Holographic Jets in Flowing Plasma

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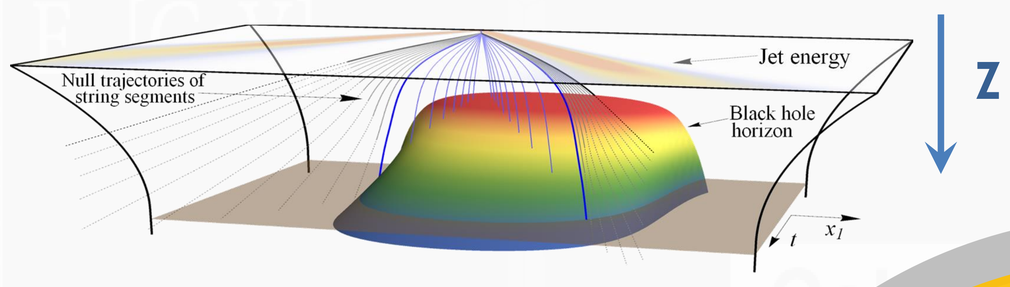
1) Introduction: Jet energy loss in holography

Bits of string (blue/black lines) fall into black hole (*thermalise*)

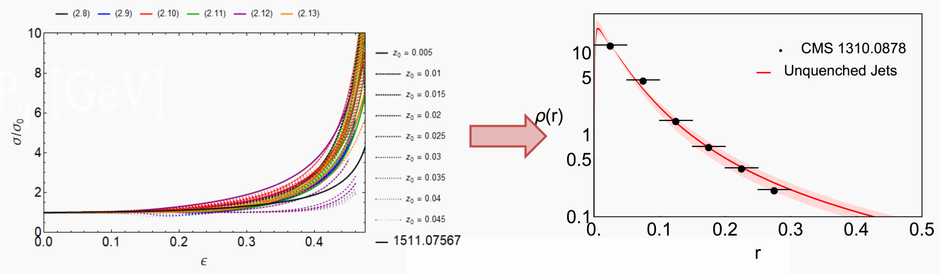
- Energy loss + final shape determined by position of string bits (Z(t))
- Initial conditions (universal profile + pQCD)
- Evolution equations (Z''(t)): **this project**



2) A universal string profile (vacuum)

Wide variety of string initial conditions give approximately **universal profile**:

- Width of jet determines energy profile accurately
- Given by normalised angle ($\sigma \approx Z'(t)$) versus normalised energy (ε)
- Width distribution (pQCD) + free scaling parameter → **CMS jet shape**



QUESTION

How do partons lose energy in a **dynamic** strongly coupled medium?

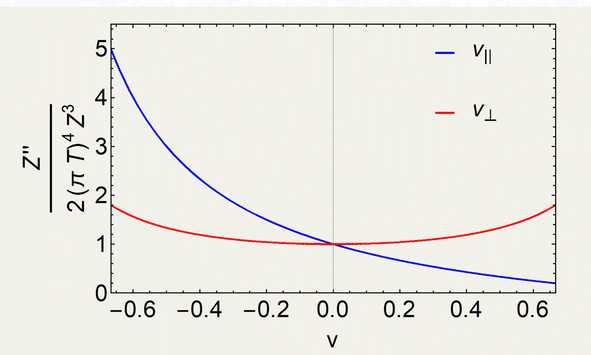
- Initial conditions from pQCD (energy+jet width distribution)
- Energy loss in AdS/CFT: follow string in black hole
- First time to **include varying temperature** + first time including **flow**

METHODS

3) A formula for flowing plasmas

- Follow string bits: every bit has different Z'(0)
- String bits in horizon are lost: $Z_{hor} = 1/\pi T(t,x)$
- `Force' Z''(t) depends on long + perp flow:
  - Strong effect going with/against flow
  - Moderate friction due to perp flow
  - *Full formula includes Z'(t) + flow gradients*

$$Z''(t) = -2\pi^4 T^4 \left(1 - v_{||}\right) Z(t)^3 \left(\frac{1 - v_{||}}{v_{||}^2 + v_\perp^2 - 1}\right)$$

