

Searching for Strangelets and Macro-SQM Candidates from Neutron Stars, Binary Mergers, and Gamma-Ray Bursts Multimessenger Constraints and Direct-Detection Prospects

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Next Frontiers in Magnetic Monopole Searches

Institute of High Energy Physics, CAS, Beijing, China

Monday 14 September 2026, 09:30 A.M.

Outline of the Talk

1 Motivation.

Why strange quark matter (SQM) is a compelling idea for the true ground state of dense QCD.

2 Theoretical framework.

The $2SC \rightarrow CFL$ phase transition, strangelet production, and the relevant cross-sections.

3 Observational strategy.

Monochromatic γ -ray lines from strangelet–anti-strangelet annihilation.

4 Three case studies.

- HESS J1731-347 — a strange quark star (SQS) candidate.
- GW170817 — the first binary neutron-star merger.
- GRB 250702B — an ultra-long gamma-ray burst.

5 Direct searches for macro-scale SQM.

Nuclearites, Q-balls, and current/future limits.

6 Summary and outlook.

Motivation: Why Strange Quark Matter?

The Bodmer–Witten–Terazawa hypothesis

Ordinary hadronic matter (nuclei, neutron stars) may *not* be the true ground state of QCD. If strange quark matter (SQM) — a phase with roughly equal numbers of up, down, and strange quarks — has a lower energy per baryon, then:

- neutron stars could convert to **strange quark stars (SQSs)**;
- stable clusters called **strangelets** could be produced in dense QCD phase transitions;
- the released energy ($\sim 10^{53}$ erg) would be comparable to a supernova.

Observational consequences

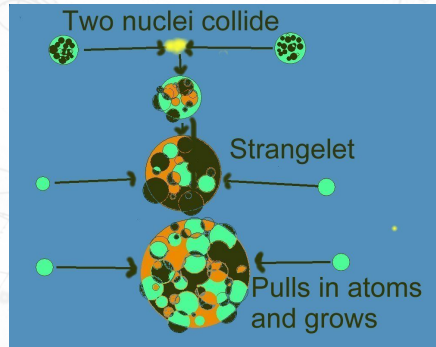
- **Monochromatic γ -ray lines** from strangelet–anti-strangelet annihilation are a direct signature.
- **Anomalous compact objects** such as HESS J1731-347 may be SQSs.
- **Direct detection** of macroscopic SQM objects (nuclearites, Q-balls) would be complementary.

No strangelets have yet been detected. Multimessenger observations with next-generation instruments may change this.

What Is a Strangelet?

A **strangelet** is a hypothetical stable cluster of **strange quark matter (SQM)**, a phase consisting of roughly equal numbers of **up**, **down**, and **strange quarks**.

- **Mass number** A (also called **baryon number**) = one third of the total quark number.
- **Charge number** Z = net electric charge in units of the elementary charge e .
- Predicted mass-to-charge ratios: $30\text{--}60 \text{ GeV}/c^2$ for $A \sim 100\text{--}10^5$.



Strangelets Are Predicted to Be Stable

A. Stable macroscopic quark matter

The most extreme possibility is that macroscopic quark matter is bound and stable at zero temperature and pressure. At first sight, one might think that this is excluded by the fact that ordinary nuclei do not spontaneously turn into the hypothetical dense quark state. This is not quite so, however. Observations of nuclear physics only show that in the absence of strange quarks, nuclear matter is more stable than quark matter. A density of strangeness does not help stabilize nuclear matter, because strange baryons are heavier than nonstrange baryons. For quark matter, the story is different. (This point has been noted before in Refs. 19 and 26.) The likely Fermi momentum in quark matter is 300–350 MeV, more than the strange-quark mass, so it is energetically favored for some of the nonstrange quarks to become strange quarks, lowering the Fermi momentum and the energy.

Edward Witten

But there is one conspicuous astrophysical environment in which quark matter can readily form and grow. This is the neutron star. It may be that when neutron stars form they already contain a small nucleus of quark matter of cosmological or cosmic-ray origin. Even if no nucleus of quark matter is present to begin with, it is very likely that the pressure at the center of a neutron star is so large that in that region quark matter will form spontaneously even without strangeness. (If three-flavor quark matter is stable at zero pressure, then two-flavor quark matter is relatively close to being stable even at zero pressure and is probably stable under the high pressure in the center of a neutron star.) One way or another, neutron stars almost surely contain a quark-matter component.

Once a quark-matter component is present in a neutron star, two things will rapidly happen. It will quickly develop the equilibrium strangeness content via weak interactions, such as $ud \rightarrow us$. The energy will be lowered as strange quarks are created one by one until equilibrium is reached. Even more important, the quark-matter com-

Strange matter, stable in bulk, may also come in small chunks for which surface effects are important and which are too small to support an electron gas within. We call these chunks of strange matter “strangelets.” These systems with baryon numbers lower than (very roughly) 10^7 are studied in Sec. III. However, we leave $A \leq 10^2$ to Sec. IV. We discuss the origin and effect of a surface tension and find that strange matter stable in bulk may be unbound for small enough baryon number. We also discuss the charge that develops on strangelets and finally how these charged systems neutralize themselves, like ordinary nuclei, by accumulating electron (or perhaps positron) clouds.

Edward Farhi and R. L. Jaffe

The Original Stability Arguments

The **Bodmer–Witten–Terazawa hypothesis** proposes that SQM is the true ground state of **quantum chromodynamics (QCD)** at high baryon density. Foundational and recent references:

- A. R. Bodmer, *Collapsed nuclei*, Phys. Rev. D **4**, 1601 (1971).
- E. Witten, *Cosmic separation of phases*, Phys. Rev. D **30**, 272 (1984).
- E. Farhi and R. L. Jaffe, *Strange matter*, Phys. Rev. D **30**, 2379 (1984).
- C. Alcock and E. Farhi, *Evaporation of strange matter in the early universe*, Phys. Rev. D **32**, 1273 (1985).
- J. Madsen, H. Heiselberg and K. Riisager, *Does strange matter evaporate in the early universe?*, Phys. Rev. D **34**, 2947 (1986).
- F. Weber, *Strange quark matter and compact stars*, Prog. Part. Nucl. Phys. **54**, 193 (2005).
- H.-S. You et al., *Strangelets at finite temperature: Nucleon emission rates, interface, and shell effects*, Phys. Rev. D **109**, 034003 (2024).
- F. Di Clemente, A. Drago and G. Pagliara, *Strange Dwarfs: A review on the (in)stability*, Universe **10**, 322 (2024).
- F. Di Clemente et al., *Strange quark matter as dark matter: 40 yr later, a reappraisal*, MNRAS **537**, 1056 (2025).
- G. Cao, *Extended Nambu–Jona-Lasinio model for quark and nuclear matters*, Phys. Lett. B **860**, 139140 (2025).
- F. Köpp et al., *Repulsive vector couplings and massive strange stars*, Astron. Nachr. **346**, e20240119 (2025).

Low- A , Negatively Charged Strangelets as a Danger

Hypothetically, a negatively charged strangelet could catalyse the conversion of ordinary matter into SQM. Foundational and recent references:

- C. Greiner, P. Koch and H. Stöcker, *Separation of strangeness from antistrangeness in the phase transition from quark to hadron matter: Possible formation of strange quark matter in heavy-ion collisions*, Phys. Rev. Lett. **58**, 1825 (1987).
- A. Kent, *Problems with empirical bounds for strangelet production at RHIC*, arXiv:hep-ph/0009130.
- R. L. Jaffe et al., *Review of speculative “disaster scenarios” at RHIC*, Rev. Mod. Phys. **72**, 1125 (2000).
- J. Madsen, *Intermediate mass strangelets are positively charged*, Phys. Rev. Lett. **85**, 4687 (2000).
- J. Madsen, *Strangelet propagation and cosmic ray flux*, Phys. Rev. D **71**, 014026 (2005).
- J. Madsen, *Universal charge-radius relation for subatomic and astrophysical compact objects*, Phys. Rev. Lett. **100**, 151102 (2008).
- S. Biswas et al., *Multifragmentation model for astrophysical strangelets*, Phys. Lett. B **715**, 30 (2012).
- M. Guerrini et al., *Role of thermal fluctuations in nucleation of three-flavor quark matter*, Universe **11**, 258 (2025).
- C. R. Das, *Finding strangelets in cosmic rays from HESS J1731-347*, Phys. Atom. Nuclei **88**, 1142 (2025); arXiv:2507.12817.

Existing Experimental Constraints

If stable and negatively charged strangelets existed, they would be observable in cosmic rays and at colliders. None have been discovered. Key references:

- A. Chodos et al., *A new extended model of hadrons*, Phys. Rev. D **9**, 3471 (1974).
- S. Ahlen et al., *Search for nuclearites using the MACRO detector*, Phys. Rev. Lett. **69**, 1860 (1992).
- K. Borer et al., *Strangelet search in S-W collisions at 200A GeV/c*, Phys. Rev. Lett. **72**, 1415 (1994).
- G. Appelquist et al., *Strangelet Search in Pb-Pb Interactions at 158 GeV/c per Nucleon*, Phys. Rev. Lett. **76**, 3907 (1996).
- A. L. S. Angelis and A. D. Panagiotou, *CASTOR: A dedicated detector for the detection of centauros and strangelets at the LHC*, J. Phys. G: Nucl. Part. Phys. **23**, 2069 (1997).
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- J. Madsen, *Strangelets, nuclearites, Q-balls — a brief overview*, arXiv:astro-ph/0612740.
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- J. Ellis et al., *Review of the safety of LHC collisions*, J. Phys. G: Nucl. Part. Phys. **35**, 115004 (2008).
- O. Adriani et al. (PAMELA Collaboration), Phys. Rev. Lett. **115**, 111101 (2015).
- S. Kasuya, M. Kawasaki and T. T. Yanagida, *IceCube potential for detecting Q-ball dark matter in gauge mediation*, Prog. Theor. Exp. Phys. **2015**(5), 053B02 (2015).
- A. Albert et al. (The ANTARES Collaboration), JCAP **2023**, 012 (2023).
- M. Bianchi et al., *Search for strange quark matter and nuclearites on board the International Space Station (SQM-ISS): A future detector to search for massive, non-relativistic objects in space*, Sensors **24**, 5090 (2024).

Instruments Referenced in This Talk

Table: Ground-based and space-based instruments used to constrain strangelet signatures.

Acronym	Full name	Role
H.E.S.S.	High Energy Stereoscopic System	Ground-based Cherenkov array in Namibia; observed HESS J1731-347.
Fermi-LAT	Fermi Large Area Telescope	Space-based γ -ray telescope; GeV constraints.
Fermi-GBM	Fermi Gamma-ray Burst Monitor	Space-based all-sky monitor of GRBs.
MAGIC-II	Major Atmospheric Gamma Imaging Cherenkov telescopes	Ground-based Cherenkov array on La Palma.
VERITAS	Very Energetic Radiation Imaging Telescope Array System	Ground-based Cherenkov array in Arizona.
CTA / CTAO	Cherenkov Telescope Array / Observatory	Next-generation Cherenkov array; tenfold improvement over H.E.S.S.
LHAASO	Large High Altitude Air Shower Observatory	Ground-based EAS array in Tibet.

