Modeling Thermal & Non-Thermal Signatures from the GC

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Workshop on Relativistic Plasma Astrophysics:

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In collaboration with:

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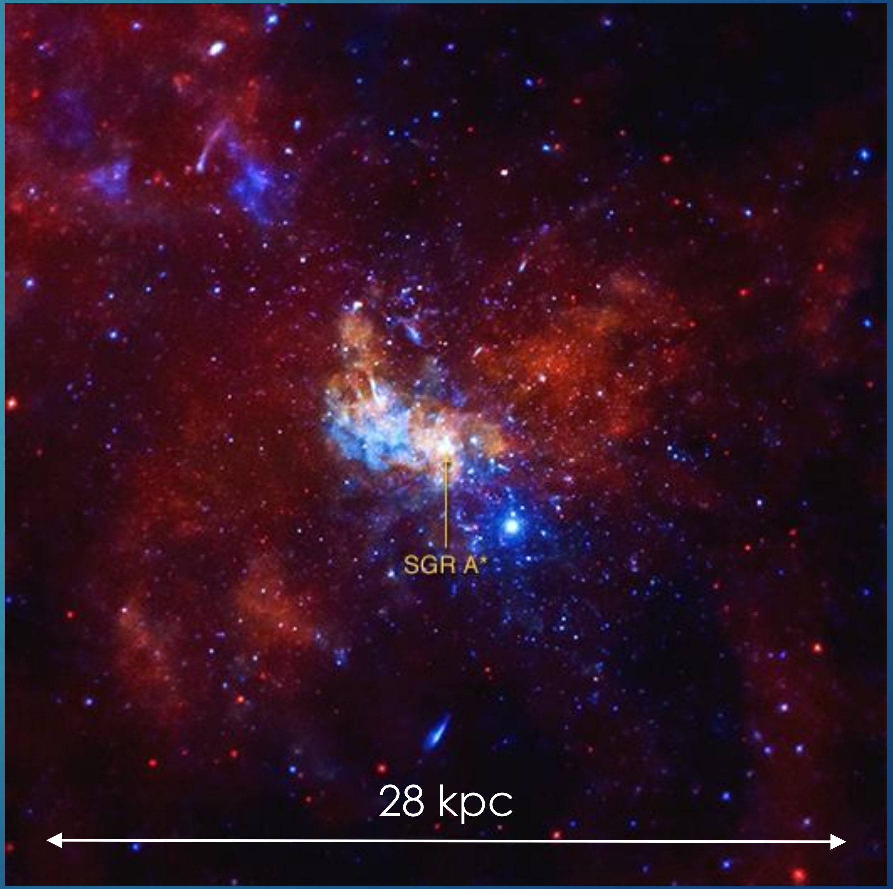
Properties of Sgr A*

- Lies in a low-luminosity X-ray emission state: $L_X \approx 2.4 \times 10^{33}\ erg\ s^{-1}$ (Baganoff et al. 2003)

- Frequent to short, X-ray flares with timescales ~ minutes to hours at $\sim 10\ R_g$ (Degenaar et al. 2013, Barrière et al. 2014)

- Our work explores possible month-long X-ray flaring events at $\sim 10^3\ R_g$ (Giannios & Sironi 2013, Giannios & Lorimer 2016, Christie et al. 2016)



Composite X-ray image (Y.Bai. et al).

Gas Density around Sgr A*

- Sgr A* is an ideal place to study quiescent accretion and properties of a geometrically thick disk.

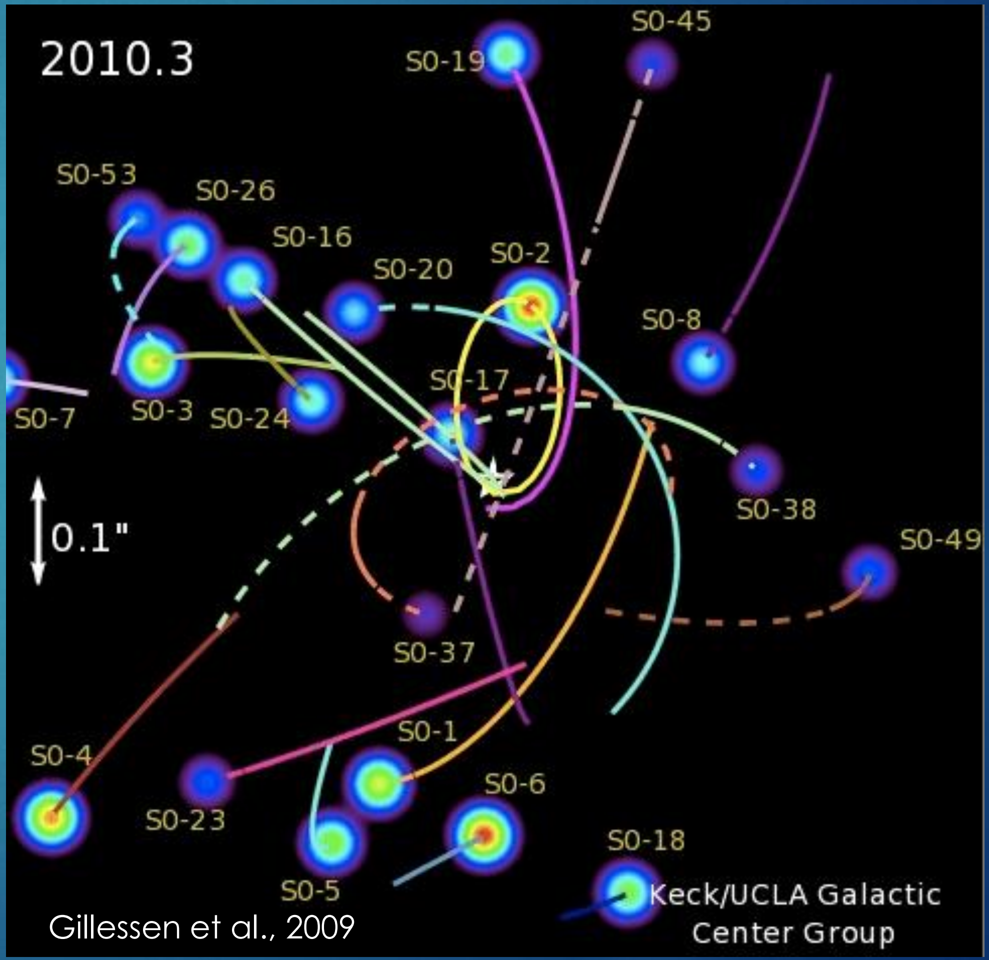
- At $R_b \sim 10^5\ R_g$, Chandra resolves X-ray, thermally emitting gas with density $n{\sim}100\ cm^{-3}$ (Baganoff et al. 2003)

