Angular Momentum Transport in Astrophysical Plasmas

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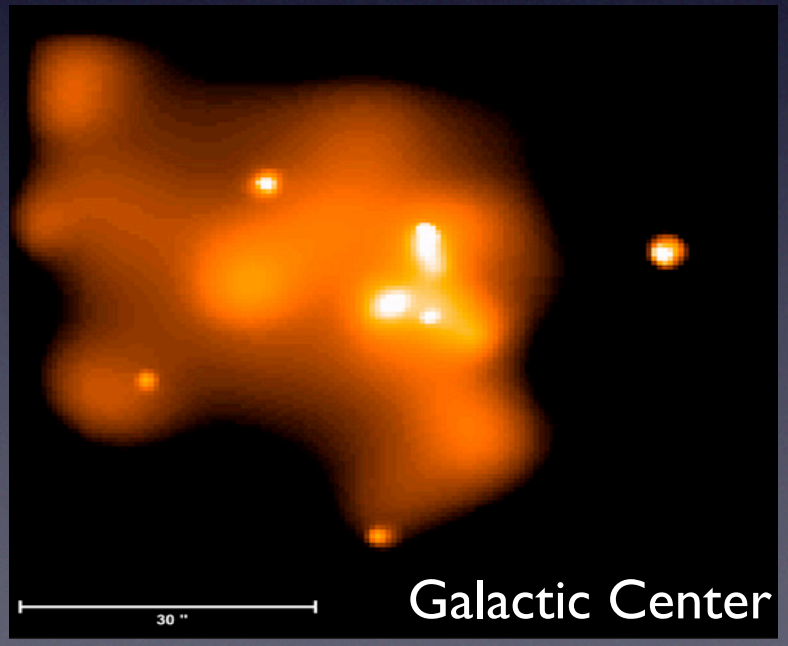
Greg Hammett (PPPL)
Mark Nornberg (Wisconsin)
Eliot Quataert (Berkeley)
Jim Stone (Princeton)

The Milky Way



Galactic Center

Overview

- Astrophysical Impt. of Angular Momentum Transport
- Key Science Questions & Opportunities
  - Accretion Disks (Jim Stone)
  - Stars: Life & Death (Matt Browning)
  - Experimental Opportunities (Mark Nornberg)
- Broader Context (Eliot Quataert)

Astrophysical Importance of Angular Momentum Transport

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- Formation of Structure in the Universe
  - galaxies & massive black holes
  - star formation & stellar death
  - planet formation

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- Powering the brightest sources of EM radiation
  - redistribution of angular momentum ⇒ accretion

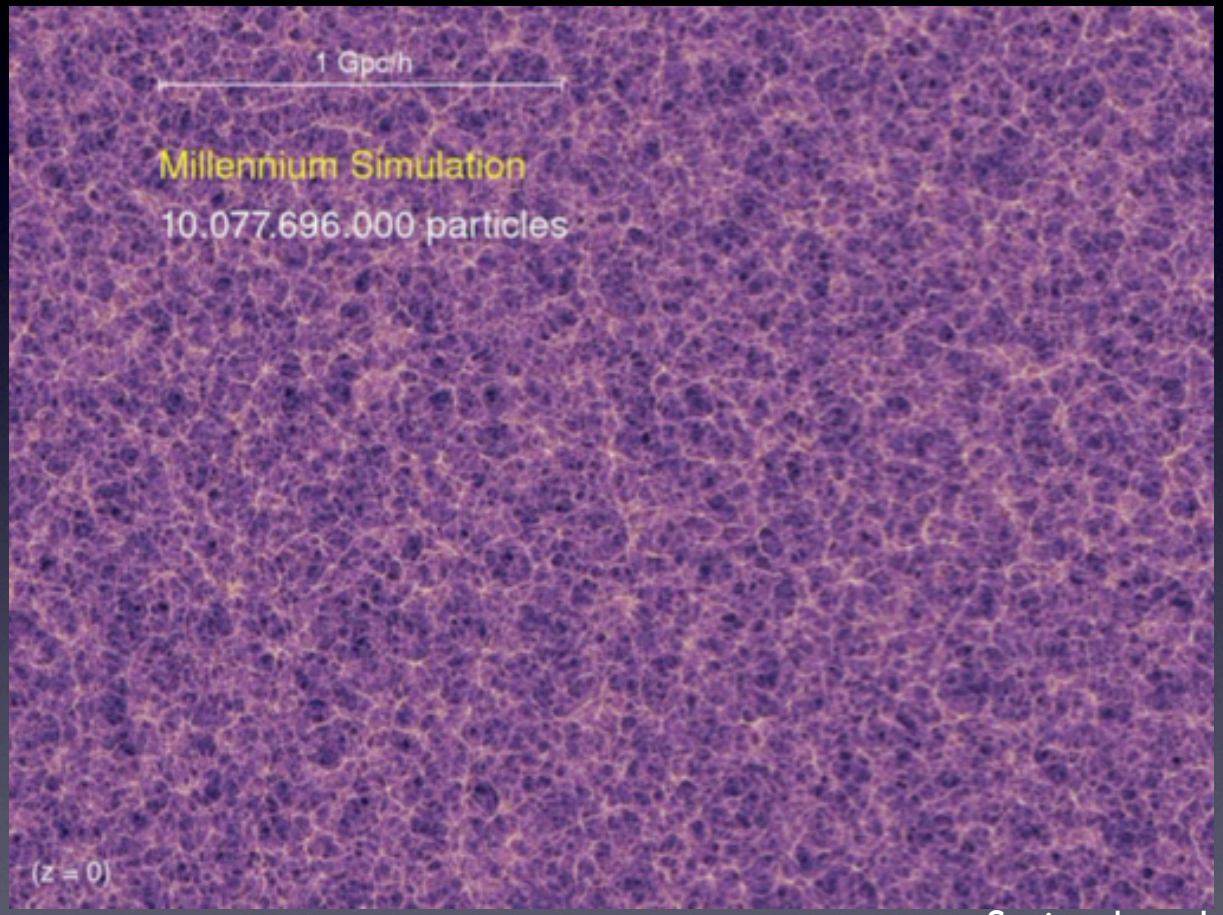
$$\dot{E} = \frac{GM\dot{M}}{R} \equiv \epsilon \dot{M} c^2$$