Summary of Key Constraints

1 Experimental limits.

- No strangelets detected in accelerators (NA52, fixed-target) or cosmic rays.
- PAMELA covers $A \sim 10\text{--}1.2 \times 10^5$ (Adriani et al. 2015).
- MACRO's nuclearite search (Ahlen et al. 1992) covers the **mass** range $10^{-10} < m < 0.1$ g, which corresponds to $A \sim 6 \times 10^{13}\text{--}6 \times 10^{22}$ (i.e. $A \sim 10^{14}\text{--}10^{23}$ for $m_N \approx 0.94$ GeV/ c^2).

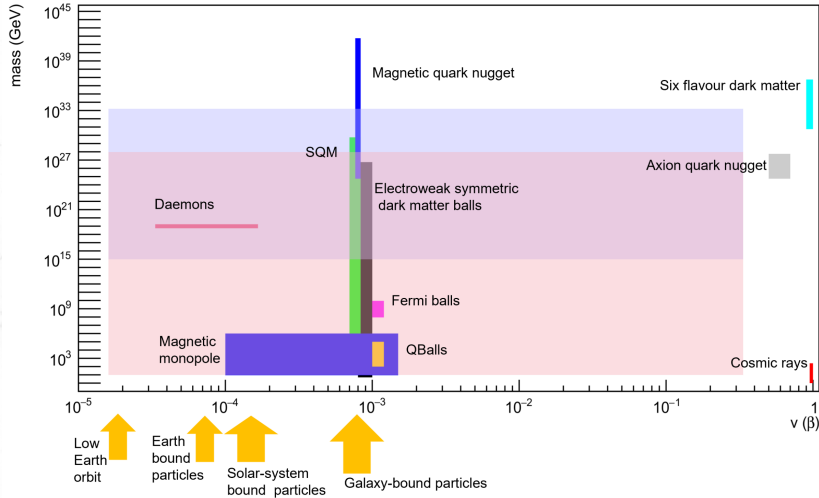
2 Astronomical limits.

- No evidence of strange matter in neutron stars.
Strangelet–anti-strangelet annihilation may produce γ rays
($S\tilde{S} \rightarrow \gamma\gamma$, $\tilde{S}$ = anti-strangelet).
- No confirmed strangelet impact events on Earth or Solar System bodies.

3 Theoretical stability.

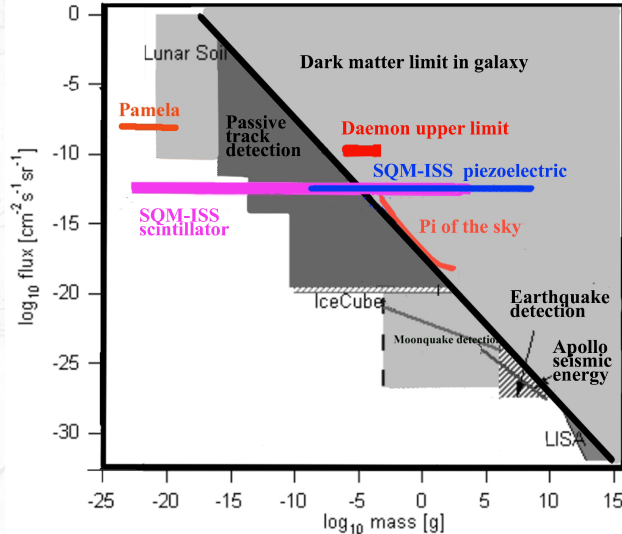
- Minimum stable baryon number $A_{\min} \sim 50\text{--}200$, depending on $B^{1/4}$ and n_A .
- NJL model: shallow, metastable bound states with $\sim 40\%$ strange-quark content for $G_V/G_S \approx 0.5\text{--}1.0$.
- Both MIT bag and NJL predict $m_S/|Z| \sim 30\text{--}60$ GeV/ c^2 for $A \sim 100\text{--}10^5$.

Strange Quark Matter (SQM) in Cosmic Rays



Velocity–mass range for hypothetical slow-moving, heavy particles. “Slow-moving” $\rightarrow$ non-relativistic or sub-relativistic; “heavy” $\rightarrow$ masses far exceeding nuclear masses.

Current Upper Bounds on SQM in Cosmic Rays



Current upper bounds on SQM searches as a function of presumed mass.

Strangelet Formation Mechanisms

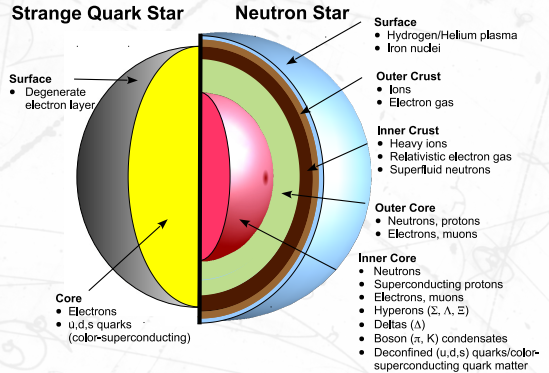
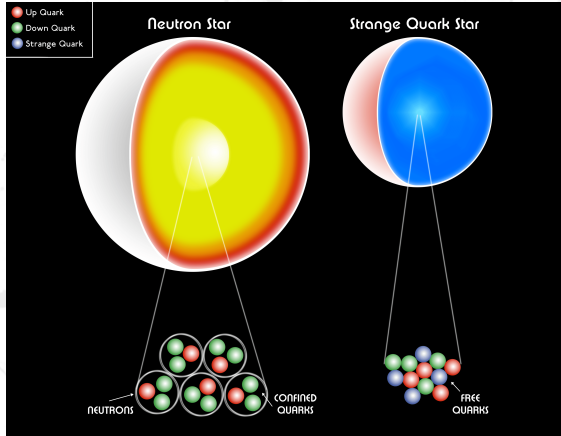
Several mechanisms can produce strangelets during the $2SC \rightarrow CFL$ phase transition:

- **Diquark condensates** (Cooper pairs of quarks) coagulate and fuse when strange quarks become involved in pairing.
- **Fragmentation** related to altering the **Fermi surfaces** during the transition.
- **Surface emission of quark clusters** from neutron-star cores under appropriate pressure and density.

Strangelet–anti-strangelet annihilation ($S\bar{S} \rightarrow \text{hadrons} \rightarrow \gamma$) could result in monochromatic γ rays.

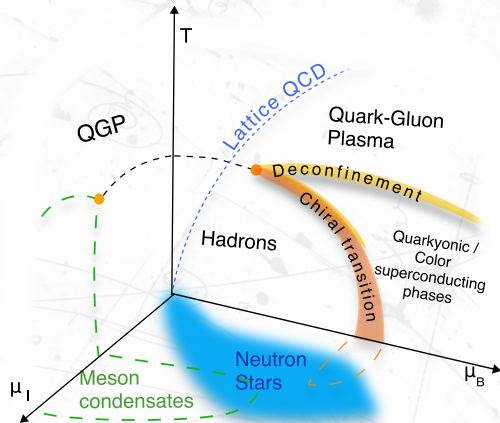
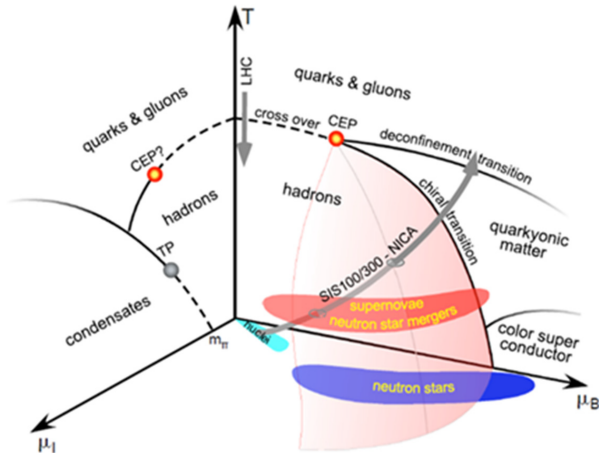
Detecting γ -ray fingerprints from HESS J1731-347 (neutron star), GW170817 (merger), or GRB 250702B would prove the existence of strangelets.

Strange Stars



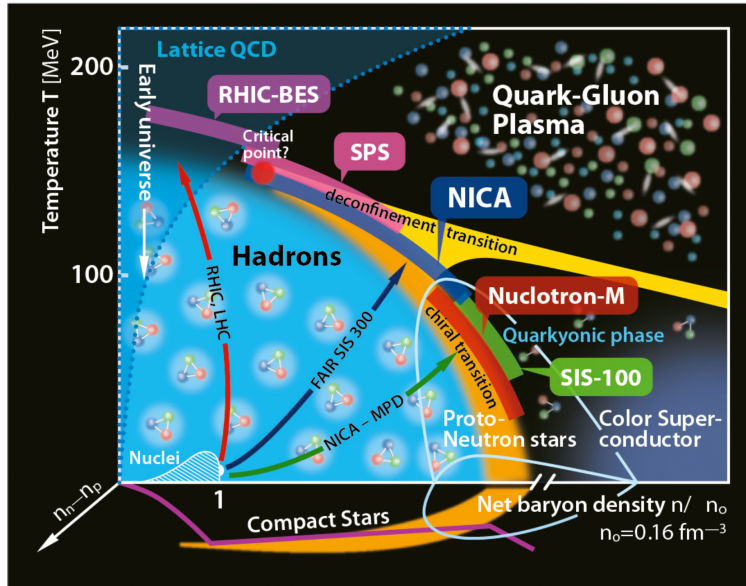
A **strange star** is a compact star whose interior is composed entirely of SQM, in contrast to a conventional neutron star whose interior is mainly neutrons.

The Colour-Flavour-Locked (CFL) Phase

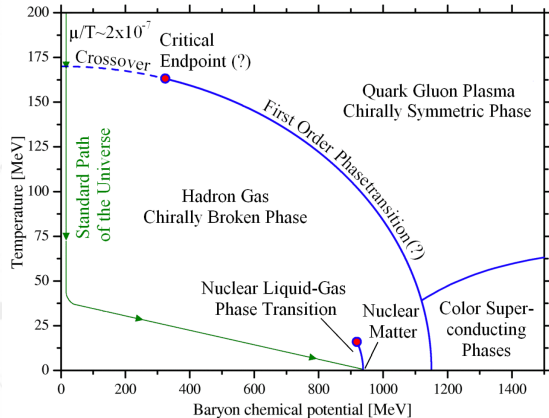


QCD phase diagram in the space of temperature T , **baryon-chemical potential** μ_B , and **isospin-chemical potential** μ_I .

