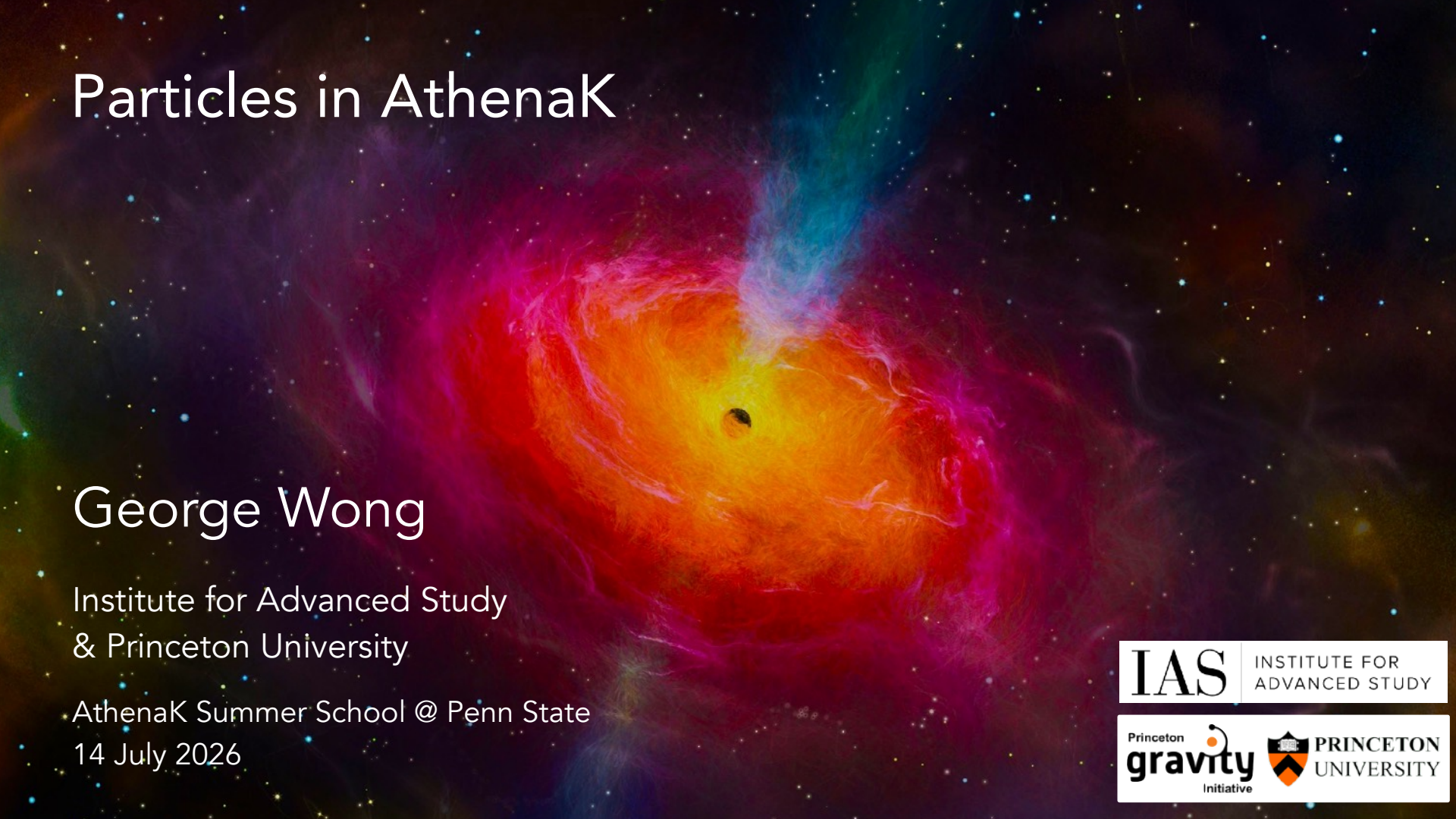
Particles in AthenaK



George Wong

Institute for Advanced Study
& Princeton University

AthenaK Summer School @ Penn State
14 July 2026

Particles in AthenaK

"a practical guide to thinking about, using, and possibly developing particles "

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IAS INSTITUTE FOR ADVANCED STUDY

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Particles in AthenaK

"a practical guide to thinking about, using, and possibly developing particles + some applications"

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outline

- introduction to particles
  - — what do we mean by particles (taxonomy)?
  - — AthenaK particle overview
  - — nuances / caveats / challenges
- mass transport in non-radiative accretion disks
  - — introduction to these accretion systems
  - — dynamics and kinematics of the flows
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  - — why you should care about jets
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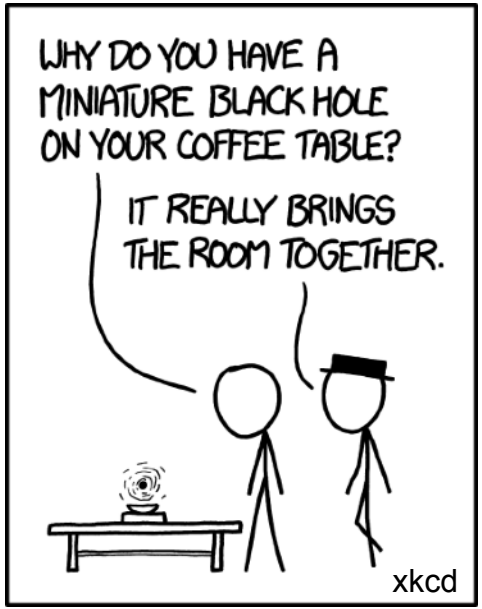
  - — entrainment via the Kelvin-Helmholtz instability



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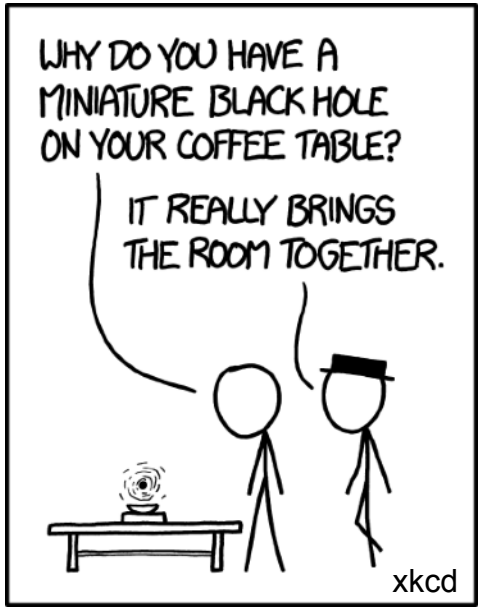
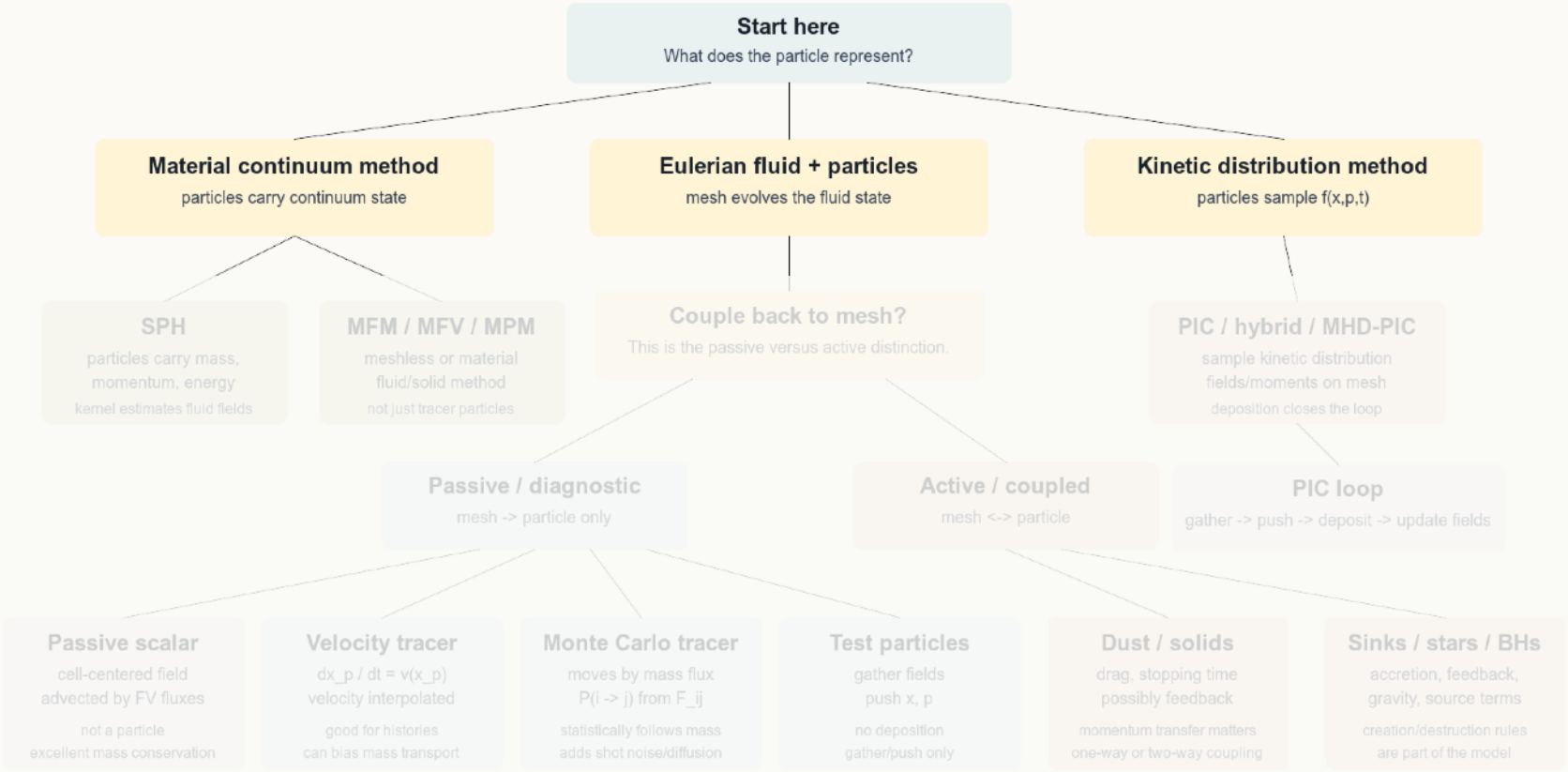


… what is a particle?

How to Think About "Particles" in Fluid Codes

First ask what the particle represents, how it moves, and whether it changes the mesh state.



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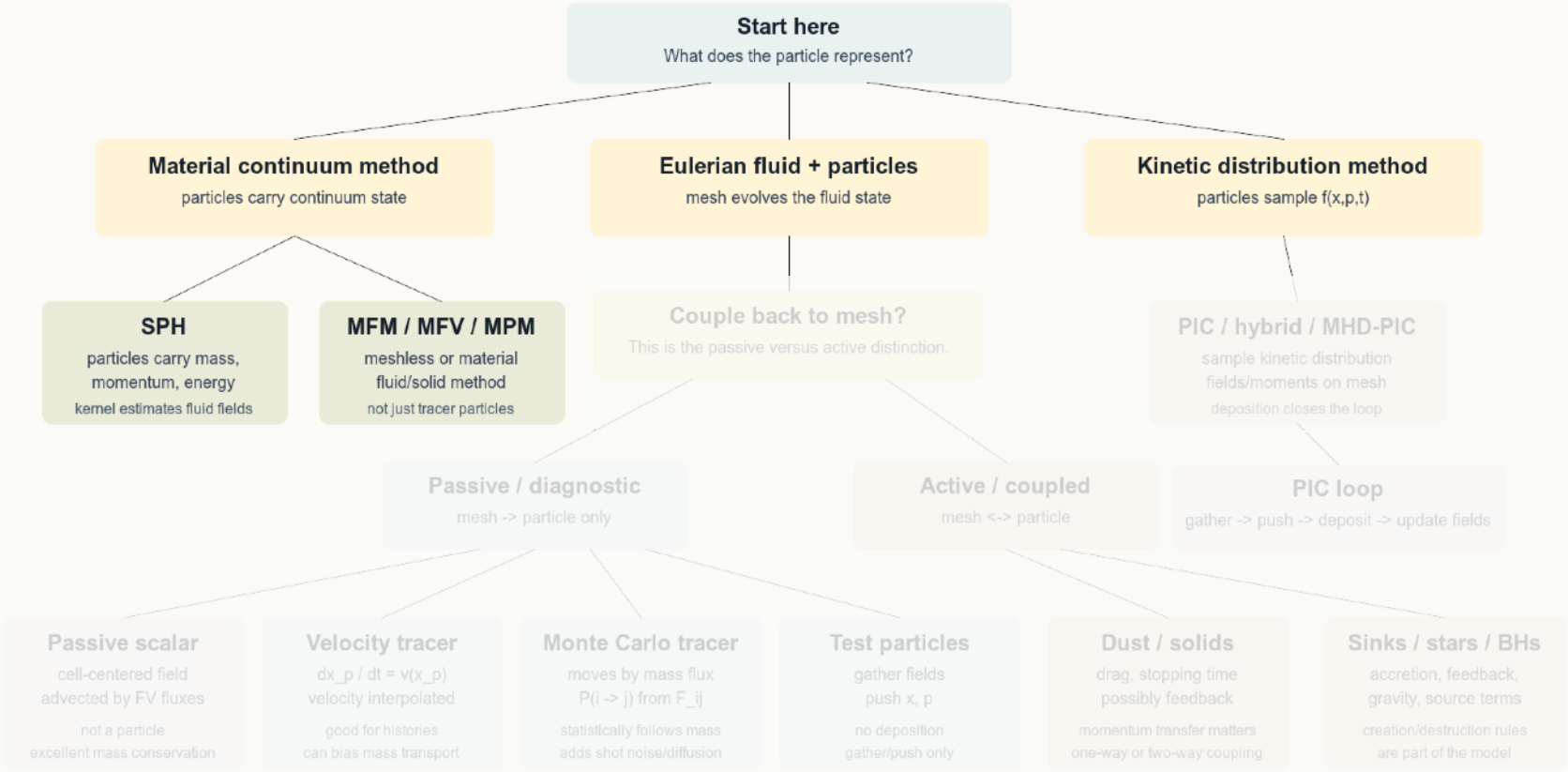

