

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

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Outline of the Talk

- ➊ **Motivation.** Why strange quark matter (SQM) is a compelling idea for the true ground state of dense QCD.
- ➋ **Theoretical framework.** The 2SC $\rightarrow$ CFL phase transition, strangelet production, and the relevant cross-sections.
- ➌ **Observational strategy.** Monochromatic γ -ray lines from strangelet–anti-strangelet annihilation.
- ➍ **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.
- ➎ **Direct searches for macro-scale SQM.** Nuclearites, Q-balls, and current/future limits.
- ➏ **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

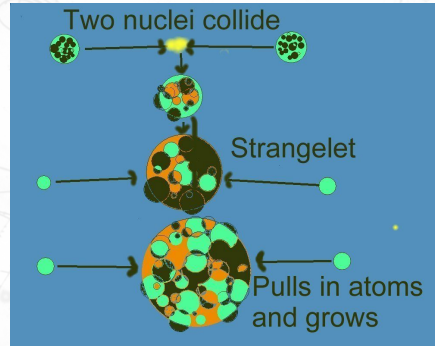
- **Monochromatic γ -ray lines** from strangelet–anti-strangelet annihilation are a direct signature.
- **Anomalous compact objects** such as HESS J1731-347 may be SQSs.
- **Direct detection** of macroscopic SQM objects (nuclearites, Q-balls) would be complementary.

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: $30\text{--}60 \text{ GeV}/c^2$.



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.

Edward Farhi and R. L. Jaffe

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.

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:

- 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, K. Riisager, Phys. Rev. D **34**, 2947 (1986).
- F. Di Clemente et al., *Strange quark matter as dark matter: 40 yr later, a reappraisal*, MNRAS **537**, 1056 (2025).
- H.-S. You et al., *Strangelets at finite temperature: Nucleon emission rates, interface, and shell effects*, Phys. Rev. D **109**, 034003 (2024).
- G. Cao, *Extended Nambu–Jona-Lasinio model for quark and nuclear matters*, Phys. Lett. B **860**, 139140 (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:

- A. R. Bodmer, *Collapsed Nuclei*, Phys. Rev. D **4**, 1601 (1971).
- 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).
- C. Greiner, P. Koch, H. Stöcker, *Separation of strangeness from antistrangeness in the quark–hadron phase transition*, Phys. Rev. Lett. **58**, 1825 (1987).
- 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).
- J. Madsen, *Strangelets, nuclearites, Q-balls — a brief overview*, arXiv:astro-ph/0612740.
- J. Ellis et al., *Review of the safety of LHC collisions*, J. Phys. G **35**, 115004 (2008).
- A. Kent, *A critical look at risk assessments for global catastrophes*, arXiv:hep-ph/0009204.
- G. Appelquist et al. (NA52), *Strangelet search in Pb–Pb interactions at 158 GeV/c per nucleon*, Phys. Rev. Lett. **76**, 3907 (1996).
- O. Adriani et al. (PAMELA), *New upper limit on strange quark matter abundance in cosmic rays with PAMELA*, Phys. Rev. Lett. **115**, 111101 (2015).
- M. Bianchi et al. (SQM-ISS), *Search for strange quark matter and nuclearites on board the International Space Station (SQM-ISS)*, 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	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 (RHIC/LHC) or cosmic rays.
- Flux limits for charges $1 \leq Z \leq 60$ and baryon numbers $4 \leq A \leq 1.2 \times 10^5$.

2 Astronomical limits.

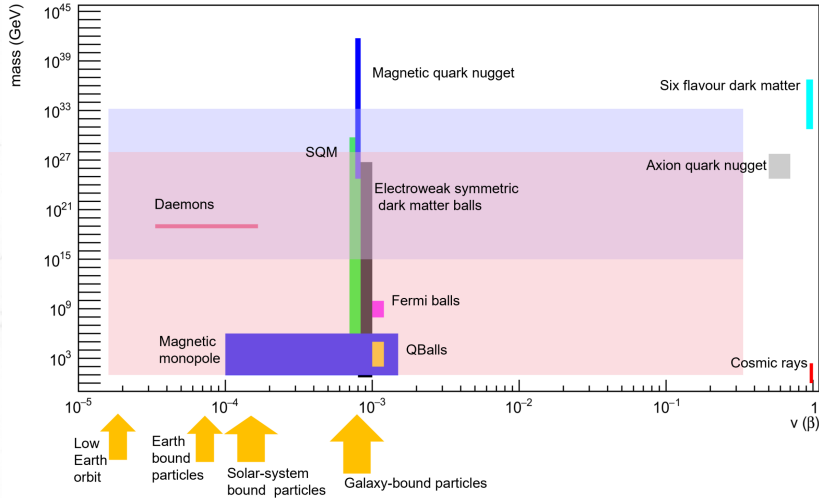
- No evidence of strange matter in neutron stars.
Strangelet–anti-strangelet annihilation may produce γ rays
($S\tilde{S} \rightarrow \gamma\gamma$, $\tilde{S}$ = anti-strangelet).
- No confirmed strangelet impact events on Earth or Solar System bodies.

A stable strangelet formed off-centre in a neutron star could trigger a phase transition converting the whole star into a strange star.

3 Theoretical stability.

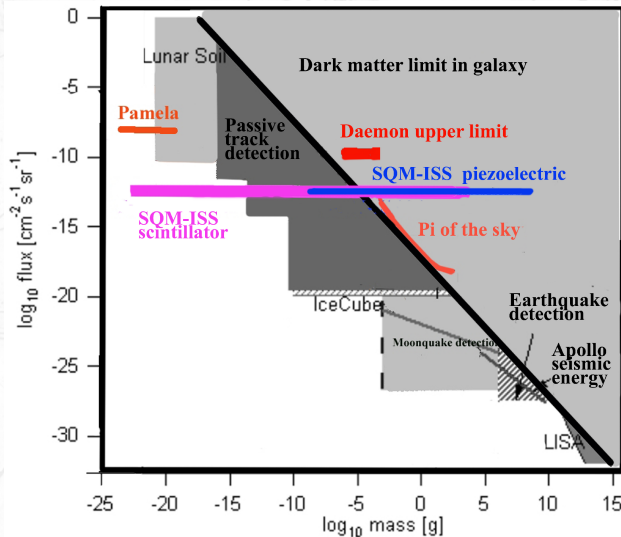
- Small strangelets ($A \lesssim 10^2$) likely unstable due to surface effects.
- Large strangelets ($A \gtrsim 10^{20}$) constrained by NS observations and dark matter.
However, $A \simeq 10$ s up to $A \simeq 10^{57}$ is possible.