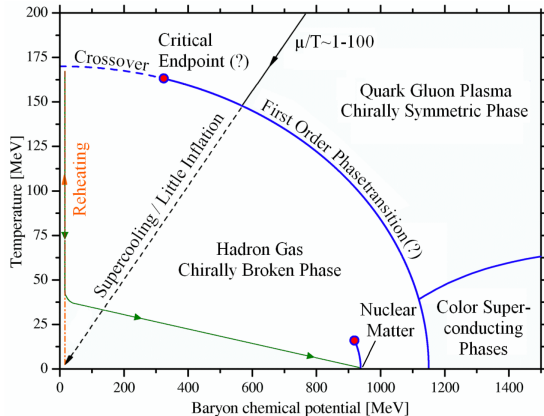
The CFL Phase: Matter Composition



The CFL Phase in Cosmology



(a)



(b)

Hypothetical QCD phase diagram:

(a) the universe's conventional evolution path;

(b) evolution path in the case of cosmic phase separation.

The 2SC and CFL Phases in Dense QCD

In **extremely dense quark matter**, quarks can form **Cooper pairs**, leading to **colour superconductivity**.

Two key phases:

- 1 **2SC (Two-Flavour Colour-Superconducting)**: pairing of up and down quarks only.

Order parameter

$$\Delta_{2SC} \propto \langle \psi^T(x) C \gamma_5 \tau_2 \lambda_2 \psi(x) \rangle \neq 0,$$

with ψ the quark field, $C = i\gamma_2\gamma_0$ the **charge conjugation** matrix, τ_2 the second **Pauli matrix** in flavour space, and λ_2 the second **Gell-Mann matrix** in colour space. Occurs when $\delta\mu = (\mu_d - \mu_u)/2 < \Delta_{2SC}/2$.

- 2 **CFL (Colour-Flavour-Locked)**: pairing of all three flavours; colour and flavour indices are “locked”. Characterised by the gap Δ_{CFL} , typically larger than Δ_{2SC} .

Transition Conditions and Strangelet Production

The **transition rate per unit volume and time** from 2SC to CFL is dominated by thermal activation:

$$\Gamma_{2\text{SC} \rightarrow \text{CFL}}^{\text{base}} = \frac{T^4}{\pi^3} \exp\left(-\frac{\delta E}{T}\right),$$

where T is the **temperature** and δE the **activation energy barrier**.

The strangelet production rate $\dot{N}(A)$ (units s^{-1}):

$$\dot{N}(A) = \dot{N}_{\text{peak}} \left(\frac{A}{A_{\text{peak}}}\right)^{2/3} \exp\left[\frac{2}{3}\left(1 - \frac{A}{A_{\text{peak}}}\right)\right],$$

with $\dot{N}_{\text{peak}}$ the **peak production rate** and A_{peak} the **baryon number at the maximum**. The $(A/A_{\text{peak}})^{2/3}$ factor reflects geometric growth; the exponential factor reflects combined **multifragmentation** and **coalescence** suppression.

Key Parameters for the 2SC $\rightarrow$ CFL Transition

Table: Parameters governing the 2SC $\rightarrow$ CFL phase transition.

Parameter	Symbol	Typical range	Description
2SC gap	$\Delta_{2\text{SC}}$	10–100 MeV	Pairing energy in the 2SC phase
CFL gap	Δ_{CFL}	15–150 MeV	Pairing energy in the CFL phase
Strange-quark mass	m_s	80–120 MeV	Current mass of the strange quark
Chemical potential	μ	400–500 MeV	Energy to add a quark
Bag constant	$B^{1/4}$	145–170 MeV	QCD vacuum-energy density scale
Vector/scalar coupling	G_V/G_S	0.5–1.0	Vector vs. scalar quark–antiquark coupling

Cross-Section Formalism for Strangelet Interactions

The **strangelet–nucleon cross-section** σ_S follows from effective QCD field theory for high-density systems:

$$\sigma_S = \sigma_0 \left(\frac{A}{100} \right)^{2/3} \left(\frac{\Delta_{2SC}}{\mu} \right)^{1.5} \exp \left(-2.0 \frac{m_s^2}{\mu^2} \right) f(\theta),$$

where $\sigma_0 \sim 1$ mb is a **reference cross-section**, Δ_{2SC} the two-flavour colour-superconducting gap, μ the quark chemical potential, m_s the strange-quark mass, and $f(\theta)$ the angular dependence on the **scattering angle** θ .

Why this form?

- $(A/100)^{2/3}$: geometrical area of a strangelet of size $R \propto A^{1/3}$.
- $(\Delta_{2SC}/\mu)^{1.5}$: superconducting gap enhances the effective cross-section.
- $\exp(-2.0 m_s^2/\mu^2)$: suppression from the finite strange-quark mass.

Specific Cross-Section: Neutrino–Strangelet

$$\frac{d\sigma_{\nu S}}{d\cos\theta} = \frac{G_F^2 \mu^2}{4\pi} \left[C_V^2(1 + \cos\theta) + C_A^2(3 - \cos\theta) \right] \left(\frac{\Delta_{\text{CFL}}}{\Delta_{2\text{SC}}} \right)^{1/2} \xi(T),$$

where G_F is the **Fermi coupling constant** ($\approx 1.17 \times 10^{-5} \text{ GeV}^{-2}$), C_V , C_A are the **vector** and **axial-vector** couplings, θ the **scattering angle**, and $\xi(T)$ a **temperature-dependent damping factor**:

$$\xi(T) = 1 - \left(\frac{T}{\Delta_{\text{CFL}}} \right)^2 \in [0, 1].$$

Annihilation Signatures in γ -Ray Spectra

For a point-like source at distance D , the photon flux at Earth is

$$\Phi_{\gamma} = \frac{2 R_{\text{ann}}}{4\pi D^2},$$

where R_{ann} is the **total annihilation rate** (s^{-1}), D the **distance** (cm), and the factor of 2 accounts for the two photons produced in $S\bar{S} \rightarrow \gamma\gamma$.

The velocity-averaged annihilation cross-section:

$$\langle \sigma_{\text{ann}} v \rangle = \frac{\pi}{m_S^2} (a + b T) \exp\left(-\frac{E_a}{T}\right),$$

with m_S the **strangelet mass**, $a \sim 1$ the **s-wave coefficient**, $b \sim 1/m_S$ the **p-wave coefficient**, and E_a an **activation energy**. A conservative value $\langle \sigma v \rangle \sim 10^{-25} \text{ cm}^3 \text{ s}^{-1}$ is adopted.

Strangelet Mass-to-Charge Ratio

$$\frac{m_s}{|Z|} \approx \frac{m_N}{Y_Q} \left[1 + \frac{2}{9\pi} \left(\frac{\mu}{m_s} \right) - \frac{1}{3} \left(\frac{\Delta_{\text{CFL}}}{\mu} \right)^{1/2} \right],$$

with the **charge fraction** Y_Q parametrically suppressed by $(m_s/\mu)^2$, since near-equal up, down, and strange quark numbers give nearly zero net charge:

$$Y_Q = \frac{Z}{A} \sim \frac{m_s^2}{\mu^2} \approx 0.02\text{--}0.03.$$

- $m_N \approx 0.94 \text{ GeV}/c^2$ is the **nucleon mass**.
- MIT-bag calculations give $Y_Q \approx 0.02\text{--}0.03$ for the parameter range adopted here ($\mu \approx 450 \text{ MeV}$, $m_s \approx 100 \text{ MeV}$).
- Typical: $m/|Z| \sim 30\text{--}60 \text{ GeV}/c^2$ for $A \sim 100\text{--}10^5$.

Colour factors: $N_c = 3$, with the colour factor absorbed into G_D .

Summary of Numerical Parameters

Table: Fixed physics parameters used throughout the paper.

Parameter	Symbol	Value
Chemical potential	μ	450 MeV
CFL gap	Δ_{CFL}	100 MeV
2SC gap	Δ_{2SC}	50 MeV
Strange-quark mass	m_s	100 MeV
Temperature	T	1 MeV
Energy per baryon	ϵ	30 MeV
Core radius	R_{core}	10 km
Production volume	V_{core}	$4 \times 10^{18} \text{ cm}^3$
Accumulation volume	V_{source}	$1.23 \times 10^{59} \text{ cm}^3$
Accumulation time	τ_{acc}	10^6 yr

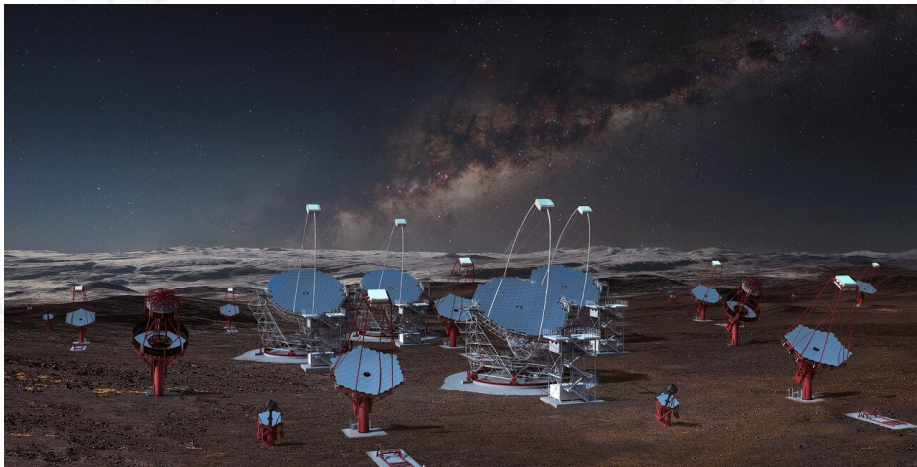
Scenario Parameters for the Production Rate

Table: Scenario parameters for the phenomenological production rate. The peak rate increases monotonically from left to right, and the peak position shifts to larger A .

Parameter	Conservative	Baseline	Optimistic
A_{peak}	10^5	10^6	10^7
$\dot{N}_{\text{peak}} \text{ (s}^{-1}\text{)}$	10^{42}	10^{47}	10^{52}

The tabulated values already include the effective efficiency factor $\eta \sim 10^{-20}$ defined via $\dot{N}_{\text{peak}} = \Gamma^{\text{base}} V_{\text{core}} \eta$.

The Cherenkov Telescope Array (CTA / CTAO)



The **Cherenkov Telescope Array** is the next-generation ground-based observatory for very-high-energy (VHE) γ rays (energies above ~ 100 GeV), detecting Cherenkov light from atmospheric showers.

HESS J1731-347: A Strange Quark Star Candidate

The object: A central compact object in the supernova remnant HESS J1731-347.

