Structure and Cooling of Compact Stars obeying Modern Constraints

David Blaschke (Wroclaw University, JINR Dubna)
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PSR J1614-2230
M=(1.97+/−0.04) M_\text{sun}

Demorest et al., Nature (2010)
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Facets of Strong Interaction Physics, Hirschegg, January 17, 2012

Neutron star in SNR Cas A
Fast cooling directly observed

Ho & Heinke, Nature (2009)
Structure and Cooling of Compact Stars obeying Modern Constraints

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Thanks to ‘cool’ coauthors: Hovik Grigorian, Fridolin Weber, Dima Voskresensky and ‘dense’ ones: Thomas Klaehn, Rafał Lastowiecki, Fredrik Sandin, Daniel Zablocki

Facets of Strong Interaction Physics, Hirschegg, January 17, 2012
PSR J1614-2230 - A new constraint for the Compact Star EoS

- NS-WD binary in Scorpius
- NS is recycled MSP with $P = 3.15$ ms
- almost edge-on, inclination $89.17^\circ$
- Shapiro delay measured!
- $M_{WD} \sim 0.5 \, M_\odot$
- $M_{NS} = (1.97 \pm 0.04) \, M_\odot$
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State-of-the-art hybrid EoS model:

- Chiral symmetry restoration
- Color superconductivity
- Vector meanfield “stiffening”

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- Chiral symmetry restoration
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Constraints from heavy-ion collisions:
- Flow constraint at high densities
- Not too early onset of quark matter

QCD phase diagram

Klähn et al., PLB (2007), arxiv:1101.6061

Phenomenological Quark Matter EoS:

$$\Omega_{QM} = -\frac{3}{4\pi} a_4 \mu^4 + \frac{3}{4\pi^2} a_2 \mu^2 + B_{\text{eff}}$$

If the critical density for chiral restoration/deconfinement is reached in the compact star core, then $M_{1614} = 1.97 \pm 0.04$ $M_\odot$ implies the following:

- Quark matter is strongly interacting, QCD corrections ($a_4$) important
- Quark matter is color superconducting: $a_2 \leq 0$
Constraints from PSR J1614-2230 for Quark Matter EoS


Phenomenological Quark Matter EoS:

\[
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- Quark matter is color superconducting: \( a_2 \leq 0 \)

L. Bonanno & A. Sedrakian, 1108.0559 (2011)
T. Klahn et al., 1111.6889; R. Lastowiecki et al. (in preparation)
Extreme States of Matter - The Phase Diagram

Partition function as a Path Integral (imaginary time $\tau = i t$)

$$Z[T, V, \mu] = \int D\bar{\psi} D\psi \exp \left\{ - \int_0^\beta d\tau \int_V d^3 x [\bar{\psi}(i\gamma^\mu \partial_\mu - m - \gamma^0(\mu + \lambda_3 \phi_3) + \gamma^0(\mu + \lambda_8 \phi_8 + i\lambda_3 \phi_3) \psi - \mathcal{L}_{\text{int}} + U(\Phi)] \right\}$$

Polyakov loop: $\Phi = N_c^{-1} \text{Tr}_c[\exp(i\beta \lambda_3 \phi_3)]$ Order parameter for deconfinement

Current-current interaction (4-Fermion coupling) and KMT determinant interaction

$$\mathcal{L}_{\text{int}} = \sum_{M=M_{\pi,\rho,\ldots}} G_M (\bar{\psi} \Gamma_M \psi)^2 + \sum_D G_D (\bar{\psi}^D \Gamma_D \psi)^2 - K[\det_\text{f}(\bar{q}(1 + \gamma_5)q) + \det_\text{f}(\bar{q}(1 - \gamma_5)q)]$$

Bosonization (Hubbard-Stratonovich Transformation)

$$Z[T, V, \mu] = \int D\Delta_M D\Delta_\Delta e^{-\sum_{M,D} \frac{\Delta_M^2}{4G_M} - \frac{\Delta_\Delta^2}{4G_D} + \frac{1}{2} \text{Tr} \ln S^{-1}[\{M_M\},\{\Delta_D\},\Phi] + U(\Phi) + \gamma_{\text{KMT}}}$$