  - ε ~ 10^{-6} for solar-type stars
  - ε ~ 0.25 for neutron stars & black holes
    - >> ε ~ 0.007 for H fusion

Structure Formation

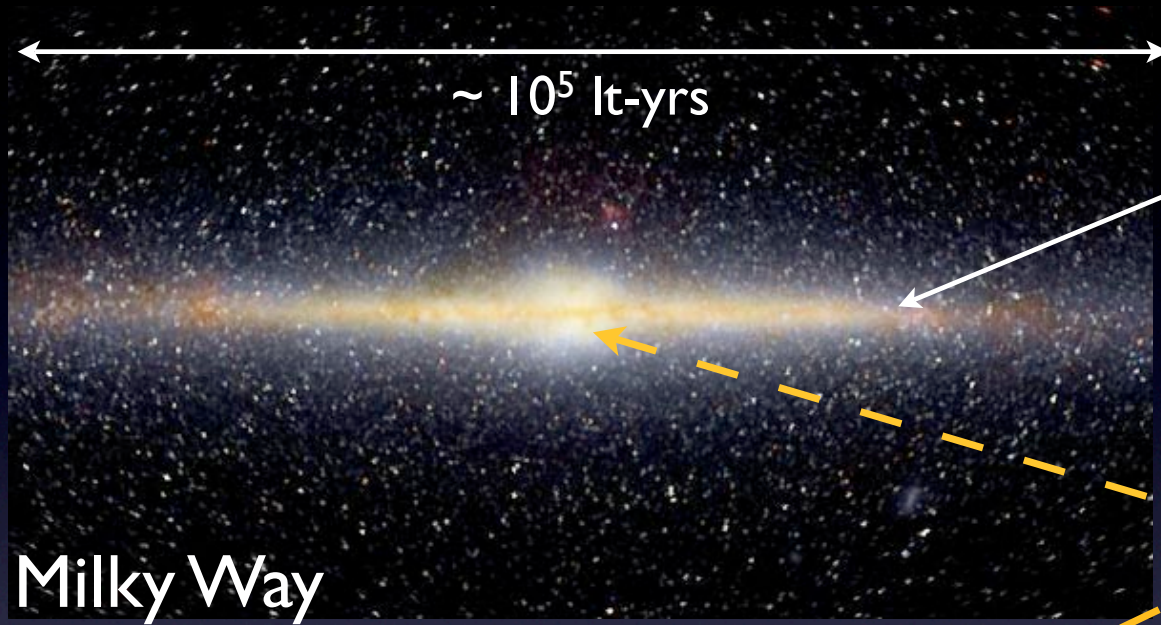
- large-scale structure set by dark matter w/ ang mom. set by tidal torques & mergers
- plasma progressively cools & sheds ang. momentum, forming
  - galaxies
    - stars & planets in galaxies
    - massive black holes in galaxies
    - ....
  - ang. mom. redistribution critical at all stages of structure formation
  - **gravity & magnetic stresses dominate: long-range**

Large-scale Dark Matter Distribution



Springel et al.