Key measurements:

$$M = 0.77_{-0.17}^{+0.20} M_{\odot}, \quad R = 10.4_{-0.78}^{+0.86} \text{ km}$$

Why it matters for strangelets:

- These low mass and radius values are **challenging for standard neutron-star models**, suggesting it could be a **strange quark star** or a hybrid star with deconfined quark matter.
- If it is a strange quark star, the transition from the 2SC to the CFL phase in its interior can **release strangelets** into the surrounding environment.
- The remnant is one of the few Galactic sources capable of accelerating hadronic cosmic rays to TeV energies, providing a **continuous injection** channel for strangelets.

Search strategy

Future Cherenkov Telescope Array (CTA) observations can search for **gamma-ray signatures** of strangelet annihilation or decay in the cosmic rays from this remnant.

Key advantage

Persistent source → steady strangelet flux, easier to model and detect than transient events.

GW170817: A Binary Neutron-Star Merger

The event: The first multimessenger binary neutron-star merger, at ~ 40 Mpc.

Why it matters for strangelets:

- The merger remnant undergoes a **hadron-to-quark transition**, releasing $\sim 10^{53}$ erg and potentially forming strangelets during the process.
- Strangelets can be produced via collisions of nuclear fragments or through a **quark nova** that ejects strange quark matter.
- The burst-like nature produces a **short-lived enhancement** in the strangelet flux, distinct from continuous sources.
- Lack of VHE emission in GW170817 constrains the geometry (jets may be off-axis), but future CTA can probe fainter signals.

Production channel

Binary mergers are a **transient factory** for strangelets, complementing steady sources like HESS J1731-347.

Key advantage

Known distance and energetics $\rightarrow$ allows quantitative predictions for the expected strangelet flux at Earth.

GRB 250702B: An Ultra-long Gamma-Ray Burst

The event: An ultra-long gamma-ray burst with a prompt duration $> 25,000$ s (rest-frame).

Why it matters for strangelets:

- Its extreme duration and energetics ($E_{\text{iso}} > 1.4 \times 10^{54}$ erg) point to an **exotic progenitor**, such as a micro-tidal disruption event or a precessing jet.
- Such extreme conditions may favor the **formation and ejection of strangelets** from the central engine.
- The long duration provides a **prolonged window** for strangelet production and escape, making it a unique laboratory for probing quark-matter formation.

Production channel

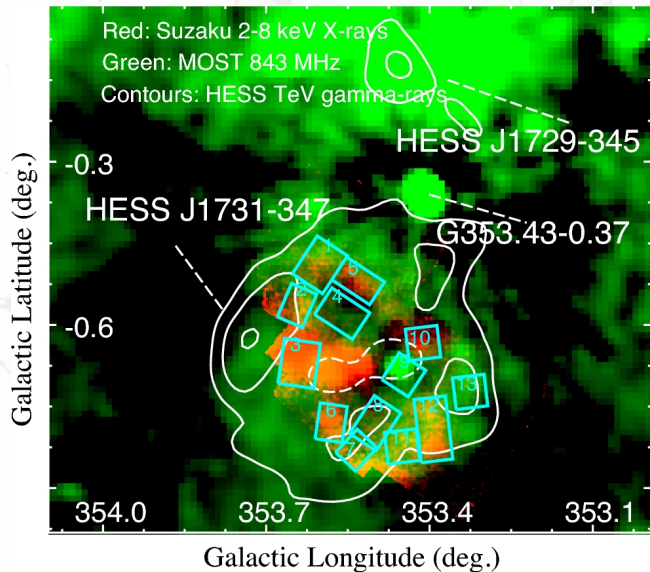
Ultra-long GRBs represent a **burst-driven** channel for strangelet production, distinct from steady and merger-driven sources.

Key advantage

Extreme conditions → potentially higher strangelet yields, making detection more feasible.

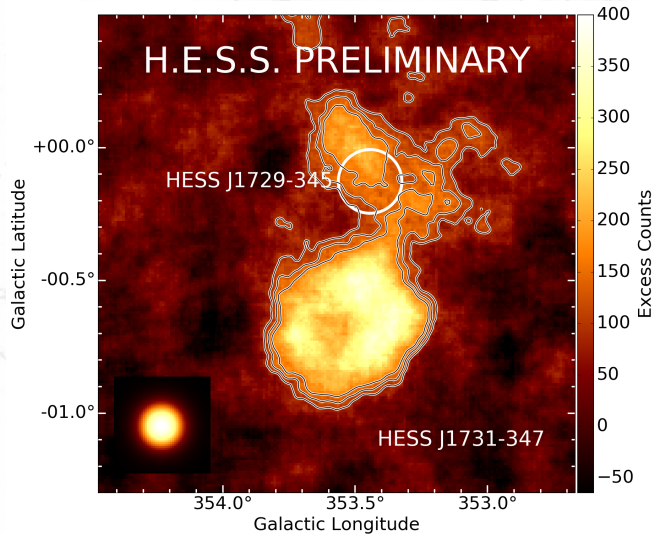
Combined power: these three objects cover **continuous, merger-driven, and burst-driven** strangelet production channels.

Case Study 1: HESS J1731-347 — Multiwavelength View



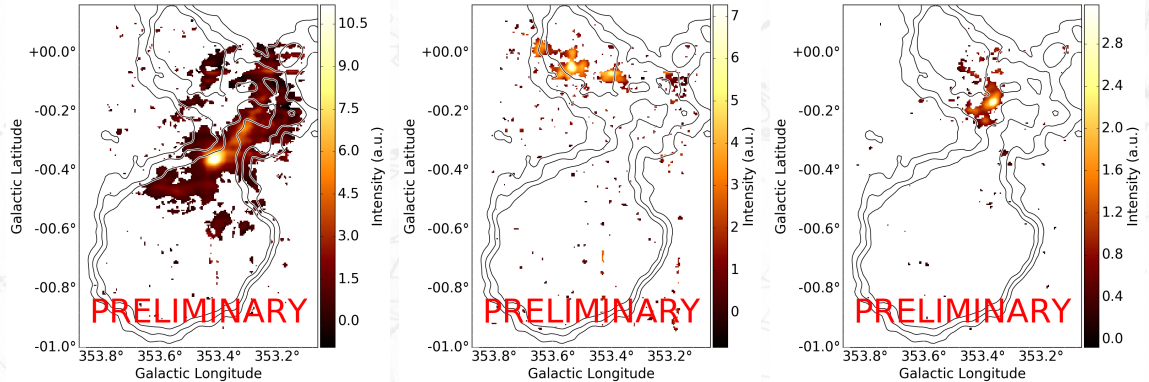
Suzaku 2–8 keV X-ray emission (red);
843 MHz radio continuum (green);
H.E.S.S. >1 TeV contours ($4, 6, 8\sigma$).
An **H II region** is a cloud of ionised
hydrogen.

HESS J1731-347: γ -Ray Morphology



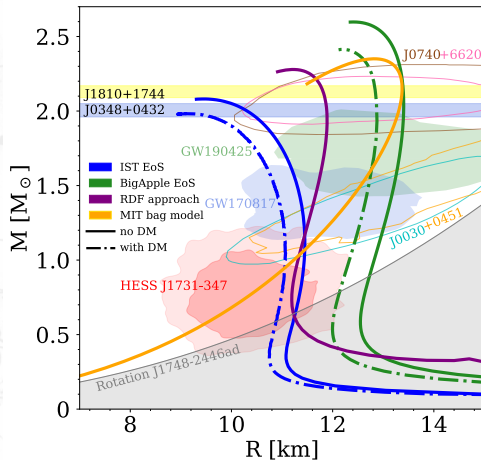
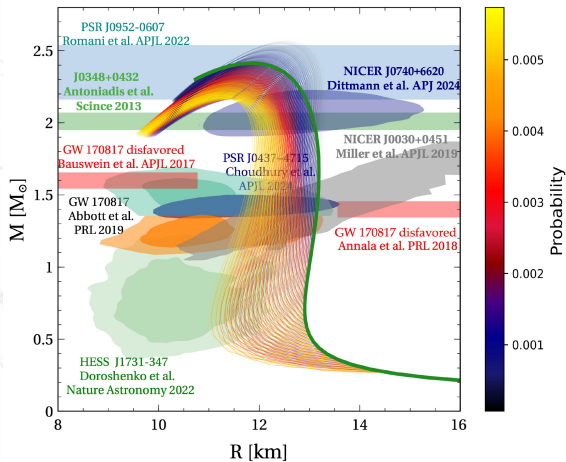
γ -ray excess counts around HESS J1731-347, with 3, 4, 5 σ contours. HESS J1731-347 is a shell-type **supernova remnant (SNR)** emitting TeV γ rays and non-thermal X rays, coincident with radio SNR G353.6-0.7.

HESS J1731-347: Velocity-Resolved Intensity Maps



Three distinct velocity ranges. Left: -27 to -72 km/s (about 3.2 kpc). Middle: around 4.5 kpc (-65 to -35 km/s). Right: -85.5 to -78 km/s (about 5 – 6 kpc). Layered 3, 4, and 5 significance contours from the source's H.E.S.S. analysis.

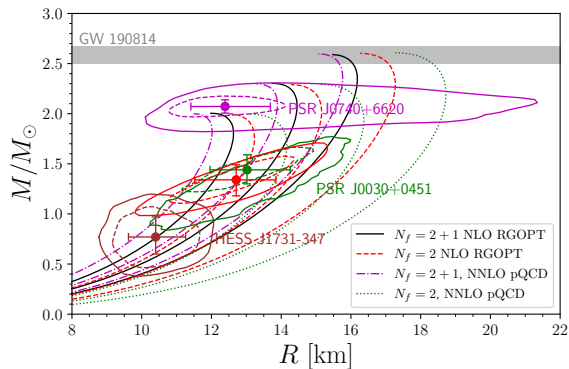
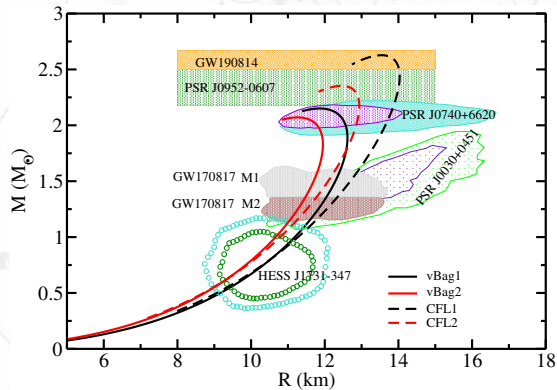
HESS J1731-347: Mass and Radius



$M = 0.77^{+0.20}_{-0.17} M_{\odot}$, $R = 10.4^{+0.86}_{-0.78}$ km,
 where $M_{\odot} = 1.989 \times 10^{30}$ kg is **solar mass**.