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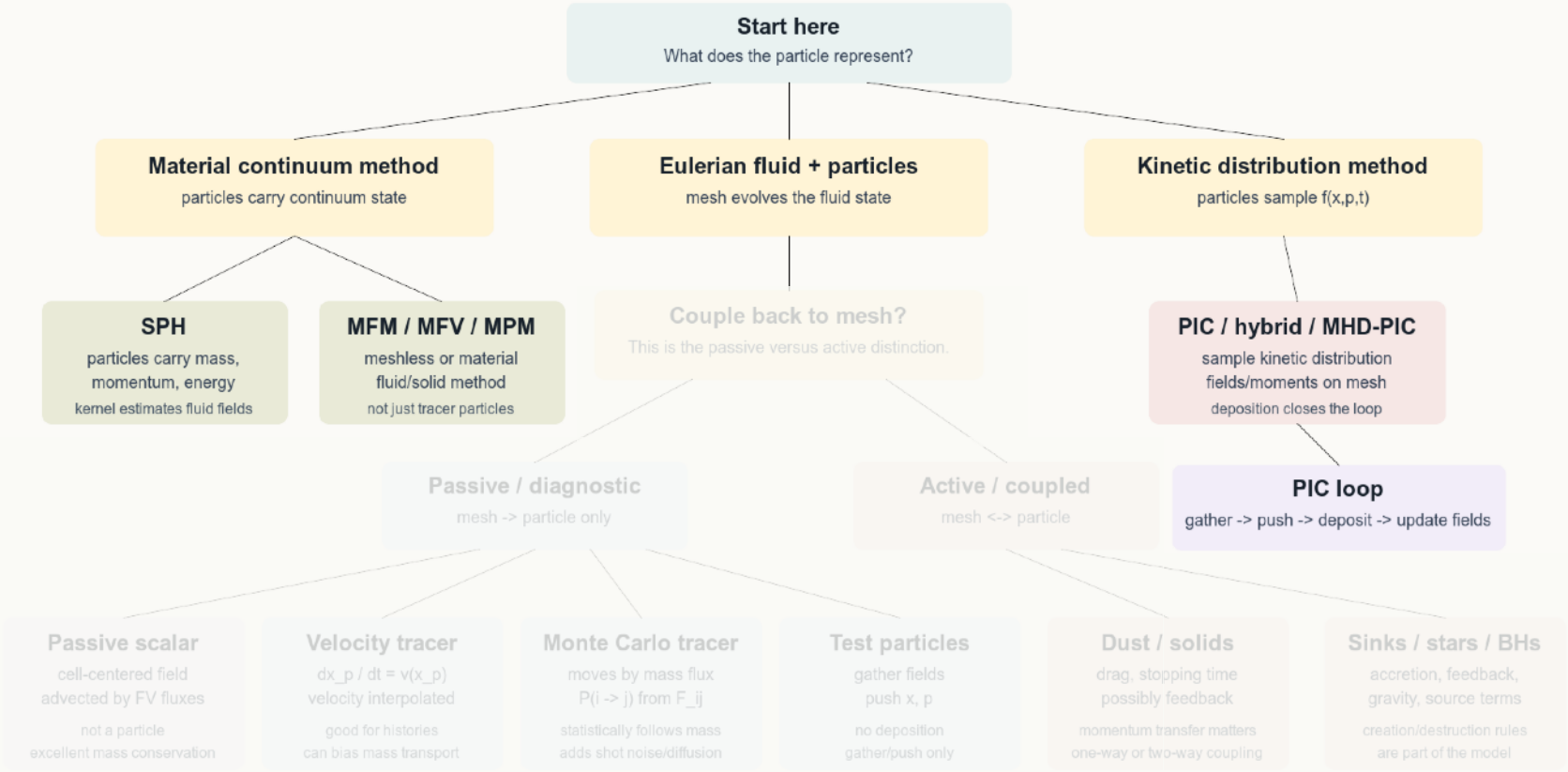

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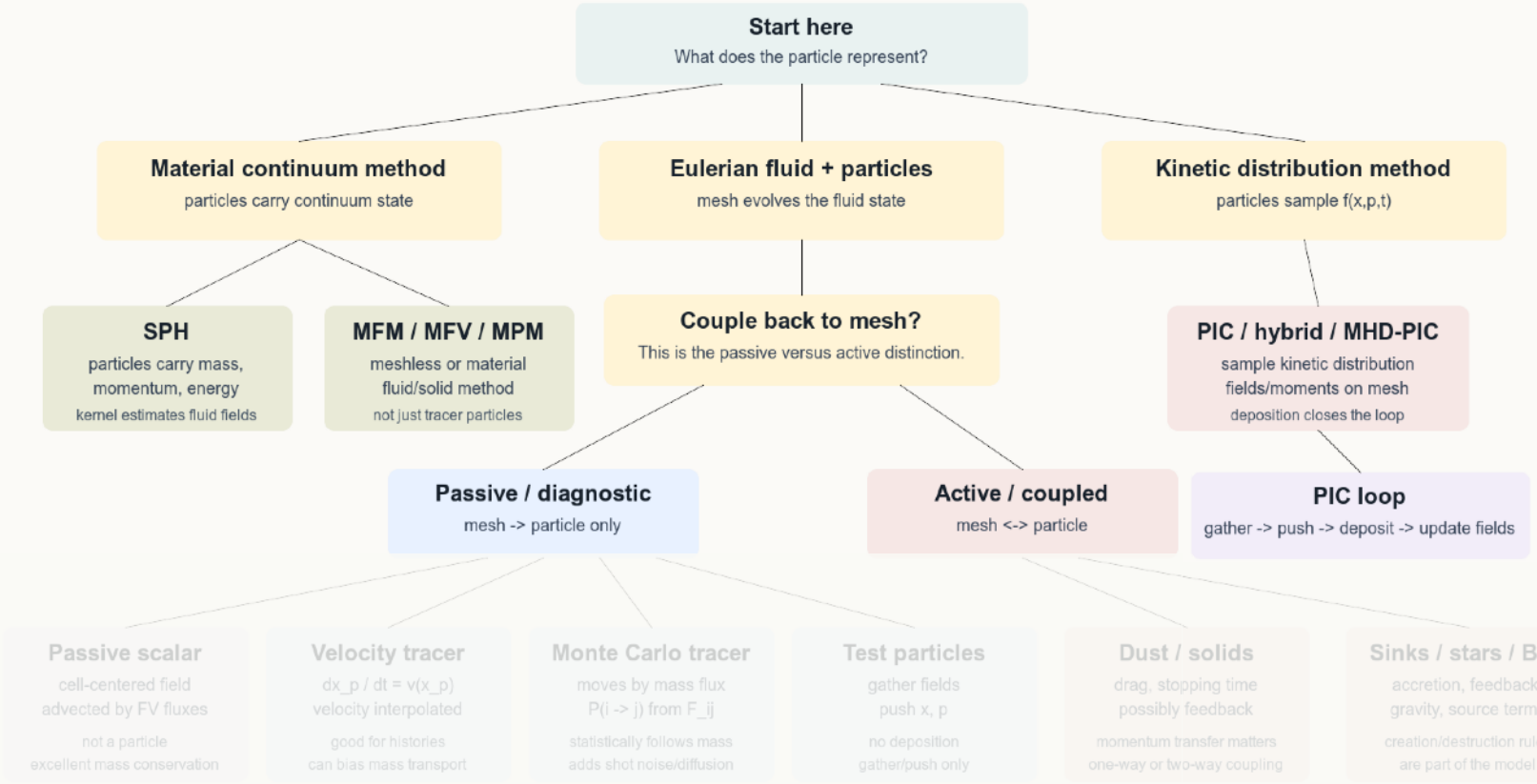

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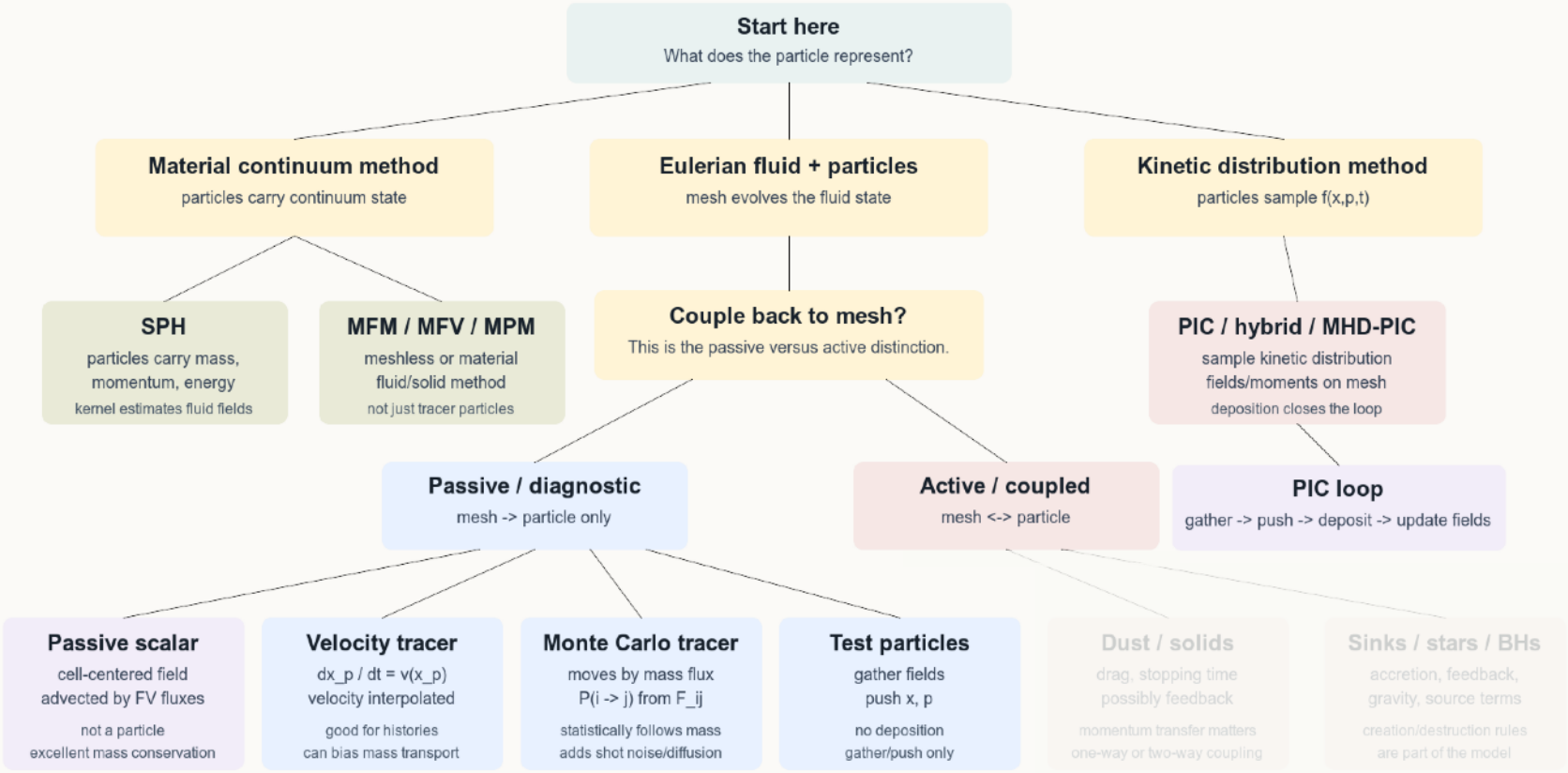

