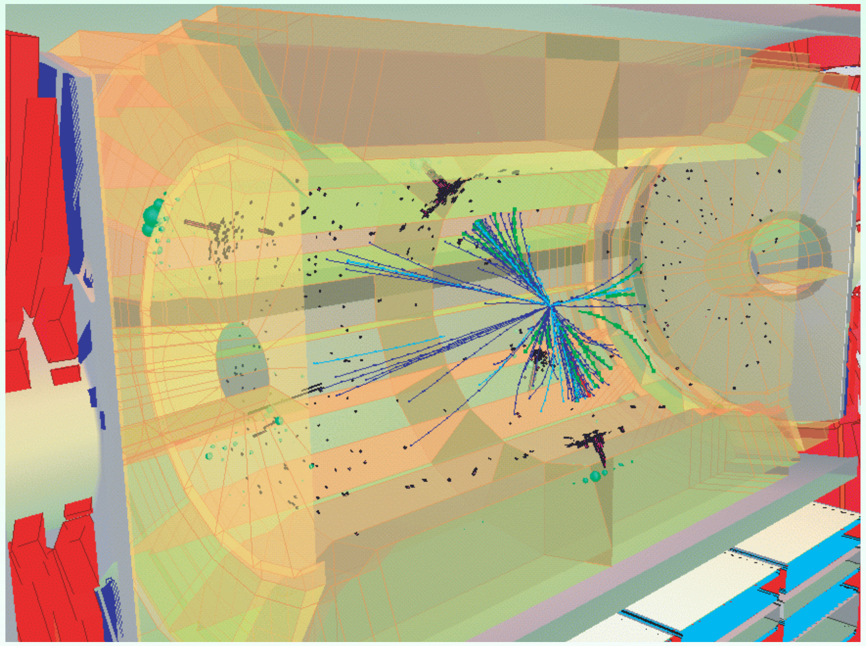
Black hole formation in high-energy particle collisions

Hirotaka Yoshino

(University of Alberta)

with V.S. Rychkov



Black hole production at the LHC?

August 25-29, 2008: Short talk @ Bremen

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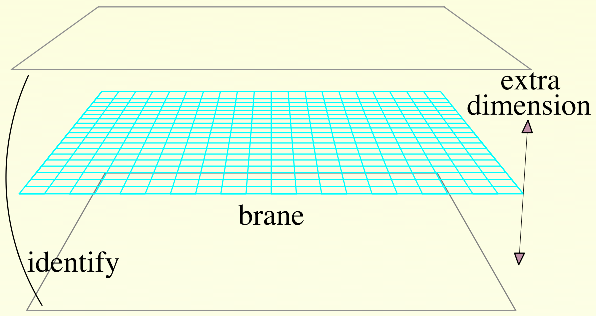
TeV gravity scenarios

Arkani-Hamed et al. (1998)



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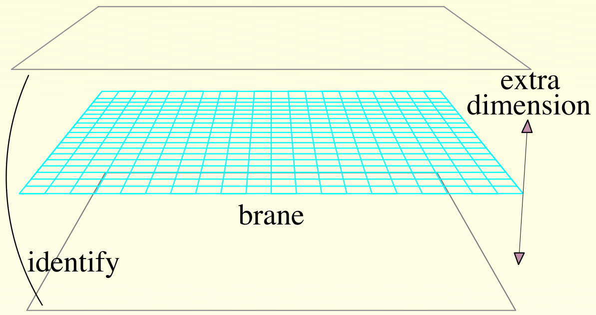

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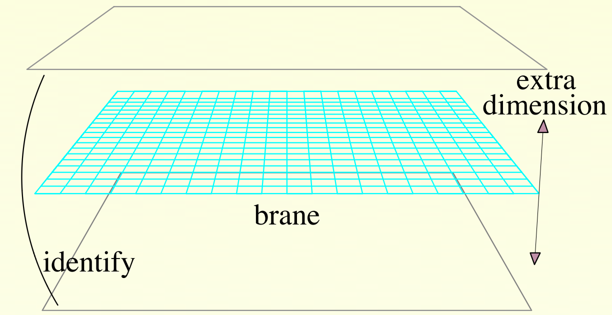

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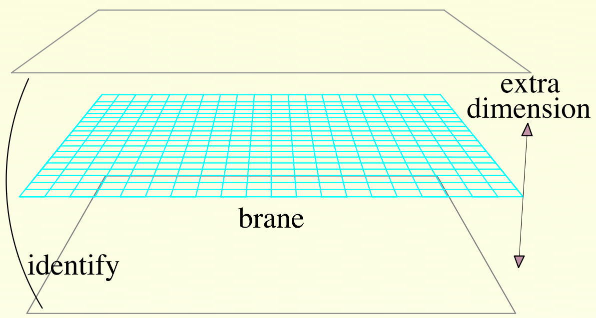

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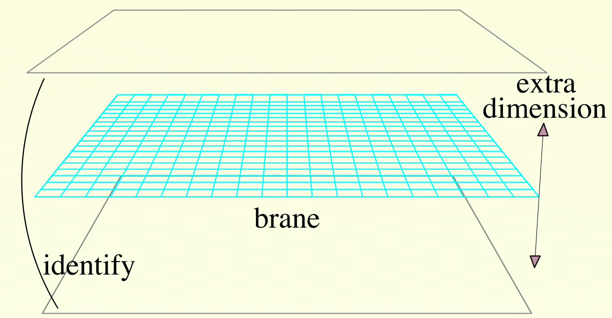

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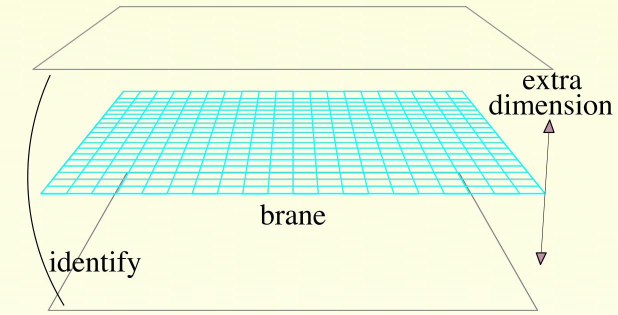

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  - (semi-)classical approximation

    mini BH production and subsequent decay.

Estimate of production rate

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Giddings & Thomas, Dimopoulos & Landsberg (2002)

$$\sigma_{pp\to bh}(\tau_m, s) = \sum_{ij} \int_{\tau_m}^{1} d\tau \int_{\tau}^{1} \frac{dx}{x} f_i(x) f_j(\tau/x) \sigma_{ij\to bh}(\tau s)$$

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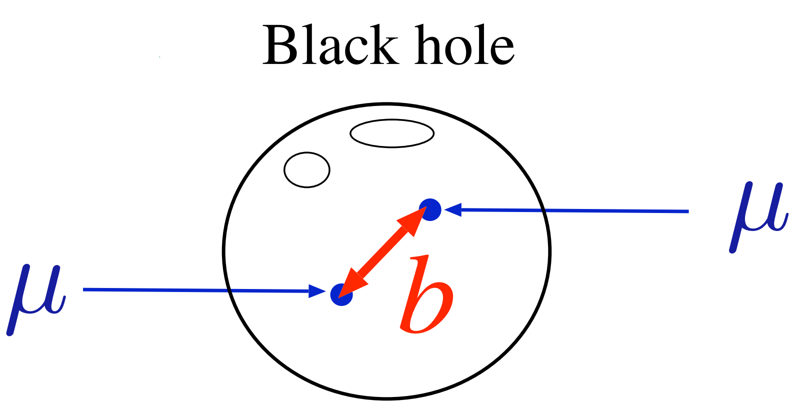

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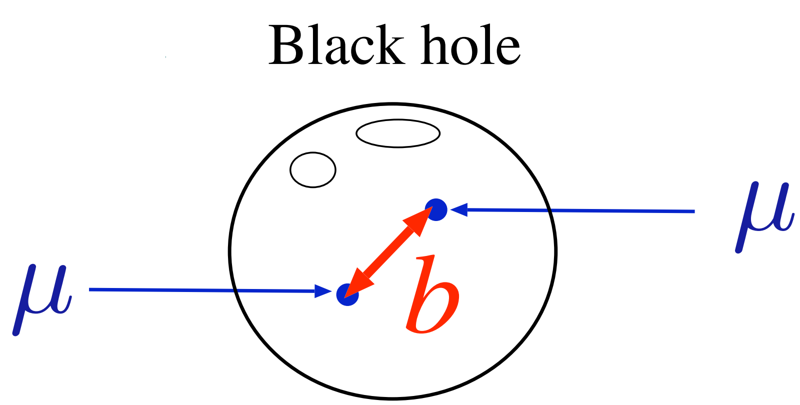

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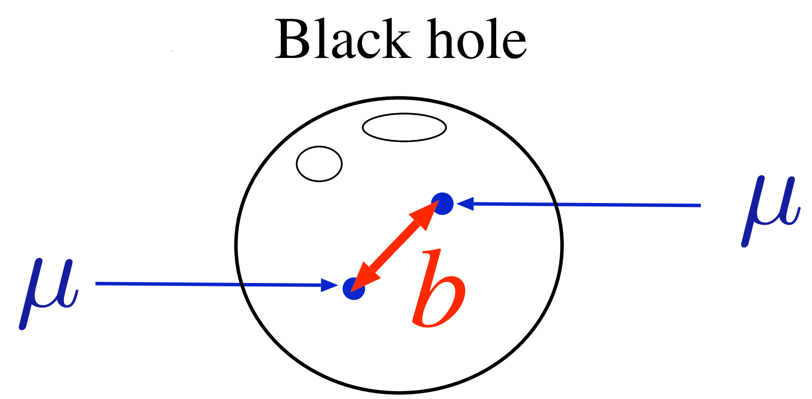

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accurate value of σ_{BH} **??** ⇒ **AH is useful.**

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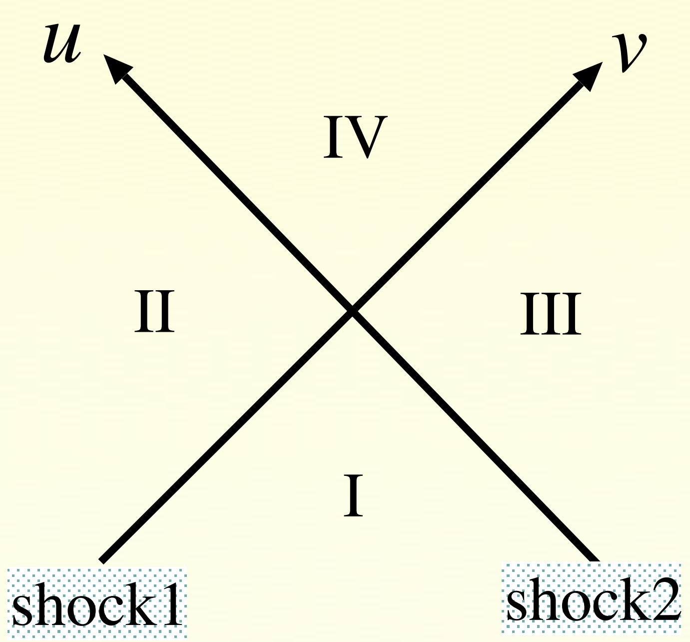

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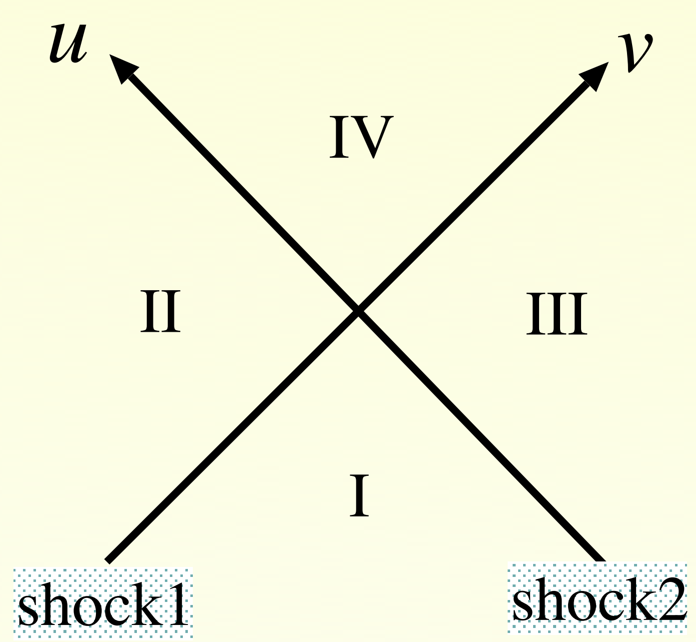

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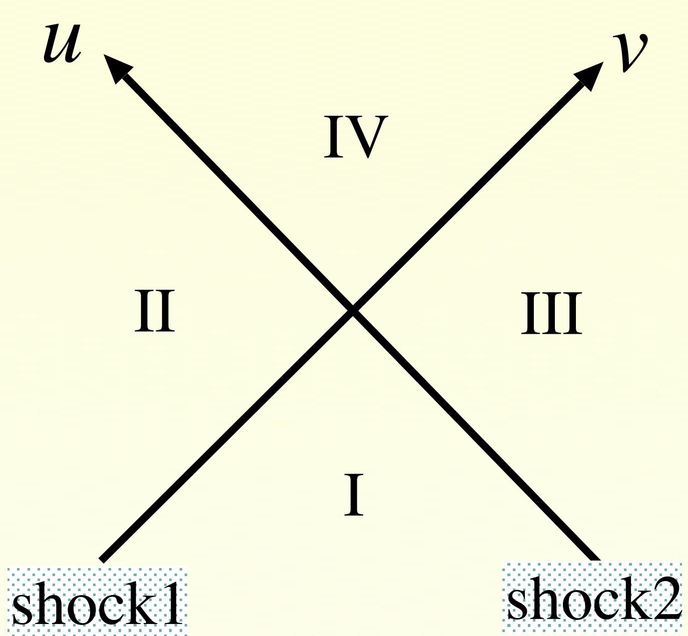

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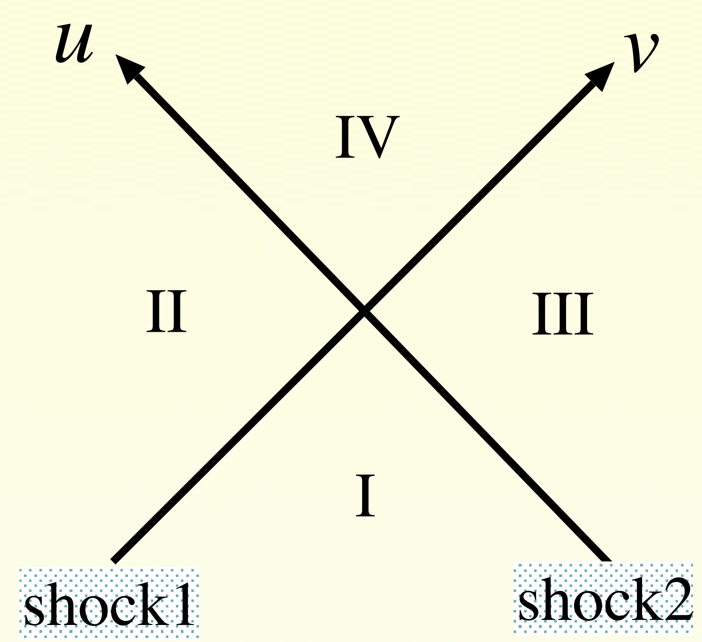

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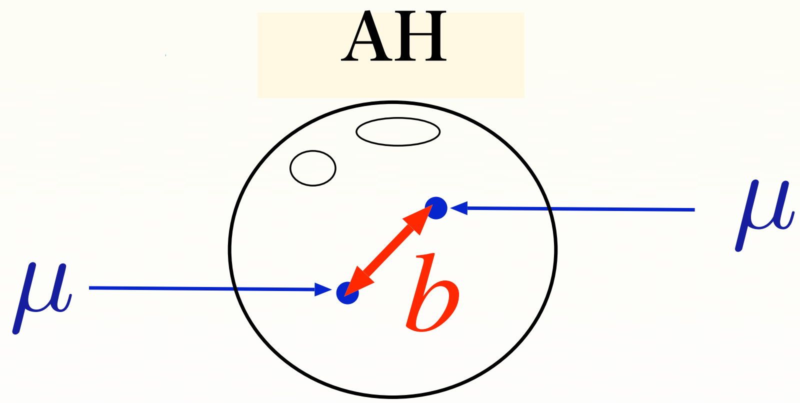

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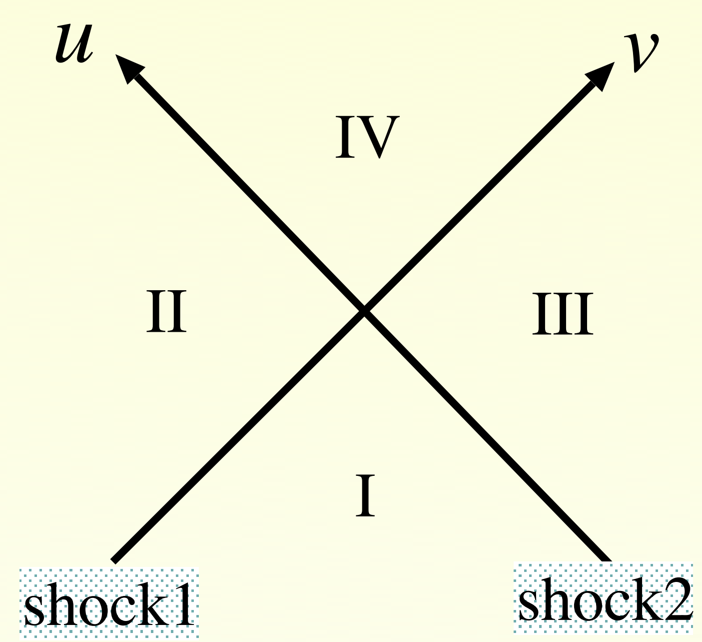

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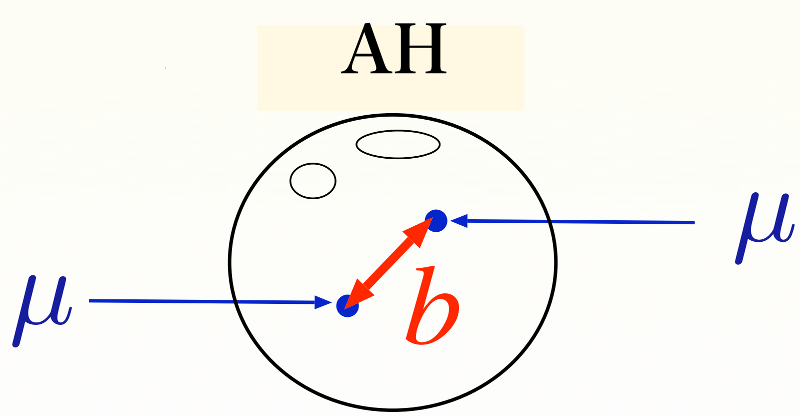

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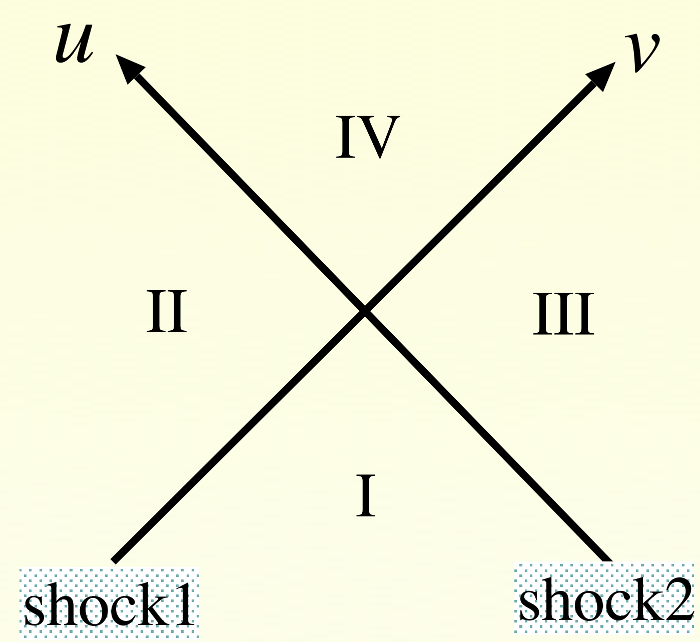

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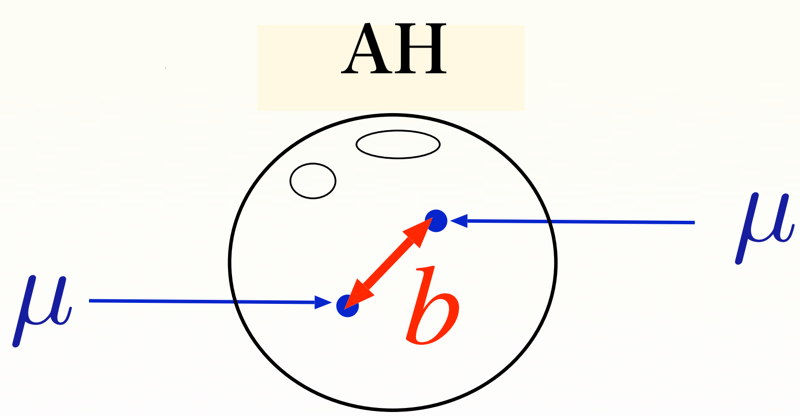

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- We will find the lower bound on $\sigma_{\rm BH}$.

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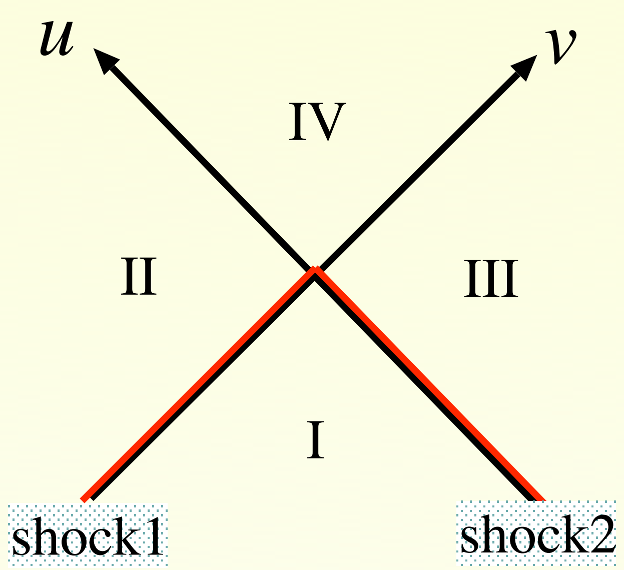

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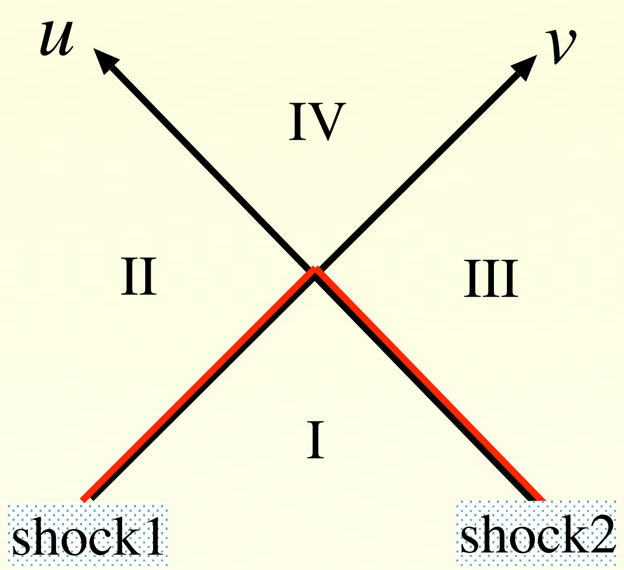

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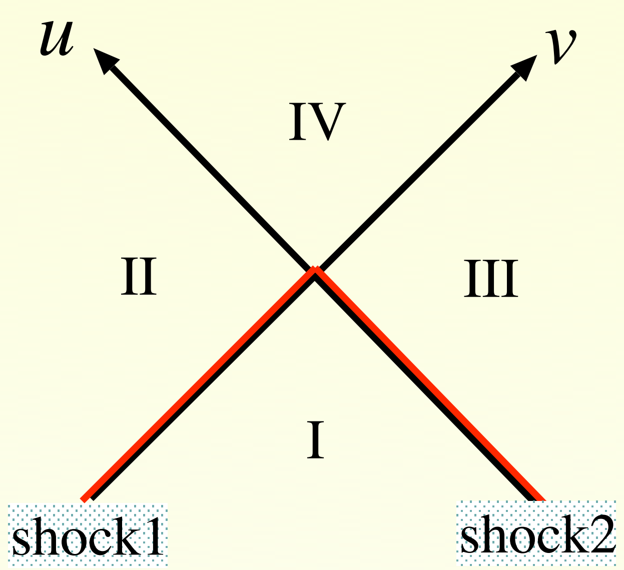

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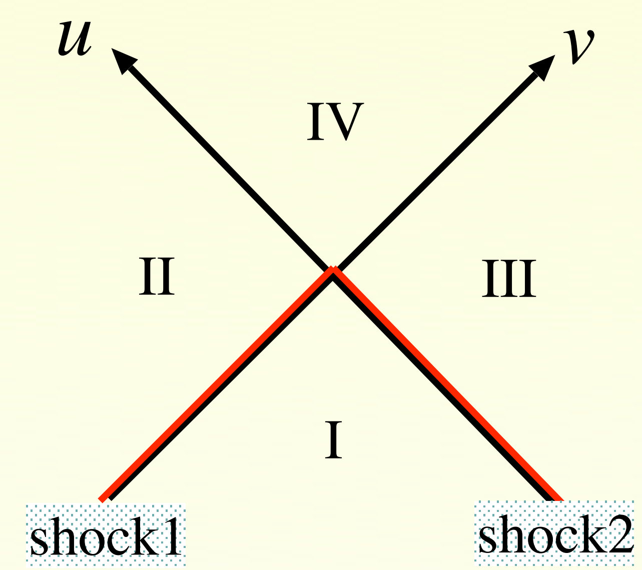

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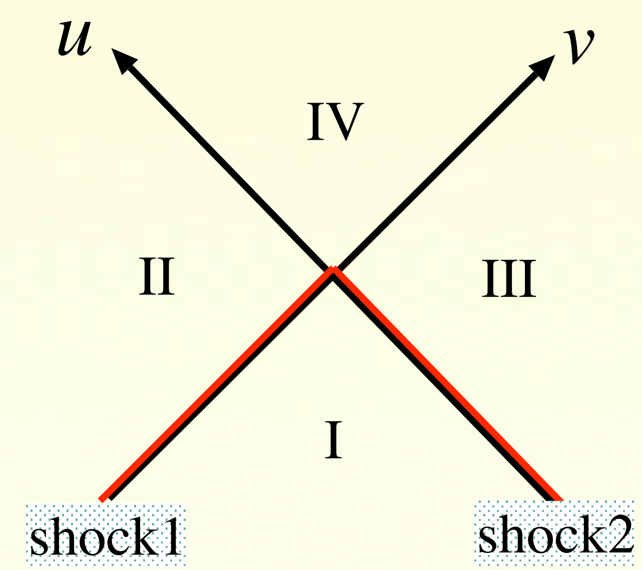

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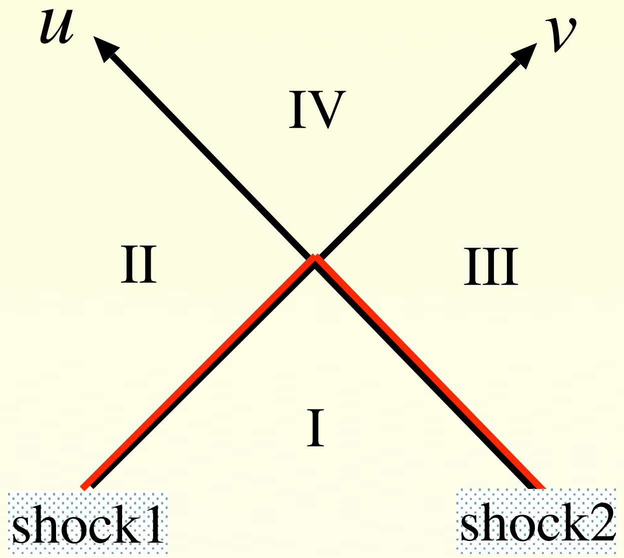

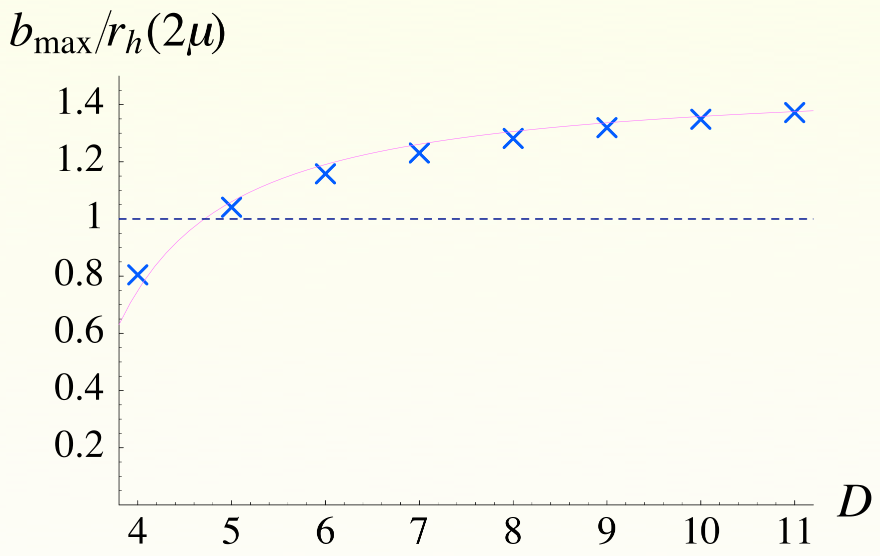

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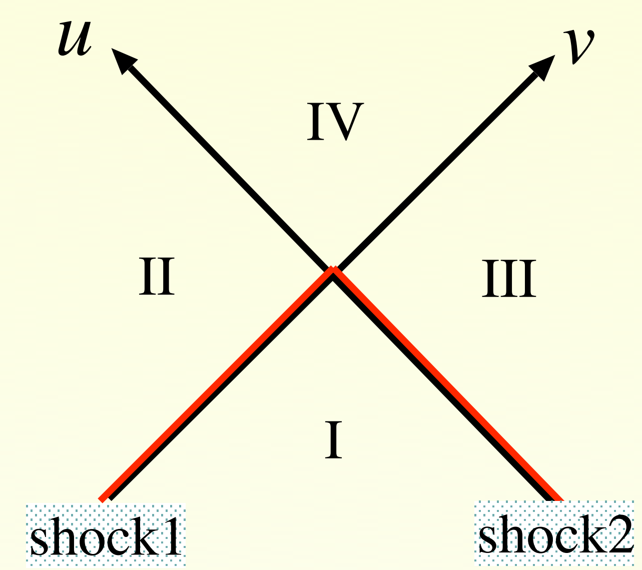

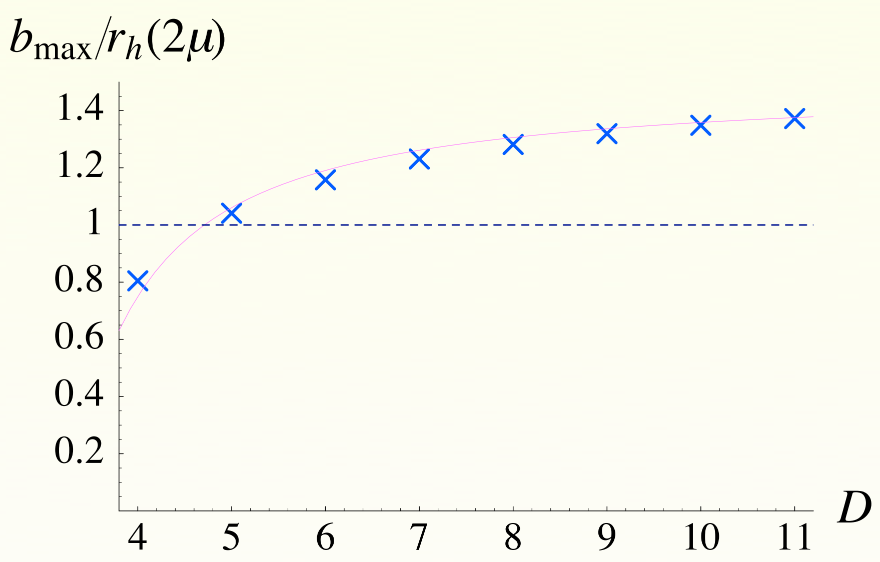

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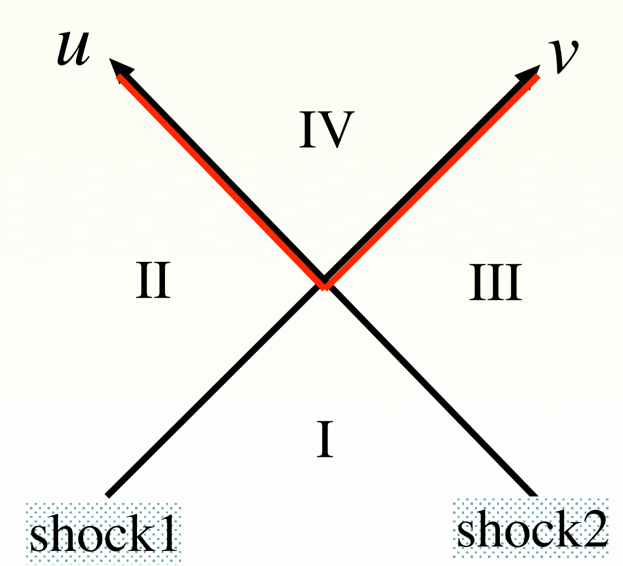

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Aichelburg-Sexl particle

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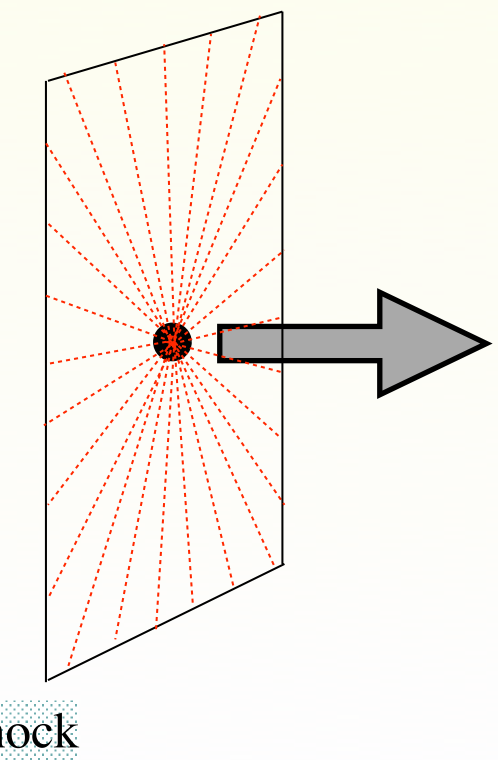

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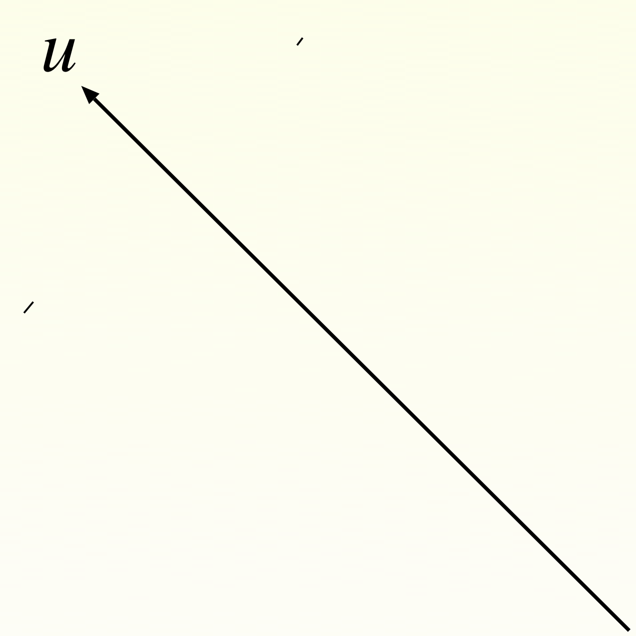