Collective quark fields: Mesons ($M_M$) and Diquarks ($\Delta_D$); Gluon mean field: $\Phi$

Systematic evaluation: Mean fields + Fluctuations

- Mean-field approximation: order parameters for phase transitions (gap equations)
- Lowest order fluctuations: hadronic correlations (bound & scattering states)
- Higher order fluctuations: hadron-hadron interactions
NJL Model for Neutral 3-Flavor Quark Matter

Thermodynamic Potential $\Omega(T, \mu) = -T \ln Z[T, \mu]$

$$\Omega(T, \mu) = \frac{\phi_u^2 + \phi_d^2 + \phi_s^2}{8G_S} + \frac{|\Delta_{ud}|^2 + |\Delta_{us}|^2 + |\Delta_{ds}|^2}{4G_D} + \frac{K(\phi_u + \phi_d + \phi_s)}{16G_S^3} - \frac{(\mu^* - \mu)^2}{4G_V}$$

$$- T \sum_n \int \frac{d^3 p}{(2\pi)^3} \frac{1}{2} \text{Tr} \ln \left( \frac{1}{T} S^{-1}(i\omega_n, \vec{p}) \right) + U(\Phi) + \Omega_e - \Omega_0.$$ 

Inverse Nambu–Goldstone Propagator $S^{-1}(i\omega_n, \vec{p}) = \left[ \begin{array}{cc} \gamma_\mu p^\mu - M(\vec{p}) + \mu \gamma^0 & \tilde{\Lambda}(\vec{p}) \\ \tilde{\Lambda}^\dagger(\vec{p}) & \gamma_\mu p^\mu - M(\vec{p}) - \mu \gamma^0 \end{array} \right].$

Fermion Determinant $(\text{Tr} \ln D = \ln \det D)$:

$$\ln \text{det} \left[ \begin{array}{cc} \beta S^{-1}(i\omega_n, \vec{p}) \end{array} \right] = 2 \sum_{a=1}^{18} \ln \left\{ \beta^2 \left[ \omega_n^2 + \lambda_a(\vec{p})^2 \right] \right\}.$$ 

Result for the thermodynamic Potential (Meanfield approximation)

$$\Omega(T, \mu) = \frac{\phi_u^2 + \phi_d^2 + \phi_s^2}{8G_S} + \frac{|\Delta_{ud}|^2 + |\Delta_{us}|^2 + |\Delta_{ds}|^2}{4G_D} + \frac{K(\phi_u + \phi_d + \phi_s)}{16G_S^3} - \frac{(\mu^* - \mu)^2}{4G_V}$$

$$- \int \frac{d^3 p}{(2\pi)^3} \sum_{a=1}^{18} \left[ \lambda_a + 2T \ln \left( 1 + e^{-\lambda_a/T} \right) \right] + U(\Phi) + \Omega_e - \Omega_0.$$ 

Color and electric charge neutrality constraints: $n_Q = n_3 = n_3 = 0$, $n_\xi = -\partial \Omega / \partial \mu_\xi = 0$.

Equations of state: $P = -\Omega$, etc.
PHASES OF QCD @ EXTREMES: NO COLOR NEUTRALITY
Phase Diagram for Symmetric Matter (HIC)

- Critical density for chiral restoration $n_\chi \geq 1.5 \ n_0$ increasing (!) with low T
- Almost crossover (masquerade!), i.e. small density jump, small latent heat/time delay in heavy-ion coll.
- High $T_c \approx 0.9 T_d$ for 2SC phase due to Polyakov loop.
- 2SC - CFL phase transition at $n \geq 6 \ n_0$ with density jump and latent heat/time delay! Provided the temperature can be kept low $T \leq 100 \text{ MeV}$


Exploring the QCD Phase Diagram: Trajectories

Heavy-Ion Collisions:

- URQMD
- $b=0$
- $b=0.5$ fm/c
- Mixed phase: RMF-2SC PNJL
- $\eta_s=0$, $\eta_V=0.25$

Supernova Explosions (15 $M_\odot$):


Liebendoerfer et al. (2005)
Sagert et al., PRL 102 (2009)

Fischer et al., arxiv: 1103.3004
Mass - radius constraints from quiescent LMXB's and RXJ 1856 $\Rightarrow$ Small AND large stars?
NJL with KMT allows for mass twins! Direct transition DBHF-CFL possible!