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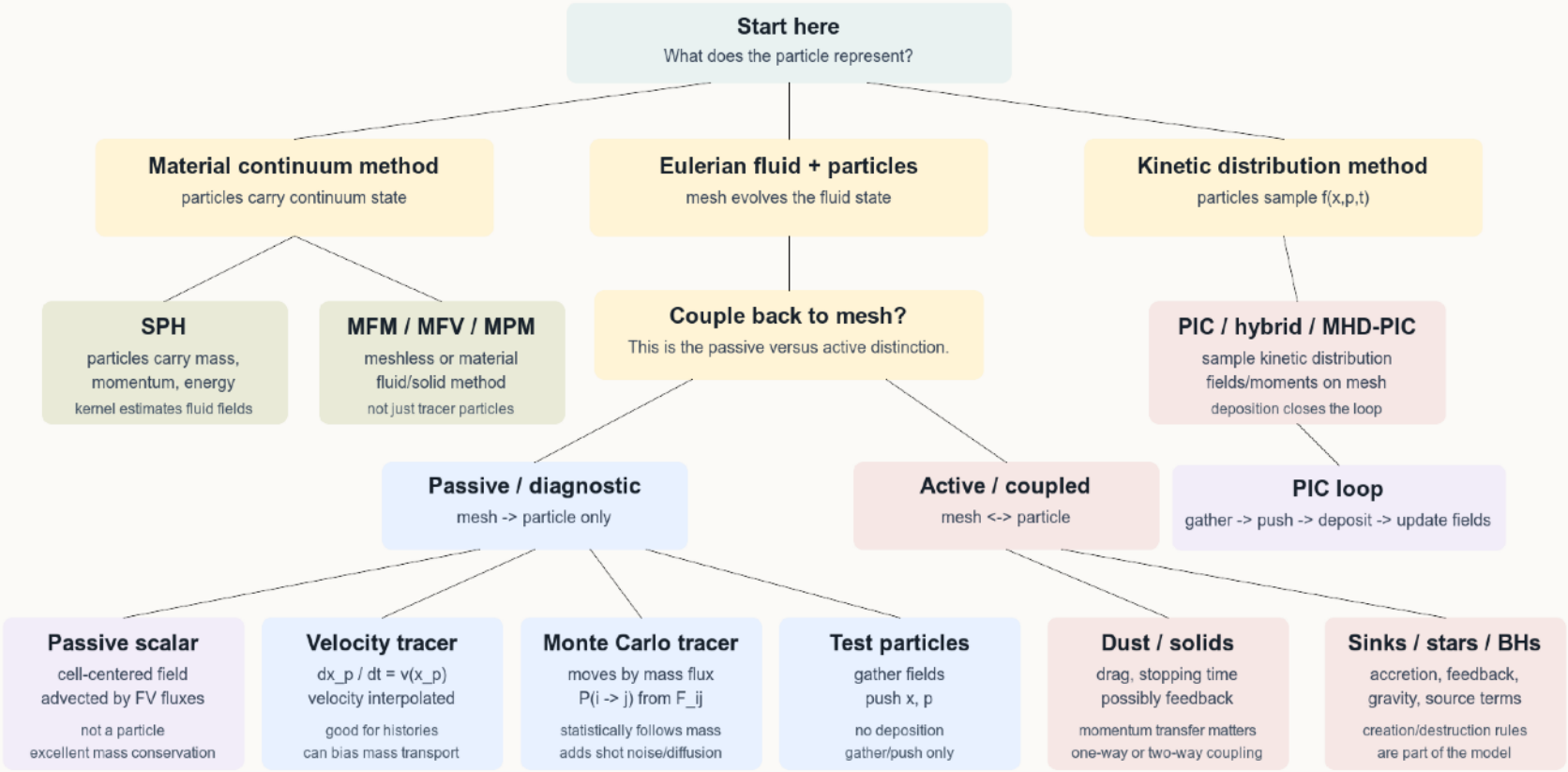

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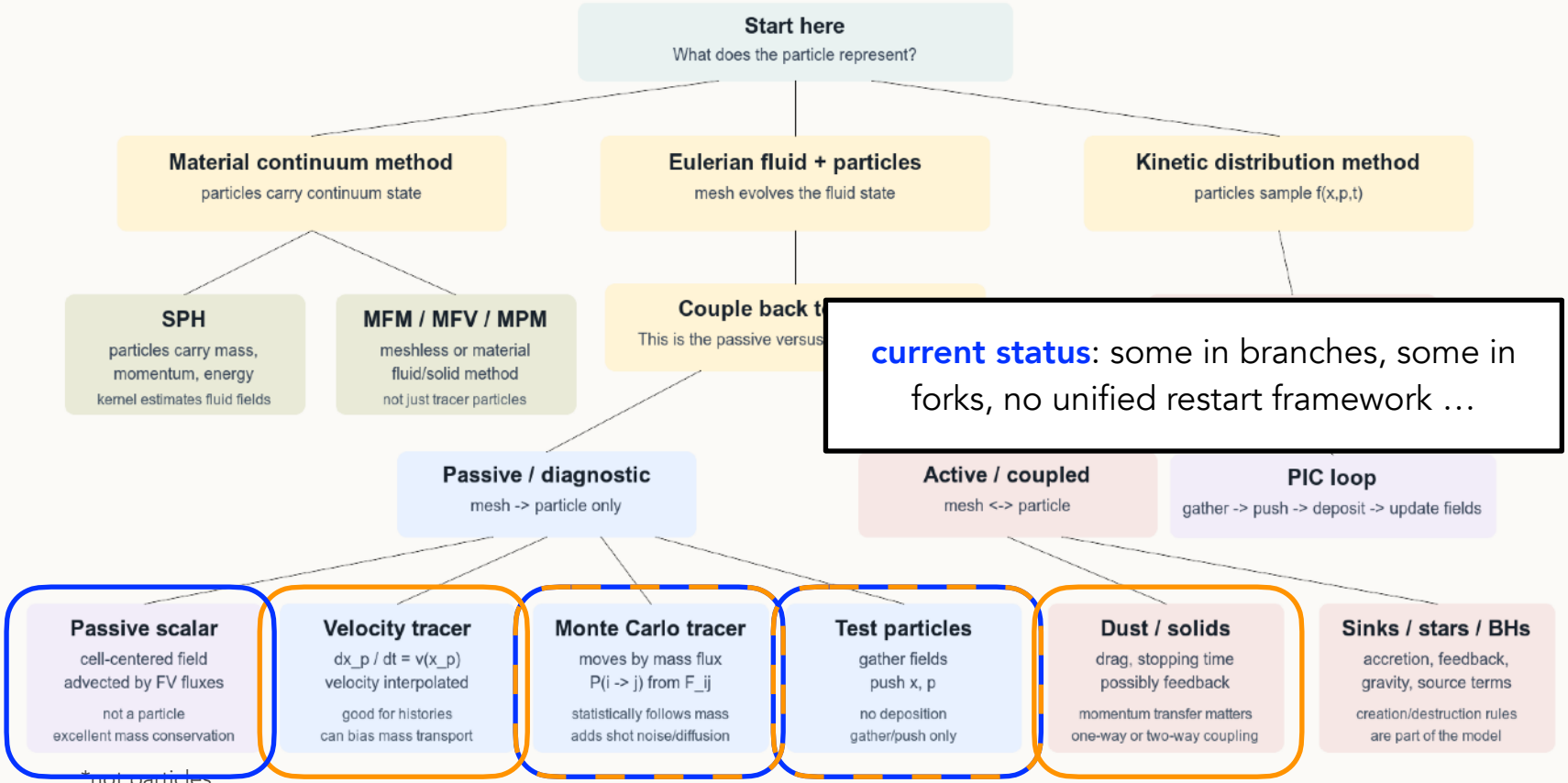

*not particles

general particle data structure

```
class Particles {
  friend class ParticlesBoundaryValues;
 public:
  Particles(MeshBlockPack *ppack, ParameterInput *pin);
  ~Particles();

  // data
  ParticleType particle_type;
  int nprtcl_thispack;             // number of particles this MeshBlockPack
  int nrdata, nidata;
  DvceArray2D<Real> prtcl_rdata;   // real number properties each particle (x,v,etc.)
  DvceArray2D<int>  prtcl_idata;   // integer properties each particle (gid, tag, etc.)
  Real dtnew;

  Real min_radius;  // particles that enter within this radius will not be updated

  ParticlesPusher pusher;

  // Boundary communication buffers and functions for particles
  ParticlesBoundaryValues *pbval_part;

  // container to hold names of TaskIDs
  ParticlesTaskIDs id;

  // functions
  ...
```

general (passive) particle update procedure

```
for each timestep n -> n+1:

  set dt from fluid / driver

  if particles are scheduled before fluid integrator:
      EvolvePassiveParticles(dt)

  advance fluid/MHD/GR fields through normal AthenaK time integrator

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  write outputs if needed
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```

```
EvolvePassiveParticles(dt):

  Task 1: Push
      for each local particle p:
          > load particle state
          > use Particles::Push(ParticlesPusher) to update state
          > store particle state

  Task 2: NewGID / ownership update
      for each particle:
          determine new(?) MeshBlock, consider boundary conditions
          mark particles that left the local rank
          freeze or destroy
  ...
  Task 5: SendP
      pack outgoing particles + send to new ranks

  Task 6: RecvP
      receive incoming particles
      insert into local particle arrays
      fill holes left by sent/destroyed particles
      resize arrays if needed
  ...
```

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          > store particle state

  Ta
  ..
  Ta
  Ta
  ..
```

```
Particles::Push(ParticlesPusher)

          if pusher == drift:
              x_p <- x_p + velocity_p * dt_eff

          if pusher == boris / GR:
              gather mesh fields at particle position
                  B, E, metric data
              update momentum/velocity with Boris / GR pusher
              update position

          if pusher == lagrangian_mc:
              read local density u1(IDN)
              read saved density fluxes uflxidnsaved
              compute outward flux probabilities
              draw random number
              move particle by at most one cell
```

particle types that have been implemented

Boris pusher (e.g., charged particles)

```
BorisStep(p, dt, update_position):

  x, u <- particle position and momentum

  x_half <- drift x by dt/2 using current u

  E, B, metric <- gather at x_half
  u <- transform to local pusher frame

  u <- u + (q/m) E dt/2          # electric half-kick
  u <- rotate u about B by dt    # magnetic Boris rotation
  u <- u + (q/m) E dt/2          # electric half-kick

  u <- transform/store updated momentum

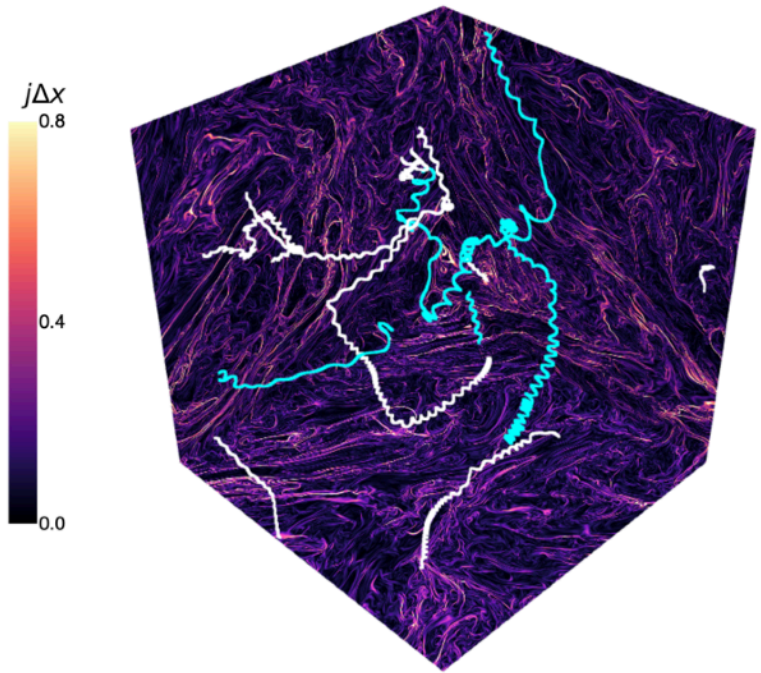
  if update_position:
      x <- drift x_half by dt/2 using updated u
      store x


FullGRStep(p, dt):   # operator split for motion in curved space

  BorisStep(p, dt/2, update_position=false)

  GeodesicStep(p, dt)

  BorisStep(p, dt/2, update_position=false)
```



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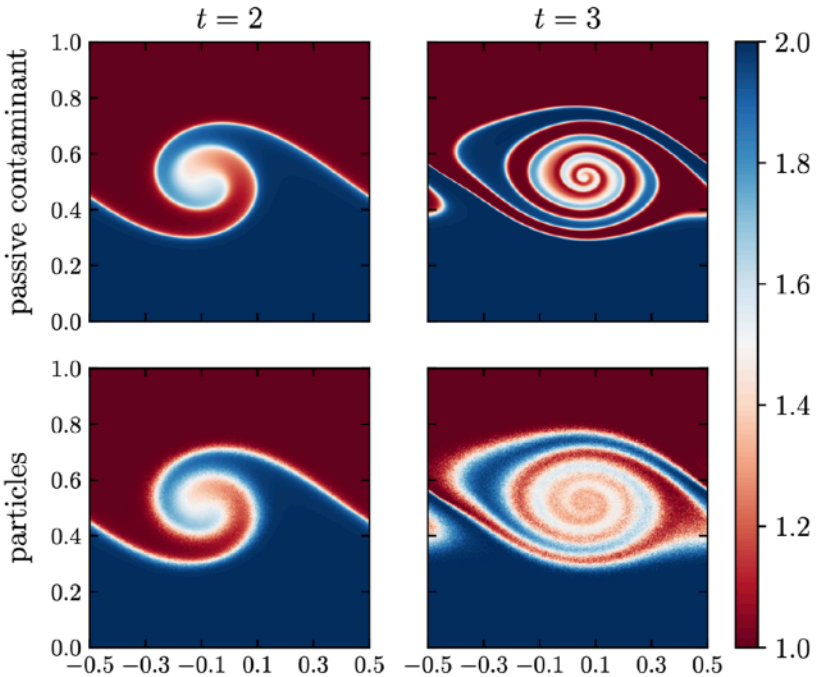

Monte Carlo Lagrangian tracers

```
LagrangianMCStep(p):

  cell <- cell containing particle

  read rho in cell
  read saved density fluxes through cell faces

  for each face:
      P(face) <- max(outward flux through face, 0) / cell_mass

  draw random number r

  if r selects a face:
      move particle to neighboring cell across that face
  else:
      leave particle in current cell

  store last move/refinement info
```

general (~~passive~~ ***active**) particle update procedure

when particles are active, the problem is more complicated:

momentum conservation
=> dp(particle) + dp(fluid) = 0

energy conservation
=> drag + heating = 0

stiffness (cf. Jake Simon's talks)

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need: conservation laws, particle -> grid kernel, implicit solve, …

general (~~passive~~ ***active**) particle update procedure

when particles are active, the problem is more complicated:

momentum conservation
=> dp(particle) + dp(fluid) = 0

energy conservation
=> drag + heating = 0

stiffness (cf. Jake Simon's talks)

```
for each active particle:
    define 27-cell deposition cloud around particle
    compute weights w_i
    distribute weighted particle momentum into those cells

solve (local) implicit momentum exchange:
    particle momentum loss/gain depends on updated gas velocity
    gas momentum gain/loss depends on updated particle momentum

for each active particle:
    update particle momentum using solved impulse J_p

for each affected gas cell:
    deposit opposite impulse: Delta P_i = - sum_p w_i J_p

if conserving total energy:
    update gas energy / heat with consistent work term
```

need: conservation laws, particle -> grid kernel, implicit solve, …

practical thoughts and caveats

Before You Run Particles

Define the **particle**:
tracer, charged test particle, MC mass tracer, dust, sink?