- At $\sim 10\ R_g$, through modeling and Faraday rotation measurements, constrain $n \sim 10^7\ cm^{-3}$ (Marrone et al. 2007, Moscibrodzka et al. 2009)

- Our work aims on bridging this gap by exploring probes of the disk density.

Stars in GC: S-Cluster & S2

- Massive, B-type stars ⟹ winds of $v \sim 10^8 cm/s$
- The brightest star, S2, is characterized by a close pericenter $\sim 10^3\ R_g$ and mass loss rate $\dot{M}_w \leq 10^{-7} M_\odot\ yr^{-1}$ (Martins et al. 2008)
- These stars, specifically S2, are ideal probes of the accretion disk of Sgr A* (Giannios & Sironi 2013)



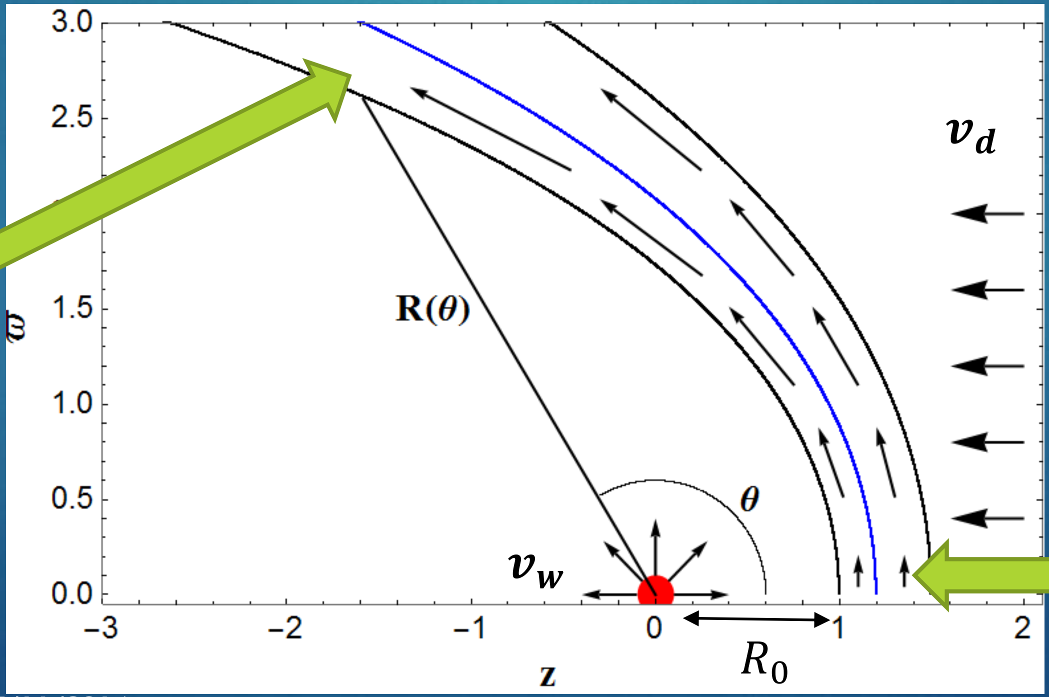
Gillessen et al., 2009

Stellar Wind – Accretion Disk Interactions

- These interactions, during the pericenter passage of a star, lead to the formation of a bow shock in the stellar winds