Flow constraint $\Rightarrow$ PT not too early! No direct DBHF-CFL trans.!

**HYBRID-EoS robust? Role of KMT det - Twins!**

- Mass - radius constraints from quiescent LMXB's and RXJ 1856 \(\Rightarrow\) Small AND large stars? NJL with KMT allows for mass twins! Direct transition DBHF-CFL possible!
  - Flow constraint \(\Rightarrow\) PT not too early! No direct DBHF-CFL trans.!

Covariant, nonlocal interaction model:

\[ \mathcal{L}_{\text{int}} = - \int d^4x \left\{ \frac{G_S f_S}{2} j_S^f(x) j_S^f(x) + \frac{H}{2} [j_B^o(x)]^\dagger j_B^o(x) + \frac{G_V}{2} j_V^o(x) j_V^o(x) \right\} \]

Nonlocal currents, e.g.

\[ j_S^f(x) = \int d^4z \ g(z) \ \bar{\psi}(x + \frac{z}{2}) \Gamma_f \psi(x - \frac{z}{2}) , \]


Recent developments: Radzhabov et al., arxiv:1012.0664; Horvatic et al., arxiv:1012.2113
Hybrid-EoS Robust? Constraints & Covariant NCQM

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Large Mass ($\sim 2 \, M_\odot$) and radius ($R \geq 12 \, \text{km}$) $\Rightarrow$ stiff EoS;

Flow in Heavy-Ion Collisions $\Rightarrow$ not too stiff EoS!

Sandin et al., CompOSE project (2009-10); See also: Klähn, D.B., Sandin, Fuchs, Faessler, Grigorian, Röpke, Trümper, PLB 654, 170 (2007)
**Mass-Radius Constraint and Flow Constraint**

- Large Mass ($\sim 2 \, M_\odot$) and radius ($R \geq 12 \, \text{km}$) $\Rightarrow$ stiff EoS;
- Flow in Heavy-ion Collisions $\Rightarrow$ not too stiff EoS!

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Implications from PSR J1614-2230 within 3fCS NJL – DBHF model


If hybrid star, Then:
- 2SC QM
- Vector MF
- HIC: \( n_c \sim 4n_0 \)

If no hybrid star, then:
- small (<0.85) diquark coupl.
- HIC: \( n_c > 4.5n_0 \)
Same hybrid model (3fCS NJL – DBHF), smaller chiral condensate (quark mass)

R. Lastowiecki et al., in preparation

If hybrid star, Then:
- 2SC QM
- Vector MF
- HIC: $n_c \sim 2-3 \times n_0$

If no hybrid star, then:
- small ($<0.85$) diquark coupl.
- HIC: $n_c > 2 \times n_0$
The question of hyperons ... ... and quark-hyperon hybrids

- Hyperonic matter without strange vector meson repulsion → too soft; Demorest constraint failed
- Inclusion of phi-meson repulsion → OK
- Phase transition: “masquerade” problem ...
- Density dependence of gluon sector (bag)!

Lastowiecki et al., 1112.6430 [nucl-th]
Exploring hybrid star matter at NICA & FAIR

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(2) Joint Institute for Nuclear Research, Dubna
(3) Department of Physics, San Diego State University, USA

Heavy-Ion Collisions

- stiff EoS (at flow limit)
- low $n_{\text{crit}}$ (at NICA fixT)
- soft EoS (dashed line)

Compact Stars

- high $M_{\text{max}}$ (J1614-2230)
- low $M_{\text{onset}}$ (all NS hybrid)
- excluded (J1614-2230)

Proposal:

1. Measure transverse and elliptic flow for a wide range of energies (densities) at NICA and perform Danielewicz's flow data analysis ---> constrain stiffness of high density EoS
2. Provide lower bound for onset of mixed phase ---> constrain QM onset in hybrid stars

Conclusions I

- PSR 1614-2230 ("Demorest-pulsar") puts strong constraints to dense matter EoS
- Both alternatives for the inner structure, hadronic and hybrid star, are viable for the Demorest pulsar; HIC favors hybrid model
- If Demorest pulsar has a quark matter (QM)core, then QM must:
  - be color superconducting
  - have a strong (vector-field) repulsion
  - occur at >2 $n_0$ in HIC, depending on $\langle \bar{q}q \rangle$
- Discriminating test? Measure M-R relation !!
Neutron Star in Cassiopeia A (Cas A)

- 16.08.1680 John Flamsteed
  - 6m star 3 Cas
- 1947 re-discovery in radio
- 1950 optical counterpart
  - $T \sim 30 \text{ MK}$
  - $V_{\text{exp}} \sim 4000 - 6000 \text{ km/s}$
- distance 11.000 ly = 3.4 kpc

picture: spitzer space telescope


Page, Prakash, Lattimer, Steiner, PRL (2011); arxiv:1011.6142

Shternin, Yakovlev, Heinke, Ho, Patnaude, MNRAS (2011); arxiv:1012.0045

Cas A Cooling Observations

Cas A is a rapidly cooling star – Temperature drop ~4% in 10 years

Cas A Cooling Observations
The influence of the (core) heat conductivity


Phase Diagram & Cooling Simulation

- Description of the stellar matter - local properties
- Modeling of the self bound compact star - including the gravitational field
- Extrapolations of the energy loss mechanisms to higher densities and temperatures
- Consistency of the approaches
Cooling Mechanism

\[ \frac{dU}{dt} = \sum_i C_i \frac{dT}{dt} = -\varepsilon_\gamma - \sum_j \varepsilon_j^i \]

Cooling Processes

- **Direct Urca:** \( n \rightarrow p + e + \bar{\nu}_e \)
- **Modified Urca:** \( n + n \rightarrow n + p + e + \bar{\nu}_e \)
- **Photons:** \( \rightarrow \gamma \)
- **Bremsstrahlung:** \( n + n \rightarrow n + n + \nu + \bar{\nu} \)
Cooling Evolution

The energy flux per unit time $l(r)$ through a spherical slice at distance $r$ from the center is:

$$l(r) = -4\pi r^2 k(r) \frac{\partial (Te^\Phi)}{\partial r} e^{-\Phi} \sqrt{1 - \frac{2M}{r}}.$$

The equations for energy balance and thermal energy transport are:

$$\frac{\partial}{\partial N_B} (le^{2\Phi}) = -\frac{1}{n} (\epsilon_\nu e^{2\Phi} + c_V \frac{\partial}{\partial t} (Te^\Phi))$$

$$\frac{\partial}{\partial N_B} (Te^\Phi) = -\frac{1}{k} \frac{le^\Phi}{16\pi^2 r^4 n}$$

where $n = n(r)$ is the baryon number density, $NB = NB(r)$ is the total baryon number in the sphere with radius $r$

$$\frac{\partial N_B}{\partial r} = 4\pi r^2 n (1 - \frac{2M}{r})^{-1/2}$$

F. Weber: Pulsars as Astro. Labs ... (1999);
Neutrino Emissivities in Quark Matter

- Quark direct Urca (QDU) the most efficient process

\[ d \rightarrow u + e + \bar{\nu} \quad \text{and} \quad u + e \rightarrow d + \nu \]

\[ \epsilon_{\nu}^{QDU} \approx 9.4 \times 10^{26} \alpha_s Y_e^{1/3} \zeta_{QDU} T_9^6 \text{ erg cm}^{-3} \text{ s}^{-1}, \]

Compression \( n/n_0 \approx 2 \), strong coupling \( \alpha_s \approx 1 \)