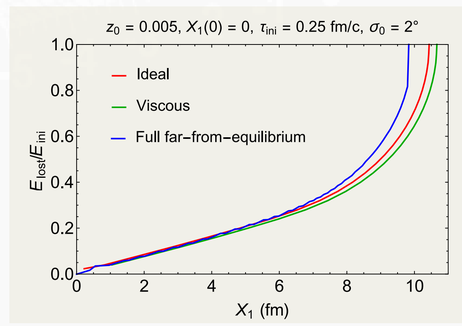


4) Viscous effects and a subtlety

- **Naïve metric ideal hydrodynamics unfeasible**
  - Z'' would contain (unphysical) term: $-\frac{\partial v_x}{\partial x}$
  - Dominates close to boundary: geodesic hits boundary!
- Either *include viscous metric*, or *explicitly ignore gradients:*

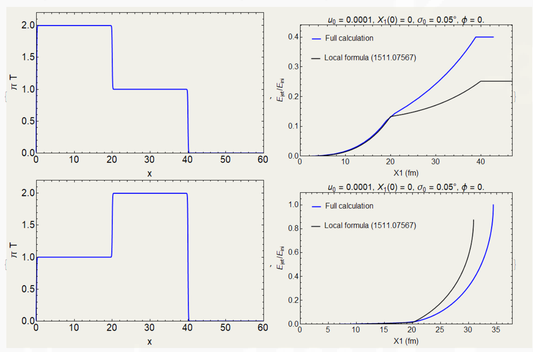
$$\Delta Z''(t) = -2\pi^4 T^3 \left(\frac{2}{3}\frac{\partial v_x}{\partial x} + 2\left(\frac{\partial v_x}{\partial x} + 2\frac{\partial v_x}{\partial t}\right) T\, Z(t)\right) Z(t)^3$$

- **Comparison in homogeneous boost-invariant example:**
  All-order versus viscous versus ideal:



5) Two examples

Toy model: 2-step temperature and E(x)

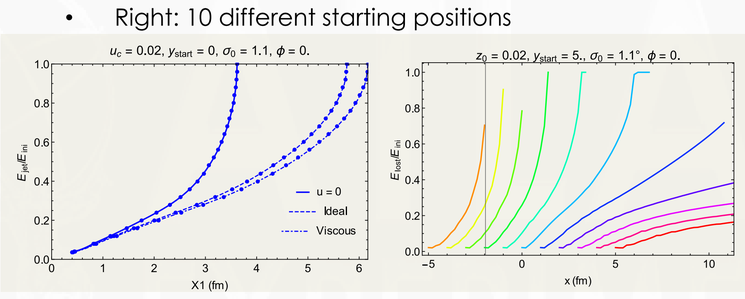


- Initial (low-temperature) phase very important!
  → **Memory effect**

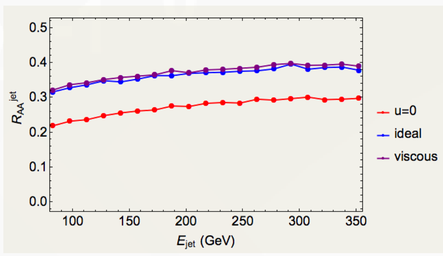
Example in expanding droplet (Gubser flow)

- Flow increases stopping distance: 3 → 6 fm
- Moderate decrease energy loss due to viscosity

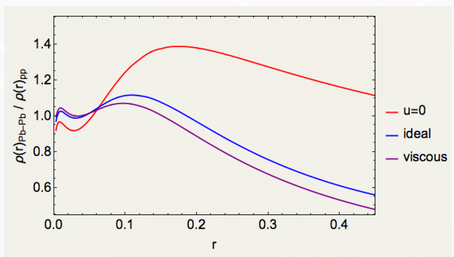
- Right: 10 different starting positions



Nuclear modification factor

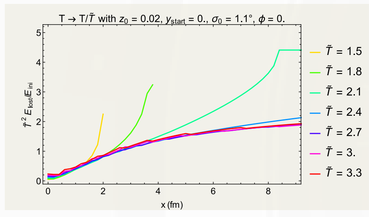


Modified jet shapes



Temperature-scaling

Approximate T^2 dependence of energy loss ($T^{3/2}$ for static plasma)



6) Results

Discussion

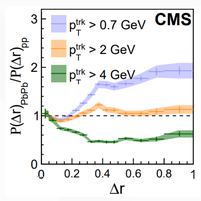
Energy loss is subtle in dynamic setting

- Varying temperature gives `non-local' energy loss
- Flow is very important phenomenologically
- Viscous effects can be subtle
- Energy loss in simple model gives initial T^2 scaling

- Outlook: simple implementation for Monte Carlo

- Easy-to-implement notebook, energy loss computation in less than 1 second/jet

- Semi-quantitative agreement with jet shapes of hard particles? (soft influenced by medium?)



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Poster design by I.D. Karemaker