Sketch of Bow Shock Model: Rest Frame of Star

Shocked Wind Material



Shocked Disk Material

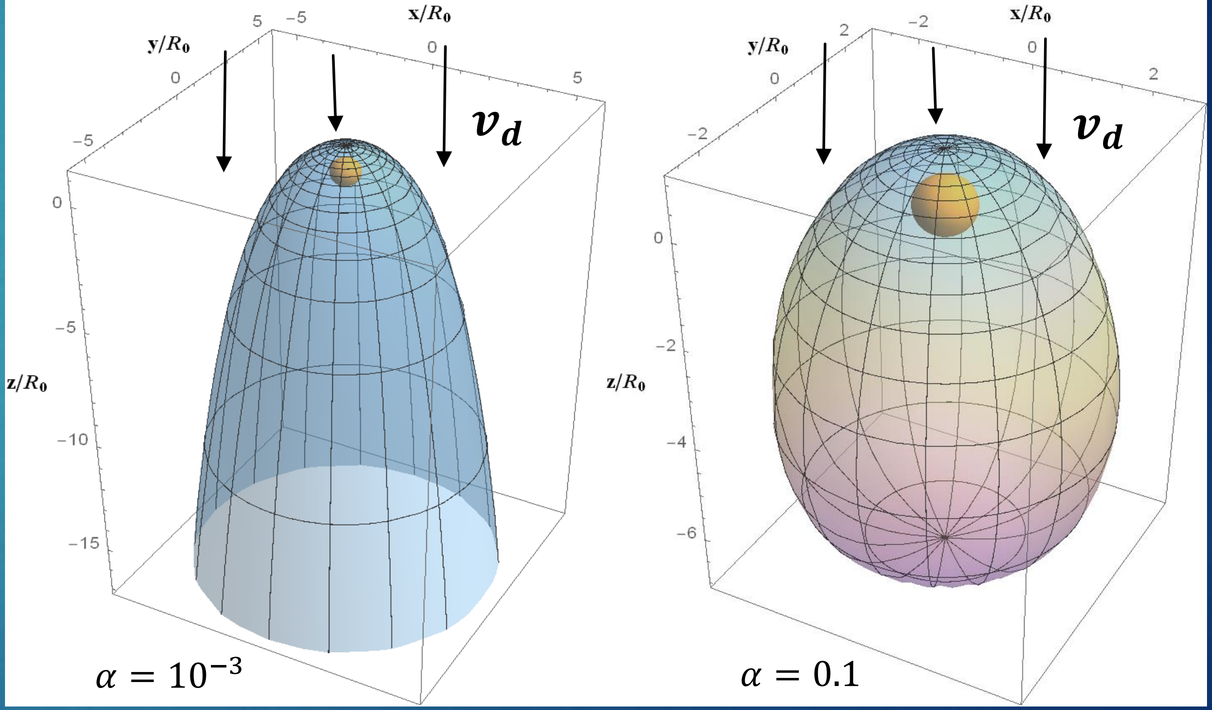
Determining Shape of Termination Shock

- Assumptions for constructing semi-analytical model:
  i. System has reached a steady state
  ii. Shocked wind region falls within thin-shell limit

- Follow a modified analysis of momentum supported bow shocks (Wilkin,1996)