- Quark Modified Urca (QMU) and Quark Bremsstrahlung

\[ d + q \rightarrow u + q + e + \bar{\nu} \quad \text{and} \quad q_1 + q_2 \rightarrow q_1 + q_2 + \nu + \bar{\nu} \]

\[ \epsilon_{\nu}^{QMU} \approx \epsilon_{\nu}^{QB} \approx 9.0 \times 10^{19} \zeta_{QMU} T_9^8 \text{ erg cm}^{-3} \text{ s}^{-1}. \]

- Suppression due to the pairing

\[ \overset{\text{QDU}}{\zeta_{QDU}} \sim \exp(-\Delta_q/T) \]

\[ \overset{\text{QMU} \; \text{and} \; \text{QB}}{\zeta_{QMU}} \sim \exp(-2\Delta_q/T) \; \text{for} \; T < T_{\text{crit},q} \approx 0.57 \Delta_q \]

- Enhanced cooling due to the pairing

\[ e^+ e^- \rightarrow e^+ e^- \nu^+ \bar{\nu} \] (becomes important for \( \Delta_q/T >> 1 \))

\[ \epsilon_{\nu}^{ee} = 2.8 \times 10^{12} Y_e^{1/3} u^{1/3} T_9^8 \text{ erg cm}^{-3} \text{ s}^{-1}, \]

Quark PBF
Surface Temperature & Age Data
Crust Model

Time dependence of the light element contents in the crust

\[ \Delta M_L(t) = e^{-t/\tau} \Delta M_L(0) \]


DU constraint

\[ n \rightarrow p + e + \bar{\nu}_e \text{ implies } p_n \leq p_p + p_e, \text{ charge neutrality results in} \]

\[
x_{DU}(x_e) \geq \frac{1}{1 + (1 + x_e^{1/3})^3}
\]

\[ x_e = n_e/(n_e + n_\mu) \]

⇒ no muons: \[ x_{DU} = 11.1\% \]

⇒ relativistic limit \((n_e = n_\mu)\): \[ x_{DU} = 14.8\% \]

\[ \text{NL}_\rho, \text{NL}_\rho \delta, \text{DBHF}: \]
DU occurs below \(2.5n_0\)
DU Thresholds

DU critical densities

\[ n_c = 2.7 \, n_0 \quad \text{NLW (RMF)} \]

\[ n_c = 5.0 \, n_0 \quad \text{HHJ (APR)} \]

DU critical masses

\[ M_c = 1.25 \, \text{M}_{\odot} \quad \text{NLW} \]

\[ M_c = 1.84 \, \text{M}_{\odot} \quad \text{HHJ} \]
DU problem & constraint
SC pairing gaps – hybrid stars

2SC phase: 1 color (blue) is unpaired (mixed superconductivity)
Ansatz  2SC + X phase:

\[ \Delta_0^X = \Delta_0 \exp \left( \alpha \left( \frac{\mu - \mu_c}{\mu_c} \right) \right) \]

<table>
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<th>Model</th>
<th>( \Delta_0 ) [MeV]</th>
<th>( \alpha )</th>
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<td>I</td>
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<td>IV</td>
<td>5</td>
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</tr>
</tbody>
</table>

Grigorian, DB, Voskresensky , PRC 71 (2005) 045801

Pairing gaps for hadronic phase (AV18 - Takatsuka et al. (2004))

SC pairing gaps – hybrid stars

Popov, Grigorian, Blaschke, PRC 74 (2006)
Influence of SC on luminosity

Critical temperature $T_c$, for the proton $^1S_0$ and neutron $^3P_2$ gaps, used in

$T_c$ ‘measurement’ from Cas A

- 1.4 M⊙ star built from the APR EoS
- Rapid cooling at ages $\sim$30-100 yrs due to the thermal relaxation of the crust
- Mass dependence