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

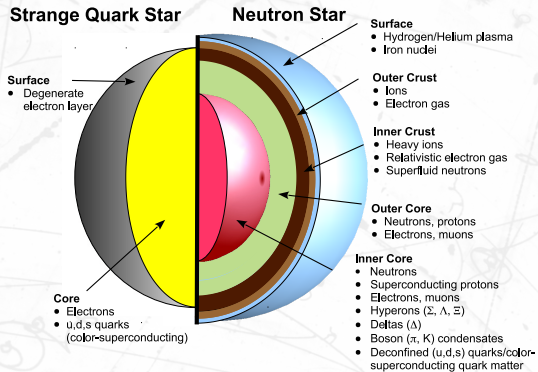
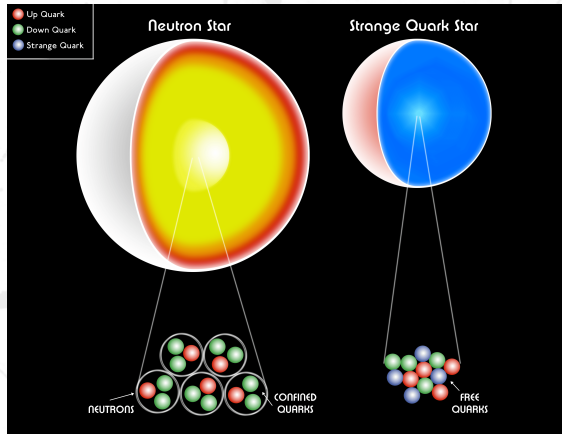
Several mechanisms can produce strangelets during the $2SC \rightarrow CFL$ phase transition:

- **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.

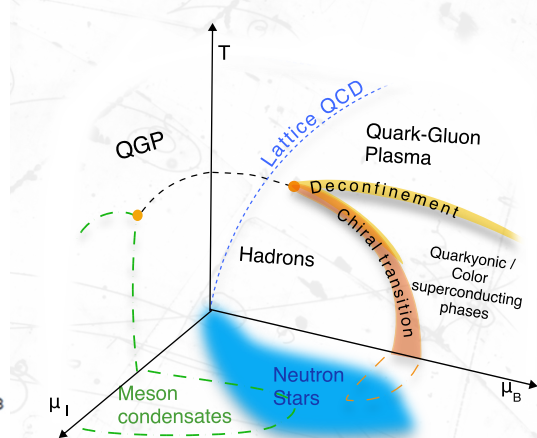
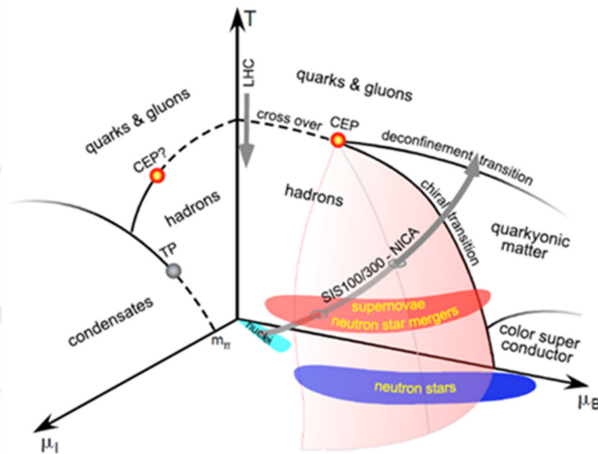
Detecting γ -ray fingerprints from HESS J1731-347 (neutron star), GW170817 (merger), or GRB 250702B would prove the existence of strangelets.

Strange Stars



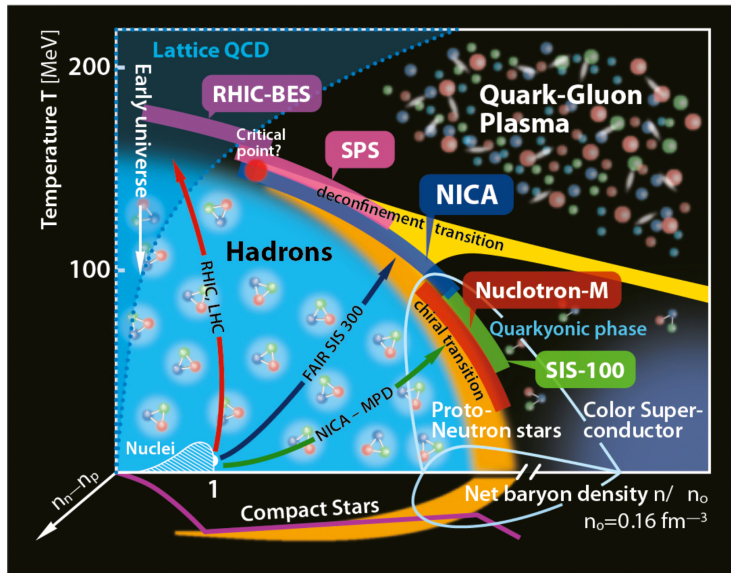
A **strange star** is a compact star whose interior is composed entirely of SQM, in contrast to a conventional neutron star whose interior is mainly neutrons.

The Colour-Flavour-Locked (CFL) Phase

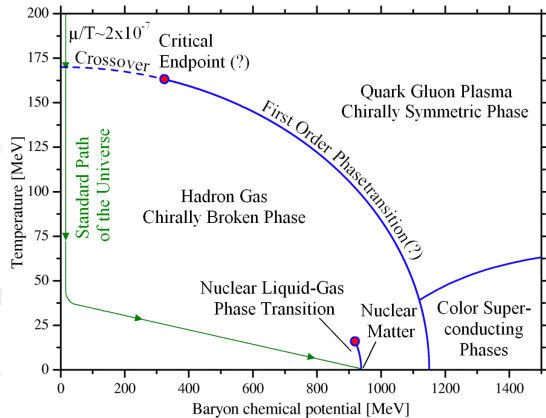


QCD phase diagram in the space of temperature T (thermal energy of the medium), **baryon-chemical potential** μ_B (energy to add a unit of baryon number), and **isospin-chemical potential** μ_I (energy to add a unit of up-down asymmetry).

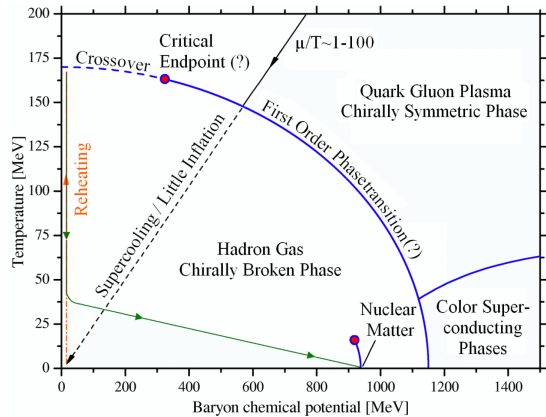
The CFL Phase: Matter Composition



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** — correlated pairs with opposite momenta and spins — 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**, δE the **activation energy barrier**. The prefactor T^4/π^3 is the unique temperature scale at the transition.