- Include thermal pressure of disk: $P_{therm} = \alpha \, P_{ram}$

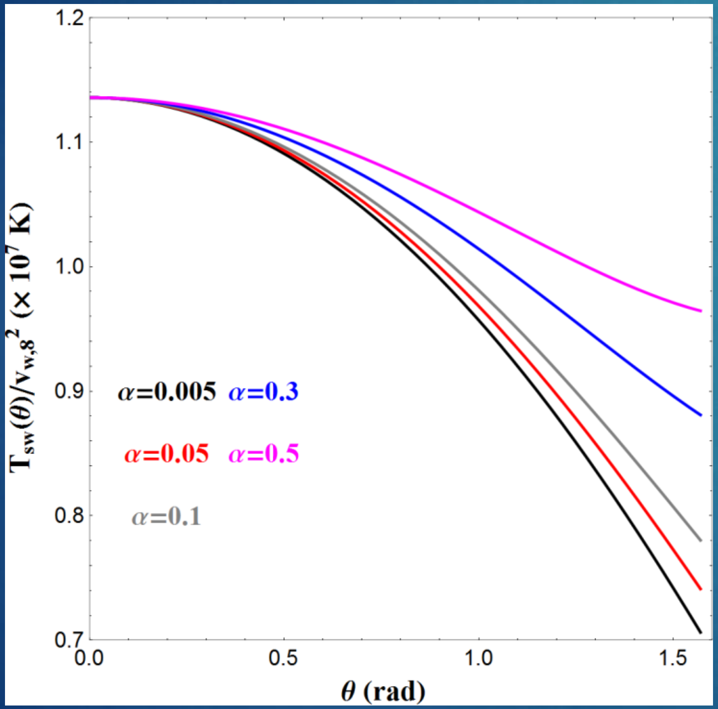
Shape of Termination Shock



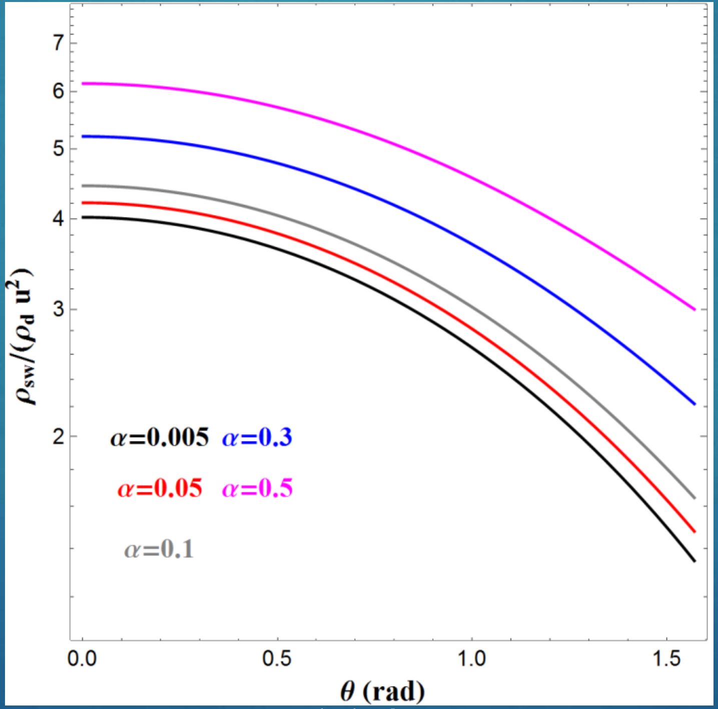
Christie et al. 2016

Properties of Shocked Stellar Wind

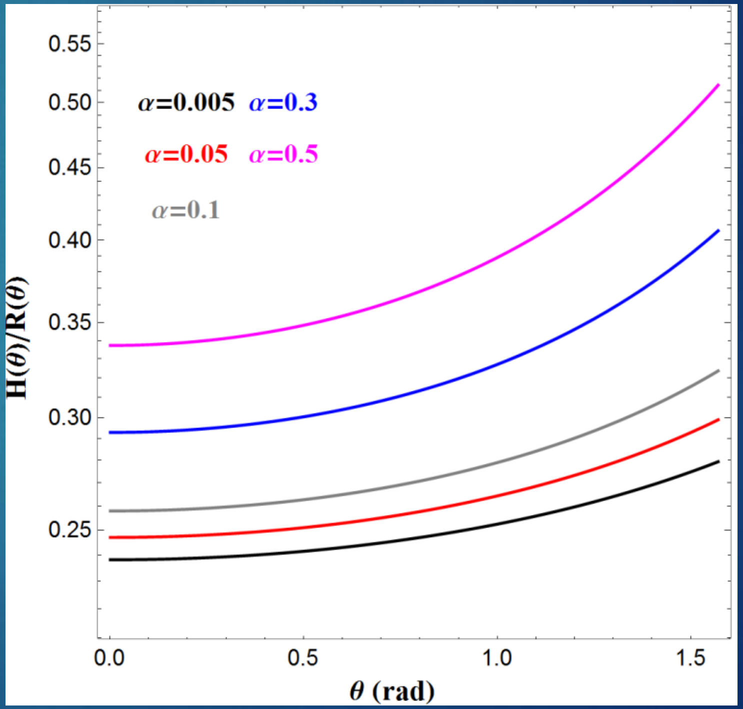
- Using shock jump conditions ⟹ derivations of $T_{sw}(\theta), \rho_{sw}(\theta)$, and $H(\theta)$ ⟹ thermal bremsstrahlung power



$T(\theta)$



$\rho(\theta)/\rho_d$

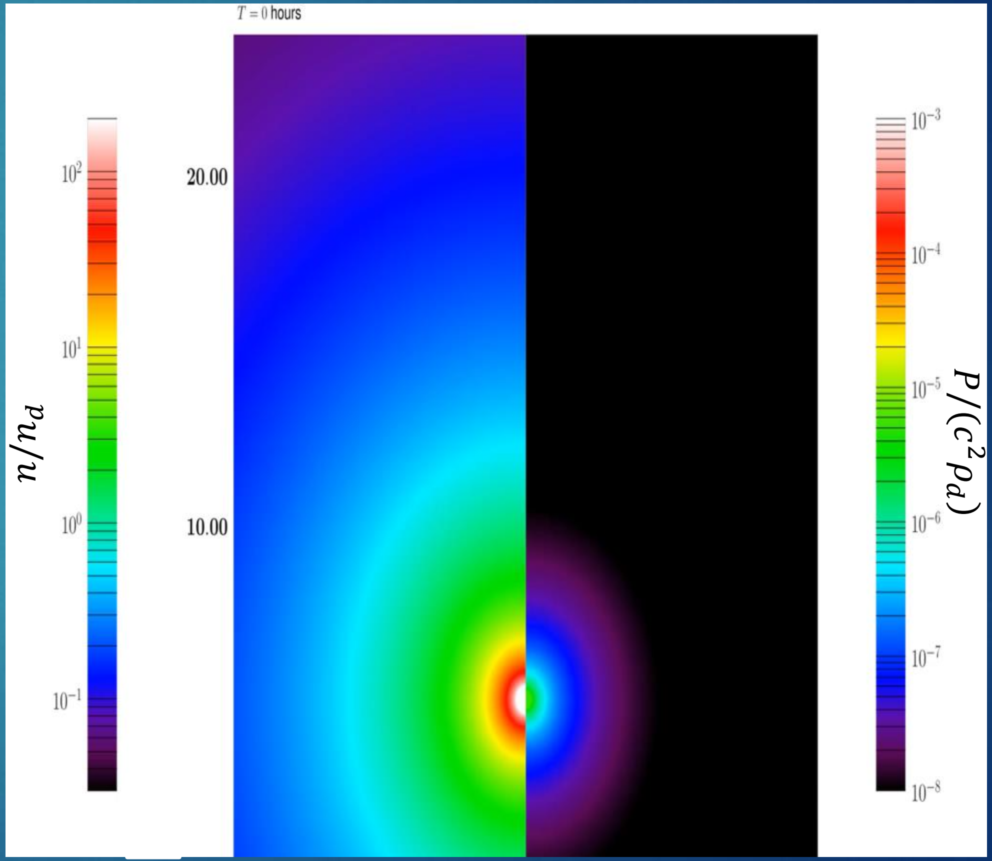


$H(\theta)/R(\theta)$

Christie et al. 2016

Testing Model Through Hydro-Simulations

- Used to make comparisons of:
  1. Our estimates of the termination shock and contact discontinuity
  2. Thermal bremsstrahlung power produced from the shell
- Large back region beyond termination shock is dominated by Kelvin-Helmholtz instabilities
- $\dot{M}_w = 10^{-7} M_\odot\, yr^{-1}$, $n_d = 10^4\, cm^{-3}$, $v_d = 8000\, km\, s^{-1}$