Medium effects in cooling of neutron stars

- Based on Fermi liquid theory: Landau (1956), Migdal (1967), Migdal et al. (1990)
- MMU – instead of MU
- PBF – fast cooling process for $T < T_c$

\[
\epsilon_{\nu}[\text{MpPBF}] \sim 10^{29} \frac{m^*_N}{m_N} \left[ \frac{p_{Fp}}{p_{Fn}(n_0)} \right] \left[ \frac{\Delta_{pp}}{\text{MeV}} \right]^7 \\
\times \left[ \frac{T}{\Delta_{pp}} \right]^{1/2} \xi_{pp}^2 \frac{\text{erg}}{\text{cm}^3 \text{sec}}, \ T < T_{cp}.
\]

\[
\frac{\epsilon_{\nu}[\text{MMU}]}{\epsilon_{\nu}[\text{MU}]} \sim 10^3 \left( \frac{n}{n_0} \right)^{10/3} \frac{\Gamma^6(n)}{[\omega^*(n)/m_\pi]^8},
\]

\[
\omega^*(n) = \frac{\omega^*(n_0)}{m_\pi} (1 - \Gamma) + \Gamma \frac{n}{n_0} (\xi_{pp} - 1) + \frac{n}{n_0} \xi_{pp} (1 - \Gamma) - \frac{n}{n_0} \xi_{pp} (1 - \Gamma).
\]
Anomalies because of PBF process

AV18 gaps, pi-condensate, without suppression of 3P2 neutron pairing - Enhanced PBF process

Gaps taken from Yakovlev at al. (2003)


The influence of the (core) heat conductivity

The influence of the (core) heat conductivity

Cas A as a Hadronic Star – arxiv:1108.4125

Evolution of T - profiles

Partial contributions to L

Pion Urca? See in 10 - 50 years!
Quark matter in compact stars: Cooling constraint

- Neutrinos carry energy off the star, Cooling evolution (schematic) by

$$\frac{dT(t)}{dt} = -\frac{\epsilon_\gamma + \sum_{j=Urca,\ldots} e_j^j}{\sum_{i=q,e,\gamma,\ldots} c_V^i}$$

- Most efficient process: Urca

- Exponential suppression by pairing gaps! $\Delta \sim 10\ldots100$ keV

Popov et al: Neutron star cooling constraints ...
PRC 74, 025803 (2006); [nucl-th/0512098]
Temperature in the Hybrid Star Interior

HYBRID STAR COOLING WITH 2SC QUARK MATTER (III)

2SC + X phase, $\Delta_0 = 5$ MeV, $\alpha = 25$
Temperature-age and Vela mass OK


Log N - Log S test passed
Cas A as an Hybrid Star
Cas A as Hybrid Star: T-profile evolution

M=1.707 M_{sun}
Hybrid: APR + 2SCX

```
M = 1.707 M_{sun}
Hybrid: APR + 2SCX
```
Conclusions II

- Cas A rapid cooling consistently described by the nuclear medium cooling model as a “first drop”, delayed by low conductivity
- Both alternatives for the inner structure, hadronic and hybrid star, are viable for Cas A; a higher star mass favors the hybrid model
- In contrast to the minimal cooling scenario, our approach is sensitive to the star mass and thermal conductivity of superfluid star core matter
- Discriminating test? Log N – Log S!?! (??)
It's cool to be a CompStar member!
Upcoming School and Conference ... 

48th Karpacz Winter School of Theoretical Physics

Cosmic Matter in Heavy-Ion Collision Laboratories

Lądek-Zdrój, Poland. February 4-11, 2012

Lecturers
J.-P. Blaizot (Saclay):
Matter under extreme conditions
W. Florkowski (Cracow):
Ultrarelativistic heavy-ion collisions
M. Gaździcki (Frankfurt/Kielce):
Energy scan programs in HIC
P. Haensel (Warsaw):
Dense matter and compact stars
G. Martinez-Pinedo (Darmstadt):
Supernovae and the origin of heavy elements
H. Satz (Bielefeld):
Analysis of matter in QCD

Local Organizers
L. Turko (Wroclaw)
D. Blaschke (Wroclaw & Dubna)
K. Redlich (Wroclaw)
A. Wergieluk (Wroclaw)
R. Łastowiecki (Wroclaw)

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CompStar: the physics and astrophysics of compact stars
Tahiti, June 4-8, 2012

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Thanks for Your attention!

Research ...

... is gong on!