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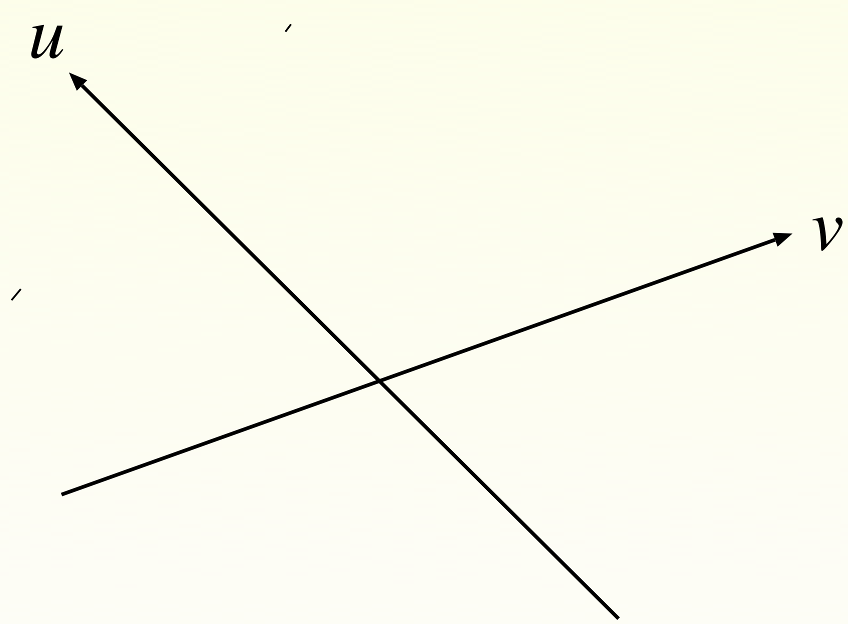

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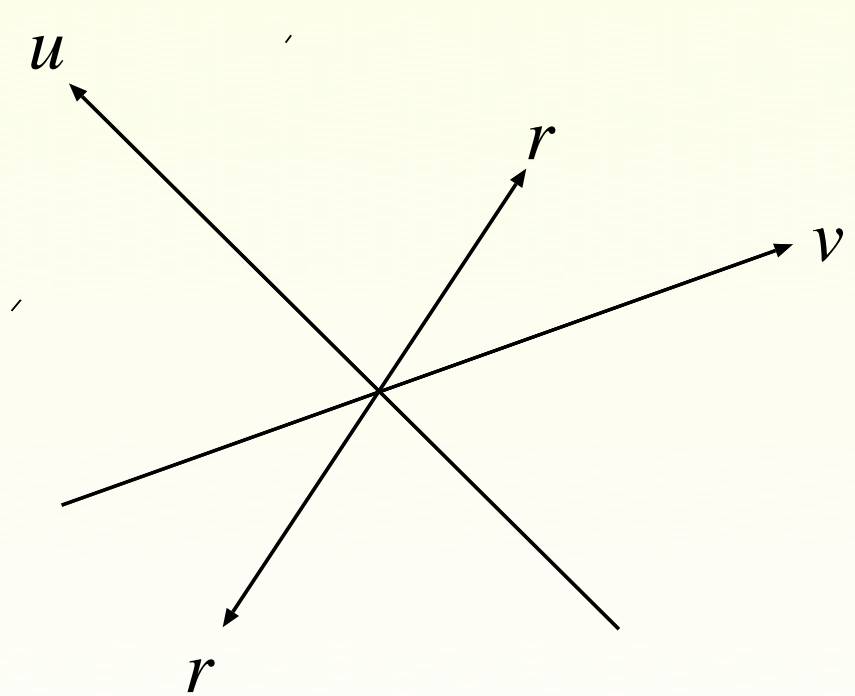

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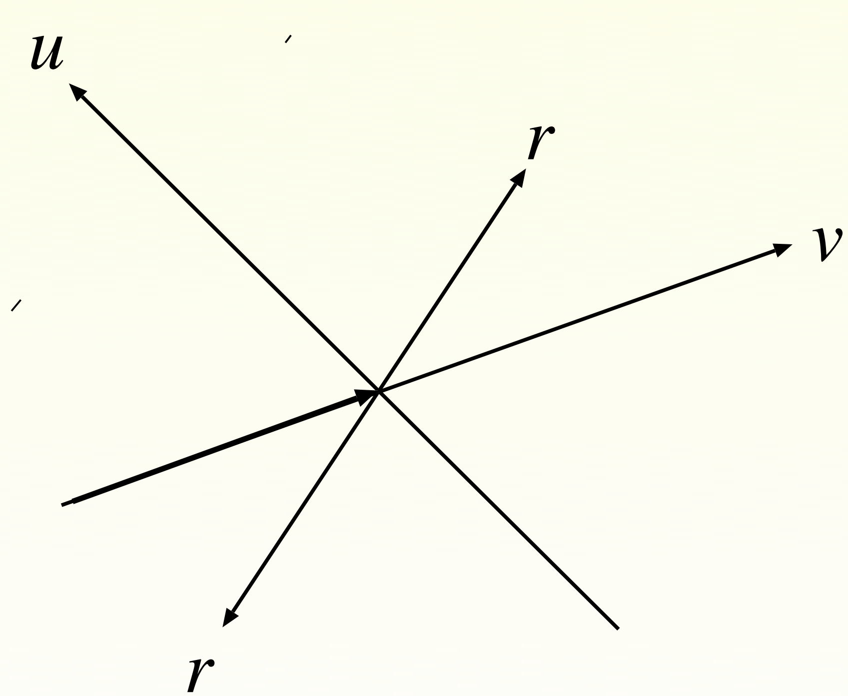

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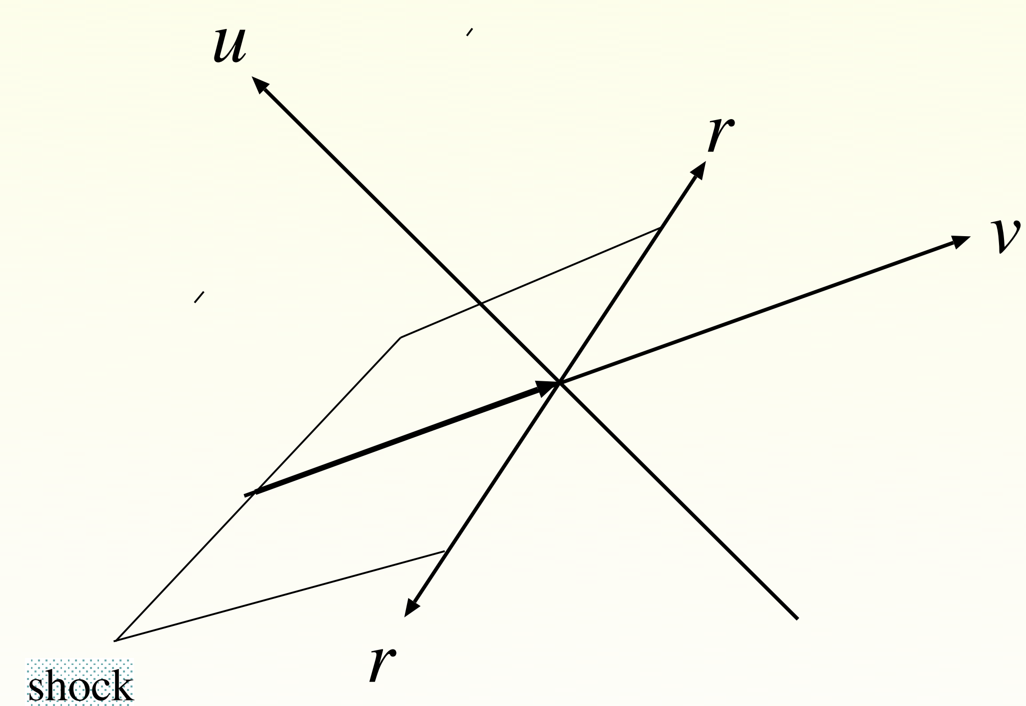

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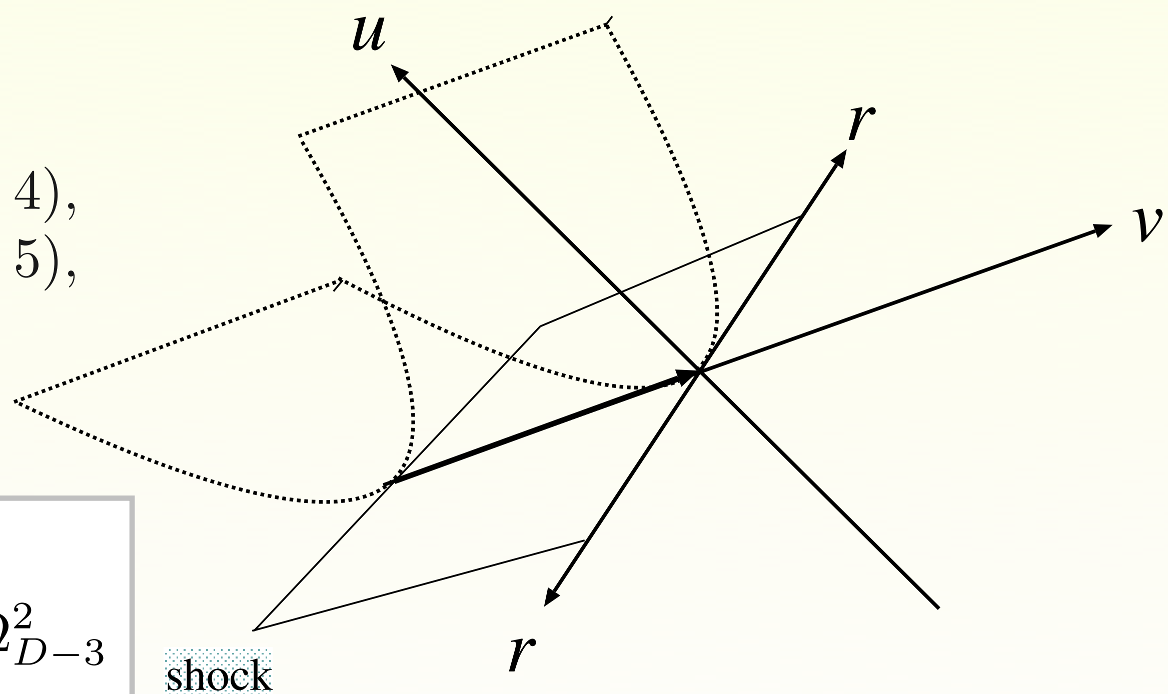

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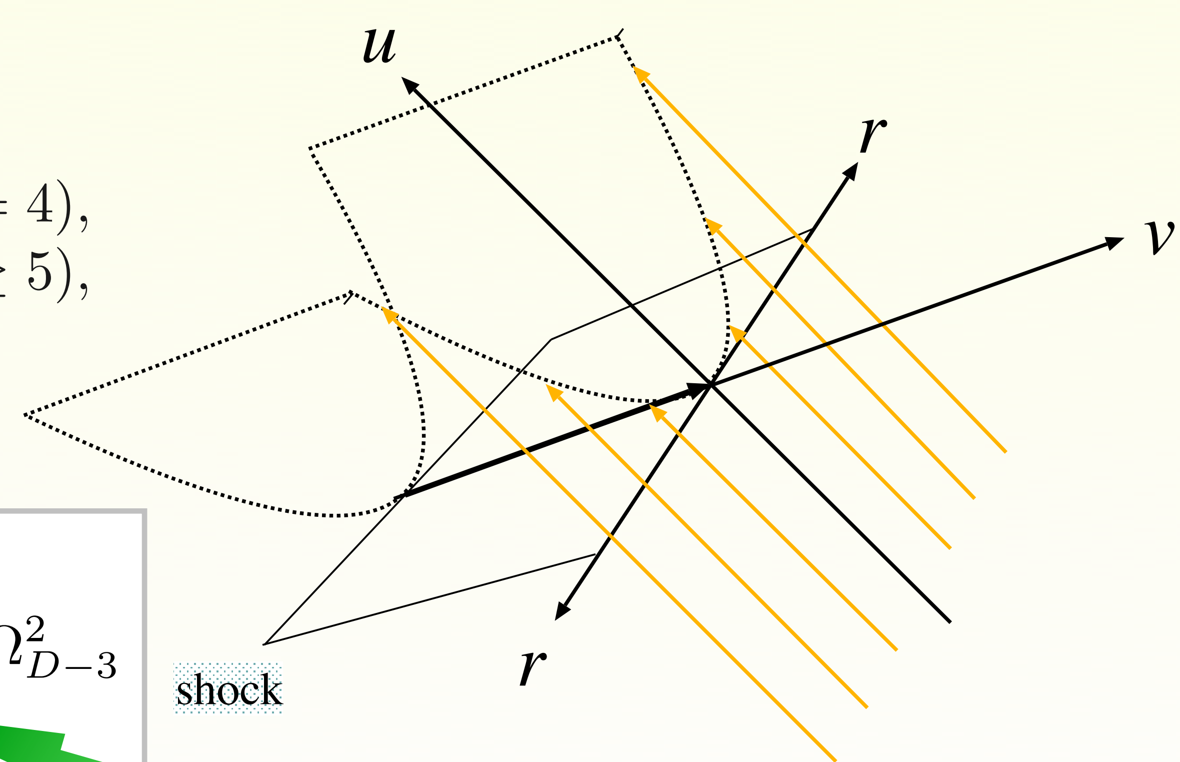

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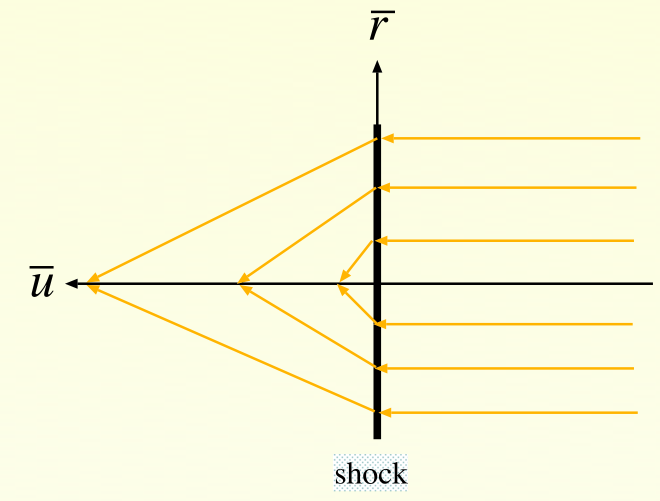

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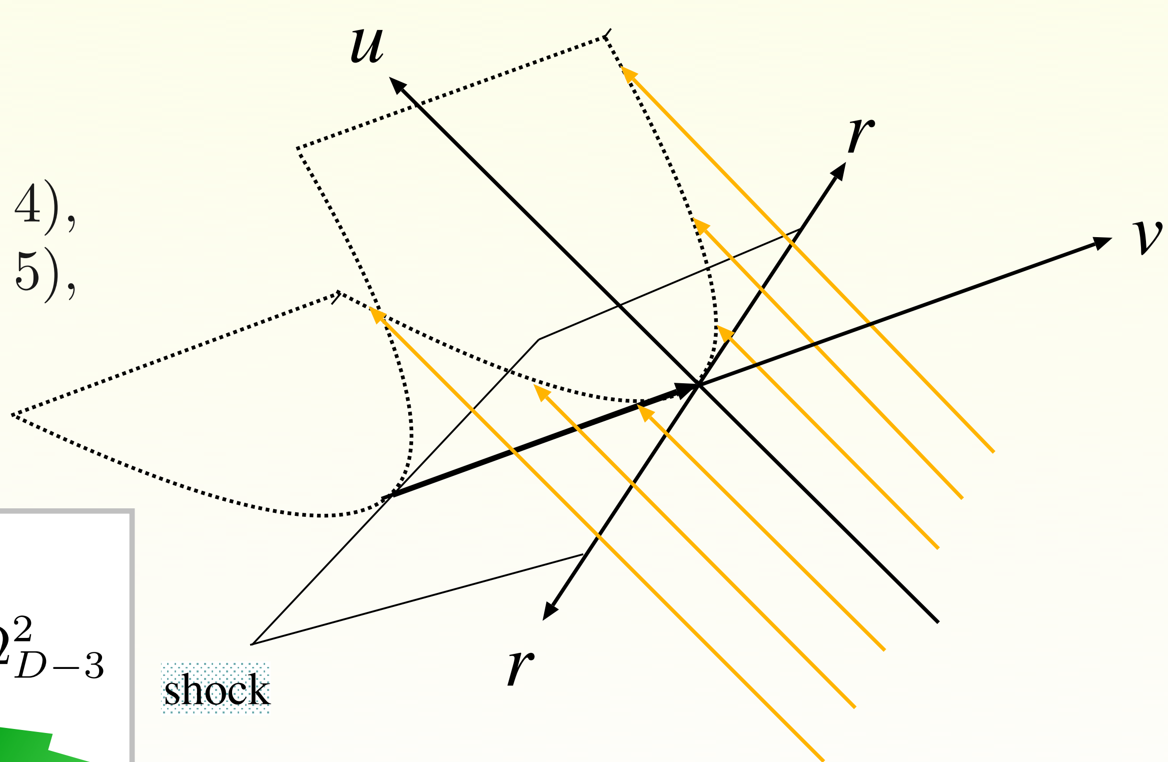

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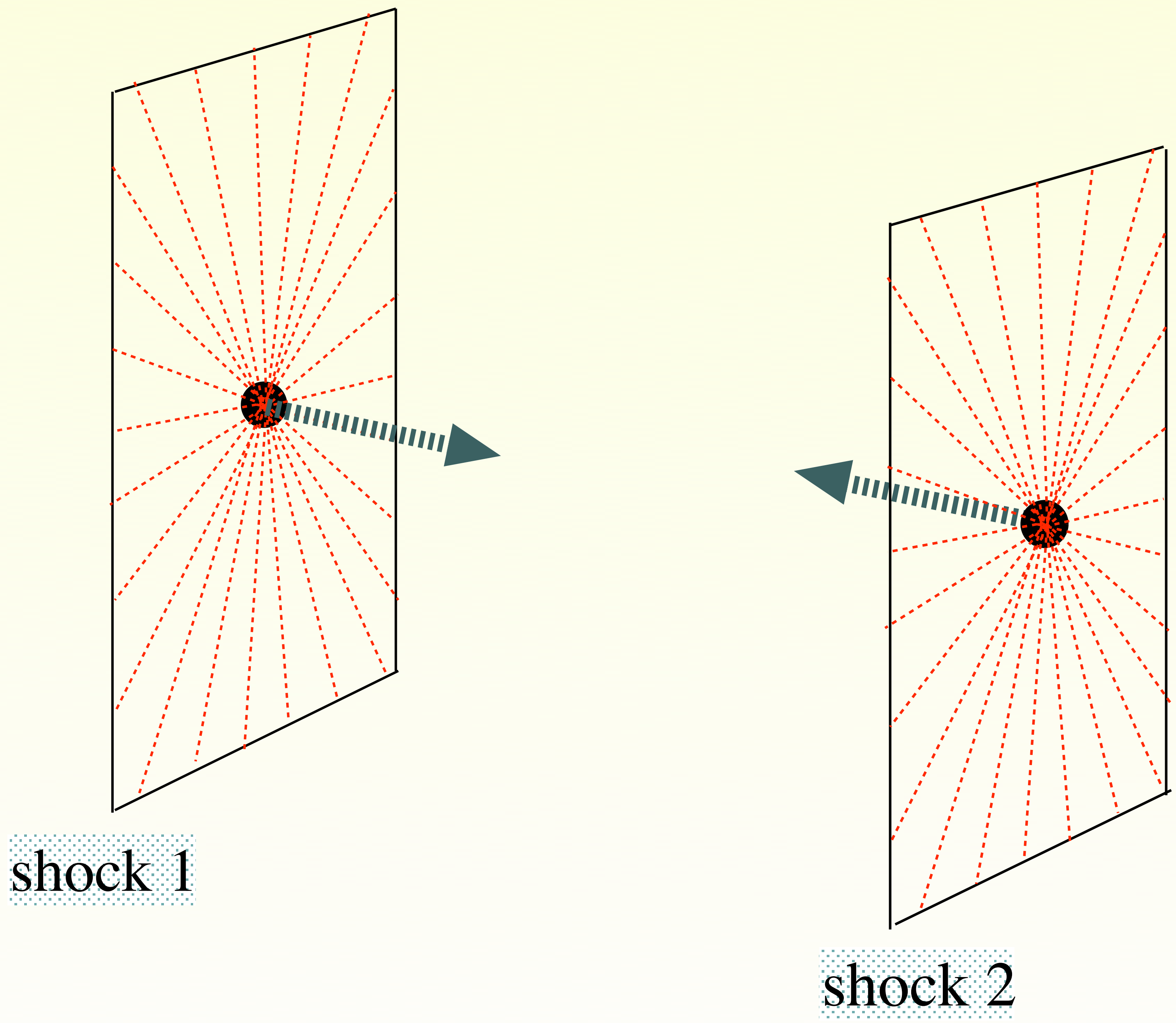
Setup of two particle system



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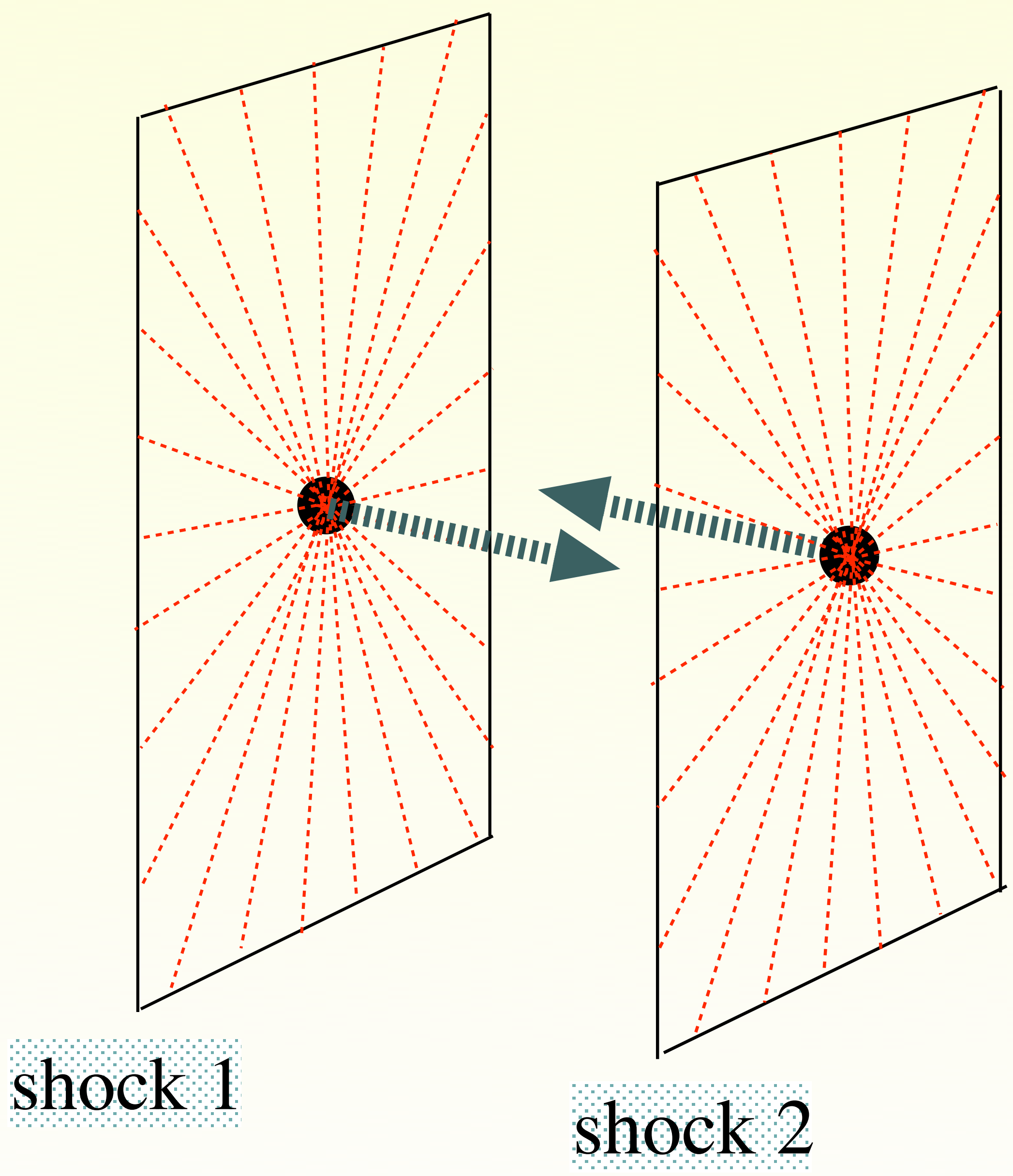

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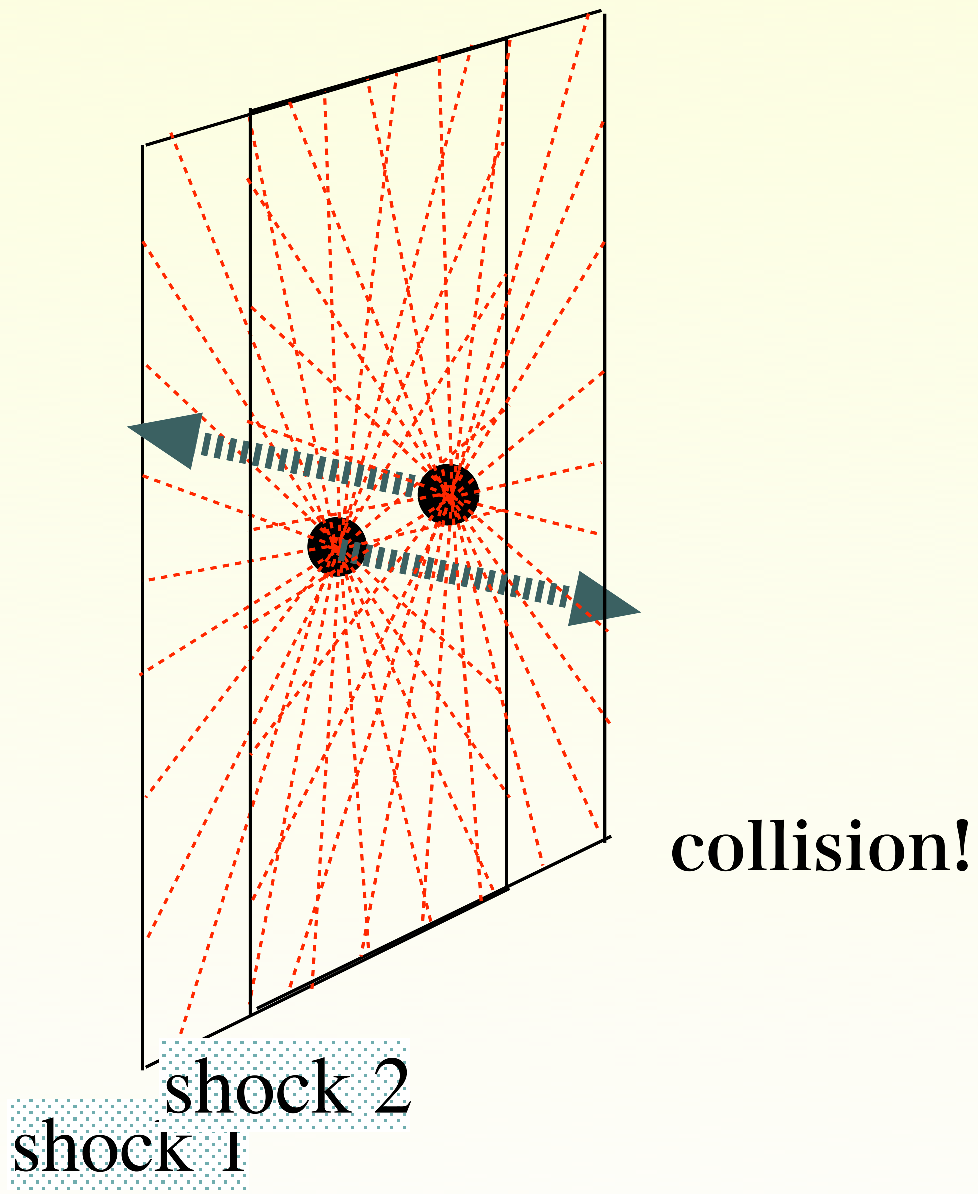
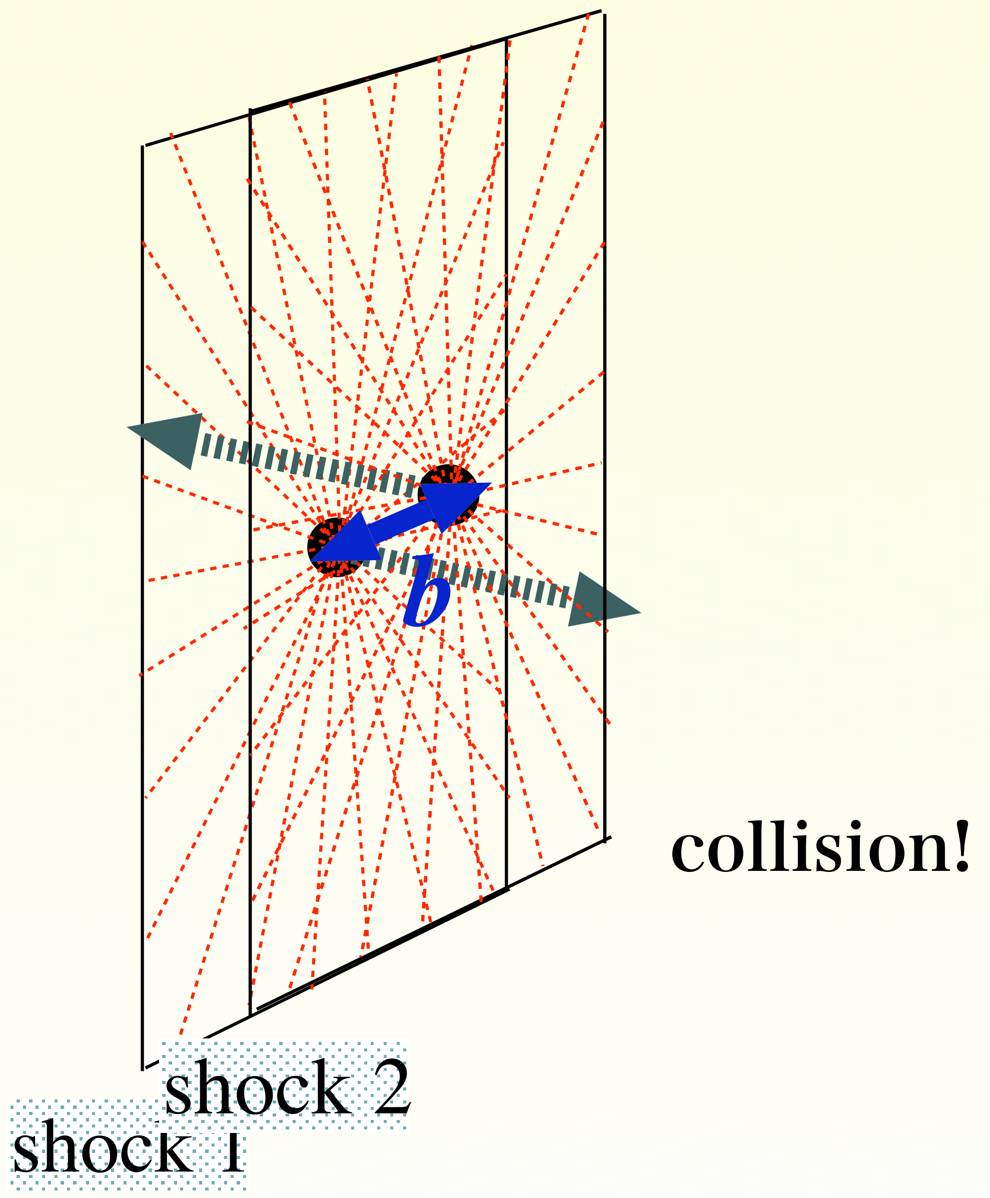


Setup of two particle system

b **: Impact parameter**



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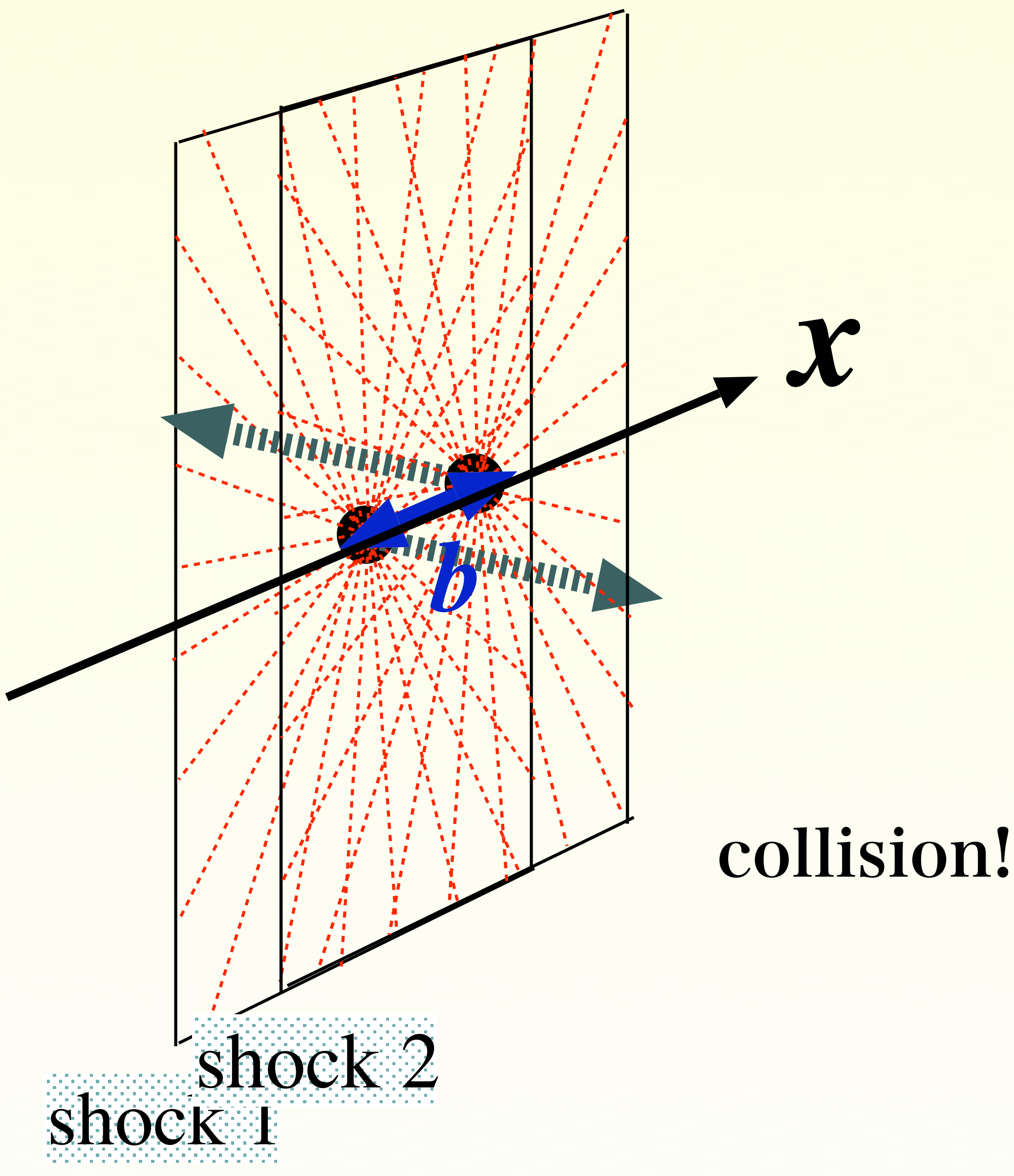