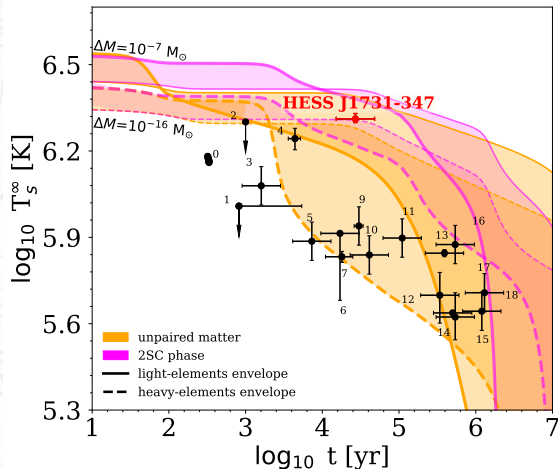
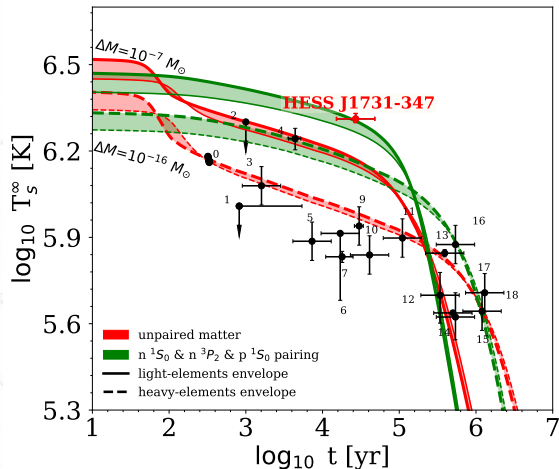
$M = 0.77^{+0.20}_{-0.17} M_{\odot}$, $R = 10.4^{+0.86}_{-0.78}$ km.

HESS J1731-347: Consistency Checks



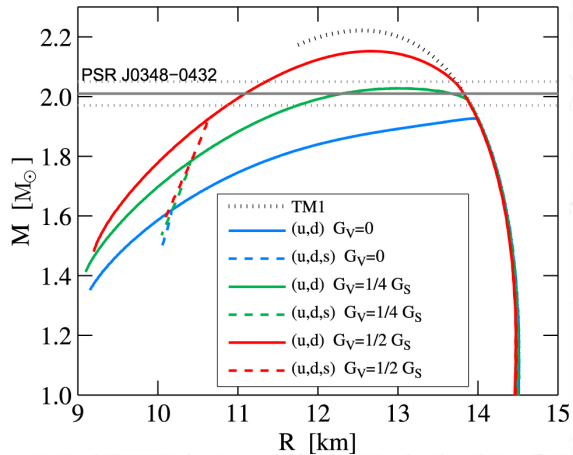
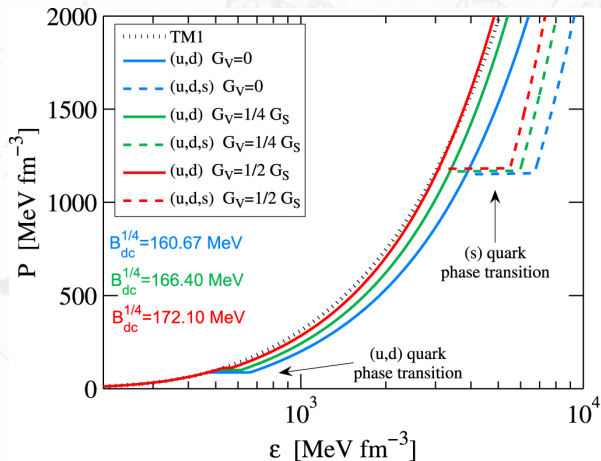
$$M = 0.77^{+0.20}_{-0.17} M_\odot, R = 10.4^{+0.86}_{-0.78} \text{ km.}$$

HESS J1731-347: Cooling Curves



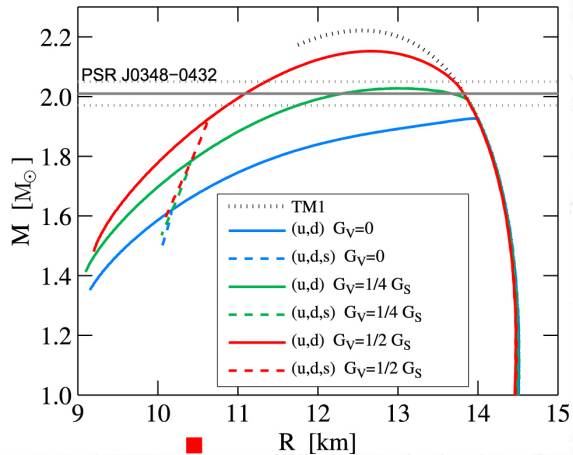
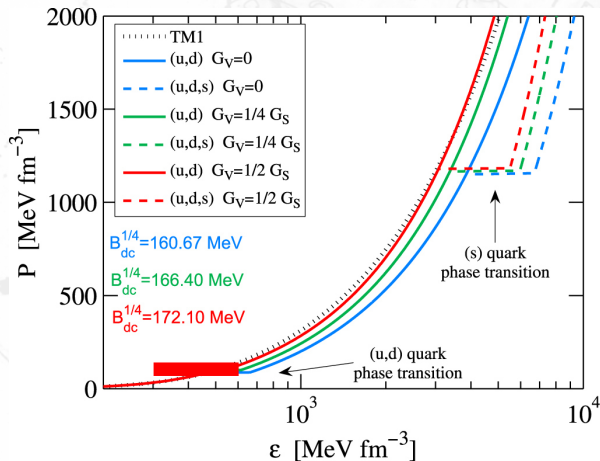
Left and right panels: **cooling curves** for neutron stars (NSs) and hybrid stars (HSs). A **hybrid star** has a quark-matter core surrounded by a hadronic envelope.

Equation of State Constraints (I)



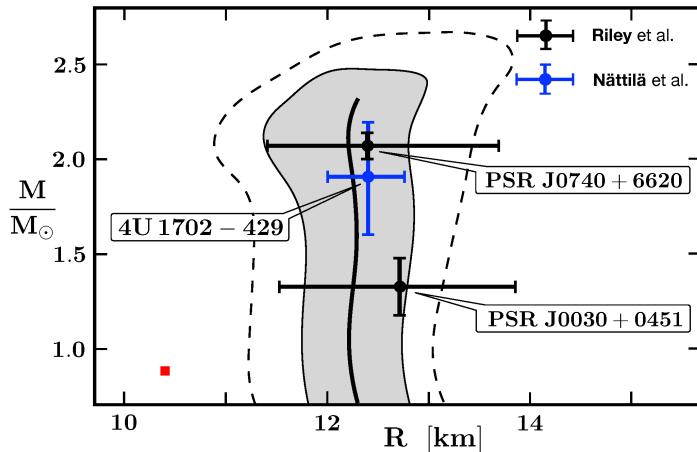
Energy density $\epsilon = 200\text{--}600$ MeV/fm 3 and pressure $P = 60\text{--}80$ MeV/fm 3
(1 fm = 10^{-13} cm).

Equation of State Constraints (II)



Energy density $\epsilon = 200\text{--}600$ MeV/fm 3 and pressure $P = 60\text{--}80$ MeV/fm 3
 (1 fm = 10^{-13} cm).

Mass–Radius Relation from TOV Equations



Numerical solution of the **Tolman–Oppenheimer–Volkov (TOV)** equations yields posterior credible bands at 68% (gray) and 95% (dashed) levels, compared with **NICER** data.

Worked Numerical Example (Baseline Scenario, $A = 100$)

Using $T = 1$ MeV and $\delta E = 10$ MeV:

$$\Gamma^{\text{base}} = \frac{T^4}{\pi^3} e^{-10} \approx 1.5 \times 10^{-6} \text{ MeV}^4 \approx 2.9 \times 10^8 \text{ fm}^{-3} \text{ s}^{-1}.$$

From $\dot{N}(A)$ at $A = 100$, $A_{\text{peak}} = 10^6$, $\dot{N}_{\text{peak}} = 10^{47} \text{ s}^{-1}$:

$$\dot{N}(100) = 10^{47} \times (10^{-4})^{2/3} \times e^{2/3} \approx 4.2 \times 10^{44} \text{ s}^{-1}.$$

Accumulating for $\tau_{\text{acc}} = 10^6 \text{ yr}$ in $V_{\text{source}} = 1.23 \times 10^{59} \text{ cm}^3$:

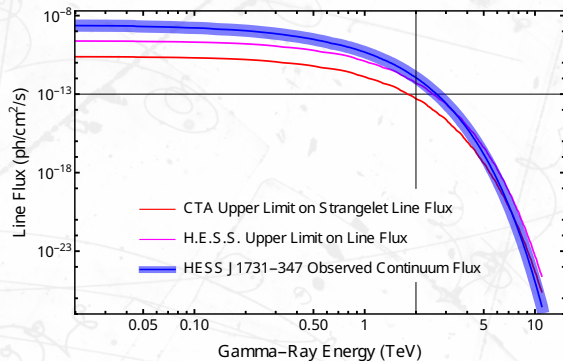
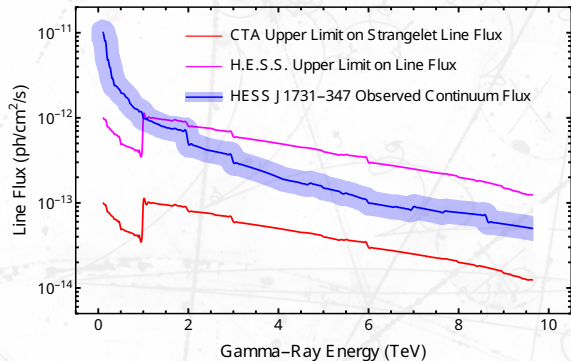
$$n_S = \frac{\dot{N}_{\text{acc}}}{V_{\text{source}}} \approx 1.1 \times 10^{-1} \text{ cm}^{-3}.$$

With $\langle \sigma_{\text{ann}} v \rangle \sim 10^{-25} \text{ cm}^3 \text{ s}^{-1}$ and $D = 3.2 \text{ kpc}$:

$$R_{\text{ann}} = n_S^2 \langle \sigma v \rangle V_{\text{source}} \approx 1.4 \times 10^{32} \text{ s}^{-1}, \quad \Phi_\gamma = \frac{2R_{\text{ann}}}{4\pi D^2} \approx 2.3 \times 10^{-13} \text{ ph cm}^{-2} \text{ s}^{-1}.$$

Each annihilation produces two photons at $E_\gamma = m_S/2 \approx 47 \text{ GeV}$.

Monte Carlo Simulations for HESS J1731-347



Left: CTA line-flux limits (0.1–10 TeV), together with H.E.S.S. (magenta) and observed continuum flux (blue). Right: same with logarithmic x-axis and enhanced Monte Carlo simulation.