$\alpha = 0.1$

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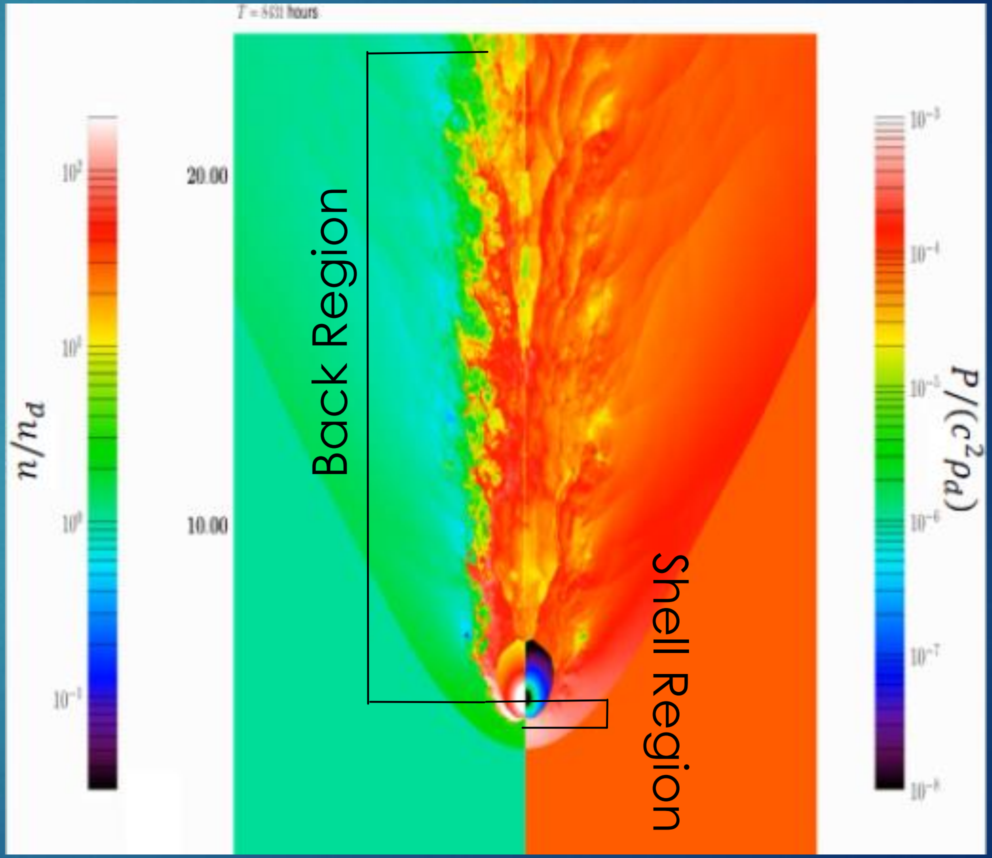
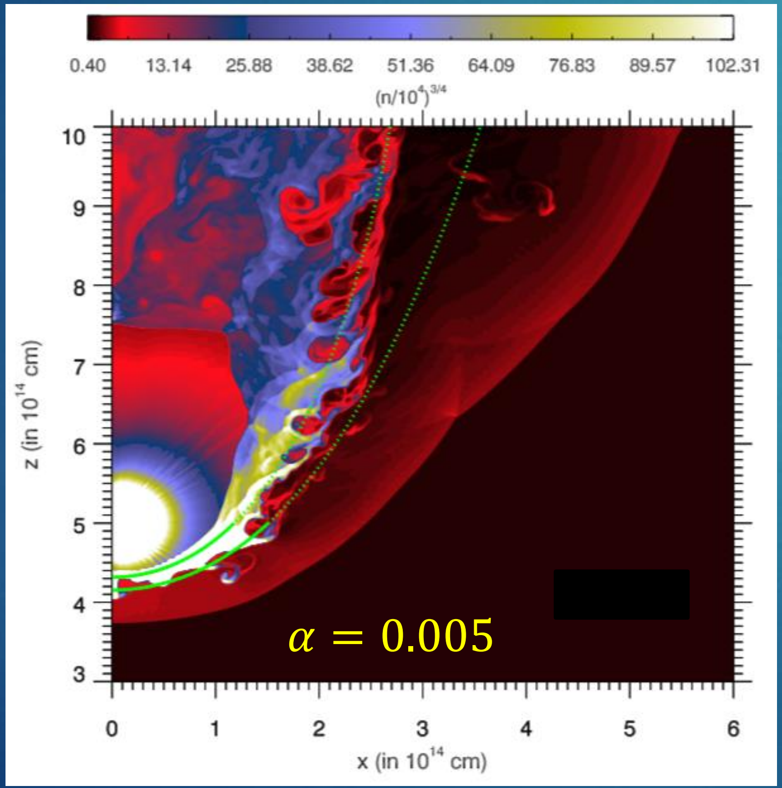
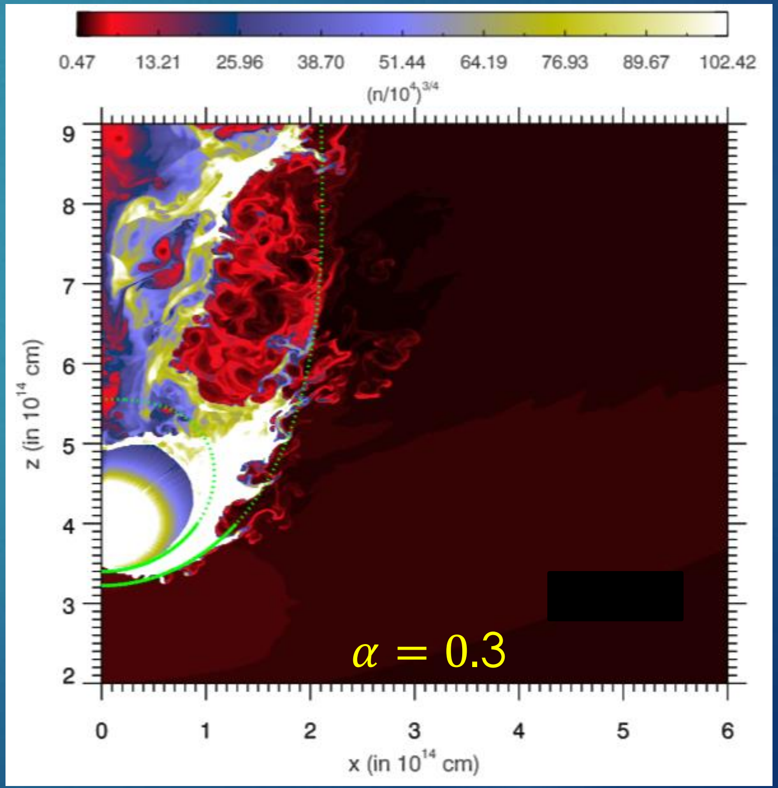