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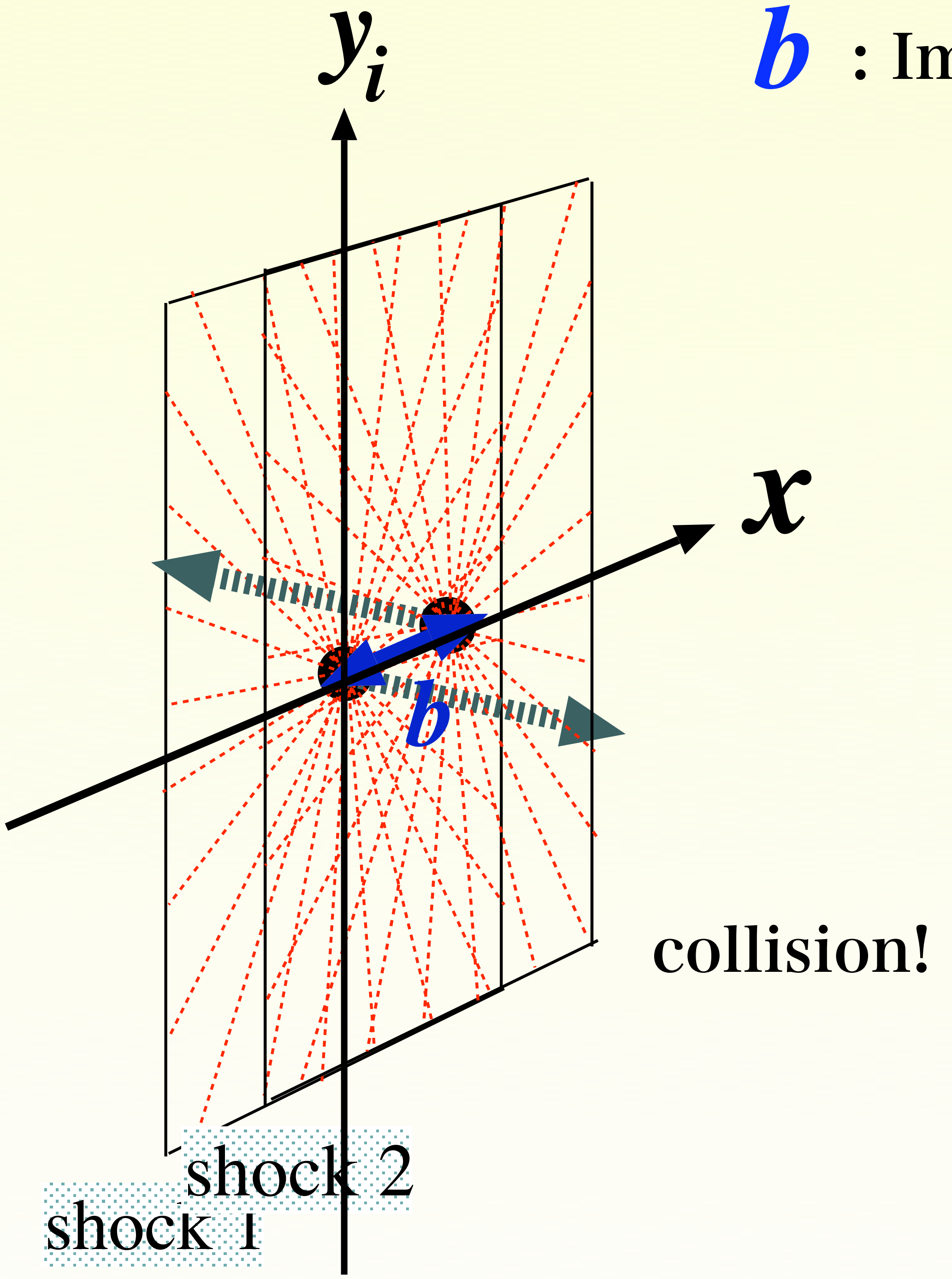

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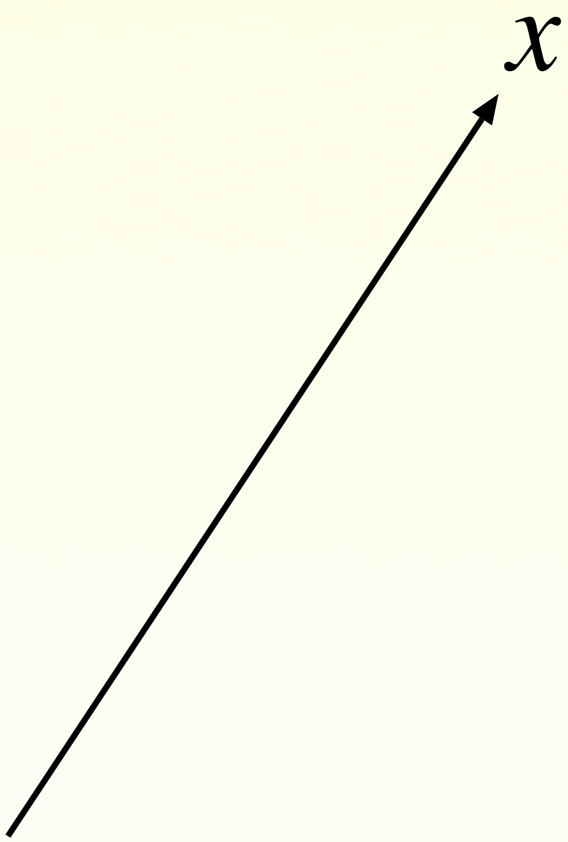

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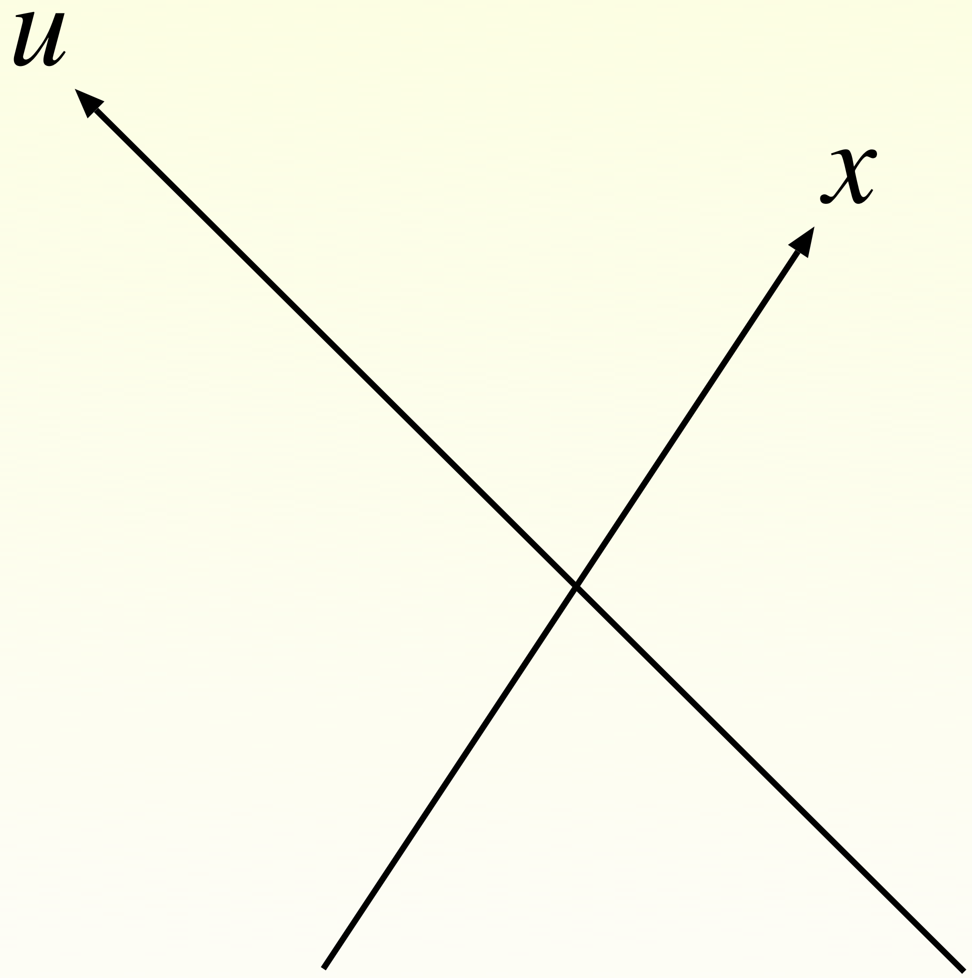

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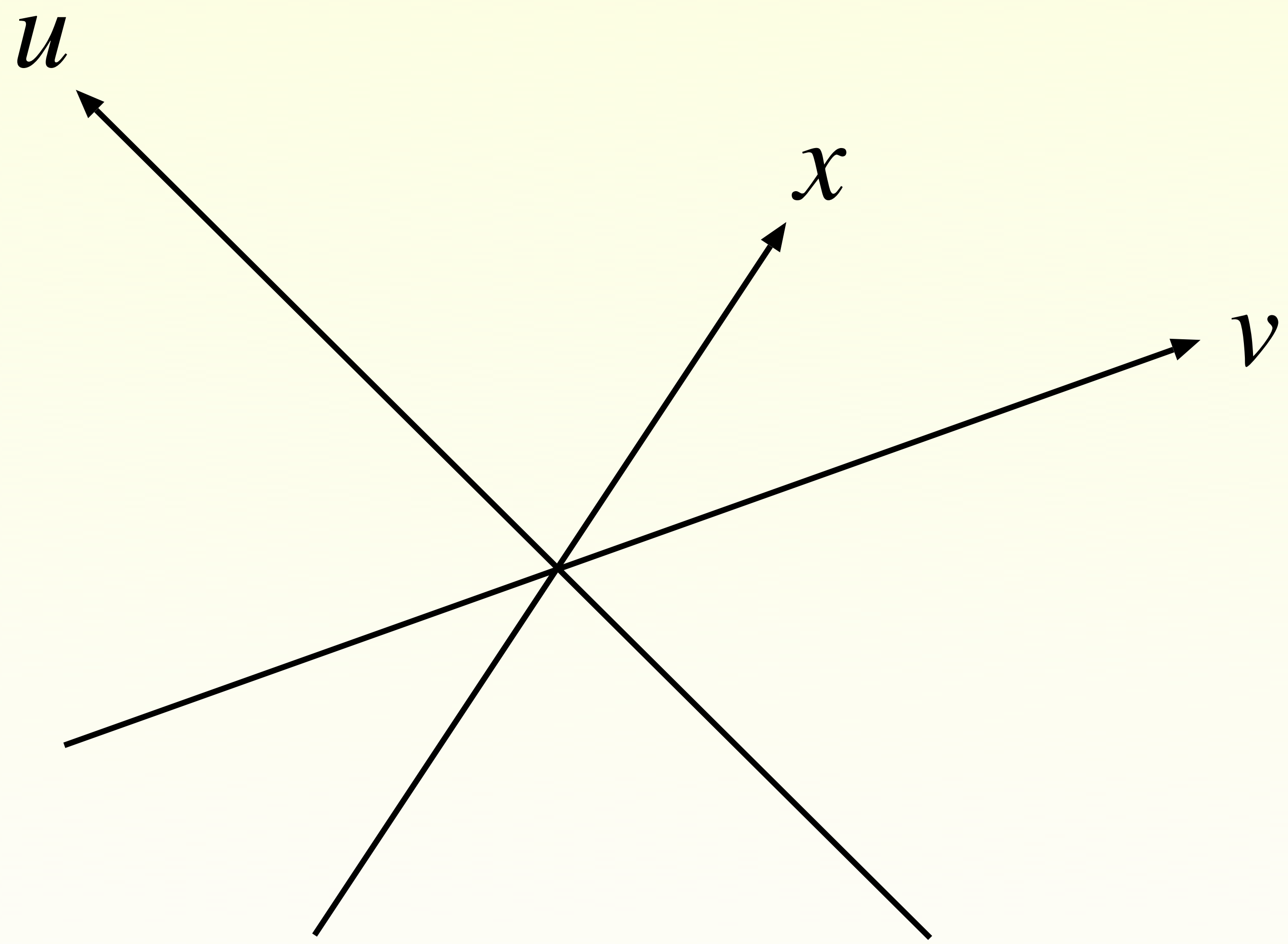

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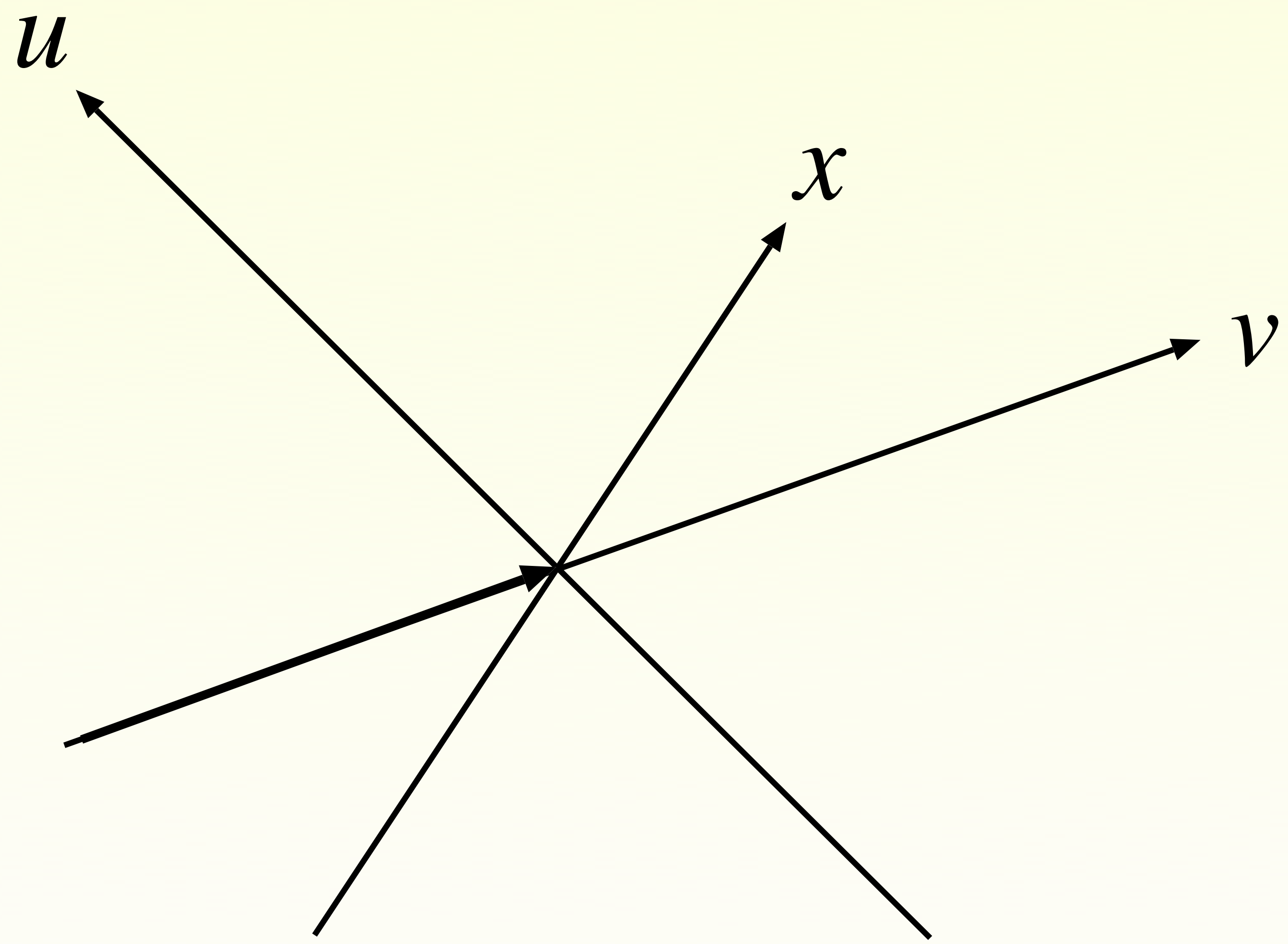

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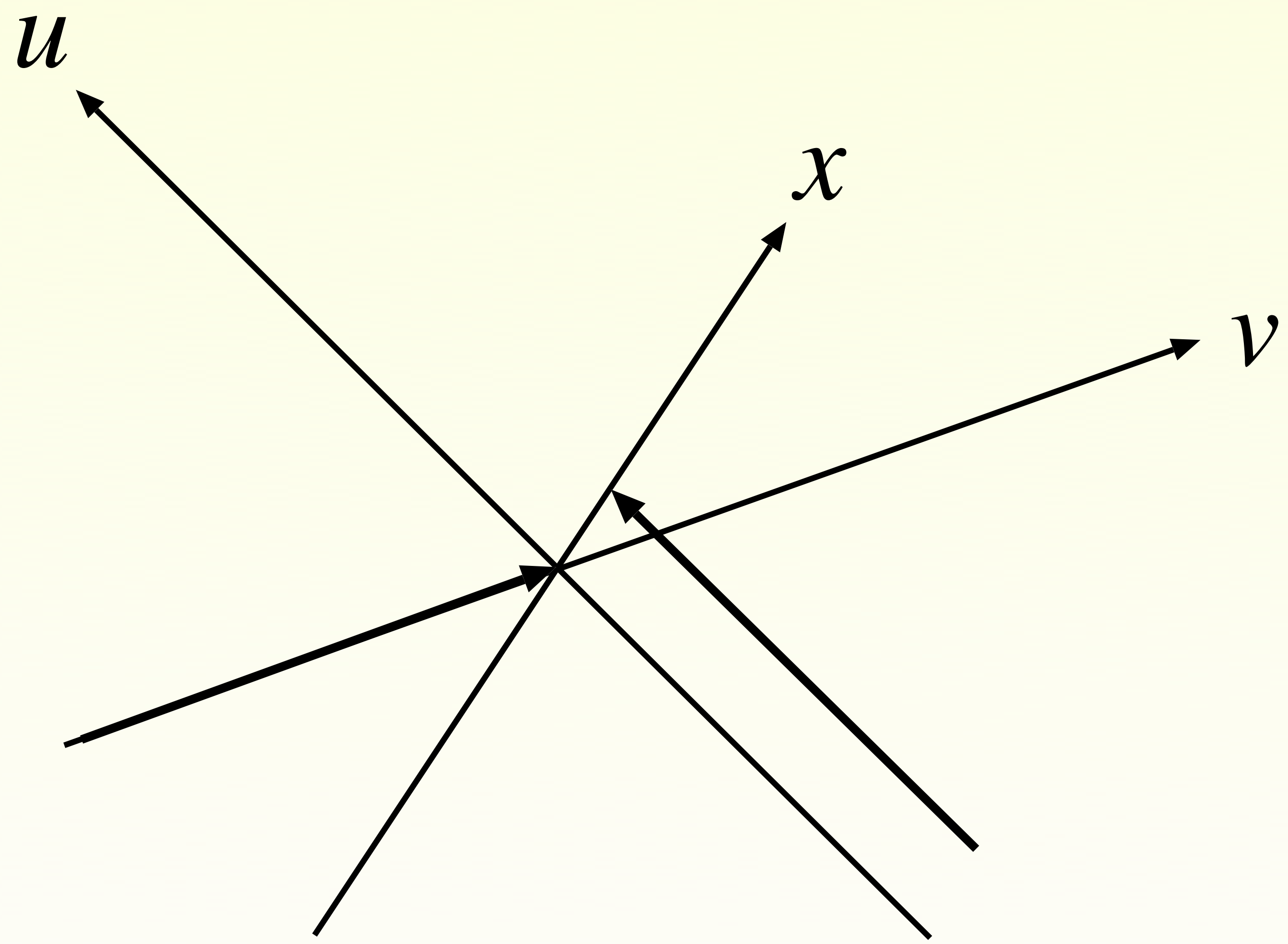

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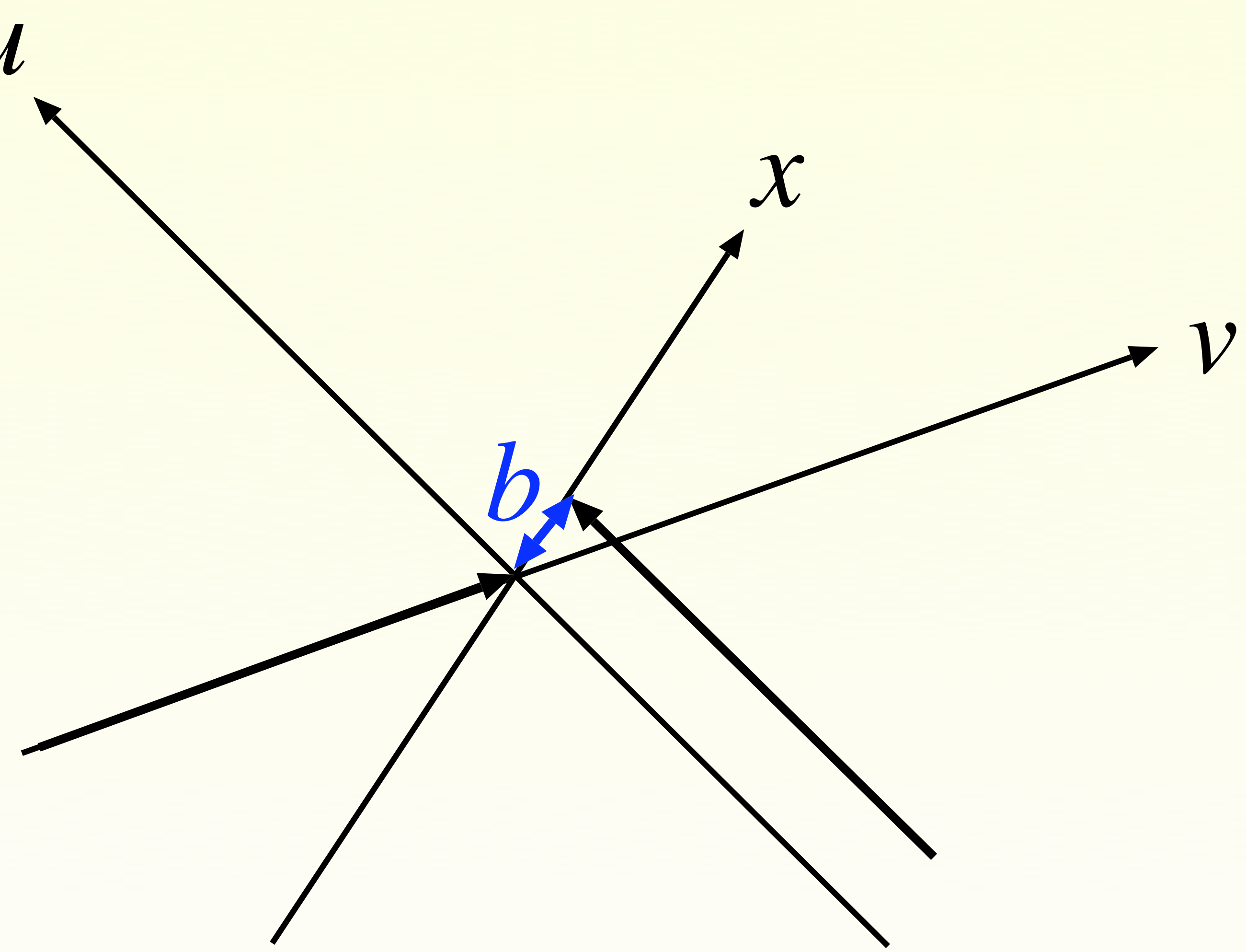

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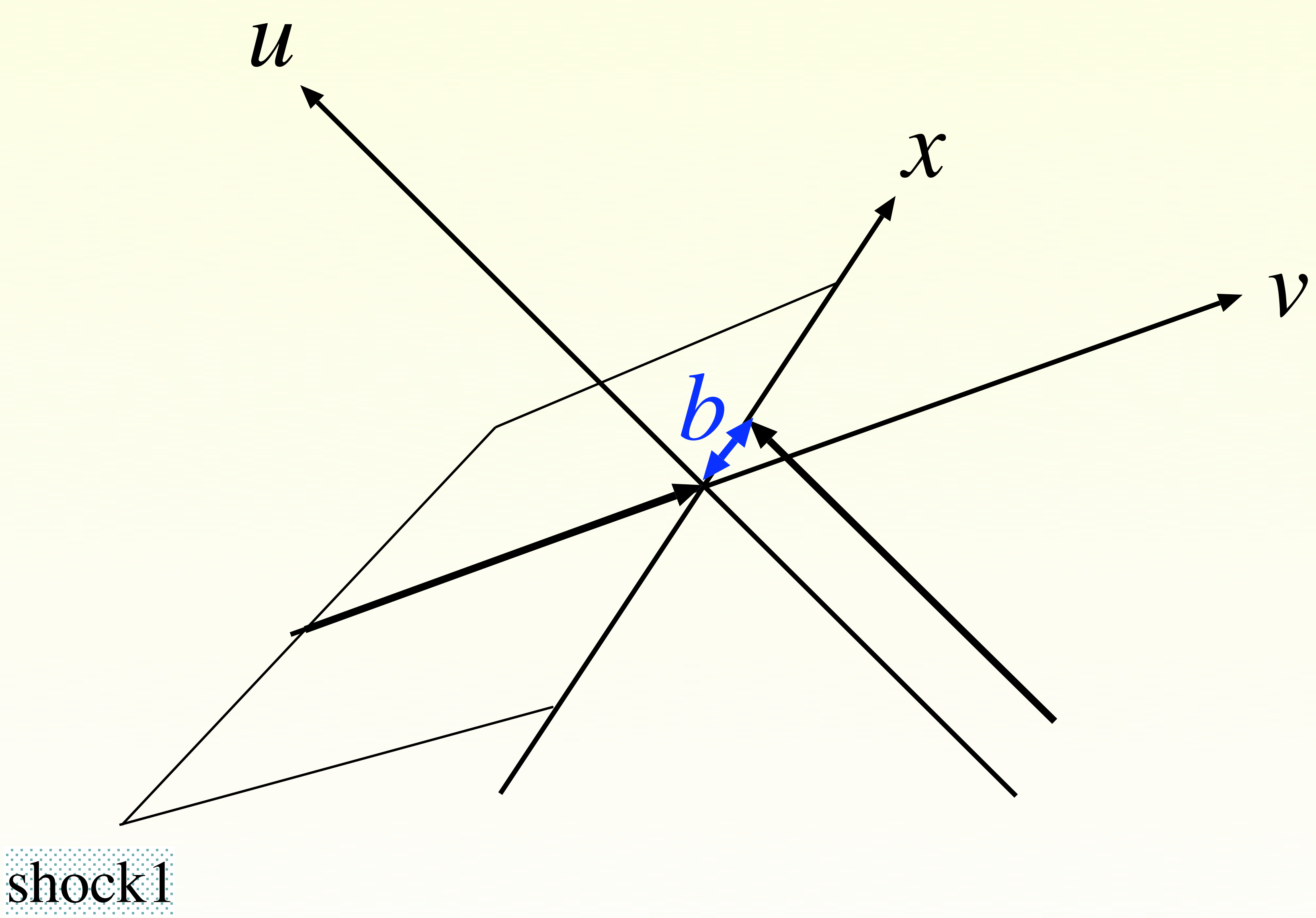

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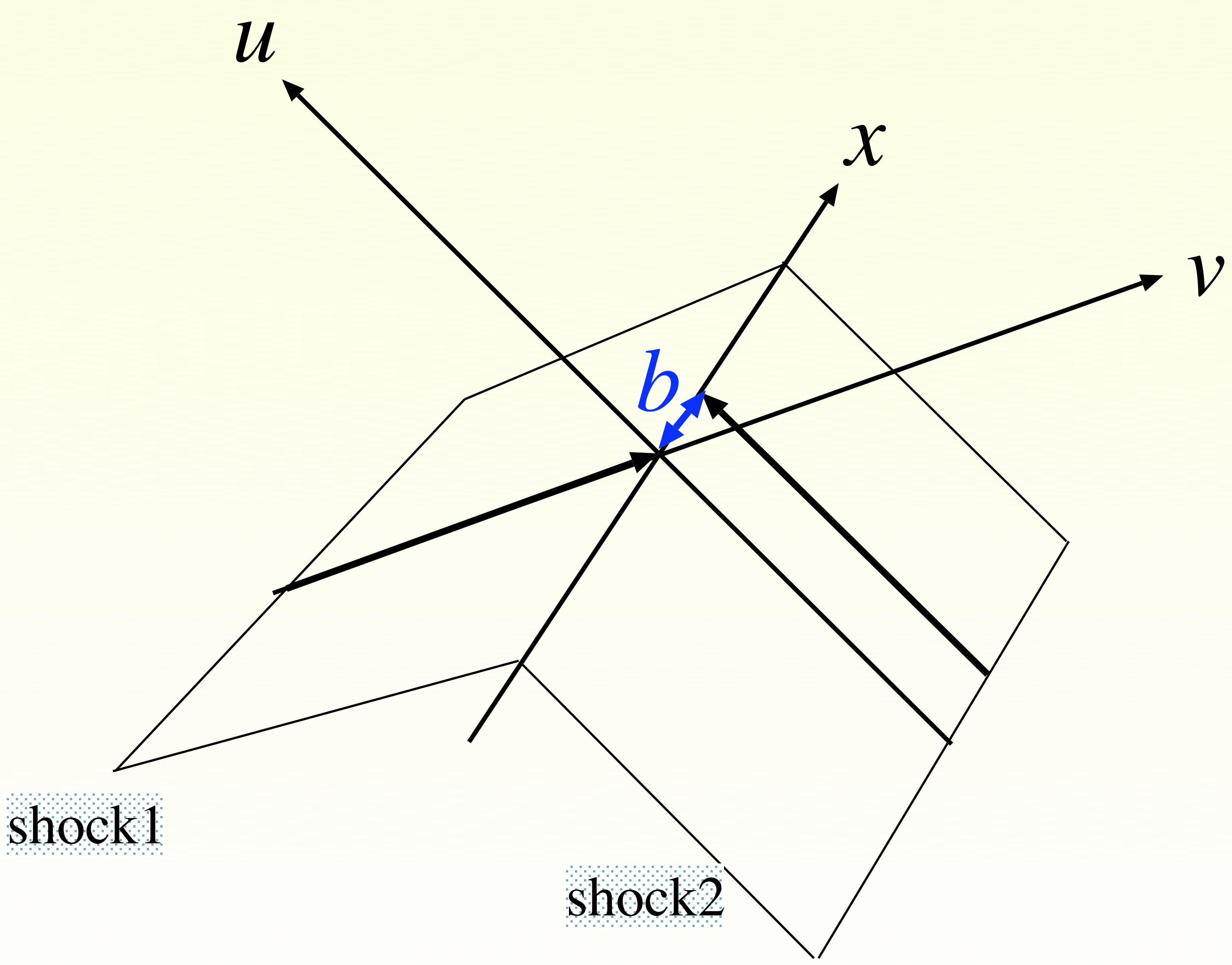

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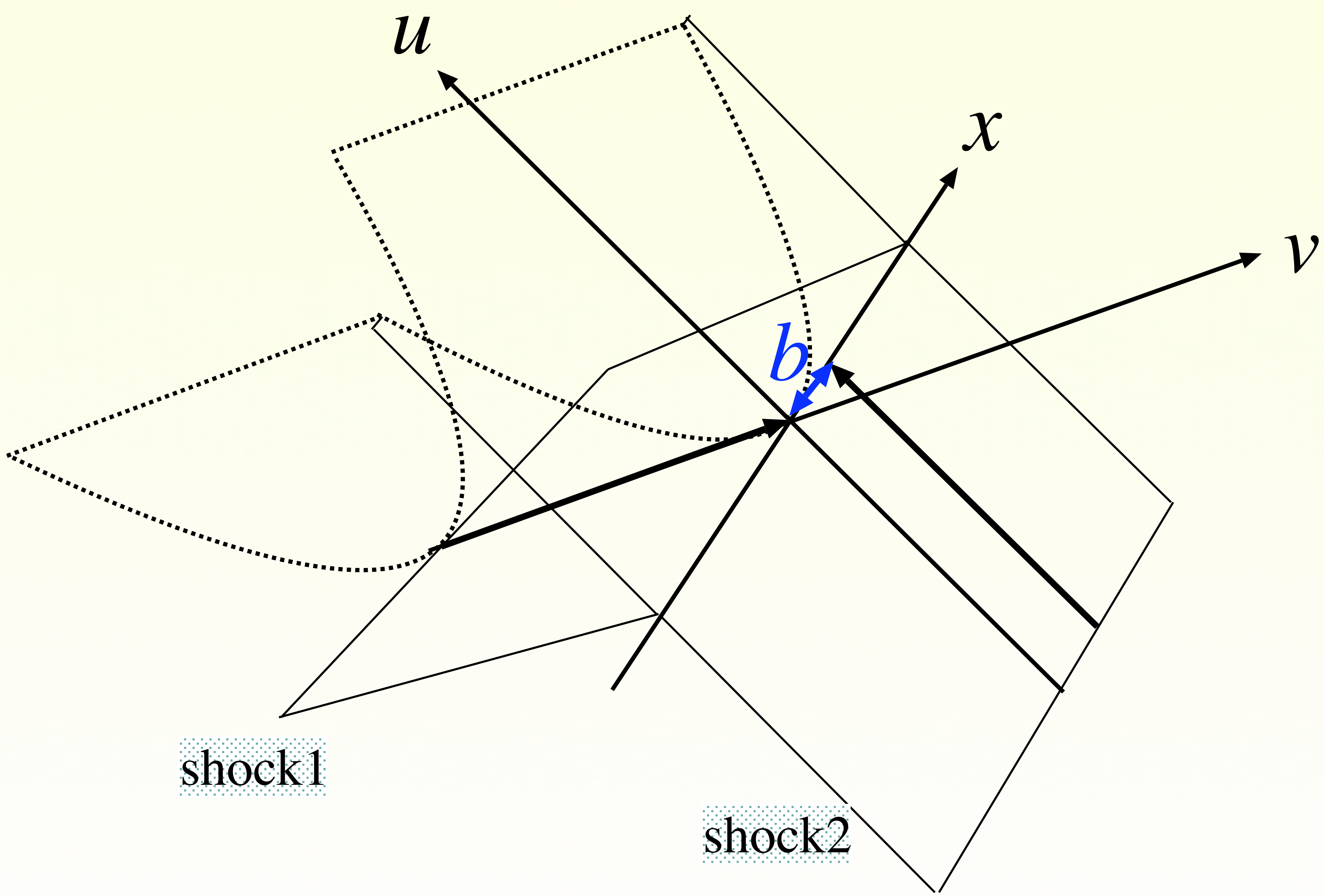

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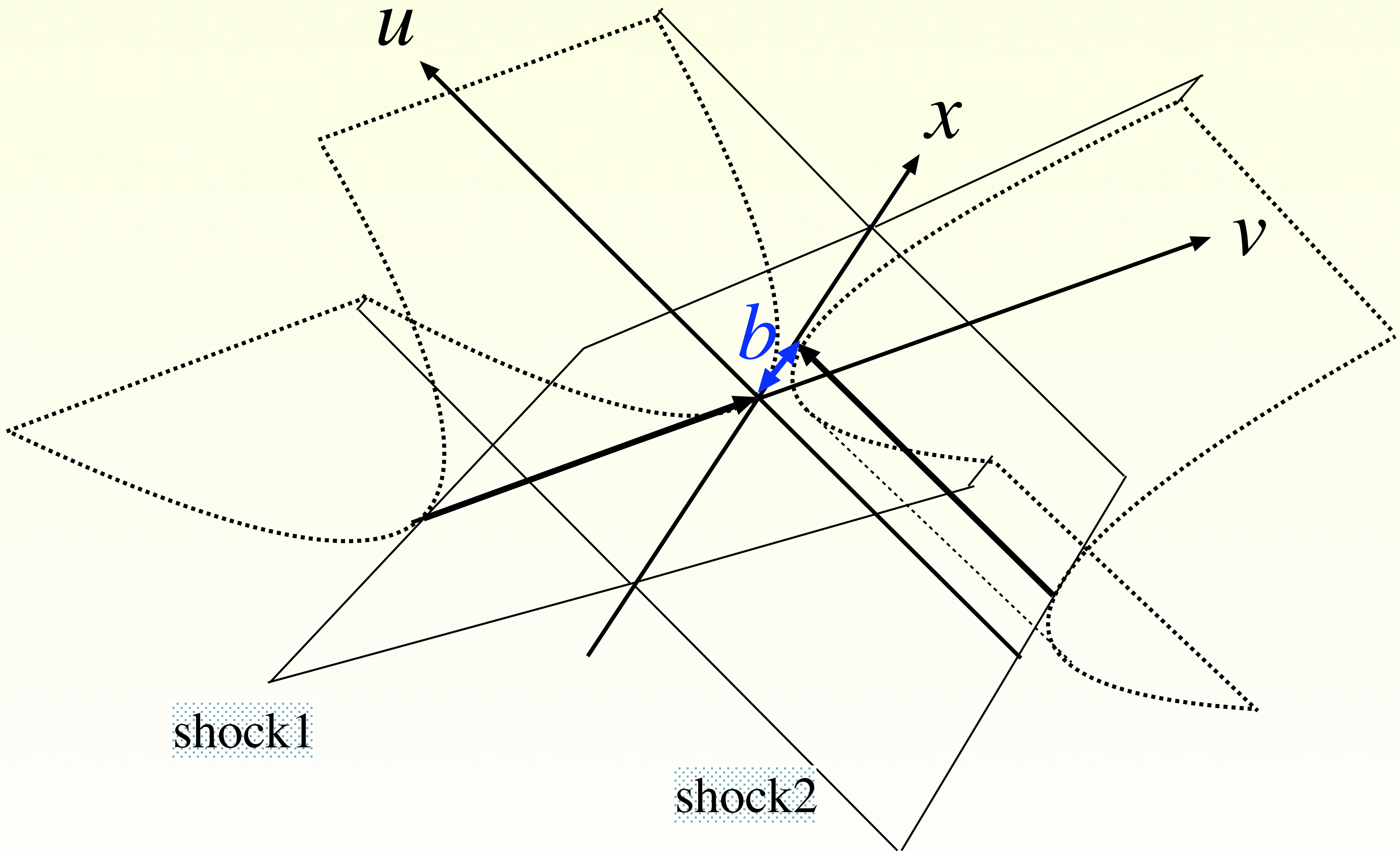

