From Di-Nuclei to Di-Stars

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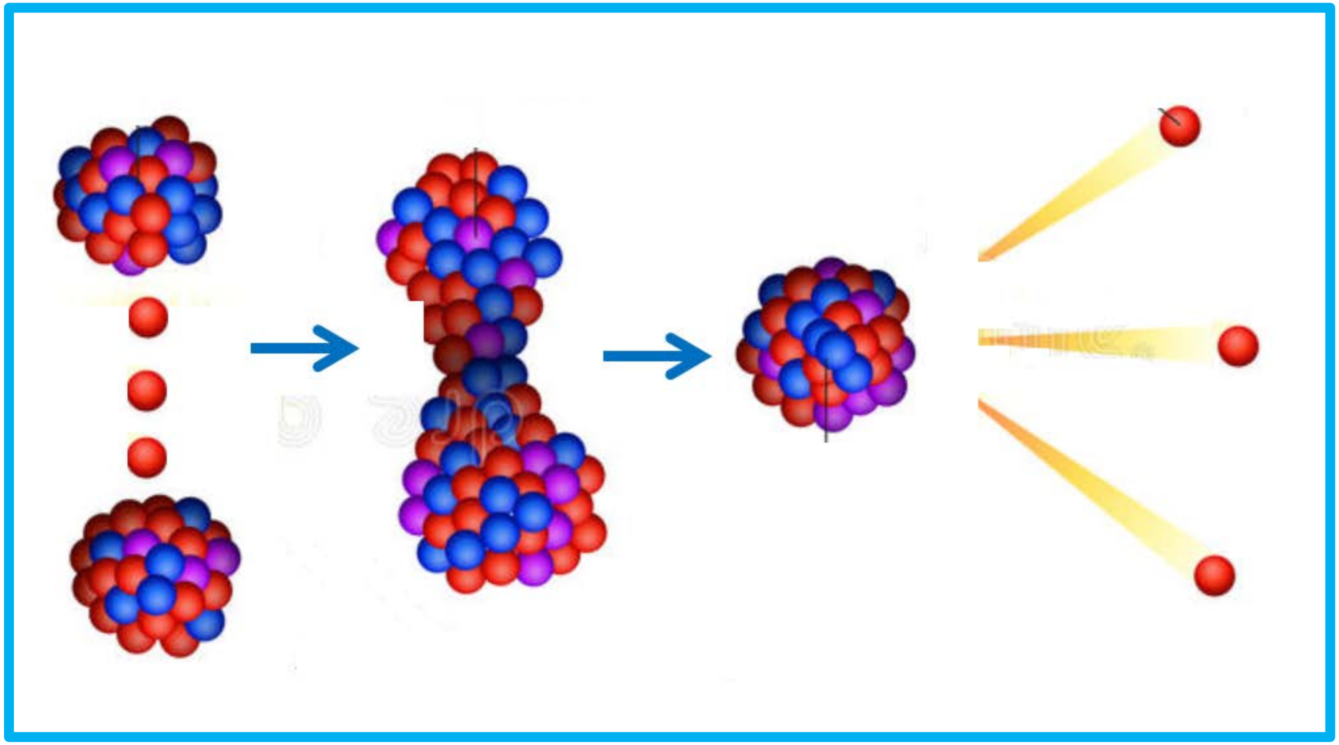
Fusion Scenario of Heavy Nuclei



- Strong interaction event at femtoscale ~10^{-15}m
- Time scale ~10^{-18}s
- Collective degrees and microscopic shell dynamics
- Short range attraction and long range Coulomb repulsion
- Small cross sections $\sigma_f \approx$ nb…fb → low fusion probability $P_f \approx 10^{-3} \ldots 10^{-12}$

Di-Star Merger Scenario vs. Nuclear Fusion

accretion ↔ mass transfer

contact ↔ neck formation

- Fusion on planetary scales ~ 10^{12}m
- Time scale ~ 10^{n} Myr, n>1
- Classical motion in 1/r potentials
- Rare event: 0.1 merger/yr out of 10^{11} stars of the Milky Way

merger ↔ fusion

Dancing stars turn on the red light

Two stars become one, and trigger a rare type of nova.

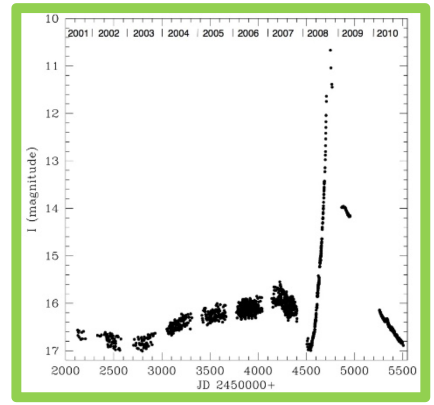
Ken Croswell

For the first time, astronomers have watched the spiralling dance performed by two stars merging into a single star. The observations, taken between 2001 and 2008, suggest a solution to the vexed problem of how rare 'red novae' form.

(Nature, Dec. 2010)

V1309 Sco - Longterm observation by the Optical Gravitational Lensing Experiment (OGLE)

V1309 Scorpii (V1309 Sco)



OGLE Data: A&A 528, A114 (2011)

...first star providing conclusive evidence that contact binary systems end in a stellar merger

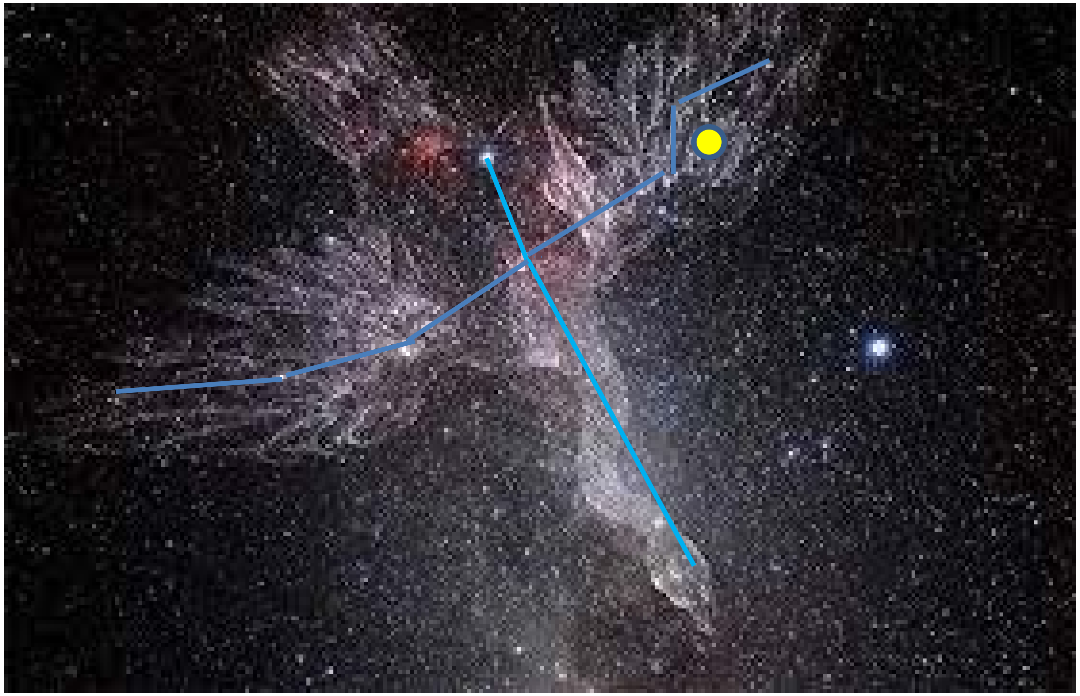
- **merger into a single star in 2008**
- **observed as a luminous red nova**
- **Distance to solar system: ≈10.000 ly (close to the galactic bulge)**
- **similarities lead to identify *a posteriori* two other stars (V838 Monocerotis and V4332 Sagittarii) as merged contact binaries**