Christie et al. 2016

Angular Profiles of Shock Surface

- The contact discontinuity becomes quickly prone to instabilities
- Estimates for the termination shock in the wind and contact discontinuity are valid to $\theta \approx \pi/2$





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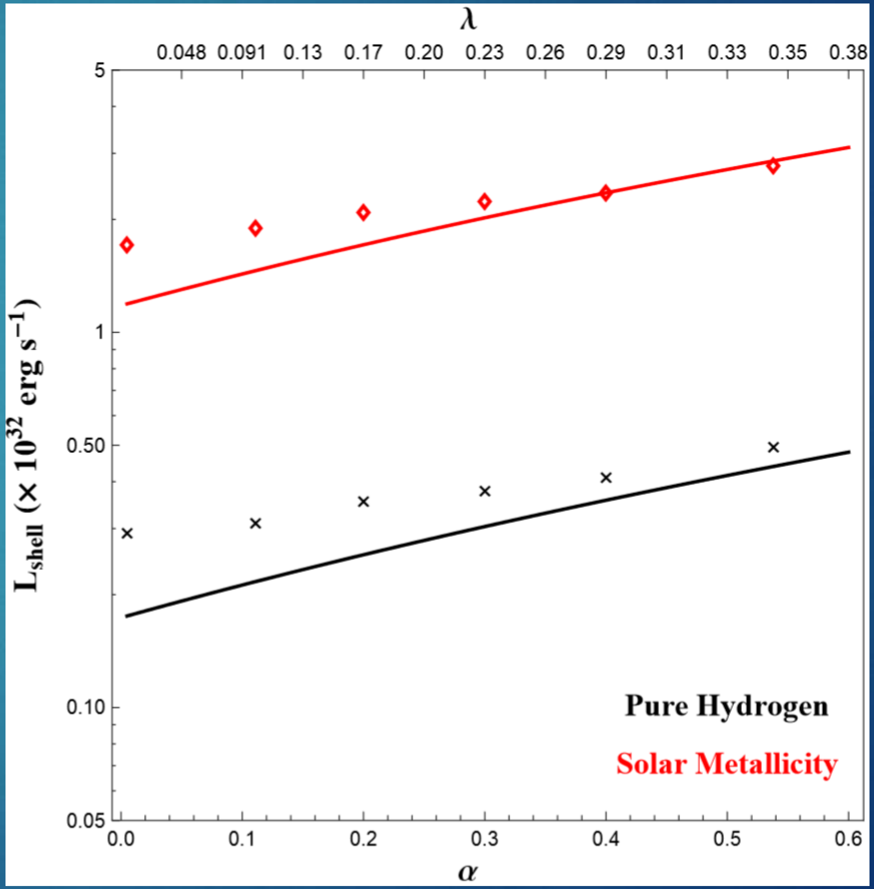
Thermal Bremsstrahlung Emission from Shell

- Computation of the thermal, radiated power is permitted up to $\frac{\pi}{2}$ using semi-analytical results
- Stellar wind composition of hydrogen with and without solar abundancies
- Appropriate scalings are derived for shell luminosity:
  i. Hydrogen: $L_{shell} \propto \dot{M}_w{}^{3/2} n_d^{1/2} \, (1 + 1.6\,\alpha^{1.4})$
  ii. SM: $L_{shell} \propto \dot{M}_w{}^{3/2} n_d^{1/2} \, (1 + 1.2\,\alpha^{1.2})$



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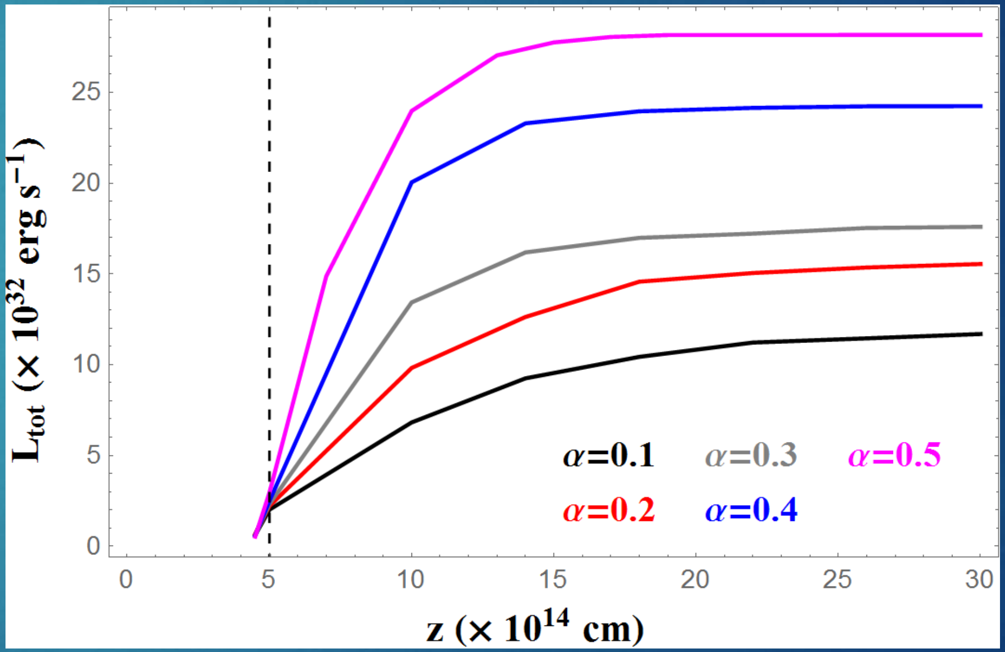
Role of Kelvin-Helmholtz Instabilities on Thermal Luminosity