Constraining the Strangelet Flux from HESS J1731-347

With a continuum flux of $\sim 10^{-12}$ ph/cm²/s at 1 TeV, CTA can probe features below 0.1% of the continuum:

$$F_s < \frac{F_{\gamma}^{\text{line}}}{N_H \cdot \sigma_s} \approx \frac{10^{-13}}{10^{23} \cdot 4 \times 10^{-26}} \approx 2.5 \times 10^{-11} \text{ ph/cm}^2/\text{s/sr}.$$

Here F_s is the strangelet-flux upper limit, F_{γ}^{line} the γ -ray line flux, $N_H \sim 10^{23} \text{ cm}^{-2}$ the average **column density** of hydrogen along the line of sight, $\sigma_s \sim 4 \times 10^{-26} \text{ cm}^2$ the strangelet–nucleon cross-section, and **sr** the steradian.

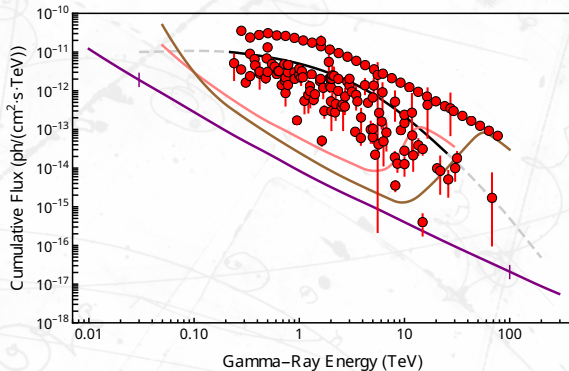
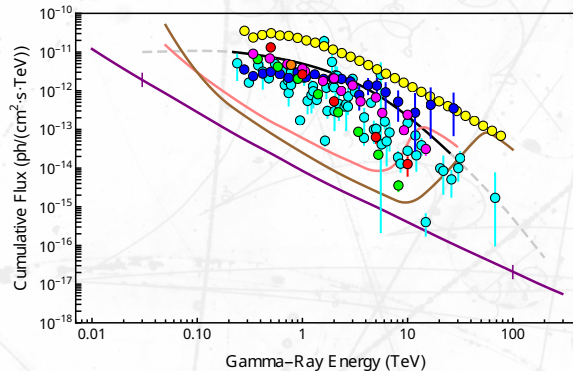
Limits from HESS J1731-347

- CTA's limit $\sim 10^{-13}$ ph/cm²/s is a tenfold improvement over H.E.S.S. ($\sim 10^{-12}$ ph/cm²/s).
- Continuum follows $dN/dE \propto E^{-2.3}$.
- Line flux limit: $F_{\gamma}^{\text{line}} < 10^{-13}$ ph/cm²/s at 1 TeV; strangelet flux $F_s < 2.5 \times 10^{-11}$ ph/cm²/s/sr.
- Number density $< 3 \times 10^{-22}$ cm⁻³; total mass contribution $< 10^{-17} M_{\odot}$.

C.R. Das, *arXiv:2507.12817*

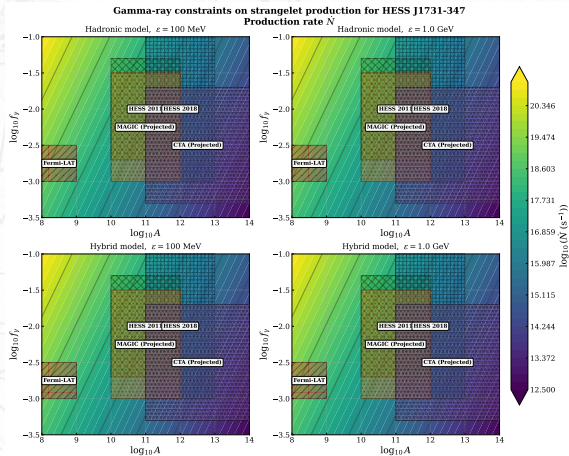
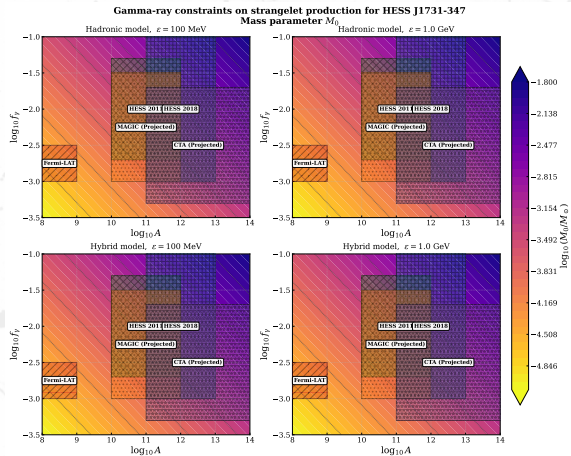
C.R. Das, Phys. Atom. Nuclei **88**, 1142-1148 (2025)

Real-Data Analysis for HESS J1731-347



Purple, brown, and pink: CTAO, H.E.S.S., MAGIC photon line-flux sensitivity upper limits. Black and dashed gray: averages of current and anticipated future data.

Real-Data Analysis: Further Panels

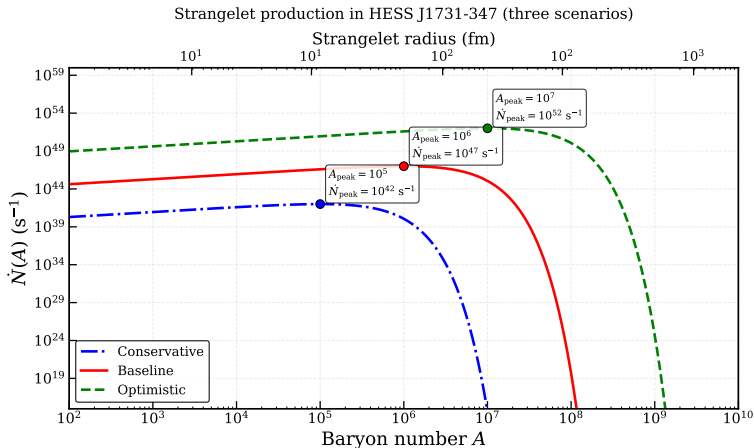


Left: the horizontal axis is $\log_{10} A$ and the vertical axis is $\log_{10} f_\gamma$, where f_γ is the fraction of strangelet interactions that produce γ rays. The colour scale shows $\log_{10}(M_0/M_\odot)$. Coloured boxes show 95% confidence-level (CL) excluded regions from the indicated instruments; “Projected” refers to the expected CTA/MAGIC-II sensitivity for 100-hour exposures.

Panels correspond to Hadronic and Hybrid models at $\epsilon = 100$ MeV and 1.0 GeV.

Right: same as Left, but the colour scale shows $\log_{10}(\dot{N} (\text{s}^{-1}))$.

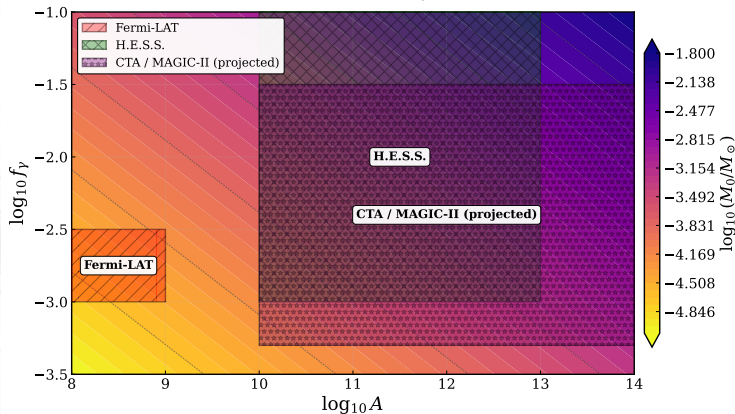
Strangelet Production in HESS J1731-347



Production rate $\dot{N} \text{ (s}^{-1}\text{)}$ versus baryon number A , with a secondary axis for radius $\approx 0.7 A^{1/3} \text{ fm}$. Conservative, Baseline, and Optimistic scenarios. Each curve has a single maximum at $A = A_{\text{peak}}$.

γ -Ray Constraints on Strangelet Parameters

Summary of gamma-ray constraints on strangelet parameters
HESS J1731-347 analysis



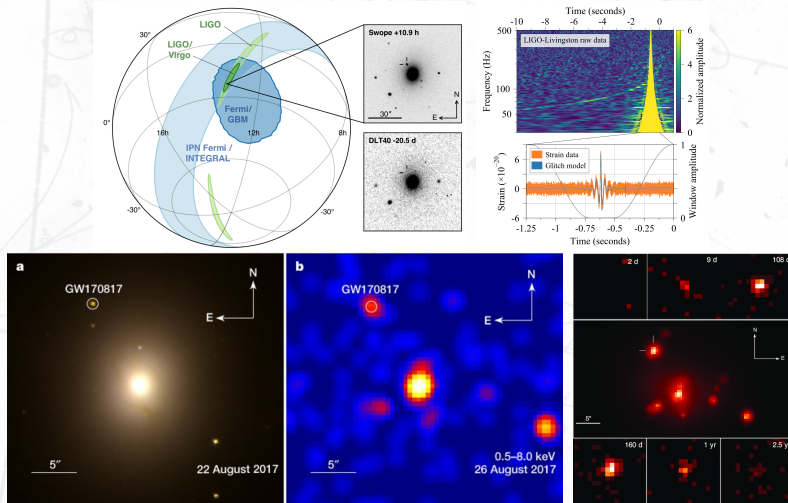
Constrained regions from Fermi-LAT, H.E.S.S. (2011, 2018), and projected CTA/MAGIC-II sensitivities in the $\log_{10} A$ vs. $\log_{10} f_\gamma$ plane, where f_γ is the γ -ray production efficiency.

Scenario Predictions versus Present and Projected Limits

Table: Comparison of scenario predictions with H.E.S.S. and projected CTA sensitivity.

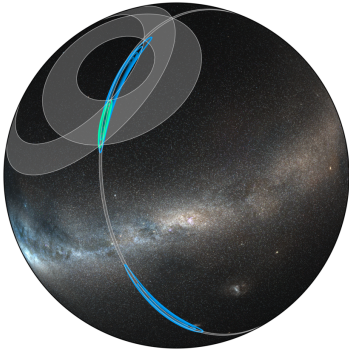
Scenario	A_{peak}	$\dot{N}_{\text{peak}} \text{ (s}^{-1}\text{)}$	Status
Conservative	10^5	10^{42}	Far below CTA sensitivity
Baseline	10^6	10^{47}	At CTA sensitivity ($\sim 10^{-13} \text{ ph cm}^{-2} \text{ s}^{-1}$)
Optimistic	10^7	10^{52}	Already excluded by H.E.S.S. ($\sim 10^{-12} \text{ ph cm}^{-2} \text{ s}^{-1}$)

Case Study 2: GW170817 — Multimessenger View

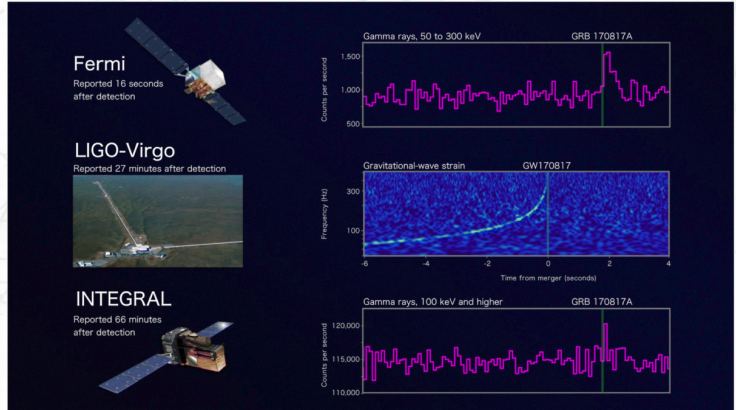


GW170817 is the first detected binary neutron-star merger (2017), at a luminosity distance of ~ 40 Mpc.