In the year 2022…

…you might (not) see a Luminous Red Nova (LRN) :

KIC 9832227

Di-star, orbiting (P~11h) - with decreasing period?



Constellation Cygnus (lat. Swan) at northern hemisphere, KIC 9832227 distance to solar system: 1843 ly

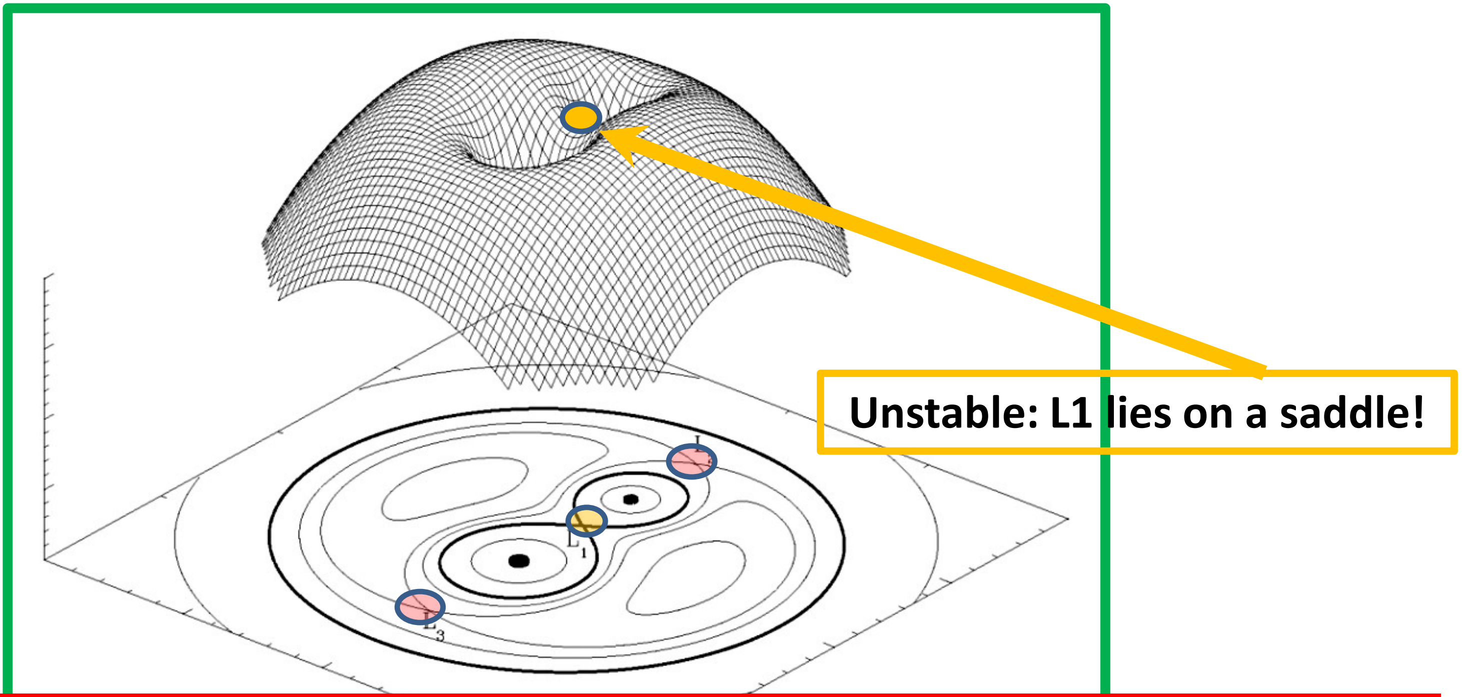
Agenda

- **Newtonian Description of Di-Stars**
- **Classification of Di-Stars**
- **DI-Star Dynamics and Mass Asymmetry**
- **Contact Di-Stars and Mergers**
- **Mergers of Binary Galaxies**
- **Summary, Conclusions, and Outlook**

…together with V.V. Sargsyan, G.G. Adamian, N.V. Antonenko
Int.J.Mod.Phys. E:271850063 (2018), Int. J. Mod. Phys. E 27:1850093 (2018)
Int.J.Mod.Phys. E28: 1950031 (2019), Acta Phys.Polon. B50 (2019) 507
Com.Theor.Phys. (in print)