Angular Momentum on Galactic Scales

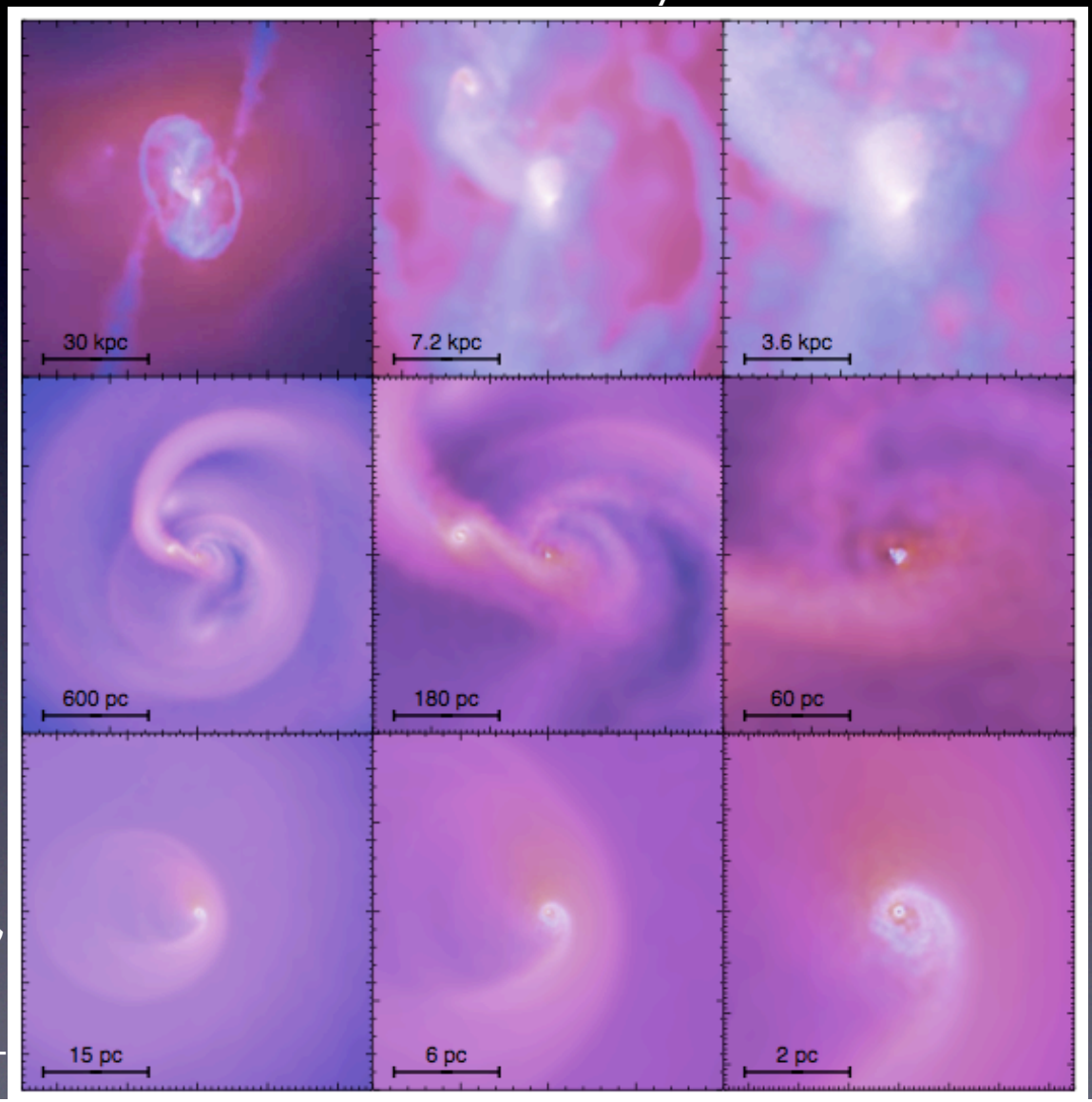


Gaseous & Stellar Disks
(size ~ set by ang. conservation)

Stellar Bulges
(~ spherical)

Formed by gas inflow; torques largely gravitational (e.g., bars)

