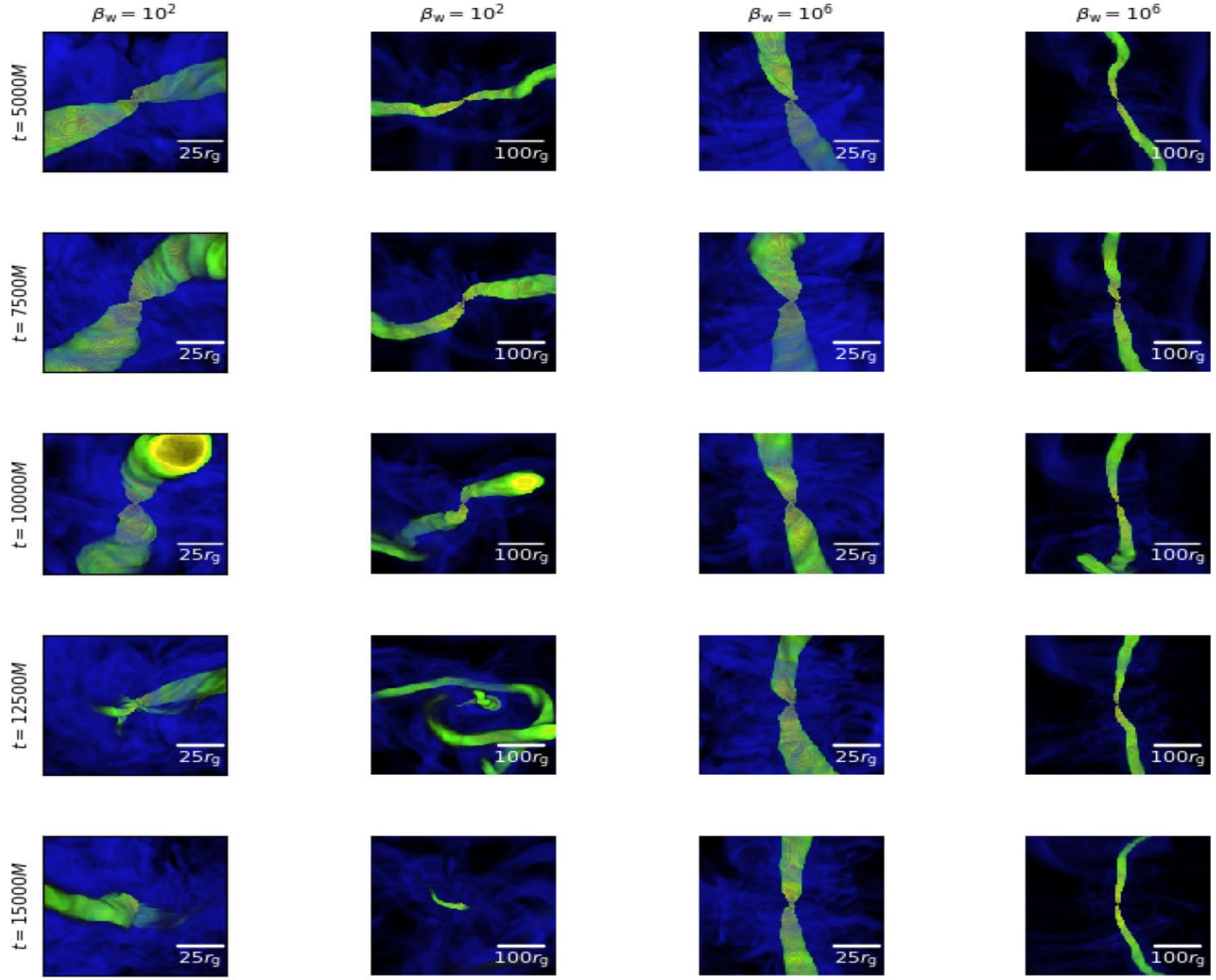
Density profile/accretion rate consistent with observations