Roche Potential and Classification of Di-Stars

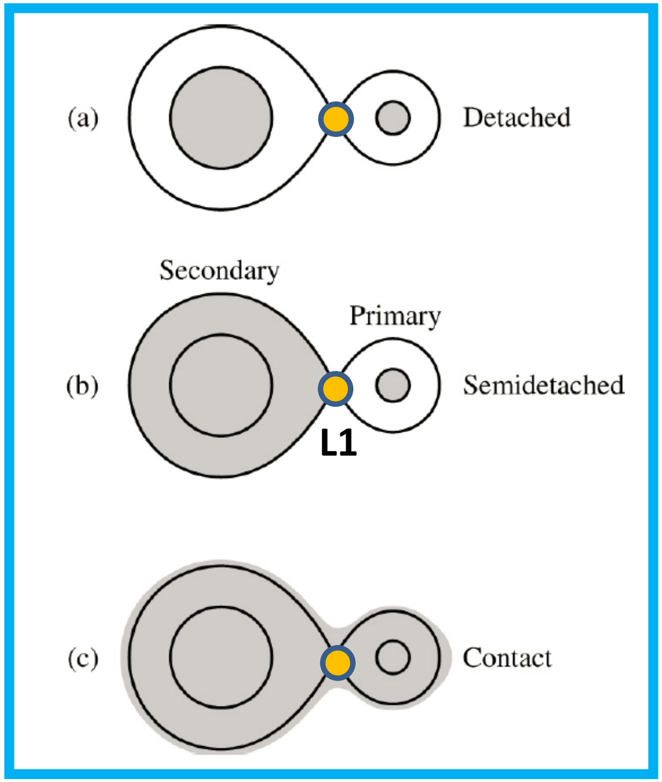
Roche Potential and Roche Lobe



Roche Lobe of a Massive Body ≅ Sphere of Gravitational Influence

- A three-dimensional representation of the Roche potential in a binary star with a mass ratio of 1:2.
- The volume of space inside of which a test particle feels a stronger pull from star 1 than star 2 defines the **Roche Lobe for star 1**.

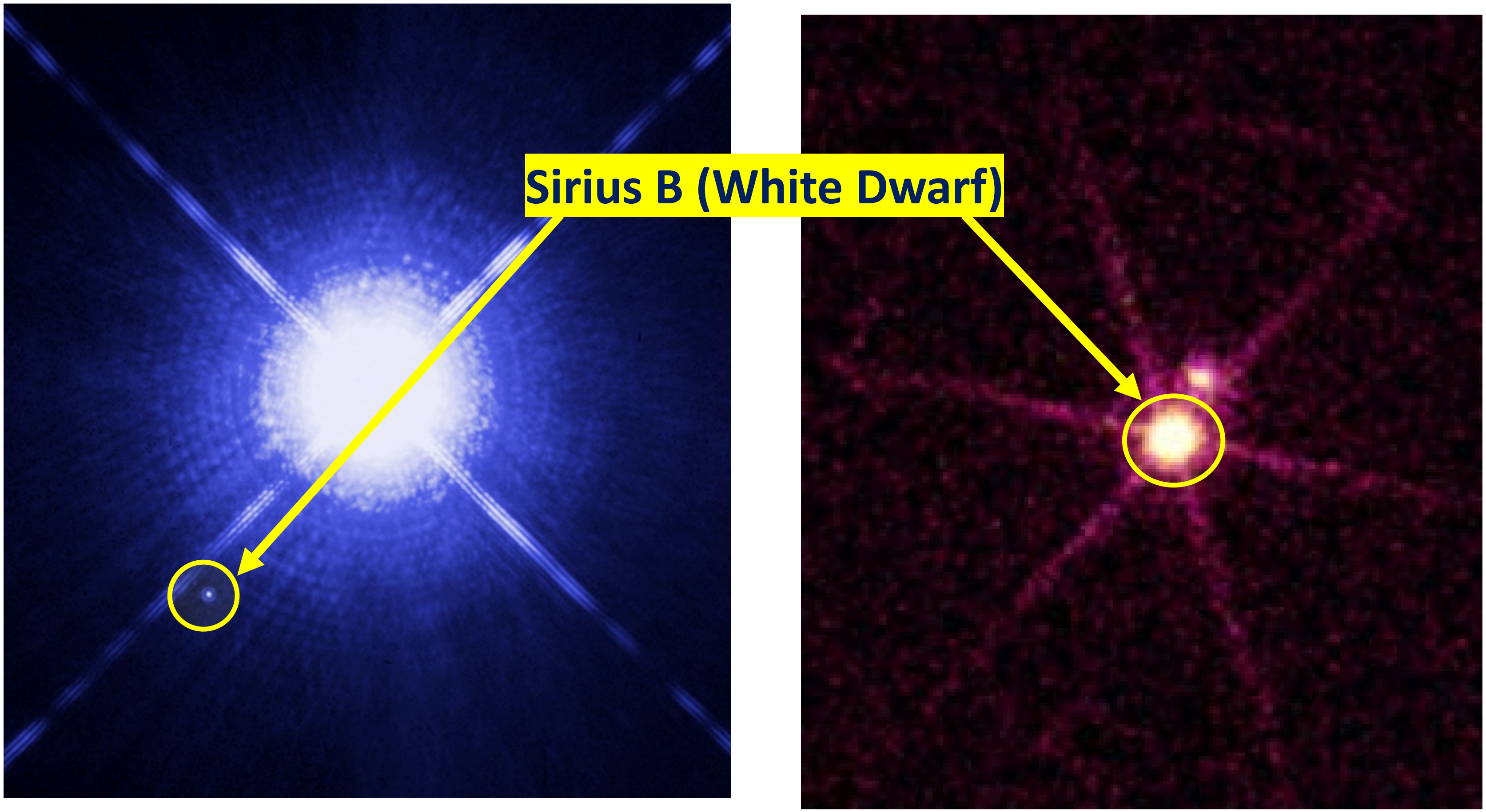
Classification of binary systems.



- **Detached Binary**: **Both stars are smaller than their respective Roche lobes; no direct influence on each other's evolution (a).**
- **Semidetached Binary**: **one star fills its Roche Lobe, mass is transferred from that star through the Lagrange point L1 to the companion star (b).**
- **Contact Binary**: **share a common atmosphere and exchange mass (c).**