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 of the formation cross-section; 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	$B^{1/4}$	145–165 MeV	QCD vacuum-energy density scale
Diquark coupling ratio	$\eta_D = G_D/G_S$	0.8–1.2	Scalar diquark vs. scalar meson coupling

Cross-Section Formalism for Strangelet Interactions

The **interaction cross-section** σ (units: area) is derived from effective QCD field theory. The basic form for the 2SC $\rightarrow$ CFL transition:

$$\sigma = \sigma_0 \left(\frac{A}{A_0} \right)^{2/3} \left(\frac{\Delta}{\mu} \right)^{1.5} \exp\left(-2.0 \frac{m_s^2}{\mu^2}\right) f(\theta),$$

where σ_0 is a **reference cross-section** (~ 1 mb), $A_0 = 100$ is a reference baryon number, Δ the relevant gap, μ the chemical potential, m_s the strange-quark mass, and $f(\theta)$ the angular dependence on the **scattering angle** θ .

Why this form?

- $(A/A_0)^{2/3}$: geometrical area of a strangelet of size $R \propto A^{1/3}$.
- $(\Delta/\mu)^{1.5}$: 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 ($C_V \sim 0.5\text{--}1.0$, $C_A \sim 0.3\text{--}0.7$), θ the **scattering angle**, and $\xi(T)$ a **temperature-dependent damping factor**:

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

Specific Cross-Section: Strangelet–Nucleon

$$\sigma_{SN} = \sigma_{NN} \left(\frac{A}{100} \right)^{2/3} \left[1 + \frac{2}{3} \left(\frac{\Delta_{\text{CFL}}}{\mu} \right) - \frac{1}{5} \left(\frac{m_s}{\mu} \right)^2 \right] \zeta(Z),$$

where

- $\sigma_{NN} \approx 40$ mb is the **nucleon–nucleon cross-section**,
- Δ_{CFL} is the CFL pairing gap,
- μ is the quark chemical potential,
- m_s is the strange-quark mass,
- $\zeta(Z)$ is a **charge-dependent factor**:

$$\zeta(Z) = 1 + 0.5 \frac{Z}{A^{2/3}},$$

with Z the **strangelet charge number**.

Specific Cross-Section: Photon–Strangelet

Photon–strangelet scattering is expected to be dominated by the resonance structure of the quark-matter spectrum:

- The absorption cross-section peaks near

$$\omega_0 \approx 2 \Delta_{\text{CFL}},$$

the **pair-breaking threshold** — a photon of that energy can just break a Cooper pair.

- Photons with $\omega < \omega_0$ cannot excite the condensate; their absorption is strongly suppressed.

In the paper, the earlier photon–strangelet absorption formula was removed because its correction factor $\eta(\omega)$ could become *negative* for large ω , which is unphysical.

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

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

with the **charge fraction**

$$Y_Q = \frac{Z}{A} \approx \frac{1}{3} - \frac{2}{9} \frac{m_s^2}{\mu^2} + \frac{1}{9} \frac{\Delta_{\text{CFL}}}{\mu}.$$

- $m_N \approx 0.94 \text{ GeV}/c^2$ is the **nucleon mass**.
- The $2/9$ coefficient follows from the MIT-bag relation $Z \approx A/3 - (2m_s^2/9\mu^2)A$.
- The $1/3$ coefficient is a leading-order result of the expansion in Δ_{CFL}/μ .
- Typical: $m/|Z| \sim 30\text{--}60 \text{ GeV}/c^2$ for $A \sim 100\text{--}10^5$.

Summary of Numerical Parameters

Table: Key numerical parameters for strangelet cross-section calculations.

Parameter	Symbol	Typical value	Dependencies
Production coefficient	κ	0.1–1.0	Interaction-model details
Base transition rate	Γ^{base}	$(T^4/\pi^3)e^{-\delta E/T}$	$T, \delta E$
Reference cross-section	σ_0	$\sim 1 \text{ mb}$	Baryon number A
Annihilation cross-section	$\langle \sigma_{\text{ann}} v \rangle$	$10^{-25} \text{--} 10^{-23} \text{ cm}^3/\text{s}$	$T, \text{ gap parameters}$
Mass-to-charge ratio	$m/ Z $	$30\text{--}60 \text{ GeV}/c^2$	$m_s, \mu, \Delta_{\text{CFL}}$

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 (minutes to days) 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 → allows quantitative predictions for the expected strangelet flux at Earth.

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

The event: The longest gamma-ray burst ever detected, 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.
- GRB 250702B is part of a growing class of events that may reveal new physics beyond standard collapsar models.

Production channel

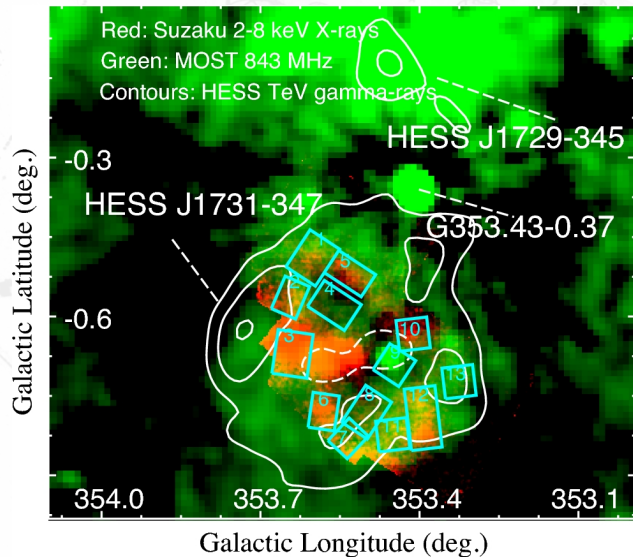
Ultra-long GRBs represent a **burst-driven** channel for strangelet production, distinct from steady and merger-driven sources.

Key advantage

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

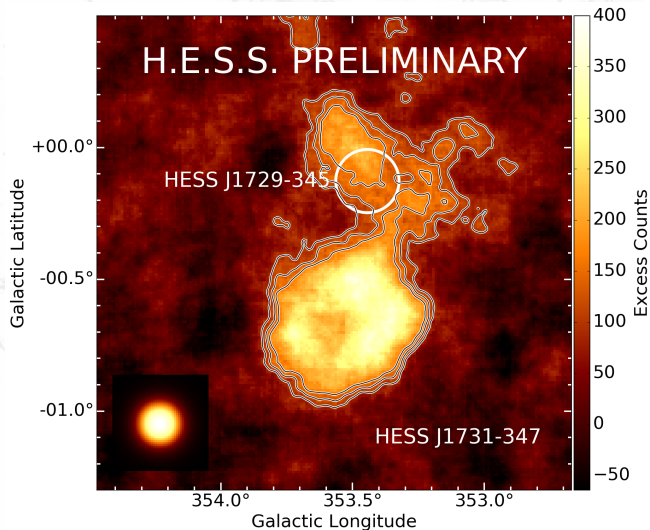
Combined power: these three objects cover **continuous, merger-driven, and burst-driven** strangelet production channels.