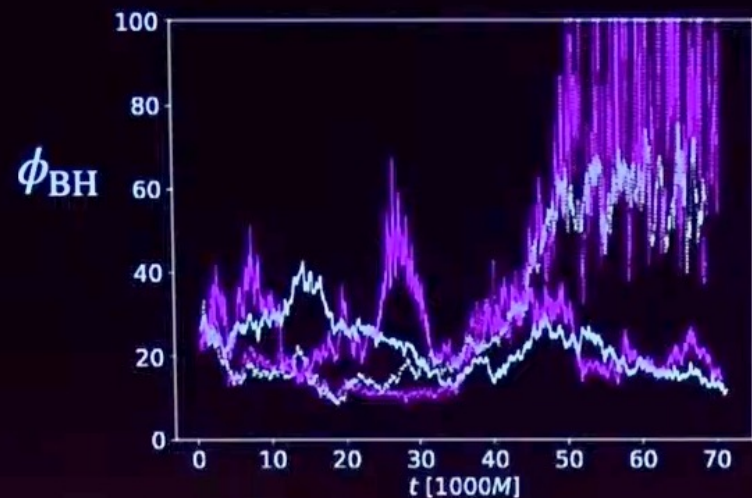
Mass Density in x-z plane



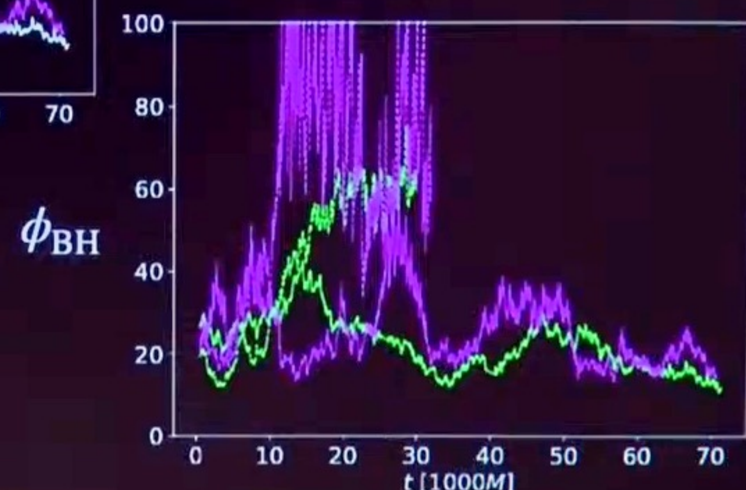
3D volume renderings of the jets with a = 0.9375 using magnetization parameter at five different times and two different spatial scales