Consider the **state**:
position, momentum/velocity, weight, tag, owner block

Check the **coupling**:
passive gather only, or active deposition back to mesh?

Describe the **lifecycle**:
initialization, injection, destruction, boundary behavior

Select how to **output**:
output cadence and format .. beware disk cost!

Choose how to perform **validation**:
what statistic should converge?
orbit error, mass distribution, flux statistics, restart continuity

Be Warned / Likely To Change

Particle behavior/implementation/support is **branch-dependent**.

Output exists, but **restarts not (formally) implemented** yet.

Current implementations** of particles are **passive**:
no back reaction … but:

Active particles are a larger, ongoing project:
coupling, deposition, conservation, and implicit stiff source terms
need to be address conceptually.

AMR behavior still **needs explicit validation**, especially across boundaries.

Particle identity can be subtle: IDs, ownership, deletion/freezing, and communication all matter.

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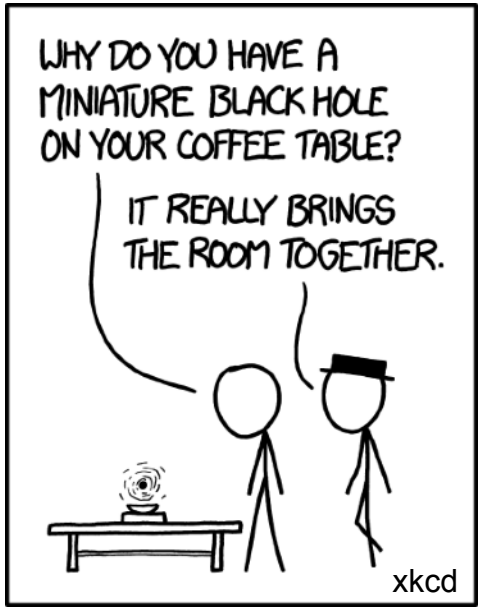


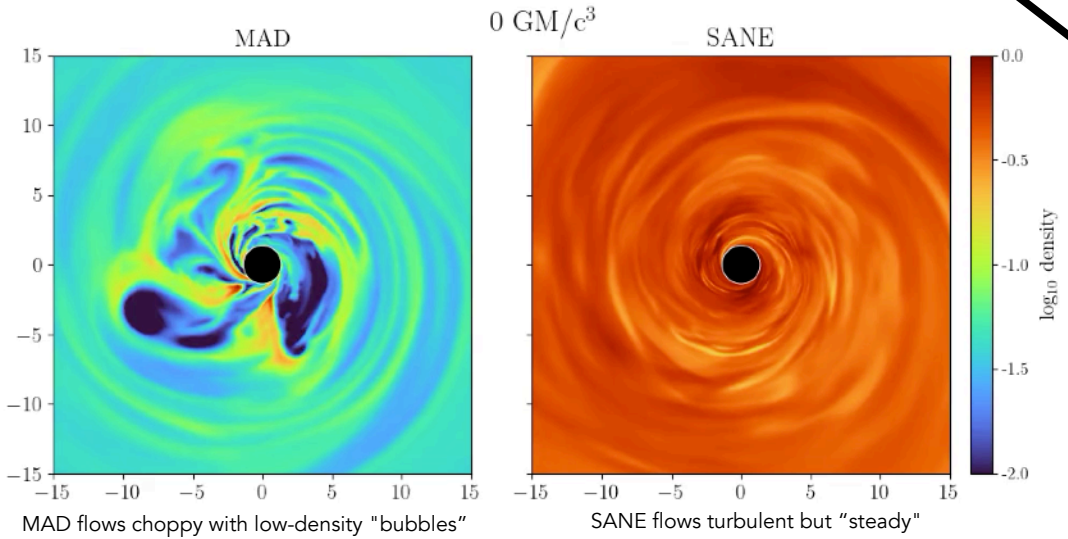
application:
kinematics + dynamics of thick-disk accretion

magnetic fields in black hole accretion

magnetic fields may **follow the turbulence** (SANE)

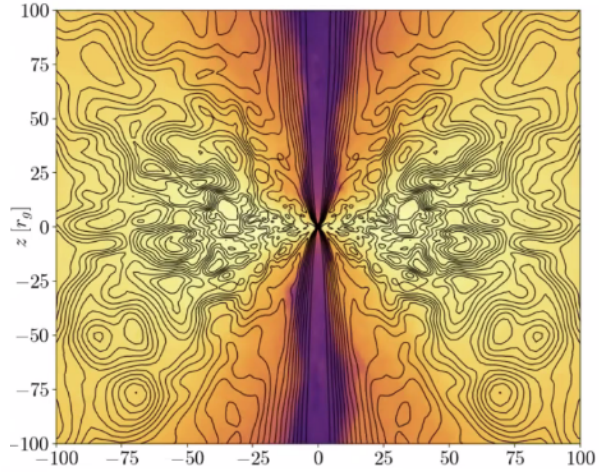
or be **dynamically important** (MAD)

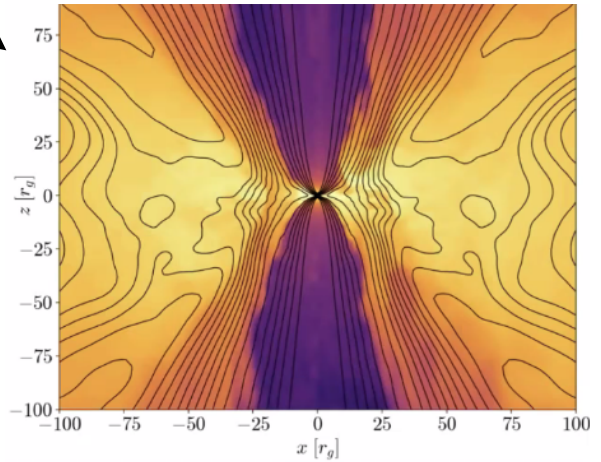
* midplane slice through simulation



MAD flows choppy with low-density "bubbles"

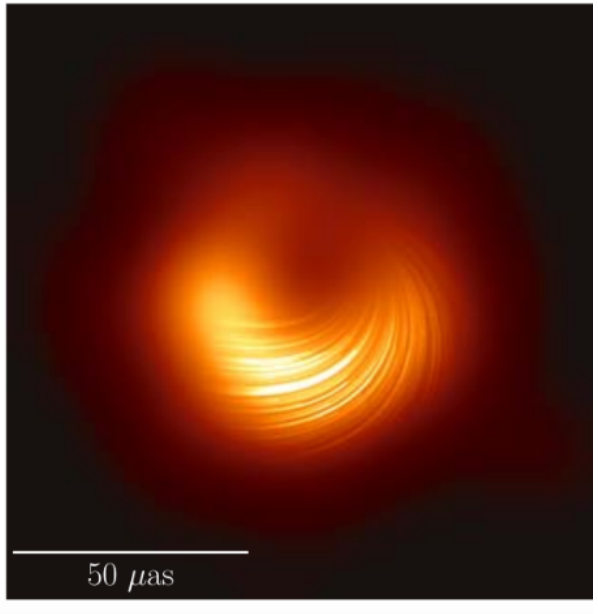
SANE flows turbulent but "steady"

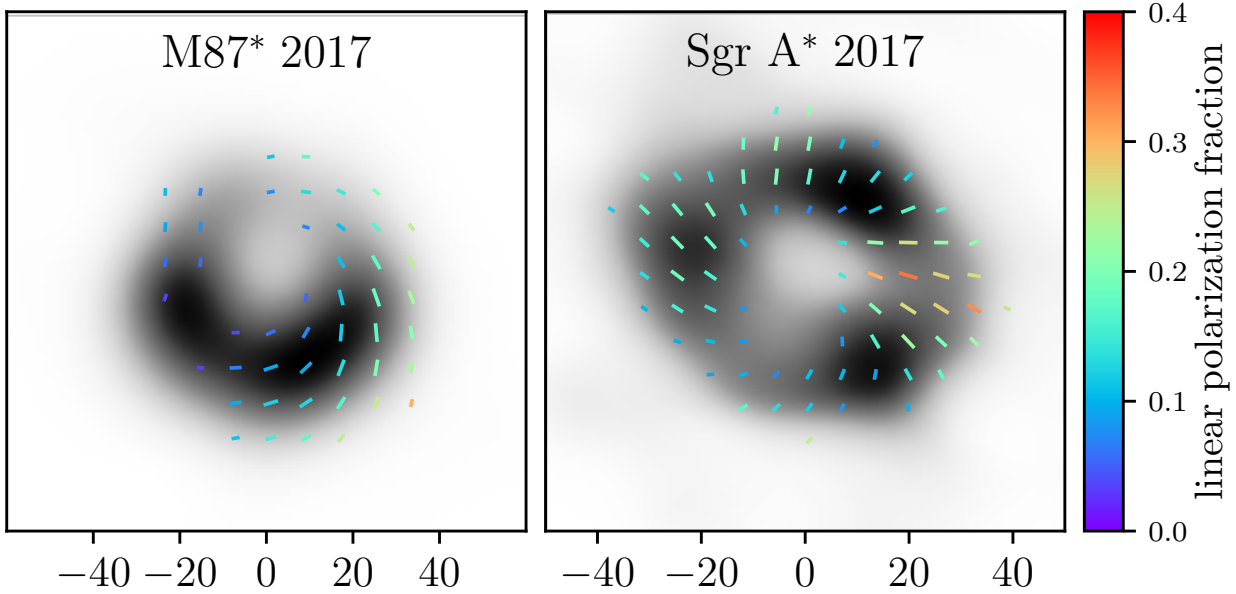




Wong+ 2022

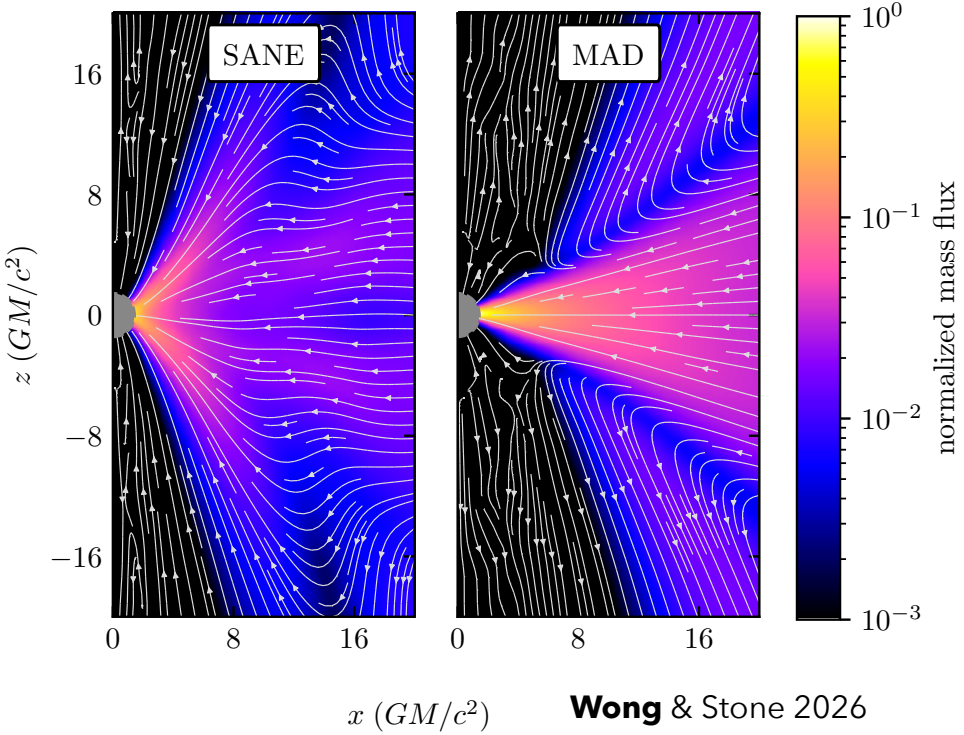
why do we care about the magnetic fields?