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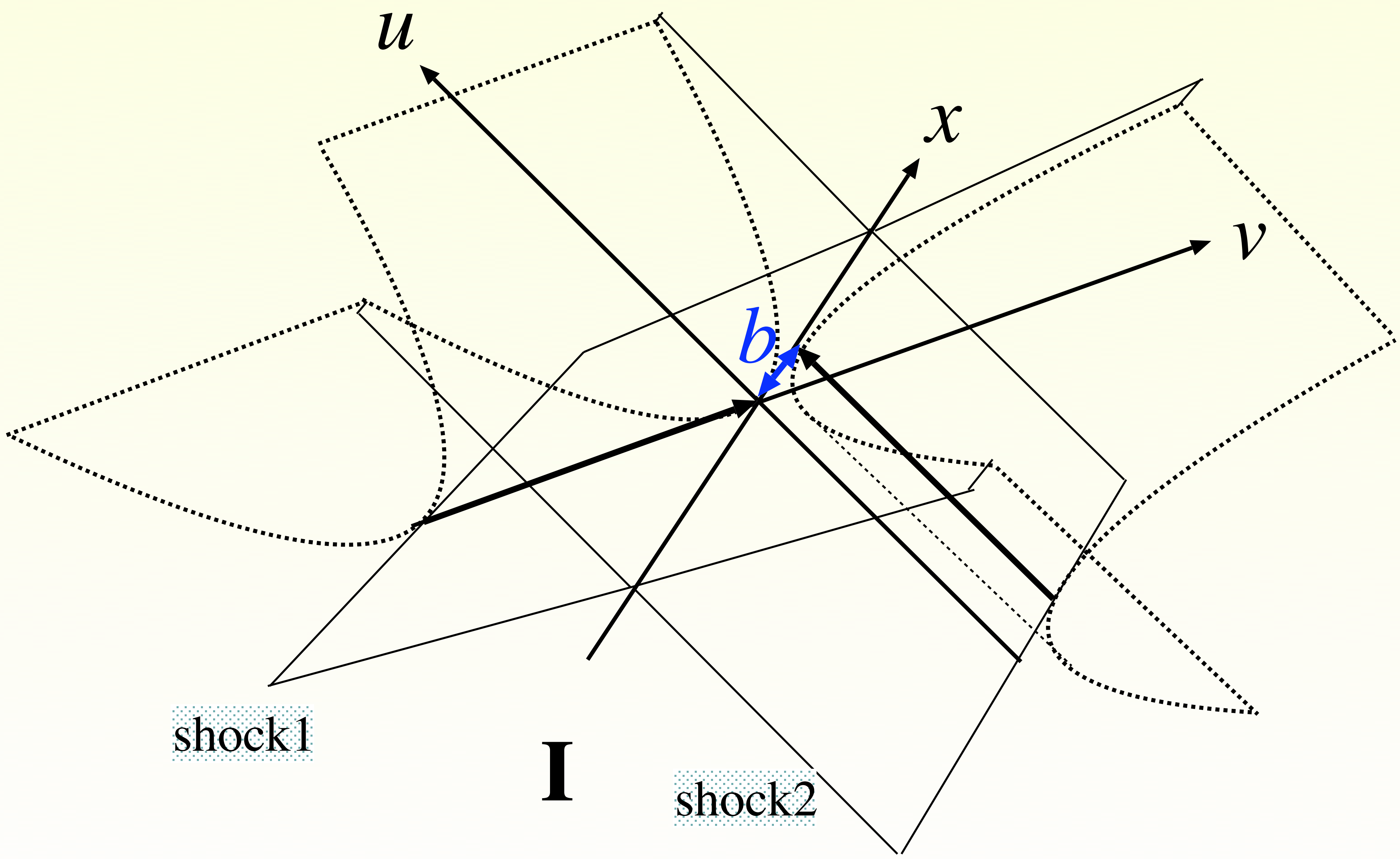

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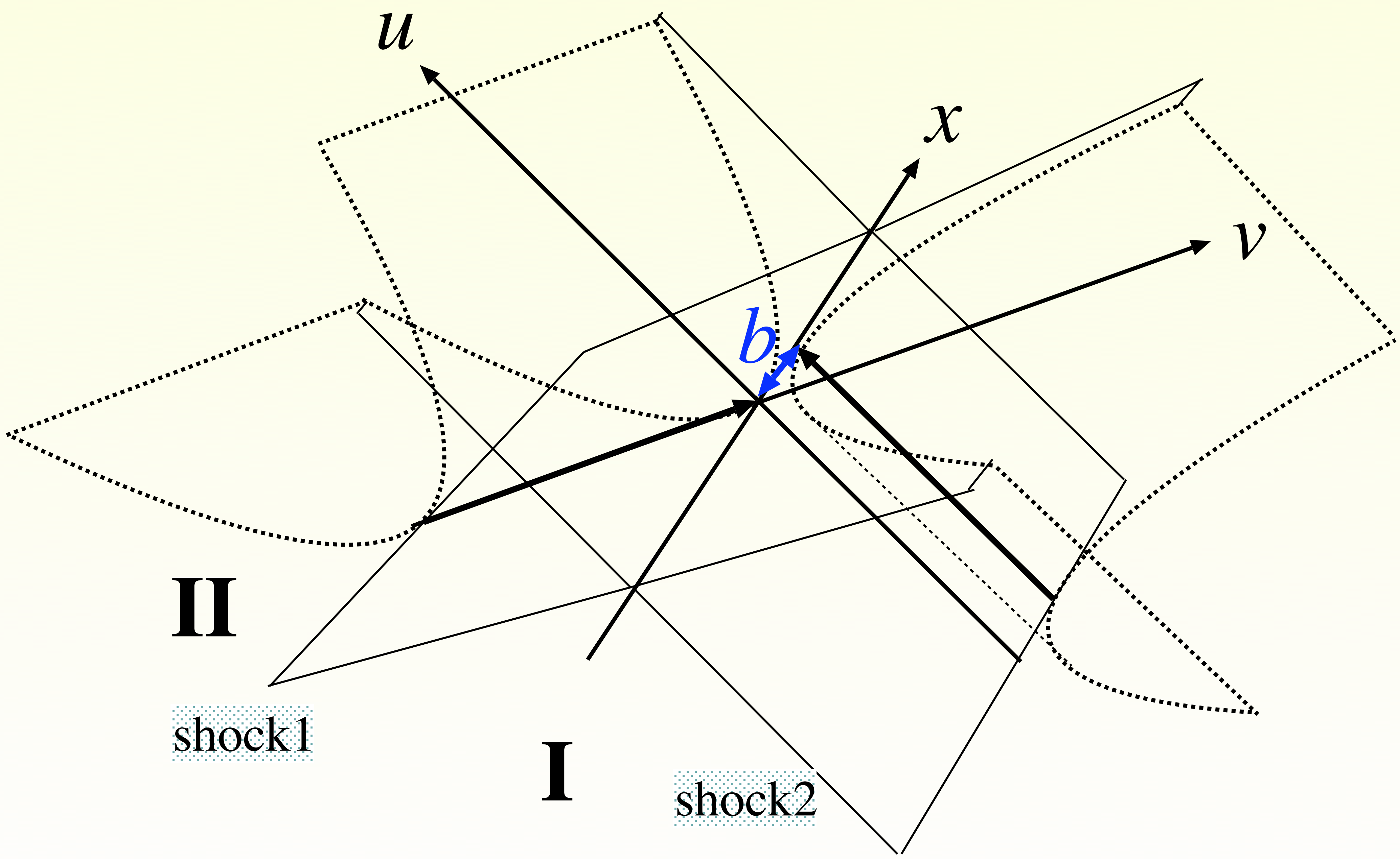

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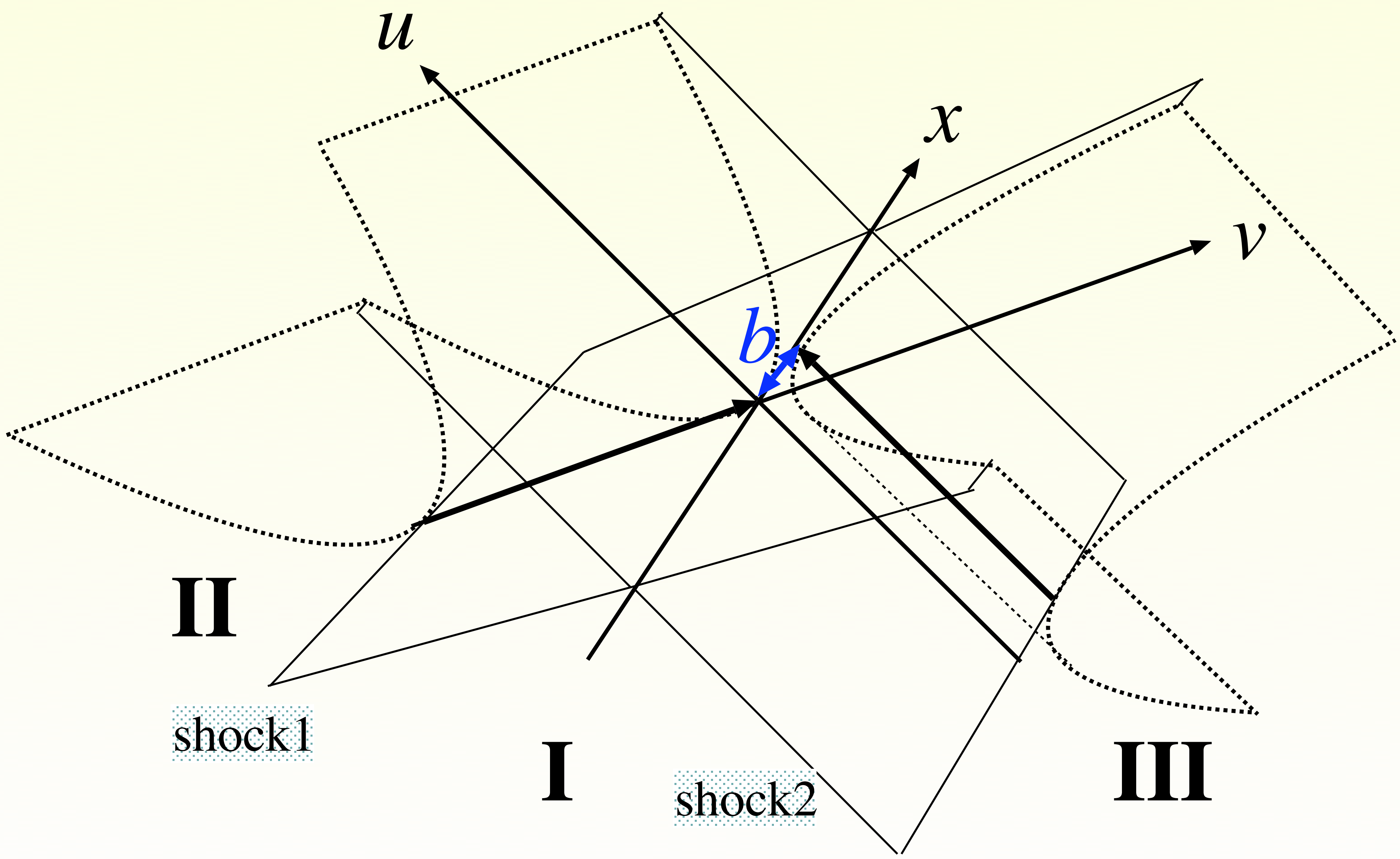

Setup of two particle system

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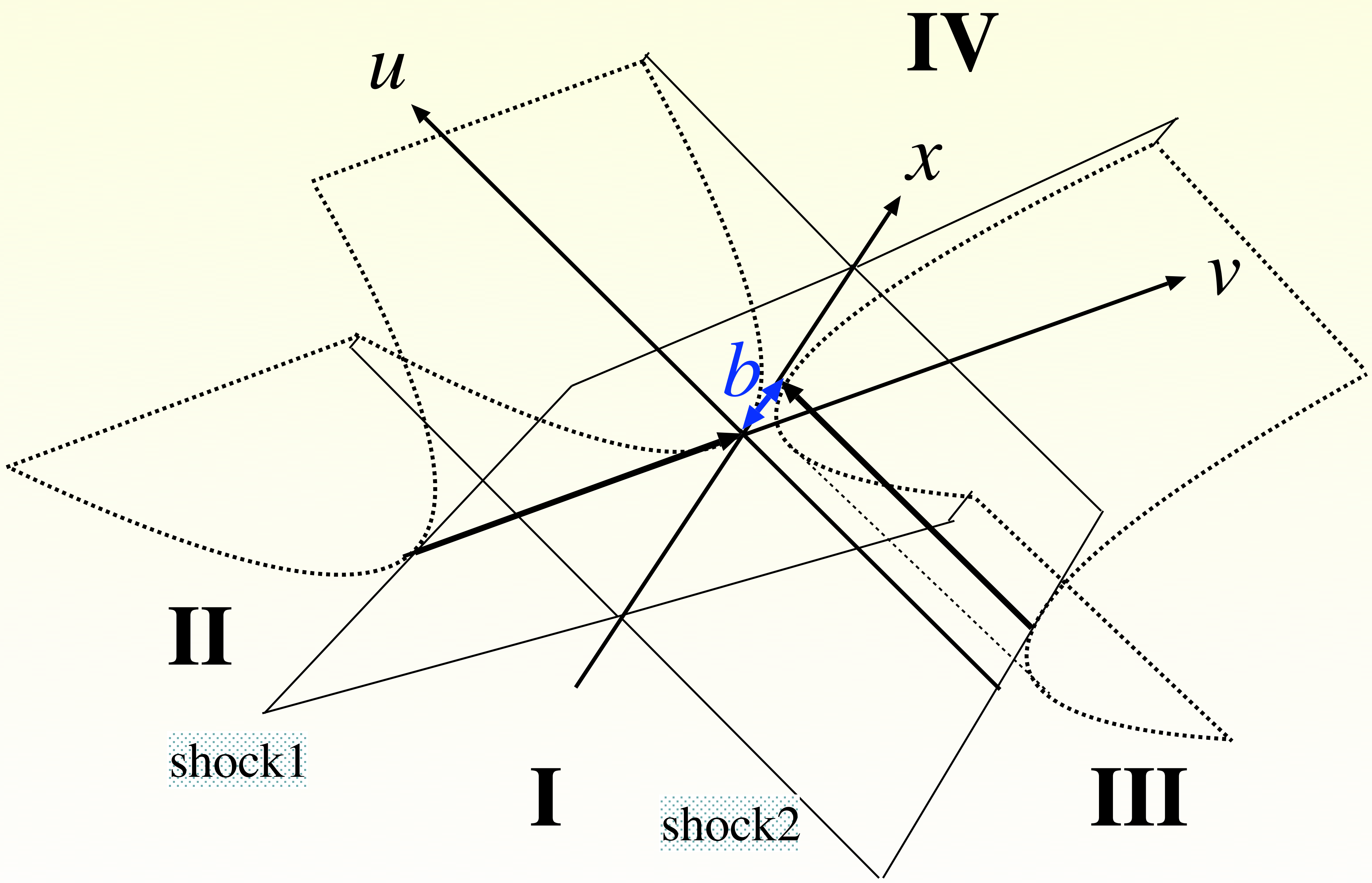

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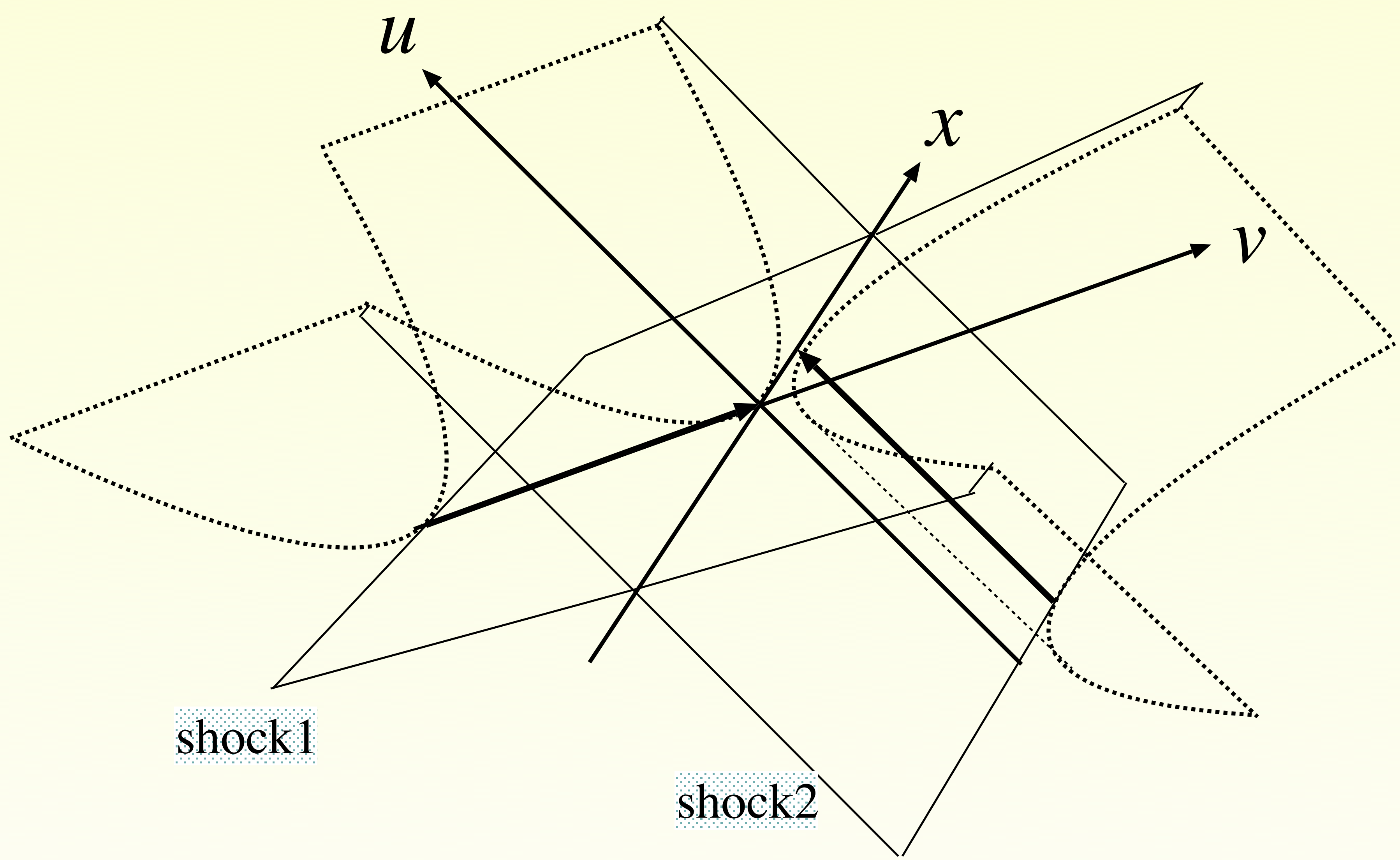
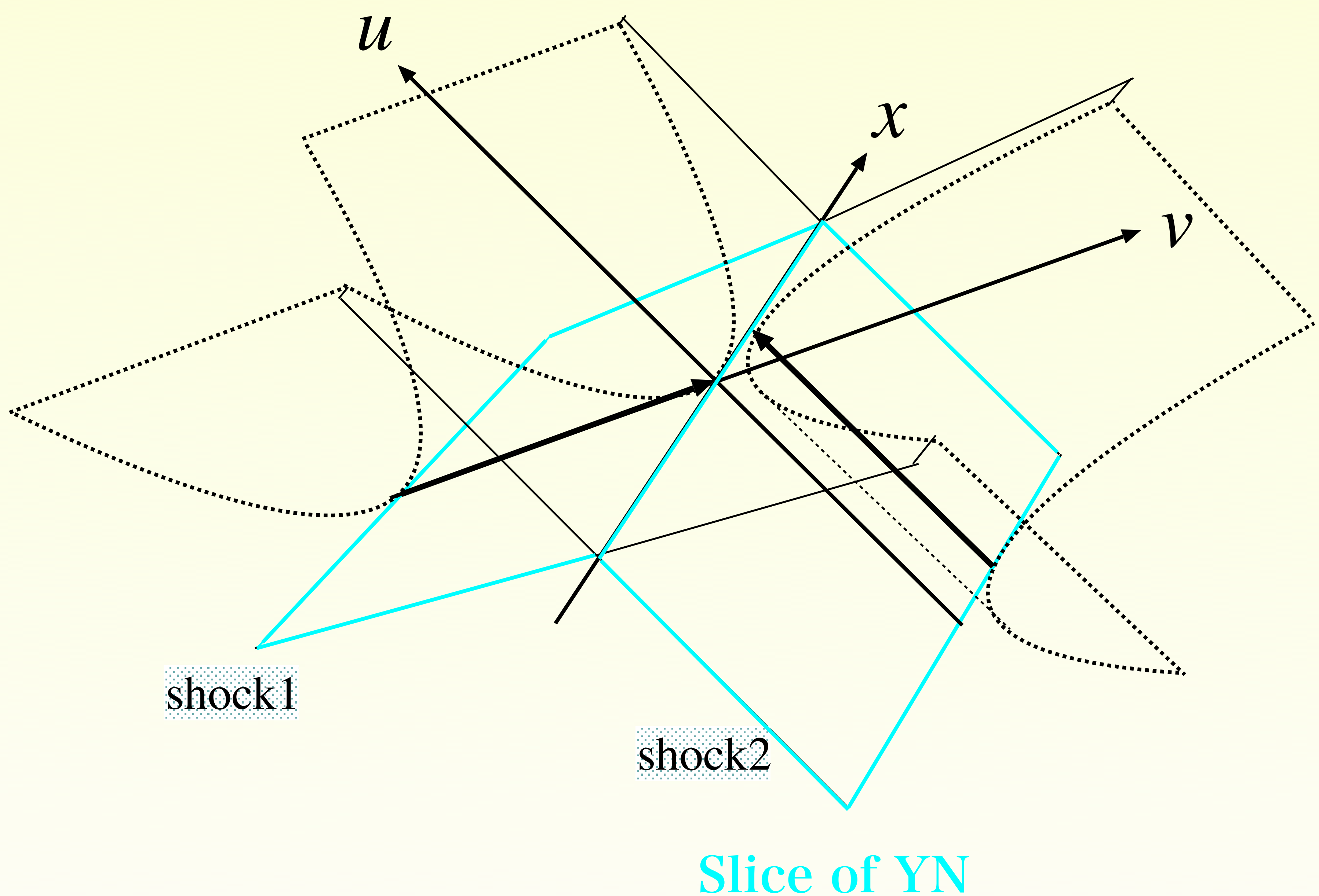
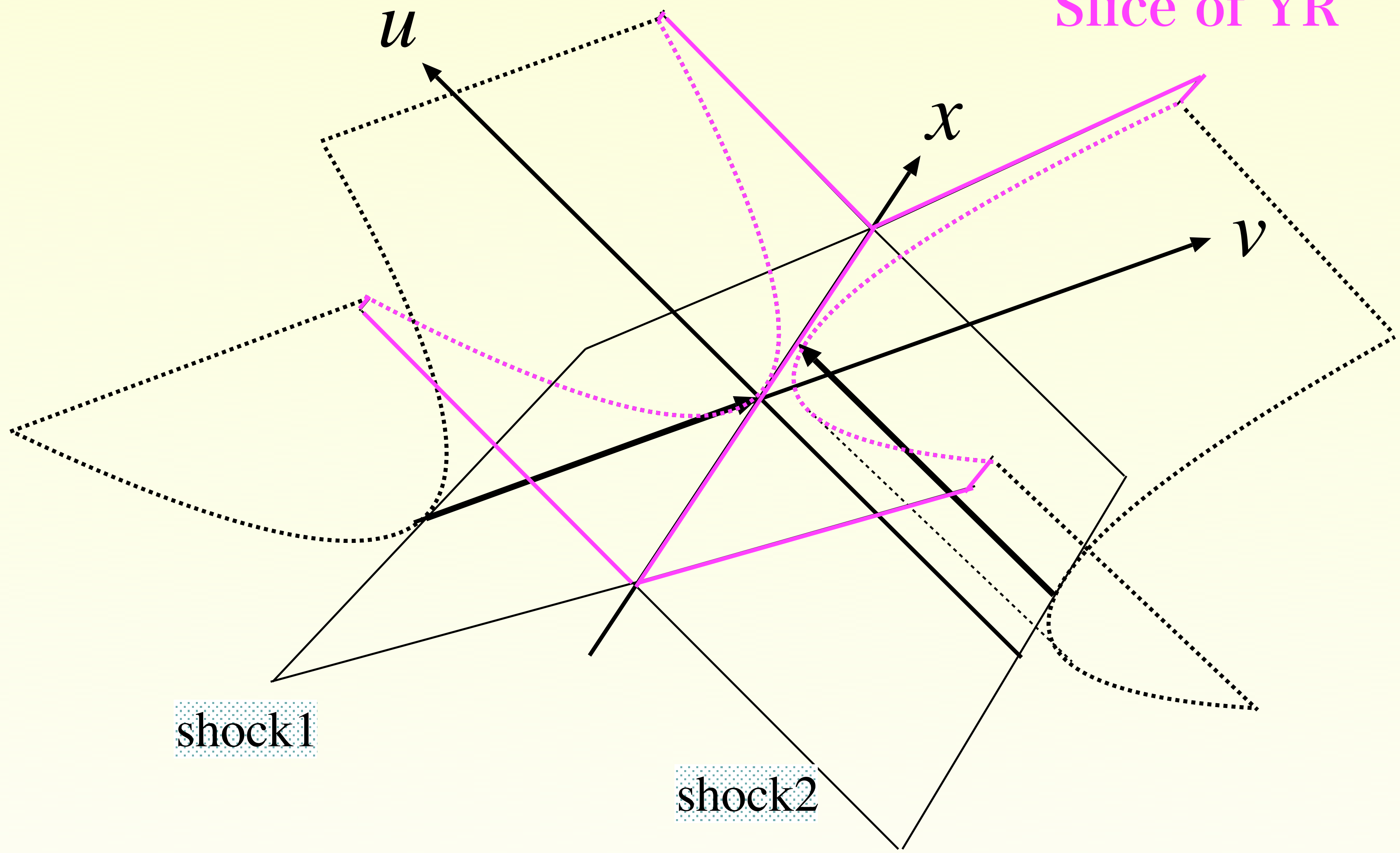
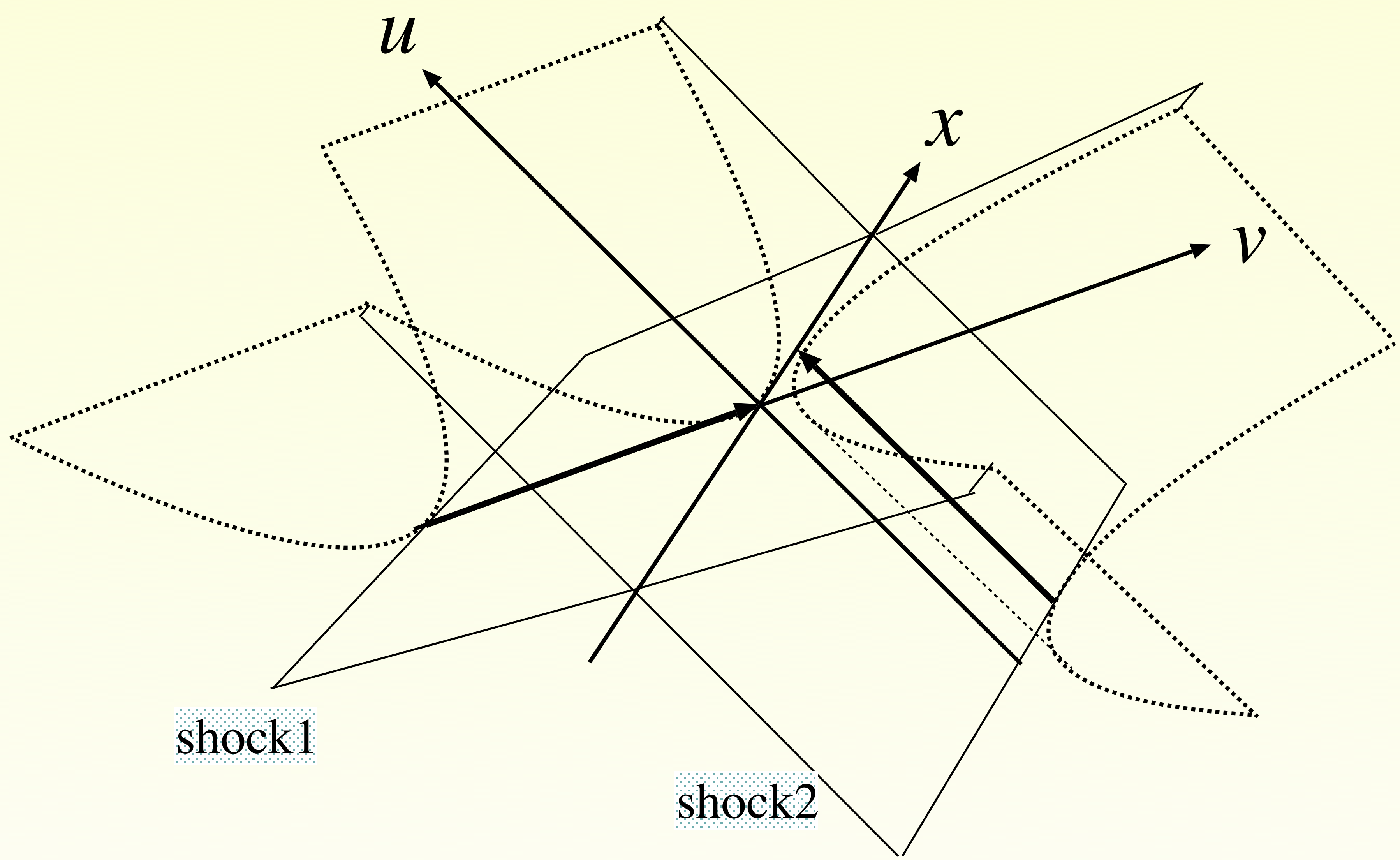

u
x
v
shock1
shock2



u
x
v
shock1
shock2
Slice of YN


Slice of YR
u
x
v
shock1
shock2


u
x
v
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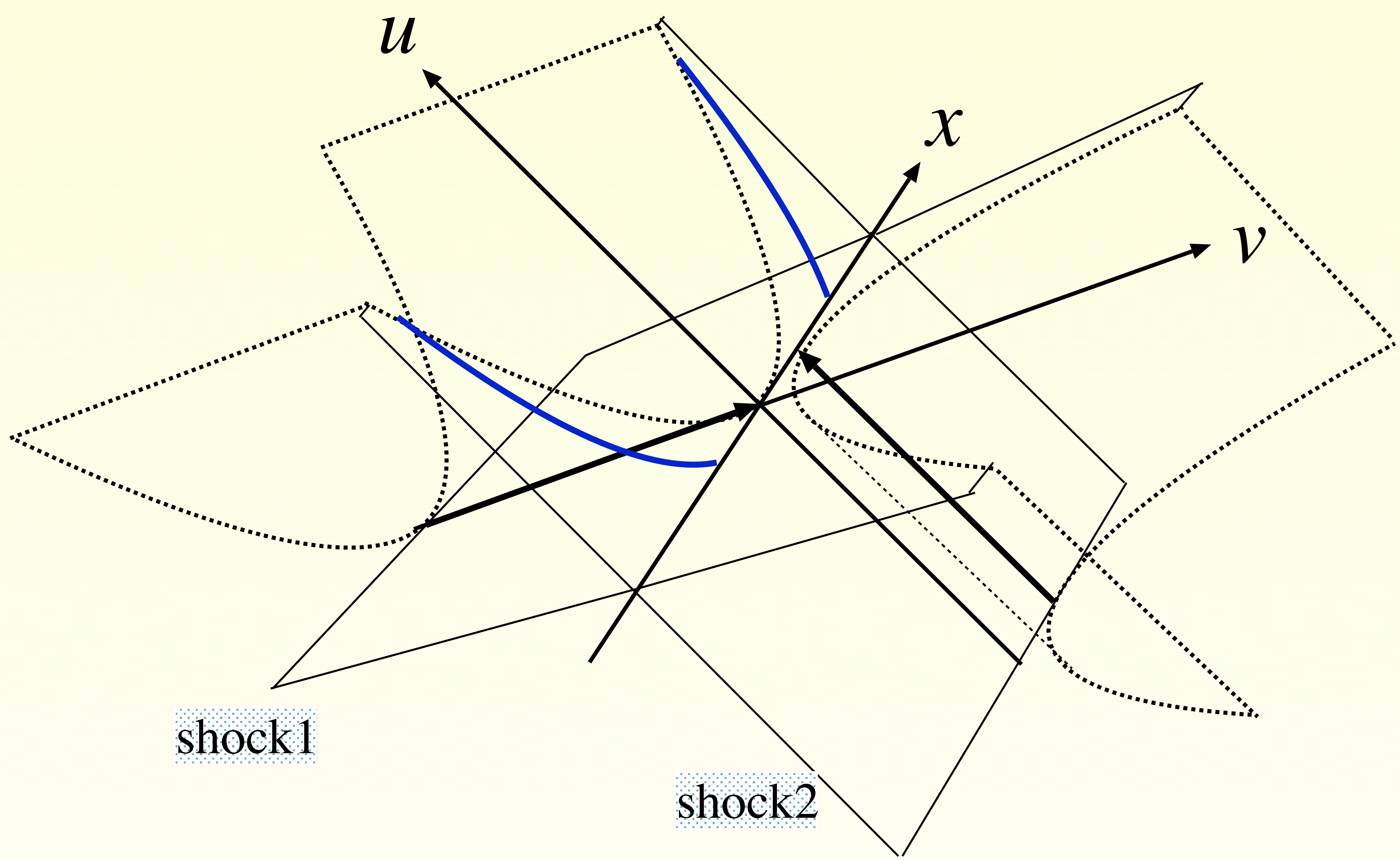
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v
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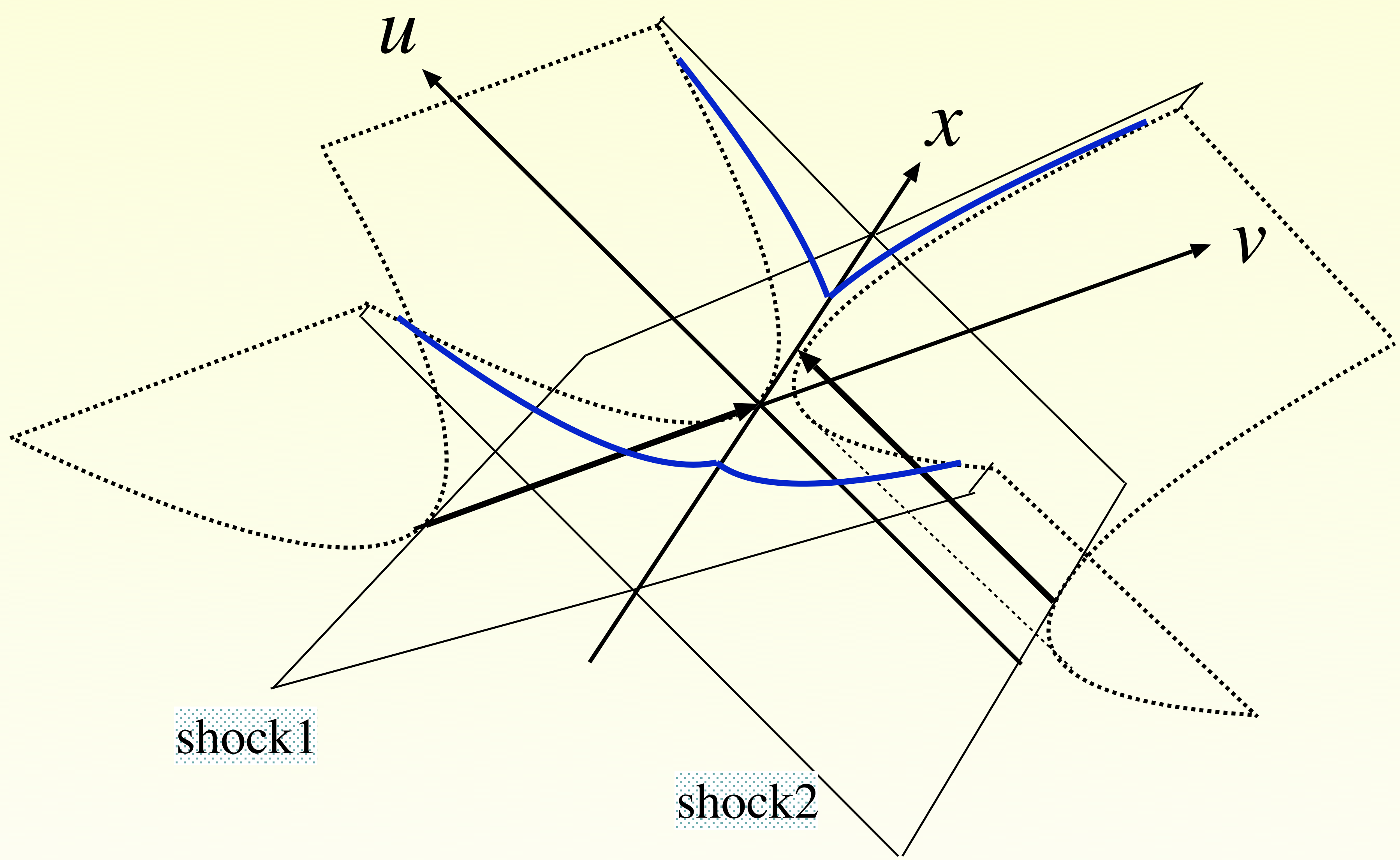
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x
v
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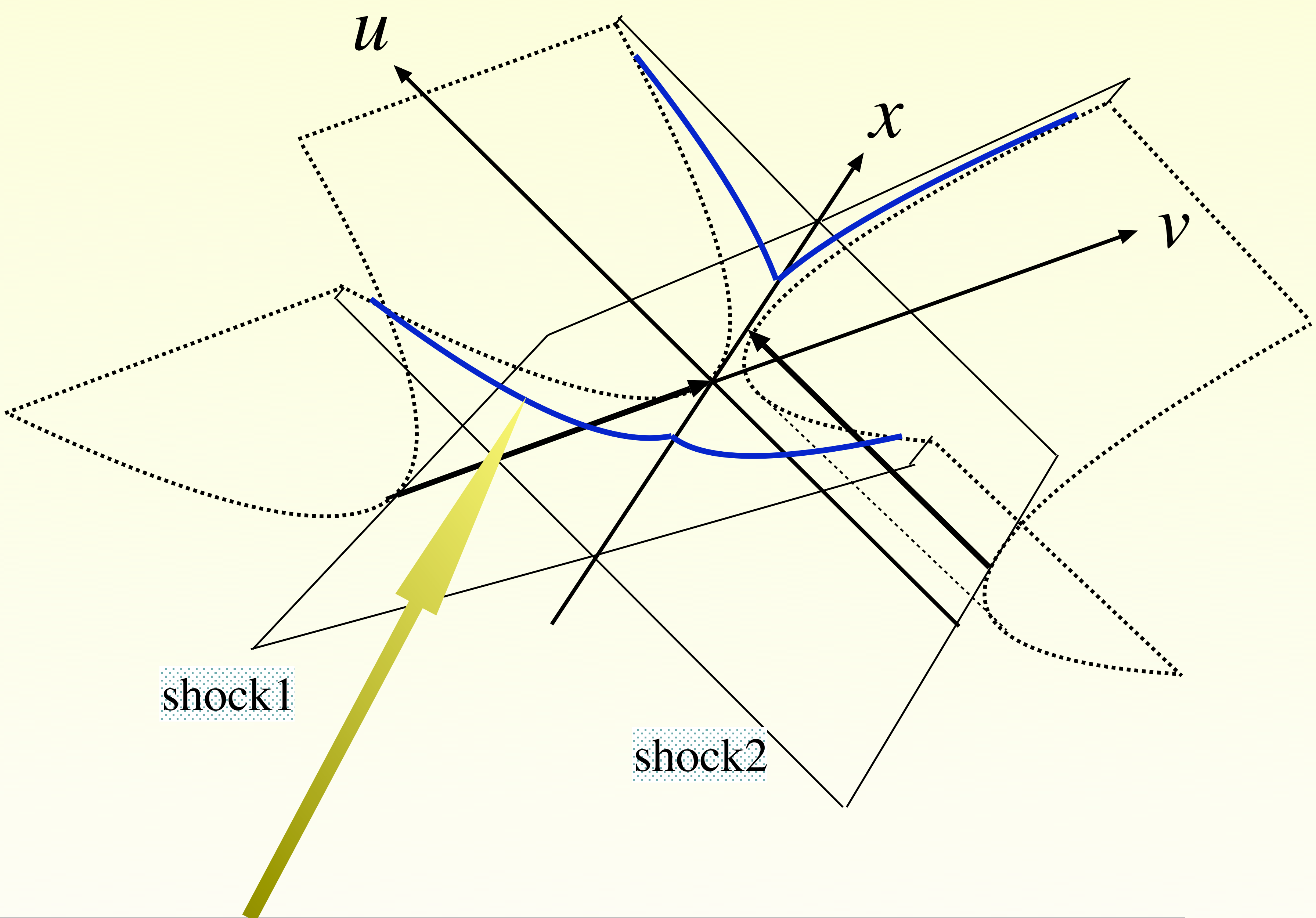