GW170817 — GW from Merging Neutron Stars

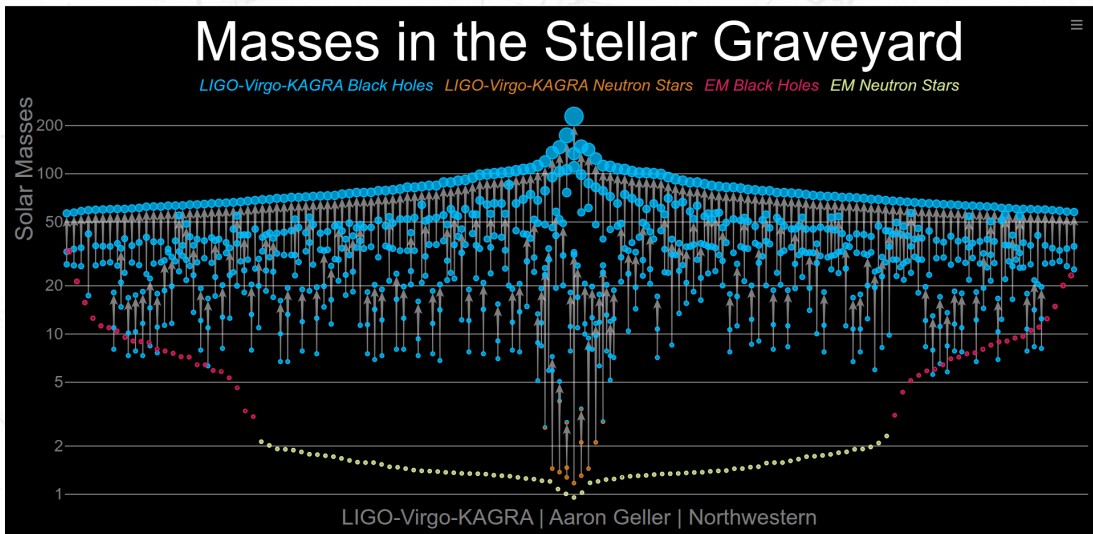


Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)



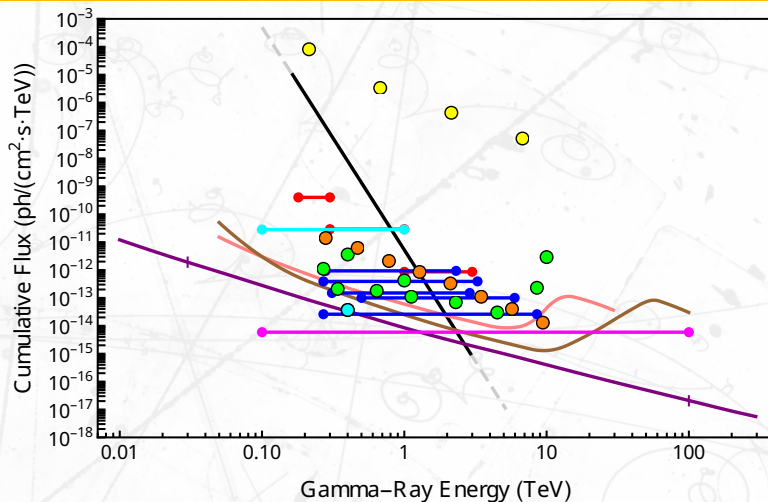
INTEGRAL search for GW counterparts and the GRB170817A/GW170817 detection.

GW170817: Masses from the Gravitational-Wave Signal



The dashed line marks the total mass. Contours indicate 50% and 90% credible regions.

Real-Data Analysis for GW170817



Purple/brown/pink: CTAO, H.E.S.S., MAGIC photon line-flux sensitivity upper limits.
Black/dashed gray: averages of current and anticipated future data.

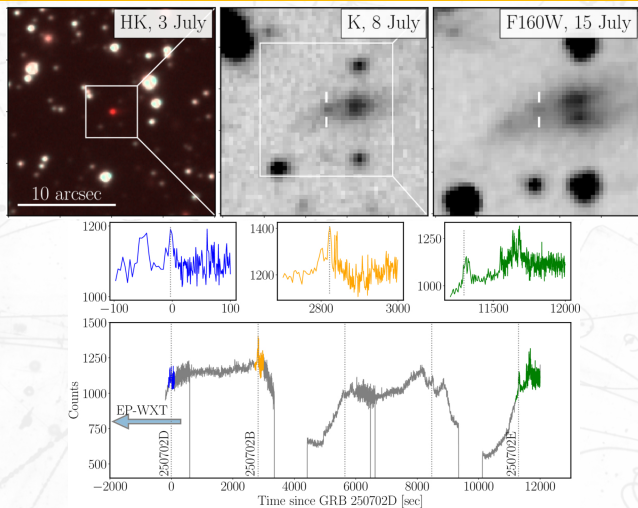
GW170817: Predicted Strangelet Flux

Applying the same production model with V_{source} the merger remnant and τ_{acc} the post-merger timescale:

- Scaling the worked example to $A \sim 10^3$ raises $\dot{N}$ by a factor ~ 4.6 relative to $A = 100$.
- **Continuous injection:** flux $\sim 10^{-25} \text{ ph cm}^{-2} \text{ s}^{-1}$.
- **Burst events:** flux $\sim 10^{-23} \text{ ph cm}^{-2} \text{ s}^{-1}$.

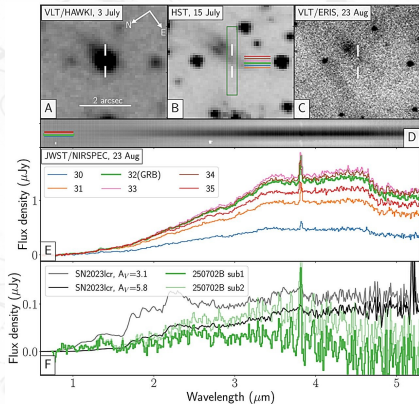
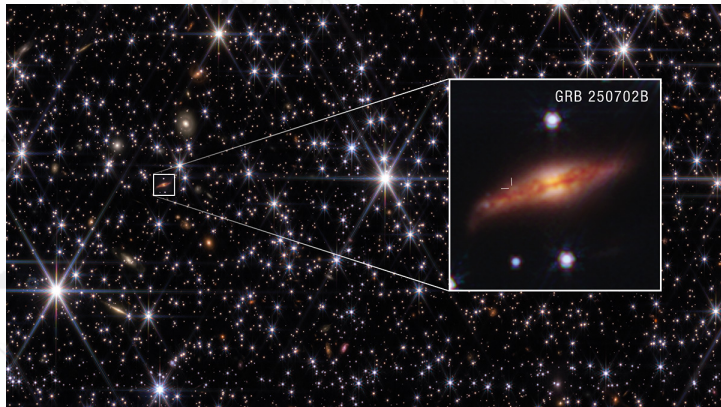
The absence of VHE signals in H.E.S.S. and MAGIC-II observations constrains post-merger scenarios.

Case Study 3: GRB 250702B



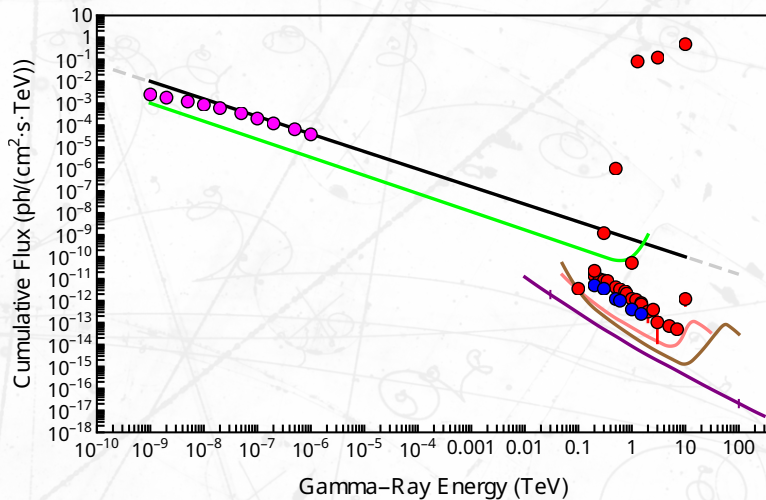
GRB 250702B is an ultra-long gamma-ray burst detected in July 2025, with duration exceeding 25 000 s and isotropic-equivalent energy $E_{\text{iso}} > 1.4 \times 10^{54}$ erg.

GRB 250702B — Longest γ -ray Blast Confuses Physicists



GRB 250702B came from the upper edge of its host galaxy's dark dust lane, revealing spatially-resolved properties of the host galaxy as well as the boundaries of supernovae.

Real-Data Analysis for GRB 250702B



Purple/brown/pink/green: CTAO, H.E.S.S., MAGIC, Fermi-GBM photon line-flux sensitivity upper limits. Black/dashed gray: averages of current and anticipated future

GRB 250702B: Predicted Strangelet Flux

Applying Eqs. for $\dot{N}(A)$ and Φ_γ to this source, for $A \sim 10^3$ and using the same production model:

- The burst produces a flux in the range

$$\Phi_\gamma \sim 10^{-13} - 10^{-11} \text{ ph cm}^{-2} \text{ s}^{-1},$$

lying within CTA's reach.

- Observations with wide-field monitors such as Fermi-GBM and Konus-Wind provide the prompt-emission baseline against which any strangelet-induced component would be searched for.

These extreme conditions naturally satisfy the four selection criteria (quark-matter reservoir, phase-transition conditions, injection channel, observability).

Direct Searches for Macroscopic SQM

A complementary question: could some SQM composites survive propagation to Earth?

While microscopic strangelets are unlikely to remain stable over interstellar distances, **macro-scale objects** such as **nuclearites** (nuggets of SQM surrounded by an electron shell, with theoretical masses 10^{-10} – 10^2 g) and **Q-balls** (non-topological solitons carrying a conserved global charge) possess extremely large mass-to-charge ratios and correspondingly high ionisation densities.

These properties enable them to traverse the interstellar medium and penetrate the terrestrial atmosphere, offering a unique opportunity for direct detection.