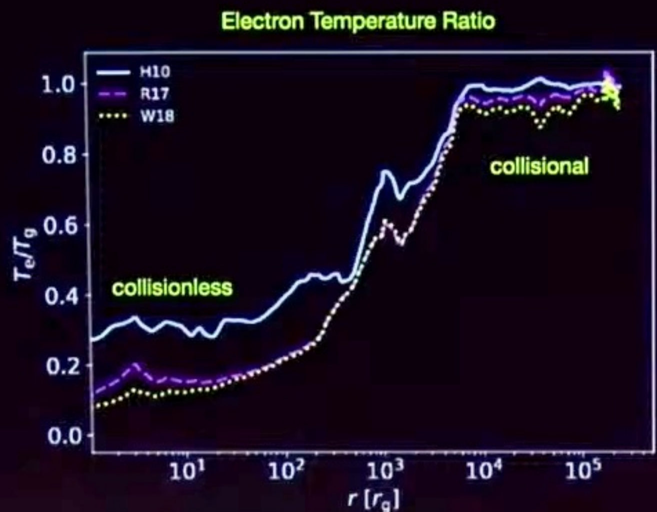
MAD Sometimes, Not Always



6/8 Simulations Magnetically Arrested

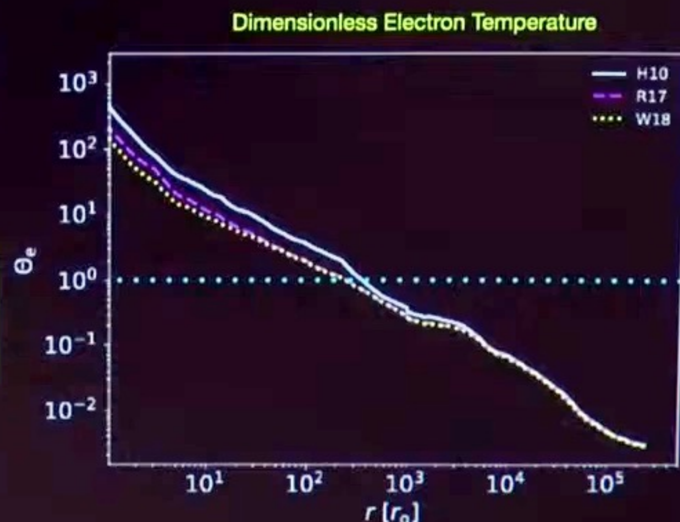


Electron Temperatures

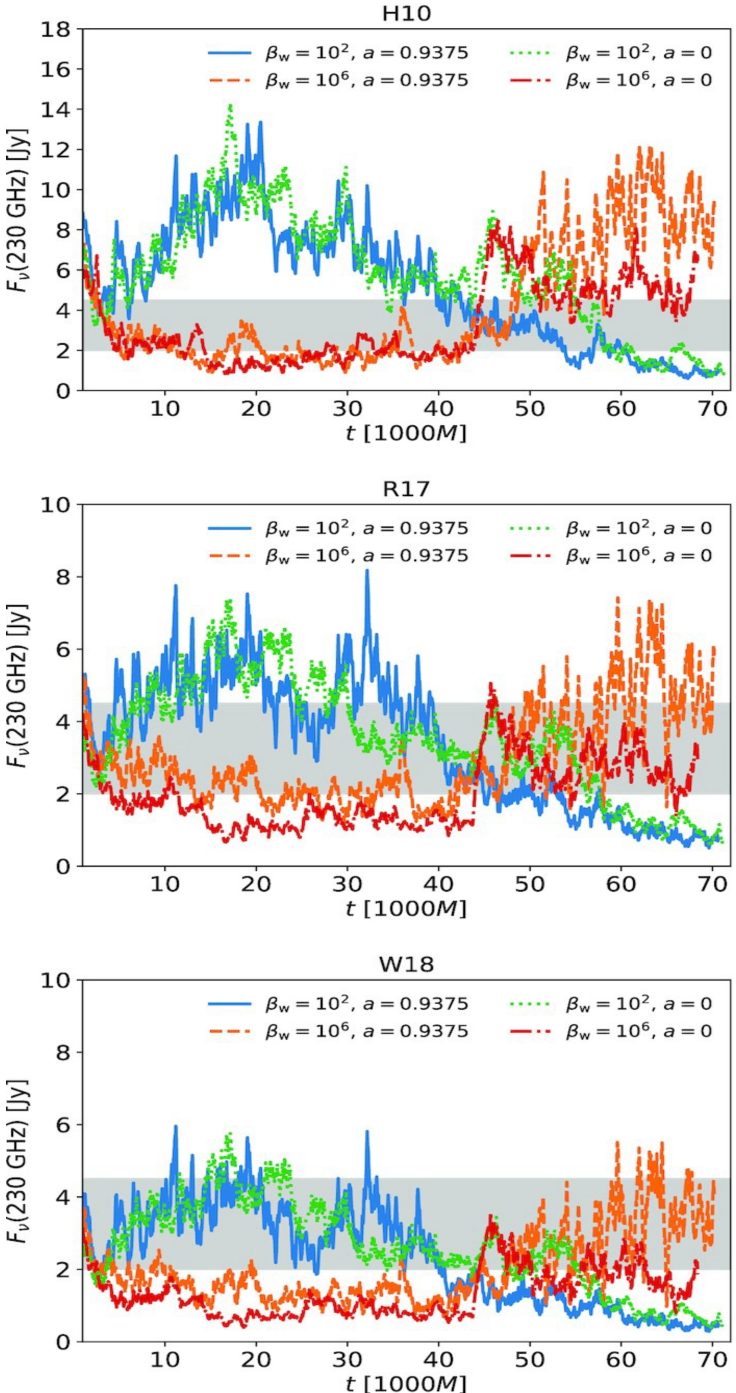


Electrons relativistic at ~ 100s of r_g

Low Electron Temperature Near Horizon



230 GHz fluxes

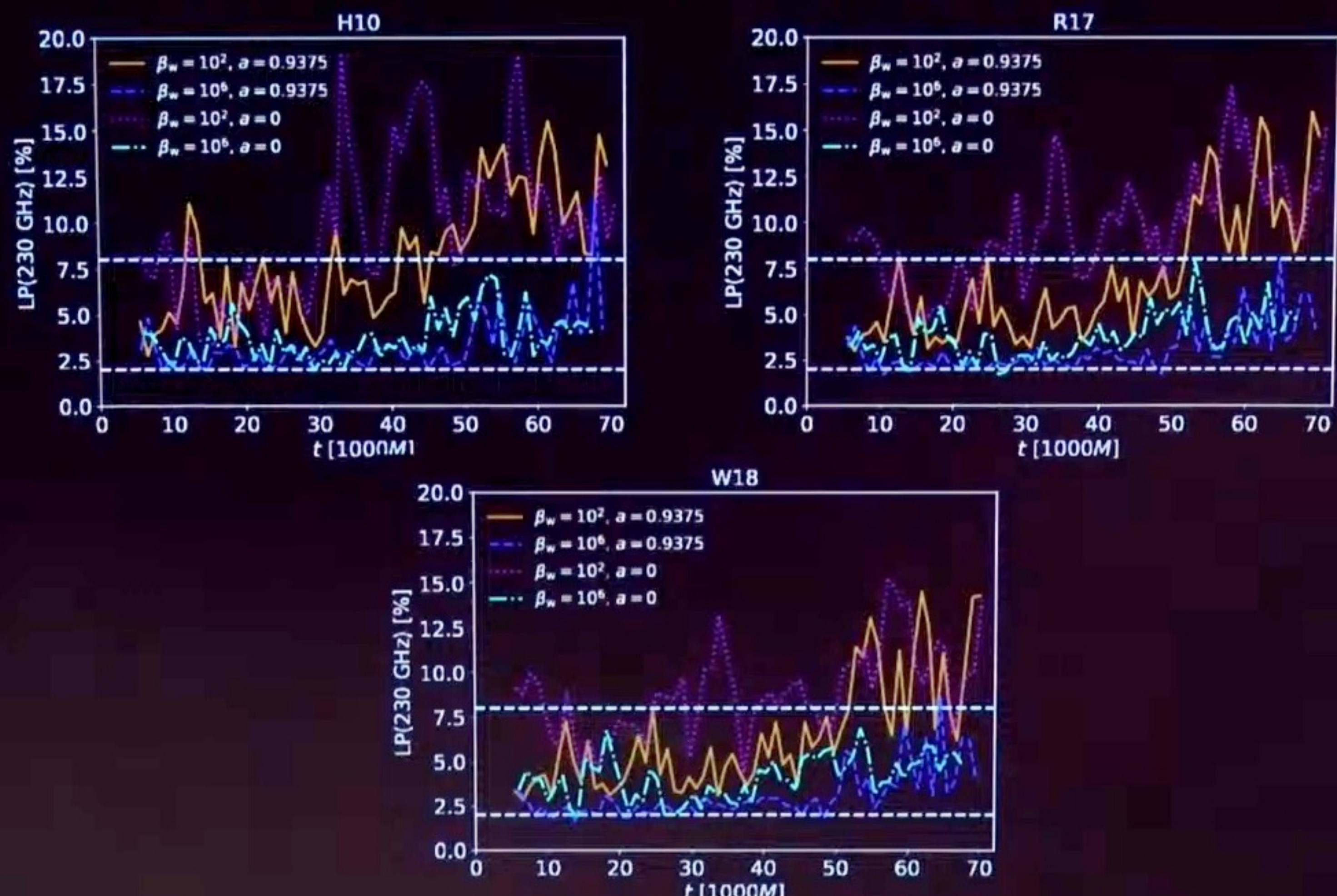


Shaded region: Observed value

Reconnection based heating better!

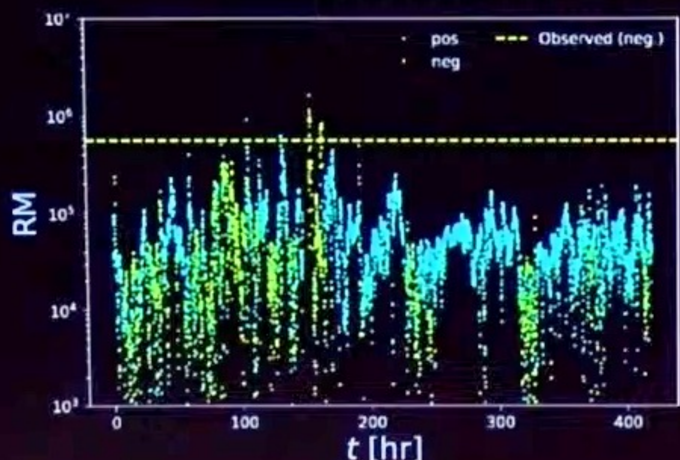
Weaker magnetic field case more favourable!

Unresolved Linear Polarization Fractions



Rotation Measure

Small-Scale Flux Simulation



Observational Definition:

$$\mathrm{EVPA} = \mathrm{EVPA}_0 + \mathrm{RM}\lambda^2$$

Theoretical Result for Relativistic Point Source

$$\mathrm{RM} \propto \int f(\Theta_e) n_e \mathbf{B} \cdot \mathbf{ds}$$

$$f(\Theta_e) \sim 1/\Theta_e^2$$

Large-Scale Flux Simulation

Conclusions

- Sagittarius A* presents unique opportunity to study AGN accretion
  1. Bondi radius resolved
  2. Stellar winds that source accretion well constrained
- Wind-fed simulations can reasonably match observations (230 GHz flux, RM, LP fraction, X-ray luminosity, density profile)
- Strongly magnetized flows are predicted (though not necessarily MAD)
- Tilted disks/jets align during peak magnetic flux [i.e., when MAD or close to MAD]
- Observed RM requires consistent large-scale B-field

The trouble with people is not that they know so little, but that what they know is largely not true.

~ Mark Twain

Thank you.