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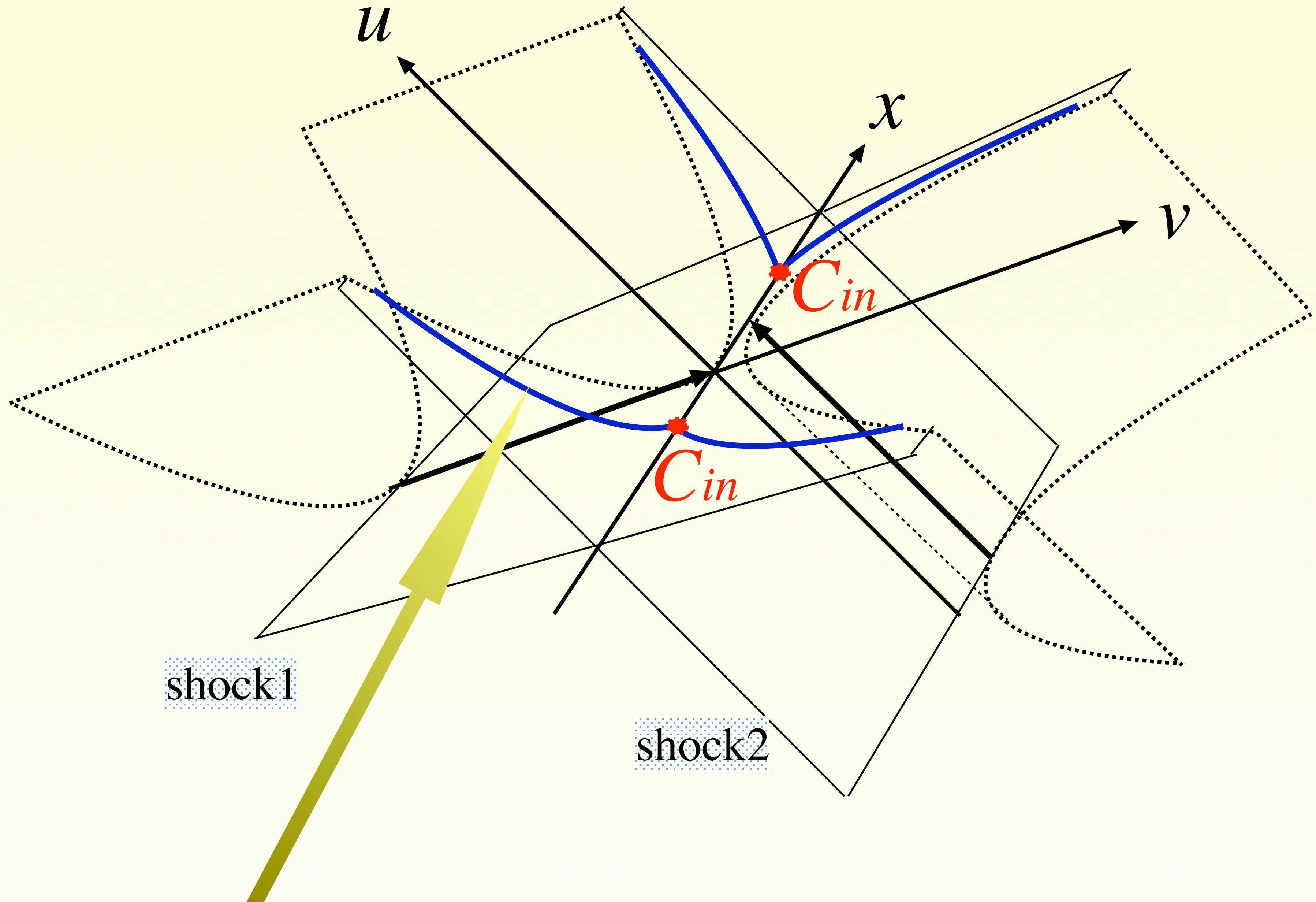

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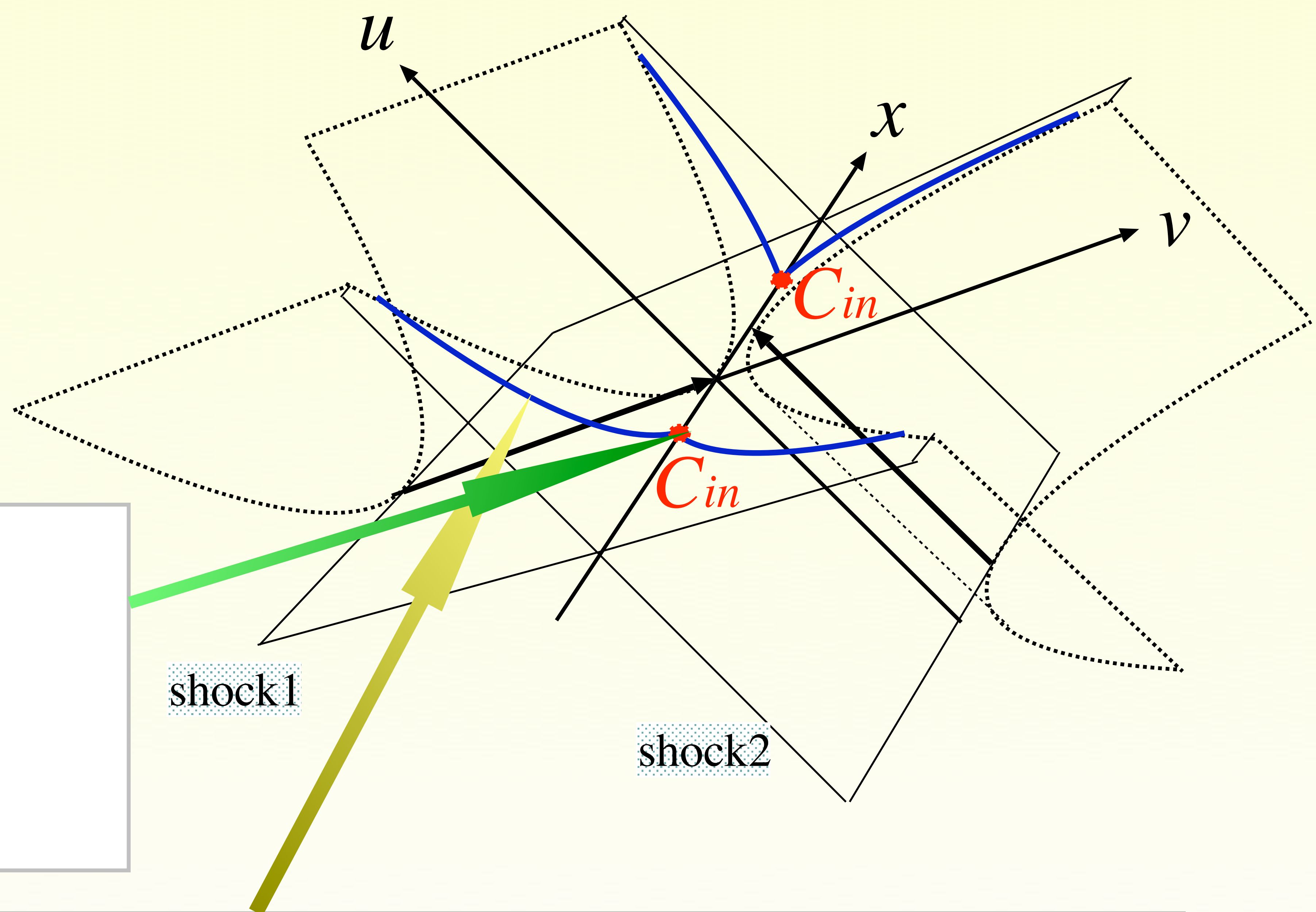
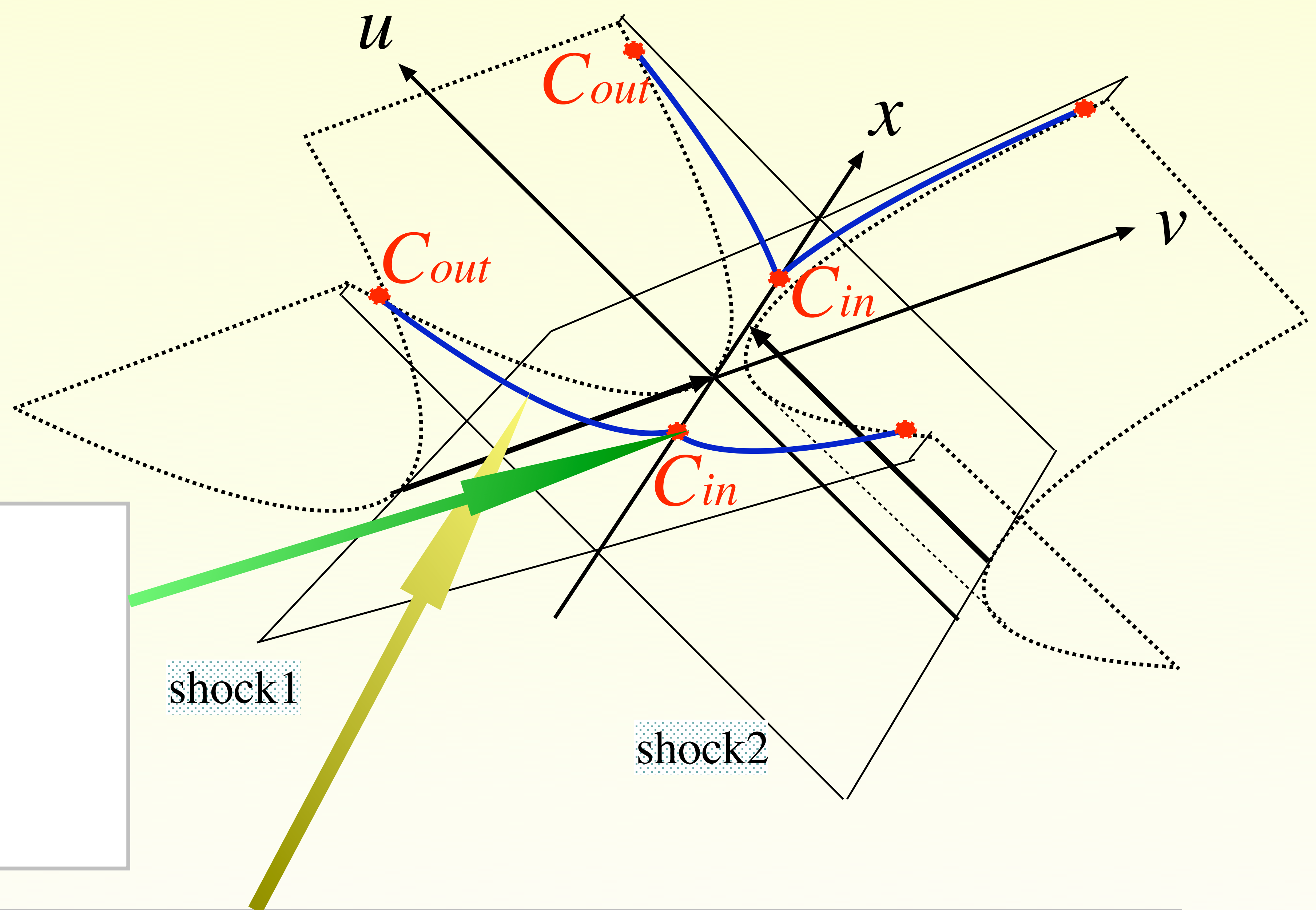


Inner boundary:

AH:



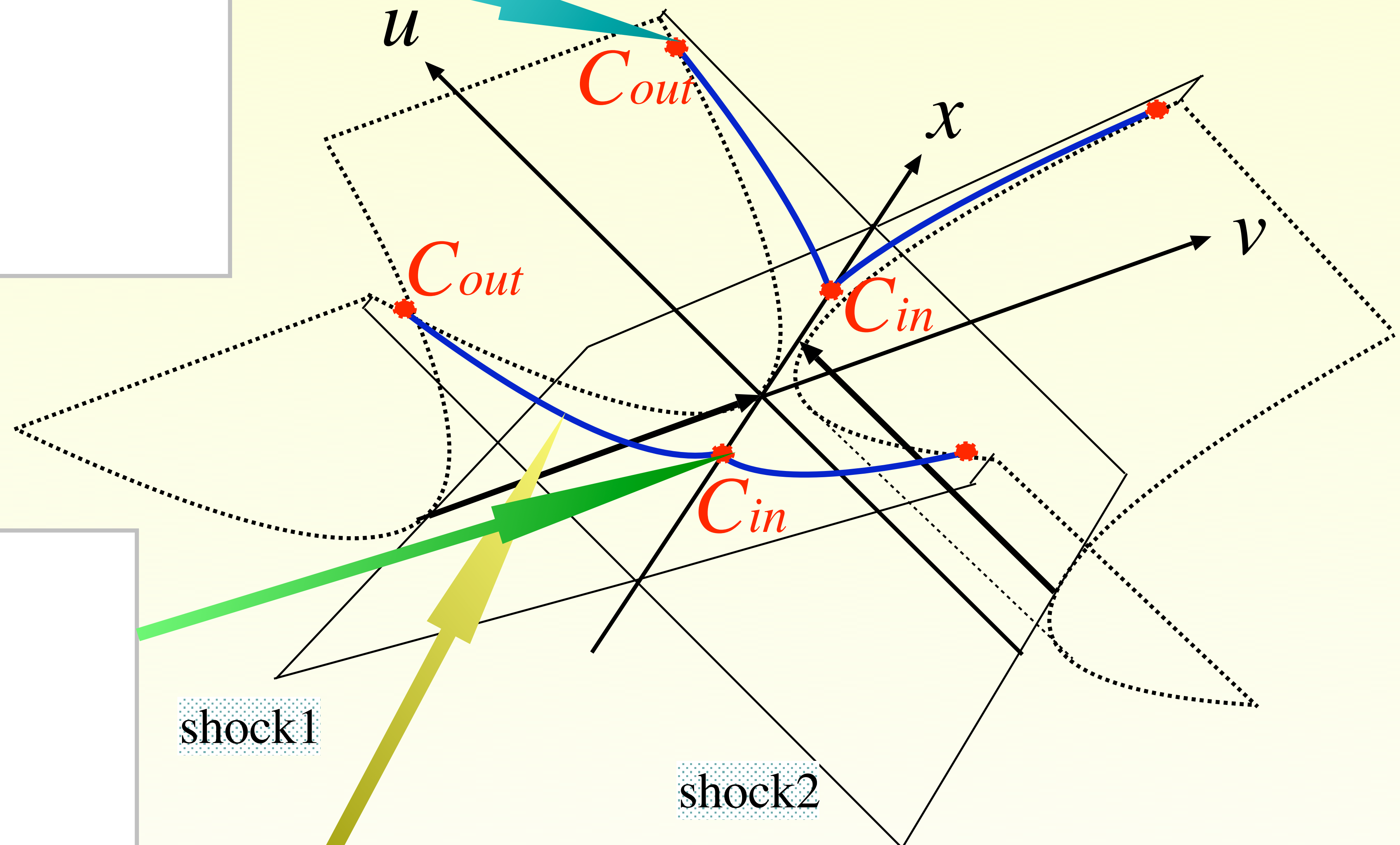
Inner boundary:

AH:

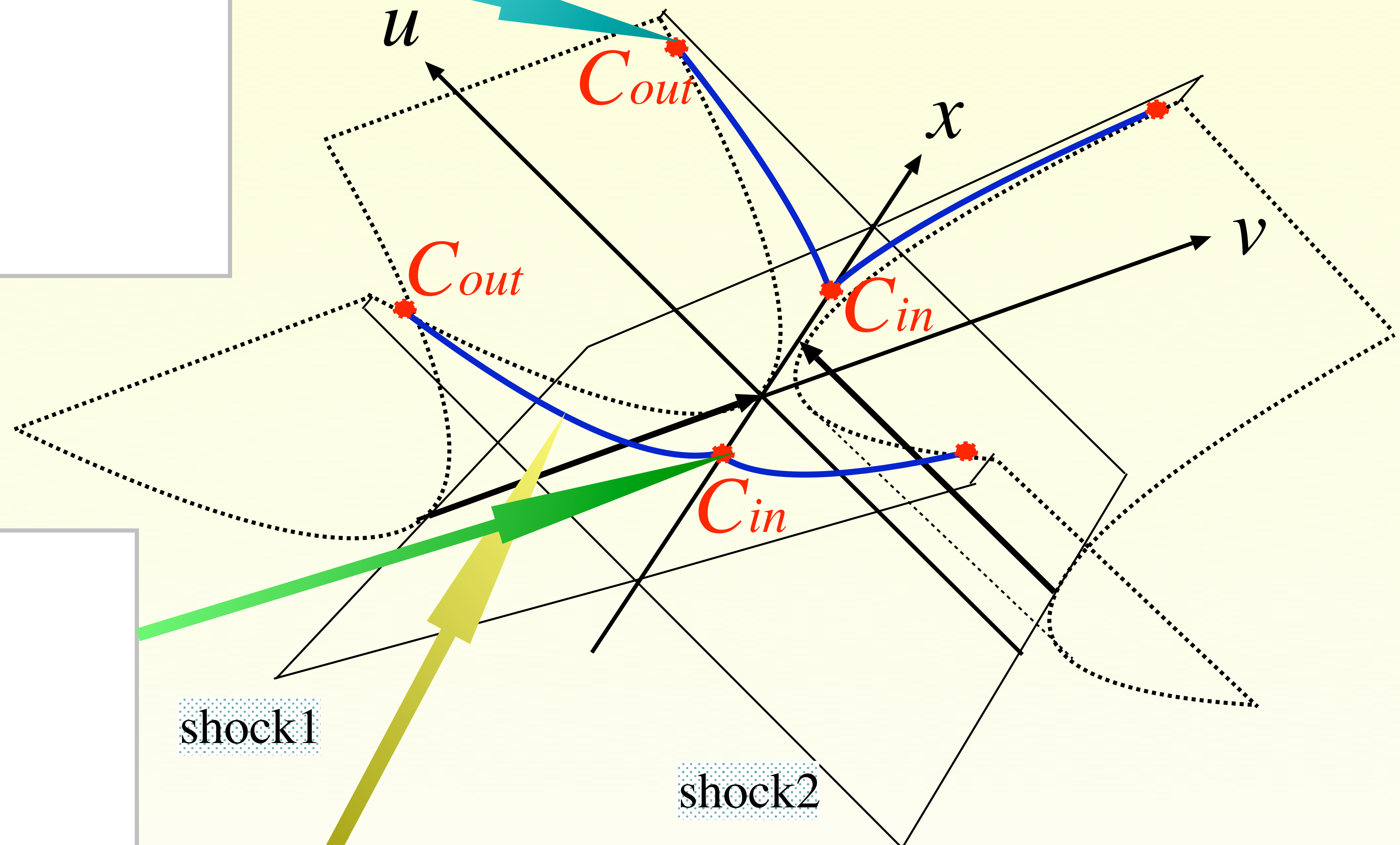
Outer boundary: $r = r_{max}$

Inner boundary:

AH:



Outer boundary: $r = r_{max}$



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AH:

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Outer boundary: $r = r_{max}$

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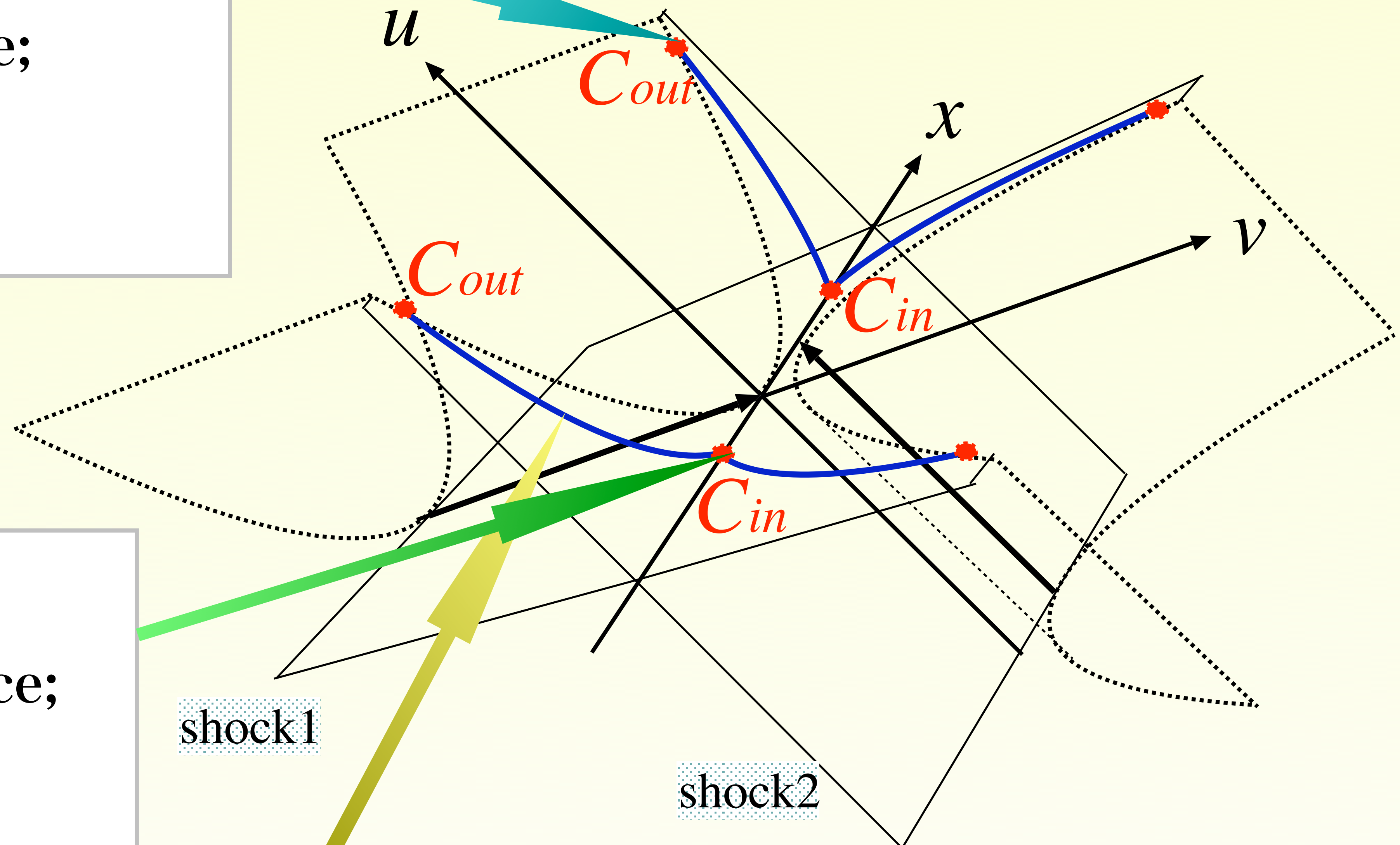

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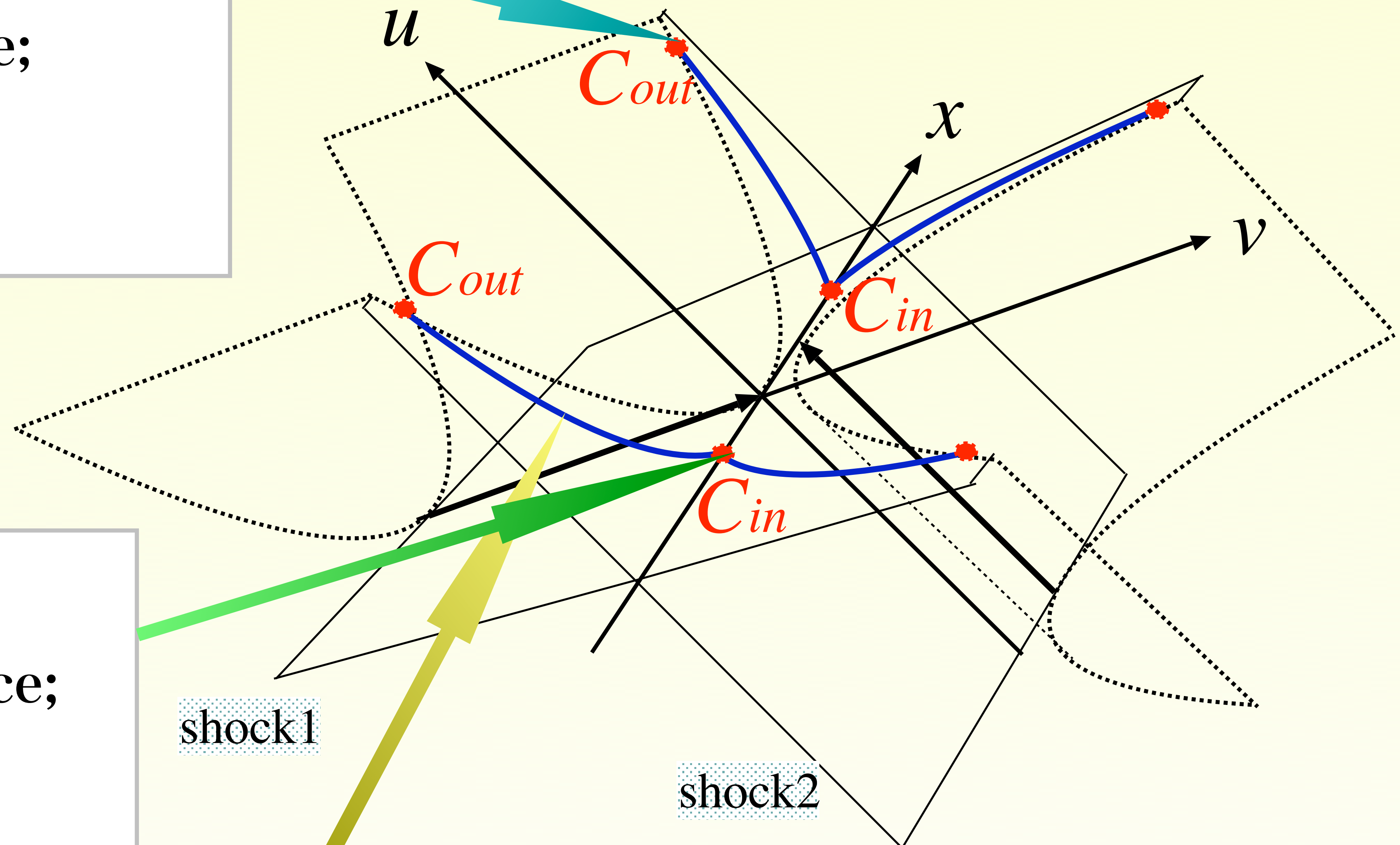

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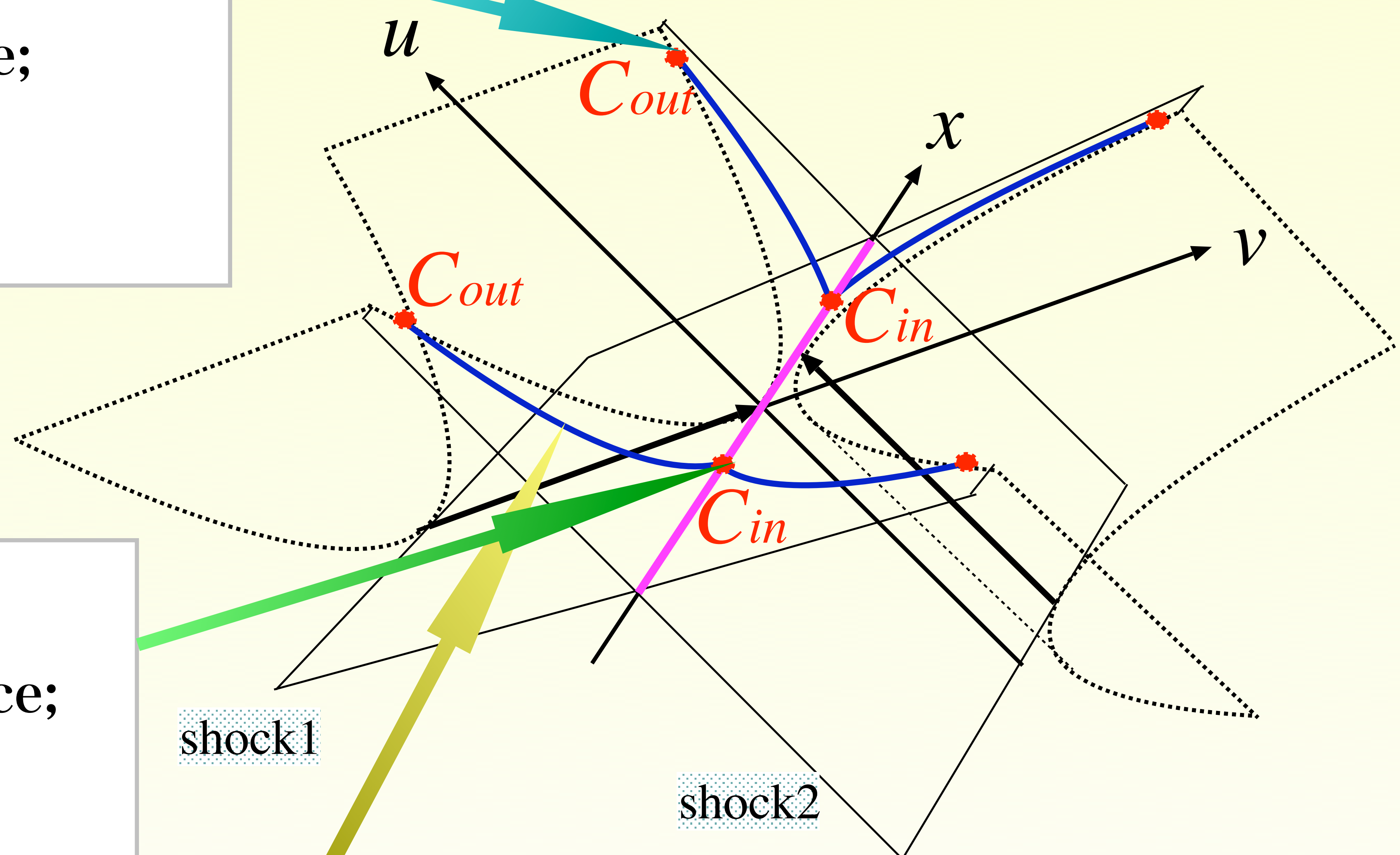

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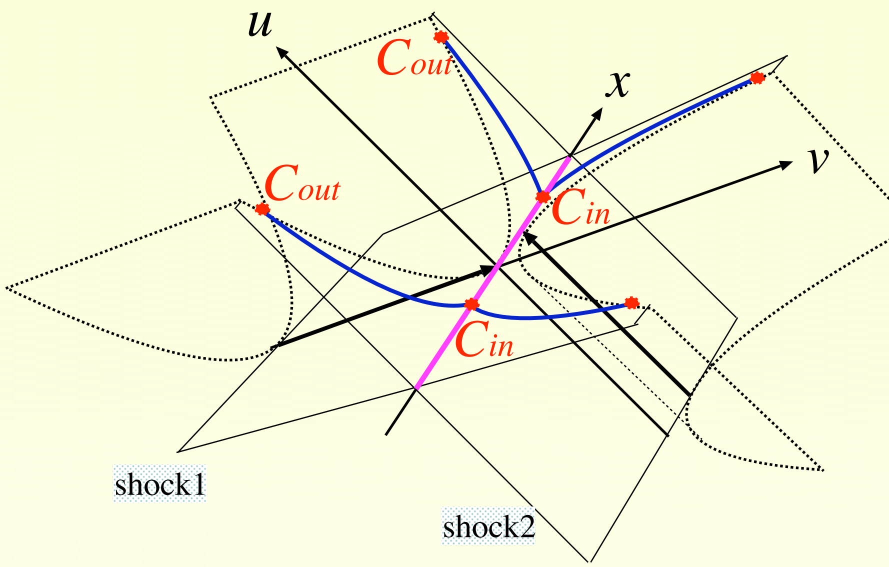