Case Study 1: HESS J1731-347 — Multiwavelength View



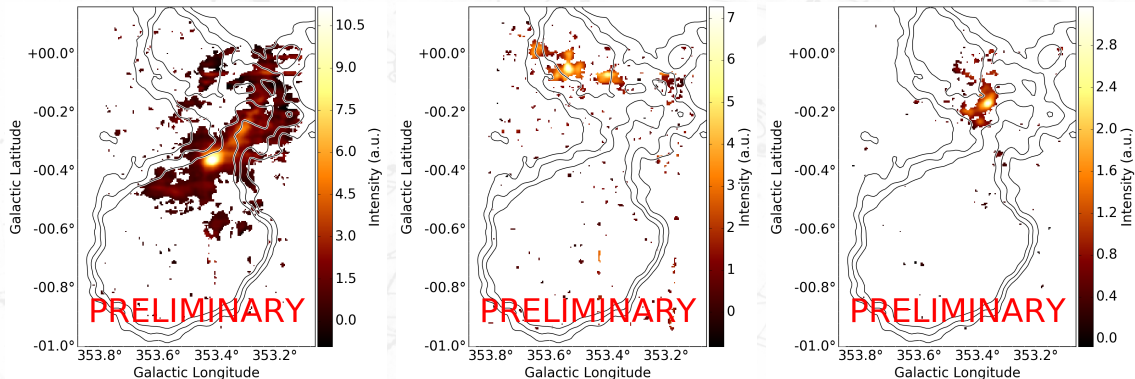
Suzaku 2–8 keV X-ray emission (red);
843 MHz radio continuum (green);
H.E.S.S. >1 TeV contours (4, 6, 8σ ,
where σ is the standard deviation of
the background). An **H II region** is a
cloud of ionised hydrogen.

HESS J1731-347: γ -Ray Morphology



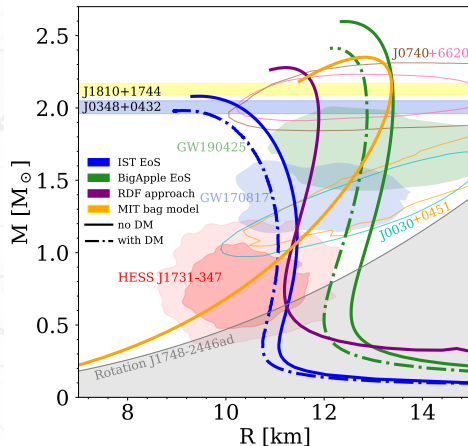
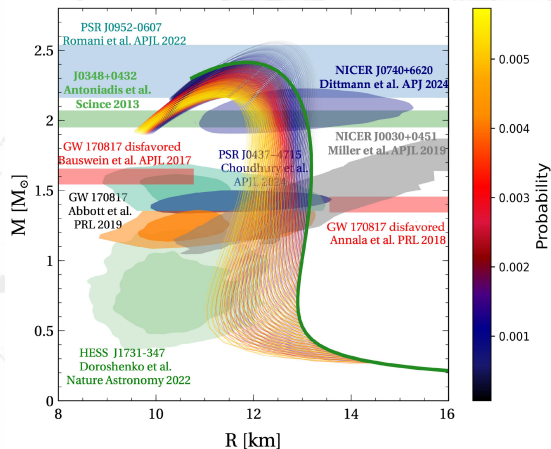
γ -ray excess counts around HESS J1731-347, with 3, 4, 5 σ contours. HESS J1731-347 is a shell-type **supernova remnant (SNR)** emitting TeV γ rays and non-thermal X rays, coincident with radio SNR G353.6-0.7. Inset: average **Point Spread Function (PSF)**.

HESS J1731-347: Velocity-Resolved Intensity Maps



Three distinct velocity ranges. Left: -27 to -72 km/s (about 3.2 kpc, with 1 kpc = 3.086×10^{18} cm). Middle: around 4.5 kpc (-65 to -35 km/s). Right: -85.5 to -78 km/s. Layered 3, 4, and 5 significance contours from the source's H.E.S.S. analysis that are shown.

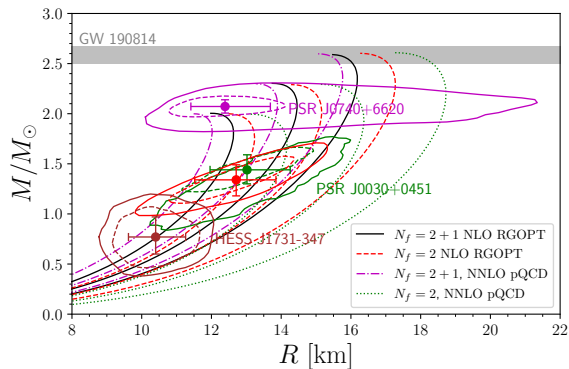
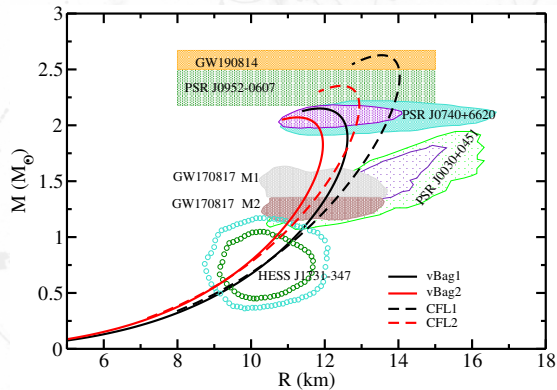
HESS J1731-347: Mass and Radius



$M \sim 0.77\text{--}0.88 M_\odot$, $R \sim 10.4$ km, where $M_\odot = 1.989 \times 10^{30}$ kg is the **solar mass**.

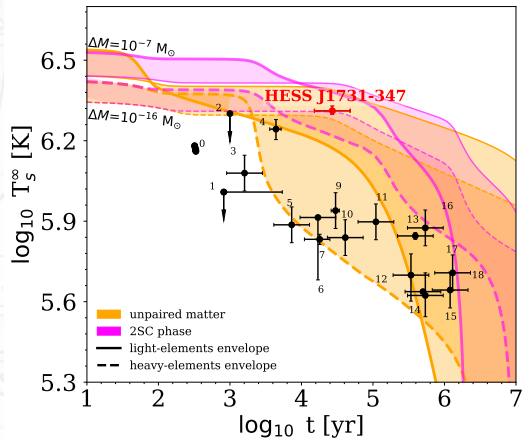
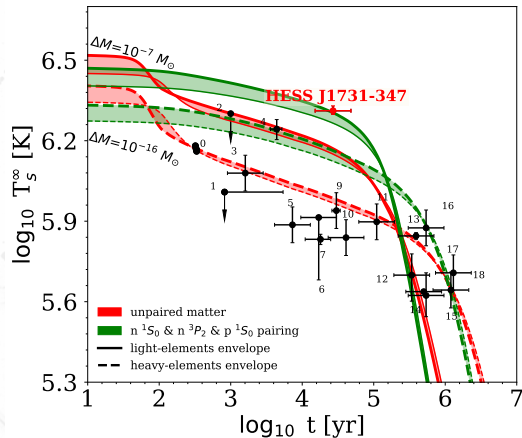
$M \sim 0.77^{+0.20}_{-0.17} M_\odot$, $R \sim 10.4^{+0.86}_{-0.78}$ km.