EHTC (2019, 2021, 2024)

SANE and MAD accrete by different channels

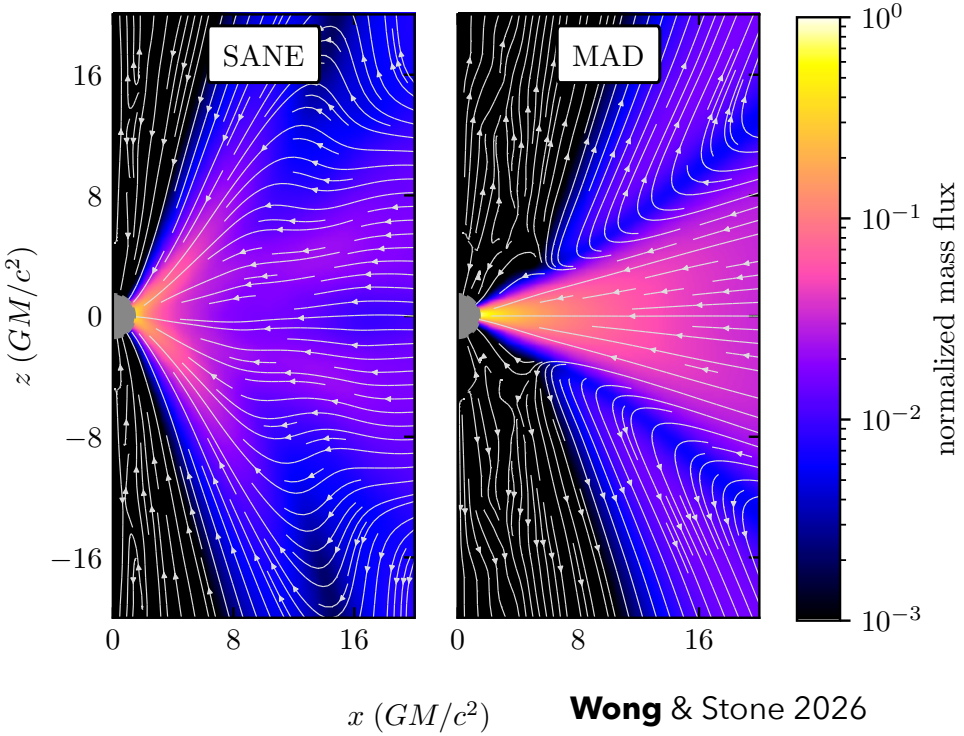


Wong & Stone 2026

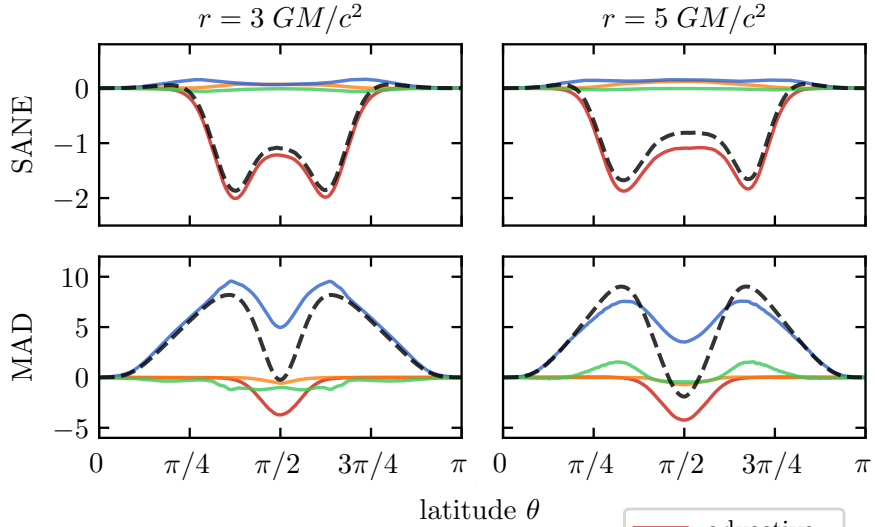
In SANEs, **vertical stratification** allows more efficient Maxwell angular momentum transport where plasma-β smaller

In MADs, nearly all of the disk is low β and **accretion can proceed** at all latitudes

SANE and MAD accrete by different channels



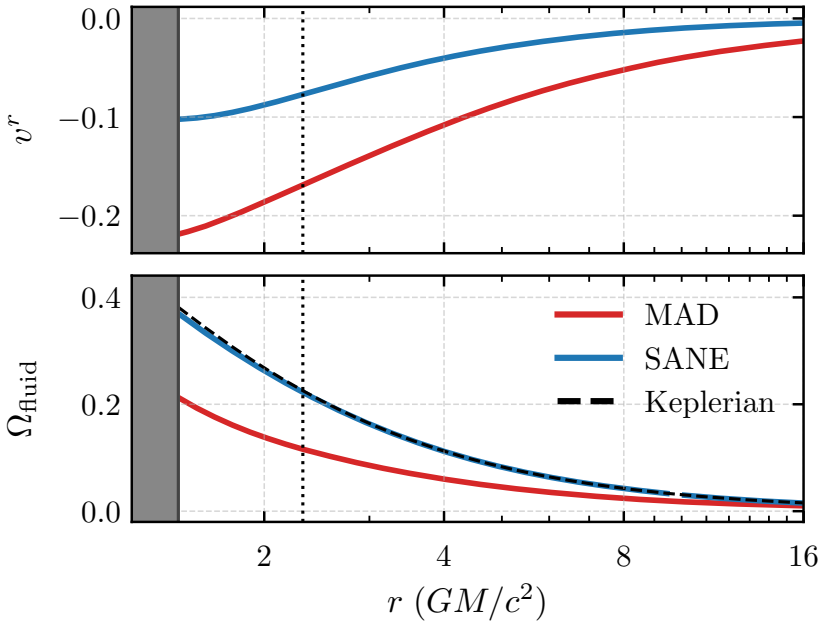
Wong & Stone 2026

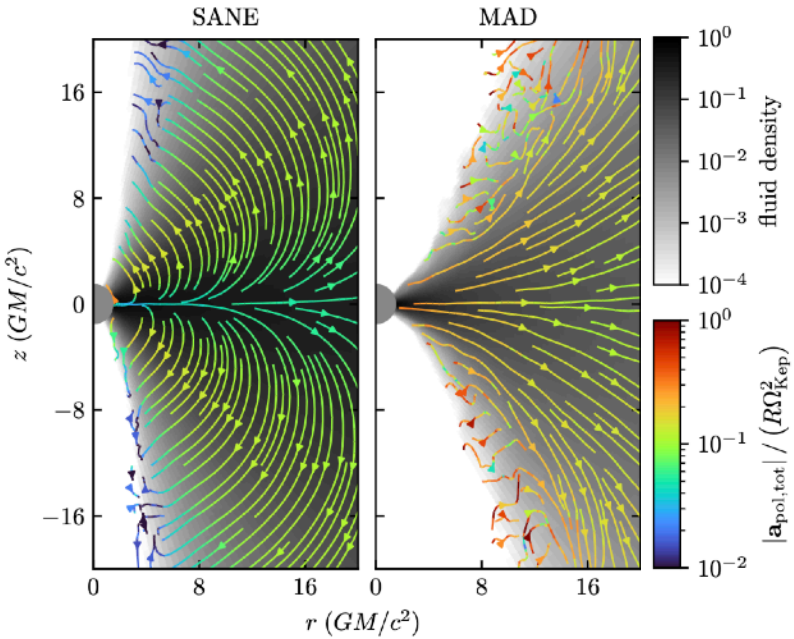


SANE dominated by **advective transport** with **Reynolds** and **Maxwell** in disk/surface

MAD dominated by **Maxwell stresses**

SANE and MAD have qualitatively distinct kinematics





Wong & Stone 2026

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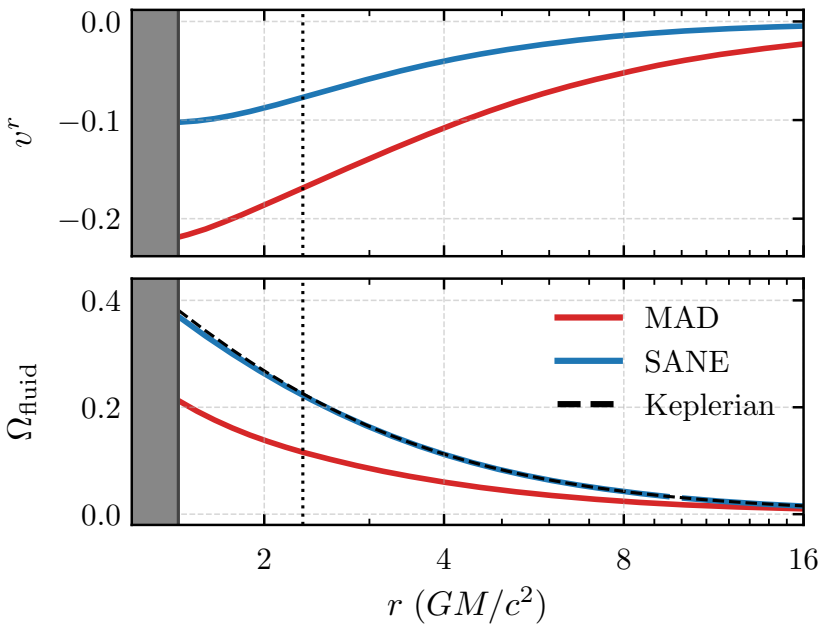

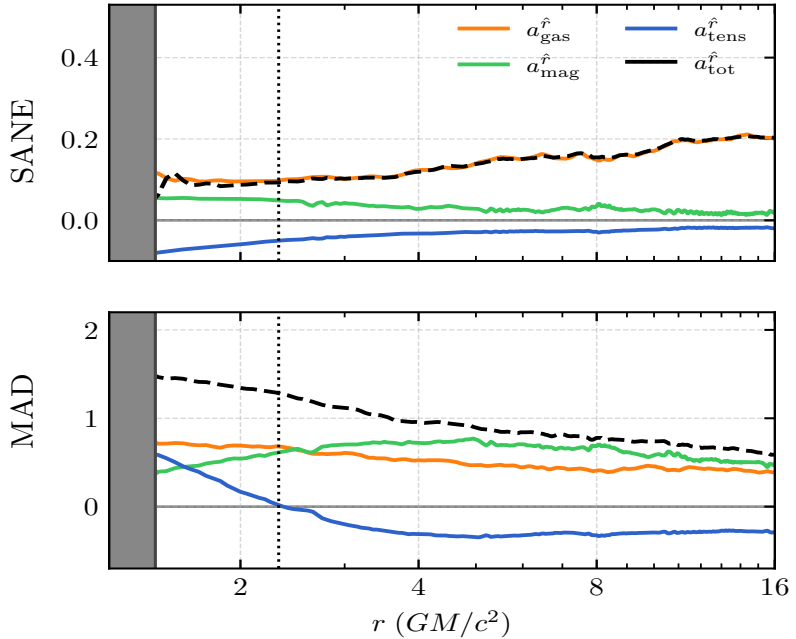

Wong & Stone 2026

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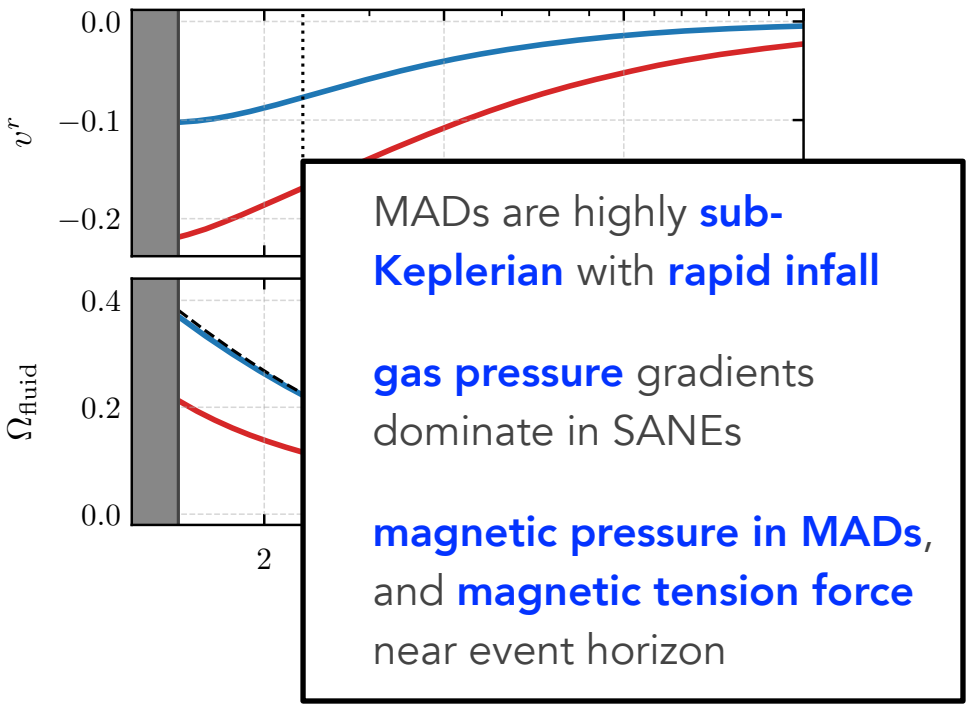
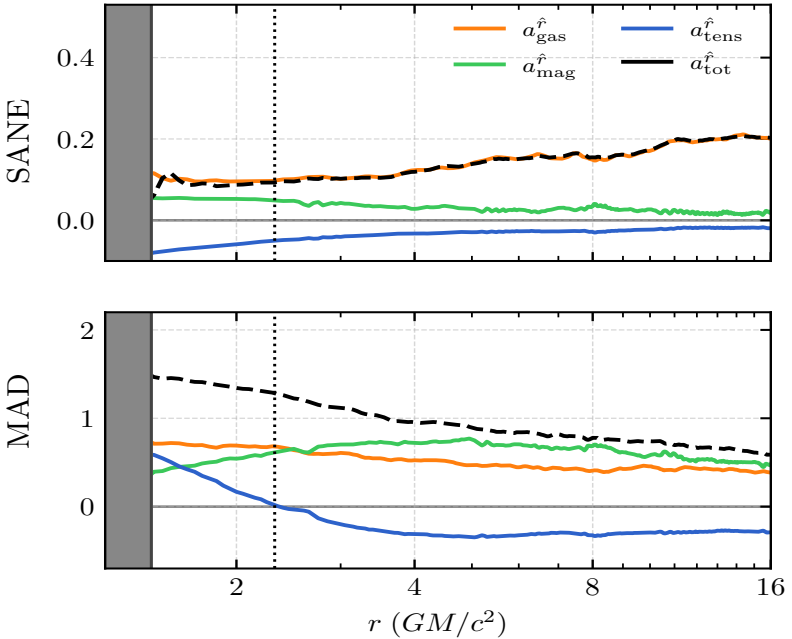