Massive Black Holes in Galactic Nuclei



$M_{BH} \sim 10^{-3} M_{Bulge}$

$J_{BH} \sim 10^{-6} J_{disk}$

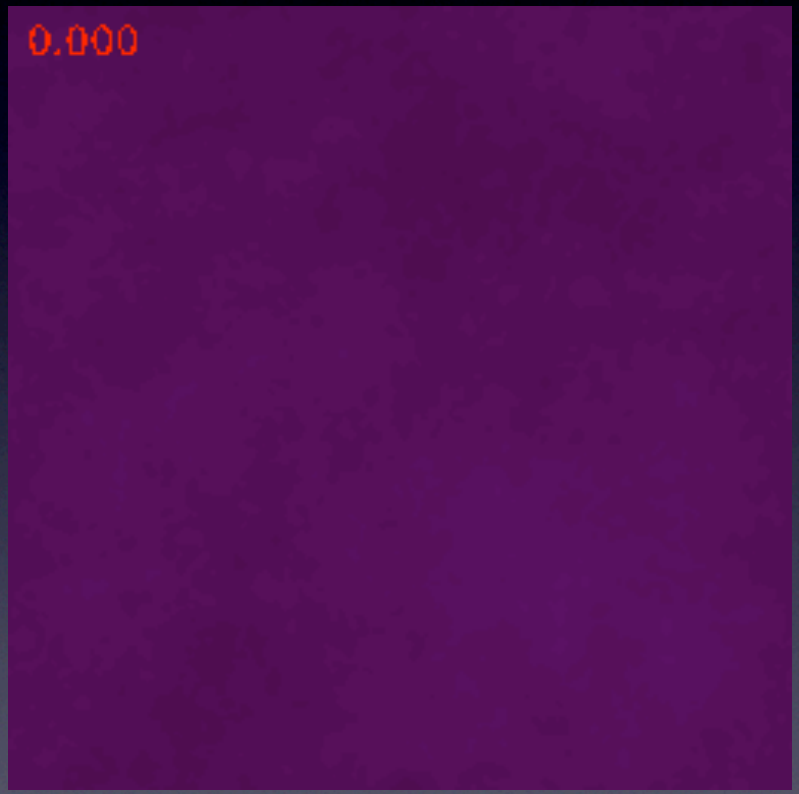
(per unit mass)

best guess ....
grav. torques bring gas to small radii where magnetic stresses take over
... but poorly understood

simulation of central kpc during merger of 2 massive galaxies

Resimulate central ~10s pc down to ~ 0.1 pc; sufficient gas inflow to fuel massive BH

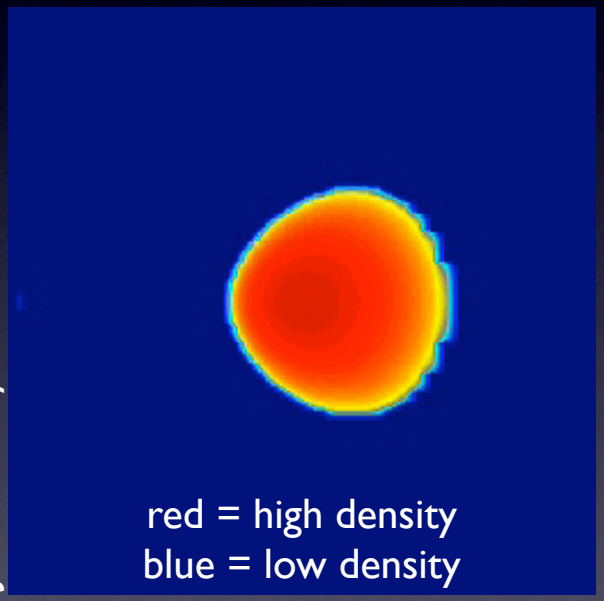
Star Formation in Galaxies



Eve Ostriker

- self-gravity & cooling ⇒ gas in galaxies collapses
- ang. mom. shed via grav. torques & large-scale B-fields
- ang mom barrier ⇒ accretion disk at final stages of inflow