HESS J1731-347: Consistency Checks



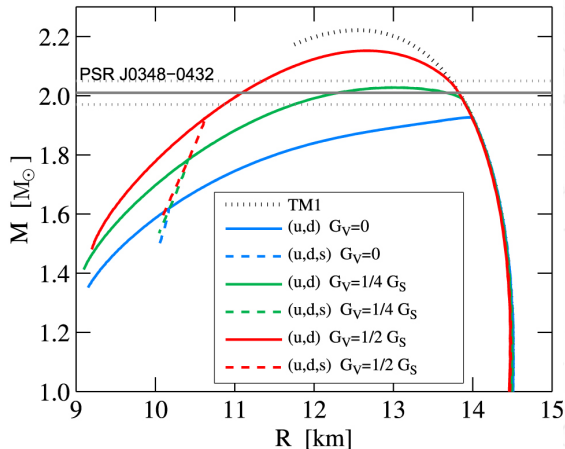
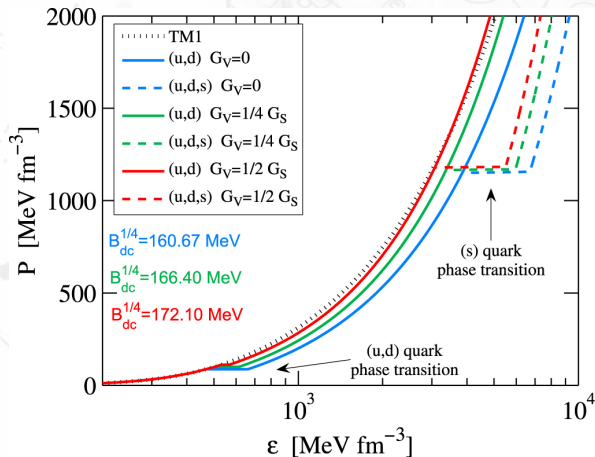
$$M \sim 0.77^{+0.20}_{-0.17} M_\odot, R \sim 10.4^{+0.86}_{-0.78} \text{ km.}$$

HESS J1731-347: Cooling Curves



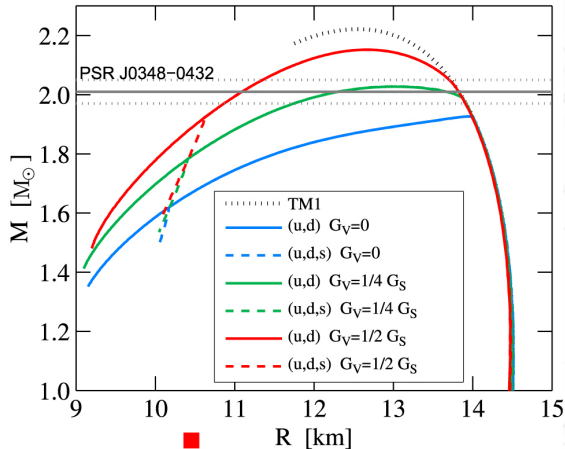
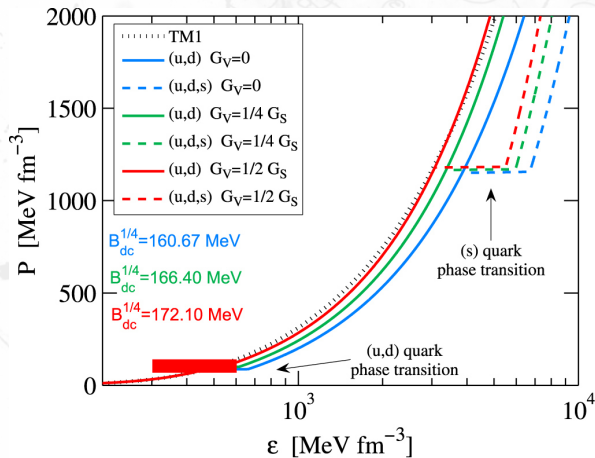
Left and right panels: **cooling curves** (surface temperature versus age) for neutron stars (NSs) and hybrid stars (HSs). A **hybrid star** has a quark-matter core surrounded by a hadronic envelope.

Equation of State Constraints (I)



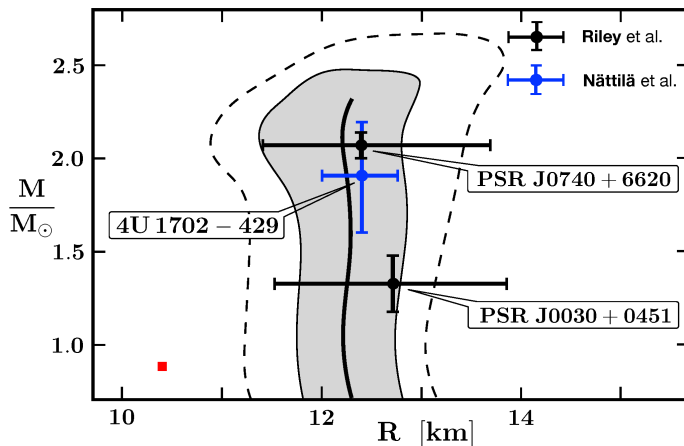
Energy density $\epsilon = 200\text{--}600$ MeV/fm³ and pressure $P = 60\text{--}80$ MeV/fm³
(1 fm = 10⁻¹³ cm).

Equation of State Constraints (II)



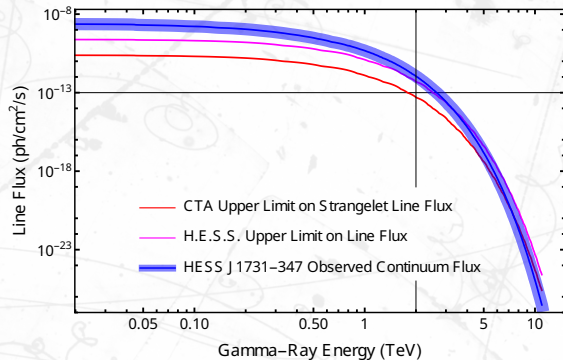
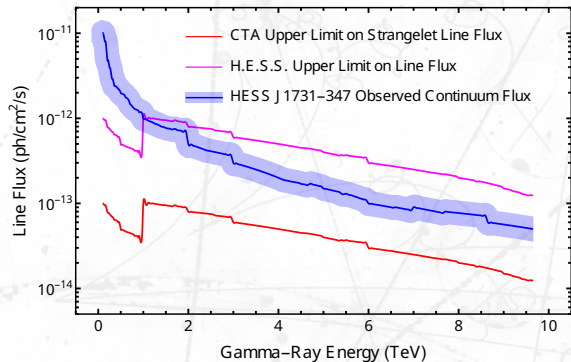
Energy density $\epsilon = 200\text{--}600$ MeV/fm³ and pressure $P = 60\text{--}80$ MeV/fm³
 (1 fm = 10⁻¹³ cm).

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.