Detection Signatures for Macro-SQM

Macro-scale SQM objects traversing a detector would generate distinctive, continuous signals:

High-ionisation tracks

- The immense mass-to-charge ratio $m/|Z|$ leads to a very high **energy-loss rate per unit path length dE/dx** via ionisation.
- This would appear as a straight, bright, continuous track in large-volume detectors (IceCube, ANTARES), in contrast to point-like neutrino events.

Thermal and luminous signatures

- The deposited energy could create a **thermal shock front** in the atmosphere, water, or ice.
- This could appear as a slow luminous transit, a bright flash, or an acoustic signal.

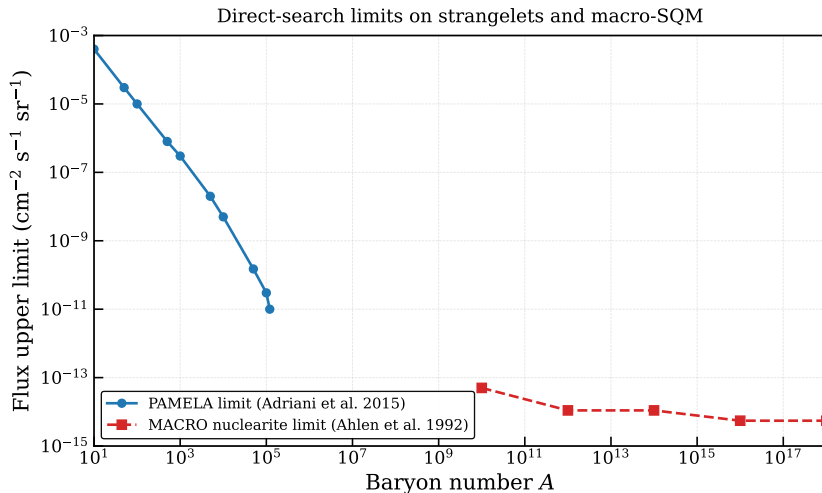
Experimental Constraints and Future Prospects

Table: Experiments and their primary sensitivity to macro-SQM signatures.

Experiment	Type	Primary sensitivity
SLIM, MACRO	Nuclear track detectors	Direct search for heavily ionising particles; flux limits for nuclearites.
ANTARES, IceCube	Neutrino telescopes	Bright, slow-moving tracks and luminous transits through large volumes of water/ice.
LHAASO (KM2A, WCDA, WFCTA)	High-altitude EAS array	Atmospheric penetration signatures (KM2A); sub-relativistic luminous events (WFCTA).

- Existing searches already constrain parts of the parameter space.
- Upcoming facilities, particularly LHAASO, will provide unprecedented sensitivity.

Direct-Search Limits on Strangelets and Macro-SQM



Blue circles: PAMELA 90% CL (**confidence level**) upper limit on strangelet flux vs. baryon number A , covering $A \sim 10\text{--}1.2 \times 10^5$, digitised from Adriani et al. (2015). Red squares: MACRO nuclearite flux limit from Ahlen et al. (1992), published for the mass window $10^{-10} < m < 0.1$ g, corresponding to $A \sim 10^{14}\text{--}10^{23}$.

Nuclearites and Q-balls: Detection Physics

Nuclearites. Electrically neutral lumps of SQM with an electron cloud. Interaction with matter is dominated by **elastic collisions**:

$$\frac{dE}{dx} = -\sigma\rho v^2,$$

where ρ is the target density and σ the cross-section. A nuclearite with galactic velocity $\beta \sim 10^{-3}$ deposits enormous energy, creating a **thermal shock front** that emits **blackbody radiation** in the visible/UV. A nuclearite crosses ~ 300 m in ~ 1 ms. Only masses $M \gtrsim 6 \times 10^{22} \text{ GeV}/c^2$ can traverse the Earth.

Detection signature: a **slow, straight, bright track** — a succession of large PMT signals in a line, with a distinct time structure ($\Delta t \sim 30\text{--}80 \text{ }\mu\text{s}$ per PMT).

Q-balls. Non-topological solitons carrying a conserved global charge, predicted by supersymmetric theories. Their passage converts ordinary quarks into squarks, releasing $\sim 1 \text{ GeV}$ per collision via **soft pion emission**, marking the track with charged particles.

Key detection channels

- **Nuclear track detectors:** CR-39, Makrofol — etchable damage from heavily ionising particles.
- **Neutrino telescopes:** Cherenkov light from thermal shock or ionisation tracks.
- **High-altitude EAS arrays:** atmospheric penetration signatures.

Nuclearites and Q-balls: Present Status

Present experimental constraints (most stringent)

- **MACRO** (Gran Sasso): flux limit $2.7 \times 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ for $\beta = 2 \times 10^{-3}$ nuclearites; also flux limits of $1.1 \times 10^{-14} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$ for $10^{-10} < m < 0.1 \text{ g}$ and $5.5 \times 10^{-15} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$ for $m > 0.1 \text{ g}$.
- **ANTARES** (Mediterranean Sea): **first neutrino-telescope limit** on nuclearites — $5 \times 10^{-17} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ for masses up to $10^{17} \text{ GeV}/c^2$.
- **SLIM** (Chacaltaya, Bolivia): $1.3 \times 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ for downgoing SQM and charged Q-balls (combined MACRO, OHYA (Tokyo, Japan), and SLIM limits).

Nuclearites and Q-balls: Future

Future facilities and their reach

- **KM3NeT/ARCA** (Mediterranean, km³-scale): projected sensitivity improves on ANTARES, especially for **high-mass nuclearites**.
- **IceCube** (South Pole): sensitive to nuclearites and Q-balls via blackbody radiation and slow tracks.
- **SQM-ISS** (International Space Station): scintillator + piezoelectric stack, searches for massive non-relativistic particles including **Q-balls, SQM, and primordial black holes** at $v \lesssim 250$ km/s.
- **LHAASO** (Tibet, KM2A + WCDA + WFCTA): atmospheric penetration and sub-relativistic luminous events.
- **Gravitational-wave observatories** (Einstein Telescope, Cosmic Explorer): can constrain Q-ball parameters through phase-transition gravitational-wave signals.

Key Results: Summary

Table: Consolidated constraints and forecasts for the three sources.

Source	Present limit ($\text{ph cm}^{-2} \text{s}^{-1}$)	CTA forecast ($\text{ph cm}^{-2} \text{s}^{-1}$)	n_S limit (cm^{-3})	Status
HESS J1731-347	$\sim 10^{-12}$	$\sim 10^{-13}$	$< 3 \times 10^{-22}$	Baseline at CTA threshold; Optimistic excluded.
GW170817	$\sim 10^{-12}$	$\sim 10^{-13}$	–	No prompt VHE emission; off-axis geometry.
GRB 250702B	10^{-13} – 10^{-11}	$\sim 10^{-13}$	–	Burst limits being derived.

The Baseline scenario for HESS J1731-347 lies at the CTA sensitivity threshold; the Conservative scenario requires a next-generation instrument.

Limitations and Open Questions

Theoretical uncertainties

- **Transition rate.** The prefactor T^4/π^3 is chosen on dimensional grounds; a full calculation requires transport coefficients not yet known for ultradense matter.
- **Annihilation cross-section.** The conservative value $\langle\sigma v\rangle \sim 10^{-25} \text{ cm}^3 \text{ s}^{-1}$ is adopted; the geometric value could be orders of magnitude larger.
- **Suppression factors.** The phenomenological form $\dot{N}(A)$ absorbs four suppression mechanisms into two parameters.
- **Mass-to-charge ratio.** The charge fraction Y_Q is inferred from MIT-bag calculations; a first-principles NJL derivation is left for future work.

Observational limitations

- Instrument limits are quoted at $\sim 1 \text{ TeV}$; the sensitivity at $\sim 47 \text{ GeV}$ is a factor of $\mathcal{O}(3\text{--}10)$ worse for imaging Cherenkov telescopes.
- The three sources are illustrative; a definitive detection would need a dedicated multi-instrument campaign.

Conclusion: Multimessenger Astronomy Is Essential!

- **Strange quark matter (SQM)** remains a compelling possibility for the true ground state of dense QCD. Signatures range from **monochromatic VHE γ -ray lines** from strangelet–anti-strangelet annihilation to **direct detection of macroscopic objects** (nuclearites, Q-balls).
- Current constraints from **H.E.S.S., Fermi-LAT, MAGIC, IceCube, ANTARES, SLIM** probe parts of the parameter space; definitive discovery needs **next-generation sensitivity**.
- Multimessenger observations of **HESS J1731-347, GW170817, GRB 250702B** provide unique laboratories.
- Future facilities are essential to:
 - search for narrow γ -ray lines with unprecedented sensitivity,
 - detect slow, highly ionising tracks and luminous transits from macro-SQM,
 - correlate GeV–TeV γ rays, neutrinos, gravitational waves, and cosmic rays,
 - constrain the QCD phase diagram and the equation of state of compact stars.

Outlook: A Multimessenger Roadmap for SQM

Only a coordinated, multi-wavelength, multi-messenger strategy can confirm or rule out the strange quark matter hypothesis.

Table: Key future facilities and their roles in probing SQM.

Facility	Messenger / technique	Primary SQM science
CTA / CTAO	VHE γ rays	Narrow spectral lines from strangelet annihilation; morphology of HESS J1731-347.
LHAASO (KM2A, WCDA, WFCTA)	EAS, γ rays, cosmic rays	Atmospheric penetration signatures; sub-relativistic luminous events; macro-SQM.
IceCube / KM3NeT	High-energy neutrinos	Slow, bright tracks from nuclearites and Q-balls; neutrino signals from mergers.
Einstein Telescope / Cosmic Explorer	Gravitational waves	Post-merger physics; constraints on the compact-star EoS.
ngVLA, SKA	Radio	Counterparts of mergers; environment of strange quark stars.

Future Multimessenger Observatories Are Necessary!

- The combination of **line searches**, **direct macro-SQM searches**, and **multimessenger follow-up** will dramatically expand the discovery potential.
- Upcoming observations will provide critical tests of the $2SC \rightarrow CFL$ transition, strangelet stability, and the cosmological abundance of SQM.

C.R. Das, Phys. Atom. Nuclei **88**, 1142-1148 (2025), *arXiv:2507.12817*.

Acknowledgments and Contact

Acknowledgments

- The Bogoliubov Laboratory of Theoretical Physics (BLTP), Joint Institute for Nuclear Research (JINR), Dubna.
- The organizers of the Next Frontiers in Magnetic Monopole Searches workshop at IHEP, CAS, Beijing.
- The H.E.S.S., MAGIC, Fermi-LAT, and CTA collaborations for making their public data and instrument-response functions available.

Contact

- Email: `das@theor.jinr.ru`
- Journal: C.R. Das, Phys. Atom. Nuclei **88**, 1142-1148 (2025), *arXiv:2507.12817*.
- Slides available on request.

Thank You Very Much for Your Kind Attention!

THANK YOU
謝謝