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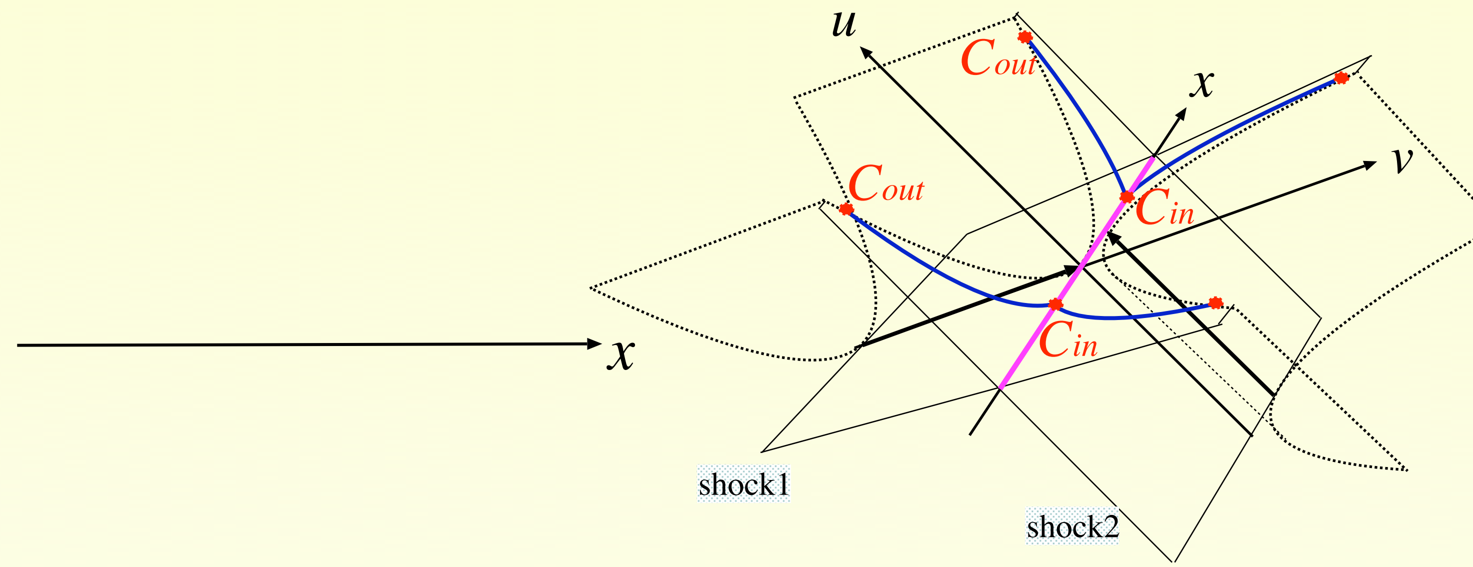

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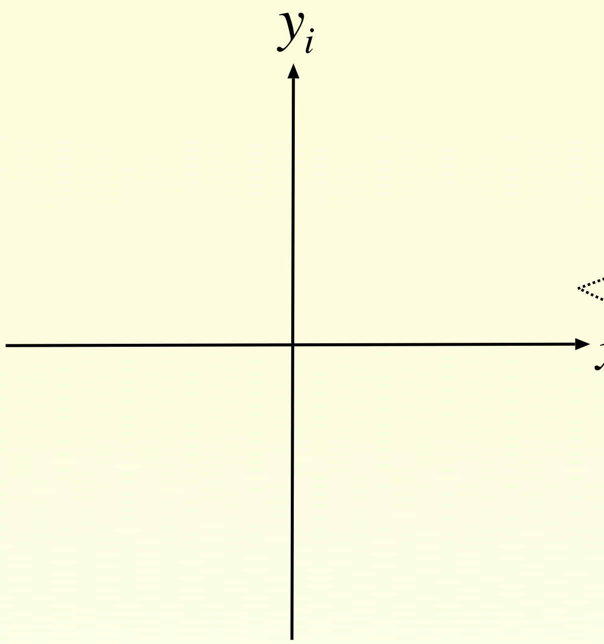

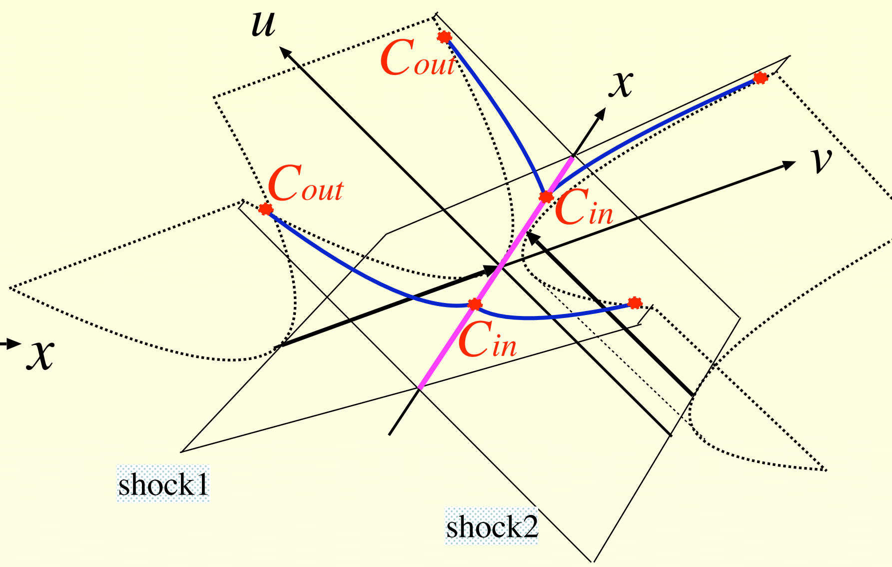

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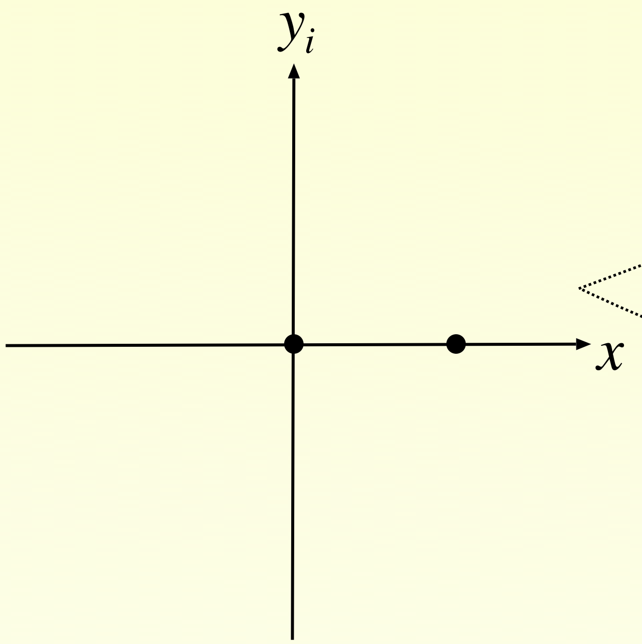

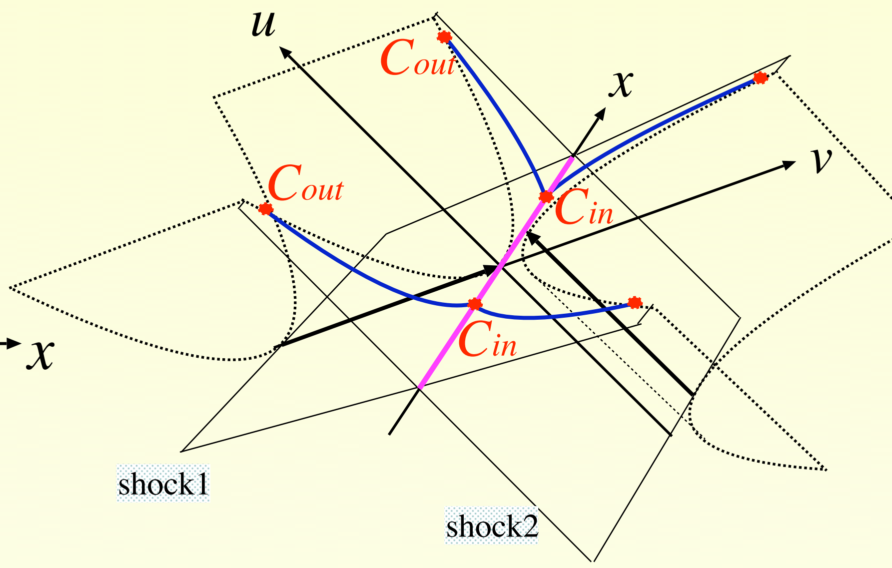

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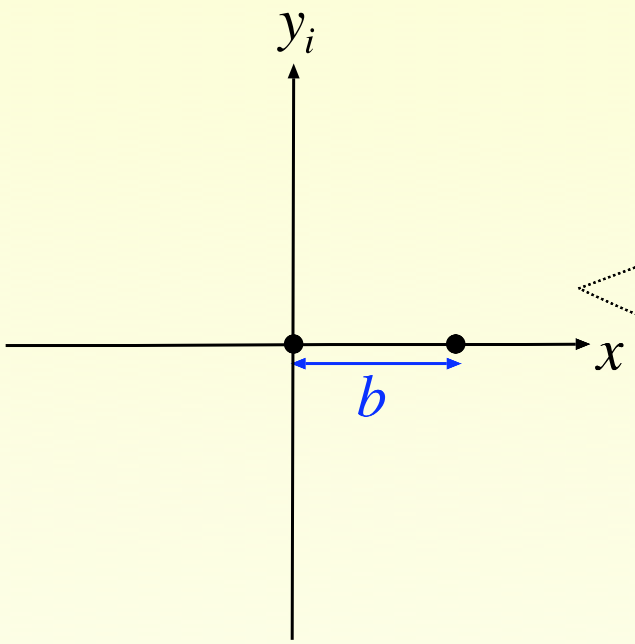

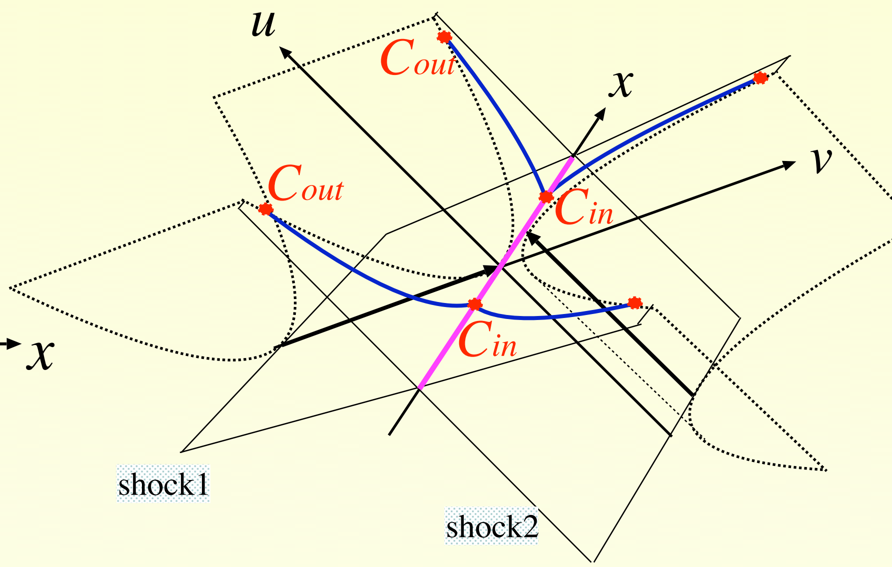

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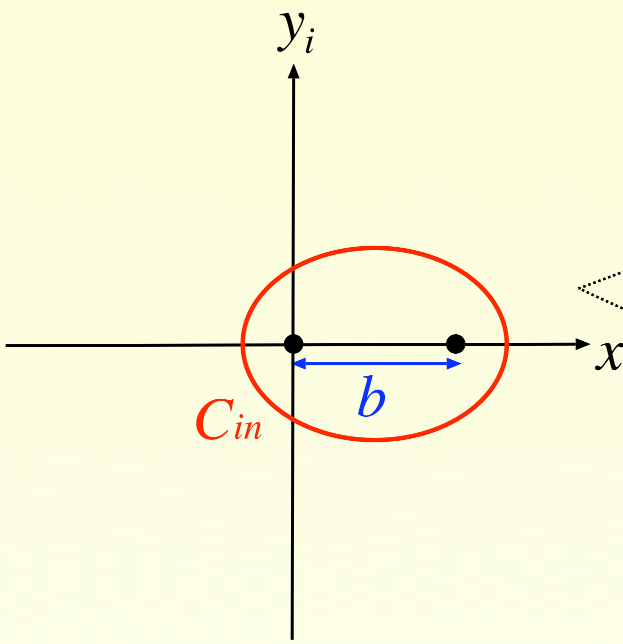

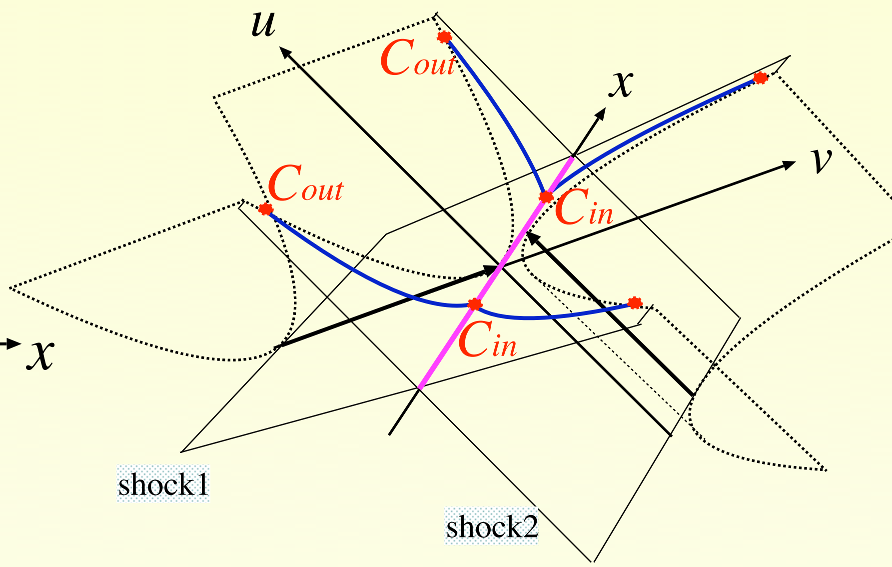

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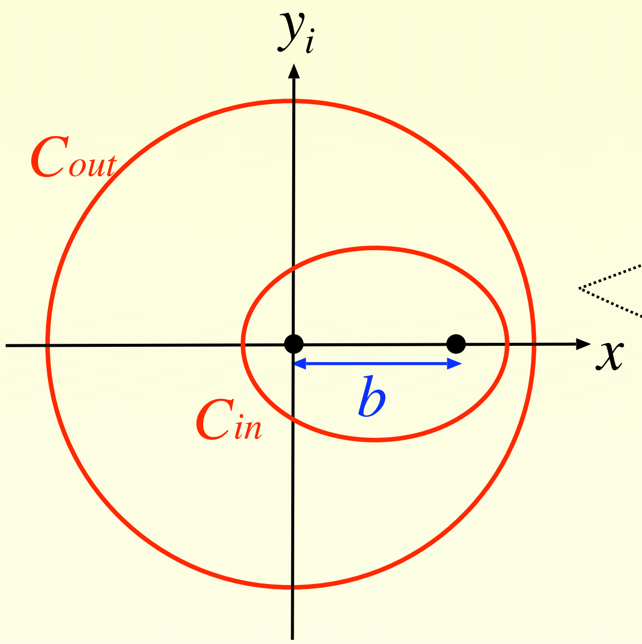

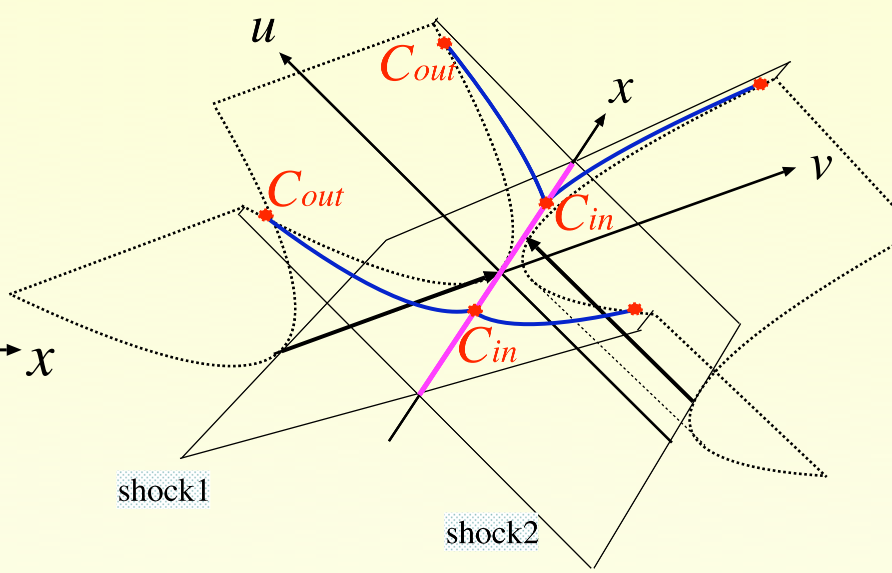

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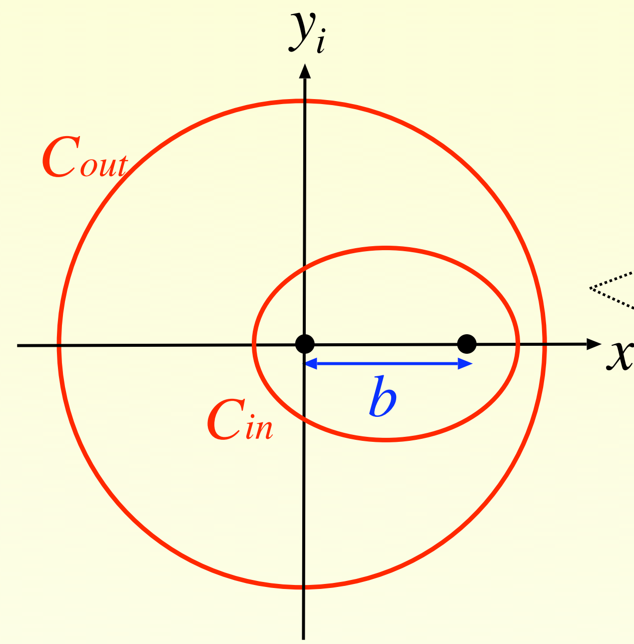

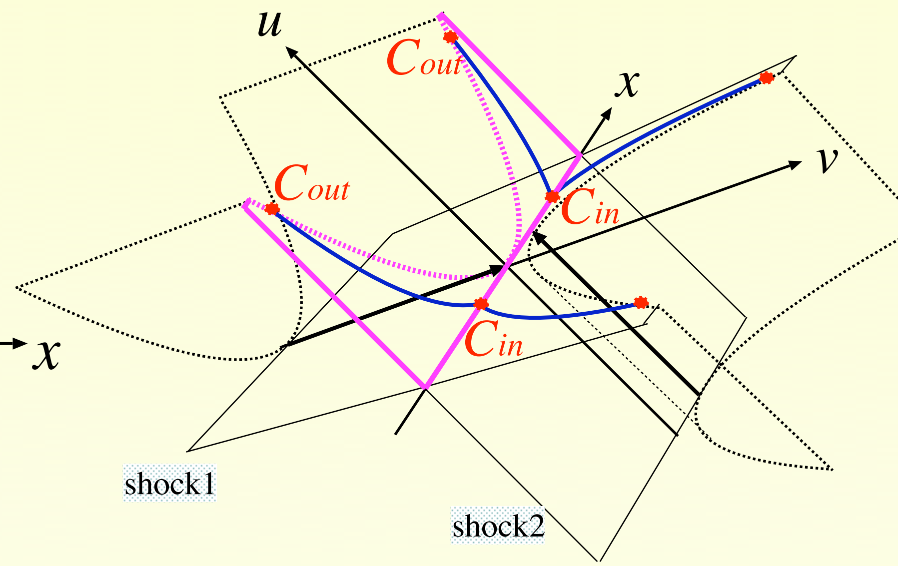

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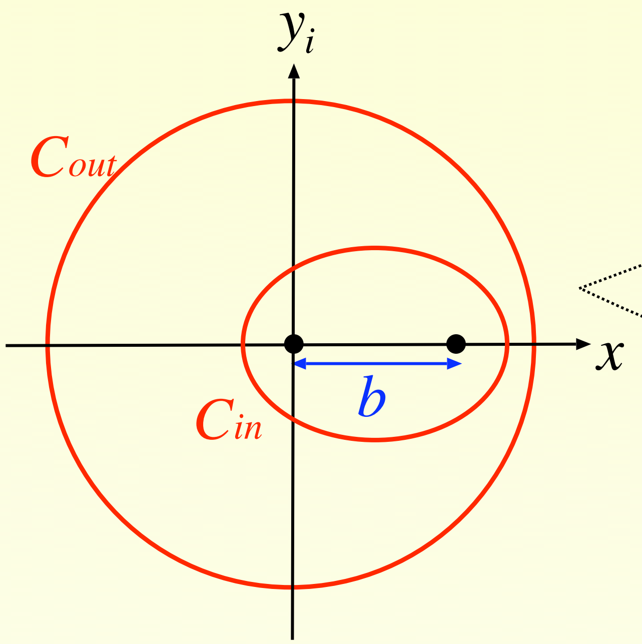

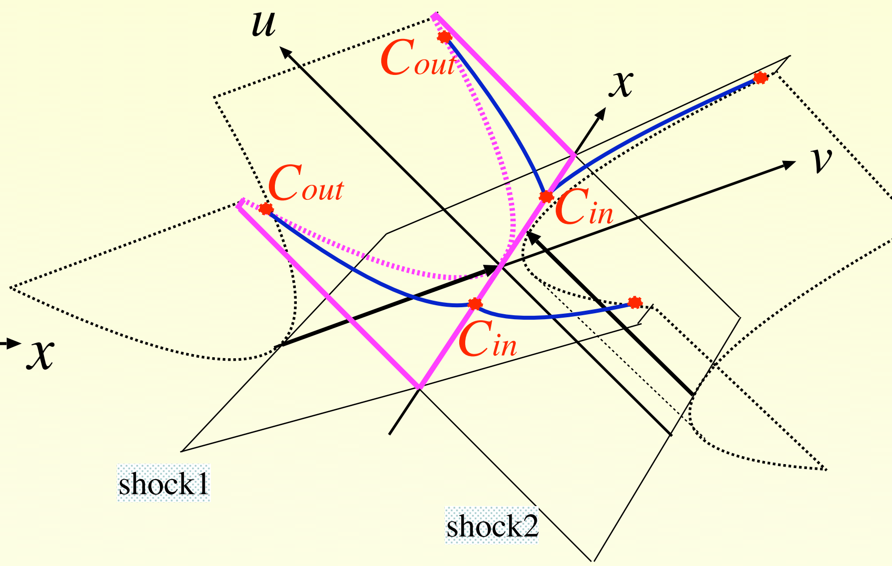

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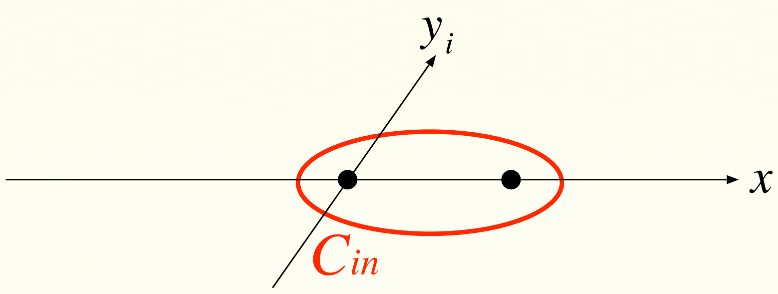

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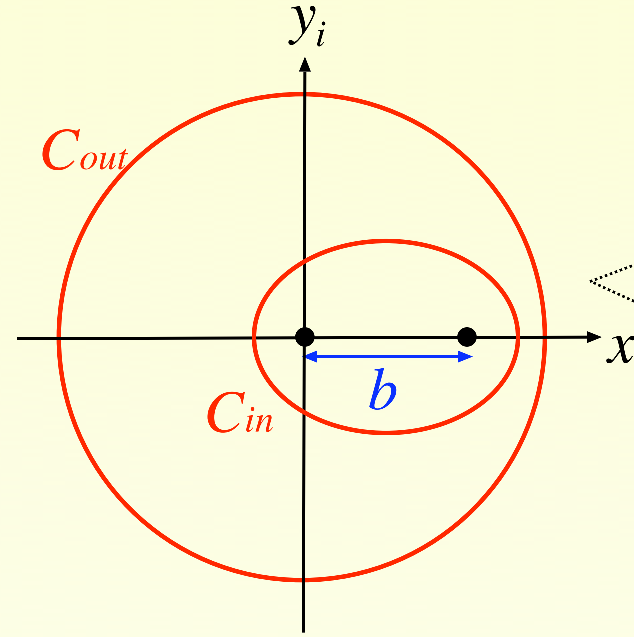

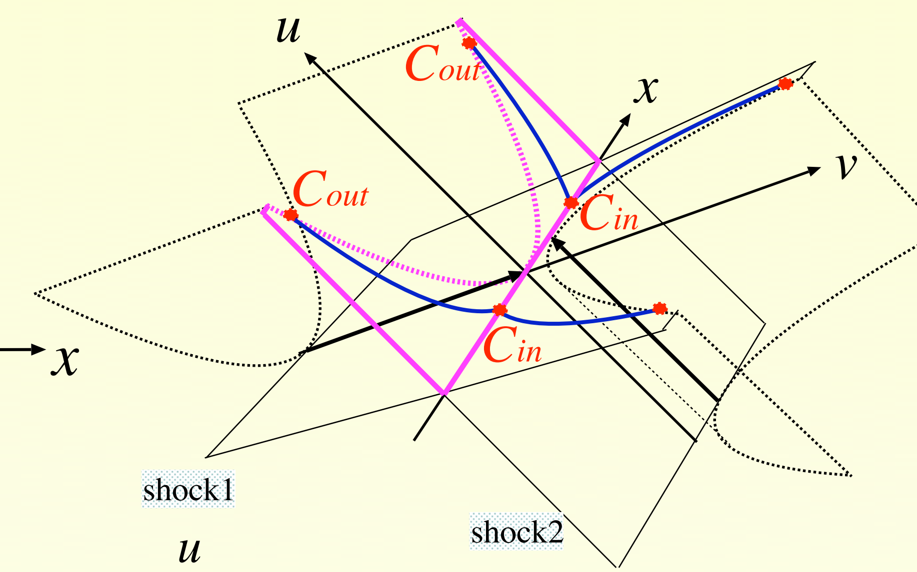

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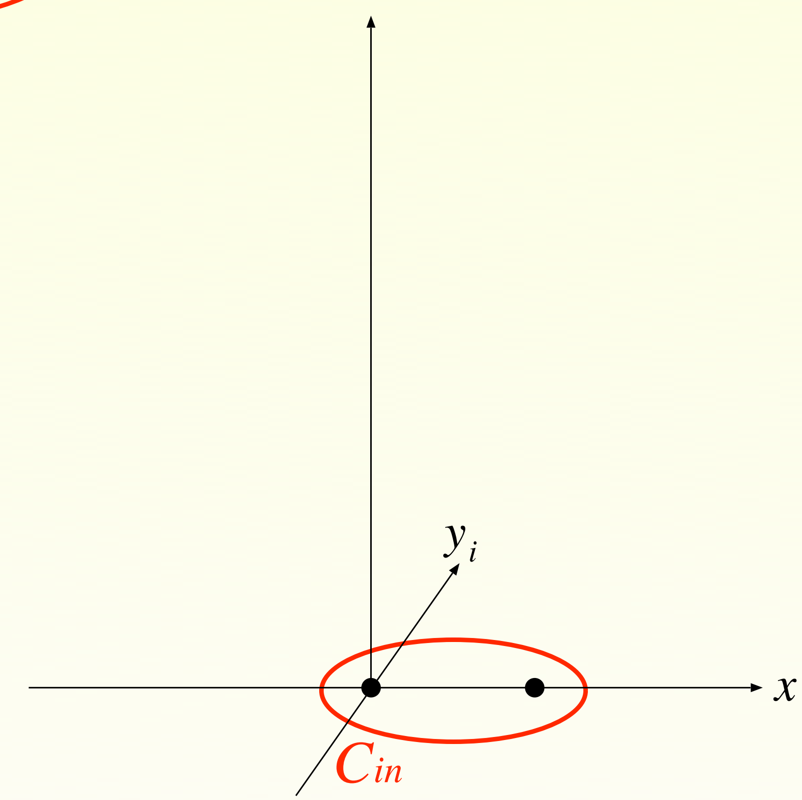

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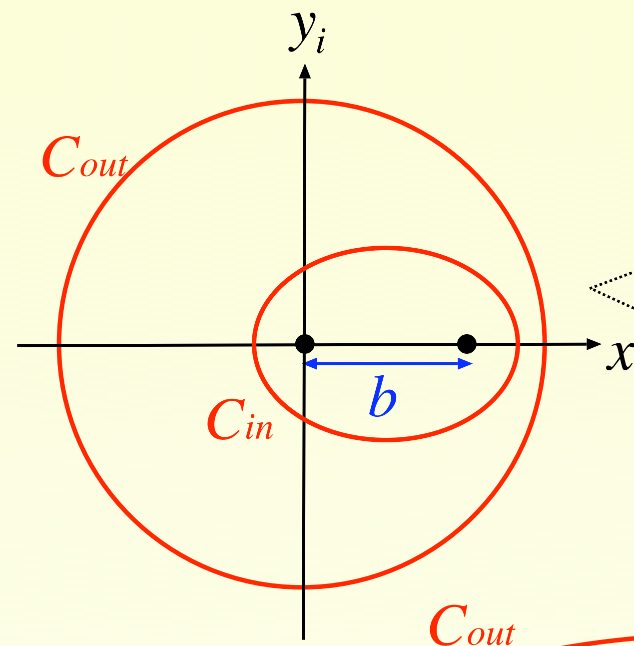

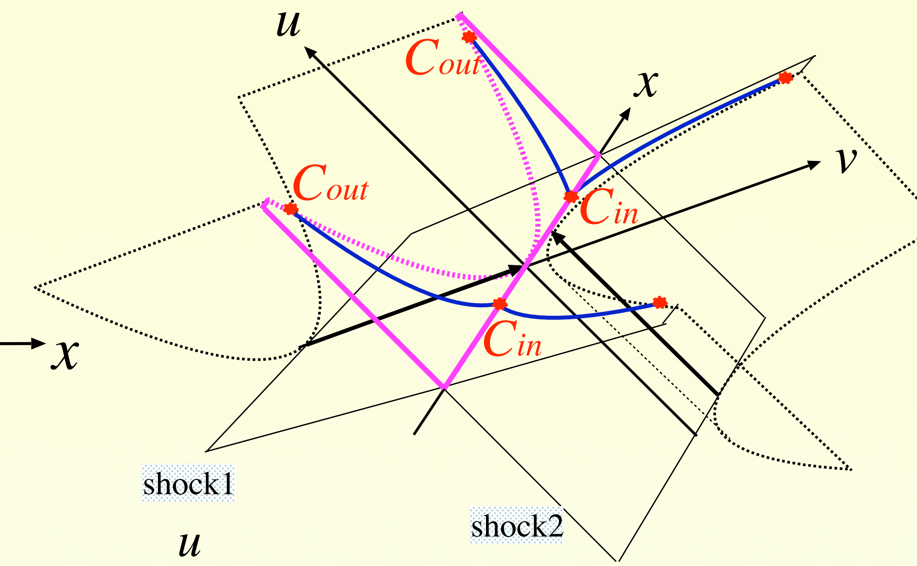

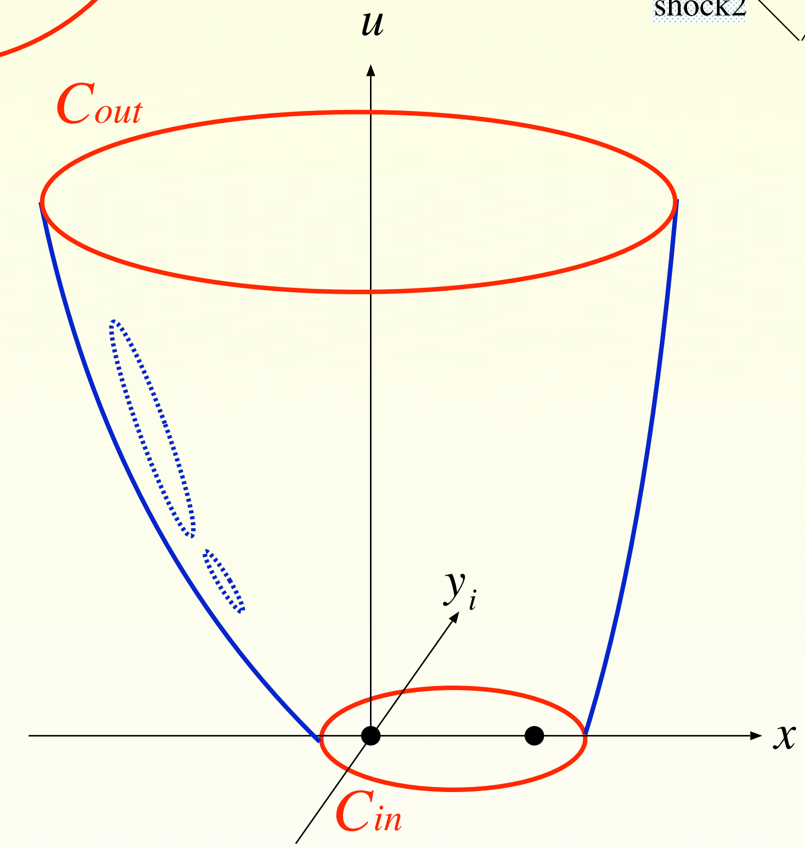

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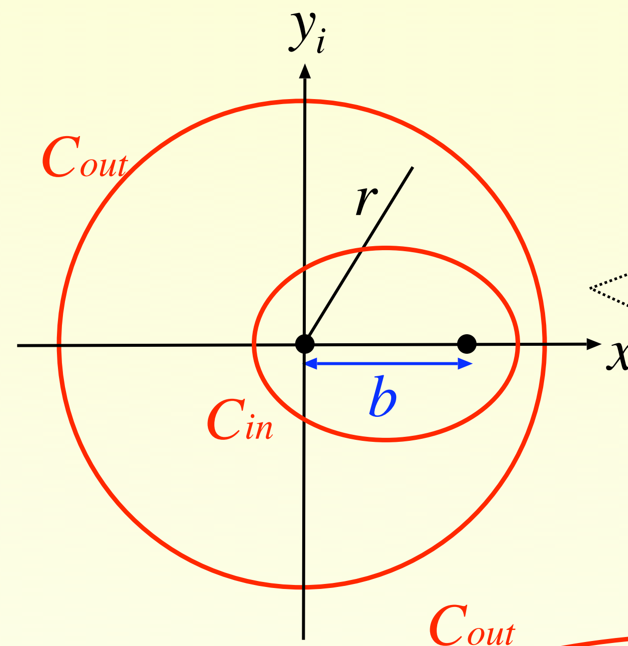

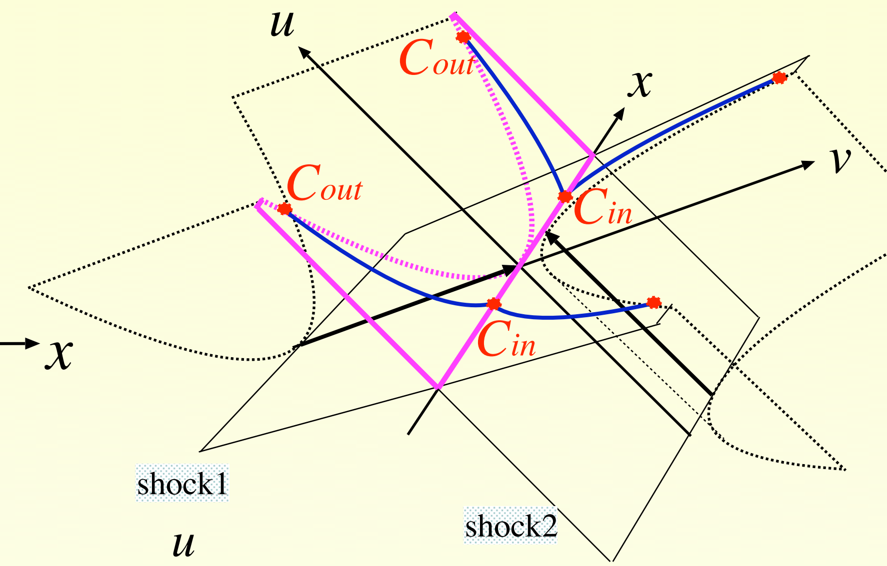

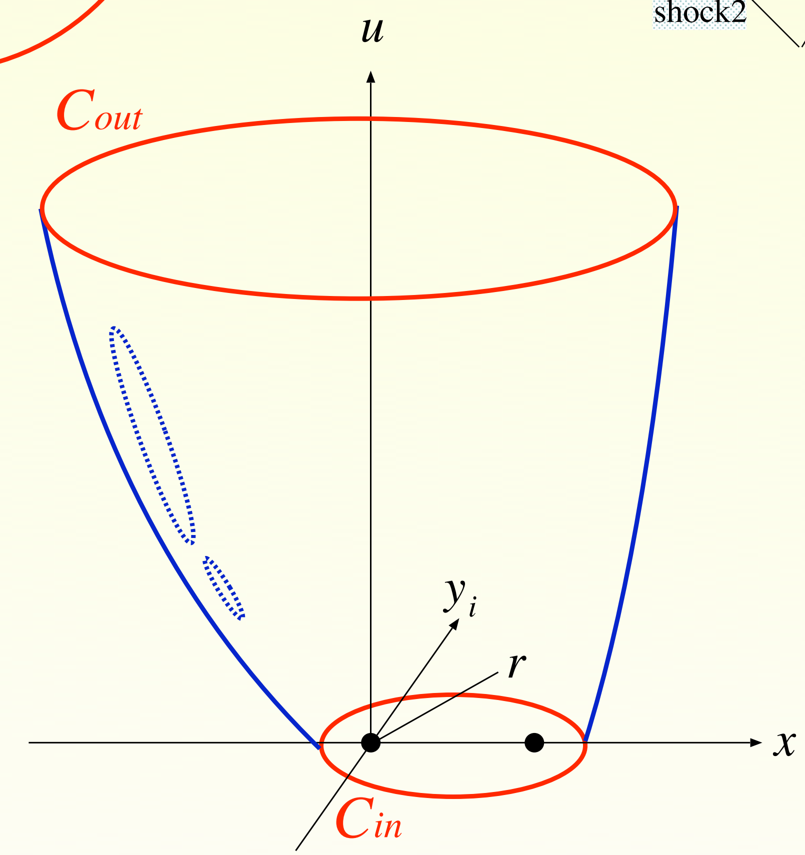

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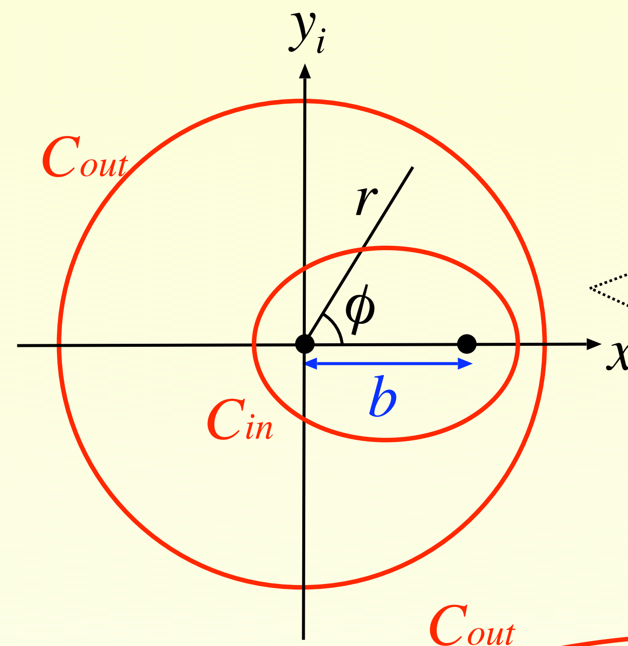