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. A **Monte Carlo simulation** means a stochastic generation of pseudo-datasets used to calibrate sensitivity.

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:

$$F_s < \frac{F_{\gamma}^{\text{line}}}{n_H \cdot \sigma_s} \approx \frac{10^{-13}}{100 \cdot 4 \times 10^{-26}} \approx 2.5 \times 10^{-11} \text{ ph/cm}^2/\text{s/sr}.$$

Here F_s is the strangelet-flux upper limit, F_{γ}^{line} the γ -ray line flux, n_H the average **column density** of hydrogen (cm⁻³), σ_s the strangelet–nucleon cross-section (cm²), and **sr** the steradian.

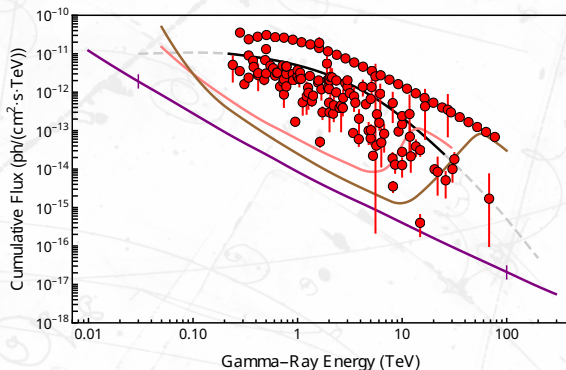
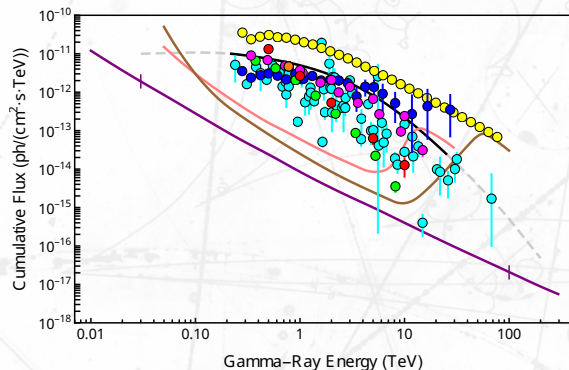
Limits from HESS J1731-347

- 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 $< 10^{-17} M_{\odot}$; production rate $< 10^{-12}$ s⁻¹.

C.R. Das, *arXiv:2507.12817*

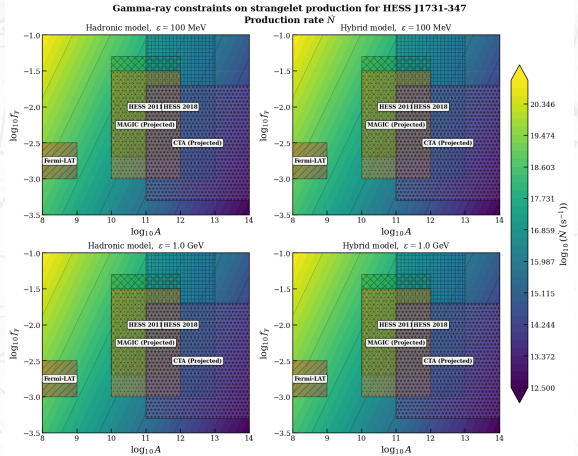
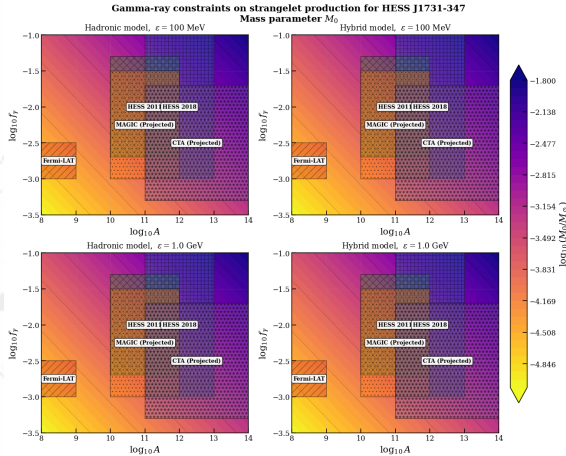
C.R. Das, Phys. Atom. Nuclei **88**, 1142-1148 (2025)

Real-Data Analysis for HESS J1731-347



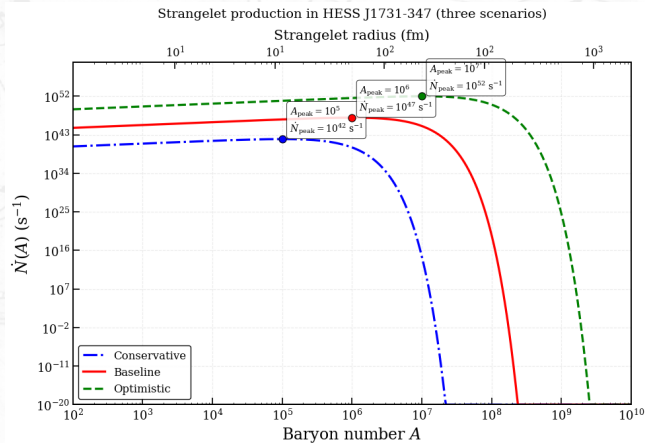
Purple, brown, and pink: CTAO, H.E.S.S., MAGIC photon line-flux sensitivity upper limits. Black and dashed gray: averages of current and anticipated future data.

Real-Data Analysis: Further Panels



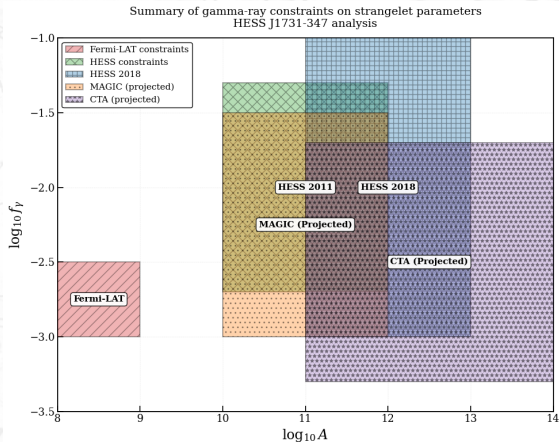
Left: the horizontal axis is $\log_{10} A$ and the vertical axis is $\log_{10} f_\gamma$, where f_γ is the fraction of strangelet interactions that produce γ rays. The colour scale shows $\log_{10}(M_0/M_\odot)$, where M_0 is the fraction of the source mass converted into SQM. Coloured boxes show 95% 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, where ϵ is the average energy per baryon available for non-thermal emission. **Right:** same as Left, but the colour scale shows $\log_{10}(\dot{N} \text{ (s}^{-1}\text{)})$, the astrophysical production rate.