Angular Momentum Transport in Accretion Disks

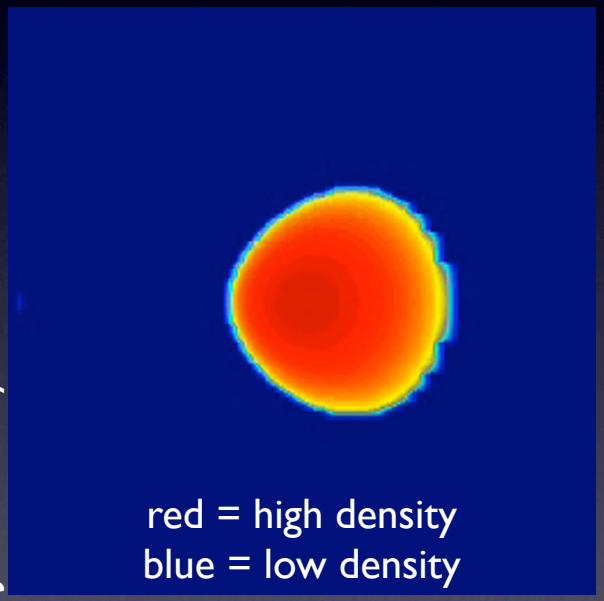


John Hawley

- Most astrophysical disks well-magnetized ($Re_M >> 1$), but not all ...
  - proto-stellar disks, in which planets form
  - outer parts of disks around compact objects
- Hydro turbulence not generic to Keplerian Ω
  - sims & PPPL expt (Hantao et al.)
- MHD turbulence generic in disks: dominant transport absent self-gravity (small radii)
  - large-scale B stresses, internal transport, or both?

(large-scale dynamo) (small-scale dynamo)

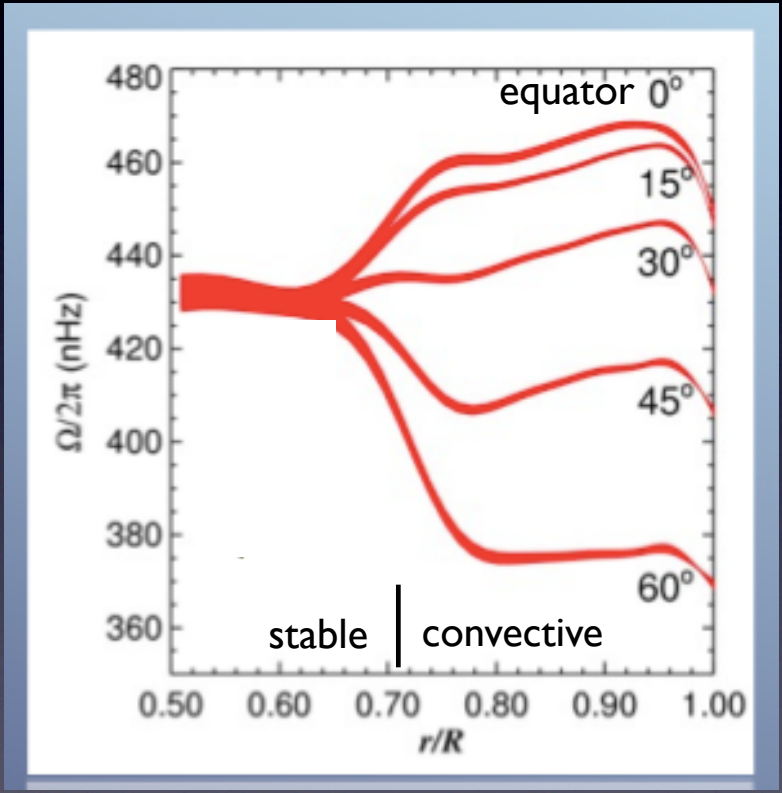
Angular Momentum Transport in Accretion Disks



John Hawley

- Analytic theory critical for isolating key physics
- Disk transport key frontier in Dynamo theory
- Significant physics reqts for realistic models
  - radiation field energetically impt (luminous BHs, NSs)
  - low ionization in proto-stellar disks
    - Hall terms & ambipolar diffusion impt
    - turbulence can influence planet formation/migration
  - kinetic theory (low-luminosity BHs, NSs)
  - radiative transfer to connect models/sims to observations