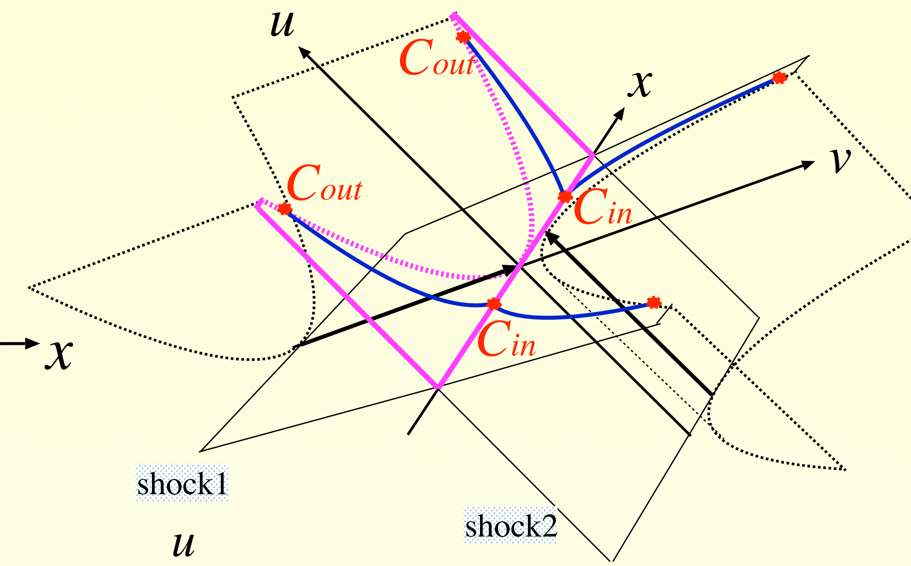

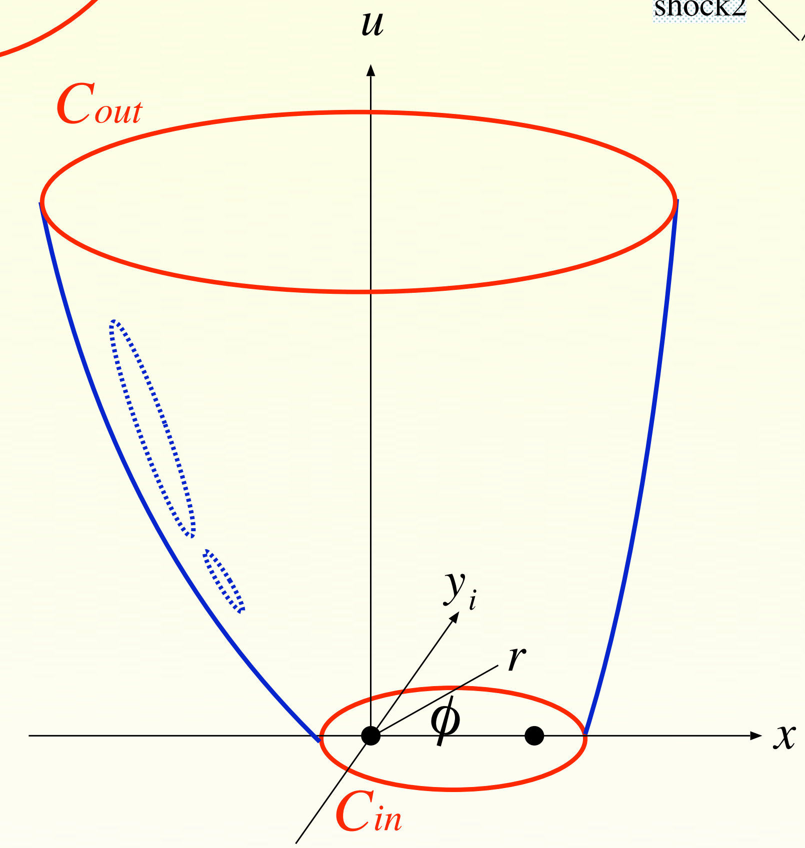

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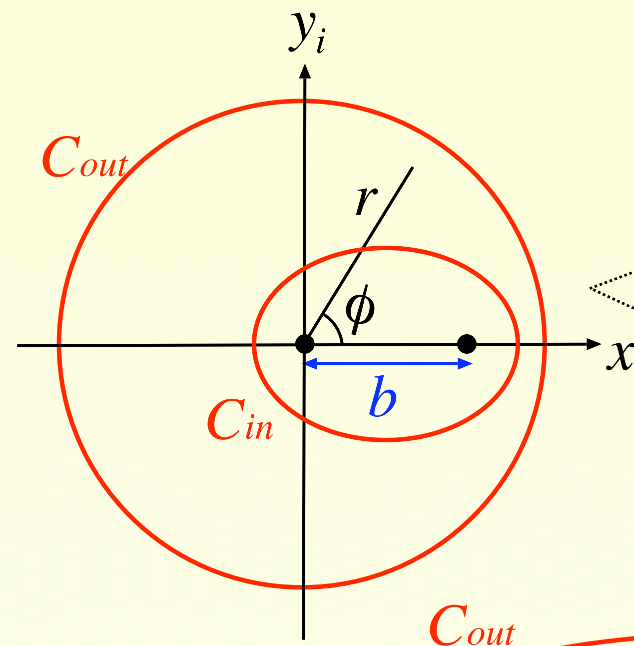

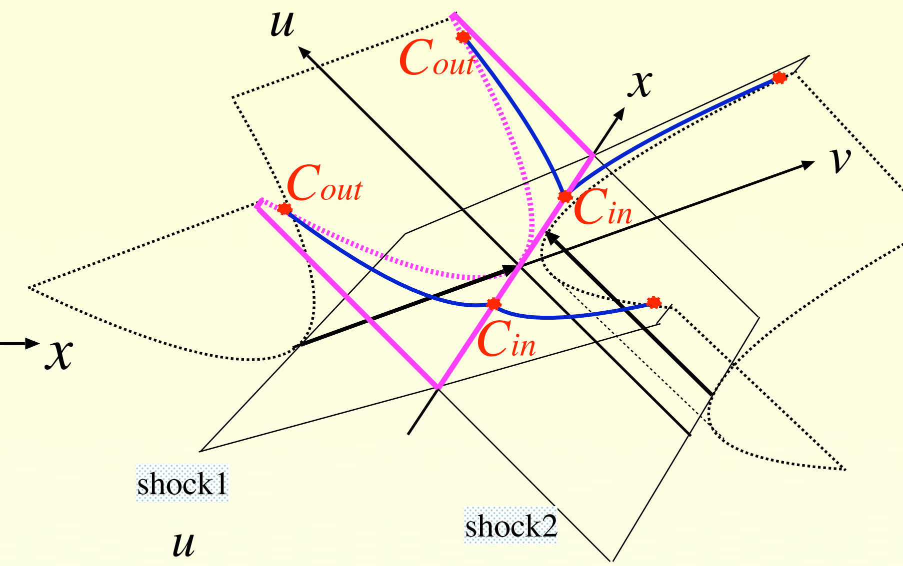

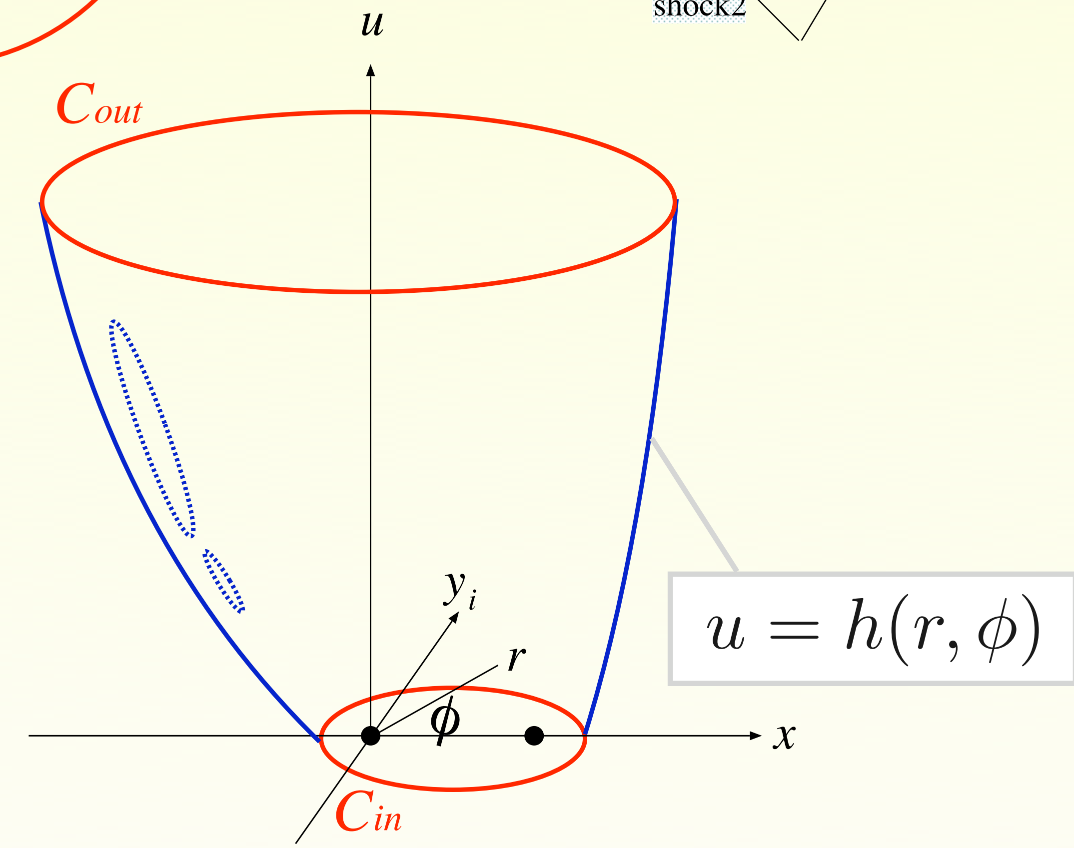

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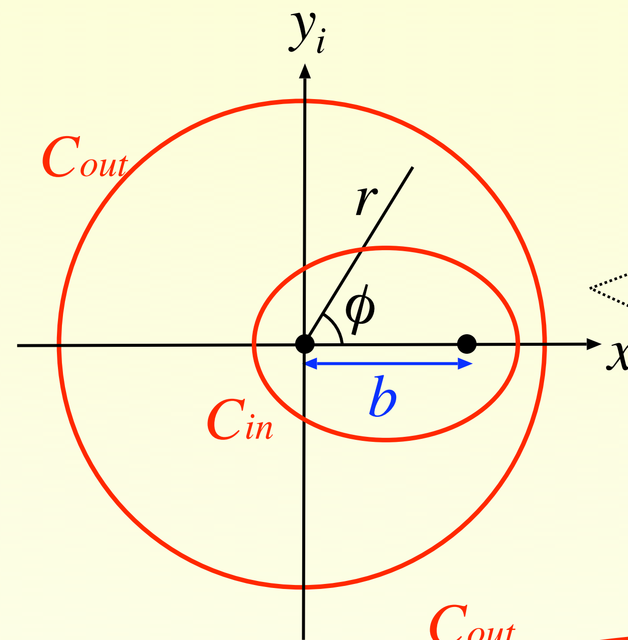

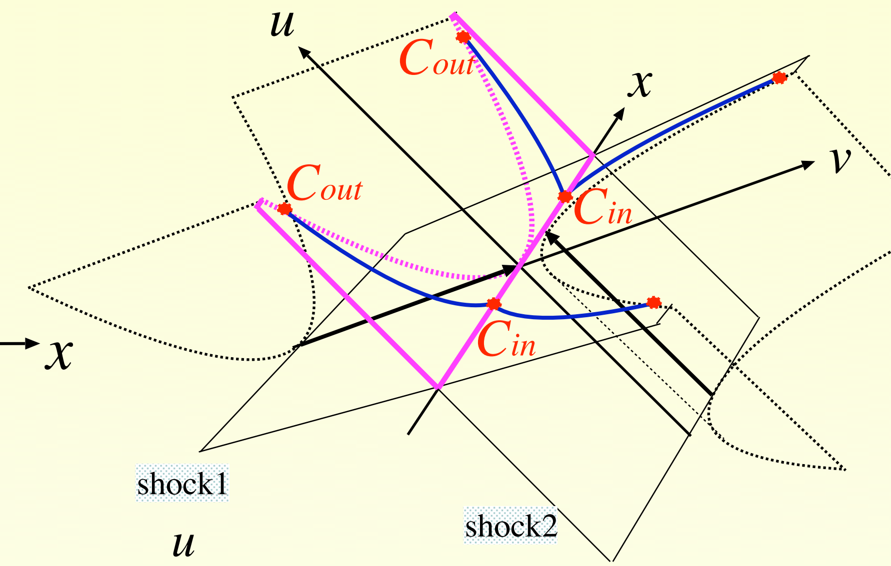

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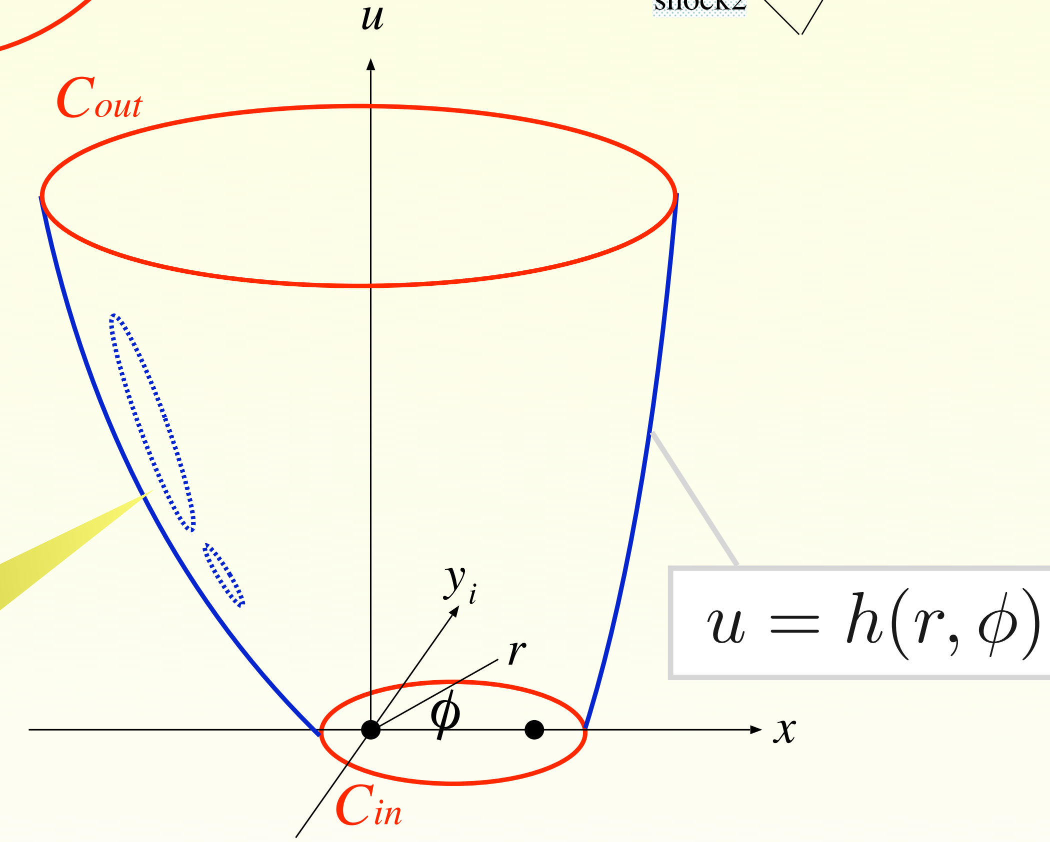
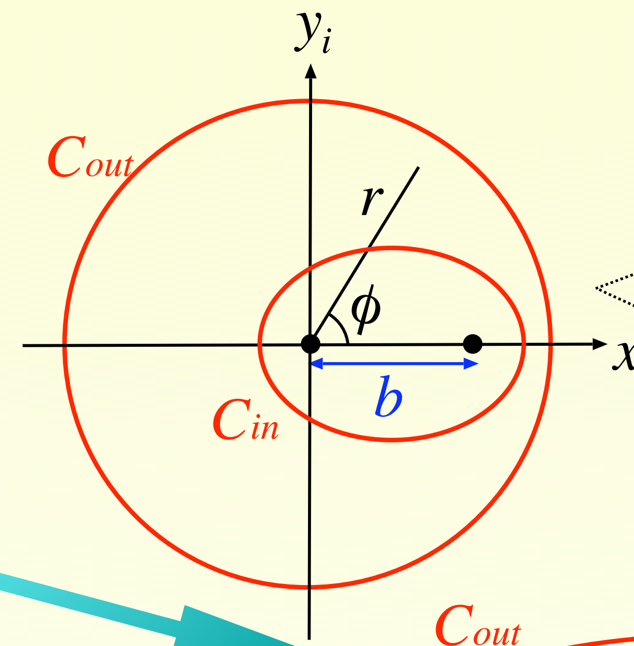


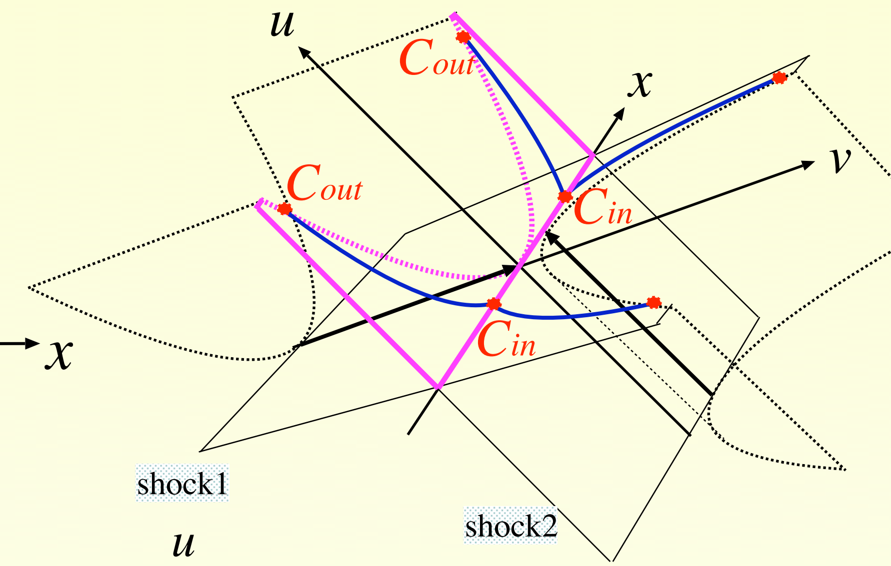
AH:

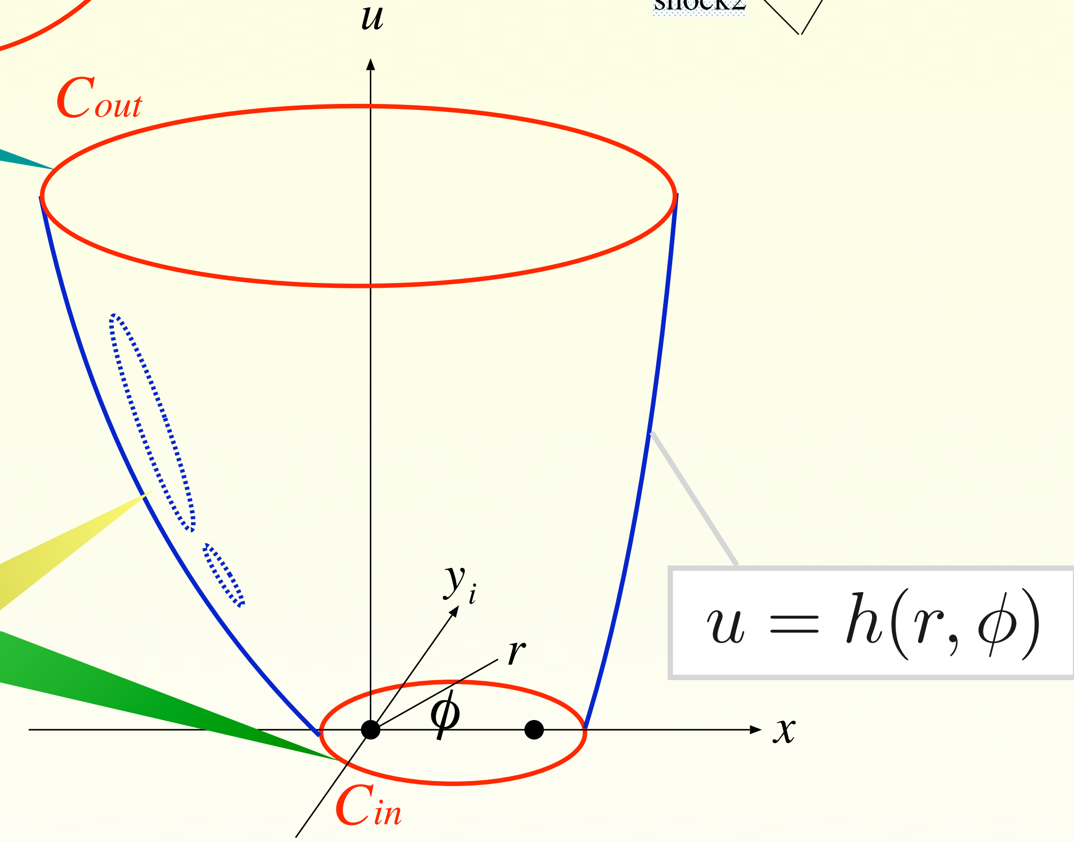
- $$\left(r^{D-2} - h\right)^2 \left\{ h_{,rr} + (D-3)\frac{h_{,r}}{r}\left[1 + \frac{(D-2)h - (3/2)rh_{,r}}{r^{D-2} + (D-3)h} + \frac{(D-2)h - (1/2)rh_{,r}}{r^{D-2} - h}\right]\right\}$$
$$+ r^{-2}\left(r^{D-2} + (D-3)h\right)^2 \left\{ h_{,\phi\phi} + (D-4)\cot\phi\, h_{,\phi} + \frac{h_{,\phi}^2}{2}\left[\frac{(D-3)}{r^{D-2} + (D-3)h} - \frac{(D-7)}{r^{D-2} - h}\right]\right\} = 0.$$

Outer boundary: $r = r_{max}$

- $h = r_{max}^{D-2}$
- $h_{,r} = (D-2)r_{max}^{D-3}\left(1 + \dfrac{1-B^2}{1+B^2+2B\cos\phi}\right),$







Inner boundary:

- $h(r,\phi) = 0$
- $(h_{,r}^2 + r^{-2}h_{,\phi}^2)\,\big|_x\,(h_{,r}^2 + r^{-2}h_{,\phi}^2)\,\big|_{x^\star} = 16,$

AH:

- $$\left(r^{D-2}-h\right)^2\left\{h_{,rr} + (D-3)\frac{h_{,r}}{r}\left[1 + \frac{(D-2)h-(3/2)rh_{,r}}{r^{D-2}+(D-3)h} + \frac{(D-2)h-(1/2)rh_{,r}}{r^{D-2}-h}\right]\right\}$$
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- High-energy two-particle system
- Finding the apparent horizon
- Numerical results
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Results of D=5

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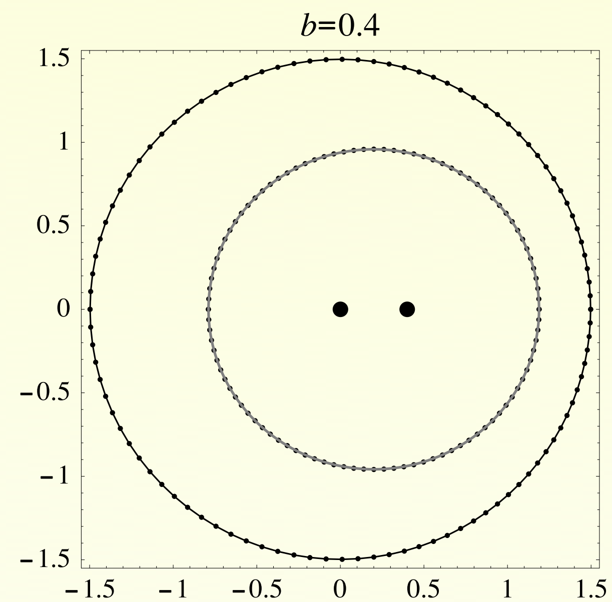

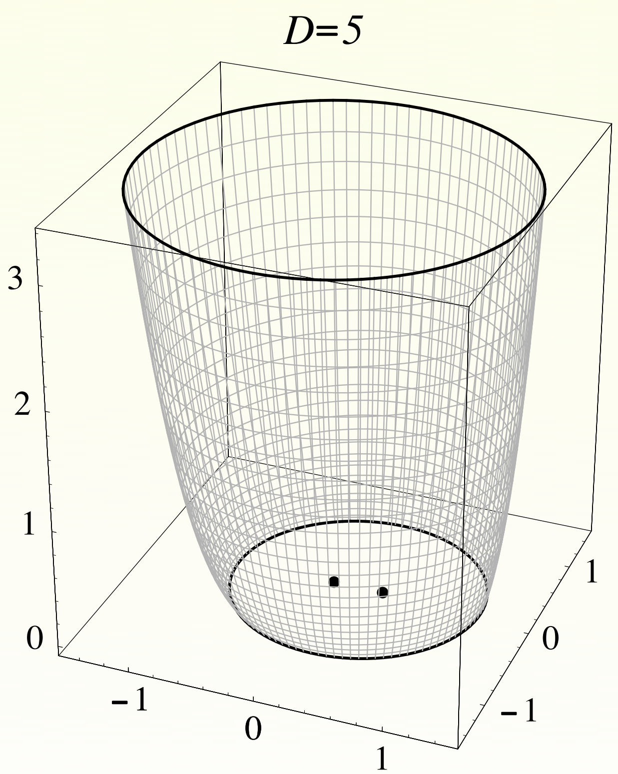

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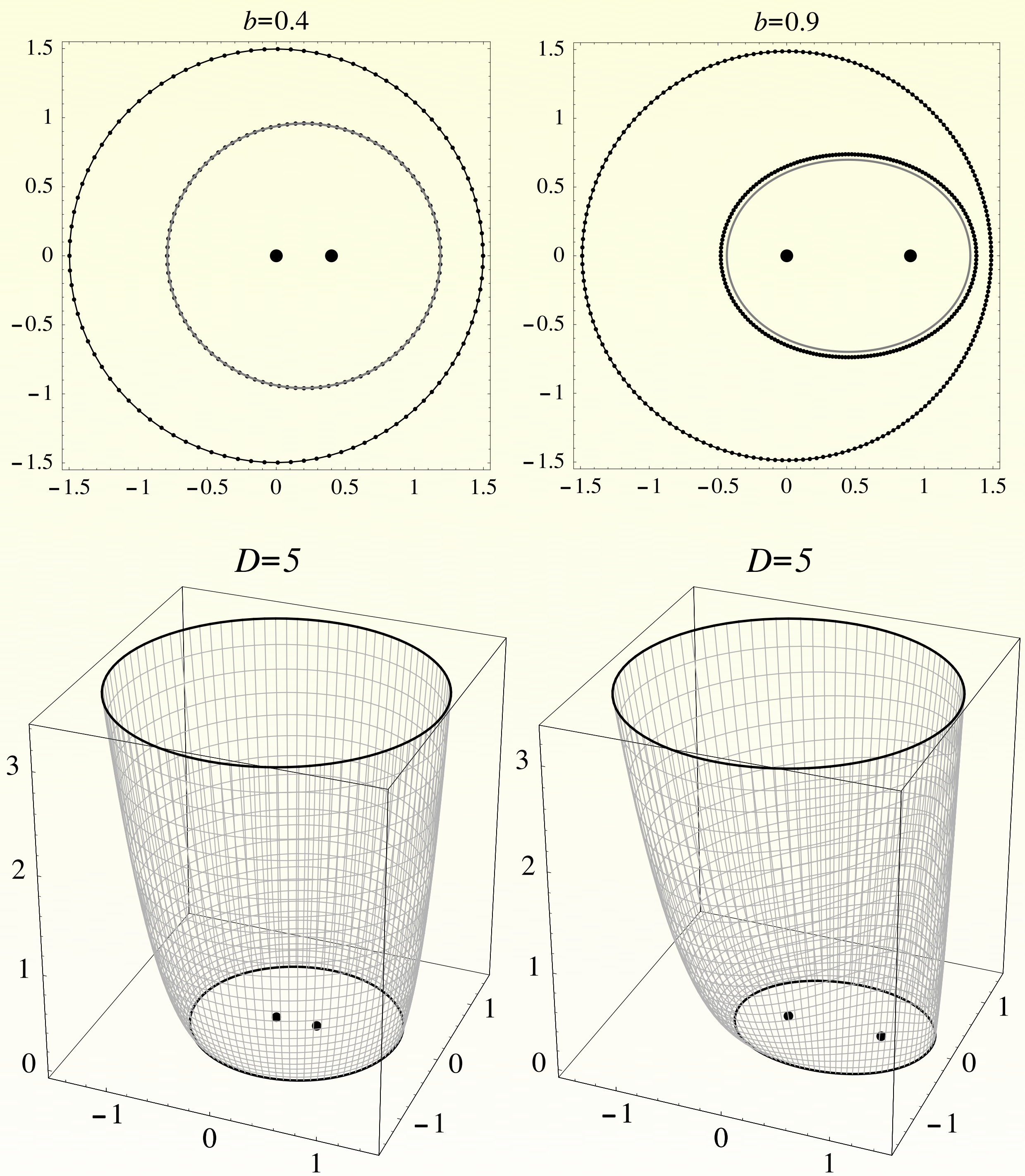

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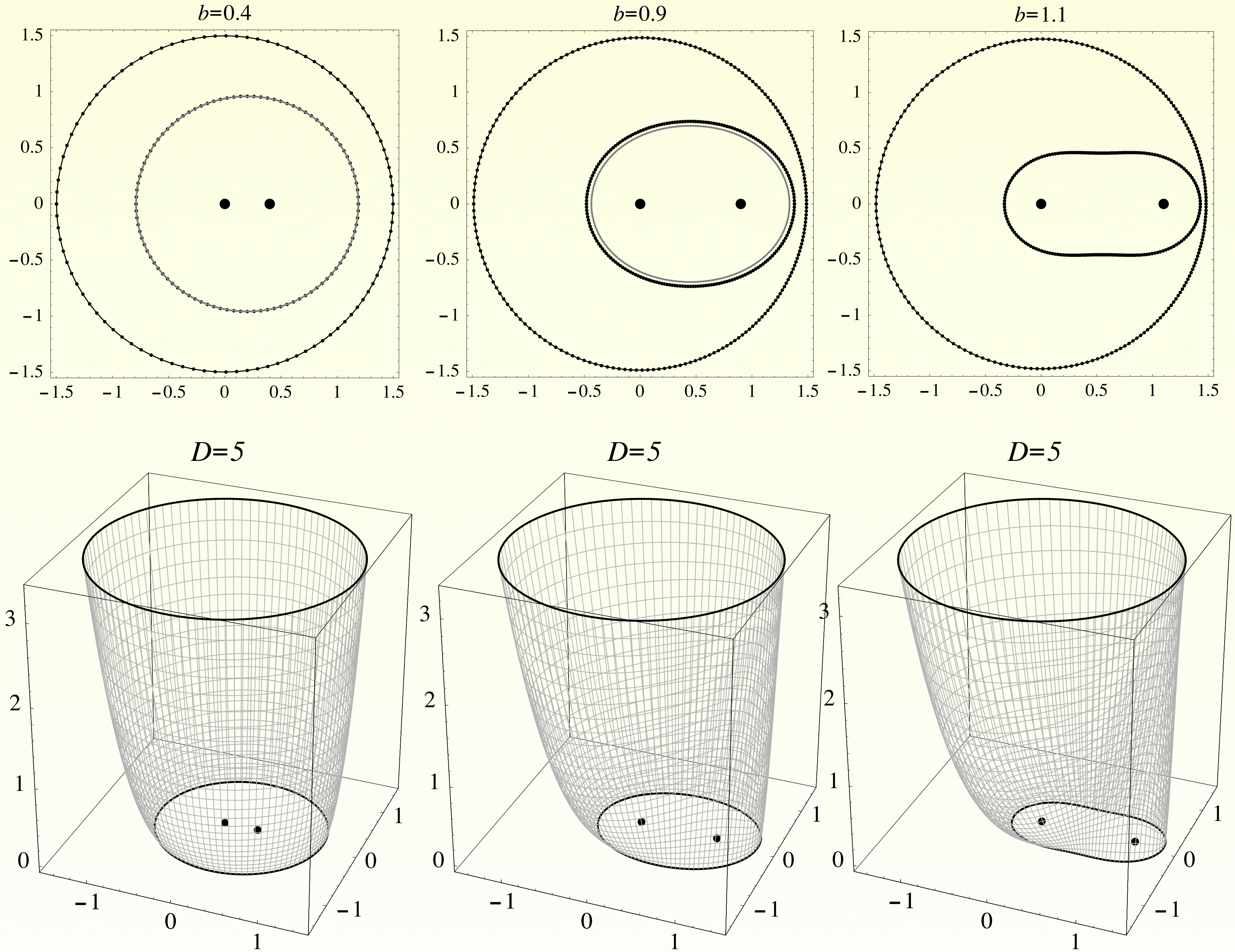
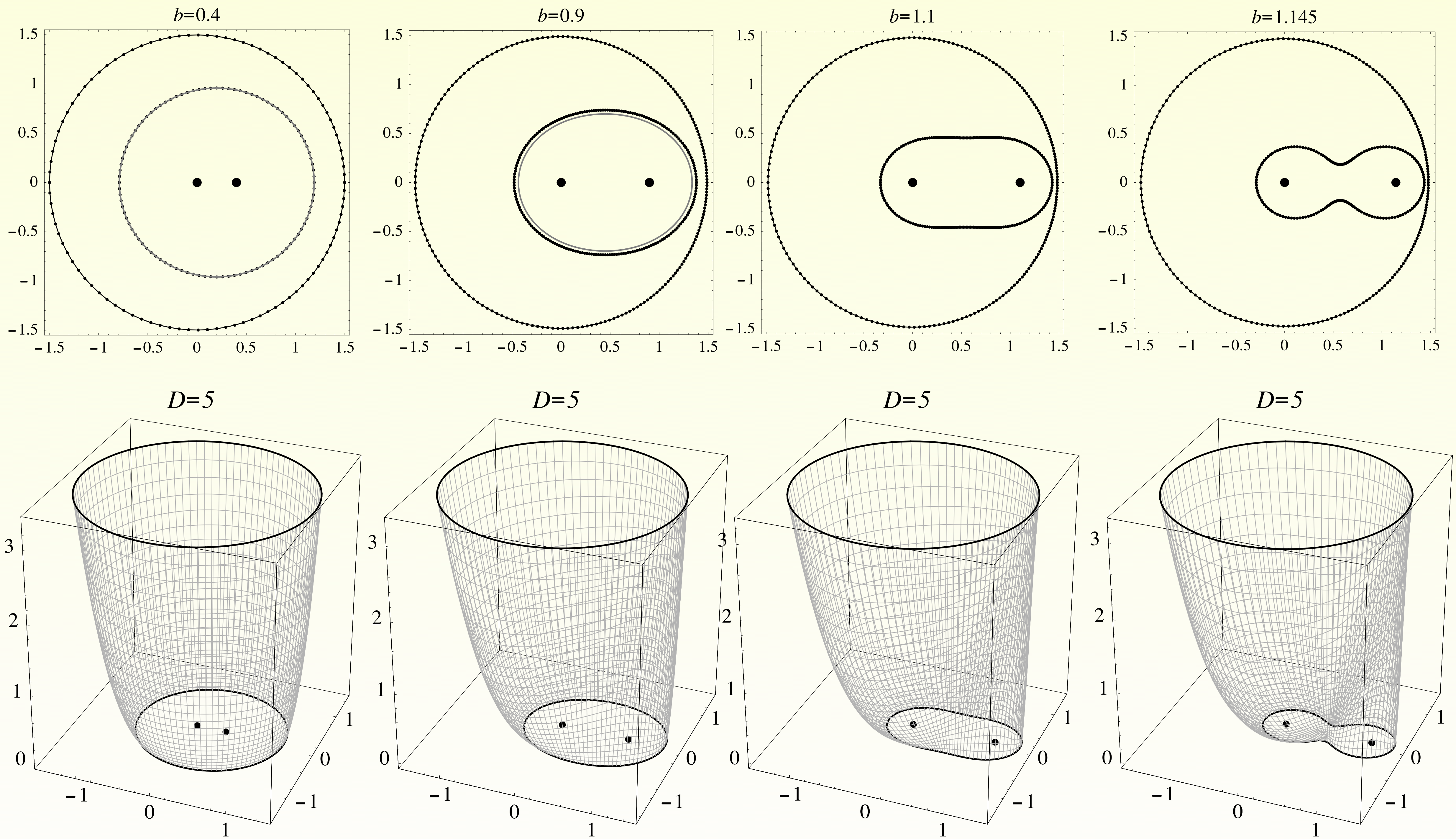