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



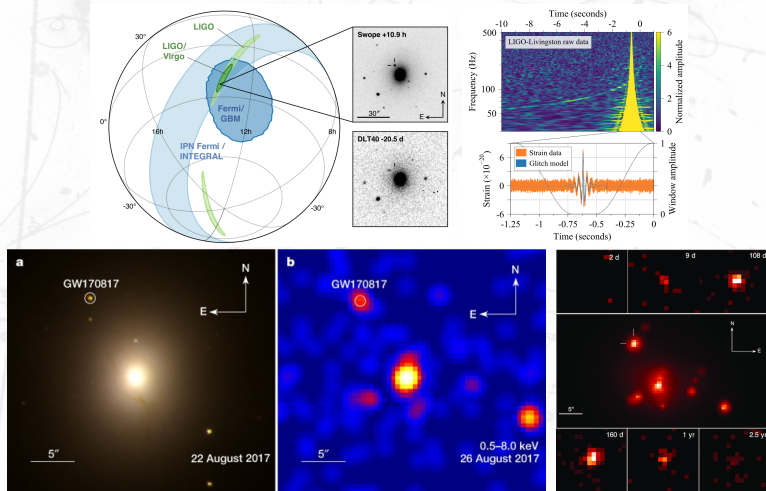
Constrained regions from Fermi-LAT, H.E.S.S. (2011, 2018), and projected CTA/MAGIC-II sensitivities in the $\log_{10} A$ vs. $\log_{10} f_\gamma$ plane, where f_γ is the γ -ray production efficiency.

HESS J1731-347: Continuous vs. Burst Scenarios

Table: Continuous injection vs. burst scenarios. n_s is the strangelet number density.

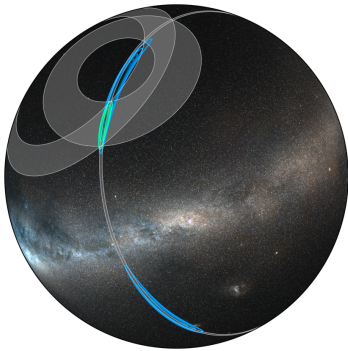
Scenario	Duration	n_s (cm^{-3})	Cumulative flux > 1 TeV ($\text{ph cm}^{-2} \text{s}^{-1}$)
Continuous injection	10^6 yr	10^{-2} – 10^{-1}	9.90×10^{-24}
Burst event	days–weeks each year	1–10	9.90×10^{-22}

Case Study 2: GW170817 — Multimessenger View

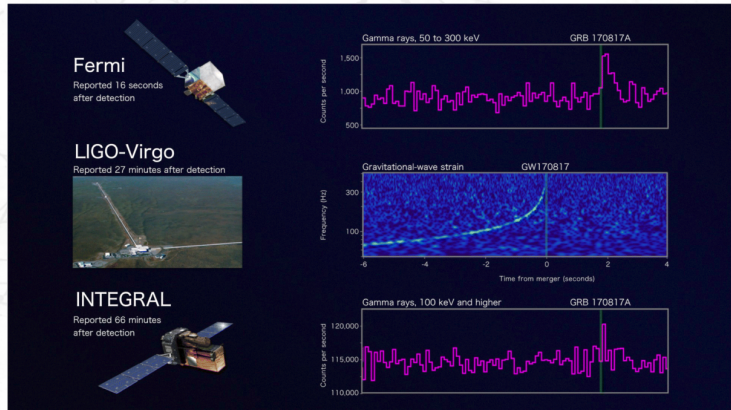


GW170817 is the first detected binary neutron-star merger (2017), at a luminosity distance of ~ 40 Mpc (with $1 \text{ Mpc} = 3.086 \times 10^{24} \text{ cm}$).

GW170817 — GW from Merging Neutron Stars

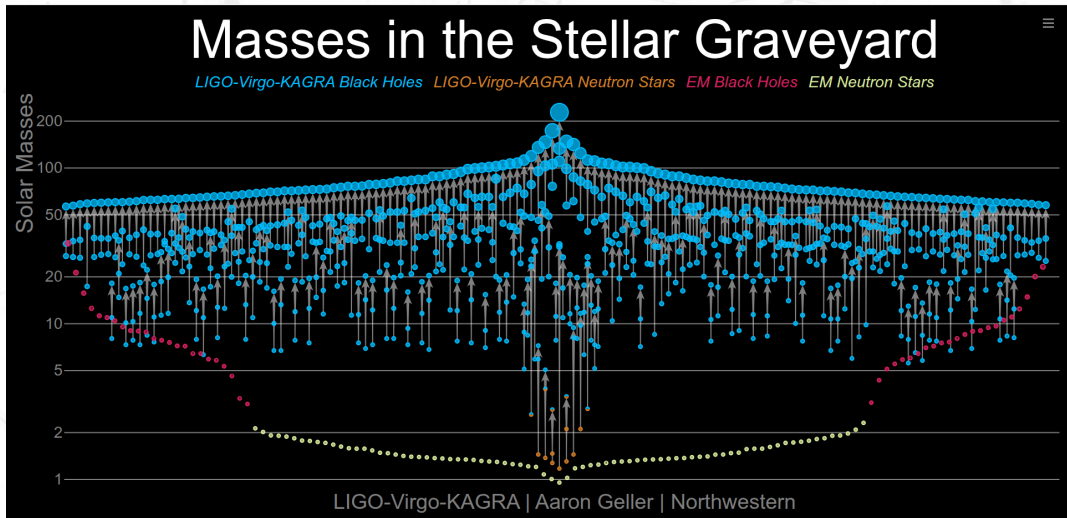


Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)



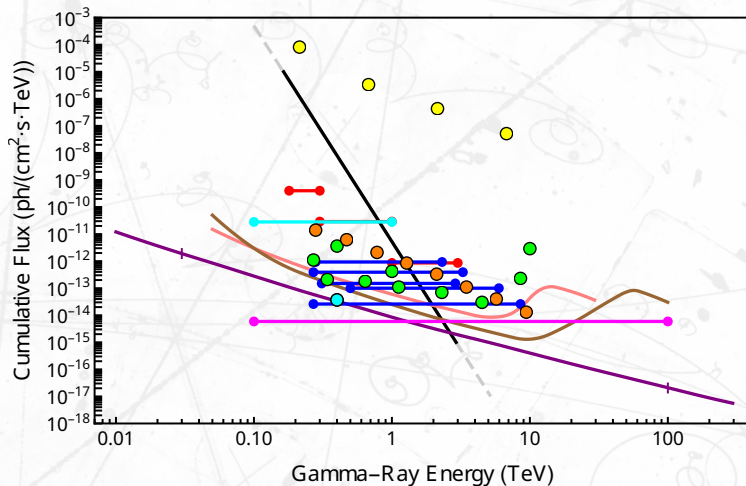
INTEGRAL search for GW counterparts and the GRB170817A/GW170817 detection.