Our closest-by di-star neighbour: detached binary Sirius A and B

Distance to solar system: 8.6 ly

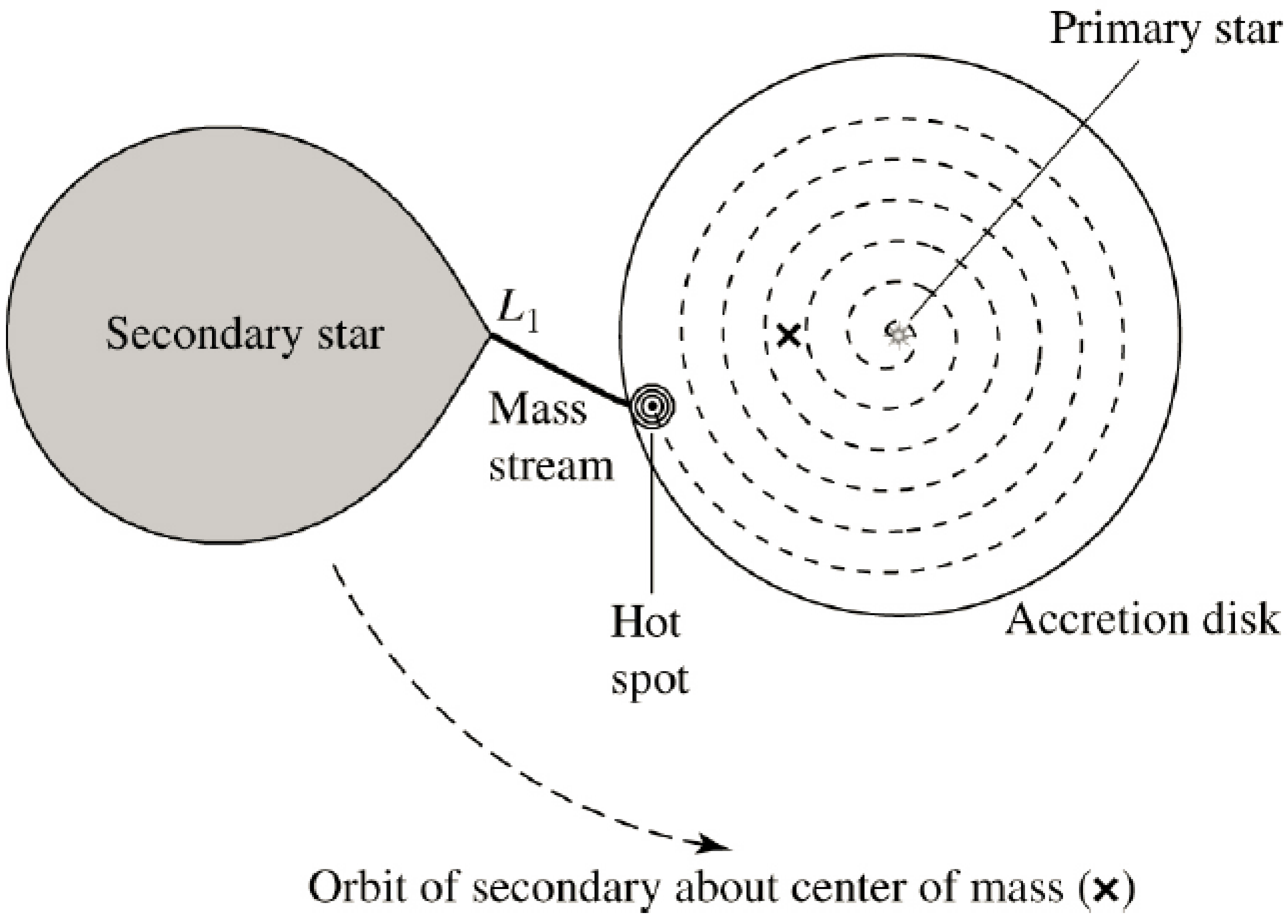


Sirius in visible light by HST

Sirius in X-ray view by CHANDRA

(Reflections due to recording devices)

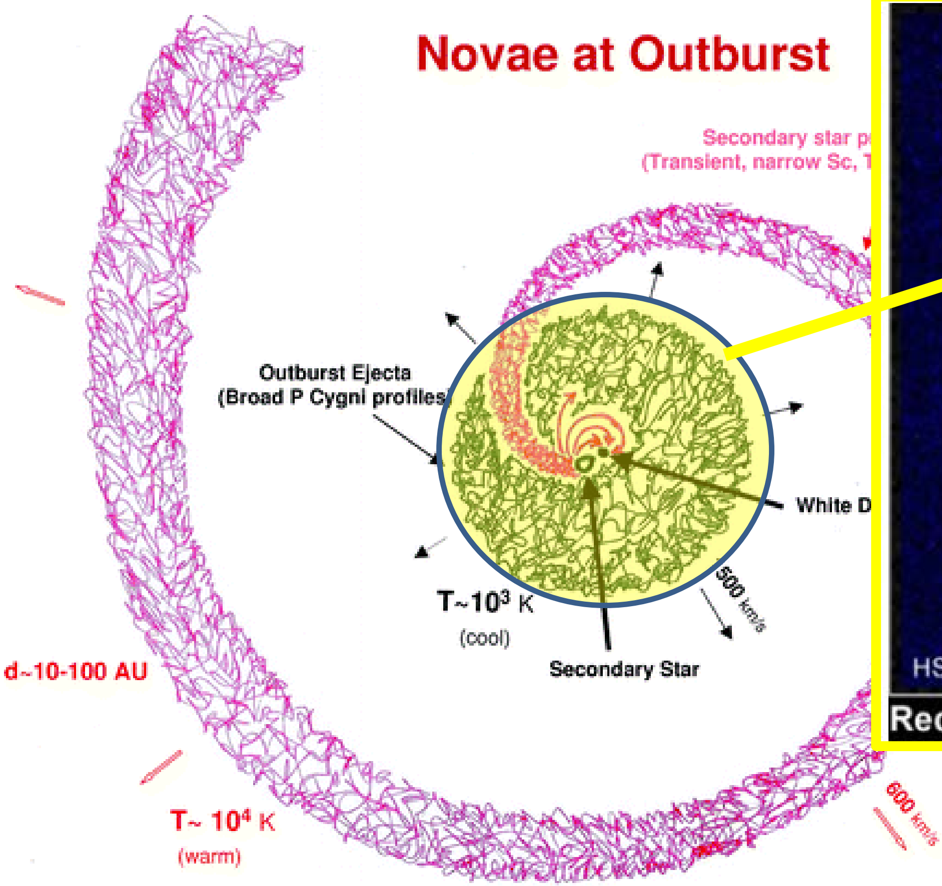
Mass Exchange Mechanism in a Semi-Detached Binary

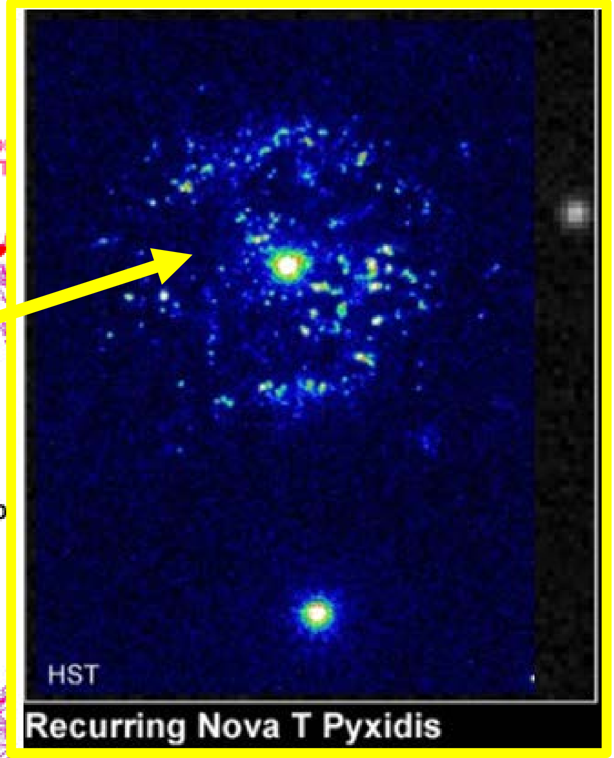


From Accretion to Nova Outburst

… Run-off and „Death Spiral“ after mass loss --> $\dot{P} \sim \dot{M}$

- **either through inner LP L1 (primary star accretes and explodes)**
- **or through outer LP L2 (ejection into space)**