- Back region composed of mixed fluids contributes large fraction of total luminosity from simulation ($\sim 10 \times L_{shell}$)

- Simulations with different $\dot{M}_w$ allow for the derived scaling factor of the total simulation luminosity:
  i. SM: $L_{tot} \propto \dot{M}_w^{1.3} n_d^{0.52} (1 + 5.5\,\alpha)$

Cumulative Plot of Total Luminosity from Simulations

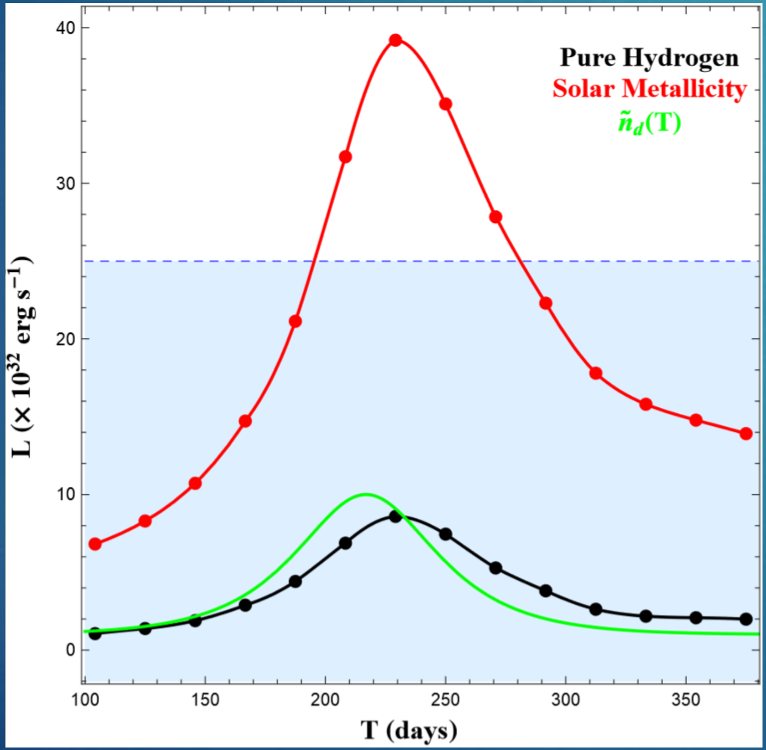


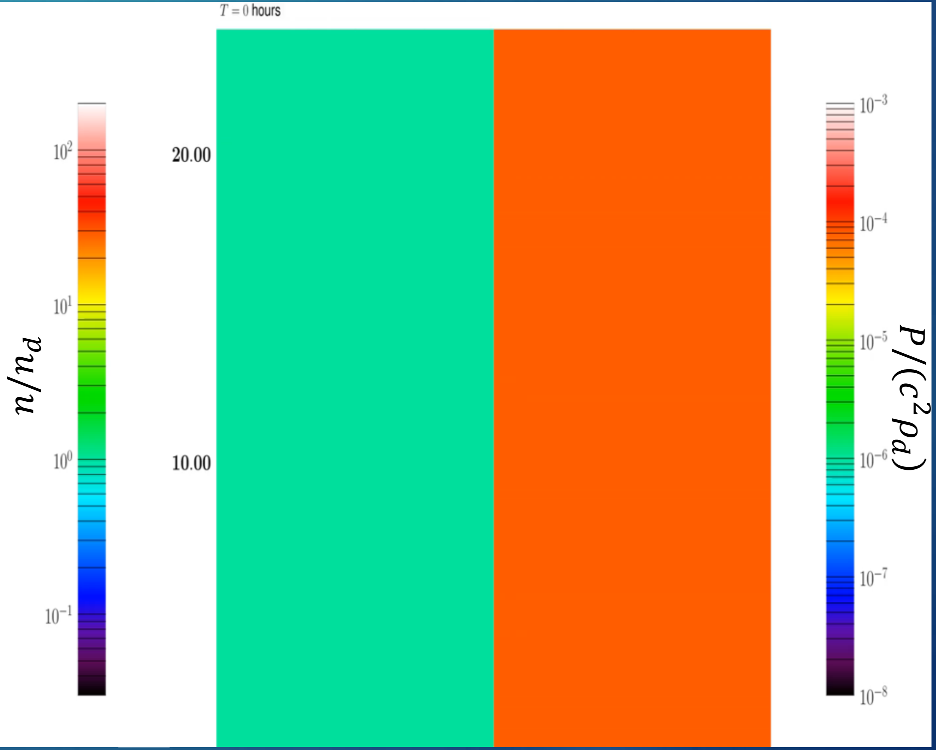
Christie et al. 2016

Time-Dependent Simulation

- Time-dependent density used to mimic transit of S2 through pericenter and study the evolution of the back, mixing region.
- Month-long flare with luminosities above quiescent emission is expected.