MADs are highly **sub-Keplerian** with **rapid infall**

gas pressure gradients dominate in SANEs

magnetic pressure in MADs, and **magnetic tension force** near event horizon

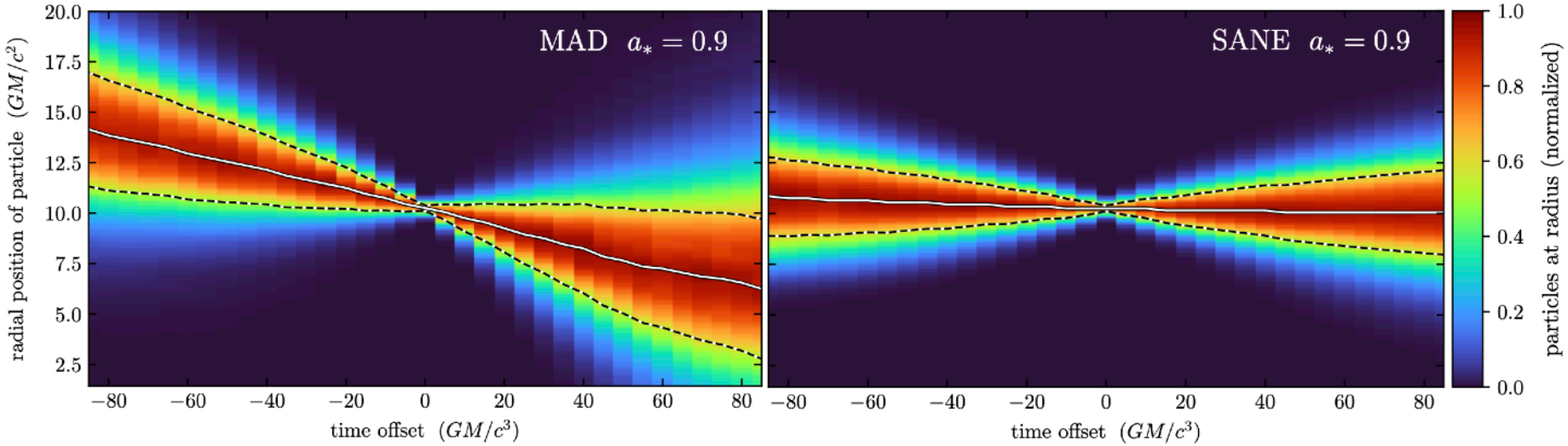


Wong & Stone 2026

mixing and advection

mass flux generally governed by advection and mixing (not necessarily diffusive … K not constant):

$$\partial_t C = \partial_r \left(K \, \partial_r C - v \, C \right) + s$$



Wong, Medeiros, Stone 2025

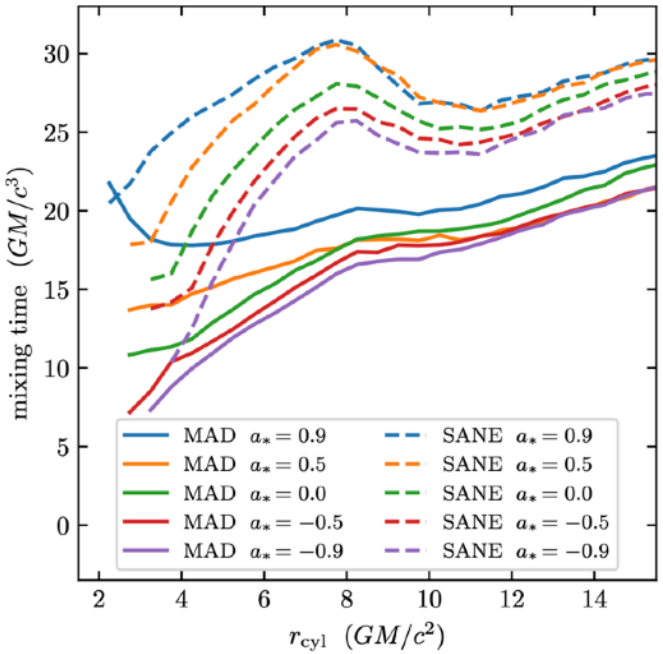
mixing and advection

Mixing consistently **faster in MADs** vs. SANEs.

Retrograde flows mix faster than prograde.

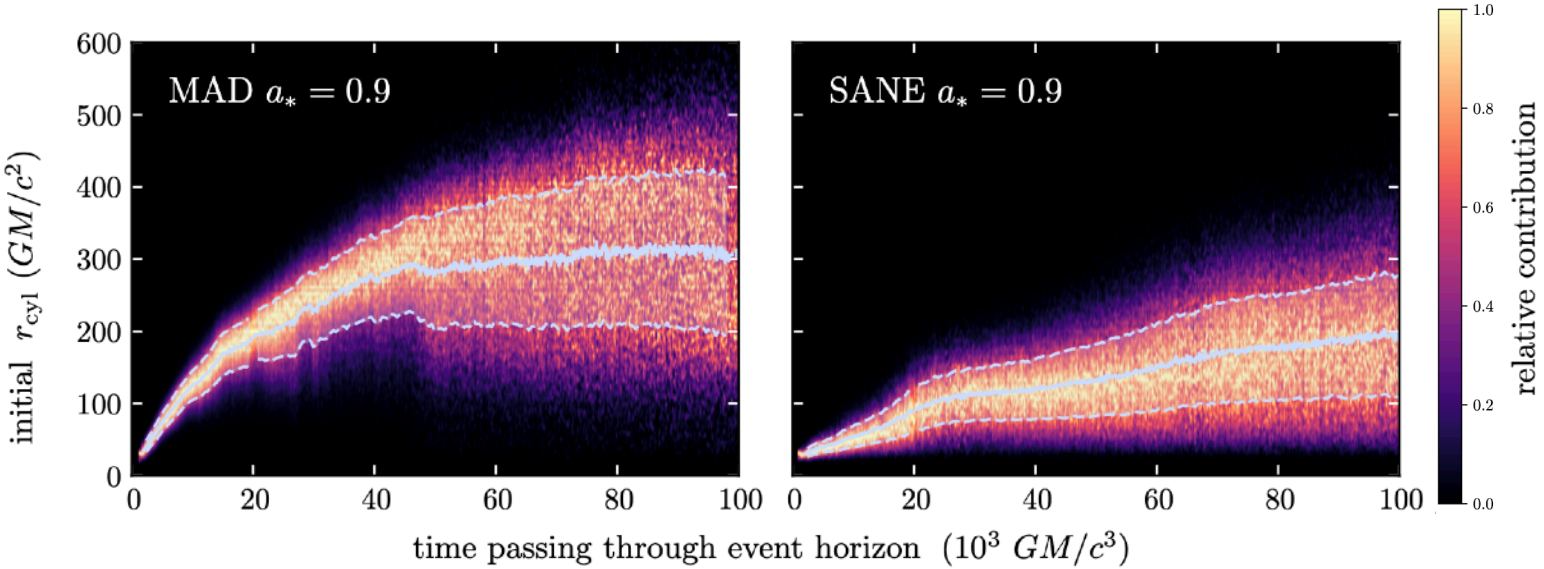
Mixing times generally **decrease toward hole** …

but not monotonic and may reflect the plasma state being "frozen" at larger radii before plunging toward the black hole.



Wong, Medeiros, Stone 2025

disk draining



Wong, Medeiros, Stone 2025

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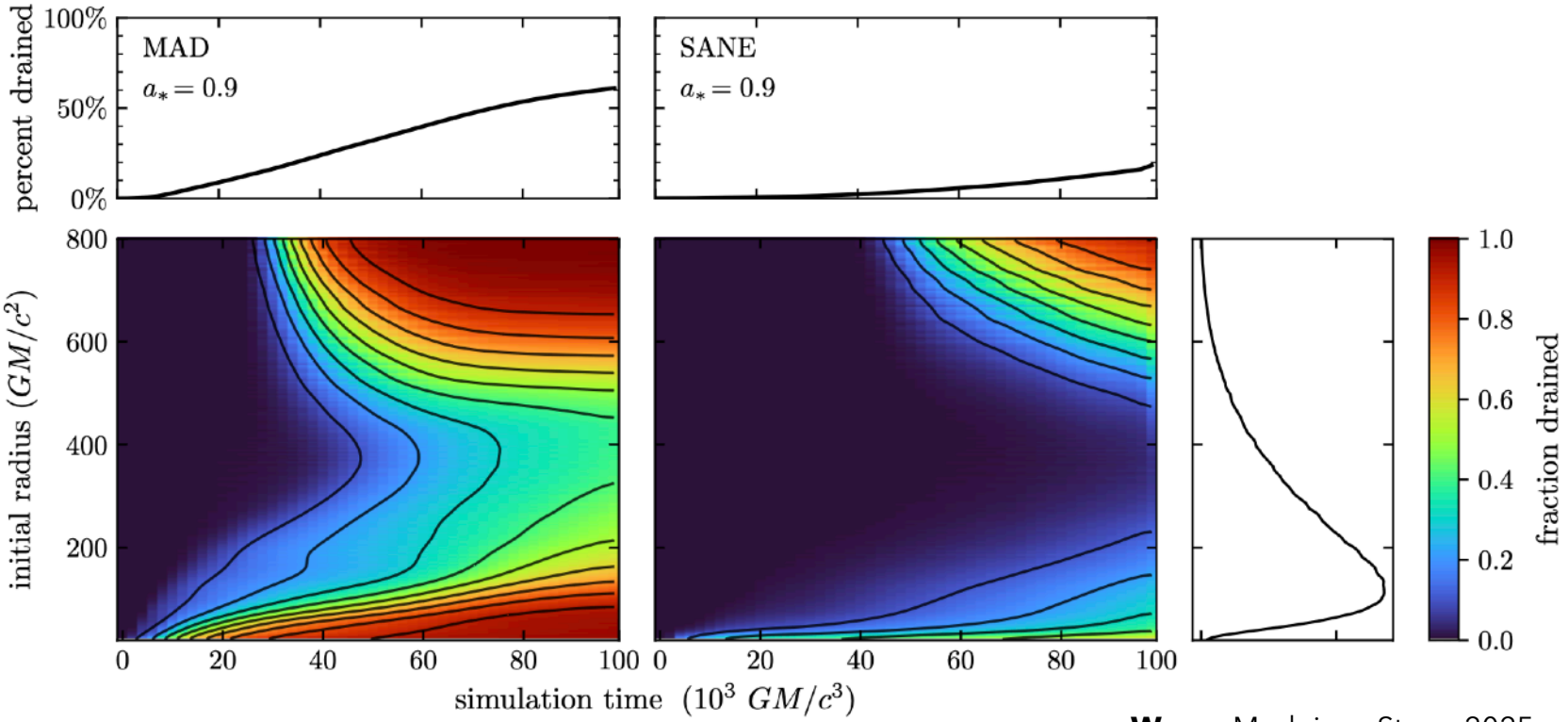

Wong, Medeiros, Stone 2025

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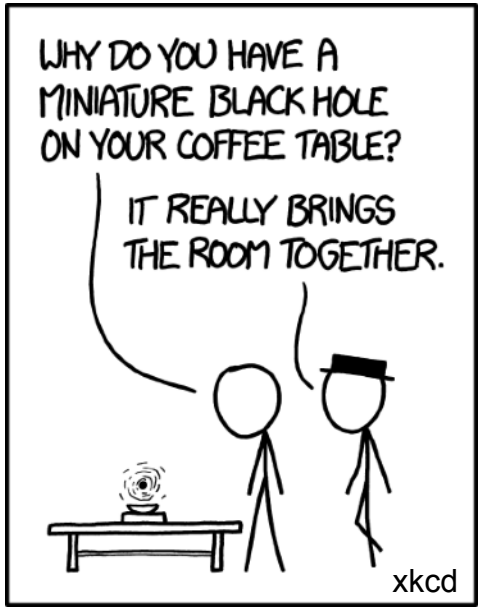
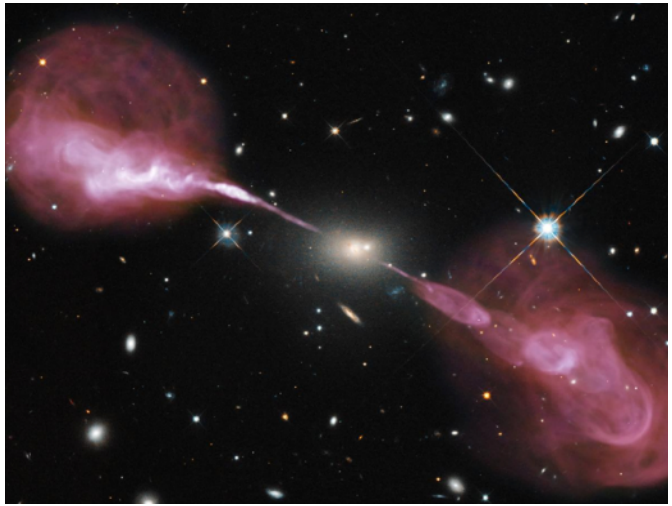