(15,600 ly to earth)

[Williams et al. 2008, ApJ, 685, 451]

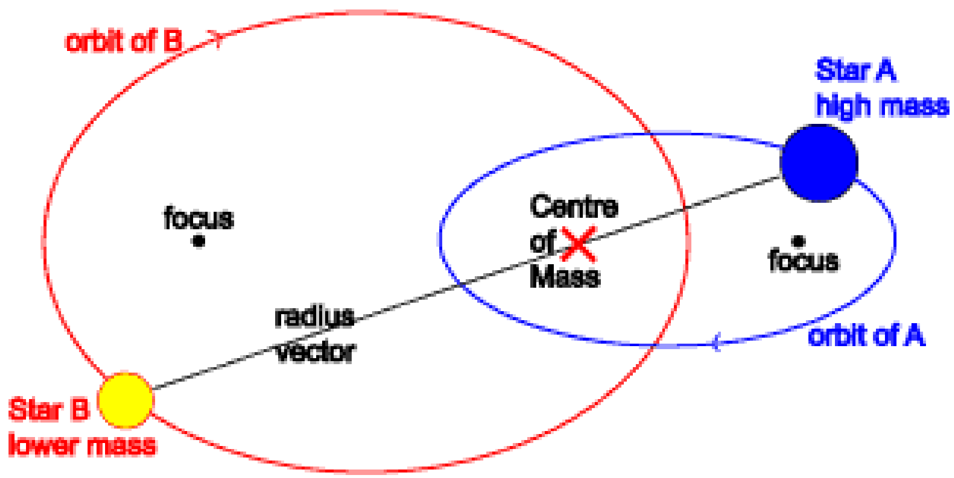
Di-Star Dynamics

Hamiltonian Mechanics of an Isolated Di-Star System
Mass Asymmetry as a Collective Variable

$$H(\vec{r}_1, \vec{p}_1, \vec{r}_2, \vec{p}_2, M_1, M_2)_{|M=M_1+M_2} = H_{cm}(\vec{P}_{cm}, M) + H_{12}(\vec{R}, \vec{P}, \eta)$$

$$\eta = \frac{M_1 - M_2}{M}; \quad \mu(\eta) = \frac{M_1 M_2}{M} = \frac{1}{4} M\left(1-\eta^2\right)$$

…plus dependencies on stellar shapes, sizes, spins, and temperatures.



Total Energy of a Binary System in the Barycentric Frame

(V.V. Sargsyan et al., Int.J.Mod.Phys. E271850063 (2018))

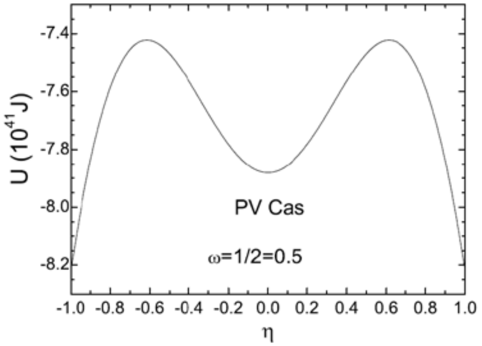
$$E = \frac{P_R^2}{2\mu} + U_1 + U_2 + V$$

Grav. kin. Radiat.

$$U_i = U_i^g + U_i^k + U_i^r \qquad U_i^r = \frac{\pi^2 V_i (kT_i)^4}{15(\hbar c)^3}$$

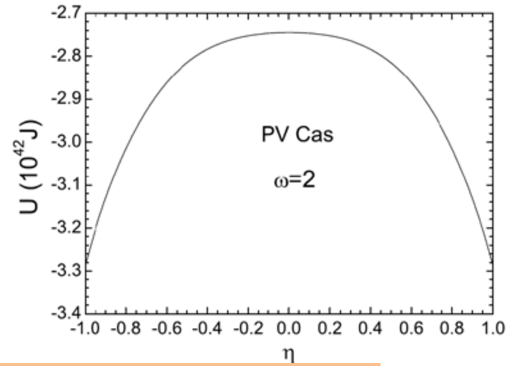
Mechanical Equilibrium ↔ Virial Theorem

$$U_i^g + 2U_i^k = 0. \quad \longleftrightarrow \quad U_i^g + U_i^k = -\omega_i \frac{GM_i^2}{2R_i} \qquad R_i = g_i M_i^{m_i}$$



Stellar EoS → Structural Factor:

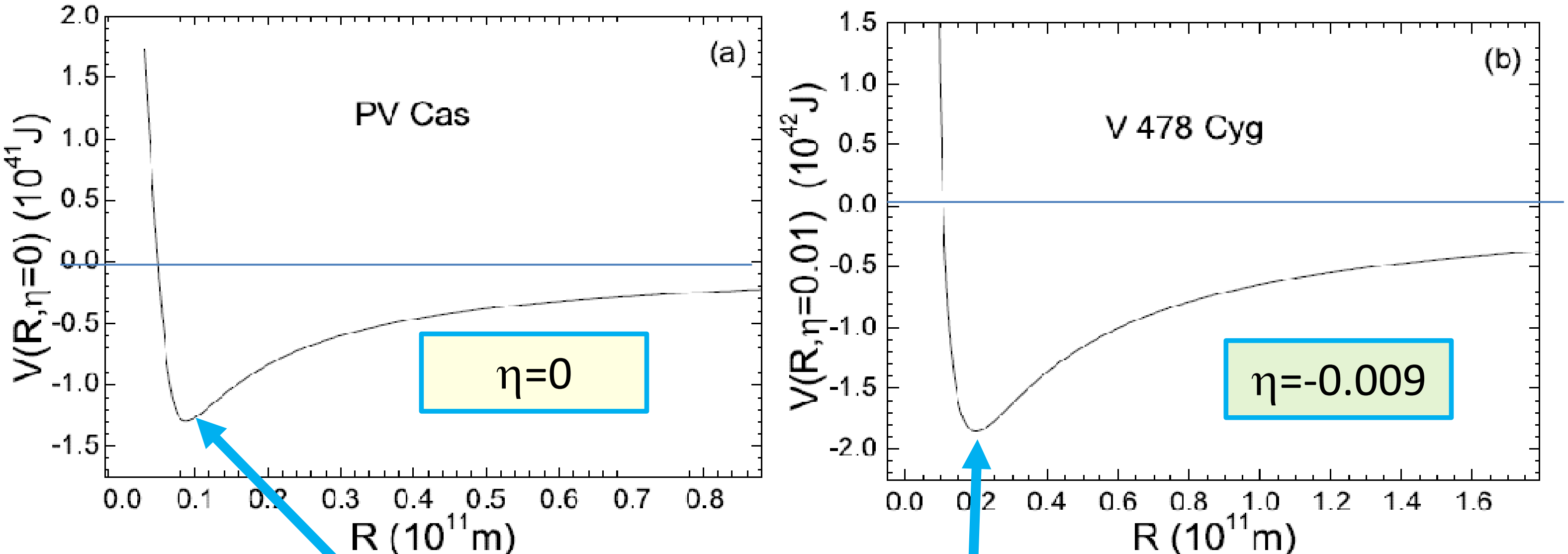
$\omega_i \geq 1/2$



EoS of main sequence stars ~ polytropes of order $3/2 \leq n \leq 3$ → $6/7 \leq \omega \leq 2$
Compact objects e.g. neutron star → $\omega \sim 0.6$

Di-Star Interaction Energies

$$V(R) = -\frac{GM_1M_2}{R} + \frac{L^2}{2\mu R^2},$$



The star-star interaction potentials for the di-stars PV Cas ($M_1 = M_2 = 2.79M_\odot$, $R_1 = R_2 = 2.264R_\odot$, $T_1 = T_2 = 11200$ K) and V 478 Cyg ($M_1 = 16.30M_\odot$, $M_2 = 16.60M_\odot$, $R_1 = R_2 = 7.422R_\odot$, $T_1 = T_2 = 29800$ K) vs R.

$$R_m = \frac{16L^2}{GM^3}\frac{1}{(1-\eta^2)^2}$$

Mass Asymmetry in Di-Stars

Constraints on Stability by Mass Asymmetry

$$\eta = \frac{M_1 - M_2}{M_1 + M_2} \quad \rightarrow \quad M_{1,2} = M\,\frac{1}{2}(1 \pm \eta)$$

U= U_1 +U_2+V in Compact Form

$$U = -\frac{G}{2}[\alpha\{(1+\eta)^{4/3} + (1-\eta)^{4/3}\} + \beta(1-\eta^2)^3] + 2\gamma(kT)^4[1+\eta^2],$$

$$\alpha = \frac{\omega M^{4/3}}{2^{4/3} g}, \quad \beta = \frac{GM^5}{64L^2}, \quad \gamma = \frac{\pi^3 g^3 M^2}{45(\hbar c)^3}$$

Shape Parameter | **Rotational Parameter** | **Thermal Parameter**

Conserved Total Energy

$$E = \frac{P_R^2}{2\mu} + U$$

...treating η as dynamical collective degree of freddom:

$$dE(\mathbf{R}, \mathbf{P}, \eta) = \frac{\partial E}{\partial t} dt + \frac{\partial E}{\partial \mathbf{R}} d\mathbf{R} + \frac{\partial E}{\partial \mathbf{P}} d\mathbf{P} + \frac{\partial E}{\partial \eta} d\eta.$$

...and for ∂E/∂t=0:

$$\frac{dE}{dt} = 0 \quad \leftrightarrow \quad \frac{\partial E}{\partial \eta}\frac{d\eta}{dt} = 0 \quad \leftrightarrow \quad \frac{\partial E}{\partial \eta} = 0$$

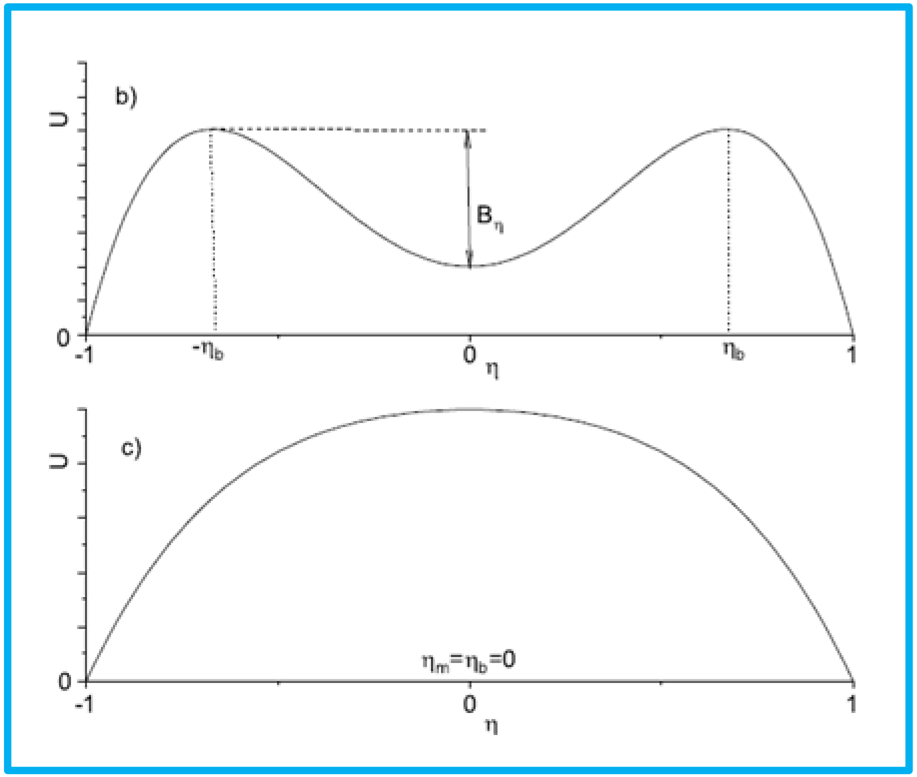
...where the last relation denotes the general solution.

NOTE: P_R=0 if the system moves on a fixed orbit → E=U !