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



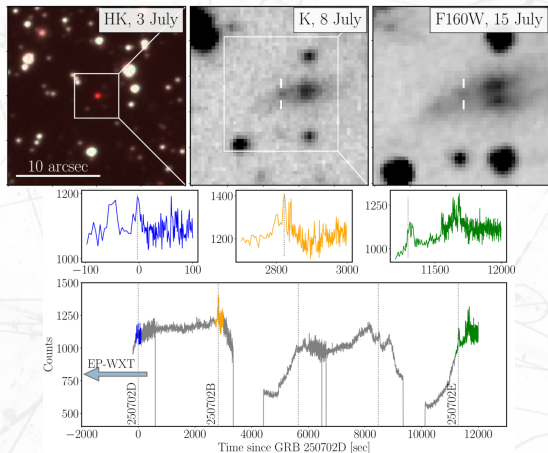
Purple/brown/pink: CTAO, H.E.S.S., MAGIC photon line-flux sensitivity upper limits.
Black/dashed gray: averages of current and anticipated future data.

GW170817: Continuous vs. Burst Scenarios

Table: Continuous vs. burst scenarios for GW170817.

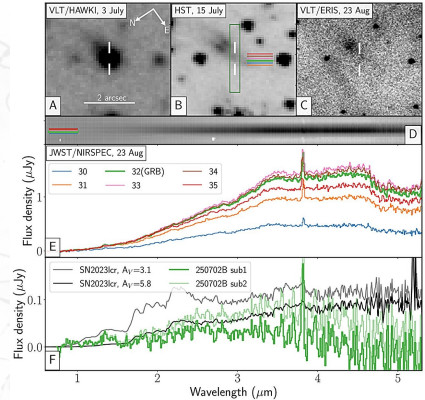
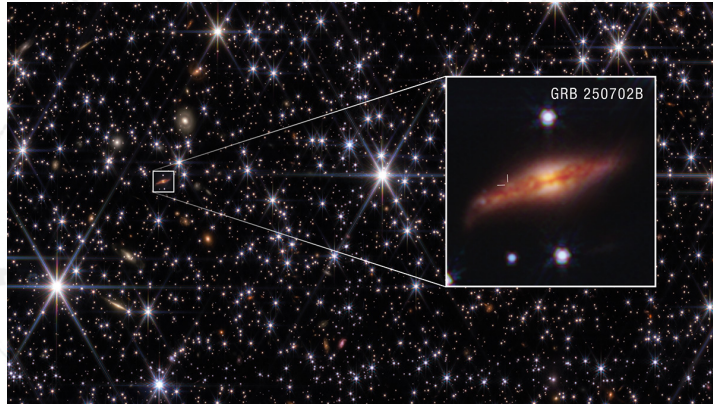
Scenario	Duration	n_s (cm $^{-3}$)	Cumulative flux > 1 TeV (ph cm $^{-2}$ s $^{-1}$)
Continuous injection	10 6 yr	10 $^{-20}$ –10 $^{-16}$	6.97 $\times$ 10 $^{-26}$
Burst event	few minutes to one day	10 $^{-14}$ –10 $^{-8}$	6.97 $\times$ 10 $^{-24}$

Case Study 3: GRB 250702B



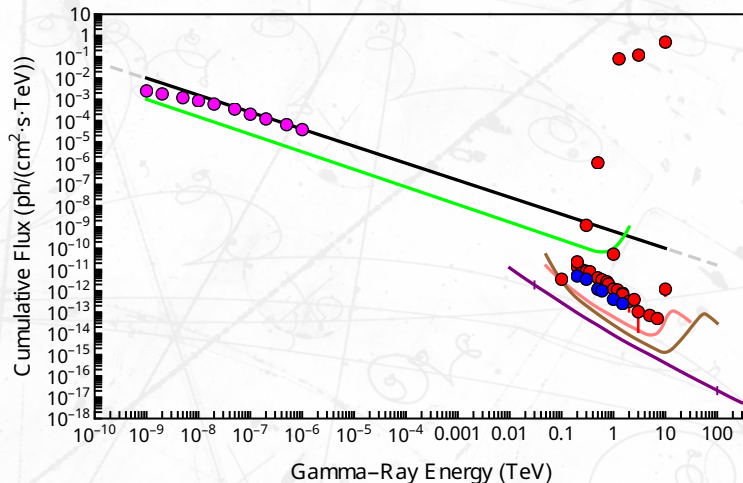
GRB 250702B is an ultra-long gamma-ray burst detected in July 2025, with duration exceeding 25 000 s and isotropic-equivalent energy $E_{\text{iso}} > 1.4 \times 10^{54}$ erg, where E_{iso} is the energy that would be released if the emission were isotropic (1 erg = 10^{-7} J).

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: Burst Scenario

Table: Burst scenario for GRB 250702B.

Scenario	Duration	n_s (cm ⁻³)	Cumulative flux > 1 TeV (ph cm ⁻² s ⁻¹)
Burst event	few minutes to one day	10^{-15} – 10^{-12}	1.1×10^{-13} to 1.1×10^{-11}

Direct Searches for Macroscopic SQM

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

While microscopic strangelets and solitonic dark-matter candidates produced in mergers or colour-superconducting transitions are unlikely to remain stable over interstellar distances, **macro-scale objects** such as **nuclearites** (nuggets of SQM surrounded by an electron shell, with 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 (units: energy/length).
- 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.

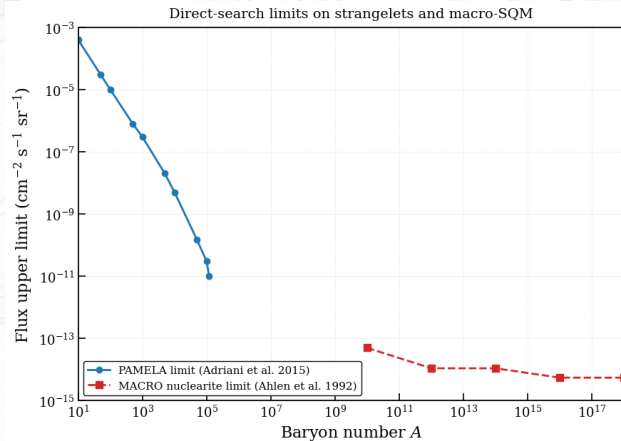
Experimental Constraints and Future Prospects

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, Ice-Cube	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 , digitised from Adriani et al. (2015). Red squares: MACRO nuclearite flux limit from Ahlen et al. (1992).

Key Results: Summary

Table: Consolidated constraints and forecasts for the three sources.

Source	Present limit ($\text{ph cm}^{-2} \text{s}^{-1}$)	flux CTA forecast ($\text{ph cm}^{-2} \text{s}^{-1}$)	n_5 limit (cm^{-3})	Status
HESS J1731-347	$\sim 10^{-12}$	$\sim 10^{-13}$	$< 3 \times 10^{-22}$	Not detected; conservative case ruled out.
GW170817	$\sim 10^{-12}$	$\sim 10^{-13}$	(burst) 10^{-14} – 10^{-8}	No prompt VHE emission; off-axis geometry.
GRB 250702B	10^{-13} – 10^{-11}	$\sim 10^{-13}$	10^{-15} – 10^{-12}	Burst limits being derived.

The Baseline scenario for HESS J1731-347 lies at the CTA sensitivity threshold.

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.

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

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- 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