application:
understanding mass-loading in relativistic jets

relativistic jets launched by black holes

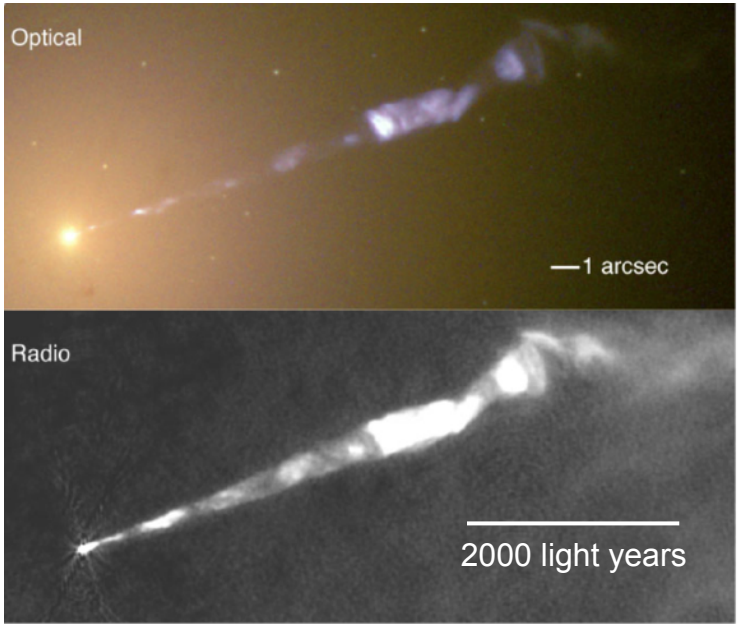
Hercules A



NASA, ESA, Baum & O'Dea, Perley & Cotton, Hubble Heritage

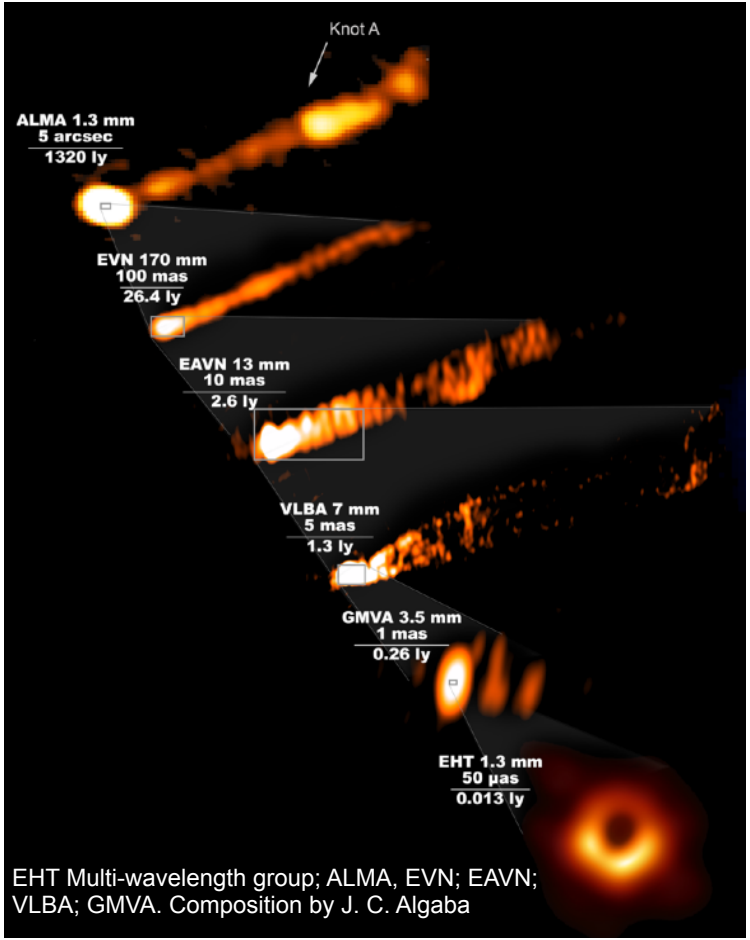
Centaurus A

NASA/CXC/CfA/R.Kraft et al./MPIfR/ESO/WFI/APEX/A.Weiss et al.

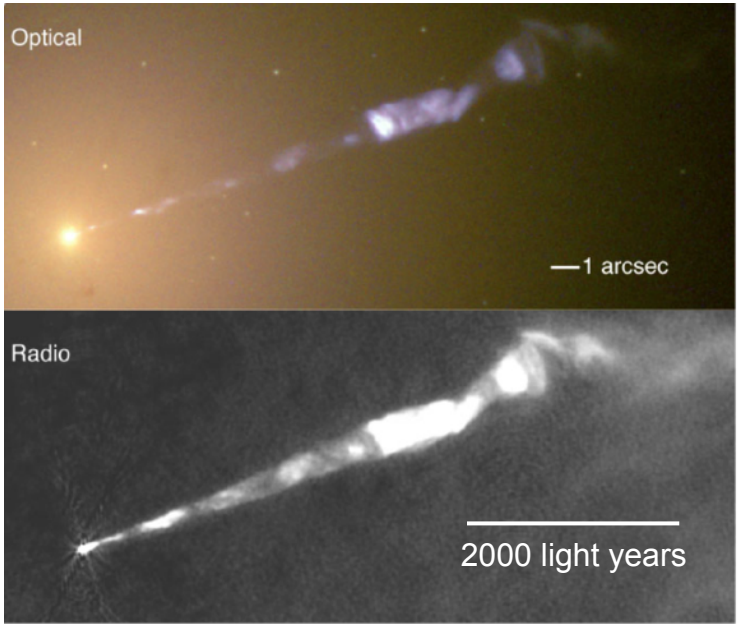


credit: J. Biretta

relativistic jets launched by black holes



EHT Multi-wavelength group; ALMA, EVN; EAVN; VLBA; GMVA. Composition by J. C. Algaba



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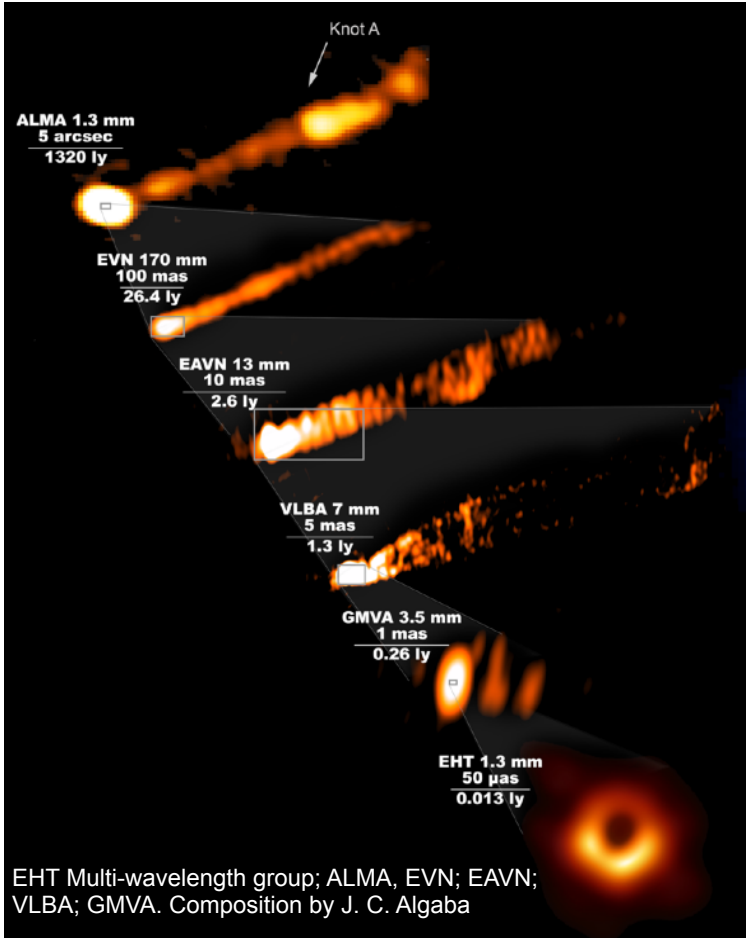

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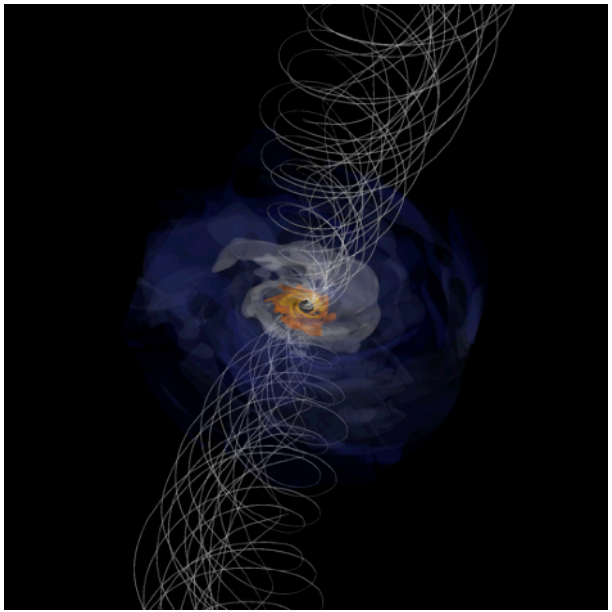
magnetic field lines advected with plasma

black holes drag spacetime as they **spin**

field twists around spin axis → Poynting flux



Wong+ 2025

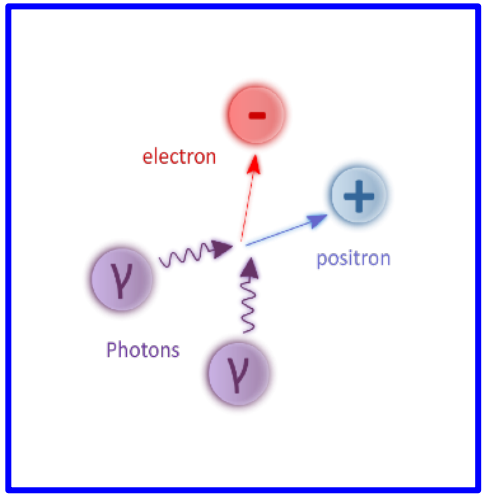
populating the jet

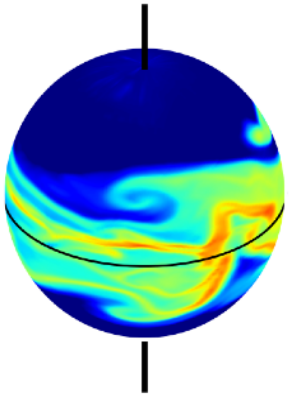
e.g., Beskin+, Hirotani & Okamoto, Ford+, Levinson & Cerutti, Chen+, Parfrey+

- electron–positron pair creation via gaps or drizzle

e.g., Mościbrodzka+, **Wong**+, Kimura & Toma, Yao+

- entrain plasma from the disk into the jet





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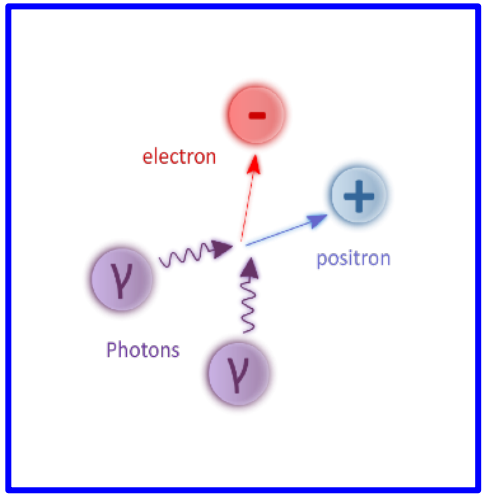
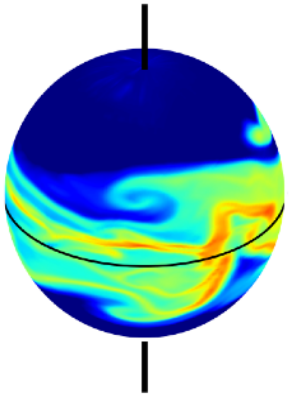
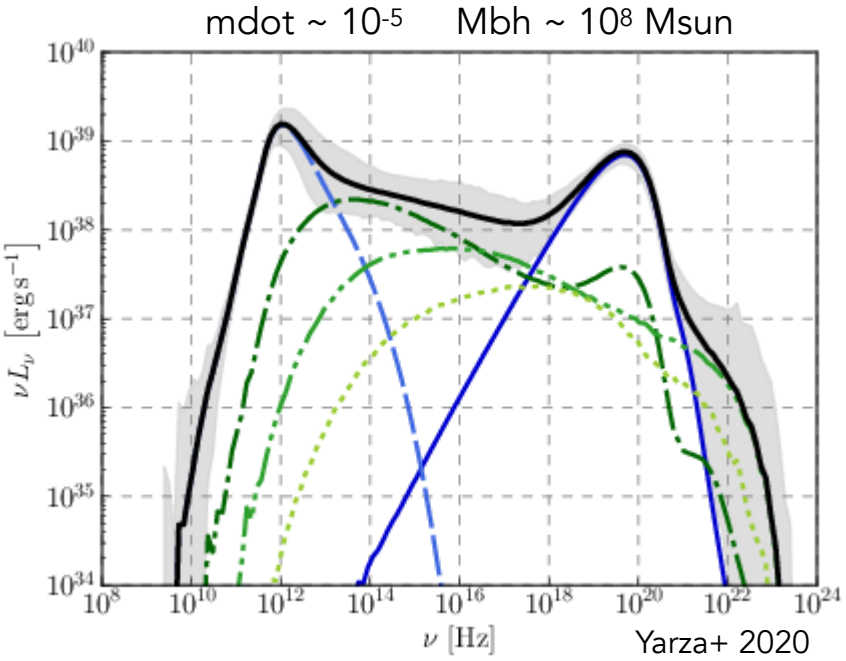