Di-Star Potential Energy – Fixed Point Analysis

$$\frac{\partial U}{\partial \eta} = -\frac{G}{2}\left[\frac{4}{3}\alpha\{(1+\eta)^{1/3}-(1-\eta)^{1/3}\}-6\beta\eta(1-\eta^2)^2\right]+4\gamma(kT)^4\eta = 0$$

…seen to be solved trivially for $\eta=\eta_m=0$:



Minimum @ $\eta=0$:

$$\frac{4}{9}\alpha < 3\beta + \frac{4}{G}\gamma(kT)^4$$

Barriers @ $|\eta| = \eta_b$

→ no merger

Maximum @ $\eta=0$:

$$\frac{4}{9}\alpha > 3\beta + \frac{4}{G}\gamma(kT)^4.$$

→ merger

Contact Di-Stars and Mergers

When do Di-stars merge?

…happens for values of the „EoS“ paramter $\alpha > \alpha_{cr}$ when $U(\eta=0)$ develops a maximum, i.e. $\eta_b \rightarrow 0$:

$$\alpha_{\rm cr} = \frac{9}{4}\left[3\beta + \frac{4}{G}\gamma(kT)^4\right] = \frac{9}{4}\left[\frac{3GM^5}{64L^2} + \frac{4}{G}\gamma(kT)^4\right]$$

Stability region:

$$0 < \eta_b < 2^{-1/2}$$

Instability region – $\eta > 2^{-1/2}$:

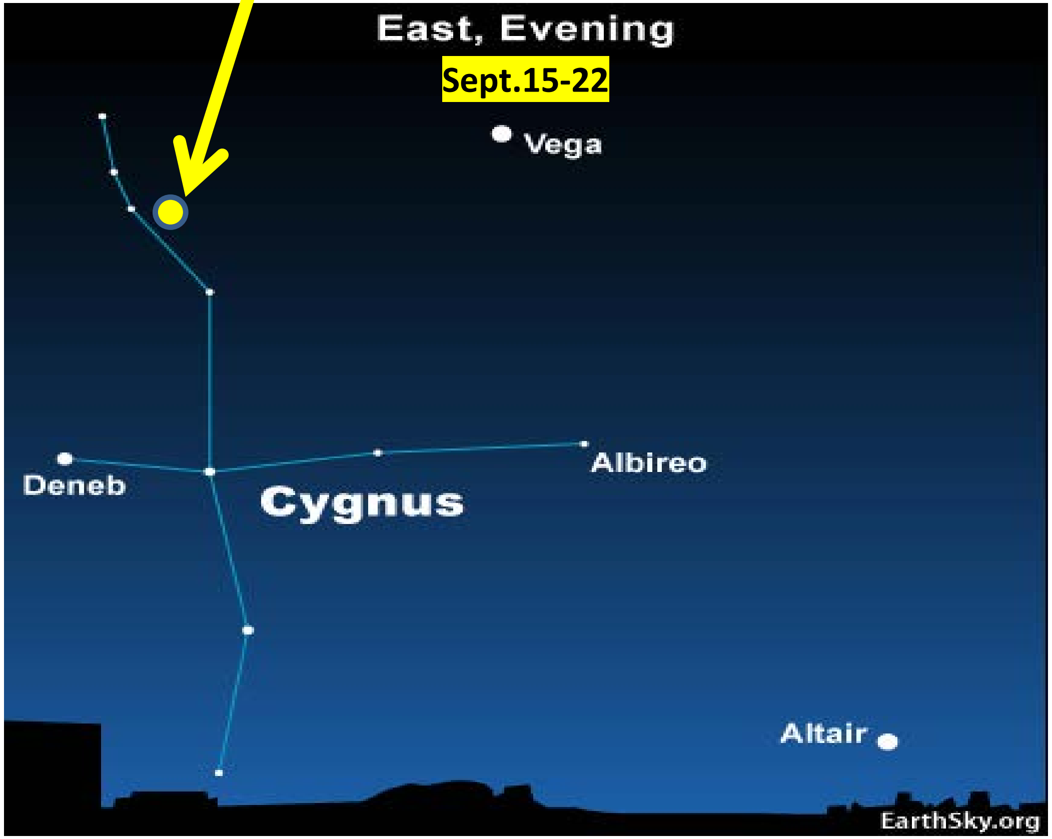
$$M_1/M_2 > (1+2^{1/2})^2 \approx 5.83$$

→ An initially asymmetric binary system ($|\eta| = |\eta_i| < \eta_b$) is driven to mass symmetry ($\eta = 0$), implying a flow of mass towards equilibrium

The contact binary KIC 9832227

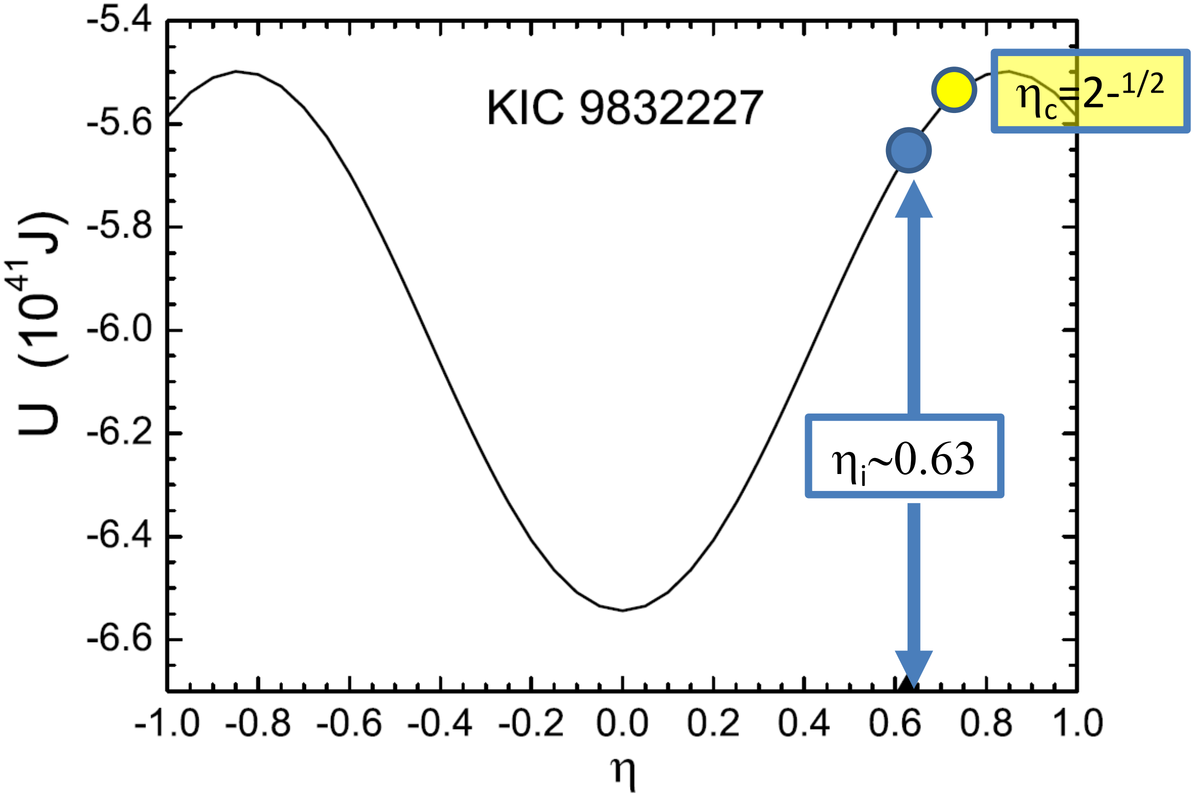
	A
Mass	1.395 $M_{\odot}$
Radius	1.581 $R_{\odot}$
Luminosity	2.609 $L_{\odot}$
Surface gravity (log *g*)	4.19 cgs
Temperature	5800 K
Rotational velocity	149.7 km/s