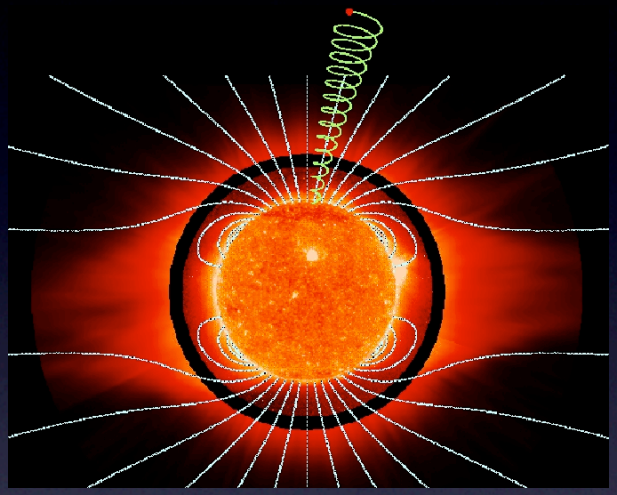
Stellar Angular Momentum Transport



Differential Rotation in the Sun from Helioseismology

- Understanding solar Ω grand challenge computational project: getting there ....
  - intimately connected to solar dynamo
  - interior solid body Ω poorly understood
- Large body of data on rotation, B, coronal activity, etc. in other stars

Stellar Angular Momentum Transport



- Stars spindown in time via magnetized winds
- core-surface coupling (i.e., internal ang. mom. redistribution) poorly understood, particularly in later stages of stellar evolution
  - critical for B & Ω of compact objects (e.g., pulsars)
  - critical for physics of stellar explosions: supernovae

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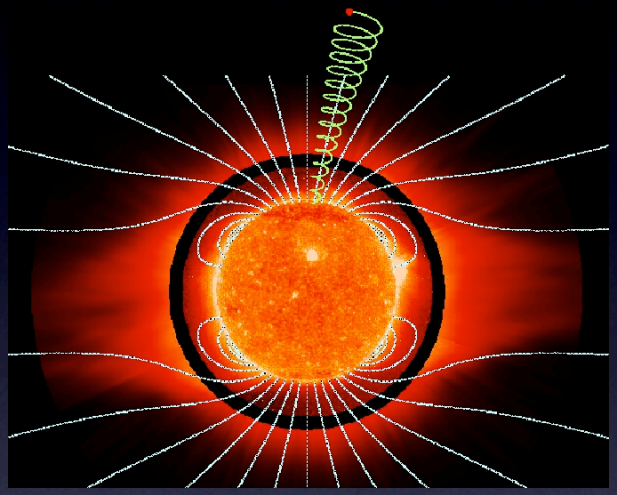

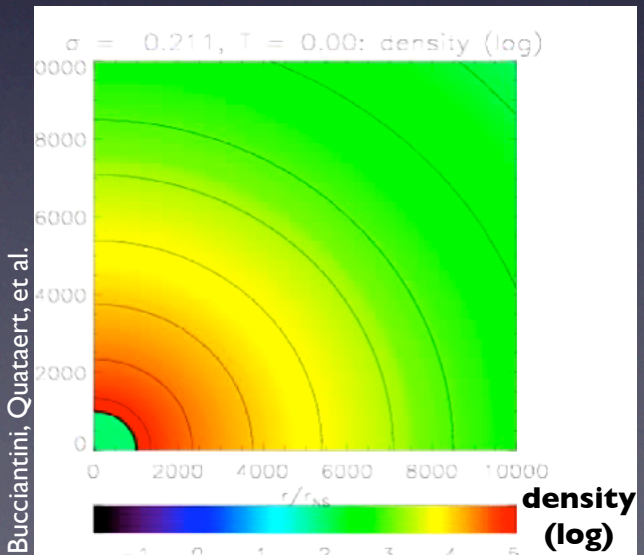

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rapid Ω
~ bipolar SN
long GRB
$\Gamma \sim 10^{2\text{-}3}$
highest z (8.3)

slow Ω
'normal' SN
~ spherical

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- B-field transport (not gravity)
- confluence of theoretical, observational, computational & experimental opportunities
- central problems in astrophysics & connections to other areas of plasmas astro

Major Questions/Opportunities

- Disks
  - How do disk dynamos operate? generation of large-scale B?
    - relation to classical dynamo work? stellar dynamos?
  - What is the origin of time-dependent, non-thermal disk emission?
    - depends on the details of energy generation and heating in disks
- Stars
  - How is angular momentum redistributed **within** stars?
    - dependence on convection, rotation (Ro), initial B, ...
    - critical for stellar evolution and stellar death
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Broader Connections

- Angular momentum transport by B-fields closely tied to origin, coherence, & destruction of magnetic fields
  - dynamos, turbulence, reconnection, & transport intimately connected
- Properties of stellar/disk turbulence and transport set the 'boundary conditions' for stellar/disk outflows: jets & winds
  - e.g., large-scale B-field?
- Proto-stellar disks fundamentally a dusty plasma!
  - physics key for planet formation & migration
- Radiation MHD crucial in Massive Stars & Luminous BH/NS Disks