Breit–Wheeler process

- $e^- e^+$ pair created by **photon–photon** interaction
- photons → ≥ rest-mass energy of pair ~ 10^{21} Hz



pair cascade model

high frequency
+
low frequency

pair drizzle model

2 photons
near threshold

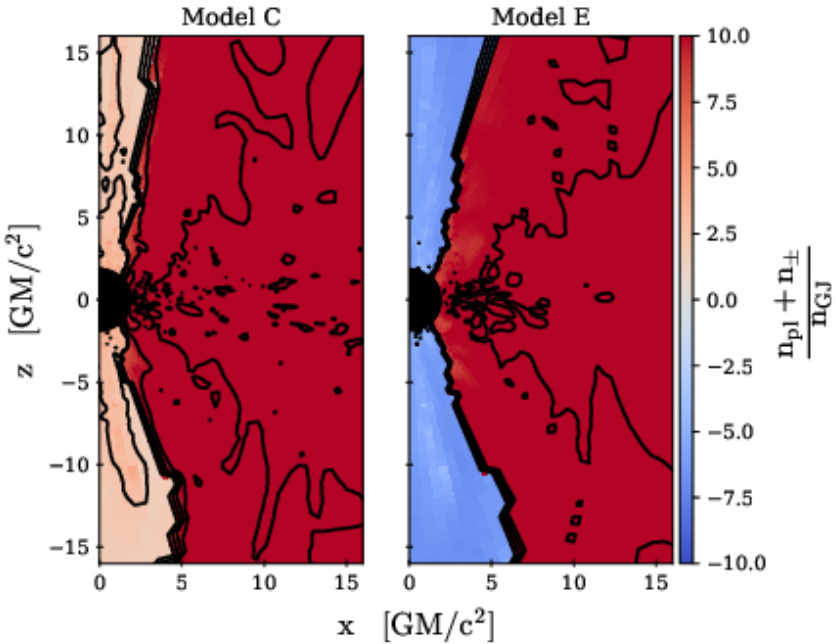
low charge regions → unscreened E fields
→ acceleration (Beskin+ 1992)

background radiation ← hot plasma
(Mościbrodzka+ 2011)

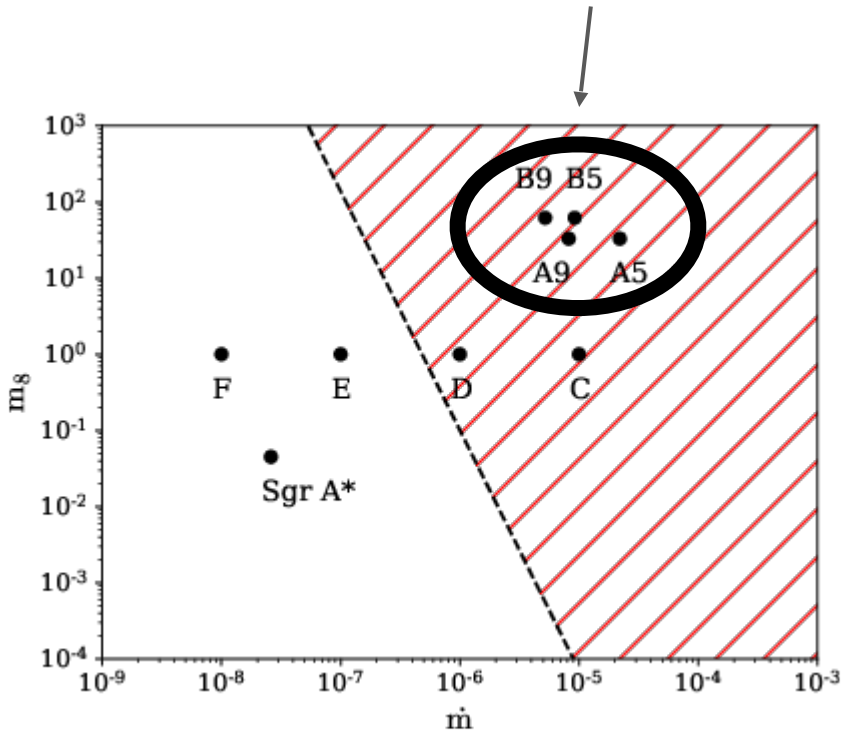
can pair cascades occur?

charge density is sufficient → no cascades?

insufficient charge to screen electric field → pair cascades?



M87 - like models



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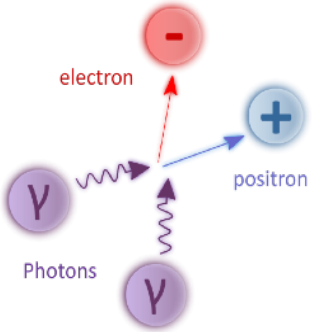
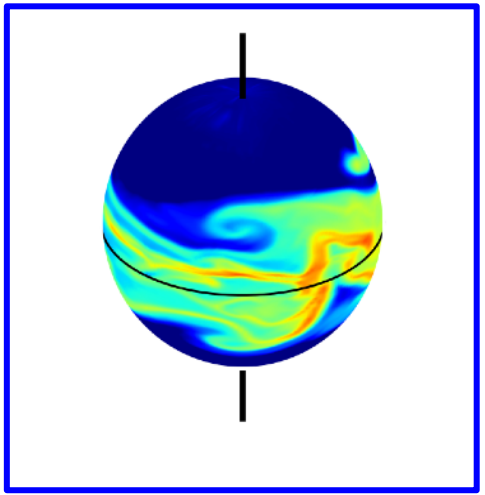




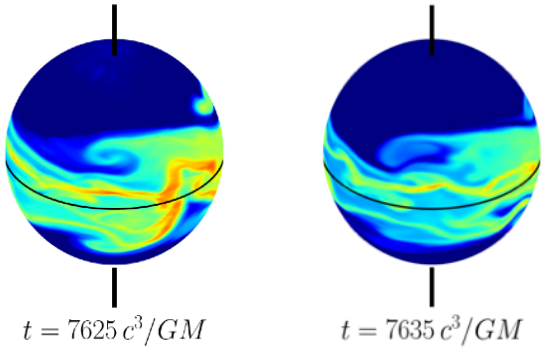
populating the jet & mass entrainment

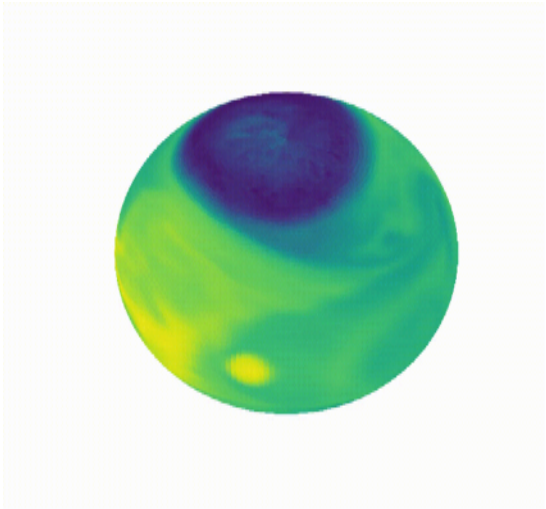
accretion flow anatomy

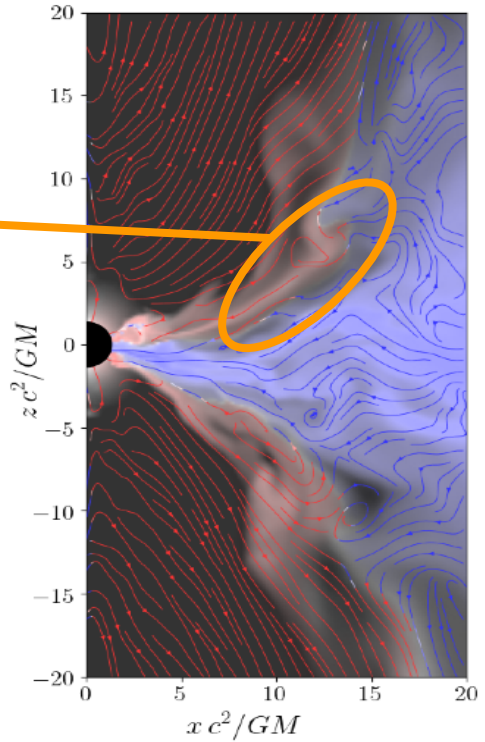
plasma flows **along magnetic field lines**

… but jet and disk are magnetically disconnected

jet–disk shear boundary layer **unstable**!







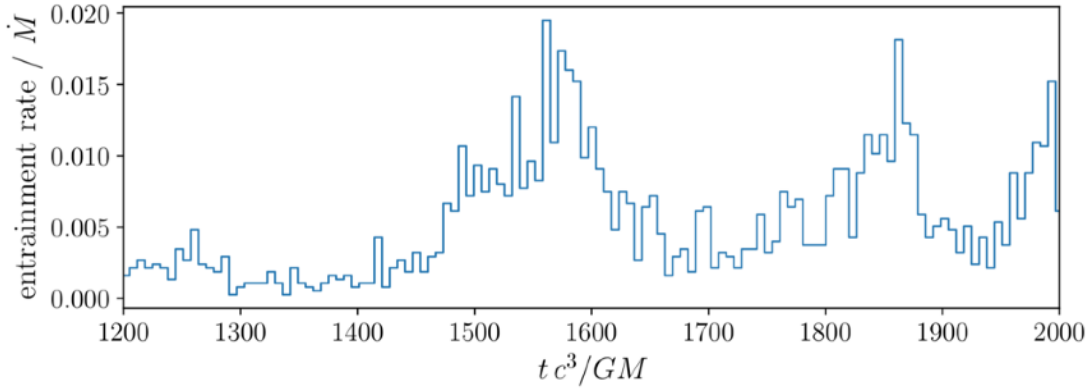
Wong+ 2021

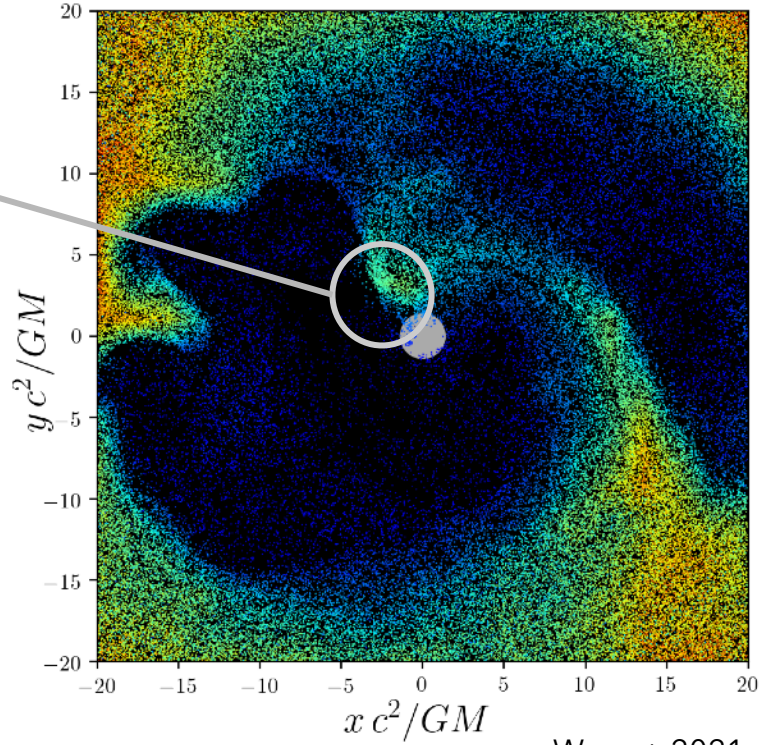
populating the jet & mass entrainment

measuring the entrainment rate

use tracer particles to track fluid motion onto the hole / are entrained into the jet

tracers are entrained at **Kelvin–Helmholtz rolls** and **magnetic torque events** (flux tube interactions) near the horizon





Wong+ 2021

What Lagrangian question does your project need to answer?

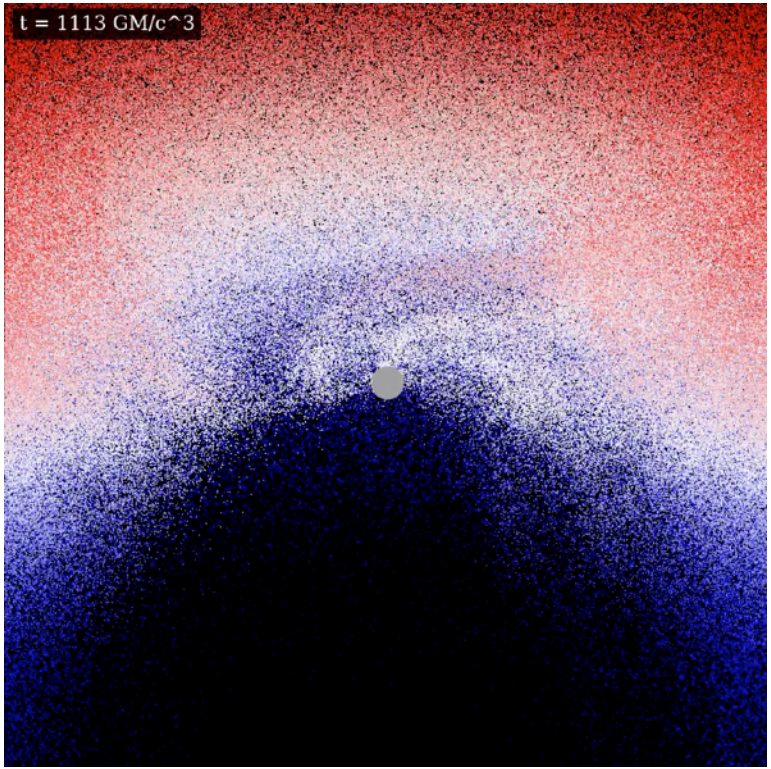
Particles can **add Lagrangian state** to grid simulations.

> Passive particles record histories.
> Active particles exchange mass, momentum, energy, … with the mesh.

Current AthenaK particle implementations are **mostly passive**:
gather -> push -> communicate -> output

Using particles well **requires practical checks**:
what state is carried?
what pusher is used?
what happens at boundaries / AMR / restart?
what statistic should converge?

Tracer science:
measure advection, mixing, residence time, and origin



Applications:
> SANE/MAD disks transport mass differently, **the initial condition matters**
> jet loading can come from **disk-jet boundary entrainment**

Thank you!