	B
Mass	0.318 $M_{\odot}$
Radius	0.830 $R_{\odot}$
Luminosity	0.789 $L_{\odot}$
Surface gravity (log *g*)	4.10 cgs
Temperature	5920 K
Rotational velocity	84.7 km/s



- LRN predicted by Molnar et al. (AAS Meeting Jan. 2017/ApJ 840:1 (2017))
- If so → First time chance to observe the progenitor of a LRN,
  → confirming the hypothesis of Soker and Tylenda (2003)
- One post-merger observation: V1309 Scorpii in 2008 (OGLE)
- Rare event: estimated 1-10 LRN/a out of the 200 billion stars in the Milky Way
- Metzger et al. (2017): Merger is unlikely

Our Prediction for KIC 9832227



- **KIC 9832227 merger is excluded: $\eta_i<2^{-1/2} = 0.717...$**
- **System driven towards mass symmetry**
- **Mass exchange oscillations around $\eta=0$**
- **Energy release during symmetrization: $\Delta E \cong \Delta U \sim 10^{41}J = 10^{48}erg$**
- **Merger ruled out by new data (**Socia *et al.*, *Ap.J.* **864** (2018) L32**)**
- **Kovacs et al., arXiv:1909.00255: it's a triple system!**

Binary Galaxies

Binary Galaxy Mergers

Merger in Progress: Binary Mice Galaxies (NGC 4676 A&B)

Mass-Radius Relation for (isolated) Di-Galaxies:

$$R_{Glx} = gM^{n}_{Glx} \quad ; \quad g = \frac{\left(R_1^{1/n} + R_2^{1/n}\right)^n}{(M_1 + M_2)^n} \quad ; \quad n \in \left[\frac{2}{5}, \frac{2}{3}\right]$$

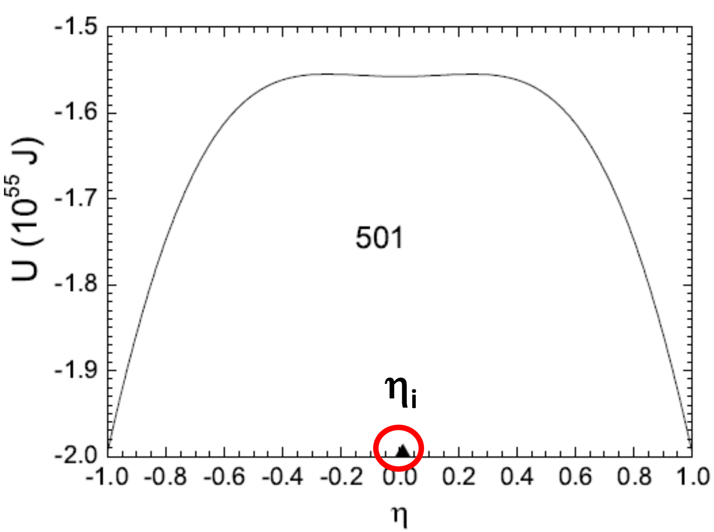
→ Int.J.Mod.Phys. E28: 1950031 (2019)

Total Potential Energy of a Binary Galaxy

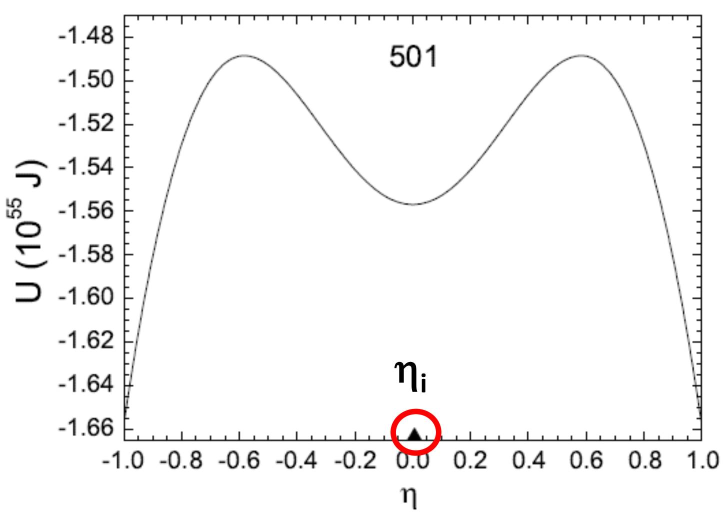
$$U = -\alpha[(1+\eta)^{2-n} + (1-\eta)^{2-n}] - \beta[1-\eta^2]^3,$$

$$\alpha = \frac{Gg}{2}\left(\frac{M}{2}\right)^{2-n} \qquad \beta = \frac{GM^2}{128}\frac{(R_{1i}^{1/n} + R_{2i}^{1/n})^4}{R_{mi}R_{1i}^{2/n}R_{2i}^{2/n}}.$$

Di-galaxy	Ty	$\frac{M}{M_\odot}$	X (kpc)	$2R_{1i}$ (kpc)	$2R_{2i}$ (kpc)	$\lvert\eta_i\rvert$	η_b
501	E-E	1.05×10^{13}	38.3	36.0	35.7	0.01	0.25



n= 2/5 → Merger



n= 2/3 → Symmetrization

Galactical Collision

(Visualization by ESO)

Summary and Conclusions

- **Newtonian dynamics of di-stars.**
- **Mass asymmetry η treated as adiabatic variable.**
- **Di-stars evolve towards mass symmetry for $|\eta|<2^{-1/2}$.**
- **Mergers of binary galaxies: shape determines fate**
- **What's next?: Dissipation, neutron stars…**

V.V. Sargsyan (AvH fellow@GI), H. L., G.G. Adamian, N.V. Antonenko

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