$\dot{M}_{-7}$, $n_{d,5}$, $v_{d,8}$





Christie et al. 2016

$\alpha = 0.1$

Limitations to S2 Application

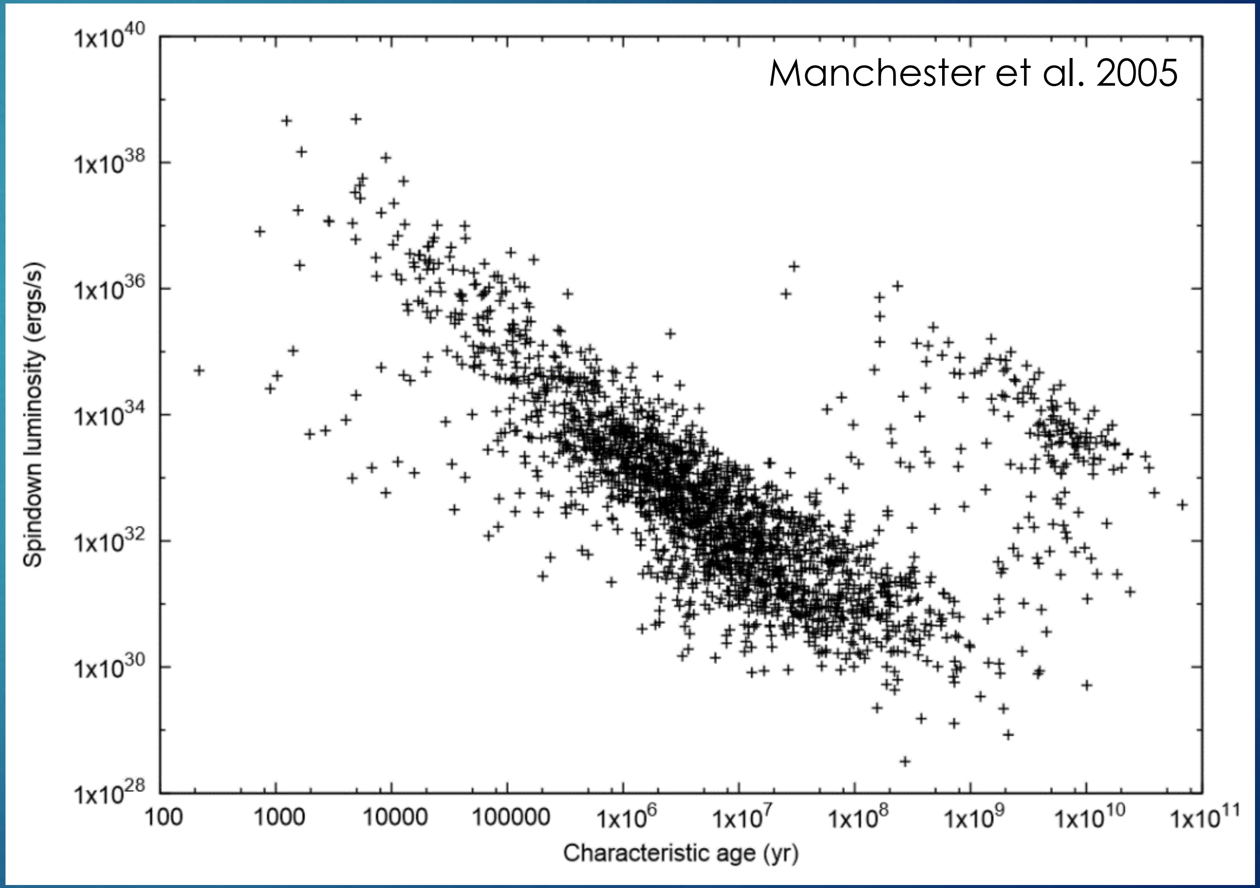
- No specific accretion disk model was adopted for time-dependent simulation.

- Tidal effects and acceleration of S2 during pericenter passage was ignored. Such effects are expected to compress and elongate the back, mixing region → increase in thermal emission from shocked wind (Ballone et al. 2013, Gillessen et al. 2014, Ballone et al. 2016)

Pulsar Population in GC

- The discovery of a magnetar, spin period $\sim 3.76\ s$, within the inner $\sim 0.1\ pc$ of the GC was achieved by *Swift* and *NuSTAR*. (Degenaar et al. 2013, Mori et al. 2013, Rea et al. 2013)
- An upper limit of ~ 200 detectable pulsars was estimated to orbit around Sgr A*. (Chennamangalam & Lorimer 2014)
- These stars are ideal probes of properties of the SMBH and its accretion disk. (Cordes & Lazio 1997)

Sample of 1982 pulsars from ANTF



Comparison of Applications

S2 & Accretion Disk :

- Non-relativistic stellar winds
- Thermal X-ray emission (bremsstrahlung cooling)
- Flaring on timescale of ~month
- Quickly prone to hydrodynamic instabilities (KHI)

GC Pulsars & Accretion Disk:

- Relativistic stellar winds
- Non-thermal emission: X-ray & Radio (synchrotron)
- Flaring on timescale of several months
- KHI grows on much larger timescales

Summary

- The formation of a bow shock structure in stellar winds through interactions is accurately described through a modified prescription of momentum-supported bow shocks.
- Application to S2's pericenter passage ⟶ month-long thermal X-ray flare with luminosities comparable to quiescent emission of Sgr A*.
- Application to pulsar-disk interactions ⟶ non-thermal, X-ray flare on timescales of months with luminosities comparable to quiescent emission.