Results of D=5



Main result

D	4	5	6	7	8	9	10	11
$b_{max}^{(\mathrm{new})}/r_0$								

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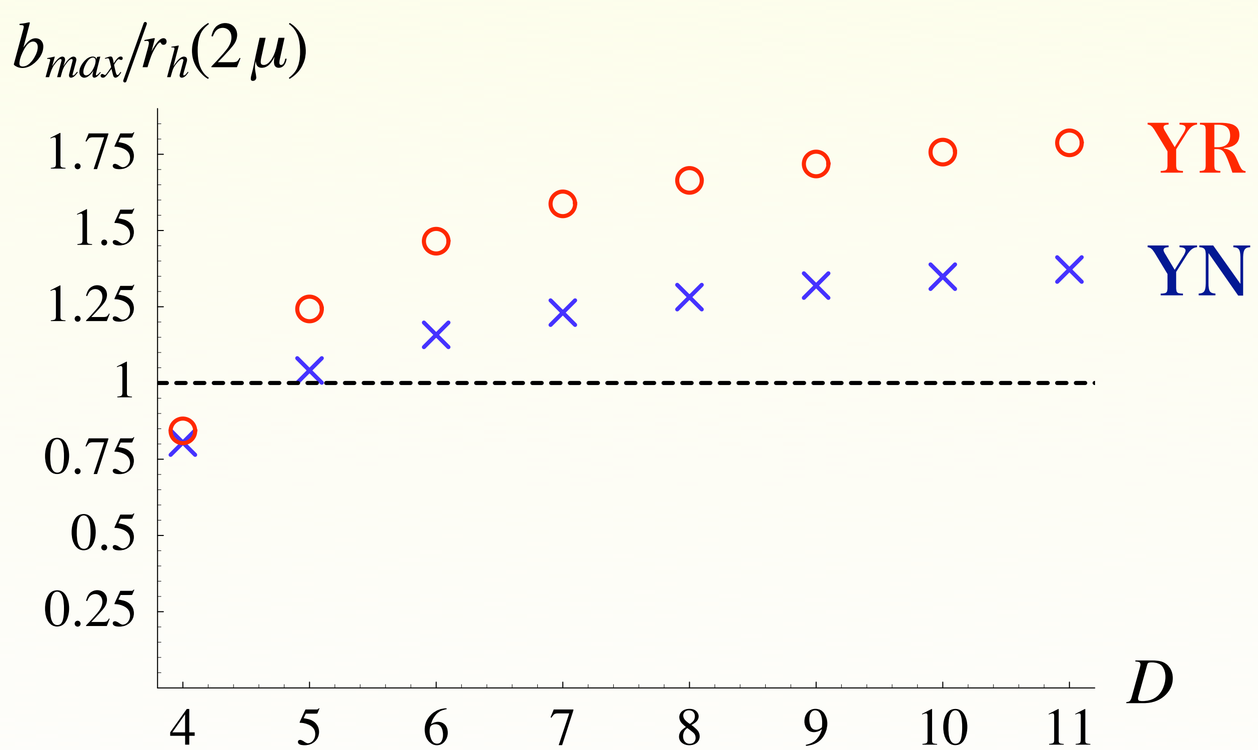

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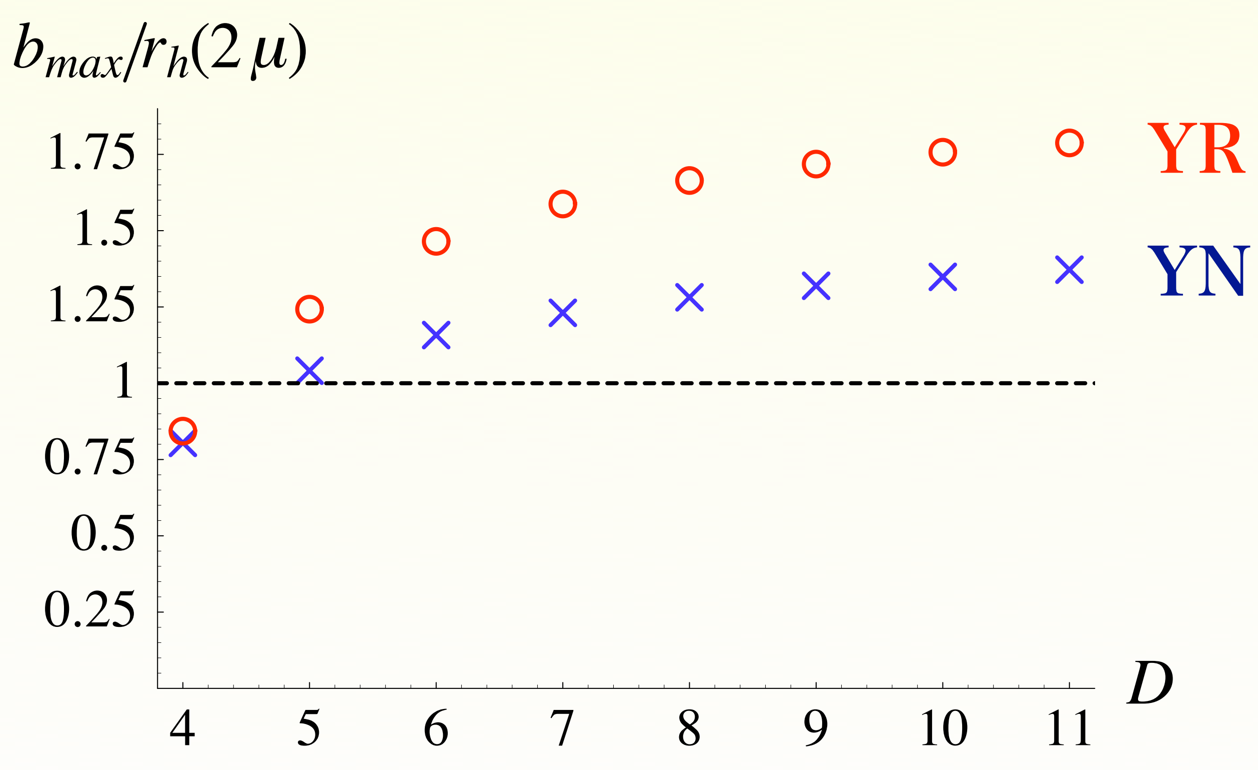

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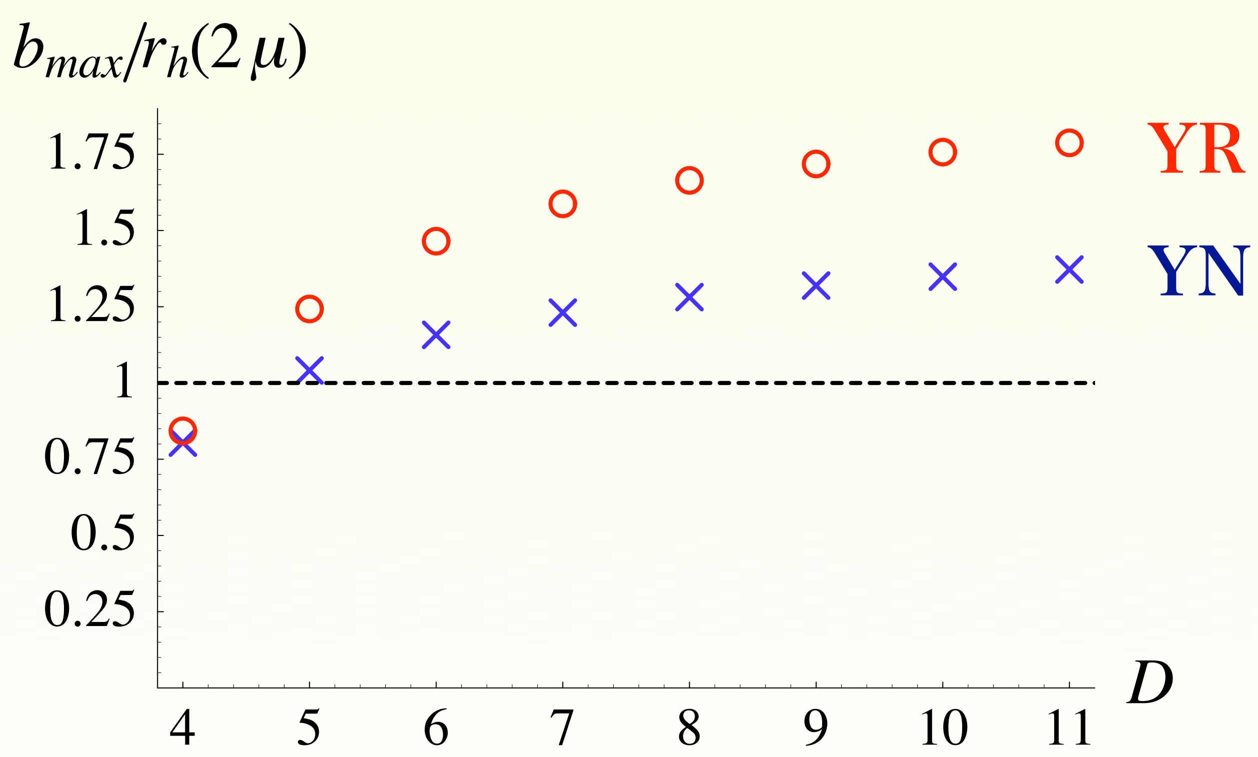

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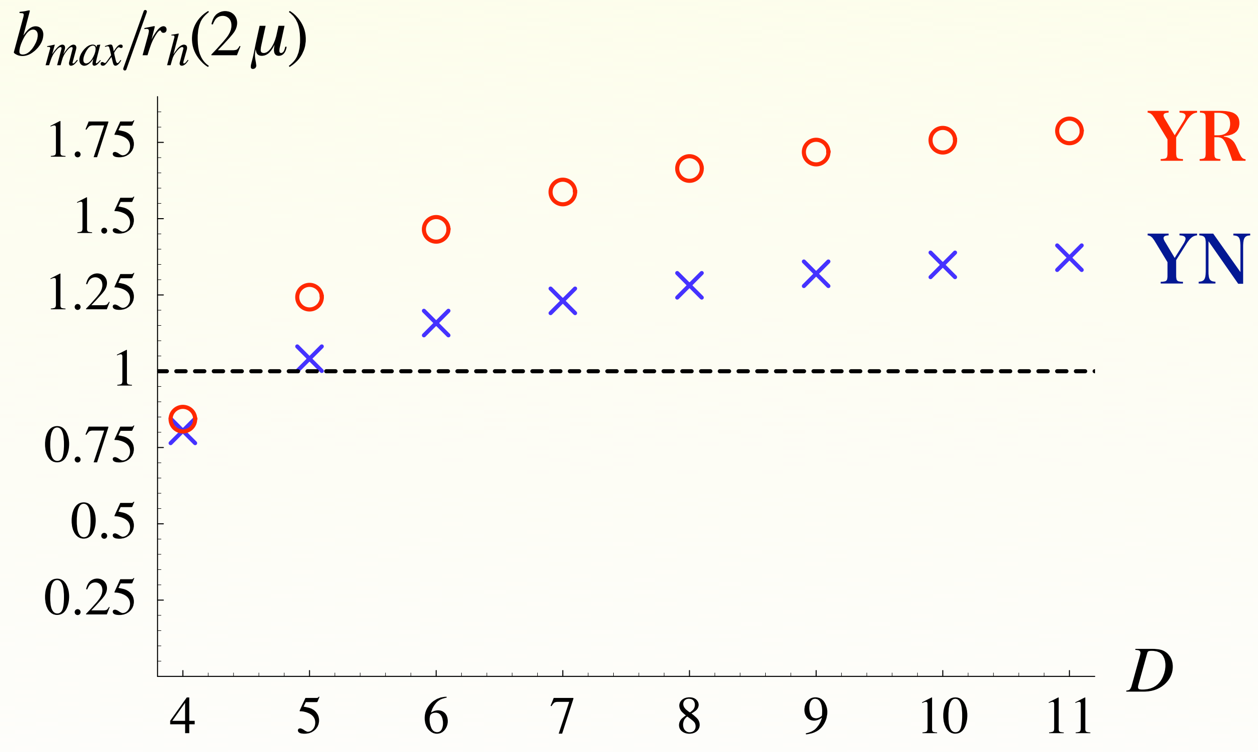

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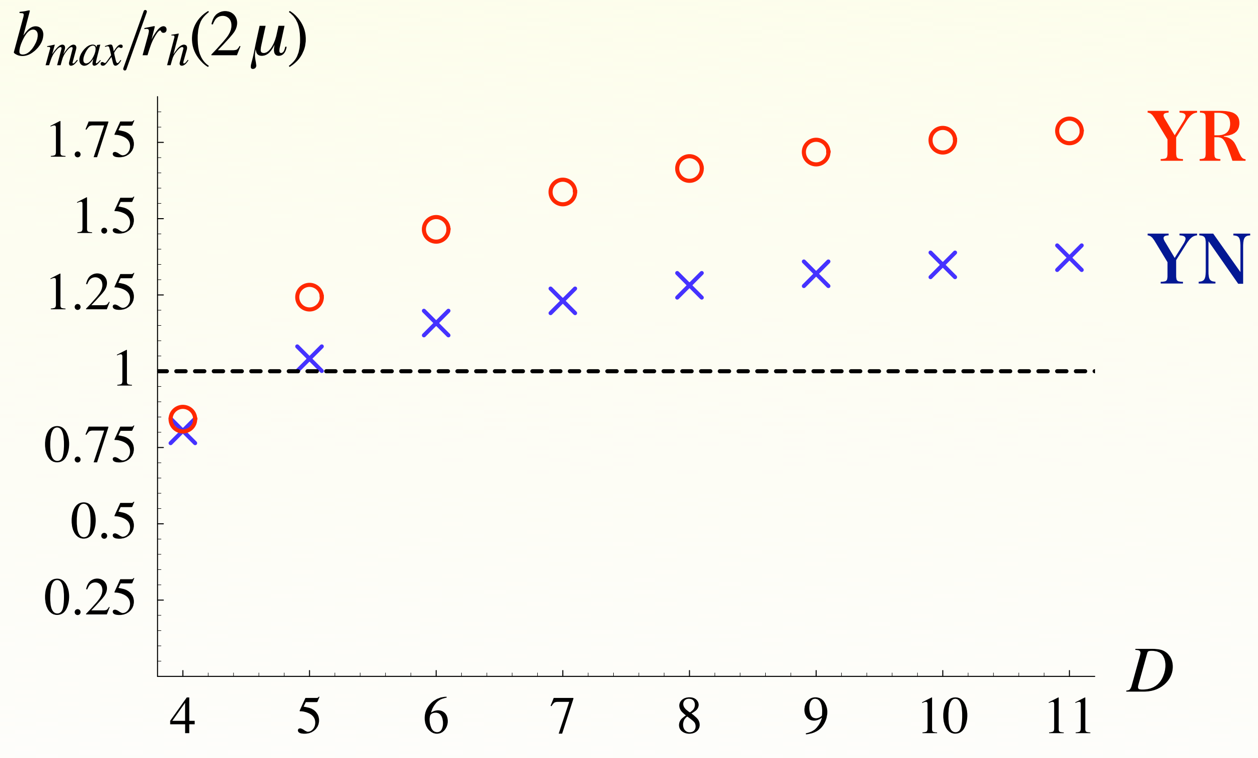

- $1.5 < \sigma_{\mathrm{AH}}/\pi\left[r_h(2\mu)\right]^2 < 3.2$
- ***BH production rate is fairly larger than 1BH/1s.***

(If the energy loss is small).

Final state restriction

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A_{AH}

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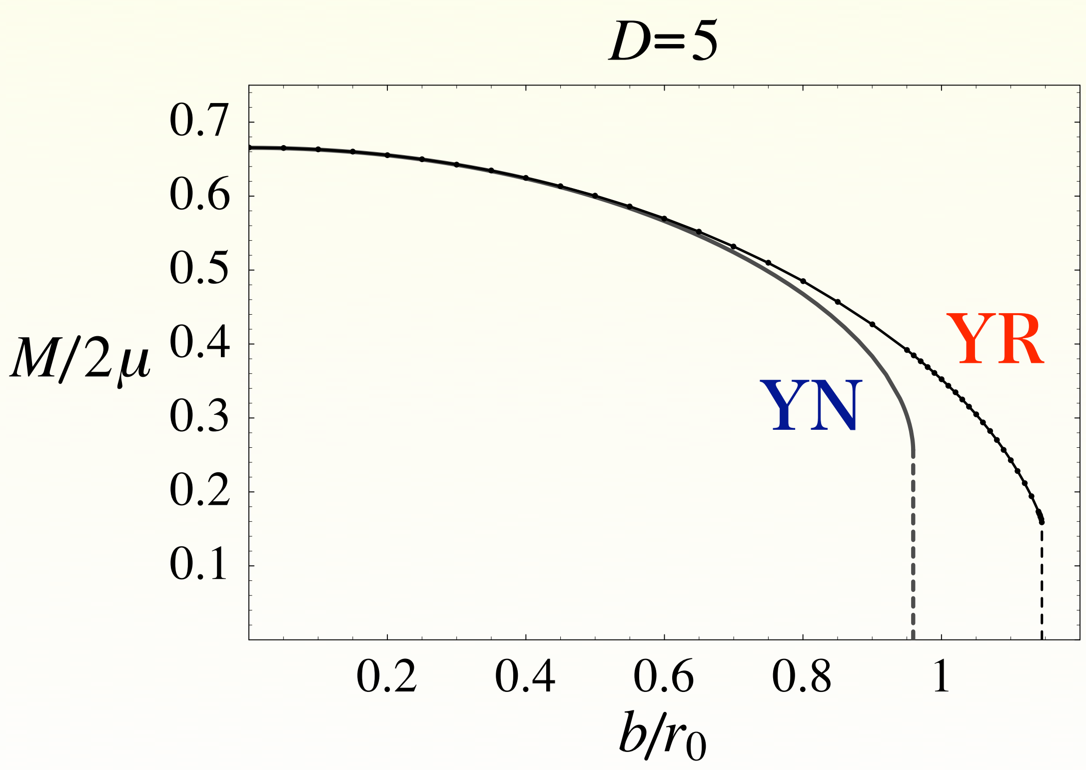

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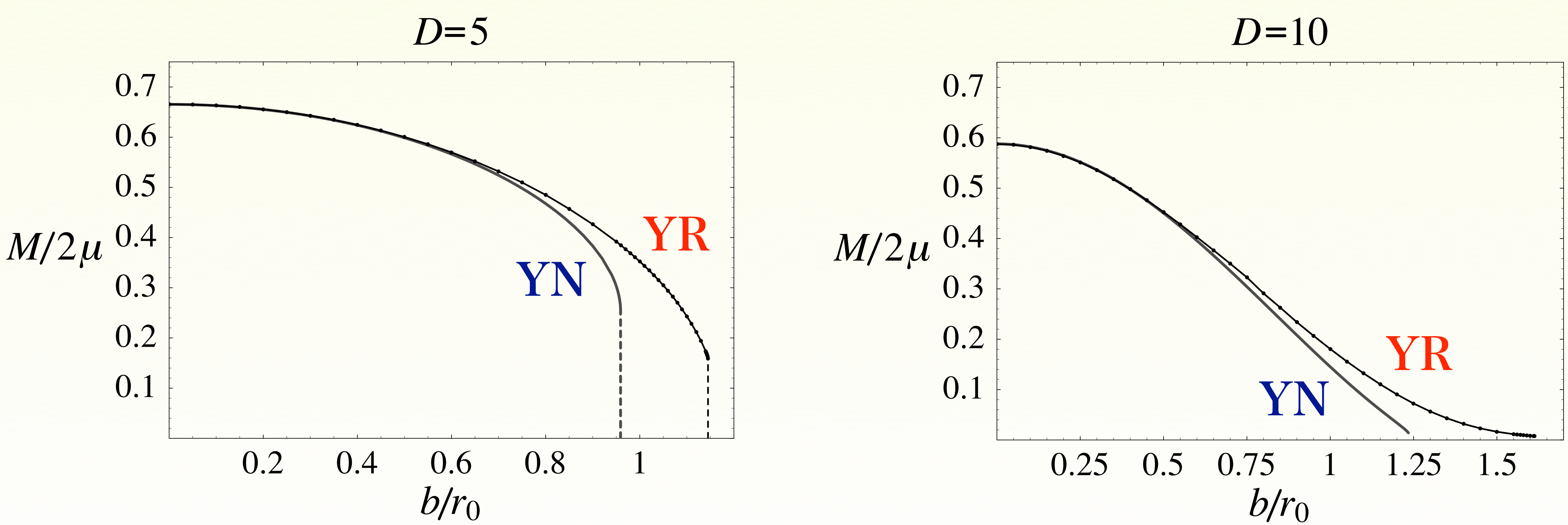

Implication for the LHC

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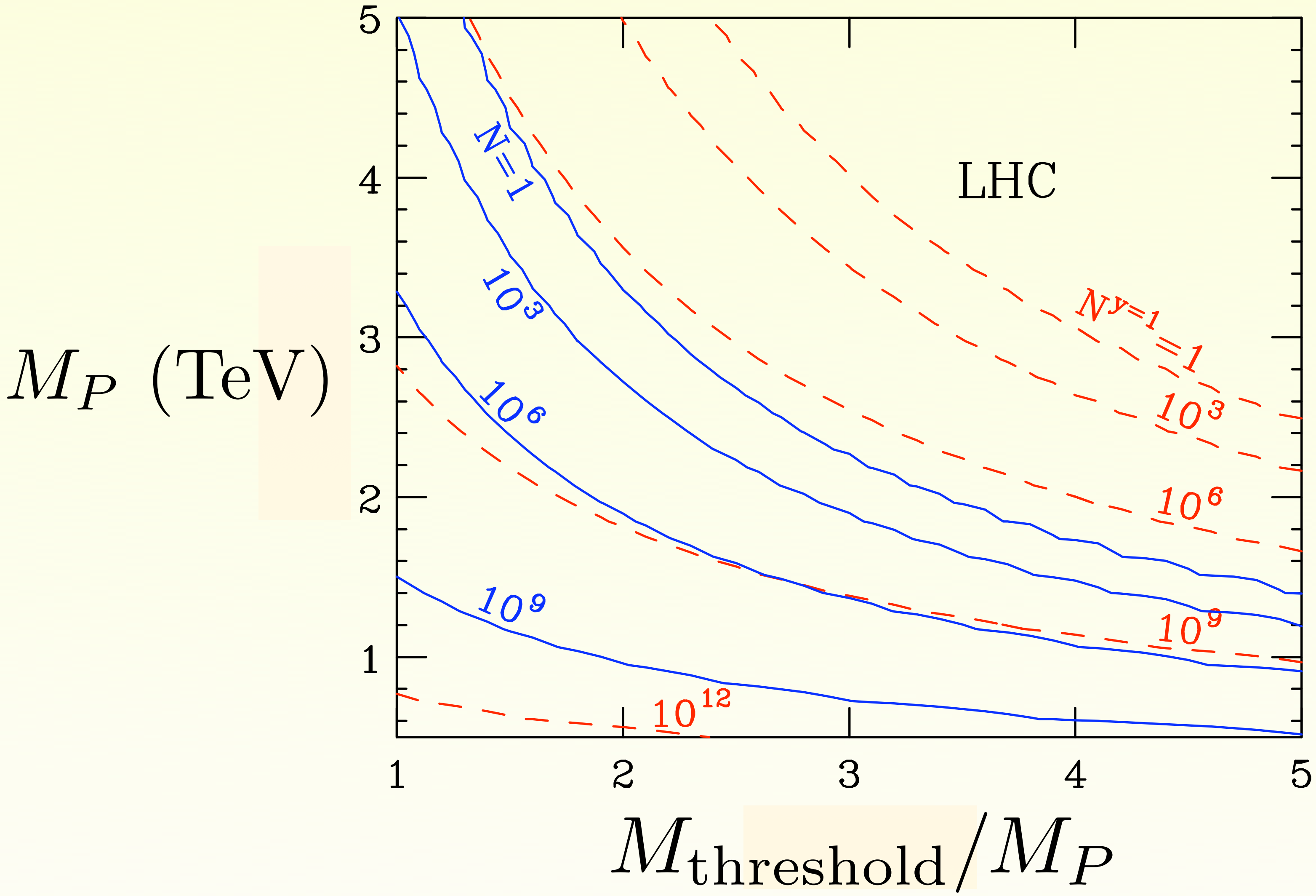
Anchordoqui, Feng, Goldberg, Shapere, Phys.Lett. B594, 363 (2004)

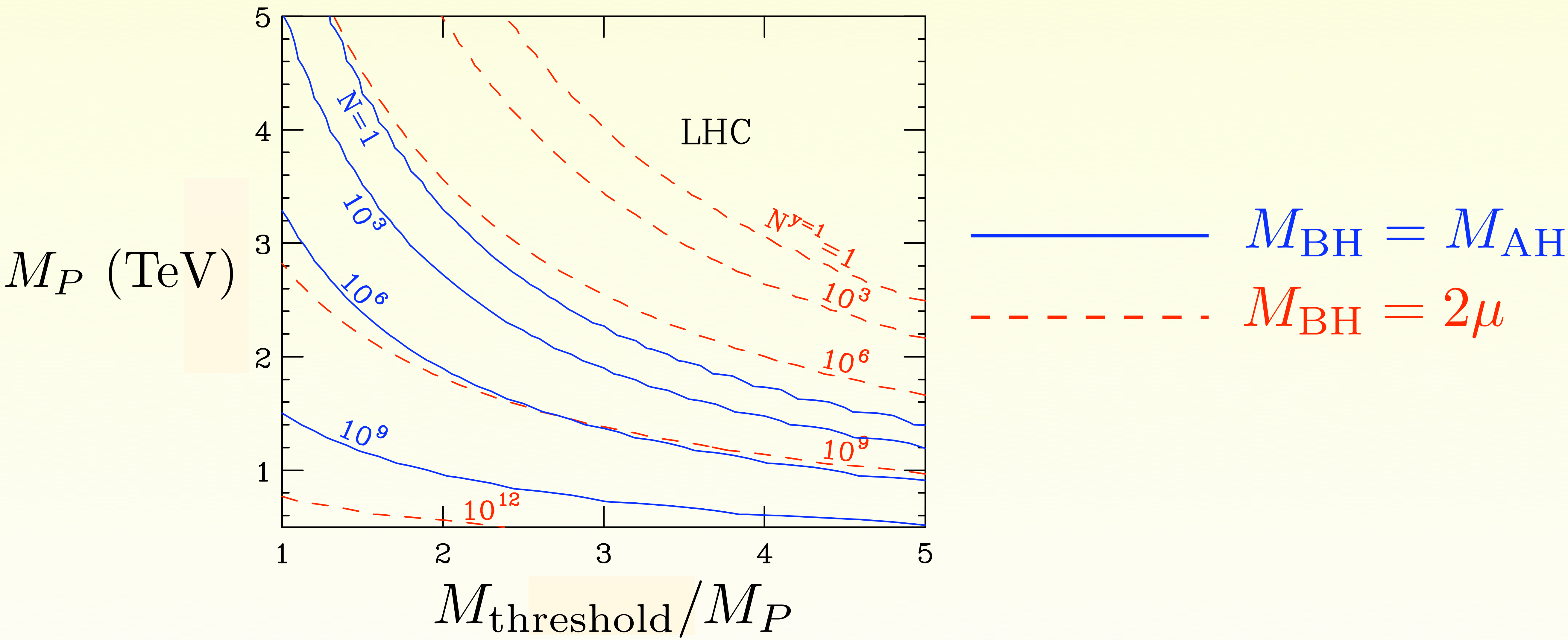


$M_{\rm BH} = 2\mu$

$M_{\rm BH} = M_{\rm AH}$

Implication for the LHC

Anchordoqui, Feng, Goldberg, Shapere, Phys.Lett. B594, 363 (2004)



- ***BH production rate highly depends on the amount of radiated energy.***

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Related studies

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- Effect of charge

  HY and R.B. Mann, PRD74 (06) 044003 [gr-qc/0605131].

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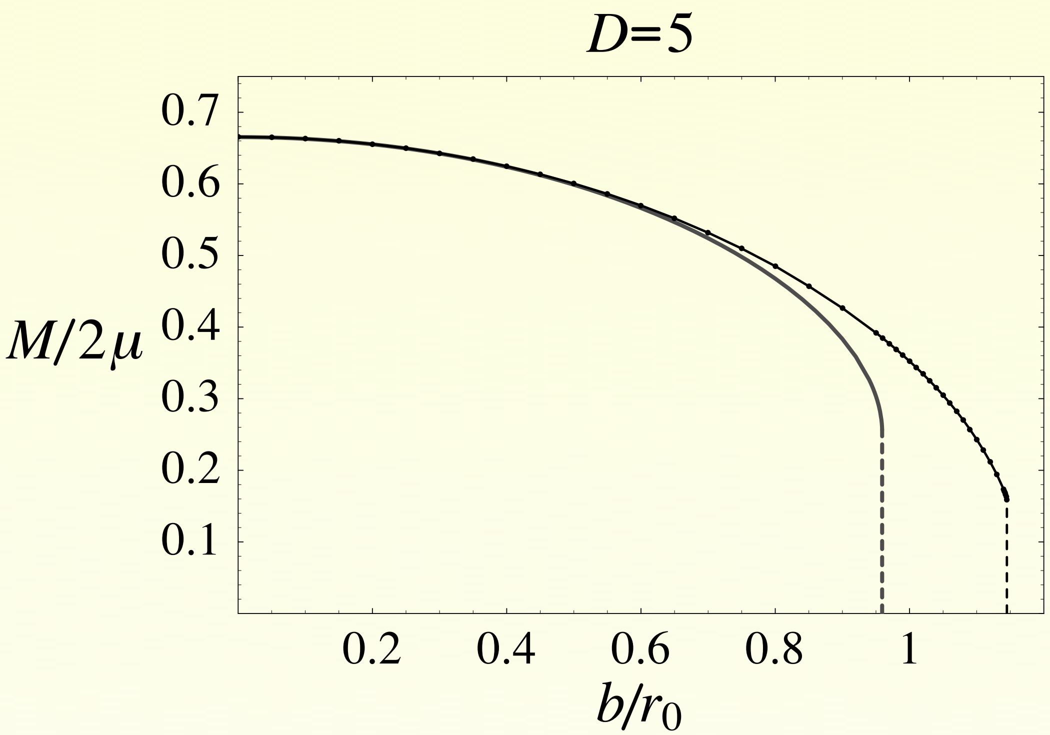
Further discussion POSTER!

Appendix

Final state restriction

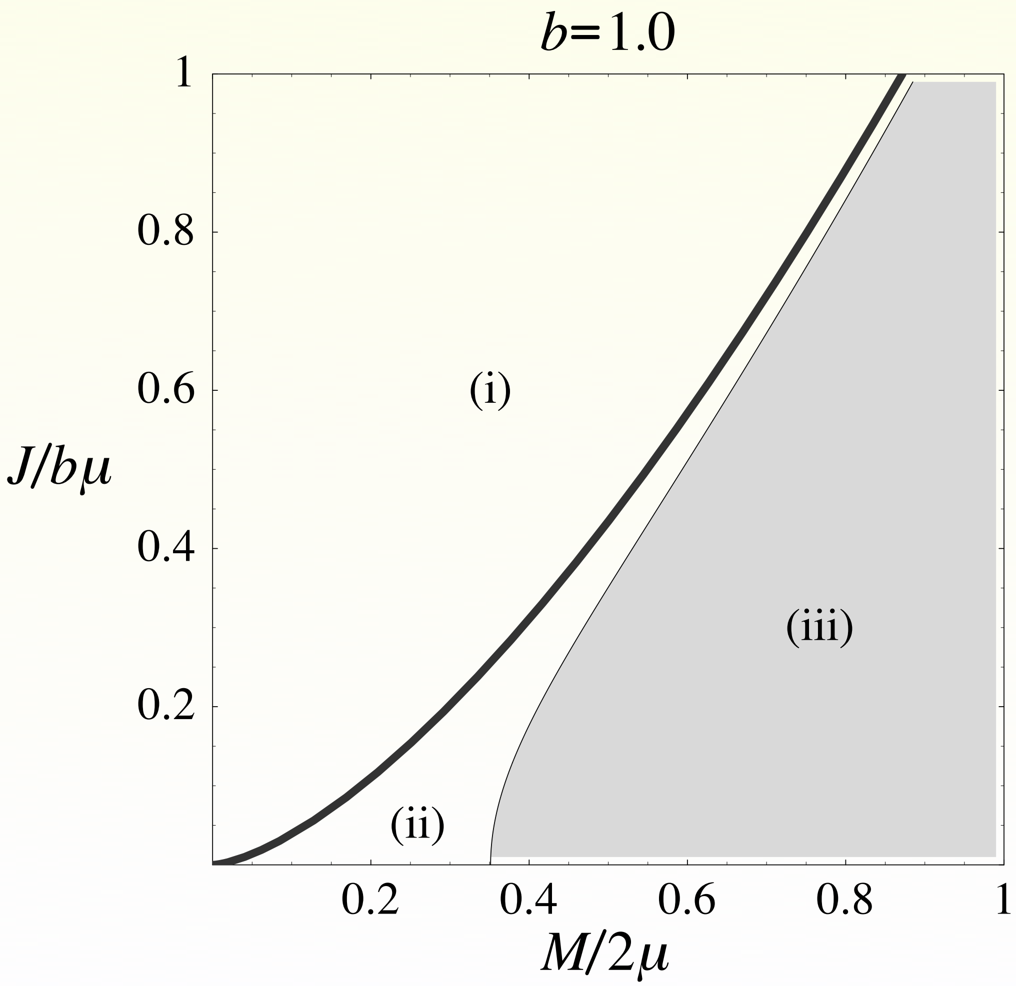
- **Quasi-local mass of the horizon**

$$M_{\rm AH} := \frac{(D-2)\Omega_{D-2}}{16\pi G_D}\left(\frac{A_{\rm AH}}{\Omega_{D-2}}\right)^{(D-3)/(D-2)}$$



- **Area theorem**

$$A_{\rm Kerr}(M,J) > A_{\rm AH}$$



Angular momentum & AH formation

- The Kerr BH is extremal if $J = J_\star(M)$

$$J_\star(M) = \begin{cases} (1/2)Mr_h(M) & (D=4) \\ (2/3)Mr_h(M) & (D=5) \end{cases}$$

- The BH (or AH) is expected to form only if

$$q \equiv J_{\rm system}/J_\star(M_{\rm system}) \lesssim 1,$$

- In our system, $q = \begin{cases} 0.84 & (D=4) \\ 0.93 & (D=5) \end{cases}$

- This criterion was well confirmed in the collapse of rapidly rotating stars in 4-dim. by many authors, e.g, Sekiguchi & Shibata